CHAPTER C: METAMORPHIC COOLING HISTORY OF THE FORTYMILE RIVER AND LAKE GEORGE ASSEMBLAGES FROM ^{40}AR/^{39}AR GEOCHRONOLOGY FROM THE NORTHEAST TANACROSS AND SOUTHEAST EAGLE QUADRANGLES, ALASKA

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INTRODUCTION

This report presents interpretations of ^{40}Ar/^{39}Ar ages of metamorphic rocks from the northeast Tanacross and southeast Eagle quadrangles, Alaska, which lie within the Yukon-Tanana Upland and cover the boundary between the Fortymile River and Lake George Assemblages (Dusel-Bacon and others, 2006). Recent 1:63,360 scale mapping by the Alaska Division of Geological & Geophysical Surveys (DGGS) (Wypych and others, 2021, sheet 1) delineated the boundary between parautochthonous North America (Lake George assemblage) and the allochthonous Fortymile River assemblage of the Yukon Tanana terrane. The exact nature of the boundary is difficult to assess due to poor exposure and segmentation of the boundary by subsequent Cenozoic strike-slip faulting, but it is mapped as an extensional detachment as proposed by Hansen and Dusel-Bacon (1998). DGGS samples for this study, reported in Naibert and others (2020) were analyzed from both sides of the detachment to confirm the mapping in areas of poor bedrock exposure. We synthesize the new data, along with ^{40}Ar/^{39}Ar and K-Ar ages from digital data in Wilson and others (2015 and references therein) and from Jones and Benowitz (2020), to further constrain the cooling histories of metamorphic rocks on either side of the detachment and to further refine the timing and rates of exhumation of the terranes on either side of the detachment.

METHODS

Methods of sample collection and preparation, analytical methods, sample descriptions, and discussion of preferred ^{40}Ar/^{39}Ar ages for the 16 metamorphic samples collected during the DGGS northeast Tanacross Quadrangle mapping project were reported in Naibert and others (2020). Muscovite is the most common potassium-bearing mineral in amphibolite-facies metasedimentary and metaplutonic rocks in both the Fortymile River and Lake George assemblages in the northeast Tanacross quadrangle, followed by biotite. Fourteen ^{40}Ar/^{39}Ar ages were calculated from muscovite-bearing samples and biotite ages were also calculated from seven of these samples. Biotite was analyzed from one sample without muscovite. Most of these samples were collected within 5 km of the detachment. Hornblende was only analyzed from one sample (18ET177) approximately 16 km south of the detachment and hornblende was not present in the rocks collected near the detachment.

Thin section descriptions in Naibert and others (2020) suggest the mica in each of these samples represent a single generation, as mica grain size and texture are consistent within each thin section. Micas define the foliation in all samples except the amphibolite sample 18ET177. Muscovite appears largely unaltered since formation. Biotite is commonly partially to completely chloritized but does not appear to be recrystallized. In a few samples, biotite was observed surrounding garnet, and could have crystallized as a replacement of garnet under upper-greenschist/lower-amphibolite retrograde conditions, but this biotite has similar color and pleochroism to the rest of the biotite in the thin section, suggesting formation under similar metamorphic conditions.

Hornblende is more abundant in the Fortymile River assemblage in the southeast Eagle Quadrangle, possibly due to more varied protoliths existing in that area, and ^{40}Ar/^{39}Ar and K-Ar horn-

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blende ages reported in Hansen and others (1991), Dusel-Bacon and others (2002), and Wilson and others (2015) are included in our interpretation. Most of these hornblende ages are from 20 to 35 km north of the detachment, though hornblende has been dated just south of the detachment at two locations. Locations of muscovite and biotite age samples range from 15 km south of the detachment to 35 km north of the detachment. Previously published $^{40}Ar/^{39}Ar$ ages used in this study include total fusion, isochron, and plateau ages. K-Ar ages are analogous to total fusions ages.

We calculated argon diffusion closure temperatures for biotite and hornblende using the CLOSURE program of Brandon and others (1998) assuming a grain size of 100 μm and a range of cooling rates of 5–25°C/million years (m.y.). The CLOSURE program applies diffusion parameters given in Grove and Harrison (1996; for biotite) and Harrison (1981; for hornblende). The calculated closure temperature for biotite is 304 ± 11°C and the estimated closure temperature for hornblende is 495 ± 14°C. We use an argon diffusion closure temperature of 410 ± 15°C for muscovite for a grain size of 100 μm and a range of cooling rates of 5–25°C/m.y. as shown in Harrison and others (2009).

RESULTS

Allochthonous Fortymile River Assemblage

Four muscovite cooling ages in the Fortymile River assemblage within 6 km of the Fortymile River-Lake George detachment (17ET038, 18MBW399, 18RN122, 18RN358; fig. 1, table 1) range from 163.9 to 149.4 Ma (Naibert and others, 2020). The step-heating spectra for muscovite from the Fortymile River assemblage are generally flat. Weighted-average ages were calculated for two of the samples without appropriate plateaus. None of these Fortymile River muscovite samples had younger ages for lower-temperature steps, and there are no indications of alteration or argon loss from a younger thermal event after cooling from peak metamorphic temperatures. Both biotite and muscovite ages were measured for sample 18RN358. The biotite step-heating spectrum has a hump shape with younger ages from the lowest and highest-temperature heating steps. A plateau age of 96.4 Ma was calculated from the intermediate-temperature heating steps, which is unlike other ages in the map area. We do not interpret this age as a reliable cooling age for the Fortymile River assemblage due to 1) the high atmospheric content and low radiogenic argon content of all heating steps in the sample, and 2) the lack of similarity to other sample ages. Sample 18RN358 was collected within 3 km of Late Cretaceous volcanic rocks and the biotite age could have been partially reset by unexposed intrusions of this age.

A 145.5 Ma $^{40}Ar/^{39}Ar$ muscovite age for sample 16-YTT-30 (Jones and Benowitz, 2020) from approximately 10 km north of the detachment is similar to the ages reported by Naibert and others (2020). A 165.6 Ma biotite age from 3 km north of the detachment (sample 90ADb17A) was previously interpreted by Dusel-Bacon and others (2002) to be Lake George assemblage or from within the detachment zone itself, but we reinterpret that sample to be part of the Fortymile River assemblage based on lithologic observations in the immediate vicinity that more closely match other Fortymile River assemblage rocks in the map area. The within-plate chemistry of nearby amphibolite previously used by Dusel-Bacon and others (2002) to assign the sample to the Lake George assemblage has not proven to be unique to Lake George amphibolites (Wypych and others, 2017; Wypych and others, 2018). Mica cooling ages reported by Flynn (2003) are similar to those reported by Naibert and others (2020), but hornblende ages reported by Flynn are more similar to the cooling ages along the Taylor Highway (discussed below).

