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PROBING THE CRUST WITH PLUTONS: REGIONAL ISOTOPIC GEOCHEMISTRY OF GRANITOID INTRUSIONS ACROSS INSULAR NEWFOUNDLAND

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ABSTRACT

This report presents an overview of Nd and O isotopic data from plutonic suites across the geographical and temporal spectrum of the Appalachian Wilson Cycle in Newfoundland, with emphasis on the Paleozoic suites. For the purposes of discussion, Newfoundland plutonic suites are divided into pre-orogenic (> 550 Ma) early orogenic (550 to 460 Ma) late orogenic (460 to 410 Ma) and post-orogenic (< 400 Ma) groupings.

Early orogenic suites, probably representing the products of arc magmatism within Iapetus, have variable but generally positive ϵ_{Nd} *(+1 to +6). Variations amongst these suites may be related to the original relative positions of different arc systems, with those closest to continental regions containing a higher proportion of older crust, or to the ages of the arcs and the material subducted beneath them. In strong contrast, ca. 460 Ma granites in south-central Newfoundland, with* ϵ_{Nd} *down to -8, were derived by melting of Gander Group supracrustals ± underlying basement, probably in response to tectonic accretion of the eastern Dunnage Zone.*

Late orogenic suites show strong isotopic variations that match their contrasts in petrology and elemental geochemistry. In the eastern part of the Central Mobile Belt, they range from S-type granites with strongly negative ϵ_{Nd} *(-5 to -8) and high* $\delta^{18}O$ *(>9) to metaluminous suites with* ϵ_{Nd} *around -3. The strongly negative granites were probably derived largely by melting of Gander Group supracrustal rocks. A regional decrease in* ϵ_{Nd} *from northeast to southwest further implicates the Gander Group, which is most abundant in the northeast, as partly responsible for these signatures. However, the persistent negative signatures on the south coast, where supracrustal rocks are rare, imply a Precambrian basement, which may also underly the northeastern Gander Zone at depth. In the northwestern Dunnage Zone, Silurian plutonic suites have largely juvenile signatures (+3 and above) that argue against the presence of Grenvillian basement rocks, and may indicate the presence of a juvenile (Paleozoic ?) lower crustal block, perhaps representing accreted arc systems. Much more work is required to confirm, characterize, and delineate this region.*

Post-orogenic suites also show very significant geographic isotopic variations. In the Avalon Zone, they have generally positive ϵ_{Nd} *values of +2 to +4 that argue against the presence of any ancient basement. In the Gander Zone, they show regional isotopic trends that resemble those of the late orogenic suites, and similarly suggest an input from the Gander Group supracrustal rocks. However, Devonian granites on the south coast still have negative* ϵ_{Nd}*, and contrast with those of the adjacent Avalon Zone. This suggests fundamental contrasts in the deep geology of these regions, and reinforces interpretation of the Dover–Hermitage Bay fault system as a major structural break. Thus, late Precambrian rocks on the south coast may not correlate directly with the 'type' Avalon Zone, although they may both be part of a single composite Precambrian terrane representing the Gondwanan side of the Orogen.*

The isotopic data are by no means complete, and further work is required to both confirm and expand some of the more tentative inferences. However, despite these and other problems, the regional isotopic data provide valuable information with which to delineate and characterize major components of the Appalachian Orogen in Newfoundland. The challenge for the final stages of the LTIHOPROBE EAST granite project is to complete the isotopic database and successfully integrate it with other relevant geophysical and geological data.

Lithoprobe contribution # 287

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INTRODUCTION

LITHOPROBE EAST is a major multidisciplinary project that aims to delineate and understand crustal and subcrustal structure within the Appalachian Orogenic Belt. Seismic reflection profiling to date has included marine profiles to the northeast and southwest of Newfoundland (Keen *et al.*, 1986; Marillier *et al.*, 1989), and, more recently, onshore Vibroseis profiles (Quinlan *et al.*, 1991). Supporting geoscience projects, in which surface-based studies seek to augment the seismic database, include a regional isotopic and geochemical study of granitoid intrusive rocks across Newfoundland (Fryer *et al.*, 1989). This is coordinated with a Geological Survey Branch (GSB) project intended to compile, augment and interpret geochemical data from these rocks (Kerr *et al.*, 1991). As granitoid plutons are at least partly derived from the deep continental crust, they provide 'windows' through which the features of lower regions imaged by seismic data may be glimpsed. Also, isotopic data from plutonic suites distributed across the spatial and temporal spectrum of an orogenic belt provide insight into the sources of granitoid magmas and their relationship to orogenic evolution.

Although a large number of isotopic analyses are now complete, these data have previously been reported only in abstract or outline form (e.g., Fryer *et al.*, 1989; Kerr *et al.*, 1990). This report is a regional overview of results and their geological and tectonic implications. It concentrates mostly upon neodymium and oxygen isotope data.

With respect to this account, two points are stressed. First, the data are not yet complete; new information may neccessitate revision of some more tentative ideas presented here. Second, data are derived from field work and sampling by several researchers whose names do not appear in the list of authors. The purpose of this contribution, as stated earlier, is to provide an overview, and to highlight some specific problems for further attention. It is anticipated that separate papers will eventually address more localized and focussed problems.

REGIONAL GEOLOGICAL AND GEOPHYSICAL FRAMEWORK

UPPER CRUSTAL SUBDIVISIONS DEFINED BY SURFACE REGIONAL GEOLOGICAL PATTERNS

Newfoundland is one of the best type-areas for Appalachian–Caledonian orogenic evolution, as it displays a relatively complete cross-section of the belt, and preserves the largest remnants of the Iapetus Ocean and/or its associated basins. The current 'plan view' of the Newfoundland Appalachians (Figure 1) comprises four main tectonostratigraphic zones (Williams, 1979; Williams *et al.*, 1988).

From west to east, these are the *Humber Zone* (the ancient North American continental margin), the *Dunnage Zone* (various remnants of the Iapetus realm, mostly comprising island arcs and back-arc basins), the *Gander Zone* (a metamorphic belt of sedimentary protolith possibly representing an opposing, Gondwanan, continental margin) and the *Avalon Zone* (a Late Proterozoic orogenic province with a thin Paleozoic cover sequence; probably a fragment of Gondwanaland developed during the Pan-African cycle). The Dunnage Zone is subdivided into two major segments, termed the *Notre Dame Subzone* and *Exploits Subzone,* which have distinct lithological, faunal and evolutionary characteristics (Williams *et al.*, 1988). The zonal scheme encounters problems on the south coast which, although traditionally placed within the Gander Zone, lacks the metasedimentary rocks that are characteristic of this division. In Figure 1, it has been retained as part of the Gander Zone, mainly because its plutonic evolution appears similar to areas farther to the northeast, and they are most conveniently discussed together.

Colman-Sadd and Swinden (1984) proposed that the eastern Dunnage Zone was allochthonous, and that metasedimentary rocks of the Gander Zone formed tectonic 'windows' within it. This concept is also supported by gravity data (Karlstrom, 1983). Marine seismic profiles (Keen *et al.*, 1986; Marillier *et al.*, 1989) also suggest that thick continental crust everywhere underlies the Dunnage Zone.

From the perspective of Paleozoic plutonism, the most important portion of the orogen is the *Central Mobile Belt* (i.e., the Dunnage and Gander zones combined), which is the locus of voluminous magmatism (Figures 1 and 2). Paleozoic plutons (of post-Silurian age) also occur in the Avalon Zone, but there are virtually none in the Humber Zone, except at its easternmost edge. Proterozoic granitoid rocks, however, are important components of both the Humber and Avalon zones, where they are manifestations of the earlier Grenvillian and Pan-African cycles, respectively (Williams *et al.*, 1989).

LOWER CRUSTAL SUBDIVISIONS DEFINED BY DEEP SEISMIC REFLECTION PROFILES

The results of marine seismic reflection profiles are discussed by Keen *et al.* (1986) and Marillier *et al.* (1989); further discussion and interpretation are presented by Stockmal *et al.* (1990). These results are interpreted in terms of three lower crustal blocks (Figure 1), defined by contrasts in the depth of the Moho, and the attitudes, positions and abundances of mid- to lower-crustal reflectors. The boundaries of these blocks are interpreted to partially coincide with surface geological boundaries, based on along-strike extrapolation using regional geophysical data. Figure 1 shows the distribution of blocks according to Marillier *et al.* (1989); however, the regional isotopic data presented in this paper are not fully supportive of this pattern.

The *Grenville Block* was interpreted to underlie the Humber Zone and at least part of the Dunnage Zone, and the *Avalon Block* was interpreted to coincide with the surface expression of the Avalon Zone. The intervening region was termed the *Central Block;* this underlies the Gander Zone

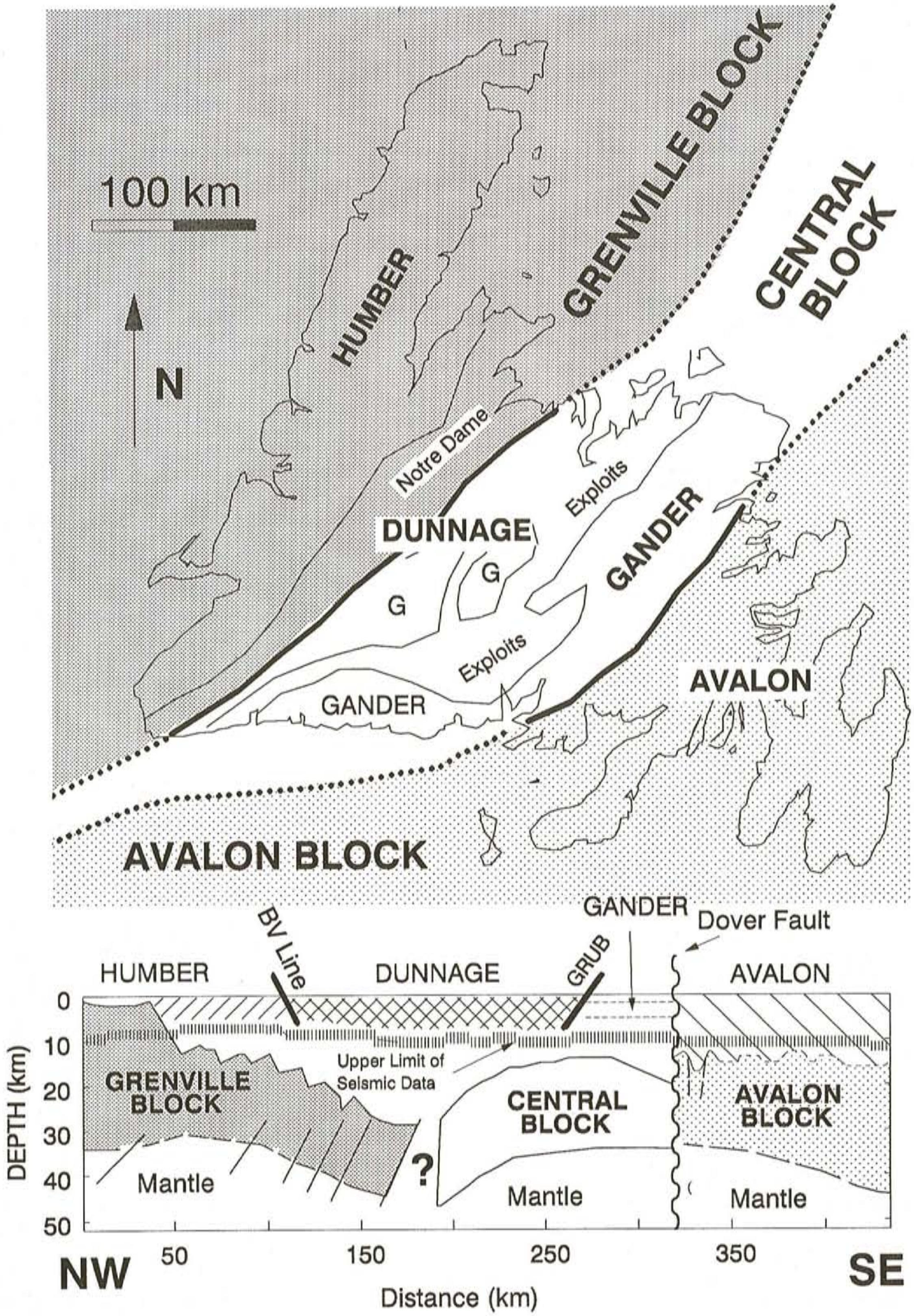

Figure 1. *Major subdivisions (tectonic zones) of the Newfoundland Appalachians (after Williams, 1979; Williams* et al., *1988) in relation to lower crustal blocks postulated from seismic transects (Keen* et al., *1986; Marillier* et al., *1989). The schematic cross-section is based on these, and other sources.*

