CHAPTER D: STRUCTURAL GEOLOGY OBSERVATIONS IN NORTHEAST TANACROSS

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INTRODUCTION

Structure orientations were measured at 951 stations in the northeast Tanacross map area, including measurements of joint planes, minor faults, dikes, foliation and schistosity planes, mineral and crenulation lineations, and fold axes. Shear sense indicators were only noted at a few locations on fault and fracture surfaces and within deformation fabrics. Faults and unit contacts were identified using lithology, magnetic susceptibility, geochemistry, and metamorphic grade at field stations, as well as interpreted from topography, satellite imagery, and published geophysical surveys (Burns and others, 2011; Emond and others, 2015).

Two metamorphic assemblages underlie most of the northeast Tanacross map area. The Fortymile River assemblage consists of amphibolite facies schist, quartzite, and paragneiss, with minor marble, intermediate to felsic metavolcanic orthogneiss, and amphibolite. The Fortymile River assemblage was previously described by Dusel-Bacon and others (2002) and interpreted as part of the allochthonous Yukon-Tanana terrane. The Fortymile River assemblage is intruded by the Late Triassic Taylor Mountain Batholith and several smaller Late Triassic to Early Jurassic plutons (Hansen and Dusel-Bacon, 1998; Werdon and others, 2001; Dusel-Bacon and others, 2002). The amphibolite facies Lake George assemblage is dominated by Mississippian-Devonian potassium-feldspar augen orthogneiss. Paragneiss, quartzite, quartz-mica schist, and granitic orthogneiss (without augen) also appear in the Lake George assemblage as host rocks for the augen gneiss. The Lake George assemblage is interpreted as part of parautochthonous North America (Dusel-Bacon and others, 2002). The Fortymile River assemblage was thrust over the Lake George assemblage during collision of the Yukon-Tanana terrane with North America after the Early Jurassic, and the Lake George assemblage was later exhumed during regional extension (Dusel-Bacon and others, 2002). Both the Lake George and Fortymile River assemblages are intruded by similar Early Cretaceous (100–110 Ma) granite plutons, and aplitic or pegmatitic dikes, which suggests that the two units were juxtaposed at a similar structural level by that time (Naibert and others, 2018).

FOLIATION MEASUREMENTS AND FOLDING

Metamorphic units in the Fortymile River and Lake George assemblages are moderately to strongly foliated, and foliations are dominantly subhorizontal to moderately dipping. Lithologic contacts are parallel to foliation at most outcrops with multiple lithologies, but limited exposure makes it unclear if this relationship is true throughout the field area. Field observations of sub-meter-scale recumbent isoclinal folds of an early generation of foliation are parallel or subparallel to the dominant foliation, which suggests that the dominant foliation is an axial-planar fabric formed after the early generation of folding, or that the early generation of foliation has been transposed by isoclinal folding into the dominant foliation (fig. 1). Outcrop-scale isoclinal recumbent folding was observed mostly in metasedimentary units, and related folding in metaplutonic rocks is likely present at different scales due to different unit thicknesses.

Observed foliations were often broadly consistent between adjacent ridgelines but varied considerably across the field area. Foliations in the Fortymile River assemblage do not have a domi-

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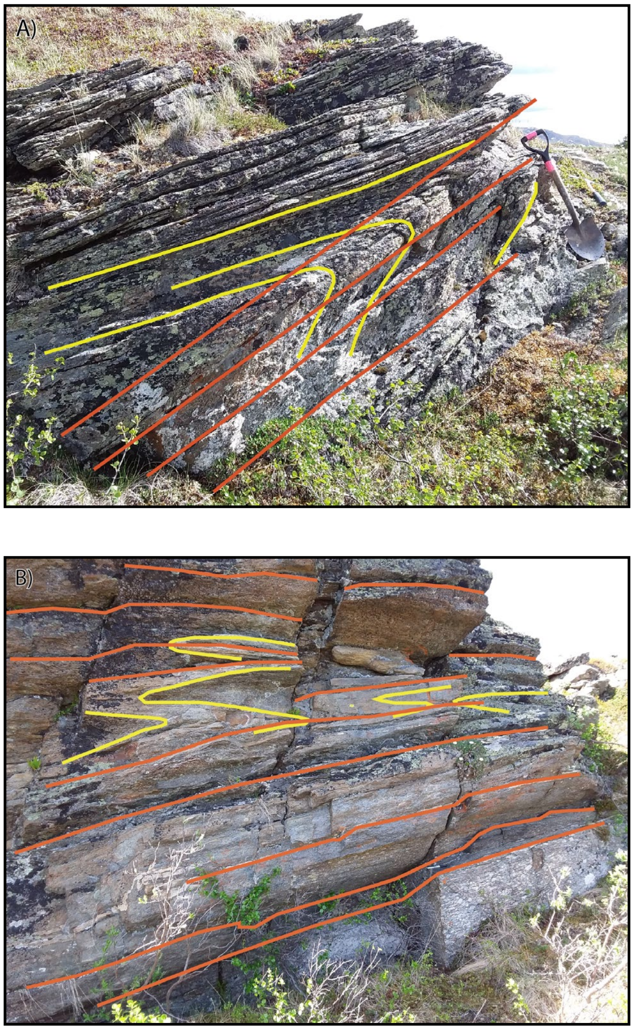

