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Critical review N. Wodicka

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New constraints on the tectonothermal history of Southampton Island, Nunavut, provided by in situ SHRIMP geochronology and thermobarometry

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Abstract: Thermobarometry and in situ SHRIMP monazite geochronology reveal a complex, polycyclic history for Southampton Island, Nunavut. Two cryptic metamorphic events have been recognized at ca. 2.6 Ga (M_1) and 2.3 Ga (M_2) followed by four Paleoproterozoic events, some accompanied by deformation. Two samples on the western side of the study area record M_3 - D_1 at 1879 ± 7 Ma and 1879 ± 8 Ma. Four samples constrain M_4 - D_2 between 1861 ± 12 Ma and 1848 ± 6 Ma, with M_4 continuing to 1841 ± 4 Ma. Four samples also record a post- D_2 , M_5 event between 1826 ± 9 Ma and 1815 ± 7 Ma, interpreted to represent a thermal culmination associated with extensive crustal melting and plutonism. Monazite growth between 1.79 Ga and 1.72 Ga likely reflects fluid ingress during cooling. These new data provide important constraints on the nature and timing of collisional events required to build robust tectonic and metallogenic models.

Résumé : La thermobarométrie et la géochronologie par datation *in situ* de la monazite à la microsonde SHRIMP révèlent une évolution polycyclique complexe de l'île Southampton, au Nunavut. Elles ont permis d'identifier deux épisodes métamorphiques cryptiques vers 2,6 Ga (M_1) et 2,3 Ga (M_2), suivis de quatre épisodes au Paléoprotérozoïque, dont certains accompagnés d'une déformation. Deux échantillons prélevés dans l'ouest de la région à l'étude révèlent un épisode de métamorphisme et de déformation M_3 - D_1 à 1879 ± 7 Ma et à 1879 ± 8 Ma. Quatre échantillons circonscrivent chronologiquement l'épisode de métamorphisme et de déformation M_4 - D_2 entre 1861 ± 12 et 1848 ± 6 Ma, avec un prolongement du métamorphisme M_4 jusqu'à 1841 ± 4 Ma. Quatre échantillons témoignent aussi d'un épisode de métamorphisme M_5 postérieur à la déformation D_2 entre 1826 ± 9 et 1815 ± 7 Ma, lequel, selon notre interprétation, représenterait un pic thermique associé à une fusion crustale à grande échelle et à une activité plutonique. La croissance de la monazite entre 1,79 et 1,72 Ga reflète probablement l'infiltration de fluides au cours du refroidissement. Ces nouvelles données fournissent des valeurs restrictives importantes sur la nature des épisodes de collision et le moment où ils se sont produits, des valeurs nécessaires à l'élaboration de modèles tectoniques et métallogéniques robustes.

INTRODUCTION

Situated within a 400 km wide gap between the mainland western Churchill Province and Baffin Island (Fig. 1), the geology of Southampton Island, Nunavut provides critical insight into the evolution of northeast Laurentia. Metamorphic studies initiated as part of the Southampton Island integrated geoscience project of the Northern Mineral Resources and Development Program constrain tectonic and regional metallogenic models, upon which exploration strategies for diamonds and precious- and base-metals in the area can be based. This report summarizes initial constraints on the pressure, temperature, and timing (P-T-t) of multiple metamorphic and deformation events on Southampton Island.

REGIONAL GEOLOGICAL SETTING

Located near the junction of five crustal blocks (Rae, Hearne, Chesterfield, Meta Incognita, and Sugluk; Fig. 1), the eastern half of Southampton Island exposes a highland of Precambrian rock comprising remnants of Archean psammite and semipelite, a potentially Paleoproterozoic carbonatequartzite cover sequence, and voluminous plutonic rocks ranging from ultramafic (peridotite-dunite) to monzogranitic compositions (Sanborn-Barrie et al., 2008; Chakungal et al., 2008). Uranium-lead crystallization ages reveal extensive Archean (ca. 2.77–2.6 Ga) and Paleoproterozoic (ca. 1.94– 1.82 Ga) magmatic activity (*see* Rayner et al., 2011), with Sm-Nd isotopic data (Whalen et al., 2011), supporting the presence of Meso- to Paleoarchean basement that correlates with Rae crust.



BP = Boothia Peninsula, Cb = Chesterfield block, Cbb = Committee Bay belt, CB = Cumberland Batholith, MI = Meta Incognita microcontinent, Pi = Piling, QM = Queen Maud, S = Sugluk block, STZ = Snowbird tectonic zone, WB = Wathaman Batholith, fz = fault zone.

Figure 1. Regional geology of the Precambrian core of Laurentia flanking Hudson Bay, modified from Berman et al. (2005).

Two penetrative deformational events are recognized in fabrics and structures observed throughout much of the study area. D, involves development of a moderately to steeply inclined, north-trending planar tectonic fabric (S_1) defined by high-grade mineral alignment and/or compositional layering. In metasedimentary rocks, S₁ is defined by aligned sillimanite, whereas orthopyroxene and biotite define S_1 in granodiorite (mangerite). During D_2 , S_1 was strongly reworked into tight, recumbent, west-trending, south-vergent F₂ folds and/or relatively straight panels of gently inclined north- and west-striking S1+S2 transposition foliation. S2 mineral assemblages indicate upper amphibolite- to granulite-facies conditions. Locally, broad, open, northeast-trending upright folds (F_2) of the transposition foliation highlight a nonpenetrative, near-horizontal component of shortening (D_2) .

Quantitative metamorphic and geochronological constraints

In order to clarify the metamorphic evolution of the region, P-T conditions were estimated using the winTWQ software (version 2.35; Berman (2007)) following the methodology summarized by Berman et al. (2005). In order to link P-T conditions to timing constraints, six metasedimentary rock samples were chosen that contained monazite of a size (>10 μ m) suitable for in situ SHRIMP analysis, carried out on 3 mm diameter cores drilled from texturally significant areas of polished thin sections with the methods of Rayner and Stern (2002). A small plug of pre-polished laboratory standard monazite (GSC monazite z3345 and z2908) was included on the mount. Stern and Berman (2000) described further analytical details. A Pb fractionation correction was applied to the Pb-isotope data in some instances (see Table 2 footnotes), the magnitude of which was determined by the analysis of monazite standards z3345 and z2908 the 207Pb/206Pb ages of which have been determined by isotope dilution methods (Stern and Berman, 2000). The error associated with the mass fractionation correction has been added quadratically to the isotopic ratios when calculating weighted mean ages. Common Pb correction utilized the Pb composition of the surface blank (Stern, 1997).

Table 1 summarizes thermobarometric and geochronological results for six, widely distributed samples (Fig. 2). Table 2 provides SHRIMP analytical data for monazite. Errors of mean ages and Concordia diagram ellipses are reported at 2σ . The geological context, textural relationships, thermobarometric data, and geochronological results for these six samples are presented below.

Sample 69HF-154a (GSC lab #8692)

Sample 69HF-154a is an archival sample from northern Southampton Island collected during reconnaissance mapping in 1969 (Heywood and Sanford, 1976). It is a garnetsillimanite-biotite paragneiss in which garnet porphyroblasts are enveloped by a strong S_2 foliation defined by matrix biotite, sillimanite, and quartzofeldspathic shape fabric. The rim of one garnet porphyroblast hosts sillimanite inclusions that outline a folded or sheared S_1 fabric at an angle to S_2 (Fig. 3a). Ilmenite, quartz, and a monazite inclusion within the core of this garnet define a weak S_1 fabric that is subparallel to the sillimanite inclusion fabric (Fig. 3a), implying garnet growth during a progression from an early, weak S_1 fabric to a coarser grained S_1 fabric at higher grade. Most garnet porphyroblasts have inclusion-poor cores with syn- S_2 rims (not shown in Fig. 3) that are elongate parallel to S_2 and have overgrown S_2 -aligned sillimanite and quartz inclusions.

Garnet cores are relatively calcic ($X_{Ca} = 0.032-0.045$) compared to syn-S₂ rims ($X_{Ca} = 0.020-0.024$). Both cores and rims have indistinguishable Fe/(Fe+Mg) between 0.71-0.72 and MnO between 0.5 and 0.6 weight per cent, probably indicating diffusive re-equilibration of the garnet core. Plagioclase is uniform in composition ($X_{Ca} = 0.26-0.28$), as is biotite (Fe/(Fe+Mg) = 0.32-0.34). Pressure-temperature conditions of 4.2 kbar and 630°C result from the rim compositions of garnet and biotite separated by quartz, and nearby plagioclase. The more calcic composition of the garnet core indicates its growth at higher pressure than garnet rims.

Five SHRIMP analyses of two monazite inclusions in the core of the garnet porphyroblast shown in Figure 3a yield a weighted mean ²⁰⁷Pb/²⁰⁶Pb age of 1879 \pm 7 Ma (Mean Square of Weighted Deviates (MSWD) = 1.5; Fig. 3b). One of these grains is equant, whereas the other is elongate parallel to several nearby inclusions of ilmenite and quartz that define the early, weak S₁ fabric (Fig. 3a). A distinctly younger weighted mean ²⁰⁷Pb/²⁰⁶Pb age of 1841 \pm 4 Ma (MSWD = 1.0; Fig. 3b) is derived from five analyses of three matrix grains interpreted as post-D₂ on the basis of their equant shapes.

Sample 07CYA-X64a (GSC lab #9477)

Sample 07CYA-X64a is a metaquartzite collected from a panel of calc-silicate-quartzite±semipelite, which was deposited after 2615 ± 23 Ma (Rayner et al., 2011) and, given the lithological association, may represent metasedimentary rocks correlative with Paleoproterozoic cover sequences on the Rae craton (Rainbird et al., 2010). The outcrop contains centimetre-sized porphyroblasts of garnet and cordierite, whereas the analyzed thin section contains the assemblage garnet-biotite-sillimanite-cordierite-K-feldspar-quartzplagioclase-ilmenite. The outer parts of anhedral garnet porphyroblasts, up to 1 cm in diameter, contain a weak fabric (S₁, Fig. 4a, b) defined by the alignment of ilmenite, monazite, and sillimanite needles within one monazite inclusion (#241, inset of Fig. 4b). This internal S, foliation is at a high angle to the main (S_2) foliation, defined by elongate quartz and feldspar grains, that envelops the garnet (Fig. 4a).



