# Paleozoic tectonic and metallogenic evolution of the pericratonic rocks of east-central Alaska and adjacent Yukon[1]

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## Abstract

*Regionally metamorphosed and deformed greenschist and amphibolite facies metasedimentary and meta-igneous rocks of Paleozoic and Proterozoic(?) protolith age comprise a vast area (~ 300 x 500 km) in east-central Alaska and adjacent Yukon Territory. These rocks crop out in the Yukon-Tanana Upland and the northern flank of the Alaska Range, and have previously been referred to as the Yukon-Tanana composite terrane. They occupy a suspect position in the northern Cordillera, lying between autochthonous or slightly displaced North American strata to the northeast and outboard allochthonous terranes to the southwest. Scattered bodies of weakly metamorphosed oceanic igneous and sedimentary rocks of the Seventymile terrane tectonically overlie, or are imbricated with, greenschist-facies rocks in the Yukon-Tanana Upland. We infer a continental margin setting and original proximity to the North American craton for most*

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[1] Data Repository items *Dusel-Bacon_DR1.xls* (Table DR1), *Dusel-Bacon_DR2.xls* (Table DR2) and *Dusel-Bacon_DR3.xls* (Table DR3) are available on the CD-ROM in pocket.

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*Paleozoic assemblages in the western and southern Yukon-Tanana Upland and the northwestern flank of the Alaska Range, based on quartz-rich metasedimentary protoliths, Precambrian inherited or detrital zircons, and radiogenic Sr and Nd isotopic compositions of meta-igneous rocks. U-Pb zircon crystallization ages in this region indicate prolonged Late Devonian to Early Mississippian magmatism (ca. 378 Ma to primarily ca. 360 Ma). Magmatism was bimodal in composition and most metabasites have within-plate geochemical signatures, as do peralkaline felsic metavolcanic rocks associated with VMS and SEDEX prospects. Other felsic meta-igneous rocks have geochemical signatures similar to average upper-continental crust. We propose that magmatism in these assemblages resulted from attenuation of the ancient continental margin of western North America and formation of a restricted marine basin or submerged continental margin. In contrast, mid-Paleozoic meta-igneous rocks in the northeastern Alaska Range and the eastern Yukon-Tanana Upland (Fortymile River and Nasina assemblages and Chicken Metamorphic Complex) have geochemical signatures indicative of arc and back-arc basin settings. The Fortymile River and Nasina assemblages contain mafic to intermediate Mississippian metaplutonic rocks (ca. 360-341 Ma) and Permian felsic metavolcanic and hypabyssal rocks. We relate attenuation of the continental margin, development of an outboard arc and back-arc region and formation of an intervening Seventymile ocean basin to east-dipping subduction during Devonian to Mississippian time. Subsequent juxtaposition of these elements resulted from southwest-dipping, right oblique subduction during Permian to Early Jurassic time, reflected in arc plutons of that age that intrude only the obducted, originally outboard arc assemblages of east-central Alaska.*

## Résumé

*Régionalement métamorphisées et déformées, des roches métasédimentaires et méta-ignées au faciès schistes verts et amphibolites d'âge protolithique paléozoïque et protérozoïque(?), caractérisent une vaste région (~ 300 km x 500 km) dans le centre-est de l'Alaska et la portion contigue du Yukon. Ces roches qui affleurent dans les Hautes terres du Yukon-Tanana et sur le flanc nord de la chaîne d'Alaska faisaient partie jadis du terrane composite de Yukon-Tanana. Leur position dans de la Cordillère septentrionale est intrigante; elles sont situées entre des strates nord-américaines autochtones ou légèrement déplacées au nord-est, et des terranes allochtones externes au sud-ouest. Ça et là des ensembles de roches océaniques ignées et sédimentaires faiblement métamorphisées du terrane de Seventymile, surplombent tectoniquement, ou sont imbriquées avec des roches au faciès des schistes verts dans les Hautes terres de Yukon-Tanana. La richesse en quartz des protolithes métasédimentaires, la présence de zircons détritiques ou issus du Précambrien, et la composition isotopique en Sr et Nd radiogénique des roches méta-ignées, nous permettent de supposer que la majeure partie des assemblages paléozoïques dans la partie ouest et nord des Hautes terres de Yukon-Tanana et du flanc nord-ouest de la chaîne d'Alaska ont été crées dans un contexte de marge continentale proche du craton nord-américain. Les âges de cristallisation U-Pb sur zircon de cette région indiquent la présence d'une phase de magmatisme prolongée s'étendant du Dévonien supérieur au Mississipien inférieur (~378 Ma à ~360 Ma principalement). Le magmatisme était de composition bimodale, et la plupart des métabasites ont des signatures géochimiques de contexte intraplaque, comme les roches métavolcaniques felsiques hyperalcalines associées aux cibles de gisement de SMV et SEDEX. D'autres roches méta-ignées felsiques ont des signatures géochimiques comparables à la moyenne des roches de la portion supérieure de la croûte. Nous proposons que le magmatisme de ces assemblages résultait d'un amincissement de l'ancienne marge continentale de l'ouest de l'Amérique du Nord et de la formation d'un bassin marin à circulation restreinte ou d'une marge continentale submergée. Par contre, les roches méta-ignées du Paléozoïque moyen de la portion nord-est de la chaîne Alaska et du flanc est des Hautes terres du Yukon-Tanana (les assemblages de Fortymile River et de Nasina, et du complexe métamorphique de Chicken) ont des signatures géochimiques caractéristiques de contextes d'arc et d'arrière-arc. Les assemblages de Fortymile River et de Nasina comprennent des roches métaplutoniques mississipiennes de composition mafique à intermédiaire (~360 à 341 Ma) et des roches métavolcaniques et hypabyssales permiennes. Nous voyons un lien entre un amincissement de la marge continentale, le développement d'une région externe d'arc et d'arrière-arc et la formation d'un bassin océanique Seventymile jouxtant une zone de subduction vers l'est du Dévonien supérieur au Mississipien inférieur. La juxtaposition subséquente de ces éléments est le résultat d'une subduction oblique droite vers le sud-ouest, du Permien supérieur au Jurassique inférieur, attestée par l'intrusion de plutons de cet âge, uniquement au travers des assemblages d'arc externe obductés du centre-est de l'Alaska.*

## INTRODUCTION

Regionally metamorphosed and deformed greenschist and amphiblite facies metasedimentary and meta-igneous rocks of Paleozoic and Proterozoic(?) protolith age comprise a vast area (~ 300 x 500 km) in east-central Alaska and adjacent Yukon. The relationship of this metamorphic province to the ancient Pacific margin of North America has been the subject of long-standing debate (Tempelman-Kluit, 1979; Hansen, 1990; Mortensen, 1992). This enigmatic metamorphic province occupies a critical position within the northern Cordillera, being bounded by the Tintina and Denali dextral strike-slip fault systems and lying between North American continental margin strata to the northeast and allochthonous terranes to the southwest (Fig. 1). Schists and gneisses of metasedimentary origin are generally quartz-rich, suggesting protolith deposition in a continental margin setting, further supported by the presence of Precambrian detrital zircons. These metamorphic rocks crop out in the Yukon-Tanana Upland and the northern flank of the Alaska Range (Fig. 2) and have previously been referred to as the Yukon-Tanana composite terrane (*e.g.*, Foster, 1992; Mortensen, 1992; Dusel-Bacon *et al.*, 1993, 2004; Foster *et al.*, 1994). Additional pieces of the puzzle consist of klippe of weakly metamorphosed oceanic rocks of the Seventymile terrane that tectonically overlie, or are imbricated with, the higher grade metamorphic rocks.

Understanding the nature, affinity and history of this extensive metamorphic province is not only critical to unraveling the history of the ancient Pacific margin of North America, but it also has practical benefits for mineral exploration. Devonian-Mississippian magmatism was widespread throughout the pericratonic tectonic assemblages of the northern Cordillera and many of the volcano-plutonic complexes and associated basinal sedimentary rocks contain volcanic-hosted massive sulphide (VMS) or sedimentary exhalative massive sulphide (SEDEX) syngenetic base-metal mineral deposits (Fig. 1), including several deposits in Alaska (Newberry *et al.*, 1997; Dusel-Bacon *et al.*, 1998). This economic potential, enhanced by recent discoveries of VMS deposits in Devonian-Mississippian metavolcanic rocks in the Finlayson Lake area of southeastern Yukon (Hunt, 1997; Fig. 1), provided a major impetus for our study of the Paleozoic geology of east-central Alaska. Restoration of 430 km of early Tertiary dextral movement along the Tintina fault (Gabrielse *et al.*, in press) juxtaposes these two areas.

The Yukon-Tanana terrane, as defined by Coney *et al.* (1980), has been subdivided into several components on the basis of differing composition and origin of protoliths, Pb isotopes, whole-rock trace-element signatures and structural and metamorphic histories (Churkin *et al.*, 1982; Foster *et al.*, 1985, 1994; Aleinikoff *et al.*, 1987; Hansen *et al.*, 1991; Pavlis *et al.*, 1993; Dusel-Bacon and Cooper, 1999; Dusel-Bacon *et al.*, 2004). Tempelman-Kluit (1976) first proposed a model in which mid-Paleozoic rifting along the continental margin of North America formed an ocean (equivalent to the Seventymile and Slide Mountain terranes) and rifted off a fragment of North America that was subsequently obducted back onto the continental margin during late Paleozoic to Triassic west-dipping subduction. Numerous studies have substantiated this hypothesis and divided the Yukon-Tanana composite terrane in Alaska into a continental component and a rifted and later rejoined (obducted) arc component (*e.g.,* Hansen, 1990; Hansen *et al.*, 1991; Hansen and Dusel-Bacon, 1998; Dusel-Bacon and Cooper, 1999; Dusel-Bacon *et al.*, 2004). All of the continental margin components of the formerly defined Yukon-Tanana composite terrane occur in Alaska (Fig. 1) and the rifted components, composed of mid-Paleozoic through Jurassic arc rocks and marginal basin metasedimentary rocks, extend from the eastern Yukon-Tanana Upland through the Yukon and into British Columbia (Fig. 1). Nelson *et al.* (this volume) retain the term Yukon-Tanana terrane for only the arc and back-arc components of the allochthonous composite terrane and refer to the continental margin components as parautochthonous North America. We discuss the various components and subcomponents of the two-fold division by assemblage or unit names and avoid using the term Yukon-Tanana terrane because of its long-standing prior usage in the literature for both components in Alaska.

This paper focuses on the Paleozoic history of the pericratonic assemblages of both the continental margin and the arc components of east-central Alaska and adjacent Yukon. We utilize U-Pb zircon ages and whole-rock trace-element geochemistry for felsic and mafic meta-igneous rocks, together with paleontologic age constraints and overall lithologic compositions, to address the origins of the various assemblages of metamorphic rocks, their relationship to one another, and to the ancient Pacific margin of North America. U-Pb zircon dates, interpreted as igneous crystallization ages, for Paleozoic meta-igneous rocks from all of the greenschist and amphibolite facies assemblages in east-central Alaska and the adjacent portion of Yukon are presented in Table 1. All the dates tabulated are based on analyses of either individual spots on single grains (by Sensitive High-Resolution Ion Microprobe; SHRIMP), or zircon fractions from a single sample (by Thermal-Ionization Mass Spectrometry; TIMS) that are concordant or only slightly discordant on a U-Pb concordia diagram. We do not report any zircon dates based on regression lines defined by highly discordant analyses (except for two unpublished dates from the Kantishna Hills) or analyses of zircons from multiple samples, as such dates are likely to date a mixture of events and thus have little geological significance. Because the origin of the Seventymile terrane bears directly on the configuration of the ancient Pacific margin, we include it in our discussion. Geologic time scale age boundaries used are those of Okulitch (2002).

## OVERVIEW OF PALEOZOIC ASSEMBLAGES AND UNCERTAINTIES REGARDING THE NATURE OF CONTACT RELATIONSHIPS

Stratigraphic relationships between the various assemblages of the Yukon-Tanana Upland are difficult to decipher due to poor exposure and limited paleontologic and isotopic age control. As a result of the shortage of unambiguous stratigraphic relationships and a paucity of kinematic data, differing hypotheses have been presented for many of the key tectonic relationships in the region. For example, the northwestern margin of the Fairbanks-Chena assemblage (thrust boundary shown on Fig. 2) was interpreted by Foster *et al.* (1983)

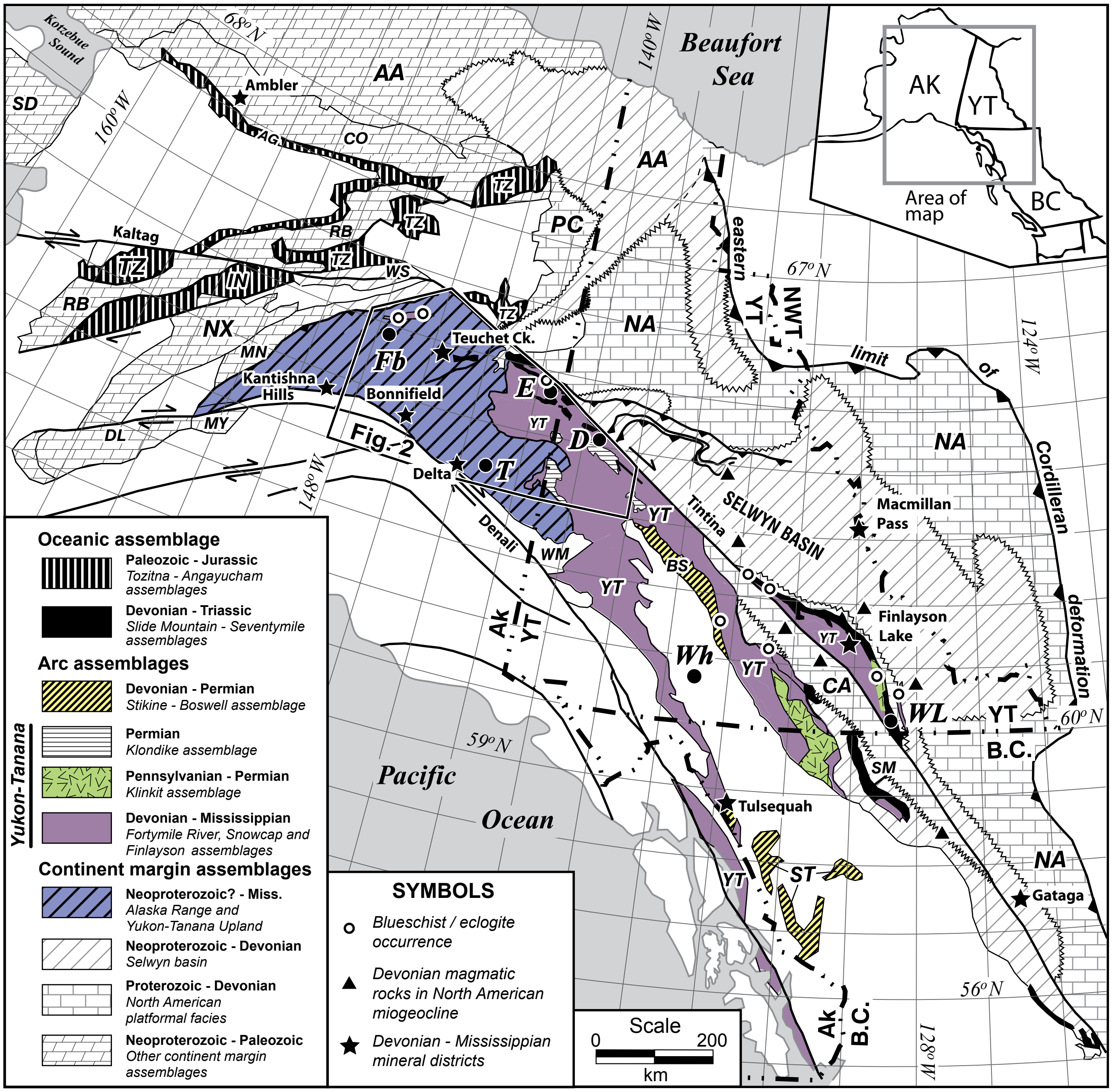


**Figure 1.** *Paleozoic tectonic assemblages of the northern Cordillera (modified after Wheeler and McFeely, 1991; Silberling* et al., *1992; and Foster* et al., *1994). Lithotectonic terranes and assemblages: AA – Arctic Alaska (includes Endicott Mountains, North Slope and Skajit allochthon); AG – Angayucham; CA – Cassiar; CO – Coldfoot (schist belt of southern Brooks Range); DL – Dillinger; IN – Innoko; MN – Minchumina; MY – Mystic; NA – North American miogeocline; NX – Nixon Fork; PC – Porcupine; RB – Ruby; SD – Seward; SM – Slide Mountain – Seventymile; ST – Stikine (Asitka); TZ – Tozitna; WM – Windy-McKinley; WS – Wickersham; YT – Yukon-Tanana in easternmost Alaska, Yukon and B.C. Other abbreviations: AK – Alaska; B.C. – British Columbia; D – Dawson; E – Eagle; Fb – Fairbanks; NWT – Northwest Territories; Wh – Whitehorse; WL – Watson Lake; T – Tok; YT – Yukon Territory. Locations of VMS and SEDEX deposits from Goodfellow* et al. *(1993), Hunt (1997), Newberry* et al. *(1997) and Dusel-Bacon* et al. *(1998).*

and Laird and Foster (1984) as a major zone of northwest-directed thrusting in which greenschist-facies quartzite and quartz-rich schist (Fairbanks schist unit of Robinson *et al.*, 1990) was emplaced on top of the Late Proterozoic to Early Cambrian Wickersham grit unit. In contrast, Weber *et al.* (1985) interpreted the Wickersham grit unit to grade downward into the quartz-rich component of the Fairbanks schist. Weber *et al.* (1985) further proposed that the Wickersham grit and Fairbanks schist are correlative with the Neoproterozoic Windermere Supergroup of the Canadian Cordillera that makes up part of the ancient North American continental margin.

Klippe containing bands and lenses of high-pressure, high-temperature eclogitic rocks, intercalated with amphibolite, impure marble, phyllitic schist and mafic glaucophane-bearing schist (Chatanika assemblage, Fig. 2) structurally overlie the Fairbanks-Chena River assemblage northeast of Fairbanks (Foster *et al.*, 1994; Newberry *et al.*, 1996).

Southeast of the disputed northwestern margin of the assemblages of the Yukon-Tanana Upland, many of the various assemblages of the Yukon-Tanana Upland have been interpreted to be in low-angle fault contact with one another in most tectonic reconstructions (*e.g.*, Nokleberg *et al.*, 1989; Hanson *et al.*, 1991; Pavlis *et al.*, 1993; Foster *et al.*, 1994; Hansen and Dusel-Bacon, 1998). These interpretations are based largely on apparent abrupt changes in metamorphic grade and (or) protolith assemblages, metamorphic cooling ages and structural data determined from reconnaissance studies. More recent mapping, aided by airborne geophysics, in several small portions of the Yukon-Tanana Upland has been interpreted to indicate an abundance of steep, parallel, predominantly northeast-, northwest- and north-trending fault segments, and very few low-angle thrust or extensional faults between lithologic assemblages (Newberry *et al.*, 1996; Werdon *et al.*, 2001; Szumigala *et al.* 2002a). These steep, mostly post-Late Cretaceous faults (Newberry *et al.*, 1995), further obscure the nature of primary relationships between many of the assemblages.

Some of the more continuous northeast-striking faults juxtapose different levels of exposure. For example, vertical movement along the Shaw Creek fault in the Big Delta quadrangle (Fig. 2), down-dropped a structurally high klippe of Seventymile terrane oceanic rocks and underlying metasedimentary and metavolcanic rocks northwest of the fault against deeper level augen orthogneiss of the Lake George assemblage southeast of the fault. In addition to dip-slip movement, as much as 48 km of left-lateral strike-slip movement is indicated along the Shaw Creek fault by aeromagnetic and geologic data (Foster *et al.*, 1979, 1994).

We infer a continental margin setting and original proximity to the North American craton for most Paleozoic assemblages in the western and southern Yukon-Tanana Upland and the northern flank of the Alaska Range (Fig 2). This setting is based on quartz-rich compositions of many metasedimentary rocks, the presence of Archean and Proterozoic inherited or detrital zircons, and radiogenic Sr and Nd isotopic compositions for Paleozoic and younger igneous rocks, and bimodal, within-plate (extensional) Late Devonian to Early Mississippian (*ca.* 378 to *ca.* 360 Ma, with a few ages as young as *ca.* 345 Ma) magmatism. In contrast, Mississippian (*ca.* 360-341 Ma) meta-igneous rocks in the eastern Yukon-Tanana Upland (Fortymile River assemblage, Chicken Metamorphic Complex and Nasina assemblage; Fig. 2) have geochemical characteristics indicative of an arc and back-arc basin setting. Permian felsic metavolcanic and hypabyssal rocks and Triassic to Jurassic plutonic rocks are restricted to the eastern (arc) assemblages.

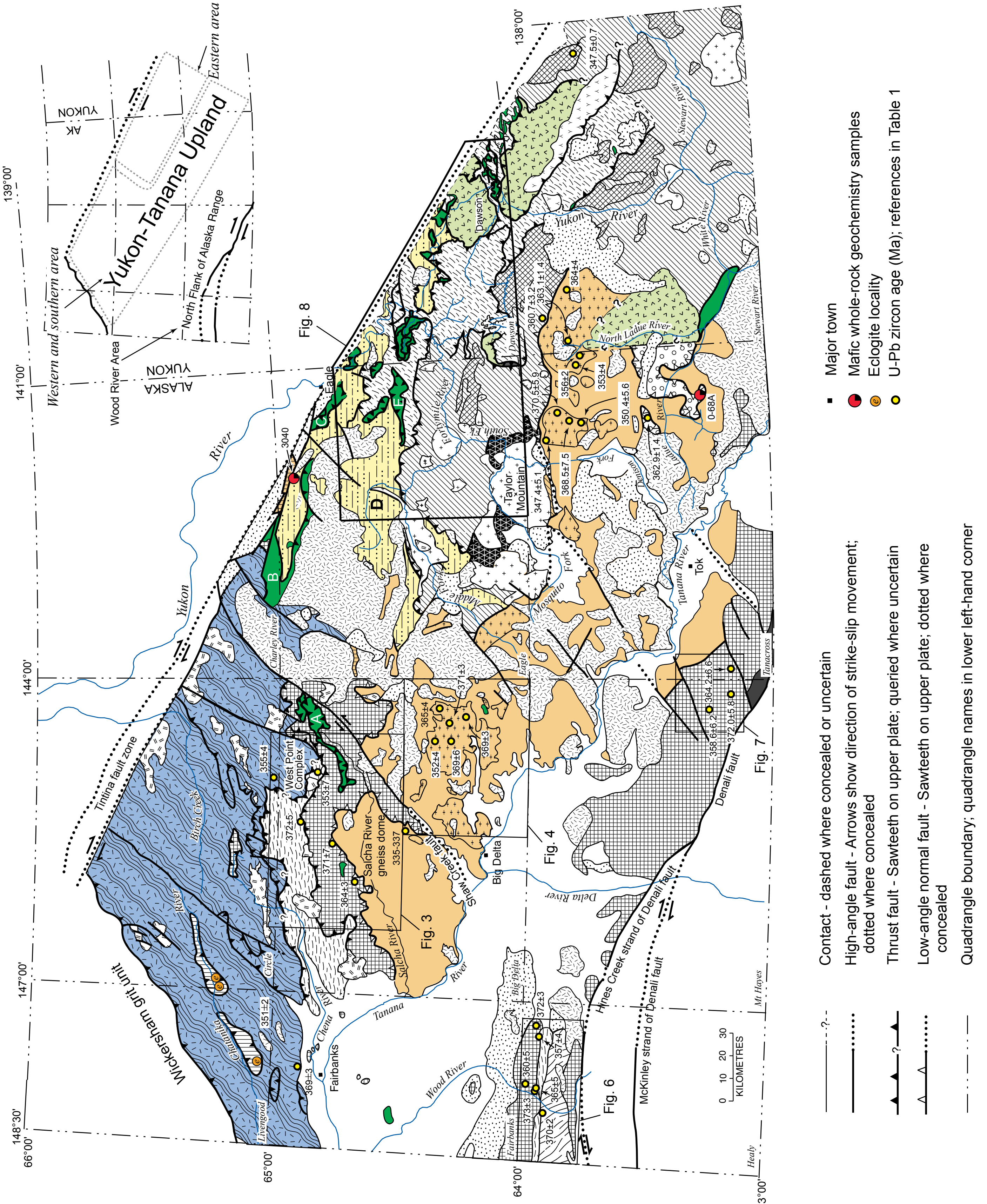
Greenschist-facies rocks similar to the Butte and Lake George assemblages in the western Yukon-Tanana Upland have been mapped along the well-exposed northern flank of the Alaska Range, south of the Yukon-Tanana Upland (Fig. 2). The lithologic similarities between rocks in these two areas have been noted by a number of workers (*e.g.*, Gilbert and Bundtzen, 1979; Smith *et al.*, 1994; Newberry *et al.*, 1996; Dusel-Bacon *et al.*, 2004). The Tanana River Valley (Fig. 2) that separates the two physiographic areas is known to be a Neogene feature (Wahrhaftig, 1987).

## CONTINENTAL MARGIN ASSEMBLAGES IN THE WESTERN AND SOUTHERN YUKON-TANANA UPLAND AND ALASKA RANGE

### Fairbanks-Chena Assemblage

The northwesternmost assemblage in the Yukon-Tanana Upland crops out south of the Wickersham grit unit. This assemblage ($Y_2$ subterrane of Foster *et al.*, 1994; herein informally referred to as the Fairbanks-Chena assemblage; Fig. 2) is composed primarily of two groups of rocks. The first, a more extensive group, consists mostly of greenschist and amphibolite facies quartzite and quartz schist and minor metavolcanic rocks (Fairbanks schist; Robinson *et al.*, 1990; Newberry *et al.*, 1996). The second group consists of amphibolite facies pelitic schist, quartzite, marble and amphibolite (Chena River sequence; Robinson *et al.*, 1990; Smith *et al.*, 1994).

Although quartzite and quartz-rich schist are the most abundant rock types in the Fairbanks schist unit, minor amounts of pelitic schist, calc-silicate rocks, mafic schist and marble are interlayered. Locally, the quartz-rich rocks contain rare to abundant clasts of quartz and less abundant feldspar, ranging from ~1 mm to ~1 cm in diameter (Foster *et al.*, 1994). A sequence of felsic schist, graphitic schist, calc-silicate rock and marble, informally named the Cleary sequence (Bundtzen, 1982; Robinson *et al.*, 1990), crops out in the Fairbanks mining district and was previously included as part of the Fairbanks schist. TIMS U-Pb analyses of fractions of euhedral zircon from a felsic rock interpreted to be a metarhyolite from the Cleary sequence defined a discordant array with an upper intercept age of 369 ± 3 Ma (Aleinikoff and Nokleberg, 1989). Aleinikoff and Nokleberg interpreted the dated sample as a metamorphosed flow or tuff, and concluded that the Late Devonian upper-intercept age dated the time of crystallization of the rhyolitic layer and the depositional age of the interlayered sedimentary rocks of the Fairbanks schist. However, Newberry *et al.* (1996) proposed that the dated metarhyolite was part of a different sequence (the Muskox Sequence), which they proposed was in fault contact with the Fairbanks schist, and hense did not provide a depositional age for the Fairbanks schist.


66°00'
148°30'
147°00'
144°00'
141°00'
139°00'
138°00'
65°00'
64°00'
63°00'
Wickersham grit unit
Tintina fault zone
Livengood
Chatanika
Circle
Birch Creek
River
Yukon
River
Charley River
West Point Complex
Salcha River gneiss dome
335-337
Shaw Creek fault
Big Delta
Fairbanks
Chena
River
Tanana
River
Salcha River
Delta River
Wood River
Big Delta
Fairbanks
Mt Hayes
Healy
Tanacross
Eagle
Tok
Tanana River
Mosquito
Fork
Middle
Fork
South Fk.
Fortymile River
Dawson
Taylor Mountain
Eagle
Dawson
Yukon
River
White River
North Ladue River
Ladue River
Stewart River
Stewart River
Hines Creek strand of Denali fault
McKinley strand of Denali fault
Denali fault
A
B
C
D
E
3040
0-68A
369±3
351±2
355±4
353±7
372±5
371±7
364±3
352±4
365±4
369±6
371±3
369±3
358.6±6.2
364.2±6.6
372.0±5.8
373±3
360±5
365±5
370±2
372±3
357±4
347.4±5.1
368.5±7.5
370.5±5.9
360.7±3.2
363.1±1.4
356±2
353±4
350.4±5.6
362.9±1.4
364±4
347.5±0.7
Fig. 3
Fig. 4
Fig. 6
Fig. 7
Fig. 8
0 10 20 30
KILOMETRES
Western and southern area
Yukon-Tanana Upland
Eastern area
Wood River Area
North Flank of Alaska Range
ALASKA
YUKON
AK
YUKON
Contact - dashed where concealed or uncertain
High-angle fault - Arrows show direction of strike-slip movement; dotted where concealed
Thrust fault - Sawteeth on upper plate; queried where uncertain
Low-angle normal fault - Sawteeth on upper plate; dotted where concealed
Quadrangle boundary; quadrangle names in lower left-hand corner
Major town
Mafic whole-rock geochemistry samples
Eclogite locality
U-Pb zircon age (Ma); references in Table 1

## EXPLANATION

- ☐ *Surficial deposits* (Quaternary)
- ▨ *Sedimentary and volcanic rocks* (Cretaceous-Tertiary)
- ▨ *Post-metamorphic granitoids* (Tertiary)
- ▨ *Post-metamorphic granitoids* (Cretaceous)
- ▨ *Syn- to post-metamorphic granitoids* (Late Triassic-Early Jurassic)

## OCEANIC AND HIGH-PRESSURE ASSEMBLAGES

- 🟩 *Seventymile terrane* Peridotite, greenstone, chert and limestone (Mississippian-Triassic)
- ▥ *Chatanika assemblage* Eclogite, marble and schist

## ARC AND BASINAL ASSEMBLAGES

- ▨ *Klondike Schist* Greenschist-facies felsic metavolcanic rocks and minor metasedimentary and mafic rocks; felsic orthogneiss shown by Y pattern (Permian)
- ▨ *Fortymile River assemblage* Amphibolite facies gneiss, amphibolite, marble, quartzite, metachert and granodioritic to tonalitic orthogneiss (shown by diamond-shaped pattern) (Mississippian)
- ▨ *Ladue River unit* Greenschist-facies schist and minor mafic and felsic meta-igneous rocks (Late Devonian-Early Mississippian)
- ▩ *Chicken Metamorphic Complex* Greenschist-facies intermediate to mafic meta-igneous rocks, marble, slate and quartzite (Mississippian?)
- 🟨 *Nasina assemblage, non-carbonaceous unit* Greenschist-facies semischist, phyllite, marble and felsic metavolcanic rocks (Early Mississippian)
- ▨ *Nasina assemblage, carbonaceous unit* Greenschist-facies carbonaceous rocks and Early Mississippian and Permian felsic metavolcanic rocks; Early Mississippian granodiorite orthogneiss shown by diagonal overprint

## CONTINENTAL MARGIN ASSEMBLAGES

- ▦ *Butte assemblage, Totatlanika Schist, Wood River assemblage and Hayes Glacier, Jarvis and Macomb belts* Greenschist-facies semischist, phyllite, marble and Late Devonian-Early Mississippian felsic rocks
- ▤ *Blackshell and Dan Creek units and Keevy Peak Fm* Greenschist-facies carbonaceous rocks, slate, marble, stretched-pebble conglomerate and Late Devonian-Early Mississippian felsic rocks
- ▧ *Healy schist* Quartz-sericite schist, quartzite, chlorite schist, marble, carbonaceous schist, metagabbro and Late Devonian metaporphyry
- 🟦 *Fairbanks-Chena assemblage* Greenschist- to amphibolite facies pelitic schist, quartzite, marble and amphibolite; minor Early Mississippian orthogneiss
- 🟧 *Lake George assemblage* Amphibolite facies pelitic schist, amphibolite and quartzite; Late Devonian and locally Early Mississippian augen gneiss shown by pattern
- ⬛ *Windy terrane* Metasedimentary rocks (Devonian and Silurian) and mafic intrusions

**Figure 2.** *Generalized geologic map of east-central Alaska and adjacent part of Yukon. Geology in Alaska from Foster (1992) and Dusel-Bacon* et al. *(1993, 2002) and in Yukon from Mortensen (1988, 1996), Gordey and Makepeace (1999) and J.K. Mortensen (unpublished mapping). Unpatterned areas are Late Proterozoic to Cambrian and Devonian sedimentary rocks north of the Tintina fault, and Quaternary surficial deposits elsewhere. Sources for U-Pb zircon dates are given in Table 1. Additional U-Pb zircon dates are shown on the more detailed figures outlined on Fig. 2. Letters A-E shown for ultramafic and associated mafic and sedimentary rocks referred to in discussion of Seventymile terrane. Abbreviated sample numbers shown for two mafic whole-rock geochemical samples discussed in text. Inset in upper right shows geographic areas discussed in text.*

U-Pb zircon geochronology in the West Point Complex also addressed the minimum protolith age of the Fairbanks-Chena assemblage. The West Point Complex comprises a nearly circular, ~150-km$^2$ area of high-grade gneiss and metasedimentary rocks in the northeastern Big Delta quadrangle (Smith *et al*., 1994; Figs. 2 and 3). This metamorphic complex consists of peraluminous granitic orthogneiss, sillimanite gneiss, quartzite and marble. Smith *et al.* (1994) reported a 671 ± 34 Ma (Late Proterozoic) upper intercept age for a highly discordant array defined by TIMS analyses of five multigrain zircon fractions from a sample of the peraluminous orthogneiss that lies in the core of the West Point Complex. Smith *et al.* (1994) interpreted this upper intercept age as the time of igneous crystallization of the orthogneiss and concluded that the metapelitic and metapsammitic wallrocks, which they correlated with the Fairbanks schist unit of Robinson *et al.* (1990), had a Late Proterozoic minimum depositional age. Subsequent ion microprobe U-Pb analysis by Dusel-Bacon *et al.* (2003) of individual spots on clear euhedral rims of magmatic zircons from the orthogneiss indicated an age of 111 ± 2 Ma for the orthogneiss, which they interpret to date the time of its igneous crystallization. Dusel-Bacon *et al.* (2003) concluded that the previously determined 671 ± 34 Ma upper-intercept age actually averaged several distinct inherited zircon populations and thus was a geologically meaningless age. At present, there is no evidence to support a Late Proterozoic crystallization or depositional age for any of the protoliths in the pericratonic assemblages in Alaska.