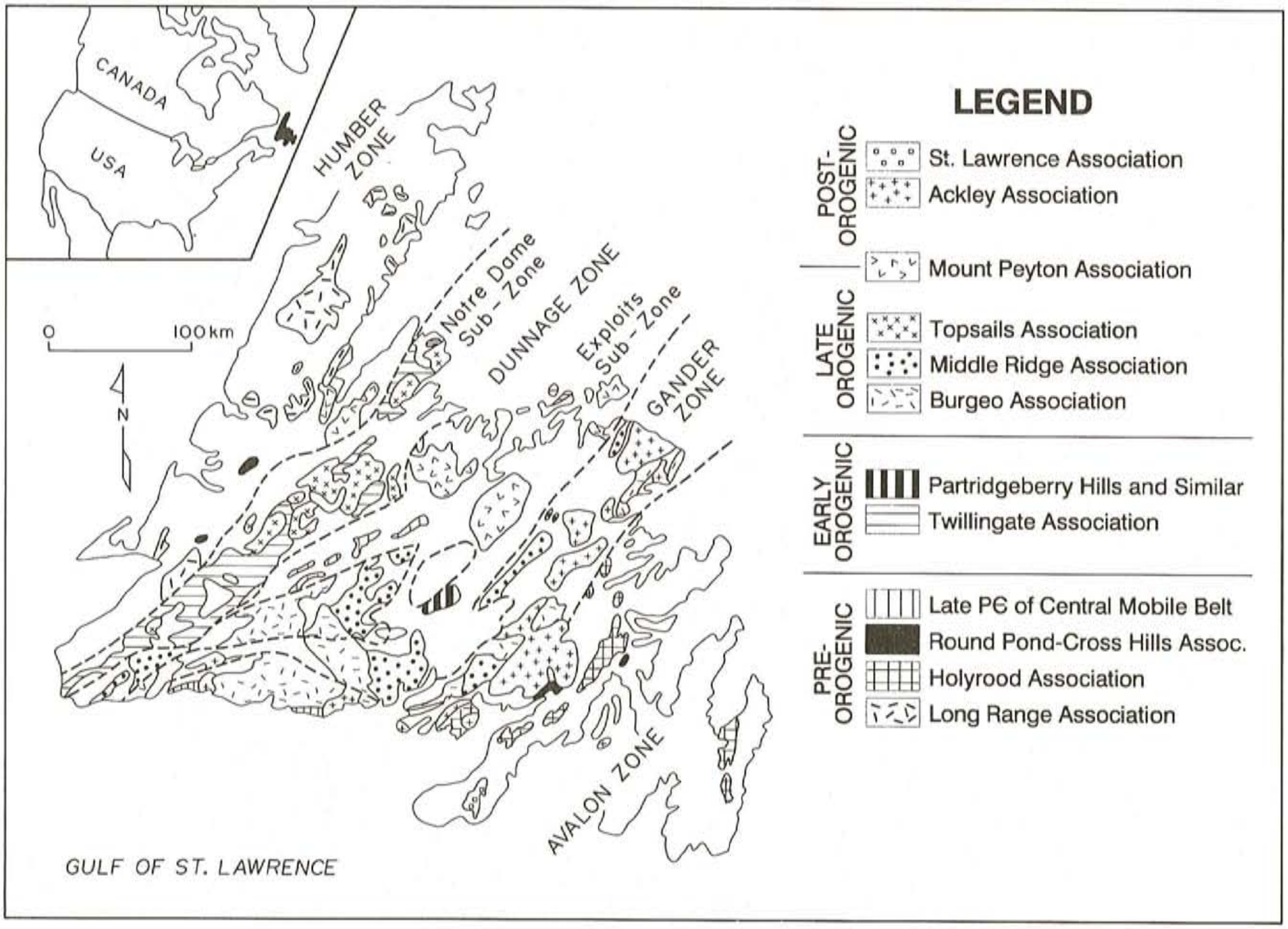

Figure 2. *Distribution and classification of plutonic suites in the Newfoundland Appalachians, after Williams* et al. *(1989) with modifications to account for post-1989 research (Dunning and O'Brien, 1989; Evans* et al., *1990; Colman-Sadd* et al., in press*).*

and much of the Dunnage Zone. The presence of thick continental crust beneath central Newfoundland implies that the oceanic terranes of the Dunnage Zone are allochthonous, with a maximum vertical extent of around 12 km (Keen *et al.*, 1986). There has been substantial discussion of the seismic interpretation, especially since the acquistion of on-land profiles (Quinlan *et al.*, 1991). However, the tripartite division outlined above remanins generally applicable in the context of this paper.

Of the three lower crustal blocks imaged by seismic reflection, only the Grenville can be studied directly. There are no exposures of 'basement' within the Avalon Zone (at least in Newfoundland), and little unequivocal sialic basement within the Gander or eastern Dunnage zones. Indirect methods are thus required to constrain their characteristics beyond the physical and structural parameters provided by seismic data. Also, any inferences from offshore profiles depend heavily upon lateral correlations of 100 km or more, and a more precise analysis of correspondance between surface and deep-crustal geology requires a method of mapping their distribution *in situ.* The onshore seismic profiles (Quinlan *et al.*, 1991) provide a partial solution to this problem, but still provide only two-dimensional vertical profiles of the crust in most areas.

GRANITOID INTRUSIONS AS WINDOWS TO THE LOWER CONTINENTAL CRUST

Plutonic rocks, particularly those of granitoid composition, provide a useful method of mapping the subsurface distribution of crustal blocks. Although there is debate about the ultimate sources of granitoid magmas, most are derived, at least in part, from rocks of the lower continental crust. Consequently, they preserve both isotopic and elemental geochemical 'images' of these lower crustal sources, and can define and delimit basement provinces and their boundaries (e.g., DePaolo, 1981; Farmer and DePaolo, 1983; Halliday, 1984; Kerr and Fryer, 1990). In addition to 'mapping' such blocks, the geochemical signatures of granitoid rocks can provide information about their age and affinities, and, perhaps most importantly, may be able to identify and delineate regions that cannot be distinguished with confidence on the basis of seismic character alone.

The interpretation of such patterns is, however, unlikely to be straightforward. Some have argued that granites provide direct images of such sources because they are derived wholly by crustal anatexis (e.g., Chappell and Stephens, 1988; Chappell *et al.*, 1988), whereas others have suggested complex blending of crustal and subcrustal (i.e., mantle-derived) components (e.g., DePaolo, 1981; Harmon *et al.*, 1984; Hildreth and Moorbath, 1988). A second problem is that granitoid magmas may be derived from contrasting crustal levels; e.g., Al-rich 'S-type' granites, commonly viewed as anatectic derivatives of sedimentary rocks (e.g., Chappell and White, 1974; White and Chappell, 1990), may not have any direct relationship to their underlying basement rocks. A third problem is that there is no requirement for interfaces between crustal blocks to be vertical, and contrasting provinces could be juxtaposed in a vertical sense by, for example, thrusting. However, in spite of these and other problems, granitoid plutonic rocks provide 'windows' through which the features of the lower crust can be visualized and mapped, and their study is a crucial component of LITHOPROBE EAST.

GRANITOID PLUTONIC ASSOCIATIONS IN NEWFOUNDLAND: AN OVERVIEW

About 35 percent of Newfoundland is underlain by rocks belonging to the granitoid clan, ranging in composition from diorite to alkali-feldspar granite, with associated mafic intrusive rocks (Figure 2). A major contribution to their study was made by D.F. Strong in conjunction with survey mapping projects (e.g., Strong *et al.*, 1974; Strong and Dickson, 1978; Payne and Strong, 1979; Strong, 1980). During the 1980's, systematic mapping has added greatly to our petrological and geochemical database (e.g., Dickson, 1983, 1990; Whalen *et al.*, 1987), and U–Pb zircon geochronology has provided a more tightly constrained temporal framework, (e.g., Krogh *et al.*, 1985; Dunning and O'Brien, 1989; Dunning *et al.*, 1987, 1990, 1991). The following overview is, as far as is possible, a 'state-of-the-art' summation, but it should be noted that many plutons are still not dated with precision; work in progress by G.R. Dunning and R.D. Tucker, in conjunction with GSB mapping projects, may result in modifications of temporal groupings.

In this paper, we adopt the generalized descriptive classification outlined by Williams *et al.* (1989), based on earlier schemes presented by Strong (1980) and Hayes *et al.* (1987). Several 'types' or associations of plutonic rocks are defined on the basis of age, petrological features and relationships to tectonic zonations, and named after prominent examples (Figure 2). The groupings are consistent with overall geochemical patterns (Dickson *et al.*, 1990; Kerr *et al.*, 1990), although geochemistry alone cannot provide absolute discrimination between associations. There are some newly recognized associations that do not readily fit into the scheme, such as Ordovician S-type granites in the Gander Zone (Colman-Sadd *et al.*, *in press*) and late Precambrian intrusions within the Dunnage Zone (Evans *et al.*, 1990), and it is viewed as an evolving, rather than a rigid, classification scheme.

In this paper, the descriptive classification of Williams *et al.* (1989) is overlain by a temporal framework, in which Newfoundland granitoid suites are divided into *pre-orogenic, early orogenic, late orogenic,* and *post-orogenic* categories. There is a general, but not exact, correspondance between these and the descriptive associations illustrated in Figure 2.

