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DEVONIAN POSTOROGENIC GRANITES ON THE SOUTHEASTERN MARGIN OF THE NEWFOUNDLAND APPALACHIANS: A REVIEW OF GEOLOGY, GEOCHEMISTRY, PETROGENESIS AND MINERAL POTENTIAL

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ABSTRACT

The southeastern margin of the Newfoundland Appalachians is characterized by major 400 to 375 Ma postorogenic magmatism, which is associated with granophile (Mo–Cu, Sn–W, Pb–Zn and F) mineralization. These plutons intrude the Gander Zone, Avalon Zone and south coast region, and appear to have been localized along their mutual boundary, as defined by the Dover–Hermitage Bay fault system.

Devonian plutonic suites in the northeast Gander Zone are typified by very coarse-grained, strongly megacrystic granites that mostly contain metasedimentary enclaves. These have less evolved compositions than the other areas, and a marked tendency toward strongly peraluminous compositions, probably reflecting substantial assimilation of local metasedimentary country rocks. They have low $\in_{Nd}$ *(-4) consistent with a contribution from the Gander Group or similar materials, but they cannot be derived entirely from such a source. South coast plutonic suites include coarse megacrystic granites, but are generally finer grained and more equigranular. Their style of intrusion includes ring-complex formations, associated with widespread subvolcanic dyke swarms, and they are inferred to be exposed at significantly higher levels. They are geochemically evolved, metaluminous to weakly peraluminous, and show trace-element compositions that, in part, correspond to so-called 'A-type' or 'within-plate' granites. They have weakly negative* $\in_{Nd}$ *(0 to -2).*

Devonian plutonic suites of the Avalon Zone range from bimodal (gabbro-dominated) complexes to weakly peralkaline granites such as the St. Lawrence Granite. Some contain evidence of a coeval mafic magma in the form of mafic enclave populations and composite dyke swarms. These plutons all appear to be exposed at very high structural levels, and their roof zones can be directly observed. In terms of elemental geochemistry, they resemble south coast suites, but have a slightly greater affinity toward agpaitic compositions and 'A-type' trace-element signatures. They have strikingly different $\in_{Nd}$ *of +2 to +4, which is higher than the expected range of Avalon Zone Precambrian crust at the time of their formation.*

The strong isotopic contrasts between Avalon and Gander zone suites affirm the Hermitage Bay Fault as a major crustal-scale structure, and suggest that the late Precambrian crust of the south coast is at least isotopically distinct from that of the type Avalon Zone. The general geochemical congruency of all these suites requires a common petrogenetic model. The proposed model calls for mixing between a mantle-derived magma with high $\in_{Nd}$ *and melts of local lower crustal rocks, with variable contributions from upper crustal sources such as the Gander Group. High-level compositional evolution was dominated by fractional crystallization, mostly of feldspars. The highest mineral potential appears to be in suites that are exposed at high structural levels, notably those of the southern Avalon Zone, where areas, up to 5 or 10 km from granite contacts, may be underlain by the roof zones of evolved granites, which are the most likely sites for development and accumulation of enriched volatile phases.*

INTRODUCTION

GENERAL STATEMENT

This overview paper summarizes a major belt of Devonian postorogenic plutons in southern and eastern Newfoundland (Figure 1), and evaluates their geochemistry, petrogenesis and mineral potential. It synthesizes data from previous work and draws upon an integrated geochemical database now compiled for Newfoundland plutonic suites (Kerr *et al.*, 1991), and upon the results of geochemical and

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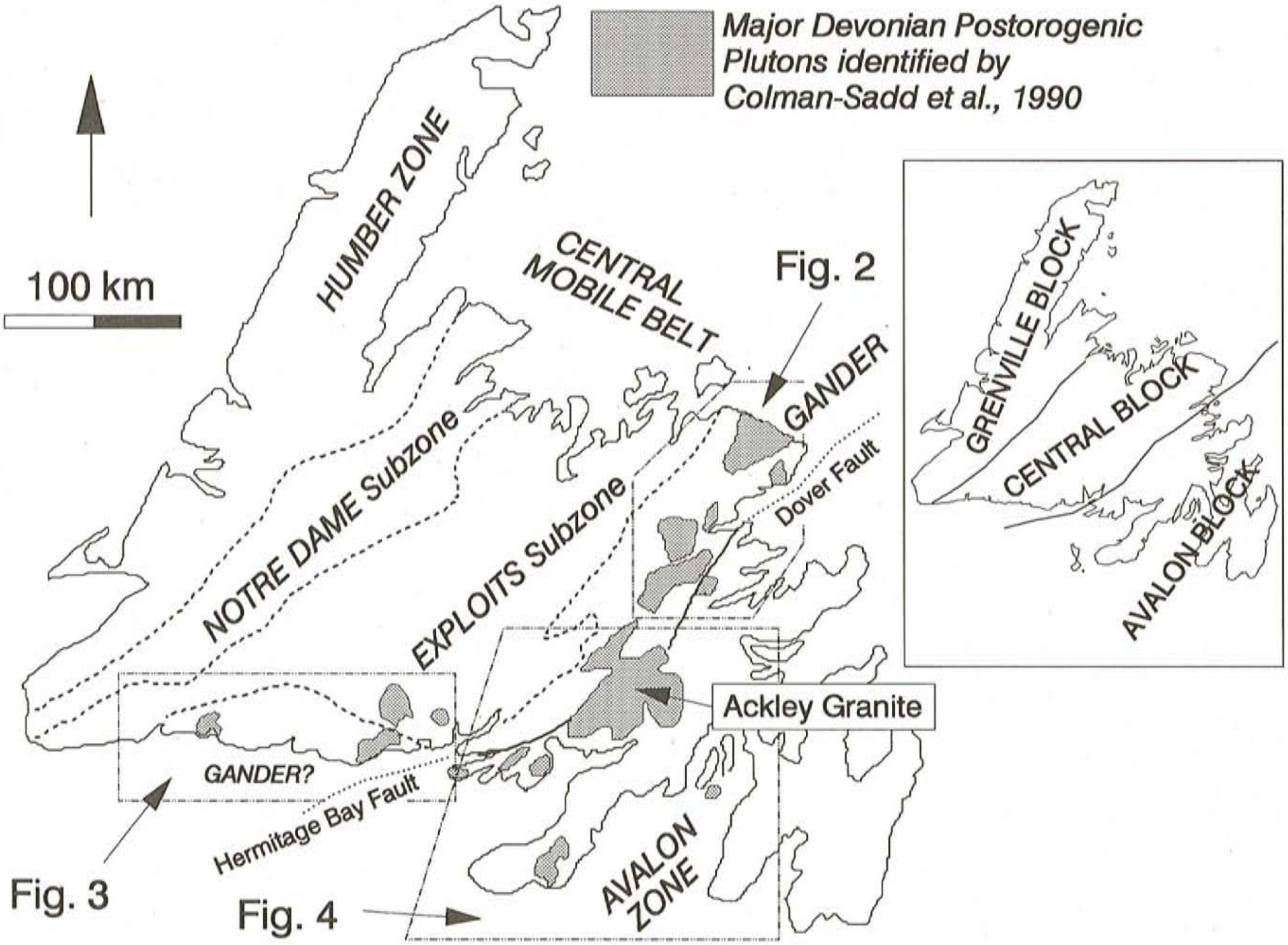

Figure 1. *Tectonostratigraphic subdivisions of the Newfoundland Appalachians and the locations of major Devonian granitoid plutonic suites in southeastern Newfoundland. Inset shows lower crustal blocks defined by seismic surveys.*

isotopic studies under LITHOPROBE East (Fryer *et al.*, 1992). It also incorporates information from regional field work conducted under the granitoid database project since 1989, by the senior author.

Devonian plutons in eastern Newfoundland include two well-known examples of granite-related mineralization, associated with the St. Lawrence and Ackley granites (e.g., Teng and Strong, 1976; Tuach *et al.*, 1986). Devonian plutonic suites also straddle the major tectonic boundary between the Avalon Zone and the Central Mobile Belt (Figure 1). The elemental and isotopic signatures of these granites may yield important clues about the nature of lower crustal basement rocks beneath these components of the orogen, and the significance of this boundary (e.g., Kerr *et al.*, 1990; Fryer *et al.*, 1992). Finally, these suites are important in the context of the wider debate concerning the petrogenesis of granitoid magmas, as they are typical of postorogenic granites found in many other belts.

REGIONAL GEOLOGICAL SETTING

The Newfoundland Appalachians are divided into four broad zones (Figure 1; Williams, 1979; Williams *et al.*, 1988). The Humber Zone of western Newfoundland represents the stable cratonic margin of North America, and is underlain by Grenville Province basement rocks. On the eastern side of the island, the Avalon Zone represents a continental block that originally lay to the east of the early Paleozoic Iapetus Ocean; this has been correlated with the late Precambrian 'Pan-African' terranes of the Gondwanaland continents (e.g., O'Brien *et al.*, 1983). The region between these two blocks (Central Mobile Belt) comprises remnants of the Iapetus Ocean (Dunnage Zone) and a belt of high-grade metasedimentary rocks intruded by numerous granites (Gander Zone). The Gander Zone has commonly been viewed as an early Paleozoic sedimentary prism developed on the Gondwanan margin of Iapetus, which was deformed and metamorphosed during the Siluro-Devonian Acadian Orogeny (e.g., Dallmeyer *et al.*, 1981). However, at least the eastern part of the Dunnage Zone is allochthonous, and was transported eastward across the Gander Zone during the Early Ordovician (Colman-Sadd *et al.*, 1992). The south coast region of Newfoundland has been variously assigned to the Gander Zone or Dunnage Zone, but lacks the characteristic metasedimentary sequence of the former or the ophiolitic rocks of the latter. This, coupled with the recognition of late Precambrian basement rocks (Dunning and O'Brien, 1989) has led to proposals that it be designated as a separate entity, perhaps related to 'Avalonia' (e.g., Barr and Raeside, 1989). However, the post-Ordovician plutonic history of the south coast region is analogous to that of the type Gander Zone, and it is viewed here (broadly) as a deeper level counterpart of this region.

The boundary between the Gander and Avalon zones is marked in the northeast by the Dover Fault (Figure 1), a major near-vertical structure that has a long history of activity dominated by Silurian dextral ductile deformation followed by late brittle deformation (Holdsworth, 1991; O'Brien and Holdsworth, 1992). In the south, its presumed equivalent is the Hermitage Bay fault (Figure 1), where extensive late brittle deformation appears to have largely obscured any earlier history of ductile motion (S. O'Brien, personal communication, 1992).

Seismic reflection studies conducted as part of the LITHOPROBE East project (Keen *et al.*, 1986; Marillier *et al.*, 1989) defined three lower crustal blocks beneath Newfoundland (Figure 1; inset). The Dover Fault is a crustal-scale vertical structure, separating an eastern (Avalonian?) crustal block from an unidentified region beneath the Central Mobile Belt (termed the Central Block). More recently, it has been proposed that the Central Block may be a continuation of composite Avalonian lower crustal materials (Quinlan *et al.*, 1992), based on their similarities in seismic structure, and poor definition of the Hermitage Bay Fault. Modifications to the tripartite lower crustal block structure were also proposed by Fryer *et al.* (1992) on the basis of isotopic data from granites across the island.

PLUTONIC EVOLUTION OF GANDER AND AVALON ZONES

Several 'granitoid associations' (defined as groups of plutonic suites having similar petrology, geochemistry and age) in the Newfoundland Appalachians can be grouped into broad preorogenic, early orogenic, late orogenic and postorogenic categories (Williams *et al.*, 1989; Kerr *et al.*, 1992).

The Gander Zone and south coast regions are typified by complex late-orogenic plutonic suites of Silurian age (Burgeo and Middle Ridge associations), dominated by megacrystic biotite granites and muscovite–biotite leucogranites respectively (Williams *et al.*, 1989). Devonian postorogenic plutons (Figure 1) are assigned to the Ackley Association of Williams *et al.* (1989); they range from megacrystic to equigranular, high-level, biotite granites. The latter are more common on the south coast.

Within the Avalon Zone, no Silurian plutonism has been recognized. Paleozoic plutonism is represented by scattered posttectonic plutons (Figure 1), that are generally equigranular, silica-rich, biotite granites (Williams *et al.*, 1989). The link between these and postorogenic suites of the adjacent Gander Zone has long been recognized (e.g., Strong, 1980), and they are also grouped as part of the Ackley Association (Williams *et al.*, 1989). The type example (Ackley Granite) is a classic 'stitching pluton', as it intrudes the Gander–Avalon boundary (Figure 1), and provides an upper limit for juxtaposition of the two tectonic zones.

GEOLOGY AND PETROLOGY OF DEVONIAN PLUTONIC SUITES

For purposes of description, Devonian plutonic suites are grouped into four geographic areas, i.e., the northeast Gander Zone, south coast region, western Avalon Zone, and eastern Avalon Zone. The Ackley Granite, which straddles the Avalon and Gander zones, is described in conjunction with south coast plutons. These divisions are not arbitrary.

This report focuses mainly upon relatively evolved, potassic, postorogenic granites that were intruded along the southeastern margin of the Newfoundland Appalachians, i.e., in the Gander Zone, Avalon Zone and south coast regions. Devonian or presumed Devonian plutons in the Dunnage Zone and correlative regions are excluded from this discussion; as many of these assignments are based on old K–Ar and Rb–Sr isotopic data, some of these rocks may actually be older. In the south coast region, two probable Devonian plutons that lie within an area of doubtful zonal affinities north of the Bay d'Est fault (Ironbound and Peter Snout granites of Chorlton and Dallmeyer, 1986) have also been excluded from the present discussion.

Geochronology is presently the weakest link in defining the precise extent and duration of Devonian plutonic events in the areas discussed. Published K–Ar and Rb–Sr isochron ages in the range 390 to 350 Ma (summarized by Mandville, 1989) provide a good indication of age for posttectonic, undeformed granites, but many are likely significantly younger than their actual emplacement ages. Our view of such rocks is based on a combination of available geochronology and field data, including lithological similarities to dated examples. More recent U–Pb zircon data (e.g., Dunning *et al.*, 1990; O'Brien *et al.*, 1991) suggests a major episode of plutonism ca. 390 Ma, although a few plutons (notably St. Lawrence and François granites) appear younger at ca. 375 Ma.

In this paper, the Devonian granites are implicitly viewed as a single 'magma sequence', i.e., as a group of intrusions that are related in space and time, but which include both older and younger members. Subsequent presentation of more detailed geochronological data may lead to an alternate viewpoint, i.e., two or more discrete pulses of magmatism.

DEVONIAN PLUTONS OF THE NORTHEAST GANDER ZONE

Regional Geology

The oldest rocks in this area (Figure 2) are metasedimentary rocks of the Gander Group, and their

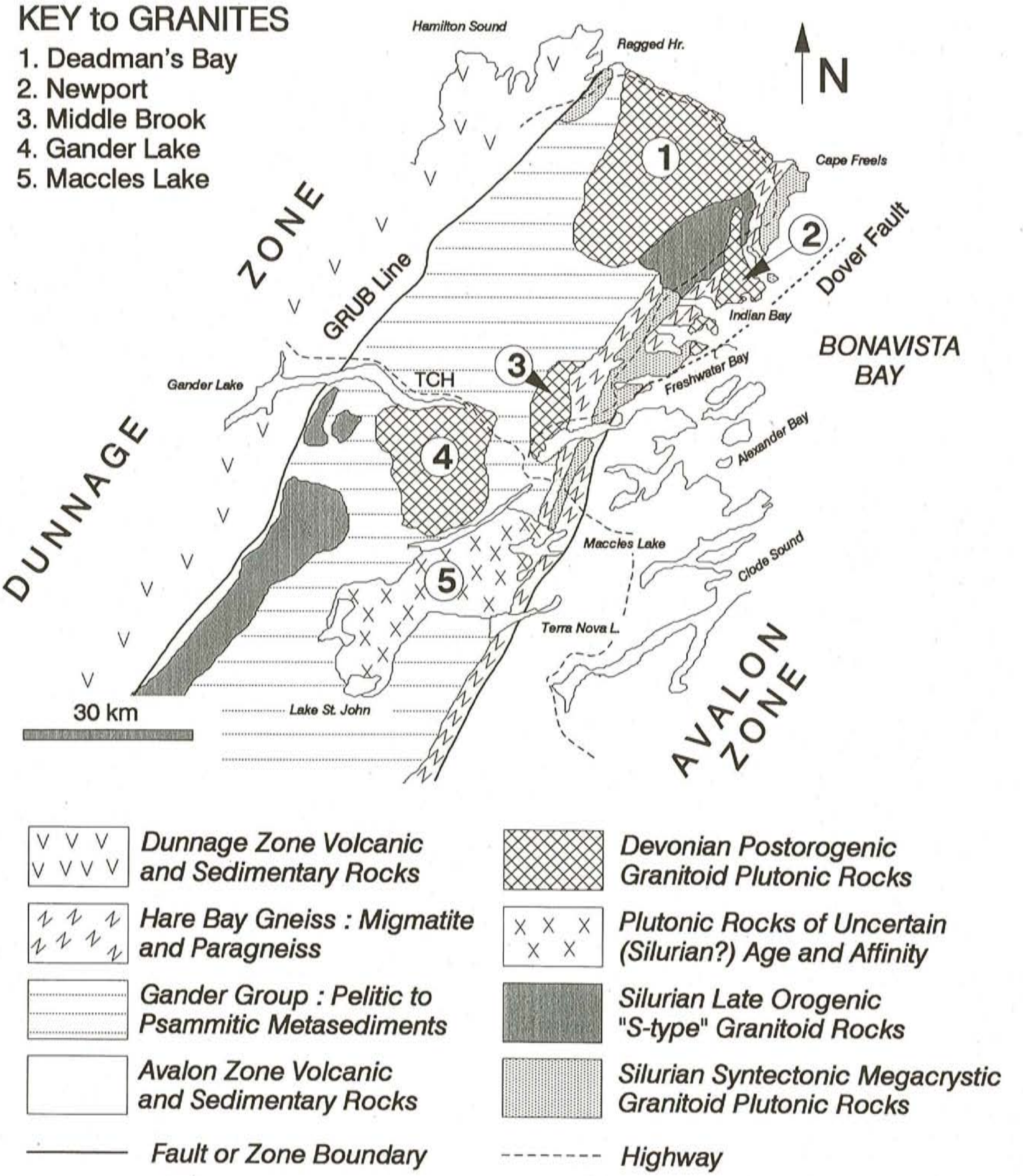

Figure 2. *Generalized geology of the northeastern Gander Zone (after Colman-Sadd* et al., *1990), and locations of Devonian plutonic suites.*

migmatitic equivalents (Hare Bay gneisses). The latter are concentrated along the eastern boundary of the Gander Zone, and become strongly mylonitic adjacent to the Dover Fault (Blackwood, 1978; Holdsworth, 1991).

Excluding possible early orthogneiss components recognized within the Hare Bay gneisses by Holdsworth (1991), the oldest plutonic rocks are syntectonic, K-feldspar megacrystic, biotite granites of Silurian age (ca. 417 Ma;

Tucker, 1990). These are cut by foliated biotite–muscovite granites on a wide variety of scales, which appear to be derived by anatexis of the supracrustal rocks. These two groups correspond broadly to the Burgeo and Middle Ridge associations (Williams *et al.*, 1989; see above). Four major posttectonic granite plutons have been defined in the northeast Gander Zone (Jayasinghe, 1978; Blackwood, 1978; Figure 2), and these have been assumed to be of Devonian age, although not all are dated by U–Pb methods. A fifth pluton, the Maccles Lake granite, is excluded from discussion as recent examination (O'Brien and Holdsworth, 1992, and AK) suggests that it corresponds closely to nearby syntectonic Silurian suites. As the western end of this pluton is unmapped, it is possible that it is composite, and also includes undeformed granitoid rocks.

Deadman's Bay Granite

The Deadman's Bay Granite (Strong *et al.*, 1974; Jayasinghe, 1978), occupies almost 1000 km² at the northeastern termination of the Gander Zone, and probably extends well offshore. The granite cuts the Hare Bay gneisses, deformed megacrystic granites, and muscovite-bearing leucogranites (Jayasinghe, 1978).

The Deadman's Bay Granite is typically a grey- to pink-weathering, homogeneous, coarse to very coarse-grained biotite granodiorite to monzogranite, characterized by large (up to 15 cm long) K-feldspar (microcline) megacrysts, locally displaying rapakivi texture. Smaller plagioclase phenocrysts are also locally present. Scattered xenoliths of biotite-rich, variably layered, hornfels are probably of metasedimentary protolith. Jayasinghe (1978) reports the presence of (cognate?) inclusions of a fine-grained, possibly marginal, phase; however, there is no evidence of chilling at the southeastern contact. The granite is commonly massive and undeformed. However, a strong phenocryst alignment is present adjacent to its southeastern contact (Strong *et al.*, 1974; Jayasinghe, 1978), and is subparallel to the regional penetrative foliation in the older metamorphic and plutonic rocks to the east. In accordance with earlier workers, this is viewed as a primary magmatic feature, rather than a penetrative fabric. R. Holdsworth and R. D'Lemos (personal communication, 1992) suggest that it may be the response of a crystal-mush intrusion to a regional stress field, i.e., a pre-full crystallization (PFC) fabric. If this is the case, it may imply that parts of the Deadman's Bay Granite were emplaced synchronously with deformation. However, marginal foliations are a common feature of diapiric intrusions and the congruency of this alignment with regional trends may be purely coincidental. A similar megacryst alignment is also seen at the northwestern margin (Strong and Dickson, 1978).

Rb–Sr studies of the granite have proved inconclusive (see summary by Strong and Dickson, 1978), and an early U–Pb zircon study by Berger and Naylor (1974) yielded inconclusive ages between 510 ± 10 Ma and 385 ± 10 Ma. Given the high probability of inheritance (suggested by the abundant xenoliths), it is unlikely that any of the older U–Pb ages are accurate. Currie (in Stevens *et al.*, 1981) reports a K–Ar age of 400 ± 13 Ma. The most recent determination is a $^{40}Ar/^{39}Ar$ total-gas biotite age of 404 ± 4 Ma from a megacrystic granite, which is consistent with a 397 ± 5 Ma plateau age from muscovite in the aureole of the granite (O'Neill and Lux, 1989). It is likely that the actual emplacement age is slightly older than the $^{40}Ar/^{39}Ar$ ages, and an earliest Devonian age is probable.

Newport Granite

The Newport Granite (Strong *et al.*, 1974; Jayasinghe, 1978) is a crosscutting, undeformed pluton (Figure 2). It clearly intrudes the Hare Bay gneisses and older foliated granitoid rocks, truncating all penetrative fabrics. The closely similar Big Round Pond granite of Jayasinghe (1978) is viewed here as a phase of the Newport Granite, as originally suggested by Jayasinghe and Berger (1976).

The Newport Granite is a homogeneous, coarse-grained, pink- to buff-coloured, K-feldspar porphyritic biotite granite, which is similar in many respects to the Deadman's Bay Granite, although finer grained and more leucocratic. Microcline megacrysts range from 2 to 4 cm in length, and are typically well-formed, with local rapakivi textures. Plagioclase phenocrysts are extremely rare. There are screens of deformed megacrystic granite adjacent to the eastern contact, but xenoliths and enclaves are otherwise rare; a few cognate inclusions of dioritic composition were observed in coastal outcrops, as were rare angular hornfels fragments. Finer grained, equigranular phases (similar to the Big Round Pond granite of Jayasinghe, 1978) are locally present on an outcrop scale, as are very coarse pegmatitic segregations.