Figure 1. Outcrop photos at (**A**) station 18MBW034 just above the detachment in the Fortymile River assemblage and (**B**) station 18AW070 in the Lake George assemblage. An early foliation (yellow) was observed in some metasedimentary units and is isoclinally folded. A later foliation (red) formed parallel to the axial planes of these folds and is the dominant foliation in the Lake George assemblage.

nant orientation—except that dips steeper than 50 degrees are uncommon (fig. 2A). Foliations in the Lake George assemblage also vary widely, but poles to foliation plot in a wide girdle pattern on a stereonet (fig. 2B), suggesting that Lake George assemblage foliations are folded around a common subhorizontal WNW-ESE axis. This interpretation matches the orientation of outcrop-scale fold axes measured in the Lake George assemblage, which are dominantly NW-SE and gently dipping, irrespective of axial plane orientation (fig. 2C). Outcrop-scale fold axis measurements from the Fortymile River assemblage are similar to those in the Lake George assemblage, despite no dominant foliation pattern at the map scale in the Fortymile River assemblage.

Meter-scale to outcrop-scale folding was observed in both the Fortymile and the Lake George assemblages and ranged from open upright folding to recumbent isoclinal folds. A consistent fold vergence direction was not observed in the field area. Hansen and Dusel-Bacon (1998) previously described open to gentle upright folding with east-west axial traces in both metamorphic assemblages. While map-scale folding is indicated by foliation measurements in a few locations, lack of exposure makes it unclear how extensive large-scale folding is. Identification of large-scale folding is also complicated by later motion on high-angle brittle faults that cut the ductile fabrics (see below).

Comparable meso-scale folding in both the Fortymile River and Lake George assemblages suggests that folding occurred during or after the assemblages were juxtaposed by Triassic to Jurassic thrusting of allochthonous assemblages over continental North America (Hansen and Dusel-Bacon, 1998). Alternatively, folding in the Fortymile and Lake George assemblages could have occurred during ductile extension along a north-dipping detachment (discussed below), which exhumed the parautochthonous Lake George assemblage in the mid-Cretaceous (Hansen and Dusel-Bacon, 1998).

LINEATION MEASUREMENTS AND LOW-ANGLE DETACHMENT

The contact between the Fortymile River assemblage and the Lake George assemblage is poorly exposed across the map area south of Liberty Creek and the Sixtymile River. We concur with the interpretation of Hansen and Dusel-Bacon (1998) that the boundary is a shallowly to moderately north-dipping extensional detachment surface (Fortymile-Lake George Detachment; fig. 3, red lines). Late Jurassic to Early Cretaceous $^{40}Ar/^{39}Ar$ metamorphic cooling ages have been reported for Fortymile River assemblage rocks north of the