Two points need to be stressed with regard to this framework. First, these terms are used with reference to the *Appalachian Orogenic Cycle;* thus, pre-orogenic intrusions may be syn-, post- or anorogenic with respect to earlier events such as the Grenvillian or Pan-African orogenic cycles. Second, the use of the term 'orogenic' does not imply a single, constrained event (as in 'Taconic Orogeny'), but rather the protracted and/or episodic tectonism that accompanied and followed the destruction of Iapetus. This usage is akin to the definition used by geologists working in Precambrian shield areas; for specific deformational markers, the term event is used here. In terms of stratigraphic terminology, these groupings are as follows:

Pre-orogenic	= Proterozoic or Eocambrian (> 550 Ma),
Early Orogenic	= Cambrian and Earlier Ordovician (550-460 Ma),
Late Orogenic	= Later Ordovician and Silurian (460-410 Ma),
Post-orogenic	= Later Silurian and younger (410-360 Ma)

These categories are not discrete 'pigeonholes', and their context is that of the Newfoundland Appalachians alone, but they form a useful framework for discussion of the isotopic data. The first group has only a tenuous connection to the Appalachian Wilson Cycle, but is of importance in that these materials may have contributed to younger magmas. These temporal groupings are summarized below; their individual components and features are discussed in subsequent sections of the report, in conjunction with the isotopic data.

Pre-orogenic Granitoid Associations

This grouping includes the Long Range, Holyrood, Round Pond and Cross Hills associations of Williams *et al.* (1989). The Long Range (≈1000 Ma) and Holyrood (≈620 Ma) associations are related to the Grenvillian and Pan-African orogenic cycles respectively, and were emplaced mostly after final deformational events in each. They are dominated by calc-alkaline to alkali-calcic, hornblende-bearing granodiorites to granites. The Round Pond (≈610 Ma) and Cross Hills (≈560 Ma) associations comprise small, variably alkaline plutons that intrude the Humber and Avalon zones respectively (Figure 2). Williams *et al.* (1989) suggested that the Cross Hills and Round Pond associations may reflect rifting to form Iapetus.

Granitoid suites of late Precambrian age also occur on the south coast and in central Newfoundland. The U–Pb ages of those on the south coast are broadly analogous to those of the 'type' Avalon Zone, and lead to suggestions that tectonostratigraphic zones should be revised in this region

(Dunning and O'Brien, 1989; O'Brien *et al.*, 1991). Deformed granites close to the Exploits–Notre Dame subzone boundary have also yielded U–Pb ages of ca. 560 Ma (Evans *et al.*, 1990). These may represent exhumed Precambrian basement that occurs at depth beneath this region. Late Precambrian intrusions in both these regions are grouped together in Figure 2.

Early Orogenic Granitoid Associations

The most widespread of these is the Twillingate Association of Williams *et al.* (1989), including a variety of generally sodic (tonalitic, trondhjemitic and granodioritic) intrusive complexes ranging in age from 510 Ma to about 460 Ma, most of which were affected by the Taconic event. Some are demonstrably allochthonous (e.g., the Little Port Complex in the Humber Arm Allochthon), and most are probably allochthonous on a crustal scale. The most extensive tonalitic granitoid terrane is in southwestern Newfoundland (Figure 2), an area once referred to poetically as a 'sea of tonalite'. Some Ordovician ages have been obtained (e.g., Dunning *et al.*, 1989), but the plutonic suites of this area remain poorly known.

These early orogenic tonalite–granodiorite suites have been widely interpreted to result from subduction-related magmatism broadly associated with island- and/or continental-arc settings (e.g., Williams and Payne, 1975; Dunning *et al.*, 1987, 1989), and they record the destruction of at least parts of Iapetus or related basins. Recent geochronological data from arc-type volcanic sequences (Dunning *et al.*, 1991) indicates that subduction commenced prior to about 513 Ma. The probable allochthonous character of these early orogenic granitoid suites implies that their geochemical and isotopic signatures may be unrelated to the lower crustal block(s) that *presently* underlie(s) the Dunnage Zone. Variations in age and petrology amongst these suites suggest that they almost certainly represent the products of more than one magmatic belt or episode, and there is every reason to expect isotopic variations linked to geography or age.

Until recently, it was considered that Ordovician plutonic suites were absent from eastern Newfoundland. However, recent U–Pb geochronology has shown that at least three intrusions within the Gander Zone crystallized between 470 and 460 Ma (Colman-Sadd *et al., in press*). These are leucocratic, locally muscovite-bearing granites that are distinct from the arc-type suites noted above. These are grouped separately in Figure 2; not all examples can be shown at the scale of the map.

Late Orogenic Granitoid Associations

This broad group comprises granitoid suites emplaced during the later Ordovician and Silurian, between about 460 and 410 Ma. Silurian magmatism and related deformation (Salinic Event) is of great importance in Newfoundland (e.g., Dunning *et al.*, 1990). The most important feature of these late orogenic suites is their marked compositional variation across the island, from west to east; the two regions are described separately below.

In the Notre Dame Subzone of the Dunnage Zone, most post-Ordovician intrusions were grouped by Williams *et al.* (1989) into the *Topsails Association* (Figure 2). The type example of this grouping is a large, metaluminous to peralkaline complex of ca. 430 to 415 Ma (Whalen *et al.*, 1987; Whalen, 1989); similar suites occur in the Springdale area and on the Baie Verte Peninsula (Coyle and Strong, 1987; Hibbard, 1983). These intrude volcanic suites of the Notre Dame Subzone, and the foliated early orogenic plutonic rocks (see above). All are variably bimodal, and most include minor mafic plutonic rocks. In a local context, these are dominantly posttectonic, being younger than the Taconic event. Williams *et al.* (1989) also included some intrusions of the easternmost Humber Zone in this group; however, Kerr *et al.* (1990) argued that geochemical data did not support this correlation. With this modification, Topsails Association plutons are entirely restricted to the Notre Dame Subzone, and probably reflect a distinct tectonic or thermal history for this region (Kerr *et al.*, 1990).

The other main locus of Silurian magmatism is in the eastern Central Mobile Belt (shown mostly as Gander Zone in Figures 1 and 2); a few examples also cut the structurally overlying Exploits Subzone. Williams *et al.* (1989) distinguished two groupings in the Gander Zone, which they termed the *Burgeo* and *Middle Ridge associations* (Figure 2). These are radically different from the Silurian suites of the western Dunnage Zone; they are dominated by metaluminous to variably peraluminous biotite- and two-mica granite suites, which intrude clastic metasedimentary rocks of the Gander Group and similar or correlative sequences. Their relationship to local deformational events is variable, and many appear to be broadly syn-tectonic, implying a major Silurian Orogenic pulse (e.g., Dunning *et al.*, 1990).

The *Burgeo association* is dominated by variably foliated, K-feldspar megacrystic, biotite granites, which are concentrated along the eastern fringe of the Gander Zone in northeastern Newfoundland, and on the south coast, in areas of relatively high metamorphic grade. The type example is a complex, polyphase batholith on the south coast; similar rock types can be traced as far as Cape Freels, west of Bonavista Bay. Subordinate biotite–muscovite granites also occur in this association, and, based on field relationships and U–Pb dates, appear to be slightly younger than the megacrystic granites, and are possibly closer in affinity to the Middle Ridge association (see below). Tonalitic and dioritic variants are also reported from the type example (Dickson *et al.*, 1989). The *Middle Ridge association* is mostly localized in interior, lower-grade areas (including parts of the Exploits Subzone) and comprises leucocratic two-mica granites having a more restricted compositional spectrum. The type example has been dated at 410 Ma (U–Pb monazite; Tucker, 1990), but reliable geochronological data are sparse elsewhere.

In compositional terms, the Burgeo and Middle Ridge associations form a continuum (Dickson *et al.*, 1990; Kerr *et al.*, 1990) from metaluminous to weakly peraluminous (Burgeo) to strongly peraluminous (Middle Ridge) suites. The Middle Ridge association exhibits many of the characteristic geochemical features of S-type granites, suggested to be derived by anatexis of metasedimentary protoliths (Chappell and White, 1974; White and Chappell, 1990).

Kerr *et al.* (1990) suggested that the features of late-orogenic suites in eastern Newfoundland might reflect *depth zonation,* with the Burgeo Association representing a deep-level magmatic environment, whereas the Middle Ridge Association was derived largely from metasedimentary materials higher in the crust, but below their current level of exposure. From the perspective of isotopic studies aimed at lower crustal blocks, inferences from the latter should perhaps be treated with caution, as they may sample a fairly restricted source region of the crust, which itself may reflect a variety of sources that have no direct connection with the basement presently beneath the area.

Post-orogenic Granitoid Associations

Post-orogenic magmatic associations, of Devonian and younger age, fall into two main groups.

The most easily defined is the *Ackley association* of Williams *et al.* (1989), comprising a major belt of posttectonic plutons of 400 to 380 Ma age stretching from the south coast to Bonavista Bay (Figure 2). The Ackley association occurs within the Gander Zone (as indicated on Figure 2) and the westernmost Avalon Zone, suggesting that these components of the orogen were juxtaposed prior to their emplacement. These plutons are dominated by siliceous, potassic biotite–monzogranite and granites, with both K-feldspar megacrystic (notably in the northeast) and equigranular variants (Dickson, 1983; Dickson *et al.*, 1989). Associated Mo–Sn–W mineralization, and ring-complex to lobate geometry, suggest relatively high emplacement levels. Williams *et al.* (1989) included the peralkaline St.Lawrence Granite (Figure 2) as part of this association. This pluton has been dated as Carboniferous (326 Ma; Bell *et al.*, 1977), but this age is likely disturbed; U–Pb zircon dating is currently underway. As the St. Lawrence Granite is geochemically unique amongst Paleozoic plutons in eastern Newfoundland, it is retained in a separate grouping, for the present, and is not discussed further.

Williams *et al.* (1989) defined the *Mount Peyton Association* to include the bimodal Late Silurian to Devonian plutons of the Dunnage Zone, concentrated mostly in the Exploits Subzone. The type example (Strong, 1978) includes extensive gabbroic to dioritic rocks, and a younger metaluminous biotite-granite; similar diorite–granite associations typify the Fogo Island and Hodges Hill complexes. The Devonian plutonic suites of the easternmost Humber Zone (formerly grouped with the Topsails) are tentatively included as part of this association. These bimodal suites are generally rather poorly known, and this subdivision has commonly become a resting place for any plutonic rocks of uncertain affinity.

The K–Ar and Ar–Ar dates suggest that the Mount Peyton Association may straddle the rather arbitrary late orogenic and post-orogenic temporal groupings used here. Mafic components typically appear of Silurian (> 420 Ma) age, whereas the granites (*ss*) yield Devonian ages; however, the data are not comprehensive at present, and U–Pb data are required to substantiate this pattern. The spatial association of mafic and felsic rocks suggests a genetic link, perhaps indirect, but it is not yet clear if they have similar ages of emplacement. We have elected to represent most of these as Devonian in our isotopic variation maps (Figures 4 to 7), but this may be subject to revisions.

ND AND O ISOTOPIC DATA: AN OVERVIEW OF THEIR USAGE

In this section, we present a brief explanation of the basic principles of Sm–Nd and O isotope geochemistry (after DePaolo, 1988; Hoefs, 1981). This is intended to provide background information relevant to discussions of data that follow, and is by no means comprehensive.

SM–ND ISOTOPIC SYSTEM

Basic Principles

· This radiogenic decay system is analogous to the more familiar Rb–Sr system, but different in important respects. The LREE parent (^{147}Sm) and daughter (^{143}Nd) elements have closely similar ionic radii and valence properties, unlike Rb and Sr. Thus, Sm and Nd are not easily separated by crustal processes such as anatexis or fractional crystallization, and the range of Sm/Nd ratios in crustal rocks is very small (0.1 to 0.3) compared to Rb/Sr ratios (< 0.01 to > 100).