The Newport Granite is almost completely undeformed. A very weak, local, phenocryst alignment is clearly a magmatic feature. Brittle faults cut the granite at one locality, indicating that the very latest motions on the Dover Fault postdated its intrusion (Holdsworth, 1991). An early Rb–Sr age of 332 ± 42 Ma (Bell *et al.*, 1977) is probably erroneously young. More recent Rb–Sr studies (B. Fryer, 1993, unpublished data) yield a good 366 ± 5 Ma isochron, which is consistent with its position as the youngest granite of the area. However, given the tendency of Rb–Sr ages to be too young, it may not reflect the actual emplacement time.

Middle Brook Granite

The Middle Brook Granite (Strong *et al.*, 1974; Blackwood, 1978; Figure 2) intrudes the Gander Group metasedimentary rocks and their migmatized equivalents, but is not in contact with older foliated plutonic suites.

The granite is a coarse-grained, pink-weathering, K-feldspar (microcline) megacrystic biotite granite that is superficially similar to the Deadman's Bay and Newport granites (see above). Plagioclase phenocrysts are subordinate to K-feldspar, and it has distinctive blue-grey quartz grains (Blackwood, 1978). The interior of the granite is largely undeformed, but a penetrative fabric, defined mostly by biotite alignment, is present near its margins and on small islands in Freshwater Bay (Blackwood, 1978; R. Holdsworth, personal communication, 1992). As discussed above, interpretation of locally developed fabrics in granites is always difficult, as the process of intrusion itself can produce such marginal features; however, the fabric developed in the Middle Brook Granite is a post-crystallization feature, and therefore contrasts with that seen at Deadman's Bay (Holdsworth, 1991), which is manifested only by megacryst alignment.

The Middle Brook Granite has yielded a Rb–Sr age of 420 ± 20 Ma (Bell *et al.*, 1977), and Ar–Ar plateau age of 379 ± 6 Ma (Dallmeyer *et al.*, 1981); the Ar–Ar age (on biotite) was interpreted to reflect metamorphism, rather than crystallization. A Silurian, rather than Devonian, age is thus permissable for this intrusion. As discussed subsequently, it has a distinctly less evolved composition than the other northeast Gander Zone plutons, which may also reflect a difference in age.

Gander Lake Granite

The Gander Lake granite (Strong *et al.*, 1974) is a rectangular body exposed south of Gander Lake (Figure 2). It displays clear intrusive contacts with the Gander Group metasedimentary rocks in many areas, with extensive hornfels development (O'Neill, 1991).

The Gander Lake granite has two textural variants. The northeastern corner of the pluton, well-exposed on the Trans-Canada Highway, consists of medium- to coarse-grained, pink, equigranular, quartz-rich, biotite granite, of fresh and undeformed appearance. Interior portions of the pluton, and exposures along Gander Lake, are coarse-grained, K-feldspar megacrystic biotite granites that resemble other northeast Gander Zone plutons (O'Neill, 1991). The K-feldspar phenocrysts range up to 6 cm in size, but are more commonly around 2 to 3 cm long. O'Neill (1991) reports the existence of a primary magmatic fabric defined by phenocryst and xenolith alignment in the northeastern part of the body, and also comments on the abundance of metasedimentary xenoliths in this area. Tourmaline-bearing pegmatitic segregations are also reported (O'Neill, 1991). The only geochronological data from the granite is a K–Ar (biotite) age of 357 ± 25 Ma (Lowden, 1960).

DEVONIAN PLUTONS OF THE SOUTH COAST REGION

Regional Geology

The general geology of the south coast of Newfoundland is illustrated in Figure 3 (after O'Brien *et al.*, 1986; Colman-Sadd *et al.*, 1990; O'Brien *et al.*, 1991). Although the post-Ordovician plutonic history here is analogous to that of the type Gander Zone, some aspects of the geology suggest comparisons with the Dunnage Zone (O'Brien *et al.*, 1986).

The oldest rocks are late Precambrian enclaves in the Grey River and Cinq Cerf areas (Figure 3). These consist of migmatitic orthogneisses, mafic and felsic supracrustal rocks, and ca. 580 to 560 Ma plutonic rocks (Dunning and O'Brien, 1989; O'Brien *et al.*, 1991). Sedimentary and volcanic rocks in the western part of the area include the Ordovician Bay du Nord Group and the Silurian La Poile Group; in the east, the Baie d'Espoir Group is probably a broad equivalent of the former sequence. The area mostly lacks the characteristic pelitic–psammitic metasedimentary sequence of the northeastern Gander Zone. However, the area between Baie d'Espoir and Hermitage Bay includes similar paragneisses, associated with voluminous biotite–muscovite (± garnet) granites, of probable anatectic origin (Little Passage gneisses). The area has a post-Precambrian to Silurian magmatic and deformational history, as evidenced by the detailed work of O'Brien *et al.* (1991), but this is beyond the scope of this report.

All of these components were affected by a major Silurian orogenic event (Dunning *et al.*, 1990), which was associated with voluminous plutonism. The Burgeo intrusive suite (Dickson *et al.*, 1989) is a composite body of foliated, K-feldspar megacrystic granodiorite to granite. Subordinate components include mafic plutonic rocks, tonalites and quartz diorites. A distinctive younger component comprises biotite–muscovite granites, that probably form part of the Middle Ridge Association. The foliated megacrystic granitoid has given a U–Pb age of 429 ± 5 Ma, and the biotite–muscovite granite was dated at 415 ± 2 Ma (Dunning *et al.*, 1990). The plutonic rock types and relationships are strikingly similar to those of the northeast Gander Zone (see above), and closely similar, syntectonic, K-feldspar megacrystic granites along the south coast have also given U–Pb ages between 430 and 420 Ma (Dunning *et al.*, 1990; O'Brien *et al.*, 1991).

Devonian posttectonic plutonic rocks on the south coast provide a lower limit for this orogenic activity. Four plutons are recognized (Figure 3). The Ackley Granite (also described in this section) is located in Figure 4.

Dolland Brook–Facheaux Bay East Granites

The North Bay Granite Suite, as defined by Dickson (1990) incorporates both syntectonic and posttectonic plutonic rock types. Older, foliated granitoid rocks are probably broad equivalents of the Burgeo and Middle Ridge associations discussed previously. However, two units of massive, largely unfoliated granite form a distinct younger component. One of these, the Dolland Brook granite, has a U–Pb zircon age of 396^{+6}_{-3} Ma (Dunning *et al.*, 1990).

The Dolland Brook granite intrudes migmatitic metasedimentary rocks (considered to be Bay du Nord Group equivalents) and foliated biotite–muscovite granites. It consists of medium- to coarse-grained, pink, K-feldspar porphyritic biotite granite, which is generally massive and undeformed. Metasedimentary xenoliths occur close to contacts with country rocks, but are otherwise rare. The smaller Facheaux Bay East Granite is a closely similar rock type (Dickson, 1990).

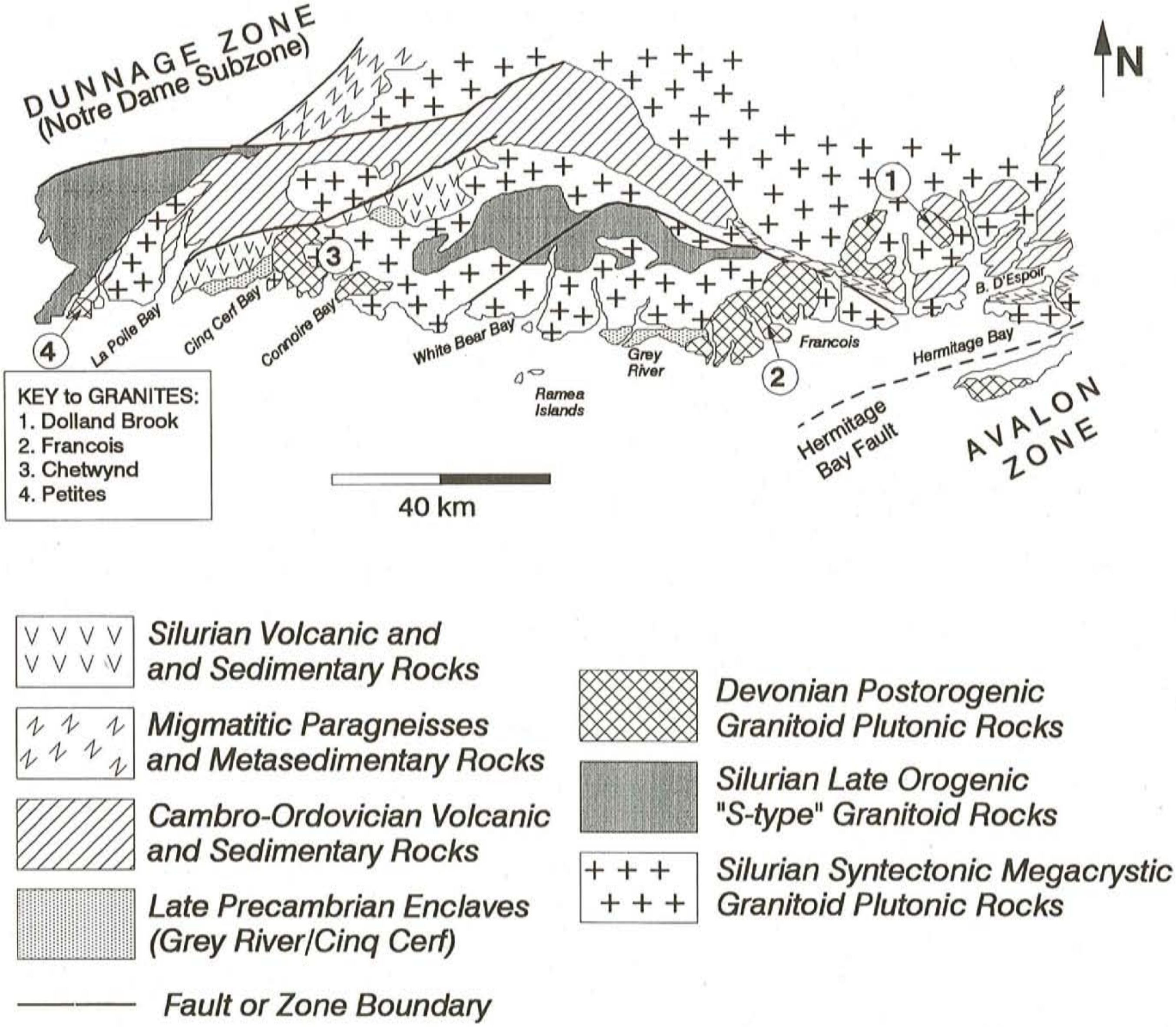

Figure 3. *Generalized geology of the south coast of Newfoundland (after Colman-Sadd* et al., *1990), and locations of Devonian plutonic suites.*

François Granite

The François Granite (Williams, 1971; Poole *et al.*, 1985; Dickson *et al.*, 1989; Figure 3) is one of the most striking and scenic elements of south coast geology. It consists of two overlapping circular plutons that show the characteristic geometry of ring-complexes. The complex intrudes late Precambrian metamorphic rocks, syntectonic Silurian granitoid rocks of the Burgeo and Gaultois granites and (as porphyry dykes) intrudes the Bay du Nord Group supracrustal rocks. It is the youngest plutonic unit on the south coast, and truncates two ductile shear zones that affect the Silurian plutonic rocks (Dickson *et al.*, 1989).

The most abundant rock type in the François Granite is a coarse-grained, massive, pink, leucocratic biotite granite, which has both equigranular and K-feldspar porphyritic variants (Poole *et al.*, 1985). A wispy biotite layering, possibly a primary 'cumulate' feature, is present locally in these units. These rock types form the outer, oldest, parts of the ring structures. A more mafic, grey, coarse-grained, plagioclase-porphyritic unit intrudes the older units, forming a near perfect ring in one complex. The final phase of intrusion is a medium-grained, buff, alaskitic, biotite granite. Fine-grained aplite and sanidine-bearing porphyry dykes, with a northerly trend, are abundant in areas around the pluton. The François Granite has no penetrative fabrics, although it is cut by very minor late brittle faults (Poole *et al.*, 1985). The plagioclase-porphyritic phase has yielded a precise U–Pb zircon age of 378 ± 2 Ma (Tucker, 1990) with no signs of an inherited component.

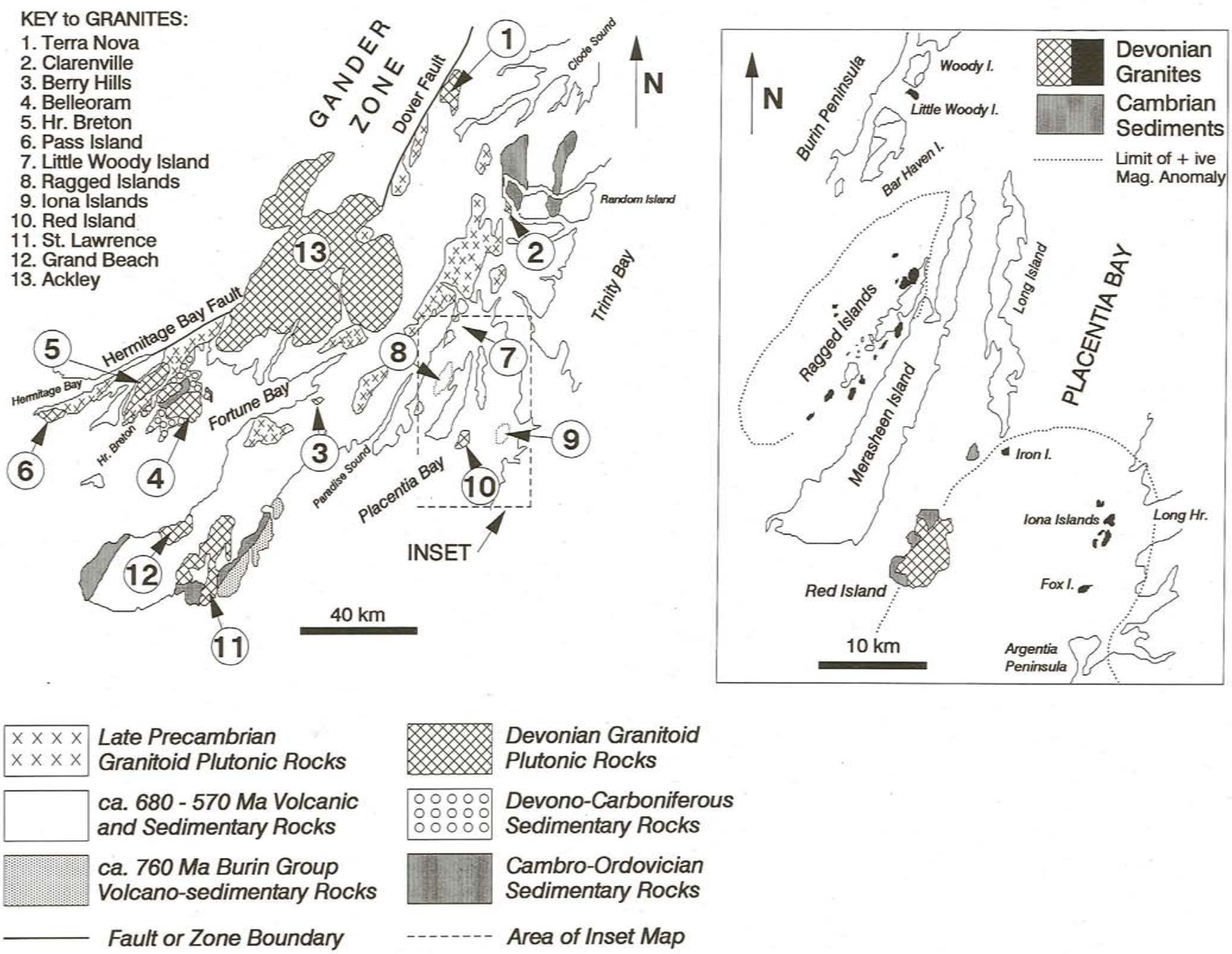

Figure 4. *Generalized geology of the Avalon Zone in Newfoundland (after Colman-Sadd* et al., *1990), with locations of Devonian plutonic suites. Inset shows details of minor intrusive suites in the Placentia Bay area.*

Chetwynd Granite

The Chetwynd Granite (Cooper, 1954) is located at the western extremity of the Burgeo Intrusive Suite (Figure 3). It intrudes late Precambrian enclaves, Silurian foliated megacrystic granites, and also crosscuts folded and deformed rocks of the Silurian La Poile Group (Dickson *et al.*, 1989; O'Brien *et al.*, 1991).

The Chetwynd Granite includes coarse-grained, generally pink, K-feldspar porphyritic biotite granite, locally with quartz phenocrysts, and coarse-grained, equigranular, quartz-rich biotite granite. The more quartz-rich, equigranular variants are common at high topographic elevations (Dickson *et al.*, 1989), suggesting that they represent a roof phase. Miarolitic cavities, pegmatite–aplite segregations and hydrothermal breccias indicate that the present erosion surface lies close to the high-level, upper contact of the pluton. Feldspar-porphyry dykes, containing sanidine, occur over a wide area adjacent to the pluton.

The Chetwynd Granite has previously given an imprecise U–Pb zircon age of 377 ± 20 Ma, and a Ar–Ar cooling age of 372 ± 5 Ma (Chorlton and Dallmeyer, 1986). A more recent, high-precision U–Pb zircon age of 390 ± 3 Ma (O'Brien *et al.*, 1991) provides the best estimate of the time of crystallization.

Petites Granite

The Petites Granite (Brown, 1976) intrudes the Bay du Nord Group and the foliated biotite–muscovite granites of the Rose Blanche Granite. It consists of medium- to coarse-grained, pink, homogeneous biotite granite. Most of the body is equigranular to seriate in texture, but K-feldspar-porphyritic variants, with up to 30 percent phenocrysts, are present locally (Brown, 1976). A finer grained phase, gradational to quartz-feldspar porphyry, is also seen in places. The granite is undeformed, but is affected by fracturing and hematization around Bay de Moine, where it is cut by a late brittle fault. A K–Ar age of 357 ± 16 Ma (Wanless *et al.*, 1967) was obtained from the pluton.

Ackley Granite

The Ackley Granite (Strong *et al.*, 1974; Dickson, 1983; Tuach *et al.*, 1986) is the largest and best known posttectonic pluton in southeastern Newfoundland. It occupies almost 3000 km² to the north of Fortune Bay (Figure 4), and is the only clear example of a 'stitching pluton' between the Avalon and Gander zones. It has a complex, lobate pattern, suggesting that it was developed by the coalescence of several discrete intrusions.

The Ackley Granite intrudes two tectonic zones; however, most of it is located within the Avalon Zone (Figure 4). Within the Gander Zone, it intrudes metasedimentary rocks that are probably broad equivalents of the Gander Group farther to the north (Figures 1 and 2). Within the Avalon Zone, it intrudes late Precambrian volcanic and sedimentary rocks, and also postdates late Precambrian plutonic rocks of the Cross Hills Plutonic Suite (Tuach, 1991). Roof pendants of late Precambrian country rocks are found in the central part of the pluton.

Dickson (1983) recognized ten major phases in the granite, but their mutual relations are hard to establish, and many are probably gradational. In the northwest, the granite is dominated by coarse-grained, variably porphyritic, K-feldspar (microcline) megacrystic biotite (± hornblende) granodiorite to granite. In the southeast, it is dominated by pink and red, medium- to coarse-grained, equigranular to K-feldspar porphyritic, quartz-rich, leucocratic biotite granites. There are fine-grained phases adjacent to the southern contact, and a general southward decrease in grain size. The granite is also increasingly miarolitic toward the southern contact, and contains other features indicative of high crustal levels, such as hydrothermal breccias ('tuffisites') and giant quartz crystals (Tuach *et al.*, 1986). There is general agreement that these finer grained phases in the southeast represent the roof zone of the pluton (Whalen, 1983; Dickson, 1983). Geochemical studies on both local and regional scales (Whalen, 1983; Tuach *et al.*, 1986) indicate progressive geochemical changes toward the southeastern contact, defined by increases in SiO_2 and incompatible trace elements, and a corresponding decrease in CaO, MgO and compatible elements. Tuach *et al.* (1986) interpreted these to reflect liquid-state fractionation processes similar to those indicated by geochemically zoned tuff sequences (e.g., Hildreth, 1981), and suggested that the Ackley Granite represented a 'frozen' zoned magma chamber. They could also be attributed to fractional crystallization processes within the magma chamber (Whalen, 1983). Tuach *et al.* (1986) also noted that relatively sharp gradients for several elements occur at the projected trace of the Gander–Avalon boundary.

Several geochronological studies have been conducted in the Ackley Granite. Bell *et al.* (1977) obtained a Rb–Sr age of 355 ± 10 Ma (recalculated for revised decay constant); this was later duplicated by Tuach (1986), who obtained 353 ± 9 Ma. A large number of K–Ar and Ar–Ar determinations of various parts of the granite have been conducted since the 1960's (see Kontak *et al.*, 1988 for a detailed summary); these have given ages from 405 to 338 Ma (the latter was for hydrothermal muscovite in a molybdenite zone). The most recent and comprehensive study is that of Kontak *et al.* (1988) who obtained Ar–Ar ages of 378 to 374 Ma for the main phases of the pluton, and 373 to 371 Ma for hydrothermal mineralization. Two areas in the northwest of the pluton, which gave ages of 410 to 392 Ma, are now been excluded from the Ackley Granite, as they likely form discrete older intrusions. The mineral prospects associated with the granite's southern contact are discussed separately.

DEVONIAN PLUTONS OF THE AVALON ZONE

Regional Geology

In Newfoundland, the Avalon Zone (Figure 4) is dominated by low-grade late Precambrian and earliest

Paleozoic volcanic, plutonic and sedimentary rocks, overlain by Cambro-Ordovician sedimentary rocks (O'Brien *et al.*, 1983, 1990).

No high-grade basement rocks have been recognized in the Avalon Zone of Newfoundland. The oldest rocks are submarine mafic volcanic and mafic plutonic rocks and clastic sediments of ca. 760 Ma age, preserved in a fault-bounded block in the Burin area. These are followed by three discrete sequences of late Precambrian volcanic and sedimentary rocks, separated by orogenic events. (O'Brien *et al.*, 1990, 1992a, 1992b). The oldest sequence formed prior to 680 Ma, and is dominated by felsic volcanic rocks of probable arc affinity. A 630 to 600 Ma sequence of felsic volcanic rocks, overlain by clastic sedimentary rocks, is the most abundant component; extensive ca. 620 Ma calc-alkaline granitoid rocks (Holyrood Association of Williams *et al.*, 1989) were probably coeval with this volcanism. A third cycle from 580 Ma to 550 Ma is characterized by terrestrial sedimentation and bimodal, locally peralkaline volcanism and plutonism. Cambro-Ordovician sedimentary sequences unconformably overlie the late Precambrian terranes.