Figure 2. Simplified geology of Southampton Island (Sanborn-Barrie et al., 2008), with abbreviated sample numbers.

				P-T es	timates1	
Sample #	Lithology	Age ± 2σ	Event	T (°C)	P(kbar)	Monazite textures
69HF-154a	Metapelite	1879 ± 7	M_3-D_1			S ₁ garnet inclusions
		1841 ± 4	M_4	630 [∟]	4.2 [∟]	late M_4 , post- D_2 ; equant matrix grains
07CYA-X64a	Metaquartzite	1879 ± 8	M_3-D_1			S ₁ garnet inclusions
		1815 ± 7	M ₅	755	7.4	post-D ₂ , equant matrix grain
		1790–1750	M ₆			
					-	
07CYA-A18a	Metasemipelite	1849 ± 6	M_4 - D_2	755	7.0	S_2 matrix grains and garnet inclusion
				655 ^P	6.6 ^P	
07CYA-M5	Metapelite	1866 ± 18	M_4-D_2			Garnet inclusion
		1826 ± 9	M ₅			post- D_2 , irregular matrix grains
07CYA-M92	Metasemipelite	1861 ± 12	M ₄ -D ₂			S_2 matrix grain and garnet inclusion
		1820 ± 7	M ₅	720	6.4	post- D_2 , equant matrix grains
					-	
07CYA-A29	Metasemipelite	1816 ± 10	M ₅	790	7.7	post-D ₂ , matrix grains and garnet inclusions
		1721 ± 36	M ₆			
Errors are report M ₁ , M ₂ based of ¹ near-peak P-1	orted at the 2σ unc on monazite ages f Γ conditions, excep	ertainty level. rom an S-type ot for: L = late.	granite (E post-D, b	Berman e ased on i	et al., unput monazite te	b. data, 2010; Rayner et al., 2011). extures. $P = prograde: note that$

Table 1. Summary SHRIMP U-Pb in situ monazite ages and pressure-temperature conditions.

 M_1 , M_2 based on monazite ages from an S-type granite (Berman et al., unpub. data, 2010; Rayner et al., 2011). ¹near-peak P-T conditions, except for: L = late, post-D₂ based on monazite textures, P = prograde; note that rims of garnet and matrix phases are assumed to have equilibrated during the last main monazite growth event recorded by each sample.

Garnet has a relatively uniform core composition, with X_{Ca} between 0.06–0.07, Fe/(Fe+Mg) = 0.69–0.72, and MnO decreasing slightly from 2.0 to 1.2 weight per cent toward the rim. The outer 50 µm of the garnet rim touching matrix K-feldspar has higher Fe/(Fe+Mg) up to 0.83, and lower X_{Ca} down to 0.033. This less calcic rim region has constant MnO (1.2 weight per cent) except for the extreme garnet rim (MnO = 2.0 weight per cent), indicating minor garnet resorption (e.g. Kohn and Spear, 2000).

Plagioclase forms mostly unzoned matrix grains $(X_{An} = 0.24-0.26)$, although one matrix grain has a more sodic core ($X_{\Delta n} = 0.18 - 0.21$). More calcic ($X_{\Delta n} = 0.30 - 0.38$) plagioclase also forms about 20 µm wide discontinuous rims on quartz inclusions in garnet, with less calcic compositions generally in contact with garnet. The occurrence of plagioclase solely as rims between quartz inclusions and garnet indicates that plagioclase formed from garnet breakdown in the presence of a fluid which removed ferromagnesium components (no biotite is present in these inclusions). One 30 µm wide plagioclase inclusion in the garnet core has $X_{An} = 0.35-0.42$. In regions around plagioclase internal to garnet, garnet composition decreases from typical core X_{Ca} values to $X_{Ca} = 0.030$ (with Fe/(Fe+Mg) remaining low (0.69–0.70)). This decrease in X_{Ca} in garnet is also consistent with garnet breakdown to form plagioclase. Matrix biotite is unzoned with Fe/(Fe+Mg) = 0.49-0.51 and TiO_2 equals about 4 weight per cent. Biotite inclusions in garnet have low TiO_2 (2.6–3.2 weight per cent) and lower Fe/ (Fe+Mg), ranging from 0.32 in contact with garnet to 0.35 in contact with quartz.

Pressure-temperature conditions of 7.4 kbar and 755°C were calculated from the rim compositions of garnet and biotite separated by matrix K-feldspar and nearby plagioclase. Cordierite could not be used because it is partially pinitized. The higher pressure conditions of garnet core formation (assumed from its more calcic composition) could not be calculated reliably, since plagioclase within garnet formed late in the history, and biotite within quartz inclusions in garnet appear to have re-equilibrated due to their contact with garnet.

The SHRIMP analyses of three aligned monazite inclusions in garnet (e.g. #241 in Fig. 4b inset) yielded a weighted mean ²⁰⁷Pb/²⁰⁶Pb age of 1879 ± 8 Ma (n = 5, MSWD = 0.42; Fig. 4c). Monazite inclusion #25, forming part of a weak internal fabric in another garnet porphyroblast, yielded an overlapping, but imprecise age (1896 ± 20 Ma, MSWD = 2.0) due to high ²⁰⁴Pb. Six SHRIMP analyses of the near-rim, very low Y region of an equant, matrix grain (#1 in Table 2) yielded a weighted mean ²⁰⁷Pb/²⁰⁶Pb age of 1815 ± 7 Ma (MSWD = 0.92). Two analyses (#1.5 and 1.6) of the higher-Y core of this grain yielded a ca. 1.84 Ga

results.	
monazite	
U-Pb	
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Table 2.	