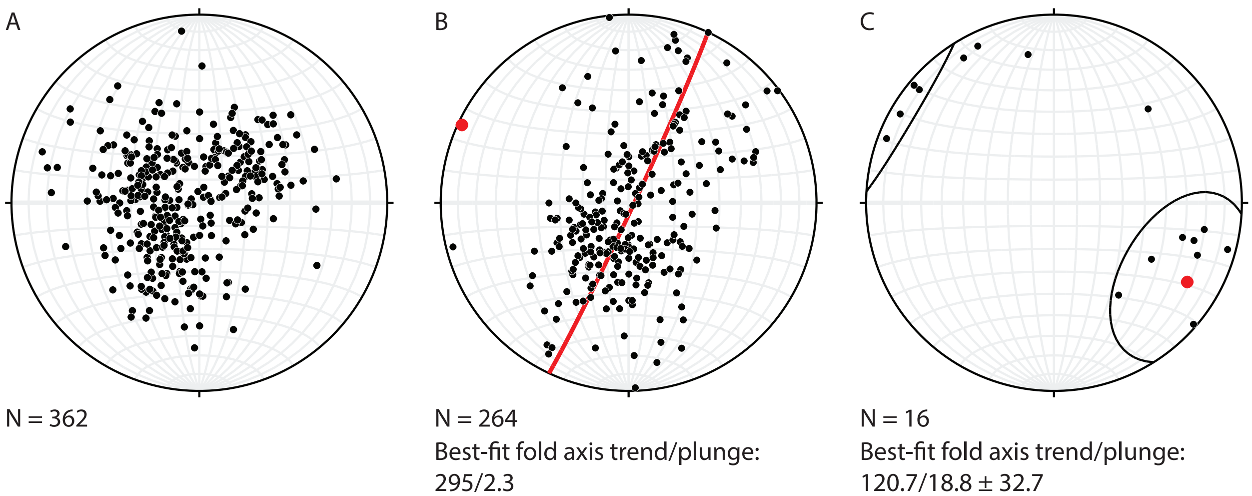

Figure 2. Lower hemisphere, equal-area stereonet plots of (**A**) poles to foliation planes in the Fortymile assemblage; (**B**) poles to foliation planes in the Lake George assemblage including a cylindrical best fit plane and axis (in red); (**C**) trend and plunge of measured fold axes in the northeast Tanacross field area in Fortymile River and Lake George assemblage metamorphic rocks, including a conical best fit axis (in red).

detachment, and Mid-Cretaceous $^{40}Ar/^{39}Ar$ metamorphic cooling ages have been reported for Lake George assemblage rocks south of the detachment (fig. 4; Hansen and Dusel-Bacon, 1998; Jones and others, 2017; Naibert and others, 2020), indicating that crustal extension along the proposed detachment and exhumation of footwall rocks likely occurred during the mid-Cretaceous. The Fortymile River and Lake George assemblages both include significant quartzite, schist, and paragneiss layers, as well as interlayered orthogneiss, and it can be difficult to differentiate the assemblage in the field at the outcrop scale. Where metamorphic cooling ages are available, the detachment has been mapped between stations with mid-Cretaceous (~100–120 Ma) and Jurassic/Early Cretaceous metamorphic cooling ages. Between $^{40}Ar/^{39}Ar$ age locations, the detachment has been mapped north of the northernmost observations of Divide Mountain augen orthogneiss (~355 Ma; Naibert and others, 2021; MDag in Wypych and others, 2021), a definitive unit in the Lake George assemblage in this part of the map area. The detachment is likely an approximately kilometer-wide fault zone in map view (structural thickness of at least 350 m) that extends north into the lower Fortymile River assemblage. Evidence for a broad shear zone includes multiple abrupt changes in foliation- orientation over short distances, increased shear of porphyroclasts and decreasing porphyroclast grain size in orthogneiss within the shear zone, and a pronounced band of conductivity in published electromagnetic surveys (Burns and others, 2011).

Mineral and stretching lineations in both the Fortymile River and Lake George assemblages are dominantly subhorizontal and trend NW-SE (fig. 5A). The exception is a population of mineral lineations in the Fortymile River assemblage between Liberty and Dewey Creeks, which are subhorizontal and trend NE-SW (fig. 5B, shown in green; fig. 3, circled in white). If mineral lineations are interpreted as a reflection of ductile shear sense, then these data are in general agreement with Hansen and Dusel-Bacon (1998), who reported northeast-directed shear sense indicators in the Fortymile River assemblage and northwest- and southeast-directed shear sense indicators in the Lake George assemblage and across the detachment in the lower Fortymile River assemblage. Hansen and Dusel-Bacon (1998) interpreted the northeast-directed shear to be due to Triassic subduction-related compression in the Fortymile River assemblage. Subduction was