The Nd isotopic variations in nature arise mostly in the partial melting of the mantle to generate crustal rocks, when the mantle retains Sm preferentially over Nd. Over geological time scales, the upper mantle has been depleted in Nd, and this 'depleted mantle reservoir' has evolved to have higher ^{143}Nd/^{144}Nd ratios. Conversely, crustal rocks are relatively depleted in Sm, and have evolved to have significantly lower ^{143}Nd/^{144}Nd ratios. Thus, if the initial ^{143}Nd/^{144}Nd ratio of a rock is known, it will reveal whether that rock formed directly from a mantle source, or includes some older pre-existing crustal source (Figure 3). The existence of the depleted mantle reservoir is confirmed by isotopic studies of mafic volcanic rocks through geological time (DePaolo, 1988).

Notation and Representation

The actual variation of ^{143}Nd/^{144}Nd in nature is very small, and a simple scaling technique is employed to give a parameter termed ϵ_{Nd}:

$$\epsilon_{Nd} = [(^{143}Nd/^{144}Nd \ / \ ^{143}Nd/^{144}Nd \ CHUR)-1] \times 10^4$$

Here, CHUR ('chondritic uniform reservoir') is a chondritic value, assumed to be representative of the bulk

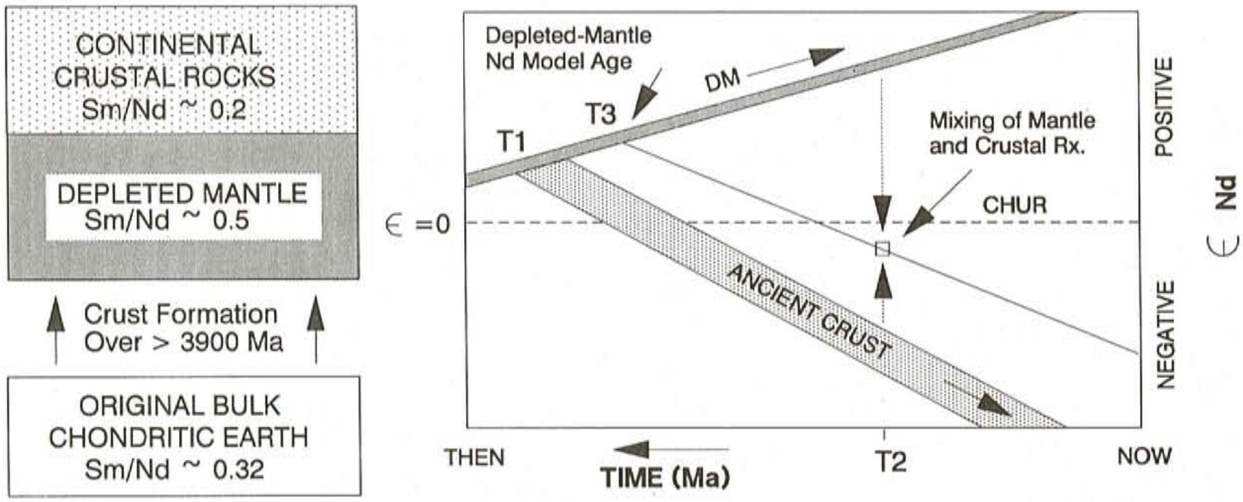

Figure 3. *Schematic representation of Nd isotopic reservoirs, and their evolution in time, and the interpretation of Nd isotopic data. Partly after Arndt and Goldstein (1987); see text for explanation and discussion.*

Earth at formation. The $\in_{Nd}$ value of any material changes with time as Sm continues to decay; thus, it is conventionally calculated for the geological age of the sample, i.e., both the Nd isotopic compositions of the sample and CHUR are corrected to 'initial' values. The $\in_{Nd}$ scale is easy to use, as it generally varies between about -20 and +10; positive values are enriched in ^{143}Nd (usually indicative of mantle origin) and negative values are depleted in ^{143}Nd (usually indicative of an older crustal component).

Interpretation of Data

The ∈ notation enables simple graphical representations of Nd isotopic data and isotopic evolution, as depicted in Figure 3 (after Arndt and Goldstein, 1987). Here, the horizontal line represents a theoretical chondritic composition, which always has $\in_{Nd}=0$. The depleted mantle (Sm/Nd > CHUR) evolves with a positive slope, tending toward higher $\in_{Nd}$ with time. Ancient crustal material (Sm/Nd < CHUR), derived from the mantle at time T1, evolves toward negative $\in_{Nd}$. If a hypothetical rock, known to have crystallized at time T2, has a slightly negative $\in_{Nd}$ value at that time, it was not derived entirely from the mantle, and must include some older crustal component.

However, there are two ways of interpreting this result. The simplest interpretation is that the rock formed via anatectic 'reprocessing' of pre-existing crust. The time at which this precursor formed is found by extrapolating the growth line of the sample backward in time until it meets the depleted mantle line. This gives the *depleted-mantle model* age, or T_{dm} (T3). This represents the maximum age of the precursor material. An alternative interpretation is that the rock formed at time T1 as a homogenized mixture of a mantle-derived magma, and older crustal rocks. This is a very likely scenario, as many models for granitoid magma genesis call upon such processes. In this case, the crustal component is significantly older than T3, and the 'model age' of the rock has no real geological meaning. Resolution of these alternatives depends on other types of data, e.g., trace-element geochemistry or analysis of zircon populations. However, the most important point, is that, in either case, the Nd isotopic signature of the granite is a sensitive indicator of the presence of older crustal rocks. Also, in either case, the model age provides a maximum for the geological age of the sample.

It should be pointed out that minor fractionation of Sm from Nd by anatexis or other processes can distort evolutionary patterns from the straight-line models assumed in Figure 3. However, such effects are very small compared to other systems (notably Rb–Sr) and can be quantified using REE patterns. The S-type leucogranites, which may be derived from garnet-bearing metasedimentary sources, are the most prone to such disturbance. The miniscule variation of Sm/Nd ratios in nature indicates that this isotopic system is, in most cases, well-behaved.

OXYGEN ISOTOPES

Oxygen isotopes (^{18}O and ^{16}O) are stable, but, as they are light, they are subject to mass fractionation. Variations are expressed as the parameter $\delta^{18}O$, calculated as:

$$\delta^{18}O = [(^{18}O/^{16}O \ / \ ^{18}O/^{16}O \ SMOW)-1] \times 10^3$$

SMOW is a standard value, referring to 'standard mean oceanic water'. This notation is analogous to the ∈ notation for Nd, except that $\delta^{18}O$ does not change with time, and the scaling factor is smaller. Variations in oxygen isotope compositions result from a wide range of processes, including evaporation, condensation, crystallization and diagenesis. Most sedimentary rocks, which have passed through the hydrosphere, have high ('heavy') $\delta^{18}O$ of > 10. Typically, granites have $\delta^{18}O$ from + 5 to + 12. Values of around + 6 resemble those of mantle-derived rock types, but values above + 9 resemble those of sedimentary rocks. Thus, $\delta^{18}O$ values are potentially useful tracers of sedimentary input into granitoid magmas.

ISOTOPIC DATA USED IN THIS PAPER

Nd and oxygen isotopic data were acquired over a three-year period, commencing in 1988. No numerical data listings are presented here.

Elemental concentrations of Nd and Sm are measured by inductively-coupled plasma mass-spectrometry (ICP-MS), using the methods of Jenner *et al.* (1990); overall uncertainties are estimated at ± 5 percent or better (2 sigma). The $^{147}Sm/^{144}Nd$ ratios used in this study are calculated from the concentration data above, and their overall uncertainties are estimated at ± 3 percent or better (2 sigma). The $^{143}Nd/^{144}Nd$ ratios are measured by thermal ionization mass spectrometry, after chemical separation of Nd from Sm and other REE by ion-exchange chemistry. Their overall uncertainty (2 sigma) is ± 0.007 percent or better. Calculations of $\in_{Nd}$ at the time of formation (or at any other time) use the standard CHUR values; present-day $^{143}Nd/^{144}Nd$ = 0.512638 and $^{143}Nd/^{144}Nd$ = 0.196593. Depleted-mantle model ages are calculated according to the models of DePaolo (1988). The overall uncertainty in the calculated $\in_{Nd}$ value for most samples is estimated at ± 0.5 ∈ units or better; in data representation, we show $\in_{Nd}$ values to the nearest whole number. It should be noted that $\in_{Nd}$ is sensitive mostly to $^{143}Nd/^{144}Nd$ ratios, and less sensitive to inaccuracies in the $^{147}Sm/^{144}Nd$ ratio. Also, the geological age of a sample is required to calculate $\in_{Nd}$, but the final value is insensitive to age variations of around ± 50 Ma. A 50 Ma age uncertainty translates to around ± 0.5 ∈ units for most samples; the younger the age, the lower the $\in_{Nd}$ value.

Oxygen isotope compositions were measured by gas source mass-spectrometry at the University of Western Ontario. The overall uncertainty in the final $\delta^{18}O$ values calculated for most samples is estimated at ± 0.2 $\delta^{18}O$ units.

REGIONAL ND AND OXYGEN ISOTOPIC PATTERNS

In this section of the paper, the regional isotopic variations amongst specific groups of plutonic suites are depicted as maps, in which calculated $\in_{Nd}$ or $\delta^{18}O$ values are shown. Some of these values represent single determinations; others are averages of more than one sample from the same location, or from closely spaced locations. For most plutons, 2 or more samples have been analyzed; where there are large variations between samples, the extreme values have been shown. As the symbols used are about 25 km in diameter, at the map scale, their positioning is approximate only, and we have not attempted to show the outlines of the plutonic suites that they represent.

PRE-OROGENIC PLUTONIC SUITES AND OTHER POTENTIAL SOURCE MATERIALS

Presently available isotopic data come mostly from suites that are related to the Appalachian cycle, and analyses of the plutonic rocks produced in the Grenvillian and Pan-African events are sparse. However, these rocks are important, as they are the only accessible representatives of potential basement blocks, and possible sources for younger Paleozoic plutonic suites. Similarly, the isotopic features of sedimentary sequences within the Central Mobile Belt (e.g., the Gander Group) are of interest, as these rocks may have been melted below the present erosion level to produce some of the granites that now intrude them.

Pre-orogenic Plutonic Suites of Western Newfoundland

The Nd isotopic compositions for these are represented at 430 Ma, rather than at their time of formation at around 1050 Ma (Figure 4a). This illustrates their features at a time when they may have been remelted to contribute to the younger Paleozoic magmas; in the context of this paper, this is probably more relevant than their original features. Early to Middle Proterozoic T_{dm} model ages of 1900 to 1500 Ma for most of these rocks are consistent with evidence that much of the Grenville Province in adjacent Labrador was initially formed during an earlier (Labradorian) orogenic cycle (e.g., Gower, 1991).

