Geochemistry and Age Constraints on Metamorphism and Deformation in the Fortymile River Area, Eastern Yukon-Tanana Upland, Alaska

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Abstract

Determining the age of deposition for many of the major rock types within the Fortymile River area is a major challenge for understanding the geologic evolution of the Yukon-Tanana tectonostratigraphic terrane of east-central Alaska. Intense dynamic metamorphism and associated recrystallization, several periods of ductile deformation, and poor outcrops conspire to conceal the age of the rocks in this important region. Definitive fossil evidence in the marble units has been obliterated; felsic gneissic horizons in the sequence could be either volcanic or intrusive in origin. To help resolve some of these issues, we present new geochemical data to further characterize the bedrock assemblage in the Fortymile River area and to address the origin of the major rock units. In addition, new U-Pb-isotopic data on zircons from the early (pre-D_1) Steele Creek Dome Orthogneiss and from a late tectonic (late-D_2) epidote-bearing leucogranite intrusion help constrain the youngest possible age for the supracrustal rocks, as well as the date of regional D_2 deformation. The Steele Creek Dome Orthogneiss crystallized at 343±4 Ma, indicating that the supracrustal sequence is partly at least Early Mississippian. The leucogranite crystallized during the waning stages of D_2 deformation at 196±4 Ma. U-Pb data on this Early Jurassic leucogranite also indicate that the inherited zircons have a complex history, with analyses yielding ages of 359±5 and 232±7 Ma. Our data confirm earlier $^{40}Ar/^{39}Ar$ ages that suggest an Early Jurassic date for the intense regional D_2 metamorphism and tectonism. However, although we have determined that the sedimentary and volcanic rocks are at least as old as Early Mississippian, the date of deposition for the major supracrustal rock packages in the Fortymile River area of the Yukon-Tanana terrane still remains a major question.

Introduction

This research has resulted from a joint effort by the U.S. Geological Survey (USGS) and the Alaska Department of Natural Resources (ADNR)'s Division of Mining, Land, and Water to establish the baseline geology, as well as the geochemistry of the rocks, soil, and plants and the surface-water quality, of the Fortymile River mining district of east-central Alaska. As part of that effort, we present new data on the geochemical composition and age constraints for rocks of the Fortymile River area. Reliable age data on the protoliths of the metamorphic rocks are some of the most important missing pieces of the puzzle in our understanding of the geologic evolution of the Fortymile River area. To that end, we have obtained new geochemical data to help characterize the bedrock units, and determined new U-Pb zircon ages on two critical units, within the Fortymile River area. These new data, coupled with the pioneering work by Foster (1969, 1976) and Foster and others (1985), as well as the later work by Hansen and others (1991), Dusel-Bacon and others (1993, 1995), Hansen and Dusel-Bacon (1998), and Dusel-Bacon and Cooper (1999), are critical in constraining the ages of bedrock, as well as in dating the ductile deformation, in the vast Yukon-Tanana upland. The geologic time scale of Haq and Van Eysigna (1998) as compiled by Wilson (2001) was used for this report.

Previous Work

Historically, the Fortymile River corridor was an important entry point for mineral exploration, trapping, and commerce during the early days of settlement of the Alaska-Yukon region. Gold placer miners traveled from the Yukon River up the Fortymile River and established communities at Fortymile, Yukon Territory, as well as such settlements as Steele Creek and Chicken, Alaska. Mertie (1938) presented the first regional perspective on the geologic setting of the Yukon-Tanana upland, including the Fortymile River area. Yeend (1996) provided an overview of the historical development of the region, as well as a characterization of the placer resources of the Fortymile River area. Foster (1969, 1976), Foster and O'Leary (1982), Wilson and others (1985), Dusel-Bacon and Hansen (1992), Mortensen (1992), Dusel-Bacon and others (1993), Foster and others (1994), Dusel-Bacon and others (1995), and Hansen and Dusel-Bacon (1998) reported on a series of geologic studies that have led to a better understanding of the regional geologic setting.

In 1997, the USGS initiated a joint research project with the ADNR to assess the effects of placer mining on the water quality of the Fortymile River (Gough and others, 1997; Wanty and others, 2000), as well as to establish the geologic framework of the area (Day and others, 2000), along with the geochemistry of soil, rock, selected vegetation, and surface waters in the area (Crock and others, 1999, 2000). Wanty and others studied the effects of suction dredging in the Fortymile River and bulldozer-operated placer mining on water quality in the area. The reconnaissance geologic study by Day and others (2000) outlined the bedrock types and compositions, as well as the polyphase deformational history, of the area. Their study showed that the earliest recognized ductile deformation (D_1) resulted in isoclinal F_1 folding, a strong regional schistosity (S_1), and an L_1 mineral lineation that is locally preserved. The second episode of ductile deformation (D_2) was associated with intense regional high-grade metamorphism (Dusel-Bacon and others, 1995), tight to isoclinal F_2 folding with coaxial L_2 lineations, and a weak S_2 cleavage that is axially planar to the F_2 folds. The L_2 lineations occur both as stretching and mineral lineations that, where preserved together, are coaxial to the F_2 folds. The youngest recognized folding event (D_3) folded the earlier ductile fabric elements about north- and south-plunging, eastward-vergent open F_3 folds, which have neither any recognizable axial planar cleavage nor mineral lineations. High-angle brittle faults represent the latest episode of deformation (Newberry and Burns, 2000; Szumigala and others, 2000a), variously uplifting the region along north- to northeast-trending block-bounding faults.

New research by the ADNR's Division of Geological and Geophysical Surveys, as reported by Szumigala (2000), Szumigala and others (2000a, b), and Werdon and others (2000), is leading to a clearer understanding of the detailed bedrock geology in the Fortymile River area. Their map patterns show continuous horizons of mafic metavolcanic rocks interlayered with biotite schist and gneissic rocks, all of which have undergone an early episode of deformation (D_1 of Day and others, 2000). They recognized that this early episode of deformation formed large-scale isoclinal to recumbent folds that were refolded during a subsequent ductile event (D_2 of Day and others, 2000). Their mapping further shows that several pulses of intrusions subsequently invaded the supracrustal rocks. Tonalite (for example, the Steele Creek Dome Orthogneiss) and leucogranite bodies crosscut the supracrustal rocks, but some of these bodies have a penetrative tectonic fabric (D_2 of Day and others, 2000), and so their emplacement preceded the regional high-grade dynamothermal recrystallization event discussed by Dusel-Bacon and others (1995). The plutonic rocks help constrain the regional tectonic history inasmuch as they represent temporal piercing points and record the stages of penetrative tectonic fabrics.

Geologic Setting

The Fortymile River area is underlain by several lithotectonic stratigraphic packages (see Dusel-Bacon and others, 1995; Hansen and Dusel-Bacon, 1998). This chapter addresses the geochemistry and geochronology of the "Taylor Mountain assemblage" of Hansen and Dusel-Bacon (1998), one of the most widespread lithotectonic assemblages in the Yukon-Tanana tectonostratigraphic terrane of east-central Alaska (fig. 1). In their report on the bedrock geology of the area, Day and others (2000) followed the terrane terminology established by Hansen and Dusel-Bacon (1998) and referred to the medium- to high-grade metamorphic rocks of the area as belonging to the Taylor Mountain assemblage. However, because of the potential confusion that can arise when discussing both the Taylor Mountain batholith, which is a Late Triassic granitoid body, and metamorphic rocks of the "Taylor Mountain assemblage," which extends far beyond the Taylor Mountain area, we, like other workers (Cynthia Dusel-Bacon, written commun., 2001), now refer to these rocks as the "Fortymile River assemblage."