Granitic orthogneiss, occurring as small intrusive bodies or sills, makes up a minor component of the Fairbanks-Chena assemblage. Early Mississippian (355 ± 4 and 351 ± 2 Ma) U-Pb zircon ages have been determined for two different orthogneiss bodies near the southern margin of the Fairbanks-Chena assemblage (Table 1).

## Chatanika Assemblage

Eclogite occurs in two klippe that were thrust over the Fairbanks-Chena assemblage in the Livengood and Circle quadrangles (Fig. 2). The klippen, previously referred to as the Chatanika terrane (Robinson *et al*., 1990; Newberry *et al*., 1996), were subsequently renamed the Chatanika assemblage by Hansen and Dusel-Bacon (1998) to emphasize the similar and likely related continental margin setting of the protoliths of this assemblage and the other assemblages in the western and southern parts of the Yukon-Tanana Upland. The Chatanika assemblage consists of high-grade metamorphic rocks, including bands and lenses of high-pressure eclogite that are intercalated with pelitic schist, impure marble, black quartzite, amphibolite and mafic, glaucophane-bearing schist (Foster *et al*., 1994, and references therein; Newberry *et al*., 1996). Garnet compositions in the eclogites are similar to those in eclogites from Alpine-type orogenic terranes (Group C of Coleman *et al*., 1965) and garnet thermobarometry indicates that eclogite formed under metamorphic conditions of 13-15 kb and 600 ± 50°C (Laird *et al*., 1984; Brown and Forbes, 1986). Whole-rock geochemistry of eclogites in the Livengood area suggests marl and graywacke protoliths (Brown and Forbes, 1986). In contrast, the protolith of eclogite in the Circle quadrangle appears to be a mafic dike, based on the fact that its margins cut across the layer-parallel foliation of the adjacent pelitic schist and quartzite (Laird *et al*., 1984). The protolith ages for the Chatanika eclogites and associated metasedimentary rocks have not been determined.

With the exception of one 240 ± 18 Ma K-Ar amphibolite age (Swainbank and Forbes, 1975), all other reliable K-Ar and $^{40}$Ar/$^{39}$Ar metamorphic cooling ages from the Chatanika assemblage are Jurassic and Cretaceous (Wilson *et al.* 1985; Pavlis *et al*., 1993; Newberry *et al*., 1996). The Jurassic and Cretaceous ages probably date the timing of subsequent retrograde metamorphism under epidote-amphibolite and greenschist facies conditions as the high-pressure rocks were exhumed from the subduction zone in which their initial metamorphism occurred (Brown and Forbes, 1986; Foster *et al*., 1987; Newberry *et al*., 1996). The maximum K-Ar age of 258 Ma allowed by analytical uncertainty is close to the Permian metamorphic cooling ages for blueschists (273-239 with a peak at *ca.* 260 Ma; Nelson *et al.,* this volume, and references therein) and the Permian high temperature metamorphic U-Pb zircon crystallization ages for eclogites (*ca.* 269 Ma, Creaser *et al*., 1997; and *ca.* 266 Ma, Fallas *et al*., 1998) that occur along the eastern margin of the Yukon-Tanana terrane in Yukon. The Chatanika eclogites, and a sliver of blueschist from a fault sliver of probable Seventymile terrane rocks just south of the Tintina fault in the Eagle quadrangle, occur along the belt of Permian high-pressure rocks in the Yukon, after movement along the Tintina fault has been restored (Nelson *et al.,* this volume), and their subduction history is generally agreed to record the closure of an ocean basin during west-dipping subduction (e.g., Erdmer *et al*., 1998, and references therein; Hansen and Dusel-Bacon, 1998; Nelson *et al.,* this volume).

## Lake George Assemblage

The Lake George assemblage forms a 75 km-wide belt of amphibolite facies rocks, north of the Tanana River, composed of pelitic, quartzose and mafic and felsic meta-igneous rocks (Foster *et al*., 1994), including large conformable bodies of Devonian and Mississippian peraluminous augen and biotite orthogneisses (Dusel-Bacon and Aleinikoff, 1985, 1996). Many rock types in the Lake George assemblage are similar to those in the Fairbanks-Chena assemblage, but the latter assemblage has appreciably more quartzite (primarily in the Fairbanks schist) and only minor Late Devonian and Early Mississippian orthogneiss or felsic volcanic rocks. In most interpretations (*e.g.*, Hansen *et al*., 1991; Pavlis *et al*., 1993; Foster, 1994; Hansen and Dusel-Bacon, 1998), the Lake George assemblage is interpreted to lie structurally beneath the amphibolite facies arc affinity rocks of the Fortymile River assemblage in the eastern Upland.

In the northern Big Delta quadrangle, a 600 km$^2$ circular area of amphibolite facies sillimanite gneiss and a flanking unit of pelitic schist, quartzite, marble, amphibolite and minor augen gneiss (unit Pzsq, Fig 3) forms the Salcha River gneiss dome (Figs. 2, 3; Dusel-Bacon and Foster, 1983; Sisson *et al*., 1990; Werdon *et al*., 2004). The nature of the contact between these amphibolite facies rocks and the overlying greenschist facies Butte assemblage (Fig. 3) is uncertain and has been interpreted as: (1) a thrust fault, with higher grade rocks forming either the footwall (Dusel-Bacon and Foster;

**Table 1.** U-Pb zircon crystallization ages for metaigneous rocks from east-central Alaska and adjacent Yukon.

| Sample No. | Rock Type | Assemblage or unit | Zircon U-Pb age | 2σ Uncertainty | Latitude (°N) | Longitude (°W) | Method | Figure showing location | 1:250K quadrangle[1] | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| 90ADb12 | Augen gneiss | Lake George assemblage | 347.4 | 5.1 | 63.908 | 141.829 | U-Pb SHRIMP | 2 | TA | I.S. Williams and C. Dusel-Bacon, unpublished data, 1997 |
| 79AFr4015 | Augen gneiss | Lake George assemblage | 350.4 | 5.6 | 63.739 | 141.623 | U-Pb SHRIMP | 2 | TA | I.S. Williams and C. Dusel-Bacon, unpublished data, 1997 |
| 90ADb6 | Augen gneiss | Lake George assemblage | 353 | 4 | 63.776 | 141.107 | U-Pb TIMS | 2 | TA | Dusel-Bacon and Aleinikoff, 1996 |
| 81ADb14 | Augen gneiss | Lake George assemblage | 356 | 2 | 63.753 | 141.025 | U-Pb TIMS | 2 | TA | Dusel-Bacon and Aleinikoff, 1996 |
| 00ADb11A | Augen gneiss | Lake George assemblage | 362 | 4 | 64.363 | 144.653 | U-Pb SHRIMP | 4 | BD | Dusel-Bacon *et al.*, 2004 |
| 99M58 | Augen gneiss | Lake George assemblage | 363.1 | 1.4 | | | U-Pb TIMS | 2 | SR | J.K. Mortensen, unpublished data, 2004 |
| TO-376A | Augen gneiss | Lake George assemblage | 364 | 4 | | | U-Pb TIMS | 2 | SR | J.K. Mortensen, unpublished data, 2004 |
| AG-3 | Augen gneiss | Lake George assemblage | 365 | 4 | 63.349 | 144.332 | U-Pb SHRIMP | 4 | BD | Day *et al.*, 2003 |
| 90ET59 | Augen-poor orthogneiss | Lake George assemblage | 368.5 | 7.5 | 63.779 | 141.600 | U-Pb SHRIMP | 2 | TA | I.S. Williams and C. Dusel-Bacon, unpublished data, 1997 |
| DDH-99-16 | Amphibole gneiss | Lake George assemblage | 369 | 3 | 64.240 | 144.403 | U-Pb SHRIMP | 4,5 | BD | Dusel-Bacon *et al.*, 2004 |
| 02AD332 | Dioritic orthogneiss | Lake George assemblage | 369 | 6 | 64.299 | 144.648 | U-Pb SHRIMP | 4 | BD | Day *et al.*, 2003 |
| 90ADb24 | Augen gneiss | Lake George assemblage | 370.5 | 5.9 | 63.836 | 141.623 | U-Pb SHRIMP | 2 | TA | I.S. Williams and C. Dusel-Bacon, unpublished data, 1997 |
| 78AFrAG5 | Augen gneiss | Lake George assemblage | 371 | 3 | 63.310 | 144.440 | U-Pb SHRIMP | 4 | BD | Dusel-Bacon *et al.*, 2004 |
| 00ADb5 | Metarhyolite | Blackshell unit | 353 | 7 | 64.851 | 144.889 | U-Pb SHRIMP | 3 | BD | Dusel-Bacon *et al.*, 2004 |
| 96ADb20 | Metarhyolite | Blackshell unit | 372 | 5 | 64.895 | 145.403 | U-Pb SHRIMP | 3 | BD | Dusel-Bacon *et al.*, 2004 |
| 96ADb24 | Augen gneiss | Butte assemblage | 364 | 3 | 64.688 | 145.967 | U-Pb SHRIMP | 3 | BD | Dusel-Bacon *et al.*, 2004 |
| 97ADb32A | Metaporphyry | Butte assemblage | 371 | 7 | 64.789 | 145.579 | U-Pb SHRIMP | 3 | BD | Dusel-Bacon *et al.*, 2004 |
| 97ADb68A | Metaporphyry | Healy schist | 370 | 2 | 63.897 | 148.007 | U-Pb SHRIMP | 6 | HE | Dusel-Bacon *et al.*, 2004 |
| 96ADb5 | Augen gneiss | Totatlanika Schist, California Creek Member | 373 | 3 | 63.919 | 147.747 | U-Pb SHRIMP | 6 | HE | Dusel-Bacon *et al.*, 2004 |
| DC98-52-54 | Metarhyolite | Totatlanika Schist | 357 | 4 | 63.923 | 147.394 | U-Pb SHRIMP | 6 | HE | Dusel-Bacon *et al.*, 2004 |
| 98ADb78A | Metarhyolite | Totatlanika Schist, Mystic Creek Member | 360 | 5 | 63.961 | 147.709 | U-Pb SHRIMP | 6 | HE | Dusel-Bacon *et al.*, 2004 |
| 98ADb80 | Metarhyolite | Totatlanika Schist, Moose Creek Member | 365 | 5 | 63.913 | 147.747 | U-Pb SHRIMP | 6 | HE | Dusel-Bacon *et al.*, 2004 |
| 97ADb57F | Metarhyolite | Totatlanika Schist, Mystic Creek Member | 372 | 3 | 63.951 | 147.323 | U-Pb SHRIMP | 6 | HE | Dusel-Bacon *et al.*, 2004 |
| N484563 | Metarhyodacite | Jarvis Belt, Drum unit | 358.6 | 6.2 | 63.262 | 144.229 | U-Pb SHRIMP | 7 | MH | Dashevsky *et al.*, 2003; J.N. Aleinikoff, unpublished data, 2002 |
| N484559 | Metadacite | Jarvis Belt, Drum unit | 364.2 | 6.6 | 63.180 | 143.897 | U-Pb SHRIMP | 7 | TA | Dashevsky *et al.*, 2003; J.N. Aleinikoff, unpublished data, 2002 |
| N484558 | Metarhyodacite | Jarvis Belt, Lagoon unit | 372.0 | 5.8 | 63.177 | 144.148 | U-Pb SHRIMP | 7 | MH | Dashevsky *et al.*, 2003; J.N. Aleinikoff, unpublished data, 2002 |
| 91BT-181 | Metarhyolite schist | Spruce Creek Sequence (Kantishna Hills) | 369 | 4 | 63.556 | 150.937 | U-Pb TIMS | 1 | MK | J.N. Aleinikoff, T.K. Bundtzen, and W.J. Nokleberg, unpublished data, 1993 |
| 84DN24 | Metarhyolite schist | Spruce Creek Sequence (Kantishna Hills) | 370 | 5 | 63.570 | 150.870 | U-Pb TIMS | 1 | MK | R.M. Tosdal and T.K. Bundtzen, unpublished data, 1991 |
| 75BT2027 | Foliated quartz monzonite | elongate foliated pluton parallel to the structural grain of metamorphic units in the Kantishna Hills | 374 | 11 | 63.737 | 150.813 | U-Pb TIMS | 1 | MK | R.M. Tosdal and T.K. Bundtzen, unpublished data, 1991 |
| RN-95-118 | Orthogneiss | Fairbanks-Chena assemblage | 351 | 2 | 65.012 | 147.458 | U-Pb TIMS | 2 | FB | Newberry *et al.*, 1998 |
| 98ADb55B | Augen gneiss | Fairbanks-Chena assemblage | 355 | 4 | 65.013 | 144.938 | U-Pb SHRIMP | 3 | CI | Dusel-Bacon *et al.*, 2003 |
| 87ANK081A | Metarhyolite | Fairbanks-Chena assemblage | 369 | 3 | 65.911 | 147.776 | U-Pb TIMS | 2 | FB | Aleinikoff and Nokleberg, 1989 |
| 98ADb13C | quartz-muscovite schist (metatuff) | Fortymile River assemblage | 341.2 | 4.8 | 64.250 | 141.771 | U-Pb TIMS | 8 | EA | J.K. Mortensen, unpublished data, 2004 |
| 98AD174 | Tonalite | Fortymile River assemblage | 343 | 4 | 64.171 | 141.272 | U-Pb SHRIMP | 8 | EA | Day *et al.*, 2002 |
| M-964 | Granodiorite gneiss | Fortymile River assemblage | 347 | 1 | | | U-Pb TIMS | 8 | DA | J.K. Mortensen, unpublished data, 2004 |
| 03RAYP037A1 | Augen orthogneiss | Fortymile River assemblage | 347.5 | 0.7 | | | U-Pb SHRIMP | 2 | SR | T.W. Ruks and S.J. Piercey, unpublished data, 2005 |
| M-929 | Granodiorite gneiss | Fortymile River assemblage | 348 | 1 | 69.013 | 140.283 | U-Pb TIMS | 8 | DA | J.K. Mortensen, unpublished data, 2004 |
| 00M95 | Quartz diorite gneiss | Fortymile River assemblage | 348.4 | 1.0 | 64.340 | 140 .8500 | U-Pb TIMS | 8 | DA | J.K. Mortensen, unpublished data, 2004 |

**Table 1.** *continued*

| Sample No. | Rock Type | Assemblage or unit | Zircon U-Pb age | 2σ Uncertainty | Latitude (°N) | Longitude (°W) | Method | Figure showing location | 1:250K quadrangle[1] | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| 98M02 | Granodiorite gneiss | Fortymile River assemblage | 348.7 | 1.4 | 64.181 | 141.344 | U-Pb TIMS | 8 | EA | J.K. Mortensen, unpublished data, 2004 |
| 00ADb16A | Tonalite gneiss | Fortymile River assemblage | 354.9 | 0.9 | 64 .2630 | 141.252 | U-Pb TIMS | 8 | EA | J.K. Mortensen, unpublished data, 2004 |
| 93ADb34 | Augen orthogneiss | Fortymile River assemblage | 355.2 | 2.1 | 64.051 | 141.684 | U-Pb TIMS | 8 | EA | J.K. Mortensen, unpublished data, 2004 |
| 98ADb16 | Augen orthogneiss | Fortymile River assemblage | 360.7 | 2.3 | 64.196 | 141.389 | U-Pb TIMS | 8 | EA | J.K. Mortensen, unpublished data, 2004 |
| 99M50A | Augen gneiss sill | Fortymile River assemblage | 360.7 | 3.2 | | | U-Pb TIMS | 2 | SR | J.K. Mortensen, unpublished data, 2004 |
| 00ADb59 | quartz-chlorite-epidote schist (orthogneiss?) | Ladue River unit | 362.9 | 1.4 | 63.478 | 141.604 | U-Pb TIMS | 2 | TA | J.K. Mortensen, unpublished data, 2004 |
| 00M103A | quartz-muscovite schist (metarhyolite?) | Nasina assemblage, non-carbonaceous unit | 347.9 | 1.7 | 64.530 | 140.475 | U-Pb TIMS | 8 | DA | J.K. Mortensen, unpublished data, 2004 |
| 00M105 | Quartz-feldspar augen schist | Nasina assemblage, carbonaceous unit | 349.4 | 0.7 | 64.560 | 140.634 | U-Pb TIMS | 8 | DA | J.K. Mortensen, unpublished data, 2004 |
| 98ADb23A | quartz-muscovite schist (metarhyolite?) | Nasina assemblage, non-carbonaceous unit | 359.5 | 11 | 64.617 | 141.327 | U-Pb TIMS | 8 | EA | J.K. Mortensen, unpublished data, 2004 |
| MLB-89-281 | Metarhyolite | Nasina assemblage, carbonaceous unit | 360.9 | 2.1 | 64.303 | 140.487 | U-Pb TIMS | 8 | DA | J.K. Mortensen, unpublished data, 2004 |
| 98ADb19 | Metarhyolite porphyry or crystal tuff | Nasina assemblage, carbonaceous unit | 253.3 | 1.0 | 64.476 | 141.043 | U-Pb TIMS | 8 | EA | J.K. Mortensen, unpublished data, 2004 |
| 98ADb29 | Metarhyolite | Nasina assemblage, carbonaceous unit | 256.2 | 1.1 | 64.559 | 141.319 | U-Pb TIMS | 8 | EA | J.K. Mortensen, unpublished data, 2004 |
| 96ADb47A | Metarhyolite | Nasina assemblage, carbonaceous unit | 256.6 | 0.9 | 64.465 | 141.113 | U-Pb TIMS | 8 | EA | J.K. Mortensen, unpublished data, 2004 |
| 89-MLB-281 | Felsic metatuff | Nasina assemblage, carbonaceous unit | 260.2 | 0.6 | | | U-Pb TIMS | 8 | DA | J.K. Mortensen, unpublished data, 2004 |
| 98ADb25 | Metarhyolite | Nasina assemblage, carbonaceous unit | 267.0 | 2.7 | 64.586 | 141.143 | U-Pb TIMS | 8 | EA | J.K. Mortensen, unpublished data, 2004 |
| 99M-20 | Felsic metatuff | Klondike Schist | 255.1 | 0.5 | | | U-Pb TIMS | 8 | DA | J.K. Mortensen, unpublished data, 2004 |
| MLB-91-108 | Metarhyolite | Klondike Schist | 256.0 | 0.5 | | | U-Pb TIMS | 8 | DA | J.K. Mortensen, unpublished data, 2004 |
| 98ADb10 | Granodiorite | Post-metamorphic dike into Fortymile River assemblage | 262.8 | 1.5 | 64.300 | 141.539 | U-Pb TIMS | 8 | EA | J.K. Mortensen, unpublished data, 2004 |

[1]Quadrangle abbreviations: BD, Big Delta; CI, Circle; DA, Dawson; EA, Eagle ; FB, Fairbanks; HE, Healy; MH, Mount Hayes; MK, Mount McKinley; SR, Stewart River; TA, Tanacross.

1983) or the hangingwall (Foster *et al.*, 1994); (2) a low-angle normal fault (Pavlis *et al.*, 1993; Oliver and Dusel-Bacon, 2003); or (3) a series of steep normal faults (Werdon *et al.*, 2004). Similarities between the Salcha River gneiss dome and the West Point Complex (Figs. 2, 3) in terms of protoliths, size, interpreted low-angle structural contacts with overlying greenschist facies rocks, and, especially, *ca.* 111-113 Ma U-Pb zircon crystallization ages of syn- to closely post-metamorphic granitoids in the cores of both bodies (Dusel-Bacon *et al.,* 2003), suggest that both of these gneiss domes were part of a related (continuous?) basement sequence and that both were exhumed during an Early Cretaceous extensional event (Pavlis *et al.*, 1993; Dusel-Bacon *et al.,* 2003; Oliver and Dusel-Bacon, 2003).

Detailed mapping by Werdon *et al.* (2004) within the area of the amphibolite facies pelitic schist, quartzite, marble and amphibolite that straddles the North and South forks of the Salcha River (Fig. 3) has revealed a two-part subdivision of the rocks in that area. These two units overlie the relatively homogeneous sillimanite gneiss of Salcha River gneiss dome. An upper unit is characterized by amphibolite, hornblende gneiss and tonalitic orthogneiss; trace-element signatures of the mafic igneous rocks indicate both calc-alkaline island arc and mid-ocean ridge (MORB) affinities. This upper unit overlies (either structurally or unconformably) a unit composed of quartzite, schist, paragneiss and amphibolite with ocean-island basalt (OIB) trace-element affinity. Structurally and metamorphically concordant bodies of ultramafic and gabbroic rocks occur either structurally above or within amphibolite of the upper unit (Werdon *et al.*, 2004).

Amphibolite facies schists and gneisses in the Goodpaster River area of the southeastern Big Delta quadrangle (Figs. 2, 4) have many similarities to those in the Salcha River area, to the northwest. Several small foliated and regionally metamorphosed ultramafic masses are infolded with (Weber *et al.* 1978) or locally structurally overlie (Day *et al.*, 2003) the amphibolite facies gneiss and schist, and contain metamorphic mineral assemblages indicative of similar conditions (Weber *et al.* 1978). However, unlike the Salcha River

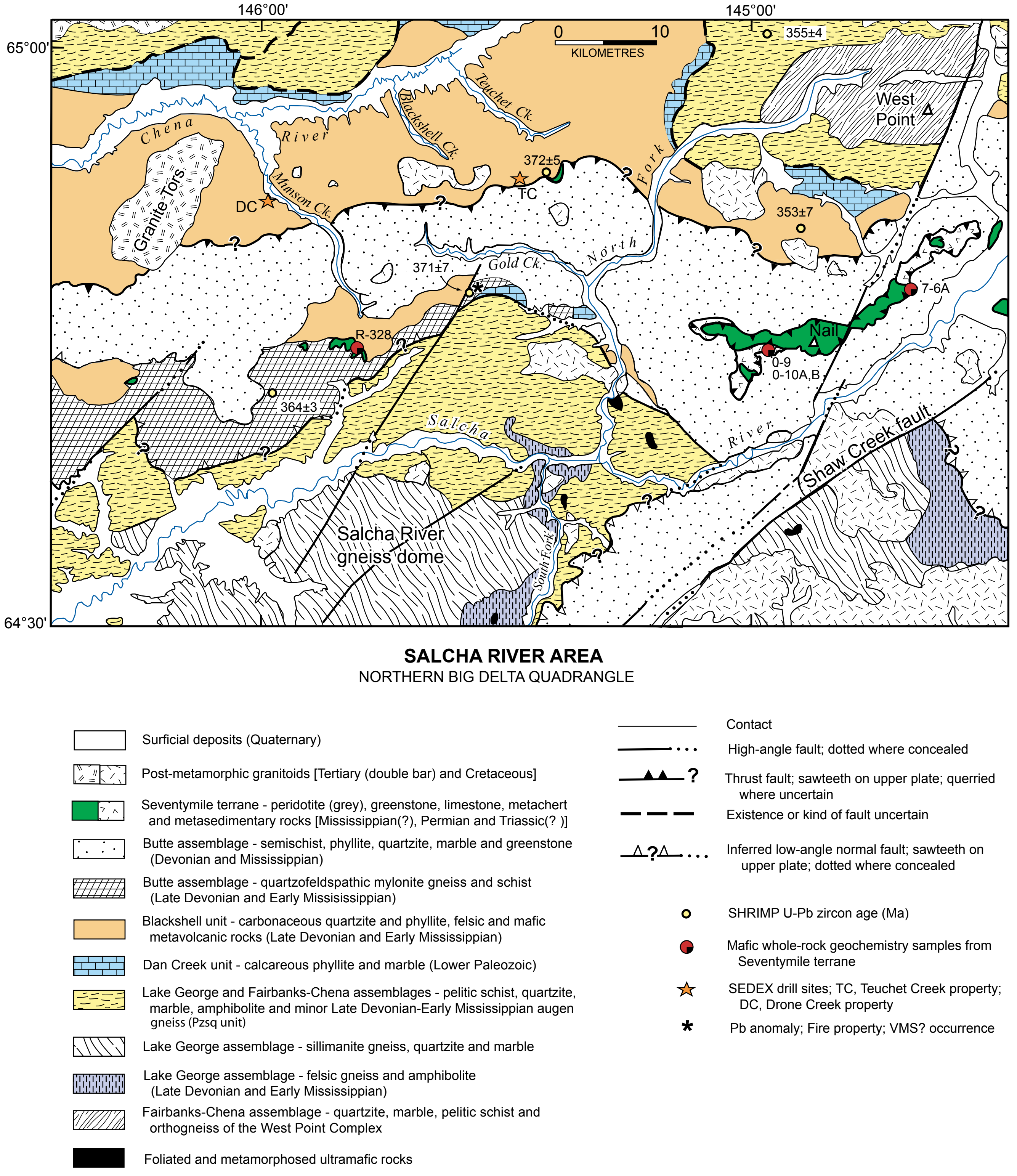


**Figure 3.** *Simplified geologic map of the Chena and Salcha River area (modified from Weber* et al., *1978, and Foster, 1992) showing U-Pb zircon ages (from Dusel-Bacon* et al., *2004) and location of metabasite geochemical samples from the Seventymile terrane.*

area, the Goodpaster River area is dominated by the Central Creek augen gneiss body, a ~700 km$^2$ batholith of Devonian biotite (± muscovite ± garnet) -bearing augen orthogneiss (Dusel-Bacon and Aleinikoff, 1985; Aleinikoff *et al.*, 1986; Dusel-Bacon *et al.*, 2002, 2004; Day *et al.*, 2003). Biotite (± muscovite ± garnet) augen-free orthogneiss, biotite ± hornblende granodiorite gneiss, amphibolite and dioritic gneiss crop out primarily around the margins of the augen gneiss body, but also as inliers within it, and biotite-sillimanite paragneiss, quartz-mica schist, quartzite and rare marble, interpreted as wallrock, crop out outboard of the above-described meta-igneous rocks (Figs. 4, 5A; Weber *et al.*, 1978; Day *et al.*, 2003*).*

SHRIMP U-Pb zircon data indicate a Late Devonian igneous crystallization age for the Central Creek augen gneiss body (*ca.* 360-372 Ma, allowing for analytical uncertainties). Zircons from two mafic gneisses within the Central Creek augen gneiss body yield Late Devonian (369 ± 3 and 369 ± 6 Ma) U-Pb ages, comparable to those from associated augen gneiss (Fig. 4; Table 1), which, together with trace-element signatures, implies coeval, bimodal magmatism (Dusel-Bacon *et al.*, 2004; Day *et al.*, 2003). The northern and northwestern margins of the augen gneiss body are relatively low-angle faults that juxtapose the augen gneiss over the underlying biotite-sillimanite and granodioritic gneisses (Fig. 4; Day *et al.,* 2003). U-Pb zircon data indicate a 367 ± 7 Ma crystallization age for granodioritic orthogneiss in the footwall of the fault (Day *et al.*, 2003; Fig. 4), allowing the possibility that the rocks on both side of the fault occurred in the same overall mid-Paleozoic tectonic setting of the Lake George assemblage. Elsewhere the lithologic contacts and metamorphic foliation of the distinctive augen gneiss layers are everywhere concordant with contacts and foliations in the adjacent country rocks, indicating either a primary sill origin for the augen gneiss protolith, or complete tectonic transposition of an originally discordant contact. The mineralogical similarity between the matrix of the Central Creek augen gneiss and the biotite orthogneiss suggest that the latter is simply a non-porphyritic compositional and textural variant of the former. Detailed mapping (Fig. 5A) confirmed that contacts between augen gneiss, biotite gneiss, dioritic gneiss/amphibolite and biotite-hornblende granodiorite are concordant, consistent with the interpretation that present-day contacts represent dynamothermally metamorphosed primary igneous contacts.