The Lake Michel Intrusive Suite, Potato Hill pluton and Long Range Inlier gneisses all have significantly negative $\in_{Nd}$ values at 430 Ma, ranging from -5 to -12 (Figure 4a). Thus, any Paleozoic granite magma derived entirely by melting of materials similar to the Long Range Inlier (i.e., the Grenville Crustal Block) should have a strongly negative signature that reflects the antiquity of this source.

Oxygen isotopic compositions (Figure 4b) vary from $\delta^{18}O$ of +7 to +9 for most Grenvillian plutonic rocks to +11 in the more leucocratic rocks with strongly negative $\in_{Nd}$; Long Range Inlier gneisses have $\delta^{18}O$ of +10 to +12.

Pre-Orogenic Plutonic Suites of Eastern Newfoundland

Very few data are currently available from Late Proterozoic suites of the Holyrood and Cross Hills associations; Nd isotopic results are illustrated in Figure 4a at 430 Ma. The Swift Current Granite has $\in_{Nd}$ of +1, and the Louil Hills Granite has $\in_{Nd}$ of +6, at their time of formation (570 Ma). The Louil Hills signature is close to depleted-mantle evolution, and suggests virtually no input from older crust. The Simmons Brook granodiorite of the Baie D'Espoir area has a strongly negative value of -6 (at 620 Ma) and has a T_{dm} model age of 1730 Ma. If this result is correct, it has important implications, as it seems to indicate a very old component in the Avalon Zone, which is not evidenced by other relevant data (see discussion).

The geochemistry of this unit appears inconsistent with an anatectic model, and it more likely represents mixing of mantle-derived magma and crustal material significantly older than 1700 Ma. Taken at face value, this suggests that there may be rocks of considerable antiquity beneath this region of the Avalon Zone. Oxygen isotopic compositions for the

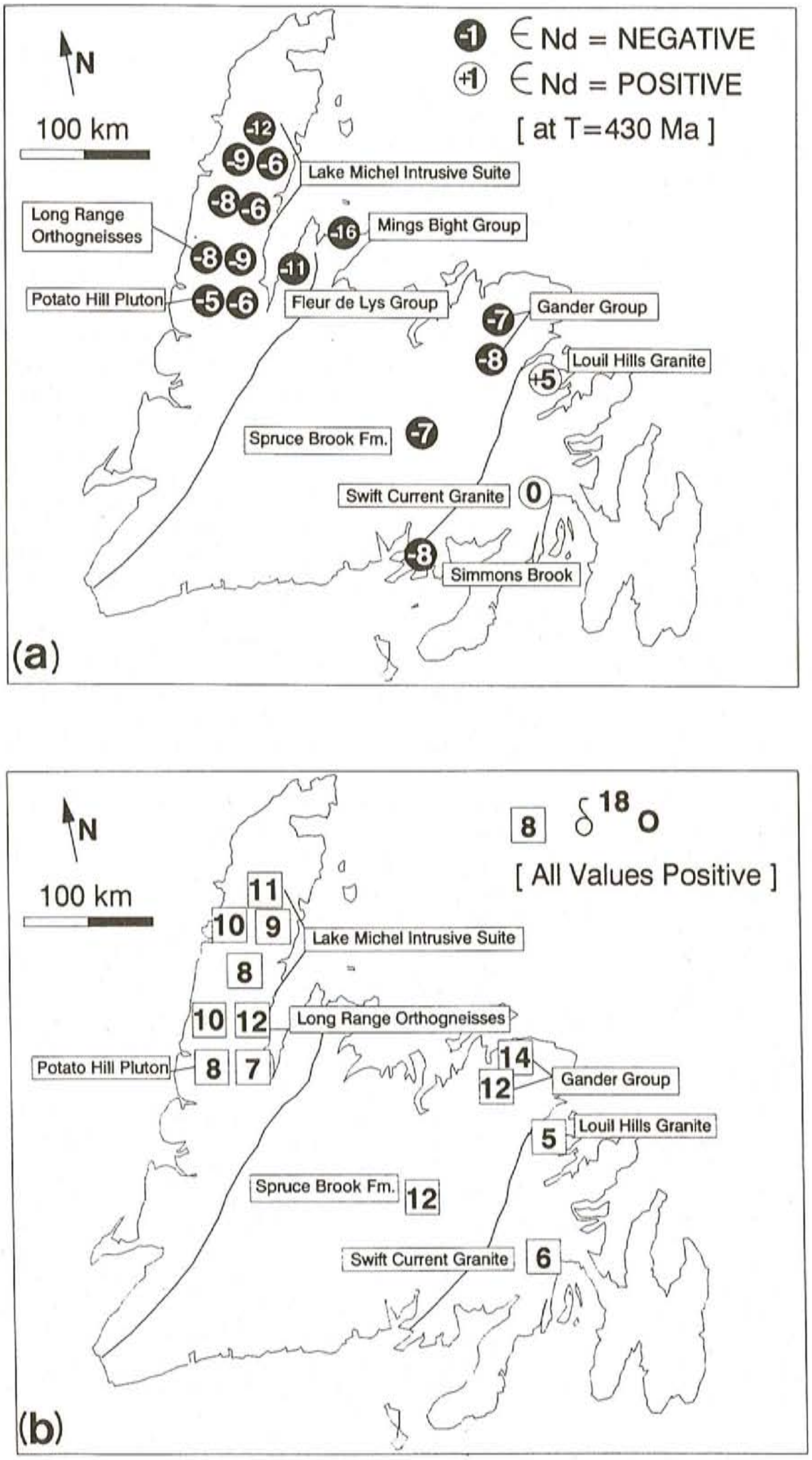

Figure 4. *The Nd and oxygen isotopic characteristics of pre-orogenic plutonic suites and other potential source terranes for Paleozoic granitoid magmas. (a)* ϵ_{Nd} *of pre-orogenic suites and metasedimentary sequences at T=430 Ma; (b)* $\delta^{18}O$ *of pre-orogenic suites and metasedimentary sequences.*

Louil Hills and Swift Current granites (Figure 4b) are characteristically light and similar to mantle values (+5 to +6).

Recalculation for 430 Ma has only minimal effects (< 2 ϵ units) upon the isotopic features of these pre-orogenic Avalon Zone granites (Figure 4a). The ϵ_{Nd} value for Simmons Brook at 430 Ma is -8, which is close to the Long Range Inlier values. If the Simmons Brook value is valid, it implies that parts of the Avalonian basement may overlap in isotopic composition with the Laurentian basement, leading to obvious discrimination problems.

Metasedimentary Sequences

Sedimentary rocks have isotopic and geochemical features that reflect their erosional sources; during subsequent metamorphic events, they may be melted to produce 'S-type' granites (Chappell and White, 1974; White and Chappell, 1990). Magmas derived from metasedimentary sources may also contaminate and/or mix with those derived from lower crustal or subcrustal regions. For these reasons, a knowledge of the isotopic features of the main metasedimentary packages in the Central Mobile Belt is very important.

The Gander Group of northeastern Newfoundland and the Spruce Brook Formation, which outcrops in structural windows within the Dunnage Zone, both have ϵ_{Nd} of about -7 at 430 Ma (Figure 4a), with model ages of 1900 to 1700 Ma. It should be noted that these values represent composite samples, not single locations, and thus represent the bulk features of these sequences. A single zircon and sphene study of a Gander Group psammite (T. Krogh, *in* O'Neill, 1991) gave a range of detrital zircon ages from 2700 Ma to 550 Ma, and sphene ages of around 540 Ma; similar detrital ages of 1600 to 1200 Ma have been reported from the Spruce Brook Formation (T. Krogh, unpublished data). This suggests that the T_{dm} values of 1900 to 1700 Ma reflect simply a mixture of older, but dominantly Proterozoic sources. Oxygen isotopic signatures of Gander Group composites are characteristically heavy, having $\delta^{18}O$ of +10 to +14.

The Fleur de Lys Supergroup, representing the continental rise prism of the ancient Laurentian margin, has ϵ_{Nd} of -11 (at 430 Ma) and model ages of 2000 Ma or older. These sediments thus contain some crustal material that is older than the gneisses sampled in the Long Range Inlier (their presumed source region). This could reflect small quantities of detritus from the central, oldest, part of the Canadian Shield.

The Ming's Bight Group, in the north of the Baie Verte Peninsula, has ϵ_{Nd} of about -16, and a model age of 2400 Ma. These sediments almost certainly contain Archean detritus; although they have been correlated with the Fleur de Lys Supergroup (Hibbard, 1983) they must have had quite different source areas. These results may argue against their correlation, but the limited information on the Fleur de Lys Supergroup may not document internal stratigraphic or geographic variations within this thick sequence. The most important point about this result is that a very ancient potential source or contaminant exists in the eastern Baie Verte Peninsula; a very small amount of Ming's Bight Group entering a rising magma could have dramatic effects on its Nd isotopic signature. This is particularly important in interpreting the rather complex patterns of Paleozoic plutonic rocks in this area (see below).

Further Work

It is clear from the above that our knowledge of the isotopic features of the late Precambrian crust of the Avalon Zone is inadequate. This places restrictions on our interpretation of data from younger suites in the Avalon and Gander zones. Several Avalonian intrusive suites were sampled in 1991, and are currently being analyzed. The present lack of data from late Precambrian metamorphic rocks and plutonic suites on the south coast (Dunning and O'Brien, 1989) and in the eastern Dunnage Zone (Evans *et al.*, 1990) is also of concern, as these represent possible basement to these areas.

Metasedimentary sequences in the Central Mobile Belt are also problematical. On the basis of existing data, they appear to be isotopically distinct, but there are not enough analyses to be certain that there are not equally significant variations *within* these sequences, or if there are systematic variations linked to stratigraphy or geography. It would also be very useful to have a firm picture of the detrital zircon populations in these rocks, preferably in a form that would allow estimates of the proportions of different-aged material to be made. The best method of obtaining the latter would be by ion-microprobe zircon studies, rather than conventional single zircon geochronology.

EARLY OROGENIC PLUTONIC SUITES

Early orogenic plutonic suites for which isotopic data are currently available fall into three clusters (Figures 5a, b).

Notre Dame Bay Area

The Twillingate trondhjemite complex (Williams and Payne, 1975; Payne and Strong, 1979) has ϵ_{Nd} of +3 to +6 at 510 Ma (Figure 5a); however, the majority of the samples lie at the high end of this range. The Burlington granodiorite and the Dunamagon granite of the Baie Verte Peninsula (Hibbard, 1983) have significantly lower ϵ_{Nd} of +1 to +2 and 0, respectively (Figure 5a). Twillingate has $\delta^{18}O$ of +8 to +10 (Figure 5b); no data are available from Burlington or Dunamagon. Recently, Jenner *et al.* (1991) examined trondhjemitic rocks of the Little Port and Bay of Islands complexes in western Newfoundland (Figure 5a). The Little Port Complex has ϵ_{Nd} of -1 to +1 at 505 Ma, which resembles the signature of Burlington. It is interpreted by Jenner *et al.* (1991) as an arc-type magma, with an older component introduced by subduction (see below). Trondhjemites of the slightly younger Bay of Islands Complex have ϵ_{Nd} of +6, and are more akin to the Twillingate data. The pre-Silurian Top Pond Brook tonalite in southwestern Newfoundland has ϵ_{Nd} of around 0.