The Fortymile River assemblage is made up of high-grade metamorphic, polydeformed supracrustal rocks that were intruded by tonalite, trondhjemite, ultramafic rocks, and monzodiorite-diorite-quartz diorite. The metasedimentary and metavolcanic(?) supracrustal rocks include biotite schist and siliciclastic metasedimentary rocks, quartzite, marble, and metagabbro and hornblende-biotite schist of basaltic composition (Dusel-Bacon and Cooper, 1999). The ages of the protoliths of the Fortymile River assemblage are poorly constrained. The intense regional dynamic recrystallization that accompanied high-grade metamorphism (Dusel-Bacon and others, 1995) has almost completely destroyed primary textures within the supracrustal rocks, and so standard fossil studies are almost hopeless. Foster (1976) assigned the metasedimentary rocks to the Paleozoic, using as evidence sparse, poorly preserved crinoid stems at a locality to the west of the Fortymile River area.

Although the primary ages of the protoliths and early (pre-Cretaceous) intrusive rocks are poorly known, cooling ages for the peak metamorphic event have been determined by using both K-Ar (Wilson and others, 1985) and $^{40}Ar/^{39}Ar$ (Cushing, 1984; Hansen and others, 1991) techniques. Wilson and others (1985) reported ages of 175 to 182 Ma on biotite and hornblende in amphibolite and gneiss from the Wade Creek area (fig. 2). Cushing's $^{40}Ar/^{39}Ar$ analysis showed that the metamorphic hornblende ranges in age from 187 to 204 Ma, the muscovite from 185 to 191 Ma, and the biotite from 186 to 188 Ma. Hansen and others (1991) analyzed hornblende and biotite from rocks in the Fortymile River area and reported $^{40}Ar/^{39}Ar$ ages on hornblende of approximately 187 Ma and on biotite of approximately 186 Ma. These data indicate that the Fortymile River assemblage underwent dynamic metamorphism and recrystallization and then cooled rapidly past the $^{40}Ar/^{39}Ar$ hornblende and mica blocking temperatures by about 185 Ma (Early Jurassic). Newberry and others (1998) provided a regional context for plutonism and mineralization by using

$^{40}Ar/^{39}Ar$ analysis of 20 samples from throughout the Yukon-Tanana terrane. They concluded that a regionally extensive Late Triassic and Early Jurassic episode of granitic magmatism occurred within the eastern part of the Yukon-Tanana terrane, followed by mid-Cretaceous calc-alkalic igneous activity.

Szumigala and others (2000a, b) reported new $^{40}Ar/^{39}Ar$ analyses of several plutonic rocks in the Fortymile River area, primarily near Chicken, Alaska. One sample (BL06790; Szumigala and others, 2000b, table 3), from a monzodiorite intrusion north of the confluence of the North and South Forks of the Fortymile River (fig. 2), yielded a hornblende plateau age of 194±2 Ma. This intrusion represents one of several weakly to moderately foliated monzodioritic to quartz dioritic bodies that crosscut the regional

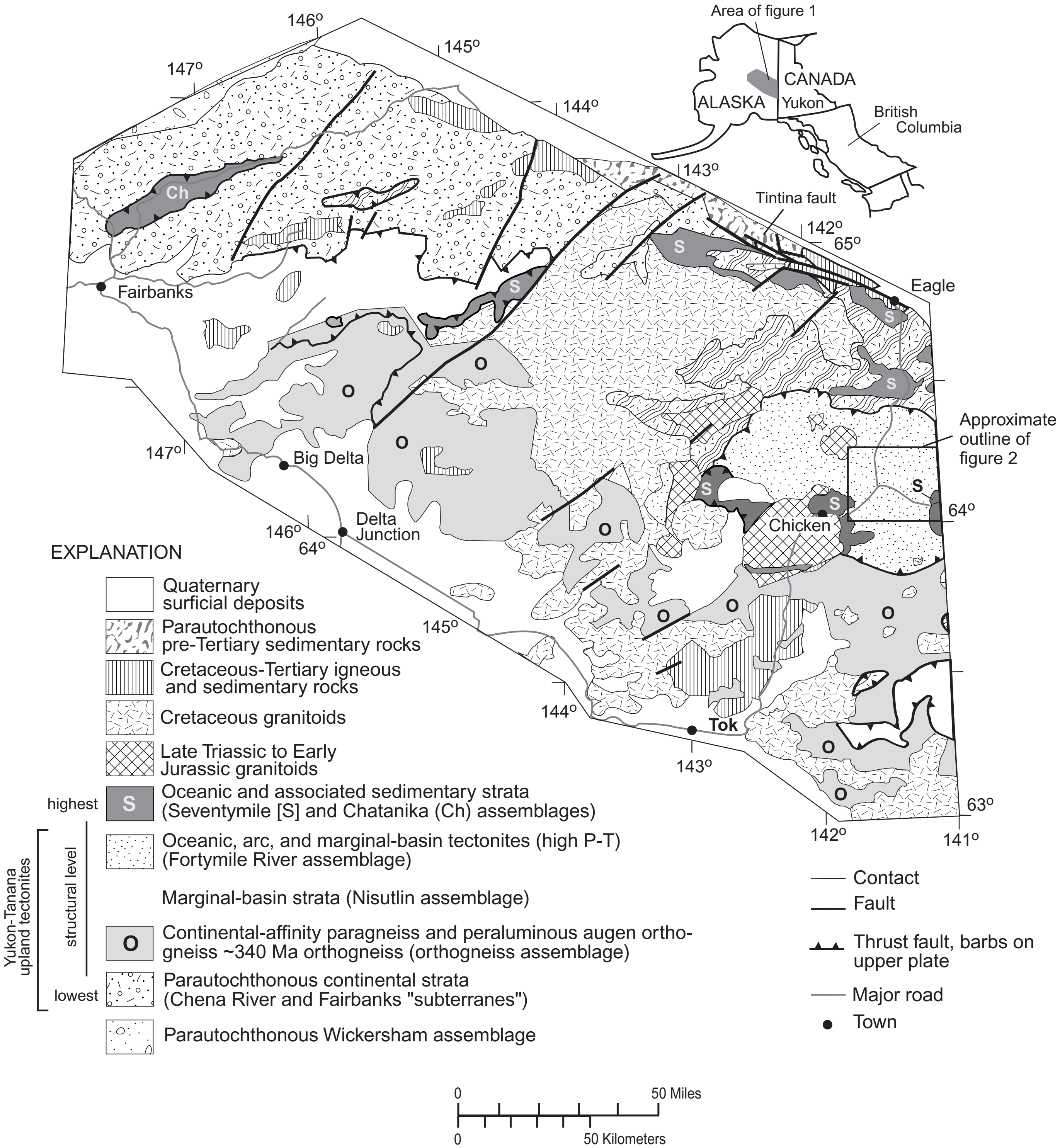

Figure 1. Geologic map of tectonic assemblage of the Yukon-Tanana tectonostratigraphic terrane, east-central Alaska, showing approximate outline of the Fortymile area (fig. 2). Modified after Hansen and Dusel-Bacon (1998).

tectonic S_1 fabric preserved in metamorphosed sedimentary and volcanic country rocks of the Fortymile River assemblage. Day and others (2000) postulated that this intrusive suite was emplaced during the waning stages of peak regional Early Jurassic D_2 tectonism. The importance of this designation is discussed below within the context of the new U-Pb zircon age for a D_2 leucogranite body exposed along the Fortymile River east of Canyon Creek.