Upper Ordovician and Silurian rocks are essentially absent from the onland stratigraphic record (O'Brien *et al.*, 1990). Devonian (and possibly Carboniferous) events are recorded by deformation, terrestrial sedimentary rocks, minor volcanic rocks, and the intrusion of several posttectonic granite plutons (Figure 4).

WESTERN AVALON ZONE PLUTONS

Terra Nova Granite

The poorly exposed Terra Nova Granite (Strong *et al.*, 1974) lies adjacent to the extension of the Dover Fault (Figure 4); it intrudes Precambrian metavolcanic and metasedimentary rocks, and a narrow offshoot also appears to intrude mylonites of the fault zone (O'Brien and Holdsworth, 1992). The most characteristic rock type, exposed near the community of Terra Nova, is a pink- to orange-weathering, friable, coarse-grained, K-feldspar porphyritic, biotite granite, locally containing hornblende. It is closely similar to megacrystic biotite granites of the adjacent Gander Zone (e.g., Gander Lake and Newport granites). O'Brien and Holdsworth (1992) report the occurrence of a finer grained, equigranular variant, and scattered hornfels xenoliths. The granite has yielded a Rb−Sr age of 328 ± 10 Ma (Bell *et al.*, 1977; recalculated for new decay constants), which is probably a severe underestimate.

Clarenville Granite

The Clarenville Granite (Strong *et al.*, 1974) is a small body exposed around the town of Clarenville, notably on the Trans-Canada Highway (Figure 4). It is a red-weathering, medium-grained, equigranular, quartz-rich, leucocratic granite, that is seen to intrude and hornfels metavolcanic country rocks. It has never been dated, and the assumption of a Devonian age is based entirely on its undeformed character and similarity to other, dated, Paleozoic granites.

Berry Hills Granite

The Berry Hills Granite (O'Brien *et al.*, 1984) is a small body located just above the kneecap of the Burin Peninsula (Figure 4); Strong *et al.* (1974) referred to it as the Bay L'Argent pluton. It intrudes metavolcanic and sedimentary rocks of the Love Cove Group. The pluton is dominated by red-weathering, fine- to medium-grained, equigranular (locally granophyric) leucocratic, quartz-rich, biotite granite, with subordinate coarser granite and aphanitic felsite. As noted by O'Brien *et al.* (1984), graphic quartz-feldspar intergrowths are widely developed in finer varieties; these imply high-level, rapid crystallization. The granite is unfoliated, except where truncated and brecciated by late fault zones; it is cut by felsite dykes (cogenetic?) and undeformed diabase. As in the case of several other Avalon Zone plutons, geochronological data are lacking; the Devonian age is based on deformation state and lithological similarity to dated examples.

Belleoram Granite

The Belleoram Granite (Widmer, 1950; Ermanovics *et al.*, 1967; Strong *et al.*, 1974; Furey, 1985) is an elliptical pluton located in northwestern Fortune Bay (Figure 4). It intrudes late Precambrian metavolcanic and metasedimentary rocks, Cambrian sedimentary rocks (Chapel Island Formation) and Devonian conglomerates (Great Bay de L'Eau Formation). The most recent study was that of Furey (1985). The following description combines Furey's observations with those of AK and R. Morrissey (personal communication, 1992).

The most abundant unit in the Belleoram Granite is a grey- to pink- or buff-coloured, medium-grained, equigranular quartz monzonite to monzogranite, containing biotite and rare hornblende as mafic phases. This rock type is characterized by ubiquitous darker-coloured, more mafic enclaves, which occur on a scale of 0.5 to 10 cm, and invariably show ellipsoidal shapes. These enclaves form a continuum from fine-grained diabase-like blobs to medium-grained intermediate plutonic rocks, to diffuse darker-coloured patches that otherwise resemble the host granite. Enclaves of fine-grained felsic plutonic rocks also occur, but are rare, as are angular xenoliths that may be derived from the country rocks. The proportion of enclaves varies widely, but very few outcrops appear devoid of them. A grey-coloured marginal phase of granodiorite to monzogranite composition is very rich in enclaves, and exhibits textures that are highly suggestive of interaction between felsic and mafic magmas; these include complex lobate and cuspate contacts between phases, and disrupted chilled margins on the relatively mafic components. Furey (1985) proposed, after Vernon (1984), that enclaves were derived from the disruption of synplutonic mafic dykes derived from a lower level of the magma chamber. A petrographic, geochemical and isotopic study of the enclaves is currently in progress by R. Morrissey.

A third, slightly younger, component consists of fine-grained, brick-red, alaskitic quartz-rich granite and granophyre that is enclave-poor to enclave-free. This forms spectacular composite dykes with diabase margins, quartz-feldspar porphyry centres and brown, intermediate (hybrid?) inner zones. The felsic centres to the dykes contain numerous rounded diabase enclaves, strongly suggestive of mixing processes. Other outcrops of this fine-grained phase display spectacular hydrothermal breccia zones; significantly, these crosscut diabase dykes that themselves intrude the granite, and demonstrate that mafic magmas coexisted with the cooling granite. The breccias, coupled with miarolitic cavities and a spectacular exposure of the upper contact of the granite, clearly indicate a high level of emplacement.

The age of the Belleoram Granite is constrained by Late Devonian plant fossils in rocks that it intrudes (Widmer, 1950), and by K–Ar (biotite) ages of 408 ± 20 Ma (Wanless *et al.*, 1965) and 349 ± 20 Ma (Wanless *et al.*, 1967). The older age is in conflict with the stratigraphic evidence, and is considered to be disturbed.

Harbour Breton Granite

The Harbour Breton Granite (Strong *et al.*, 1974) consists of two narrow, elliptical plutons, located west of the Belleoram Granite (Figure 4; Greene and O'Driscoll, 1976; Furey and Strong, 1986). Both plutons display variable composition and texture, particularly around their margins. The plutons intrude a variety of units, including late Precambrian volcanic and metaplutonic suites (Connaigre Bay Group and Simmons Brook Granodiorite), and Cambrian sedimentary rocks of the Chapel Island Formation. The eastern pluton (Old Woman Stock) intrudes the Devonian conglomerates of the Pools Cove Formation (Greene and O'Driscoll, 1975; Furey and Strong, 1986).

Furey and Strong (1986) defined six units in their 'Harbour Breton Complex', and suggested that both plutons had a generally concentric structure. This subdivision is impractical on the basis of field characteristics, and three broader units are recognized here. The most abundant phase is a pink- to white-weathering, medium- to coarse-grained, variably textured biotite granite, ranging in places to a plagioclase-free alkali-feldspar granite. The texture varies from equigranular to K-feldspar porphyritic, and locally is also quartz-porphyritic. Plagioclase-bearing variants typically have a speckled appearance, with pale-green sericite alteration of plagioclase grains. All are leucocratic, with 2 percent or less mafic minerals; hornblende is rare. Many areas near the margins of the plutons consist of a brick-red fine-grained quartz-feldspar or feldspar-porphyritic granite of alaskitic character; according to Furey and Strong (1986), this is gradational with the main phase.

As in the case of the Belleoram Granite, the widespread occurrence of miarolitic cavities, rapid textural variations, quartz veining, and minor Mo–F mineralization, collectively suggest a high level of emplacement. Dykes and stockworks of equigranular granite are commonly observed in the surrounding country rocks, notably along the Northeast Arm of Harbour Breton, and suggest that the roof of the pluton lies close to the erosion surface over wide areas.

The age of the Harbour Breton Granite is constrained stratigraphically, as it intrudes Devonian conglomerates. A Rb–Sr age of 343 ± 10 Ma was reported by Strong (1980) (K. Bell, personal communication), but no analytical data were ever presented. This age is probably an underestimate.

Pass Island Granite

The Pass Island Granite (Strong *et al.*, 1974; Greene and O'Driscoll, 1976) is located at the western tip of the Hermitage Peninsula (Figure 4). The granite intrudes the gabbro and diorite of the late Precambrian Grole Intrusive Suite (O'Brien *et al.*, 1992b), and dykes of fine-grained granite cut the diorites 2 to 3 km from the contact.

At least three phases are present in the Pass Island Granite. The most abundant is a pink-weathering, coarse- to very coarse-grained, equigranular biotite granite, commonly friable and rubbly weathering in outcrop. This is in contact with a medium-grained, massive, slightly K-feldspar porphyritic buff granite, which resembles some of the dykes seen to cut the Grole diorites. Age relations are equivocal. A third phase consists of a grey-weathering, seriate to porphyritic biotite granite containing phenocrysts of both K-feldspar and plagioclase. The rock types exposed within the Pass Island pluton are strongly reminiscent of the François Granite, which is only about 30 km west of Pass Island. There are no firm constraints on the age of the Pass Island Granite, beyond the fact that it intrudes Precambrian rocks. However, its undeformed character, and lithological similarities to François and Harbour Breton granites, indicate a Devonian age.

Little Woody Island Granite

O'Driscoll (1976) defined a composite granitoid unit in northwestern Placentia Bay, termed the 'Sall the Maid Granite', after earlier workers, and suggested that it was of Paleozoic (possibly Devonian) age. Subsequent examination by AK suggests that there are two ages of granites within this unit. The more abundant (Figure 4; inset), is a grey, hornblende-rich quartz diorite to granodiorite that is locally foliated and recrystallized, and variably epidotized. This rock is cut by schistose, foliated metadiabase dykes, and also by fresh diabase dykes. Its general appearance, and the presence of deformed dykes, suggest that it may be late Precambrian, perhaps related to the nearby Swift Current Granite.

However, a younger phase is also present. On Woody Island, green-grey granodiorite cut by chloritized schistose dykes is cut by a dyke of fresh, pink, granite. The same contact relationship is seen on adjacent Little Woody Island (Figure 4; inset), which consists mostly of fine-grained, red-weathering, equigranular quartz-rich granite, cut only by fresh diabase dykes. Although there is brittle deformation and fracturing around faults, this granite appears otherwise undeformed, and it is a good candidate for a Devonian intrusion. The informal term 'Little Woody Island granite' is used here for this small body. It appears to be a high-level cupola, where many miarolitic cavities are common, and the outcrops are riddled with quartz veins, many of which are vuggy.

EASTERN AVALON ZONE PLUTONS

Ragged Islands Granites

The Ragged Islands intrusions (O'Driscoll and Muggridge, 1979) occupy hundreds of tiny islands and skerries located northwest of Merasheen Island in central Placentia Bay (Figure 4; inset). The intrusions were termed the 'Tack's Beach pluton' by Strong *et al.* (1974). Granite assigned to the suite is observed to cut late Precambrian volcanic rocks at several localities.

The Ragged Islands intrusions are somewhat variable in composition, as noted by O'Driscoll and Muggridge (1979). In the northwest, they include a homogeneous, white-weathering, hornblende—biotite quartz diorite to granodiorite. Although it lacks any sign of deformation, this rock is reminiscent of probable Precambrian granites on Bar Haven Island. To the southeast, adjacent to Merasheen Island, there is a homogeneous, pink granite, having an equigranular to plagioclase-porphyritic texture. This has a vuggy texture, where vugs are filled with pistachio-green epidote, and some contain a white fibrous mineral and/or sulphide. Plagioclase phenocrysts have greenish sericite—clay mineral alteration. According to O'Driscoll and Muggridge (1979), this rock intrudes the white granodiorite seen in the west. In many respects, this situation resembles that in the Woody Island area, and it is possible that only the pink granite is truly of Paleozoic age.

Iona Islands Intrusions

The Iona Islands Intrusions, a bimodal suite of gabbro, diorite and granite (McCartney, 1967; Peckham, 1992) form the most easterly expression of Paleozoic Appalachian plutonism in Newfoundland (Figure 4; inset). Both phases intrude and hornfels late Precambrian sedimentary rocks; their petrology and geochemistry was recently discussed by Peckham (1992); the following description is based on this work and observations by AK.

About 90 percent of the suite consists of a medium-grained, grey to black pyroxene—hornblende—biotite gabbro to diorite, which exhibits wide textural variations. This is cut and net-veined by fine-grained, pink to red equigranular biotite granites; the contact relations of granitic pipes, dykes and sills with their gabbroic host are complex, and there are strong indications of magma interaction and mixing. Granitic bodies commonly include numerous pillowform mafic enclaves, on all scales from 1 cm to 2 m. Minor potassic hornblende monzonites are probably 'hybrid' rock types, and similarly attest to mixing processes (Peckham, 1992). Some of the granitic components are tourmaline-bearing, and the hornfelsed country rocks are variably tourmalinized, suggesting boron metasomatism.

Peckham (1992) obtained a Rb—Sr age of 364 ± 12 Ma from granites in the Iona Islands. The gabbros had a small range in Rb/Sr ratios and were difficult to date; however, these rocks, and hybrid rock types appear to lie on the same isochron. The date is probably a slight underestimate of emplacement age, but suggests a Devonian age for these rocks. Although small, The Iona Islands Intrusions are significant, as they provide clear evidence for Devonian mafic magmatism associated with granite formation.

Red Island Granite

The Red Island granite (Hogg, 1954; Strong *et al.*, 1974; O'Driscoll and Muggridge, 1979) underlies most of Red Island, in Placentia Bay, and extends as far north as Iron Island (Figure 4; inset). The granite, and associated gabbroic rocks, intrude and contact metamorphose clastic sedimentary rocks of Cambrian age; on Iron Island, red granite intrudes a grey quartz diorite to granodiorite.

The most abundant rock in the Red Island granite is a brick-red, medium-grained, generally equigranular, quartz-rich, leucocratic, biotite granite. In many areas, quartz occurs as rounded, phenocryst-like grains, imparting the appearance of a quartz porphyry (although the K-feldspar actually has a similar grain size). The granite contains only minor plagioclase, and some examples appear devoid of it. Although mostly homogeneous, a few small, rounded, enclaves of fine-grained mafic material are present; these are reminiscent of textures in parts of the Belleoram Granite. The mafic rocks associated with the Red Island granite are dominated by fine- to medium-grained diabasic gabbro, which commonly takes the form of sills interlayered with sedimentary rocks. Hogg (1954) commented on the more extensive alteration and hornfelsing at granite—sediment contacts, which presumably reflect the influence of hydrothermal solutions. On Red Island, hornfelsed sediments are impregnated with sulphides.

Leech *et al.* (1963) report a K—Ar (biotite) age of 390 ± 30 Ma from granite on Iron Island, which they correlated with the Red Island granite. As noted above, there are two phases on Iron Island, and it is not absolutely clear, which was sampled. However, the result certainly implies that the younger red granite (which is akin to the Red Island granite) is of Devonian age.

Evidence for a Placentia Bay 'Batholith'

Geophysical evidence strongly suggests that there is a substantial Paleozoic intrusive body beneath Placentia Bay. Regional aeromagnetic patterns (Figure 4; inset) indicate that there is a strong positive magnetic anomaly associated with the Red Island granite. This anomaly continues, unbroken, through Iron Island to the Iona Islands and the Argentia

Peninsula, and is considerably broader than the exposed area of granite and gabbro. A similarly prominent, but discrete, magnetic anomaly is associated with the Ragged Islands intrusions (Figure 4; inset). This information suggests that the Red Island granite and the Iona Islands Intrusions are protuberances from a much larger, batholithic body; the Ragged Islands intrusions might be a satellite body of this 'Placentia Bay batholith', as we term it here. As discussed subsequently, patterns of metallogenesis in the Placentia Bay region may also fit this general model.

St. Lawrence Granite

The St. Lawrence Granite (Van Alstine, 1948; Teng and Strong, 1976; Strong *et al.*, 1977, 1984; Collins and Strong, 1988) is located at the heel of the Burin Peninsula (Figure 4). It is one of the best-known plutons in eastern Newfoundland, largely due to its extensive vein-type fluorite mineralization, and has a long history of investigation. Although previously regarded as Carboniferous, new geochronological data (see below) indicate a Late Devonian age. The descriptions that follow are based largely on published accounts (see above), combined with field observations by AK. No attempt is made here to summarize the fluorite deposits, discussed in detail by Howse *et al.* (1983).

The St. Lawrence Granite covers a large, irregular area, and has a complex outcrop pattern, interpreted to reflect proximity of the present erosion surface to the roof of the pluton (Teng and Strong, 1976; Figure 4). It intrudes late Precambrian metasedimentary rocks of the ca. 760 Ma Burin Group, felsic metavolcanic rocks of the ca. 620 Ma Marystown Group, and shallow-water clastic sediments of the Cambrian Inlet group. The Cambrian rocks display well-developed contact metamorphism, and are commonly observed as stoped blocks near contacts. The geometry of the pluton has been interpreted to reflect emplacement along north–south extensional faults

The most common rock type is a medium-grained, equigranular, orange to brick-red, leucocratic alkali-feldspar granite with virtually no mafic minerals. Persistent (hydrothermal?) alteration is manifested by extensive hematization of feldspar, and the rock is commonly friable and rotten. Smoky quartz is present in quartz-porphyritic variants. Plagioclase is present locally, but many examples are hypersolvus granites containing perthitic alkali feldspar as the main phase. The distinctive sodium-rich minerals reibeckite–arfvedsonite and aegirine are present (although locally hard to recognize through the alteration), and in places, are associated with chloritized biotite. External contacts are generally sharp, and the marginal facies are typically finer grained, grading locally to quartz-feldspar porphyry; miarolitic cavities are common, as are millimetre- to centimetre-scale fluorite veinlets and 'tuffisite' breccia zones. As much of the area around St. Lawrence is probably near the roof of the pluton, these porphyritic variants are widespread. Fine-grained quartz-feldspar porphyry dykes are common to the west of the pluton, and volcanic rocks of similar aspect (Winterland porphyry and Rocky Ridge complex) occur in the north. The Grand Beach complex (Figure 4), a quartz-feldspar porphyry that is part intrusive and part extrusive, is also similar lithologically to finer grained portions of the St. Lawrence Granite, and has been viewed as genetically related (e.g., Strong *et al.*, 1977; Krogh *et al.*, 1988).

Several attempts have been made to date the St. Lawrence pluton. Bell *et al.* (1977) obtained a Rb–Sr age of 334 ± 5 Ma (315 Ma when recalculated for revised decay constant). This age led to a view of the St. Lawrence Granite as the only Carboniferous pluton in Newfoundland. Krogh *et al.* (1988) obtained a tentative U–Pb zircon age of 394^{+6}_{-4} Ma from the Grand Beach Porphyry, using two fractions only; they suggested that this age could be extrapolated to the St. Lawrence Granite on the basis of lithological and geochemical correlations. A concordant U–Pb zircon age of ca. 375 Ma has recently been obtained from a porphyritic granite (Dunning, 1992). This new result may not invalidate previous correlation of the granite and the Grand Beach Porphyry, as the age from the latter is non-precise.

MINERALIZATION AND ECONOMIC GEOLOGY

Introduction

No attempt is made here to give a detailed account of each and every mineral occurrence related to the granites described above, but a regional overview of metallogenic associations linked to particular suites is useful.

Northeast Gander Zone

The northeast Gander Zone is not renowned as an area of high mineral potential. The best-known mineral occurrences in this region are spectacular crystals of beryl contained in coarse-grained muscovite–tourmaline (± garnet) pegmatites (Gale, 1967). Although these are clearly of granophile origin, the host rocks are most commonly gneisses and biotite–muscovite granites that predate the Devonian plutonic suites. Mineralization in Devonian plutons is restricted to disseminated molybdenite occurrences in the Deadman's Bay Granite (Strong *et al.*, 1974) and in a granite sheet of uncertain affinity observed to cut migmatitic gneisses (Jayasinghe, 1978). No mineral occurrences are reported from the Newport granite. The Deadman's Bay Granite, particularly in the Lumsden area, is well-established as a potential source of high-quality dimension stone (Meyer *et al.*, 1992).

South Coast Region

The Ackley Granite is one of the best-known examples of a mineralized pluton in Newfoundland, and has been extensively studied (e.g., Whalen, 1983; Dickson, 1983; Tuach, 1986; Tuach *et al.*, 1986). However, comparatively little is known about other south coast Devonian granites.

The history of exploration in the Ackley Granite dates back to the late 19th century. The first discoveries were of disseminated molybdenite hosted by aplitic granites and quartz-rich pegmatites (described in detail by White, 1940 and Whalen, 1980); cassiterite-bearing greisens were later discovered during regional mapping (Dickson, 1983; Tuach, 1984). Both types of occurrences are concentrated in the same general area, along the southern margin of the pluton, adjacent to the contact with late Precambrian country rocks. The following summary is mainly extracted from Whalen (1980) and Tuach (1984).

Molybdenite deposits are small, with total tonnages of around 1 million tonnes grading 0.14 percent MoS2 for the largest occurrence (Tuach *et al.*, 1986). The immediate host-rocks are fine-grained siliceous aplites associated with quartz-rich pegmatitic phases, although leucogranites and quartz-feldspar porphyries also occur; the latter are commonly younger, post-mineralization intrusions. Molybdenite occurs in aplite and pegmatite as disseminations, fracture fillings and coarse-grained high-grade pods and patches, associated with variable amounts of pyrite. Associated minerals include barite, purple fluorite, sphalerite and chalcopyrite; possible alteration minerals include muscovite, sericite and possibly kaolinite. Adjacent to the showings, the Ackley Granite is an alaskitic granite with abundant miarolitic cavities and minor hydrothermal breccia veinlets, indicative of high-level emplacement and volatile exsolution (Whalen, 1980; Dickson, 1983). Significantly, molybdenite mineralization of closely similar aspect is reported in a small granite stock over 10 km south of the granite contact, on a small island in Fortune Bay (Whalen, 1980); this may imply a flat-lying southern contact and the presence of granite at shallow depths over considerable areas.

Sn-bearing greisens and related W–Mo–F mineralization are also localized along the southern contact of the Ackley Granite, some 15 to 20 km east of the main molybdenite showings (Dickson, 1983; Tuach, 1985). The principal host rock is a quartz-topaz (± muscovite) rock (greisen), which forms veins both in country rock and fine-grained alaskitic granites. Mineralization occurs as sporadically disseminated cassiterite, associated with fluorite, wolframite, molybdenite and pyrite.

The link between these Mo and Sn–W prospects and the Ackley Granite is well-established. The gradual changes in the character and composition of the granite from northwest to southeast, approaching the southern contact, have long been attributed to proximity to the roof zone. Mineralization is causally linked to the ponding of hydrothermal fluids of broadly magmatic origin, in which Mo, Sn and F were concentrated, either by fractional crystallization processes (Whalen, 1980) or liquid-state processes such as thermogravitational diffusion or convective fractionation (Tuach *et al.*, 1986). The geochemical zonation observed in the Ackley Granite represents the imprint of these processes, and may be a useful indicator to apply to other suites.

Other south coast plutons are less well-characterized. The François Granite is the source of a prominent U–Mo–W–F lake-sediment anomaly and an airborne radioelement anomaly (e.g., Davenport, 1982). In geochemical terms, it is highly evolved (see Table 1, and next section). Follow-up geochemical surveys confirmed these results, but no significant mineralization has ever been recorded. Poole *et al.* (1985) report minor fluorite and anomalous radioactivity, and also trace amounts of molybdenite in aplitic dykes that are probably related to the granite. McConnell (1985) reports several scheelite-bearing quartz-tourmaline veins in the area of the Dolland Brook granite. The Chetwynd Granite was examined and sampled by Tuach (1986) as part of a regional assessment in southwestern Newfoundland, but was not noted as having any particular potential. Dickson *et al.* (1989) note that some parts of the intrusion are highly differentiated.

