Current Research (2017) Newfoundland and Labrador Department of Natural Resources
Geological Survey, Report 17-1, pages 41-60

U–Pb GEOCHRONOLOGY OF THE WESTERN PART OF THE NAIN PLUTONIC SUITE, KINGURUTIK LAKE AREA (NTS 14D/15)

B. Ryan, J. Connelly[1] and D. James[2]
Regional Geology Section
[1]Centre for Star and Planet Formation, Natural History Museum of Denmark
University of Copenhagen, Øster Voldgade 5-7, Copenhagen, Denmark
[2]Geoscience and Mines Branch, Department of Natural Resources, 1701 Hollis Street, Halifax, NS, B3J 2T9

ABSTRACT

Geochronological investigations, using U–Pb dating of zircons, have been conducted on several different rock types within the Mesoproterozoic Nain Plutonic Suite (NPS) from the region directly west of Kingurutik Lake in north-central Labrador. Leuconoritic rocks crystallized at 1349 ± 1 Ma, contemporaneous with a granitic body at 1348 ± 1 Ma. A composite 'dioritic' association was intruded ca. *1342-1341 Ma, and leucogranite dykes were emplaced at 1337 ± 1 Ma. The geochronological results reported herein enhance existing data showing that the western part of the NPS contains relatively undeformed plutonic rocks that are tens of millions of years older than similar ones from the eastern region. The ages bolster the currently existing geochronological framework that magmatism giving rise to the NPS began in the west and migrated eastward.*

INTRODUCTION

The Nain Plutonic Suite (NPS) of north-central Labrador is a batholithic aggregation of hundreds of coalesced Mesoproterozoic plutons, encompassing a varied array of rocks (Ryan and Morse, 1985; Ryan, 2000; Figure 1) and having a temporal span from *ca.* 1360 Ma to *ca.* 1290 Ma (*see* below). The NPS underlies an exposed geographic area of approximately 18 500 km^2, and may occupy an additional area one-quarter that size submerged to the east below the Atlantic Ocean (Funk *et al.*, 2000). Anorthositic (*s.l.*) and pyroxene- and olivine-bearing granitic plutons are predominant and are preserved to different degrees. They are manifested as hundreds-of-square-metres-scale remnants of once larger bodies (*see, e.g.*, maps by Ryan and James, 2004; James and Byrne, 2005) as well as hundreds-of-square-kilometres-scale, clearly defined, intact plutons (*see, e.g.*, compilation map of Ryan, 1990; map of the Kiglapait Intrusion by Morse, 1969; map of Tigalak intrusion by Wiebe, 1983).

The NPS forms a plutonic welt stitching two crustal blocks, the Nain and Southeastern Churchill provinces (Figure 1), that were tectonically fused at *ca.* 1860 Ma (Wardle *et al.*, 2002). The NPS is thought to be an earmark of Mesoproterozoic crustal extension, allowing mantle- and crustal-derived magmas to rise and solidify within 6 to 14 km of the surface (Berg, 1979) and, likely, also to ascend to the surface to generate contemporaneous volcanic centres. The temporal niche occupied by NPS magmatism is anorogenic (*see* Emslie, 1978a), hundreds of millions of years after the *ca.* 1860 orogenic activity, and the NPS has not been affected by any later regional Mesoproterozoic (*i.e.*, Grenvillian) events. The tectonic setting has been compared by Emslie (1978b) to intracontinental rift locales; Gower and Krogh (2002) postulate magmatism above an extensive, subhorizontal, subducted oceanic slab beneath thickened continental crust; and Bybee *et al.* (2014) raise the possibility of a connection to long-lived (and spatially far-removed) Andean-type continental margin subduction zones.

The rocks of the NPS span a wide compositional spectrum, and most lack modally significant hydrous minerals. As noted above, anorthositic and pyroxene-bearing granitic rocks are the most widespread, although compositions range from peridotite to leucogranite. Typifying the NPS are areally extensive intrusions of anorthosite (including leuconorite and leucotroctolite), granite (including monzonite, quartz monzonite, and syenite, many containing fayalite and clinopyroxene), ferrodiorite (iron-rich gabbronoritic rocks having abundant metallic oxide and apatite) and troctolite. Peridotite is uncommon, mainly disposed as metre-scale inclusions in other rocks and as ultramafic cumulates in layered basic intrusions. Leucogranite constitutes centimetre- to metre-scale dykes in other rocks.

Several different isotopic age-determination techniques have been brought to bear on the rocks of the NPS since

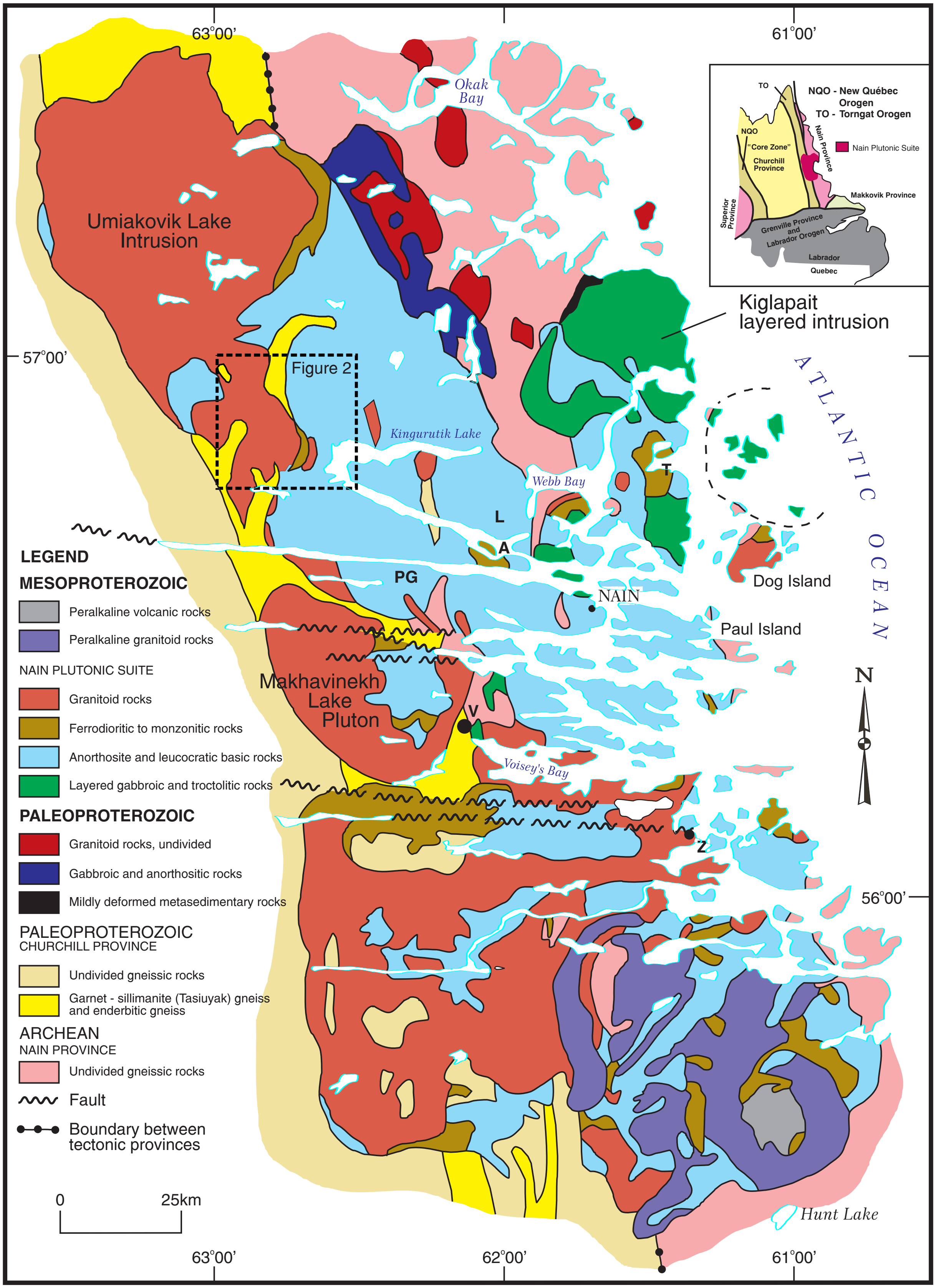

Figure 1. *Caption* see *page 43.*

1960; for example, pre-1980 K–Ar, Rb–Sr, and U–Pb studies firmly established its Precambrian age. Since the 1980s the application of precise U–Pb dating of zircon, monazite and baddeleyite has advanced understanding of the crystallization sequence of the intrusions and provided a temporal envelope for discussing the longevity of the magmatism that gave rise to the NPS. The current consensus from the age studies is that the NPS is a result of prolonged Mesoproterozoic magmatism, the oldest plutons forming perhaps as early as 1370 Ma (*see* below). Plutonism continued for tens of millions of years thereafter, with intrusions of contrasting composition being emplaced both simultaneously and periodically throughout the whole temporal span. The U–Pb geochronological studies have laid to rest the view that NPS magmatism may have been short-lived (see, *e.g.*, Wiebe, 1990, page 2; Snyder and Simmons, 1992) and the notion that there was systematic compositional differentiation (de Waard, 1974) and age progression (Emslie, 1978a) from 'old' basic rocks to 'young' silicic ones. However, a general temporal and geographic pattern to the NPS magmatism has emerged from the geochronological investigations over the last couple of decades, namely, that the rocks decrease in age from west to east and north to south (Hamilton, 1994, 2008).

Herein we present U–Pb ages that strengthen the conclusion regarding the antiquity of the western NPS relative to the eastern side. The isotopic investigations were undertaken on samples collected during a 2004 regional mapping program by the Geological Survey of Newfoundland and Labrador (James and Byrne, 2004, 2005), covering NTS map sheet 14D/15, in the Kingurutik River–Kamanatsuk River area (Figure 2). The age determinations were carried out at the University of Texas in Austin, Texas (*see* below; Connelly, 2005; Appendix).

OVERVIEW OF SOME PREVIOUS GEOCHRONOLOGICAL STUDIES

One of the earliest investigations of the geochronology of NPS plutonic rocks in the Nain region was undertaken by Beall *et al.* (1963). Their samples were from granites cutting the troctolitic Kiglapait layered intrusion of the northeast NPS (*see* Morse, 1964; Figure 1). A K–Ar age of 1480 ± 50 Ma was obtained from biotite within a granodiorite emplaced into the north margin of the intrusion, and an age of 1140 ± 40 Ma was returned from biotite from the Manvers granite, a pink aplitic to pegmatitic stockwork cutting the eastern part of the Kiglapait body. A similar late Mesoproterozoic K–Ar age, 1170 ± 40 Ma, was acquired from a (Manvers?) granitic pegmatite dyke in the Kiglapait Intrusion by Wanless *et al.* (1973), and interpreted (by F.C. Taylor) as the crystallization age. It was complemented by a K–Ar "age of intrusion" of 1175 ± 40 Ma for a granitic pluton south of Voisey's Bay.

Rb–Sr dating was applied to the Nain rocks in the 1970s. Barton (1974) derived an isochron age of 1418 ± 25 Ma for a lensoid, pegmatitic, plagioclase–clinopyroxene segregation in anorthosite on Paul Island (Figure 1) utilizing analyses of the feldspar, the pyroxene and interstitial trondhjemitic granophyre. He interpreted the data to signify the crystallization age of the lens and the enclosing anorthosite. He also examined the K–Ar characteristics of biotite from the Manvers granite and derived an age of *ca.* 1240 Ma, a multi-million year difference from the ages determined earlier by Beall *et al.* (1963) and Wanless *et al.* (1973). A Rb–Sr study of an amazonite crystal from the Manvers granite returned an age of *ca.* 1274 Ma, isotopic evidence that this was a minimum age for the crystallization for the Kiglapait Intrusion (*see* also the 'minimum' crystallization age implied by the earlier granodiorite data of Beall *et al.*, *op. cit.*).

