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DUNNAGE-GANDER RELATIONSHIPS AND ORDOVICIAN OROGENY IN CENTRAL NEWFOUNDLAND: A SEDIMENT PROVENANCE AND U/Pb AGE STUDY

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ABSTRACT. The Dunnage Zone is interpreted as the remains of the Early Paleozoic Iapetus Ocean, and the Gander Zone as a continentally-derived sedimentary wedge at its eastern margin. Part of the Dunnage Zone, the Exploits Subzone, is considered to be allochthonous on the Gander Zone. Sedimentary provenance and geochronological studies in central Newfoundland have been undertaken to determine the history of interaction between the Exploits Subzone and the Gander Zone.

Llanvirn-Llandeilo limestone conglomerate, previously included in the Gander Zone clastic succession of the Mount Cormack window, contains detritus from both ophiolitic rocks of the Exploits Subzone and previously deformed Gander Zone sedimentary rocks. It indicates emergence and erosion of ophiolite and the Gander Zone in the Llanvirn.

Ophiolite emplacement is constrained to the late Arenig by a zircon age (474 + 6/−3 Ma) on the Partridgeberry Hills Granite, which intrudes ophiolite and the Gander Zone, and by previously reported fossils and regional relationships. A zircon age (468 ± 2 Ma) on the Twillick Brook Member of the Baie d'Espoir Group indicates post-emplacement volcanism and marine sedimentation during the early Llanvirn; this unit has an age similar to the late Arenig-early Llanvirn rocks that postdate ophiolite emplacement in northeast Newfoundland and overlap onto the Gander Zone. Monazite ages (465 ± 2 Ma) of Gander Zone migmatite and tonalite record a Llanvirn tectonothermal event, accompanied by intrusion of the Through Hill and the Great Burnt Lake granites (zircon ages of 464 + 4/−3 Ma and 464 ± 2 Ma, respectively). Metamorphism and plutonism principally affected Gander Zone rocks but was synchronous with volcanism in the overlying Exploits Subzone and with the emergence and erosion implied by the Llanvirn-Llandeilo limestone conglomerate. It is inferred that Middle Ordovician to Early Silurian limestones, black shales, and turbidites are largely unconformable on older parts of the Exploits Subzone and that they and late Arenig-early Llanvirn sequences were deposited on a composite crust of continental basement and allochthonous oceanic rocks.

Exploits-Gander relationships in Newfoundland have parallels in New Brunswick and Maine. Although late Arenig ophiolite emplacement is restricted to Newfoundland, its effects resemble those of the Penobscot Orogeny in Maine, and this name is adopted for the event. The Penobscot and Taconian orogenies involved late Arenig ophiolite emplacement onto opposing continental margins of the Iapetus Ocean, but they did not cause final ocean closure. Evidence for subsequent continental separation is provided by ophiolites of the Fournier Com-

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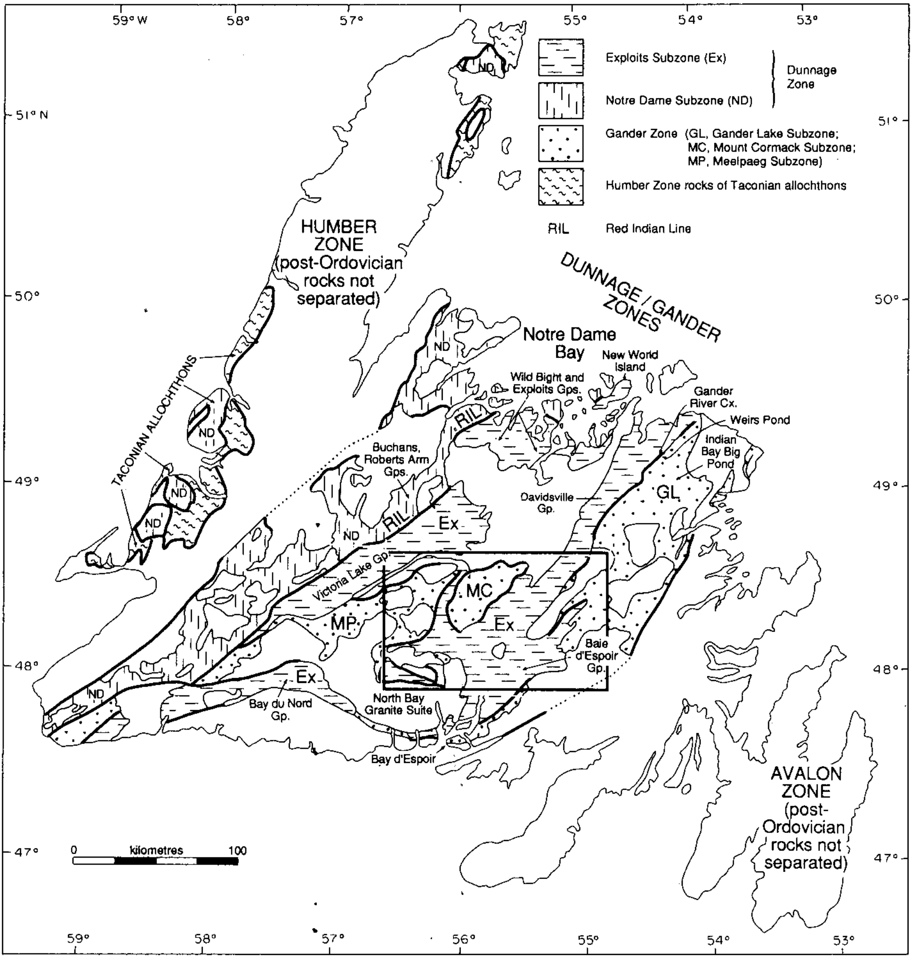

Fig. 1. Distribution and subdivision of the Dunnage and Gander zones in Newfoundland, simplified from Colman-Sadd, Hayes, and Knight (1990). The rectangle shows the location of figure 2, and heavy lines indicate major faults.

plex in New Brunswick, which are younger than and unrelated to those involved in the late Arenig orogenies, and by faunal provinciality, which continued until the late Llanvirn.

INTRODUCTION

For nearly twenty-five years, the Newfoundland Appalachians have been regarded as the relic of a continental collision, which preserved both sides of the Early Paleozoic Iapetus Ocean, as well as rocks that underlay the ocean itself (Williams, 1964; Wilson, 1966; Dewey and Bird, 1970; Stockmal and others, 1987). The two continents that are thought to have

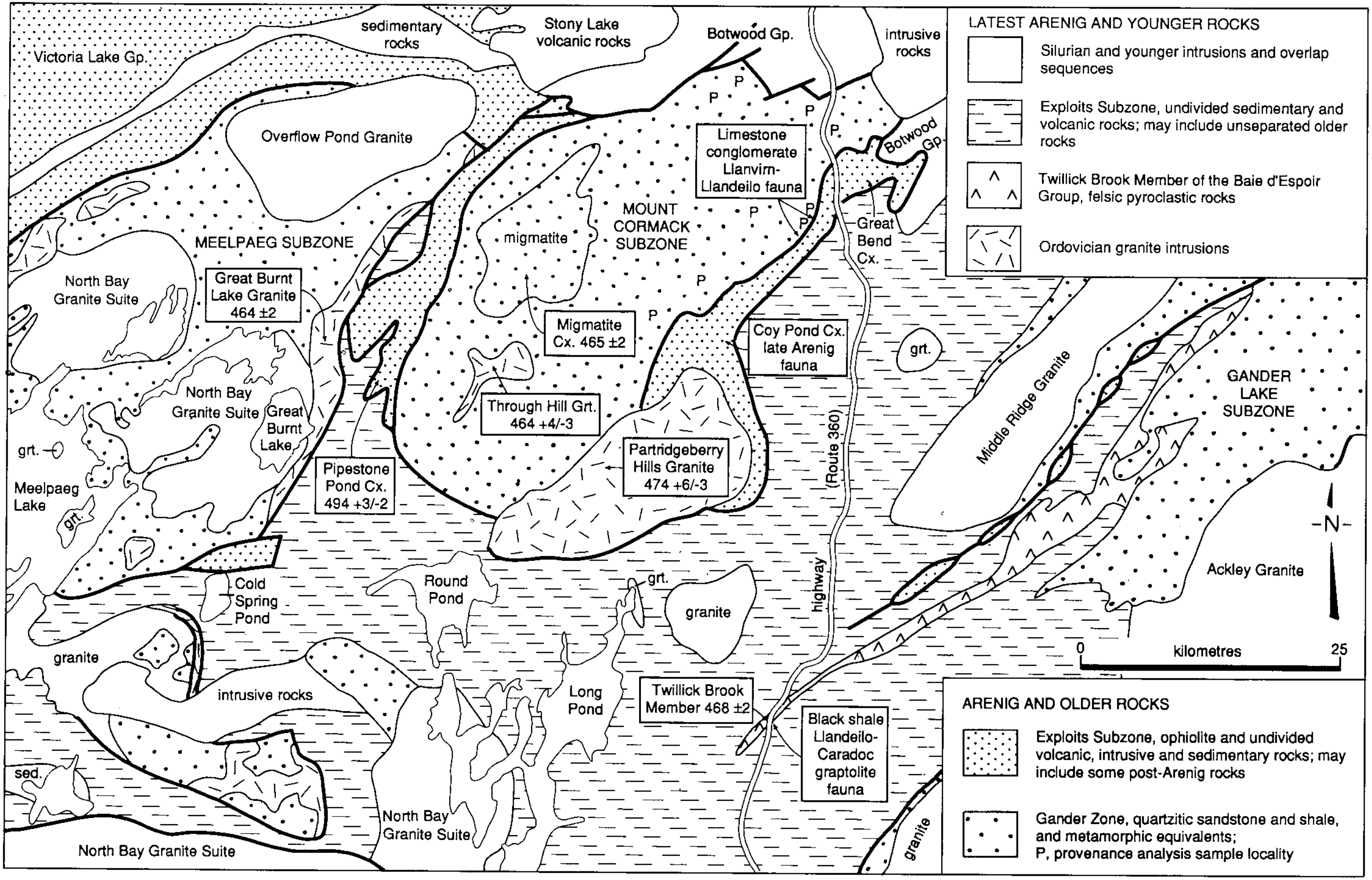

Fig. 2. Geological map of the Mount Cormack Subzone and adjacent areas (simplified from Colman-Sadd, Hayes, and Knight, 1990), showing units and sample localities. Sources for fossil determinations and the age of the Pipestone Pond Complex are referenced in the text. Heavy lines indicate major faults.

collided are Laurentia in the west, represented by the Humber Zone (fig. 1) and its Grenvillian basement, which is contiguous with the Canadian Shield, and Gondwana in the east, represented by the Avalon Zone, which has a Proterozoic and Early Paleozoic history comparable to the Pan-African belts of the present African continent (O'Brien, Wardle, and King, 1983). Between these are the Dunnage Zone, formed mainly of Early Paleozoic island arc and back-arc basin rocks, and the Gander Zone, in which a monotonous sedimentary succession is characterized by quartz-rich sandstones of apparent continental provenance.

The relationship between the Dunnage and Gander zones is of key importance in understanding the development of the Newfoundland Appalachians, because, like the boundary between the Dunnage and Humber zones, it represents the interface between oceanic and continental realms. The distinction between the two zones was first made in the Gander area by Williams, Kennedy, and Neale (1972) on the basis of work by Kennedy and McGonigal (1972). Mapping in central Newfoundland during the past decade has demonstrated a complex outcrop pattern, in which isolated portions of the Gander Zone are surrounded by Dunnage Zone rocks. This led Colman-Sadd and Swinden (1982, 1984a) to propose that the Dunnage Zone is allochthonous on the Gander Zone and that the latter is exposed as tectonic windows; the hypothesis complemented the conclusions of Karlstrom (1983) based on the reinterpretation of published gravity data.