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Mut 1996 4966 1175 0 0 <th< td=""><td>Mat</td><td>4252</td><td>59976</td><td>14.1</td><td>10281</td><td>55</td><td>2.81E-05</td><td>1.10E-05</td><td>0.0004</td><td>4.0838</td><td>0.0308</td><td>5.012</td><td>0.137</td><td>0.3224 0</td><td>0080 0</td><td>.9464 (</td><td>1127 0</td><td>0.0010 1</td><td>802</td><td>39 18</td><td>21</td><td>3 184</td><td>4</td><td>97</td><td>1</td></th<>	Mat	4252	59976	14.1	10281	55	2.81E-05	1.10E-05	0.0004	4.0838	0.0308	5.012	0.137	0.3224 0	0080 0	.9464 (1127 0	0.0010 1	802	39 18	21	3 184	4	97	1
Mit Tipolog State State <th< td=""><td>Mat</td><td>9495</td><td>49697</td><td>5.2</td><td>11707</td><td>38</td><td>8.86E-06</td><td>8.16E-06</td><td>0.0001</td><td>1.5753</td><td>0.0099</td><td>4.928</td><td>0.098</td><td>0.3186 C</td><td>0061 0</td><td>9798 0</td><td>1122 0</td><td>0.0005 1</td><td>783</td><td>30 18</td><td>07 1</td><td>7 183</td><td>22</td><td>26</td><td>$\overline{\Sigma}$</td></th<>	Mat	9495	49697	5.2	11707	38	8.86E-06	8.16E-06	0.0001	1.5753	0.0099	4.928	0.098	0.3186 C	0061 0	9798 0	1122 0	0.0005 1	783	30 18	07 1	7 183	22	26	$\overline{\Sigma}$
Mit61061	Mat	11589	29883	2.6	9216	43	8.78E-06	2.71E-06	0.0001	0.7508	0.0037	4.507	0.098	0.2973 0	0059 0	.9484 (1100 0	0.0008 1	678	29 17	32 1	8 179	9	60	0
Mint6303176161716107171071	Mat	10847	43076	4.0	10356	28	6.10E-06	3.91E-06	0.0001	1.1658	0.0047	4.468	0.095	0.2913 0	0058 0	0 6096	1112 0	0.0007 1	648	29 17	25 1	8 182	1	6	9.0
Mit 3143 3143 3143 3143 3143 3143 3144 3143 3144 3143 3144 3144 3144 3144 3144 3144 3144 3144 3144 3145 3145 3154 3155 3154	Mat	6340	35175	5.5	8142	123	4.16E-05	6.94E-06	0.0006	1.6275	0.0048	4.911	0.092	0.3258 0	0059 0	.9863	.1093 0	0.0003	818	29 18	04	6 178	89	101	\sim
Girls Tibe Bibit Sint Condition	Mat	3164	31150	9.8	5733	124	8.67E-05	2.09E-05	0.0013	2.8518	0.0183	4.680	0.095	0.3174 0	0061 0	.9645 (.1069 0	0.0006 1	777	30 17	64 1	7 174	8	101	\sim
Girls277663786107638761076377610461280.203461170.20340.1150.001194326189217913Girls277681310181750.00153850.004053850.004054850.01753430.1150.011193220189317101Girls22335210221803011121520023850.004053750.004053750.004053750.004153750.004153750.00113920.001139323232323Girls22336110215724111021572461245600.0046547500.0041547510.0041146510.0041147510.0041 </td <td>Grt-S,</td> <td>1399</td> <td>28614</td> <td>20.5</td> <td>4741</td> <td>481</td> <td>7.61E-04</td> <td>1.19E-04</td> <td>0.0118</td> <td>6.3905</td> <td>0.0457</td> <td>5.159</td> <td>0.1685</td> <td>0.3125 0</td> <td>0079 0</td> <td>.8378</td> <td>.1197 0</td> <td>0.0022</td> <td>753</td> <td>39 18</td> <td>46 2</td> <td>195</td> <td>8</td> <td>80</td> <td>8</td>	Grt-S,	1399	28614	20.5	4741	481	7.61E-04	1.19E-04	0.0118	6.3905	0.0457	5.159	0.1685	0.3125 0	0079 0	.8378	.1197 0	0.0022	753	39 18	46 2	195	8	80	8
Circly2x78will10112x7610112x1610112x161011	Grt-S,	2176	32613	15.0	5487	801	7.70E-04	5.39E-05	0.0119	4.1623	0.0167	5.377	0.1559 (0.3310 0	0087 0	.9434 (.1178 0	0.0011	843	42 18	81 2	5 192	0 1	96	8
Circly2232281228111034130128260.00436.54560.00436.54560.00436.54560.00436.54560.00436.54560.00436.75760.1160.01110150.01110150.01110150.0110.01110150.011<	Grt-S,	2476	48134	19.4	8001	381	3.24E-04	2.36E-05	0.0050	5.6458	0.0234	5.258	0.112	0.3311 0	0066 0	.9678	.1152 0	0.0006	844	32 18	62 1	8 185	33	6	<u>o</u> ;
Girsl 2333 510 233 610 513 610 613 610 613 610 613 610 613 610 613 610 613 610 613 610 613 610 613 610 613 610 613 610 613 610 613 610 613 610 613 610 613 610 613 611 710 611 717 610 713 610 713 610 713 610 713 610 714<	Grt-S,	2224	62422	28.1	10341	301	2.75E-04	3.12E-05	0.0043	8.2645	0.0474	5.465	0.157	0.3433 0	0600.	.9434 (.1155 0	0.0011	902	43 18	95 2	186	1	100	8
Girls, Zass Sinter Sinter <td>Grt-S,</td> <td>2342</td> <td>52100</td> <td>22.2</td> <td>8383</td> <td>215</td> <td>1.99E-04</td> <td>3.25E-05</td> <td>0.0031</td> <td>6.5795</td> <td>0.0288</td> <td>5.150</td> <td>0.187</td> <td>0.3222 0</td> <td>0112 0</td> <td>.9751 (</td> <td>.1159 0</td> <td>1.0009</td> <td>800</td> <td>55 18</td> <td>44 3</td> <td>30 185</td> <td>5</td> <td>36</td> <td>0</td>	Grt-S,	2342	52100	22.2	8383	215	1.99E-04	3.25E-05	0.0031	6.5795	0.0288	5.150	0.187	0.3222 0	0112 0	.9751 (.1159 0	1.0009	800	55 18	44 3	30 185	5	36	0
Girls, 2324 3110 151 4324 2349 1516 2333 0101 1516 3330 01187 00001 1587 321 1393 233 323 323 323 323 323 323 323 323 323 323 323 323 323 323 323 323 323 324 311 323 324 311 323 324 313 324 313 324 313 324 313 324 313 324 313 324 313 324 314 324 314 313 324 314 324 313 324 314 313 324 314 313 324 314 313 324 314 313 313 314 314 313 313 314 313 313 314 313 313 314 313 313 313 313 313 313 313 313 313	Grt-S,	2323	51670	22.2	8031	256	2.42E-04	3.57E-05	0.0038	6.4299	0.0585	5.036	0.116	0.3173 0	.0063	.9159 (.1151 0	0.0011	777	31 18	25 1	9 185	-	6	4
Circle, Circle, <t< td=""><td>Grt-S,</td><td>2269</td><td>36560</td><td>16.1</td><td>6432</td><td>308</td><td>2.84E-04</td><td>3.66E-05</td><td>0.0044</td><td>4.7720</td><td>0.0434</td><td>5.455</td><td>0.155</td><td>0.3334 0</td><td>0080</td><td>.8930</td><td>.1187 0</td><td>0.0015 1</td><td>855</td><td>39 18</td><td>94 2</td><td>193</td><td>0 20</td><td>6</td><td>8</td></t<>	Grt-S,	2269	36560	16.1	6432	308	2.84E-04	3.66E-05	0.0044	4.7720	0.0434	5.455	0.155	0.3334 0	0080	.8930	.1187 0	0.0015 1	855	39 18	94 2	193	0 20	6	8
CH-N Control C	Grt-S,	2242	48110	21.5	7905	1580	1.42E-03	8.20E-05	0.0220	6.0470	0.0424	6.013	0.162	0.3403 0	0074 0	.8680	.1281 0	0.0017	888	36 19	78 2	3 207	çi Çi	t 91	-
Chr3, 70 7 239 8.9 12164 197 5.81-60 1.426-76 0.000 2.5169 0.0164 5.156 0.128 0.0004 0.941 0.173 0.0001 1825 41 1833 17 932 MH-5, 2303 3726 15.5 569 191 1686-04 2.445-65 0.0026 4.4739 0.0139 0.013 0.001 1825 0.011 1825 41 1833 17 932 MH-5, 245 45 567 15 1.686-04 1.886-05 0.0026 4.4739 0.0139 0.0139 0.0094 0.941 0.113 0.0011 1825 30 1731 24 1838 17 93 MH-5, 245 45 567 15 11 1566-04 1.886-05 0.0026 4.4739 0.0291 5.032 0.0139 0.0093 0.9494 0.1176 0.0011 1825 30 1731 102 MH-5, 245 45 567 15 11 1566-04 1.886-0 2.286-05 0.0026 4.4793 0.0291 5.032 0.012 0.0092 0.9999 0.1171 0.0011 1755 30 1731 102 MH-5, 241 4.413 0.0021 4.4130 0.0291 5.021 4.430 0.0291 5.020 0.049 0.944 0.1156 0.0010 1819 46 129 1844 13 102 MH-5, 284 4313 175 567 154 13.51-04 2.0602 0.0003 1.4413 0.0391 5.74 0.117 0.339 0.0009 0.9494 0.1156 0.0010 1746 20 1859 19 1844 13 102 MH-5, 284 4313 175 564 1.286-04 1.986-05 0.0003 1.4413 0.0393 5.74 0.117 0.339 0.0009 0.9494 0.1156 0.0010 1746 20 1869 12 100 MH-5, 283 216-04 2.286-04 2.986-0 0.0003 5.0304 0.017 0.339 0.0013 0.9494 0.1126 0.0009 1746 20 1869 12 100 MH-5, 284 4319 2.12 401 2.226-04 2.966-0 0.0003 5.031 0.231 0.005 0.995 0.113 0.0000 1746 20 186 22 1860 12 93 MH-5, 284 4319 2.12 401 1.926-04 2.966-0 0.0030 5.011 0.231 0.005 0.995 0.113 0.0000 1746 20 186 29 18 97 MH-5, 284 4319 2.12 401 1.926-04 2.966-0 0.0024 4.869 0.0030 5.013 0.0005 0.955 0.113 0.0001 1740 2010 1770 201 1819 20 MH-5, 284 411 7.2 411 7.2 411 7.2 414 7.2 414 7.2 418 7.2 414 MH-5, 284 414 7.2 414 7.2 414 7.2 414 7.2 414 7.2 414 7.2 414 MH-5, 284 4.4 4.4 4.8 6.0023 4.4 4.0 0.012 0.012 0.005 0.955 0.114 0.0001 7.96 2.1 80 MH-5, 284 4.4 7.8 6.4 4.4 1.8 6.0 2.2 2.0 0.000 4.104 0.011 0.0000 1.7 6.0 000 1.7 6.1 120 0.0000 1.7 6.1 120 0.0001 1.9 9.7 1 MH-5, 284 4.4 1.8 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4	Grt-S ₂	6569	61785	9.4	11730	237	7.74E-05	1.22E-05	0.0012	2.6906	0.0116	5.172	0.128	0.3254 0	00200	.9175 0	1153 0	0.0011 1	816	34 18	48 2	11 185	1	96	4