The $^{40}Ar/^{39}Ar$ method was employed by Yu and Morse (1993) as a means to ascertain emplacement ages for Nain anorthosites, by examining the argon closure temperatures of plagioclase and biotite from several plutons as well as hornblende and biotite from the country-rock envelope. The span of the $^{40}Ar/^{39}Ar$ results, from 1284 Ma to 1086 Ma, certainly leaves much room for discussion of its significance with respect to "emplacement ages". Nevertheless, the data array proved amenable to the erection of a broad tripartite chronological framework for the NPS that corroborated a general intrusive sequence suggested earlier by Morse (1983) on the basis of field relationships. Yu and Morse (1993) evaluated the data most critical to establishing the span of NPS anorthosite magmatism and estimated that the duration of such activity was about 23 million years.

Krogh and Davis (1973) were the first to apply U–Pb dating of zircon to the NPS. An "almost concordant" $^{207}Pb/^{206}Pb$ age of 1295 Ma was obtained from zircon

Figure 1. *Geological map of the Nain Plutonic Suite (NPS) and its surroundings. The Mesoproterozoic NPS obscures part of the junction, a* ca. *1860 Ma collisional suture, between the Archean Nain Province and the Paleoproterozoic Churchill Province; its setting in relation to the tectonic framework of Labrador is shown in the inset map. The study area for the dating reported in this paper is shown by the box, and some of the major plutonic NPS units and geographic locations mentioned in the text are labelled. Key to letters: T – Tigalak intrusion; L – Mount Lister intrusion; A – Akpaume intrusion; PG – Pearly Gates intrusion; V – Voisey's Bay intrusion; Z – Zoar (abandoned). The large black dot near Voisey's Bay shows the site of the nickel–copper–cobalt deposit.*

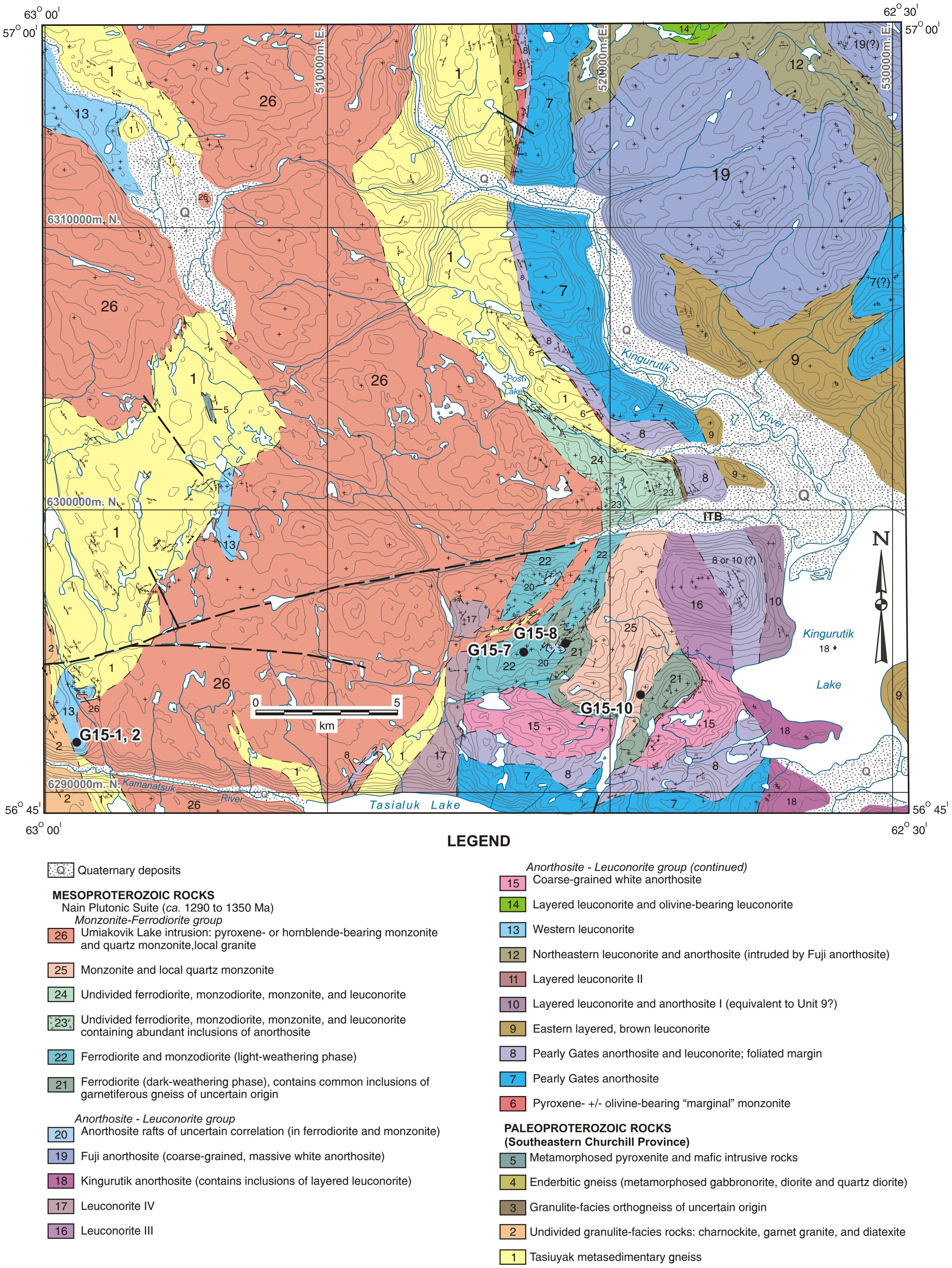

Figure 2. *Geological map of the Kingurutik River–Kamanatsuk River area (from James and Byrne, 2005), showing the general locations of the collection sites for the geochronological sample suites described in this paper.* See *text for sample details, precise locations of the sampled outcrops, and the results of the age determinations. ITB – Ittidlub Tunua brook.*

extracted from a granitic intrusion "near the eastern margin of the Nain anorthosite body" [sample from Dog Island, 35 km east of Nain (Morse, 1976); Figure 1]. The U–Pb technique has subsequently been the preferred method for unravelling the absolute intrusive sequence among the plutons. A tabulation of the myriad ages resulting from the zircon studies is beyond the scope of the present contribution, but some highlights and general observations are worthwhile. The reader is referred to geochronological details presented by Hamilton (1994, 1997) and Hamilton *et al.* (1994, 1998) for additional information. For purposes of this discussion, the *ca.* 1290-1270 Ma peralkaline granitoid and volcanic rocks to the north of Hunt Lake (Figure 1; *see* Hill, 1982; Krogh, 1993), south of Nain, are considered to be unrelated to NPS plutonism although the two plutonic terranes are contiguous. Nevertheless, a temporal argument can be made that the peralkaline plutons (Flowers River intrusions) and their rhyolitic carapace (Nuiklavik volcanic rocks) record the last gasps of that Mesoproterozoic event (*see* Hamilton, 2008; Myers *et al.*, 2008).

Magmatism giving rise to the NPS may have been initiated at the crust–mantle interface as early as 1440 Ma, the chronological signature (*i.e.*, model age) of which is preserved in Nd–Sm isotopes from megacrystic, high-alumina, orthopyroxene antecrysts or xenocrysts in some anorthosites (Bybee *et al.*, 2014). This magmatism may have fed mid- to upper-crustal level magma chambers for some 150 million years thereafter. Zircon antecrysts having U–Pb crystallization ages *ca.* 1370 Ma are known from the *ca.* 1340 Ma Pearly Gates anorthosite intrusion, along the western side of the NPS (Tettelaar, 2004; PG, Figure 1). Anorthositic plutons were emplaced periodically until at least *ca.* 1295 Ma (*see* Hamilton *et al.*, 1994). The U–Pb ages from zircon in granitic rocks record silicic magmatism extending from *ca.* 1360 Ma (Tettelaar, 2004; Myers *et al.*, 2008) to *ca.* 1290 Ma (*see* Ryan *et al.*, 1991). Ferrodioritic (oxide- and apatite-rich gabbronoritic) rocks are not volumetrically abundant among the NPS intrusions. They seem to be most widely developed within the plethora of post-1330 Ma intrusions; they persist in the geological record of the NPS until *ca.* 1298 Ma. Wiebe (1980) has shown that these intrusions comprise both independent plutons and spatial accompaniments to contemporaneous granitic plutons. Troctolitic rocks span an interval of some 25 million years. An intrusion in the Voisey's Bay area, built up from amalgamated basic and sulphidic magmas and hosting a world-class Ni–Cu–Co deposit (Evans-Lamswood *et al.*, 2000; Figure 1), was emplaced at 1333 ± 1 Ma (Amelin *et al.*, 1999), and is the oldest major pluton of this type, whereas the youngest, the Kiglapait layered intrusion (Figure 1), crystallized *ca.* 1306 Ma (T. Krogh, quoted in Yu and Morse, 1993; Hamilton, 1997). From the foregoing condensed review it is clear that the NPS is a result of diverse magmas pulsing through the crust over tens of millions of years. The magmas ascended to mid- to upper-crustal levels and amassed as a batholithic expanse of nested and impinging intrusions of varied composition.

LITHOLOGICAL ARCHITECTURE OF THE KINGURUTIK RIVER AREA

The 1:50 000-scale mapping of NTS map area 14D/15 by James and Byrne (2005) showed that the Kingurutik River–Kamanatsuk River area can be broadly subdivided into two lithological domains (Figure 2). The eastern one-third is underlain mainly by NPS anorthositic rocks of various types, including massive pegmatitic anorthosite, diffusely layered leuconorite and foliated leuconorite. These are disposed in both bulbous plutons and gently to steeply inclined tabular intrusions. The central and western parts of the region comprise mainly the *ca.* 1319-1316 Ma Umiakovik Lake granitoid pluton (Emslie and Loveridge, 1992) and its Paleoproterozoic country-rock host, the *ca.* 1940 Ma Tasiuyak paragneiss (Scott and Gauthier, 1996), and subordinate basic intrusions. The topographic distribution and outcrop pattern of the granite allow the inference that it is disposed as a thin sheet atop a floor of gneiss. In all, over twenty different plutonic units, constituting whole plutons or parts thereof, are evident within the NPS of the Kingurutik River region (Figure 2).