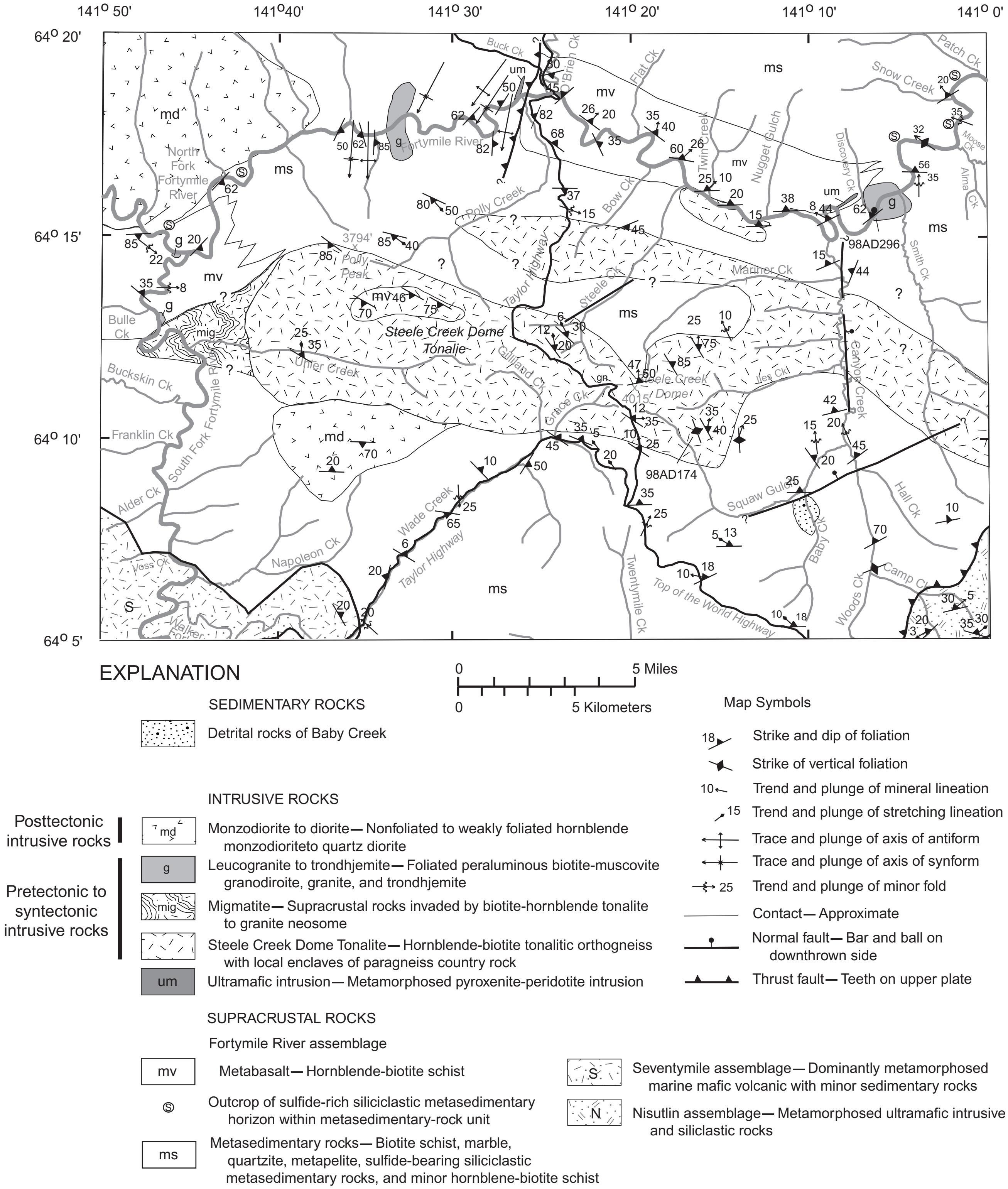

Figure 2. Simplified bedrock geologic map of the Fortymile River area, east-central Alaska (see fig. 1 for location).

Geochemistry

The data discussed here were published in two previous reports: The 97xx sample series used here is from the report by Crock and others (1999), and the 98xx sample series from the report by Crock and others (2000). These combined data sets are discussed here to more fully describe the bedrock geochemistry of the region.

Metavolcanic Rocks

Hornblende-biotite schist and amphibolite of basaltic composition form an important part of the early supracrustal-rock package of the Fortymile River assemblage. The protolith of the mafic schists is thought to be basaltic flows, tuffs, and (or) dikes that were erupted in the original pretectonic host environment; however, the regional metamorphic recrystallization does not allow for a confident classification of the primary mode of deposition. Day and others (2000) recognized two distinct suites of mafic metavolcanic rocks (figs. 3*A*, 3*B*) on the basis of geochemistry: a light-rare-earth-element (REE)-depleted suite (group I) and a light-REE-enriched suite (group II). Group I mafic metavolcanic rocks have light-REE contents with depleted light-REE and relatively flat middle- and heavy-REE patterns (fig. 3*A*). Group II mafic metavolcanic rocks are relatively enriched in light REEs, with a general negative slope with decreasing chondrite-normalized REE patterns through heavy REEs (fig. 3*A*). Although temporal control on the eruption and (or) intrusion of these suites is poorly constrained, the

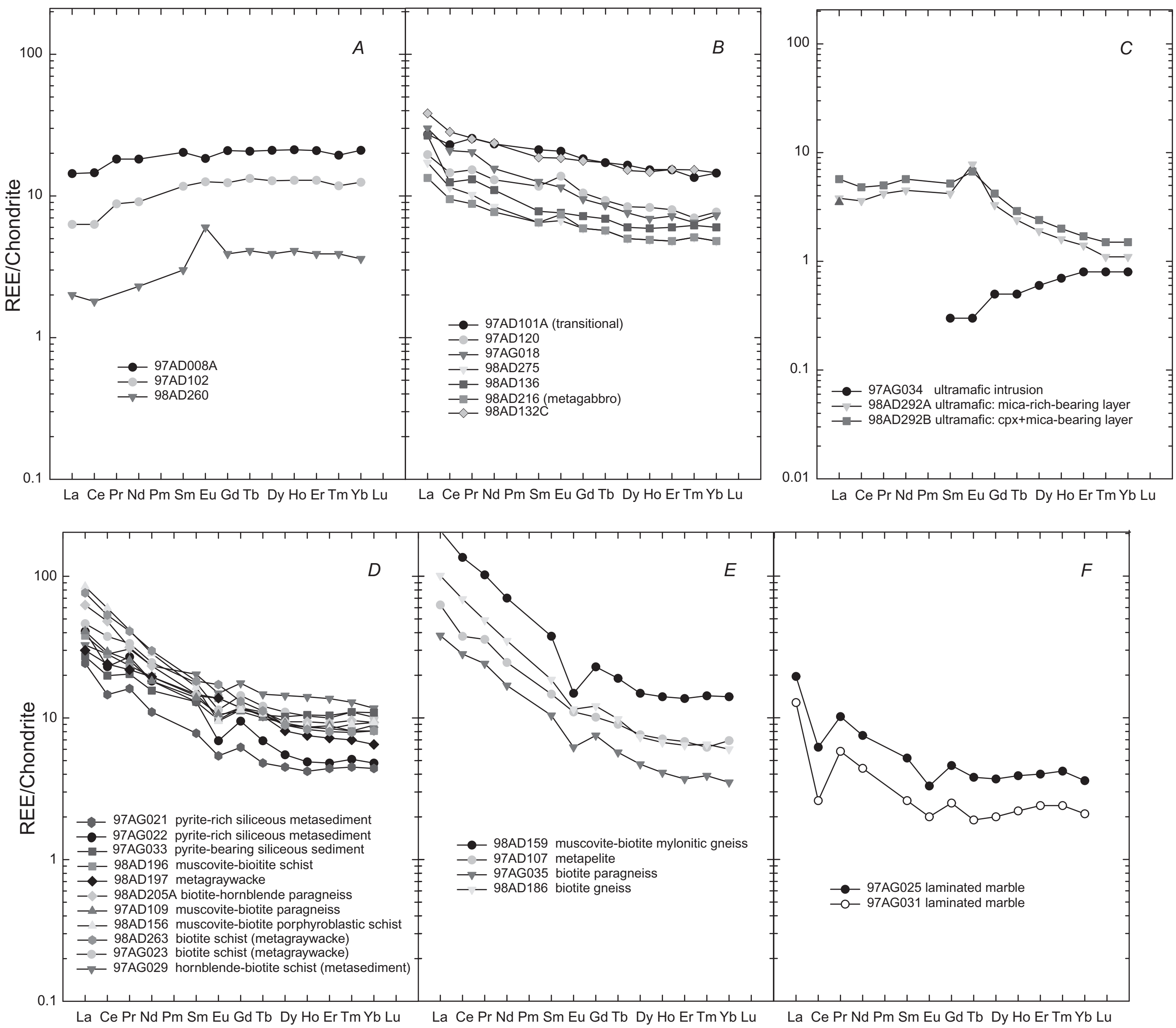

Figure 3. Chondrite-normalized rare-earth-element diagrams for metamorphosed supracrustal rocks of the Fortymile River assemblage. *A*, Group I mafic metavolcanic(?) rocks. *B*, Group II mafic metavolcanic(?) rocks. *C*, Metamorphosed ultramafic rocks. *D*, Siliciclastic metasedimentary rocks (now biotite schist). *E*, Paragneiss. *F*, Laminated marble. Data from Crock and others (1999, 2000).