The proposal of Colman-Sadd and Swinden (1982, 1984a) was founded on geological mapping in the Mount Cormack area of central Newfoundland, where an almost continuous belt of ophiolite surrounds an elliptical area of Gander Zone rocks, the Mount Cormack window (fig. 2). Except within very broad constraints, the time of emplacement of Dunnage on Gander remained unknown. This paper reports work aimed at establishing the history of Dunnage-Gander interaction, using provenance analysis of sediments from a key fossil locality (Dec) and U/Pb radiometric dating of critical units (Dunning). Efforts to date units paleontologically have also met with success and are reported elsewhere (Williams and others, 1991).

EXISTING AGE CONSTRAINTS ON DUNNAGE-GANDER INTERACTION

Williams, Colman-Sadd, and Swinden (1988) divided the Dunnage Zone into the Notre Dame and Exploits subzones on the basis of contrasting stratigraphies and excluded from it overlap sequences of Silurian subaerial and shallow marine deposits. The Notre Dame Subzone lies northwest of a fundamental structure, Red Indian Line, and is not in contact with the Gander Zone at the present erosion level, except possibly along a steep fault in southwest Newfoundland (Colman-Sadd, Hayes, and Knight, 1990). Tectonic windows of Gander Zone occur exclusively within the Exploits Subzone, and studies of faunal provinciality suggest that amalgamation of the Exploits Subzone and the Gander Zone preceded linkage of the two halves of the Dunnage Zone (Neuman, 1984). The geology of the Notre Dame Subzone is, therefore, not directly relevant to the problem of Dunnage-Gander interaction.

Stratigraphic contrasts are used to distinguish the Gander Zone from the Exploits Subzone (Williams, Colman-Sadd, and Swinden, 1988), so linkage is younger than the sequences that display these contrasts. On the other hand, it is older than overlap sequences, detritus shed from one terrane to the other, and common plutonic, metamorphic, and structural events (Coney, Jones, and Monger, 1980).

Age constraints in the Gander Zone.—The Gander Zone is divided into the Gander Lake, Mount Cormack, and Meelpaeg subzones or windows (Williams, Colman-Sadd, and Swinden, 1988) (figs. 1 and 2), which are separated from each other at the surface by rocks of the Exploits Subzone. Each part of the Gander Zone is dominated by similar monotonous sequences of interbedded quartzite, psammite, and pelite.

In the Gander Lake Subzone, sedimentary rocks are assigned to the Gander Group (McGonigal, ms), which is subdivided into the conformable Jonathans Pond and Indian Bay Big Pond formations (O'Neill and Knight, 1988; O'Neill and Blackwood, 1989). The latter is considered to be stratigraphically higher, so late Arenig-early Llanvirn brachiopods and trilobites in associated loose blocks (Wonderley and Neuman, 1984; Boyce and others, 1988) provide a younger age limit for the Jonathans Pond Formation. The Indian Bay Big Pond Formation has some features (for example, pillow lavas) normally associated with the Exploits Subzone, and it is not truly representative of the distinct Gander Zone lithofacies. A probable maximum age for the Gander Group is 569 Ma, the age of the youngest detrital zircon in the Jonathans Pond Formation (T. Krogh, personal communication, 1987; O'Neill, 1991).

The Spruce Brook Formation in the Mount Cormack window is lithologically similar to the Jonathans Pond Formation. It was previously thought to be Middle Ordovician on the basis of fossils in limestone conglomerate within its outcrop area (Colman-Sadd and Swinden, 1984a; Boyce, 1987). However, the critical contacts are unexposed, and provenance studies described below indicate that the conglomerate is younger than the Spruce Brook Formation and is not conformable with it. The formation is therefore older than the Llanvirn-Llandeilo age of the conglomerate but is otherwise undated. The comparable sedimentary succession in the Meelpaeg window has provided no age information.

Age constraints in the Exploits Subzone.—The Exploits Subzone (figs. 1 and 2) is much more varied than the Gander Zone, reflecting a more dynamic depositional history, much of it in an active oceanic environment. Age control is good by comparison with the Gander Zone but still not sufficient to give a clear understanding of the subzone's complex history. There is a broad lithostratigraphic division into a Cambrian to mid-Ordovician (Llandeilo) volcano-sedimentary succession, overlain by mid-Ordovician to Early Silurian shale-turbidite deposits.

The oldest rocks in the volcano-sedimentary succession belong to the bimodal Tally Pond (513 ± 2 Ma) and Tulks Hill ($498 + 6/-4$ Ma) volcanic belts (Evans, Kean, and Dunning, 1990; Dunning and others, 1991), which are parts of the Victoria Lake Group. Swinden, Kean, and Dunning (1988) have suggested that the Tulks Hill belt may represent an island arc that was rifted during generation of the ophiolite complexes surrounding the Mount Cormack window to the east. The ophiolites (fig. 2) record the transition from an island-arc to back-arc environment (Swinden, 1988; Jenner and Swinden, 1989) during an extended time interval in the Early Ordovician. Trondhjemite of the Pipestone Pond Complex has yielded a U/Pb age of 494 + 3/−2 Ma (Tremadoc) (Dunning and Krogh, 1985), and sedimentary rocks, interpreted to be conformable on pillow lava of the Coy Pond Complex and defined as a part of the complex (Colman-Sadd, 1985a), contain late Arenig graptolites and trilobites (Williams and others, 1991).

Ophiolite of the Gander River Complex (undated), which marks the Exploits-Gander boundary in the northeast, is in faulted contact with basal units of the Davidsville Group. The latter contain ophiolitic detritus (Blackwood, 1982; O'Neill, 1991) and a late Arenig-early Llanvirn brachiopod and trilobite fauna (McKerrow and Cocks, 1977; Boyce and others, 1988) similar to that in the Indian Bay Big Pond Formation. The detritus indicates the earliest erosion of the ophiolites and suggests that the Davidsville fauna is younger than that at the top of the Coy Pond Complex, even though the two are not resolvable paleontologically. The Gander River Complex is unconformably overlain by Llanvirn-Llandeilo limestone (Blackwood, 1978; Stouge, 1980a), which is comparable in age to a number of limestone localities in central Newfoundland, including the limestone conglomerate in the Mount Cormack window.

In the northeast part of the Exploits Subzone, in Notre Dame Bay, the volcano-sedimentary Summerford Group includes fossiliferous units ranging from Tremadoc to Llandeilo (Kay, 1967; Neuman, 1976; Elliott, Barnes, and Williams, 1989). The neighboring Exploits and Wild Bight groups, however, have not yielded significant faunas and are generally thought to be Llanvirn-Llandeilo (for example, Swinden, ms) because of their assumed conformity with overlying Llandeilo shale. Volcanic rocks of the Wild Bight Group show a geochemical transition from an island arc to back-arc environment, comparable to that seen in the Pipestone Pond Complex (Swinden and others, 1990).

Two other volcanic units in the Exploits Subzone have been dated. Rhyolite porphyry, in a part of the Victoria Lake Group distinct from the Tulks Hill and Tally Pond belts, has yielded a U/Pb date of 462 + 4/−2 Ma (Dunning and others, 1987), consistent with the Llanvirn-Llandeilo age of a nearby conodont locality (Kean and Jayasinghe, 1982). In the Bay du Nord Group of the Hermitage Flexure, felsic tuff has yielded a similar U/Pb age of 466 ± 3 Ma (Llanvirn; Dunning and others, 1990), falling within the Arenig-Caradoc range of fossils in the nearby Baie d'Espoir Group (Dunlop, ms; Colman-Sadd, 1976).

The younger half of the Exploits Subzone succession is dated paleontologically and consists of Llandeilo to Ashgill black shale, gradationally overlain by turbiditic sandstone, conglomerate, and mélange, ranging in age from Caradoc to late Llandovery (Dean, 1978; Arnott, McKerrow, and Cocks, 1985; Williams, 1989). Except for a few thin tuff beds, these rocks have no volcanic component and are interpreted as deposits of residual marine basins (Arnott, McKerrow, and Cocks, 1985). Although the best documented sections are in the Notre Dame Bay area, rocks of equivalent age have been identified in central Newfoundland, overlying the Victoria Lake Group (Kean and Jayasinghe, 1982), and in southern Newfoundland, where they are included in the Baie d'Espoir Group (Williams, 1991a,b).

Age constraints on Silurian overlap sequences.—The part of the Silurian overlap sequence (Williams, Colman-Sadd, and Swinden, 1988) that overlies the Exploits Subzone has yielded Llandovery to Ludlow fossils from the Botwood Group (Williams, 1972) and a U/Pb age of 423 + 3/−2 Ma from rhyolite at Stony Lake (Dunning and others, 1990) (fig. 2). The sequence is both conformable and unconformable on rocks of the Exploits Subzone (Eastler, 1969; Kean and Jayasinghe, 1980) but is only in contact with the Gander Zone in one place, where ophiolitic melange marks a fault between the Botwood Group and the northern margin of the Mount Cormack window (Colman-Sadd, 1989). Since there is no known stratigraphic overlap across the Exploits-Gander boundary, the overlap sequence is of little value in constraining the age of the boundary.

Age constraints on cross-cutting plutons.—Four radiometrically dated plutons intrude both the Exploits Subzone and the Gander Zone (fig. 2). The oldest of these, the Middle Ridge Granite, has yielded a U/Pb age of 410 ± 2 Ma (R. D. Tucker, personal communication, 1990). The relevance of this age to the problem is compromised by the composite nature of the Middle Ridge Granite and the very poor exposure along the contacts (Blackwood, 1983). The Ackley Granite cuts the same zone boundary and has yielded a large number of Ar/Ar and Rb/Sr mid-Devonian to earliest Carboniferous ages (Dallmeyer and others, 1983; Kontak and others, 1988).

The boundary between the Exploits Subzone and the Meelpaeg window is cut by the Overflow Pond Granite (Kean and Jayasinghe, 1980). Both U/Pb and Ar/Ar ages for this granite group around 390 Ma (Dallmeyer and others, 1983). Various plutons of the North Bay Granite Suite (Dickson, 1991) also intrude the Exploits-Meelpaeg boundary, and one phase of the suite has been dated at 396 + 6/−3 Ma (Dunning and others, 1990); however, it is uncertain whether this particular phase has a cross-cutting relationship.

Age constraints on common metamorphic and structural events.—Dated metamorphic events in two parts of the Gander Zone provide time constraints on linkage with the Exploits Subzone. At Bay d'Espoir, Dunning and others (1990) determined U/Pb ages of 423 + 5/−3 Ma on migmatite of the Little Passage gneisses and 421 ± 2 Ma on the Gaultois Granite, which intrudes them. Both units are regarded as synkinematic with major sinistral shear along the boundary between the southwest extension of the Gander Lake Subzone and the Exploits Subzone (Piasecki, 1988) and therefore date this movement.

In the northeastern part of the Gander Lake Subzone, O'Neill (1990) mapped a metamorphic progression from chlorite to andalusite grade that straddles the Exploits-Gander Lake boundary, defined by the Gander River Complex. The metamorphism is probably late Silurian or early Devonian, as indicated by the U/Pb age of the Middle Ridge Granite, just to the south, and by Ar/Ar ages of 398 ± 5 to 378 ± 4 Ma from micas in the Jonathans Pond Formation of the Gander Group to the northeast (O'Neill and Lux, 1989).

EXISTING AGE CONSTRAINTS AND THE PURPOSE OF THIS STUDY

Linkage of the Exploits Subzone and the Gander Zone postdated deposition of the Jonathans Pond Formation and the generation of Exploits Subzone ophiolites. The Jonathans Pond Formation is older than the late Arenig-early Llanvirn fossiliferous rocks of the Indian Bay Big Pond Formation, and the ophiolites have a minimum age of late Arenig, determined from fossils in the uppermost, sedimentary layer of the Coy Pond Complex. Linkage must have predated the 423 + 5/−3 Ma metamorphic peak in the Little Passage gneisses, which coincided with sinistral shear along the zone boundary. Thus, the possible range is from late Arenig (about 470 Ma, Tucker and others, 1990) to 420 Ma or from Early Ordovician to Late Silurian.