U–Pb AGES FROM THE KINGURUTIK RIVER AREA

The U–Pb ages of zircons reported here were acquired from samples of plutonic rocks exposed between the western end of Kingurutik Lake and the Kamanatsuk River (James and Byrne, 2005). No geochronological data were available for this area prior to the current investigation, so the results presented here fill this void. The general locations of the collection sites in relation to the rock units of the map area are portrayed on Figure 2, and more precise locations, in terms of the UTM (Universal Transverse Mercator) grid for Zone 20V and the North American Datum of 1927 (NAD27), accompany the summary descriptions and data compilation below. The sample site notes are supported by photographs depicting the rocks at each of the targeted outcrops. The age determinations were carried out by Connelly (2005) using Thermal Ionization Mass Spectrometry (TIMS). The analytical procedures for the zircon investigations are outlined in the appendix, and the supporting descriptive and analytical information for the analyzed minerals, including the grain sizes and the number of zircons in some of the fractions, are listed in Table 1. The compilation of the geochronological data herein was undertaken by the first author (B. Ryan), who also added petrographic information for representative examples of rocks from the

Table 1. U–Pb zircon data for samples analyzed from Kingurutik River–Kamanatsuk River area, Labrador

		Concentration		Measured		Corrected Atomic Ratios*							Age (Ma)		
Fraction	Weight (mg)	U	Pb rad (ppm)	total common Pb (pg)	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{206}Pb}{^{238}U}$	±	$\frac{^{207}Pb}{^{235}U}$	±	$\frac{^{207}Pb}{^{206}Pb}$	±	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$
G15-1															
Z1 22 lg irreg frags	0.203	57	15.7	2	71791	0.2874	0.23216	52	2.7685	64	0.08649	6	1346	1347	1349
Z2 11 lg irreg frags	0.129	36	10.6	2	29365	0.4078	0.23195	52	2.7668	60	0.08651	10	1345	1347	1350
Z3 same as Z2	0.115	32	9.5	2	23253	0.3989	0.23212	54	2.7687	64	0.08651	10	1346	1347	1350
G15-2															
Z1 20 med elong pcs	0.040	70	17.2	6	6709	0.1718	0.22862	58	2.7109	70	0.08600	12	1327	1331	1338
Z2 8 med 1 lg med brn	0.082	58	14.8	24	2907	0.1994	0.22932	62	2.7185	72	0.08598	10	1331	1334	1338
Z3 26 med lt brn frags	0.064	83	53.2	7	11211	2.1451	0.22952	52	2.7192	64	0.08593	8	1332	1334	1337
G15-7															
Z1 25 lg irreg frags	0.185	14	3.7	4	8861	0.2869	0.23085	50	2.7420	62	0.08615	10	1339	1340	1341
Z2 med-lg irreg elong	0.206	18	5.0	4	14807	0.3001	0.23080	58	2.7416	70	0.08615	8	1339	1340	1342
G15-8															
Z1 med lg lt bg frags	0.104	14	3.9	3	6482	0.2992	0.23141	62	2.7488	80	0.08615	12	1342	1342	1342
Z2 dk lg-med frags	0.057	18	5.0	1	11316	0.2899	0.23119	62	2.7453	78	0.08612	12	1341	1341	1341
G15-10															
Z1 sm-lg lt bg frags	0.065	18	4.8	2	11050	0.2680	0.23213	60	2.7665	76	0.08644	10	1346	1347	1348
Z2 as Z1 med-lg bg clr	0.031	22	6.3	2	4315	0.3546	0.23223	66	2.7685	82	0.08646	10	1346	1347	1348

Notes: Abbreviations: bg=beige; brn=brown; clr=clear; lt=light; elong=elongate; frags=fragments; pcs=pieces; irreg= irregular; lg=large (>100um); med=medium (75-100um); sm=small (<50um).

*Ratios corrected for fractionation, 1 pg and .25 pg laboratory Pb and U blanks, respectively, and initial common Pb calculated using Pb isotopic compositions of Stacey and Kramers (1975). All fractions are zircons and are extensively abraded (Krogh, 1973). Two-sigma uncertainties on isotopic ratios are reported after the ratios and refer to the final digits.

archived geochronology collection, as well as preparing short commentaries pertaining to the ages and their regional significance.

LEUCONORITE, SAMPLE G15-1
(UTM 500950; 6291702)

Rock Type and Setting

A seriate-textured leuconorite occupies part of a rolling landscape of small mounds just north of the Kamanatsuk River. It is designated as Unit 13 on maps of James and Byrne (2004, 2005; Figure 2). The rock is medium to coarse grained (1–5 cm plagioclase), brownish-grey-weathering, and friable (Plate 1). In overall aspect, it is very much like a body referred to by Ryan *et al.* (1998) as the “Tallifer Lake pluton” on map sheet 14E/02 to the north. The leuconorite is characterized by abundant flakes of bronze mica, and has a brown-sugar colour on freshly broken surfaces. Throughout the rock are individual white plagioclase megacrysts (xenocrysts?) up to 20 cm in length, as well as inclusions of white anorthosite from tens of centimetres to several metres on a side. A set of leuconorite samples, having an average grain size of 1 cm, was collected for dating.

Petrographic Character

The analyzed leuconorite is fresh and unrecrystallized, having a grain size from the millimetre to centimetre scale. The plagioclase is equant to tabular, and up to 2 cm long, some being zoned and slightly deformed (bent; undulatory extinction). It contains needles and plates of Fe–Ti oxides and it is mildly antiperthitic, traits common to feldspar in many NPS leuconoritic rocks. The intercumulus orthopyroxene has the characteristics of an inverted pigeonite, exhibiting blebs and lamellae, as well as rinds, of clinopyroxene. Deep-reddish-orange flakes of biotite occur mainly as rims on opaque oxides and pyroxene. The oxides and coarse (up to 6.5 mm across) cumulus apatite are the main accessory minerals, and late-magmatic quartz and potassium feldspar occupy some inter-grain spaces. The rock examined in thin section also contains a lone anhedral zircon, as an interstitial, 0.8-mm-long, triangular wedge, bordered by plagioclase and pyroxene; it is interpreted to be an autocrystic product of the leuconorite crystallization and not inherited or xenocrystic.

Plate 1. *Leuconorite sampled at site G15-1. Rock has average grain size of 1 cm; cm-scale plagioclase megacrysts (xenocrysts?) at centre and top.*

Isotopic Age Determination

The leuconorite sample collection yielded a single population of light- to medium-beige zircon fragments (Figure 3). Some of these fragments show crystal faces, possibly from larger euhedral grains broken during crushing or, alternatively, the straight edges of grains like the triangular one seen in the intercumulus space of the rock in the thin section specimen. The morphology of the grains and the simple population are consistent with an igneous origin for the zircons, reinforcing the interpretation from the microscopic setting of the grain in the representative sample. The isotopic analyses of three fractions, composed of 11 to 22 grains (Table 1), overlap each other and have a concordant $^{207}Pb/^{206}Pb$ age 1349.5 ± 1 Ma (Figure 3). The age is interpreted as the time of crystallization of the body.

Comment

The targeted rock comes from a relatively small basic body to the west of the Umiakovik Lake intrusion. It is one of three assigned to a “western leuconorite” (Unit 13) by James and Byrne (2005; Figure 2), likely the remnants of a more extensive leuconorite body that has been intruded by, and perhaps underlies, the Umiakovik Lake granite of this area. The “Tallifer Lake pluton” on map sheet 14E/02, referred to above as being superficially similar to the unit dated here, is likewise intruded by the Umiakovik Lake granite, but its crystallization age is unknown. A map compiled by Taylor (1977) portrays a large, hook-shaped body of anorthositic rocks in the same relative geographic position as the “western leuconorite” – engulfed by the western side of the Umiakovik Lake intrusion (Figure 1) – 25 km northwest of the collection site described above. The northernmost body shown by James and Byrne (2004, 2005; Figure 2) corresponds to the easternmost part of the larger body depicted on Taylor’s map. In addition, a manuscript map prepared in the early-1970s by E.P. Wheeler 2nd, based on his reconnaissance survey of the Labrador plateau, portrays a small, crescent-shaped anorthosite body occurring west of the Umiakovik Lake granite, 65 km to the northwest (Figure 1; *see* also Wheeler, 1969, Figure 1). The temporal relationship between each of these “western leuconorite” occur-

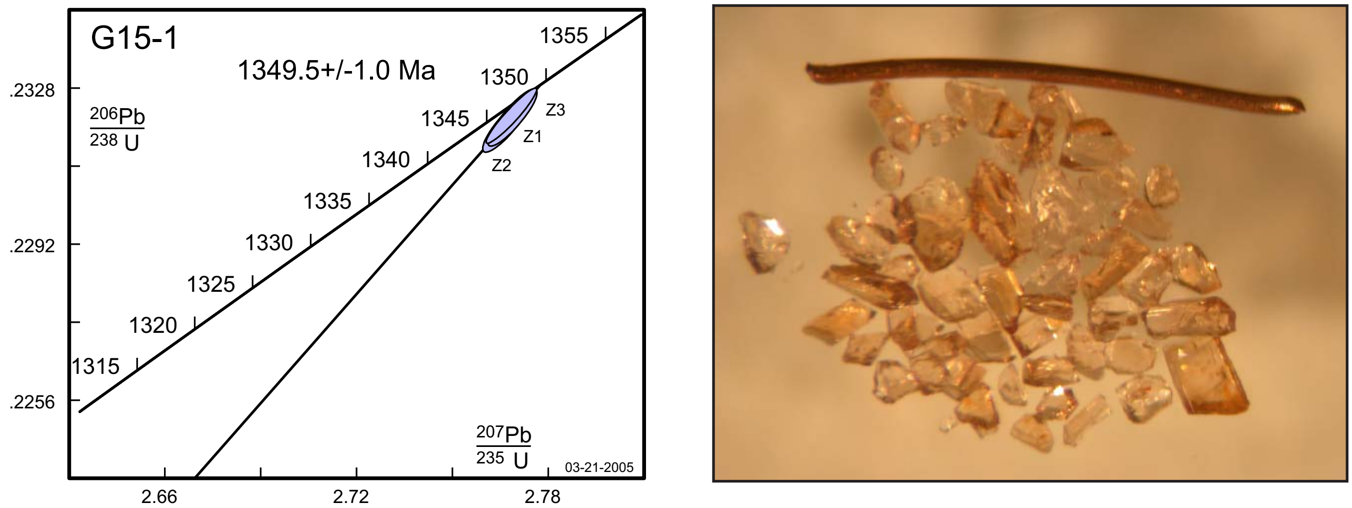

Figure 3. *U–Pb concordia diagram (left) for isotopic results derived from zircons (photo, right) separated from seriate leuconorite of the Kamanatsuk River area. A summary of the characteristics of the analyzed fractions selected from the pictured zircon population is given in Table 1. The fragment of wire used for scale in the photograph is 100 microns (0.1 mm) in diameter.*

rences is not known, but they may all be part of the *ca.* 1349 magmatism exemplified by sample G15-1.

Zircons in leuconoritic and anorthositic rocks of the NPS are, in most cases, found as euhedral, centimetre-scale, stubby and acicular grains in pockets of biotite-bearing, granitic material between plagioclase (± pyroxene) crystals. The granitic 'pods' are interpreted to be the last vestiges of magmatic liquid trapped between the cumulus feldspar (Hamilton *et al.*, 1998). The plagioclase–pyroxene-bounded, interstitial, setting for zircon in the analyzed "western leuconorite" is not a common one in these sorts of NPS rocks. However, another example of zircons having an interstitial setting relative to plagioclase is illustrated and described by Tettelaar (2004) from the foliated border zone of the Pearly Gates anorthosite south of Tasisuak Lake on NTS map sheet 14D/10. The *ca.* 1335 Ma age derived from these zircons is considered by her to signify the final crystallization of the host. The foregoing occurrences of interstitial zircon raise the possibility, albeit tenuous, that this setting is a habit restricted to anorthositic intrusions that are older than 1330 Ma.