Marks, 2006 3152 16.1 6.248 181 1.66E-04 2.44E-05 0.0026 4.5178 0.024 5.068 0.143 0.3259 0.004 0.9617 0.1133 0.0011 1755 30 1791 1685 168 1839 195 951 Marks, 241 4.966 15. 6558 154 1.56E-04 1.84E-05 0.0026 4.4730 0.0291 0.3029 0.3029 0.0969 0.9691 0.1131 0.0010 11755 30 1791 19 1953 15 951 Marks, 241 4.966 15. 6578 154 1.31E-04 1.38E-05 0.0026 4.4730 0.0291 4.805 0.112 0.3129 0.0099 0.9994 0.112 0.0001 1755 30 1798 25 1839 14 96 Marks, 282 4.318 15. 770 333 2.42E-04 2.01E-0 0.0026 4.473 0.0391 5.74 0.117 0.3399 0.0099 0.9994 0.112 0.0009 1764 33 1965 19 1941 13 10.2 Marks, 282 4.318 15.3 770 33 2.42E-04 2.01E-0 0.0027 4.478 0.038 5.74 0.117 0.3399 0.0073 0.9994 0.113 0.0009 1764 33 1965 19 1941 13 10.2 Marks, 281 4318 15.3 770 33 2.42E-04 2.01E-0 0.0024 5.003 0.2014 5.010 0.057 9.487 0.110 0.3199 0.0099 0.9994 0.113 0.0009 1764 38 1960 19 91 Marks, 281 4312 1.7 594 197 132 0.002 2.22E-04 0.0027 5.039 0.021 4.825 0.111 0.3399 0.0073 0.8940 0.113 0.0016 1764 27 1896 29 96 Marks, 281 4312 1.7 594 197 132 0.002 2.22E-04 0.0027 5.0391 0.0073 5.041 0.3093 0.0074 0.8927 0.113 0.0016 1764 2.46 97 97 97 Marks, 281 4312 14 7 79 4368 154 197 12.22E-04 1.0264 4.809 0.057 4.817 0.147 0.3399 0.0073 0.8940 0.113 0.0016 1764 2.4 187 Marks, 281 4312 14 7 79 4368 154 197 12.22E-04 1.0264 4.817 0.045 5.014 0.3392 0.0073 0.9840 0.113 0.0016 1764 2.4 187 Marks, 281 4312 14 7 79 191 12.22E-04 1.0264 4.069 0.039 0.101 0.3193 0.0073 0.9847 0.113 0.0016 1794 2.4 187 Marks, 281 486 41 17 0.000 1.100 0.110 0.319 0.0109 1.174 0.011 176 0.011 176 0.011 1755 19 12 Marks, 284 444 456 19 1.48E-0 0.022 4.887 0.111 0.3199 0.0016 0.9112 0.0016 1764 24 1897 29 189 Marks, 284 444 456 10 1.48E-0 0.022 4.887 0.112 0.026 0.993 0.994 0.112 0.0016 1764 24 169 72 189 Marks, 284 486 41 100 1.112 0.0016 1.174 0.011 176 0.011 176 0.011 176 0.112 1000 Marks, 284 486 19 10 1.48E-0 0.023 4.887 0.011 0.3191 0.0016 1.756 21 179 20 191 191 Marks, 284 486 19 10.146 0.023 4.887 0.140 0.123 0.024	$Grt-S_2$	7047	62390	8.9	12164	197	5.91E-05	1.42E-05	0.0009	2.5108	0.0164	5.156	0.122	0.3304 0	0073 0	.9615 (1132 0	0.0007 1	840	35 18	45 2	20 185	1	6	4
Matt, 2005 3112 155 5269 158 168E-04 188E-05 0.0026 44730 0.0312 4.835 0.12 0.3259 0.004 0.9617 0.113 0.001 1755 30 1791 19 184 189 95. Matt, 2245 4050 15. 5678 154 1.36E-04 184E-05 0.0026 44745 0.0391 24.835 0.141 0.3139 0.0069 0.9464 0.1126 0.001 1755 44 1786 26 189 184 189 0.3 Matt, 2244 4139 15. 771 133 2.42E-04 124E-05 0.0027 4476 0.0393 2.74 0.117 0.3399 0.0069 0.9464 0.1126 0.0003 1866 39 186 19 1841 19 184 Matt, 2244 4139 15. 771 554 201 221E-04 2.01E-05 0.0024 4478 0.0393 5.74 0.117 0.3399 0.0069 0.9464 0.116 0.0003 1866 39 1861 20 183 0.41 Matt, 244 389 352 177 554 201 221E-04 104E-04 0.0037 4478 0.0393 5.74 0.117 0.3399 0.0069 0.9464 0.116 0.0003 1866 39 1861 20 189 1941 13 102. Matt, 234 4313 217 564 201 221E-04 104E-04 0.0034 7501 5.21 0.141 0.3399 0.007 0.9464 0.116 0.0003 1868 39 1861 20 189 0.919 Matt, 244 30 132 172 6911 193 1.72E-04 1.92E-05 0.0027 4.8610 0.0303 5.10 0.3190 0.0073 0.840 0.119 0.0012 1740 27 174 24 1857 29 95 Matt, 241 4913 19 1.72E-04 1.92E-04 1.92E-05 0.0027 4.810 0.2030 5.109 0.219 0.2030 0.006 0.953 0.113 0.0012 176 0.012 1740 27 179 40 Matt, 244 650 0.0023 4.810 0.0230 4.810 0.219 0.2110 0.319 0.0012 176 0.0012 176 21 189 0.11 199 0.10 Matt, 244 650 0.0023 4.860 0.0030 5.109 0.211 0.3190 0.0012 1618 0.012 1618 20 189 19 97 Matt, 244 650 0.0023 4.860 0.0030 5.109 0.2130 0.005 0.953 0.113 0.0012 176 0.010 176 0.012 176 0.010 196 199 Matt, 244 650 0.0023 4.860 0.0030 5.109 0.2130 0.005 0.954 0.113 0.0012 176 0.010 176 0.18 0.18 0.19 0.11 Matt, 253 44 0.05 0.023 4.960 0.0023 4.960 0.0130 4.960 0.0301 0.014 0.010 0.012 0.0003 176 0.002 176 0.002 186 0.19 0.10 Matt, 224 400 0.0020 4.960 0.0023 4.960 0.014 0.010 0.0110 0.010 0.012 0.000 0.954 0.19 0.010 177 0.90 186 Matt, 224 400 0.000 0.954 4.960 0.023 4.960 0.014 0.001 0.011 0.010 0.011 0.010 0.011 0.012 0.010 0.112 0.000 Matt, 224 4.000 0.002 4.960 0.0023 4.960 0.014 0.014 0.010 0.011 0.010 0.011 0.011 0.010 0.112 0.000 Matt, 224 4.000 0.0000 0.954 4.900 0.0	Mat-S ₂	2309	37276	16.1	6248	181	1.68E-04	2.44E-05	0.0026	4.6178	0.0214	5.068	0.143	0.3272 0	0084 0	.9441 0	1123 0	0011 1	825	41 18	31 2	183	8	6	ς.
Matts, 2452 40502 165 6568 181 1.65E-04 1.84E-05 0.0026 4.8194 0.0312 4.835 0.112 0.3199 0.0068 0.9663 0.1124 0.0001 1755 30 1791 19 1834 18 94.3 Add 126 0.0018 155 6578 131 1.65E-04 1.38E-0 0.0027 4.4476 0.0368 4.820 0.147 0.3399 0.9663 0.9464 0.1126 0.0008 1868 33 1865 19 1841 13 10.2 Matts, 2824 231 75 5594 201 2.28E-04 2.0165 0.0033 5.0303 5.030 0.021 0.332 0.0063 0.9464 0.1126 0.0008 1868 35 1861 20 1853 12 10.2 Matts, 177 5594 201 2.28E-04 2.0165 0.0033 5.0303 5.030 0.2010 0.332 0.0073 0.894 0.1130 0.019 1764 36 1814 25 1848 10 10 Matts, 177 5594 201 2.28E-04 1.04E-04 0.0037 5.810 0.0275 5.951 0.147 0.3399 0.0073 0.894 0.1130 0.019 1764 36 1814 25 1848 10 1 Matts, 2712 6911 193 1.75E-04 1.04E-04 0.0037 5.930 5.109 0.073 0.894 0.1130 0.010 176 37 1794 24 1877 25 931 Matts, 2813 214 7594 197 1.92E-04 1.04E-0 0.0037 6.2173 0.042 5.011 0.3193 0.0073 0.894 0.113 0.0016 1740 37 1794 24 1877 25 931 Matts, 2849 4368 258 7.17 691 193 1.75E-04 1.02E-0 0.0027 6.348 0.011 0.3193 0.0073 0.8950 0.113 0.0016 1740 37 1794 24 1857 25 931 Matts, 2849 4368 163 708 709 1.5E-04 1.02E-05 0.0027 4.8107 0.0259 4.882 0.114 0.3190 0.0016 1756 32 1800 19 97 Matts, 2849 4368 164 862 233 1.14E-04 5.0027 4.8660 0.0395 5.148 0.312 0.0008 0.957 0.113 0.0010 1756 21 189 0.13 Matts, 2849 430 0.107 0.8660 0.9953 4.180 0.018 0.310 0.008 0.978 0.1112 0.0008 1756 42 178 Matts, 312 7.164 2.26E-05 0.0023 4.4660 0.0365 4.417 0.146 0.317 0.0080 0.927 0.113 0.0008 1756 42 178 Matts, 312 145 726 3.1179 0.0009 0.974 0.113 0.0000 1756 42 178 Matts, 316 1.495 0.001 1.771 4.0 1871 2.28 Matts, 3304 8.568 101 1.496-0 0.0033 5.496 0.120 0.038 0.486 0.113 0.0008 1756 42 178 Matts, 316 1.495 0.001 1.771 4.0 1817 2.4 Matts, 3304 8.568 101 1.400-0 1.100 0.010 0.011 1.71 4.0 1817 2.1 Matts, 324 4.44 1.44 1.44 1.44 1.44 1.44 1.44 1.	Mat-S ₂	2005	31152	15.5	5269	158	1.69E-04	1.89E-05	0.0026	4.4730	0.0291	5.092	0.158).3259 C	.0094 0	.9617 (.1133 0	0.0010	819	46 18	35 2	6 185	33	36	2
Matt.S, 2841 40966 155 6578 154 1:31E-43 3:36E-05 0.0024 44405 0.0286 4.820 0.171 0.3399 0.0069 0.9464 0.172 0.3009 1754 44 1788 25 18:39 145 13 0.003 Matt.S, 185 4383 2:42E-04 2:22E-04 2:28E-05 0.0037 5.0030 5.021 0.525 0.073 0.3030 0.0073 0.5940 0.1132 0.0008 1686 36 1861 23 1853 12 1002 Matt.S, 175 4584 201 2:22E-04 1.04E-04 0.0034 5.0030 0.0071 0.557 4.967 0.113 0.0008 1686 36 1861 36 1861 20 1853 12 1002 Matt.S, 177 5594 271 2:22E-04 1.04E-04 0.0037 5.0301 0.0575 4.957 0.141 0.3399 0.0073 0.5930 0.013 0.5001 1784 36 184 22 1848 29 51 Matt.S, 2247 4813 2:14 759 197 1.32E-04 1.04E-05 0.0027 5.034 0.0463 4.852 0.141 0.3193 0.0013 0.5901 0.178 0.0019 1784 36 184 22 184 Matt.S, 2240 4105 158 7066 199 1.72E-04 1.76E-05 0.0027 6.273 0.042 5.07 0.110 0.3193 0.0056 0.555 0.113 0.0008 1786 32 1820 18 197 Matt.S, 2849 4356 15. 7069 197 1.32E-04 1.76E-05 0.0023 6.109 0.221 0.228 0.013 0.506 0.555 0.113 0.0008 1786 32 1820 19 187 Matt.S, 2849 4356 15. 7066 185 1.52E-04 1.76E-05 0.0023 4.869 0.018 4.800 0.140 0.319 0.0012 1756 24 187 Matt.S, 2849 4356 161 913 1.32E-04 1.76E-05 0.0023 4.8197 0.140 0.3110 0.0008 0.974 0.113 0.0010 1756 31 1799 19 186 Matt.S, 2849 4356 161 913 1.32E-04 1.26E-05 0.0023 4.860 0.194 4.800 0.140 0.3110 0.0008 1756 4.2 1788 25 1890 19 97. Matt.S, 2849 4356 161 913 1.45E-04 1.86E-05 0.0023 4.8107 0.0559 4.810 0.140 0.3110 0.0008 1756 4.2 1788 25 1890 19 97. Matt.S, 2899 456 0.971 0.9549 0.130 0.008 0.974 0.113 0.0010 1756 21 1892 11 92 Matt.S, 2894 4569 19 9.4660 0.0033 4.800 0.184 4.800 0.140 0.110 0.010 1771 4.0 1817 22 1890 11 92 Matt.S, 2894 4569 9.77 4800 9.261 4.966 0.0034 4.866 0.199 9.30 Matt.S, 2894 0.010 9.011 0.011 0.010 1771 4.0 1817 2.2 1890 19 9.3 Matt.S, 2894 4569 9.7 1499 0.191 0.0001 0.156 0.0010 1.71 4.90 1817 22 1870 11 Matt.S, 2894 4.9028 1.9 196-05 0.0014 2.7766 0.0016 5.240 0.1018 0.0016 0.956 0.112 0.0001 1771 4.0 1817 2.1 180 Matt.S, 2844 4.47 Matt.S, 284 4.484 4.4956 0.0014 2.465 0.0014 2.496 0	Mat-S ₂	2452	40502	16.5	6568	181	1.65E-04	1.84E-05	0.0026	4.8194	0.0312	4.835	0.112	0.3129 0	.0062	98668.	1121 0	0.0011	755	30 17	91	9 183	4	6	2