It is clear that these suites do not contain very large amounts of older crust. This is consistent with their interpretation as products of subduction-related magmatism in an 'oceanic' domain, where older continental crust is not present in direct form (see below). Studies of arc-volcanic rocks in the ocean basins (e.g., White and Patchett, 1984) indicate that most have lower ϵ_{Nd} than the modern depleted-mantle (as represented by MORB), and must therefore include minor older crustal material. The most likely explanation is that continent-derived sediments were subducted into the zones of magma generation. The contrasts in ϵ_{Nd} amongst these suites may reflect contrasts in their positions (relative to continental margins) or in the age of the oceanic crust (and hence the thickness of its sediment cover) that was subducted. However, the probable major strike-slip displacements following closure of Iapetus render any attempt to relate present-day and original positions intrinsically hazardous. Nevertheless, we suspect that systematic geographic isotopic variations lurk within the Ordovician plutonic suites; finding these, and integrating the data with isotopic studies of volcanic suites, are major challenges for future work.

South-Central Newfoundland

The Partridgeberry Hills, Great Burnt Lake and Through Hill granites are now known to be Ordovician (ca. 470 Ma; Colman-Sadd *et al.*, *in press*). The first two have ϵ_{Nd} of -7 and -2 respectively (Figure 5a) and $\delta^{18}O$ of +9 to +11 (Figure 5b). These obviously have radically different origins from the Ordovician suites of Notre Dame Bay. The Partridgeberry Hills granite is within the spectrum of Gander Group metasedimentary rocks (Figure 4a). This, combined with its 'S-type' compositional affinities, indicates that it could have been derived largely by melting of the Gander Group. The high $\delta^{18}O$ values also support this interpretation.

The timing of emplacement of the eastern Dunnage Zone over the Gander Zone has been a subject of much debate, and there is growing evidence that this event occurred during the Ordovician (e.g., Dec and Colman-Sadd, 1990; Colman-Sadd *et al.*, *in press*). Ordovician granites in this area may

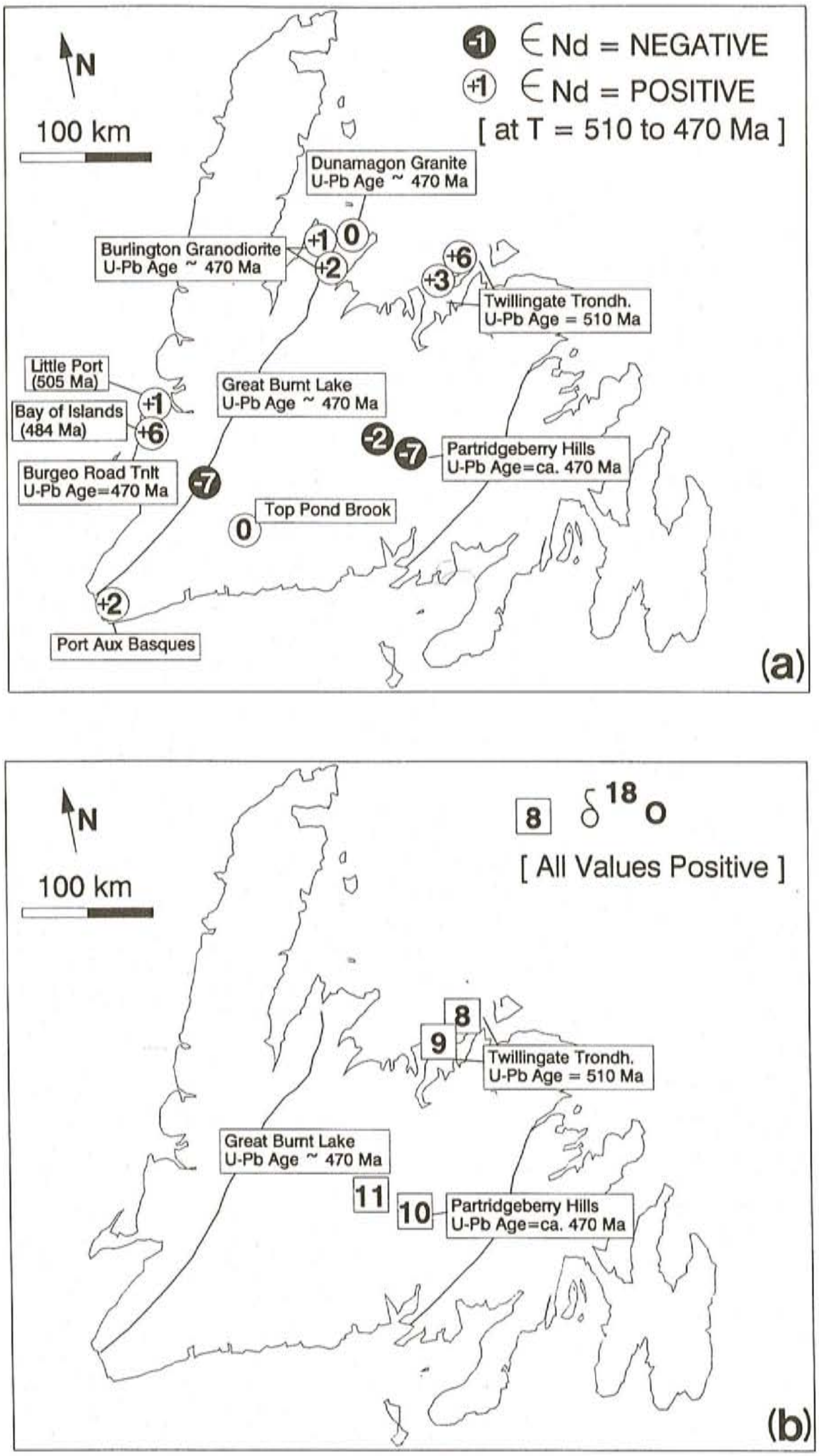

Figure 5. *The Nd and oxygen isotopic characteristics of early orogenic plutonic suites. (a)* ϵ_{Nd} *at formation; (b)* $\delta^{18}O$ *variations.*

thus reflect the thermal consequences of accretion within the underlying Gander Zone. Interpretation of the Great Burnt Lake result is more difficult, as this granite could not come entirely from a Gander Group source. One possibility is that its signature instead reflects a largely unexposed basement terrane below the supracrustal cover of the Gander Zone. This option, and the possible nature of this basement, are discussed further below.

Southwestern Newfoundland

Here, Dunning *et al.* (1989) report a U–Pb zircon age of ca. 460 Ma from a foliated tonalite that intrudes ophiolitic remnants. A sample from this unit displays a strongly negative ϵ_{Nd} (-7) at 470 Ma (Figure 5a); this value clearly indicates that the tonalite includes *very significant* amounts of old crust.

There are several ways to interpret this result, and more data are required before any preference can be established. Dunning *et al.* (1989) identified a significant proportion of older 'inherited' zircons, yielding an upper intercept of ca. 1430 Ma. The trace-element signature is strongly depleted in incompatible elements, and seems inconsistent with an origin by anatexis of Grenville Province gneisses or metasedimentary cover. A second alternative is mixing between a tonalitic magma and rocks including a very old component; e.g., something akin to the Ming's Bight Group, which probably contains Archean detritus. A third option is that the sample is a Proterozoic component of the Grenville Province, but this seems at variance with the geochronological evidence. Clearly, more data are required in order to understand this rather puzzling result. Southwestern Newfoundland represents a significant gap in the present isotopic database, and more work is needed in this area, where tonalitic rocks of both Proterozoic and Paleozoic age may be present.

Another potentially interesting result in this area comes from the Port-aux-Basques granite, which has ϵ_{Nd} of +2. The age of this is not documented; van Staal *et al.* (1991) suggest that it has experienced all the deformational events in this area, implying that it may be Ordovician. This is a muscovite-bearing granite with the hallmarks of an anatectic 'S-type' magma, presumably derived from the enveloping paragneisses.

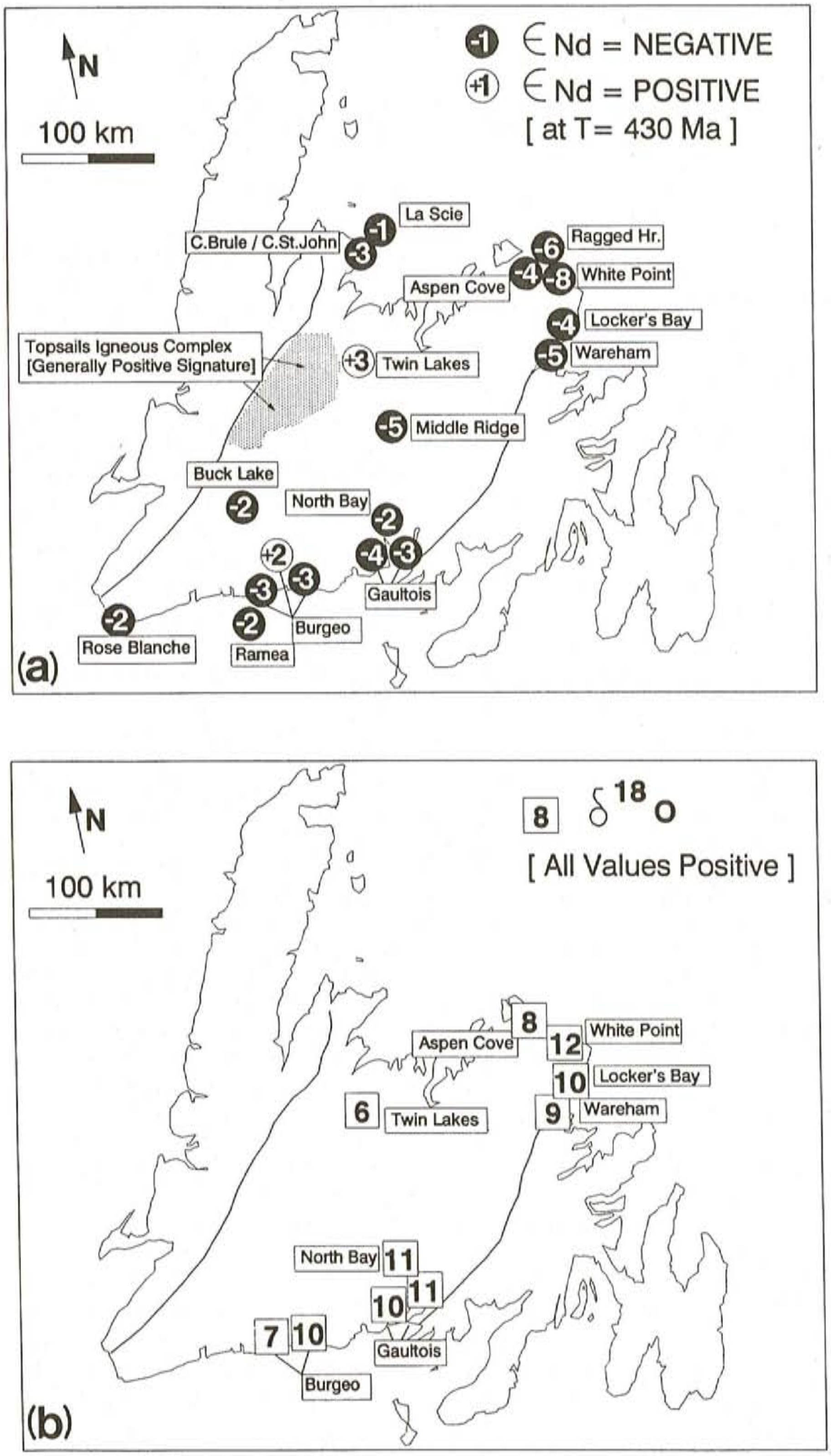

Figure 6. *The Nd and oxyten isotopic characteristics of late orogenic plutonic suites. (a)* ϵ_{Nd} *at formation, calculated for 430 Ma; (b)* $\delta^{18}O$ *variations.*

LATE OROGENIC PLUTONIC SUITES

The Nd and O isotopic data from plutonic suites of Silurian age are illustrated in Figure 6. Note that some intrusions discussed later under 'post-orogenic suites', may also be of Silurian age. For the sake of simplicity, an age of 430 Ma has been used for all ϵ_{Nd} calculations.