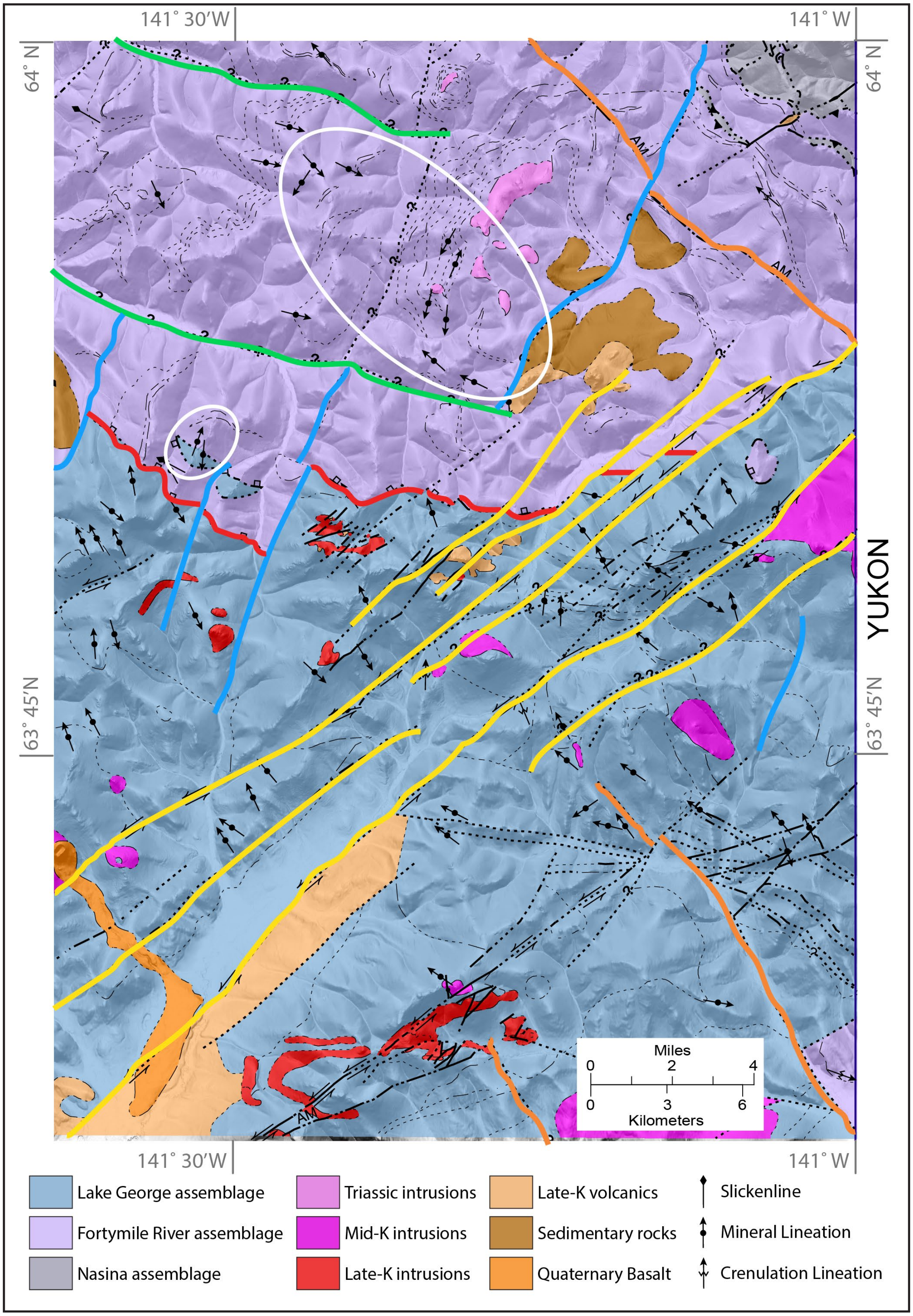

Figure 3. Map of the northeast Tanacross area showing major structures: Fortymile-Lake George Detachment (red); Sixtymile-Pika fault zone (yellow); NE-SW high-angle fault set (blue); WNW-ESE Liberty Creek and Dewey Creek faults (green); and NW-SE high-angle faults (orange). Areas circled in white are a population of NE-SW-trending lineations depicted in figure 5B. Map unit colors are as indicated on the northeast Tanacross Geologic Map (Wypych and others, 2021).