Thickness of the Central Creek augen gneiss body is inferred to be as much as 760 m on the basis of discontinuous outcrop exposures (Weber *et al.*, 1978; Day *et al.*, 2003; J.R. Bressler, unpublished mapping). A simplified lithologic section of a 300+ m diamond-drill core (Fig. 5B) reveals that ~8 m-thick layers of augen gneiss, interpreted as sills to the main batholith, are interlayered with the mixed gneiss package of feldspar-quartz-biotite gneiss and lesser amounts of amphibolite and mafic gneiss. The upper contact of the thickest and shallowest interval of augen gneiss with biotite gneiss appears to be conformable, but the lower contact of the augen gneiss layer is a fault zone, marked by broken gneiss, Fe-stained calcite-rich, locally silicified gouge zones, and anomalous geochemical concentrations of gold and other metals. Although the fault zone is not exposed on the surface, similar geochemical values detected in soil samples at the surface projection of the fault intercept suggest a steep fault (Corbett and Bressler, 2000; Fig. 5B), similar to the others in the area. Approximately 10 intervals of amphibolite and mafic gneiss are interlayered with the biotite gneiss and augen gneiss layers, including a 38 m-thick layer of amphibolite gneiss that gave the 369 ± 3 Ma U-Pb zircon age (Dusel-Bacon *et al.*, 2004; Fig. 5B). The protolith of the amphibolite and mafic gneiss could have been a series of (cognate?) dikes or sills within the granitoid batholith (Dusel-Bacon *et al.*, 2004; Day *et al.*, 2003).

Peraluminous augen gneiss near the eastern margin of the Lake George assemblage in the vicinity of the Alaska-Yukon border (Fig. 2) gives a broader range of Late Devonian-Early Mississippian U-Pb zircon ages. In the northern Tanacross quadrangle, U-Pb ages for three samples of augen orthogneiss and one of augen-poor orthogneiss range from 347.4 ± 5.1 to 370.5 ± 5.9 Ma (Fig. 2, Table 1). Although shown as a single augen gneiss body on Figure 2, the rocks have differing textures, degrees of deformation and inferred igneous crystallization ages; and probably represent the products of multiple magmatic pulses over a protracted interval (C. Dusel-Bacon and I.S. Williams, unpublished data, 1997). U-Pb ages for augen gneiss from the nearby Fiftymile batholith, which spans the Alaska-Yukon border, range from 353 ± 4 to 364 ± 4 Ma (Fig. 2; Table 1). Dusel-Bacon and Aleinikoff (1996) proposed that the Fiftymile batholith was intruded in multiple stages, from slightly differing sources (reflected by differing orthogneiss mineralogy), and therefore is a composite body. U-Pb zircon data from Sierra Nevada batholith in California indicate that the Tuolumne Intrusive Suite was assembled incrementally over a period of at least 10 m.y. in the Cretaceous (Coleman *et al.*, 2004), comparable to the extended crystallization history we propose for the augen gneiss bodies.

## Carbonaceous Metasedimentary Rocks and Felsic and Mafic Metavolcanic Rocks

Sequences of greenschist facies carbonaceous and siliceous metasedimentary rocks — variably carbonaceous phyllite, calc-phyllite, quartz-eye schists (reworked tuffs?) and minor marble and quartzite; and felsic and mafic metavolcanic and subordinate metaplutonic rocks crop out in the western Yukon-Tanana Upland (Figs. 2, 3) and along much of the northern flank of the Alaska Range (Figs. 1, 2 and 6). These sequences host most of the VMS and SEDEX syngenetic base-metal mineral deposits in east-central Alaska (Gilbert and Bundtzen, 1979; Newberry *et al.*, 1997; Dusel-Bacon *et al.*, 1998). Our discussion of these rocks focuses on the detailed geologic and U-Pb zircon studies conducted in three separate areas, discussed separately below. U-Pb zircon ages (Table 1) indicate Late Devonian and earliest Mississippian protolith ages for felsic meta-igneous rocks. Correlative volcanic and sedimentary sequences and VMS occurrences crop out in the Kantishna Hills (Fig. 1; Bundtzen, 1981; Gilbert and Bundtzen, 1979; Newberry *et al.*, 1997), west of the Bonnifield mining district (Wood River area).

### *Salcha River Area, Northern Big Delta Quadrangle*

Greenschist facies rocks underlie a large part of the Salcha River and Chena River watersheds in the western Yukon-Tanana Upland (Fig. 3). The stratigraphically lowest assemblage consists of thin-

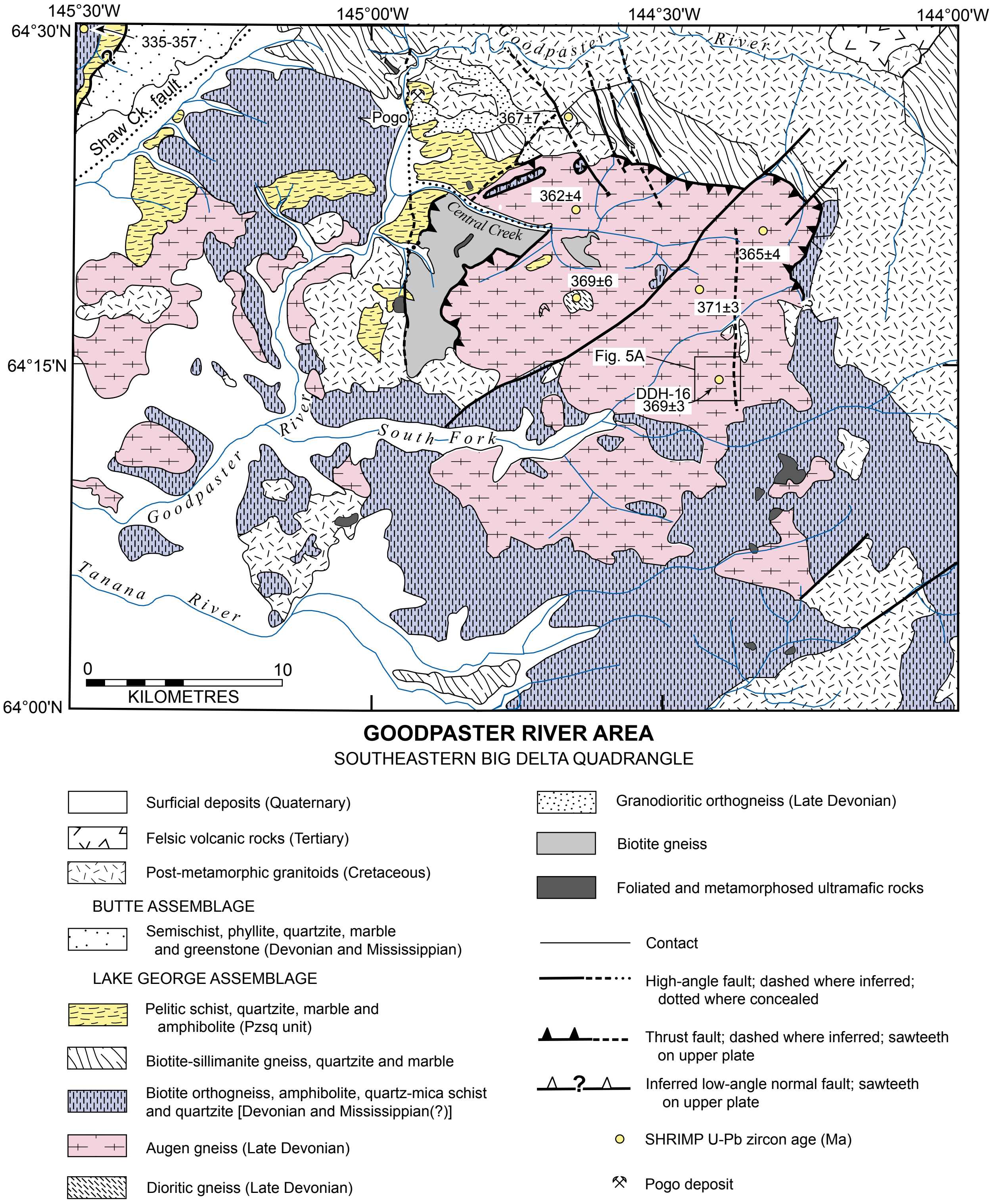


**Figure 4.** *Simplified geologic map of the Goodpaster River area (modified from Weber* et al.*, 1978, and Day* et al.*, 2003) showing U-Pb zircon ages and location of diamond drill hole. Sources for U-Pb zircon dates are given in Table 1.*

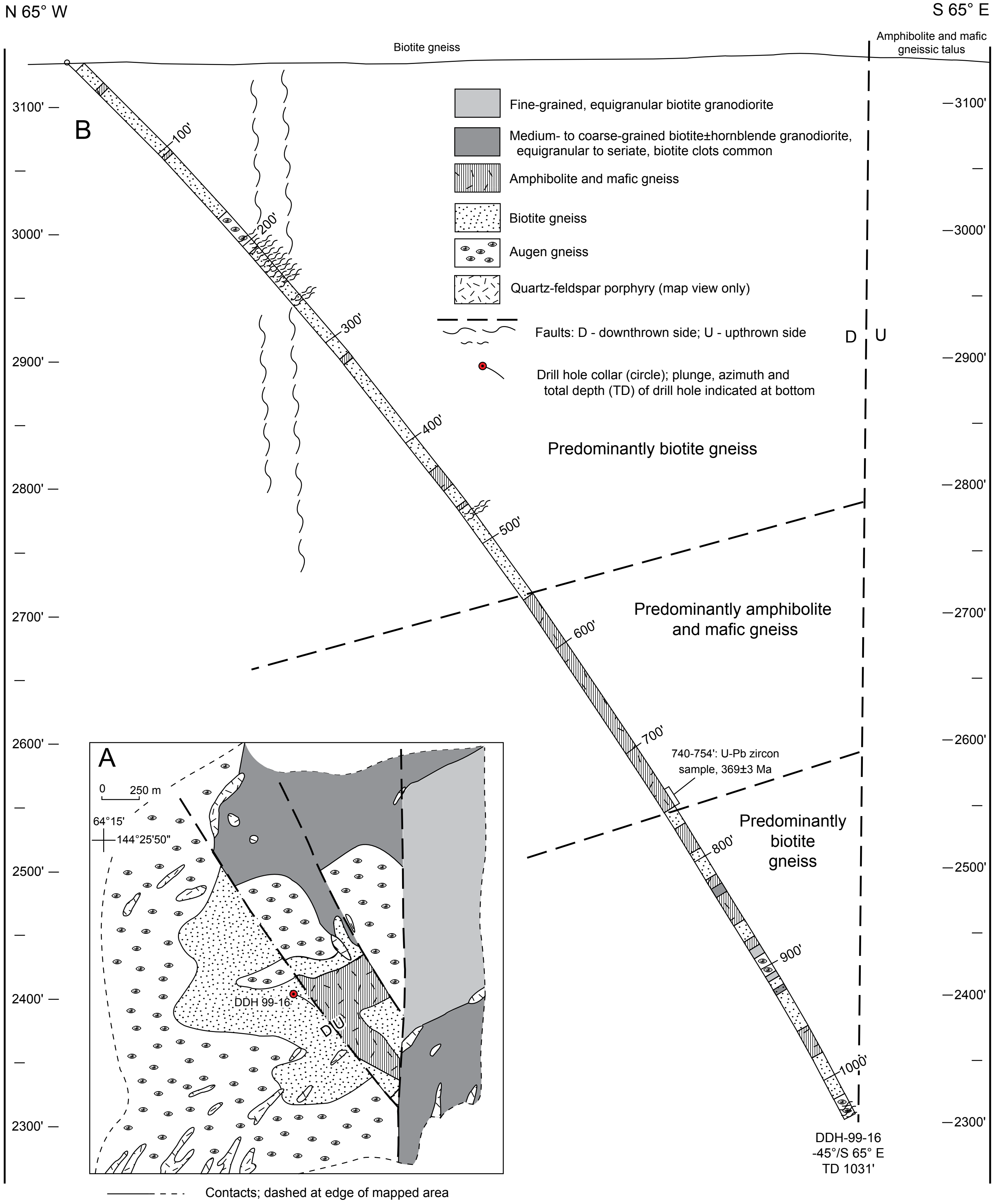


**Figure 5.** *(caption on facing page)*

layered calc-phyllite and carbonate layers (Dan Creek unit of Smith *et al.*, 1994). *Favosites* corals, found in siliceous calcphyllite float within the Chena River drainage, were interpreted to have been derived almost certainly from the Dan Creek unit; they indicate a depositional age between Late Ordovician and Middle Devonian (Smith *et al.*, 1994). The Dan Creek unit is overlain by a much thicker section of carbonaceous quartzite, phyllite and subordinate felsic and mafic metavolcanic rocks referred to as the Blackshell unit by Smith *et al.* (1994). The Blackshell unit was previously correlated with the Nasina assemblage in Canada (Foster *et al.*, 1994; Smith *et al.,* 1994; Dusel-Bacon *et al.*, 1998, 2004), but we now restrict the use of the Nasina assemblage name in Alaska to the rocks in the eastern Yukon-Tanana Upland that contain Permian and Mississippian felsic rocks and appear to grade into the Fortymile River assemblage, discussed in a later section. Smith *et al.* (1994) proposed a compositionally gradational contact between the Dan Creek and Blackshell Creek units, and between the Dan Creek unit and the underlying amphibolite facies Chena River sequence, just west of West Point (Fig. 3). Other workers (Foster, 1992; Foster *et al.*, 1994) interpreted the contact between the Dan Creek unit and amphibolite facies rocks as a fault (Fig. 3). South of the Chena River, carbonaceous phyllite of the Blackshell unit is host to stratiform SEDEX base-metal mineralization (Dusel-Bacon *et al.*, 1998).

The Blackshell unit is overlain by the Butte assemblage, which consists of quartzofeldspathic mylonitic rocks of probable hypabyssal origin (quartzofeldspathic mylonitic unit; Fig. 3), and quartz-feldspar-eye semischist or grit, phyllite, metasandstone, quartzite, marble and greenstone (Weber *et al.*, 1978; Foster *et al.*, 1994; Dusel-Bacon *et al.*, 2004; Werdon *et al.*, 2004). We interpret the finer grain size of the igneous quartz and feldspar grains in the semischists of the Butte assemblage, relative to those in the quartzofeldspathic mylonitic unit, to suggest a shallower, extrusive origin for the former and/or a possible reworked (epiclastic? turbiditic?) tuffaceous origin for many of the quartz-feldspar-eye semischists and grit. Detailed mapping of the Butte assemblage (L.E. Young, written communication to Dusel-Bacon, 1996; Werdon *et al.*, 2004) indicates that the quartz-feldspar-eye semischists, grit and metasandstone occur at the top of the Butte assemblage.

The northern contact of the Butte assemblage with the underlying Blackshell unit has been interpreted as a thrust fault (Foster, 1992; Smith *et al.*, 1994). This interpretation is consistent with the occurrence of a sliver of ultramafic rock, assumed to be a part of the oceanic Seventymile terrane, at the contact south of Teuchet Creek (Fig. 3; Dusel-Bacon *et al.*, 2004). As mentioned in the previous section, the nature of the contact between the greenschist facies Butte assemblage and the underlying amphibolite facies pelitic schist and associated rocks, which form the flanks of the Salcha River gneiss dome, is controversial, but we show its northeast-trending contacts as queried low-angle normal faults (Fig. 3) on the basis of kinematic data and geologic reasoning presented in Pavlis *et al.* (1993) and Oliver and Dusel-Bacon (2003). However, metabasites from both the amphibolite facies unit and overlying greenschist facies assemblages have similar trace-element signatures (discussed later in the paper).

Devonian igneous crystallization ages are indicated by SHRIMP U-Pb zircon ages for both K-feldspar-bearing augen gneiss (364 ± 3 Ma) and metaporphyry (371 ± 7 Ma) from the quartzofeldspathic mylonitic unit of the Butte assemblage and for metarhyolite porphyry (372 ± 5 Ma) from the carbonaceous Blackshell unit near the headwaters of Teuchet Creek (Dusel-Bacon *et al.*, 2004; Fig. 3). These overlapping crystallization ages for the felsic protoliths in both of these units suggest a geologic link between the two, as do similarities in whole-rock trace-element signatures for both felsic and mafic meta-igneous rocks (Dusel-Bacon *et al.*, 2004), discussed in a subsequent section.

Metarhyolite from a ~20 cm-thick concordant layer (tuff?) within carbonaceous rocks in the eastern part of the Blackshell unit, southwest of West Point, yielded a small number of zircons with very complex U-Pb systematics, in which SHRIMP spot analyses indicate two different Paleozoic ages (Dusel-Bacon *et al.*, 2004): (1) eight grains yield an average U-Pb crystallization age of 353 ± 7 Ma, with the three oldest grains (358, 359, 361 Ma) indicating that the sample may be at least 361 Ma, given the disturbance of the zircons' U-Pb systematics; and (2) nine grains, some having low Th and high U, possibly indicating growth from metamorphic fluids, give ages from 310 to 180 Ma, with seven of the grains suggesting an age of *ca.* 250 Ma. Alternatively, if the *ca.* 250 Ma ages are igneous crystallization ages (a possibility we consider less likely), then this implies that either basinal deposition extended from Late Devonian to Late Permian time or that an unrecognized unconformity separates two lithologically very similar depositional sequences, one of Late Devonian-Early Mississippian age and the other of Permian age.

### *Wood River Area, Central Alaska Range*

Greenschist facies metavolcanic and metasedimentary rocks in the Wood River area of the north-central Alaska Range form range-parallel, east-trending belts (Figs. 2, 6) (Wahrhaftig, 1968, 1970; Gilbert, 1977; Gilbert and Bundtzen, 1979), north of the Hines Creek strand of the Denali fault system (Fig. 2). Protoliths of all map units consist of varying amounts of felsic and mafic volcanic and shallow-level intrusive rocks interlayered with carbonaceous and siliciclastic sedimentary rocks (Fig. 6), indicative of a submarine, basinal setting.

Quartz-sericite schist, quartzite, chlorite schist and subordinate carbonaceous schist and marble of the Healy schist (Newberry *et al.*, 1997; Birch Creek Schist of former usage: Wahrhaftig, 1968; Gilbert, 1977; Gilbert and Bundtzen, 1979) core a regional anticline.

**Figure 5.** *(facing page) (A) Detailed geologic map of the Brink gold property in the eastern part of the Goodpaster River area (see Fig. 4) showing the location of diamond drill hole DDH-16. (B) Simplified geologic cross section from diamond drill hole DDH-16. Mapping and drilling conducted by WGM, Inc., Anchorage, Alaska on behalf of Metal Mining Agency of Japan and Sumitomo Metal Mining America Inc. (Corbett and Bressler, 2000).*

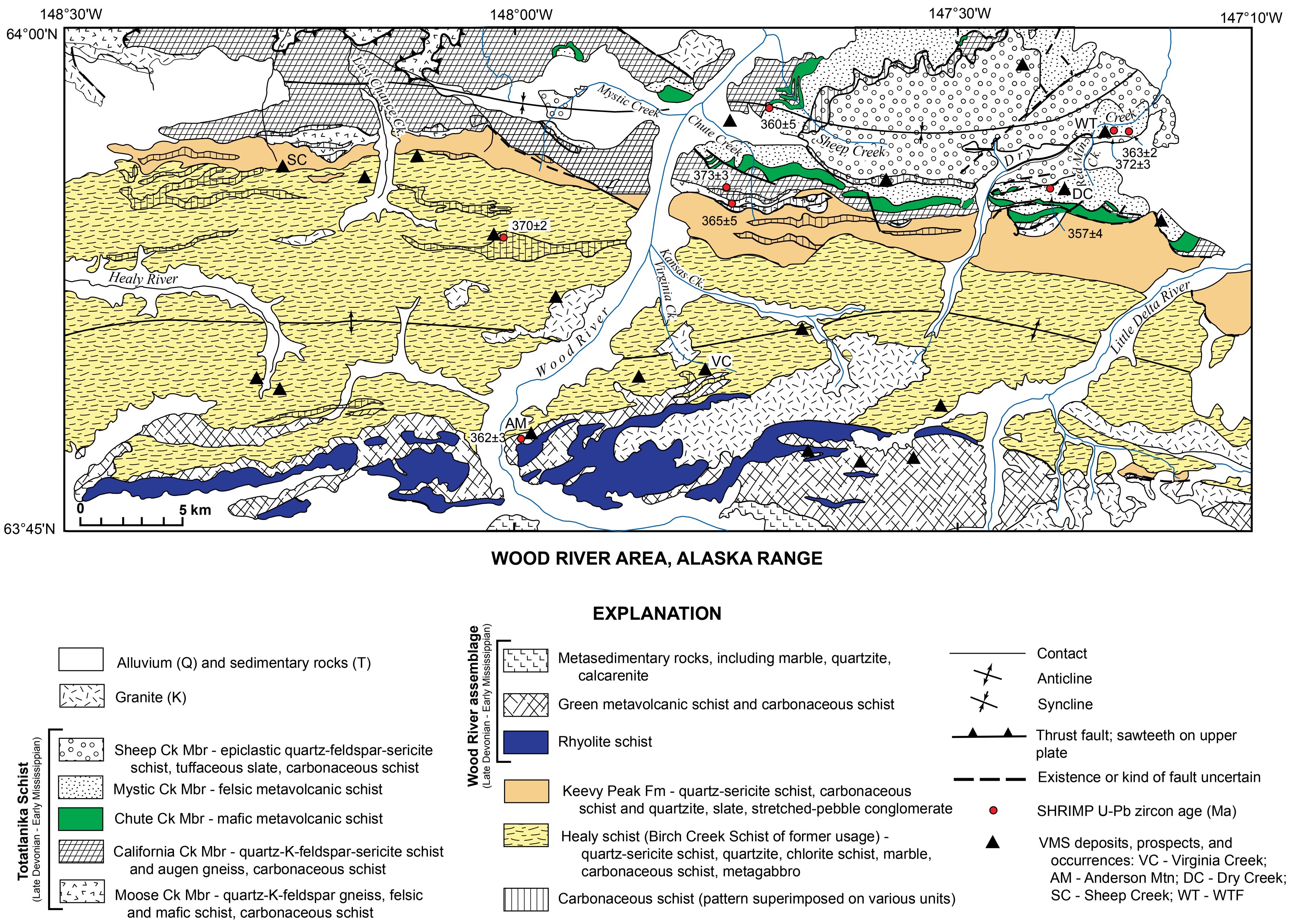


**Figure 6.** *Simplified geologic map of the Wood River area (after Wahrhaftig, 1968, 1970; Gilbert, 1977) showing U-Pb zircon ages (Dusel-Bacon* et al.*, 2004, 2005) and location of VMS deposits, prospects and occurrences (Newberry* et al.*, 1997; Cox* et al.*, 1989; Gilbert and Bundtzen, 1977). Abbreviations for VMS prospects: AM - Anderson Mountain; DC - Dry Creek; SC - Sheep Creek; VC - Virginia Creek; WT - WTF.*

Carbonaceous metasedimentary rocks and minor stretched pebble conglomerate and felsite of the Keevy Peak Formation crop out north of, and stratigraphically above the Healy schist.

Bimodal meta-igneous and associated carbonaceous and siliceous metasedimentary rocks of the Totatlanika Schist overlie the Keevy Peak Formation. Wahrhaftig (1968) divided the Totatlanika Schist into five members: in ascending order these are the Moose Creek, California Creek, Chute Creek, Mystic Creek and Sheep Creek Members (Fig. 6). Contacts are thought to be mostly depositional, but locally are faulted. The Moose Creek, California Creek and Mystic Creek Members are primarily composed of metafelsite, although mafic schist also occurs in the Moose Creek Member. Metarhyolite, much of which is interpreted to be metamorphosed crystal tuff, is the dominant felsic lithology in the Mystic Creek Member and augen gneiss/schist, grading to metarhyolite porphyry, predominates in the California Creek Member. The Chute Creek Member is composed of metabasite (primarily metabasalt), which interfingers with both the underlying California Creek and the overlying Mystic Creek Members. The Sheep Creek, the uppermost member, consists of quartzofeldspathic schist derived from an epiclastic (near source) reworked volcanic deposit, metasiltstone, metatuff and marble. Black phyllite, indistinguishable from that in the Keevy Peak Formation, is found within all members of the Totatlanika Schist. These rocks occur in a syncline with the Sheep Creek Member occupying its core (Fig. 6).

A lithologically similar package of mafic and felsic metavolcanic rocks and metasedimentary rocks, including carbonaceous phyllite and schist, occurs on the south flank of the anticline cored by Healy schist (Fig. 6). These rocks, informally called the Wood River assemblage by Newberry *et al.* (1997), have been proposed to be equivalent to the Totatlanika Schist (*e.g.*, Gilbert and Bundtzen, 1979). Metarhyolites in the Wood River assemblage near the Anderson Mountain VMS deposit and the Mystic Creek Member near the WTF VMS deposit (Fig. 6) have identical SHRIMP U-Pb zircon ages of 363 ± 2 Ma; however, Sm–Nd systematics and trace-element signatures of their felsic and mafic metavolcanic rocks differ suggesting different magmatic sources (Dusel-Bacon *et al.*, 2005).

All of the paleontologically and isotopically dated metamorphic rocks in the Wood River area have Late Devonian to Early Mississippian protolith ages. SHRIMP U-Pb zircon igneous crystallization ages from felsic intrusive or extrusive rocks from the Mystic Creek, California Creek and Moose Creek Members of the Totatlanika Schist, and from metarhyolite from the Healy schist have a range of 376-353 Ma (including analytical uncertainties; Table 1; Dusel-Bacon *et al.*, 2004). Comparable Late Devonian (369 ± 4 and 370 ± 5 Ma) TIMS U-Pb zircon crystallization ages were determined for metarhyolite schist in the Kantishna Hills (J.N. Aleinikoff, R.M. Tosdal and T.K. Bundtzen, unpublished data, 1991, 1993; Fig. 1, Table 1) west of the Wood River area. The dated metarhyolite schist is interlayered with mafic metavolcanic and carbonaceous metasedimentary rocks of the Spruce Creek Sequence, which is correlated by Bundtzen (1981) with the Keevy Peak Formation. Conodonts of Middle Devonian to Early Mississippian age have been identified at one location within the Mystic Creek Member of the Totatlanika Schist, and conodonts of Late Devonian age have been found at another locality within the green metavolcanic schist unit of the Wood River assemblage (Csejtey *et al.*, 1992).

Gilbert and Bundtzen (1979) correlated the carbonaceous Keevy Peak Formation with the Nasina Quartzite identified by Tempelman-Kluit (1976) as a component of the Yukon Crystalline Terrane in Yukon. Several other studies (*e.g.*, Weber *et al.*, 1978; Smith *et al.*, 1994; Foster *et al.*, 1994) have proposed correlation of the carbonaceous Blackshell unit and the overlying Butte assemblage in the Salcha River area with the Keevy Peak Formation and the Totatlanika Schist, respectively, of the Alaska Range. Based on similarities in lithologies, U-Pb zircon ages and whole-rock trace-element geochemistry, Dusel-Bacon *et al.* (2004) also proposed correlation of the Totatlanika Schist with the Butte assemblage, but do not support a unique correlation of the Blackshell unit with the Keevy Peak Formation, given that carbonaceous intervals of substantial thickness are present in almost all members of the Totatlanika Schist as well (Fig. 6).

### *Delta Mineral Belt, Eastern Alaska Range*

The carbonaceous, siliceous and volcanic assemblage, which dominates the geology north of the Denali fault in the Alaska Range, has been extensively studied in the Delta mineral belt, ~175 km east of the Bonnifield mining district (Figs. 2, 7). The Delta mineral belt is divided into three metamorphic belts, named the Macomb, Jarvis and Hayes Glacier belts (Dashevsky *et al.*, 2003), which strike northwest-southeast and dip to the southwest (Fig. 7). The belt boundaries are roughly equivalent to the boundaries of the Macomb, Jarvis Creek Glacier and Hayes Glacier subterranes of the Yukon-Tanana terrane of Nokleberg *et al.* (1992a). Rocks of all three belts are highly deformed and locally have been intruded by a suite of gabbroic sills of Triassic age (225.8 ± 0.7 Ma, TIMS U-Pb zircon crystallization age; J.K. Mortensen and S.S. Dashevsky, unpublished data; Dashevsky *et al.*, 2003). Volcanogenic massive sulphide occurrences are present in both the Jarvis and Hayes Glacier belts.

The Macomb belt in the northeastern (structurally/stratigraphically lowest) part of the mapped area consists of pelitic schist, calcareous schist, rare amphibolite, felsic- to intermediate-composition intrusive orthogneiss; and mylonitic rocks of upper greenschist to epidote-amphibolite metamorphic facies. The Macomb belt was assigned a Devonian (and older?) age based on a 372 ± 8 Ma TIMS U-Pb upper intercept age of a highly discordant array of fine-grained zircon fractions from two metaplutonic samples from the Macomb belt, as well as four metavolcanic samples from the Jarvis and Hayes Glacier belts, with samples spanning the width of the entire Mount Hayes quadrangle (Fig. 2; Aleinikoff and Nokleberg, 1985; Nokleberg *et al.*, 1992b). Although this combining of samples is not a valid dating approach, the resultant age is consistent with our correlation of the Macomb belt with the Lake George assemblage on the basis of its lithology and metamorphic grade.

The Jarvis belt, which includes the most significant syngenetic massive sulphide occurrences in terms of size and grade, contains interlayered, submarine, schistose, felsic- to intermediate-composition-dominated metavolcanic rocks and metasedimentary rocks.

Recent mineral exploration has been guided by the recognition of five metamorphic sub-units within the Jarvis belt (Fig. 7). In order from structurally deepest and presumably oldest to highest and youngest, these are the Tushtena Pass, Lagoon, Tiger, Drum and Tok River units (Dashevsky *et al.*, 2003), which represent a revision of the nine units described by previous workers (Nauman *et al.*, 1982; Duke, 1985).

The Tushtena Pass unit is dominated by metasedimentary rocks that have calc-arenite, limestone and siltstone protoliths. Interbedded metavolcanic rocks have trachyandesite-andesite to rhyodacite protoliths with a minor basaltic component. The ratio of sedimentary to volcanic protoliths is approximately 2:1. Local chloritic and magnetite-bearing bands may represent deformed mafic volcanic horizons or fine-grained mafic sills.

The Lagoon unit is a thick metavolcanic-metasedimentary unit that hosts a number of important massive sulphide deposits and prospects. The metavolcanic rocks are typically rhyodacite-dacite, but a significant proportion is andesite and basalt (Dashevsky *et al.*, 2003). It consists of a basal section of banded, medium- to coarse-grained, quartz-sericite-chlorite schist and carbonaceous schist. Protoliths in the basal section are immature sedimentary rocks or wackes, mudstone, quartzarenite and lesser calc-arenite and carbonate units. The upper Lagoon section has more metavolcanic rocks and is dominated by white to pale green, massive to laminated, quartz-eye bearing, quartz-sericite-chlorite-pyrite metavolcanic schist with lesser black phyllitic metamudstone and thin intercalations of quartzite and fine-grained metagrit.

The Tiger unit is a distinctive metavolcanic unit, barren of massive sulphide mineralization, composed of banded pale to dark green and gray chlorite schist with variable amounts of quartz, sericite, stilpnomelane and rare biotite. Thin, but laterally extensive, carbonaceous phyllite horizons mark the occasional pause in volcanic activity in the otherwise monotonous stratigraphy. Volcanic protolith compositions in the Tiger unit are rhyodacite-dacite with minor andesite and basalt.