The wide uncertainty exists because the data were collected to solve other problems. This study specifically addresses the problem of linkage and concentrates on aspects of the geology that are most likely to define its age:

1. Provenance of fossiliferous Llanvirn-Llandeilo limestone conglomerate within the Mount Cormack window. The clast composition of the conglomerate and the geochemistry of detrital components can be used to establish whether there was linkage between the Exploits Subzone and the Gander Zone at the time of deposition.
2. U/Pb dating of critical units (fig. 2):
   A. The Partridgeberry Hills Granite, which has the map pattern of a stitching pluton, intruded into the Spruce Brook Formation in the Mount Cormack window and the Coy Pond Complex in the Exploits Subzone.
   B. The Twillick Brook Member of the Baie d'Espoir Group, which is a felsic pyroclastic unit occurring principally within the volcano-sedimentary succession of the Exploits Subzone, but also extending into the Gander Zone.
   C. The Through Hill Granite and associated migmatites, which are temporally and spatially related to regional metamorphism in the Mount Cormack window. Isograds show a spatial relationship to the boundaries of the window, implying that metamorphism postdated linkage and was related to the domal structure that has caused the present outcrop pattern.

D. The Great Burnt Lake granite, which is located at the eastern edge of the Meelpaeg window and has been strongly deformed by ductile movements at the Gander-Exploits boundary. The granite does not intrude rocks of the Exploits Subzone and its outcrop is interrupted by an arm of the subzone.

PROVENANCE ANALYSIS

The Gander Zone rocks of the Mount Cormack window are mostly included in the Spruce Brook Formation. The variably metamorphosed quartzites and shales of the formation have previously been regarded as Middle Ordovician on the basis of two limestone conglomerate exposures within their outcrop area; fossils in clasts and matrix of the conglomerate in one locality (L1, Dec and Colman-Sadd, 1990; NTS 2D/12, northing 5374600, easting 608600) were dated as late Arenig to early Caradoc, but most probably Llanvirn, by R. Neuman (Colman-Sadd and Swinden, 1984a), and in a second locality 1.75 km to the southwest (L2; NTS 2D/12, northing 5372900, easting 608100) as late Llanvirn to Llandeilo by Boyce (1987). The conglomerate exposures occur near the tectonic contact between the Spruce Brook Formation and ultramafic rocks of the Coy Pond and Great Bend complexes, both of which are Exploits Subzone ophiolites (fig. 2). The complexes include all the components of typical ophiolites and are in faulted contact to the southeast with volcanic and sedimentary rocks of the Baie d'Espoir Group. The contacts of the limestone conglomerate with the surrounding siliciclastic rocks of the Spruce Brook Formation are not exposed but were interpreted as conformable by Colman-Sadd and Swinden (1984a).

Quartzite from the Spruce Brook Formation and samples of the limestone conglomerate have been examined petrographically to determine when deposition of ophiolitic detritus began in the Mount Cormack area (Dec and Colman-Sadd, 1990). Ophiolitic detritus was found in the limestone at both localities but not in the quartzite, and the major-element composition of detrital chromite has been determined from locality L2 for comparison with chromite in nearby ophiolite complexes.

Quartzite of Spruce Brook Formation

Quartzite samples were collected from the Spruce Brook Formation in the eastern quarter of the Mount Cormack window, where metamorphism is no higher than biotite grade. All samples sites are within 20 km of the two limestone localities, which lie close to the confluence of the Northwest Gander and Little Gull rivers (fig. 2; see Dec and Colman-Sadd, 1990, for precise locations).

The quartzite beds are mostly about 30 cm thick and are well sorted with a grain size of generally less than 2 mm. They are interbedded with pelitic beds, containing thin beds and laminae of sandstone and siltstone. The pelite beds have a well developed penetrative cleavage, generally parallel to bedding and locally overprinted by a crenulation cleavage.

The quartzite has a composition that is most compatible with derivation from continental plutonic and metamorphic rocks (Colman-Sadd and Swinden, 1984a). Angular and subangular, mono- and polycrystalline quartz is abundant and is accompanied by accessory plagioclase, microcline, muscovite, chlorite (after biotite?), zircon, tourmaline, and opaque grains. A few shale and phyllite rock fragments are possible rip-up intraclasts and have a superimposed sericite foliation. There are also ubiquitous aggregates of quartz ± muscovite ± chlorite (after biotite?) ± albite, which probably represent fragments of two-mica schist; they appear to be discordant with the sericite-muscovite foliation of the enclosing rock. Although contacts between the detrital grains are welded, quartz overgrowths are commonly preserved. Secondary sericite, muscovite, and biotite generally define a foliation, and other low-grade metamorphic phases are epidote, granular titanite, apatite, calcite, chlorite, magnetite, and pyrite.

Limestone Conglomerate

About 60 percent of the conglomerate consists of fragments, generally surrounded by a calcarenite matrix. Calcarenite also forms beds in one of the localities that are up to 60 cm thick and interbedded with the conglomerate. The fragments, formed principally of sparry limestone, are subangular to subrounded, up to 15 cm across, and very poorly sorted. Microstylolites and dissolution seams provide the only evidence of deformation. The calcarenite matrix has been produced largely by remolding of fragments during resedimentation and is formed of the same variety of components as the fragments themselves.

Three main fragment-types have been identified in the conglomerate, and these in turn contain smaller detrital phases:

1. Limestone and calcarenite fragments are composed of mainly sparry calcite and dolomite containing chalcedony–calcite–dolomite–pyrite nodules. Grains of euhedral to subrounded chromite and angular to rounded quartz form accessory clasts.

2. Siliciclastic calcarenite fragments consist of poorly sorted sand grains in a sparry carbonate cement. Most of the grains are formed of angular monocrystalline quartz, although some quartz grains are rounded and embayed and appear to be of volcanic origin. Rare polycrystalline quartz has either a polygonal or a foliated and sutured texture. The calcarenite fragments also contain accessory euhedral to subrounded chromite and clasts of intermediate or mafic volcanic rocks, extramicrite, phyllite, and quartzite. The quartzite itself contains accessory detrital plagioclase, muscovite, zircon, and titanite.

3. Bioclastic calcarenite fragments contain abundant organic and non-organic carbonate grains, which together with monocrystalline quartz form 90 percent of the detrital phase. Sorting within the fragments is very good to poor, and most of the constituent grains are very well rounded. Organic detritus includes the blue-green algae, *Girvanella* and *Nuia*, as well as fossils listed by Colman-Sadd and Swinden (1984a) and Boyce

(1987). Some of the monocrystalline quartz grains have deep corrosion embayments, indicative of a volcanic origin, and others have abraded overgrowths which imply recycling from a lithified sedimentary rock. Within the bioclastic calcarenite fragments, there are also clasts of foliated or unfoliated polycrystalline quartz grains, felsic and mafic volcanic rocks, quartz arenite, quartzite, and quartz-muscovite schist. Accessory minerals within the fragments are chromite, zircon, tourmaline, epidote, feldspar (albite), muscovite, biotite, and chlorite. Zircon and tourmaline also occur as accessory minerals within the quartz and quartzite clasts.

Provenance of Limestone Conglomerate

The limestone conglomerate is interpreted to have formed by downslope resedimentation of partially lithified limestones and calcarenites, which were initially deposited in a warm-water, agitated, shallow-marine environment. This setting for the source sediments is indicated by the faunal assemblage (Wray, 1977) and supported by the textures in the calcarenite fragments, such as very good internal sorting and grain roundness.

The main detrital components of the original limestone and calcarenite deposit have the following features:

1. Siliciclastic detritus consists of quartz arenite, quartzite, phyllite, and schist clasts, as well as recycled mono- and poly-crystalline quartz grains. Likely sources are the Spruce Brook Formation or rocks from which the formation was derived. The quartz arenite and quartzite clasts contain quartz grains with in situ overgrowths and detrital titanite, zircon, tourmaline, muscovite, and plagioclase. They strongly resemble rock types of the Spruce Brook Formation but are unlike any clasts observed within it. The recycled quartz grains have overgrowths like those that have grown in situ on quartz grains in the Spruce Brook Formation, but no grains have been observed in the formation itself that had preexisting overgrowths. This detritus is therefore inferred to have been derived from the formation. Other siliciclastic detritus, particularly phyllite and quartz-muscovite schist, is similar to rock types of the Spruce Brook Formation but is not clearly distinguishable from clasts contained within it, so the source is ambiguous.

2. Volcanogenic detritus includes felsic to mafic rock fragments, plagioclase, epidote, and embayed monocrystalline quartz grains. Potential sources are the Coy Pond Complex, which contains both felsic and mafic components, and the Baie d'Espoir Group, in which the volcanic rocks are principally felsic (Colman-Sadd, 1985a).

3. Intrabasinal carbonate detritus consists of fossil debris and nonorganic carbonate grains.

4. Ultramafic detritus is principally represented by chromite grains, whose frequency in the bioclastic calcarenite fragments and in the matrix is 2.1 and 1.5 percent respectively. The overall abundance and angularity of euhedral grains suggest deposition of the primary limestones and calcarenites close to exposed ultramafic rocks. The Great Bend Complex,

within 5 km of the two conglomerate outcrops, is an obvious candidate, and the color range and grain-size distribution of the detrital chromite match chromite in serpentinized peridotite of the complex.

In order to test this potential source, detrital chromite grains were separated for microprobe analysis from a sample of limestone conglomerate (CS-81-012; loc. L2 of Dec and Colman-Sadd, 1990) and compared with chromite grains in peridotites of both the Great Bend and Gander River complexes. The limestone was crushed down to pebble-size fragments and dissolved in 15 percent acetic acid. Angular to subrounded euhedral chromite grains were hand-picked from the wet-sieved, sand-grade residue and mounted in epoxy resin and polished. Fifty-four detrital grains and 83 grains in polished thin sections of peridotite were analyzed using the JEOL SUPERPROBE 733 at Dalhousie University with 53IN8 chromian spinel as a standard. All concentrations were automatically converted to wt percent and corrected for matrix effects following the ZAF procedure.

The detrital chromite grains show no zoning and are characterized by high Cr#'s (Cr# = (Cr × 100)/(Cr + Al)), ranging from 67.07 to 90.86 (avg 79.48), and low TiO_2 content (0-0.27 wt percent, avg 0.06 wt percent) (table 1; fig. 3). The Cr#'s display a bimodal distribution which appears to reflect derivation of the chromite detritus from two sources. Grains with Cr# less than 80 (avg 72.43) match chromite from the Great Bend and Gander River complexes. Those with Cr# greater than 80 (avg 86.03) do not correspond to samples from either of these complexes, but similar analyses have been reported by Malpas and Strong (1975) from the Pipestone Pond Complex. The high Cr#/Mg# ratios (Mg# = (Mg × 100)/(Mg + Fe^{+2})) and low TiO_2 contents of both the detrital and in situ chromite grains are characteristic of arc-related, "Type III" alpine peridotites (Dick and Bullen, 1984; Hébert and Laurent, 1987), consistent with geochemical results from higher levels of the ophiolite suites (Swinden, 1988; Jenner and Swinden, 1989).

Implications for timing of events.—It is concluded from the provenance study that ultramafic rocks were exposed and being eroded during Llanvirn-Llandeilo times at the original site of deposition of the limestone. The available microprobe data indicate that the Great Bend, Pipestone Pond, and Gander River complexes are reasonable sources for the ophiolitic detritus.

