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**Employing contact metamorphism to assess the conditions
of pluton emplacement and timing of recrystallization in
southwestern Kellys Mountain, Cape Breton Island, Nova
Scotia**

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Manuscripts

1 **Employing contact metamorphism to assess the conditions of pluton emplacement**
2 **and timing of recrystallization in southwestern Kellys Mountain, Cape Breton**
3 **Island, Nova Scotia**

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14

Abstract

At Kellys Mountain, Cape Breton Island, Nova Scotia, the late Neoproterozoic Glen Tosh formation (a low-grade metapsammite-metapelite unit of the George River Metamorphic Suite) has been intruded by diorite, granodiorite and granite plutons, and the diorite hosts a narrow contact metamorphic aureole. New mapping and sampling in the contact aureole reveals that the metasedimentary rocks have reached amphibolite-facies metamorphism resulting in the development of neoformed biotite, muscovite, cordierite, ilmenite, garnet, andalusite, sillimanite, monazite, and spinel within the metapelite, a mineral assemblage also found in the Kellys Mountain Gneiss as a result of low-pressure regional metamorphism. Neoformed minerals and the disappearance of foliation defines a contact metamorphic aureole within 300 m of the pluton contacts.

Petrographic and microprobe analyses of equilibrium assemblages in metapelitic units of the contact aureole yielded metamorphic pressures of 250 MPa, implying an intrusion depth of ca. 9 km, with temperatures ranging from 365 to 590°C. The presence of earlier-formed andalusite and garnet indicates the rocks may have initially undergone a low-pressure regional metamorphic event prior to contact metamorphism. Monazite in the contact aureole was dated using *in-situ* U-Pb methods and yielded an age of 480.9 ± 3.7 Ma, interpreted as the time of formation of the contact metamorphic aureole.

38 Résumé

39 Au mont Kellys, île du Cap-Breton, Nouvelle-Écosse, le Néoprotérozoïque tardif
40 de la formation de Glen Tosh présente une métapsammite-métapelite faiblement
41 métamorphisée appartenant au complexe métamorphique de George River. Cette
42 formation a subi une intrusion par des plutons (diorite, granodiorite et granite) et présente
43 une auréole de contact étroit autour de diorite. La nouvelle cartographie et le prélèvement
44 d'échantillons dans l'auréole de contact démontrent que les roches méta-sédimentaires
45 ont atteint le faciès métamorphique d'amphibolite. Ceci résulte du développement de
46 minéraux néoformés tels que: biotite, muscovite, cordiérite, ilménite, grenat, andalousite,
47 sillimanite, monazite, et spinelle présents dans le métapelite. Cet assemblage de minéraux
48 est aussi trouvé dans le gneiss de Kellys Mountain à la suite du métamorphisme régional
49 de basse pression. Cependant, la distribution des minéraux néoformés résultant du
50 métamorphisme est limitée à moins de 300 m du contact avec le pluton, ce qui implique
51 que la chaleur était l'agent de métamorphisme de l'auréole.

52 Les analyses pétrographiques et de microsonde du métapelite montrent que la
53 pression du métamorphisme était de près de 250 MPa, correspondant à des températures
54 de 365 à 590°C, ce qui implique une intrusion à des profondeurs jusqu'à 9 km.
55 Cependant, la formation d'andalousite et de grenat indique que les roches peuvent avoir
56 d'abord subi un événement métamorphique régional de basse pression avant cet
57 événement de métamorphisme de contact. La monazite dans l'auréole de contact a été
58 datée *in situ* en utilisant les méthodes de $^{207}\text{Pb}/^{235}\text{U}$. Les résultats indiquent que la
59 recristallisation du métamorphisme de contact est datée de $480,9 \pm 3,7$ Ma, ce qui est
60 interprété comme le temps de formation de l'auréole métamorphique.

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62 Keywords: contact metamorphism, Bras d'Or terrane, pluton emplacement

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Introduction

Kellys Mountain lies in Cape Breton Island, a geologically complex area of the northern Appalachian Orogen, and the site of deformation, regional metamorphism and plutonism associated with terrane amalgamation. Barr and Raeside (1989) identified portions of three terranes and a cryptic Grenvillian inlier (Blair River Inlier) in Cape Breton Island. Kellys Mountain is situated in the Bras d'Or terrane, which is located mainly in central Cape Breton Island between the Aspy terrane to the northwest and the Avalonian Mira terrane to the southeast (Fig. 1) (Barr and Raeside 1989).

The Bras d'Or terrane is a suspect terrane that extends to the northeast where it has been correlated to rocks in southern Newfoundland and similar units also exist in southern New Brunswick in the Brookville terrane (Barr and Raeside 1989, White and Barr 1996, Barr et al. 1998). It is largely composed of late Neoproterozoic to Paleozoic units, defined by Raeside and Barr (1990) as: (i) the Bras d'Or Metamorphic Suite; (ii) Neoproterozoic generally low-grade metamorphic rocks; (iii) Late Neoproterozoic to Cambrian supra-subduction zone intrusive units; and (iv) younger intrusive units (Fig. 1). The two metamorphic components, the high-grade Bras d'Or Metamorphic Suite and the low-grade metamorphic rocks are jointly referred to as the George River Metamorphic Suite. Together, these components make up the outboard margin of Ganderia (Hibbard et al. 2006) and the metamorphic units have been correlated regionally to the Brookville Gneiss and Green Head Group of the Brookville terrane of southern New Brunswick (Barr et al. 2013).

Kellys Mountain is a microcosm of the Bras d'Or terrane, displaying elements of all four of the defining components of the terrane. The Bras d'Or Metamorphic Suite is

represented by the Kellys Mountain Gneiss, which was studied by Jamieson (1984) to determine the peak metamorphic conditions. Field relations, petrology, and geochemistry of the diorite and leucogranite plutons, elements of the two plutonic components of the Bras d'Or terrane, were investigated by Barr *et al.* (1982) to discern the affinities of the granitoid bodies. The metapelitic and meta-semipelitic rocks of Kellys Mountain are part of the generally low-grade metamorphic component and have not previously been studied in detail. They have been informally assigned to the Glen Tosh formation in a complementary study by Barr *et al.* (2013) who provided whole-rock chemical and Nd isotopic analyses to compare the Glen Tosh formation with the Kellys Mountain Gneiss. That study indicated that the two units are compositionally, chemically and isotopically similar, and that the detrital components of both units were derived from the same or similar sources, likely an eroding active continental margin containing 2 Ga and Late Neoproterozoic components.

The main purposes of this study are to determine the depth of intrusion of the pluton(s) responsible for the contact metamorphic aureole, as indicated by the conditions of metamorphism in the contact aureole, to ascertain the degree to which the pluton(s) is/are agent(s) of metamorphism, and to determine the timing of the events. With improved understanding of the nature and timing of metamorphism, it will be possible to evaluate if the proposed correlation (Barr *et al.* 2013) of the Neoproterozoic Glen Tosh formation with the Kellys Mountain Gneiss is viable, and speculate more rigorously on its significance for the other metamorphic components of the Bras d'Or terrane. This study also addresses the question why the regional metamorphism of the Glen Tosh

formation in general is of much lower grade than the Kellys Mountain Gneiss and whether they record the same or different metamorphic events.