LEUCOGRANITE, SAMPLE G15-2 (UTM 501495; 6291868)

Rock Type and Setting

The steep west wall and adjacent flatland area of a small north-northwest-trending canyon off Kamanatsuk River comprises the same friable "Tallifer Lake"-type seriate-textured leuconorite as the G15-1 sample site. Leuconorite exposed on a hillside rock face here, located several hundred metres east of the collection site of G15-1, is intruded by a subhorizontal, 5- to 15-cm-thick, fine-grained, white, alkali-feldspar leucogranite dyke (Plate 2). Similar dykes occur in the canyon walls where the side canyon intersects the main river valley. The canyon floor below, and the eastern wall of the canyon, comprise chocolate-brown, friable, augite + hornblende-bearing quartz monzonite of the *ca.* 1319–1316 Ma Umiakovik Lake intrusion. The trace of the lithological junction between the leuconorite and the rusty granitic rock signifies that either this contact is the west wall of the Umiakovik Lake intrusion, or else the Umiakovik Lake intrusion plunges westward beneath the leuconorite.

Plate 2. *Leucogranite dyke sampled at site G15-2. Dyke is subhorizontal and occupies the fracture in the leuconorite (the rock type sampled at G15-1). The analyzed sample collection was broken from the split piece of dyke near notebook.*

Petrographic Character

The leucogranite is mineralogically quite unlike the adjacent pyroxene + hornblende-bearing Umiakovik Lake quartz monzonite. Sample G15-2 is an alkali-feldspar granite comprising predominantly orthoclase and quartz, and devoid of plagioclase or significant mafic minerals. In most cases, the minerals are directly abutting, but in some parts of the rock they are cemented by intimately intergrown quartz and feldspar of graphic granite type. Orthoclase (up to 3 mm in maximum size) is mildly to heavily kaolinized, and many grains are perthitic. The alkali feldspar has Carlsbad twins, and some grains also exhibit a sharp, ribbon-type exsolution, superficially similar to albite twinning or pronounced cleavage, which is at a high angle to the Carlsbad twin plane. Quartz is oval to subhedral, comprising single or polycrystalline grains (having a maximum diameter of 2 mm) and (synneusis?) grain clusters, but an 'angular' type infills interstices. Clots of brown serpentine or mica rosettes are interpreted to be a replacement of orthopyroxene. Deep-brown mica is a minor mineral. A few allanite grains are scattered through the sample; zircon is present as minute, isolated, oval to prismatic grains and aggregated as small clusters; and opaque minerals occur in trace amounts.

Isotopic Age Determination

The crushed sample yielded a simple population of light-beige to medium-brown, subhedral to euhedral zircons. The crystal morphology and simple population are consistent with an igneous origin. The analyses of three fractions, comprising 8, 20 and 26 grains from the zircon population (Table 1), overlap and are slightly discordant (Figure 4), and yield an upper intercept age of 1337.3 ± 1.2 Ma. This date is interpreted to signify the final crystallization of the granitic dyke.

Comment

Outcrops (Plate 2) demonstrate that this dyke, and others like it, intrude the "western leuconorite" (G15-1; *see* above), and the age determinations support that field relationship. The leucogranitic composition of these dykes contrasts sharply with the augite + hornblende(± fayalite) quartz monzonite and granite of the Umiakovik Lake intrusion directly to the east. James and Byrne (2005) have recorded outcrop relations showing that the Umiakovik granitoid rocks are younger than the leucogranite dykes, and the isotopic results from the zircons analyzed here confirm the dyke is considerably older than the adjacent Umiakovik Lake intrusion. The analyses offer no hint that the U–Pb isotopic system in the zircons of this dyke, or the leuconoritic rocks of G15-1, was affected by any significant thermal disturbance during emplacement of the directly abutting Umiakovik Lake intrusion.

LEUCODIORITE (LEUCONORITE), SAMPLE G15-7 (UTM 516615; 6294897)

Rock Type and Setting

A prominent 2800 ft. (854 m) mountain west of Kingurutik Lake is underlain by a bewildering array of rock types occurring over a restricted area. Dominant among them are rocks equated with a group of 'diorites' investigated near 'Post Lake', 8 km to the north, by Brand (1976). The name

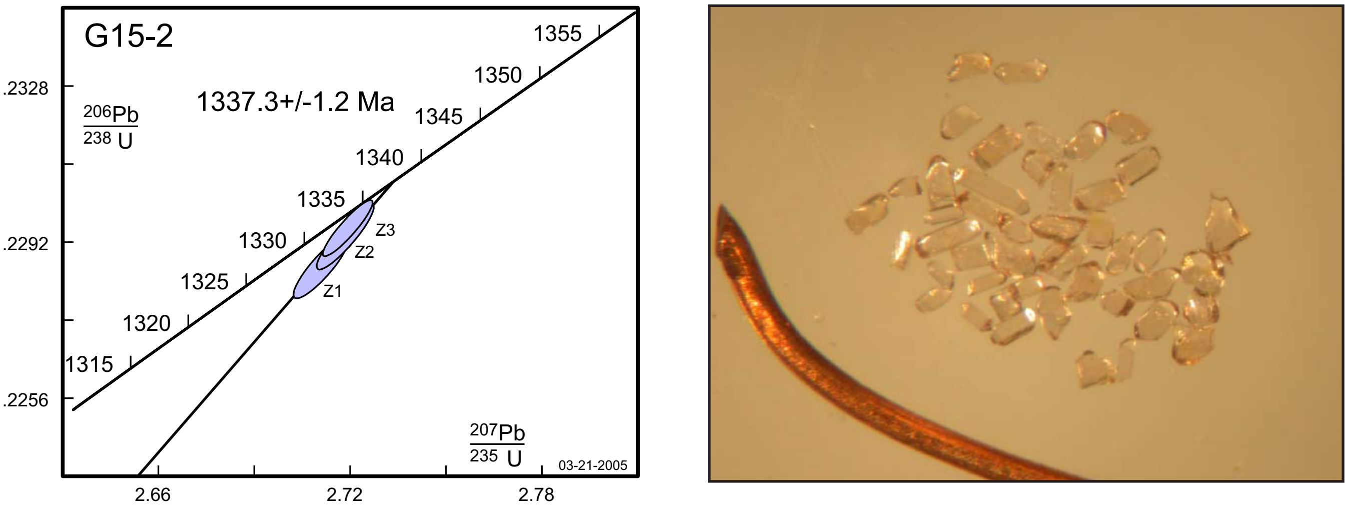

Figure 4. *U–Pb concordia diagram data plot for the leucogranite dyke (left) and a photo of the population of analyzed zircons (right) from which the age was obtained. Dyke crosscuts the leuconorite intrusion from the same area (*see *Figure 3).* See *Table 1 for characteristics of analyzed fractions selected from the pictured zircons. Wire used for scale is 100 microns (0.1 mm) in diameter.*

‘diorite’ was employed for some of the basic plutonic rocks by Brand on the basis of the andesine composition of their plagioclase, and we retain that historic designation herein for that particular lithological group. However, their modal minerals (plagioclase and orthopyroxene; *see* below) support the use of ‘noritic’ as a more appropriate term, and thus that designation is added as an alternate in the descriptions immediately below and for sample G15-8 to follow.

Creamy-white ‘leucodiorite’ (leuconorite) (Unit 22 of James and Byrne, 2005; Figure 2) is well-exposed, and was sampled, in extensive bare, generally flat outcrops on a bench on the west flank of the mountain. It is characterized by 0.5 to 1 cm equant to tabular plagioclase, and interstitial granular pyroxene. It supports silvery-grey and white megacrysts of plagioclase up to 15 x 5 cm (Plate 3) and has rare anorthositic fragments up to 1.5 x 0.6 m.

Plate 3. *Leucodiorite (leuconorite) sampled at site G15-7. Note the dark plagioclase megacryst at right.*

Petrographic Character

The rock, as indicated above, is mineralogically a leuconorite, comprising plagioclase and orthopyroxene. It has the abundant apatite and opaque oxides that characterize the ‘ferrodioritic’ (oxide–apatite gabbronoritic) group of the NPS but the mafic mineral content is less than in typical ferrodiorite. Plagioclase (andesine) is as relatively coarse (mainly >3 mm), generally equant grains, riddled with stringlet to patch blebs of antiperthite and containing rare needles and mauve plates of Fe–Ti oxide. Minor K-feldspar and quartz constitute ‘cement’ between some of the plagioclase crystals. The mafic mineral in this rock is a crudely poikilitic hypersthene. Many of the these poikilitic grains have extremely fine clinopyroxene exsolution lamellae parallel to cleavage as well as coarser sets at a high angle to the fine ones. The hypersthene is anhedral to oval, and not of the intercumulus type common to the leuconoritic variants (such as G15-1) of the NPS anorthositic intrusions. Apatite is abundant, as oval grains, multigrain clusters, and prismatic crystals having smooth, rounded terminations. Opaque oxides are prominent and scattered through the rock. Minor myrmekite marks some feldspar boundaries, and there is a trace of hornblende surrounding opaque oxides and pyroxene. One oval zircon (0.2 mm in diameter) is evident in the thin section of the ‘leucodiorite’ examined.

Isotopic Age Determination

A simple, medium-beige to light-brown zircon population was extracted from the crushed samples (Figure 5). The population included fragments having crystal faces, presumed to be chips derived from fractured larger, subhedral

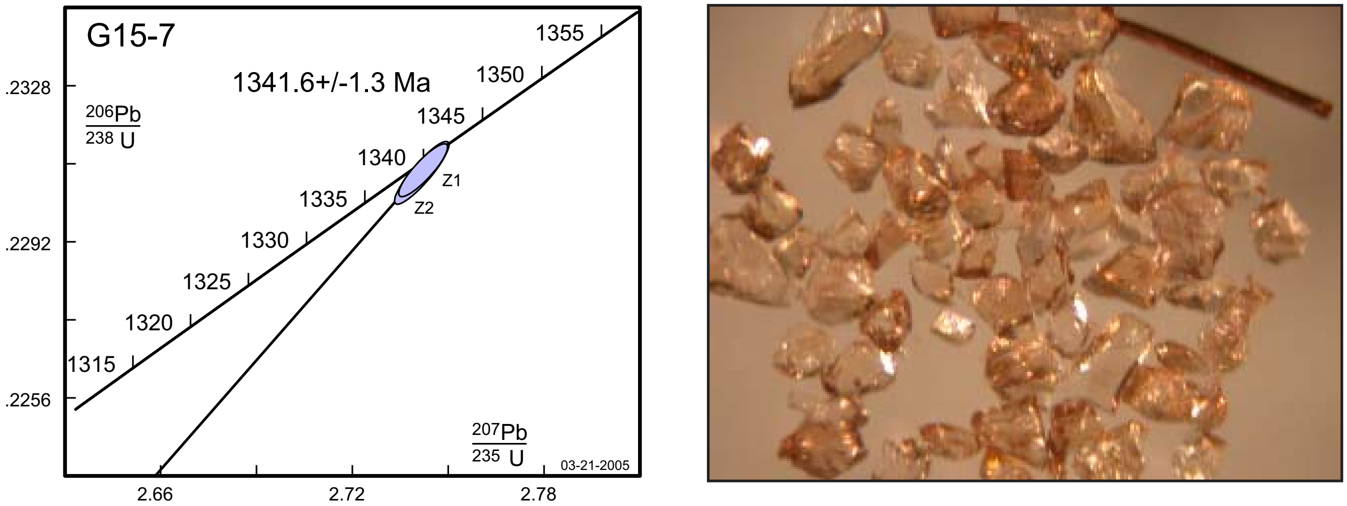

Figure 5. *U–Pb concordia diagram (left) for two fractions of zircons, like those shown in the photograph (right), separated from the pyroxene leucodiorite (leuconorite).* See *Table 1 for characteristics of analyzed fractions selected from the pictured zircons. Wire is 100 microns (0.1 mm) across.*

to euhedral grains. Two fractions of the zircon population were analyzed (Table 1). Both sets of data overlap concordia and provide an average age of 1341.6 ± 1.3 Ma (Figure 5), interpreted to signify the ultimate crystallization of the intrusion.