Probable detritus from the Spruce Brook Formation in calcarenite fragments of the limestone conglomerate suggests an unconformity between the two units. The presence, within individual fragments, of quartzite, chromite, and diagnostic fossils indicates that the Spruce Brook Formation was in exposed contact with ophiolitic rocks by Llanvirn-Llandeilo time. This conclusion is also implied by the location of the conglomerate within the outcrop area of the Spruce Brook Formation and the observation that the fragments were incompletely lithified before redeposition, indicating the passage of a negligible amount of time between deposition and redeposition. There is no evidence that ophi-

TABLE 1

Representative microprobe analyses of chromite grains from the limestone conglomerate (loc. L2) and the peridotite of the Great Bend and Gander River complexes (wt percent)

Sample Number	Grain Number	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	FeO	MnO	MgO	NiO	Total	Cr#	Mg#
A. Limestone Conglomerate													
CS-81-012	48	0.00	0.00	4.51	66.82	1.70	15.92	0.30	10.83	0.00	100.08	90.86	54.81
CS-81-012	55	0.02	0.00	5.95	64.72	1.76	17.35	0.30	10.08	0.00	100.18	87.95	50.87
CS-81-012	71	0.03	0.07	7.45	59.72	3.64	21.74	0.42	7.36	0.03	100.45	84.32	37.64
CS-81-012	35	0.00	0.03	9.32	59.06	2.03	20.03	0.34	8.46	0.00	99.27	80.96	42.95
CS-81-012	43	0.00	0.11	10.02	54.10	6.40	22.08	0.38	7.43	0.00	100.52	78.36	37.49
CS-81-012	58	0.01	0.00	12.82	54.85	3.65	18.20	0.32	10.16	0.00	100.04	74.16	49.87
CS-81-012	22	0.00	0.02	14.89	52.68	2.21	20.21	0.34	8.90	0.00	99.25	70.36	43.97
CS-81-012	20	0.00	0.03	16.92	51.36	1.63	20.36	0.30	9.16	0.00	99.75	67.07	44.51
B. Great Bend Complex													
CS-81-001	207	0.00	0.10	9.91	57.72	3.12	20.16	0.36	8.60	0.00	99.96	79.62	43.20
CS-81-001	209	0.00	0.00	13.53	53.22	3.87	20.11	0.35	8.95	0.00	99.99	72.52	44.24
CS-81-001	211	0.00	0.02	14.65	51.38	3.99	19.99	0.32	9.05	0.00	99.40	70.17	44.67
CS-81-001	212	0.00	0.01	14.26	52.88	3.46	20.42	0.35	8.89	0.00	100.27	71.33	43.70
CS-82-215	158	0.00	0.08	14.58	52.47	3.68	18.86	0.30	9.94	0.00	99.91	70.71	48.45
CS-82-215	167	0.00	0.07	15.14	51.91	3.39	19.00	0.31	9.84	0.00	99.66	69.70	48.00
CS-82-215	162	0.00	0.06	14.98	51.71	3.81	18.90	0.30	9.88	0.00	99.64	69.84	48.23
CS-82-215	160	0.00	0.04	14.98	51.54	3.10	18.40	0.29	10.15	0.00	99.40	69.77	49.58
CS-82-211	175	0.00	0.12	12.44	54.34	3.76	19.32	0.33	9.37	0.00	99.69	74.56	46.36
CS-82-211	178	0.00	0.10	12.16	54.89	3.67	19.01	0.35	9.53	0.00	99.71	75.18	47.20
CS-82-211	172	0.00	0.11	12.05	54.45	3.79	19.96	0.33	8.90	0.00	99.60	79.19	44.29
CS-82-211	173	0.01	0.09	12.21	53.57	4.31	20.45	0.35	8.55	0.00	99.54	74.64	42.70
C. Gander River Complex													
ON-86-39	128	0.00	0.04	13.65	52.89	3.80	20.27	0.35	8.85	0.00	99.85	72.22	43.77
ON-86-39	138	0.00	0.03	12.92	53.32	4.10	20.59	0.30	8.59	0.00	99.85	73.46	42.65
ON-86-39	132	0.00	0.01	15.39	50.84	4.06	20.11	0.28	9.16	0.00	99.85	68.91	44.81
ON-86-39	125	0.00	0.00	14.33	51.75	4.45	20.29	0.33	8.94	0.00	100.10	70.78	43.99

Notes: $Cr\# = (Cr \times 100)/(Cr + Al)$ $Mg\# = (Mg \times 100)/(Mg + Fe^{+2})$

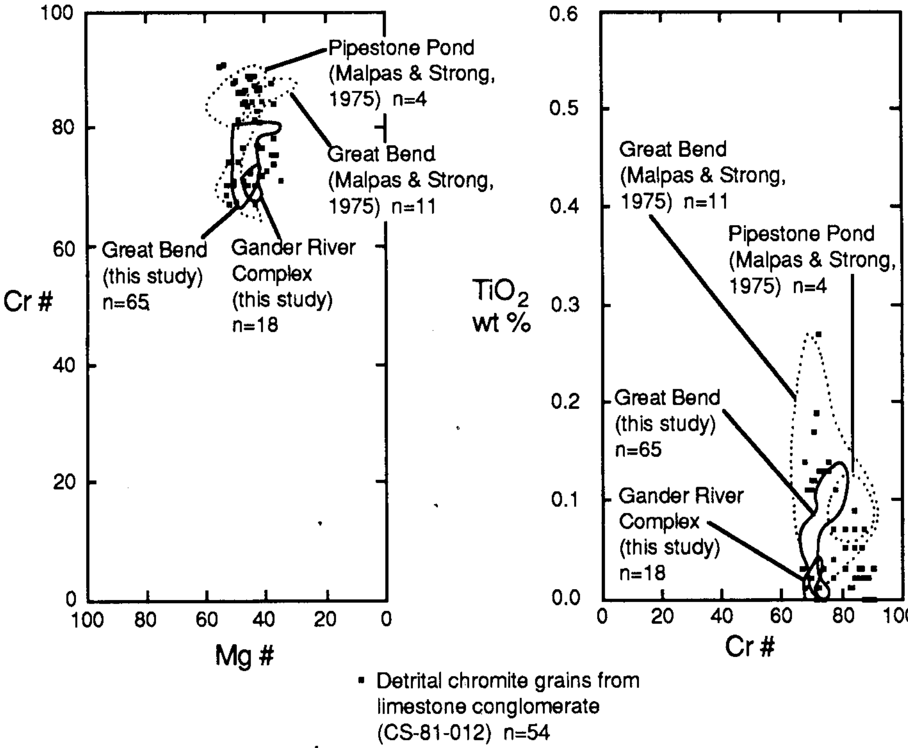

Fig. 3. Major element geochemistry plots of detrital chromite from limestone conglomerate and in situ chromite from the Great Bend, Pipestone Pond, and Gander River complexes. Cr# = (Cr × 100)/(Cr + Al); Mg# = (Mg × 100)/(Mg + Fe^{+2}); n = number of analyzed chromite grains.

olitic rocks were exposed during the earlier deposition of the Spruce Brook Formation.

Foliated clasts, probably derived from the Spruce Brook Formation, suggest deformation of the formation before deposition of the conglomerate, as does the general state of strain in the two units. However, the provenance studies do not prove conclusively the timing of the main deformation and metamorphism in the Spruce Brook Formation, because the origin of those clasts that are clearly metamorphic is ambiguous.

GEOCHRONOLOGY

All six units selected for U/Pb dating yielded suitable zircon or monazite fractions. Mineral separation, dissolution, and analytical techniques are as reported by Dunning and others (1990). Decay constants used are those of Jaffey and others (1971). Two sigma uncertainties reported on the ratios were calculated according to the procedure of Ludwig (1980). Discordia lines were calculated using the procedure of Davis (1982), and uncertainties on the ages are cited at the 95 percent confidence interval.

Sample Descriptions and New U/Pb Age Determinations

Partridgeberry Hills Granite.—The granite includes biotite and biotite-muscovite phases (Colman-Sadd and Swinden, 1982), and both have been extensively chloritized. It is deformed, especially along its southern boundary with the Baie d'Espoir Group, where it is locally mylonitic. This contact was previously interpreted as intrusive (Colman-Sadd, 1980a, 1985a), but reexamination has failed to identify definite intrusive relationships, and the widespread shearing suggests that a tectonic break is more likely. The granite is in unexposed contact with the Spruce Brook Formation along its northwest margin. Its northeast and southwest ends cut across ophiolites of the Coy Pond and Pipestone Pond complexes respectively. There is an exposure gap of several meters between the granite and the Coy Pond Complex, but the sinuous nature of the contact suggests that it is intrusive. A sharp, apparently intrusive contact with sheared and brecciated ultramafic rock occurs where the boundary between the Exploits and Mount Cormack subzones is cut by the western end of the granite (Colman-Sadd, 1985a). This ultramafic rock belongs to one of several tectonic slices that occur between the main body of the Pipestone Pond Complex and the granite but are too small to be shown on figure 2. Elias and Strong (1982) reported a Rb/Sr whole-rock isochron (MSWD = 12; errorchron) for the granite of 431 ± 5 Ma but considered it unreliable because its slope is strongly controlled by a single point.

Sample A (CS-85-316) was taken from an exposure of the biotite phase of the granite, just over 1 km south-southwest of the confluence of Spruce Brook and the Northwest Gander River (NTS 2D/5, northing 5352700, easting 590300) (fig. 2). The locality is about 1.5 km southeast of the contact of the granite with the Spruce Brook Formation and about 2 km west of exposures of the biotite-muscovite phase of the granite. The sampled rock is unfoliated, coarse grained, microcline porphyritic, biotite granite in which much of the biotite has been altered to chlorite.

The zircon grains vary from long-prismatic needles to equant euhedral prisms. Three fractions of needles yield $^{207}Pb/^{206}Pb$ ages of 472 to 473 Ma and are free of inherited older zircon. A discordia line (52 percent probability of fit) through these gives an upper intercept age of 474 +6/−3 Ma (fig. 4A). The lower intercept is 63 ± 138 Ma or 0 Ma within uncertainties. One additional fraction of needles and two of equant grains are displaced to the right of this line and contain significant amounts of older zircon. The two abraded fractions of equant grains (5, 6) yield average ages of inheritance, projected from 474 Ma, of 1662 and 1814 Ma respectively.

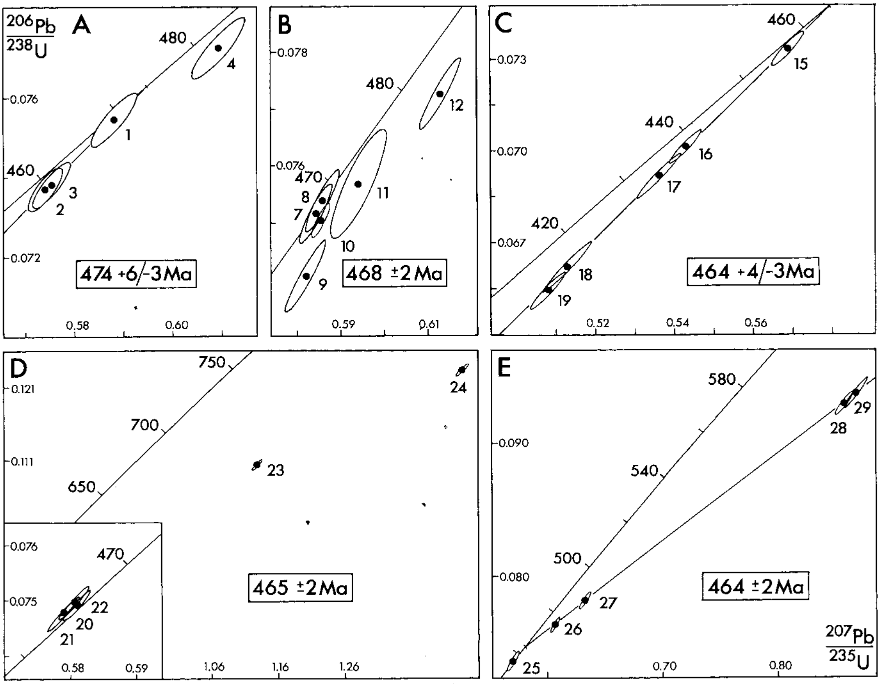

Fig. 4. Concordia diagrams for units dated in this study: (A) Partridgeberry Hills Granite, (B) Twillick Brook Member of the Baie d'Espoir Group, (C) Through Hill Granite, (D) Mount Cormack migmatite and tonalite (inset shows monazite points at enlarged scale), (E) Great Burnt Lake granite.

Twillick Brook Member of the Baie d'Espoir Group.—The Twillick Brook Member is a quartz-plagioclase porphyry exposed along a strike length of almost 70 km. The largest part of it is enclosed in the Baie d'Espoir Group of the Exploits Subzone, but it also borders and extends into the outcrop area of the Gander Group. Near its southwestern extremity, Colman-Sadd (1980a) described the member as a pyroclastic deposit consisting of quartz and plagioclase crystals suspended in a fine grained quartz–feldspar–muscovite matrix; a few semipelitic sedimentary lithic fragments are included, and the unit has a moderate tectonic fabric.