Geology of Kellys Mountain

Kellys Mountain (Fig. 2) is typical of the Bras d'Or terrane, being underlain by all four of its constituent elements (Raeside and Barr 1992). Two of these components are represented by metamorphic units, both of which are intruded by plutons (the two intrusive components of the Bras d'Or terrane) and both of which display evidence for having undergone two metamorphic events. The Bras d'Or Metamorphic Suite in this area is represented by the Kellys Mountain Gneiss (Fig. 2), in which the age of the metamorphism has been determined by U-Pb dating techniques to be 515 ± 1 Ma from monazite in cordierite-bearing migmatite (Keppie *et al.* 1998) and 496 ± 5 Ma from titanite in amphibolite (Dunning *et al.* 1990). The Kellys Mountain Granite (Barr *et al.* 2013), formerly referred to as the Kellys Mountain leucogranite, intruded the Kellys Mountain Gneiss on its southwest side (Fig. 2) (Barr *et al.* 1982) and has been dated at 498 ± 2 Ma using U-Pb isotopic methods on zircon (Barr *et al.* 1990). The Kellys Mountain Gneiss is also in contact with dioritic rocks and with outlying granitic bodies that have been correlated with the Kellys Mountain Granite (Jamieson 1984; Fig. 2).

Jamieson (1984) identified four lithological components of the Kellys Mountain Gneiss: biotite gneiss, cordierite-biotite gneiss, migmatitic cordierite-aluminosilicate gneiss, and amphibolite. Metamorphic petrology, AFM projections of coexisting phases, and mineral analysis were done by Jamieson (1984) to determine the peak metamorphic conditions of the Kellys Mountain Gneiss, estimated to be at 100–350 MPa and 580–

700°C. Jamieson (1984) established the upper limits of these conditions based on good preservation of the reaction:

(mineral abbreviations throughout this paper follow the recommendations of Fettes and Desmons, 2007).

Low-grade metamorphic rocks are found in the southwestern end of Kellys Mountain (Fig. 2) and have been informally referred to as the Glen Tosh formation (Barr *et al.* 2013). The unit can be traced to the north into the Cape Breton Highlands (Fig. 2), where metamorphic grade gradually increases to upper amphibolite facies, and where the unit has been termed the Barachois River Metamorphic Suite (Fig. 1; Raeside and Barr 1992). The Glen Tosh formation is composed mainly of metamorphosed quartz wacke, also described as metasiltstone and metagreywacke by Barr *et al.* (1982) and is similar to other low-grade metapelitic units across the Bras d'Or terrane (Blues Brook Formation in the Creignish Hills, Malagawatch Formation in the North Mountain, Benacadie Brook Formation in Boisdale Hills, McMillan Flowage Formation in the eastern Cape Breton Highlands), which are collectively termed the Georges River Metamorphic Suite (Barr *et al.* 2013). The semipelitic and pelitic rocks of the Glen Tosh formation were intruded by the same dioritic and granitic units as was the Kellys Mountain Gneiss.

Throughout southwestern Kellys Mountain the Glen Tosh formation mainly consists of meta-quartz wacke, with scattered pods of andesitic meta-tuff and more micaceous phyllite. For the most part, outcrops of the Glen Tosh formation are grey, very fine grained rocks with a weak foliation. More pelitic rocks are phyllite, with a more pronounced muscovite-dominated foliation, oriented biotite and local large cordierite

155 knots, up to 3 cm across (Fig 3A). More siliceous rocks are more massive and display
156 less obvious foliation in outcrop, however the presence of a weak foliation, even in
157 psammitic rocks is an indicator that the unit underwent regional metamorphism prior to
158 contact metamorphism. Immediately adjacent to the plutonic rocks in central Kellys
159 Mountain, the meta-quartz wacke lacks foliation and displays a hornfelsic texture in
160 which the muscovite and biotite do not exhibit a preferred orientation and neo-formed
161 cordierite ranges up to 0.2 mm in diameter (Fig. 3B).

162 Metapelitic and metapsammitic rocks consist primarily of quartz and plagioclase,
163 with significant detrital K-feldspar, biotite, muscovite, and opaque minerals in most
164 samples (Table 1). Garnet occurs sparsely throughout the metapelite unit. Cordierite and
165 andalusite were found in some samples located within the contact aureole, and
166 porphyroblastic cordierite occurs in scattered localities throughout the Glen Tosh
167 formation. Sillimanite and spinel were identified in one sample of hornfels (NS-030),
168 within 50 m of the igneous contact (Fig 3C). The zone of hornfels extends up to 300 m
169 from the plutonic contact. Retrograde chlorite, secondary muscovite, sericite, and pinite
170 after cordierite were all observed as alteration products. Accessory apatite, titanite, rutile,
171 zircon, monazite, and xenotime also occur in these rocks.

172 Although both the Kellys Mountain Gneiss and the Glen Tosh formation exhibit
173 regional metamorphic fabrics, metamorphism in the Glen Tosh formation occurred at
174 lower grade, with most assemblages exhibiting greenschist-facies mineralogy, except for
175 a few local reports of andalusite and cordierite (Barr *et al.* 2013). In the aureole, the
176 metamorphic conditions are typical of contact metamorphism based on the presence of
177 co-existing cordierite and sillimanite, and the decussate textures in semipelitic lithologies.

The Kellys Mountain Gneiss and the Glen Tosh formation have both been affected by regional metamorphic and deformational events, which is evident from the foliation developed in them. However, the Glen Tosh formation metamorphism occurred at a much lower grade, as it has developed only low-grade greenschist-facies assemblages, although cordierite and andalusite have been reported in some localities (Barr *et al.* 2013).

The recognition of the Kellys Mountain Gneiss and the Glen Tosh formation (and by extension the Barachois River Metamorphic Suite) as parts of the two metamorphic components of the Bras d'Or terrane is not without difficulty. A similar situation exists between the Brookville Gneiss and the Green Head Group in the Brookville terrane of southern New Brunswick (White and Barr 1996, Barr *et al.* 2014). The Kellys Mountain Gneiss was assigned to the regional low-pressure, high-grade gneiss component on the basis of cordierite- and sillimanite-bearing assemblages and widespread gneissic foliation, but the unit lacks the marble and calc-silicate lithologies typical of other blocks of gneiss in the Bras d'Or terrane, e.g., Lime Hill Gneissic Complex, Frenchvale Road Metamorphic Suite, Skye Mountain Metamorphic Suite (Fig. 2). The similar lithological composition (although very different grade of metamorphism) between the Kellys Mountain Gneiss and the Glen Tosh formation (Table 1) led Barr *et al.* (2013) to investigate the whole-rock chemistry and Sm-Nd isotopic characteristics of both units, wherein their similarity was validated.

Both the Kellys Mountain Granite and the Kellys Mountain dioritic rocks are in contact with the Glen Tosh formation (Fig. 4A). Xenoliths derived from the Glen Tosh formation were observed within diorite providing firm evidence for the later intrusion of

the diorite. Several attempts to map the plutonic rocks in Kellys Mountain (Barr *et al.* 1982, Barr *et al.* 1992) were summarized by Barr *et al.* (2013). The granitic and dioritic rocks are irregularly distributed throughout southwestern Kellys Mountain, east of the Glen Tosh formation, indicating the two units are closely associated and may be co-magmatic (Barr *et al.* 2013). Leucogranitic dykes of the Kellys Mountain Granite were found within the diorite providing evidence that intrusion of the granite was at least in part after the emplacement of the diorite (Fig. 4B). Most recently Barr *et al.* (2013) combined the various granitic components of Kellys Mountain into one pluton named the Kellys Mountain Granite, and described it as consisting of leucogranite, syenogranite, monzogranite and granodiorite. The Kellys Mountain dioritic rocks are more varied in composition and include diorite, quartz diorite, tonalite, granodiorite, quartz monzonite, and hornblendite (Barr *et al.* 2013).