The Gander Zone

With only two exceptions, late orogenic suites from this area have negative ϵ_{Nd}, ranging from -2 to -8 (Figure 6a), and heavy $\delta^{18}O$, generally > +9 (Figure 6b). Muscovite-bearing leucogranite intrusions (e.g., the Middle Ridge, Aspen Cove, Ragged Harbour and White Point granites) have the lowest values (Figure 6a). Their ϵ_{Nd} ranges from values that resemble the Gander Group (-7) to slightly higher values (-5 to -4). An exception is the North Bay granite in south-central Newfoundland (-2). However, this is a composite batholith (Dickson, 1990), and this single determination may not be fully representative of it.

The negative ϵ_{Nd} and heavy $\delta^{18}O$ of the Middle Ridge association granites, in conjunction with their peraluminous 'S-type' geochemistry (e.g., Williams *et al.*, 1989; Kerr *et al.*, 1990), support their derivation largely by anatexis of metasedimentary rocks similar to the Gander Group. The closest fit to Gander Group isotopic compositions is shown by the Ragged Harbour and White Point granites of the Carmanville area (Strong and Dickson, 1978; Currie *et al.*, 1980). The latter is a nebulitic granite associated with migmatites; both appear to be products of local anatexis.

The Middle Ridge granite includes a complex, inherited zircon population (Tucker, 1990), which may be as old as Middle Proterozoic (ca. 1600 Ma). This is consistent with derivation from the Gander Group, in which detrital zircons of this general age are abundant (T. Krogh, *in* O'Neill, 1991). However, this example, and other representatives, have slightly higher $\in_{Nd}$ than the Gander Group composites. Similar displacement from host metasediments is shown by S-type granites of the Lachlan Fold Belt in Australia (McCulloch and Chappell, 1982), and the South Mountain Batholith of Nova Scotia (Clarke *et al.*, 1988).

As is commonly the case with isotopic data, this can be interpreted in two ways. First, they could be derived from an unexposed metasedimentary package that has a younger provenance than the Gander Group, or include a component from an underlying basement complex having a shorter crustal residence period. Second, they could be mixtures of a mantle-derived magma (with neutral or positive $\in_{Nd}$) and melts generated from metasedimentary rocks. There is no evidence of contemporaneous mafic magmatism in these intrusions, and most are characterized by extremely restricted compositional spectra (Kerr *et al.*, 1990). Thus, the first alternative is preferred. As is discussed below, the identity and nature of a possible basement to the Gander Zone is an important and (as yet) unresolved issue. The Rose Blanche granite in southwestern Newfoundland, grouped with the Middle Ridge association by Williams *et al.* (1989), has $\in_{Nd}$ of -2, suggestive of a source significantly different from the Gander Group.

The Burgeo association plutonic suites are characterized by negative $\in_{Nd}$ in almost all areas, but typically have $\in_{Nd}$ of -3 or higher (Figure 6a), above the upper limit of most Middle Ridge association granites. Indeed, if the Gander Zone is viewed in its entirety, it displays systematic variation in $\in_{Nd}$, from values down to -8 in the northeast, to around -3 on the south coast (Figure 6a). It is not clear if a comparable pattern exists in the relatively sparse oxygen data (Figure 6b). This variation correlates with the distribution of metasedimentary rocks of the Gander Group and its equivalents, which are concentrated in the northeast, but rare or absent on the south coast. The empirical link suggests that the Gander Group supracrustal rocks are in part responsible for these negative signatures, as suggested above. It also supports regional depth zonation, with the south coast representing deeper levels of erosion, where the influence of supracrustal rocks is significantly diminished.

In the Burgeo Intrusive Suite, 5 samples that represent a compositional range from megacrystic biotite–granite to muscovite-bearing leucogranite all have $\in_{Nd}$ of around -3. This suggests that these varied components of the suite had similar sources, and may be part of a single magma series. The Gaultois, Ramea and Buck Lake granites have comparable signatures; the slightly more negative character of the Locker's Bay and Wareham granites suggests a greater input from Gander Group materials, consistent with their location. An earlier determination of a ca. 410 Ma muscovite granite sample from the Burgeo Suite yielded a surprisingly juvenile value of +2 (Figure 6a). This result seems at odds with all of the other data from this area, and requires confirmation by re-analysis. There are also tonalitic rocks within the area of the Burgeo Intrusive Suite (Dickson *et al.*, 1989), which have not yet been analyzed. These may provide evidence of a juvenile (subcrustal) component involved in magma generation. Burgeo association suites could therefore be a mixture of three separate components, i.e., a mantle-derived magma, sialic crustal rocks of probable Precambrian age, and metasedimentary rocks with an ancient provenance, particularly in northeastern Newfoundland.

Western Newfoundland

There are presently few data from central and western Newfoundland, although some samples have been analyzed by J. Whalen and G.A. Jenner (unpublished data) and more are currently being processed from 1991 field work by A. Kerr.

On the Baie Verte Peninsula, two volcanic or subvolcanic suites of presumed Silurian age (Cape Brule Porphyry and Cape St. John Group) both yield $\in_{Nd}$ of around -3 (Figure 6a). It is hard to interpret these in isolation, but they appear inconsistent with data from the Topsails Complex and post-orogenic intrusive suites in this area, which are generally positive (see below). The proximity of the Mings Bight Group ($\in_{Nd}$ = -16 at 430 Ma), raises the possibility of high-level contamination, and their features may not be representative of deep geology. More samples are being analyzed from this area.

The largest Silurian intrusive complex in the Notre Dame Subzone, the Topsails Intrusive Suite, has not been studied as part of this project. However, J. Whalen (personal communication, 1991) reports that many of the A-type granites within the suite display positive $\in_{Nd}$ indicative of mantle derivation or only minimal contamination by older crust. Dioritic rocks of the ca. 435 Ma Twin Lakes intrusion also show positive signatures of ca. +3 (Figure 6a) and mantle-like $\delta^{18}O$ values (Figure 6b). Although this would be expected for mafic magmas, the spatially associated Hodges Hill Granite (see below) has almost identical isotopic features. Thus, although the picture is far from complete, the Silurian plutonic suites of the western Dunnage Zone appear to differ radically from those of the Gander Zone, as would also be inferred from the strong contrasts in their elemental geochemistry (e.g., Strong, 1980; Kerr *et al.*, 1990).

POST-OROGENIC PLUTONIC SUITES

The regional Nd and O isotopic variations amongst these suites are illustrated in Figure 7. Note that geochronological studies may force revision of some earlier ages based on Rb–Sr, K–Ar or Ar–Ar data. For the sake of simplicity, an age of 400 Ma has been used in all calculations of $\in_{Nd}$.

Southeastern Newfoundland

The most coherent grouping of Devonian plutons in Newfoundland is the Ackley association of Williams *et al.* (1989). The 14 suites analyzed to date fall into two distinct geographic and isotopic groups (Figure 7).

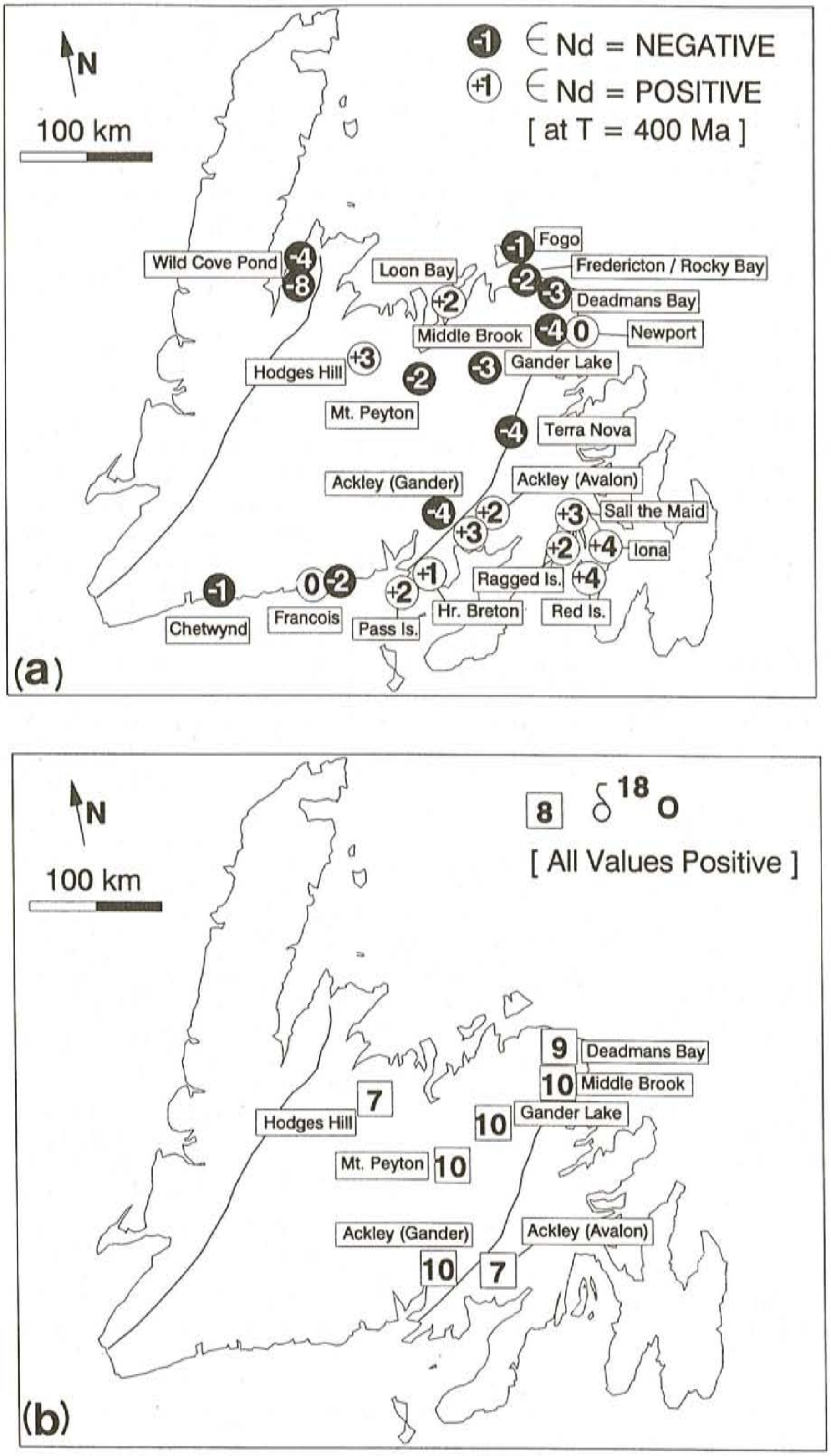

Figure 7. *The Nd and oxygen isotopic characteristics of post-orogenic plutonic suites. (a)* $\in_{Nd}$ *at formation, calculated for 400 Ma; (b)* $\delta^{18}O$ *variations.*

Within the Avalon Zone, almost all have $\in_{Nd}$ in the range +1 to +4 (Figure 7a); there seems to be an eastward increase in $\in_{Nd}$. Note, however, that the Ragged Islands and Sall the Maid plutons are assumed to be Devonian purely on the basis of lack of deformation, which may not be a fully reliable criterion in the eastern Avalon Zone. These values are not high enough to be purely mantle signatures, but they do suggest the absence of very old crust beneath most of the Avalon Zone. The unusual negative value from the 620 Ma Simmons Brook Granodiorite (Figure 4a; see earlier discussion) is the only countering observation. The Terra Nova Granite has $\in_{Nd}$ of -4 (Figure 7a), which resembles Gander Zone examples. However, this is very close to the inferred Gander–Avalon boundary, and the crust below it may not be part of the Avalon Block. Relatively few oxygen determinations are available, but the Avalon side of the Ackley Granite has mantle-like $\delta^{18}O$ of +7 (Figure 7b).