Two $^{40}Ar/^{39}Ar$ samples from rocks mapped by Wypych and others (2021) as Fortymile River assemblage have Cretaceous cooling ages (fig. 1). The cooling age for biotite from sample 18MLW132 is 123.9 Ma, which is only slightly older than Lake George assemblage samples (discussed below) and

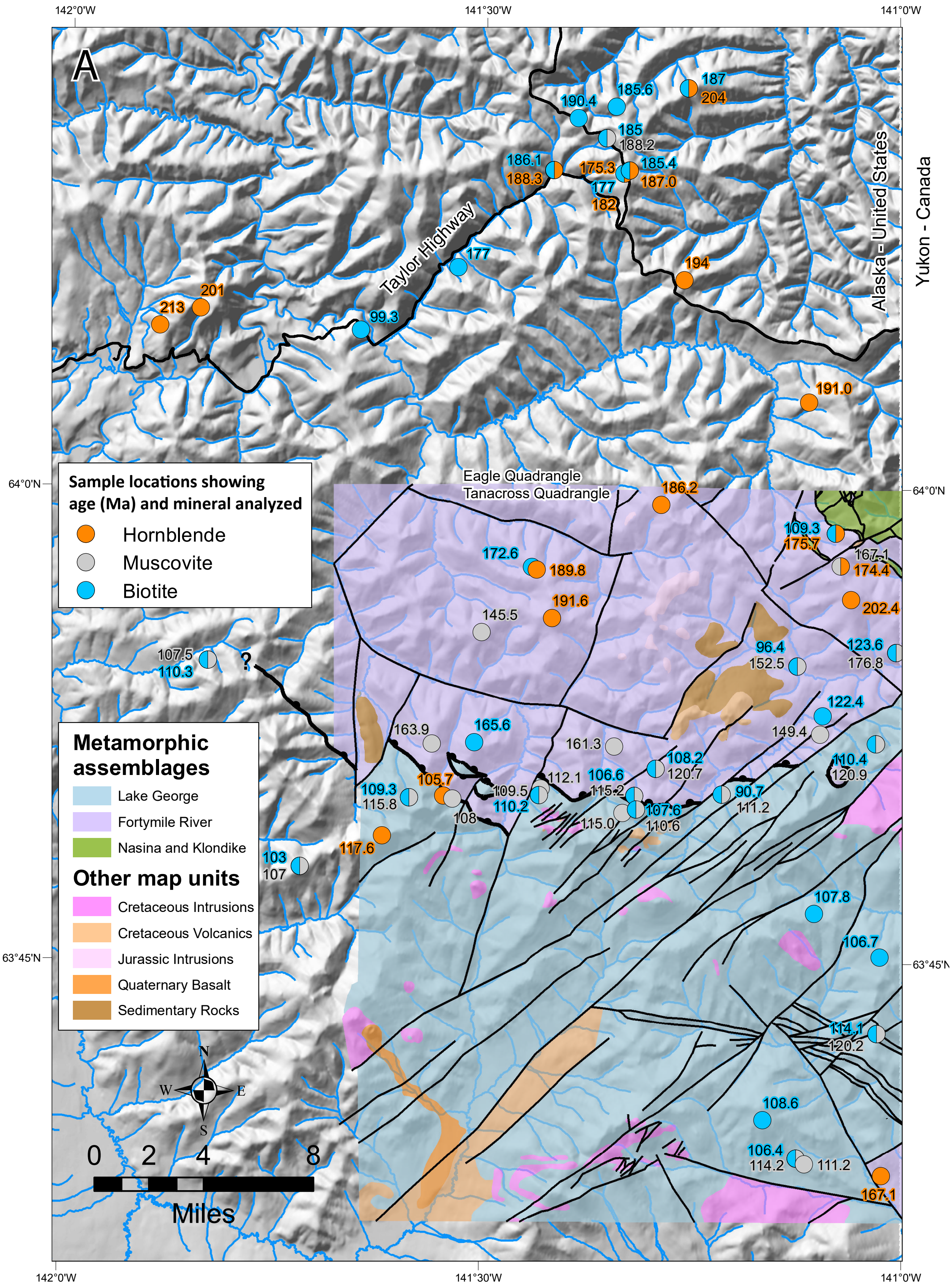

Figure 1A. Location of $^{40}Ar/^{39}Ar$ and K-Ar cooling ages in the northeast Tanacross Quadrangle and southeast Eagle Quadrangle. Map units and faults are from Wypych and others (2021), including the position of the Fortymile River-Lake George detachment (thick line with teeth on hanging wall).

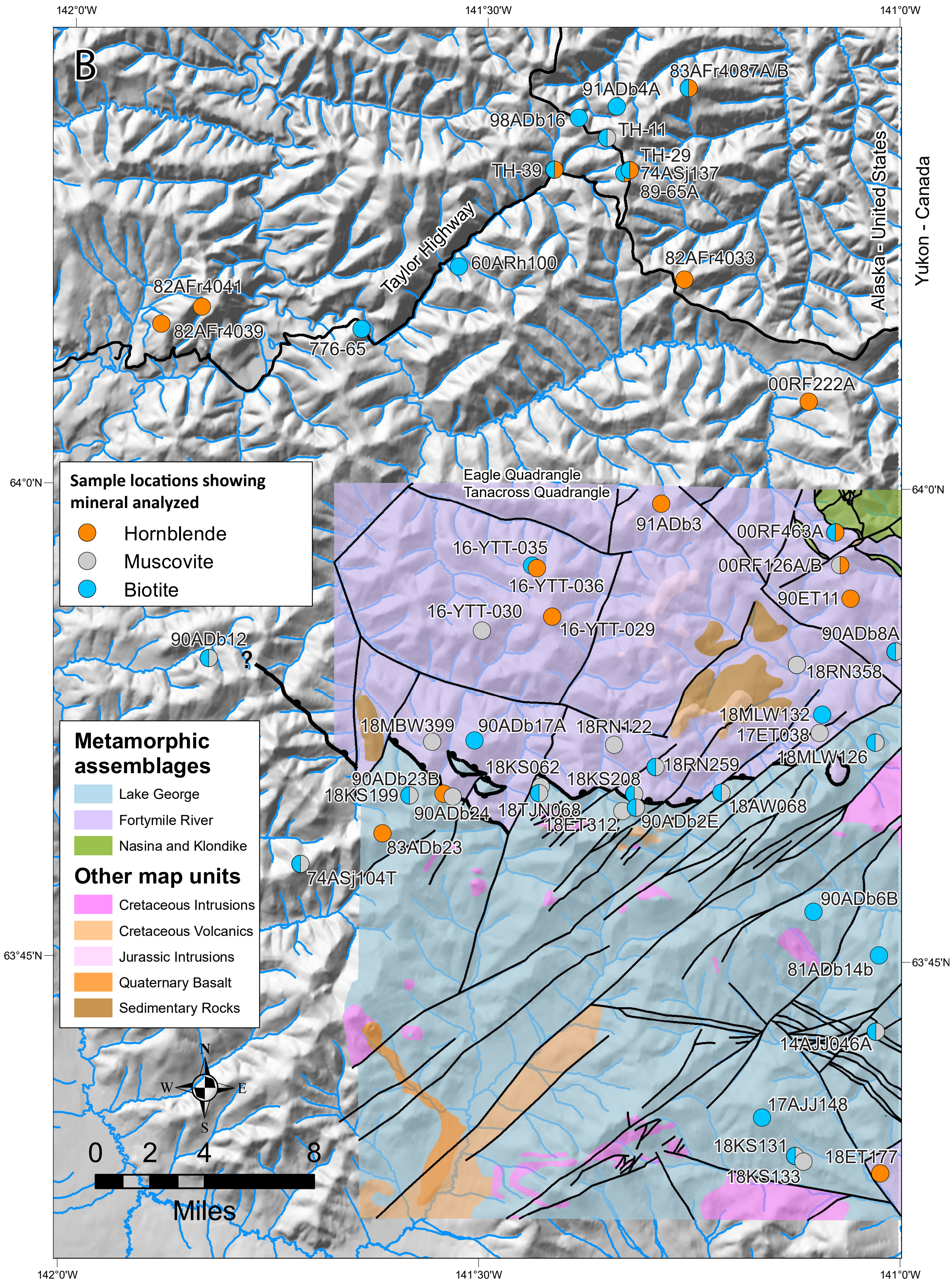

Figure 1B. Sample numbers in the northeast Tanacross Quadrangle and southeast Eagle Quadrangle. Map units and faults are from Wypych and others (2021), including the position of the Fortymile River-Lake George detachment (thick line with teeth on hanging wall).