Petrography

In thin section, the rocks of the Glen Tosh formation are very fine-grained and moderately homogeneous. In some areas, the unit is well bedded and foliated, but elsewhere it is more psammitic, lacks oriented mica, and appears granoblastic. Sedimentary laminations are commonly well preserved and cross-bedding has been observed. Biotite is for the most part aligned parallel to bedding and primary muscovite typically also appears as aligned grains, in some places in biotite-rich layers. In most samples within the contact aureole, cordierite is present as large poikiloblasts composed of aggregates of several grains and parts of the adjacent matrix. Scarce garnet is generally altered, but where well-preserved is highly variable in Ca, Mn, Mg and Fe content

(Shawwa 2013). Sillimanite is found interlocking between quartz grains (Fig. 3C). Biotite is found overgrowing andalusite (Fig. 3D); and in one sample, cordierite overgrows andalusite. The opaque minerals are ilmenite, magnetite, and hematite. Trace amounts of zircon, monazite and xenotime are also present.

The quartz-rich rocks of the Glen Tosh formation are only slightly altered. In some cases, the cordierite has been altered to pinitite, and garnet has been altered to chlorite. Meta-tuff tends to display more extensive alteration with the development of sericite after feldspar, and chlorite after actinolite, although some chlorite is also prograde. In adjacent granite, the main form of alteration is sericitization of feldspar.

Mineral Chemistry

Overview

Eight samples were selected for analysis of coexisting plagioclase, K-feldspar, biotite, muscovite, cordierite, garnet and ilmenite, where available, using the JEOL JXA-8200 Superprobe in the Robert M. MacKay Laboratory of the Dalhousie Regional Electron Microprobe Facility. Quantitative WDA was done using an accelerating voltage of 15 kV, beam current of 20 nA, typical beam diameter of 1 μm , peak count time of 20 s and background count time of 10 s. Standards employed were sanidine (K), Cr-metal (Cr), jadeite (Na), Garnet12442 (Al, Fe, Si), pyrolusite (Mn) and Kanganui kaersutite (Ca, Ti, Mg). For thermodynamic calculations, the aluminosilicate minerals are assumed to be pure and grains were not analyzed by electron microprobe. All calculations were done assuming the iron is Fe^{2+} .

Mineral assemblages were further assessed using petrographic studies and phase relation diagrams to determine which reactions have occurred prior to determination of the pressures and temperatures of metamorphism using the TWQ software (Berman, 2007). Representative analyses are presented in Table 2; full details of all analyses were presented by Shawwa (2013).

Glen Tosh formation

Plagioclase in the Glen Tosh formation at a distance from the contact metamorphic aureole vary from An₂₂ to An₃₁ (e.g. DM-14 and RR-202). Low metamorphic grade rocks closer to the contact aureole also have constant but elevated compositions of An₃₄ to An₃₈ (e.g. NS-032). Lower grade contact metamorphic rocks in the contact aureole, but distant from the contact are highly variable in composition, ranging from An₂₂ to An₄₅ in a single rock (NS-30). The grains with the highest An contents may represent detrital grains derived from different sources. Closer to the contact, higher grade rocks have relatively constant compositions of An₂₅ to An₂₇ (e.g. NS-028). No compositional zoning was detected in plagioclase. K-feldspar ranges from Or₉₁ to Or₉₉ in very low grade rocks to Or₈₀ to Or₉₆ nearer the contact.

Biotite compositions are uniform within samples, but appear to vary with grade. The lowest grade biotite has the lowest FeO and TiO₂ contents. Muscovite Na/(Na + K + Ca) ratios decrease from the regionally metamorphosed rocks into the aureole.

Garnet (Fig. 5A) is present in only two of the analyzed samples. In sample RR-202 it is unzoned, as shown by back-scattered electron imaging (Fig. 5B) and WDA analysis, with Alm₅₄Sps₂₉Prp₁₀Grs₇. In sample DM91-14 it is mildly zoned from

Alm₃₇Sps₃₉Prp₁₀Grs₁₄ (core) to Alm₄₃Sps₃₇Prp₁₂Grs₇ (rim). Almandine content varies inversely with spessartine and grossular content.

Cordierite in the rocks of the contact metamorphic aureole (Fig 5B) ranges in Mg/(Mg+Fe) ratio from 0.60 to 0.72 and is uniform within samples in the contact aureole. Andalusite and sillimanite, Al₂SiO₅, were both observed in the Glen Tosh formation (Table 1). The average (Fe+Mn)/(Fe+Ti+Mn) ratio in ilmenite indicates it conforms closely to the ideal formula (Fe,Mn)TiO₃, with up to 17% MnTiO₃ component.

Kellys Mountain Gneiss

For comparative purposes, and to distinguish the contact metamorphism from the regional metamorphism at Kellys Mountain, mineral analyses were also obtained by electron microprobe for a sample (NS-026) of the Kellys Mountain Gneiss. Plagioclase, K-feldspar, biotite, cordierite, and ilmenite were analyzed (Table 2). Jamieson (1984) also reported mineral analyses for plagioclase, K-feldspar, cordierite, biotite, oxides, aluminosilicate minerals, and retrograde phases.

As in some of the higher grade rocks of the Glen Tosh formation, plagioclase in the Kellys Mountain Gneiss sample has low and uniform anorthite contents of An₂₂ to An₂₆, comparable to values of An₂₂ to An₃₀ reported by Jamieson (1984). K-feldspar in the Kellys Mountain Gneiss has lower and variable orthoclase contents of Or₈₁ to Or₉₄ similar to the higher grade samples of the Glen Tosh formation, and to the results reported by Jamieson (1984), which vary from Or₇₇ to Or₉₅.

The compositions of both biotite and cordierite from the Kellys Mountain Gneiss sample are also similar to the compositions of these phases in higher grade rocks of the

Glen Tosh formation with a Fe/(Fe+Mg) ratio ranging from 0.46 to 0.54 (Table 2), almost identical to that reported by Jamieson (1984). Titanium content in the biotite from the Kellys Mountain Gneiss is also similar to the higher grade samples of the Glen Tosh formation.

As also reported by Jamieson (1984), ilmenite in the Kellys Mountain Gneiss departs from the ideal formula, suggesting a ferric iron (hematite) component in solid solution between $(\text{Fe}^{2+}\text{Mn})\text{TiO}_3$ and Fe_2O_3 .

Metamorphic Conditions

KFMASH Relationships

Univariant metamorphic reactions in the model pelitic system KFMASH are shown in Fig. 6, as used for the Ballachulish contact aureole by Pattison and Harte (1985). The reactions delimit the pressure and temperature conditions in the Glen Tosh formation based on the mineral assemblages. The temperature of metamorphism can also be determined for the Kellys Mountain Gneiss sample, which can be compared to results of Jamieson (1984).

The plot on Fig. 6 incorporates the P-T conditions that would be encountered in high-heat flow metamorphism. In the Glen Tosh formation, an upper limit for temperature is the appearance of melt, which is nowhere found as a separate component in the aureole.

The mineral assemblage of sample NS-030 (see Fig. 2 for location) includes quartz–biotite–cordierite–sillimanite–spinel–K-feldspar, and therefore is constrained to lie on the univariant line of reaction (Fig. 6)

316 Recognizing limitations involving the understanding of iron-magnesium solid solution in
 317 cordierite (Martignole and Sisi 1981; Bhattacharya 1986), the pressure and temperature
 318 conditions of this reaction line are poorly constrained. Based on the presence of
 319 sillimanite, the reaction is limited to the high temperature side of the And = Sil reaction
 320 line. Also for reaction (1), the pressure and temperature conditions are limited by the
 321 absence of silicate melt (L) in the reaction (Fig. 6),

323 This constrains the pressure and temperature of sample NS-030 to the range of 200 to 230
 324 MPa at 630 to 675°C.

325 Sample NS-032 (see Fig. 2 for location) consists of the equilibrium assemblage
 326 quartz–biotite–cordierite–andalusite–K-feldspar. The pressure and temperature conditions
 327 of this sample can also be constrained to lie on the univariant line, reaction (1). However,
 328 based on the presence of andalusite, it is limited to the lower temperature side of the And
 329 = Sil reaction line. Reaction (1) plots in the divariant field of Mg-chlorite breaking down
 330 to biotite and cordierite, which is represented by (Fig. 6)

332 This indicates that sample NS-032 crystallized at a pressure ranging up to 200 MPa and
 333 temperature up to 630°C.

334 Sample DM-14 (see Fig. 2 for location) consists of the assemblage quartz–biotite–
 335 muscovite–K-feldspar, and it is therefore not a good indicator of pressure, but does
 336 indicate a possible temperature range. Based on the absence of silicate melt, the upper

temperature is limited by reaction (2). The temperature is also limited by the divariant reaction (Fig. 6)

The absence of cordierite in this sample suggests that it equilibrated on the low temperature side of reaction (4). Reactions (2) and (4) intersect at 655°C, thereby indicating the maximum temperatures sample DM-14 could have reached during metamorphism, but the actual conditions cannot be constrained beyond the divariant field bounded by these two reactions.