The Drum unit is a relatively thin sequence of predominantly metarhyodacite and metadacite schist that hosts several massive sulphide deposits and prospects. Metavolcanic rocks consist of white to pale gray-green, rusty weathering, fine quartz-eye bearing quartz-sericite (± chlorite, ± pyrite) schists, with minor gray to black carbonaceous phyllite and rare chloritic phyllite interbeds. The ratio of volcanic to sedimentary protoliths is approximately 2:1.

The uppermost unit in the Jarvis belt, the Tok River unit, is a thick, metasedimentary rock-dominated assemblage of chloritic phyllite, quartz-sericite-chlorite schist, variably phyllitic quartz-eye metagrit, carbonaceous phyllite and minor marble. Some of the metagrit contains feldspathic detritus and is locally calcareous. The ratio of sedimentary to volcanic protoliths is approximately 3:1, with sedimentary protoliths containing only thin and volumetrically minor interbeds of felsic volcanic rocks that have rhyodacite-dacite compositions similar to those in the Drum unit. Massive sulphide mineralization in the Tok River unit is thin and discontinuous.

Massive sulphide occurrences in the Jarvis belt are mostly associated with the metarhyolite to metadacite rocks of the Drum and upper Lagoon units, which are separated by the barren Tiger unit. Less well-studied, but potentially significant, volcanic-associated sulphide minerals occur in the sediment-dominated sections of the middle and lower Lagoon unit. The Lagoon unit has been dated at 372 ± 6 Ma, based on a SHRIMP U-Pb zircon age for rhyodacite at the LZ East massive sulphide prospect, and the Drum unit has been dated near the Devonian-Mississippian boundary, based on SHRIMP U-Pb zircon ages of 359 ± 6 Ma for metarhyodacite at the DD South deposit and 364 ± 7 Ma for metadacite at the HD South mineralized horizon (Fig. 7; J.N. Aleinikoff, written communication, 2002, *in* Dashevsky *et al.*, 2003). The age of the Tok River unit is considered Early Mississippian, based on its conformable relationship to the underlying Drum unit volcanics.

The Hayes Glacier belt in the southwestern part of the map is dominated by fine-grained phyllitic, schistose and mylonitic metasedimentary and metavolcanic rocks (Duke, 1985). The basal part of the unit consists of mafic- to intermediate-composition metavolcanic rocks, overlain by interbedded felsic metavolcanic rocks and extensive pelitic and graphitic metasedimentary rocks.

## MARGINAL BASIN AND ARC ASSEMBLAGES IN THE EASTERN YUKON-TANANA UPLAND

### Fortymile River Assemblage

The Fortymile River assemblage crops out in the southern Eagle and northeasternmost Tanacross quadrangles in Alaska and the adjacent Dawson and Stewart River sheets in Yukon (Figs. 2, 8). It consists mainly of amphibolite-facies amphibolite, garnet amphibolite, quartz-biotite ± hornblende ± garnet schist and lesser amounts of feldspathic orthogneiss (primarily of granodioritic, tonalitic or trondhjemitic composition), metapelite, quartzite, metachert, marble and sulphide-bearing siliciclastic metasedimentary rocks, (Foster, 1976; Day *et al.*, 2000, 2002; Werdon *et al.*, 2001; Szumigala *et al.* 2002a; J.K. Mortensen and C. Dusel-Bacon, unpublished data, 2000). Locally intermixed with these lithologies are small masses of hornblendite, metadiabase, metagabbro, pyroxenite and serpentinized peridotite (Foster, 1976). Bands of massive marble, up to several hundred metres thick, form prominent markers in several areas. Foster (1976) grouped all of the amphibolite facies rocks as a single gneiss and schist unit, although some compositional variance was indicated on her maps. More recent and detailed mapping (Day *et al.*, 2000, 2002; Werdon *et al.*, 2001; Szumigala *et al.,* 2002a) has delineated numerous lithologic subdivisions within the Fortymile River assemblage, including a larger, and more compositionally diverse, number of orthogneiss bodies than were originally mapped (*cf.* Foster, 1976).

U-Pb zircon analyses from intermediate-composition gneiss (Steele Creek Dome Orthogneiss unit of Day *et al.*, 2002) and associated, likely co-magmatic, granodiorite and volumetrically minor augen gneiss and metarhyolite tuff(?) in the Eagle and Dawson quadrangles, yielded Early Mississippian crystallization ages. With the exception of one 360.7 ± 2.3 Ma U-Pb date from a sample of augen

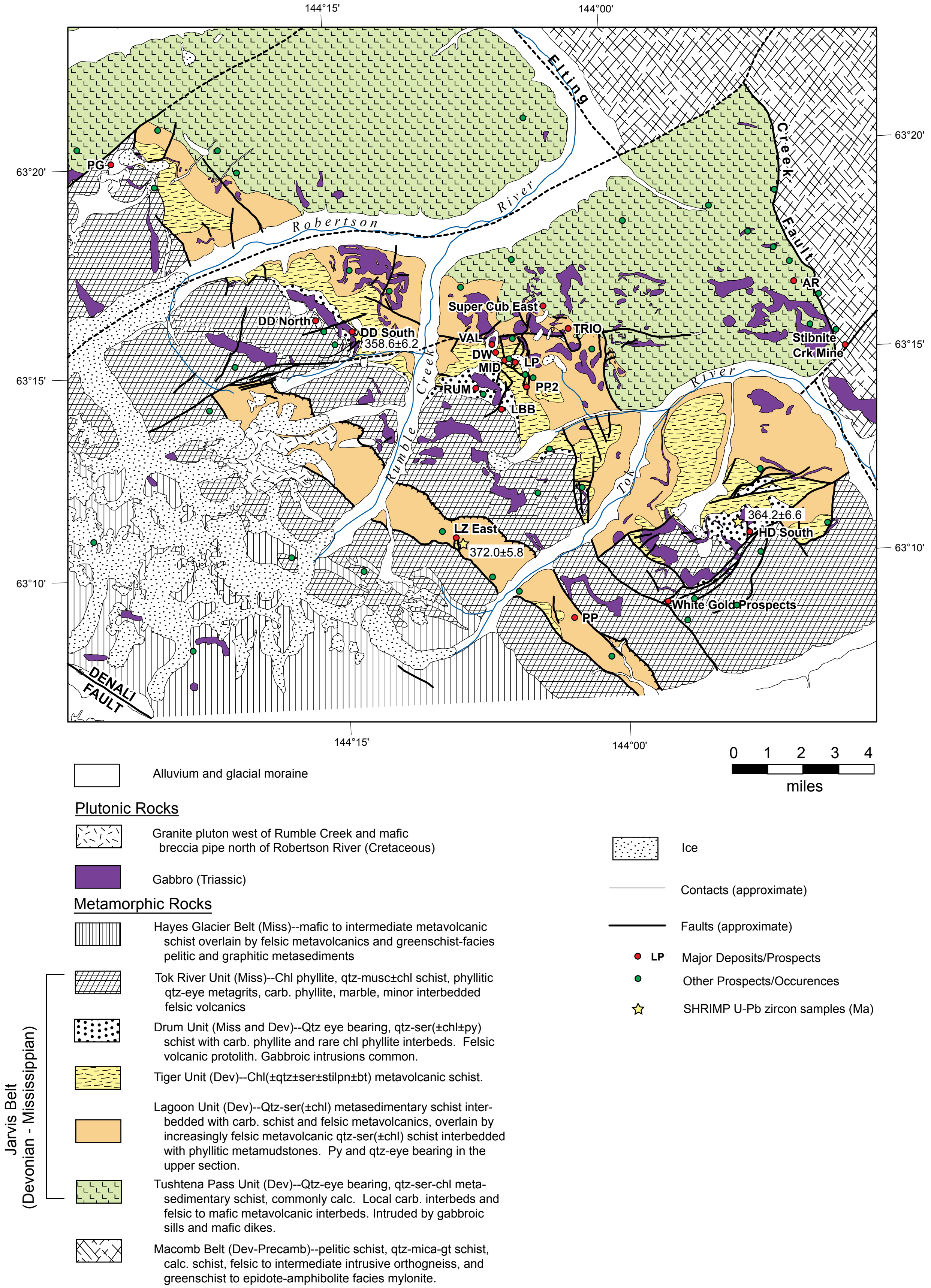


**Figure 7.** *Simplified geologic map of the Delta mineral belt showing U-Pb zircon ages (modified from Dashevsky* et al.*, 2003).*

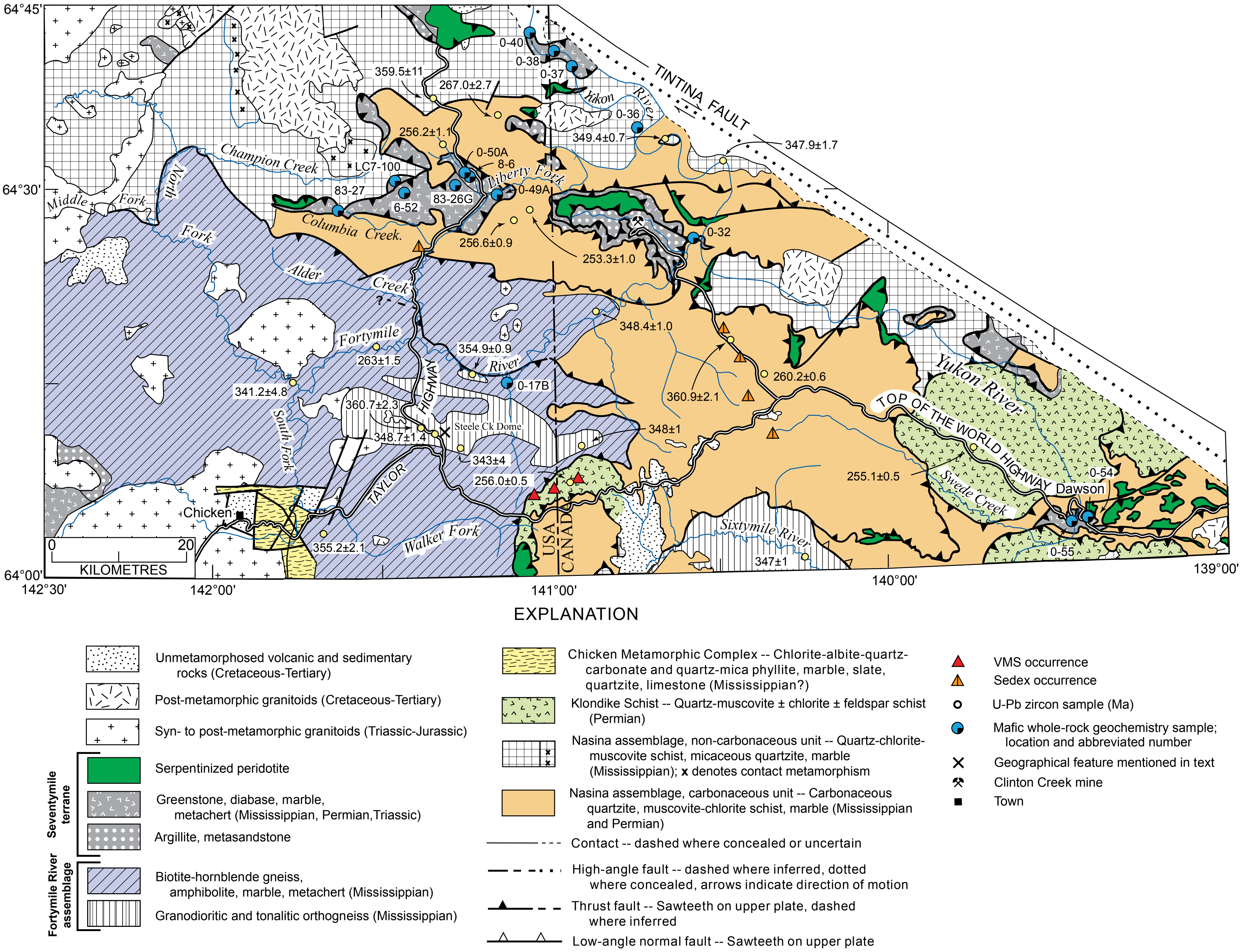


**Figure 8.** *Generalized geologic map of easternmnost Alaska and adjacent parts of Yukon (modified from Foster, 1976, 1992; Mortensen, 1988; Werdon* et al.*, 2001; Day* et al.*, 2003; J.K. Mortensen and C. Dusel-Bacon, unpublished mapping, 2000) showing U-Pb zircon ages and location of metabasite geochemical samples from the Seventymile terrane and Fortymile River assemblage (one sample). Sources for U-Pb zircon dates given in Table 1.*

orthogneiss, all of the other dates from felsic and intermediate-composition meta-igneous rocks in this assemblage give ages that range from 355.2 ± 2.1 to 341.2 ± 4.8 Ma (Table 1). Zircon U-Pb crystallization ages (360-345 Ma) of metaplutonic rocks in the Fortymile River assemblage in the adjacent Stewart River quadrangle in Yukon overlap this range (Villeneuve *et al.*, 2003). The younger end of the U-Pb age range is consistent with a Late Meramecian to early Sakmarian (mid-Mississippian to early Early Permian) age range for conodonts from a marble body near Alder Creek (Fig. 8; Dusel-Bacon and Harris, 2003). A minimum protolith age is tentatively provided by a poorly constrained TIMS U-Pb zircon date of 263.0 ± 1.5 Ma from an undeformed granite dike that intrudes the assemblage along the Fortymile River (Table 1; Fig. 8).

Use of the name "Fortymile River assemblage" was recently adopted (Werdon *et al.*, 2001; Dusel-Bacon *et al.*, 2002; Szumigala *et al.*, 2002a) to describe these rocks. Previously, these amphibolite-facies rocks were referred to as the $Y_4$ subterrane of the Yukon-Tanana terrane (Foster *et al.,* 1994), the Teslin-Taylor Mountain terrane (Hansen, 1990), the Taylor Mountain terrane (Dusel-Bacon *et al.*, 1995), and most recently, the Taylor Mountain assemblage (Hansen and Dusel-Bacon, 1998).

Geochemical compositions of the Fortymile River assemblage amphibolites, discussed more thoroughly below, and their association with mafic- to intermediate-composition metaplutonic rocks, indicates that the entire magmatic suite probably formed in a volcanic arc environment; although amphibolites from a few small areas have tholeiitic to MORB signatures (Dusel-Bacon and Cooper, 1999; Day *et al.*, 2002; Szumigala *et al.*, 2002b) and rarely within-plate signatures (Werdon *et al.*, 2001; Szumigala *et al.*, 2002a). Quartz-biotite schist has non-carbonaceous siliciclastic protoliths that, along with regionally extensive marble units that occur within both the Fortymile River assemblage and the adjacent parts of the Nasina assemblage, represent background sedimentation during the construction of the volcanic edifices. Small, isolated marble bodies may be derived from small patch reefs developed around individual volcanic centers. Day *et al.* (2000) locally observed preserved relict bedding typical of turbidite sequences within the biotite-schist lithology, and suggested that its protolith probably includes both turbidite and pelagic sediment.

The Fortymile River assemblage was considered to have a different origin than the rest of the Yukon-Tanana terrane in Alaska on the basis of differences in protoliths, structural and metamorphic histories; and the presence of an older (Triassic and Jurassic) group of plutons that intrude it and adjacent parts of the Nasina assemblage, but are not present in the other assemblages of the Yukon-Tanana Upland (*e.g.,* Churkin *et al.*, 1982; Foster *et al.*, 1985, 1994; Hansen *et al.*, 1991; Dusel-Bacon and Cooper, 1999). Garnet is common in many Fortymile River amphibolites and associated pelitic schists, and geothermobarometry indicates middle amphibolite facies metamorphic conditions and, at least locally, pressures to 12 kbar (Dusel-Bacon *et al.*, 1995). $^{40}Ar/^{39}Ar$ metamorphic cooling ages from Fortymile River assemblage tectonites are latest Triassic and Early Jurassic, and are interpreted to record post-metamorphic cooling during obduction of this assemblage onto the continental margin (Lake George assemblage) and adjacent marginal basin (Nasina assemblage; *e.g.*, Foster *et al.*, 1985; Hansen *et al.*, 1991; Dusel-Bacon and Hansen, 1992; Dusel-Bacon *et al.,* 1995, 2002).

Structural data support this assertion. In Alaska, the northern contact of the Fortymile River assemblage was interpreted as a complex, 1-3 km wide, east-southeast-striking, north-vergent thrust zone (Foster *et al.,* 1985) that structurally juxtaposes amphibolite facies Fortymile River rocks above greenschist facies carbonaceous and siliceous phyllite and schist of the Nasina assemblage; locally the contact is a straight, steep, northeast-trending fault (Fig. 8; Foster, 1976; Dusel-Bacon *et al.*, 2002). A wide, shallowly north-dipping, poorly exposed ductile fault zone separates the Fortymile River assemblage from the underlying Lake George assemblage just south of latitude 64° north (Fig. 2; Dusel-Bacon *et al.*, 1995; Hansen and Dusel-Bacon, 1998).

## Nasina Assemblage

The Nasina assemblage in the eastern Yukon-Tanana Upland (Eagle, Dawson and Stewart River quadrangles) is a greenschist facies sequence of variably carbonaceous quartzite, phyllite and schist, marble (locally, up to 100m in thickness), greenstone and minor metatuff and, in Yukon, stretched-pebble conglomerate (Foster, 1992; Mortensen, 1996; Dusel-Bacon *et al.*, 1998; Figs. 2, 8). There are two subunits: (1) a carbonaceous unit characterized by pale- to dark-gray carbonaceous quartzite and phyllite; and (2) a non-carbonaceous unit characterized by quartz-white mica-chlorite ± carbonate schist and phyllite. Marble, greenstone and metatuff are present in both subunits. Felsic metatuff in both the carbonaceous and non-carbonaceous units give Early Mississippian U-Pb zircon crystallization ages of *ca.* 359 and 349 Ma (Fig. 8; Table 1). Devonian-Mississippian Pb isotope model ages have also been obtained from four separate Nasina-hosted syngenetic base metal occurrences (Mortensen, 1992; Dusel-Bacon *et al.*, 1998; Mortensen *et al.*, this volume). Poorly preserved conodonts from non-carbonaceous rocks, exposed along the banks of the Yukon River, indicate a possible Mississippian age for at least part of the Nasina assemblage (Dusel-Bacon and Harris, 2003).

Permian (267-253 Ma) U-Pb zircon ages were obtained for several concordant felsic layers that are interpreted as metatuffs or, in two localities, as hypabyssal sills, within the carbonaceous rocks (Fig. 8; Table 1). The occurrence of both Early Mississippian and Permian felsic interlayers implies that either: (1) basinal deposition of Nasina assemblage sedimentary rocks extended from Early Mississippian to Late Permian time; (2) an unrecognized unconformity separates two lithologically very similar depositional sequences, one of Early Mississippian age and the other of Permian age; or (3) some of the felsic layers are transposed dikes.

Although the metamorphic grade of the Nasina is difficult to establish in some areas because of the typically quartz-rich or carbonaceous compositions, the presence of white mica and chlorite suggests greenschist facies metamorphism for most parts of this unit, at least in Alaska. In the Dawson map-area in western Yukon, biotite is common, and garnet and rarely sillimanite have been recorded, indicating metamorphism locally to at least lower amphibolite facies.

Metamorphic grade generally increases westerly across the southwestern Dawson map-area (J.K. Mortensen and C. Dusel-Bacon, unpublished mapping, 2000). In Alaska, biotite is uncommon and mostly of contact metamorphic origin (Foster, 1992; Fig. 8).

The Nasina assemblage passes laterally into interlayered amphibolite, quartz-biotite schist and marble of the Fortymile River assemblage near the Yukon-Alaska border (Fig. 8). Foster (1976) mapped mainly Fortymile River assemblage in the southeastern portion of the Eagle quadrangle immediately west of the border, whereas Mortensen (1988, 1996) showed adjacent areas in Yukon to be primarily Nasina assemblage, resulting in a “border fault” in the vicinity of the Yukon-Alaska border (*e.g.*, Dusel-Bacon *et al.*, 1998). Mortensen (1988) recognized some interlayering of Fortymile River and Nasina assemblages just east of the border, and additional observations along the Fortymile River in the same area have shown that rock types characteristic of the two assemblages are interlayered on a scale of tens to hundreds of metres (J.K. Mortensen and C. Dusel-Bacon, unpublished mapping, 2000). Elsewhere, and typically, thrust faults separate the Nasina and Fortymile River assemblages along much of their contact (Foster, 1992; Fig. 8).

## Chicken Metamorphic Complex

The Chicken Metamorphic Complex of Werdon *et al.* (2001) consists of greenschist facies metavolcanic rocks and subordinate metagabbro, metadiabase, marble, slate, quartz-mica phyllite and minor quartzite (Figs. 2, 8; Werdon *et al.*, 2001). At one locality along the South Fork of the Fortymile River, marble interlayered with greenstone yielded fossil crinoid columnals indicative of a general Paleozoic age (Foster, 1969); and poorly preserved conodonts from the same outcrop area are of late Paleozoic, possibly Mississippian, age (Dusel-Bacon and Harris, 2003). The metavolcanic rocks are mostly fine-grained, chlorite-albite-quartz-carbonate phyllite, whose trace-element composition is interpreted by Werdon *et al.* (2001) to indicate a basaltic protolith. Werdon *et al.* (2001) proposed that some phyllitic rocks are tuffs of possible andesitic to rhyolitic composition, that metagabbro and metadiabase may have originated as a sill or dike swarm, and that the entire complex comprises a volcanic arc upon which the subordinate sedimentary rocks and limestone were deposited. Foster *et al.* (1994) previously correlated these rocks with the Seventymile terrane. However, as pointed out by Werdon *et al.* (2001), the absence of ultramafic rocks and the presence of intermediate and felsic metavolcanic rocks in this complex are atypical of the Seventymile terrane.

The relationship of the Chicken Metamorphic Complex to the Triassic Taylor Mountain batholith is difficult to determine with certainty, in part because of poor exposure. Foster (1976) interpreted the contact between the batholith and this complex as intrusive, and observed contact metamorphic affects in the adjacent greenstone. Subsequent mapping by Werdon *et al.* (2001) revealed no hornfels in the metavolcanic rocks nor skarn in associated carbonate rocks, leading them to conclude that present contacts between the Chicken Metamorphic Complex and the batholith were faulted (Fig. 8). However, because abundant quartz diorite dikes, presumed to emanate from the Taylor Mountain batholith, cut the Chicken Metamorphic Complex, Werdon *et al.* (2001) concluded that the original contacts with the batholith were intrusive.

## Klondike Schist

The Klondike Schist, as defined by Mortensen (1990, 1996), comprises three main lithologies: (1) fine-grained quartz-muscovite schist and quartz (± feldspar) augen schist that are interpreted to be derived from felsic volcanic and subvolcanic rocks, respectively; (2) mafic schist and metagabbro derived from mafic to intermediate volcanic rocks and mafic intrusions, respectively; and (3) tan to buff, fine-grained quartz-mica schist and quartzite that represent fine-grained metaclastic rocks. Most of the Klondike Schist appears to have experienced metamorphism at middle to upper greenschist facies. Small syngenetic base-metal occurrences have been identified in many localities within the Klondike Schist near the Alaska/Yukon border (Fig. 8), indicating that much of the volcanism occurred in a submarine setting. Weakly to strongly foliated bodies of quartz monzonitic to granitic composition are also associated with the assemblage. Middle to Late Permian U-Pb zircon ages have been determined for layers of muscovite-quartz schist, interpreted to be felsic tuff, and for several of the quartz monzonitic to granitic metaplutonic bodies (Mortensen, 1990, 1992; Villeneuve *et al.*, 2003). Felsic metaplutonic and metaporphyry bodies of similar age locally intrude the Fortymile River and Nasina assemblages (Table 1), suggesting a shared tectonic setting during the Permian.

This assemblage is overthrust by and, in places, imbricated with amphibolite facies rocks of the Fortymile River assemblage and greenschist facies rocks of the carbonaceous and non-carbonaceous units of the Nasina assemblage (Figs. 2, 8; Foster *et al.*, 1994; Mortensen, 1996).

## Ladue River Unit

An area of dominantly greenschist facies metasedimentary rocks, herein referred to as the Ladue River unit, crops out in the southeastern corner of the Tanacross quadrangle (Fig. 2). Foster (1970) initially mapped these rocks as a unit of uncertain Precambrian to Paleozoic age, composed of greenschist facies quartz-white mica-chlorite ± epidote schist, quartz-actinolite schist and feldspar-quartz-sericite schist, with minor chlorite schist and biotite schist, and locally abundant sulphides. She correlated this unit with the Klondike Schist unit of Cockfield (1921) across the border in the Yukon. Petrographic and limited scanning electron microscope examination of recently collected rocks indicate that they are highly strained and exhibit medium-grained greenschist facies mineral assemblages. The majority of samples contain various combinations and proportions of quartz, albite, muscovite, chlorite and epidote-group minerals, noted by Foster (1970). The highly siliceous composition, well-developed muscovite folia and subtle compositional layering in these rocks suggest a sedimentary protolith, but the presence of albite and epidote implies a volcanic component. Meta-igneous rocks are few: medium- and fine-grained, equigranular metabasite (probably metabasalt or metadiorite) contains chlorite, epidote, zoisite/clinozoisite and albite, and trace amounts green amphibole; quartz-microcline gneiss is interpreted to have a felsic granitoid or volcanic protolith.

Two small (~200 m) serpentinized ultramafic bodies crop out, and are most likely fault slivers of Seventymile terrane rocks.

The Ladue River unit is retrograded from upper greenschist facies or lower amphibolite facies conditions, as indicated by chloritization of biotite and garnet and by replacement of a 0.5 cm green amphibole crystal with a mat of fine-grained acicular amphibole. Many of the metasedimentary schists contain 4-10 mm-long albite porphyroblasts with inclusion trails of quartz, epidote-group minerals, or carbonaceous material. The internal inclusion trails are generally parallel to the external foliation, and the albite porphyroblasts have elongate shapes with long dimensions aligned parallel to the foliation, indicating that they grew late in the tectonometamorphic history of the rocks, with or without accompanying sodium metasomatism. Small (<1mm) unaltered idioblastic garnets may have formed by contact metamorphism from nearby Cretaceous granitoids.

Correlation of this unit with other assemblages in the eastern Yukon-Tanana Upland is problematic. Zircons recovered from a quartz-muscovite-chlorite (after biotite)-epidote schist appear to be igneous, and give a concordant TIMS U-Pb age of 362.9 ± 1.4 Ma (Table 1; Fig. 2). This age, if truly the intrusive age of the sample, precludes correlation with the Permian Klondike Schist that consists primarily of felsic metavolcanic rocks, and suggests correlation with either the Lake George or the Fortymile River assemblage. However, the protolith of the dated sample is uncertain; and it is possible that the zircons are detrital and were locally derived from the mid-Paleozoic orthogneisses and provide only a maximum depositional age for the unit. Trace-element abundances for the only analyzed metabasite from this unit (Table DR1 [see footnote 1]), discussed in a subsequent section, are consistent with trace elements in a minor population of rocks in either the Lake George or the Fortymile River assemblage, but are unlike those in the Klondike Schist.

## OCEANIC ROCKS OF THE SEVENTYMILE TERRANE

The Seventymile terrane consists of a discontinuous belt of fault-bounded slices of variably serpentinized peridotite; weakly metamorphosed mafic volcanic rocks, including pillowed greenstone; and Mississippian to Upper Triassic sedimentary rocks (Foster *et al.*, 1994, and references therein). In the north-central Eagle quadrangle (Fig. 8), this entire package is considered to be part of a dismembered ophiolitic assemblage (Keith *et al.*, 1981). The oceanic rocks of the Seventymile terrane in Alaska are generally considered to be equivalent to the Slide Mountain terrane of northern British Columbia, as proposed by Harms *et al.* (1984; Fig. 1). Unlike the various pericratonic assemblages, rocks of the Seventymile terrane are not penetratively deformed.

### Ultramafic Rocks

The largest outcrops and the most diagnostic rock type of the Seventymile terrane are alpine-type ultramafic rocks: peridotites, originally derived from the mantle and representing the lower portion of oceanic lithosphere (Coleman, 1977). From northwest to southeast, the largest peridotite bodies are: in Alaska, the peridotites of Salcha River (offset from the rest of the belt by left-lateral movement along the Shaw Creek fault), Mount Sorenson and American Creek (Foster *et al.*, 1994, and references therein; Fig. 2, bodies labeled A, B and C, respectively); and in adjacent Yukon, the peridotites of Clinton Creek (just east of the Alaska-Yukon border) and Dawson City (Mortensen, 1988, 1996; Fig. 8). The ultramafic rocks are variably serpentinized harzburgite and dunite with minor clinopyroxenite; bodies of coarse-grained cumulate gabbro are associated with peridotite at Mount Sorenson (Foster and Keith, 1974; Keith *et al.*, 1981). Asbestos veins cutting the serpentinized peridotite of Clinton Creek were mined by open pit methods between 1967 and 1978 (Yukon MINFILE occurrence 116C 025; Deklerk and Traynor, 2005). Silica-carbonate alteration zones are well developed at the base of the peridotite of Salcha River and are locally developed in the peridotite of Mount Sorenson (Foster *et al.*, 1994) and at Clinton Creek (J.K. Mortensen, unpublished mapping).

Numerous small serpentinized bodies (too small to show at the scale of our map figures) crop out as lenses or pods in the Big Delta (Weber *et al.*, 1978), Eagle (Foster and Keith, 1974; Foster *et al.*, 1994) and Dawson quadrangles (Mortensen, 1988). Near contacts with country rock, the small serpentinized bodies locally have a rind of actinolite and/or chlorite, or hard slip-fiber serpentine, indicating a tectonic contact with the adjacent rocks (Foster *et al.*, 1994). One of the small serpentinized bodies (labeled D, Fig. 2) in the central Eagle quadrangle contains chrysotile asbestos in potentially commercial quantities (Foster *et al.*, 1994, and references therein; Foster and Keith, 1974).

### Weakly Metamorphosed Volcanic Rocks

The vast majority of volcanic rocks included in the Seventymile terrane are greenstone bodies that originated as basaltic pillow lava and lava flows. In Alaska, the largest body was referred to by Foster *et al.* (1994) as the greenstone of Wolf Mountain. This body, located just north of Columbia Creek in the eastern Eagle quadrangle (E, Figs. 2, 8), is associated with chert, weakly metamorphosed sedimentary rocks, silicified felsic tuff and small exposures of serpentinized peridotite, the largest occurring at the western end of the greenstone body.

Weakly metamorphosed diabase dikes and plugs and cumulate gabbros are locally associated with the Seventymile terrane peridotites, particularly at Mount Sorenson (Keith *et al.*, 1981). Low-grade silicic volcanic rocks, including tuff, are locally associated with the greenstone such as Mount Sorenson (Foster *et al.*, 1994) and with Seventymile metasedimentary rocks at the eastern end of the greenstone of Wolf Mountain, along the Taylor Highway (Foster, 1976; Fig. 8).

### Weakly Metamorphosed Sedimentary Rocks

Weakly metamorphosed sedimentary rocks within the Seventymile terrane primarily include chert, argillite, sandstone, conglomerate, graywacke and fine-grained, dark grey limestone. Many of the sedimentary rocks were deposited alternately with submarine basaltic lava flows (now greenstone), and in local basins (Foster *et al.*, 1994).

Mississippian to Late Triassic fossil ages have been recovered from chert, calcareous sedimentary rocks, dolomite and limestone interlayered with the metamorphosed mafic volcanic rocks.