Table 1. $^{40}Ar/^{39}Ar$ and K-Ar age data in the northeast Tanacross and southeast Eagle quadrangles from metamorphic samples in the Fortymile River and Lake George assemblages. Reported ages are preferred ages with 1-sigma uncertainty. Locations are in the WGS84 datum. Distance (m) is map distance to the Fortymile River-Lake George detachment.

Sample	Mineral	Dating Method	Age Type	Age	Assemblage	Latitude WGS84	Longitude WGS84	Distance (m)	Source
00RF126A	Muscovite	$^{40}Ar/^{39}Ar$	integrated	167.1 ± 0.8	Fortymile River	63.95964467	-141.0719656	12161	Flynn, 2003
00RF126B	Hornblende	$^{40}Ar/^{39}Ar$	plateau	174.4 ± 3.2	Fortymile River	63.95964426	-141.0727822	12161	Flynn, 2003
00RF222A	hornblende	$^{40}Ar/^{39}Ar$	plateau	191.0 ± 1.6	Fortymile River	64.046217	-141.110096	21930	Flynn, 2003
00RF463A	Biotite	$^{40}Ar/^{39}Ar$	plateau	109.3 ± 0.6	Fortymile River	63.97706972	-141.0776282	14113	Flynn, 2003
00RF463A	Hornblende	$^{40}Ar/^{39}Ar$	plateau	175.7 ± 1.6	Fortymile River	63.97706972	-141.0776282	14113	Flynn, 2003
16-YTT-029	hornblende	$^{40}Ar/^{39}Ar$	plateau	191.6 ± 1.5	Fortymile River	63.93196	-141.4174	9256	Jones, written communication, 2018; Jones and others, 2017
16-YTT-030	muscovite	$^{40}Ar/^{39}Ar$	weighted average	145.5 ± 1.1	Fortymile River	63.92421	-141.50203	8313	Jones, written communication, 2018; Jones and others, 2017
16-YTT-035	hornblende	$^{40}Ar/^{39}Ar$	plateau	189.8 ± 1.3	Fortymile River	63.95756	-141.43656	12066	Jones, written communication, 2018; Jones and others, 2017
16-YTT-036	biotite	$^{40}Ar/^{39}Ar$	plateau	172.6 ± 0.7	Fortymile River	63.95889	-141.44202	12218	Jones, written communication, 2018; Jones and others, 2017
17ET038	Muscovite	$^{40}Ar/^{39}Ar$	weighted average	149.4 ± 2.0	Fortymile River	63.871074	-141.09595	1482	Naibert and others, 2020
18ET177	Hornblende	$^{40}Ar/^{39}Ar$	weighted average	167.1 ± 2.7	Fortymile River	63.638082	-141.023323	23706	Naibert and others, 2020
18MBW399	Muscovite	$^{40}Ar/^{39}Ar$	plateau	163.9 ± 2.7	Fortymile River	63.865231	-141.560388	1452	Naibert and others, 2020
18MLW132	Biotite	$^{40}Ar/^{39}Ar$	weighted average	122.4 ± 2.1	Fortymile River	63.880768	-141.092841	2419	Naibert and others, 2020
18RN122	Muscovite	$^{40}Ar/^{39}Ar$	plateau	161.3 ± 2.9	Fortymile River	63.864276	-141.342487	2490	Naibert and others, 2020
18RN259	Biotite	$^{40}Ar/^{39}Ar$	weighted average	108.2 ± 3.0	Fortymile River	63.852687	-141.292813	1970	Naibert and others, 2020
18RN259	Muscovite	$^{40}Ar/^{39}Ar$	plateau	120.7 ± 2.0	Fortymile River	63.852687	-141.292813	1970	Naibert and others, 2020
18RN358	Biotite	$^{40}Ar/^{39}Ar$	plateau	96.4 ± 2.3	Fortymile River	63.90686	-141.123432	5662	Naibert and others, 2020
18RN358	Muscovite	$^{40}Ar/^{39}Ar$	plateau	152.5 ± 1.9	Fortymile River	63.90686	-141.123432	5662	Naibert and others, 2020
60ACh100	biotite	K-Ar		177	Fortymile River	64.116667	-141.533333	26425	Wilson and others, 2015
74ASj137	biotite	K-Ar		177 ± 5	Fortymile River	64.166667	-141.333333	35805	Wilson and others, 2015
74ASj137	hornblende	K-Ar		182	Fortymile River	64.166667	-141.333333	35805	Wilson and others, 2015
776-65	biotite	K-Ar		99.3 ± 3	Fortymile River	64.083333	-141.65	20676	Wilson and others, 2015
82AFr4033	hornblende	$^{40}Ar/^{39}Ar$	plateau	194 ± 2	Fortymile River	64.110667	-141.260667	29422	Wilson and others, 2015
82AFr4039	hornblende	$^{40}Ar/^{39}Ar$	plateau	213 ± 2	Fortymile River	64.084667	-141.892167	15529	Wilson and others, 2015
82AFr4041	Hornblende	$^{40}Ar/^{39}Ar$	plateau	201 ± 5	Fortymile River	64.094167	-141.843333	17541	Wilson and others, 2015

Table 1, continued. $^{40}Ar/^{39}Ar$ and K-Ar age data in the northeast Tanacross and southeast Eagle quadrangles from metamorphic samples in the Fortymile River and Lake George assemblages. Reported ages are preferred ages with 1-sigma uncertainty. Locations are in the WGS84 datum. Distance (m) is map distance to the Fortymile River-Lake George detachment.