Sample RR-202 (see Fig. 2 for location) consists of the assemblage quartz–plagioclase–K-feldspar–muscovite–biotite–cordierite, and like sample DM-14, it is also a much better indicator of temperature than of pressure. It too is limited by reactions (2) and (4) indicating it has reached maximum temperatures of 655°C. The lower limit of temperature would be reaction (3), thereby constraining temperature for this sample to the range of 490 to 655°C.

One sample from the Kellys Mountain Gneiss (NS-026) was analyzed for comparison to the contact metamorphic rocks (see Fig. 2 for location). It consists of quartz–K-feldspar–cordierite–biotite–plagioclase, with cordierite sparsely developed in the paleosome, but abundant in the leucosome indicating partial melting. Assuming $f_{\text{H}_2\text{O}} = 1$, it therefore plots on the univariant reaction line for (Fig. 6)

but the absence of sillimanite limits it to pressure lower than about 27 MPa by the reaction 1 (Fig. 6). This suggests that the temperature of equilibration of the Kellys

Mountain Gneiss was approximately 725°C, consistent with the results of Jamieson (1984).

Geothermobarometry

Methodology

Geothermobarometric analysis was done using winTWQ (version 2.3), a software package for performing internally consistent thermobarometric calculations (TWQ; Berman 2007). This method determines the positions of all possible equilibria implied by a given mineral assemblage in terms of P-T- X_{H_2O} space. Using mineral analyses (Table 2), it determines the equilibration conditions recorded by that mineral assemblage, assuming that all components within the rock were in equilibrium with each other during metamorphism and that the conditions for closure of reactions were the same. Multiple reactions can be determined using the program's internally consistent set of thermodynamic parameters, and where these coincide the best estimate of pressure and temperature conditions available can be ascertained.

The use of geobarometry and geothermometry is dependent on a thorough understanding of mineral and textural conditions as seen in thin section. Necessary limitations that must be considered when using these tools are (i) the extent of equilibrium at the metamorphic peak, (ii) the effect of retrograde re-equilibrium, (iii) analytical uncertainties, and (iv) the simplifications introduced into thermodynamic formulations of non-ideal solutions (Berman 2007).

With regard to (i) and (ii) above, equilibration and retrogression are best evaluated using a combination of textural analysis and careful scrutiny of the mineral

382 compositions. Rocks that have not equilibrated and/or undergone retrogression show
383 recognizable disequilibrium textures, such as partial or complete replacement, as well as
384 mineral zoning and inter-grain mineral heterogeneity. Such rocks/minerals were avoided
385 in making TWQ calculations. Error in the analysis may arise from retrograde
386 metamorphic re-equilibration, especially in cordierite, garnet, biotite, and muscovite,
387 therefore this possibility must be considered in some samples. Complete replacement by
388 lower grade minerals can be easily identified, but in some minerals homogenization may
389 have occurred or low-grade overgrowths may have formed on the rims. Cordierite, biotite
390 and muscovite are homogeneous within any one sample, and garnet shows less than 5%
391 variation in composition in one sample and is homogeneous in another (Fig. 5).

392 Individual grains of plagioclase have different compositions, but it was not used in the
393 pressure and temperature determinations using TWQ. Analytical uncertainty (iii above)
394 and overall microprobe data quality were evaluated by making multiple analyses of
395 grains within any given sample and selecting representative analyses. Lastly, the
396 thermodynamic properties used, both standard state values and solution models, are the
397 most up-to-date values available for TWQ (Berman 2007). Non-ideal activity models
398 were used for biotite, garnet, muscovite, and cordierite (Berman 2007). K-feldspar was
399 assumed to be ideal. A non-ideal activity for K-feldspar (Fuhrman and Lindsley 1988)
400 was tested but yielded identical results to ideality presumably because the K-feldspar
401 present is nearly pure (Or_{94}). The $a_{\text{H}_2\text{O}}$ was assumed to be 1.0 in all geothermobarometric
402 calculations. The rocks contain no carbonate (to produce CO_2) or carbon (to produce
403 CH_4) and the only phases seen are hydrous. Furthermore, where multiple reactions can be
404 calculated, the best agreement of invariant conditions occurs if $a_{\text{H}_2\text{O}}$ is set to 1.0. Hydrous

reactions (and their invariant points) all have H₂O on the high-T/low-P side of the reactions. Reducing the activity of H₂O expands the H₂O-bearing fields and pushes the equilibria to slightly lower temperatures, thereby causing the hydrous invariant point to differ from other invariant point derivations.

Most of the calculated equilibria yield results that confirm previous work and are broadly compatible with field observations. However, equilibria involving muscovite are particularly sensitive to the muscovite composition and the determined pressure conditions of metamorphism in the Glen Tosh formation have higher error bars. Though sample NS-032 yielded a pressure of 250 MPa (Fig. 7A), which is expected in this area of low-pressure metamorphism and compatible with the mineral assemblage, sample NS-030 from less than 300 m away yielded a significantly higher pressure of 460 MPa (Fig. 7B). In the case of NS-030, P–T conditions are determined by multiple overlapping invariant points, which suggests that the rock has reached equilibrium and that the activity models for all minerals are appropriate. For NS-032, 300 m farther from the pluton, TWQ calculations produce a plot with a wide web of equilibria and multiple non-overlapping invariant points, which suggests that the minerals did not attain equilibrium. Only the equilibria involving biotite, cordierite, muscovite, quartz and andalusite yield P–T conditions that are reasonable (Fig. 7A). The Fe–Mg exchange between biotite and cordierite is kinetically the most favourable and is likely to be correct. The only other equilibria that cross this reaction at reasonable P–T conditions are the two end-members of the reaction

These reactions do not involve H_2O and thus are not affected by its activity. The invariant point defined by these reactions is shown on Fig. 7A. The discrepancy in recorded pressures between NS-030 (460 MPa) and NS-032 (250 MPa) suggests that either muscovite is not in equilibrium with biotite and cordierite in NS-032 (and the recorded pressure is spurious) or that the higher pressures recorded by multiple invariant points in NS-030 are real and the result of an increase in pressure associated with the intrusion (forceful intrusion).

Only temperature could be determined for 3 samples, as shown for samples DM-14 (Fig. 7C), RR-202 (Fig. 7D), and NS-026 (Fig. 8).

Results - Regional Metamorphism, Glen Tosh Formation

The bulk compositions of many of the rocks in the Glen Tosh formation do not generally lend themselves to the development of abundant metamorphic indicator minerals. However, detailed sampling permitted the location of sufficiently low-variance mineral assemblages to provide geothermobarometric analysis. Two samples of the Glen Tosh formation from outside the contact aureole with the dioritic rocks, DM-14 and RR-202 (Fig. 2), provide only maximum temperatures (Fig. 7C & 7D). These rocks likely document the conditions of regional metamorphism as they are remote from the contact, lack cordierite, and have maintained a foliation. Garnet is present in both these samples, so the garnet-biotite ion-exchange reaction (Ferry and Spear 1978) was used to determine the maximum temperature conditions of regional metamorphism. Sample DM-14, approximately 2 km from the exposed contact, contains quartz-plagioclase-K-feldspar-biotite-garnet. The resulting Fe-Mg exchange reaction between biotite and garnet (Fig.