Along its northwest margin, the Twillick Brook Member is in contact with thick bedded sandstone and pelite, volcaniclastic sedimentary rocks, graphitic slate, and conglomerate of the Exploits Subzone. It is fragmental at the contact with the conglomerate and apparently grades into it (Blackwood, 1983). Along most of the southeast margin of the member, there is a unit of black graphitic slate, 0.5 to 1 km wide, which contains graptolites indicative of a Llandeilo or Caradoc age (Williams, 1991a, b). Colman-Sadd (1980a) reported that the member is fragmental near this contact and that nearby graphitic slate contains interbedded crystal tuff. The northeastern end of the Twillick Brook Member has a sinuous, but unexposed, boundary with the Gander Group, and the two were interpreted to be concordant by Blackwood (1983).

Sample B (84GD11) was collected from a roadside quarry on Route 360, near the southwest end of the unit (NTS 2D/4, northing 5325800, easting 606100) (fig. 2). It contains euhedral prismatic to subrounded zircon grains, as well as needle-like grains. Two fractions of abraded needles are concordant and overlap with an age of 468 ± 2 Ma (fig. 4B). Analyses 9 to 14 (table 2) of prisms, prism tips, or fragments all contain inherited zircon. Projected from 468 Ma, analyses 11 and 13 yield average inheritance ages of 1130 and 2185 Ma respectively, demonstrating the heterogeneous nature of the inherited material and the potential presence of an Archean component.

Through Hill Granite.—This pegmatitic muscovite-garnet-tourmaline granite is restricted to the central part of the southern metamorphic culmination in the Mount Cormack window. It has exposed intrusive contacts with the Spruce Brook Formation and crosscuts the main fabric and the sillimanite (+muscovite) isograd. Other smaller bodies of similar granite occur close to the sillimanite (+muscovite) isograd around the more northerly culmination. Colman-Sadd and Swinden (1984a) proposed that the granite was a product of anatexis during metamorphism and that its local discordancy indicated crystallization shortly after the metamorphic peak. Elias and Strong (1982) reported a Rb/Sr whole-rock isochron age (MSWD = 2.7) for the granite of 429 ± 2 Ma.

Sample C (CSG-87-001) was collected from an exposure 1 km northwest of Through Hill (NTS 2D/5, northing 5359900, easting 577900) (fig. 2). The exposure is located in the central part of the granite, 750 m from the nearest contact with the country rock, which consists of sillimanite grade pelite and quartzite of the Spruce Brook Formation. At the sample locality, the rock is an unfoliated, white, pegmatitic, garnet–tourmaline–muscovite granite.

The zircon population is primarily composed of rounded and resorbed grains inherited from the source rocks. A small number (less than 0.5 mg) of fine-grained needles were also separated and were selected for analysis, along with one fraction of tiny brown equant prisms. The very high uranium and low thorium, reflected in the low $^{208}Pb/^{206}Pb$ ratio, is characteristic of zircon grown from hydrous S-type melts and in migmatites. The five abraded fractions are 2.1 to 13.5 percent discordant on a discordia line (18 percent probability of fit) that yields an upper intercept age of crystallization of 464 + 4/−3 Ma (fig. 4C). The lower intercept is 38 ± 40 Ma.

Mount Cormack Migmatite complex.—The migmatitic complex occurs in the center of the northerly metamorphic culmination in the Mount Cormack window. There is a metamorphic progression in the Spruce Brook Formation from chlorite grade rocks through the biotite, andalusite, and sillimanite-muscovite isograds (Colman-Sadd, 1985a). At

TABLE 2

U-Pb data

Fractions			Concentrations		Measured		Atomic Ratios							Age
No.	Properties	Wt. (mg)	U (ppm)	Pb (rad) (ppm)	total common Pb (pg)	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	+/-	$^{207}Pb/^{235}U$	+/-	$^{207}Pb/^{206}Pb$	+/-	$^{207}Pb/^{206}Pb$
A. Partridgeberry Hills Granite														
1	N0 -100 needles Abr	0.093	213.4	16.1	10	8361	0.0998	0.07544	16	0.5881	22	0.05653	6	473
2	N0 -200 clr needles	0.314	344.9	24.6	144	3235	0.0701	0.07371	19	0.5741	19	0.05651	6	472
3	N0 -200 clr needles	0.266	344.2	24.6	80	4722	0.0716	0.07382	24	0.5753	21	0.05652	6	473
4	N0 -200 needles Abr	0.062	288.5	21.8	7	8501	0.0802	0.07724	36	0.6094	27	0.05722	13	500
5	N0 -200 equant Abr	0.185	244.2	23.5	9	14650	0.1031	0.09536	38	0.9051	37	0.06883	9	894
6	N0 -100 equant Abr	0.284	203.8	29.2	13	22216	0.1249	0.13712	39	1.6646	53	0.08804	7	1383
B. Twillick Brook Member														
7	M1 -100 needles Abr	0.097	161.5	12.4	10	7789	0.1248	0.07537	25	0.5861	21	0.05641	8	468
8	M1 -100 needles Abr	0.092	172.9	13.1	8	9910	0.1145	0.07514	24	0.5844	21	0.05641	8	469
9	M1 -100 cracked prisms	0.454	211.4	15.9	30	11568	0.1248	0.07405	30	0.5821	25	0.05701	8	492
10	M1 -100 fragments Abr	0.128	182.1	13.9	10	5808	0.1302	0.07502	13	0.5856	11	0.05661	5	476
11	M1 -70 prism tips Abr	0.024	327.1	24.3	6	5512	0.0866	0.07566	40	0.5943	35	0.05697	18	490
12	M1 -100 prisms Abr	0.246	175.5	13.8	52	3324	0.1229	0.07724	29	0.6131	25	0.05757	8	513
13	M1 -100 prisms Abr	0.259	185.9	13.9	23	6905	------	0.07799	43	0.6439	30	0.05988	20	599
14	M1 -100 equant prisms Abr	0.751	191.1	16.9	96	4234	0.1188	0.08724	31	0.7717	29	0.06415	9	747

TABLE 2

(continued)

C. Through Hill Granite														
15	M10 fine needles Abr	0.004	7539.4	502.4	24	5702	0.0018	0.07328	27	0.5691	22	0.05633	8	465
16	5 clear needles Abr	0.012	6182.7	393.6	97	3386	0.0004	0.07011	26	0.5431	21	0.05619	10	460
17	M10 fine needles Abr	0.076	7655.7	480.9	1574	1619	0.0006	0.06916	36	0.5364	30	0.05624	7	462
18	Equant prisms brn Abr	0.067	11603.2	697.8	1739	1872	0.0008	0.06621	42	0.5129	34	0.05618	7	459
19	M10 needles brn Abr	0.018	6113.1	363.8	372	1229	0.0019	0.06544	28	0.5079	24	0.05629	9	464
D. Mount Cormack Migmatite Complex														
20	M1.0 clr monazite Abr	0.046	4768.2	1063.5	31	32839	2.3861	0.07491	26	0.5811	22	0.05626	5	463
21	M1.0 euhed monazite Abr	0.082	4628.4	1036.9	44	40582	2.4081	0.07476	31	0.5791	25	0.05618	5	460
22	M1.0 clr monazite Abr	0.062	4806.3	1073.3	40	34717	2.3881	0.07496	31	0.5808	26	0.05619	5	460
23	N0 -100 clr euhed Abr	0.118	224.7	26.1	22	8168	0.1509	0.11018	65	1.1289	66	0.07431	13	1050
24	N0 -100 clr euhed Abr	0.132	186.2	24.3	10	18465	0.1471	0.12314	62	1.4363	74	0.08459	11	1306
E. Great Burnt Lake Granite														
25	M1.0 clr monazite Abr	0.089	773.7	971.3	50	6408	18.6083	0.07363	33	0.5693	26	0.05607	10	455
26	M0 -100 euhed Abr	0.168	359.5	27.2	99	2922	0.0928	0.07634	22	0.6062	20	0.05759	7	514
27	M0 -200 euhed needles Abr	0.119	384.9	29.7	13	16859	0.0872	0.07818	28	0.6324	23	0.05866	8	555
28	M0 -100 clr euhed Abr	0.059	284.5	26.2	10	10133	0.0871	0.09295	39	0.8586	37	0.06699	9	837
29	M0 -100 clr euhed Abr	0.113	265.5	25.1	6	16700	0.1038	0.09371	56	0.8688	52	0.06724	10	845

Notes:
1. N0, M0, M10, non-magnetic, magnetic at 0 or 10 degree tilt on Frantz separator; -100, grain size between 100 and 200 mesh. clr=clear, brn=brown, euhed=euhedral, Abr=abraded (Krogh, 1982).
2. Uncertainty in sample weight +/-0.006 mg (2 sigma).
3. Measured 206/204 ratio is corrected for fractionation and common Pb in the spike.
4. Atomic ratios corrected for fractionation and spike, 4-10 pg lab procedure blank (25pg - monazite) initial common Pb (Stacey and Kramers, 1975) and 2 pg U blank.

about the level of the sillimanite-potassium feldspar isograd, the rocks become migmatitic, and the bedding is disrupted. With increasing proportion of melt, the prevalent rock type becomes a finely banded equigranular gneiss, segregated into biotite-rich bands and a quartz-feldspar leucosome that is gradational with concordant and discordant granitoid veins. The gneiss grades into but is also clearly intruded by biotite-muscovite granitoid. Blocks of psammite and quartzite in the gneiss and granitoid are probably refractory remains of sedimentary beds and support derivation of these units by melting of the Spruce Brook Formation.

Samples D1 and D2 (89GD10, 11) were collected from the southwestern part of the migmatite complex (NTS 2D/5, northing 5369900, easting 580000), 9 km north-northeast of Mount Cormack and 6 km from the nearest exposures of non-migmatitic Spruce Brook Formation (fig. 2). Sample 89GD10 is from a melt pod in migmatite, and 89GD11 consists of homogeneous gray, porphyritic, biotite-muscovite tonalite. It contains metasedimentary xenoliths, and, within the exposure, it has intruded migmatitic biotite gneiss and is itself cut by garnet-muscovite granite veins, similar to the Through Hill Granite. Fibrolitic sillimanite is present in both the tonalite and the gneiss.

The melt pod yielded rounded zircon and monazite; one fraction of monazite (table 2; 20) is concordant within uncertainties at 465 ± 2 Ma (fig. 4D), and this is interpreted to be the age of migmatization.

Two fractions of monazite from the tonalite are marginally above concordia with $^{206}Pb/^{238}U$ ages of 465 and 466 Ma and $^{207}Pb/^{235}U$ ages of 464 and 465 Ma respectively. The $^{207}Pb/^{206}Pb$ ages are lower at 460 Ma, but the best estimate of the crystallization age is 465 ± 2 Ma from the Pb/U ages (fig. 4E). These monazites are the same age as and similar in U content and $^{208}Pb/^{206}Pb$ ratio to the monazite in the melt pod, supporting a common metamorphic origin for the melt pods and the tonalite. Two abraded fractions of euhedral zircon in the tonalite contain abundant older inherited zircon and plot far to the right of concordia. Projected from 465 Ma, these analyses (table 2; 23, 24) yield upper intercept average ages of inheritance of 1574 and 1833 Ma.

Great Burnt Lake granite.—The intrusion consists of pink, megacrystic, biotite granite and has a very strong foliation or lineation, which in several places is clearly composite. It extends in a narrow, discontinuous belt along the entire eastern edge of the Meelpaeg window (Colman-Sadd and Swinden, 1984b, 1989; Colman-Sadd and Russell, 1988). Many of the contacts of the granite with the Gander Zone metasedimentary and migmatitic rocks may now be tectonic, but the metasedimentary rocks and the granite appear to have the same deformational history, so the original relationship is likely to have been intrusive (Colman-Sadd, 1985b). The contact of the granite with units in the Exploits Subzone (Baie d'Espoir Group and the Cold Spring Pond Formation) is not exposed. It is interpreted to be faulted because of the sharp increase in deformation across it, the shearing of adjacent rocks, and the presence of small slices of serpentinite (Swinden, 1988). Kinematic indicators related to the sub-horizontal linear structures in the granite indicate dextral movement, and those related to steeply plunging structures in the adjacent Exploits Subzone indicate downthrow on the eastern, Exploits, side (Piasecki, Williams, and Colman-Sadd, 1990).