Sample	Mineral	Dating Method	Age Type	Age	Assemblage	Latitude WGS84	Longitude WGS84	Distance (m)	Source
83AFr4087A	hornblende	$^{40}Ar/^{39}Ar$	plateau	204 ± 4	Fortymile River	64.211833	-141.256	40681	Wilson and others, 2015
83AFr4087B	biotite	$^{40}Ar/^{39}Ar$	plateau	187 ± 2	Fortymile River	64.211833	-141.256	40681	Wilson and others, 2015
89-65A	hornblende	K-Ar		175.3 ± 5.1	Fortymile River	64.166667	-141.333333	35805	Wilson and others, 2015
90ADb17A	Biotite	$^{40}Ar/^{39}Ar$	weighted average	165.6 ± 0.8	Fortymile River	63.866167	-141.5095	2960	Dusel-Bacon and others, 2002
90ADb8A	Biotite	$^{40}Ar/^{39}Ar$	weighted average	123.6 ± 0.7	Fortymile River	63.914167	-141.005333	7009	Dusel-Bacon and others, 2002
90ADb8A	Muscovite	$^{40}Ar/^{39}Ar$	platuea	176.8 ± 0.9	Fortymile River	63.914167	-141.005333	7009	Dusel-Bacon and others, 2002
90ET11	hornblende	$^{40}Ar/^{39}Ar$	total fusion	202.4 ± 1.6	Fortymile River	63.942	-141.059	9205	Dusel-Bacon and others, 2002
91ADb3	hornblende	$^{40}Ar/^{39}Ar$	total fusion	186.2 ± 1.3	Fortymile River	63.992	-141.287167	16257	Dusel-Bacon and others, 2002
91ADb4A	biotite	$^{40}Ar/^{39}Ar$	total fusion	185.6 ± 0.4	Fortymile River	64.202	-141.343333	39187	Dusel-Bacon and others, 2002
98ADb16	biotite	$^{40}Ar/^{39}Ar$	plateau	190.4 ± 1.8	Fortymile River	64.195833	-141.389167	37573	Dusel-Bacon and others, 2002
TH-11	biotite	$^{40}Ar/^{39}Ar$	isochron	188.2 ± 1.0	Fortymile River	64.1852	-141.3548	37264	Hansen and others, 1991
TH-11	muscovite	$^{40}Ar/^{39}Ar$	isochron	185.0 ± 0.6	Fortymile River	64.1852	-141.3548	37264	Hansen and others, 1991
TH-29	biotite	$^{40}Ar/^{39}Ar$	isochron	185.4 ± 0.3	Fortymile River	64.1682	-141.327	35963	Hansen and others, 1991
TH-29	hornblende	$^{40}Ar/^{39}Ar$	isochron	187.0 ± 0.2	Fortymile River	64.1682	-141.327	35963	Hansen and others, 1991
TH-39	biotite	$^{40}Ar/^{39}Ar$	isochron	186.1 ± 1.0	Fortymile River	64.1682	-141.4185	34180	Hansen and others, 1991
TH-39	hornblende	$^{40}Ar/^{39}Ar$	isochron	188.3 ± 0.3	Fortymile River	64.1682	-141.4185	34180	Hansen and others, 1991
14AJJ046A	biotite	$^{40}Ar/^{39}Ar$	isochron	120.2 ± 0.8	Lake George	63.71301	-141.0285	15350	Jones, written communication, 2018; Jones and others, 2017
14AJJ046A	Muscovite	$^{40}Ar/^{39}Ar$	plateau	114.1 ± 1.1	Lake George	63.71301	-141.0285	15350	Jones, written communication, 2018; Jones and others, 2017
17AJJ148	Biotite	$^{40}Ar/^{39}Ar$	plateau	108.6 ± 1.0	Lake George	63.667571	-141.164124	20127	Jones, written communication, 2018; Jones and others, 2017
18AW068	Biotite	$^{40}Ar/^{39}Ar$	plateau	90.7 ± 2.0	Lake George	63.839244	-141.213635	934	Naibert and others, 2020
18AW068	Muscovite	$^{40}Ar/^{39}Ar$	plateau	111.2 ± 1.4	Lake George	63.839244	-141.213635	934	Naibert and others, 2020
18ET312	Muscovite	$^{40}Ar/^{39}Ar$	plateau	115.0 ± 1.5	Lake George	63.829381	-141.331759	831	Naibert and others, 2020
18KS062	Muscovite	$^{40}Ar/^{39}Ar$	plateau	112.1 ± 1.6	Lake George	63.841915	-141.429834	587	Naibert and others, 2020

Table 1, continued. $^{40}Ar/^{39}Ar$ and K-Ar age data in the northeast Tanacross and southeast Eagle quadrangles from metamorphic samples in the Fortymile River and Lake George assemblages. Reported ages are preferred ages with 1-sigma uncertainty. Locations are in the WGS84 datum. Distance (m) is map distance to the Fortymile River-Lake George detachment.

Sample	Mineral	Dating Method	Age Type	Age	Assemblage	Latitude WGS84	Longitude WGS84	Distance (m)	Source
18KS131	Biotite	$^{40}Ar/^{39}Ar$	weighted average	106.4 ± 0.3	Lake George	63.647391	-141.124253	22460	Naibert and others, 2020
18KS131	Muscovite	$^{40}Ar/^{39}Ar$	plateau	114.2 ± 2.9	Lake George	63.647391	-141.124253	22460	Naibert and others, 2020
18KS133	Muscovite	$^{40}Ar/^{39}Ar$	plateau	111.2 ± 1.7	Lake George	63.644343	-141.114449	22820	Naibert and others, 2020
18KS199	Biotite	$^{40}Ar/^{39}Ar$	plateau	109.3 ± 1.3	Lake George	63.836759	-141.58707	1716	Naibert and others, 2020
18KS199	Muscovite	$^{40}Ar/^{39}Ar$	plateau	115.8 ± 3.0	Lake George	63.836759	-141.58707	1716	Naibert and others, 2020
18KS208	Biotite	$^{40}Ar/^{39}Ar$	weighted average	106.6 ± 1.4	Lake George	63.838378	-141.317977	24	Naibert and others, 2020
18KS208	Muscovite	$^{40}Ar/^{39}Ar$	plateau	115.2 ± 2.0	Lake George	63.838378	-141.317977	24	Naibert and others, 2020
18MLW126	Biotite	$^{40}Ar/^{39}Ar$	plateau	110.4 ± 2.1	Lake George	63.8659	-141.029008	2207	Naibert and others, 2020
18MLW126	Muscovite	$^{40}Ar/^{39}Ar$	plateau	120.9 ± 1.4	Lake George	63.8659	-141.029008	2207	Naibert and others, 2020
18TJN068	Biotite	$^{40}Ar/^{39}Ar$	plateau	110.2 ± 2.1	Lake George	63.838531	-141.431765	947	Naibert and others, 2020
18TJN068	Muscovite	$^{40}Ar/^{39}Ar$	plateau	109.5 ± 1.8	Lake George	63.838531	-141.431765	947	Naibert and others, 2020
74ASj104T	biotite	K-Ar		103	Lake George	63.8	-141.716667	6554	Wilson and others, 2015
74ASj104T	Muscovite	K-Ar		107	Lake George	63.8	-141.716667	6554	Wilson and others, 2015
81ADb14b	biotite	K-Ar		106.7	Lake George	63.753333	-141.025	10440	Wilson and others, 2015
83ADb23	Hornblende	$^{40}Ar/^{39}Ar$	weighted average	117.6 ± 1.2	Lake George	63.816667	-141.618833	4209	Dusel-Bacon and others, 2002
90ADb12	biotite	$^{40}Ar/^{39}Ar$	plateau	110.3 ± 1.1	Lake George	63.908333	-141.829167	2736	Dusel-Bacon and others, 2002
90ADb12	Muscovite	$^{40}Ar/^{39}Ar$	plateau	107.5 ± 0.6	Lake George	63.908333	-141.829167	2736	Dusel-Bacon and others, 2002
90ADb23B	Hornblende	$^{40}Ar/^{39}Ar$	total fusion	105.7 ± 1.3	Lake George	63.837833	-141.546333	3	Dusel-Bacon and others, 2002
90ADb24	Muscovite	$^{40}Ar/^{39}Ar$	total fusion	108 ± 0.3	Lake George	63.836333	-141.535333	7	Dusel-Bacon and others, 2002
90ADb2E	Biotite	$^{40}Ar/^{39}Ar$	total fusion	107.6 ± 0.3	Lake George	63.831167	-141.315833	522	Dusel-Bacon and others, 2002
90ADb2E	Muscovite	$^{40}Ar/^{39}Ar$	total fusion	110.6 ± 0.7	Lake George	63.831167	-141.315833	522	Dusel-Bacon and others, 2002
90ADb6B	Biotite	$^{40}Ar/^{39}Ar$	total fusion	107.8 ± 0.3	Lake George	63.776333	-141.103333	7685	Dusel-Bacon and others, 2002