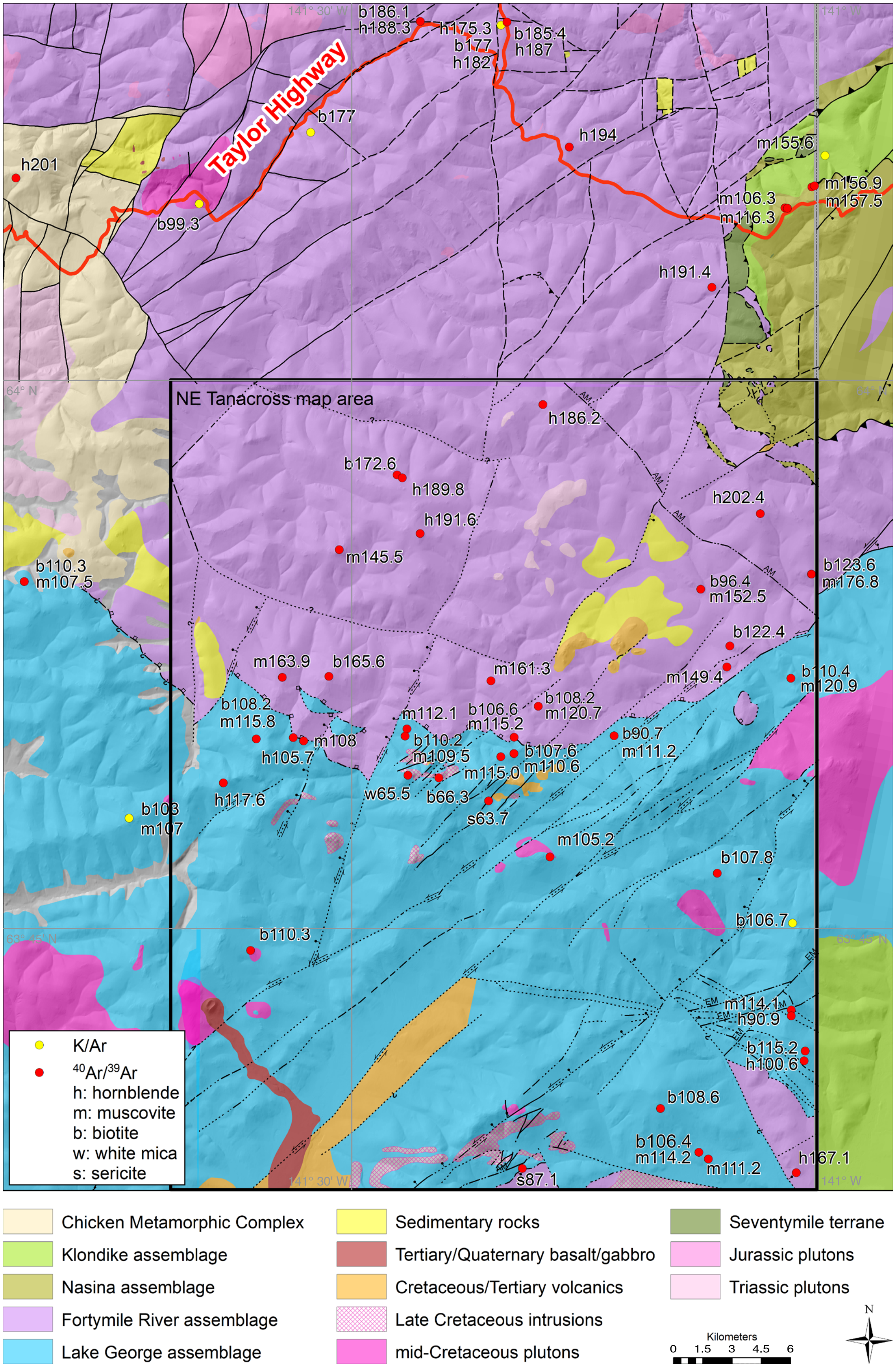

Figure 4. Map of the northeast Tanacross map area and the surrounding area showing $^{40}Ar/^{39}Ar$ cooling ages in the Fortymile and Lake George assemblages near the interpreted low-angle detachment. Ages as reported in Dusel-Bacon and others, 2002; Jones and others, 2017, Wilson and others, 2015, and Naibert and others, 2018, 2020.