Comment

This rock is considered to be part of a polyphase "dioritic" association (diorite, monzodiorite, meladiorite) first outlined, as noted above, near 'Post Lake' by Brand (1976) as part of his Ph.D. research on rocks of the western interior NPS. It is designated as Unit 22 on the map of James and Byrne (2005; Figure 2), a "light weathering phase" ferrodiorite and monzodiorite, having numerous, white, blocky plagioclase xenocrysts and containing wispy patches of garnetiferous gneissic rocks (*see* below). No garnetiferous patches or gneissic inclusions were seen at the sample site. James and Byrne (2005) further note that these 'dioritic' (noritic) rocks, as a whole, are compositionally and texturally "unusual" for the northwestern part of the NPS. This rock seems to be correlative with Brand's "monzodiorite" to the north, which he documented (Brand, 1976, page 85) as being internally composite and having several rock types: "diorite, leucodiorite, quartz monzodiorite, and leuco-quartz monzodiorite". Brand summarized the salient traits of the unit at 'Post Lake' as being fine to medium grained and having scattered plagioclase megacrysts in a matrix of antiperthitic plagioclase, orthopyroxene (ferrohypersthene having ferroaugite exsolution), quartz, apatite and perthitic alkali feldspar, with accessory clinopyroxene, rutile, zircon and ilmenite. Brand (*op. cit.*) did not recognize any garnetiferous enclaves in the rock of the 'Post Lake' area, but he noted an abundance of anorthositic inclusions near Ittidlub Tunua brook.

'MAGGOTY' MELADIORITE (MELANORITE), SAMPLE G15-8 (UTM 518433; 6295514)

Rock Type and Setting

Hummocky ground at the top of the 2800 ft. (854 m) mountain mentioned above is underlain by 'meladiorite' (oxide-apatite melanorite), typified by equant to tabular, mm to cm scale (generally about a cm, but up to 4 cm), white and creamy-white, plagioclase crystals set within, and largely supported by, a dark-green to black pyroxene-rich groundmass (Plate 4). The white plagioclase surrounded by the dark matrix prompted Brand (1976) to refer to the meladiorite as appearing to be "maggoty", an apt textural term retained by us. This melanocratic rock is designated as Unit 21 on the provisional maps of James and Byrne (2004, 2005; Figure 2), a "dark-weathering phase" ferrodiorite, and described as a grey, green and black-and-white, pyroxene-rich rock having an abundance of opaque oxides. Diffuse to sharp compositional layering is widespread, defined by variation in the volumes of pyroxene. Plagioclase xenocrysts, white anorthosite fragments and rusty-brown gneissic rafts are locally prevalent.

Plate 4. *Typical texture of the 'maggoty' meladiorite (melanorite) at site G15-8. Feldspars are supported by a pyroxene-rich matrix containing abundant ilmenite and apatite.*

This unit is also regionally characterized by massive to layered, lensoid to amoeboid enclaves of generally fine-grained, granular, leucocratic to mesocratic, spinel-rich 'noritic granulite' (allotriomorphic-textured plagioclase + orthopyroxene rock), many of which have mm-scale granular garnets within the interior of feldspathic wisps. The garnets are disposed as single crystals and polycrystalline aggregates, their microscopic setting being as overgrowths on spinel or as atolls around granoblastic aggregates of spinel and plagioclase. The origin of the leucocratic garnetiferous enclaves is uncertain but they appear to be polymetamorphic restite from Tasiuyak gneiss (*see* discussion below).

Petrographic Character

The representative sample from this geochronological target is a melanocratic variant of G15-7, in which the orthopyroxene is overwhelmingly oikocrystic. The meladioritic (melanoritic) sample comprises antiperthitic plagioclase (An_{44}), like G15-7, disposed as independent crystal aggregates and also enclosed by cm-scale oikocrysts of very weakly pleochroic orthopyroxene, the latter exhibiting fine-scale clinopyroxene lamellae parallel to cleavage and rarer, coarser, lamellae across the dominant cleavage. The exsolution structure of the hypersthene is that of an inverted pigeonite; integrated analyses of the orthopyroxene host and the clinopyroxene lamellae in an equivalent rock to the north point to the precursor (primary) pyroxene as having been a ferriferous pigeonite (Brand, 1976). Some of the oikocrysts lack the exsolution or show just incipient development. The oikocrysts have an extraordinary abundance of apatite granules, far more than among the plagioclase aggregates, and likewise the opaque minerals are more concentrated within the pyroxene domains than in the feldspar ones. There is a trace of ‘free’ clinopyroxene in the rock, as well as minor potassium feldspar; the latter comprises cores to a few plagioclase grains and occurs among the plagioclase aggregates (perhaps a result of exsolution). No zircon is evident in the studied petrographic thin section.

Isotopic Age Determination

A simple population, comprising euhedral and subhedral zircons and angular fragments of broken zircon crystals, was liberated from the rock sample. Two fractions of medium (75–100 microns) to large (>100 microns), light-beige zircons were analyzed (Table 1), their analytical ellipses overlapped each other and concordia (Figure 6). The concordant age derived from the data set is 1341.3 ± 1.7 Ma. It is likely that this age denotes the time of crystallization of the meladiorite (melanorite), and it is statistically indistinguishable from the U–Pb age of the ‘leucodiorite’ sample (G15-7) above. These results reinforce the field impressions and interpretations that the two rocks are co-magmatic, variants of an internally composite and polyphase intrusion.

Comment

This rock, like G15-7, is also considered to be a southward extension of part of the group of heterogeneous ‘dioritic’ (andesine plagioclase + hypersthene) rocks mapped by Brand (1976) in the ‘Post Lake’ area, corresponding to his meladiorite subdivision. He described and portrayed the unit there as having a dyke-like form, exhibiting a steeply dipping igneous banding (*i.e.*, layering) and a “linear flow structure”. Brand did not document any inclusions in this unit, but a brief examination of the southernmost part of his study area north of Ittidlub Tunua brook by B. Ryan in 2004 indicates that the “maggoty” melanocratic rock there encloses numerous anorthosite blocks and it also contains granular felsic enclaves having aggregates of red garnet. Brand described the dominant rock of the ‘Post Lake’ sector as a fine- to medium-grained one having, as noted, a “maggoty” appearance (in reference to the contrast offered by the white, antiperthitic plagioclase phenocrysts supported and outlined by the dark, mafic-rich matrix; *see* above and Plate 4). He reported the matrix as comprising poikilitic ferrohypersthene (containing ferroaugite lamellae where derived from inverted pigeonite), antiperthitic andesine plagioclase, apatite and ilmenite, having accessory quartz, alkali feldspar, rutile, and zircon. Brand particularly singled out the abundance of apatite in this unit, noting its inclusion relation to the pyroxene.

The general aspects of these melanocratic rocks (*e.g.*, the poikilitic pyroxene, abundance of oxides) conform to those of the melanocratic ferrodiorites (gabbronorites) in other parts of the NPS, but the regional pyroxene-rich nature, the “maggoty” texture, and the abundance of garnetiferous enclaves are not features prevalent in the ferrodiorite group. The garnetiferous enclaves, especially, are unusual (*see* discussion section below), and are considered to be variably digested xenoliths derived from the regional garnet- and sillimanite-bearing Tasiuyak gneisses, the rusty-weathering metre-scale gneissic rafts being better preserved remnants of that older rock.

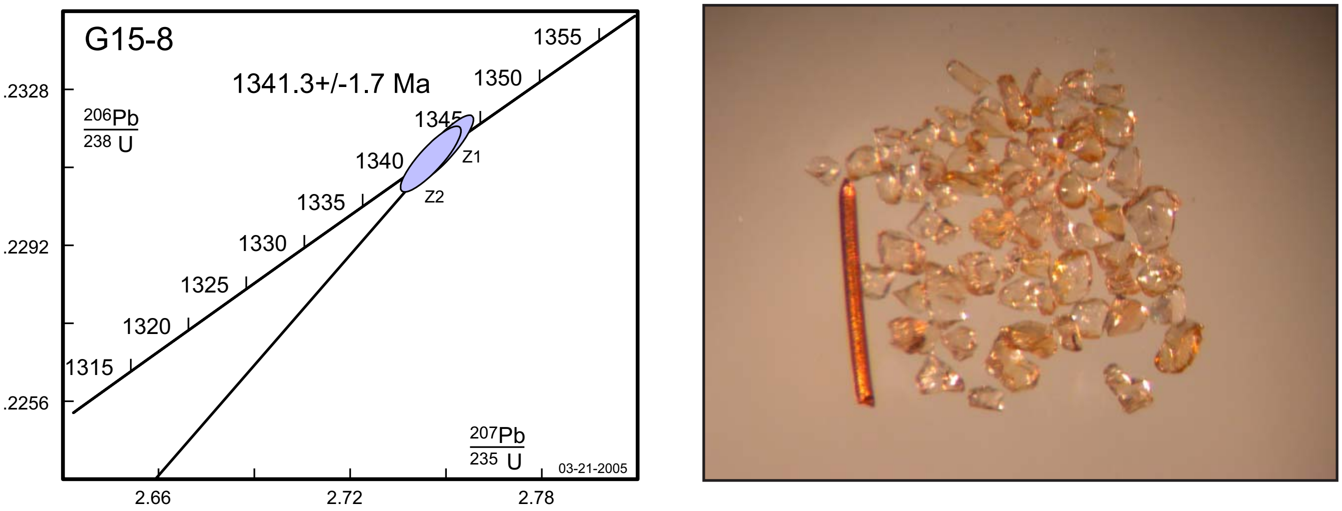

Figure 6. *U–Pb concordia plot (left) for isotopic data from two fractions of the zircon grains, selected from those shown in the photograph (right), from the “maggoty” meladiorite (melanorite). Wire used for scale in photograph is 100 microns (0.1 mm) across.*

PYROXENE + OLIVINE GRANITE, SAMPLE G15-10 (UTM 521163; 6293920)

Rock Type and Setting

Small knolls and ridges west of Kingurutik Lake are underlain by a quartz-rich, alkali-feldspar-porphyritic, pyroxene-bearing monzonitic or granitic rock characterized by a slightly rusty-orange patina (Plate 5), designated as Unit 25 by James and Byrne (2005; Figure 2). This granitoid unit occurs proximal to the Umiakovik Lake intrusion, Unit 26 of James and Byrne (2005), but its quartz-rich nature is uncharacteristic for rocks of that pluton. In addition, the outcrops of this rock lack the deeply weathered and friable aspect of most exposures of Umiakovik Lake granite. The two granitic units are physically separated by the 'dioritic' rocks described above (Figure 2), so the quartz-rich one was targeted for geochronological investigation to ascertain its temporal relationship to the Umiakovik Lake intrusion. The freshly broken surfaces of the granitoid rock at the collection site have the dark-bluish-green colour that typifies NPS rocks containing clinopyroxene and/or olivine. Feldspar crystals are rarely more than 2 cm in maximum size, and have anhedral to subhedral form. Most quartz is irregular (anhedral), but some grains have an oval ('drop') morphology akin to those of rapakivi granites and possibly a result of magmatic resorption of larger grains. No inclusions or enclaves of any kind were seen in the sampled outcrop area.