field evidence is consistent with a coeval history, implying that two distinct mantle sources were being tapped, possibly concurrently, during their (pre-D_1) eruption and (or) intrusion.

In their study of regional metabasaltic rocks from the Yukon-Tanana upland, Dusel-Bacon and Cooper (1999) also deduced two geochemical groups (tholeiitic and calc-alkalic). They concluded that minor- and trace-element abundances indicate that the metabasaltic rocks formed in a volcanic-arc environment. Such a paleoenvironment is supported by field evidence, such as the close spatial association of the metabasaltic rocks with marble, metagraywacke, quartzite, and chert horizons, which, in aggregate, is consistent with an arc or marginal-plate setting.

Ultramafic Rocks

Ultramafic bodies intruded the supracrustal rocks of the Fortymile River assemblage (Foster, 1976). Two such ultramafic bodies are exposed along the Fortymile River west of O'Brien Creek and downstream from the mouth of Canyon Creek (fig. 2). Both intrusions show evidence of regional metamorphism and deformation, suggesting that they were emplaced at least before D_2 and, probably, pre-D_1 tectonism. One sample from the ultramafic body near O'Brien Creek (sample 97AG034, fig. 3*C*) has a relatively depleted light-REE pattern (concentrations are below detection limits) and middle-REE contents. The ultramafic body exposed downstream from Canyon Creek is a layered pyroxenite intrusion with varying amounts of biotite (phlogopite?) alteration. Two samples from the intrusion near Canyon Creek have relatively elevated light-REE patterns, a positive Eu anomaly, and negatively sloping middle- and heavy-REE patterns (fig. 3C). The ultramafic body near O'Brien Creek (sample 97AG034) may represent a mafic cumulate phase petrogenetically related to the group I mafic metavolcanic rocks, whereas the pyroxenite body near Canyon Creek (samples 98AD292A, 98AD292B) may be related to the group II mafic volcanic rocks.

Rocks with Presumed Sedimentary Protoliths

Interlayered with the mafic metavolcanic rocks in supracrustal rocks of the Fortymile River assemblage are horizons of biotite schist—whose protolith probably ranged from graywacke to silicic epiclastic sedimentary rocks—as well as felsic paragneiss and marble. The REE distributions observed in samples of biotite schist, felsic paragneiss, and marble from the Fortymile River area are plotted in figures 3*D*, 3*E*, and 3*F*, respectively. The variations in REE composition of the biotite schist are wide but generally typical of those of Phanerozoic metagraywacke, as reported by Taylor and McLennon (1985). The light-REE contents range from approximately 30 to 90 times chondritic values, and the heavy-REE components of their patterns are relatively flat.

The felsic paragneiss horizons occur interlayered with other supracrustal rocks. These horizons consist of strongly foliated, medium- to fine-grained gray biotite gneiss with compositional layering. The protolith for these felsic paragneiss could be either sedimentary or volcanic layers, however, inasmuch as their primary depositional textures are not preserved, owing to the intensive metamorphic (D_1, D_2) recrystallization. Day and others (2000) noted a distinct absence of demonstrable felsic metavolcanic rocks within high-grade metamorphic rocks of the Fortymile River area. The REE abundances vary widely but overlap those observed in rocks more readily identified as metasedimentary in origin (figs. 3*D*, 3*E*).

Marble commonly is laminated, with metamorphosed clay-rich horizons and thin quartzite horizons. The marble horizons represent metamorphosed carbonate mud and quartz sand-rich interlayers deposited as lithoclastic wackestone, algal beds, and carbonate reef deposits (Day and others, 2000). The REE contents of two marble samples are plotted in figure 3*F*. The overall REE contents of these samples are as low as 20 times chondritic values for light REEs, with pronounced negative Ce and Eu anomalies and flat heavy-REE patterns 2 and 4 times chondritic values. Ce can exist in nature in either a 3+ or 4+ valence state. In marine environments, Ce^{4+} is the dominant valence, and Ce is thought to precipitate onto the sea floor in manganese nodules (Goldberg, 1961; Fleet, 1984), leaving a relative negative Ce anomaly in seawater. Thus, the negative Ce anomaly preserved in these marble samples could represent original Ce depletion in the paleoceanic seawater. The negative Eu anomaly in the marble is less readily explainable but probably also reflects a relative Eu depletion in the local seawater at the time of deposition of the carbonate protoliths.

Steele Creek Dome Orthogneiss and Related Rocks

Day and others (2000) defined the Steele Creek Dome Tonalite as a body, emplaced before D_1 tectonism, made up of tonalite with rafts of supracrustal xenoliths. Subsequent detailed mapping by D.J. Szumigala and coworkers from the Alaska Division of Geological and Geophysical Survey (D.J. Szumigala, unpub. data, 2000), however, has shown that a distinct tonalite intrusion makes up Steele Creek Dome and that several other tonalitic horizons are interlayered with (intrude?) the supracrustal sequence. Their work indicates that the unit is more areally restricted than shown on the bedrock geologic map (fig. 2). As such, the tonalitic samples originally presented by Day and others (2000) as the Steele Creek Dome Tonalite may be petrogenetically related but are not from a single, conterminous intrusion. Therefore, the informally named Steele Creek Dome Tonalite (Day and others, 2000, 2001) is abandoned and herein named the "Steele Creek Dome Orthogneiss."

Each of Day and others' (2000) samples shares similar mesoscopic characteristics, in that they are composed of gray biotite-hornblende tonalite to granodiorite with a medium-grained, foliated texture. REE patterns (fig. 4*A*) vary widely, but all the samples have relatively elevated light-REE contents, varying Eu anomalies, and flat to depleted heavy-REE patterns. The SiO_2 content of the samples ranges from 63.6 to 75.7 weight percent (fig. 4*A*). The least evolved (lowest SiO_2 content) samples (98AD277, 63.6 weight percent SiO_2; 97AG027, 63.7 weight percent SiO_2, respectively) have similar REE patterns that fall in the midrange. The more evolved samples (with higher SiO_2 contents) have divergent REE patterns: The most highly evolved samples are either enriched (sample 98AD178, 70.7 weight percent SiO_2) or relatively