7C) yields a temperature of 595°C, assuming a pressure of 300 MPa. Sample RR-202 contains quartz–plagioclase–muscovite–biotite–garnet–ilmenite, and also produced a reaction line from the Fe–Mg exchange between biotite and garnet (Fig. 6D), with a similar maximum temperature of 585°C, assuming a pressure of 300 MPa. These temperatures are consistent with results obtained for the Kellys Mountain Gneiss by Jamieson (1984) who established temperatures that range from 580 to 700°C and pressures that range from 100 to 350 MPa.

Contact Metamorphism, Eastern Glen Tosh formation.

Two hornfelsed samples from within 300 m of contact with the dioritic rocks, NS-030 and NS-032 (Fig. 2), were analyzed. Sample NS-030, <50 m from the contact, contains the assemblage quartz–plagioclase–K-feldspar–biotite–muscovite–cordierite–sillimanite–spinel, which defines 10 different mineral reactions that all meet at the same invariant point. The reactions are overdetermined (two sets of linearly dependent reactions) and the fact that all the reactions meet at a single invariant point within the stability field of sillimanite provides a robust determination of maximum pressure and temperature conditions of contact metamorphism of 460 MPa at 745°C (Fig. 7B).

Sample NS-032 consists of a similar mineral assemblage, but contains andalusite instead of sillimanite, which could indicate either a lower temperature or pressure, or both. The assemblage defines three reactions, the positions of which were established from TWQ, yielding a pressure of 250 MPa and a temperature of only 365°C (Fig. 7A).

Regional Metamorphism, Kellys Mountain Gneiss

For comparison, a maximum regional metamorphic temperature was established from sample NS-026, from the Kellys Mountain Gneiss. The mineral assemblage of quartz–plagioclase–K-feldspar–muscovite–biotite–cordierite–ilmenite allows the use of a cordierite–biotite exchange reaction, yielding a temperature of 715°C (Fig. 8), assuming a pressure of approximately 300 MPa. This temperature is slightly higher than the range established by Jamieson (1984) of 580–700°C, but is within the probable error of $\pm 25^\circ$.

U/Pb Monazite Dating

Methodology

Monazite was dated in polished thin sections using a Resonetics RESolution™ Series M-50-LR 193nm excimer laser ablation system coupled with an Agilent 7700x quadrupole ICP-MS equipped with dual external rotary pumps. A crater size of 13 μm , 3 Hz repetition rate, $\sim 2 \text{ J/cm}^2$ fluence, 30 second ablation time following 30 seconds of background collection was used. Ablation sequences comprised at least 15 well-characterized U-Pb age standards (GSC-8153 monazite) that were distributed so as to bracket blocks of 3 to 5 unknowns. Additional standards (e.g., 44069 monazite) were also included and used to check the accuracy of the method. Ablated aerosols were carried out of the Laurin Technic two-volume sample cell using pure He at a flow rate of 750 mL/min. This was mixed with 650 mL/min of Ar carrier gas and 2.8 mL/min N_2 which is used to enhance ionization efficiency in the ICP-MS plasma. Before entering the ICP-MS torch, the combined gas stream passes through a smoothing device (Laurin Technic ‘squid’). The Agilent 7700x ICP-MS was operated at an RF power of 1450W with ion lenses tuned to obtain $<0.3\%$ ThO^+/Th and $\text{U}^+/\text{Th}^+ \sim 1.05$ as measured on NIST610

reference glasses. One sweep of the ICP-MS quadrupole comprised a rapid (0.01 sec) measurement of a guide mass (e.g., ^{31}P for monazite) followed by ^{204}Pb (0.08 sec), ^{206}Pb (0.03 sec), ^{207}Pb (0.07 sec), ^{208}Pb (0.01 sec), ^{232}Th (0.01 sec), and ^{238}U (0.02 sec). This gave a total measurement time of ~0.25 seconds per sweep or ~120 measurements per 30 second ablation. The ICP-MS datafile (data as counts/sec) and laser sequence log file were combined offline in Iolite v. 2.5 and ages calculated using the VizualAge U-Pb geochronology data reduction scheme described by Petrus et al., (2011). Additional details concerning the technique used are provided in McFarlane (2015).

Results

Monazite was analyzed in sample NS-030, from within 50 m of the contact with the Kellys Mountain dioritic rocks. This rock exhibits a hornfelsic texture in hand specimen, and is completely recrystallized in thin section, with a well-developed fine-grained triple point fabric among quartz and feldspars and no relict foliation. It is compositionally layered, with a dominant quartz–plagioclase–K-feldspar–biotite–muscovite–sillimanite assemblage and subordinate plagioclase–cordierite–ilmenite–spinel domains. Monazite occurs in both domains, but is larger, up to 100 μm across, and idioblastic in the latter domain, where it was analyzed. No zoning in the monazite was detected optically.

The results of in-situ U-Pb monazite dating are given in Table 3. Common Pb is less than 2% of total Pb analyses in most cases. Four analyses identified in Table 3 comprise a cluster of concordant overlapping ellipses and yield the youngest near-concordant data (Fig. 9). The blue ellipse, which yields an age of 480.9 ± 3.7 Ma,

represents the weighted mean error ellipse for the population and is taken as the best estimate of the timing of monazite (re)crystallization.

The age of regional metamorphism in Kellys Mountain has previously been determined as 515 ± 1 Ma (Keppie *et al.* 1998) in the Kellys Mountain Gneiss. The co-magmatic granitic and dioritic rocks then intruded at 498 ± 2 Ma (Barr *et al.* 1990), followed by rapid exhumation of plutonic rocks and gneiss through the closure temperatures of titanite (U/Pb) and hornblende ($^{40}\text{Ar}/^{39}\text{Ar}$) at 496 ± 5 Ma and 495.8 ± 2.8 Ma respectively (Keppie and Dallmeyer 1989, Keppie *et al.* 1998). The monazite crystallization age of 481 ± 4 Ma (Fig. 9) determined for sample NS-030 in this study using *in-situ* U-Pb methods indicates that plutonism must have continued for another 15 m.y., which is compatible with the observation that several plutons have been mapped in this area. This younger age is presumably restricted to the contact aureole in the Glen Tosh formation.

Discussion

Conditions of regional and contact metamorphism

Regional metamorphism in the study area ranges from biotite grade phyllite through andalusite and cordierite-bearing phyllite and metamorphosed quartz wacke, to sillimanite-cordierite gneiss in the Kellys Mountain block. Previously, it was thought that these comprised two separate regional metamorphic events (Barr *et al.* 1995), but the results of this study and a parallel investigation by Barr *et al.* (2013) now call this interpretation into question. Superimposed on the low-grade regional metamorphism of the Glen Tosh formation is a narrow metamorphic contact aureole located west of the

Kellys Mountain diorite intrusion. The rocks of the contact metamorphic zone contain sillimanite and cordierite, indicating higher temperatures of metamorphism compared to the regional metamorphism of the Glen Tosh formation.

