Two flysch belts having distinctly different provenance suggest no stratigraphic link between the Wrangellia composite terrane and the paleo-Alaskan margin

Chad P. Hults1, Frederic H. Wilson1, Raymond A. Donelick2, and Paul B. O’Sullivan2

1U. S. GEOLOGICAL SURVEY, 4210 UNIVERSITY DRIVE, ANCHORAGE, ALASKA 99508, USA
2APATITE TO ZIRCON, INC., 1075 MATSON ROAD, VIOLA, IDAHO 83872, USA

ABSTRACT

The provenance of Jurassic to Cretaceous flysch along the northern boundary of the allochthonous Wrangellia composite terrane, exposed from the Lake Clark region of southwest Alaska to the Nutzotin Mountains in eastern Alaska, suggests that the flysch can be divided into two belts having different sources. On the north, the Kahlítna flysch and Kuskokwim Group overlie and were derived from the Farwell and Yukon-Tanana terranes, as well as smaller related terranes that were part of the paleo-Alaskan margin. Paleocurrent indicators for these two units suggest that they derived sediment from the north and west. Sandstones are predominantly feldspathic wackes that contain abundant quartz grains, lithic rock fragments, and detrital mica, which suggest that these rocks were derived from recycled orogen and arc sources. Conglomerates contain limestone clasts that have fossils matching terranes that made up the paleo-Alaskan margin. In contrast, flysch units on the south overlie and were derived from the Wrangellia composite terrane. Paleocurrent indicators for these units suggest that they derived sediment from the south. Sandstones are predominantly feldspathic wackes that contain abundant plagioclase grains and volcanic rock fragments, which suggest these rocks were derived from an arc. Clast compositions in conglomerate south of the boundary match rock types of the Wrangellia composite terrane.

The distributions of detrital zircon ages also differentiate the flysch units. Flysch units on the north average 54% Mesozoic, 14% Paleozoic, and 32% Precambrian detrital zircons, reflecting derivation from the older Yukon-Tanana, Farewell, and other terranes that made up the paleo-Alaskan margin. In comparison, flysch units on the south average 94% Mesozoic, 1% Paleozoic, and 5% Precambrian zircons, which are consistent with derivation from the Mesozoic oceanic magmatic arc rocks in the Wrangellia composite terrane. In particular, the flysch units on the south contain a large proportion of zircons ranging from 135 to 175 Ma, corresponding to the age of the Chitina magmatic arc in the Wrangellia terrane and the plutons of the Peninsular terrane, which are part of the Wrangellia composite terrane. Flysch units on the north do not contain significant numbers of zircons in this age range. The flysch overlying the Wrangellia composite terrane apparently does not contain detritus derived from rocks of the paleo-Alaska margin, and the flysch overlying the paleo-Alaskan margin apparently does not contain detritus derived from the Wrangellia composite terrane.

The provenance difference between the two belts helps to constrain the location of the northern boundary of the Wrangellia composite terrane. Geophysical models place a deep, through-going, crustal-scale suture zone in the area between the two flysch belts. The difference in the provenance of the two belts supports this interpretation. The youngest flysch is Late Cretaceous in age, and structural disruption of the flysch units is constrained to the Late Cretaceous, so it appears that the Wrangellia composite terrane was not near the paleo-Alaskan margin until the Late Cretaceous.