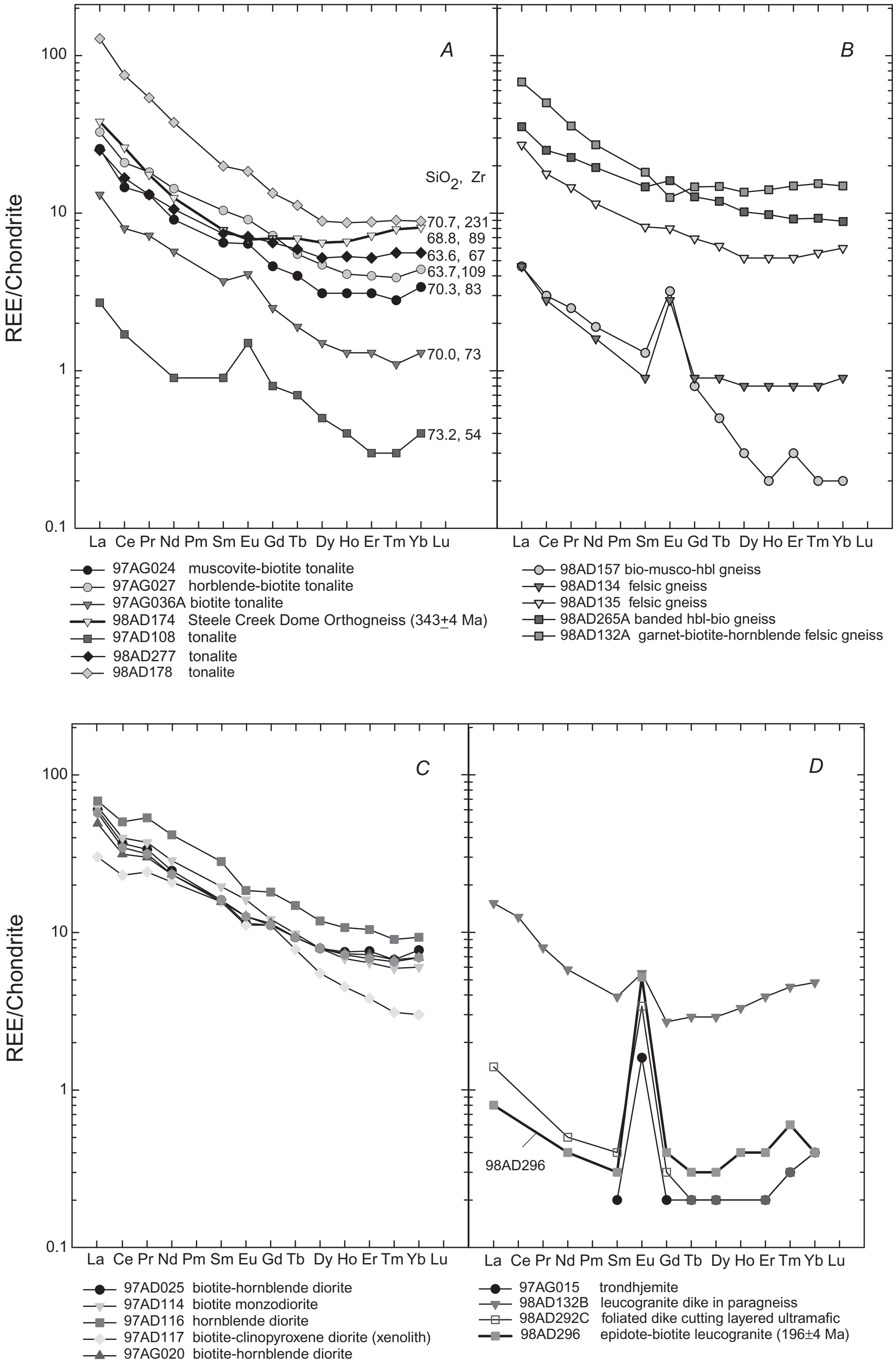

Figure 4. Chondrite-normalized rare-earth-element diagrams for intrusive rocks of the Fortymile River assemblage. *A*, Steele Creek Dome Orthogneiss. *B*, Monzodiorite-diorite to quartz diorite suite. *C*, Horizons of felsic orthogneiss within the supracrustal rocks. *D*, Leucogranite intrusions. Data from Crock and others (1999, 2000).

depleted (sample 97AD108, 73.2 weight percent SiO_2) in total REE content.

There are two possible explanations for the apparent symmetry between the SiO_2 and total REE contents of this rock suite: One is that the SiO_2 and total REE contents are completely fortuitous; the other is that an underlying petrogenetic process links the samples. In the second explanation, the apparent symmetry may reflect intrusion of material from a common parental source that was sampled at different stages of crystal fractionation. Typically, as crystal fractionation proceeds, REEs are partitioned into the silicate melt, assuming that enough of a trace mineral with a high affinity (mineral distribution coefficient, $K_d^{mineral}$>1) for REEs (for example, zircon, monazite, or apatite) has not crystallized in the bulk fractionated material such that the whole-rock distribution coefficient for the REEs is minimal ($K_d^{wholerock}$<<1). When a mineral such as monazite or zircon becomes stable, REEs partition into the residual solid, leaving the resulting silicate melt relatively depleted in REEs, yet its SiO_2 content will continue to increase as crystal fractionation proceeds.

Support for the second explanation is evident in the Zr data (fig. 4*A*), where the least highly evolved (lowest SiO_2 content) samples (97AG024, 98AD277, 97AG027, 98AD174) generally have intermediate Zr contents, ranging from 67 to 109 parts per million. One of the more highly evolved samples (98AD178) has the highest Zr content (231 parts per million, fig. 4A). The samples with the lowest REE contents have high SiO_2 but relatively low Zr contents (samples 97AG036A, 97AD108). In addition, these samples have relatively high modal feldspar contents (Day and others, 2000, table 1). Therefore, the least evolved samples (97AG024, 98AD277, 97AG027, 98AD174) could represent earlier melts that evolved by crystal fractionation into compositions like that of the high SiO_2 and Zr contents in sample 98AD178. As crystal fractionation proceeded, zircon crystallization would result in a depletion of Zr (and the REEs) in the melt, yet the SiO_2 content in the melt will continue to increase, yielding melts that would look something like samples 97AG036A and 97AD108.

Felsic orthogneiss forms interlayers, as much as several meters thick, within supracrustal rocks of the Fortymile River area. The felsic orthogneiss shows no textural evidence for a sedimentary origin, such as the relict sedimentary structures seen in the equally deformed and metamorphosed biotite schist, which had a graywacke protolith. On the basis of REE contents, these rocks fall into two categories: one with relatively high and another with both relatively low REE contents and pronounced positive Eu anomalies (fig. 4*B*). These ranges, which are seen in rocks mapped as the Steele Creek Dome Orthogneiss (fig. 4*A*), may represent tonalitic to granitic intrusive sills or dikes that predated D_1 tectonism. Alternatively, the felsic orthogneiss could represent felsic volcanic rocks that are interlayered within the supracrustal sequence. This second explanation could have significant ramifications, inasmuch as precise, reliable geochronologic (U-Pb zircon) data for the age of deposition for the entire supracrustal sequence are absent. As such, the interlayers of felsic orthogneiss are prime targets for further investigation, although deciding between a volcanic or intrusive lineage will be difficult.

Leucogranite and Trondhjemite Bodies

Leucogranite and trondhjemite occur throughout the Fortymile River area as small intrusions and late-stage dikes that consist of weakly to moderately foliated, light-gray, medium-grained rocks containing biotite and, locally, garnet and epidote. The moderate to weak tectonic foliation and absence of tectonic lineation indicate that the dikes probably were not affected by the entire regional ductile deformational history and, thus, postdate the intense D_1 deformation event. REE patterns are unique in that they have relatively low total REE contents, with a marked positive Eu anomaly (fig. 4*D*) reflecting their high feldspar and low mafic- and accessory-mineral contents. Zircon mineral separates from one such intrusion (sample 98AD296, table 1) were analyzed by using the U-Pb method (see below).