The granite is interrupted by an arm of the Exploits Subzone at Cold Spring Pond. On the north side of the arm, poor exposure obscures the relationship, but in the south a fault slice of the granite has been deflected to the northwest along the contact and reduced to a thin band of mylonite before being pinched out (Colman-Sadd and Swinden, 1989). The Great Burnt Lake granite is not known to intrude rocks of the Exploits Subzone.

Sample E (88GD01) was taken from an exposure 4.5 km north-northeast of Great Burnt Lake (NTS 12A/8, northing 5361200, easting 561700) (fig. 2). At this locality, the outcrop area reaches its greatest width of about 3 km, and the rock is less intensely deformed than elsewhere. Between the sample site and the eastern contact of the granite is a narrow zone of metasedimentary rock, similar to that found in the main part of the Meelpaeg window, and a presumed fault slice of peridotite (Swinden, 1988). The rock is a coarse grained biotite granite containing abundant megacrysts of pink microcline; the megacrysts form augen within a strong LS fabric defined by biotite and elongated aggregates of polygonized quartz.

Equant euhedral plate-like and needle-like zircon grains occur in the sample, and four abraded fractions define a mixing line (22 percent probability of fit) with a lower intercept age of crystallization of 464 ± 2 Ma (fig. 4F). The upper intercept age of 1533 ± 20 Ma represents the average for the inherited component. A single analysis of monazite is slightly above concordia with $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages of 458 Ma. The monazite may represent igneous crystallization better than the zircon mixing line, or it may have crystallized when the granite was deformed.

Implications for Timing of Events

Partridgeberry Hills Granite.—Since none of the contacts of the granite is unambiguously exposed, there can be no definite conclusions about its relationships. However it is likely that its contact with the Coy Pond Complex, at least, is intrusive, which requires that these rocks are Arenig or older. Such a conclusion is compatible with existing U/Pb and fossil ages (Dunning and Krogh, 1985; Williams and others, 1991).

The Partridgeberry Hills Granite has no exposed contacts with the Spruce Brook Formation so the nature of the relationship is unknown. Two indirect lines of evidence suggest that the contact is intrusive. The granite appears to cut disrupted ophiolitic rocks at its southwest end, which implies prior deformation of the ophiolite, possibly caused by emplacement onto the Gander Zone. Secondly, inherited Precambrian zircon and a strongly negative epsilon-Nd value (B. J. Fryer and others, in press) indicate derivation from a source similar to the Gander Zone rather than in situ oceanic crust; samples from both the Pipestone Pond and Coy Pond complexes have no inheritance. Thus the granite appears to have been intruded after ophiolite emplacement onto the Gander Zone, and this age determination, in combination with the fossils in the Coy Pond Complex, dates emplacement as late Arenig.

The probable tectonic contact of the Partridgeberry Hills Granite with the Baie d'Espoir Group requires only that tectonic activity took place after the late Arenig but places no further constraints on the geological history.

Twillick Brook Member of the Baie d'Espoir Group.—The pyroclastic unit is an integral part of the Baie d'Espoir Group, and its age indicates that at least part of the group is of early Llanvirn age. This is compatible with the late Arenig to early Caradoc uncertainty range of brachiopods from an exposure about 20 km to the south (Neuman, *in* Colman-Sadd, 1976). However, it is somewhat older than Llandeilo or Caradoc graptolites in black shales that occur immediately southeast of the Twillick Brook Member and elsewhere in the Baie d'Espoir Group (Williams, 1991a, b; Williams and others, in press). It is likely, therefore, that there is either a disconformity, condensed sequence, or tectonic contact on the southeast side of the member. Blackwood (1983) showed the Twillick Brook Member extending northeast into the outcrop area of the Gander Group and interpreted the contact as concordant. If the member overlies the Gander Group stratigraphically, the latter must be early Llanvirn or older, which agrees with the relationship at Indian Bay Big Pond (O'Neill, 1991). Whatever the true nature of the contact, inherited Precambrian zircon in the Twillick Brook Member indicates contamination by continental material, implying extrusion through Gander Zone crust.

Through Hill Granite and Mount Cormack Migmatite complex.—Both the granite and the migmatite appear to be partial melts of the Spruce Brook Formation, formed close to the time of peak metamorphism in the Mount Cormack window (Colman-Sadd and Swinden, 1984a). The ages show that this event was Llanvirn and provide upper and lower limits on deformations affecting the rocks before and after peak metamorphism. They agree with the conclusion of the provenance study that the Llanvirn-Llandeilo limestone conglomerate lies unconformably on previously deformed and metamorphosed Spruce Brook Formation.

Inheritance in the zircons of both the Through Hill Granite and the migmatite is attributed to derivation of the melt from the Spruce Brook Formation, which Krogh (1986) has shown to be rich in Proterozoic detrital zircon.

Great Burnt Lake granite.—The age determination shows that dextral shearing along the boundary between the Meelpaeg window and the Exploits Subzone was late Llanvirn or younger. This must also be the age of the tectonic contacts between the window and the arm of the Exploits Subzone that interrupts the outcrop of the Great Burnt Lake granite at Cold Spring Pond.

An ophiolitic mélange at Cold Spring Pond, adjacent to the granite, was interpreted by Williams and Piasecki (1990) as a product of earliest Meelpaeg-Exploits interaction. The mélange is overprinted by structures that also occur in the granite, so the present proximity of the two results from the later shearing. The age determination does not constrain the time of formation of the mélange or the initial emplacement of ophiolite on the Gander Zone, but it does indicate major structural reworking of the original Exploits-Gander contact.

DISCUSSION

Geological Development of East-Central Newfoundland

Arenig and older rocks.—With a few exceptions, Arenig and older rocks of the Gander Zone and the Exploits Subzone show clear contrasts, which reflect development in entirely different tectonic environments. The exceptions, most notably the Partridgeberry Hills Granite and fossiliferous rocks at Gander Lake and Indian Bay Big Pond, are all late Arenig or Arenig-Llanvirn and so are potentially younger than the contrasting sequences, even though the resolution of the age control is insufficient to prove this.

The sedimentary rocks that form the bulk of the Gander Zone have an obvious continental provenance, with quartz-rich sandstones and an old, diverse detrital zircon population (Krogh, 1986). Although the beginning of sedimentation is difficult to define precisely, broad limits indicate deposition occurred between the latest Precambrian and the late Arenig. It is still not known whether the Gander Zone sediments were deposited on a continental basement, but it is certain that they must have been derived by erosion of such a basement.

In contrast, the ophiolite complexes of the Exploits Subzone indicate the formation of Tremadoc and Arenig oceanic crust in an island arc and back-arc environment. Associated sedimentary rocks, derived from ophiolitic rocks, show no obvious continental component, and U/Pb dating shows no inheritance of older material. The fossils contained in shale at the top of the Coy Pond Complex (Williams and others, 1991) indicate that this environment persisted into late Arenig time.

Two other parts of the Exploits Subzone are known to be Arenig or older. Both the Tally Pond (513 ± 2 Ma) and Tulks Hill (498 ± 6/−4 Ma) volcanic belts of the Victoria Lake Group have geochemistry indicative of island arc environments, and the lack of U/Pb inheritance suggests minimal continental influence (Dunning and others, 1991). The oldest dated rocks of the Summerford Group on New World Island are fossiliferous limestone lenses of Tremadoc age, associated with pillow lavas (Kay, 1967). The geochemistry of lavas from elsewhere in New World Island has been characterized as ocean island or MORB (Jacobi and Wasowski, 1985; Reusch, ms), but age control is not precise. Reusch (ms) assigned some to the Arenig and others to the Llandeilo on the basis of nearby fossil localities (Neuman, 1976; Dean, 1971). The fossiliferous late Arenig rocks resemble, both paleontologically and lithologically, those at

Indian Bay Big Pond (Neuman, 1976; Wonderley and Neuman, 1984) and, like the latter, should probably be considered as slightly younger than the contrasting Exploits and Gander sequences, represented by ophiolite complexes and quartzitic sedimentary rocks respectively. The Llandeilo fossils are contained in limestone, similar to the widespread Llanvirn-Llandeilo occurrences in the Exploits Subzone (Bergström, Riva, and Kay, 1974) and the limestone clasts in the conglomerate of the Mount Cormack window.

The Wild Bight Group, interpreted as recording the rifting of an island arc to form a back-arc basin (Swinden, ms; Swinden and others, 1990), formed in an ensimatic environment similar to that found in Arenig and older rocks elsewhere in the Exploits Subzone. The group is presently considered to be conformable beneath Llandeilo shales, but Llanvirn-Llandeilo fossils above a probably correlative volcanic sequence in the Exploits Group (O'Brien, 1991) raise the possibility that it may be somewhat older.

Ophiolite emplacement and the extent of composite crust.—Linkage between the Gander Zone and the Exploits Subzone is dated as late Arenig by comparing the age of the fossils in the Coy Pond Complex with the U/Pb age on the Partridgeberry Hills Granite (fig. 5). It resulted from the overthrusting of ophiolite and other volcanic and sedimentary rocks across the Gander Zone, creating a composite crust of continental material overlain by oceanic rocks. Its age coincides with the late Arenig-early Llanvirn change in lithofacies between the Jonathans Pond and Indian Bay Big Pond formations, which Williams and Piasecki (1990) suggested was a sedimentary response to ophiolite emplacement farther to the west.

Ordovician and earliest Silurian rocks that were deposited after ophiolite emplacement have been assigned to the Exploits Subzone by Williams, Colman-Sadd, and Swinden (1988). However, they are actually an overlap sequence on both Exploits and Gander rocks and do not have the tectonostratigraphic significance of the pre-emplacement part of the subzone (Williams and Piasecki, 1990). The change is reflected in the contamination of magmas by continental material. Although no U/Pb inheritance has been found in units of the Exploits Subzone that pre-date the Partridgeberry Hills Granite, inheritance is present in all but one of the dated post-Arenig units.

Contamination of magmas with older zircon can be used to show the extent of the continental substrate beyond its western-most surface exposures. Precambrian inheritance in Victoria Lake Group rhyolite, dated at 462 + 4/−2 Ma (Llanvirn-Llandeilo) (Dunning and others, 1987), suggests that the substrate extends all the way to Red Indian Line (fig. 1) in central Newfoundland, as it does farther south, and was in this position during Llanvirn-Llandeilo times. The substrate, however, is not exclusively Gander Zone. Late Precambrian intrusions at Valentine and Crippleback lakes (563 ± 2 and 565 ± 4/−2 Ma, respectively; Evans, Kean, and Dunning, 1990) are tectonically emplaced samples of crust that are older than the Gander Zone sediments. They resemble the Rose