Marks, 2824 34318 15.3 7/01 2332 2.42E-04 2.28E-05 0.0037 5.44478 0.0269 5.274 0.17 0.3399 0.0069 0.944 0.1126 0.0008 1866 33 1865 19 184. 13 102.4 0.008 Marks, 175 584 201 2.22E-04 2.01E-05 0.0033 5.001 0.027 5.4967 0.147 0.3389 0.0073 0.830 0.1330 0.0019 1784 36 181 22 184. 29 0.85 Marks, 2513 4315 172 6911 193 1.72E-04 1.92E-05 0.0037 5.934 0.0457 4.967 0.147 0.3389 0.0073 0.830 0.1130 0.0019 1784 36 181 22 18-04 Marks, 2513 4315 172 6911 193 1.72E-04 1.92E-05 0.0037 5.934 0.0457 5.4967 0.141 0.3399 0.0073 0.830 0.1130 0.0019 1784 36 181 22 18-04 Marks, 2513 4315 172 6911 193 1.72E-04 1.92E-05 0.0027 5.034 0.0457 5.4967 0.110 0.3193 0.0065 0.955 0.1137 0.0008 1784 36 181 22 18-04 Marks, 2547 48113 214 7594 197 1.92E-04 1.92E-05 0.0024 4.6690 0.0396 5.109 0.071 0.890 0.0071 0.863 0.1132 0.0011 1784 36 186 189 13 Marks, 2549 4315 154 72E-04 1.72E-05 0.0024 4.6690 0.0396 5.109 0.211 0.3129 0.0013 1784 36 180 1756 24 1817 24 Marks, 289 4258 161 8197 1.92E-04 2.02E-0 0.0024 4.6690 0.0396 4.480 0.140 0.3130 0.0065 0.957 0.1132 0.0010 1755 1179 0.191 9.97 Marks, 289 4258 161 8197 208 1.51E-04 2.02E-0 0.0023 4.4809 0.0189 4.800 0.140 0.3130 0.0091 0.764 0.1132 0.0010 1755 21 180 22 186 Marks, 289 4258 161 8197 208 1.51E-04 2.02E-0 0.0023 4.4897 0.0365 4.4817 0.140 0.3110 0.0010 1756 4.4 1788 22 1860 19 13 96 Marks, 289 4258 161 9.97 208 1.51E-04 2.02E-0 0.0023 4.969 0.011 0.3100 0.964 0.0112 0.0008 1756 4.4 1788 22 1860 19 13 96 Marks, 289 4258 161 9.97 208 1.51E-04 2.02E-0 0.0033 4.4969 0.014 0.3010 0.970 0.971 0.971 4.01 187 Marks, 3304 5588 161 9.976 0.9003 5.284 0.023 4.984 0.140 0.310 0.366 0.9112 0.0010 1771 4.0 1817 2.3 1870 112 9.4 Marks, 3304 5688 9.7 148 9.5 186 0.0014 2.776 0.0166 5.224 0.188 0.0016 0.956 0.112 0.0010 1971 4.9 181 12 182 Marks, 3304 4.959 191 9.916-04 0.0014 2.776 0.0016 5.240 0.189 0.0017 0.954 0.113 0.0010 1771 4.0 1817 2.3 1870 112 9.4 Marks, 44 178 44 178 44 178 Marks, 45 44 178 44 178 44 178 44 178 Marks, 45 44	Mat-S ₂	2641	40986	15.5	6578	154	1.31E-04	3.36E-05	0.0020	4.4405	0.0286	4.820	0.147	0.3109 0	0089	.9663	.1124 0	1.0009	745	44	88	5 183	6	1 94	<u>o</u> :
Marcs, 1885 3332 177 554 723 178 1280 2.012-05 0.0034 5.0030 0.0575 4.367 0.147 0.3382 0.0074 0.9607 0.1130 0.0019 1784 36 184 22 184 29 965 Marcs, 2115 4.55 112 193 1.7554 193 1.7554 193 1.7554 193 1.7554 193 1.7554 193 1.7554 193 1.7554 193 1.7554 193 1.7554 193 1.7554 193 1.755 Marcs, 2137 4.551 193 1.7554 193 1.7554 193 1.7554 193 1.7554 193 1.755 Marcs, 2147 4913 21.4 759 193 1.7554 193 1.7554 193 1.7554 193 1.755 Marcs, 2247 4813 21.4 759 197 1.955-0 0.027 5.034 0.0463 4.852 0.141 0.309 0.0076 0.852 0.113 0.0016 1740 37 174 24 187 25 935 Marcs, 2247 4813 21.4 759 197 1.955-0 1.756 0.0024 4.860 0.0390 5.109 0.211 0.3199 0.0066 0.957 0.113 0.0011 175 31 1799 19 189 Marcs, 2589 4.355 161 1917 2.061 105 2.0024 4.8107 0.0359 4.800 0.112 0.130 0.0012 1818 65 183 36 186 0.12 Marcs, 2589 4.353 1.1599 13 1.555-04 0.0022 4.8107 0.039 4.800 0.120 0.312 0.0008 0.957 0.112 0.0008 1756 4.1 778 24 1819 13 95 Marcs, 2389 4.355 161 1917 2.03 1.916-04 2.065-0 0.0023 4.817 0.146 0.3710 0.0010 0.973 0.0010 1755 31 1799 19 186 11 94 Marcs, 238 161 8197 228 100 1.495 0.0023 4.917 0.048 2.816 0.0112 0.0008 1756 4.4 1788 25 186 Marcs, 2394 556 169 7.36 1.916-04 2.075-0 0.0033 4.917 0.146 0.371 0.006 0.976 0.1112 0.0008 1756 4.4 1788 25 186 Marcs, 2304 5568 169 7.56 1.916-04 2.075-0 0.0033 4.917 0.146 0.371 0.0068 0.976 0.1112 0.0008 1756 4.4 1788 25 186 Marcs, 2304 5568 169 7.36 1.916-04 2.075-0 0.0033 5.496 0.121 0.3017 0.964 0.1112 0.0000 1771 40 187 Marcs, 2304 5568 19.7 4405 Marcs, 2304 5568 0.177 0.0018 0.971 0.964 0.1109 0.011 771 Marcs, 2187 0.187 Marcs, 2304 2.965 0.0014 2.776 0.0016 5.224 0.108 0.271 0.0016 0.911 Marcs, 23187 0.117 0.011 1771 40 187 Marcs, 247 Marcs, 247 Marcs, 249 4.95 Marcs, 247 Marcs, 249 4.95 Marcs, 249 4.95 Marcs, 247 Marcs, 249 4.95 Marcs, 249 4.95 Marcs, 249 4.95 Marcs, 249 Marcs, 241 Marcs, 241 Marcs, 240 Marcs, 241 Marcs, 241 Marcs, 241 Marcs, 241	Mat-S	2824	43183	15.3	7701	333	2.42E-04	2.28E-05	0.0037	4.4478	0.0398	5.274	0.117	0.3399 0	0069	.9494 (.1126 0	0.0008	886	33 18	65 1	9 184	÷ E	102	4
Marks, 1779 45668 25, 1723 6111 137 2.19E-04 1.04E-04 0.0024 7.5810 0.0757 4.967 0.147 0.3199 0.0073 0.8340 0.1136 0.0019 1784 35 1914 25 1867 25 937 Marks, 2513 43125 17.2 6911 137 1.75E-04 1.92E-05 0.0027 5.0348 0.0463 4.852 0.141 0.3099 0.0073 0.8627 0.1136 0.0101 1740 37 1794 24 1857 25 937 Marks, 2473 4313 214 7584 197 1.25E-04 1.92E-05 0.0023 6.2173 0.0463 4.852 0.114 0.3193 0.0073 0.8677 0.1137 0.0008 1786 32 1820 18 1860 12 897. Marks, 2600 4105 15.8 7066 185 1.5E-04 1.76E-05 0.0024 4.8680 0.0390 5.109 0.211 0.3139 0.0073 0.9677 0.113 0.0010 1755 31 1799 19 1860 11 997. Marks, 2849 43585 16.5 7087 209 1.77E-04 5.02E-05 0.0024 4.8680 0.0396 5.109 0.211 0.3139 0.0013 1755 31 1799 19 1861 16 94. Marks, 2314 3605 16.3 7087 209 1.51E-04 2.02E-05 0.0023 4.8107 0.0256 4.817 0.146 0.371 0.068 0.978 0.1172 0.0008 1776 42 1786 24 189 13 96. Marks, 2314 3605 16.3 786 16.1 8197 2.26E-05 0.0023 4.8706 0.140 0.3110 0.0319 0.0010 1755 31 1799 19 1891 13 96. Marks, 2314 3605 16.1 8197 200 1.51E-04 2.02E-05 0.0023 4.8706 0.140 0.371 0.0808 0.974 0.1132 0.0010 1756 31 1789 21 1890 13 96. Marks, 2314 3605 16.9 7367 180 14.557 0.0023 4.3706 0.0036 4.817 0.146 0.371 0.0808 0.974 0.1132 0.0001 1756 21 1789 21 1860 12 92. Marks, 2314 3605 16.9 7367 19.0 14.567 0.0023 4.8706 0.0036 4.817 0.146 0.371 0.0808 0.974 0.1132 0.0001 1776 4.4 1788 25 1890 12 92. Marks, 3304 5558 16.9 9260 286 1.901 4.565 0.0023 4.876 0.0166 5.24 0.180 0.371 0.086 0.976 0.976 0.173 0.0001 1771 4.0 1817 23 1870 15 94. Marks, 3304 5558 9.7 1827 9.9 19 90E-06 0.0014 2.776 0.0036 5.240 0.031 0.536 0.0066 0.9550 0.173 0.0001 1771 4.0 1817 23 1870 15 94. Marks, 3304 5558 9.7 1827 9.9 19 9.05E-06 0.0014 2.776 0.0016 5.24 0.180 0.271 0.0061 0.975 0.0119 0.010 1771 4.0 1817 23 1870 15 94. Marks, 44 44 44 44 44 44 44 44 44 44 44 44 44	Mat-S2	1885	33352	17.7	5594	201	2.22E-04	2.01E-05	0.0034	5.0030	0.0210	5.251	0.124	0.3362 0	0074 0	.9607	.1133 0	0.0008	868	36 18	61 2	185	33	9 10	<u>.</u>
Mar-S, 2513 43125 172 6911 193 1.73E-104 1.9867 2.0483 8.0393 0.0074 0.8802 0.1137 0.0006 1740 24 1857 24 9637 Mar-S, 2267 48113 214 0.5034 0.4463 4.865 0.0306 5.103 0.0137 0.9656 1726 26 1860 12 961 Mar-S, 2600 4105 1.6 0.024 4.6680 0.0390 5.1037 0.0056 0.855 31 1794 24 1857 29 961 Mar-S, 2600 4150 1.56-04 4.6680 0.0390 5.1037 0.0056 0.9536 0.1137 0.0016 1766 26 1857 186 185 186 193 1861 1861 1861 1861 1866 12 964. Mar-S, 2849 4551 6.026 0.0021 4.8610 0.0396 5196 0.112 0.0112 181	Mat-S ₂	1779	45868	25.8	7123	178	2.19E-04	1.04E-04	0.0034	7.5810	0.0575	4.967	0.147	0.3189 0	0073 0	.8340 (1130 0	0.0019	784	36 18	14	5 184	8	6	5
Marcs 2247 40113 21.4 7564 157 0.0030 5.103 0.0055 0.1137 0.1002 1.86 1.882 18 1.86 1.86 1.86 1.86 1.86 1.86 1.86 1.86 1.86 0.0034 0.6036 0.013 0.0055 0.1137 0.0006 1.86 1.86 1.86 0.18 1.86 1.86 1.86 1.86 0.0034 1.86 0.013 0.0112 1.86 6 1.86 1.86 1.96 1.9 1.76 9.1 1.86 1.9 1.36 9.1 9.1 Mart-S 2864 456 1.6 0.013 0.0166 0.140 0.313 0.0066 0.113 0.0010 1756 31 1798 19 19 13 96.1 Mart-S 2854 16.1 8197 206 1.860 0.0033 4.817 0.146 0.313 0.0010 1756 41 186 13 96. Mart-S </td <td>Mat-02</td> <td>2513</td> <td>43125</td> <td>17.2</td> <td>6911</td> <td>193</td> <td>1.73E-04</td> <td>1.92E-05</td> <td>0.0027</td> <td>5.0348</td> <td>0.0463</td> <td>4.852</td> <td>0.141</td> <td>0.3099</td> <td>0074 0</td> <td>.8802</td> <td>1136 0</td> <td>0.0016 1</td> <td>740</td> <td>37 17</td> <td>94 2</td> <td>185</td> <td>2</td> <td>6</td> <td>2</td>	Mat-02	2513	43125	17.2	6911	193	1.73E-04	1.92E-05	0.0027	5.0348	0.0463	4.852	0.141	0.3099	0074 0	.8802	1136 0	0.0016 1	740	37 17	94 2	185	2	6	2
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Matcaccia 2849 4585 16.5 7081 50027 50172 00173 00100 1755 21 17.99 19 1831 16 94.3 Matcaccia 2689 45580 16.4 6926 253 2.186-04 5.0026 4.8107 0.1355 4.810 0.140 0.3132 0.0006 1756 4.1 1785 2.4 1819 13 96.5 MatcS 31 3558 16.1 9.13 0.0006 0.317 0.0008 0.376 0.1112 0.0008 1756 2.4 1890 13 96.5 MatcS 31 5058 16.9 736 0.1112 0.0008 1756 2.4 189 13 96.5 MatcS 3304 5558 16.9 756 0.0013 5.244 0.0235 4.817 0.146 0.316 0.113 0.0008 1756 21 1862 12 28.5 MatcS 3304 55588 16	Mat 02	2600	41005	15.8	7066	185	1.52E-04	1.76E-05	0.0024	4.6680	0.0390	5.109	0.221	0.3258 (.0133 0	.9687	.1138	0.0012	818	65 18	88	186	0	6	
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war-v ₂ 2/24 #0vz 16.9 /360 286 11.9 1.48C-40 1.0023 4.396 0.0204 4.360 0.171 0.3459 0.0071 0.3548 0.1139 0.0009 1.78 35 1.795 21 1872 15 94.7 Matt-s 3504 5556 16.9 9260 286 14.9 9260 286 14.9 9260 5.024 3.077-65 0.0014 2.7796 0.0166 5.224 0.140 0.3616 0.0066 0.9566 0.1128 0.0006 1867 22 1867 18 1845 10 1012 Matt-s 35 4.377 9.4 4.4 181 4.4 181 7 2.2 187 18 184 10 1012 Matt-s 35 4.347 9.4 4.4 181 4.4 181 7 2.2 187 18 184 1.0 1012 Matt-s 35 4.347 9.4 112 0.0016 1.0016	Mat.C	3143	89999	1.01	7001	807	1.51E-04	2.29E-U5	0.0000	4./ /06	G050.0	4.81/	0.146	1/02/0	6800.	9/04	2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2	8000.0	97./	44 21 21				200	×.
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1971-G. AMAN AAAKI UMU YANTUN INTI YANTUN UNUU AAMAN UUUUNI AAMA UUUUNI AAMAN UUUUNI UMUU UUNUU IVAA UUUNU AAYA	Mat-S.	10.0	14044	- 0 0	0210	- 04	7 P7E-06	0.100-100	0.0010	2001.2		10201	0.100	1120.0		1012	1100		700	2 4	0 0	φ 1 α		δ G	5 6