Petrographic Character

This rock is a fresh granite (charnockite), and it has an unusual vermicular quartz-feldspar matrix as well as wormy olivine–quartz intergrowths. Quartz is quite coarse (>5 mm in many cases) and shows only minor strain shadows. Coherent, anhedral plagioclase domains are similar to quartz in size, but they are encased and seemingly partly replaced by a graphic-textured 'matrix' (*see* below). Potassium feldspar has a 'chunky' habit, like plagioclase, but also occurs as poikilitic grains enclosing clinopyroxene; it shows some perthitic exsolution, and has a relation to the matrix similar to that of the plagioclase. Examples of both rapakivi (plagioclase surrounding potassium feldspar) and anti-rapakivi (potassium feldspar enclosing plagioclase) microtextures are evident. Clinopyroxene in the granite comprises anhedral grains of 'augite' as well as grains of inverted pigeonite partly replaced by a subsolidus intergrowth of fayalite and wormy quartz, the latter pyroxene type being like those described and illustrated by Wheeler (1965, 1969), Smith (1974) and Brand (1976). Some such vermicular intergrowths seem to be a direct replacement of primary orthopyroxene. Augite locally exhibits distinct compositional zoning, the core having fine exsolution lamellae, but most pyroxene here shows coarsely exsolved lamellar structure; some of the olivine-bearing pseudomorphs of inverted pigeonite still retain augite lamellae, mirroring textural features portrayed by Wheeler (1969) and Brand (1976). The matrix of the rock is a wormy and blebby intergrowth between plagioclase, potassium feldspar and quartz, in which some K-feldspar is perthitic and the quartz is mainly as blebs or droplets. The general aspect of the matrix is that it is a late-stage magmatic crystallization feature, but subsolidus exsolution cannot be entirely ruled out. This vermicular quartzofeldspathic matrix has, in places, a transitional contact with coarser and more coherent feldspar, a relationship seeming to indicate that the crystallizing groundmass corroded, partly resorbed and formed shells around the coarser grains. Zircon is quite abundant in the rock, as oval to prismatic grains, and apatite and opaque minerals are scattered throughout.

Plate 5. *Texture of the homogeneous, charnockitic, olivine-bearing quartz monzonite to granite collected at site G15-10.*

Isotopic Age Determination

The sample collected from the intrusion yielded just a small zircon population, surprising for a NPS granitoid rock and in contrast to the petrographic observations (*see* above). The liberated grains are clear, light to medium beige, and include subhedral to euhedral crystals as well as crystal fragments (Table 1). Two fractions, one of fragments and the other of subhedral grains, were analyzed. They plot on concordia, the concordant ^{207}Pb/^{206}Pb age of 1348.2 ± 1.4 Ma (Figure 7) considered to be the time of crystallization of the intrusion.

Comment

The sample comes from a north–south-oriented granitoid unit west of Kingurutik Lake, Unit 25 of James and Byrne (2005; Figure 2). The unit comprises "monzonite and local quartz monzonite", pyroxene-bearing, alkali-feldspar-porphyritic rocks in which feldspar phenocrysts and trains

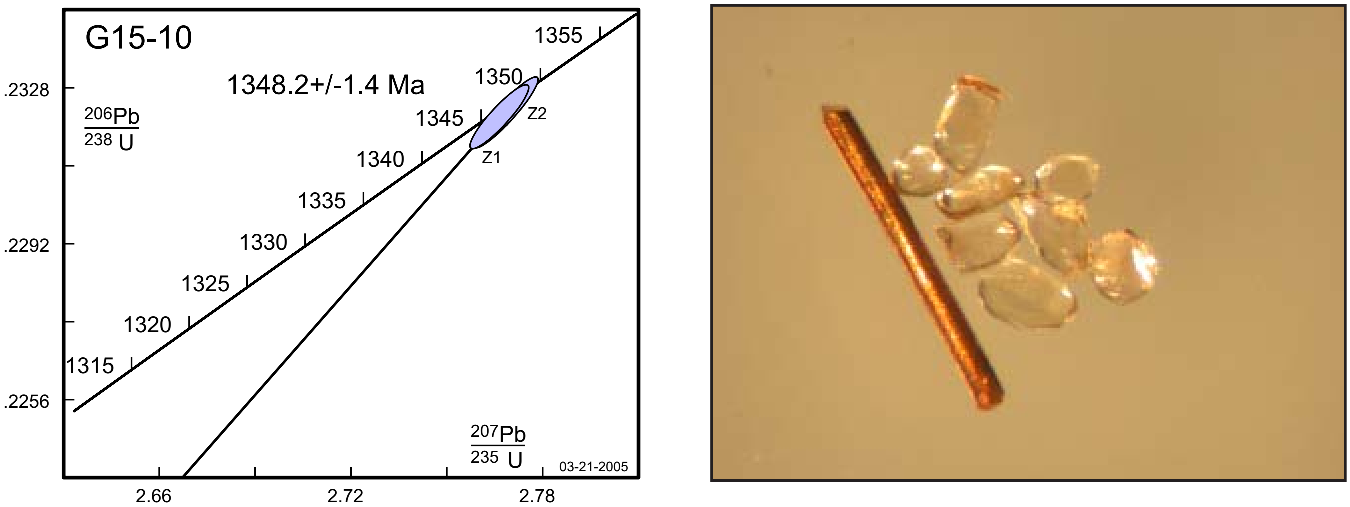

Figure 7. *U–Pb concordia diagram (left) derived from isotopic analyses of two fractions of zircons, selected from the small group shown in the photograph (right), separated from the pyroxene–olivine granite (charnockite). Wire for scale in photograph is 100 microns (0.1 mm) across.*

of mafic minerals outline a primary planar fabric. Petrographic details given above highlight the olivine-bearing and charnockitic nature. James and Byrne (2005) noted that correlation of these granitoid rocks with the Umiakovik Lake intrusion to the west is not a certainty, but the field investigations led to the provisional conclusion that there is a "transitional" contact between this dated unit and the "ferrodiorite" (their Unit 21; *see* sample G15-8 above) immediately to the west. They further posed the possibility that dioritic rocks (their units 21 to 24; *see* Figure 2) could constitute a floor to a magma chamber in which the Unit 25 monzonite (charnockite) and the Umiakovik Lake intrusion (Unit 26) crystallized. The absolute crystallization age derived from the zircons in this rock does not support the preliminary field interpretations. The unit is some 30 million years older than the Umiakovik Lake intrusion, so this clearly removes any notion that the two are temporally equivalent. It is also millions of years older than the "ferrodiorite and monzodiorite" bounding its western side (*ca.* 1342 to 1341 Ma; *see* G10-7 and G10-8 above), thus nullifying the case for proposing that these western rocks are a contemporaneous mafic substrate to the olivine-bearing monzonite and quartz monzonite. The difference in ages also could be cited as implying that the 'dioritic' rocks have an intrusive relationship to the adjacent granitic ones, but no field evidence has been documented that would verify that relative relationship.

This is the oldest of any undeformed NPS granitoid rock of significant size yet analyzed for geochronological study, but as indicated from data above (sample G15-2) there were local dykes of leucogranite intruded *ca.* 1337 Ma. The next oldest of the large, undeformed, granitoid intrusions is a massive fayalite–augite syenite south of Kingurutik Lake, outlined originally by Wheeler (1960) and later investigated by Ryan and James (2004), emplaced and crystallized at 1333 ± 3 Ma (Kamo, 2003). Unlike the foregoing, most of the other old granitic rocks have structures varying from a weak mineral foliation to a discrete gneiss-like layering, *viz.*, (i) a monzonite along the eastern margin of the Mount Lister intrusion (1343 ± 3 Ma; Connelly and Ryan, 1994), (ii) the Hare Hill intrusions east of the Pearly Gates anorthosite (*ca.* 1351 ± 3 Ma; Connelly, 1993) and (iii) the Tessiaruyungoakh intrusion along the western side of the Pearly Gates intrusion (*ca.* 1360 ± 4 Ma; 1363 ± 3 Ma; Tettelaar, 2004).

DISCUSSION OF THE 2004 GEOCHRONOLOGY RESULTS

The crystallization ages determined in this study for the rocks west of Kingurutik Lake are suggestive of an extensive 'early' component to the NPS in this area. The ages of the major units examined range from *ca.* 1349 Ma to *ca.* 1341 Ma, and a leucocratic granitic dyke crosscutting one of the basic intrusions crystallized at *ca.* 1337 Ma.

The 1349 ± 1 Ma age for the "western leuconorite" (possibly correlative with the "Tallifer Lake pluton" to the north; Ryan *et al.*, 1998) near Kamanatsuk River is noteworthy because this age places the leuconorite among the oldest known such basic intrusions in the NPS. It is also significant because the rock lacks the recrystallization and deformation seen in other presently known 'old' NPS basic intrusions, such as the Mount Lister and Pearly Gates anorthosites (Ryan and James, 2003; Tettelaar, 2004; Figure

1). Indeed, deformation and recrystallization have been assumed to be a hallmark of all 'early' intrusions, the current geochronology database indicating that they are all likely to be greater than 1330 Ma. Undeformed and mildly recrystallized leuconoritic and anorthositic rocks have, on the other hand, been assumed to be 'young', because all such relatively pristine ones previously investigated have yielded ages younger than 1330 Ma. The geochronological result here shows that such an assumption, predicated largely on mesoscopic appearance, is erroneous. Deformation and recrystallization may, in fact, be confined solely to large, coarse-grained to pegmatoidal anorthosite–leuconorite bodies that were emplaced principally as solid-state intrusions, of which the Pearly Gates and Mount Lister anorthosites cited above are probable examples. Other 'old' leuconoritic intrusions may have been emplaced as more 'normal' crystal-laden magmatic bodies and crystallized *in situ*. It is worthwhile to note here that whereas there is a seemingly close temporal relationship between some directly abutting anorthosites and granites (the Makhavinekh Lake granite pluton and its anorthositic core being an example; *see* Hamilton, 1997; Figure 1) such a case cannot be made between the "western leuconorite" and the Umiakovik Lake granite of this area.

The 1348 ± 1 Ma emplacement age for the charnockitic intrusion (monzonite and quartz monzonite) west of Kingurutik Lake is particularly significant because that body likely postdates the deformation and recrystallization evident in the nearby foliated leuconoritic margin of the Pearly Gates intrusion (James and Byrne, 2005; Figure 2) – the two are apparently not in direct contact – and it thus provides a probable lower limit on the age of the deformation evident in that particular anorthositic intrusion. The lack of a regional penetrative fabric provides a strong contrast to the intensely deformed granitic sheath directly adjacent to the foliated western margin of the Pearly Gates anorthositic pluton to the south of Tasialuk Lake (Ryan and James, 2003). The close similarity in the age of the massive charnockitic rock and the aforementioned "western leuconorite", 20 km to the west, shows that these plutons were intruded contemporaneously. The results from these two rocks reinforce the conclusion from existing geochronology that magmas of highly contrasting composition were being emplaced simultaneously during the NPS event [*e.g.*, the *ca.* 1333 Ma syenite south of Kingurutik Lake (Kamo, 2003), the *ca.*1332 Ma Akpaume ferrodiorite (Hamilton, 1997), and the *ca.* 1333 Ma Voisey's Bay troctolite intrusion (Amelin *et al.*, 1999); Figure 1].