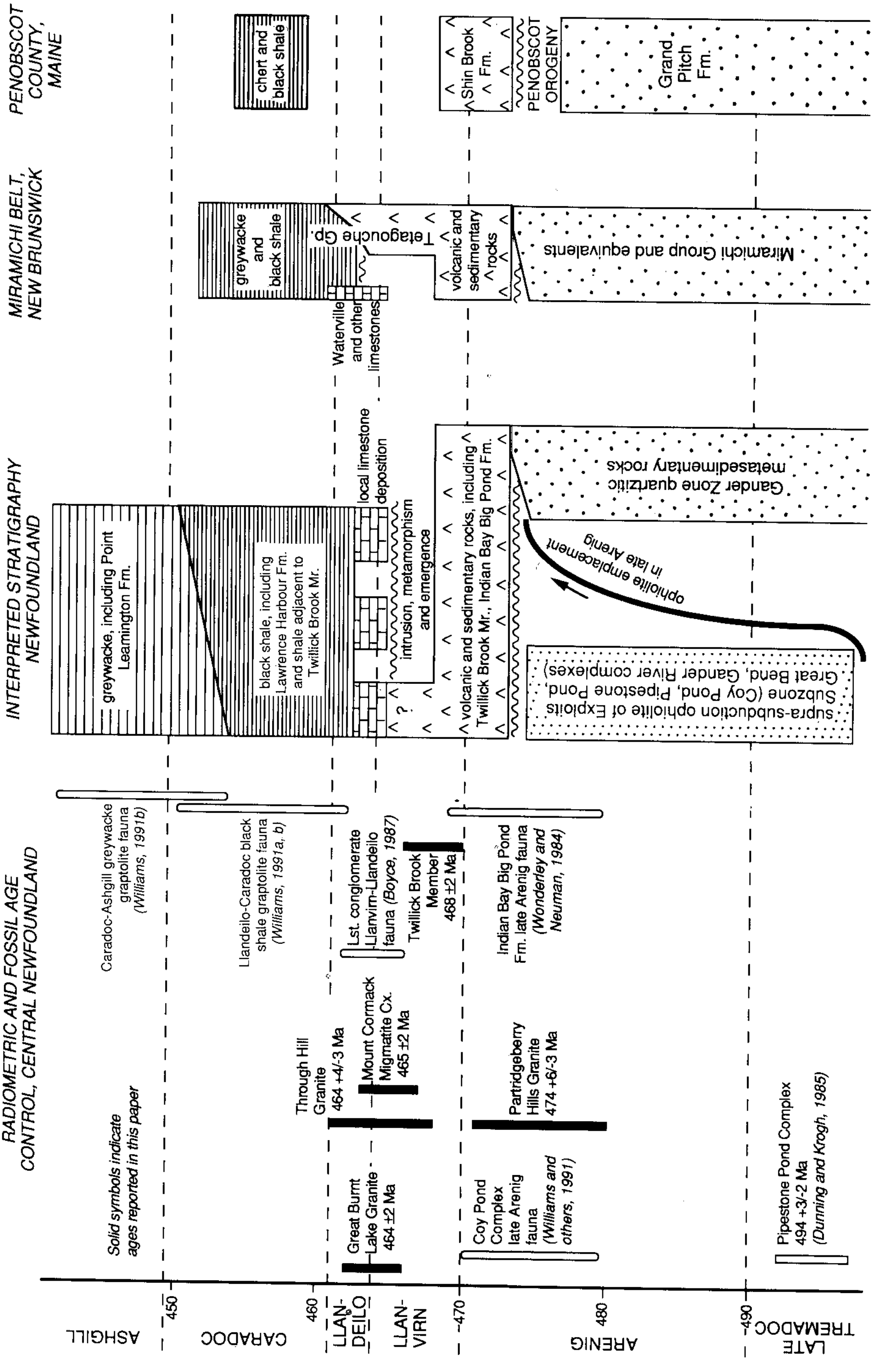

Fig. 5. Summary chart of age control in central Newfoundland and the interpreted stratigraphic evolution of the Exploits Subzone and Gander Zone. Schematic stratigraphic columns for New Brunswick and Maine based on references given in the text. Time scale from Tucker and others (1990).

plutonic suite of the Avalon Zone (sensu lato; O'Brien, O'Brien, and Dunning, 1991), and the Gander Zone may be terminated against the structure that brings them to surface. Alternatively they may represent the basement on which the Gander Zone was deposited.

In the northern part of the Exploits Subzone, the Coaker Porphyry, which outcrops just south of New World Island (fig. 1), has yielded an age of 467 ± 5 Ma (Elliott, Dunning, and Williams, 1991), equivalent within error to the Llanvirn metamorphic and plutonic events in the Mount Cormack and Meelpaeg windows. The porphyry has both zircon inheritance and S-type chemistry (Lorenz, ms), indicating a probable magma source in continental crust. This crust can only have extended farther west, to where Red Indian Line outcrops in western Notre Dame Bay, if the age of the ensimatic Wild Bight Group is Arenig or older, rather than Llanvirn-Llandeilo as is suggested by current evidence (Swinden, ms).

The eastern limit of composite Gander-Exploits crust is defined by the eastern edge of allochthonous ophiolite structurally overlying Gander Zone. In the northeastern part of the Gander Zone (Gander Lake Subzone), the limit is located between the outcrops of the Gander River Complex and the Indian Bay Big Pond Formation (fig. 1). Basal parts of the Davidsville Group interpreted to have been deposited on the Gander River Complex after emplacement resemble, in age and lithology, the Indian Bay Big Pond Formation that overlies quartz-rich rocks of the Gander Zone directly, with apparent conformity and no intervening ophiolite (Williams and Piasecki, 1990; O'Neill, 1991). The eastern limit of allochthonous ophiolite can be located in southern Newfoundland (fig. 2) using similar reasoning. The age of the Twillick Brook Member shows that it was deposited after ophiolite emplacement. Assuming that it overlies the Gander Group stratigraphically (Blackwood, 1983), the eastern limit of ophiolite is located between the member and the ophiolite occurrences just northwest of it.

Llanvirn-Llandeilo tectonothermal events and emergence.—The Indian Bay Big Pond Formation and the Twillick Brook Member show that submergent conditions prevailed in latest Arenig and early Llanvirn time along the southeast margin of the overthrust ophiolitic rocks (fig. 5) and were probably continuous from before emplacement (O'Neill, 1991). Fossiliferous late Arenig-early Llanvirn rocks associated with the Gander River Complex reveal that such conditions also existed shortly after ophiolite emplacement even where the ophiolite was thick (McKerrow and Cocks, 1977; Boyce and others, 1988), but ophiolitic detritus in these same rocks provides evidence of local emergence (O'Neill, 1991). In Notre Dame Bay, fossiliferous rocks in the Summerford Group (Neuman, 1976) and probably the Exploits Group (O'Brien, 1991) indicate marine deposition in late Arenig-early Llanvirn time in the northern part of the Exploits Subzone where the presence of a continental substrate is less certain.

It is unknown whether there was post-emplacement sedimentation in the central part of the Exploits Subzone during the late Arenig and early Llanvirn, but the U/Pb ages from the granites and migmatites within the Mount Cormack window show that, by the mid-Llanvirn, a major tectonothermal event was affecting underlying rocks of the Gander Zone. Intrusive and metamorphic evidence for the event has only been observed in Gander Zone rocks, probably because only these rocks were sufficiently deep to be affected. Depth control is reflected in the isograd distribution which shows a progressive decrease in metamorphic grade toward the overlying ophiolitic rocks (Colman-Sadd and Swinden, 1984a), except where the contact has been modified by later faulting. Possible igneous manifestations of the event at shallower depths may be contemporaneous volcanic activity represented by dated rhyolites in the Victoria Lake and Bay du Nord groups (Dunning and others, 1987, 1990).

The Llanvirn deep tectonothermal activity was matched in the stratigraphic record by the emergence and erosion recorded in the Llanvirn-Llandeilo limestone conglomerate of the Mount Cormack window. The location of the conglomerate and the nature of the detritus indicate that, by the end of the Llanvirn, there had been sufficient erosion in this area to unroof ultramafic rocks of the ophiolite and underlying Gander Zone sedimentary rocks. Limestones of Llanvirn-Llandeilo age occur at Red Indian Lake and in boulders at Sops Arm, near the western margin of the Exploits Subzone, and on New World Island and at Weirs Pond, in the northeast part of the subzone (Bergström, Riva, and Kay, 1974; Stouge, 1980b). Unequivocal evidence of preceding erosion is seen only at Weirs Pond, where limestone unconformably overlies ultramafic rocks of the Gander River Complex and contains ophiolitic detritus (Blackwood, 1978; O'Neill, 1991), but all the occurrences indicate at least some shallowing of the sea.

Emergence or a reduced sedimentation rate during the Llanvirn is also suggested by the contrast between the 468 ± 2 Ma (early Llanvirn) age of the Twillick Brook Member and the Llandeilo or Caradoc graptolites in adjacent black shale (Williams, 1991a,b; Williams and others, in press).

Llandeilo-Caradoc transgression.—Black shales of Llandeilo to Ashgill age are widespread across the Exploits Subzone (Dean, 1978; Williams, 1991a,b) and have generally been considered to overlie earlier volcano-sedimentary units conformably. Emergence during the Llanvirn-Llandeilo interval makes it likely that at least some of the shales overlie an unconformity and, rather than merely representing deepening of the ocean (Dean, 1978), are in fact transgressive (compare Wignall, 1991) (fig. 5). An erosional unconformity was indeed suggested by Hibbard and Williams (1979) at Cheneyville on New World Island, where a basal unit of conglomerate and black shale overlies the Dunnage Mélange; pebbles in the conglomerate resemble the Llanvirn Coaker Porphyry (Kay, 1972).

The Middle Ordovician black shales pass gradationally into a Late Ordovician and earliest Silurian turbidite succession (Dean, 1978), which is overlain, in turn, by the shallow marine and subaerial Botwood Group. This group and related rocks are of Early to Late Silurian age (Eastler, 1969; Williams, 1972; Dunning and others, 1990) and signal the major emergence that occurred as orogeny reached its climax in Newfoundland during the Late Silurian (Dunning and others, 1990).

Transcurrent movement.—Several of the presently exposed contacts between the Gander Zone and the Exploits Subzone are the locus of ductile shearing which indicates overall transport of the Exploits Subzone southwestward across the Gander Zone (Hanmer, 1981; Piasecki, 1988; Piasecki, Williams, and Colman-Sadd, 1990). One of these shear zones occurs at the eastern boundary between the Meelpaeg window and the Exploits Subzone, where it has caused mylonitization of the Great Burnt Lake granite. The age of the granite, post-dating emplacement of ophiolitic rocks on the Gander Zone, confirms the view of Piasecki, Williams, and Colman-Sadd (1990) that orogen-parallel ductile shearing was not related to ophiolite emplacement but was a later event superimposed on an already composite crust. The Great Burnt Lake granite requires only that the shearing be Middle Ordovician or later. However, if this event is the same as that affecting the Gaultois Granite and Little Passage gneisses in the Bay d'Espoir Shear Zone at the southeastern edge of the Exploits Subzone, U/Pb ages for these units date it more precisely as mid-Silurian (Piasecki, 1988; Dunning and others, 1990) (figs. 1 and 5).

Significance of the present outcrop pattern.—Three episodes of tectonic activity (fig. 5), one involving ophiolite emplacement and emergence in the late Arenig, and two involving a combination of deformation, metamorphism, and emergence in the Llanvirn and Silurian, might be expected to produce a complicated map pattern of disrupted units and overlap sequences. The much quoted (but incorrect) view that deposition in the Exploits Subzone continued uninterrupted from the time of ophiolite formation to the mid-Silurian (for example, Dean, 1978; Colman-Sadd, 1980b; Elliott, Barnes, and Williams, 1989) shows that the stratigraphic indications of tectonic activity are cryptic.

Overlap of late Arenig and early Llanvirn rocks across the eastern limit of ophiolite emplacement is probable in the cases of the Indian Bay Big Pond Formation and the Twillick Brook Member. However, overlap of late Llanvirn and younger units onto the Gander Zone is inferred in only one example, the limestone conglomerate in the Mount Cormack window. The general scarcity of overlap could be explained if the overthrust ophiolite was still flat and unbreached by erosion at the time of Middle Ordovician transgression, but the inferred Mount Cormack unconformity shows that this was not the case. An alternative explanation is that the principal areas of uplift and erosion in the Llanvirn maintained their positive relief during the subsequent transgression, so that there was only limited deposition of Llandeilo to Late Silurian rocks directly on the Gander Zone.

Relationships across Strike

The history of interaction between the Exploits Subzone and the Gander Zone implies that they have, for the most part, behaved as a single entity since the Early Ordovician. Interaction between them and the Notre Dame Subzone to the northwest and the Avalon Zone to the southeast (fig. 1) is not nearly as well controlled, and the earliest definite linkage that has been established is Late Paleozoic.