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9472-3.5	Mat-S ₂	4783	55747	11.7	9765	273	1.25E-04	1.24E-05	0.0019	3.3134	0.0129	4.974	0.100 0.	.3198 0.	0061 0	9756 0	1128 0.	2005 17	6	30 181	10	7 1845	00	96
9472-3.6	Mat-S ₂	6230	59839	9.6	10927	363	1.31E-04	1.42E-05	0.0020	2.8008	0.0213	4.846	0.127 0	.3108 0.	0078 0	.9845 0	.1131 0.	2005 17-	44	1790	3	2 1850	80	94.
9472-3.7	Mat-S ₂	6430	60223	9.4	11351	226	7.74E-05	2.23E-05	0.0012	2.7322	0.0146	4.986	0.117 0	.3183 0.	0071 0	.9786 0	.1136 0.	2006 17	22	35 181	2(0 1858	6	95.
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9475-20.2	Mat	2013	46007	6 66	6778	67	1.10F-04	2.24E-05	0.0017	0.2000 6.4843	0.0460	4.703	0.129 0	3070	0 6200	9611 0	1111 0.	21 6000	4 90	176		3 1818	2 4	
9475-20.3	Mat	2716	59686	20.02	8863	64	5.35E-05	1.70E-05	0.0008	6.1919	0.0369	4.717	0.117 0.	3095 0.	0 0200	9456 0	1105 0.	21 6000	2 62	35 1770		1 1808	12	96
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9475-20.5	Mat	2122	48112	201	2007	96	1.09E-04	5.66F-05	0.0017	6.6735	0.0652	4.542	0.198 0	2894 0	0 6200	7136 0	1138 0.	0035 16	68	1730	1 6	6 1861	22	8
9475-20.6	Mat	2241	51280	6 66	7168	112	1 20F-04	2 33F-05	0 0019	6.5416	0 0404	4 472	0 185 0	2895 0	0114 0	9747 0	1120 0	0010 16:	0	1726		4 1833	17	68
9475-20.7	Mat	2126	47868	22.5	6695	60	1.04E-04	2.05E-05	0.0016	6.5223	0.0342	4.434	0.105 0.	2856 0.	0061 0	9471 0	1126 0.	2009 16:		1719		9 1842	4	87
9475-221	Mat	5552	47330	8	8967	89	2 32E-05	5 07E-06	0 0004	2 4591	0.0217	4 875	0 120 0	3137 0	0062	REFO 0	1127 0	171 47100		1798		1 1844	: 6	95
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9473-32.2	Mat	3533	31035	0 00	6232	88	2 27E-05	6 73F-06	0.0004	2 5992	0.0122	5 050	0.105 0	3298 0	0065	9783 0	1111	0005 18:		1828	1 +	7 1817	2 00	5
9473-3.1	Mat	3161	23504	7.4	4733	33	2.27E-05	7.50E-06	0.0004	2.1542	0.0086	4.892	0.112 0	3182 0.	0064 0	9184 0	1115 0.	010 17		31 180	-	9 1824	16	97.
9473-3.2	Mat	3243	17883	5.5	3764	27	1.96E-05	9.93E-06	0.0003	1.5989	0.0113	4.593	0.117 0.	2972 0.	0070 0	9534 0	1121 0.	0009 16 ⁻	82	35 1748	10	1 1833	14	91.
9473-3.3	Mat	1752	2562	1.5	1083	22	3.14E-05	9.90E-06	0.0005	0.4082	0.0054	4.292	0.095 0	.2836 0.	0058 0	.9554 0	1098 0.	2007 16	60	9 1692	1	8 1796	12	.68
9473-10.1	Mat	1233	4225	3.4	1166	26	4.77E-05	1.53E-05	0.0007	0.9843	0.0107	4.569	0.119 0.	.3145 0.	0072 0	9262 0	1054 0.	010 17	33	86 174	4	1 1721	18	102.
9473-12.1	Grt	2456	4900	2.0	1850	4	4.09E-06	3.63E-06	0.0001	0.5801	0.0113	4.705	0.185 0.	.3101 0.	0 9600	.8523 0	1100 0.	023 17.	11	176	33	2 1800	37	.96
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Loc (monazite	textural lo	onvenuon cation): M	X-y.z; wire at = matrix	ere x ≃ × grain;	Crd, Grt	e numbe = (cordier	r, y = yrann r rite, garnet)	iumpet, and inclusions in	f = spurnur host minera	nber. Iviuii I; S ₂ = alig	IPIE analys ned with S	Ses III an I 3, fabric; S	naiviauai s, , = aligned	potare lau with S ₁ fal	ellea as A bric	-y.z.z								
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*Refers to radi	ogenic Pb	(corrected	d for comm	non Pb); concort	dance rela	ative to origi	וויפ דוו 1 = 100 * (²⁰⁸	b/ ²³ Pb age)/(²⁰⁷ Pb/ ²⁰⁶	Pb age))	n nach lioi	o ure surrac	e ulalık (4	100-0 -01	.n, 1/0. n.	09,000, 0VG	. 2.13040						
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Analylical deta IP363 (sample	alls: 8692): 16	um snot	e scans. e	arror in	²⁰⁶ Ph/ ²³⁸ U	l calibratic	on :%8.0 nc	L concentral	ion standan	1 No mass	s fractionat	tion correc	tion was at	pallac										
IP458 (all sam	ples excep	ot 8692): 1	6 µm spot	t, 5 sca	ins; error	in ²⁰⁶ Pb/ ²³	U calibratio	n 1.7%; U cc	ncentration	standard E	3153, 2065	5 ppm; Th/	U calibratic	n: F = 0.8	5700									
Mass fraction: Corr Coeff = c	ation correc orrelation c	ction = +0. soefficient,	.4% was a ; Conc. = (toncon	to the Pb- dance	-isotope ra	atios.																	