The *ca.* 1342-1341 Ma age of the composite 'diorite' intrusion underlying the mountain south of Ittidlub Tunua brook makes it the oldest of the dioritic (oxide–apatite gabbronoritic) rocks thus far identified in the NPS. The antiquity may be an explanation for the atypical character of the most melanocratic rocks of the association. None of the other dioritic (noritic) units known in the NPS, as far as we are aware, are characterized by the regional and unusual 'maggoty' porphyritic texture exhibited by the melanocratic member, although the 'clot porphyry' locally along the contact between the *ca.* 1322 Ma Makhavinekh Lake granite and its underlying anorthosite (Figure 1) is superficially similar (Ryan and Lee, 1995). The 'clot porphyry' is different, however, inasmuch as it is a fayalite–augite–ilmenite-rich rock and likely the cumulate floor to the granite. Another anomalous, area-wide, feature of this rock is the profusion of schlieric, wispy, garnetiferous gneissic enclaves. These are interpreted to be metasedimentary restite, variably 'digested' fragments of the regionally metamorphosed, garnet- and sillimanite-bearing Tasiuyak gneiss (Figure 2). They differ, however, from the more common contact metamorphosed Tasiuyak gneiss in having garnets that can be interpreted as 'new' rather than being remnants of the regional assemblage. In the more common occurrences, the regional garnet porphyroblasts and sillimanite prisms have been consumed by contact metamorphic reactions and replaced by varying combinations of cordierite, hypersthene, plagioclase, spinel, and corundum (*see*, for example, Berg, 1977; Lee, 1987; Tettelaar and Indares, 2007), mineral reactions evident to the north and west in the study area where the gneiss lies adjacent to the Umiakovik Lake intrusion (James and Byrne, 2005). The fact that garnet in the enclaves comprises masses of granular individuals overgrowing (contact metamorphic) spinel, implies that the garnets are not relict regional porphyroblasts, but are products of contact metamorphism. The wispy garnetiferous streaks are, thus, interpreted as polymetamorphic relicts of Tasiuyak gneiss in which regional metamorphic garnets had been present, were subsequently destroyed by an early episode of contact metamorphism, and were later regenerated. The contact effects are likely a consequence of more than one pluton-related thermal metamorphism, but it is possible they are related to prolonged immersion, and substantial modification, of the Tasiuyak gneiss fragments in the high-temperature magma from which the 'meladioritic' rock was derived. We know of just one other example of this phenomenon – Berg and Wiebe (1985) have documented the regrowth of garnet in ferro-aluminous metasedimentary gneissic xenoliths enclosed by a narrow "hybrid zone" of ferrodiorite and granite at Zoar (Figure 1). It is also noteworthy that no relicts of diagnostic textural features (*e.g.*, oval garnet porphyroblasts, folia of prismatic sillimanite) predating the contact metamorphism of the Tasiuyak gneiss are evident in the wispy inclusions, an absence echoed in the contact-metamorphic, aluminous, restite of Tasiuyak gneiss within the Voisey's Bay troctolite (*see* Li and Naldrett, 2000).

In summary, the whole NPS terrane mapped by James and Byrne (2004, 2005) west of Kingurutik Lake on NTS map sheet 14D/15 in 2004 contrasts with the 14D/16 area to the east mapped by Ryan and James (2004) in 2003. The area west of the lake has herein been shown to contain undeformed basic and silicic rocks older than *ca.* 1335 Ma. By contrast, the extant geochronology for the eastern area points to rocks older than *ca.* 1333 Ma there as being all significantly deformed and recrystallized, the undeformed anorthositic and leuconoritic ones yielding crystallization ages *ca.* 1326 Ma (Loewy, 2004; Connelly, 2005). We are confident that the U–Pb results from the zircons of the Kingurutik River–Kamanatsuk River region are singular ages of igneous crystallization, and propose that this sector of the NPS likely contains other genuinely 'old' intrusions. There is no compelling evidence in the physical character of the zircons or in the U–Pb data to contemplate inheritance from pre-existing crust, in spite of field evidence that many of the plutonic rocks of the area contain gneissic rafts in various states of disaggregation and assimilation. The zircons chosen for analyses were isolated on the basis of uniformity in colour, size and shape, and were free of discrete visible cores. Replicated analyses of abraded multigrain fractions from each of the populations are tightly clustered on or near concordia and lack the dispersion likely to result if the grains were mixtures of magmatic and 'residual' country-rock zircons (*see* Figures 3 to 7). The results suggest that any xenocrystic zircons liberated from older rocks were efficiently digested by the hosting NPS magmas, and that no remnant insoluble grains were encased by zircons subsequently nucleated in the Mesoproterozoic intrusions.

The foregoing statements regarding the differences between the structural aspects of the rocks crossing eastern Kingurutik Lake as compared to those examined from the western area can, as alluded to above, be applied to the NPS regionally. To reiterate, anorthositic intrusions older than 1330 Ma elsewhere commonly have a prominent marginal zone of strongly deformed rocks. Peripheral granitic and monzonitic sheaths to these anorthositic plutons are similarly deformed (*see*, for example, Ryan and James, 2004; Tettelaar, 2004; Myers *et al.*, 2008). Only younger (post-1330 Ma) intrusions lack any significant penetrative deformation. The results obtained from rocks of the Kingurutik Lake–Kamanatsuk River region could be an indication that other undeformed NPS rocks pre-dating the Umiakovik Lake intrusion in the north (*see* Taylor, 1977; Ryan *et al.*, 1998) are also plutons emplaced during the early stages of NPS magmatism. The ages of the undeformed rocks investigated during this study also show they are tens of millions of years older than mesoscopically similar rocks of the eastern coastal zone.

ACKNOWLEDGMENTS

This geochronological study was funded by Natural Resources Canada under the second-phase Targeted Geoscience Initiative (TGI-2). This financial support continued the decades-long tradition, begun in the 1970s, of professional collaboration between the Geological Survey of Canada and the Geological Survey of Newfoundland and Labrador, aimed at deciphering the geology, establishing a geochronological framework, and investigating the mineral potential of the Canadian Shield in Labrador.

Dixon Byrne served as the senior assistant on the 2004 geological field-mapping program. The undergraduate student field assistants were Krista Reddy, Nancy Normore, and Jon Williams, as well as 'volunteers' Wilf Nicholls and Shawn Garland from the Botanical Garden at Memorial University. Helicopter support for the program was contracted to Canadian Helicopters Limited in Goose Bay, and pilots Jim Abbott and John Danby guided the daily transportation needed to undertake the regional mapping and geochronological sampling.

Critical and comprehensive reviews of the initial version of this report were provided by Dr. Charles Gower and Dr. Alana Hinchey, both of whom pointed out informational shortcomings and offered copious comments for consideration. These readers are sincerely thanked for their service, and we have taken their constructive reviews to heart!

REFERENCES

Amelin, Y., Li, C. and Naldrett, A.J.
1999: Geochronology of the Voisey's Bay intrusion, Labrador, Canada, by precise U–Pb dating of co-existing baddeleyite, zircon and apatite. Lithos, Volume 47, pages 33-51.

Barton, J.M.
1974. Progress of isotopic and geochemical investigations, coastal Labrador, 1973. *In* The Nain Anorthosite Project, Labrador: Field Report, 1973. *Edited b*y S.A. Morse. University of Massachusetts, Geology Department, Contribution No. 13, pages 19-28.

Beall, G.H., Hurley, P.M., Fairbairn, H.W. and Pinson (Jr.), W.H.
1963: Comparison of K–Ar and whole-rock Rb–Sr dating in New Québec and Labrador. American Journal of Science, Volume 261, pages 571-580.

Berg, J.H.
1977: Dry granulite mineral assemblages in the contact aureoles of the Nain Complex, Labrador. Contri-

butions to Mineralogy and Petrology, Volume 64, pages 33-52.

1979. Physical constraints and tectonic setting of the Nain Complex. Geological Association of Canada – Mineralogical Association of Canada. Joint Annual Meeting, Québec City, Program with Abstracts, Volume 4, page 39.

Berg, J.H. and Wiebe, R.A.
1985: Petrology of a xenolith of ferro-aluminous gneiss from the Nain Complex. Contributions to Mineralogy and Petrology, Volume 90, pages 226-235.

Brand, S.R.
1976: Geology, petrology, and geochemistry of the lower Kingurutik River area, Labrador, Canada. Unpublished Ph.D. thesis, Purdue University, West Lafayette, IN, 265 pages.

Bybee, G.M., Ashwal, L.D., Shirey, S.B., Horan, M., Mock, T. and Andersen, T.B.
2014: Pyroxene megacrysts in Proterozoic anorthosites: Implications for tectonic setting, magma source and magmatic processes at the Moho. Earth and Planetary Science Letters, Volume 389, pages 74-85.

Connelly, J.N.
1993: U–Pb geochronological research agreement: final report for the Newfoundland Department of Mines and Energy, Labrador Mapping Section. Unpublished report, Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey Branch, Open File LAB/0978.

2005: Report on U–Pb geochronology results for the Newfoundland and Labrador Geological Survey Branch, Nain area, Labrador. Unpublished report, Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey Branch, 6 pages (plus figures and tables).

Connelly, J.N. and Ryan, B.
1994: Late Archean and Proterozoic events in the central Nain craton. *In* LITHOPROBE: Eastern Canadian Shield Onshore-Offshore Transect (ECSOOT), Report of Transect Meeting (December 10-11, 1993). *Compiled by* R.J Wardle and J. Hall, Université du Québec à Montréal, LITHOPROBE Report No. 36, pages 53-61.

de Waard, D.
1974: Petrology and structure of some North American anorthosite massifs. *In* Anorthosites and Their Environment. Centenaire de la Société Géologique Belgique, Geologie des Domaines Cristallins, Liege, pages 324-332.

Emslie, R.F.
1978a: Elsonian magmatism in Labrador: age, characteristics and tectonic setting. Canadian Journal of Earth Sciences, Volume 13, pages 438-453.

1978b: Anorthosite massifs, rapakivi granites, and the Late Proterozoic rifting of North America. Precambrian Research, Volume 7, pages 61-98.

Emslie, R.F. and Loveridge, W.D.
1992: Fluorite-bearing Early and Middle Proterozoic granites, Okak Bay area, Labrador: geochronology, geochemistry and petrogenesis. Lithos, Volume 28, pages 87-109.

Evans-Lamswood, D.M., Butt, D.P., Jackson, R.S., Lee, D.V., Muggeridge, M.G. and Wheeler, R.I.
2000: Physical controls associated with the distribution of sulfides in the Voisey's Bay Ni–Cu–Co deposit, Labrador. Economic Geology, Volume 95, pages 749-769.

Funk, T., Louden, K.E. and Reid, I.D.
2000: Wide-angle seismic imaging of a Mesoproterozoic anorthosite complex: The Nain Plutonic Suite in Labrador, Canada. Journal of Geophysical Research, Volume 105, pages 25,693-25,707.

Gower, C.F. and Krogh, T.E.
2002: A U–Pb geochronological review of the Proterozoic history of the eastern Grenville Province. Canadian Journal of Earth Sciences, Volume 39, pages 795-829.

Hamilton, M.A.
1994: Review of isotopic data for the Nain Plutonic Suite. *In* Anorthositic, Granitoid, and Related Rocks of the Nain Plutonic Suite: Guidebook to a field excursion to the Nain area, August 4-10, 1994. *Edited by* J.H. Berg, R.F. Emslie, M.A. Hamilton, S.A. Morse, A.B. Ryan, and R.A. Wiebe. International Geological Correlation Program Projects #290 and #315, pages 15-19.

1997: New U–Pb geochronological results from the Mesoproterozoic Nain Plutonic Suite, Labrador, and implications for the origin and emplacement of massif anorthosites and related rocks. COPENA Conference "Proterozoic Orogenies and Plate Interactions: The

North Atlantic Region in Space and Time", Trondheim, Norway, August 18-22, Norges Geologiske Undersøklese, Report 97.131, pages 43-44.

2008: Geochronological synopsis of the Nain Plutonic Suite, Labrador: age variations, patterns of AMGC magmatism, and Gardar connections revisited. Geological Association of Canada – Mineralogical Association of Canada – Society of Economic Geologists – Society for Geology Applied to Mineral Deposits, Joint Annual Meeting, Toronto, Abstracts, Volume 33, page 69.