significantly younger than other Fortymile River assemblage samples. Biotite in sample 18MLW132 is interpreted as primary biotite, though biotite observed in thin section around garnet grains could potentially be secondary. Similar color and pleochroism suggest that all biotite formed under similar conditions and cooled at the same time. Cooling ages of 120.7 Ma for muscovite and 108.2 Ma for biotite from sample 18RN259 are also similar to Lake George assemblage cooling ages. Both of these samples were collected along ridges composed primarily of metasedimentary units—including graphitic quartzite—that most closely resemble rocks of the Fortymile River assemblage. Age spectra for biotite separates from both samples stepped up to older ages at higher heating steps. The highest heating steps record ages of 129 Ma for 18MLW132 (represented by over 50 percent of the argon released) and 125 Ma for 18RN259, which predate Lake George cooling, post-date Fortymile River cooling, and might indicate bulk argon loss after initial cooling. We continue to interpret these samples as Fortymile River assemblage based on their similarities with other lithologies common to the assemblage.

A biotite age of 109.3 Ma from a biotite-hornblendite sample in the Fortymile River assemblage was interpreted as the age of a thermal resetting event by Flynn (2003). The thermal resetting event may be related to mid-Cretaceous intrusions and pegmatite dikes in the area. Hornblende from the same sample has a cooling age of 175.7 Ma and is similar to other cooling ages in the Fortymile River assemblage. A K-Ar biotite age of 99.3 Ma from sample 776-65 (Wilson and others, 2015) is also significantly younger than other nearby Fortymile River cooling ages and we do not consider the age to be a reliable cooling age.

A cooling age for hornblende from sample 18ET177 is 167.1 Ma. The sample is from an amphibolite collected in the southeastern corner of the Northeast Tanacross map area (fig. 1). Abundant actinolite was observed in thin section, indicating that the sample has undergone incomplete retrograde greenschist-grade metamorphism of hornblende to actinolite. High Ca/K ratios in high-temperature heating steps used for the weighted-average age indicate the $^{40}Ar/^{39}Ar$ age may be from the retrograde actinolite, a Ca-rich amphibole. We interpret this sample to be from the allochthonous Yukon Tanana terrane and not from the Lake George assemblage as the cooling age is significantly older than Lake George assemblage cooling ages. If the sample is from the Fortymile River assemblage it suggests that the detachment is folded or faulted and that hanging wall rocks are exposed in the area south of the northeast Tanacross map of Wypych and other (2021). This is supported by mapped allochthonous rocks with cooling ages greater than 200 Ma (Jones and others, 2017) in the area around the Ladue River in the eastern Tanacross Quadrangle and across the international border in Yukon.

Parautochthonous Lake George Assemblage

Seven cooling ages for muscovite from Lake George assemblage samples (18AW068, 18ET312, 18KS062, 18KS199, 18KS208, 18MLW126, 18TJN068; fig. 1) from within 5 km (map view) of the Fortymile River-Lake George detachment range from 120.9 to 109.5 Ma (Naibert and others, 2020). Biotite cooling ages from four of these samples (18KS199, 18KS208, 18MLW126, 18TJN068) range from 110.4 to 106.6 Ma. Muscovite from sample 18TJN068 yielded a younger cooling age than biotite from the same sample, but the ages are within analytical error. The other three samples have younger biotite ages than muscovite ages, as expected based the difference in estimated closure temperatures of biotite (304 ± 11°C) and muscovite (410 ± 15°C).

Two samples (18KS131, 18KS133) with muscovite cooling ages of 114.2 and 111.2 Ma were collected from Lake George assemblage schist and orthogneiss about 20 km south of the Fortymile River-Lake George detachment. A biotite age of 106.4 Ma was also measured for sample 18KS131.

These ages are similar to other Early Cretaceous ages for the Lake George assemblage reported by Dusel-Bacon and others (2002) and Jones and Benowitz (2020).

A 90.7 Ma $^{40}Ar/^{39}Ar$ biotite age from Lake George assemblage sample 18AW068 is 15 m.y. younger than other Lake George assemblage biotite samples and over 20 m.y. younger than muscovite from the same location. The age spectrum has young ages at lower heating steps, indicating that a younger alteration or argon loss event affected the biotite after initial cooling. Chloritic alteration of biotite and minor epidote were observed in thin section, indicating the sample experienced some retrograde greenschist-grade metamorphism. The age spectrum does have an acceptable age plateau over the highest heating steps. It is possible that the age and shape of the age spectrum resulted from argon loss during retrograde metamorphism, due to unidentified fluid flow along the nearby Fortymile River-Lake George detachment, or due to unidentified magmatic activity nearby. We hesitate to interpret the 90.7 Ma age as a cooling age for the Lake George assemblage from amphibolite-facies temperatures because it is so much younger than nearby samples.

DISCUSSION

Both the Lake George and Fortymile River assemblages are interpreted by Dusel-Bacon and others (2002) to have reached amphibolite facies metamorphism at temperatures above the $^{40}Ar/^{39}Ar$ closure temperatures of muscovite, biotite, and hornblende, which resulted in diffusive loss of radiogenic argon produced prior to cooling. It is therefore appropriate to interpret data from all three minerals as post-metamorphic cooling ages for the Fortymile River and Lake George assemblages (Warren and others, 2012). Post-cooling neocrystallization of micas is not indicated by the petrographic descriptions in Naibert and others (2020). Dusel-Bacon and others (2002) ascribed $^{40}Ar/^{39}Ar$ ages in the Fortymile River assemblage (between 191 and 185 Ma) to rock uplift during northwest-directed thrusting of the allochthon over North American continental-margin rocks of the Lake George assemblage during the Late Triassic to Early Jurassic. They attribute younger cooling ages (between 120 and 108 Ma) in the Lake George assemblage to a southeast-directed extensional event that caused footwall exhumation below a shallow-dipping ductile detachment. Structural data presented by Hansen and Dusel-Bacon (1998) support this two-stage model of thrusting followed by extension in the Fortymile River and Lake George assemblages in the northeast Tanacross Quadrangle.

$^{40}Ar/^{39}Ar$ ages presented in Naibert and others (2020) are also interpreted to record cooling following amphibolite facies metamorphism. Consistent with results from Dusel-Bacon and others (2002), the $^{40}Ar/^{39}Ar$ ages presented in Naibert and others (2020) indicate that the Fortymile River and Lake George assemblages cooled at different times and rates. However, they differ in that Fortymile River samples within 10 km (map view) of the detachment are 20–40 m.y. younger than Fortymile River samples reported by Dusel-Bacon and others (2002) from 20–35 km north of the detachment. Cooling ages in the Fortymile River assemblage previously reported by Hansen and others (1991), Dusel-Bacon and others (2002), and Wilson and others (2015) were mostly from samples collected along the Taylor Highway in the Eagle Quadrangle (fig. 1). These locations are 20–35 km north of the detachment and have cooling ages 20–40 m.y. older than cooling ages from samples collected closer to the Fortymile River-Lake George detachment reported by Naibert and others (2020). Figure 2 shows these geographical differences in cooling ages from within 20 km of the detachment and cooling ages from more than 20 km from the detachment along the Taylor Highway.