Geochronologic Data

Method

Zircons were extracted from samples weighing 2 to 5 kg, using routine mineral-separation techniques, including crushing and pulverizing, followed by separation with a Wilfley table, Frantz magnetic separator, and methylene iodide. Individually hand-picked zircons were mounted in epoxy, ground to nearly half-thickness by using 1500-grit wet-dry sandpaper, and polished with 6- and 1-µm abrasive. Each grain was photographed in transmitted and reflected light and imaged in cathodoluminescence. All isotopic analyses were done on the USGS/Stanford sensitive-high-resolution-ion-microprobe reverse-geometry (SHRIMP RG) instrument at Stanford University during a 36-hour session. The primary oxygen-ion beam operated at about 8 nA and excavated a pit about 25 µm in diameter and 1 µm deep. The magnet was cycled through the mass stations six times per analysis. Elemental fractionation was corrected by analyzing a zircon of known age (standard R33, 418 Ma; Roland Mundil, unpub. data, 1999) every fourth analysis. The age of each sample was determined by calculating the weighted average of $^{206}Pb/^{238}U$ ages, which accounts for the analytical errors. Raw data were reduced and plotted by using the Squid and Isoplot/Ex programs of Ludwig (1999, 2001); age errors were calculated at the 95-percent-confidence limit.

Sample Descriptions and Results

The new geochronologic data presented here help constrain the youngest possible age of the protoliths for the supracrustal rocks of the Fortymile River assemblage by dating two intrusive phases using the SHRIMP RG technique on zircon mineral separates. One sample (98AD174, table 1) was from the type locality for the Steele Creek Dome Orthogneiss. The

Table 1. Radiometric data on zircons from granitoids of east-central Alaska, using the sensitive-high-resolution-ion-microprobe reverse-geometry (SHRIMP RG) U-Pb analytical method.

[Sample locations: 98AD174, lat 64.1708° N., long 141.2716° W.; 98AD296, lat 64.3604° N., long 141.1179º W. U contents are ±20 percent. $^{206}Pb/^{238}U$, $^{238}U/^{206}Pb$ and $^{207}Pb/^{206}Pb$ ratios, corrected for common Pb, are based on the model of Stacey and Kramers (1975); errors are ±1σ. Constants: $^{235}\lambda=9.8485\times10^{-10}$ yr^{-1}, $^{238}\lambda=1.55125\times10^{-10}$ yr^{-1}, $^{238}U/^{235}U=137/88$ mol/mol (Steiger and Jäger, 1977)]

Sample	Measured $^{204}Pb/^{206}Pb$ ratio	Measured $^{207}Pb/^{206}Pb$ ratio	% common ^{206}Pb	U (ppm)	Th/U ratio	$^{206}Pb/^{238}U$ age (Ma)	Error (Ma)	$^{238}U/^{206}Pb$ ratio	Error (pct)	$^{207}Pb/^{206}Pb$ ratio	Error (pct)
Sample 98AD174, Steele Creek Dome Orthogneiss											
AD174–1.1	0.00031	0.056	0.58	310	0.53	18.12	1.5	0.0509	4	347.4	5.2
AD174–2.1	—	.058	0	202	.3	18.17	1.6	.0585	2.9	343.2	5.6
AD174–3.1	—	.058	0	214	.34	18.06	1.6	.058	2.8	345.5	5.5
AD174–4.1	—	.059	0	153	.35	18.24	1.8	.0591	4.1	341.7	6
AD174–5.1	.00038	.056	.7	227	.48	18.6	2.1	.0499	6	338.9	6.9
AD174–6.1	.00026	.055	.48	446	.48	17.97	1.5	.0516	3	350	5.1
AD174–7.1	—	.056	0	307	.51	19.44	2.2	.056	3	322.1	7.1
AD174–8.1	—	.059	0	144	.3	18.22	1.7	.0592	5.1	341.9	6
AD174–9.1	—	.059	0	225	.39	18.45	1.8	.0593	2.8	337.7	6.1
AD174–10.1	.00048	.059	.88	200	.36	19.05	1.7	.0518	8.7	330.4	5.4
AD174–11.1	.00045	.054	.83	235	.37	18.63	1.6	.0474	8.3	339.5	5.3
AD174–12.1	.00048	.058	.87	189	.32	17.92	1.6	.0509	6.6	351.2	5.6
AD174–13.1	—	.056	0	369	.57	18.21	1.5	.056	2.8	343.5	5.1
AD174–14.1	—	.054	0	164	.41	18.01	1.7	.0541	3.3	348.1	5.8
Sample 98AD296, leucogranite											
AD296–1.1	0.00091	0.059	1.67	205	0	32.55	1.8	0.0456	12.5	196.1	3.4
AD296–2.1	.00024	.056	.45	265	0	32.92	1.7	.0521	5	192.4	3.2
AD296–3.1	.00055	.052	1.02	390	0	33.11	2.2	.0442	11.8	193.2	4.2
AD296–4.1	—	.053	0	1,123	.75	17.45	1.4	.0532	1.2	359.4	4.8
AD296–5.1	.00034	.058	.62	188	.38	30.4	1.8	.0526	6.4	208.1	3.6
AD296–6.1	.00018	.054	.33	580	.01	31.38	1.7	.0512	3.8	201.9	3.4
AD296–7.1	.00013	.051	.24	592	0	27.32	2.8	.0491	3.7	232.3	6.5
AD296–8.1	.00036	.057	.67	544	0	33.2	1.8	.0513	4.7	191	3.4
AD296–9.1	.00021	.052	.38	5,842	.02	31.98	1.4	.0493	2.3	198.7	2.7
AD296–10.1	.0042	.105	7.73	80	0	40.89	3.6	.0422	42.2	157.1	5.3
AD296–11.1	.00021	.052	.39	1,439	.01	33.42	1.4	.0488	2.9	190.3	2.6
AD296–12.1	.00054	.052	1	658	0	32.13	1.8	.0442	7	199	3.6
AD296–13.1	—	.05	0	529	0	31.9	3.2	.0498	2.5	199	6.4

sample is a gray, medium-grained, foliated biotite-hornblende tonalite (fig. 5*A*). The ductile fabric is thought to include D_1 deformation, and so the age of this sample provides a minimum age for protoliths of the metamorphosed supracrustal sequence in the Fortymile River area. Likewise, the age of the Steele Creek Dome Orthogneiss represents a maximum age of the regional D_1 tectonic event.

The other sample (98AD296, table 1) was from a leucogranite body exposed along the Fortymile River downstream from Canyon Creek (fig. 2). This weakly foliated intrusion is composed of medium-grained epidote-bearing biotite leucogranite (fig. 5*B*). The epidote forms equant, subhedral crystals, as large as 1 mm in diameter (fig. 5*B*), which crystallized either before or during the peak of high-pressure metamorphism (D_2). As such, the epidote could be a primary magmatic phase indicating a moderately high pressure (Zen and Hammerstrom, 1984; Hammerstrom and Zen, 1992) of emplacement regime for the leucogranite corresponding to lower-crustal depths, consistent with the conclusions of Dusel-Bacon and others (1995) for the high-pressure nature of the regional Jurassic metamorphism.

The weak foliation indicates that the leucogranite intrusion was emplaced after the main pulses of intense D_1 and D_2 ductile deformation. However, a considerable amount of recrystallization is evident in the groundmass, as well as in some porphyroclasts (fig. 5*B*), indicating that the intrusion underwent some dynamic recrystallization during D_2 tectonism. The weak foliation in combination with the evidence of recrystallization indicates that the leucogranite body was emplaced, at the earliest, during the waning stages of the D_2 tectonism.