The Glen Tosh formation is a regional low-grade metamorphic unit typical of the Bras d'Or terrane that underwent low-grade low-pressure, high-heat flow metamorphism prior to undergoing contact metamorphism at 480.9 ± 3.7 Ma. Multi-equilibrium calculations derived from TWQ have yielded metamorphic pressures in the range of 250 to 460 MPa and temperatures that range from 365 to 760°C, which are compatible with the observed mineral assemblages. The progressive appearance of andalusite, sillimanite and cordierite in samples with hornfelsic texture closer to the contact supports the conclusion that these rocks underwent a superimposed contact metamorphism. The visible effects of neocrystallization and hornfels development extend up to 300 m from the plutonic contacts, suggesting a steep contact.

The estimated pressure of 250 MPa indicates that the plutons of Kellys Mountain intruded at depths of 9-10 km below the surface. Although the two plutonic units of Kellys Mountain most likely intruded at similar times, based on field observations, temperatures up to 590°C in the hornfelsed aureole indicate that the hotter Kellys Mountain diorite and not the Kellys Mountain Granite were likely the principal agent of contact metamorphism.

The much higher pressure of 460 MPa and temperature of 745°C from a rock immediately adjacent to the contact with the diorite is anomalous, being higher than any other P–T conditions determined in Kellys Mountain. These conditions result from calculations involving two separate invariant systems (Fig. 7B), and hence we conclude

that they are robust, and indicate that the rocks closest to the contact have been exhumed from greater depths, possibly implying forcible intrusion of the diorite.

Kellys Mountain Gneiss Comparison

Regionally metamorphosed rocks in the Kellys Mountain Gneiss have a similar mineral assemblage to the Glen Tosh formation. At the highest grade, both andalusite and sillimanite have been reported in a sample of cordierite migmatite (Jamieson 1984). Calculated temperatures range from 580 to 715°C at pressures ranging from 100 to 350 MPa, which overlap the range of pressure and temperature conditions seen in the contact metamorphism in the Glen Tosh formation, but exceed the temperatures recorded by the regional metamorphism of the Glen Tosh formation.

Barr *et al.* (2013) compared the whole-rock and Nd isotopic compositions of the Glen Tosh formation and the Kellys Mountain Gneiss and established that they are geochemically and isotopically similar. Furthermore, Barr *et al.* (2013) provided rare-earth element distribution patterns that are identical for the two units, and concluded that the Glen Tosh formation and the Kellys Mountain Gneiss are of the same protolith and may have been affected by the same regional metamorphic history. If the Kellys Mountain Gneiss is correlated with the Glen Tosh formation, as suggested by Barr *et al.* (2013), regional metamorphic grade must increase from the southwest to northeast along Kellys Mountain.

Dating of the Kellys Mountain Gneiss has previously established ages of 515 ± 1 Ma (U-Pb in monazite, Keppie *et al.* 1998) and 496 ± 5 Ma (U-Pb in titanite, Dunning *et al.* 1990) and several $^{40}\text{Ar}/^{39}\text{Ar}$ ages ranging from 498 ± 3.5 to 493 ± 1.5 Ma (Reynolds *et*

al. 1989; Keppie and Dallmeyer 1989) (Fig. 2). The older 515 Ma monazite age was interpreted by Keppie *et al.* (1998) to be the result of heating of earlier metamorphosed rocks, not themselves dated on Kellys Mountain, by the intrusion of the Kellys Mountain Granite. The titanite age aligns with various $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages. This study provides the youngest age, 480 ± 3.7 Ma, from the rocks of the contact metamorphic aureole, which suggests that the pluton that formed the contact aureole is younger still.

Tectonic Implications

This investigation of the petrology, geothermobarometry and isotopic dating of the Kellys Mountain Gneiss and Glen Tosh formation shows that they could have initially undergone a regional, low-pressure, high-heat flow regional metamorphic event at the same time.

Low-pressure regional metamorphism, like that preserved in the Kellys Mountain Gneiss and the Glen Tosh formation, can develop in several tectonic environments: (i) crustal thickening (Looseveld and Etheridge 1990, Sandiford and Powell 1991), (ii) high-heat flow metamorphism (De Yoreo *et al.* 1991) (iii) rifting and associate magma upwelling (De Yoreo *et al.* 1991), and (iv) low-angle extension core complex with mantle upwelling (Wernicke 1985).

A continental collision zone and associated crustal thickening can produce heat derived from the greater thickness of continental crust with its higher radioactive element content, and is commonly associated with S-type plutonism (Looseveld and Etheridge 1990, Sandiford and Powell 1991), such as the Kellys Mountain Granite. Above a subduction zone calc-alkaline plutons of the same age as the metamorphism would be

expected to be present (De Yoreo *et al.* 1991), and this is the case for the calc-alkaline plutons in Kellys Mountain (Fig. 2; Keppie and Dallmeyer 1989, Barr *et al.* 1990) and the extensive suite of supra-subduction zone plutons north of Kellys Mountain in the Cape Breton Highlands.

The other proposed mechanisms for high-heat flow metamorphism are less likely in Kellys Mountain. Rift-related metamorphism from crustal thinning and magmatic upwelling (De Yoreo *et al.* 1991) or Wernicke-type metamorphic core complex development (Wernicke 1985) would likely be accompanied by extension, such as graben development and associated faulting, not recognised in the Bras d'Or terrane.

Hence we conclude that a collision zone and associated crustal thickening occurring above an island arc or continental margin subduction zone is the most plausible setting for the metamorphic events that occurred at Kellys Mountain. Plutons of similar ages as the metamorphism are present (Fig. 2) and the protolith of the metapsammite of the Glen Tosh formation (quartz-wacke), a lithology likely incorporated into a subduction zone complex prior to undergoing metamorphism, is representative of the accretionary prism of an subduction zone. Low-pressure regional metamorphism is a result of crustal thickening and is also seen in extensions of the Bras d'Or terrane in the Grey River Gneiss, Newfoundland (Raeside and Barr 1990), and the Brookville terrane of southern New Brunswick (White and Barr 1996).

Following the period of high-heat flow metamorphism, emplacement of the Kellys Mountain Granite and the Kellys Mountain dioritic rocks caused contact metamorphism, overprinting the regional metamorphism. Calculated conditions of metamorphism of 250 MPa and temperatures up to 590°C at 480.9 ± 3.7 Ma imply that

the plutons intruded at about 9 km depth. Higher calculated pressure conditions immediately adjacent to the pluton contact imply forcible intrusion and uplift of rocks from deeper levels in the crust.

Comparison of metamorphic units within the Bras d'Or terrane

The Bras d'Or terrane contains numerous other metamorphic units including the Lime Hill Gneissic Complex, Skye Mountain Metamorphic Suite and the Frenchvale Road Metamorphic Suite, all of which have been included with the Kellys Mountain Gneiss as the Bras d'Or Metamorphic Suite (Raeside and Barr 1990, White et al. 2016) (Fig. 1). Metamorphic conditions in these units range from a pressure less than 400 MPa at over 650°C (Lime Hill Gneiss: Raeside 1990) to 280 MPa at 580°C (Frenchvale Road Metamorphic Suite: Walker 1988) and to 200 to 350 MPa at 525 to 650°C (Whycocomagh Mountain Gneiss: Armitage 1989, Swanton *et al.* 2010).

Other metamorphic units of the Bras d'Or terrane include the generally low-grade components of the George River Metamorphic Suite, which typically display greenschist-facies metamorphic assemblages. Only where they extend north into the Cape Breton Highlands do they display amphibolite-facies metamorphism.

Metamorphism in the Glen Tosh formation, as a component of the George River Metamorphic Suite, and the Kellys Mountain Gneiss, as a component of the Bras d'Or Metamorphic Suite, is characteristic of the broader area of the Bras d'Or terrane. Both units underwent relatively low-pressure regional metamorphic events, however, in Kellys Mountain the intrusion of supra-subduction zone plutonic rocks resulted in continued

high-heat flow metamorphism in the higher grade units and the last pulse of metamorphism was limited to contact metamorphic effects in lower grade rocks.