Early to mid-Mississippian (Osagean to likely Meramecian) radiolarians (Foster *et al.*, 1994; Dusel-Bacon and Harris, 2003) were recovered from chert overlain by greenstone from the Mount Sorenson body. Farther east, fine-grained quartzitic sandstone and siltstone in fault slices of Seventymile terrane near the Tintina fault contain Middle Permian (Wordian) fusilinids and brachiopods (Foster, 1976; Stevens, 1995; Dusel-Bacon and Harris, 2003). Chert interlayered with greenstone associated with the peridotite of Salcha River yielded conodonts and radiolarians of middle Early Permian (Sakmarian-early Artinskian) age (Foster *et al.*, 1978; Dusel-Bacon and Harris, 2003).

Late Triassic (late Carnian and early Norian) conodonts have been recovered from carbonaceous limestone at several localities near the Alaska-Yukon border, including two localities from the sedimentary unit associated with the Wolf Mountain greenstone body, north of Columbia Creek (Fig. 8; Foster *et al.*, 1994; Dusel-Bacon and Harris, 2003). The western sample is from drill core from the Lead Creek prospect, located in an arcuate-shaped sliver of Seventymile terrane metasedimentary rocks that lies north of the greenstone body (Fig. 8). The northern contact of the low-grade sedimentary rocks hosting the Lead Creek prospect was interpreted by WGM, Inc. (2001), to be a high-angle normal fault, downdropped to the north; and the southern contact with greenstone and minor diabase, limestone and metachert of the Seventymile terrane was interpreted by Foster (1992) as a thrust fault. At the eastern Late Triassic locality, on the Taylor Highway, weakly metamorphosed sedimentary rocks and silicified tuff, comparable to those drilled at Lead Creek, were interpreted by Foster (1976) to lie in depositional contact with the greenstone of Wolf Mountain. Foster *et al.* (1994) noted that some of the weakly metamorphosed sedimentary rocks at the conodont locality along the Taylor Highway are similar to those described by Abbott (1982) at the Clinton Creek open-pit asbestos mine 25 km east in Yukon (Fig. 8). Conodonts from the main pit at Clinton Creek and another locality 5 km southeast also indicate Late Triassic, tentatively Norian ages (Abbott, 1982; Orchard, this volume). Faults have been mapped between the Triassic sedimentary rocks, the greenstone and peridotite components of the Seventymile terrane and the Nasina assemblage near the Clinton Creek body (Fig. 8; Mortensen, unpublished mapping, 1988); thus the implications of the Triassic ages for the evolution of the Seventymile terrane are uncertain.

## Tectonic and Metamorphic Relationships

Ultramafic and mafic igneous rocks, and most sedimentary rocks, of the oceanic Seventymile terrane mostly structurally overlie (Foster, 1992), or are imbricated with (Mortensen, 1992, and references therein; unpublished mapping, 1996) the penetratively deformed rocks of the Nasina, Butte and Fortymile River assemblages, and the Blackshell unit (Figs. 2, 3 and 8). Bounding thrust planes are generally subhorizontal, and isolated thrust remnants are themselves cut by internal high-angle and thrust faults. The best exposed basal contact of a Seventymile terrane klippe in Alaska is on the south side of the peridotite of Salcha River, where it is interpreted as a low-angle thrust fault (Foster *et al.*, 1994). Kinematic analysis from amphibolite facies quartzite and amphibolite developed directly beneath the peridotite of Salcha River suggests a top-to-the-northeast motion for the shear zone at the base of the Seventymile terrane, interpreted as the direction of thrusting of the klippe (Pavlis *et al.*, 1993). Seventymile terrane rocks near Clinton Creek were interpreted by Mortensen (unpublished mapping, 1988) to underlie, overlie, and include an imbricate sliver of Nasina assemblage rocks along low-angle brittle structures that may include thrust faults. The faults are rarely well exposed, but are traced as lithological contacts marked by discontinuous occurrences of greenstone and (or) ultramafic rocks in felsenmeer or float.

Metamorphic grade differs between individual thrust slices; metamorphic mineral assemblages in greenstones indicate that temperature conditions were transitional between those of the prehnite-pumpellyite and greenschist facies (Dusel-Bacon *et al.*, 1993). At one locality near the Tintina fault in the northern Eagle quadrangle (location 3040, Fig. 2), glaucophane, epidote, garnet and titanite occur in greenstone, indicating high-pressure, low-temperature blueschist facies conditions (Foster, 1976; Dusel-Bacon *et al.*, 1993).

It is generally agreed that the Seventymile, and the likely equivalent Slide Mountain terrane, represent oceanic crust and associated sedimentary rocks from an ocean basin that opened between the continental margin of North America and an outboard crustal fragment. It is also widely accepted that an arc(s) developed on the outboard crustal fragment as the ocean basin closed during late Paleozoic to early Mesozoic west-dipping subduction (*e.g.*, Foster and Keith, 1974; Templeman-Kluit, 1979; Foster *et al.*, 1985; Hansen, 1990; Nelson *et al.*, 2002; Dusel-Bacon *et al.*, 2004). As the ocean basin closed, remnants of the telescoped ocean basin were obducted onto, or imbricated with, the continental margin and the marginal basin (in Alaska, primarily the greenschist facies rocks of the Butte and Nasina assemblages, respectively [*e.g.*, Foster *et al.* 1994, and references therein; Dusel-Bacon *et al.*, 1995; Hansen and Dusel-Bacon, 1998]). The outcrop of glaucophane-bearing greenstone probably is part of a fault sliver that was dragged to a greater depth in a subduction zone or transpressive boundary along the convergent margin.

# TRACE ELEMENT SIGNATURES OF META-IGNEOUS PROTOLITHS

Whole-rock trace-element geochemistry can provide valuable information about the tectonic setting and petrogenesis of meta-igneous rocks, provided that the elements employed are those that have been shown to be relatively immobile during metamorphism up to middle amphibolite facies and hydrothermal alteration at low water:rock ratios (*e.g.*, Pearce, 1982; Pearce *et al.*, 1984). These include the high-field-strength elements (HFSE) Zr, Hf, Nb, Ta and Ti, rare-earth elements (REE) La through Lu (except Eu), Y and Ga, and, to a lesser degree, Th and Al. Because of major element mobility, especially of alkalis, and silicification, we identify protolith magma composition utilizing the $Zr/TiO_2$ *vs.* Nb/Y diagram of Winchester and Floyd (1977) (not shown), in which the $Zr/TiO_2$ ratio serves as a fractionation index and the Nb/Y ratio serves as an alkalinity index.

## Tectonic Fingerprinting of Mafic rocks

The tectonic settings in which basaltic protoliths potentially formed can be assessed using primitive mantle (PM)-normalized multi-element diagrams (Fig. 9). Figure 9A shows PM-normalized plots of global averages for modern normal mid-ocean-ridge basalt (N-MORB), enriched mid-ocean-ridge basalt (E-MORB), ocean-island basalt (OIB), a representative calc-alkaline arc basalt (CAB) and a representative island-arc tholeiite (IAT). Some chemical variability exists, however, in these nominal categories, so comparisons with them must be made in conjunction with as many geologic factors as possible (Arculus, 1987; Wilson, 1989). Ocean-island basalt shows a steep overall negative slope from left to right as a result of high abundances of HFSE, light rare earth elements (LREE) and middle rare earth elements (MREE). In OIB, Nb and Ta are elevated with respect to Th and La, producing a "hump", a hallmark of the magma type. Basalts with OIB-like chemistry are derived from incompatible element-enriched mantle sources in a wide range of settings, including ocean islands, oceanic plateaus, continental flood basalt environments and within-plate rifting of both continental and oceanic plates (*e.g.*, Wilson, 1989). For this reason, some have used the term "within-plate basalt" (WPB) to describe this enriched geochemical type (*e.g.*, Meschede, 1986). However, the geochemical setting term (OIB or WPB) may not necessarily correspond with the most likely tectonic setting for a given geologic situation. CAB has a pattern similar to that of E-MORB, with the exception that it has higher Th values and low normalized abundances of Nb and Ta relative to Th and La, producing a distinctive trough, considered a hallmark of modern arc rocks (Sun and McDonough, 1989). Both E-MORB and CAB show a weak depletion in Ti relative to adjacent elements. Island-arc tholeiite (IAT) is derived from a melt whose source is similar to that of N-MORB, but also has an added subduction-zone metasomatic input. IAT have flat PM-normalized patterns with a Nb and Ta trough.

Calc-alkaline basalts and andesites typically reflect the mature stages of arc development, whereas island arc tholeiites are generally associated with the early stages of arc development, before the arc edifice has reached a significant thickness. Piercey *et al.* (2004; this volume) identify a magma type in the Canadian portion of the arc component of the pericratonic rocks described as LREE-enriched island arc tholeiites (L-IAT) that is a hybrid between the IAT and the CAB, and likely represents either derivation from an E-MORB source with a subduction zone component or an IAT that has been weakly contaminated with continental crust. Calc-alkaline magmatic suites can be differentiated from tholeiitic magmatic suites by their high Zr/Y, La/Yb and Th/Yb ratios (Lentz, 1998; Barrett and MacLean, 1999; Piercey *et al.*, 2004, this volume). Lentz (1998) proposed a compositional classification in which Zr/Y ratios are >7 in calc-alkaline rocks, <4 in tholeiitic rocks and between 7 and 4 in transitional rocks.

The immobile trace-element diagrams shown in Fig. 10 are effective in discriminating between arc and non-arc basaltic magma sources, and in separating the non-arc rocks into subgroups. The Hf-Th-Ta diagram (Figs. 10A, B) was designed to distinguish MORB from OIB and destructive plate-margin basalts (arc basalts). However, continental basalts are not confined to the OIB field and continental basalts that have experienced crustal contamination can plot in the arc field (*e.g.*, Wood *et al.*, 1979; Wang and Glover, 1992). The location of average upper continental crust (UCC, Figs. 10A, B) within the calc-alkaline end of the arc basalt field highlights the importance of crustal contamination in lavas from attenuated continental settings (Pearce, 1995). The Y-La-Nb diagram (Figs. 10C, D) discriminates arc from MORB and alkalic rocks and identifies contamination by continental crust, and the Nb-Zr-Y diagram (Figs. 10E, F) effectively separates N-MORB from E-MORB.

Finally, we utilize the HFSE/HREE ratio plot of Th/Yb versus Nb/Yb, which has been shown to be relatively unaffected by partial melting and fractional crystallization and to reflect mantle sources of basalt (Pearce, 1983; Pearce and Peate, 1995). Global averages or typical values for characteristic magma settings, as well as trends for within-plate enrichment, crustal contamination and subduction-zone enrichment (slab metasomatism) are shown for comparative purposes on these ratio plots (Figs. 10G, H).

### *Metabasite in the Western Yukon-Tanana Upland and Alaska Range*

Trace-element geochemistry of metabasite has previously been presented for rocks in the Totatlanika Schist of the Wood River area, the Blackshell unit and Butte assemblage in the Salcha River area, and in the Lake George assemblage from the Salcha River area to the Canadian border (Dusel-Bacon *et al.*, 2004, Dusel-Bacon and Cooper, 1999). These studies showed that the vast majority of the metabasites from these units have $Zr/TiO_2$ and Nb/Y ratios indicating an alkali basalt composition. All of these metabasites, except three of the 14 Lake George samples, have PM-normalized multi-element plots (Fig. 9B) similar to OIB. Although most of these metabasites exhibit the distinctive Nb and Ta "hump" relative to Th and La, five of the Lake George samples from the Goodpaster River area have PM-normalized Th contents that are elevated with respect to Nb (ruled pattern on Fig. 9B). These elevated Th contents result in the appearance of a Nb-Ta "trough", but concentrations of Nb and Ta in these five samples are high, relative to a typical calc-alkaline basalt, and Dusel-Bacon *et al.* (2004) conclude, on the basis of other trace-element relationships, that the elevated Th is a result of crustal contamination in a within-plate setting. The other three Lake George metabasites have lower concentrations of incompatible elements and flatter patterns, similar to N- and E-MORB.

The more alkalic metabasite samples plot within the OIB field or between the calc-alkalic arc basalt and the OIB fields on the Hf-Th-Ta diagram (Fig. 10A), straddle the boundary between the alkalic - E-MORB and the adjacent continental crust field on the Y-La-Nb diagram (Fig. 10C), plot in the WPB field on the Nb-Zr-Y diagram (Fig. 10E), and plot between or above the global averages for OIB and E-MORB on the Th/Yb-Nb/Yb diagram (Fig. 10G). Newberry

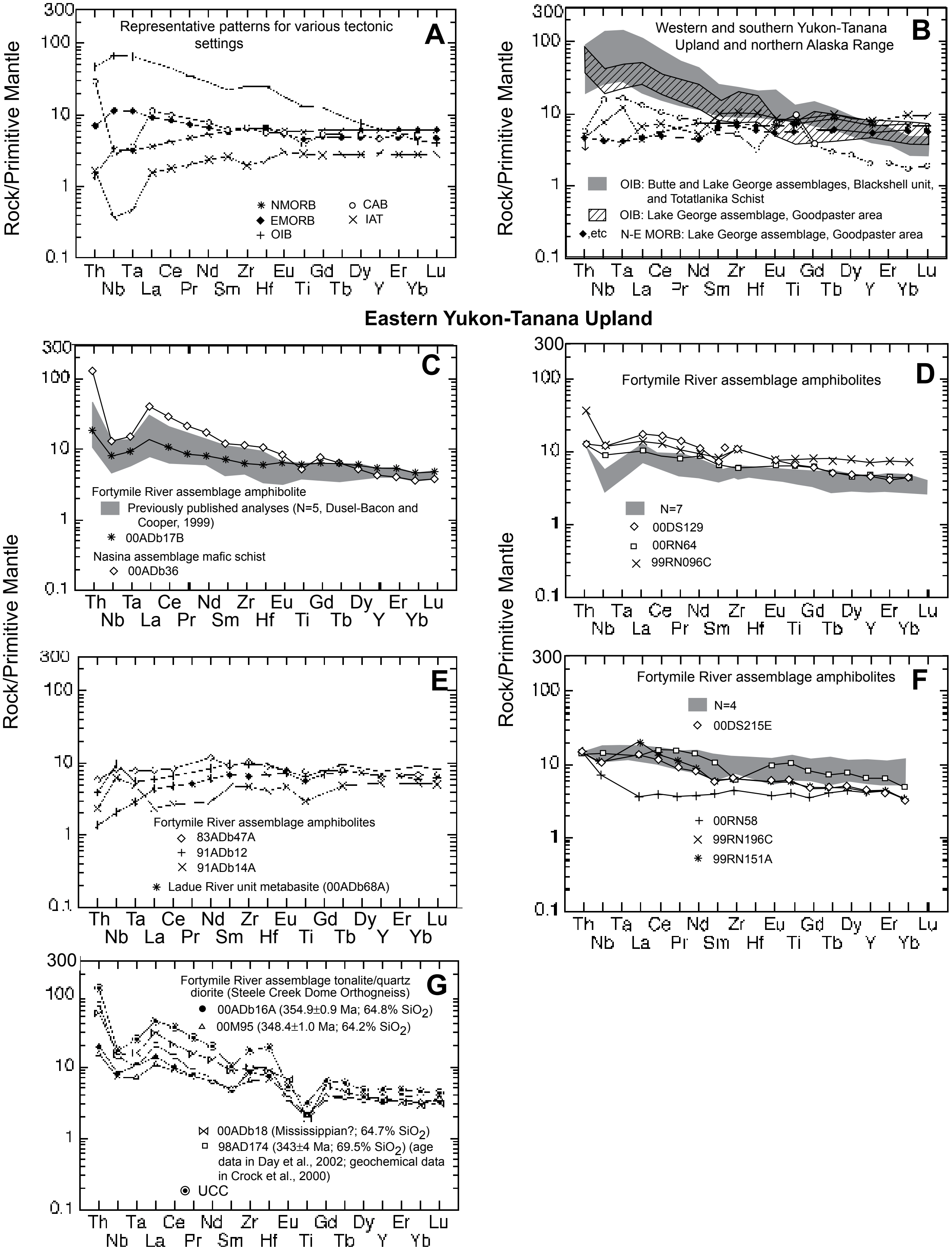


**Figure 9.** *(caption on facing page)*

*et al.* (1996) demonstrated a within-plate origin for amphibolites of the Fairbank Schist, as well, based on their Zr-Ti-Y ratios.

### *Metabasites and Tonalite-Quartz Diorite from the Eastern Yukon-Tanana Upland*

Trace-element geochemistry for metabasites (primarily amphibolites and garnet amphibolites) from the Fortymile River assemblage in the eastern Yukon-Tanana Upland indicates four different tectonic signatures (in decreasing order of abundance): arc, N-MORB, EMORB and OIB. Primitive mantle-normalized multi-element plots of Fortymile River samples show one suite of samples with arc characteristics (shown by the Nb-Ta trough, Figs. 9C, D) and another suite with N-MORB to E-MORB characteristics (Figs. 9E-F); these settings also are indicated by discrimination plots for data from the above studies and those by Day *et al.* (2000, 2002), Crock *et al.* (1999, 2000), Werdon *et al.* (2000, 2001), Szumigala *et al.* (2000, 2002b) (Figs. 10B, D, F, H).

Primitive mantle-normalized plots of the Fortymile River assemblage arc rocks have weakly negative slopes from La through Lu at a ratio of ~ 10, low Th concentrations (~3 to <1 ppm), and only moderately well developed Nb(-Ta) troughs (Figs. 9C, D). This PM-normalized multi-element pattern appears to be transitional between IAT and CAB and similar to the LREE-enriched IAT magma type (L-IAT) described for some of the mafic meta-igneous rocks in the Finlayson Lake area in southern Yukon (Fig. 1; Piercey *et al*., 2004, this volume). The Nb-Zr-Y plot (Fig. 10F) of a larger data set (including data without REE analyses from studies by Werdon *et al*., 2000, Szumigala *et al.,* 2000, 2002b) indicate that most of these samples fall in the E-MORB, VAB/WPB tholeiitic and N-MORB/VAB fields, as well as a newly identified component with within-plate (OIB) affinities (Fig. 10F). Zr/Y ratios for those Fortymile River assemblage amphibolites that exhibit Nb troughs average 3.8 and thus fall in the range of tholeiitic to transitional arc magmas (Lentz, 1998). The relatively high Th/Hf ratios of the Fortymile River amphibolites, shown on the Hf-Th-Ta diagram (Fig. 10E), cause them to plot in the calc-alkaline basalt field rather than in the primitive arc tholeiite field. Piercey *et al.* (2004, this volume) describe mafic rocks from the Finlayson Lake and Stewart River areas in Yukon with similar geochemical characteristics as L-IAT, and ascribe the high Th values to crustal contamination of IAT; we propose this is also the case with the Fortymile River arc amphibolites.

Primitive mantle-normalized multi-element plots for four samples of tonalite/quartz diorite from the Steele Creek Dome Orthogneiss unit of the Fortymile River assemblage (Fig. 9G) resemble those of the arc-like Fortymile River amphibolites (Figs. 9C, D), in terms of their overall negative slopes, Nb and Ta troughs and absolute abundances. The two tonalite/quartz diorite samples with the highest Th values have Nb-Ta troughs similar to CAB (Fig. 9A). The shape of these patterns are also very similar to that of UCC (Fig. 9G), although absolute abundances are distinctively greater in the UCC than in our CAB example. We interpret the composition of the Steele Creek Dome Orthogneiss to reflect an arc origin with some crustal contamination, as was the case with the largest group of Fortymile River amphibolites. Zr/Y ratios for the four tonalite/quartz diorite samples range from 4.61 to 6.86 (average 6.09), consistent with a composition transitional between a calc-alkaline and a tholeiitic suite.

Analysis of a single sample from the non-carbonaceous unit of the Nasina assemblage has a distinctly CAB composition (Table DR1 [see footnote 1]; Figs. 9C and 10B, D, F, H); its Zr/Y ratio is 6.55. Its arc chemistry is similar to, albeit more calc-alkalic, than one of the suites in the Fortymile River assemblage. This is consistent with the observation that, at least locally (in the vicinity of the Fortymile River near the Alaska-Yukon border), the Fortymile River assemblage has a gradational contact with the carbonaceous unit of the Nasina assemblage, suggesting an original proximity of the two as-

**Figure 9.** *(facing page) Primitive mantle-normalized trace-element plots of metabasites. Elements are arranged in order of decreasing incompatibility during mantle melting. (A) Plots of compiled global average values for modern N-MORB (normal mid-ocean ridge basalt), E-MORB (enriched mid-ocean ridge basalt), OIB (ocean island basalt) (Sun and McDonough, 1989), a typical CAB (calc-alkalic arc basalt; values are for sample LC88-1398 from the Lassen volcanic field in the Cascade arc; Bacon* et al*., 1997) and IAT (Island arc tholeiite; average of 11 samples of low-K tholeiite from the South Sandwich island arc; Pearce* et al*., 1995). (B) Metabasites from the Big Delta, Tanacross and Healy quadrangles. Gray colour: OIB signature with the "Nb-Ta hump" (from the Lake George assemblage [N = 6], Butte assemblage [N = 4], Blackshell unit [N = 3], Pzsq unit of the Lake George assemblage [N = 5], Totatlanika Schist [N = 5]). Diagonal ruled pattern: OIB signature with elevated Th (Lake George assemblage in the Goodpaster River area [N = 6]). Individual sample plots: Lake George assemblage with N- to E-MORB signature (N=4) (data and individual profiles in Dusel-Bacon and Cooper [1999] and Dusel-Bacon* et al. *[2004]). (C, D) Metabasites from the Eagle quadrangle with arc geochemistry (data for numbered samples in Figure 9C are from this study [Fig. 8; Table DR1]; data for samples in Figure 9D are from Szumigala* et al. *[2000], Szumigala* et al. *[2002b], Werdon* et al. *[2000], and R.J. Newberry, written communication [2004]). (E, F) Metabasites from the Eagle quadrangle with EMORB or NMORB geochemistry (data for FRA samples in Figure 9E are from Dusel-Bacon and Cooper [1999] and data for Ladue River unit from this study [Fig. 2; Table DR1]; data for samples in Figure 9F are from Szumigala* et al. *[2000], Szumigala* et al. *[2002b], Werdon* et al. *[2000], and R.J. Newberry, written communication [2004]). (G) Tonalite/quartz diorite samples from Steele Creek Dome Orthogneiss (U-Pb zircon ages and normalized $SiO_2$ contents indicated; ages shown on Fig. 8) (age and geochemical data for sample 98AD174 from Day* et al. *[2002] and Crock* et al. *[2000], respectively; all other age and geochemical data from J.K. Mortensen and C. Dusel-Bacon, unpublished data); values for average upper continental crust (UCC) from McLennan (2001). Primitive mantle values from Sun and McDonough (1989).*

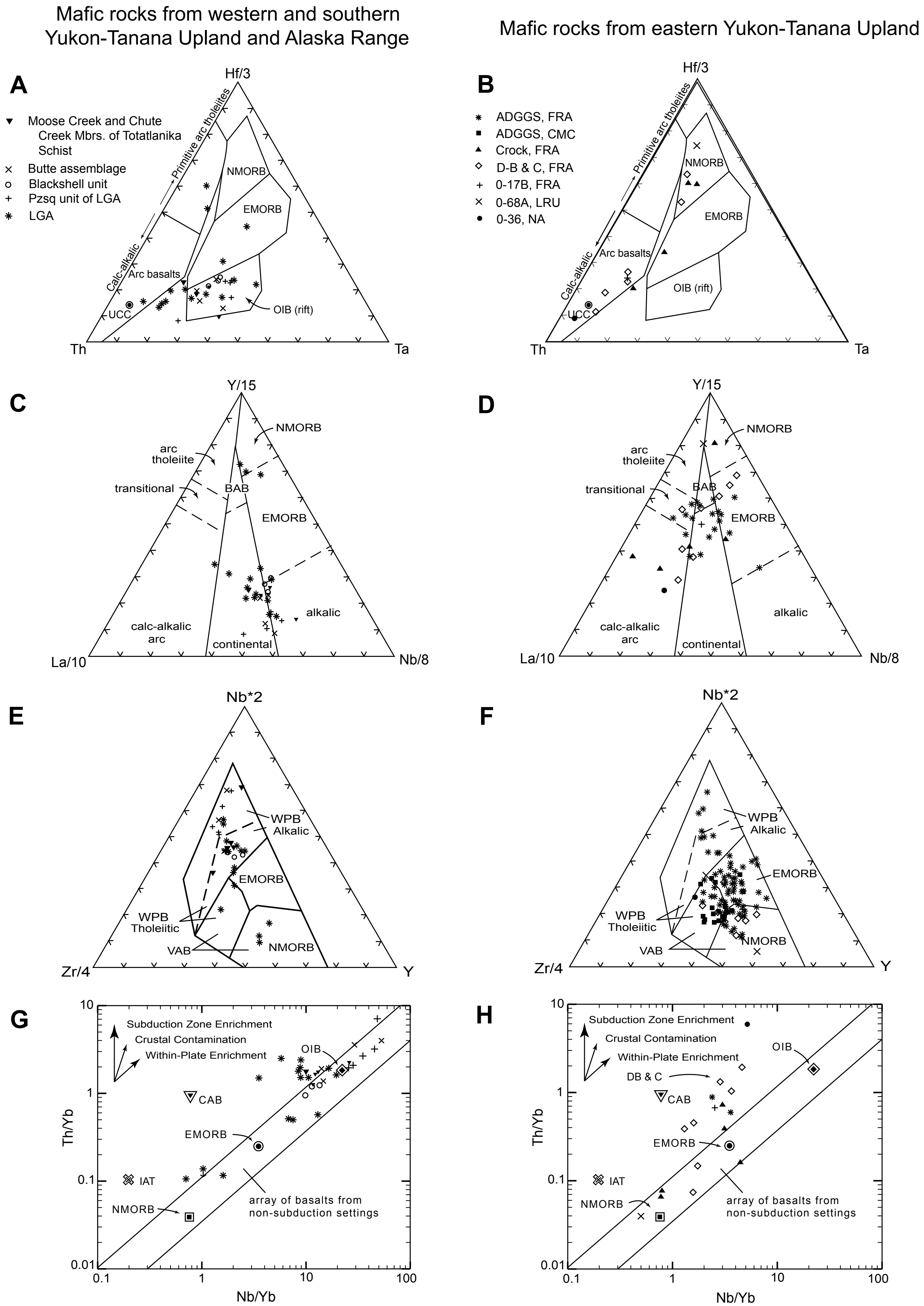


**Figure 10.** *(caption on facing page)*

semblages in an arc setting adjacent to a marginal basin. Available Nb, Zr and Y data from the Chicken Metamorphic Complex also plot in the volcanic arc field (Fig. 10F), in agreement with the interpretation by Werdon *et al.* (2001) that this complex represents a volcanic arc upon which felsic, intermediate and mafic volcanic products and subordinate sedimentary rocks and limestone were deposited.

Trace element data for a single mafic sample from the Ladue River unit indicate a distinctly N-MORB composition (Table DR1; Figs. 9E and 10B, D, F, H). This geochemical signature is found in both the Lake George and Fortymile River assemblages, but has not been described for the Klondike Schist.

The effect of within-plate enrichment, crustal contamination and subduction-zone enrichment (slab metasomatism) in the Fortymile River samples and other units from the eastern Yukon-Tanana Upland (excluding amphibolites from the Lake George assemblage in the Tanacross quadrangle that are discussed above) can be evaluated using the Th/Yb *vs.* Nb/Yb systematics (Fig. 10H). Mafic rocks from the Fortymile River for which these trace element ratios are available plot either in the N-MORB to E-MORB fields, or form an array outside of the band that defines non-subduction settings, suggesting either subduction-zone enrichment or crustal contamination of an E-MORB source.

**Figure 10.** *(facing page) Immobile trace-element discrimination plots of metabasite samples from east-central Alaska. (A, B) Hf-Th-Ta diagram of Wood (1980). Values for average upper continental crust (UCC) from McLennan (2001). (C, D) Y-La-Nb diagram of Cabanis and Lecolle (1989). (E, F) Nb-Zr-Y diagram of Meschede (1986). (G, H) Th/Yb* vs. *Nb/Yb ratio plots from Pearce (1983) and Pearce and Peate (1995). Data sources for Figs. 10A, C, E, G: Dusel-Bacon and Cooper (1999); Dusel-Bacon* et al. *(2004). Data sources for Figs. 10B, D, F, H: D-B & C = Dusel-Bacon and Cooper (1999); Crock = Crock* et al. *(1999, 2000); ADGGS = Alaska Division of Geological and Geophysical Surveys publications (Szumigala* et al. *[2000], Szumigala* et al. *[2002b], and Werdon* et al. *[2000]); data for numbered samples from this paper (Figs. 2 or 8; Table DR1). Geologic unit abbreviations: CMP, Chicken Metamorphic Complex; LGA, Lake George assemblage; FRA, Fortymile River assemblage; LRU, Ladue River unit; NA, Nasina assemblage. Primitive mantle values from Sun and McDonough (1989). N-MORB, normal mid-ocean ridge basalt; E-MORB, enriched mid-ocean ridge basalt; OIB, ocean-island basalt; VAB, volcanic-arc basalt; WPB, within-plate basalt. Values for average N-MORB, E-MORB and OIB and typical CAB and IAT and sources of geochemical data as in Figure 9.*

### *Greenstone from the Seventymile Terrane*

Greenstone, commonly massive and locally pillowed, was collected from several different fault-bounded bodies from the Seventymile terrane, including greenstone associated with: (1) the peridotites of the Salcha River (A, Fig. 2; Fig. 3), Clinton Creek and Dawson (Fig. 8); (2) a small serpentinized ultramafic body in the northern Big Delta quadrangle (Fig. 3); and (3) the large greenstone body and associated low-grade metasedimentary unit at Wolf Mountain, north of Columbia Creek (Fig. 8). Whole-rock analyses for these metabasites are presented in Table DR1 (see footnote 1) and locations (using an abbreviation of the sample number given in Table DR1 and Fig. 11, and used in the discussion below) are shown on either Figures 2, 3 or 8.

Comparison of PM-normalized multi-element plots for the Seventymile terrane greenstones (Figs. 11B-E) with those from diverse magma types (Fig. 11A) reveals that the majority of the greenstones have N- to E-MORB patterns (N = 12) and a minority have arc (N = 5) or OIB (N = 3) patterns. The three samples with the OIB pattern plot in the alkali basalt field, and the other samples plot in either the andesite/basalt or the subalkaline basalt fields of Winchester and Floyd (1977).

The samples with the N- or E-MORB PM-normalized patterns plot in the N-MORB field on the Hf-Th-Ta diagram (Fig. 12A), near the intersection of the the N-MORB, E-MORB and back-arc-basin basalt (BAB) fields on the Y-La-Nb diagram (Fig. 12B), and near average N-MORB or between it and average EMORB on the Th/Yb *vs.* Nb/Yb diagram (Fig. 12C). These N- to E-MORB- or BAB-like signatures are associated with the Dawson and Clinton Creek peridotite bodies, the greenstone body that spans the Alaska-Yukon border along the Yukon River, two of the seven samples (0-49A and 83-27) from the Wolf Mountain greenstone body or associated Seventymile terrane sedimentary rocks (Fig. 8); the glaucophane-bearing greenstone occurrence near the Tintina fault, northwest of Eagle (locality 3040, Fig. 2); and greenstone associated with the peridotite of Salcha River and a small serpentinized peridotite body further west, near the headwaters of Munson Creek (Fig. 3).