Two populations of zircons (elongate and equant) from sample 98AD174 (tonalitic orthogneiss) were analyzed. Cathodoluminescence images of all zircons from this sample show concentric oscillatory zoning, typical of an igneous origin. Most of the grains are light brown, clear, and uncracked and contain a few acicular inclusions. Individual $^{206}Pb/^{238}U$ ages and uncertainties from 13 of 14 grains were averaged to obtain an age of 343±4 Ma (fig. 6). No differences in isotopic systematics or U contents were detected between the two populations (table 1). One analysis was excluded from the weighted average calculation because it gave a slightly younger age of 322 Ma. Because this analysis is from the center of a euhe-

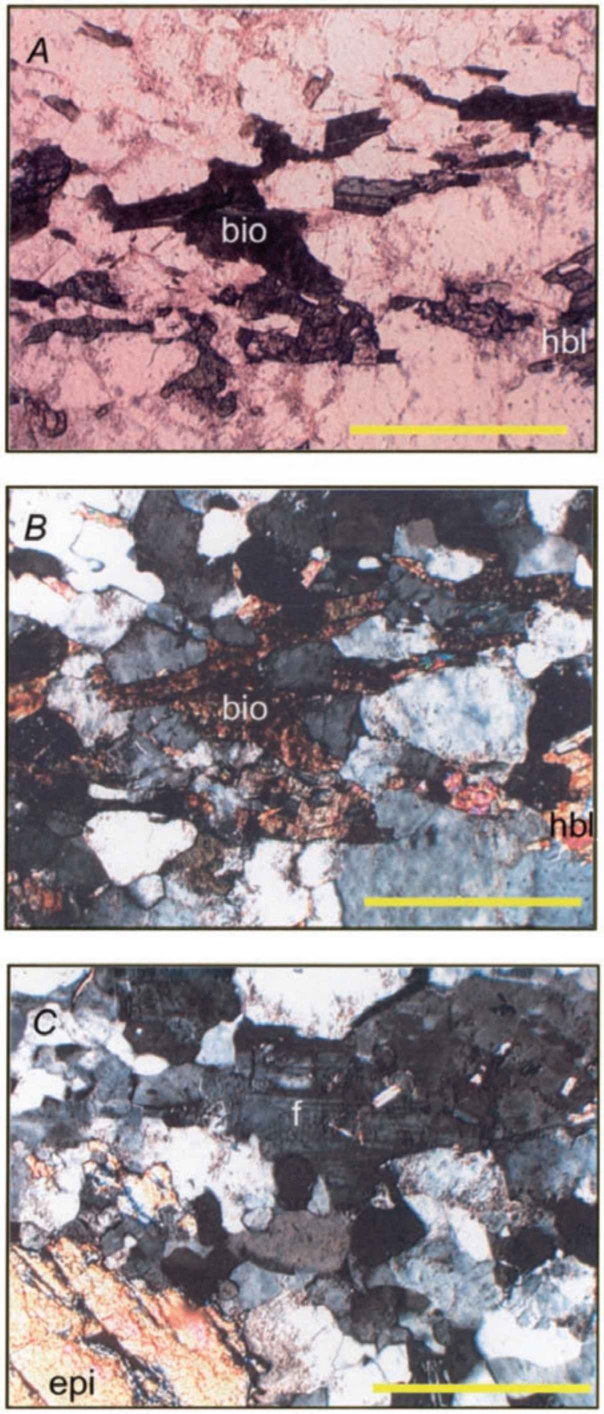

Figure 5. Photomicrographs of samples from the Fortymile River area, east-central Alaska, dated by using sensitive-high-resolution-ion-microprobe reverse-geometry U-Pb method. Bar in each photomicrograph is 0.5 mm long. *A* (plane light) and *B* (crosspolarized light), Sample of Steele Creek Dome Orthogneiss with foliation preserved in biotite (*A*), as well as mortared texture between quartz and feldspar (*B*) recording dynamic recrystallization. *C* (crosspolarized light), Sample 98AD296 (table 1), showing nonfoliated texture of a late-D_2 leucogranite body exposed along the Fortymile River near mouth of Canyon Creek. Note recrystallization (late D_2) of feldspar porphyroblast (center right) and equigranular epidote (lower left). bio, biotite; epi, epidote; f, feldspar; hbl, hornblende.

dral grain, we suspect that this age is due to minor Pb loss, rather than representing an additional event.

Zircons from sample 98AD296 (leucogranite) are medium to dark brown, euhedral, prismatic, and highly fractured (fig. 7). Many contain cores visible in cathodoluminescence and transmitted-light images. The numerous cracks made it difficult to find areas suitable for SHRIMP RG analysis. Individual $^{206}Pb/^{238}U$ ages and uncertainties from 10 analyses were averaged to obtain an age of 196±4 Ma (fig. 6). The relatively high uncertainty probably is due to scatter in the data caused by varying degrees of Pb loss from unavoidable cracks. Thus, this age is a minimum age for the leucogranite. Two older ages were measured: analyses 4.1 and 7.1 (table 1) gave ages of 359±5 and 232±7 Ma, respectively. Analysis 4.1 is of a grain that appears to be a xenocryst; it has a different morphology (that is, it is lighter brown, less cracked, and more stubby) than all the other analyzed zircons from sample 98AD296. Analysis 7.1 is from a rounded core of a cracked grain; the core probably is inherited and acted as a seed around which igneous zircon crystallized at about 196 Ma. Analysis 10.1 (age, 157±5 Ma; table 1) is from the uncracked tip of a zircon. This area of the zircon has a U content of only 80 ppm, much lower than the rest of the grain (as shown by contrasting zoning in cathodoluminescence). This tip appears to be a different generation of zircon than most other grains in sample 98AD296, and because it is undamaged, the young age may represent a distinct event in the region, although more data are needed to verify this hypothesis.

Discussion and Conclusions

The new data presented here place important constraints on the age of the protolith of the metamorphosed supracrustal sequence and on our understanding of the tectonism of the Fortymile River assemblage, as well as of the tectonic and plutonic history of the broader Yukon-Tanana tectonic terrane of Alaska. The assemblage is at least as old as the 343±4 Ma (Early Mississippian) Steele Creek Dome Orthogneiss. Foster (1976) observed crinoid stems in carbonates, indicating that the sequence is probably no older than Cambrian. A study of the morphology of zircons from the horizons of felsic gneiss interlayered within the metamorphic sequence may help constrain their volcanic or sedimentary origin. Even if the protoliths of the felsic gneiss are found to be sedimentary (if the zircons are detrital), because the area is thought to have been developed as juvenile crust in an island-arc sequence, the detrital zircons could reflect the age of volcanism and so yield an important age for the Fortymile River tectonic assemblage. Regardless, the Early Mississippian age presented here yields the oldest possible age for regional deformation, inasmuch as the tonalite was deformed during both D_1 and D_2 events.

Aleinikoff and others (1987) dated an augen gneiss from west of the Fortymile River area in the Big Delta 1:250,000 quadrangle north of Delta Junction, Alaska (unit O, fig. 1) at approximately 343 Ma. This augen gneiss, which is part of the Yukon-Tanana upland tectonites as defined by Hansen and Dusel-Bacon (1998), is essentially equivalent in age to the Steele Creek Dome Orthogneiss. Mortensen (1992) discussed the pre-middle Mesozoic tectonic evolution of the Yukon-Tanana terrane throughout Alaska and Canada. He outlined three main pulses of magmatism, with episodes in