Contemporary events in the Notre Dame Subzone.—The presence of ophiolites in both the Notre Dame and Exploits subzones was a principal factor in grouping the included rocks together in the Dunnage Zone and separating them from the other zones of the Newfoundland Appalachians (Williams, 1978; Williams, Colman-Sadd, and Swinden, 1988). In some respects the results of this study and of Williams and others (1991) reinforce this view. They show that ophiolites in both subzones were not only generated during the same time span, in the Tremadoc and Arenig (Dunning and Krogh, 1985), but that they were also emplaced onto adjacent continental margins at the same time, in the late Arenig (Stevens, 1970; Botsford, ms) (fig. 5). Furthermore geochemical studies have shown that both sets of ophiolites formed in similar supra-subduction zone environments (Coish, Hickey, and Frey, 1982; Swinden, 1988; Jenner and Swinden, 1989; Jenner and others, 1991).

However this correspondence between the ophiolites in the two subzones is misleading, and other evidence indicates enough geographic separation in the Early Ordovician to preclude direct correlation. The late Arenig graptolite and trilobite fauna at the top of the Coy Pond Complex has a Gondwanan affinity (Williams and others, 1991), whereas faunas of equivalent age in the Notre Dame Subzone are Laurentian (for example, Nowlan and Thurlow, 1984; O'Brien and Szybinski, 1989). The two subzones were probably located on opposite sides of the Iapetus Ocean, as proposed by Neuman (1984) on the basis of Arenig-Llanvirn faunas and stratigraphic contrasts.

Furthermore, despite the synchroneity of ophiolite emplacement, the direction of transport was apparently in opposite directions and onto opposite continental margins. Even though kinematic indicators for the earliest movements are largely obscured by later structures, regional considerations support a general westerly transport direction for the Bay of Islands Complex in the Notre Dame Subzone (Williams, 1975), while the apparent conformity of pre- and post-emplacement rocks at Indian Bay Big Pond implies transport of Exploits ophiolite in an easterly direction.

There are also other contrasts. The Notre Dame Subzone shows a classic pattern of obduction, in which the base of the ophiolite, marked by a dynamothermal aureole, overlies stacked sedimentary and volcanic thrust sheets derived principally from continental margin deposits (Williams and Cawood, 1989). The whole assemblage was emplaced onto a carbonate bank, and the pattern is closely matched in other parts of the Appalachians (Williams and Hatcher, 1983) and in Mesozoic-Cenozoic orogenic belts (for example, the Alpine-Himalayan Orogen, Searle and Stevens, 1984). The absence of a carbonate bank in the Gander Zone suggests a climatic difference and supports geographic separation (Neuman, 1984), while the lack of a dynamothermal aureole and stacked thrust assemblage may indicate a difference in the mechanics of emplacement.

Contemporary events in the Avalon Zone.—The Avalon Zone in Newfoundland consists of Late Proterozoic volcano-sedimentary sequences, unconformably overlain by a clastic shelf succession of latest Precambrian to earliest Ordovician age (O'Brien, Wardle, and King, 1983). The shelf succession contains a trilobite fauna of Gondwanan affinity (Hutchinson, 1962) and is approximately coeval with the Gander Zone and older rocks of the Exploits Subzone. Its deposition closely followed the last widespread Avalonian magmatic event (580-563 Ma) (O'Brien and others, 1991), which produced bimodal, largely subaerial volcanic rocks and accompanying intrusions. These rocks provide a possible source for the youngest detrital zircon found in the Gander Zone (569 Ma).

Unfortunately no Ordovician rocks younger than early Arenig are exposed onshore in the Avalon Zone, so it is not possible to determine whether the tectonic events that began farther west in the late Arenig are reflected in Avalonian stratigraphy. Evidence that the Avalon Zone was affected by central Newfoundland tectonics comes from the Valentine Lake and Crippleback Lake intrusions, which have yielded U/Pb ages that correspond to the 580 to 563 Ma Avalonian event and which appear to have been structurally emplaced into the Exploits Subzone (Evans, Kean, and Dunning, 1990). O'Brien, O'Brien, and Dunning (1991) have proposed that the intrusions indicate Avalonian crust beneath central Newfoundland, forming a structural basement to the ophiolites and older volcanic rocks of the Exploits Subzone, but perhaps representing the stratigraphic basement on which the Gander Zone sedimentary sequence was deposited.

Relationships along Strike

Correlation has long been made between rocks of the Miramichi Highlands of central New Brunswick and those of the Gander Zone and Exploits Subzone in Newfoundland (Rast, Kennedy, and Blackwood, 1976; Swinden and Thorpe, 1984). The Miramichi Group (van Staal and Fyffe, 1991) consists of quartzite and phyllite, containing Tremadoc-Arenig graptolites (Fyffe, Forbes, and Riva, 1983). It is overlain by fossiliferous late Arenig rocks of the Tetagouche Group (Fyffe, 1976; Nowlan, 1981), in a relationship comparable to that between the Gander Group and the Indian Bay Big Pond Formation in Newfoundland (Wonderley and Neuman, 1984; O'Neill and Knight, 1988) (fig. 5). Volcanic units of the Tetagouche Group have yielded U/Pb ages of 472 ± 4 and 466 ± 5 Ma (R. Sullivan *in* van Staal, Winchester, and Bédard, 1991; Sullivan and van Staal, 1990). The first of these ages overlaps that of the Twillick Brook Member, and the second also overlaps the ages of rhyolite porphyry and tuff in the Victoria Lake and Bay du Nord groups farther to the west in the Exploits Subzone (Dunning and others, 1987, 1990). Van Staal (1987) and van Staal, Winchester, and Bédard (1991) interpreted the chemistry of Tetagouche Group volcanic rocks as indicating eruption through continental crust of the Miramichi Group, a parallel scenario to that suggested here for most or all of the post-Arenig volcanism of the Exploits Subzone.

U/Pb ages, indicating for the first time Ordovician metamorphism and granite intrusion in the Gander Zone of Newfoundland, overlap within error age determinations reported from the Miramichi Highlands for the Fox Ridge augen granite (451 + 15/−1 Ma) and the Trousers Lake felsic orthogneiss (434 + 29/−6 Ma) (Fyffe, Barr, and Bevier, 1988). The high-grade metamorphic rocks have many lithological similarities to migmatites in the Gander Zone, and the Fox Ridge augen granite bears a striking resemblance to the Great Burnt Lake granite.

The Llanvirn-Llandeilo limestones of the Exploits Subzone and the Mount Cormack window are matched in the Miramichi Highlands by the Waterville limestone (Nowlan, 1981), which has an almost identical conodont fauna to limestones in Newfoundland and elsewhere along the Appalachian-Caledonian Orogen (Bergström, Riva, and Kay, 1974). Graptolitic black shales of Llandeilo-Caradoc age occur on the southeastern side of the Miramichi Highlands, where they pass upward into graywacke. Significantly they are underlain, beneath an erosion surface, by quartzite and slate capped by fossiliferous Arenig rocks (Fyffe, Forbes, and Riva, 1983), in a relationship that is predicted to occur in Newfoundland, but that has yet to be observed.

A major difference between the Miramichi Highlands of New Brunswick and the correlative parts of Newfoundland is the age of associated ophiolites (van Staal and Fyffe, 1991). Whereas the Newfoundland ophiolites are Early Ordovician and were emplaced in the late Arenig, those in New Brunswick, included in the Fournier Group, have been dated as late Llanvirn to early Caradoc (464 ± 1 and 460 ± 1 Ma) (Sullivan, van Staal, and Langton, 1990) and were probably emplaced on top of the Tetagouche Group in Late Ordovician or Silurian time (van Staal and others, 1990). Thus the ophiolite complexes in the Exploits Subzone of Newfoundland have no recognized counterparts in New Brunswick, but the disturbance related to their emplacement *is* recorded in the stratigraphic record, in much the same way as at Indian Bay Big Pond. If oceanic crust of the same age as the New Brunswick ophiolites exists in Newfoundland, it should be located between the Exploits-Gander composite crust and the parts of the Notre Dame Subzone that began obduction in the late Arenig. The Buchans-Roberts Arm belt occupies this geographic position, and part of it (the Cutwell Group) contains conodonts as young as late Llanvirn (O'Brien and Szybinski, 1989).

The correlation with New Brunswick supports the view that the Avalon Zone in Newfoundland contributed detritus to Gander Zone sediments and was possibly their stratigraphic basement (O'Brien and others, 1991). Detrital zircon from the Miramichi Group has ages (680–610, 2000 Ma) characteristic of Avalonian geology (David, Gariépy, and Machado, 1991), and an Avalonian basement to the group is suggested by paleomagnetic evidence (van der Pluijm and van der Voo, 1991).

The Miramichi Group has been correlated with slate and quartzite of the Grand Pitch Formation in Maine, and the lower parts of the Tetagouche Group with the Shin Brook Formation (Neuman, 1968) (fig. 5). The Grand Pitch Formation contains *Oldhamia smithi* and is probably at least in part Early Cambrian (Neuman, 1962). It is unconformably overlain by tuff and volcaniclastic sediments of the Shin Brook Formation, which contains late Arenig fossils. The event responsible for the unconformity was named the Penobscot Orogeny (as "Penobscot disturbance") by Neuman (1967) and almost certainly correlates with emplacement of Exploits Subzone ophiolite onto the Gander Zone in central Newfoundland. Thus, this study provides the evidence for the Penobscot Orogeny in Newfoundland that Neuman and Max (1989) noted was previously lacking. As well as considerably expanding the known extent of the orogeny, it also provides much new detail on the tectonic processes involved.

CONCLUSIONS

Enough data are now available to reconstruct the history of the Exploits Subzone and the Gander Zone in Newfoundland through most of the Ordovician and Silurian. An orogenic event in the late Arenig, correlated with the Penobscot Orogeny of Maine, emplaced oceanic crust of the Exploits Subzone onto the continental margin of Gondwana, represented by the Gander Zone. Tectonism continued in the mid-Ordovician with deformation, metamorphism, and emergence, followed by renewed marine sedimentation from the mid-Ordovician until the onset of major orogenic activity in the Silurian. The similarity with the geological history of New Brunswick and Maine indicates that the same tectonic processes affected a significant portion of the eastern margin of Iapetus. The Penobscot Orogeny was roughly synchronous with the Taconian Orogeny on the opposite margin of Iapetus, in which ophiolite of the Notre Dame Subzone was emplaced westward onto the continental margin of Laurentia, represented by the Humber Zone.

The combined result of the Penobscot and Taconian orogenies was to bring about a fundamental change in the geology of Newfoundland at the end of the Arenig. Much of what is currently included in the Dunnage Zone was transformed from autochthonous oceanic crust, that was in a true sense a part of the Iapetus Ocean, to allochthonous ophiolite thrust onto the neighboring continental margins. Most of the Dunnage Zone rocks formed after these events are best described as overlap sequences (Williams and Piasecki, 1990; van Staal and Williams, 1991), because they are inferred to have been deposited on allochthonous rocks that structurally overlay continental crust, and because locally they extend beyond the limits of the allochthons and lie directly on continental margin deposits.

Although most of what now constitutes the Dunnage Zone was either displaced from the oceanic realm in the late Arenig or was deposited on top of displaced rocks, the Penobscot and Taconian orogenies did not result in complete ocean closure (Neuman and Max, 1989). In New Brunswick the generation and consumption of oceanic crust continued into the latter half of the Ordovician (Sullivan, van Staal, and Langton, 1990; van Staal, Winchester, and Bédard, 1991), and in Newfoundland the Buchans-Roberts Arm belt records arc volcanism that may have extended to the end of the Llanvirn (O'Brien and Szybinski, 1989; Swinden, Kean, and Dunning, 1988). The geographic separation implied by these oceanic rocks is reflected by continued faunal provinciality. The Arenig-Llanvirn rocks that were deposited just after ophiolite emplacement on the Gander Zone contain Celtic faunas of peri-Gondwanan character distinct from Laurentian faunas of western Newfoundland (Neuman, 1976, 1984). The barrier to migration was not overcome until the late Llanvirn-early Llandeilo, when Laurentian faunas appeared in the scattered limestone deposits of the Exploits and Mount Cormack subzones (Dean, 1971; McKerrow and Cocks, 1977; Boyce and others, 1988).

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