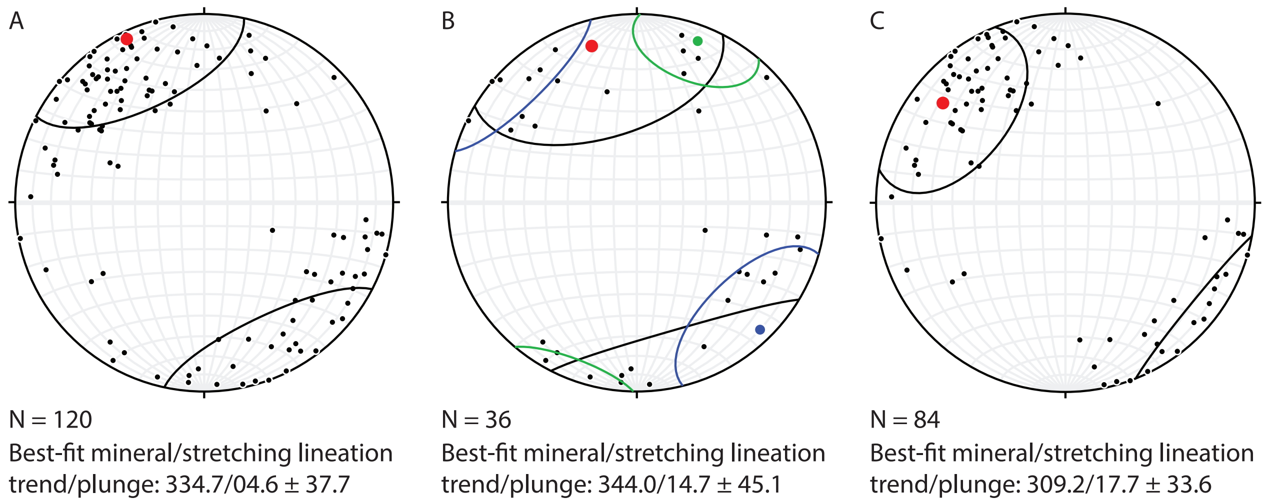

Figure 5. Lower hemisphere, equal-area stereonet plots of (**A**) mineral lineations and stretching lineations in the NE Tanacross field area with NW-SE subhorizontal mean direction. **B.** Mineral lineations and stretching lineations in the Fortymile River assemblage including overall mean direction (red) and the mean directions of two sub-populations (NE-SW population mostly between Liberty and Dewey Creeks in green and NW-SE population in blue). **C.** Mineral lineations and stretching lineations in the Lake George assemblage with NW-SE subhorizontal mean direction.

followed by northwest-directed Jurassic thrusting of the Fortymile River assemblage over the parautochthonous Lake George assemblage. Subsequent southeast-directed mid-Cretaceous extension caused exhumation of the Lake George assemblage. Measured NE-SW stretching lineations between Liberty Creek and Dewey Creek (fig. 5B, in green) may record the earlier northeast-directed compression in the Fortymile River assemblage. The dominant NW-SE orientation of stretching lineations in the Fortymile River assemblage (fig. 5B, in blue), including observations multiple kilometers north of the mapped detachment surface, suggest that evidence of northeast-directed compression was overprinted by subsequent northwest-directed compression or southeast-directed extension throughout much of the Fortymile assemblage in the field area. These observations indicate that NW-SE ductile shear is widespread at lower structural levels within the allochthonous units, as described by Hansen and Dusel-Bacon (1998). Our field data included limited observations of shear sense and it is unclear if the dominant NW-SE lineations recorded across the field area were formed during northwest- or southeast-directed shear, or a combination of both.

HIGH-ANGLE FAULTING

Few direct fault measurements were possible in the map area due to poor exposure. Minor fault planes measured in the field area did not have a dominant orientation, possibly due to multiple fault generations or to rotation of structural blocks on unmeasured faults. Multiple orientations of high-angle faults cut the map area and were interpreted using field relations, aeromagnetic and electromagnetic surveys (Burns and others, 2011; Emond and others, 2015), and linear stream valleys or aligned topographic saddles along ridges. Interpreted faults were broadly similar to faults identified by Sánchez and others (2014) using a multi-dataset stacking methodology.