Fortymile River Assemblage

Cooling rates and exhumation rates can be calculated for samples with cooling ages from multiple minerals that have different argon closure temperatures. Hornblende and biotite ages from samples

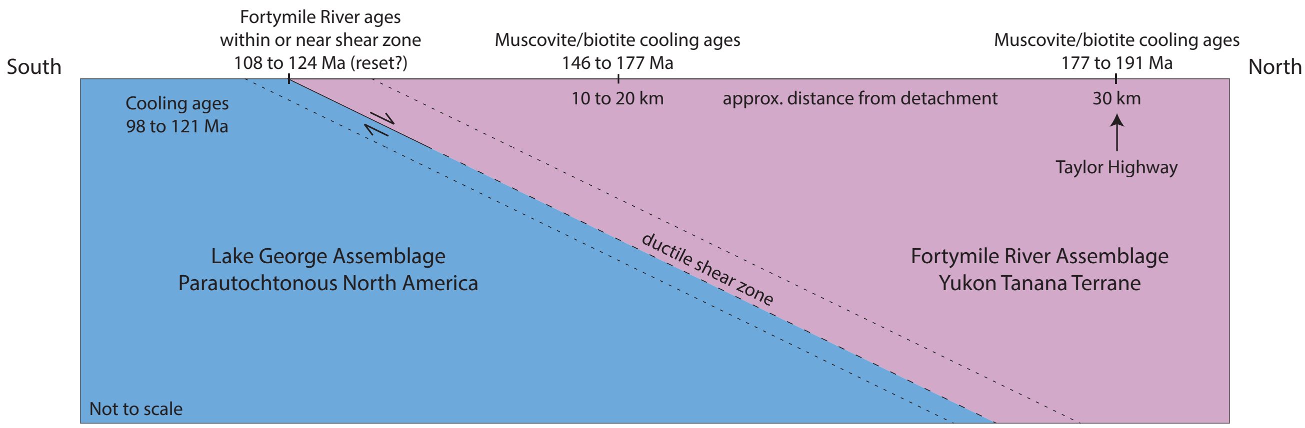

Figure 2. Schematic illustration showing cooling ages in relation to the ductile detachment separating the Fortymile River assemblage of the Yukon Tanana terrane from the Lake George assemblage of parautochthonous North America.

83AFr4087A and 83AFr4087B were collected in the Fortymile River assemblage about 40 km north of the detachment. The cooling ages differ by 17 m.y. (Wilson and others, 2015), indicating a cooling rate of 11.2°C/m.y. using the closure temperatures calculated above and an exhumation rate of 0.4 km/m.y. assuming a geothermal gradient of 25°C/km. Hornblende and biotite ages closer to the detachment (about 12 km) from samples collected less than 2 km apart also vary by over 17 m.y. (16-YTT-035 and 16-YTT-036 in Jones and Benowitz, 2020) and record an exhumation rate of 0.4 km/m.y. Paired hornblende and muscovite ages from 00RF126A and 00RF126B (Flynn, 2003), also 12 km north of the detachment, differ by 7.3 m.y. and suggest a cooling rate of 11.6°C/m.y. and an exhumation rate of 0.5 km/m.y. between 175 and 167 Ma.

Paired biotite and hornblende cooling ages were analyzed from both samples TH-29 and TH-39 (Hansen and others, 1991). These samples were collected from the Fortymile River assemblage along the Taylor Highway more than 30 km from the detachment. $^{40}Ar/^{39}Ar$ cooling ages from these minerals vary by less than 2.3 m.y., and imply cooling rates of 87 to 119°C/m.y. Assuming a geothermal gradient of 25°C/km, the cooling rates suggest very high exhumation rates of 3.5 to 4.8 km/m.y. during the Late Triassic to Early Jurassic thrust event proposed by Hansen and Dusel-Bacon (1998).

The calculated exhumation rates indicate a period of tectonic uplift of 0.4-0.5 km/m.y. between 204 and 167 Ma for a large area north of the Fortymile River-Lake George detachment. A period of more rapid 4 km/m.y. exhumation is implied for an area along the Taylor Highway at around 185 Ma. This exhumation rate is as high as periods of rapid uplift in the eastern syntaxis of the Himalaya (Bracciali and others, 2016) and much higher than other studied orogens. We therefore suggest that rapid uplift was very local or short-lived, or the $^{40}Ar/^{39}Ar$ hornblende and biotite ages from samples TH-29 and TH-39 actually record heating by a nearby unseen intrusion. Early Jurassic plutons have been mapped near the sample locations (Werdon and others, 2001). Alternatively, the apparent rapid exhumation rate could also be a result of misinterpretation of the hornblende cooling ages. We are not able to determine if the hornblende in the samples from Hansen and others (1991) contained phyllosilicate inclusions or exsolution lamellae, since K/Ca ratios were not provided. If phyllosilicate inclusions were present, hornblende closure temperatures would be lower than expected (Baldwin and others, 1990), which would result in calculated exhumation rates being too high. Additionally, if cooling rates were greater than 25°C/m.y. the closure ages used for biotite and hornblende in this modeling would not be valid.

Two Fortymile River assemblage samples with anomalous Cretaceous cooling ages were collected within 2 km of the mapped Fortymile River-Lake George detachment and it is possible that the detachment is a wide shear zone that incorporated slivers of hanging-wall Fortymile River rocks into the footwall during exhumation. If that were the case, then the Fortymile River slivers, represented by samples 18MLW132 and 18RN259, would have been rapidly uplifted and cooled along with the Lake George assemblage (fig. 2). It has also been documented that crustal-scale extensional faults advect sufficient heat in their exhuming footwalls to reset thermochronometers in the overlying hanging walls (Dunkl and others, 1998). Therefore, it is possible that Fortymile River rocks proximal to the detachment were partially reset within or adjacent to the shear zone by hot lower plate rocks. Alternatively, hydrothermal fluid flow in the shear zone from nearby magmatism (e.g. the Cretaceous granite (Kg) south of the detachment) may have provided a heat source for partial resetting of the argon system in the adjacent hanging wall. Though the nearest mapped pluton is kilometers away, abundant aplite and pegmatite dikes with the same age and composition have been mapped throughout the area and could be responsible for local heating of surrounding rocks.

We interpret the Fortymile River-Lake George detachment as a north-dipping shear zone that separates the Fortymile River assemblage (hanging wall) from the Lake George assemblage (footwall). The detachment has been segmented by subsequent left-lateral strike-slip faults, including the Sixtymile-Pika fault zone (Wypych and others, 2021). The dip of the detachment is not well determined but is estimated to be shallow and between 15 and 30 degrees (Wypych and others, 2021). Figure 3 shows K-Ar and $^{40}Ar/^{39}Ar$ cooling ages versus structural distance above or below the detachment, assuming a 15 degree dip to the north. Hornblende cooling ages in the Fortymile River assemblage range from 213 to 175 Ma. Hornblende ages do not vary systematically with structural distance, though hornblende ages have not been reported within 2500 meters of the detachment. The lack of a trend in hornblende ages with distance to the detachment suggests the entire Fortymile River assemblage in the study area cooled through approximately 500°C in the Early Jurassic. Muscovite and biotite ages from more than 6000 m above the detachment range from 194 to 177 Ma. As expected, mica cooling ages are younger than hornblende cooling ages, consistent with lower closure temperatures for the micas. The similar range of cooling ages suggests rapid cooling of Fortymile River assemblage from approximately 500°C to 300°C in the Early Jurassic. At structural distances less than 6,000 m above the detachment muscovite and biotite ages range from 177 to 146 Ma. There may be several interpretations for the younger, more heterogeneous muscovite and biotite ages within 6,000 m of the detachment. It is possible that the cooling from 500°C to 300°C was much slower in this part of the Fortymile River assemblage, though there is no structural data to support a difference in tectonic history between the upper and lower parts of the Fortymile River assemblage. Our preferred interpretation is that young and heterogeneous muscovite and biotite ages represent a Jurassic partial retention zone (PRZ) for micas.