Significant tungsten mineralization has been known for many years at Grey River (Figure 3), where it occurs in several discordant quartz (± carbonate) veins cutting deformed syntectonic granites, and Precambrian rocks of the Grey River Enclave (Higgins, 1985; Dickson *et al.*, 1989). The veins represent multiple cycles of tensional fracturing and mineral deposition, and are characterized by coarse wolframite and scheelite, associated with chalcopyrite, native bismuth and Ag-bearing sulphides. They are described in detail by Higgins (1985), who argued against a relationship with the the adjacent Burgeo Intrusive Suite granites, suggesting instead a link to an unexposed posttectonic granite similar to late granite veins that are locally abundant. More recently, Higgins *et al.* (1990) presented a 412 ± 5 Ma Rb–Sr isochron from the Burgeo Intrusive Suite, similar to U–Pb ages reported by Dunning *et al.* (1990), whereas K–Ar ages of micas from tungsten veins and related greisens range from 386 to 352 Ma. These data support the concept of tungsten mineralization at Grey River as related to an subjacent posttectonic Devonian pluton represented by abundant late sheets and dykes; in this context, it may be significant that the western edge of the François Granite is approximately 10 km east of the Grey River deposits. However, the average composition of posttectonic 'leucogranites' at Grey River (Higgins, 1985) is distinct from typical François Granite examples, being higher in Sr and Ba, and lower in Rb, U, Nb and other LIL and HFS elements.

Western Avalon Zone

Very little exploration attention has been paid to Devonian granite plutons of the western Avalon Zone. No mineral occurrences have been reported from the Terra Nova or Clarenville granites. The Little Woody Island granite exhibits some potential signs of hydrothermal alteration (e.g., strong hematization and possible sericitization), and is riddled with small quartz veins. Analyses of the quartz veins, however, were completely barren.

In the Fortune Bay area, Furey (1985) and Furey and Strong (1986) note the occurrence of small purple fluorite veins in the roof zone of the Belleoram Granite on Chapel Island, and disseminated molybdenite in chilled alaskitic granites. It is not clear if the latter are late intrusions cutting other phases of the granite. Furey (1985) also describes galena and sphalerite from a 'breccia zone' at Farmer's Cove on

Chapel Island. The eastern stock of the Harbour Breton Granite ('Old Woman Stock' of Widmer, 1950 and Furey and Strong, 1986) hosts a zone of low-grade, greisen-like Mo—F mineralization that is well-exposed in a gravel pit on the Belleoram—Pool's Cove road. In this area, the marginal phase of the Harbour Breton Granite is highly altered and friable, with a pale-green 'soapy' appearance highly suggestive of sericitization and/or kaolinitization. Hydrothermal breccias, with quartz veins and highly altered fragments, are widely developed. The zone is cut by sheeted quartz veins or quartz-rich greisens from a few centimetres to 1 m in width. Molybdenite is sporadic in distribution, and random grab samples of vein material contained anomalous, but far from economic, Mo (up to 22 ppm). Furey and Strong (1986) also report bornite from this zone. A number of similar vein-type Mo (± F) occurrences are indicated on the maps of Furey and Strong (1986), mostly around the edges of the 'Old Woman Stock'. Furey and Strong (1986) note that 'similar but much less abundant' mineralization is present in the main stock of the Harbour Breton Granite. To date, no mineralization has been reported from the Pass Island Granite, although this unit has received attention for high-quality dimension stone (Meyer *et al.*, 1992). Minor fluorite veinlets were reported in the Berry Hills Granite by O'Brien *et al.* (1984) who also report a small quartz vein containing molybdenite near the granite contact.

Eastern Avalon Zone

The best-known granophile mineral deposit in Newfoundland is located in the St. Lawrence area, where the St. Lawrence Granite and spatially associated units host a large number of fluorite veins, which were discovered by the pioneering J.B. Jukes in 1843, and have been mined discontinuously for almost 50 years. The characteristics of mineralization at St. Lawrence have been reviewed by Van Alstine (1948), Teng and Strong (1976), Howse *et al.* (1983), Strong *et al.* (1984) and Collins and Strong (1988). Fluorite is almost exclusively hosted by tensional vein structures, commonly with hydrothermal breccia textures and evidence of multiple deposition episodes. Quartz and barite are common gangue minerals, and sulphides are commonly present in minor amounts; galena, sphalerite, pyrite and chalcopyrite are reported. Uranium mineralization (as pitchblende) has also been reported from skarn-like zones developed at contacts between the granite and Cambrian sedimentary rocks. Strong *et al.* (1977) also report skarn-like Pb—Zn—Ag occurrences in country-rock limestones, and disseminated molybdenite within the granite in inland areas. Collins and Strong (1988) suggested deposition from a magmatic fluid, over a temperature range from 500 to 100°C, with base metals being precipitated from relatively high-temperature fluids. Leaving aside the details of metallogenesis, the most important characteristic of St.Lawrence mineralization is that it is truly a polymetallic association, characteristic of other mining districts such as the English Pennines, and that fluorite does not represent the only potential target.

Information concerning other eastern Avalon Zone plutons is sketchy. In the Iona Islands area, McCartney (1967) reported a small fluorite vein cutting gabbro; on this basis, he correlated the Iona Islands granites with those at St. Lawrence. Peckham (1992) searched for this vein without success, and it must be of very limited extent. As noted previously, some granites on the Iona Islands are tourmaline-bearing. The Red Island granite was investigated by Hogg and Hawkins (1955) on behalf of NALCO. The main focus of prospecting was an extensive rusty zone at the northwest tip of the island, which is developed in Cambrian sedimentary rocks adjacent to the contact with the granite. The sediments are baked and hornfelsed, and contain abundant garnet, suggesting a skarn affinity. There is heavy pyritization, with minor pyrrhotite, chalcopyrite and bornite. Grab samples of pyritized hornfels collected in 1989 yielded anomalous (but uneconomic) Cu and Zn (up to 200 ppm), and minor enrichment in Ni and Ag.

Circumstantial evidence for distal mineralization possibly related to a 'Placentia Bay batholith' of Devonian age is present in the form of widespread barite and galena-bearing veins in the western Avalon Peninsula and Isthmus of Avalon areas. The geology of barite occurrences in Newfoundland has recently been reviewed by Howse (1992). More than 40 barite veins are reported in these areas, and field relations indicate a post-Cambrian age. In addition to barite-only veins, barite occurs as a gangue mineral in Pb—Zn—Ag veins at La Manche and Southern Harbour, on the Avalon Isthmus, and at the Silver Cliff prospect near Argentia. Fluid-inclusion studies conducted by Maloney (1991) suggested high temperatures (> 300°C), which are suggestive of magmatic involvement; other barite occurrences had fluid temperatures in the 100°C range. In conjunction with the occurrence of Devonian granites in Placentia Bay, and the geophysical evidence for a body of major extent related to the Iona Islands and Red Island—Iron Island intrusions (see above), it seems reasonable to suggest that these Pb—Zn—Ba (± Ag) occurrences may represent a related distal mineralization. This metal association is characteristic of distal, low-temperature mineralization in many other 'granophile' provinces (e.g., Strong, 1981).

GEOCHEMISTRY

PREVIOUS WORK AND SOURCES OF INFORMATION

Excluding those of the south coast, all of the Devonian plutons were initially examined by the regional study of Strong *et al.* (1974); these samples were reanalyzed in 1990. Over 300 samples were collected on a structured grid pattern from the Ackley Granite (Dickson, 1983). Mapping on the south coast led to the collection of similarly large structured datasets from both the Chetwynd and François granites (Dickson *et al.*, 1989) and Devonian intrusions in the North Bay Granite Suite (Dickson, 1990). Field work conducted as part of the granitoid database project has resulted in further sampling in virtually all of the granites described above. A subset of representative samples have also been analyzed for an extended trace-element suite (including the REE) by ICP-MS at Memorial University, in conjunction with isotopic studies.

Table 1. Average major- and trace-element compositions of Devonian Plutonic Suites

	NORTHEAST GANDER ZONE								SOUTH COAST REGION									
PLUTON	Deadman's Bay		Newport		Middle Brook		Gander Lake		Chetwynd		Francois		Dolland Brook		Ackley		Terra Nova	
N of Analyses	52		21		19		19		48		169		30		492		16	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
SiO_2	68.20	3.39	70.31	3.34	62.57	4.58	71.05	3.20	73.39	3.91	74.56	2.47	70.76	2.58	73.86	3.74	73.05	4.84
TiO_2	0.66	0.25	0.47	0.22	0.88	0.26	0.41	0.28	0.30	0.18	0.17	0.10	0.38	0.14	0.28	0.18	0.29	0.25
Al_2O_3	14.25	0.84	13.86	1.12	15.85	1.45	13.60	0.95	13.63	1.36	13.46	1.15	14.94	1.02	13.07	1.27	12.99	1.60
Fe_2O_3	1.03	0.48	0.80	0.41	1.61	0.55	0.95	0.58	0.79	0.45	0.50	0.25	0.64	0.32	0.54	0.41	0.65	0.30
FeO	2.33	0.81	1.73	0.63	3.23	1.03	1.47	0.86	0.63	0.67	0.70	0.37	1.26	0.65	1.06	0.68	1.41	0.93
MnO	0.10	0.03	0.07	0.03	0.11	0.03	0.08	0.04	0.04	0.03	0.05	0.02	0.04	0.02	0.05	0.02	0.04	0.03
MgO	1.09	0.49	0.70	0.38	2.10	0.70	0.62	0.44	0.38	0.50	0.22	0.18	0.65	0.27	0.43	0.51	0.47	0.68
CaO	1.63	0.67	1.52	0.65	3.44	1.24	0.85	0.61	0.80	0.60	0.63	0.38	1.53	0.58	0.89	0.74	0.95	0.88
Na_2O	3.14	0.35	3.36	0.32	3.00	0.27	3.33	0.59	3.54	0.40	3.69	0.46	3.79	0.45	3.46	0.39	3.23	0.28
K_2O	4.68	0.58	4.89	0.66	4.19	0.75	4.68	0.53	5.67	0.99	5.19	0.80	4.90	0.76	5.00	0.58	5.19	0.67
P_2O_5	0.26	0.10	0.13	0.07	0.31	0.11	0.23	0.07	0.06	0.05	0.04	0.03	0.13	0.07	0.06	0.06	0.07	0.09
LOI	1.39	0.47	0.96	0.34	1.59	0.51	1.19	0.35	0.57	0.20	0.60	0.15	0.66	0.13	0.82	0.31	1.01	0.43
TOTAL	98.76		98.80		98.88		98.46		99.80		99.81		99.68		99.52		99.35	
Li	47.4	15.6	34.7	15.6	35.1	11.9	57.8	24.5	19.4	9.1	52.3	31.9	56.3	25.4	40.5	22.0	19.7	15.5
Be	4.4	1.0	4.2	1.2	4.2	0.5	5.6	2.0	3.0	1.0	6.4	5.5	4.2	1.0	5.8	3.4	3.2	1.4
F	838.9	334.0	554.5	272.4	783.3	262.3	494.2	290.6	396.7	276.8	484.0	410.9	605.1	324.7	717.7	552.5	241.1	230.9
V	55.2	25.5	36.4	20.7	104.7	35.9	36.0	26.0	15.8	26.4	6.0	8.9	35.9	16.3	18.9	24.2	19.3	29.3
Cr	11.3	5.0	5.1	3.9	33.8	14.5	9.7	7.6	11.9	23.3	9.4	6.3	6.9	4.1	6.7	7.5	5.8	14.2
Ni	6.3	3.3	2.2	1.9	15.6	5.4	6.6	3.3	2.5	6.5	1.3	0.8	2.6	1.6	44.4	26.6	4.8	5.7
Cu	8.8	3.8	6.3	3.4	17.3	5.3	8.4	3.4	4.2	3.7	3.6	5.2	8.2	4.6	3.2	3.7	3.8	5.9
Zn	67.1	20.4	53.7	16.7	77.0	20.5	45.5	18.7	33.1	17.2	32.9	13.5	51.7	18.1	19.3	24.6	35.2	17.2
Ga	22.8	3.7	21.2	3.4	24.8	4.7	19.5	4.0	28.4	17.7	21.4	3.8	19.4	2.7	16.9	3.8	18.0	3.1
Rb	209.2	40.0	203.3	34.8	181.6	35.1	289.8	89.7	233.8	65.9	383.8	175.5	200.6	51.2	280.3	109.4	197.3	24.2
Sr	272.8	103.4	182.1	69.8	277.3	67.2	126.5	72.4	71.8	56.6	77.6	68.1	260.1	105.3	104.1	122.8	102.1	82.1
Y	26.5	8.1	33.3	15.0	29.3	6.7	24.9	26.8	46.2	24.6	50.6	33.0	16.0	9.1	54.7	30.8	27.2	10.0
Zr	290.8	94.5	241.2	78.9	310.8	94.0	184.7	111.3	166.3	136.5	108.8	55.3	175.0	70.0	160.5	64.4	201.3	76.2
Nb	17.3	3.7	19.1	5.8	16.1	3.7	22.9	7.2	21.6	9.3	29.5	16.1	13.8	5.5	35.4	22.2	14.4	7.6
Mo	3.8	0.9	4.0	1.1	3.7	1.2	5.1	1.2	3.0	4.1	2.3	0.9	2.1	0.7	7.3	61.3	4.1	0.5
Ba	738.9	267.6	548.6	237.8	919.2	208.6	386.2	204.3	254.1	219.9	211.3	183.5	740.6	278.4	299.3	239.9	416.8	335.4
La	53.8	14.8	54.4	25.0	50.8	11.9	32.1	16.6	42.0	37.5	32.4	32.1	44.8	22.1	40.4	20.1	38.4	20.5
Ce	112.9	29.5	115.1	47.8	106.3	23.4	67.6	32.6	115.3	76.7	85.9	46.9	99.0	56.9	147.6	74.2	88.8	31.1
Pb	23.2	6.8	19.5	4.6	17.3	8.5	15.3	4.2	25.5	5.9	31.8	11.7	29.8	15.3	27.3	11.1	16.6	5.0
Th	23.6	11.1	25.4	10.5	15.0	6.0	13.4	7.0	28.5	13.6	41.6	15.7	23.5	11.1	31.3	14.9	31.3	22.2
U	3.7	1.6	4.5	1.6	3.4	1.1	8.4	5.7	3.9	2.1	10.2	6.9	4.9	2.3	5.8	3.9	5.5	3.6

The database used in this report is a combination of all the above, i.e., reanalyzed samples from the Strong *et al.* (1974) survey, data from the Ackley and south coast mapping projects, and data collected since 1989 as part of the Granitoid Database Project. The distribution of samples on a pluton-by-pluton basis is unrepresentative, as areas covered by grid-based sampling, and the St.Lawrence Granite, have a very high sampling density. In order to illustrate data variations, these densely sampled plutons are represented in graphs by a smaller subset (approximately 25 percent) of the data, selected at random by the SPSS-X statistical program. In order to verify that data subsets were truly representative of variation, their univariate statistics were compared with those of the full dataset; in all cases, the differences in the mean values and standard deviations were insignificant. However, in numerical analyses, such as mean compositions of plutons (e.g., Table 1), the full complement of samples was retained.

SUMMARY OF NUMERICAL DATA

Table 1 lists average major- and trace-element compositions for all of the Devonian plutonic suites, excluding the Petites granite, for which no data are presently available. The summary statistics provided are not the most ideal measures of bulk composition, but provide a general indication of compositional contrasts between plutons. However, in the case of bimodal associations (notably the Iona

Table 1. Continued

WESTERN AVALON ZONE												EASTERN AVALON ZONE							
Clarenvile		Little Woody Island		Berry Hills		Belleoram		Harbour Breton		Pass Island		Iona Islands		Ragged Islands		Red Island		St. Lawrence	
8		4		5		15		33		14		10		11		17		99	
Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
74.62	1.37	67.81	11.94	76.55	0.81	64.66	2.57	74.94	2.70	71.04	2.40	67.02	13.71	65.55	7.87	69.06	9.80	76.08	3.01
0.13	0.02	0.42	0.38	0.13	0.07	0.84	0.19	0.22	0.09	0.27	0.10	0.85	1.00	0.59	0.37	0.59	0.69	0.15	0.15
12.68	0.58	13.71	0.85	12.10	0.24	15.14	0.66	12.58	1.12	14.01	0.84	13.64	1.94	15.20	2.00	13.35	1.31	11.52	1.07
0.70	0.50	1.73	1.63	0.39	0.26	2.00	0.27	0.65	0.33	0.61	0.34	1.42	1.07	1.91	1.01	2.15	3.55	1.27	0.76
0.70	0.37	1.03	0.92	0.84	0.29	2.23	0.67	0.80	0.32	1.72	0.53	2.90	3.74	2.05	1.25	1.26	1.57	0.66	0.61
0.05	0.01	0.06	0.06	0.03	0.01	0.09	0.02	0.04	0.01	0.07	0.03	0.08	0.07	0.11	0.05	0.07	0.06	0.03	0.03
0.23	0.19	0.90	1.37	0.19	0.10	1.51	1.00	0.29	0.24	0.33	0.22	1.93	2.78	1.40	1.09	1.49	2.44	0.21	0.49
1.02	1.18	2.14	3.21	0.38	0.13	2.29	0.70	0.50	0.36	1.09	0.38	2.71	3.60	2.86	2.27	2.20	2.98	0.55	0.95
3.30	1.35	4.44	0.48	3.29	0.16	4.36	0.38	3.54	0.65	3.74	0.45	3.76	0.42	4.39	0.49	3.62	0.22	3.63	0.81
4.44	0.45	3.42	0.75	4.72	0.18	4.30	0.48	4.66	0.53	5.13	0.57	3.81	1.72	4.00	0.91	4.37	1.67	4.61	1.05
0.04	0.01	0.12	0.14	0.02	0.01	0.24	0.06	0.04	0.03	0.06	0.04	0.18	0.23	0.21	0.15	0.10	0.13	0.02	0.04
2.01	1.36	3.40	4.88	0.81	0.16	1.32	0.41	1.14	0.46	0.99	0.30	0.92	0.91	1.21	0.35	0.88	0.46	0.90	0.33
99.92		99.18		99.45		98.98		99.40		99.06		99.22		99.48		99.14		99.63	
5.3	3.1	7.9	9.4	4.2	2.2	30.0	10.5	19.3	14.2	32.8	14.0	23.5	11.9	11.0	5.9	27.3	13.4	21.2	19.6
2.6	0.7	2.5	0.5	3.9	0.7	8.1	12.0	3.8	0.9	4.6	0.6	4.8	2.2	2.7	0.3	3.9	1.2	7.8	3.4
53.5	25.1			257.2	227.9	570.2	185.4	245.7	142.6	272.1	116.9					438.5	156.7	1084.3	1177
5.8	1.9	43.0	70.1	5.0	4.6	61.2	17.0	12.2	11.4	13.2	9.9	77.2	110.9	73.2	58.5	65.9	107.0	5.0	24.7
2.0	0.8	22.3	39.8	2.4	0.6	7.7	3.1	4.3	7.7	3.7	2.1	18.6	28.9	7.6	9.1	24.7	59.8	1.8	3.9
1.4	0.5	8.0	12.1	1.8	0.5	6.3	2.6	2.0	1.2	1.6	0.5	17.0	26.8	3.6	3.2	8.8	18.9	1.8	1.6
7.6	9.1	12.8	4.4	3.0	2.8	14.3	6.0	11.5	26.9	4.1	2.8	17.7	17.8	30.9	22.4	14.8	19.8	7.2	7.0
28.6	7.3	41.5	27.0	20.8	8.8	79.9	22.8	43.5	48.3	46.6	15.1	68.2	40.6	65.1	25.2	48.8	30.7	58.2	55.1
15.5	1.4	17.0	4.2	15.8	0.8	23.3	2.6	17.4	3.1	20.8	2.9	25.3	7.7	21.6	4.2	20.2	5.6	27.9	5.0
152.0	34.1	84.3	17.9	259.2	27.3	149.1	30.2	204.9	67.1	199.6	34.3	125.9	72.1	127.6	48.0	128.8	53.6	261.4	81.6
65.1	20.6	196.0	222.3	28.6	10.3	239.5	36.4	73.2	67.1	76.3	44.5	276.4	331.0	373.3	289.3	184.5	211.7	30.1	99.6
14.3	2.9	14.8	3.2	32.0	7.8	38.9	2.6	30.4	15.7	28.4	11.5	24.7	6.3	20.1	7.6	25.0	7.3	95.4	41.3
133.4	15.6	183.3	36.8	124.2	29.8	486.5	83.7	179.3	58.9	288.4	212.5	196.2	82.4	162.3	39.9	181.5	44.2	576.4	342.2
12.4	2.3	9.5	3.3	23.8	4.3	26.7	1.6	20.8	6.0	19.1	7.3	31.7	11.6	7.5	4.4	30.7	14.0	82.9	52.2
3.5	0.5	3.3	0.5	4.6	0.6	5.3	0.9	5.1	3.5	4.1	1.0	4.4	0.7	3.8	0.6	5.5	1.4	5.0	1.8
713.5	510.0	764.8	238.0	189.0	134.2	684.3	114.2	370.7	385.7	255.3	139.1	389.7	150.0	1244.3	453.6	505.9	242.8	107.0	158.2
31.3	6.9	23.8	4.6	23.8	8.4	52.5	3.9	34.9	10.0	71.8	86.2	36.5	8.7	31.6	4.6	39.2	16.4	55.9	23.1
59.5	12.8	51.0	8.6	60.4	14.8	106.8	5.2	76.0	16.1	146.6	160.4	73.5	12.6	67.5	13.4	76.5	28.7	132.5	46.4
7.3	4.6	5.0	2.2	10.2	4.8	27.9	19.6	15.0	7.4	19.5	3.7	15.1	9.8	9.0	2.5	10.4	4.7	29.8	35.4
23.9	4.9	6.8	4.0	34.6	10.5	12.7	3.4	21.4	8.6	26.1	8.7	22.3	15.5	15.8	8.6	17.1	8.1	30.2	17.4
3.8	1.2	1.4	0.6	6.3	2.2	3.3	0.8	4.8	1.9	5.0	1.7	4.4	2.8	3.2	0.6	4.1	1.7	8.1	4.5

Islands Intrusions), mean compositions are of limited value, as they are averages of gabbro and granite.