The most prominent fault system in the field area is the Sixtymile-Pika fault zone (striking 45–50 degrees) that extends from the Yukon border to the East Fork of the Denison Fork River and offsets the Fortymile-Lake George boundary detachment (fig. 3, yellow lines). The fault zone includes numerous parallel fault strands. We interpret this fault zone to be dominantly left-lateral strike-slip, though a small-scale fault with similar orientation was observed near Divide Mountain with apparent left-lateral-normal oblique slip. We have mapped a series of parallel left-lateral faults throughout the central and southern parts of the map area (Wypych and others, 2021). We mapped similar Cretaceous granites (Kg in Wypych and others, 2021) on both sides of the Sixtymile-Pika fault near the Yukon Border and just west of Prindle volcano. If these granites are part of the same intrusion, then approximately 33 km of left lateral slip has occurred on the Sixtymile-Pika fault system since the mid-Cretaceous. Quaternary basanite flows erupted from Prindle Volcano are likely structurally controlled by the Sixtymile-Pika fault zone and contain ultramafic xenoliths, which resemble mantle material. These observations suggest that the Sixtymile-Pika fault system is a deep feature that extends through the crust.

A second set of sinistral, strike-slip faults exist in the map area and have strikes from 15 to 30 degrees (fig 3, blue lines). The most prominent of these faults cuts through three saddles just to the east of Dude Creek north of the Fortymile-Lake George boundary detachment. It is unclear if these faults offset, are offset by, or are mutually offsetting the main NE-SW oriented faults. These faults could have formed as R shears to the main Sixtymile-Pika fault set.

Two parallel NW-SE faults (290–300 degree strike) were interpreted within the Fortymile assemblage in the valleys of Liberty and Dewey creeks based on parallel linear valleys (fig. 3, green lines). These faults appear to offset the NE-SW striking faults, but age relationships are difficult to determine due to poor exposure. A fourth set of high-angle faults and aeromagnetic lineations with 300–330-degree strikes are offset by NE-SW striking faults (fig. 3, orange lines). This set of faults could be R' shear to the main Sixtymile-Pika fault set, but it is unclear if these faults are strike-slip or dip-slip from map relations.

Poorly consolidated conglomerates and sandstones (Kc in Wypych and others, 2021) in the northern half of the map area suggest local sedimentary depocenters or preservation of more extensive sedimentary units near some of the mapped faults, possibly due to normal or oblique-normal motion during mid-Cretaceous extension and exhumation of the Lake George assemblage or continuing extension since the Cretaceous. Similar sedimentary rocks in the Mount Fairplay area have moderately to steeply dipping beds (Foster, 1967) indicating post-deposition tilting, possibly due to local faulting. Bedding measurements in sedimentary rocks were not possible in the northeast Tanacross map area due to poor exposure; similar sedimentary rocks were noted at similar elevations on both sides of high-angle faults, ruling out significant throw on these faults. The exposure of Late Cretaceous intrusive rocks near similar age volcanic units in the map area and the adjacent Mount Fairplay area further suggests vertical fault block movement occurred to juxtapose rocks from different depths since the Cretaceous.

DIKES

Granitic dikes with both aplitic and pegmatitic textures are common throughout the map area and are especially clustered in a few areas, including in the area surrounding Cretaceous granite (Kg in Wypych and others, 2021) intrusions near the Yukon border, as well as in the area surrounding Prindle Volcano, and on Hill 3916 west of McElfish Creek. These dikes are likely related to larger Cretaceous granite intrusions. The dikes were observed to be both concordant and discordant with foliation in metamorphic host rocks. Dikes sometimes appear to be folded within the Lake George assemblage. It is possible the dikes intruded along previously folded foliation planes. Weak foliation was rarely observed within the dikes. Dike orientations were similar in both aplite and pegmatite dikes and grouping by texture did not result in any preferred orientations. Both dike textures have similar geochemistry and are part of the same magmatic system. Aplite dikes were often crosscut by pegmatite dikes, indicating the pegmatite phase intruded later, but the two textures also were gradational in some instances, indicating close timing of intrusion.

A muscovite $^{40}Ar/^{39}Ar$ age of 105.2 ± 0.7 Ma from a pegmatite dike is similar to metamorphic cooling ages of the host Lake George assemblage (Naibert and others, 2018), which suggests dike intrusion occurred before or during the mid-Cretaceous extension and uplift of the Lake George assemblage. Measured dike orientations fall into two broad populations: steeply dipping north-south dikes and subhorizontal sills. About 30 percent of dikes do not fit well into either of these populations. The two populations both have better grouping before correction for foliation orientation of their host rocks than after unfolding (fig. 6). This indicates that dikes were likely intruded after ductile folding. The apparent folding of some dikes with the host metamorphic rocks may indicate that dike intrusion did overlap the end of ductile deformation or the apparent folded dikes resulted from intrusion along previously folded foliation planes.