Figure 3. a) Backscattered scanning electron microscope image of textural relationships in sample 69HF-154a; note that right side of garnet is composite image showing sillimanite inclusion fabric (S₁); 2011-003; b) Concordia diagram of SHRIMP U-Pb results. Grt = garnet, Qtz = quartz, IIm = ilmenite, Bt = biotite, Mnz = monzonite, PI = plagioclase.



Figure 4. a), b) Backscattered scanning electron microscope image of textural relationships in 07CYA-X64a. Inset in (b) is Y map of analyzed monazite grain that is elongate parallel to weak internal S₁ fabric in garnet and which has overgrown S₁-parallel sillimanite needles; 2011-004, 2011-005. **c)** Concordia diagram of SHRIMP U-Pb results. Hatched ellipses are analyses of the core of a matrix monazite. Grt = garnet, IIm = ilmenite, Qtz = quartz, Kfs = K-feldspar, Sil = sillimanite, Mnz = monazite.

age. The older of these two analyses (#1.5) has distinctly higher Th/U ratio (14.1) than all other analyses (Th/U <6), suggesting that the core of this monazite grain crystallized during an earlier, ca. 1.84 Ga event than the rim. One small matrix grain that is not aligned with the S_2 foliation yields two disparate ca. 1.77 Ga results (grain #5, Table 2).

Sample 07CYA-A18a (GSC lab #9472)

Sample 07CYA-A18a is a metapsammite with the assemblage garnet-orthopyroxene-cordierite-sillimanitebiotite-K-feldspar-plagioclase-quartz-ilmenite collected from an outcrop with visible orthopyroxene and some leucosome. The single strong foliation at this outcrop is oriented at 336/36°NE. It is interpreted as the regional S₂ foliation that has been deflected from the typical southwest-strike (e.g. 260/29°N) observed several kilometres to the northeast at station 07CYA-A19. In sample 07CYA-A18a, garnet porphyroblasts up to 1 cm in diameter are equant, variably embayed, and wrapped by the main foliation (S_2) defined by elongate grains of quartz, K-feldspar, and cordierite (Fig. 5a). The largest garnet contains small ilmenite and rutile needles that are parallel to S_{2} (Fig. 5a), whereas smaller garnet porphyroblasts contain randomly oriented inclusions of quartz and plagioclase. Sparse, S2-parallel sillimanite is intergrown with matrix cordierite, commonly in areas with relict, Zn-bearing spinel. Sparse biotite forms scattered matrix grains.

Garnet has uniform Fe/(Fe+Mg) between 0.60 and 0.61, except for an increase up to 0.64 at rims touching cordierite. Garnet cores are calcic ($X_{Ca} = 0.06-0.08$), decreasing to 0.046-0.049 at rims touching matrix plagioclase or quartz and at the location of plagioclase inclusions. No zoning in MnO is discernible. Matrix plagioclase is uniform in composition ($X_{C_a} = 0.40-0.42$). Plagioclase inclusions in garnet have sodic cores ($X_{Ca} = 0.32-0.35$) that increase to more calcic rims (up to $X_{Ca} = 0.49$) in contact with garnet. Matrix biotite varies in Fe/(Fe+Mg) between 0.35 and 0.37, with TiO₂ between 6.2–6.6 weight per cent. One biotite inclusion partly surrounded by plagioclase in garnet has Fe/ (Fe+Mg) = 0.21-0.22 and $TiO_2 = 2.0-2.5$ weight per cent, suggesting that it crystallized at lower grade than matrix biotite. Cordierite forming partial rims on garnet is uniform in composition.

The compositions of randomly oriented plagioclase and biotite inclusions in garnet (Grt-1, Fig. 5a), together with calcic garnet near these inclusions yield pressure and temperature conditions of 6.6 kbar and 655°C, interpreted to represent prograde conditions prior to the onset of D_2 . Pressure and temperature conditions of 7 kbar and 755°C result from the rim compositions of garnet touching cordierite, together with nearby biotite and plagioclase.

The weighted average ²⁰⁷Pb/²⁰⁶Pb age of 23 analyses from 4 low-Y, elongate, S₂-parallel matrix monazite grains (i.e. Mnz-3; Fig. 5b), is 1848 \pm 6 Ma (MSWD = 0.78; Fig. 5c).



Figure 5. a) Backscattered scanning electron microscope image of textural relationships in sample 07CYA-A18a. Inset is Y map of analyzed monazite grain. **b)** Backscattered scanning electron microscope image of elongate matrix monazite parallel to S₂. Inset is composite Y map of analyzed monazite grain; 2011-006, 2011-007. **c)** Concordia diagram illustrating SHRIMP U-Pb results. Grt = garnet, Qtz = quartz, Crd = cordierite, IIm = ilmenite, Kfs = K-feldspar, Mnz = monazite.

Two analyses of an S₂-parallel, monazite inclusion (Mnz-4, Fig. 5a) within garnet (Grt-2, Fig. 5a) possibly indicate an older component (ca. 1.86 Ga); however, this is not statistically distinguishable from the age of matrix monazite in this sample. The weighted mean age of all 25 monazite analyses (matrix and inclusion) is 1849 ± 6 Ma (MSWD = 0.89).

Sample 07CYA-M5 (GSC lab #9475)

This sample was collected from garnet-rich metapelite that forms rare, 2–10 cm wide layers within poorly exposed metaquartzite felsenmeer. Large (centimetre diameter), embayed garnet porphyroblasts are wrapped by the main foliation defined by coarse sillimanite needles and a preferred shape fabric in quartz and K-feldspar. Plagioclase is not present in this sample, which prevents calculation of pressure-temperature conditions.

Fifteen analyses from two, moderate-Y monazite grains that occur along the edge of a garnet porphyroblast (Fig. 6a) yield an average ${}^{207}\text{Pb}/{}^{206}\text{Pb}$ age of 1826 ± 9 Ma (MSWD = 0.68, Fig. 6b). Two analyses of a small, moderate-Y monazite inclusion in garnet yield a weighted mean ${}^{207}\text{Pb}/{}^{206}\text{Pb}$ age of 1866 ± 18 Ma (MSWD = 0.38, Fig. 6b).

Sample 07CYA-M92 (GSC lab #9476)

This sample from a raft of rusty metapelite included within diorite near the eastern coast of Southampton Island contains the assemblage garnet-biotite-cordierite-sillimanite-plagioclase-quartz. Garnet forms centimetre-sized, variably embayed porphyroblasts that are wrapped by a strong external fabric (S_2) defined by biotite, quartz, and feldspar (Fig. 7a). The cores of some garnet porphyroblasts contain inclusions of quartz and biotite that form a moderate internal fabric that is parallel to the external S_2 fabric. Some garnet has 0.3 mm wide rims of cordierite with minor quartz.

Inclusion-rich garnet cores are more calcic ($X_{Ca} = 0.065 -$ 0.086) than clear rims ($X_{Ca} = 0.041$), with relatively uniform Fe/(Fe+Mg) between 0.70–0.72. The slight enrichment in MnO of garnet rims (1.0 weight per cent) relative to cores (0.75–0.80 weight per cent) likely occurred during partial breakdown of rims to cordierite. The Fe/(Fe+Mg) of matrix biotite near garnet, but surrounded by quartz increases from 0.4 to 0.45 with proximity to garnet, and is considered to reflect Fe enrichment during partial garnet breakdown (e.g. Kohn and Spear, 2000). Pressure and temperature conditions of 6.4 kbar and 720°C (with garnet-cordierite and garnetbiotite Fe-Mg exchange temperatures agreeing within 20°C) were calculated from the compositions of garnet just inside the MnO-enriched rim, biotite furthest removed from garnet, cordierite adjacent to garnet, and matrix plagioclase. Lack of appropriate inclusions in garnet preclude calculation of the conditions of garnet core formation.



Figure 6. a) Backscattered scanning electron microscope image of textural relationships in sample 07CYA-M5; 2011-008.
b) Concordia diagram illustrating SHRIMP U-Pb results. Grt = garnet, Qtz = quartz, Mnz = monazite.

Two SHRIMP analyses of a S₂-aligned, moderate- to high-Y monazite inclusion (#20) in garnet and one analysis of a small, S₂-parallel, moderate-Y, matrix grain (#27) yield a weighted mean ²⁰⁷Pb/²⁰⁶Pb age of 1861 ± 12 Ma (MSWD = 0.31, Fig. 7b). Nine analyses of equant, low-Y matrix grain #6 (Fig. 7b), which has a thin, very high-Y, unanalyzed rim, and one analysis of a small matrix grain (#10) that lies at a high angle to S₂, yield a weighted mean ²⁰⁷Pb/²⁰⁶Pb age of 1820 ± 7 Ma (MSWD = 1.08, Fig. 7b). A small monazite inclusion in garnet (#12) that is intersected by a large fracture gave a ²⁰⁷Pb/²⁰⁶Pb age of 1791 ± 16 Ma (2 σ), interpreted as a mixed age based on the distinct Y zonation in Mnz-12 parallel to this fracture.