In general, all of the plutons have evolved major-element compositions, with SiO_2 greater than 70 percent, and Na_2O + K_2O greater than 8 percent. Virtually all are potassic, with K_2O in excess of Na_2O. However, each geographical grouping of plutons exhibits a range of major-element compositions (Table 1). In the northeast Gander Zone, SiO_2 ranges from 62.5 to 71 percent, and the two possibly older plutons (Middle Brook and Deadman's Bay) have less-evolved average major-element compositions than the Newport and Gander Lake granites. South coast plutons, and the Ackley Granite, are all highly evolved, with SiO_2 ranging from 70 to 75 percent, and K_2O of 5 percent or more. Plutons of the western Avalon Zone are similarly evolved, with the Berry Hills Granite displaying the highest SiO_2 content at 76.5 percent. The Belleoram Granite is a notable exception, with a modest average SiO_2 content of 64.7 percent, and subequal K_2O and Na_2O. With the exception of the highly evolved St. Lawrence Granite, granite plutons of the eastern Avalon Zone appear to have somewhat lower average SiO_2 contents of 65 to 69 percent; however, the mean composition for the Iona Islands Intrusions is misleading, and the granites are actually highly evolved, with SiO_2 contents of around 72 percent (Peckham, 1992).

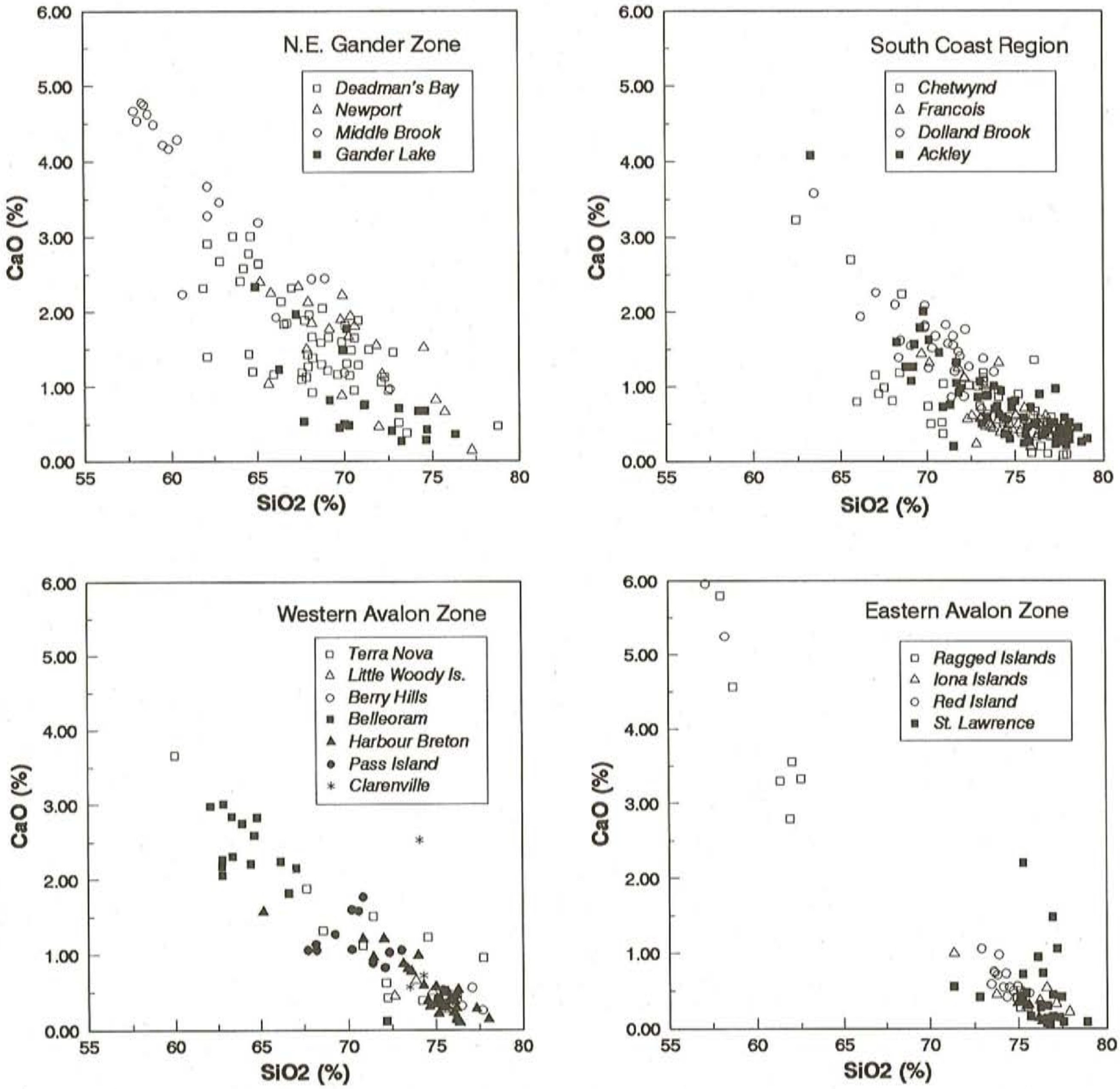

Figure 5. *CaO–SiO₂ variation diagrams for Devonian suites.*

DATA REPRESENTATION

In order to represent geochemical variation in graphical form (see Figures 5 to 16), the Devonian plutons have been subdivided into four groups corresponding to the geographic groupings. Note that the south coast plutons, the Ackley Granite and the St. Lawrence Granite are all represented in graphs by a small subset (20 to 25 percent) of the available geochemical data.

MAJOR-ELEMENT TRENDS AND CHARACTERISTICS

All of these plutons show major-element trends that conform to the general patterns shown by most igneous suites. These include a progressive decrease in FeO (total), CaO, MgO, TiO_2 and Al_2O_3, and a less marked increase in K_2O and Na_2O, with increasing SiO_2. These major-element trends are exemplified by the strong negative correlation of CaO and SiO_2 (Figure 5). The least evolved suites in each geographic area are distinguished by their higher CaO; e.g., the Middle Brook and Deadman's Bay granites of the northeast Gander Zone and the Belleoram Granite of the western Avalon Zone. Amongst eastern Avalon Zone plutons, some samples from the Ragged Islands intrusions (mostly granodiorites and quartz monzonites) are similarly distinguished by high CaO and low SiO_2; however, granites *(sensu stricto)* from the Ragged Islands area plot in the same general area as more evolved granites such as those from Red Island and St. Lawrence.

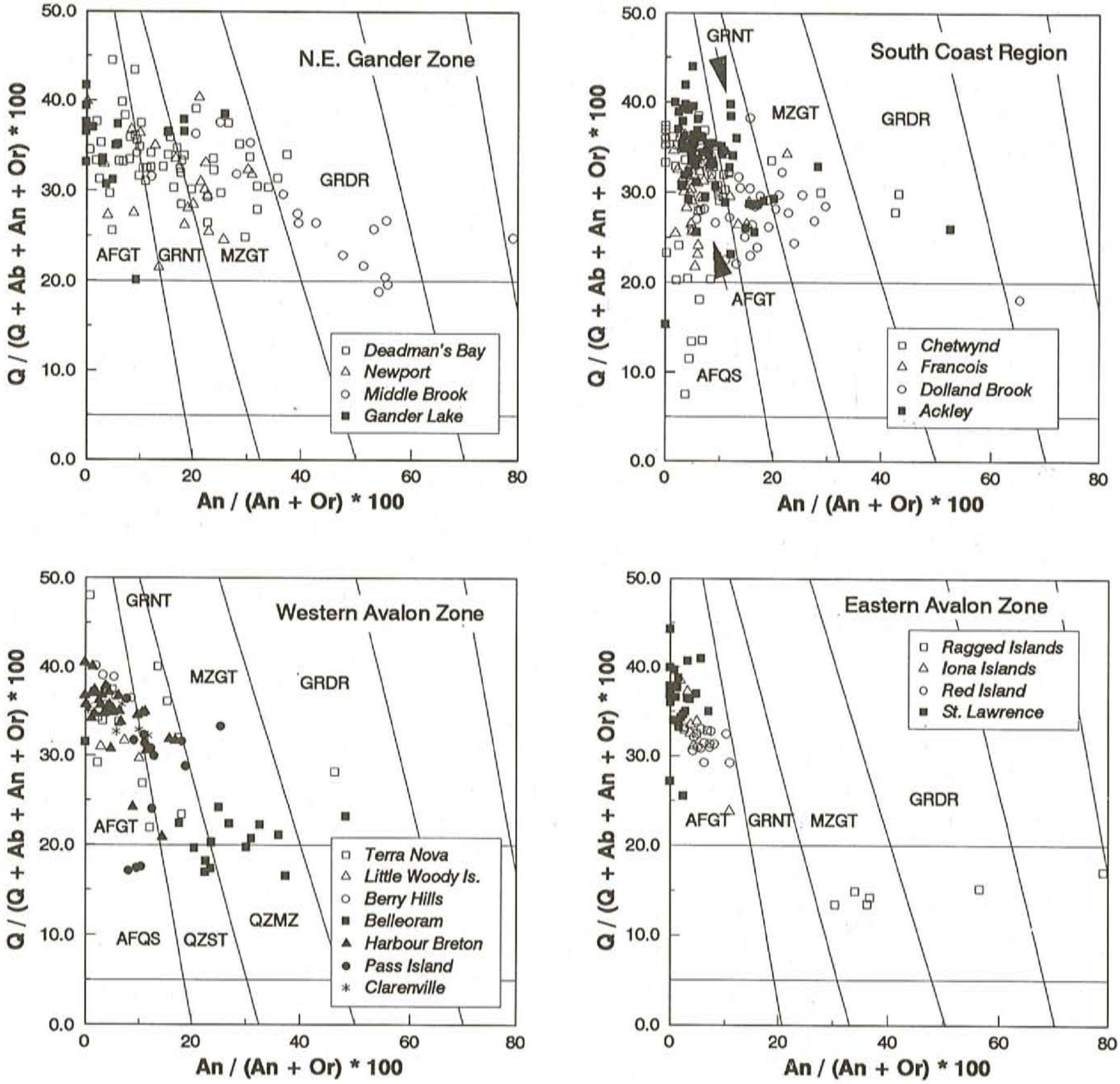

Figure 6. *Q'–ANOR variation diagrams (after Streckheisen and LeMaitre, 1979) for Devonian suites.*

As discussed previously, it is possible that some of the less evolved rocks in the Ragged Islands are of Precambrian age.

The compositional affinities of these suites are summarized by the normative equivalent to the IUGS classification (Streckeisen and LeMaitre, 1979), which utilizes two calculated normative parameters that reflect silica saturation and An/Or ratios (Figure 6). In the northeast Gander Zone, the Middle Brook Granite falls largely in the granodiorite and monzogranite fields, whereas the Deadman's Bay Granite has a much wider compositional range. The Newport and Gander Lake granites are tightly clustered in the granite and alkali-feldspar granite fields. South coast plutons and the Ackley Granite have much more restricted distributions than the northeast Gander Zone suites, being largely confined to the granite and alkali-feldspar granite fields; some samples from the Chetwynd Granite have syenitic affinities, consistent with their very high K_2O. Western Avalon Zone plutons have similarly restricted distributions, except for the Belleoram Granite, which falls mostly in the quartz monzonite, quartz syenite and monzogranite fields. Eastern Avalon Zone plutons (excluding monzonitic parts of the Ragged Islands intrusions) are almost entirely restricted to the alkali-feldspar granite field.

A plot of the molecular parameters A/CNK (Al_2O_3/CaO + Na_2O + K_2O) and Agpaitic Index (K_2O + Na_2O/Al_2O_3) reveals geographic contrasts amongst the Devonian plutons

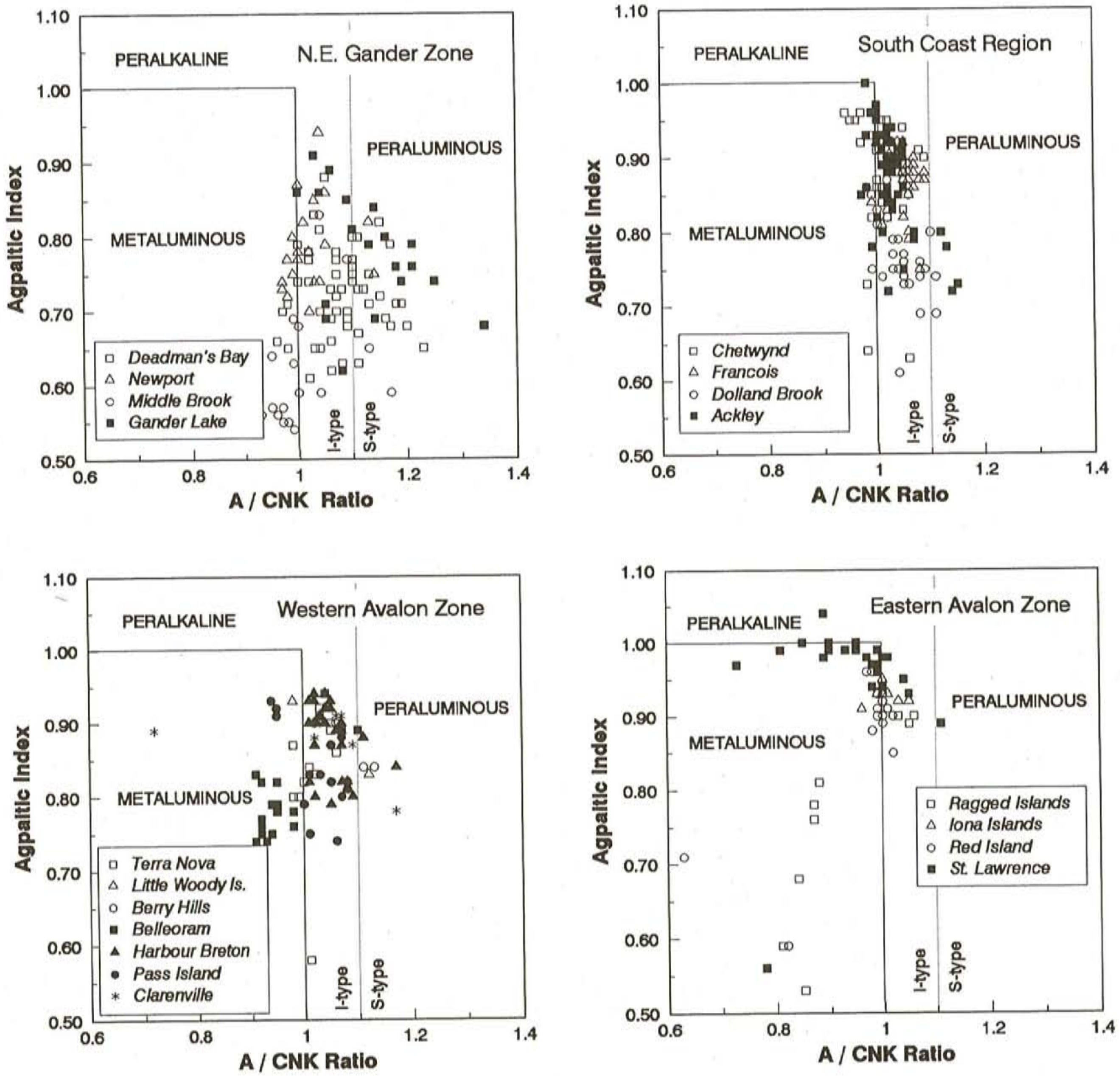

Figure 7. *Agpaitic Index–A/CNK ratio variation diagrams for Devonian suites.*

(Figure 7). Northeast Gander Zone plutons have peraluminous compositions, and parts of the Deadman's Bay and Gander Lake granites correspond (in this sense) to so-called 'S-type' granites (Chappell and White, 1974), which have A/CNK > 1.1. Peraluminous tendencies are least marked in the Newport Granite. In contrast, south coast plutons mostly have A/CNK between 1 and 1.1, i.e., they are slightly peraluminous but well within the spectrum of so-called 'I-type' granites (Chappell and White, 1974). Closely similar patterns are shown by western Avalon Zone plutons, with the exception of the Belleoram Granite, which has low A/CNK consistent with its high CaO and lower alkali content. Eastern Avalon Zone plutons, on the other hand, appear to have higher agpaitic indices (generally > 0.9) than the other groupings; such affinities are most marked in the St. Lawrence Granite, which is in part peralkaline. However, it should be noted that only a small proportion (13 percent) of the samples from this granite in the database (all data) actually have Agpaitic Indices > 1, and none display values above 1.04. The suite is thus best described as 'slightly peralkaline'.

The FeOt/(FeOt + MgO) ratios also illustrate significant geographic contrasts (Figure 8). Northeast Gander Zone plutons have lower values (< 0.85) than most plutons of the south coast and the Avalon Zone, at high SiO_2 contents (> 70 percent). However, some individual plutons (notably the Harbour Breton Granite) display wide variations in FeO/(FeO + MgO) that do not appear strongly correlated with SiO_2.

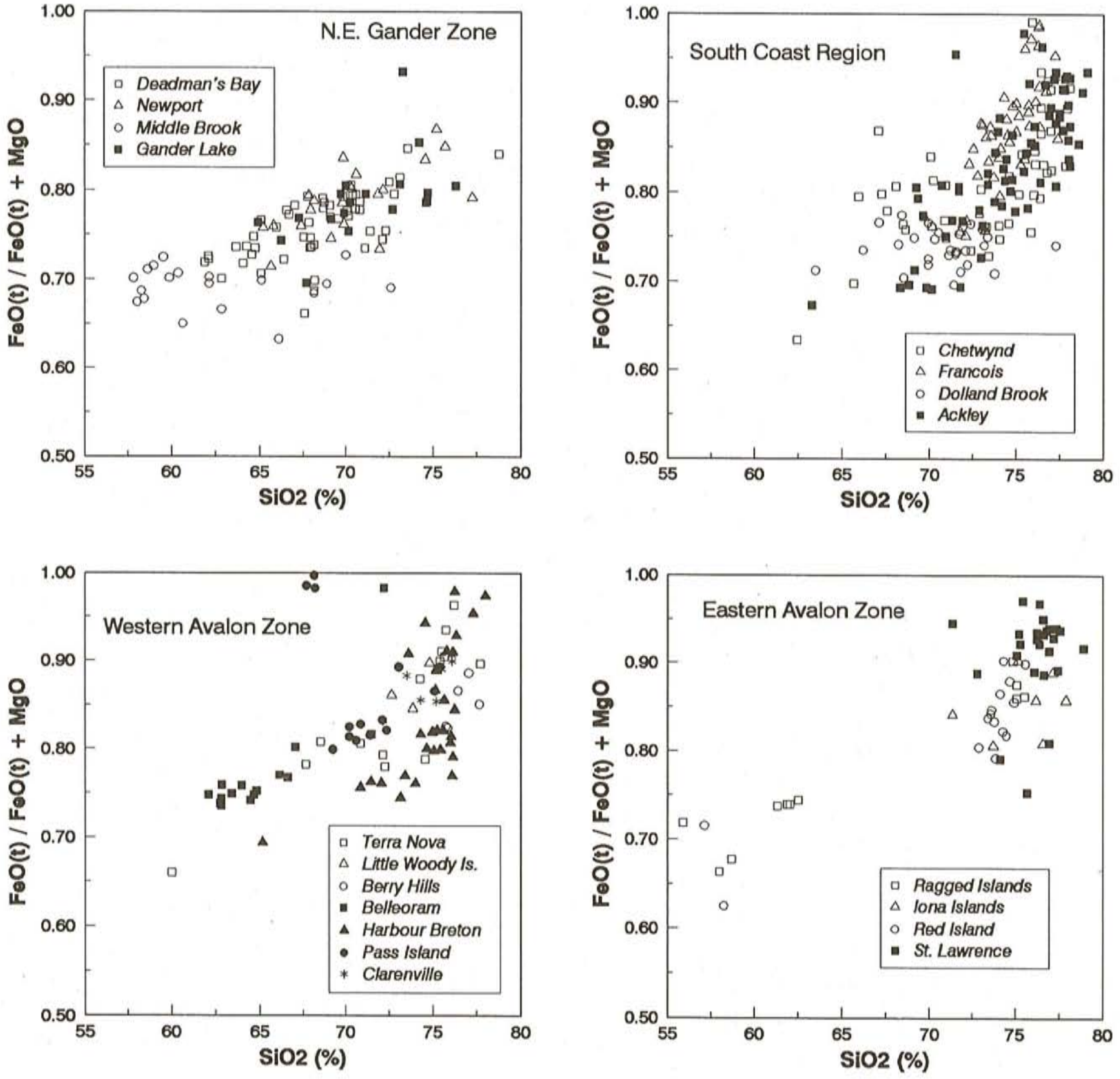

Figure 8. *FeOt/(FeOt + MgO)–SiO_2 variation diagrams for Devonian suites.*

TRACE-ELEMENT TRENDS AND CHARACTERISTICS

In general terms, all the plutons have trace-element patterns that are typical of high-SiO_2, low-CaO, potassic granites (Table 1). These include low abundances of compatible trace elements such as V (5 to 100 ppm), Cr (2 to 34 ppm), and enrichment in large-ion lithophile (LIL) elements such as Rb (125 to 400 ppm), Th (7 to 45 ppm) and U (4 to 11 ppm). There are good inverse correlations between most compatible trace elements and SiO_2, but correlations of incompatible elements and SiO_2 are far less marked, probably reflecting the mobile nature of these elements during hydrothermal activity and weathering. Sr and Ba are variable, but most plutons have between 120 to 250 ppm Sr and 400 to 900 ppm Ba. The lowest Sr and Ba concentrations are shown by the most evolved (highest SiO_2) plutons, such as the François, Berry Hills and St. Lawrence granites. The Ba–Sr plots (Figure 9) show well-defined positive trends for all groups, with average Ba/Sr ratios of 2 to 5 for most samples from the northeast Gander Zone and the south coast. The samples with the lowest Ba and Sr abundances are those with the highest SiO_2 contents; note that strong depletion in Ba and Sr is not seen amongst northeast Gander Zone plutons. Trends of this type are almost certainly due to the extraction of feldspars, notably K-feldspar, from the parent magmas. K-feldspar has a strong affinity for both Ba and Sr, and leads to depletion of both elements,

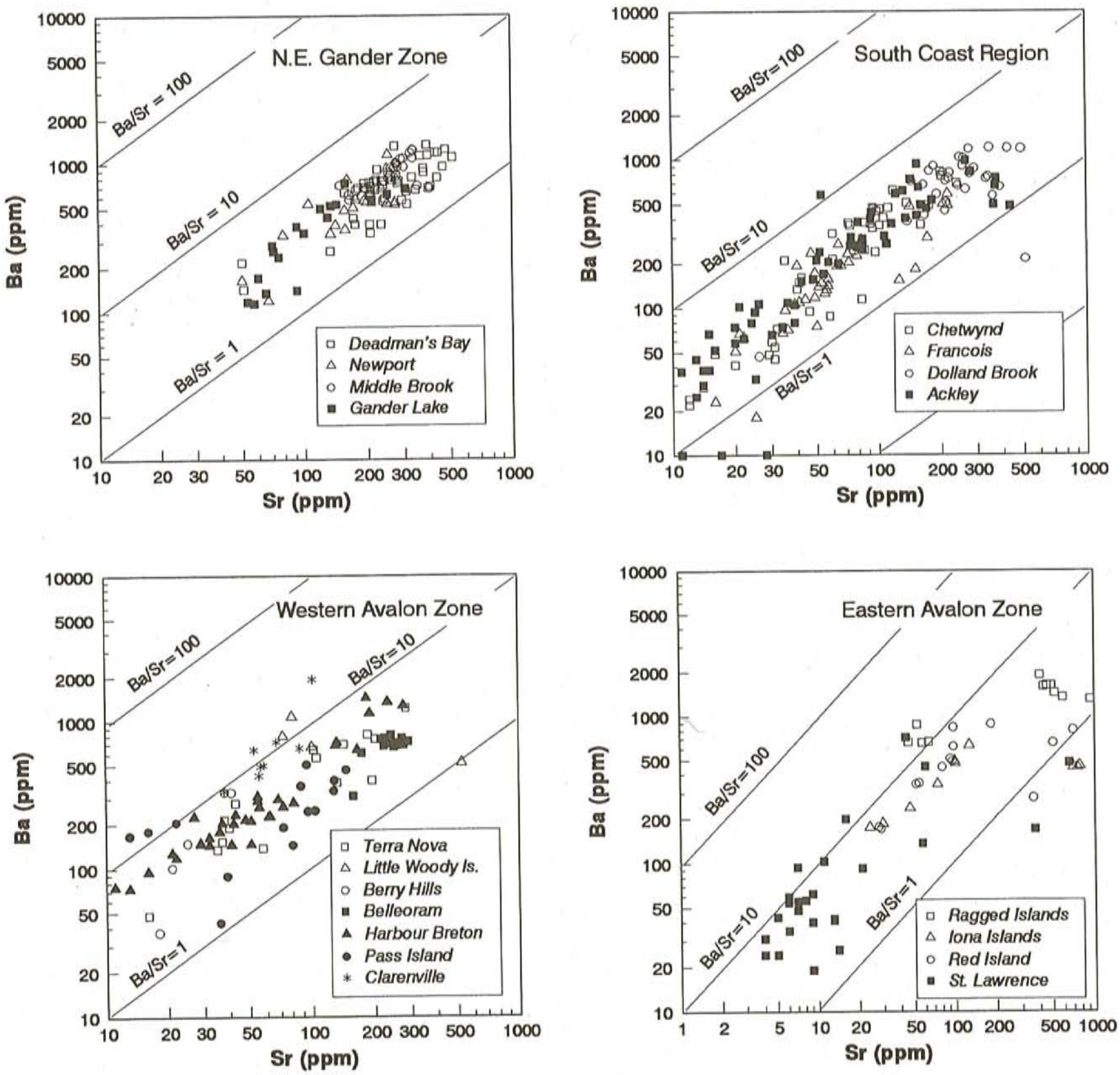

Figure 9. *Ba–Sr variation diagrams for Devonian suites.*

without significant alteration of Ba/Sr ratios. Similar, but more variable, trends are shown by the Avalon Zone plutons; the trends likewise suggest a major role for the fractionation of K-feldspar, but the scatter probably implies a wider range in the original Ba/Sr ratios of the magmas or, alternatively, some influence from plagioclase fractionation, which has a greater capacity to disturb Ba/Sr ratios. The Clarenville and Little Woody Island granites, in particular, have unusually high Ba/Sr (> 10), perhaps reflecting early plagioclase fractionation. South coast plutons and the St.Lawrence Granite show the lowest absolute concentrations of Ba and Sr, suggesting that these magmas underwent the greatest amount of fractionation.