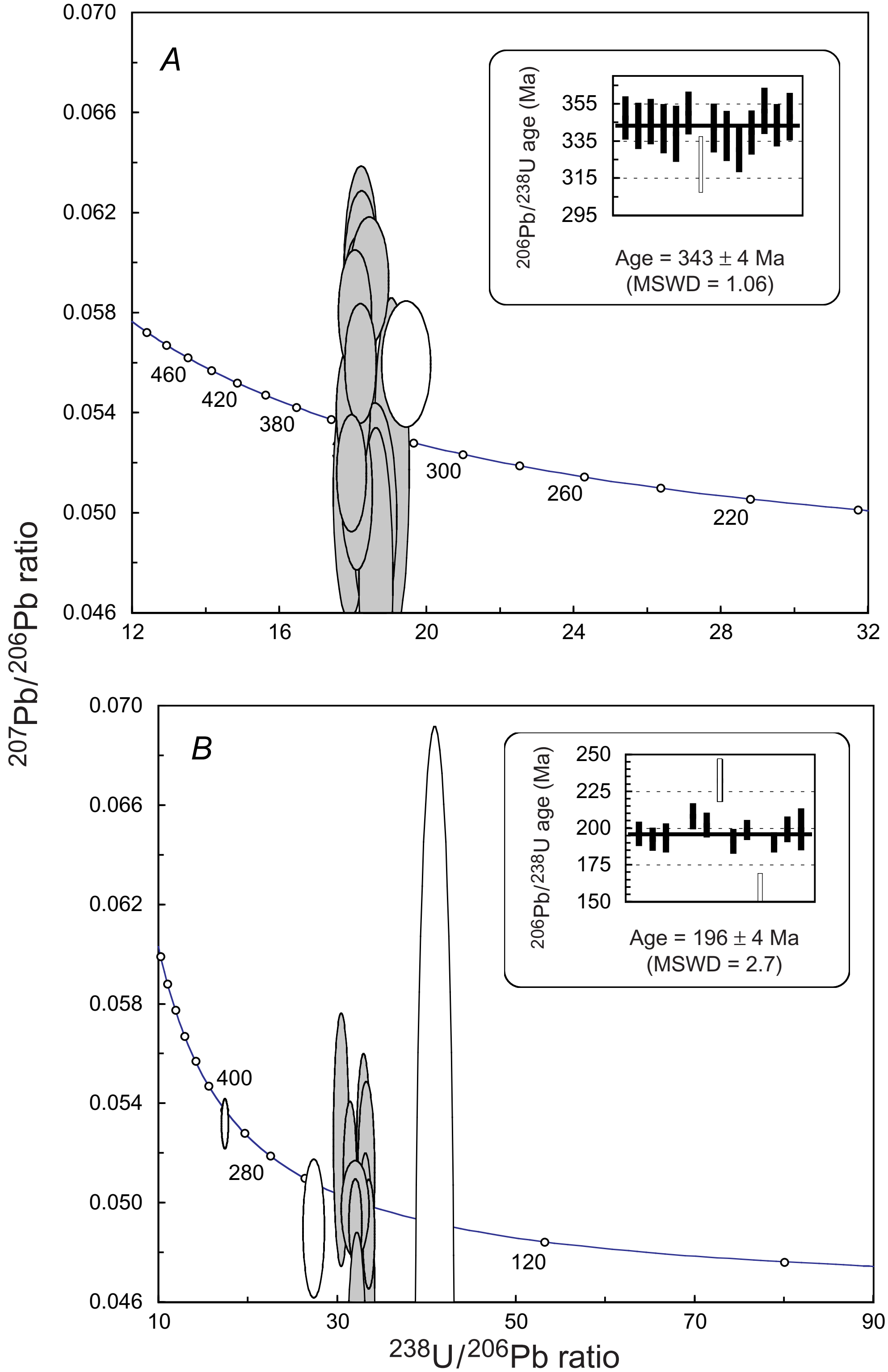

Figure 6. Tera-Wasserburg plots of U-Pb-isotopic data for zircons from the Fortymile River area, east-central Alaska. *A*, Sample 98AD174 (table 1). *B*, Sample 98AD296 (table 1). Error ellipses, 1σ; weighted average error bars, 2σ. Filled error bars, corresponding to filled error ellipses, were used in weighted-average calculations. MSWD, mean square of weighted deviates.

Devonian and Mississippian, mid-Permian, and Late Triassic and Early Jurassic time. Creaser and others (1999) dated eclogites from the eastern part of the Yukon-Tanana terrane in Canada and noted that their basaltic protoliths had diverse origins. They found that eclogites from the Stewart Lake and Simpson Range were generated in a subduction environment and record Mississippian high-pressure metamorphism. Eclogites from Faro, the Ross River, and Last Peak had both midplate basalt and normal midoceanic-ridge basaltic (n-MORB) protoliths with small subduction components and record Permian high-pressure metamorphism and cooling. The Mississippian Steele Creek Dome Orthogneiss was emplaced during the regional Devonian and Mississippian plutonism and deformation observed in the Delta Junction area (Aleinikoff and others, 1987), as well as in Canada (Mortensen, 1992; Creaser and others, 1999). The D_1 tectonic fabrics could have been formed either during the Devonian and Mississippian regional event or during the Permian high-pressure regional metamorphism.

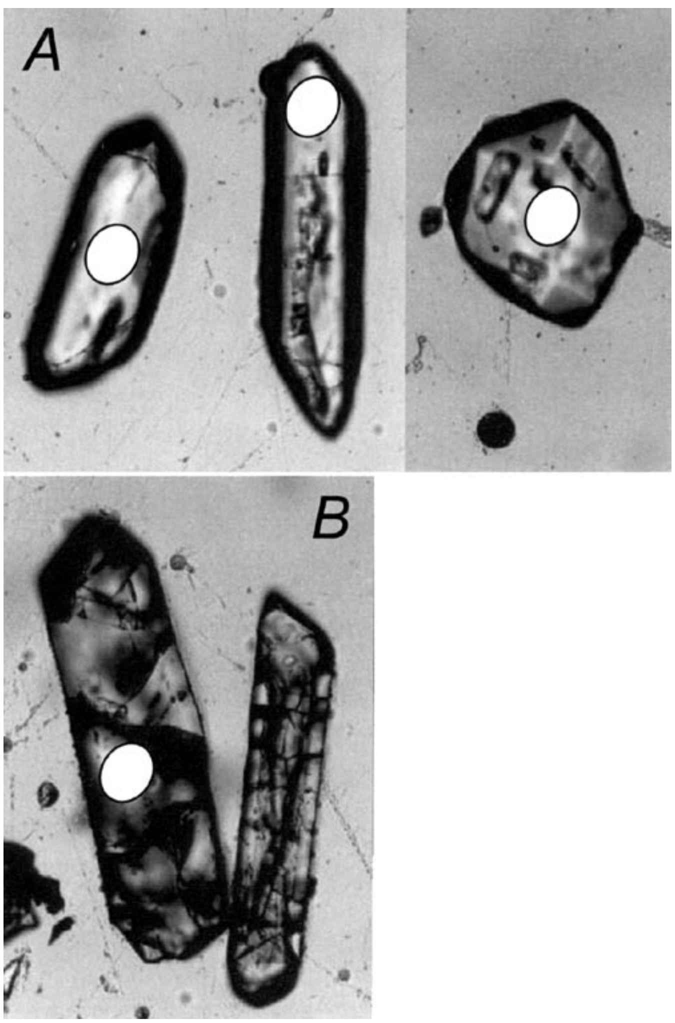

Figure 7. Representative zircons in dated samples from the Fortymile River area, east-central Alaska. White ellipses show locations of sensitive-high-resolution-ion-microprobe reverse-geometry analyses. *A*, Sample 98AD174 (table 1), showing elongate and equant zircons. *B*, Sample 98AD296 (table 1).

The 196±4-Ma crystallization age for leucogranite is essentially equivalent to the K-Ar and $^{40}Ar/^{39}Ar$ ages reported previously (Cushing, 1984; Wilson and others, 1985; Hansen and others, 1991) for the Jurassic regional tectonometamorphic event that affected the Fortymile River assemblage (Hansen and Dusel-Bacon, 1998). It is also equivalent to the age of emplacement of the granitic to granodioritic Chicken pluton (Szumigala and others, 2000a, b), exposed immediately to the southwest of the study area near Chicken, Alaska, and the Jurassic Napoleon Creek pluton, which is a member of the monzodiorite-diorite-quartz diorite suite. These monzodioritic to quartz dioritic bodies are weakly foliated (Szumigala and others, 2000a), which we interpret as indicating emplacement during the waning stages of the regional Early Jurassic deformation (D_2). The 157±5-Ma age (analysis 10.1) may represent a postcrystallization age related to a still-unrecognized event.

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