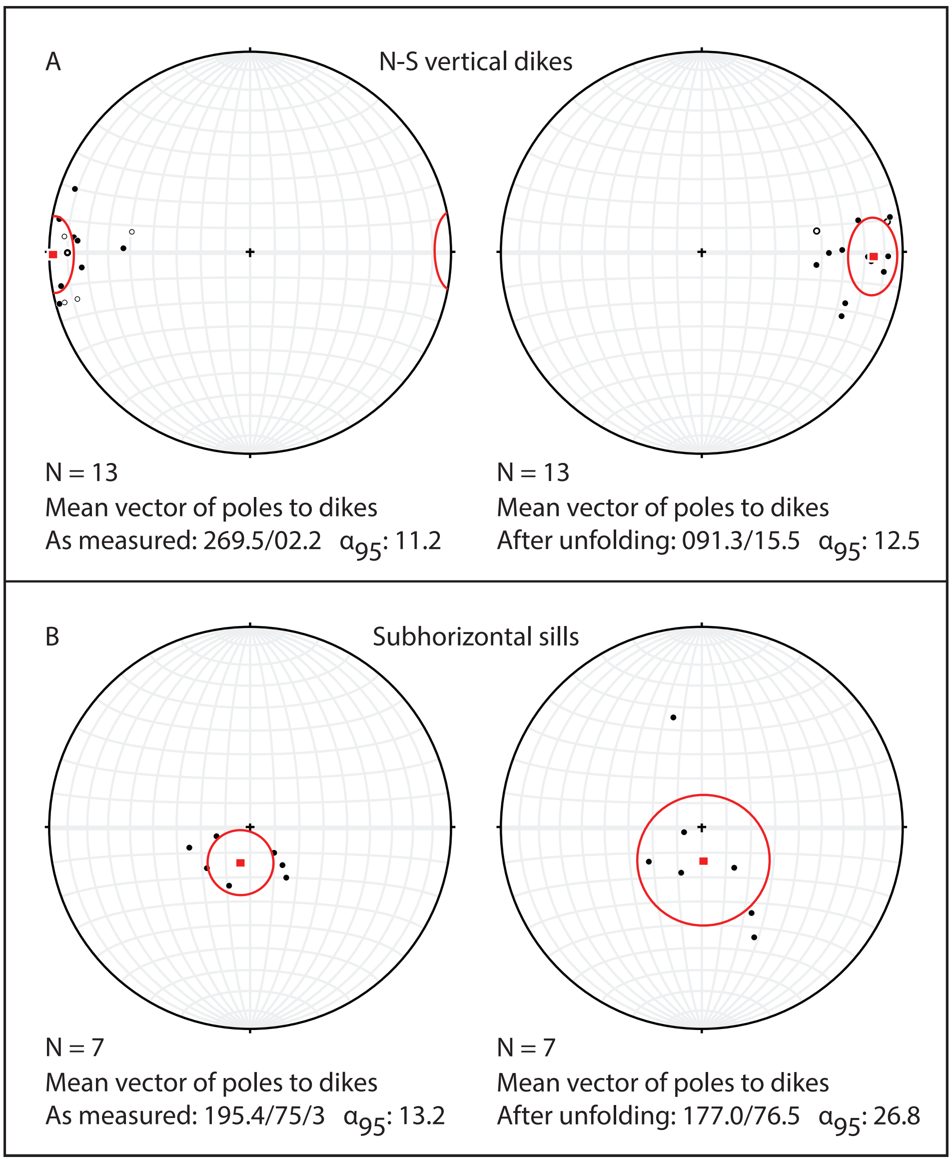

Figure 6. Lower hemisphere, equal-area stereonet plots of poles to two populations of measured dike planes as measured and after unfolding (using foliation measurements taken at the same outcrops). **A.** Data from a population of nearly vertical aplite and pegmatite dikes with north-south strikes. **B.** Data from a population of subhorizontal aplite and pegmatite sills. Closed circles indicate poles in the lower hemisphere and open circles indicate poles in the upper hemisphere. Mean vectors are reported with the half-apical angle of 95 percent confidence (α95). Measurements from both populations are more clustered as measured than after unfolding, indicating that folding in the host rocks occurred prior to dike intrusion.

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