The Rb–(Y+Nb) plot of Pearce *et al.* (1984) discriminates between various geographic areas (Figure 10). Northeast Gander Zone plutons plot in the 'volcanic-arc granite' (VAG) field, close to the triple point, although the Gander Lake granite partly lies within the 'syn-collisional granite' (syn-COLG) field. In contrast, south coast plutons cover a much wider spectrum, with the Ackley and Chetwynd granites falling mostly in the 'within-plate granite' (WPG) field. The François Granite, due to its high average Rb content, plots mostly in the syn-COLG field. Western Avalon Zone plutons cluster mostly in the triple point area, except for the Clarenville and Little Woody Island granites. The very wide variation shown by eastern Avalon Zone plutons partly reflects the inclusion of mafic rocks from both the Iona Islands

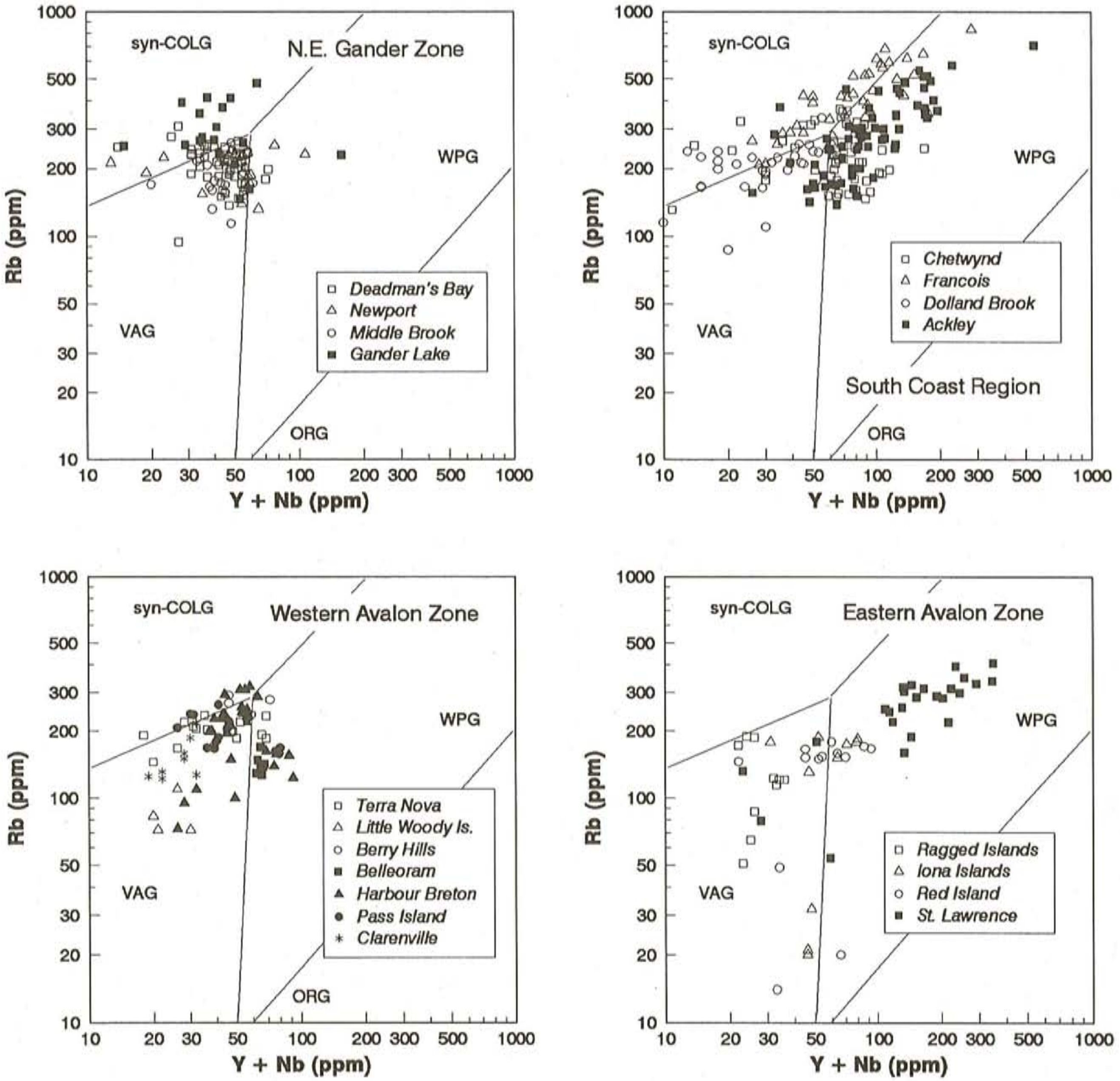

Figure 10. *Rb−(Y + Nb) variation diagrams (after Pearce* et al., *1984) for Devonian suites.*

and Red Island granite; most of the true granites from these suites cluster along the VAG−WPG boundary, in a position similar to the western Avalon plutons. St. Lawrence, as would be expected from its peralkaline character, plots well within the WPG field, with most samples having (Y + Nb) of 100 ppm or more. The Rb−(Y + Nb) plot was designed as a discrimination diagram for various tectonic settings, but obviously has little applicability to these suites, which are unlikely to represent three contrasting environments. The strong contrast between the St. Lawrence Granite (WPG field) and the François Granite (syn-COLG field) is particularily relevant, as these two suites have virtually identical U−Pb ages, and are geographicallly close, suggesting a common origin. However, Pearce *et al.* (1984) note that post-collisional granite suites commonly overlap the VAG, WPG and syn-COLG fields.

Contradictory results are also suggested by the Zr vs Ga/Al diagram of Whalen *et al.* (1987), where samples from all areas straddle the boundary between so-called 'A-type' granites and other granite types (Figure 11). However, eastern Avalon Zone granites have higher Ga/Al than other geographic areas, and qualify mostly as A-type granites. The highest Zr contents are shown by the St. Lawrence and Belleoram granites, with the northeast Gander Zone suites showing the next-highest values.

The chondrite-normalized La/Y plot (Figure 12) provides a useful method of assessing REE patterns, as Y mimics heavy

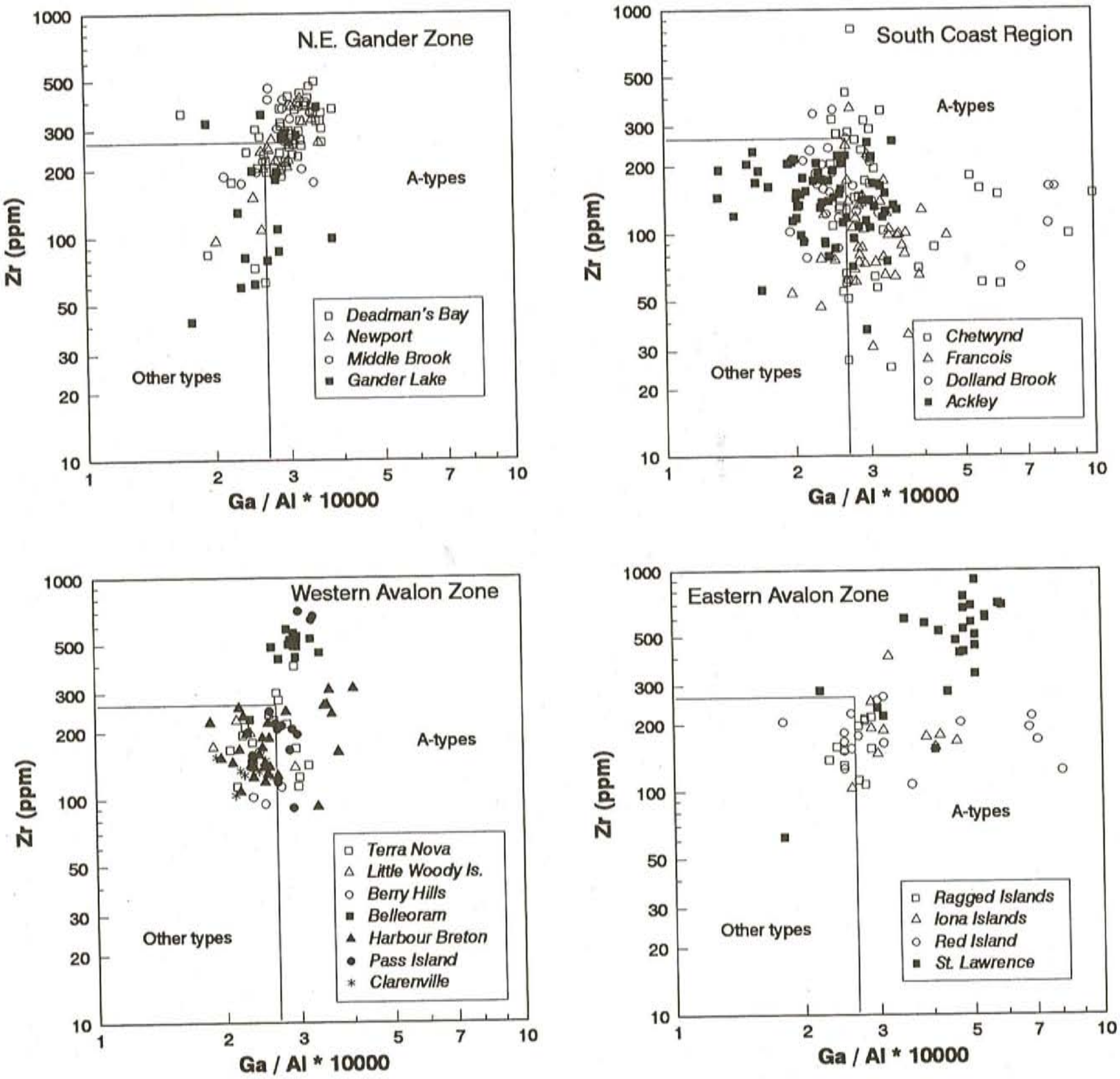

Figure 11. *Zr–(Ga/Al) variation diagrams (after Whalen* et al., *1987) for Devonian suites.*

rare-earth elements (HREE) such as Yb. Most granites have fairly constant $(La/Y)_N$ ratios of 5 to 20. Granites of the northeast Gander Zone have by far the smallest range in $(La/Y)_N$ (about 10), except for the Gander Lake granite, which exhibits considerable scatter. This pattern contrasts strongly with that of south coast granites, which have much lower $(La/Y)_N$ of 2 to 10, implying that they have relatively flat REE patterns. Some of the scatter in these data may reflect fractionation of REE-bearing accessory phases (such as titanite, allanite or zircon) at late stages in magmatic evolution. Similar patterns are shown by western Avalon Zone plutons; anomalously high $(La/Y)_N$ ratios (> 25) are shown by three REE-enriched samples from the Pass Island Granite. Eastern Avalon Zone plutons mostly have $(La/Y)_N$ ratios below 10 (i.e., similar to south coast and western Avalon examples), and the St. Lawrence Granite is characterized by distinct HREE enrichment, with $(La/Y)_N$ of 2 to 5.

MULTIELEMENT TRACE-ELEMENT PATTERNS

Selected discrimination diagrams (Figures 9 to 12) have been used to summarize the most obvious features. A series of 'spidergrams' are used to present multielement variation patterns, defined by ICP-MS analyses of representative samples from each pluton (Figures 13 to 16). The chosen normalization factors are the 'primitive mantle' values of Taylor and MacLennan (1985).

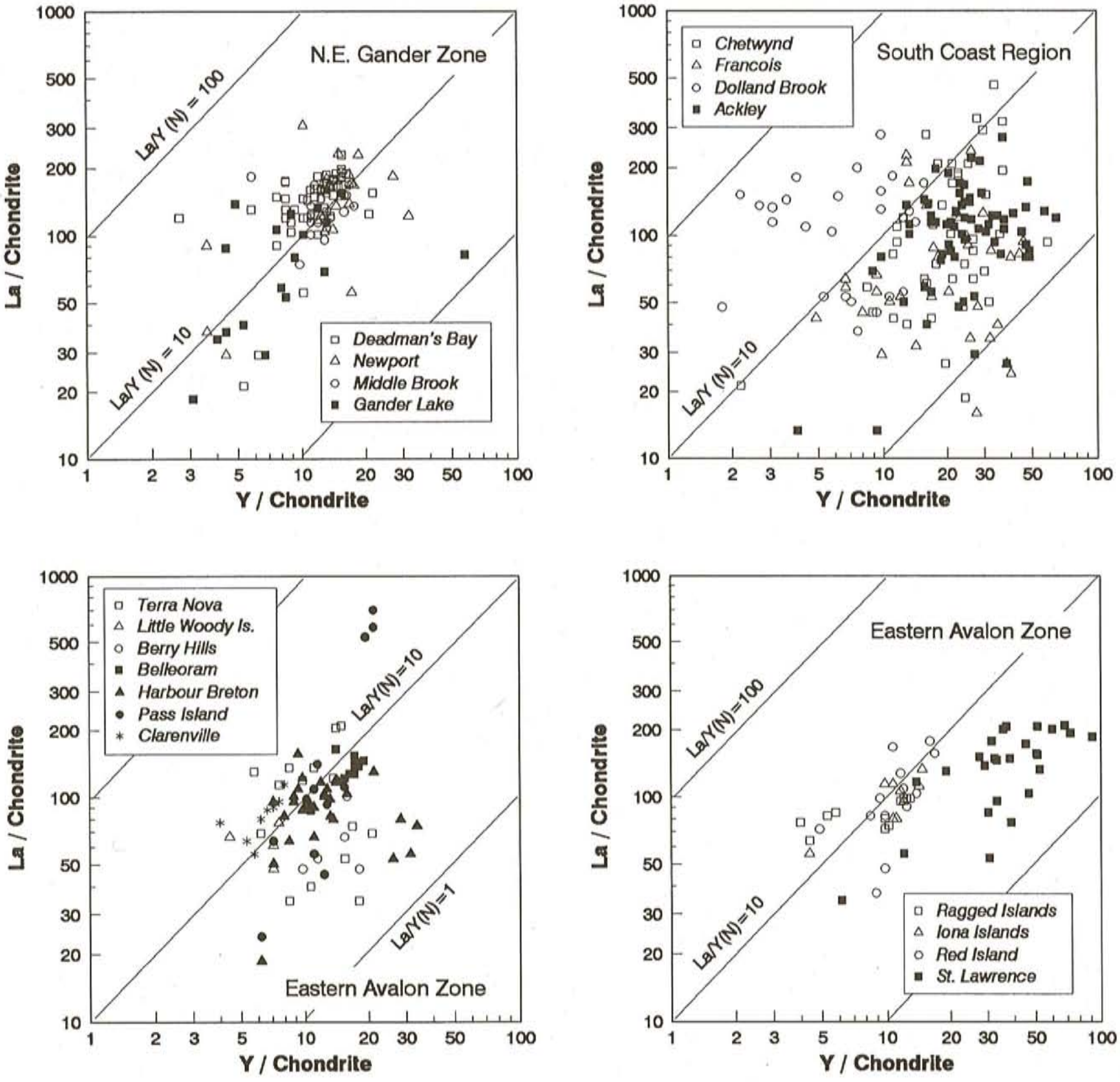

Figure 12. *La_N−Y_N variation diagrams for Devonian suites.*

Northeast Gander Zone plutons display broadly similar trace-element patterns (Figure 13). Modest negative Ba, Sr and Eu anomalies are characteristic of the more evolved Newport and Gander Lake granites, but only a Sr anomaly is visible in the Middle Brook Granite. These anomalies are a reflection of feldspar fractionation, as are Ba−Sr trends (Figure 9), and simply imply a greater amount of fractionation from the more evolved granites, as one would expect.

South coast plutons (Figure 14) are strongly evolved compared to those of the northeast Gander Zone, as illustrated by very prominent negative Ba, Sr and Eu anomalies, and strong enrichment in incompatible LIL elements such as Rb and U (notably in the François Granite). The deep Ba, Sr and Eu anomalies clearly suggest extended fractionation of feldspars from the parent magmas to these suites. Ta and Nb anomalies are also developed in these suites, most notably in the Chetwynd Granite. There are also differences in the REE patterns of these suites. The François and Ackley granites have essentially flat HREE patterns, whereas the Chetwynd Granite displays strong HREE fractionation, perhaps indicative of amphibole fractionation not recorded in the other plutons.

Western Avalon Zone plutons have similar trace-element patterns, but less pronounced Ba, Sr and Eu anomalies (Figure 15). As would be expected from major-element patterns, the Belleoram Granite has a distinctly unevolved

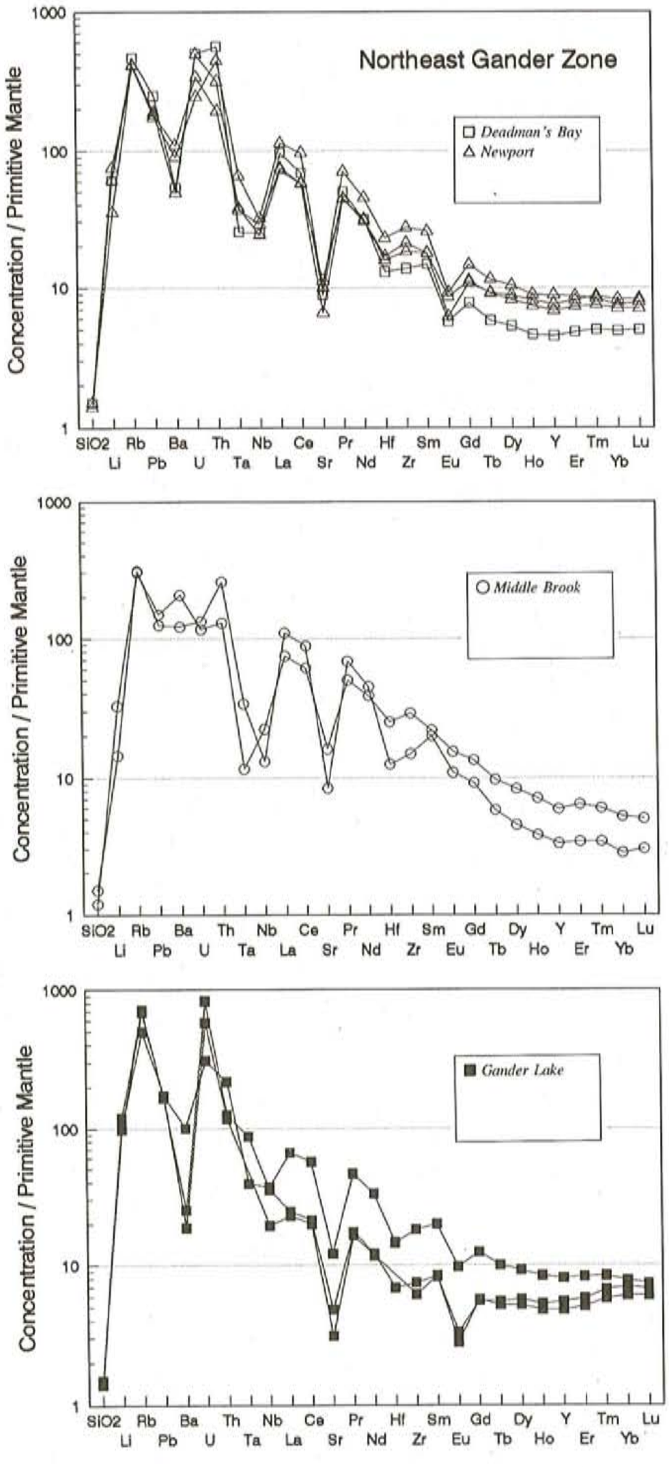

Figure 13. *Primitive mantle–normalized trace-element plots for Devonian suites of the northeast Gander Zone.*

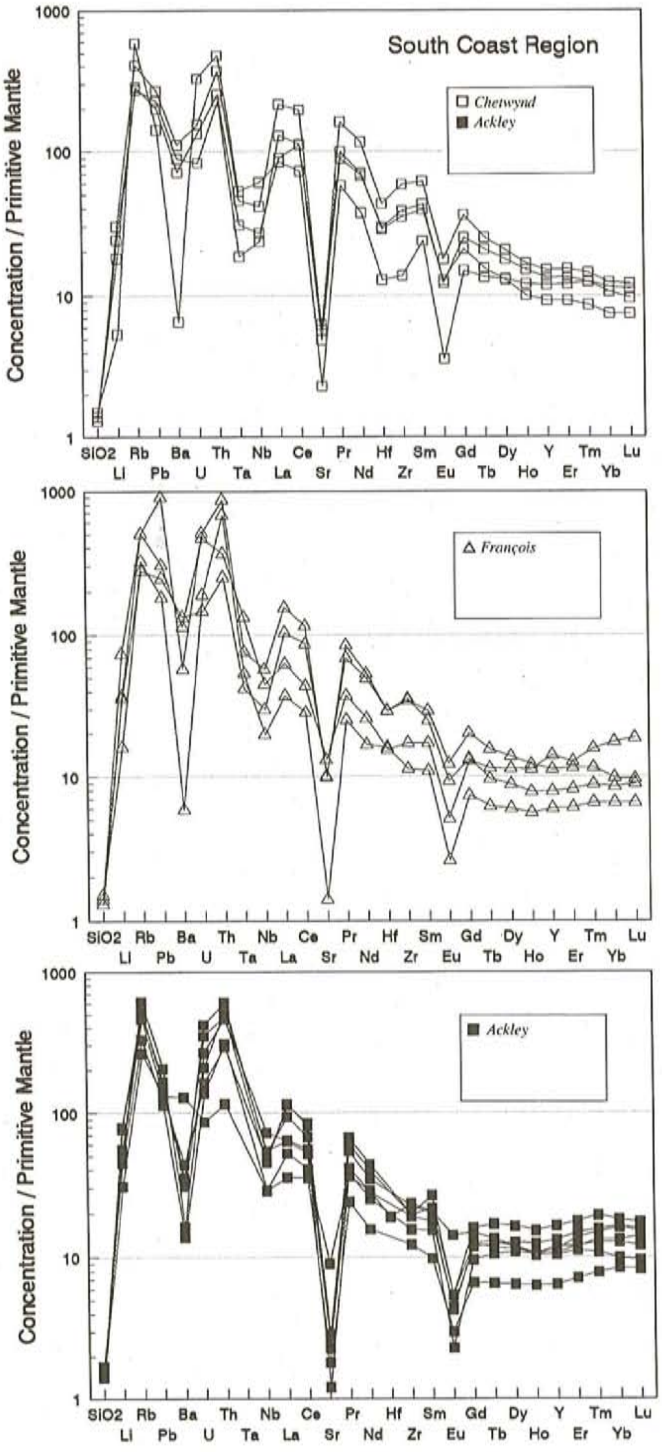

Figure 14. *Primitive mantle–normalized trace-element plots for Devonian suites of the south coast.*

trace-element pattern. The Pass Island Granite has by far the most evolved pattern, and displays a strong similarity to the François Granite. All have prominent negative Ta–Nb anomalies that resemble those of south coast plutons. Their REE patterns are also similar, with flat HREE spectra, except for the Terra Nova Granite, which has a fractionated HREE pattern like that of the Chetwynd Granite, and some northeast Gander Zone plutons. The Harbour Breton Granite is notable for a wide variation in REE abundances (HREE from 6 to 30 x primitive mantle).