Sample 07CYA-A29 (GSC lab #9473)

Sample 07CYA-A29 is a granulite-facies metapsammite (Fig. 2) with the assemblage garnet-orthopyroxene-biotite-K-feldspar-plagioclase-quartz-ilmenite. Irregular, embayed garnet porphyroblasts up to 7 mm in diameter are wrapped



Figure 7. a) Backscattered scanning electron microscope image of textural relationships in sample 07CYA-M92. Inset shows Y map of analyzed monazite inclusion in garnet; 2011-009. b) Concordia diagram illustrating SHRIMP U-Pb results. Inset shows Y map of equant monazite grain with high-Y undated rim. Grt = garnet, Bt = biotite, Qtz = quartz, PI = plagioclase, Mnz = monazite.

by the main foliation (S_2) defined by alignment of biotite, orthopyroxene, and ilmenite with the preferred shape of quartz and feldspar (Fig. 8a). Smaller, relict garnet is surrounded and in places replaced by biotite.

Garnet porphyroblasts have texturally indistinct calcic core regions ($X_{Ca} = 0.14-0.17$) surrounded by less calcic regions and rims ($X_{Ca} = 0.093-0.102$). The Fe/(Fe+Mg) and MnO are uniform (0.73-0.74 and 0.9-1.0 weight per cent, respectively), except for relict garnet, which has higher Fe/(Fe+Mg) and MnO (0.76-0.78, and 1.2 weight per cent, respectively). Plagioclase is very consistent in composition ($X_{Ca} = 0.38-0.42$), except where it is adjacent to relict garnet ($X_{Ca} = 0.48$). Also relatively uniform in composition are orthopyroxene (Fe/(Fe+Mg) = 0.48-0.51; Al₂O₃ = 1.4-1.7



Figure 8. a) Backscattered scanning electron microscope image of textural relationships in sample 07CYA-A29. Inset shows Y map of monazite #3; 2011-010 b) Concordia diagram illustrating SHRIMP U-Pb results. Hatched ellipse is analysis of monazite inclusion in garnet. Grt = garnet, Qtz = quartz, PI = plagioclase, Opx = orthopyroxene, Kfs = K-feldspar, Mnz = monazite.

weight per cent) and biotite (Fe/(Fe+Mg) = 0.43-0.45, TiO₂ = 5.1-5.3 weight per cent). Pressure-temperature conditions of 7.7 kbar and 790°C result from rim compositions of garnet separated from orthopyroxene and biotite by plagioclase.

Six analyses, from two matrix grains and one inclusion in garnet, yield a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1816 ± 10 Ma (MSWD = 0.99, Fig. 8b). One of these matrix grains (#3) is at a high angle to S₂ (Fig. 8a), whereas the other (#32) is a stubby grain (2:1 aspect ratio) parallel to S₂. A discrete, low-Th rim of grain #3 gives a nominally younger age (1796 ± 24 Ma, Fig. 8b) that nevertheless is statistically indistinguishable from the mean. One analysis of monazite (#10) within biotite adjacent to relict garnet gives a much younger age, 1721 ± 36 Ma, interpreted as dating this garnet breakdown reaction.

DISCUSSION

The quantitative metamorphic and geochronological data presented above provide first-order constraints on the tectonometamorphic evolution of Southampton Island, with evidence for four distinct metamorphic events and two penetrative deformational events. The nomenclature used below for these events (Table 1) is predicated on evidence of M_1 at ca. 2.6 Ga and M_2 at ca. 2.3 Ga, as derived from preliminary monazite data (Berman et al., unpub. data, 2010) for a ca. 2.68 Ga S-type granite (Rayner et al., 2011).

M₃-D₁ at 1.88 Ga

Samples 07CYA-X64a and 69HF-154a both display a weak first generation (S_1) foliation within garnet that is oriented at a high angle to the main S₂ foliation. In both samples, elongate monazite inclusions contribute to S₁, and yield near-identical 1879 ± 7 Ma and 1879 ± 8 Ma ages for M₂ at an early stage of D₁ deformation. The occurrence of monazite within the calcic cores of garnet in both samples indicates that M₃-D₁ occurred at relatively high pressure, strengthening a potential link with the Chesterfield block to the west (Fig. 1), where 7-10 kbar pressures are recorded at ca. 1.89-1.88 Ga (Berman et al., 2007). The 1.88 Ga event is considered to reflect microcontinent accretion to the Rae craton during an early stage of Hudsonian Orogeny (Berman et al., 2005, 2007). At present the 1.88 Ga event is evident only in two samples on west side of the study area (Fig. 2). Further studies are underway to determine the areal extent of this event on Southampton Island, and should better constrain the tectonic boundary conditions of this event.

M₄-D, at 1.86–1.84 Ga

Four samples widely distributed across Southampton Island record evidence for a 1.86-1.84 Ga event (Fig. 2). Monazite inclusions in garnet form a texturally distinct population of high-Y grains in three samples (07CYA-M5, 07CYA-A18a, and 07CYA-M92). The nominally older age of these inclusions in two of the samples (1866 \pm 18 Ma and 1861 ± 20 Ma for 07CYA-M5 and 07CYA -A18a, respectively) are similar to the 1861 ± 12 Ma age of S₂-aligned matrix monazite and garnet inclusions in sample M92, suggesting that they may date the early stages of D_2 deformation and M_4 garnet growth. Elongate matrix monazite grains in sample 07CYA-A18a record a slightly younger age of 1848 ± 6 Ma. Equant matrix monazite in sample 69HF-154a may indicate that D_{2} had ended in the north by 1841 ± 4 Ma, whereas S_2 -foliated 1852 ± 8 Ma granodiorite and 1842 ± 5 Ma diorite (Rayner et al., 2011) establish that D₂ was ongoing across the south until at least ca. 1840 Ma. The occurrence of only syn-M₄-D₂ monazite in sample 07CYA-A18a suggests that the calculated pressure-temperature values for this sample (6.6 kbar and 655°C and 7 kbar and 755°C, Table 1) constrain a clockwise pressure-temperature-time path for the M_4 event.

The M_4 - D_2 event at 1.86–1.84 Ga overlaps with the 1852 ± 6 Ma age of granodiorite plutonism on Southampton Island (Rayner et al., 2011). Given the strong penetrative deformation characterizing this event, the clockwise pressure-temperature path determined for sample 07CYA-18a, the monazite evidence that this event began prior to 1852 Ma, and the geochemistry of 1852 Ma granodiorite (Whalen et al., 2011), M₄-D₂ is consistent with a collisional event involving crustal thickening. This collisional event is also believed to have resulted in northwest-vergent folding and thickening that induced 1.86-1.84 Ga monazite growth further northwest in the Committee Bay belt (Berman et al., 2005). Crustal thickening at this time may have been driven by the ca. 1.88–1.86 Ga collision of Meta Incognita microcontinent with the southeastern flank of the Rae craton (St-Onge et al., 2006; Berman et al., 2005).

M₅ at 1.82 Ga

Four samples across Southampton Island (07CYA-M5, 07CYA-M92, 07CYA-A29, 07CYA-X64a) record evidence of an M₅ event, with statistically indistinguishable ages, ranging from 1826 \pm 9 Ma to 1815 \pm 7 Ma (Table 1). In agreement with the 1822 ± 3 Ma age of a late- to post-tectonic monzogranite (Rayner et al., in 2011), the M_e event is interpreted as post-D, based on textural evidence that all monazite (except for #32 in CYA-07-A29; see above) is either equant in shape, or elongate at a high angle to the S₂ fabric. The extremely low-Y content of most of the 1.82 Ga grains (e.g. Fig. 7b inset) suggests a high-grade event during which garnet was stable, rather than releasing yttrium during breakdown. Pressure-temperature conditions for this event are consistent with this interpretation, with results calculated from rim compositions in three samples ranging between 6.4 kbar and 720°C and 7.7 kbar and 790°C (Table 1).

The M_5 event is similar in age to a metamorphic event dated on southwest Baffin Island (Rayner et al., 2008), and appears to represent a regional thermal culmination associated with voluminous crustal melting and plutonism dated at 1.83–1.82 Ga on Southampton Island and southwest Baffin Island (Rayner et al., 2008, 2011).

M₆ at ca. 1.79–1.72 Ga

Monazite growth at this time is recorded in sample 07CYA-A29, where 1.72 Ga monazite is associated with garnet breakdown, and in 07CYA-X64a, where a single, post- D_2 matrix grain ranges in age between 1.79 Ga and 1.75 Ga. The authors interpret these ages to reflect fluid influx during regional cooling.

CONCLUSIONS

Thermobarometric and in situ SHRIMP monazite geochronology provide the first constraints on Southampton Island's metamorphic and deformational history which are required to improve regional tectonic and metallogenic models. The new data reveal a complex, polycyclic evolution with the possibility of six metamorphic and two penetrative deformational events. Preliminary monazite ages from ca. 2.68 Ga S-type granite suggest M₁ at ca. 2.6 Ga and M₂ at 2.3 Ga (Berman et al., unpub. data, 2010). Monazite inclusions in garnet from two samples on the western side of the study area define M₂-D₁ at ca. 1880 Ma, which may mark an early accretionary event in the region. M_4 - D_2 , initiated by 1861 ± 12 Ma with garnet growth, and continued until at least 1848 ± 6 Ma. Equant matrix monazite in one sample suggests that post-D₂, M₄ metamorphism affected the northern part of exposed basement at 1841 ± 4 Ma, whereas deformation continued across the south until at least 1842 \pm 5 Ma. The timing of the M₄-D₂ event is consistent with age constraints on Baffin Island (St-Onge et al., 2007) for the accretion of Meta Incognita microcontinent to the southeastern flank of the Rae Province. Four samples also record a post-D₂, M₅ event between 1826 ± 9 Ma and 1815 ± 7 Ma, which is interpreted to represent a thermal culmination associated with extensive crustal melting and ca. 1.83-1.82 Ga post-D₂ plutonism (Rayner et al., 2011). Monazite ages of ca. 1.79 Ga and 1.72 Ga may correspond to fluid influxes during regional cooling.

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