Greenstone with OIB geochemical characteristics has been identified at one locality (samples 0-9, 0-10A; Fig. 3) along the southern margin of the peridotite of Salcha River, and at another locality (0-38) within the greenstone body that spans the Alaska-Yukon border (Fig. 8). In both areas, nearby samples have N- to E-MORB or BAB trace-element signatures.

All five of the greenstone samples with apparent arc geochemical signatures (Figs. 11E and 12) are from the Wolf Mountain greenstone body (6-52, 8-26G) or the associated sedimentary unit of the Seventymile terrane (LC7-100, 8-6 and 0-50A; Fig. 8). The elevated Th values, relative to Nb, seen in PM-normalized plots (Fig. 11E), are shown by the enrichment arrows on the Th/Yb-Nb/Yb diagram (Fig. 12C) to be a result of either subduction-zone enrichment or crustal contamination. One potential way to resolve whether Th enrichment represents a true subduction component or assimilation of continental crust is to plot the samples on the Shervais (1982) Ti-V diagram (Pearce, 1995). Pearce (1995) stated that true volcanic arc basalts should plot in the volcanic arc field on both projections, whereas contaminated basalts from attenuated continental lithosphere should plot in the volcanic arc field on the Hf-Th-Ta diagram, but in the MORB + BAB field on the Ti-V diagram. All of these "arc-like" Seventymile terrane greenstone samples plot in the MORB + BAB field on the Ti-V diagram (not shown), as their Ti:V ratios are between 23 and 50 (Table DR1). Taken at face value, this would suggest that these samples may instead represent magmas formed in a within-plate extensional (OIB) or a crustally contaminated mid-ocean ridge (E-MORB) setting. However, we recognize that V is very sensitive to redox conditions during mantle melting and fractional crystallization of basalt magma and, therefore, do not regard this ratio as an infallible test. Because three of these potentially arc-like samples are associated with Triassic sedimentary rocks that are interpreted to either depositionally overlie (samples 8-6 and 0-50A) or be faulted against (sample LC7-100) the Wolf Mountain greenstone body, their relationship to the other Seventymile terrane greenstone bodies, and to the two MORB-like greenstones from the Wolf Mountain body, all of which could be as old as Mississippian, is uncertain.

## Tectonic Fingerprinting of Felsic Rocks

Determining the tectonic setting in which felsic magmas were generated is a much more difficult task than is the case with mafic rocks. For example, felsic magma derived in a non-arc setting can acquire an arc-like geochemical signature as a result of generation in or contamination by continental crust. In addition, felsic magmas can represent blending of partial melt contributions from many different continental lithologies (*e.g.*, Piercey *et al.*, 2001). Finally, the abun-

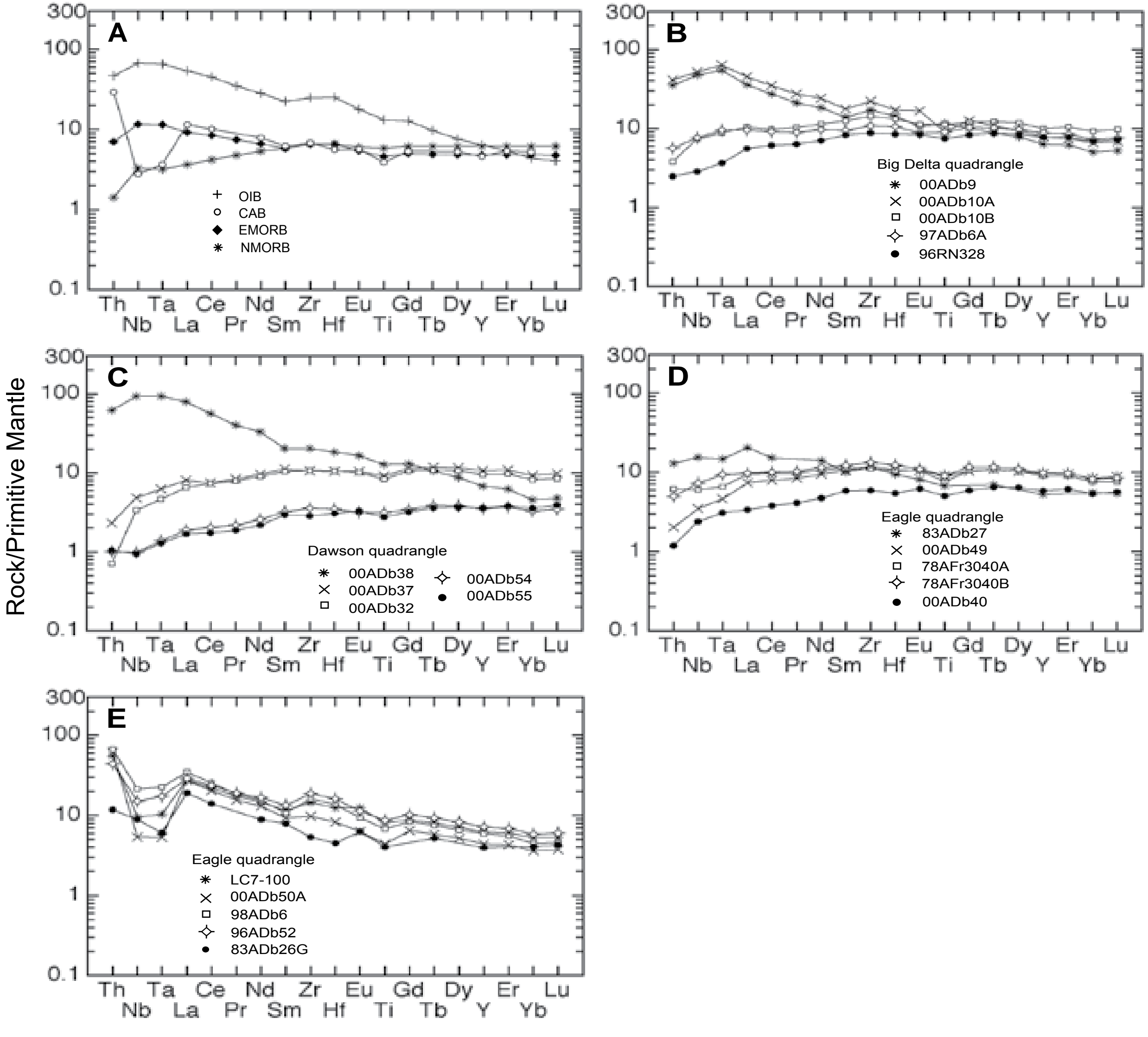


**Figure 11.** *Primitive-mantle-normalized trace-element plots of metabasite from the Seventymile terrane. (A) Examples of typical magma types as in Figure 9. (B-E) Plots for metabasite (greenstone) from the study. Location of samples shown on Figs. 3 and 8; data in Table DR1.*

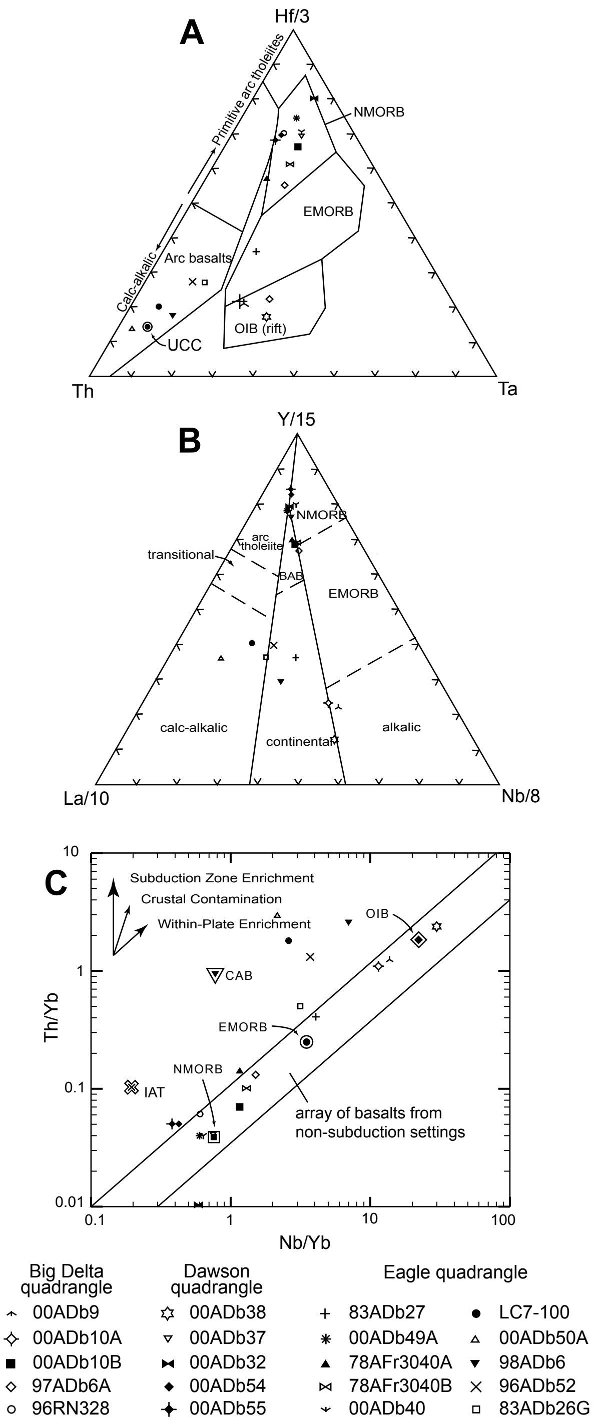


**Figure 12.** *Immobile trace-element discrimination plots of metabasite from the Seventymile terrane. (A) Hf-Th-Ta diagram of Wood (1980). Values for average upper continental crust (UCC) from McLennan (2001). (B) Y-La-Nb diagram of Cabanis and Lecolle (1989). (C) Th/Yb* vs. *Nb/Yb ratio plots from Pearce (1983) and Pearce and Peate (1995). Location of geochemical samples shown on Figs. 3 and 8; data in Table DR1.*

dances of some HFSE (including Ti, Zr and Hf) and REE are extremely sensitive to accessory mineral fractionation and removal from the melt. For this reason, our interpretation of trace-element plots for felsic meta-igneous rocks must consider the entire geologic setting and the less ambiguous implications of our mafic rock geochemistry.

We use upper continental crust (UCC)-normalized multi-element plots to provide information about magma sources and to compare sample groups to one another and to representative samples from known tectonic settings (Fig. 13A). Within-plate rocks are represented by rhyolite from the Yellowstone Plateau volcanic field (Hildreth *et al.*, 1991), an unambiguous intracontinental setting. Because the chemistry of continental margin arc magmas is quite variable and depends on local crustal composition and thickness (Hildreth and Moorbath, 1988), we include plots of both a continental-margin arc emplaced on thick (70-80 km) crust (Central Andes, Chile; Lindsay *et al.*, 2001) and on thinner (~40 km) crust composed of accreted terranes (Mount Mazama, Crater Lake, Oregon; Bacon and Druitt, 1988).

### *Late Devonian-Early Mississippian Felsic Meta-igneous Rocks from the Alaska Range*

In the Wood River area of the Alaska Range, felsic metavolcanic rocks of the Mystic Creek Member of the Totatlanika Schist have extremely high HFSE and REE contents (Dusel-Bacon *et al.*, 2004). On the Zr/$TiO_2$-Nb/Y diagram of Winchester and Floyd (1977) they plot as peralkaline rhyolites (comendites). Their UCC-normalized multi-element patterns (Fig. 13B) are similar to the Yellowstone within-plate example (Fig. 13A) in having Nb-Ta "humps" and negative Eu-Ti anomalies. A subset of the Mystic Creek samples (group 2; Fig. 13B) have, in addition, a slight to pronounced depletion in LREE (La, Ce, Pr and Nd) values relative to the adjacent HFSE elements. This LREE depletion may have resulted from separation of accessory phases such as allanite, monazite or chevkinite (Dusel-Bacon *et al.*, 2004 and references therein). The high Nb, Ta, Zr and Y contents of Mystic Creek peralkaline metarhyolites cause them to plot in the within-plate granite field of Pearce *et al.* (1984; Fig. 14A and Dusel-Bacon *et al.*, 2004). In contrast, felsic metavolcanic or augen gneiss samples from the other Totatlanika Schist members and from the Keevy Peak Formation, Healy schist and the Wood River assemblage have lower HFSE and REE contents. Zr/$TiO_2$-Nb/Y ratios indicate a rhyolite to rhyodacite/dacite protolith, and their UCC-normalized multi-element plots show slight negative Nb-Ta and Ti anomalies, and lower total REE values that are close to unity (Fig. 13A). Their moderate to low values for Nb, Ta, Zr and Y cause them to either plot in the upper corner of the volcanic arc granite field of Pearce *et al.* (1984) near the ratio for average upper continental crust, or in the case of several Healy schist and Wood River assemblage samples, to plot just into the within-plate fields (Fig. 14A and Dusel-Bacon *et al.*, 2004). Samples that show the within-plate geochemical characteristics are those that host or are associated with the VMS mineral deposits or occurrences of the Bonnifield mining district (Dusel-Bacon *et al.*, 2004).

Although the weakly developed negative UCC-normalized Nb-Ta and Ti anomalies of the felsic rocks from the Sheep, California and Moose Creek Members of the Totatlanika Schist and the Keevy Peak Formation are somewhat similar to the pattern for arc rocks (Fig. 13A), the only unequivocal conclusion that can be drawn for those rocks is that the melts were derived from or included a large component of continental crust. The incorporation of old continental crust is also shown by Archean and Proterozoic U-Pb zircon inheritance ages determined during SHRIMP analysis of some of the geochemical samples (Dusel-Bacon *et al.*, 2004).

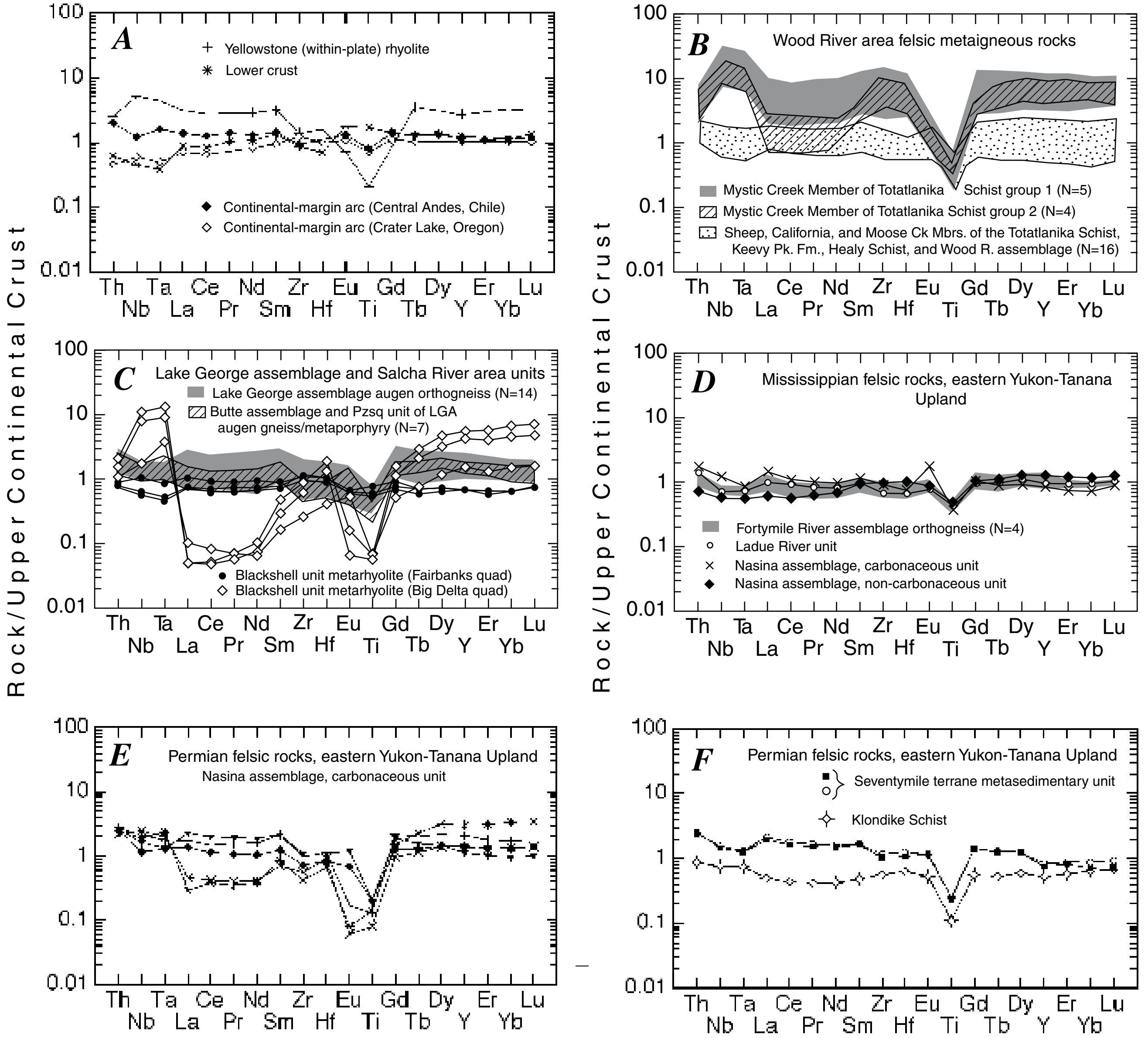
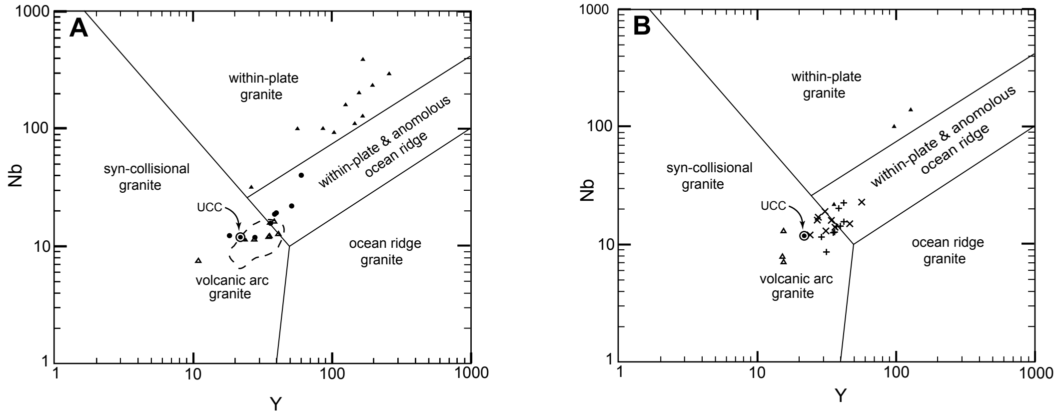


**Figure 13.** *Upper continental crust (UCC)-normalized trace-element plots of felsic rocks. (A) Average or representative trace-element compositions of characteristic magma types. Data sources for felsic analyses of magmatic rocks from known environments: Yellowstone (within-plate) rhyolite = average of 3 intracaldera flows (76.9%* $SiO_2$*) from the Yellowstone Plateau volcanic field representing one of the world's largest silicic volcanic centers, associated with lesser volumes of basalt in a within-plate continental setting (Hildreth* et al.*, 1991); continental margin arc (Central Andes, Chile) = average of 2 Atana dacite pumice samples (Lari-96h-6 x-rich and Quis-96h-9 x-rich; 67.1%* $SiO_2$*) from a large Pliocene ignimbrite erupted through 70-80 km-thick crust (Lindsay* et al.*, 2001); continental margin arc (Crater Lake, Oregon) = sample "Avg 3 CIP" from Bacon and Druitt (1988), representing average of pumice (70.4%* $SiO_2$*) from Holocene climactic eruption of Mount Mazama on ~ 40 km-thick crust of Tertiary-Paleozoic accreted terranes; L (lower) crust (Wedepohl, 1995). (B-F) Felsic meta-igneous rocks from east-central Alaska and the adjacent portion of Yukon. LGA, Lake George assemblage. Data sources given in text. Average upper continental crust values from McLennan (2001).*

A limited suite of trace elements has been determined for Jarvis belt meta-igneous (presumably metavolcanic) rocks from the Delta mineral belt, ~175 km to the east (Fig. 1; Dashevsky *et al.*, 2003). A subset (N = 73) of the least altered, highest-quality analyses are presented in Table DR2 (see footnote 1). Zr/$TiO_2$-Nb/Y ratios indicate a wider range of compositions, ranging from rhyodacite through dacite to andesite and andesite/basalt (Dashevsky *et al.*, 2003), than is present in the chemically bimodal igneous rocks of the Bonnifield mining district (Dusel-Bacon *et al.*, 2004). The Devonian to Mississippian greenschist facies metavolcanic rocks in the Delta mineral belt plot in the upper corner of the volcanic-arc field on the Nb-Y diagram near the values for UCC (Fig. 14A). Zr/Y ratios for the Jarvis belt meta-igneous rocks (Table DR2) range from 3.34 to 8.77 (average 5.69), suggesting a magmatic suite of transitional to calc-alkalic composition. As with the isotopically dated rocks from the Wood River area, Precambrian U-Pb zircon inheritance ages (Dashevsky *et al.*, 2003) confirm the incorporation of continental crust in the felsic melts.



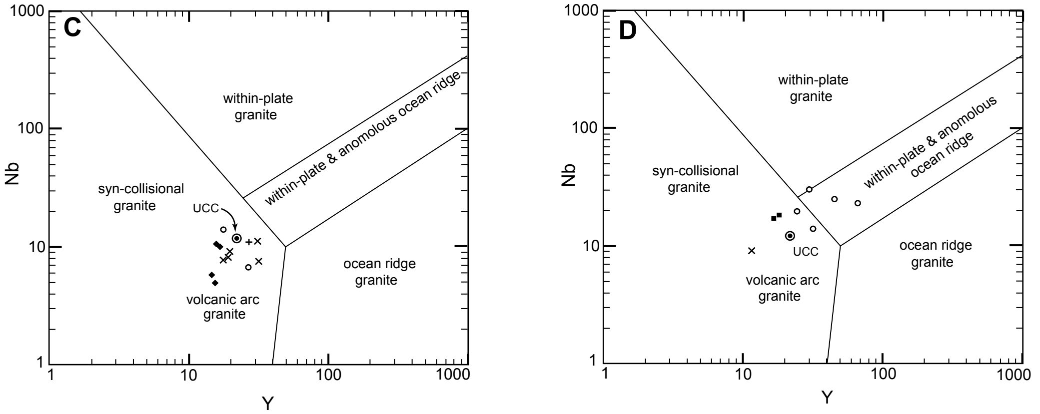
Devonian-earliest Mississippian felsic meta-igneous rocks, Alaska Range

Wood River area felsic rocks
- ▲ Mystic Creek Member of the Totatlanika Schist
- △ Sheep, California, and Moose Creek Members of the Totatlanika Schist
- ● Keevy Peak Fm., Healy Schist, and Wood River assemblage

Delta mineral belt felsic and intermediate-composition rocks (normalized $SiO_2$=55-79%)
- ( ) Field of Drum, Lagoon, and Tiger units (N=71; Table DR2)

Devonian-earliest Mississippian felsic meta-igneous rocks, Lake George assemblage and Salcha River area units/assemblages

- × LGA augen gneiss
- + Butte assemblage and Pzsq unit of LGA augen gneiss/metaporphyry
- △ Blackshell unit metarhyolite (Fairbanks quad.)
- ▲ Blackshell unit metarhyolite (Big Delta quad.)



Mississippian felsic meta-igneous rocks, eastern Yukon-Tanana Upland

- × Fortymile River assemblage felsic orthogneiss and metatuff
- + Ladue River unit
- ○ Nasina assemblage
- ◆ Fortymile River assemblage tonalite/quartz diorite

Permian felsic meta-igneous rocks, eastern Yukon-Tanana Upland

- ○ Nasina assemblage
- × Klondike schist assemblage
- ■ Seventymile terrane metasedimentary unit

**Figure 14.** *Nb-Y discrimination diagram of Pearce* et al. *(1984) showing data for felsic and, in the case of the Fortymile River assemblage, also intermediate-composition, meta-igneous samples from various assemblages from east-central Alaska and the adjacent portion of Yukon. LGA, Lake George assemblage. Data sources given in text. UCC — values for average upper continental crust (values from McLennan, 2001).*

### *Late Devonian-Early Mississippian Felsic Meta-igneous Rocks from the Lake George Assemblage and Salcha River Area*

Augen gneiss from the Lake George assemblage, augen gneiss and metaporphyry from the Salcha River area (Butte assemblage and the Pzsq unit), and metarhyolite from the Blackshell unit in the Fairbanks quadrangle (Figs. 2-4) all have flat UCC-normalized multi-element patterns close to unity, with weakly developed negative Nb-Ta and Ti anomalies (Fig. 13C; Dusel-Bacon *et al.*, 2004). These patterns are similar to those of upper continental crust and to continental-margin arcs generated on thick continental crust (Central Andes example; Fig. 13A). These felsic rocks plot in the rhyodacite/dacite field on the Zr/TiO$_2$-Nb/Y classification diagram and in the upper right-hand corner of the volcanic arc granite field of Pearce *et al.* (1984; Fig. 14B). With the exception of the Blackshell metarhyolite from the Fairbanks quadrangle, which plots well into the volcanic arc field, the rest of the above samples have higher Ta, Nb, Y and Yb values than average upper continental crust and plot near the boundary between the within-plate and volcanic arc fields (Fig. 14B and Dusel-Bacon *et al.*, 2004), similar to Wood River area samples, exclusive of the Mystic Creek metarhyolites (Fig. 14A).

In contrast, metarhyolites from the Blackshell unit in the Big Delta quadrangle have much higher HFSE and HREE contents, which cause them to plot in the comendite/pantellerite field or rhyolite field on the Zr/TiO$_2$-Nb/Y classification diagram and in the within-plate granite field of Pearce *et al.* (1984; Fig. 14B and Dusel-Bacon *et al.*, 2004). Their elevated UCC-normalized Nb, Ta and HREE contents resemble the within-plate Yellowstone example, but their extreme depletion in LREE, MREE and Ti (Fig. 13C) likely reflects the separation of LREE- and MREE-rich accessory phases, as was proposed by Dusel-Bacon *et al.* (2004) for some Mystic Creek metarhyolites (Fig. 13B), and was proposed by Dusel-Bacon and Aleinikoff (1985) for trace-element depletions in concordant aplitic gneiss layers within augen gneiss in the Goodpaster River area. As is the case with the within-plate metarhyolites from the Mystic Creek Member that host, or are associated with, the largest VMS occurrences in the Bonnifield district, the within-plate metarhyolite tuff layers occur within the carbonaceous Blackshell unit that is host to SEDEX mineralization in the Chena slate belt, discussed below.

### *Early Mississippian Felsic Meta-igneous Rocks from the Eastern Yukon-Tanana Upland*

Known or inferred Mississippian felsic rocks from the eastern Yukon-Tanana Upland all plot in the rhyodacite/dacite (granodiorite) compositional field on the Zr/TiO$_2$-Nb/Y classification diagram, consistent with their 71.1-74.3% normalized SiO$_2$ contents. These rocks include granodiorite gneiss, augen orthogneiss, and probable metatuff from the Fortymile River assemblage, a felsic metavolcanic layer from the non-carbonaceous unit of the Nasina assemblage and a quartz-chlorite-epidote schist (00ADb59; Fig. 2) from Ladue River unit in the southeastern Tanacross quadrangle (Fig. 2). U-Pb zircon ages for the felsic rocks of the Fortymile River overlap those for the intermediate-composition quartz diorite/tonalite orthogneiss of the Steele Creek Dome Orthogneiss unit, described above in the mafic geochemistry section of this chapter.

The UCC-normalized multi-element patterns of the Fortymile River felsic rocks and the Ladue River unit are generally flat, with values close to 1, and have minor depletions in Nb, Ta and Ti, relative to UCC (Fig. 13D). These patterns are similar to those of the Lake George, except that the UCC-normalized trace elements in the Lake George samples (Fig. 13C) occur at higher concentrations (>1). The two Nasina assemblage felsic metavolcanic(?) samples have flat patterns hovering around 1; one sample displays a slight Nb and Ta trough and the other only shows a slight increase in Th, relative to adjacent elements.

As discussed in the above section on mafic geochemistry, the majority of the Fortymile River amphibolites have either arc (CAB to IAT) or E-MORB affinities, and the PM-normalized patterns of the spatially associated intermediate-composition Steele Creek Dome Orthogneiss unit have arc trace-element signatures that indicate a CAB origin with some influence or contamination from UCC. Nb-Y ratios for the felsic Nasina assemblage and the Ladue River unit, and both the felsic and the intermediate-composition rocks of the Fortymile River assemblage, plot in the volcanic arc field (Fig. 14C). As expected, the tonalite/quartz diorite samples from the Steele Creek Dome Orthogneiss plot lowest in the arc field and farthest away from the Nb and Y values for average UCC. The felsic meta-igneous rocks all plot either near the UCC or in an intermediate position between that of the Steele Creek Dome Orthogneiss samples and the UCC (Fig. 14D), consistent with formation in a volcanic arc developed on continental crust. Proterozoic and Archean inheritance in zircon from meta-igneous rocks in the Fortymile River and Nasina assemblages (J.K. Mortensen, unpublished data, 2004) provides additional evidence of continental crustal involvement.

### *Permian Felsic Meta-igneous Rocks from the Eastern Yukon-Tanana Upland*

Permian felsic metavolcanic rocks from the Klondike Schist, the carbonaceous unit of the Nasina assemblage, and the metasedimentary unit of the Seventymile terrane (near the Taylor Highway west and north of Liberty Fork; Fig. 8), plot either within or near the rhyolite compositional field, consistent with their high normalized SiO$_2$ contents (78.5 to 81.7%). The unusually high SiO$_2$ contents in some samples probably reflect minor silicification of the rhyolite.

Upper continental crust-normalized profiles for two Seventymile terrane metarhyolite samples (interpreted to be silicified tuff) and three felsic schists that occur within carbonaceous quartz-mica schist of the Nasina assemblage, have moderately developed Nb and Ta troughs and moderately high abundances of REE and HFSE (Figs. 13E, F), characteristic of a continental margin arc developed on thick continental crust (Central Andes example, Fig. 13A). However, two other Permian metarhyolite samples from the carbonaceous unit of the Nasina assemblage have higher Nb, Ta, Y and HREE contents (Fig. 13E), similar to within-plate rhyolite (Fig. 13A). These two within-plate-like samples also exhibit a noticeable depletion in LREE, relative to UCC, likely due to separation of LREE-enriched accessory phases during magma differentiation, as discussed above. Nb-Y ratios for the two Seventymile samples and two of the Nasina samples plot in the volcanic arc granite field near the value for UCC; the other three Nasina samples plot just inside the within-plate fields (Fig. 14D).

A single sample of Klondike Schist (Fig. 13F) has the lowest HFSE and HREE contents of any of the Permian rocks and has a flat UCC-normalized profile similar to the pattern for a Crater Lake-type continental-margin arc; Nb-Y ratios plot in the volcanic arc field, in a position more primitive than that of UCC (Fig. 14D). Limited trace-element data for other felsic samples from the Klondike Schist also suggest calc-alkalic arc signatures (Piercey *et al.*, this volume).