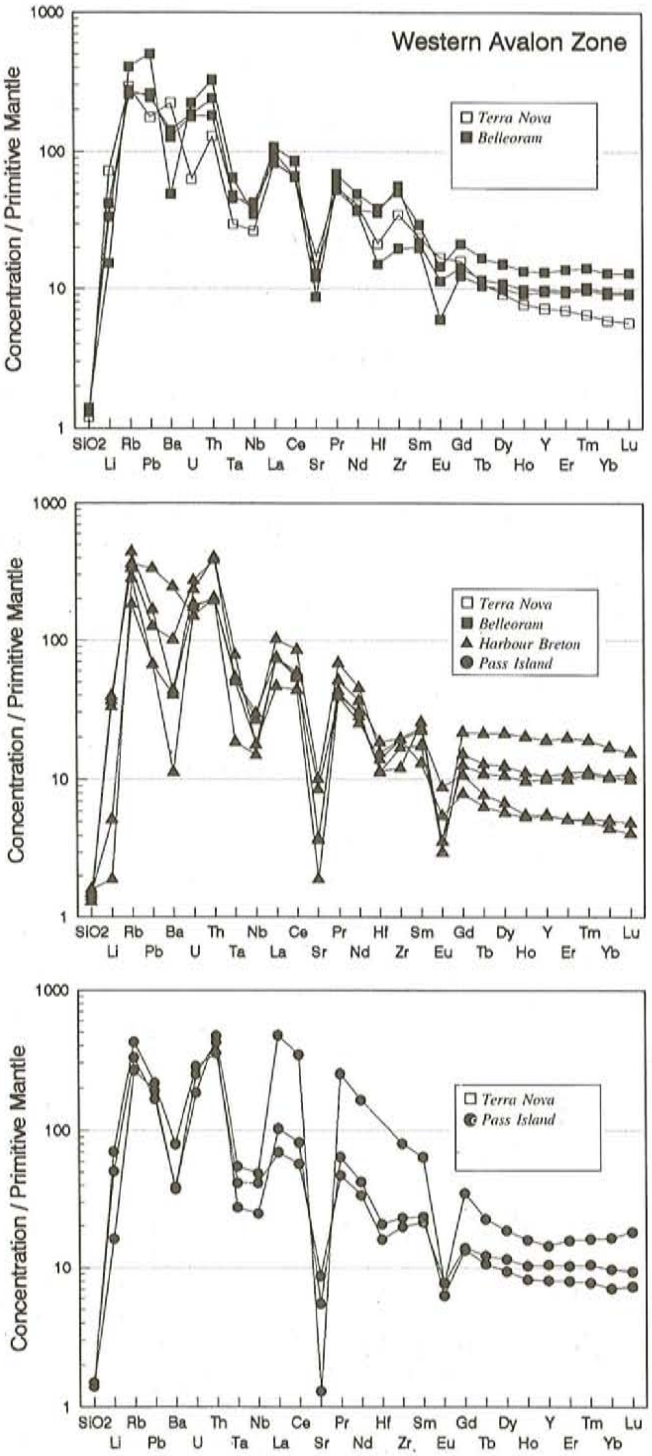

Figure 15. *Primitive mantle–normalized trace-element plots for Devonian suites of the western Avalon Zone.*

Eastern Avalon Zone plutons are more variable (Figure 16), but granites from Red Island and the Iona Islands have patterns that are closely similar to the south coast and western Avalon Zone granites. However, negative Ta–Nb anomalies are very poorly developed in the eastern Avalon suites, with the exception of the Ragged Islands granites and one sample from Red Island. The St. Lawrence Granite has a very distinctive pattern typified by deep negative Ba, Sr and Eu anomalies, and REE enrichment. This pattern is closely similar to the trace-element pattern of the nearby Grand Beach Porphyry, and strongly suggests that the two are related, despite the apparent difference in their U–Pb zircon ages.

NEODYMIUM AND STRONTIUM ISOTOPE GEOCHEMISTRY

The Nd and O isotopic studies of Newfoundland plutonic suites have been conducted under the auspices of the LITHOPROBE Program (e.g., Fryer *et al.*, 1992). The Sr-isotope data are less abundant and mainly derived from geochronological studies in the 1970's. Both datasets provide useful information that is highly relevant to the petrogenesis of the Devonian plutonic suites.

Sr-Isotope Data

Sr-isotope data is confined to the data presented by Bell *et al.* (1977), and subsequent geochronological studies. Ages and initial Sr-isotope ratios are listed in Table 2. An immediate question of reliability arises from these data, as several of these ages are now known to be incorrect. However, the initial ratio for the isochron is controlled by the point with the lowest Rb/Sr, which is least subject to disturbance by loss of radiogenic Sr. The effects of isotopic disturbance upon initial Sr isotope ratios are less severe than on apparent age. For example, in the case of the Newport Granite, the initial ratio of a recent determination (B. Fryer, unpublished data) is very close to the original estimate by Bell *et al.* (1977), although the earlier age is probably a severe underestimate.

Initial ratios of Devonian granite plutons range from a low of 0.7031 ± 3 in the Iona Islands (Peckham, 1992) to a high of 0.7220 ± 30 at St. Lawrence (Bell *et al.*, 1977). However, given the high average Rb/Sr of this pluton, and the erroneous isochron age, there is reason to treat the latter value as suspect. The high initial Sr-isotope ratio is inconsistent with Nd data for this pluton (see below). If this ratio is excluded, the highest initial Sr-isotope ratio is shown by the Middle Brook Granite, at 0.7077 ± 8 (Bell *et al.*, 1977). There appear to be no differences between any of the geographic areas, but the small amount of data by no means precludes systematic geographic variations. The most striking feature of the data is that most of the granites have low initial Sr ratios of 0.706 or less. This value lies at the upper end of the spectrum of isotopic compositions expected for a variably depleted upper mantle at ca. t=400 Ma, as defined by worldwide Sr patterns (e.g., Faure, 1978); the Iona Islands initial ratio (0.7031) is at the lower end of the mantle spectrum.

More than anything else, the abysmal Sr isotope database for Devonian granites illustrates an interesting and useful research project. The analysis of mineral separates (e.g., apatite and sphene, which are almost devoid of Rb) provides a method of obtaining initial Sr isotope data directly from single samples. Such information would be very useful, in conjunction with the Nd and O isotope data (see below).

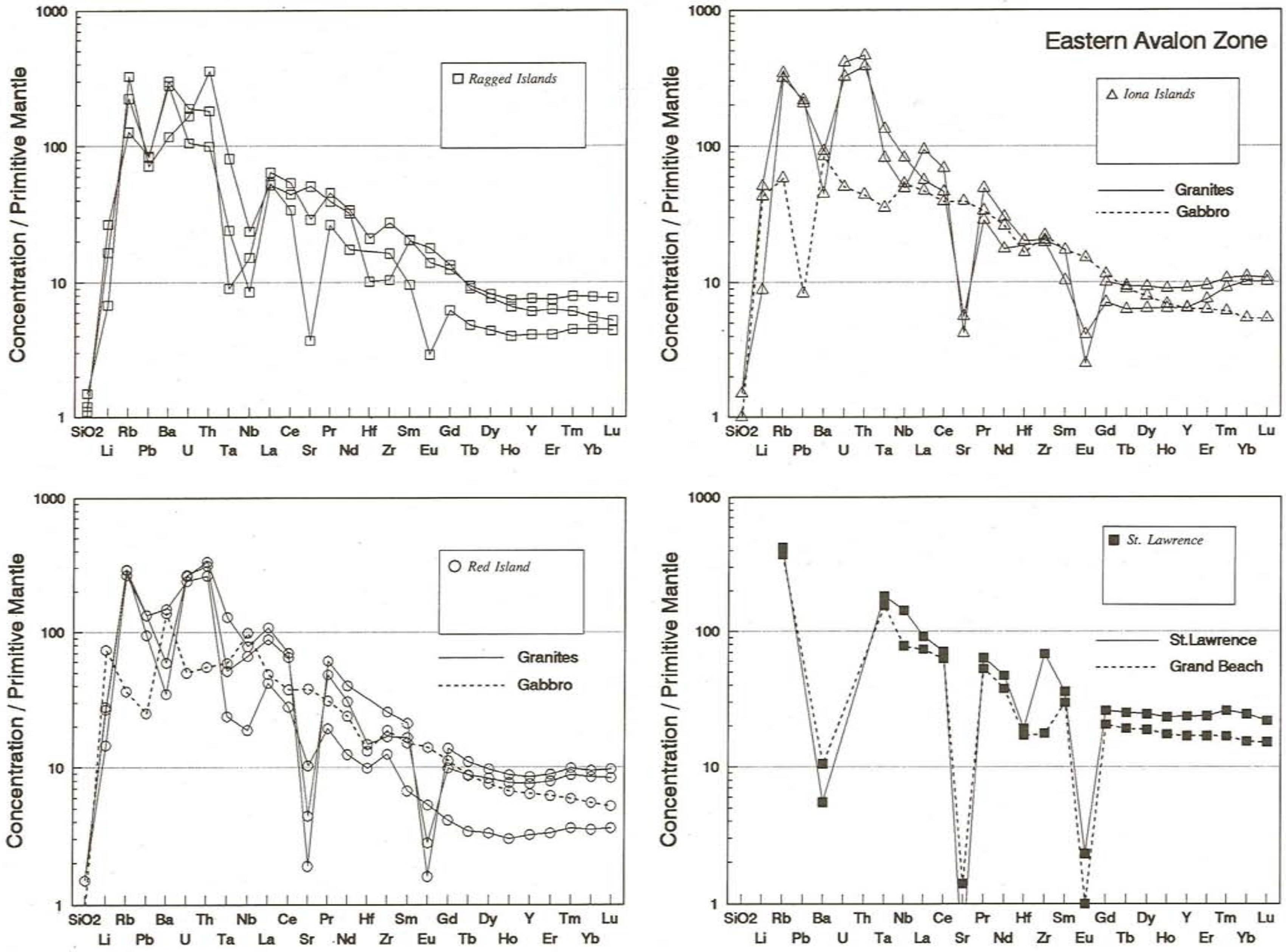

Figure 16. *Primitive mantle–normalized trace-element plots for Devonian suites of the eastern Avalon Zone.*

Table 2: Initial $^{87}Sr/^{86}Sr$ ratios reported from Rb–Sr isochron studies of Devonian plutonic suites

Pluton	Isochron Age	Initial Sr Ratio	Reference
Newport Granite	332 ± 42 Ma	0.7059 ± 20	Bell *et al.*, (1977)
Newport Granite	366 ± 5 Ma	0.7053 ± 2	Fryer (unpubl.)
Middle Brook	420 ± 20 Ma	0.7077 ± 8	Bell *et al.* (1977)
Terra Nova	328 ± 10 Ma	0.7050 ± 6	Bell *et al.* (1977)
Ackley Granite	345 ± 5 Ma	0.7048 ± 5	Bell *et al.* (1977)
Ackley Granite	353 ± 5 Ma	0.7063 ± 4	Tuach (1986)
Ackley Granite	370 ± 15 Ma	0.7049 ± 7	Tuach (1986)
St. Lawrence	315 ± 5 Ma	0.7220 ± 30	Bell *et al.* (1977)
Harbour Breton	343 ± 10 Ma	0.7080 ± 10	Strong (1980)
Iona Islands	364 ± 12 Ma	0.7031 ± 3	Peckham (1992)

Nd-Isotope Geochemistry

The principles of Nd-isotope geochemistry, as applicable to studies of Newfoundland plutonic suites, have been discussed in a previous current research article (Fryer *et al.*, 1992). Figure 17 illustrates $\in_{Nd}$ values (calculated with reference to chondritic values) for various Devonian plutons, for an arbitrary Early Devonian age of 400 Ma. Some of these data were previously presented by Fryer *et al.* (1992). The Nd-isotope data reveal strong systematic differences linked to geography and tectonic zones. The data can be divided into three, and possibly four groups.

The most obvious first-order contrast is between Gander Zone and south coast plutons and those of the Avalon Zone. Excluding the Newport Granite and part of the François Granite (see below), all of the former group have negative $\in_{Nd}$ of -1 to -4 at 400 Ma. There is also a marked polarity, with the northeast Gander Zone plutons showing values below -3, whereas those of the south coast have values of 0 to -2. Avalon Zone plutons, with the exception of the Terra Nova Granite, have positive $\in_{Nd}$ of +1 to +4 at 400 Ma. The most strongly positive values are from the Iona Islands and Red Island intrusions, and there may perhaps be a trend toward higher values in the east, although the differences are not compelling. The contrasts across the Dover–Hermitage Bay fault system are also preserved on the scale of a single pluton; the Ackley Granite has $\in_{Nd}$ of +2 to +3 on the Avalon side, and -4 on the Gander side; the latter value is akin to those seen in granites from the northeast Gander Zone.

These patterns have been discussed in general terms by Fryer *et al.* (1992), and they provide fundamental information about deep-crustal geology and also the petrogenesis of individual suites. These aspects are discussed in more detail in the final section of this paper.

Oxygen Isotope Geochemistry

Figure 18 illustrates variations in oxygen isotope compositions (expressed as $\delta^{18}O$, relative to standard mean ocean water) amongst Devonian plutons (data from Fryer *et al.*, 1992). There is evidence that contrasts between the Avalon and Gander zones are also expressed by oxygen. Gander Zone plutons have heavy $\delta^{18}O$ of greater than +9, whereas the Avalon Zone (as defined by parts of the Ackley Granite) has more moderate values of around +7. Contrasts in oxygen isotope compositions within the Ackley Granite have also been discussed by Tuach *et al.* (1988). Clearly, more analyses of O-isotope compositions are needed to confirm and expand this pattern, and link it to the Nd-isotope variations.

SUMMARY, DISCUSSION AND INTERPRETATION

REGIONAL GEOLOGICAL AND PETROLOGICAL VARIATIONS

There are clear contrasts in the regional geological settings of the Devonian plutons in southern and eastern Newfoundland. In the northeast Gander Zone, the predominant host rocks are metasedimentary rocks and migmatites of the Gander Group and Hare Bay gneiss complex, together with assorted Silurian granites. In the south coast region, the dominant host rocks are Silurian intrusive complexes, with subordinate supracrustal rocks. These contrasts probably reflect varying depths within the eastern Central Mobile Belt crust. Avalon Zone Devonian granites intrude low-grade metavolcanic and metasedimentary rocks of late Precambrian age. These general contrasts are accompanied by changes in the petrology and contact relationships of the Devonian granite plutons, as outlined below.

Northeast Gander Zone plutons are dominantly coarse- to very coarse-grained, strongly K-feldspar megacrystic biotite granites, as exemplified by the Deadman's Bay Granite, although minor equigranular phases occur in the Newport Granite and in the Gander Lake granite. The Deadman's Bay and Gander Lake granites also contain metasedimentary inclusions and xenoliths, some of which display K-feldspar phenocryst development indicative of chemical interaction with their hosts. The inclusion population of the northeast Gander Zone granites also suggests significant assimilation of metasedimentary rocks by these magmas, except for the Newport Granite, which is inclusion-poor. South coast

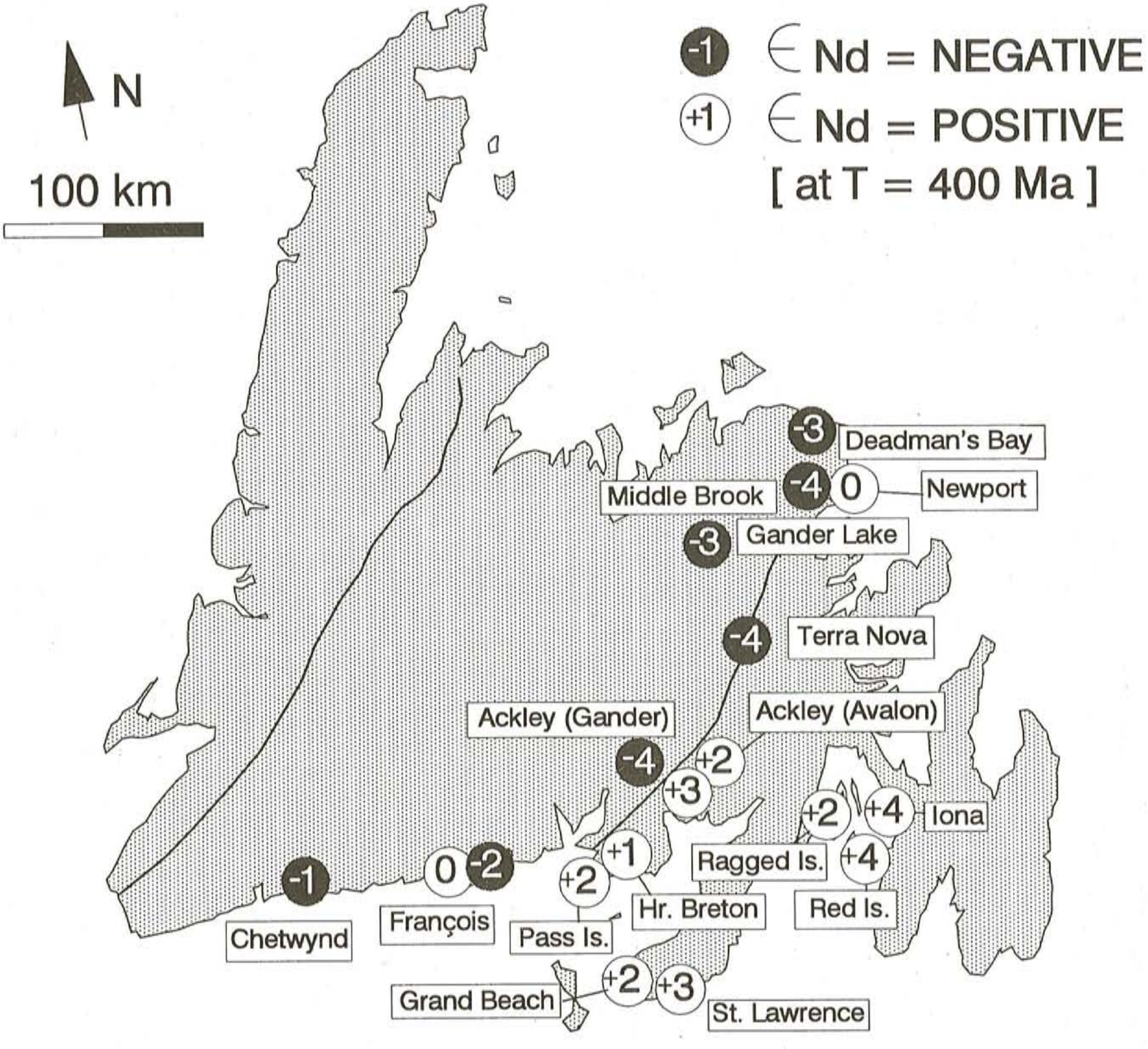

Figure 17. *Nd isotopic variations in Devonian plutonic suites, expressed as* $\in_{Nd}$ *(CHUR). Partly after Fryer* et al., *1992, with additional data.*

granites also include megacrystic variants (notably in the Chetwynd Granite), but they are dominated by medium- to coarse-grained equigranular granites. They are relatively inclusion-poor. The large Ackley Granite is an in-between situation, as it includes coarse megacrystic granites, but is dominated by medium-grained, equigranular phases on the Avalon side (Dickson, 1983; Tuach *et al.*, 1986).

This petrological shift is accompanied by a more significant contrast in contact relationships. The Chetwynd and François granites are associated with quartz-feldspar (sanidine) porphyry and felsite dykes of subvolcanic appearance, which can be traced up to 20 km from the outer contacts of the granites. The François Granite is also notable for its striking ring-complex geometry (Poole *et al.*, 1985; Figure 2). Both features appear to be largely absent from the northeast Gander Zone examples, although poorer exposure may render them harder to detect. It is likely that the ductility of the country rocks has some influence on generation of satellite dyke swarms, but it should not influence the overall grain size and lithology of plutons. Thus, these contrasts suggest a contrast in structural levels from north to south; the features of the Chetwynd and François granites imply a higher level setting where brittle, tensional, failure of country rocks was an important mechanism of intrusion. If this is the case, it implies that, during the Devonian, the south coast region was at a higher level in the crust than the northeast Gander Zone.