INTRODUCTION

For more than three decades, geologists have debated the timing and latitude of accretion of the Wrangellia composite terrane (Fig. 1; see summaries in Coney et al., 1980; Plafker et al., 1989; Plafker and Berg, 1994; Cowan et al., 1997). Paleomagnetic data from the Wrangellia composite terrane suggest the terrane was located 20°−40° south of its present position relative to the North American continent during the Late Triassic and Jurassic, 20°−60° south during the Early Cretaceous, and 20°−30° south during the Late Cretaceous (Coe et al., 1985; Hillhouse, 1987; Hillhouse and Coe, 1994; Bogue et al., 1995; Wynne et al., 1995; Ague and Brandon, 1996; Irving et al., 1996; Stamatakis et al., 2001; Krijgsman and Tauxe, 2006). However, interpretation of geologic relationships along major fault systems of the Cordillera suggests different constraints on the timing and location of accretion to the southern Alaska margin. Some workers suggested the Wrangellia composite terrane accreted in the Jurassic and translated less than 10° latitude along the North American margin (Gehrels et al., 1991; Rubin and Saleeby, 1991a, 1991b; McClelland et al., 1992a, 1992b; van der Heyden, 1992; Monger et al., 1994, 1996; Ridgway et al., 2002; Trop et al., 2002; Trop and Ridgway, 2007), whereas others suggested the Wrangellia composite terrane accreted in the middle to Late Cretaceous and had very large translations (20°−30° latitude) since then (Jones et al., 1977; Csejty et al., 1982; Nokleberg et al., 1985; Crawford et al., 1987; Plafker et al., 1989; Hollister and Andronicos, 1997; Andronicos et al., 1999).

In southern Alaska, the Wrangellia composite terrane is outboard of the Yukon-Tanana composite and Farewell terranes (Fig. 1), which were the largest terranes thought to have made up the paleo-Alaskan margin during accretion of the Wrangellia composite terrane (Csejty et al., 1982; Plafker et al., 1989; Plafker and Berg, 1994; Decker et al., 1994). Structural
and stratigraphic correlations along the Tintina fault, located on the northeast side of the Yukon-Tanana terrane, suggest that the Yukon-Tanana terrane has been offset ~450 km (<5° latitude) relative to rocks of the North American continent (Fig. 1; Gabrielse, 1985, 1991; Gabrielse et al., 2006). However, paleomagnetic data from Upper Cretaceous volcanic rocks overlying the Yukon-Tanana terrane suggest that it was located 17°–26° south of its present position relative to the North American continent during that time (Enkin et al., 2003, 2006).

Regardless of the paleolatitude of the terranes of southern Alaska, or the timing of accretion of the Wrangellia composite terrane, the present-day location of the northern boundary of the Wrangellia composite terrane in Alaska is not yet resolved. Researchers have proposed varying locations for the northern boundary of the Wrangellia composite terrane (Fig. 1): Chilchitna fault of Wallace et al. (1989), Talkeetna fault of Wallace et al. (1989), Valdez Creek shear zone (Davidson et al., 1992), or the Broxson Gulch thrust (Stout and Chase, 1980; Nokleberg et al., 1985).
fault represented a protracted suture zone of the Wrangellia composite terrane that they called the Alaska Range suture zone. The northern boundary of the Wrangellia composite terrane apparently lies between the Denali fault system on the north and the Talkeetna fault on the south.

Analysis of the time of accretion of the Wrangellia composite terrane and the location of its northern boundary largely depends on the interpretation of the depositional contacts and structural relationships of the flysch units lying between it and the terranes to the north (Fig. 1). However, only a handful of depositional contacts of the flysch units with underlying rock units have been recognized, and the units are structurally disrupted and locally metamorphosed, and fossils are sparse. Due to a deficit of directly observable stratigraphic or structural relationships, compositional and paleocurrent data combined with detrital zircon provenance provide useful tools for delineating the monotonous and often complexly deformed flysch units. With these tools, it is possible to test for stratigraphic links between terranes by comparing the provenance of the flysch units to possible source rocks in nearby terranes.

As a test of the Wrangellia composite terrane accretion models, the following logic is applied: If the provenance of a flysch unit overlying the Wrangellia composite terrane shows a distinct match to a paleo-Alaskan margin source (or the other way around), then it can be inferred that the Wrangellia composite terrane accreted to the paleo-Alaskan margin prior to or during deposition of the flysch unit. Alternatively, if the provenance of the flysch units matches sources on their respective sides, then it is possible that the Wrangellia composite terrane accreted to the paleo-Alaskan margin after deposition of the flysch units. To test these hypotheses, sandstone samples were collected from either side of proposed boundaries of the Wrangellia composite terrane (Fig. 1), sandstone point-counts were conducted, and select samples were analyzed for detrital zircon ages. These data are presented in context with previously published detrital zircon data, compositional data, paleocurrent indicators, and contact relationships in order to delineate seven flysch units. These data are used to test for stratigraphic links between the Wrangellia composite terrane and the paleo-Alaskan margin, and they are compared to proposed locations of the northern boundary of the Wrangellia composite terrane.