Within the Gander Zone, these granites are significantly more varied in isotopic composition. As in the case of Silurian suites (Figure 6), they display a regional variation (Figure 7a) from northeast ($\in_{Nd}$ of about -4) to the south coast ($\in_{Nd}$ = -2 to -1).The northeastern values are slightly higher than those of nearby Silurian plutonic suites. Their $\delta^{18}O$ values are also distinctly higher (around +10) than on the Avalon Zone side (Figure 7b). The regional isotopic trends, in our view, are once again linked to the distribution of Gander Group supracrustal rocks, and suggest that a contribution from these materials is *in part* responsible for the negative signatures. However, metasedimentary rocks cannot be entirely responsible, as they are rare on the south coast, where the Nd isotopic signatures of south coast granites remain distinct from those of Avalon Zone examples by 3 to 4 ∈ units (Figure 7a).

Dunning and O'Brien (1989) present evidence for the existence on the south coast of late Precambrian rocks that have compositional and temporal affinities with the lower-grade rocks of the type Avalon Zone. However, contrasts across the Hermitage Bay Fault at the western unit of the Avalon Zone (Figure 7), and the predominantly negative character of all plutonic suites on the south coast may imply significantly older (unexposed ?) crust with ages up to 1700 to 1300 Ma, or that the identified late Precambrian remnants were themselves derived from older material. Thus, late Precambrian 'basement rocks' on the south coast, although of similar age to the Avalon Zone, may have somewhat different affinities and origins. These problems can be investigated relatively simply by establishing the isotopic features of these enclaves *directly,* which should be a priority for the near future.

The strong contrasts across the Dover–Hermitage Bay fault system support the inferences of Keen *et al.* (1986) and Marillier *et al.* (1989) that this structure is a vertical, crustal-scale break. However, one of the more curious features of the onland transect (Quinlan *et al.*, 1991) is the lack of definition of the Hermitage Bay structure. One possiblity is that the structure may be difficult to image because it is sealed by a 'stitching pluton' similar to the Ackley Granite, several kilometres below the surface. On the basis of the isotopic contrasts displayed in Figure 7, we suggest that the Dover–Hermitage Bay fault *does* represent a major break, although it may perhaps only separate different segments of a composite 'Gondwanan' Precambrian terrane.

The Ackley Granite, which intrudes the Dover–Hermitage Bay fault and 'stitches' the Gander and Avalon zones, exhibits internal Nd isotopic contrasts, from -4 on the Gander side to +3 on the Avalon side, and also shows a contrast in oxygen isotopic compositions, as noted by Tuach *et al.* (1988). This large high-silica magma chamber has inherited and somehow retained the features of two separate source terranes. These variations suggest that it is a composite pluton or, alternatively, they place limits on the scale of any internal homogenization processes (e.g., convection) that operated within a large magma chamber of the type envisaged by Tuach *et al.* (1986).

The François Granite (ca. 380 Ma; Tucker, 1990) also displays interesting isotopic variations. The $\in_{Nd}$ value ranges from -2 in the oldest phases to around 0 in the youngest component, an evolved U-rich granite that forms the core of one of two ring-complexes. This suggests significant changes in the petrogenesis of magmas during the evolution of the complex, and stresses the importance of analyzing several samples from lithologically varied suites.

The other exception to the general negative pattern of Gander Zone intrusions is the Newport Granite of Bonavista Bay, whose $\in_{Nd}$ averages around 0. This is also a young granite, and lies immediately west of the Gander–Avalon zone boundary.

Western Newfoundland (Humber Zone)

The only analyses to date are from the Wild Cove Pond Intrusive Suite of the western Baie Verte Peninsula (Hibbard, 1983). This composite batholith includes dioritic rocks and K-feldspar megacrystic granites that (at least superficially) resemble those of the northeast Gander Zone. Subordinate muscovite-bearing leucogranites, locally foliated, are also present. Nd isotopic compositions are related to lithology; dominant megacrystic biotite-granites have $\in_{Nd}$ of about -4, whereas foliated leucogranites have lower values of around -8. The latter is similar to the composition of Grenville material at about 400 Ma, but slightly higher than typical Fleur de Lys Supergroup (-11 at 400 Ma; Figure 4d). The presence of gabbroic and dioritic rocks in the Wild Cove Pond Suite suggests that mantle-derived magmas may be implicated in its generation, and it seems reasonable to suggest mixing of this material with Grenville crust and/or Fleur de Lys metasediments. The leucogranites perhaps represent the crustal end-member component of the mixture.

Central Newfoundland

Small amounts of interesting data are available from central Newfoundland. In the Notre Dame Subzone, the Hodges Hill granite (ca. 410 Ma; Rb–Sr; B. Fryer, unpublished data) and the Loon Bay Granodiorite (408 ± 2 Ma; U–Pb, Elliot *et al.*, 1990) both have $\in_{Nd}$ of +2 to +3. Neither result seems consistent with the presence of significant amounts of Grenville basement beneath this area, as originally suggested by the offshore seismic-reflection lines (Keen *et al.*, 1986). Coupled with data from the Twin Lakes Diorites (Figure 6a) and the Topsails Intrusive Suite (J. Whalen, personal communication, 1991), these may argue for the presence of a relatively juvenile, possibly early Paleozoic crustal block in this area, rather than the Grenville crust suggested previously. This is a critical area for future data acquisition.

In contrast, plutonic suites that are close to the Dunnage–Gander boundary (e.g., Mt. Peyton; Fredericton and Rocky Bay plutons) have $\in_{Nd}$ of around -2, similar to signatures from those parts of the Gander Zone where metasedimentary sequences are poorly developed. The Fogo granite has a rather indeterminate signature of around -1; the abundant dioritic rocks at Fogo have not been analyzed yet.

On a first-order basis, the boundary between the positive and negative domains appears to be roughly coincident with the Red Indian Line, defined by Williams *et al.* (1988) as the boundary between the Notre Dame and Exploits subzones of the Dunnage Zone. There also appear to be contrasts in elemental geochemistry between the post-orogenic intrusive suites on either side of this line (Kerr *et al.*, 1990), but the data are not sufficient to draw firm conclusions. The correspondance with the Red Indian Line is not exact, as the Loon Bay Granodiorite actually lies within the Exploits Subzone.

The isotopic data do, however, suggest some fundamental significance for the Red Indian Line, which is roughly coincident with the western limit of typical Gander Zone isotopic signatures. The nature of the material to the northwest of the Red Indian Line is conjectural; it is possible that it represents a zone of relatively juvenile sialic crust, perhaps representing material generated at arcs developed at various times and places within Iapetus.

CONCLUDING REMARKS

It is clear that we do not yet fully comprehend the details of the isotopic patterns discussed in this report, and that many gaps remain in our knowledge. However, several points emerge; some have fundamental geological significance, whereas others point mostly at directions for continued research in the final year of the project.

1. The features of the Grenville Block are relatively well-established, although some data from the Indian Head Complex in southwestern Newfoundland are required.

2. The features of the Avalon Block are very poorly known. The present Nd and O isotope data do not characterize the late Precambrian crust of this area with enough reliability to allow it to be recognized elsewhere. It is also vital that late Precambrian rocks from the south coast and central Newfoundland be characterized, as these represent potential basement to the Gander Zone. The possibility of a late Precambrian 'Gondwanan' basement in central Newfoundland renders studies of the 'type' Avalon Zone very important.

3. Both the Gander Group–Spruce Brook formation and the Fleur de Lys Supergroup have T_{dm} model ages that are older than the Avalon and Grenville blocks, respectively. However, the first observation is tentative in view of our poor isotopic knowledge of Avalonian rocks. The Ming's Bight Group has a very ancient provenance; this material could have a powerful impact on any magma that encounters or digests it. In general, there is a requirement for more systematic studies of these sequences to establish if there are systematic stratigraphic and/or geographic isotopic variations within them.

4. Isotopic variations amongst Ordovician trondhjemite–tonalite–granodioritic suites may be related to the original locations of different arc systems relative to North America or Gondwanaland and/or their age. Ordovician 'S-type' granites in south-central Newfoundland record metamorphism and anatexis of the Gander Group, probably related to the accretion of the eastern Dunnage Zone. The isotopic features of probable Ordovician suites in the southwest Dunnage Zone are not well established.

5. The signatures of Silurian plutonic suites in the Gander Zone are consistent with the concept of a Late Proterozoic basement overlain by a supracrustal package derived from significantly more ancient Early and Middle Proterozoic sources. This is in accordance with geochronological data, but the relationship between this 'basement' and the type Avalon Zone may not be simple and direct. In the northwestern Dunnage Zone, it appears that most Silurian Suites had relatively juvenile characteristics; these argue against the presence of Grenvillian basement rocks, and perhaps indicate a discrete lower crustal block in this region, possibly representing arc systems accreted to North America.

6. Devonian plutonic suites show strong contrasts across the Gander–Avalon boundary. These isotopic contrasts between the Avalon Zone and Gander Zone plutons persist on the south coast, where metasedimentary rocks cannot be implicated for negative signatures within the latter. The Dover–Hermitage Bay fault system is thus an important isotopic break, despite problems in imaging it in the onland seismic data, and Upper Proterozoic basement west of it may not be *exactly* correlative with the type Avalon Zone, although the two could be parts of a single composite terrane. In central Newfoundland, plutons northwest of the approximate position of the Red Indian Line display relatively juvenile signatures compared to those to the southeast.

7. The Nd and O isotopic data should be augmented with information from other isotopic systems. On the basis of studies elsewhere (e.g., Ayuso, 1986; Ayuso and Bevier, 1991), whole-rock and/or feldspar Pb-isotopic studies are the most promising, as these have defined major crustal blocks and boundaries in a manner similar to that demonstrated here. In combination, the two methods are more powerful than each in isolation, and are more likely to provide unique solutions.

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