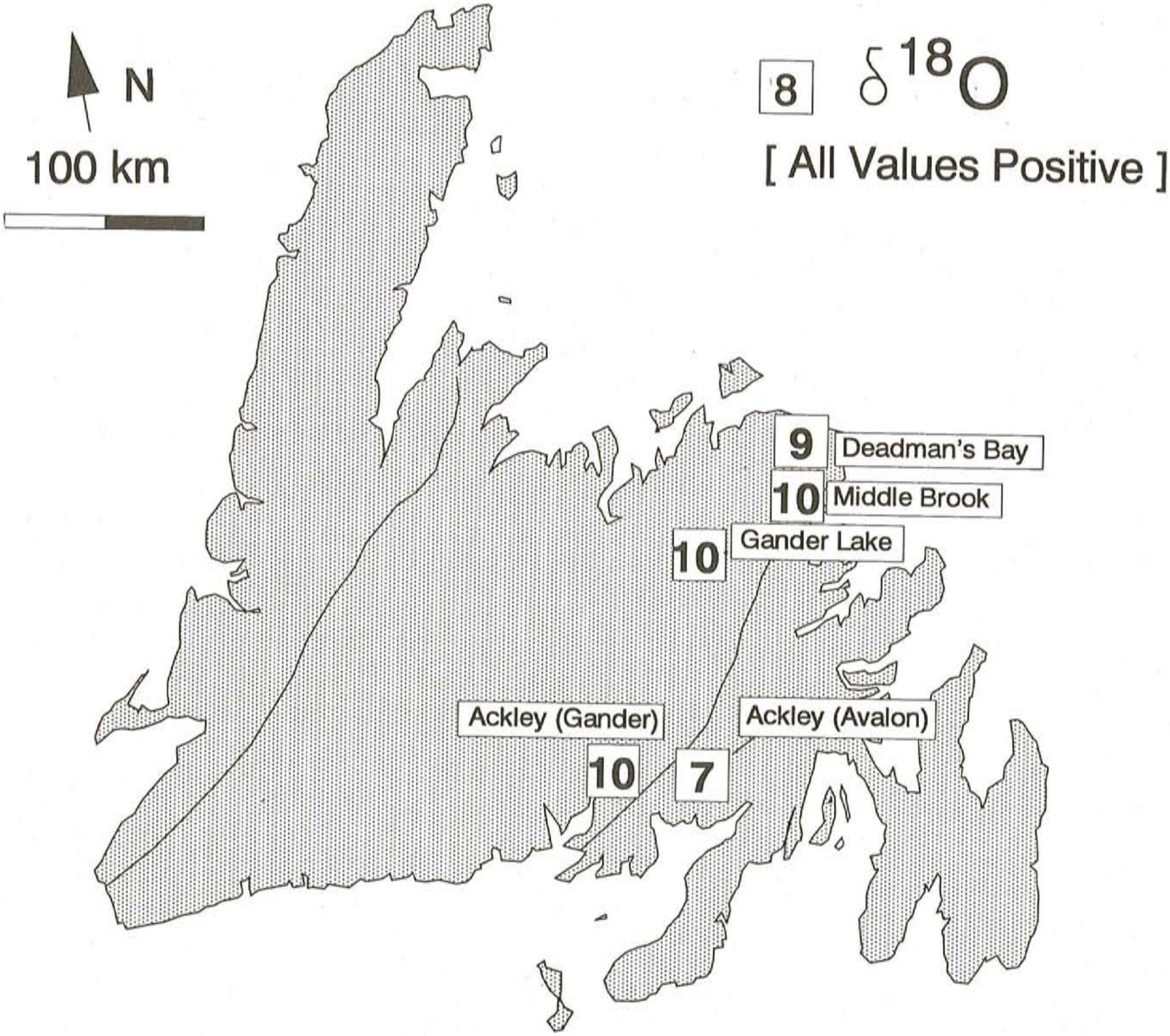

Figure 18. *Oxygen isotopic variations in Devonian plutonic suites, expressed as* $\delta^{18}O$ *Nd (SMOW). After Fryer* et al., *1992.*

Avalon Zone plutonic suites are also exposed at high structural levels. The Belleoram and Harbour Breton granites preserve superb cross-sections of their roof zones, and are associated with spectacular composite dykes. The St. Lawrence Granite is associated with a very extensive dyke swarm of 'rhyolite porphyries', and also has preserved parts of its volcanic cover. Excluding Terra Nova, which is a megacrystic biotite granite similar to those of the northeast Gander Zone, all are equigranular to locally porphyritic, and generally of medium grain size. Some phases of the Harbour Breton, Pass Island, Red Island and St. Lawrence granites are quartz-porphyritic, which is another indication of shallow depth. Miarolitic cavities, gas-breccias and vuggy pegmatite segregations, all indicative of volatile exsolution, are common. The presence of hydrothermal mineralization is also indicative of the upper levels of the magma chambers, as such features are invariably concentrated in the roof zones. It is our impression that Avalon Zone Devonian plutons are exposed at significantly higher structural levels than south coast examples, which are in turn exposed at higher structural levels than those of the northeast Gander Zone.

In petrological terms, Avalon Zone plutons resemble those of the south coast region, but include subordinate to dominant gabbro and diabasic intrusions. The best example of such a bimodal assemblage is the Iona Islands Intrusions, where spectacular zones of magma interaction, and hybrid monzonitic rocks, suggest that the mafic and felsic magmas were broadly coeval (Peckham, 1992). Mafic rocks also occur at Red Island, and the mafic enclaves of the Belleoram Granite

(Furey, 1985; R. Morrissey, personal communication, 1992) probably reflect a subjacent mafic intrusion (cf. Vernon, 1984).

In summary, there are contrasts in the settings, petrology and structural emplacement levels of these plutons in different regions. However, the greatest contrasts are from north to south, rather than east to west, in spite of the presence of a major structural boundary along the Dover–Hermitage Bay fault system. The most diagnostic feature of Avalon Zone intrusions is their local tendency toward bimodal magmatism.

GEOCHEMICAL CONTRASTS

The geochemical similarities between these Devonian plutonic suites outweigh differences between them. All are relatively evolved, potassic, SiO_2-rich granites with low levels of FeO(t), MgO and CaO. They are enriched in incompatible elements and depleted in compatible elements relative to average granites. As such, they are highly typical of post-orogenic magmatism in ancient orogenic belts, which have a distinct commonality throughout the world and through geological time (e.g., Pitcher, 1983). However, although the contrasts in their geochemistry are subtle, they are significant, and can be linked to the general variations in petrology and setting discussed above.

There are several important distinctions between the northeast Gander Zone granites and those of the south coast region. First, some of the former, notably the Deadman's Bay and Middle Brook granites, are relatively unevolved. This could reflect contrasts in structural level noted above, but may also be a function of their ages, which are probably slightly older. It is common in any igneous province for 'cycles' of magmatism to be developed, in which the younger members are more evolved; the Newport Granite is clearly more evolved than the lithologically similar, but older, Deadman's Bay Granite. Contrasts in the molecular ratios A/CNK and Agpaitic Index are also significant. Northeast Gander Zone granites (excluding Newport) have a tendency toward high A/CNK ratios, which likely relates to their regional geology, as they have intruded and assimilated metasedimentary rocks with high Al_2O_2. Also, similar indications of this effect are seen in other parameters, notably the Nd and Sr isotopes (see below).

South coast and Avalon Zone granites do not display this tendency, although many have A/CNK between 1.0 and 1.1. They instead show an opposing tendency toward high agpaitic indices (> 0.9), and FeOt/(FeOt + MgO). Such features are regarded as typical of so-called 'anorogenic' or 'within-plate' or 'A-type' granites (e.g., Pitcher, 1983; Eby, 1990), although only the St. Lawrence Granite is marginally peralkaline. A wide range of other geochemical parameters are consistent with this general contrast. Trace-element discrimination diagrams are ineffective in categorizing these suites, as is commonly the case with postorogenic granites, but the south coast and Avalon Zone granites do show features that are transitional to those of 'A-type' granites.

COMPOSITIONAL EVOLUTION

Primitive-mantle normalized diagrams invariably display deep, negative Sr, Ba and Eu anomalies, with the most evolved, high-SiO_2 granites showing the most pronounced depletion. Such features could reflect melting of a feldspar-rich source, but the Ba depletion requires significant K-feldspar, which is unlikely to be a residual mineral in crustal melting. It is more likely that these patterns indicate an extensive fractional crystallization history, dominated by the removal of feldspars, initially plagioclase, but followed by extensive K-feldspar fractionation. Direct evidence for this is provided by the presence of K-feldspar (± plagioclase) as common phenocryst phases; indeed, strongly megacrystic plutons such as the Deadman's Bay Granite may be 'cumulates' in the broadest sense of the word.

The Ba–Sr trends are also consistent with a model that invokes feldspar fractionation as a major compositional control. It is important also to note that all are characterized by relatively high Ba (≈ 1000 ppm) and Sr (≈ 500 ppm), in rocks with SiO_2 below 67 percent. Such features, particularly the high Sr, are inconsistent with derivation by melting of typical crustal sources. Also, the predominantly flat HREE patterns of most plutons are inconsistent with derivation by melting a hornblende-bearing source material such as a metabasic lower crust.

There has been much discussion of various 'categories' of granites and on distinctions between so-called 'A-type' granites and 'fractionated I-type' granites (e.g., Whalen *et al.*, 1987). Such distinctions are of limited value, as they are predicated on the idea that these different granitoid associations can be explained by melting of particular source rocks (e.g., Chappell *et al.*, 1987). We prefer to think of a continuum of compositions created by the superposition of local variations upon a common process. For example, the high A/CNK of some northeast Gander Zone granites probably reflects assimilation of Gander Group-like materials, rather than a fundamentally different source region. The variations amongst south coast and Avalon Zone granites are viewed as manifestations of a common process that has produced a range of plutons spanning a largely illusory gap between so-called 'I-type' and 'A-type' granites. This is discussed in more detail below, in a discussion of petrogenesis.

ISOTOPE GEOCHEMISTRY PATTERNS

The most compelling evidence concerning the petrogenesis and sources of Devonian granites in southeastern Newfoundland comes from Nd isotope systematics (Figure 17).

The variation in ϵ_{Nd} signatures from $\approx$ -4 in northeast Gander Zone granites to $\approx$ -1 in those of the south coast is entirely consistent with the suggestion that magmas in the former area incorporated a significant metasedimentary component. The Gander Group had an ancient source region, and would have had $\in_{Nd}$ of around -8 at t=400 Ma (Fryer *et al.*, 1992). It represents a powerful isotopic contaminant. However, as the Devonian granites of this area have $\in_{Nd}$ of -3 to -4, they cannot be derived entirely from the Gander Group; they must include significant amounts of material with higher $\in_{Nd}$. South coast granites obviously did not encounter and assimilate this ancient supracrustal material, and it has not influenced their signatures.

This model is not only consistent with a general pattern amongst these rocks, but explains two prominent exceptions. The Terra Nova Granite has a close petrological resemblance to northeast Gander Zone plutons, but is located within the Avalon Zone. However, it has a typical Gander Zone Nd isotope signature. This suggests that the granite was derived from a Gander-type source at depth, implying that the Dover fault may dip eastward, at least in this area. The Newport Granite lacks the low $\in_{Nd}$ of other Gander Zone granites; the only equivalent neutral signature is given by parts of the François Granite. The Newport Granite has the least tendency toward peraluminous compositions, and it also has a low initial Sr isotope ratio. Such observations suggest that it did not assimilate Gander Group-type materials to any significant extent. As it is the youngest granite in this area, and its dominant country rocks are high-grade migmatites, it is possible that much of the low-melting point contaminants had been consumed by the time of its intrusion. Note that other northeast Gander Zone plutons intrude lower grade portions of the Gander Group.

It is instructive to also consider potential sources for the south coast granites. The oldest rocks on the south are the Grey River Enclave and similar late Precambrian remnants (Dunning and O'Brien, 1989). No Nd isotope data are currently available from these. However, late Precambrian granitoid rocks in central Newfoundland, probably representing exhumed basement slices, would have $\in_{Nd}$ of -2 to -4 at t=400 Ma (A. Kerr and B. Fryer, unpublished data). This is slightly below the range of $\in$ values exhibited by south coast granites of both Silurian and Devonian age (Fryer *et al.*, 1992). Thus, a similar conclusion may apply in this region, i.e., the Nd isotope signatures of the granites require that they include a component with relatively high $\in_{Nd}$, in addition to material derived from local basement rocks. This requires confirmation by further analysis of south coast late Precambrian rocks (currently in progress).

The isotopic signatures of Avalon Zone granites are positive, with $\in_{Nd}$ ranging from +1 to +4. It is clear that they do not include significant amounts of older crust. The Nd isotope data from Avalon Zone late Precambrian plutonic suites, which are likely candidates for basement, yields similar conclusions. At the time of their formation ($\approx$600 Ma) late Precambrian plutonic rocks of the Avalon Peninsula had $\in_{Nd}$ of +1 to +6, except for the anomalous Simmons Brook Granodiorite (Fryer *et al.*, 1992; A. Kerr and B. Fryer, unpublished data). However, the very high values are from Eocambrian peralkaline complexes such as the Louil Hills Granite and Cross Hills Plutonic Suite, which represent only a tiny volumetric fraction of the late Precambrian crust of the region. Excluding these, the bulk of Avalonian plutonic rocks had $\in_{Nd}$ of +1 to +3 at 600 Ma, and would have had $\in_{Nd}$ of -1 to +1 at 400 Ma. For the most part, Devonian plutons in the Avalon Zone have $\in_{Nd}$ that is significantly higher than this projected range, particularly in the eastern Avalon Zone (Figure 17). Thus, these magmas must include a significant contribution from a source that has a higher $\in_{Nd}$ value than the local basement rocks.

Devonian suites across southern Newfoundland exhibit strong decoupling of elemental and isotopic signatures (Kerr *et al.*, 1990). The elemental geochemical variation amongst plutons of the Avalon Zone is greater than the differences between Gander Zone and Avalon Zone plutons. This could be explained in two ways. If the magmas were derived by melting of crustal rocks, it would indicate source materials of closely similar elemental composition, but with quite different isotopic signatures (and also that the degree of partial melting was equivalent). Alternatively, crustal sources may have been less important than material derived from beneath the crust, and any elemental differences between crustal blocks were subdued and diluted by this material. The distinctive isotopic signatures of the two lower crustal blocks were, however, preserved in the magmas. This latter proposal is more consistent with the implication that a source component with $\in_{Nd}$ higher than local basement must have been involved in magma genesis.

A PETROGENETIC MODEL

Elemental and isotopic data strongly suggest that these Devonian plutonic suites cannot be explained in terms of any one source component. In all areas, their $\in_{Nd}$ values are *higher* than surrounding country rocks or similar materials. Their initial Sr-isotope ratios are low (< 0.706), and the least differentiated members of most suites have high Ba and Sr contents. All of these features implicate a source component with high $\in_{Nd}$, low $^{87}Sr/^{86}Sr$, and high Ba and Sr, which must have interacted with crustal rocks. The most likely candidate for such a source is a mantle-derived magma of mafic or intermediate composition. The model proposed for these Devonian suites is a multicomponent one, in which mantle-derived magmas interact with various components of the continental crust. It is influenced by models presented for correlative Caledonian granites in northern Britain (e.g., Harmon *et al.*, 1984; Halliday, 1984).

West of the Dover–Hermitage Bay fault system, it is suggested that granite magmas include three source components. In all areas, they include a mantle-derived magma, and a component derived from the probable late Precambrian sialic basement of the eastern Central Mobile Belt. These sources were joined by a third component where the granites were emplaced through a Paleozoic sedimentary cover with ancient sources (the Gander Group and its equivalents). This had a very significant effect on isotopic signatures; and also on elemental geochemistry, leading to peraluminous tendencies and negative $\in_{Nd}$. One marginal Avalon Zone granite (Terra Nova) had essentially similar sources, suggesting superposition of Avalon over Gander along parts of their mutual boundary. The youngest granite in the northeast Gander Zone (the Newport Granite) did not assimilate metasedimentary materials to the same extent.

'Fossilized' evidence of a mixing process may be preserved in Nd isotopic variations within single plutons. In the François Granite, analyses of different ring-complex units suggest a range in $\in_{Nd}$ of -2 to almost +1. In three samples, there is a quasi-linear inverse relationship between $^{143}Nd/^{144}Nd$ and Nd concentrations. This is supportive of, but not diagnostic of, a mixing relationship where Nd is being contributed largely by a crustal source with lower $\in_{Nd}$. A fourth sample, representing the youngest, most evolved phase, lies off this trend, with the highest $\in_{Nd}$, and thus has a distinct, more primitive source. In the Newport Granite, the value of 0 displayed on Figure 17 is actually an average of seven values ranging from -0.7 to +1.3. The relationship between isotopic compositions and concentrations of Nd is not as clear as at François, but in a 3-component situation, simple linear or hyperbolic relationships are unlikely.

In the Avalon Zone, Devonian plutons are also suggested to be mixtures of mantle-derived magmas and late Precambrian crustal rocks. As the latter themselves had significantly more 'juvenile' characteristics than the crust of the eastern Central Mobile Belt, the signatures of the mixtures are quite different to those of the south coast area. In the Avalon Zone, there is direct evidence of a mantle-derived mafic magma in the form of plutons with bimodal affinities, such as the Iona Islands Intrusions and the Red Island granite, and the enclave-rich Belleoram Granite, which appears to have coexisted with a largely unseen mafic intrusion.

In both areas, the subsequent high-level evolution and fractionation of the Devonian granites were dominated by fractional crystallization, primarily of feldspars, with early plagioclase fractionation giving way eventually to a K-feldspar dominant assemblage. These rocks do not contain significant amounts of 'restite' in the sense of Chappell *et al.* (1987), and they are considered to have originated as largely liquid bodies.

It is presently difficult to refine this model to include firm estimates of the proportions of mantle and crustal end-members involved in the genesis of these granites, although there may be up to 50 percent mantle derivation. There is presently little direct information about the chemical and isotopic features of the mantle-derived component, as rarely is it seen in an unmodified form. Gabbroic rocks from Iona Islands and Red Island have alkali-basalt affinities (Peckham, 1992). Fine-grained Paleozoic gabbro–diabase sills in the Cape St. Mary's area have $\in_{Nd}$ of +5 at 400 Ma (A. Kerr and B. Fryer, unpublished data), but this is a lower limit only, as there is likely some crustal contamination even in mafic rocks. Attempts will be made to refine the model when more data are available from mafic plutonic rocks. The causes of melting within the mantle to produce this component are also hard to establish. However, several models for the Appalachian orogenic belt call upon lithospheric delamination at the crust–mantle boundary in order to accomodate continued post-closure shortening (e.g., Colman-Sadd, 1982; Quinlan *et al.*, 1991; Sachs and Secor, 1990). This provides a possible mechanism for upwelling of deeper, hotter regions in the mantle, and for melting by decompression.

NATURE OF THE DOVER–HERMITAGE BAY FAULT SYSTEM

The radical differences in isotopic compositions between south coast and Avalon Zone plutons (Figure 17) provide compelling evidence for the importance of the Hermitage Bay fault system. Although there have been problems in seismically imaging this structure (Quinlan *et al.*, 1992) there can be no doubt that it is a major crustal-scale feature. Although the late Precambrian basement rocks of the eastern Central Mobile Belt may have affinities to those of the type Avalon Zone, it is unlikely that they are directly equivalent. The possibility that the Hermitage Bay fault system is sealed at depth by Devonian plutonic suites must also be considered in interpretation of the seismic data. The 2700 km² Ackley Granite, which totally obliterates the fault, indicates the volume of magma that has ascended in this region, and much of this would probably have been channeled along the fault zone. As outlined above, there is evidence for mantle involvement in petrogenesis, so such effects could extend to considerable depths.

MINERAL POTENTIAL

The first, general, observation made here echoes the assessment of Strong *et al.* (1974). There is little doubt that the highest priority targets for granophile mineralization amongst these suites are to be found in southern Newfoundland. It is in this area that the two best-known examples of granite-related mineralization in the Province are situated, and it contains some of the most evolved granites in Newfoundland. The Avalon Zone side, in particular, represents high structural levels, where the roof zones of plutons are exposed, and regional outcrop patterns suggest subjacent granitoid bodies over significant areas. The Ackley Granite, particularly on its southern margin, is a prime target in this area. The Harbour Breton Granite also deserves special mention, for it is a highly evolved pluton, with similarities to the Ackley Granite, and its roof zone is very close to the erosion surface. There is direct evidence of hydrothermal activity, notably around the 'Old Woman Stock'. In the eastern part of the Avalon Zone, the St. Lawrence Granite is well known as a peralkaline intrusion hosting fluorite. There has been some assessment of its potential for rare-metal mineralization (R. Miller, personal communication, 1992), but this does not appear high, consistent with its only marginal peralkalinity. There may, however, be a more significant potential for epigenetic Pb–Zn–Cu (± Ag) mineralization, but the size of such vein-style deposits related to plutonic suites tend to be small. However, in terms of regional metallogenic associations, the area at the foot of the Burin Peninsula remains one of the most attractive in the Avalon Zone. Last, but not least, the Placentia Bay area should not be ignored; there is direct evidence of hydrothermal activity in the skarn zone on Red Island, and geophysical patterns indicate that there may be a substantial 'Placentia Bay batholith' in this region, which may be linked to barite veins, associated with Pb–Ag, in surrounding areas (Howse *et al.*, 1992).

Plutonic suites on the south coast of Newfoundland also represent high levels of emplacement, but there is less direct evidence for their mineral potential. The highly evolved François Granite is the source of prominent geochemical and geophysical anomalies. However, mapping of the pluton has not revealed any economic mineralization. Follow-up of geochemical anomalies by McConnell (1985) proved negative, although minor topaz (suggestive of greisens) was located in float. These initial results are disappointing but, by any standards, the François Granite qualifies as a specialized granite, and it is certainly worthy of close investigation in any regional exploration program. The discovery of tourmaline–scheelite veins in the Dolland Brook Granite during similar follow-up activity is a positive indication that geochemical anomalies are linked to bedrock mineralization in this area. Mapping of the Chetwynd Granite (O'Brien *et al.* 1986) has not revealed any mineralization, but its proximity to the Hope Brook mine site lends a new accessibility to this region. The main example of granite-related mineralization on the south coast, the Grey River tungsten prospect, also appears to be linked to a largely unseen Devonian granite body (Higgins *et al.*, 1990). This hints at potential for similar occurrences, and also at a more general point.

Paradoxically, the best places to search for granite-related prospects in Newfoundland, and elsewhere, may be in areas where the granites themselves are unexposed, but are inferred to lurk at shallow depths. Most endocontact-type showings are localized in cupolas and protrusions on the intrusion roof, in many cases where competent, impervious country rocks have encouraged the ponding of hydrothermal fluids. High-potential areas may thus exist some distance from the outer contacts of plutons, and the linked plutonic suites may have limited surface expression. The Grey River tungsten prospect is one example; the Mo showing on a small island in Fortune Bay described by Whalen (1980) may illustrate the potential for mineralization well to the south of the known contact of the Ackley Granite, which is already well-established as a zone of mineral potential.

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