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Table Captions

Table 1. List of mineral assemblages $\pm$ zircon, monazite and xenotime for relevant samples. x = present, 1 = prograde, 2 = retrograde, h = hematite, i = ilmenite, m = magnetite, c = chloritized, p = pinitized.

Table 2. Electron microprobe analyses of co-existing minerals for various samples that were subsequently input into TWQ.

Table 3. Isotope data acquired to calculate ages of monazite using a laser ablation ICP-MS. The four bolded rows represent data used to calculate the Concordia age, which correspond to the black ellipses in Fig. 9. It should be noted that the symbol * represents analyses where xenotime was possibly measured rather than monazite based on the Nd and U contents.

Figure Captions

Fig. 1. Regional geology of the Bras d'Or terrane, Cape Breton Island where the location is given relative to Nova Scotia. Red box indicates location of Kellys Mountain.

Modified from Barr *et al.* (2013). Abbreviations: BBF = Blues Brook Formation, BF = Benacadie Brook Formation, BRMS = Barachois River Metamorphic Suite, FRMS = Frenchvale Road Metamorphic Suite, GTf = Glen Tosh formation, KMG = Kellys Mountain Gneiss, LHGC = Lime Hill Gneissic Complex, MFF = McMillan Flowage Formation, MF = Malagawatch Formation, SMMS = Skye Mountain Metamorphic Suite. Inset: location of Cape Breton Island in the northern Appalachian orogen.

Fig. 2. The geology of Kellys Mountain and Big Hill, Cape Breton Island, Nova Scotia, with locations of previous dating work and U/Pb monazite dating of this study. Modified from Barr *et al.* (2013). The Glen Tosh formation (grey) extends from the western end of Kellys Mountain into Big Hill and north into the southern Cape Breton Highlands. Samples found in the area shown on the map have undergone electron microprobe analysis. Modified from Barr *et al.* (2013).

Fig. 3. Photomicrographs of psammitic and pelitic rocks of the Glen Tosh formation. A) Sample NS-034, ca. 1 km from contact, showing well-developed foliation, and large altered cordierite clusters (Crd). B) Sample NS-030 from adjacent to the contact showing the same lithology as in a), recrystallized as hornfels. Cordierite is visible as altered grains of moderate relief in the lower left. C) Sample NS-030 showing sillimanite (Sil) interlocking between quartz grains. D) Sample NS-032 showing biotite overgrowing

andalusite (And). Scale bars in a-c are 200 μm , in d 100 μm .

Fig. 4. Field photographs of outcrops found at Kellys Mountain. A) Contact between meta-quartz wacke of the Glen Tosh formation and dioritic rocks along the Great Bras d'Or shoreline. B) Photograph taken by S.M. Barr of the Kellys Mountain Granite (pink) cross-cutting the Kellys Mountain dioritic rocks (grey). Outcrop is approximately 5 metres high.

Fig. 5. Backscatter electron images. A, cordierite in a recrystallized matrix of plagioclase and ilmenite, sample NS-030. B, garnet in a matrix of foliated biotite, muscovite and quartz and feldspar in sample RR-202.

Fig. 6. Phase diagram of KFMASH system, $a_{\text{H}_2\text{O}} = 1$. Modified from Pattison and Harte (1985), $a_{\text{H}_2\text{O}} = 1$. Numbered reactions correlate to reactions given in text.

Fig. 7. Pressure and temperature conditions of the Glen Tosh formation. A) TWQ results for sample NS-032 providing pressures of 250 MPa and temperatures of 365°C. B) TWQ results for sample NS-030 providing pressures of 460 MPa and temperatures of 745°C. C) TWQ results for sample DM-14 providing a maximum temperature of 595°C. D) TWQ results for sample RR-202 providing a maximum temperature of 585°C.

Fig. 8. TWQ results for Kellys Mountain Gneiss sample NS-026 providing a maximum temperature of 715°C.

846

847 **Fig. 9.** U/Pb monazite dating results of sample NS-030. The blue ellipse is the concordia
848 age of the weighted mean of the data points based on the four black ellipses.

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Sample #	UTM coordinates	Lithology	Qz	Pl	Kfs	Bt	Ms	Crd	Grt	And	Sil	Opq	Tur	Ep	Ser	Chl
NS-026	690477, 5125013	Paragneiss	x	x	x	x	1 2	x	x			x i	x		2	2
NS-028	687546, 5117892	Meta-psammite	x	x	x	x	1	x				x i m	x			
NS-030	687596, 5117831	Meta-psammite	x	x	x	x	1 2	x	c		x	x i m	x			2
NS-032	687598, 5117587	Meta-psammite	x	x	x	x	1 2	x		x		x i m	x			
NS-034	687342, 5117287	Meta-psammite	x	x		x	2	p				x i h	x			2
RR86-202	687755, 5117349	Meta-psammite	x	x		x	1 2	x	x			x i m				
DM91-14	684371, 5114745	Meta-psammite	x	x	x	x	1		x			x i m		x	2	2
DM91-32	686376, 5115414	Meta-psammite	x	x	x	x	2	p		x		x i	x	x	2	

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Sample	NS-026					NS-030					NS-032	
Rock Type	Kellys Mountain Gneiss					Meta-psammite of the Glen Tosh fm					Meta-psam	
Mineral	Pl	Kfs	Bt	Crd	Ilm	Pl	Kfs	Bt	Ms	Crd	Pl	
SiO ₂	61.11	64.11	35.37	48.08	0.10	60.65	63.78	36.29	46.61	47.77	57.43	
TiO ₂	0.00	0.00	2.98	0.01	44.55	0.00	0.04	3.61	0.00	0.00	0.00	
Al ₂ O ₃	23.67	18.50	18.43	32.44	0.01	23.93	18.15	18.50	31.32	32.71	25.69	
FeO	0.01	0.01	19.29	7.27	48.12	0.11	0.22	17.66	3.65	6.53	0.33	
MnO	0.00	0.00	0.23	0.68	3.88	0.01	0.05	0.33	0.00	0.55	0.00	
MgO	0.00	0.00	8.93	8.18	0.08	0.00	0.02	10.16	1.17	9.08	0.00	
CaO	5.48	0.01	0.03	0.03	0.07	6.11	0.07	0.02	0.00	0.03	7.98	
Na ₂ O	8.36	0.59	0.28	0.35	0.03	8.25	0.57	0.32	0.14	0.28	6.99	
K ₂ O	0.40	15.87	9.72	0.02	0.05	0.21	15.74	9.69	10.56	0.01	0.15	
BaO	—	0.58	—	—	—	—	0.37	—	—	—	—	
Total	99.03	99.66	95.26	97.05	96.87	99.27	99.00	96.57	93.44	96.96	98.56	
Number of cations in formula based on n oxygen anions												
n	8	8	11	18	3	8	8	11	11	18	8	
Si	2.74	2.98	2.70	5.01	0.00	2.72	2.99	2.71	3.20	4.97	2.61	
Ti	0.00	0.00	0.17	0.00	0.91	0.00	0.00	0.20	0.00	0.00	0.00	
Al	1.25	1.01	—	—	0.00	1.26	1.00	—	—	—	1.38	
Al ^{IV}	—	—	1.30	0.99	—	—	—	1.29	0.80	1.03	—	
Al ^{VI}	—	—	0.36	2.99	—	—	—	0.33	1.73	2.97	—	
Fe	0.00	0.00	1.23	0.63	1.09	0.00	0.01	1.10	0.21	0.57	0.01	
Mn	0.00	0.00	0.02	0.06	0.09	0.00	0.00	0.02	0.00	0.05	0.00	
Mg	0.00	0.00	1.02	1.27	0.00	0.00	0.00	1.13	0.12	1.41	0.00	
Ca	0.26	0.00	0.00	0.00	0.00	0.29	0.00	0.00	0.00	0.00	0.39	
Na	0.73	0.05	0.04	0.07	0.00	0.72	0.05	0.05	0.02	0.06	0.62	
K	0.02	0.94	0.95	0.00	0.00	0.01	0.94	0.92	0.92	0.00	0.01	
Ba	—	0.01	—	—	—	—	0.01	—	—	—	—	
Fe/(Fe+Mg)	—	—	0.55	—	—	—	—	0.49	—	—	—	
Na/(Na+K + Ca)	—	—	—	—	—	—	—	—	0.02	—	—	
Mg/(Mg+Fe)	—	—	—	0.67	—	—	—	—	—	0.71	—	
(Fe+Mn)/(Fe+Ti+Mn)	—	—	—	—	0.57	—	—	—	—	—	—	
	X _{Ca} = 0.26	X _{Ca} = 0.00				X _{Ca} = 0.29	X _{Ca} = 0.00				X _{Ca} = 0.38	
	X _{Na} = 0.72	X _{Na} = 0.05				X _{Na} = 0.70	X _{Na} = 0.05				X _{Na} = 0.61	
	X _K = 0.02	X _K = 0.95				X _K = 0.01	X _K = 0.94				X _K = 0.01	