Hamilton M.A., Emslie, R.F. and Roddick, J.C.
1994: Detailed emplacement chronology of basic magmas of the Mid-Proterozoic Nain Plutonic Suite, Labrador: insights from U–Pb systematics in zircon and baddeleyite. Eighth International Conference on Cosmochronology and Isotope Geology, United States Geological Survey Circular 1107, page 124.

Hamilton, M.A., Ryan, A.B. and Emslie, R.F.
1998: Identification of Paleoproterozoic anorthositic and monzonitic rocks in the vicinity of the Mesoproterozoic Nain Plutonic Suite – U–Pb evidence. *In* Radiogenic Age and Isotopic Studies: Report 11. Geological Survey of Canada, Current Research 1998-F, pages 23-40.

Hill, J.
1982: Geology of the Flowers River – Notakwanon River area, Labrador. Government of Newfoundland and Labrador, Department of Mines and Energy, Mineral Development Division, Report 82-6, 140 pages.

James, D. and Byrne, D.
2004: Preliminary geological compilation map, unpublished, exhibited at Geological Survey of Newfoundland and Labrador, Review of Activities, November, 2004, supplemental to "The Mesoproterozoic Nain Plutonic Suite and rocks of the southeastern Churchill Province in the lower Kingurutik River area (NTS map sheet 14D/15)". *In* Report of Activities. Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey, pages 16-17.

2005: A note on the Mesoproterozoic Nain Plutonic Suite and rocks of the southeastern Churchill Province, lower Kingurutik River area (NTS map sheet 14D/15). *In* Current Research. Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey, Report 05-1, pages 93-99.

Kamo, S.
2003: U–Pb ages of late Grenvillian intrusions from the eastern Grenville Province, and from the Nain Plutonic Suite, Labrador. Government of Newfoundland and Labrador Department of Mines and Energy, Geological Survey of Newfoundland and Labrador, Unpublished report, 4 pages [File LAB/1581].

Krogh, T.E.
1973: A low-contamination method for hydrothermal decomposition of baddeleyite and extraction of U and Pb for isotopic age determination. Geochimica et Cosmochimica Acta, Volume 46, pages 637-649.

1993: Report on Labrador geochronology, 1992-93. Unpublished report, Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey Branch, File#LAB/0977, 75 pages.

Krogh, T.E. and Davis, G.L.
1973: The significance of inherited zircons on the age and origin of igneous rocks - an investigation of the Labrador adamellites. Carnegie Institution of Washington Yearbook, Volume 72, pages 610-613.

Lee, D.V.
1987: Geothermobarometry and petrologic history of a contact metamorphosed section of the Tasiuyak gneiss, west of Nain, Labrador. B.Sc. Honours thesis, Memorial University of Newfoundland, St. John's, NL, 111 pages.

Li, C. and Naldrett, A.J.
2000: Melting reactions of gneissic inclusions with enclosing magma at Voisey's Bay, Labrador, Canada: Implications with respect to ore genesis. Economic Geology, Volume 95, pages 801-814.

Loewy, S.
2004: Report on U–Pb isotopic age determinations from rocks of the Kingurutik Lake area. Unpublished report, Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey of Newfoundland and Labrador, 4 pages.

Morse, S.A.
1964: Age of Labrador anorthosites. Nature, Volume 203, pages 509-510.

1969: The Kiglapait Layered Intrusion, Labrador. Geological Society of America, Memoir 112, 204 pages.

1976: Introduction and Review. *In* The Nain Anorthosite Project, Labrador: Field Report, 1975. *Edited by* S.A. Morse. University of Massachusetts, Department of Geology and Geography, Contribution No. 26, pages 1-5.

1983: Emplacement history of the Nain Complex. *In* The Nain Anorthosite Project, Labrador: Field Report, 1981. *Edited by* S.A. Morse. University of Massachusetts, Department of Geology and Geography, Contribution No. 40, pages 9-15.

Myers, J.S., Voordouw, R.J. and Tettelaar, T.A.
2008: Proterozoic anorthosite-granite Nain batholith: structure and intrusion processes in an active lithosphere-scale fault zone, northern Labrador. Canadian Journal of Earth Sciences, Volume 45, pages 909-934.

Ryan, A.B.
1990: Preliminary geological map of the Nain Plutonic Suite and surrounding rocks (Nain-Nutak, NTS 14SW). Scale 1:500 000. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey Branch, Map 90-44.

2000: The Nain–Churchill boundary and the Nain Plutonic Suite: A regional perspective on the geological setting of the Voisey's Bay Ni–Cu–Co deposit. Economic Geology, Volume 75, pages 703-724.

Ryan, B. and James, D.
2004: The Mesoproterozoic Nain Plutonic Suite and its country rocks in the Kingurutik Lake–Fraser River area (NTS 14D/9 and 16). *In* Current Research. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey, Report 04-1, pages 235-258.

Ryan, B. and Lee, D.
1995: Geological map of the Reid Brook area (14D/8). Map 95-017, Version 1.0. Scale 1:50 000. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey, Open File 14D/08/0051.

Ryan, B. and Morse, S.A.
1985: Nain Plutonic Suite. *In* Lexicon of Canadian Stratigraphy, Volume VI: Atlantic Region. *Edited by* G.L. Williams, L.R. Fyffe, R.J. Wardle, S.P Colman-Sadd, R.C. Boehner, and J.A. Watt. Canadian Society of Petroleum Geologists, pages 266-267.

Ryan, A.B. (compiler), Krogh, T.E., Heaman, L., Schärer, U., Philippe, S. and Oliver, G.
1991: On recent geochronological studies in the Nain Province, Churchill Province, and Nain Plutonic Suite, north-central Labrador. *In* Current Research. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey Branch, Report 91-1, pages 257-261.

Ryan, B., Phillips, E., Shwetz, J. and Machado, G.
1998: A tale of more than ten plutons (Geology of the region between Okak Bay and Staghorn Lake, Labrador, parts of NTS maps 14E/2, 7, 8). *In* Current Research. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey, Report 98-1, pages 143-171.

Scott, D.J. and Gauthier, G.
1996: Comparison of TIMS (U–Pb) and laser ablation microprobe ICP-MS techniques for age determination of detrital zircons from Paleoproterozoic metasedimentary rocks from northeastern Laurentia, Canada, with tectonic implications. Chemical Geology, Volume 131, pages 127-142.

Smith, D.
1974: Pyroxene-olivine-quartz assemblages in rocks associated with the Nain anorthosite massif, Labrador. Journal of Petrology, Volume 15, pages 58-78.

Snyder, G.A. and Simmons, E.C.
1992: Intrusion of the Elsonian (c. 1303 Ma) Nain Anorthosite Complex over a contracted time interval: Current geochronological evidence. Geological Society of America, Abstract with Programs, Annual Meeting, Cincinnati, Ohio, pages A94-A95.

Stacey, J.S. and Kramers, J.D.
1975: Approximation of terrestrial lead isotope evolution by a two-stage model. Earth and Planetary Science Letters, Volume 26, pages 207-221.

Taylor, F.C.
1977: Geology, Tasisuak Lake. Scale 1:250 000. Geological Survey of Canada, Map 1438A.

Tettelaar, T.A.
2004: Emplacement history of the Pearly Gates anorthosite pluton and spatially related Tessiarsuyungoakh intrusion, and metamorphic petrology of the adjacent Tasiuyak paragneiss, northern Labrador. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, 214 pages.

Tettalaar, T.A. and Indares, A.,
2007: Granulite-facies regional and contact metamorphism of the Tasiuyak paragneiss, northern Labrador: textural evolution and interpretation. Canadian Journal of Earth Sciences, Volume 44, pages 1413-1437.

Wanless, R.K., Stevens, R.D., Lachance, G.R. and Delabio, R.N.
1973: Age determinations and geological studies: K–Ar

isotopic ages, Report 11. Geological Survey of Canada, Paper 73-2, 139 pages.

Wardle, R.J., James, D.T., Scott, D.J. and Hall, J.
2002: The Southeastern Churchill Province: synthesis of a Paleoproterozoic transpressional orogen. Canadian Journal of Earth Sciences, Volume 39, pages 639-663.

Wheeler, E.P. 2nd
1960: Anorthosite-adamellite complex of Nain, Labrador. Geological Society of America, Bulletin 71, pages 1755-1762.

1965: Fayalitic olivine in northern Newfoundland-Labrador. Canadian Mineralogist, Volume 8, pages 339-346.

1969: Minor intrusives associated with the Nain anorthosite. *In* Origin of Anorthosite and Related Rocks. *Edited by* Y.W. Isachsen. New York State Museum Science Service, Memoir 18, Albany, New York, pages 189-206.

Wiebe, R.A.
1980: Commingling of contrasted magmas in the plutonic environment: examples from the Nain anorthosite complex. Journal of Geology, Volume 88, pages 197-209.

1983: Fractional crystallization and magma mixing in the Tigalak layered intrusion, the Nain anorthosite complex, Labrador. Contributions to Mineralogy and Petrology, Volume 84, pages 327-344.

1990: Evidence for unusually feldspathic liquids in the Nain Complex, Labrador. American Mineralogist, Volume 75, pages 1-12.

Yu, Y. and Morse, S.A.
1993: ^{40}Ar/^{40}Ar chronology of the Nain anorthosites, Canada. Canadian Journal of Earth Sciences, Volume 30, pages 1166-1178.

APPENDIX: ANALYTICAL PROCEDURES

The following is an overview of analytical methods used to generate the geochronological data presented in this report. A more comprehensive treatment of the procedures, following the established protocols for zircon selection and preparation, is given by Connelly (2005).

The rock samples were processed at the Geochronology Laboratory of The University of Texas at Austin. The zircons were collected from mineral separates acquired through standard laboratory procedures by using a Wilfley table, sieves, heavy liquids and a Franz magnetic separator, and examined under reflected-light and petrographic microscopes. The highest quality grains were isolated for analyses. The selected grains were abraded, washed in nitric acid, water and acetone, and subsequently loaded dry into Teflon™ capsules along with a mixed ^{205}Pb/^{235}U tracer. After zircon dissolution in HF and HNO_3, chemical separation of U and Pb was carried out using minicolumns, producing procedural blanks of 1 pg for Pb and 0.25 pg for U. Lead, uranium, silica gel and phosphoric acid were loaded onto a zone-refined Re ribbon filament and analyzed by a Finnigan-Mat 261 thermal ionization mass spectrometer. Larger samples were measured using Faraday cups in static mode, whereas smaller samples were measured in dynamic mode using a secondary electron multiplier ion counting (SEM-IC) system. The corrected isotopic compositions, as well as final ages based on regressions of multiple analyses, were calculated using an in-house computer program written by J. Connelly. The results of the analyses are reported with 2σ errors in Table 1.

Added in Proof

The age-range of the Umiakovik Lake granite (*ca.* 1319-1316 Ma) used for discussions of local relationships in this paper is that given by Emslie and Loveridge (1992) for the unit 60 km to the north, based on U–Pb isotopic study of zircon. Brand (1976, page 166) had earlier calculated a whole-rock Rb–Sr isochron age of 1.45 ± 0.3 b.y. (1450 ± 300 Ma) for the granite from the Kingurutik River area, specifically, from near ‘Post Lake’. The writers consider the U–Pb age of Emslie and Loveridge (*op. cit.*), however, to be a better estimate than the Rb–Sr one for the emplacement and crystallization age for the granite of the Kingurutik River–Kamanatsuk River region as well.