## PALEOZOIC SYNGENETIC HYDROTHERMAL MINERALIZATION

### Devonian-Mississippian VMS Mineralization in the Bonnifield and Kantishna Districts

The Bonnifield mining district, located along the northern flank of the Alaska Range in east-central Alaska, includes 26 known volcanogenic massive sulphide (VMS) prospects (mostly for Zn-Pb-Cu-Ag; Newberry *et al.*, 1997, and references therein; Fig. 6). Protoliths consist of varying amounts of felsic and mafic volcanic and shallow-level intrusive rocks interlayered with carbonaceous and siliciclastic sedimentary rocks, indicative of a submarine, basinal setting (Wahrhaftig, 1968, 1970; Gilbert, 1977; Gilbert and Bundtzen, 1979). Protoliths of felsic metavolcanic rocks and subvolcanic intrusions were Late Devonian to Early Mississippian (376-353 Ma) based on U-Pb zircon analyses (Fig. 6; Dusel-Bacon *et al.*, 2004). Lead-isotopic compositions of sulphides are consistent with a syngenetic origin for the mineralization (Mortensen *et al.*, this volume). Whole-rock trace-element data and geologic relationships indicate that magmatism was bimodal and occurred in an extensional setting, interpreted by Dusel-Bacon *et al.* (2004) to have been the attenuating continental margin of ancestral North America.

Two of the largest prospects in the Bonnifield district, the Dry Creek (*a.k.a.* Red Mountain) deposit and the WTF deposit, are hosted in the Mystic Creek Member of the Totatlanika Schist in the northeastern part of the Wood River area (Fig. 6). There, mineralization occurs near the contact between phyllitic felsic metavolcanic and subordinate carbonaceous rocks of the Mystic Creek Member and the overlying, predominantly metasedimentary, rocks of the Sheep Creek Member (Newberry *et al.*, 1997; Smit, 1999). Drilling at Red Mountain, named for its distinctive quartz-sericite-pyrite alteration, discovered the DC North and DC South massive sulphide horizons (Szumigala and Swainbank, 1998; Smit, 1999; DC, Fig. 6). Two styles of mineralization are evident in the DC North horizon (Smit, 1999): (1) "Discovery-style" mineralization, which consists of massive to semi-massive Zn-Pb-Ag-rich sulphides that occur within, and at the base of, an aphanitic, intensely quartz-sericite-pyrite altered siliceous rock referred to as the "mottled metarhyolite". This mineralization is generally associated with overlying stringer and disseminated chalcopyrite-pyrite mineralization; (2) "Fosters Creek-style" mineralization, which is hosted by a brown pyritic metamudstone unit in the hanging wall of, and along strike from, the "mottled metarhyolite". This mineralization comprises disseminations and wispy laminae of sulphides, and zones of semi-massive to massive pyrite, sphalerite, galena and chalcopyrite. Precious metals are especially enriched in the footwall portion of the mineralization. An inferred resource of 3.2 million tons (2.9 Mt) of 4.4% Zn, 1.9% Pb, 0.2% Cu, 3.01oz. per ton (103.5 g/t) Ag and 0.018 oz. per ton (0.62 g/t) Au has been calculated for the DC North horizon (Szumigala and Swainbank, 1998). Host rocks of the "Fosters Creek-style" mineralization are interpreted to have been deposited in a synvolcanic sedimentary basin (Smit, 1999).

The WTF deposit (WT, Fig. 6) is located ~3 km northeast of Red Mountain, but the structural and stratigraphic relationship between the WTF and the Dry Creek deposits is ambiguous: One interpretation places the WTF and the Dry Creek deposits on the northern and southern limbs, respectively, of a syncline (Smit, 1999); another places the Dry Creek deposit in a separate and lower stratigraphic interval (Newberry *et al.*, 1997). An inferred resource of 3.09 million tons (2.8 Mt) of 6% Zn, 2.5% Pb, 0.1% Cu, 5.73 oz. per ton (196.5 g/t) of Ag and 0.029 oz. per ton (0.99 g/t) Au has been identified for the WTF (Szumigala and Swainbank, 1998).

Sulphide mineralization also occurs in felsic rocks within the Healy schist (Fig. 6). Several VMS prospects, including the Anderson Mountain prospect (AM, Fig. 6) and the Virginia Creek prospect (VC, Fig. 6), occur within Wood River assemblage felsic metavolcanic rocks and black graphitic schist. The Zn- and Sn-rich Sheep Creek prospect (SC, Fig. 6) is hosted in quartz-sericite-graphite-chlorite schist within the lower part of the underlying Keevy Peak Formation (Newberry *et al.*, 1997, and references therein).

Devonian VMS occurrences in the Kantishna Hills (Fig. 1) include the Lloyd prospect and the Kakone Peak and Chitsia Mountain occurrences (Gilbert and Bundtzen, 1979; Bundtzen, 1981; Newberry *et al.*, 1997). Mineralization in all three areas occurs in discontinuous lenses. At Kakone Peak, numerous centimetre-scale bands of pyrite, chalcopyrite and sphalerite, with lesser galena and tetrahedrite, and gossanous stratiform silicified zones occur within chloritic metatuff interlayered with metafelsite and graphitic schist. The Lloyd prospect consists of thin bands of pyrite, sphalerite and chalcopyrite, with minor galena and pyrrhotite, within a white vitreous quartz matrix interlayered with garnetiferous quartz-muscovite and actinolite schist (Newberry *et al.*, 1997). The Chitsia Mountain occurrence consists of conformable lenses of barite interlayered with fine-grained galena and sphalerite within a felsic metavolcanic tuff sequence. Devonian (*ca.* 370 Ma) metavolcanic rocks within the Spruce Creek sequence (Table 1) are believed to be associated with the mineralization (T.K. Bundtzen, written communication, 2005). A U-Pb age of 338 ± 9 Ma was determined from a rhyolite porphyry flow or sill that lies stratigraphically above Chitsia mountain barite-sulphide occurrence (T.K. Bundtzen and R.M. Tosdal, unpublished data, 1991). Lead isotopic ratios for sulphides from the Lloyd prospect (Gaccetta and Church, 1989) are consistent with a Devonian-Mississippian age for mineralization (Newberry *et al.*, 1997; Dusel-Bacon *et al.*, 1998).

## Devonian-Mississippian VMS Mineralization in the Delta Mineral Belt

Late Devonian to Early Mississippian volcanic-hosted massive sulphide deposits of the Delta mineral belt developed along five horizons within the Drum and Lagoon units of the Jarvis metamorphic belt (Dashevsky *et al*., 2003; Fig. 7). The age of mineralization in the Lagoon unit (*ca.* 372 Ma) is estimated from the results of a single SHRIMP U-Pb zircon age determination from the LZ East deposit (372 ± 6 Ma: J.N. Aleinikoff *in* Dashevsky *et al*., 2003). The dated drill core sample was from a rhyodacite layer internal to multiple bands of sulphide mineralization in a structurally repeated section of lower Lagoon unit. The timing of subsequent mineralization in the Drum unit (*ca.* 362 Ma) is estimated from SHRIMP U-Pb zircon ages determined on two drill core samples: one from rhyodacite in the footwall 3 m below the DD South deposit (359 ± 6 Ma), and the other from a dacite layer 1.5 m below the HD South mineralized horizon (364 ± 7 Ma; Dashevsky *et al*., 2003). A broadly syngenetic origin for the VMS mineralization is suggested by Pb isotopic data for sulphides from the Delta mineral belt that yielded Devonian-Mississippian model ages (Lange *et al*., 1993, and references therein; Newberry *et al*., 1997). Sulphur isotope values for Delta District sulphides range from about 1-10 per mil (Newberry *et al*., 1997, and references therein). This range of sulphur isotope values overlaps the value for ambient seawater during Devonian-Mississippian time minus 17 per mil. These values are consistent with a syngenetic hydrothermal origin for the Delta deposits, owing to reduction of ambient seawater sulfate during formation of the deposits (Newberry *et al*., 1997, and references therein).

Massive and semi-massive sulphide occurrences in the Lagoon and Drum units of the Jarvis belt are typically layered and laminated pyrite- and/or pyrrhotite-rich deposits, with lesser sphalerite, galena, chalcopyrite and arsenopyrite. All of the Jarvis belt massive sulphide deposits are polymetallic, with zinc > lead >> copper. Gold is distributed erratically, and only is significant locally, whereas elevated silver concentrations are more common. Metal zoning on a district scale is not well defined, but the metal ratios and abundances are characteristic of volcanogenic mineralization in rifted arc settings as at the Kuroko (Franklin *et al*., 1981; Cathles *et al*., 1983) and Myra Falls (Robinson, 1994) deposits.

Gangue mineralogy is mostly quartz, chlorite, sericite and carbonate. Associated hydrothermal alteration is represented by chlorite, quartz, pyrite and chalcopyrite beneath the sulphides, with quartz, sericite, pyrite and carbonate above the mineralized horizon. Barite is largely absent from the deposits, except in narrow intervals above Drum unit sulphide deposits. The configuration of massive sulphide deposits in both the Lagoon and the Drum units is consistent with an upright position, as mineralization generally is sandwiched between a chloritic, magnesium-enriched and sodium-depleted footwall alteration assemblage and a sericitic and barite-enriched hangingwall alteration unit. This pattern of hydrothermal alteration is characteristic of intact and upright Kuroko-style VMS deposits (Ishikawa *et al*., 1976; Date *et al*., 1983; Urabe *et al*., 1983).

Duke *et al*. (1984) inferred a Devonian age for the gabbro sills and suggested that mineralization was related to emplacement of mafic sills in a Guaymas-like rift setting. However, subsequent mapping and extensive drill core observations indicated that the gabbro sills are younger features that locally crosscut bedding, inflate stratigraphy, and truncate massive sulphide occurrences (Dashevsky *et al*., 2003; Lange *et al*., 1993), and thus postdate mineralization. As mentioned above, U-Pb zircon data now indicate a mid-Triassic crystallization age for the sills.

The lowermost Lagoon unit is dominated by graphitic metasedimentary rocks and thin interbedded felsic metavolcanic rocks. Base- and precious-metal concentrations in massive sulphide mineralization from this horizon are the highest in the district, twice to four times greater than those of deposits drilled in the upper Lagoon unit. Thick, sericite-pyrite-silica alteration intersected by drilling in the lower Lagoon unit indicates that a large hydrothermal system was active in the central Delta mineral belt prior to the full onset of effusive volcanics. The high-grade LZ sulphide prospects provide additional evidence that the lower Lagoon horizon was the site for deposition of base- and precious-metal rich sulphide deposits over a broad reach of the Devonian seafloor, before the onset of major volcanism. The close association of graphitic and volcanic rocks suggests that these sulphide deposits may represent a hybrid of volcanogenic and sedimentary exhalative types (Dashevsky *et al*., 2003).

Massive sulphide mineralization developed along the Drum stratigraphic unit typically has higher copper and gold values (by a factor of 2) than those developed in the metavolcanic rocks of the upper and middle Lagoon stratigraphic unit (Dashevsky *et al*., 2003). Although the Drum unit is relatively thin and poorly exposed, mineralization developed across the district in this interval is consistently higher in grade. The Drum unit hosts a number of massive sulphide prospects and significant occurrences, including DD, Rum, LBB, CC and HDS (Fig. 7).

The Tushtena Pass and Tok River units of the Jarvis belt contain several stratiform pyrite and pyrrhotite mineral occurrences, but thus far these have proven barren of economic mineralization. In the Hayes Glacier belt, extensive pyrite-silica alteration is common, but economic mineralization has not been discovered.

Most exploration within the Delta mineral belt has focused primarily on the extensive, thick, sheet-like (6-12 m thick) massive sulphide deposits in the DW-LP system (Lagoon unit) east of Rumble Creek. The more restricted lens-shaped sulphide deposits in the DD system (Drum unit) west of Rumble Creek have been a secondary focus. Exploration has also examined several gold prospects in the AR area and on the White Gold prospects (Dashevsky *et al*., 2003; Fig. 7). An inferred resource (CIM, 1994), modeled conservatively by Schaefer and Oliver (1999), for the DW-LP, PP2 and DD deposits totals 19 million tons (17.2 Mt) of massive sulphide at an overall average grade of 0.6% copper, 2.0% lead, 4.6% zinc, 73 ppm (g/t) silver and 1.9 ppm (g/t) gold (Grayd, 1999).

The interlayered metasedimentary and metavolcanic rocks of the Jarvis belt record a history of deposition on the flanks of a volcanic arc (Dashevsky *et al*., 2003). Incipient seafloor hydrothermal systems were active early in the deposition of the section during periods of volcanic activity recorded by the Tushtena Pass unit.

Remnant exposures of these systems are typically thin, iron-sulphide dominated occurrences with minor zinc and weak copper enrichments. Moving up-section within the Jarvis belt, a marked period of quiescent volcanic activity is indicated by the thick accumulation of clastic and carbonaceous sedimentary rocks in the lower Lagoon unit. In the lower Lagoon we find the earliest evidence for formation of precious- and base-metal enriched sulphide systems in the region. Significantly elevated Hg, As, Sb trace-element chemistry in surface and drill samples is suggestive of hybrid epithermal-VMS mineralized systems formed in this basinal sedimentary environment (lower Lagoon unit) adjacent to the volcanic arc. As volcanic deposition increases upward in the Lagoon stratigraphy, an attendant volumetric increase in sulphide deposition on the sea floor is also found. These formed the thick and extensive (as yet undelineated) sheet-like deposits in the middle and upper parts of the Lagoon unit.

The overlying Tiger metavolcanic unit records a nearly continuous effusive volcanic period that snuffed out the mineralizing seafloor hydrothermal systems. Mineralization resumed during the intermittent cycles of volcanism recorded by the Drum unit, in which sulphides pooled in local basins on the flanks of local felsic volcanic piles. The mineralized horizons occurring near the base and at the top of the Drum may represent a single horizon in which sulphides precipitated on a seafloor surface that extended from a central volcanic pile to the outer sediment-volcanic interface. Waning volcanism and increased clastic sedimentation recorded in the overlying Tok River unit brought to a close the period of metallic sulphide deposition in the Jarvis belt.

## Devonian-Mississippian SEDEX Mineralization in Chena Slate Belt and Fortymile Area

Carbonaceous quartzite, slate and phyllite of the Blackshell unit hosts stratiform sedimentary exhalative (SEDEX) mineralization in the area between the Chena and Salcha Rivers in the northern Big Delta quadrangle (Fig. 3; Dusel-Bacon *et al.*, 1998; Menzie and Foster, 1978). The informal name "Chena slate belt" was coined by WGM, Inc. geologists for the 75 km-long belt of siliceous and carbonaceous rocks in which mineralization occurs. Exploration by WGM, Inc., delineated three Zn-Pb targets in a section of sericitic phyllite underlain by interlayered gray to black siliceous phyllite and quartzite in the vicinity of Teuchet Creek (TC, Fig. 3), and another target in carbonaceous and calcareous slate at Drone Creek, 25 km to the west (DC, Fig. 3).

The best mineralization at the Teuchet Creek property yielded intersections of up to 5% disseminated and foliation-parallel pyrite, sphalerite and galena in carbonaceous phyllite and quartzite over intervals of 18 m to 61 m. Pyrite occurs locally in massive layers up to 52 cm thick with bands of red-brown sphalerite, galena and pyrite up to 12 cm thick. Sphalerite (~84%ZnS) occurs as lenses of anhedral grains, and galena forms interstitial fillings in areas rich in pyrite and sphalerite. Boulangerite (PbSbS) and vermicular, selenium-rich galena occur along with more sulphur-rich galena in one sphalerite-rich interval of core (Dusel-Bacon *et al.*, 1998). Chalcopyrite, pyrrhotite and arsenopyrite are present in minor amounts. An interval of sulphide-rich stretched-pebble conglomerate is interpreted to represent deposition of coarse-grained clastic rocks along a basinal growth fault penecontemporaneous with syngenetic base-metal mineralization (Bressler and Corbett, 2002).

Approximately 45 m of sulphide-bearing zones, including a 17 m interval of black, very carbonaceous slate with laminae of sphalerite, galena, pyrite and pyrrhotite aggregating 5-7% total sulphides was intersected at the Drone Creek Property.

Pb isotopic data for galena from the Chena slate belt overlap the values from the Bonnifield mining district and the Delta mineral belt in the Alaska Range (Mortensen *et al.*, this volume), suggesting a syngenetic, mid-Paleozoic age for the hydrothermal mineralization and similar source rocks for the three areas.

In the northwesternmost exposure of the Blackshell unit (northeastern corner of the Fairbanks quadrangle; Fig. 2), ~1 m-thick concordant layers of Fe-stained, buff-coloured quartzite and quartz-white mica schist occur within the carbonaceous sequence. Other than the sparse preservation of pyrite, no other sulphides were observed in the buff- to orange-coloured layers, but barium contents are high in most samples and abundant barite was observed in one sample (Table DR3 [see footnote 1]). We interpret these layers to have originated either as exhalative seafloor emanations and (or) submarine deposits of a distal tuff within a restricted basin.

SEDEX-type mineralization also occurs in the Nasina assemblage in the Fortymile area (Fig. 8; Dusel-Bacon *et al.*, 1998; Hunt, 1997). Three localities of sphalerite-bearing quartzite crop out along a 3 km stretch of the Taylor Highway near the mouth of Columbia Creek (Dusel-Bacon *et al.*, 1998; shown by a single symbol on Fig. 8). Carbonaceous quartzite is the dominant lithology at all three localities but mineralization was observed only in carbon-free or carbon-poor quartzite (metachert?). At the southernmost and middle localities (bu7rrow pits; sample localities 96ADb32 and 96ADb37, respectively; Table DR3), dark foliaform laminae of reddish-amber sphalerite >>pyrite >galena >chalcopyrite occur within scattered blocks of buff-coloured, celsian (barium silicate)-bearing quartzite (91-93% $SiO_2$). Strained, elongate quartz grains and thin folia of tabular celsian define a penetrative fabric. Celsian-bearing quartzites from both sites are high in Ba (1.6 and 3.6%), Zn (1.8 and 2.7%) and Pb (3,980 and 1,040 ppm; Dusel-Bacon *et al.*, 1998; Table DR3).

The northernmost locality (96ADb63) consists of variably rusty-weathering, tan to pale grey, slightly muscovitic and carbonaceous quartzite (78% $SiO_2$) exposed in outcrop and landslide debris just east of the mouth of Columbia Creek (Fig. 8). Interlayered with the quartzite are 10-20 cm-thick layers of more muscovite-rich quartzite, including some layers of muscovite schist. These layers may have originated as felsic tuffs. The sulphides (amber-brown sphalerite>>galena, chalcopyrite) occur within the quartzite in discontinuous lenses 1-2 cm thick. A grab sample of sphalerite-bearing quartzite yielded 8.1% Zn (Dusel-Bacon *et al.*, 1998; Table DR3).

Four showings of stratiform Pb-Zn mineralization, similar to those in the Columbia Creek area, occur in Nasina assemblage quartzite in the Dawson 116C quadrangle of Yukon (Mortensen, 1992; Hunt, 1997; Fig. 8). At one of these showings (MORT), 1-3 mm-thick laminae of galena or cerussite ± sphalerite are present in buff-coloured muscovitic quartzite interlayered with muscovite schist.

Grab sample 96ADb41B, from a cerussite-bearing quartz-rich layer, yielded 4.3% Pb and 54 g/t Ag (Dusel-Bacon *et al.*, 1998; Table DR3).

Lead isotopic analyses of galena from the southernmost locality on the Taylor Highway and from the other occurrences in the Nasina in the Dawson quadrangle indicate a mid-Paleozoic age for mineralization (Mortensen *et al.*, this volume), consistent with a syngenetic origin for the mineralization.

Sulphides were also observed within layers of rusty-weathering muscovite-quartz schist that crops out along the Fortymile River within the amphibolite-biotite gneiss sequence of the Fortymile River assemblage (Table DR3). These layers locally contain abundant pyrite and small amounts of disseminated galena and sphalerite. Scatter in the Pb isotopic compositions of galena, together with high bismuth contents for two of the samples (96ADb39A and C), are more consistent with a Mesozoic epigenetic, intrusion-related origin for the mineralization than with a Paleozoic syngenetic origin (Mortensen *et al.*, this volume).

### Possible Devonian-Mississippian Syngenetic Mineralization in the Butte Assemblage

A possible base-metal syngenetic (VMS? transitioning to SEDEX?) occurrence was identified south of Gold Creek in the northern Big Delta quadrangle in the early 1990s (Fire property in unpublished Big Delta Program reports by Teck Cominco American staff, including Lorne Young; Fig. 3). Mineralization at the Fire occurrence lies within a highly deformed cyclic sequence composed of (from top to bottom) black carbonaceous phyllite, sericitic to chloritic phyllite and calc-phyllite. Milled arsenopyrite occurs in black chlorite interlayers within aluminous quartz schist, and galena, along with lesser sphalerite, is contained in black siltite interlayers within mottled (tan-to-green-to-black weathering) chlorite-muscovite-quartz eye schist. The mottled schist also hosts chalcopyrite and pyrite. Thin chalcopyrite layers also are present at the base of a marble layer ~500 m north of the main occurrence. Soil anomalies at the Fire occurrence contain up to 1% Pb and appeared to define separate Cu-, Zn- and Pb-rich zones.

Subsequent examination of the Fire occurrence revealed intense folding and crenulation of sericite and chlorite layers and polygonization of quartz layers and veins into fine-grained mosaics. These textures indicate two phases of deformation and also may indicate a late episode of thermal metamorphism, such as that which affected calc-silicate rocks associated with a Cretaceous diorite intrusion at The Butte mountain ~5 km southwest of the Fire occurrence (Weber *et al.*, 1978). Whole-rock analyses for 10 mineralized samples (Table DR3; samples from the Big Delta D-4 quadrangle) indicate that six of the samples had moderately high Pb contents and several also had high concentrations of various combinations of Zn, Ag, As and Sb. Bismuth values (elevated values sometimes being used as a proxy to indicate intrusion-related mineralization), were below detection (<2 ppm) in all of the samples, with the exception of one sample of quartz-sericite phyllite that had 48 ppm Bi.

The Fire occurrence is the easternmost of seven base-metal occurrences that define a 20 km-long east-trending belt and occur almost exclusively within the Butte assemblage. In most of the occurrences, sparse but widespread quartz (sericite) meta-exhalite layers contain pyrite and chalcopyrite, and less commonly galena and sphalerite (unpublished Big Delta Program reports by Teck Cominco American staff). The origin and age of the mineralization within the belt is unknown. Eight Pb isotope measurements from five base-metal occurrences in the 20 km-long belt have model ages that range from Triassic to Devono-Mississippian (unpublished Big Delta Program reports by Teck Cominco American staff, early 1990s). Former Cominco geologist Lorne Young (written communication, 1999) interprets the mineralization at the Fire occurrence to be Cu-rich VMS-type hosted in the mottled phyllite/schist lithology and to pass laterally into SEDEX-type mineralization hosted in the Blackshell unit, which also hosts the mineralization of the Chena slate belt. However, the wide range in Pb isotope model ages may indicate that the sulphides formed during more than one mineralization event. The annealed quartz fabrics are consistent with a contact metamorphic episode, but low Bi contents argue against an intrusion-related style of mineralization.

### Permian VMS Mineralization in Klondike Schist

Two small, stratabound Pb-Zn(-Ba) occurrences lie within an east-west-trending band of felsic metavolcanic rocks of the Klondike Schist that straddles the Alaska-Yukon border (Mortensen, 1988; Hunt, 2002; Mortensen *et al.*, this volume; Fig. 8). The Boundary and Baldy occurrences consist of narrow (<1 m thick) bands of disseminated to locally semi-massive galena, sphalerite, rare chalcopyrite and minor barite hosted within weakly pyritic quartz-muscovite schist. Lead isotopic analyses of galena from these and other similar base-metal occurrences within Klondike Schist yield a tight cluster of isotopic compositions that are consistent with a syngenetic origin (Mortensen *et al.*, this volume). Limonitic quartz-mica schist from the Boundary occurrence assayed 0.53% Cu, 2.6% Pb, 0.43% Zn and 154 g/tonne Ag (Morin, 1981), and a specimen from the Baldy occurrence (sample 96ADb62A; Table DR3) contained 0.99% Zn, 0.18% Pb and 0.16% Ba.

## PALEOZOIC EVOLUTION OF THE PERICRATONIC ASSEMBLAGES OF EAST-CENTRAL ALASKA

### Proximity to Precambrian Basement

Weber *et al.* (1985, 1992), were the first to propose, based on lithologic similarity, that the Wickersham grit and Fairbanks schist are correlative with the Windermere Supergroup of the Canadian Cordillera that makes up part of the North American continental margin (Gabrielse and Campbell, 1991). Several subsequent workers (Dover, 1994; Murphy and Abbott, 1995) also correlated units north of Fairbanks, including the Wickersham grit and the Fairbanks schist, with units of unambiguous North American affinity across the Tintina fault in the western Selwyn basin, on the basis of stratigraphic as well as deformational similarities. They concurred with Weber *et al.*'s (1985, 1992) hypothesis that at least some of the fault-bounded assemblages of the Yukon-Tanana Upland are not exotic, but comprise the tectonically disrupted edge of the ancient North American continental margin. The occurrence of *Oldhamia,* a Cambrian trace fossil, in maroon and green slates in both the Wickersham unit in the Livengood quadrangle (Churkin and Brabb, 1965; Weber *et al.*, 1992) and the Hyland Group of the Selwyn basin in the Yukon (Hofmann and Cecile, 1981) was one of the lines of evidence used by Weber *et al.* (1992) to correlate the two groups of rocks that are now offset by the Tintina fault. Precambrian zircon inheritance, a Paleoproterozoic Sm-Nd whole-rock model age, and a high initial $^{87}Sr/^{86}Sr$ ratio of 0.728 ± 0.002 for augen gneiss from the Lake George assemblage (Aleinikoff *et al.*, 1986) provided early isotopic evidence for an old crustal component in this assemblage. In a number of tectonic models (*e.g.*, Hansen, 1990; Hansen *et al.*, 1991; Dusel-Bacon *et al.*, 1995), this old crust was interpreted to be derived from cratonal North America.

Similar Archean to Neoproterozoic U-Pb detrital zircon ages have been determined for quartz-rich rocks from several of the pericratonic continental margin assemblages in Alaska (Aleinikoff *et al.* 1995; Ross *et al.*, 2005; Bradley *et al.*, in press) and from the Hyland Group of the Selwyn basin in Yukon (Ross *et al.*, 2005). For example, TIMS analyses of detrital zircons and monazite from the Hyland Group and the Fairbanks schist are similar, supporting correlation of the units across the Tintina fault; zircon populations in both units are dominated by 1.01-1.45, 1.80-2.00 and 2.60-2.90 Ga ages (Ross *et al.*, 2005). Overlapping ages were obtained from multigrain detrital zircon analyses of the Fairbanks schist (Aleinikoff *et al.*, 1995). SHRIMP U-Pb detrital zircon ages for a grit sample from the Wickersham unit, collected approximately 130 km northwest of Fairbanks in the Tanana quadrangle, have major age clusters at 1.78-1.85 and 1.93-1.96 Ga, with minor clusters at 2.09-2.13, 2.31-2.38 and 2.54-2.57; the youngest grain has an age of 1.20 Ga (Bradley *et al.*, in press). These detrital ages support correlation of the source areas for the Wickersham and Fairbanks sedimentary rocks. Similar aged basement source terranes are indicated by SHRIMP U-Pb detrital zircon ages for quartz-eye grit from the Butte assemblage in the northern Big Delta quadrangle (1.80, 1.90, 1.98, 2.02, 2.06, 2.43, 2.56, 2.59, 2.63, 2.64 and 2.69 Ga; J.L. Wooden and C. Dusel-Bacon, unpublished data, 1996) and for quartzite from the Jarvis belt in the Mount Hayes quadrangle (1.75–1.95, 2.20 and 2.57–2.69 Ga; I.S. Williams and C. Dusel-Bacon, unpublished data, 2005).

Late Archean and Paleoproterozoic to Mesoproterozoic U-Pb zircon core (inherited) ages (especially *ca.* 2.6 Ga and 1.8 Ga and smaller populations of *ca.* 1.4 and 1.1 Ga) are widespread in felsic meta-igneous rocks from the Lake George and Butte assemblages and Blackshell unit in the Yukon-Tanana Upland, and the Totatlanika Schist and Healy schist in the Alaska Range (Aleinikoff *et al.*, 1986; Heslop *et al.*, 1995; Dusel-Bacon and Aleinikoff, 1996; Dusel-Bacon *et al.*, 2004). These inherited core ages overlap the detrital zircon age groupings for the above described (meta)sedimentary rocks in east-central Alaska, suggesting several hypotheses: (1) shared depositional settings and basement provenances for the Fairbanks-Chena assemblage, Lake George assemblage, Butte assemblage, Blackshell unit, Totatlanika Schist and Healy schist; (2) both the inherited crustal component in the magmatic rocks and the sedimentary protoliths of the country rock were derived from common basement provenances; and (3) the above-discussed (meta)sedimentary rocks in east-central Alaska were the inherited crustal component in the felsic magmas.

A comparison of the ages for detrital and inherited (core) zircons in east-central Alaska, with the ages for basement provinces of the western Canadian Shield (*e.g.*, Hoffman, 1989; Ross, 1991; Villeneuve *et al.*, 1993), shows possible sources for most grain populations. We interpret this to imply that the quartz-rich metasedimentary rocks and the inherited components in the Devonian and Mississippian meta-igneous rocks in east-central Alaska were derived from nearby North American basement provinces, although zircon grains may have been cycled through one or more sedimentary units prior to their final deposition. The depositional age(s) of most of the continental margin metasedimentary wallrocks to the mid-Paleozoic magmatic rocks in the Yukon-Tanana Upland and adjacent Alaska Range is only broadly constrained. Geologic and isotopic data constrain their depositional age(s) to predate the Late Devonian or Early Mississippian intrusive ages of the orthogneiss bodies that intrude them; and to post-date the Mesoproterozoic (1035.0 ± 1.4 Ma) TIMS age of the youngest detrital zircon from the Fairbanks schist (J.K. Mortensen, unpublished data, 2002), or the youngest concordant SHRIMP U-Pb age of *ca.* 980 Ma determined for an inherited Neoproterozoic zircon core from the mid-Paleozoic magmatic rocks (Totatlanika Schist; Dusel-Bacon *et al.*, 2004; J.L. Wooden, written communication, 2004). Scant paleontologic evidence, discussed above in the regional geologic setting of the parautochthonous assemblages, suggests a depositional age between Late Ordovician and Middle Devonian for calc-phyllite of the Dan Creek unit in the Yukon-Tanana Upland and Late Devonian to Early Mississippian for the Totatlanika Schist and Wood River assemblage in the Alaska Range.

## Mid-Devonian to Early Mississippian Extension of the Continental Margin

U-Pb zircon and geochemical data from the western Yukon-Tanana Upland and adjacent Alaska Range elucidate the development of Late Devonian to Early Mississippian magmatism over a period of *ca.* 20 m.y. Allowing for $2\sigma$ analytical uncertainties, the following overlapping U-Pb zircon crystallization age ranges are indicated for meta-igneous rocks: 376-353 Ma in the Totatlanika Schist, Healy schist and Jarvis belt of the Alaska Range; 378-346 Ma in the Butte assemblage and Blackshell unit in the Salcha River; 376-358 Ma in the Lake George assemblage in the Goodpaster River area and ranging to possibly as young as 342 Ma in the northeastern Tanacross quadrangle; and 359-349 Ma in the Fairbanks-Chena assemblage (Fig. 15; Table 1).