An argon PRZ was defined by Baldwin and Lister (1998) as the range of depths in the crust where temperatures allow radiogenic argon to be partially retained and partially diffused from potassium-bearing minerals. The proportion of argon that is retained will vary with grain size and the residence time in the PRZ. When subsequently uplifted, the apparent age of samples from within the PRZ will be younger than the initial tectonic event and older than later tectonic events. The PRZ depths for different potassium-bearing minerals are related to their closure temperatures, with higher closure temperature correlating with deeper partial retention zones, though the zones can overlap (Baldwin and Lister, 1998). Consequently, all potassium-bearing minerals will record a tectonic event at shallow levels, but at deeper levels, the ages from lower-closure-temperature minerals will be heterogeneous and younger than

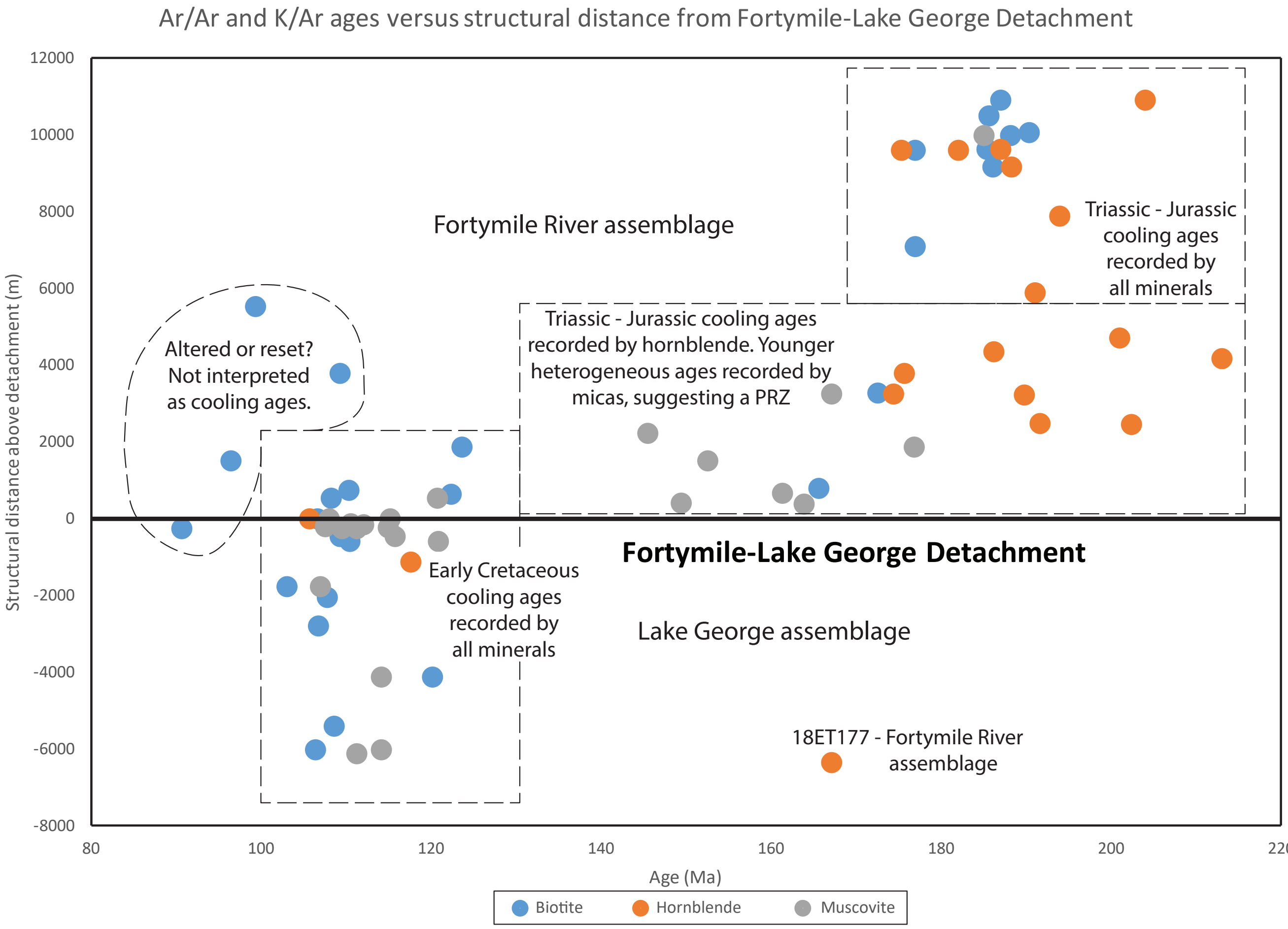

Figure 3. Plot of $^{40}Ar/^{39}Ar$ and K-Ar cooling ages of metamorphic rocks versus structural distance from the Fortymile River-Lake George detachment, assuming a 15 degree north dip on the detachment. Cooling ages of all potassium-bearing minerals from higher structural levels in the Fortymile River assemblage record Late Triassic–Jurassic exhumation. Heterogeneous cooling ages at lower structural levels in the Fortymile River assemblage suggest a fossil partial retention zone is exposed at the surface. Cooling ages in the Lake George assemblage and within the shear zone record Early Cretaceous exhumation due to extension on the detachment.

the tectonic event. The cooling ages in the Fortymile River assemblage from hornblende, muscovite, and biotite record Late Triassic-Jurassic uplift at structural distances more than 6,000 m above from the detachment (fig. 3). Hornblende records similar cooling ages within 6,000 m of the detachment, but mica cooling ages are younger and heterogeneous, suggesting Late Triassic-Jurassic PRZs for both biotite and muscovite (fig. 3). The cooling ages record broad uplift of the Fortymile River assemblage across the northeast Tanacross and southeast Eagle quadrangles and imply subsequent northward tilting of the Fortymile River assemblage to expose the fossil biotite PRZ and muscovite PRZ north of the Fortymile River-Lake George detachment (fig. 4). Cooling ages range from mid-Jurassic to mid-Cretaceous at the structural level of the proposed fossil muscovite and biotite PRZs (fig. 3), with most of the ages between 176 and 146 Ma. The youngest cooling ages in this layer are mid-Cretaceous, which suggests that this structural level of the Fortymile River assemblage cooled below the temperatures of partial argon retention during or after the mid-Cretaceous.