mite of the Glen Tosh fm				RR86-202 Meta-psammite of the Glen Tosh fm					DM91-14 Meta-psammite of the Glen Tosh fm			
Kfs	Bt	Ms	Crđ	Pl	Bt	Ms	Grt	Ilm	Pl	Kfs	Bt	Grt
64.06	35.40	46.55	47.70	61.64	35.01	45.81	37.28	0.23	61.57	63.12	35.77	37.54
0.00	2.58	0.00	0.00	0.00	1.55	0.17	0.12	50.49	0.00	0.00	1.36	0.05
17.98	18.71	31.78	32.55	23.07	18.73	33.64	20.98	0.05	22.77	18.67	17.23	20.69
0.01	18.49	3.55	8.65	0.20	17.65	2.53	23.61	37.18	0.00	0.00	14.30	16.29
0.00	0.23	0.00	0.58	0.00	0.21	0.00	12.38	8.04	0.00	0.00	0.39	16.82
0.02	8.89	0.61	7.47	0.00	10.81	0.69	2.51	0.03	0.00	0.00	13.31	2.45
0.00	0.01	0.00	0.01	4.85	0.00	0.00	2.27	0.12	4.87	0.24	0.01	4.89
0.60	0.21	0.16	0.18	8.84	0.09	1.20	0.03	0.02	8.71	0.10	0.08	0.02
15.34	9.70	10.10	0.01	0.06	9.50	9.45	0.01	0.04	0.11	0.30	9.06	0.03
0.00	—	—	—	—	—	—	—	—	—	15.62	—	—
98.00	94.23	92.75	97.15	98.66	93.55	93.48	99.19	96.21	98.02	98.05	91.50	98.78
8	11	11	18	8	11	11	18	3	8	8	11	18
3.01	2.72	3.21	4.99	2.77	2.70	3.12	3.02	0.01	2.65	2.98	2.77	3.03
0.00	0.15	0.00	0.00	0.00	0.09	0.01	0.01	0.99	0.01	0.00	0.08	0.00
1.00	—	—	—	1.22	—	—	2.00	0.00	1.31	1.04	—	1.97
—	1.28	0.79	1.01	—	1.30	0.87	—	—	—	—	1.23	—
—	0.42	1.78	3.01	—	0.40	1.82	—	—	—	—	0.34	—
0.00	1.19	0.20	0.76	0.01	1.14	0.14	1.60	0.81	0.01	0.00	0.93	1.10
0.00	0.02	0.00	0.05	0.00	0.01	0.00	0.85	0.18	0.01	0.00	0.03	1.15
0.00	1.02	0.06	1.17	0.00	1.24	0.07	0.30	0.00	0.02	0.00	1.54	0.30
0.00	0.00	0.00	0.00	0.23	0.00	0.00	0.20	0.00	0.33	0.00	0.00	0.42
0.05	0.03	0.02	0.04	0.77	0.01	0.16	0.00	0.00	0.69	0.01	0.01	0.00
0.92	0.95	0.89	0.00	0.00	0.93	0.82	0.00	0.00	0.03	0.03	0.89	0.00
0.00	—	—	—	—	—	—	—	—	—	0.94	—	—
—	0.54	—	—	—	0.48	—	—	—	—	—	0.38	—
—	—	0.02	—	—	—	0.16	—	—	—	—	—	—
—	—	—	0.61	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	0.50	—	—	—	—
X _{Ca} = 0.00				X _{Ca} = 0.23			X _{Alm} = 0.54		X _{Ca} = 0.23	X _{Ca} = 0.01		X _{Alm} = 0.37
X _{Na} = 0.06				X _{Na} = 0.76			X _{Sps} = 0.29		X _{Na} = 0.76	X _{Na} = 0.03		X _{Sps} = 0.39
X _K = 0.94				X _K = 0.00			X _{Prp} = 0.10		X _K = 0.01	X _K = 0.97		X _{Prp} = 0.10
							X _{Grs} = 0.07					X _{Grs} = 0.14

Sample #	Analysis #	Approximate concentrations (ppm)				$^{204}\text{PbCps}$	2σ int	$^{206}\text{Pbcps}/^{204}\text{PbCps}$	%Pb*
		Nd	U	Th	U/Th				
NS-030	Mz-1	140700	863	55300	0.02	17	18	724	99.23
NS-030	Mz-2*	710	14700	11800	1.25	15	16	150	99.97
NS-030	Mz-3	145500	2084	50000	0.04	19	19	1225	98.01
NS-030	Mz-4	136800	1043	53200	0.02	-1	12	-13120	98.98
NS-030	Mz-5	132900	2940	45800	0.06	32	17	219	92.40
NS-030	Mz-6a*	5680	2639	2031	1.30	-9	15	-3403	99.61
NS-030	Mz-6b*	3770	13140	583	22.54	2	14	75500	99.96
NS-030	Mz-7	143000	2967	54800	0.05	4	18	8535	98.97
NS-030	Mz-9	138100	1213	65600	0.02	2	15	7485	99.06
NS-030	Mz-12	131000	1560	43800	0.04	-2	15	-10100	98.68

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Final isotope ratios							Ages (Ma)		
²⁰⁷ Pb/ ²³⁵ U	2σ	²⁰⁶ Pb/ ²³⁸ U	2σ	err. corr.	²⁰⁷ Pb/ ²⁰⁶ Pb	2σ	²⁰⁷ Pb/ ²³⁵ U	2σ	²⁰⁶ Pb/ ²³⁸ U
0.845	0.056	0.099	0.004	0.45	0.0607	0.0035	622	30	606
1.080	0.140	0.130	0.006	0.31	0.0608	0.0074	752	64	790
0.714	0.036	0.079	0.002	0.47	0.0649	0.0029	549	22	492
0.705	0.030	0.087	0.002	0.28	0.0570	0.0022	539	18	538
0.453	0.019	0.069	0.002	0.00	0.0470	0.0010	379	13	430
0.610	0.020	0.078	0.001	0.31	0.0547	0.0018	483	13	482
0.596	0.011	0.076	0.001	0.61	0.0559	0.0009	475	7	474
0.604	0.019	0.077	0.002	0.37	0.0568	0.0016	479	12	479
0.628	0.027	0.079	0.002	0.10	0.0560	0.0023	497	17	492
0.696	0.032	0.086	0.002	0.24	0.0577	0.0027	537	19	530

2σ	% conc
22	97.4
32	105.1
10	89.6
11	99.8
14	113.5
7	99.7
7	99.7
9	99.9
9	99.0
10	98.8

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