Metabasites of known and presumed Late Devonian-Early Mississippian age in the Lake George assemblage (including the Pzsq unit), Butte assemblage, Blackshell unit and Totatlanika Schist all have elevated HFSE and REE contents indicative of a within-plate (extensional) tectonic setting. Amphibolites from the Chena River sequence and the Fairbanks schist also have alkalic within-plate trace element signatures (Newberry *et al.*, 1996, and R.J. Newberry, oral communication, 1998). The similarities in the range of U-Pb zircon crystallization ages, and the composition of felsic meta-igneous rocks and trace-element signatures for mafic meta-igneous rocks, suggest that: (1) the Lake George assemblage may be equivalent, in part, to the Fairbanks-Chena assemblage; and (2) the Lake George assemblage, Butte assemblage and Blackshell unit are all genetically related, despite differences in metamorphic grade and proposed fault contacts between some of the assemblages/units (Dusel-Bacon *et al.*, 2004).

Late Devonian to Early Mississippian bimodal magmatism is indicated by the intimate association of mafic and felsic metavolcanic rocks in the Totatlanika Schist and the Wood River assemblage, and by the U-Pb zircon crystallization ages from mafic gneiss associated with the Central Creek augen gneiss body in the Goodpaster River area (Dusel-Bacon *et al.*, 2004; Day *et al.*, 2003). The similarity of trace-element signatures, and known or inferred ages for the mafic and felsic meta-igneous rocks throughout the western and southern Yukon-Tanana Upland and the Wood River area of the Alaska Range, indicates that the prolonged magmatic episode is regional in scope.

As discussed above, trace-element geochemistry of felsic rocks is less reliable as an indicator of original tectonic setting than is the geochemistry of mafic rocks. With the exception of the Mystic Creek Member of the Totatlanika Schist and the three metarhyolite samples from the Blackshell unit that clearly have within-plate signatures, felsic meta-igneous samples from the Alaska Range and the Yukon-Tanana Upland have geochemical signatures that are similar to those of average upper-continental crust and continental-margin arc rocks generated in thick continental crust (*e.g.*, Central Andes; Fig. 13A). On the basis of the more reliable mafic trace-element signatures indicating within-plate magmatism, the differences between the geochemical signatures of the coeval felsic rocks with either within-plate or crustal chemistry most likely reflect the degree of involvement of continental crust during magma generation and ascent, rather than actual difference in tectonic settings.

Based on the bimodal composition of the Late Devonian to Early Mississippian magmatism and the alkalic within-plate chemistry of the mafic rocks and some of the felsic rocks, previous studies (Dusel-Bacon and Cooper, 1999; Dusel-Bacon *et al.,* 2004) proposed that this prolonged magmatic episode resulted from attenuation of the ancient continental margin of western North America. According to Dusel-Bacon *et al.* (2004), attenuation of the continental margin was accompanied by underplating of mafic magmas, high heat flow and crustally derived or crustally contaminated felsic magmas. Some crustal contamination of the mafic magmas is evidenced by the Y-La-Nb plots (Fig. 10C) in which many samples fall in the continental crust field, and the Th enrichment of some metabasites from the Goodpaster River area. Dusel-Bacon *et al.* (2004) speculated that the distinctly peralkaline within-plate metarhyolites of the Mystic Creek Member of the Totatlanika Schist may have been partial melts of underplated, deep-crustal alkalic gabbros that also were the source of the alkalic, within-plate metabasite of the Chute Creek Member. Elevated $\varepsilon Nd_t$ values for Mystic Creek metarhyolites (-1.0, -1.5, -1.6) and Chute Creek metabasalts (+1.7 and +5.3) indicate an enriched mantle component for both members of the bimodal suite (Dusel-Bacon *et al.*, 2005), consistent with this interpretation.

The presence of carbonaceous layers throughout the Totatlanika Schist, Keevy Peak Formation and Healy schist sections in the Wood River area and the Blackshell unit in the Salcha River area, together with the occurrence of associated VMS and SEDEX hydrothermal mineralization, indicate a restricted marine basin or submerged continental margin into which volcanic ejecta and epiclastic material were periodically deposited.

## Devonian and Mississippian Arc and Back-Arc Magmatism

Devonian to Mississippian greenschist-facies metavolcanic rocks in the Delta mineral belt of the northern Alaska Range include a wider range of compositions (including a large percentage of rhyodacites to dacites and lesser andesites; Dashevsky *et al.*, 2003) than is present in the chemically bimodal volcanic and subvolcanic rocks of the Bonnifield mining district, 175 km to the west. Most interpretations of the Delta mineral belt favour an arc, or possibly a back-arc environment (Nokleberg and Aleinikoff, 1985; Lange *et al.*, 1993; Dashevsky *et al.*, 2003). The absence of trace-element data for the minor component of associated mafic rocks precludes an unequivocal determination of the tectonic setting of the Jarvis Belt magmatic suite, but the overall compositional makeup of the magmatic suite points to an arc origin. Zr/Y ratios for all but one sample (N = 73) of the primarily intermediate to felsic meta-igneous rocks of the Jarvis Belt are >4 and average 5.7 (Table DR 2 [see footnote 1]), thus suggesting a transitional (between tholeiitic and calc-alkalic) to calc-alkalic magma suite. The overlap of the *ca.* 378-353 Ma U-Pb zircon ages from the Bonnifield district and Delta mineral belt (Fig. 15; Table 1) allows for the possibility that the host rocks of the Delta mineral belt formed an outboard arc adjacent to the proposed attenuating continental margin setting (Dusel-Bacon *et al.*, 2004). Zircons from felsic meta-igneous rocks of the Delta mineral belt contain Precambrian inheritance (J.K. Mortensen and J.N. Aleinikoff, personal communication, 2003), and the Precambrian ages determined for detrital zircons from Jarvis belt quartzite (I.S. Williams and C. Dusel-Bacon, unpublished data, 2005) indicate that magma was generated close to or within continental crust that included some of the same age provenances that are present in the Lake George assemblage.

Limited evidence suggests that the Wood River assemblage in the southern Bonnifield district also originated as an arc developed on continental crust. Metabasalt has a weakly developed arc signature but felsic meta-igneous rocks from the Wood River assemblage have trace-element signatures similar to continental crust and a $\varepsilon Nd_t$ value of -4.5 that indicates a crustal component (Dusel-Bacon *et al.*, 2005). This interpretation implies that the coeval Mystic Creek Member of the Totatlanika Schist could have formed in an extensional (back-arc) basin that was associated with an outboard volcanic arc that included rocks of the Wood River assemblage (Dusel-Bacon *et al.,* 2005).

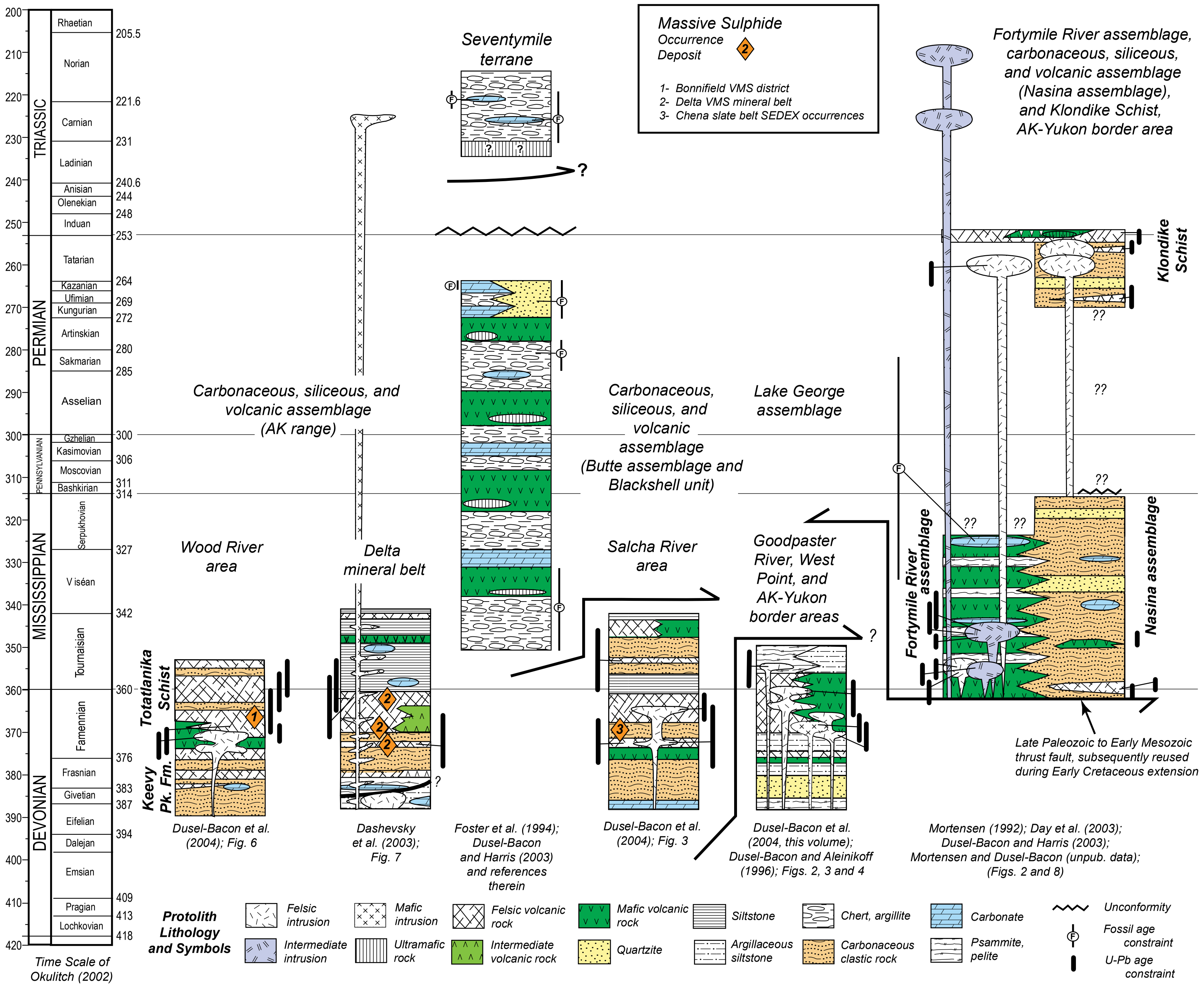


**Figure 15.** *Simplified stratigraphic columns for east-central Alaska and adjacent part of the Yukon showing generalized protolith lithologies, fossil ages and representative U-Pb zircon crystallization ages (see Table 1 for a complete listing of U-Pb ages and corresponding references).*

As discussed in a previous section, the Fortymile River assemblage has been proposed to consist of a substrate of a rifted fragment of North America, intruded by Paleozoic to early Mesozoic intermediate-composition arc-related plutons, that was obducted onto the continental margin (including the Lake George and Fairbanks-Chena assemblages) during Permian to early Mesozoic west-dipping subduction (Hansen and Dusel-Bacon, 1998; Dusel-Bacon *et al.*, 2002). U-Pb zircon analyses for intermediate and felsic meta-igneous rocks from the Fortymile River and Nasina assemblages yield Mississippian ages (360 ± 2 to 341 ± 5 Ma; Fig. 15; Table 1). The older Fortymile River assemblage crystallization ages overlap the younger ages from the assemblages that we interpret to be rifted continental margin, thus allowing the possibility that at least some of the Fortymile River assemblage may have formed an outboard arc to the proposed rifted continental margin rocks. However, the majority of crystallization ages in the Fortymile River postdate the initial, largely within-plate, magmatism in the inferred rifted continental margin assemblages by as much as 20-30 m.y. Regional geologic and geochemical considerations in the Finlayson Lake area in southern Yukon (summarized in Murphy *et al.*, this volume; Piercey *et al.*, this volume; Fig. 1) help constrain the tectonic setting of the Fortymile River and Nasina assemblages. Palinspastic restoration of 430 km of right-lateral offset along the Tintina fault (Gabrielse *et al,* in press) brings the Finlayson Lake rocks into close proximity with the Fortymile River assemblage. U-Pb zircon ages of *ca.* 365-345 Ma (Murphy, 2001) for host rocks of VMS deposits in the Finlayson Lake area overlap the younger half of the 378-353 Ma range of U-Pb ages from the Alaska Range and the Yukon-Tanana Upland, and are similar to those in the Fortymile River and Nasina assemblages. In the Finlayson Lake area, Late Devonian to Early Mississippian metavolcanic and metaplutonic rocks of arc character are located west or southwest of coeval rocks of back-arc character, implying east- or northeast-dipping subduction throughout this period (Piercey *et al.*, 2001, 2004; Murphy *et al.*, this volume).

Although several different geochemical signatures are present in the amphibolites of the Fortymile River assemblage, an arc signature is indicated for the majority of the amphibolite layers or bodies and the associated tonalite/quartz diorite intrusions (Steele Creek Dome Orthogneiss). A smaller number of Fortymile River amphibolites have N-MORB to E-MORB or OIB characteristics. A variety of arc, MORB and OIB magma compositions has been observed in regions of modern volcanic arcs (*e.g.*, Dungan *et al.*, 2001), modern intracontinental back-arc basins (*e.g.*, Okinawa Trough and the Lau Basin; Shinjo *et al.*, 1999; Hawkins, 1995), and in other geochemically well-studied mid-Paleozoic portions of the Yukon-Tanana terrane in Yukon, interpreted as extending arc or back-arc regions (Piercey *et al.*, 2004, this volume).

The non-carbonaceous to locally carbonaceous siliciclastic rocks and marble beds in the Fortymile River assemblage record background sedimentation during construction of a submarine volcanic arc. The Mississippian to Permian age range for conodonts from one of the marble beds (Dusel-Bacon and Harris, 2003) is consistent with the post-Devonian age inferred for the Fortymile River assemblage on the basis of U-Pb zircon ages. Proximity of the Fortymile River assemblage to continental basement (either a craton or a rifted continental fragment) is indicated by the elevated Th contents, Y-La-Nb systematics and the trend in Th/Yb-Nb/Yb ratios in mafic rocks, and the geochemical similarity of felsic rocks to average upper continental crust, as well as a minor amount of Proterozoic inheritance in zircons from felsic meta-igneous rocks. The similarities between the protolith lithologies, arc geochemical signatures and late Paleozoic conodont age range of the amphibolite facies Fortymile River assemblage and the greenschist facies Chicken Metamorphic Complex suggest a shared origin for the two units.

## Setting of the Nasina Assemblage Basin

Although the contacts between the Fortymile River and Nasina assemblages are locally faulted, the following features suggest a geologically-related (adjacent) original setting for the two assemblages: (1) the locally interlayered and transitional nature of the contact between the metasedimentary rocks of both assemblages near the Alaska-Yukon border; (2) the close association of both assemblages with mafic to intermediate Mississippian metaplutonic rocks with arc signatures; (3) the overlapping U-Pb zircon crystallization ages (*ca.* 360- *ca.* 348 Ma for the Nasina and *ca.* 360- *ca.* 341 Ma for the Fortymile River; Fig. 15; Table 1); and (4) marble beds with late Paleozoic, possibly Mississippian, conodonts in both assemblages. We infer that the volcanic edifices and reefs of the Fortymile River assemblage developed adjacent to or within the marginal basin that collected the sedimentary rocks of the Nasina assemblage, and that subsequent thrust faulting juxtaposed rocks from different parts of a marginal/back-arc basin tectonic setting outboard of the North American continental margin. Continuation of this associated primary tectonic setting for the Fortymile River and Nasina assemblages into latest Paleozoic and early Mesozoic time is indicated by the occurrence of Permian felsic metavolcanic and hypabyssal rocks in both assemblages, a Permian dike that intrudes Fortymile River assemblage rocks at one locality (Table 1), and the presence of Late Triassic to Early Jurassic plutons that crosscut both units in at least one area in Alaska (Dusel-Bacon *et al.*, 2002). These Permian to Early Jurassic magmatic rocks are interpreted to have been generated in the hangingwall (arc and marginal basin tectonic assemblages) to west-dipping subduction, and are absent from the footwall (pericratonic continental margin assemblages; *e.g.*, Hansen *et al.*, 1991; Hansen and Dusel-Bacon, 1998).

The relationship between the carbonaceous, siliceous and volcanic rocks of the Nasina assemblage with those of the Blackshell unit in the Salcha River area is conjectural. However, several differences between the two shed light on their relationship: (1) the former appears to be locally intercalated with the Mississippian(?) metasedimentary and mafic metavolcanic rocks of the Fortymile River assemblage, whereas the latter likely grades downward into a calcareous unit (Dan Creek) in which a poorly preserved fossil suggests a Late Ordovician and Middle Devonian depositional age; (2) felsic magmatism in the former occurred in both earliest Mississippian and Permian time, whereas it occurred only in Late Devonian to Mississippian time in the latter; (3) trace-element signatures for mafic meta-igneous rocks in the Nasina indicate arc (L-IAT transitional to CAB), whereas those in the Blackshell indicate OIB; and (4) Triassic and Jurassic granitoids with arc geochemical signatures intrude the Fortymile River assemblage and the adjacent portion of the Nasina assemblage but are absent from the Blackshell unit. We interpret these relationships to indicate that the sedimentary rocks of the Blackshell unit originated within a restricted marginal basin that formed during subsidence of the extending continental margin of North America. In contrast, the Nasina assemblage formed in a basin(s) associated with the Early Mississippian arc and (or) back-arc environment of the Fortymile River assemblage; and both assemblages are likely continuations of similar rocks in the Finlayson Lake area in Yukon (Colpron *et al.*, this volume; Murphy *et al.*, this volume; Nelson *et al.*, this volume).

## Tectonic Setting of the Seventymile and Slide Mountain Terranes

General agreement exists that the Seventymile and Slide Mountain terranes represent a basin floored by oceanic crust off the western margin of ancestral North America, but the original width of the ocean basin is disputed. For example, Nelson (1993) depicted the Slide Mountain ocean as a narrow ocean that was depositionally tied to ancestral North America, whereas other workers have modeled it as a vast, Pacific-scale ocean in Paleozoic time (Harms and Murchey, 1992; Monger *et al.*, 1991). Proximity to a continental source is required by the presence of some quartz-rich rocks in these oceanic terranes, but that continental source could be either the ancestral continental margin of North America or the rifted continental fragment proposed to have been derived from it (Tempelman-Kluit, 1979; Nelson *et al.*, this volume).

Nelson *et al.* (2002) proposed a tectonic model in which VMS, SEDEX and more inboard Mississippi Valley-type deposits in the northern Cordillera formed during episodic extension within and behind a Devonian-Mississippian arc developed above an east-dipping subduction zone along the continental margin of ancestral North America. According to this model, extension during Devonian-Mississippian time was driven by slab rollback. Rifting of the arc and back-arc region culminated in the opening of a marginal ocean, represented by the Slide Mountain and Seventymile terranes, between the pericratonic arc elements in the northern Cordillera and cratonal North America (Nelson *et al.*, this volume).

Dusel-Bacon *et al.* (2004) proposed that the Fortymile River and the Delta mineral belt were elements of this arc in Alaska, but that the other pericratonic continental margin elements in the western and southern Yukon-Tanana Upland (Fairbanks-Chena, Lake George and Butte assemblages, and the Blackshell unit) and the Wood River area of the northern Alaska Range (Totatlanika Schist and associated units) originated on the inboard (cratonal) side of the Slide Mountain ocean, rather than on the outboard side of it, as proposed by Nelson *et al.* (2002). An inboard location for these assemblages is consistent with stratigraphic similarities noted by Dover (1994) and Murphy and Abbott (1995) between Yukon-Tanana rocks north of Fairbanks and proposed equivalents of North American affinity across the Tintina fault in the western Selwyn basin. It is difficult to place a structural break or to identify a change in the overall original tectonic setting (*i.e.*, continental margin with extensional signature mafic rocks) or in the U-Pb zircon crystallization and inheritance ages of the metamorphic sequences as one moves outboard from the rocks north of Fairbanks through the central Yukon-Tanana Upland to the north flank of the Alaska Range. This supports the possibility that, if the rocks north of Fairbanks originated as part of North America, so too may have the above-named pericratonic continental margin elements in the western and southern Yukon-Tanana Upland and the Wood River area of the northern Alaska Range.

The predominance of N-MORB to E-MORB geochemical signatures in greenstones from the Seventymile terrane (Figs. 14, 15) is consistent with the oceanic basin or back-arc basin setting proposed for the terrane in most models (*e.g.*, Foster *et al.*, 1994; Hansen and Dusel-Bacon, 1998; Dusel-Bacon and Cooper, 1999). Mafic rocks from the correlated Slide Mountain terrane in the Canadian Cordillera exhibit primarily N-MORB geochemical characteristics (Nelson, 1993; Ferri, 1997; Roback *et al.*, 1994; Plint and Gordon, 1997; Lapierre *et al.*, 2003; Piercey *et al.*, this volume). However, as is the case with our Seventymile terrane greenstone dataset, a subset of enriched, alkalic (OIB) basalt has been documented for rocks from the Slide Mountain terrane (Aggarwal *et al.*, 1984; Lapierre *et al.*, 2003), likely indicating enriched mantle input in a back-arc setting.

A maximum Early Mississippian (Osagean; *ca.* 351 ± 4 Ma) age for the Seventymile terrane ocean basin is inferred on the basis of paleontologic ages for the sedimentary rocks of the Seventymile terrane (Dusel-Bacon and Harris, 2003, and references therein). This maximum age for the Seventymile terrane sedimentary rocks overlaps the crystallization ages of the majority of magmatic rocks of the Fortymile River and Nasina assemblages, supporting the proposed link between the development of the Fortymile River arc above an east-dipping subduction zone and the development of the Seventymile ocean basin behind it. A Late Devonian age for initiation of the related Slide Mountain ocean basin is provided by *ca.* 365-360 Ma ages for mafic metavolcanic rocks and smaller volumes of mafic and ultramafic subvolcanic metamorphosed intrusions that make up much of the Fire Lake formation in the Finlayson Lake area (Murphy *et al.*, this volume). These mafic and ultramafic rocks are interpreted by Piercey *et al.* (2004) to represent the commencement of the separation of the arc and back-arc components of the Yukon-Tanana composite terrane from the North American cratonal margin and initiation of a marginal (back-arc) basin — now the Slide Mountain terrane — inboard of the arc system in the Canadian Cordillera. If this older age estimate for the initial formation of the Slide Mountain and, by inference, the Seventymile ocean basin is correct, it better supports the proposed link between east-dipping subduction causing arc magmatism in the Delta district, Fortymile River and Nasina assemblages, Chicken metamorphic complex, and the originally nearby Finlayson Lake area, extension in the continental margin (Lake George assemblage and other rocks of the western Yukon-Tanana Upland and adjacent Alaska Range), and the spreading of the Slide Mountain/Seventymile ocean basin between them.

### Permian to Jurassic Southwest-Dipping Subduction and Ocean Closure

There is general agreement that the ocean basin (Seventymile-Slide Mountain terrane, equivalent to the Anvil ocean in the original tectonic model of Tempelman-Kluit, 1979) which lay outboard of the ancient Pacific margin, was consumed along its western margin by southwest-dipping, right-oblique subduction during Permian to Early Jurassic time (Tempelman-Kluit, 1979; Hansen, 1990; Mortensen, 1992; Creaser *et al.*, 1997; Hansen and Dusel-Bacon, 1998; Dusel-Bacon *et al.*, 2002). This tectonic scenario requires a flip in the subduction zone from east-dipping in Devonian and Mississippian time to southwest-dipping during closure of the ocean basin. We interpret the Permian (*ca.* 267-253 Ma) felsic metavolcanic rocks from the Klondike Schist, the Fortymile River and the Nasina assemblages and the metasedimentary unit of the Seventymile terrane to represent part of a calc-alkaline arc that developed over the southwest-dipping subduction zone. The trace-element signatures that we report for many of these Permian felsic metavolcanic rocks are characteristic of a continental margin arc developed on thick continental crust, with a smaller subset exhibiting some within-plate characteristics, suggestive of intra-arc extension. The southwest-dipping subduction zone ultimately brought Permian eclogite and blueschist (including Chatanika eclogites, blueschist from a fault sliver of probable Seventymile rocks adjacent to the Tintina fault in the Eagle quadrangle, and the belt of Permian high-pressure rocks in the Yukon), and outboard assemblages (Fortymile River and Nasina assemblages and Seventymile-Slide Mountain terrane) onto the continental margin of North America (*e.g.*, Hansen *et al.*, 1991; Mortensen, 1992; Creaser *et al.*, 1997; Nelson *et al.,* this volume). Subduction continued in Late Triassic to Early Jurassic time as evidenced by arc granitoids of this age in the Fortymile River and Nasina assemblages in Alaska (Dusel-Bacon *et al.,* 2002) and comparable arc assemblages in the Yukon (Johnston *et al.*, 1996). It is important to note that there are no documented examples of Late Triassic to Early Jurassic calc-alkaline plutons that intrude the Lake George assemblage or the Cassiar terrane — packages of rocks inferred to be part of parautochthonous North America, originally east of the Seventymile-Slide Mountain-Anvil Ocean (Hansen and Dusel-Bacon, 1998; Dusel-Bacon *et al.*, 2002).

The occurrence of giant parafusulinids in the Seventymile terrane within the same stratigraphic interval that produced poorly preserved Permian brachiopods places these beds in the middle Guadalupian, and positions the terrane at tropical to subtropical latitudes near ancestral North America during the Middle Permian (Stevens, 1995; Dusel-Bacon and Harris, 2003). A more southerly Permian paleolatitude for the Slide Mountain terrane also is suggested by a giant-parafusulinid locality in the Sylvester allochthon of northern British Columbia (Ross, 1969) and by an Early Permian paleomagnetic pole from a unit correlative with Pennsylvanian and Permian volcanic rocks of the Sylvester allochthon, which restores to the approximate latitude of northern California (Richards *et al.*, 1993). Thus, plate motion in Permian to early Mesozoic time not only closed the ocean basin, but also brought it northward. If significant portions of the Slide Mountain ocean floor have moved northward by this amount, it implies that the rifted and later rejoined arc component part of the previously defined Yukon-Tanana composite terrane proposed to have lain outboard of this ocean basin also must have moved north a similar amount.

Late Carnian and early Norian (Late Triassic) conodonts occur in weakly metamorphosed sedimentary rocks of the Seventymile terrane in the Fortymile River area of east-central Alaska and are widespread in the Canadian Cordillera and in central and southeastern Alaska (Dusel-Bacon and Harris, 2003, and references therein). It was previously proposed by Nelson (1993) that Middle(?) and Upper Triassic siliciclastic-carbonate strata of the Sylvester Allochthon represent an overlap sequence which loosely links North America and the Slide Mountain terrane. Considerable uncertainty exists, however, regarding the nature of the original contact, now generally faulted, between the Upper Triassic rocks and both oceanic rocks of the Seventymile and Slide Mountain terranes and continental margin rocks of the pericratonic assemblages and ancestral North America (*e.g.*, Nelson, 1993; Harms, 1986; Dusel-Bacon and Harris, 2003, and references therein). Following Dusel-Bacon and Harris (2003), we interpret the wide distribution of Late Triassic conodonts in the various allochthonous terranes and in the North American continental margin to indicate that these areas shared approximately similar warm, normal-marine conditions along the Late Triassic continental margin, but not that they represent an overlap assemblage draping across contacts between outboard allochthonous pericratonic and arc fragments and the ancient Pacific margin.

## UNRESOLVED QUESTIONS AND FOCUS OF FUTURE WORK

Although the above tectonic model explains many of the relationships observed in east-central Alaska and is consistent with most models proposed for the Canadian Cordillera, several outstanding uncertainties remain and warrant further consideration.

Confirmation of an attenuated continental margin setting for magmatism in the assemblages of the western and southern Yukon-Tanana Upland and the northern flank of the Alaska Range would be aided if an outboard subduction-zone and arc were definitively located. Truncation of the southern margin of the continental margin assemblages by the Denali fault zone has added to the difficulty of tectonic reconstruction of Alaska's ancient Pacific margin. Possible analogues of continental margin provinces that contain voluminous crustally-derived granitoids associated with coeval rhyolite-dominated bimodal volcanics often have controversial origins themselves. One possible analog is the Late Devonian to Early Carboniferous, extension-related silicic volcanism in the northern New England Fold Belt of Queensland, Australia (Bryan *et al.*, 2004). Both the large scale (extending 500 km orthogonal to the plate margin) and the duration (*ca.* 15 m.y.) of the silicic magmatism in Queensland are comparable to that in east-central Alaska.

A related problem consists of differentiating supra-subduction granitoids from texturally and compositionally similar rocks formed in an extensional environment. Specifically, correctly interpreting the tectonic origin of: (1) peraluminous K-feldspar augen gneiss in the Lake George assemblage that we infer to have formed during extension within the ancestral margin of North America inboard of the arc and the Seventymile terrane; and (2) much less widespread exposures of augen gneiss within the Fortymile River assemblage or other assemblages in the Finlayson Lake area, believed to be part of the arc that developed outboard of the Seventymile (or Slide Mountain) terrane. Although the degree of incompatible-element enrichment is generally higher in Lake George augen gneiss than in felsic orthogneiss from the Fortymile River assemblage, the trace-element signature of associated, coeval mafic rocks is a more reliable indicator of tectonic setting of the augen gneiss bodies. The reliability of mafic geochemical signatures as an indicator of the tectonic setting of coeval granitoids is illustrated by Sisson *et al.* (1996) for a mafic sill complex in the Mesozoic Sierra Nevada batholith. Although the batholith includes vast areas of megacrystic granitoids similar in texture and composition to the protoliths of the Lake George assemblage augen gneiss bodies, the Sierra Nevada mafic sills have arc trace-element signatures, unlike the within-plate and subordinate MORB signatures for mafic rocks associated with Lake George augen gneisses.

Finally, the boundary needs to be better defined between the proposed allochthonous (arc and associated marginal basin) and parautochthonous (extended continental margin) parts of the ancient Pacific margin in east-central Alaska and the adjacent Yukon. In Alaska, we have defined that boundary to be between the allochthonous Fortymile-Chicken metamorphic complex-Nasina rocks and the parautochthonous Lake George-Blackshell-Fairbanks-Chena rocks. The northwestern margin of this boundary is marked by large Cretaceous plutons in the western Eagle and easternmost Big Delta quadrangles (Foster, 1992; Fig. 2). A newly recognized northeast-trending tectonic zone with recurrent mid-Cretaceous to late Tertiary movement has been identified at the western end of this plutonic belt and lies directly above a northeast-trending aeromagnetic anomaly between the Denali and Tintina fault systems (O'Neill *et al.*, 2005). This tectonic zone likely played a key role in controlling emplacement of the associated Cretaceous plutons and Tertiary volcanic rocks (O'Neill *et al.*, 2005). It may represent a reactivated lithospheric shear zone between the Lake George and Fortymile River assemblages. Identification of an allochthonous/parautochthonous boundary at the southeastern margin of the Lake George assemblage is more uncertain (Nelson *et al.*, this volume).

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