Lake George Assemblage

The Lake George assemblage in the study area is dominated by Mississippian potassium feldspar augen-bearing Divide Mountain orthogneiss

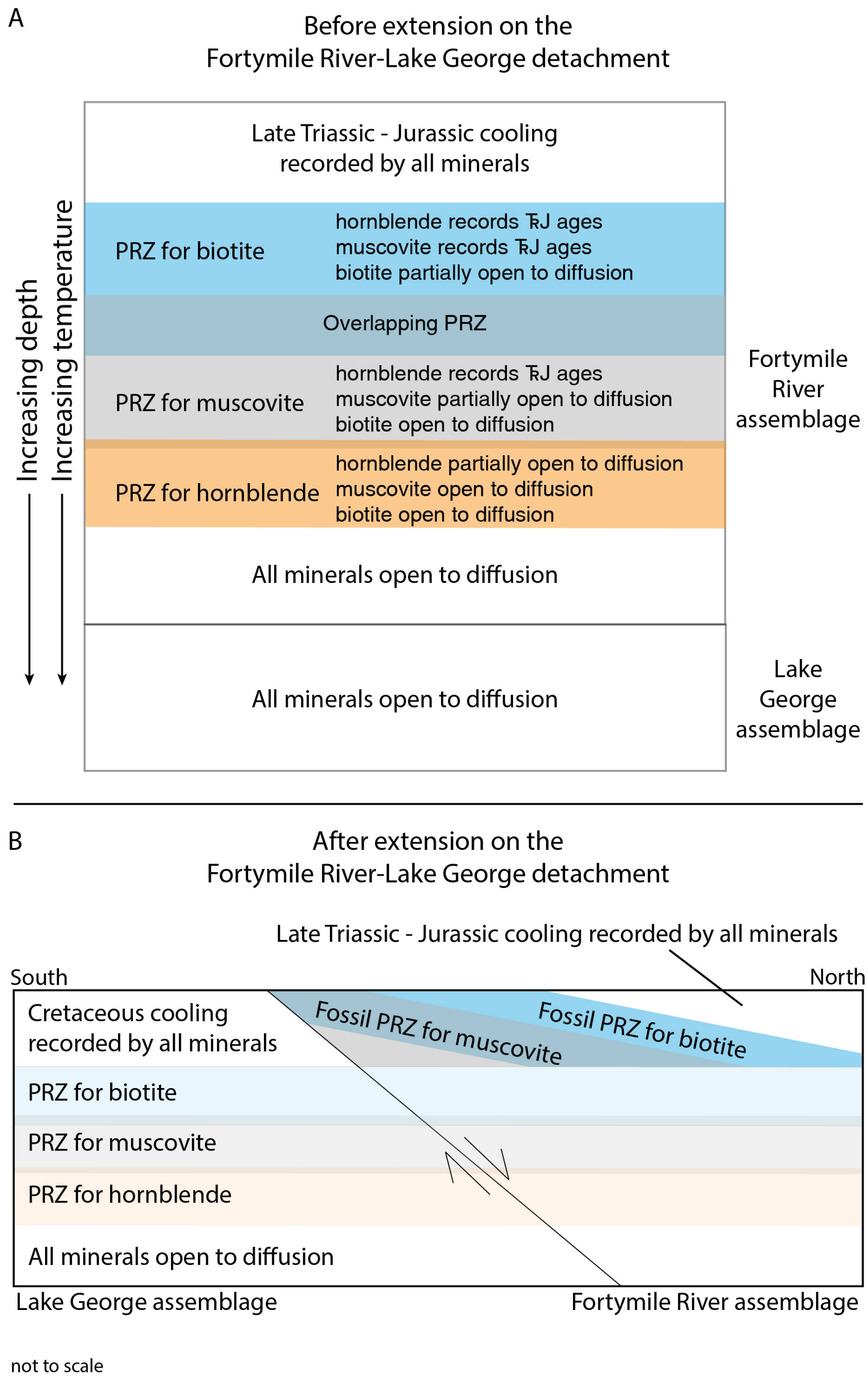

Figure 4. Schematic cross-section showing $^{40}Ar/^{39}Ar$ and K-Ar cooling ages and partial retention zones (PRZ) in the study area. **A.** Expected cooling ages in the Fortymile River assemblage after Late Triassic-Jurassic thrust faulting and before Cretaceous extension on the Fortymile River-Lake George detachment. **B.** Cooling ages in both assemblages after Cretaceous extension on the detachment, showing both present (since the post-Cretaceous) PRZs and fossil Triassic-Jurassic PRZs.

(Wypych and others, 2021). The Cretaceous cooling ages across the map area confirm that the Divide Mountain orthogneiss underwent similar uplift and cooling wherever it is exposed. Therefore, the location of the shallowly north-dipping Fortymile River-Lake George detachment can confidently be mapped north of the northern-most observation of Divide Mountain orthogneiss and north of similar Early Cretaceous cooling ages within other Lake George assemblage units.

Cooling rates between 10.1 and 16.3°C/m.y. were calculated from three paired muscovite/biotite samples from Naibert and others (2020). Assuming a geothermal gradient of 25°C/km, these cooling rates suggest extensional exhumation between 0.4 and 0.7 mm/year between 121 and 106 Ma along the nearby detachment. Slightly higher exhumation rates of 1.1 and 1.4 mm/year were calculated for samples 74ASj104T (Wilson and others, 2015) and 90ADb2E (Dusel-Bacon and others, 2002) with paired muscovite and biotite ages. These samples are all within 7 km of the Fortymile River-Lake George detachment. A cooling rate of 13.6°C/m.y. and an exhumation rate of 0.5 mm/year were calculated for sample 18KS131 from 20 km south of the detachment. The calculated exhumation rate is similar to the rates closer to the detachment. These data support a model of broad uniform uplift and cooling in the Lake George assemblage across the northeast Tanacross Quadrangle between 121 and 98 Ma (fig. 2).

CONCLUSIONS

Our preferred interpretation of exposed structural levels after Triassic-Early Jurassic thrust faulting and Cretaceous extension is shown in figure 4. The Fortymile River assemblage was uplifted during Triassic-Early Jurassic thrust faulting and the northern part of the Fortymile River assemblage around the Taylor Highway was exhumed through the argon closure temperatures of all the potassium-bearing minerals at that time (fig. 4A). The southern part of the Fortymile River assemblage was exhumed through the closure temperature of hornblende during thrust faulting but likely remained at temperatures high enough to allow partial argon diffusion from muscovite and biotite. Exhumation in the Fortymile River assemblage during thrusting was around 0.4–0.5 mm/year. Higher exhumation rates may have occurred locally or over short time periods. Muscovite and biotite partial retention zones were then exhumed during mid-Cretaceous extension on the Fortymile River-Lake George detachment by northward tilting in the hanging wall of the detachment followed by erosional unroofing (fig. 4B). Lake George assemblage rocks in the footwall were exhumed through the argon closure temperature of all three minerals during the mid-Cretaceous (Fig. 4B). Consistent Cretaceous cooling ages and exhumation rates of 0.4 to 1.4 mm/year across the Lake George assemblage suggest broad-scale uplift without major tilting or internal deformation in the footwall of the detachment. One 167 Ma hornblende $^{40}Ar/^{39}Ar$ cooling age from the southeast corner of the study area is presumably Fortymile River assemblage or another allochthonous unit, indicating that the Fortymile River-Lake George detachment may be folded and exposed to the south of the study area. Further geochronology and future mapping is needed to identify allochthonous units in the eastern Tanacross Quadrangle.

Future $^{40}Ar/^{39}Ar$ studies would benefit from dating multiple potassium-bearing minerals at the same location or at nearby locations so that cooling and exhumation rates can be calculated, and so fossil partial retention zones can be identified or verified.

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