Underlying Terranes

Wrangellia Composite Terrane

From west to east, the Wrangellia composite terrane is made up of the Peninsular, Wrangellia, and Alexander terranes (Fig. 1; Nokleberg et al., 1994). This study focuses on the northern boundary of the Wrangellia composite terrane in southern Alaska, along the northern margins of the Peninsular and Wrangellia terranes; accordingly, the Alexander terrane is not shown in Figure 1 and will not be discussed in detail. These terranes were most likely connected together by the Late Triassic (Gardner et al., 1988; Plafker et al., 1989; Nokleberg et al., 1994). The primary units of the Peninsular terrane are the Lower Jurassic Talkeetna Formation volcanic rocks and latest Triassic to Middle Jurassic plutonic rocks, which together make up the Talkeetna oceanic magmatic arc (Plafker et al., 1989). The pre-arc rocks consist of upper Paleozoic metamorphosed igneous and sedimentary rocks and Triassic limestone and greenstone (Plafker et al., 1989) that are mapped as the Tlikakila and Kakhonak complexes (Wilson et al., 2006). The terrane is intruded by a younger phase of Middle to Late Jurassic plutons (included in the mJ-eK plutons in Fig. 1; Rioux et al., 2007, 2010; Plafker et al., 1989; Reed and Lanphere, 1973) and overlain by Jurassic to Tertiary clastic, carbonate, and volcanic rocks (Plafker et al., 1989).

Jones et al. (1977) identified a distinctive tectonostratigraphic sequence of the Wrangellia terrane as Upper Triassic carbonate rocks that overlie a thick package of Carnian, dominantly subaerial, basalt flows. In Alaska, this sequence overlies a Pennsylvanian to Permian oceanic magmatic arc basement (Plafker et al., 1989). Two Mesozoic magmatic arcs intrude parts of the Wrangellia terrane: the Chitina magmatic arc (135–175 Ma; Hudson, 1983; Plafker et al., 1989; Roeske et al., 2003) and the Chisana magmatic arc (115–135 Ma; Berg et al., 1972; Barker, 1987; Snyder and Hart, 2007). The plutons cropping out in the Wrangell–St. Elias Mountains are the “type area” for the arcs, but the plutonic rocks (145–175 Ma) cropping out along the Wrangellia-Peninsular terrane boundary south of the Clearwater Mountains (Fig. 1) are similar in age to the Chitina arc (Turner and Smith, 1974; Wilson et al., 1994). Additionally, the Peninsular terrane also contains Middle Jurassic to Late Jurassic plutons (Fig. 1; Wilson et al., 2012). Together, these plutonic bodies form a nearly continuous belt across the Wrangellia composite terrane of southern Alaska (mJ-eK plutons in Fig. 1).

Terranes of the Paleo-Alaskan Margin

The two largest terranes inboard of the Wrangellia composite terrane are the Farewell and Yukon-Tanana terranes (Fig. 1; Silberling et al., 1992). The Farewell terrane (Decker et al., 1994; Bundtzen et al., 1997) consists of Precambrian metamorphic basement overlain by Neoproterozoic and lower to middle Paleozoic carbonate platform and deep-marine rocks of the Nixon Fork and Dillinger subterrane (Fig. 1). The Mystic subterrane overlies and is structurally imbricated with the Dillinger subterrane and consists of slivers of Ordovician shale, Silurian carbonate rocks, and pillow basalt in melange; Upper Devonian carbonate rocks; and upper Paleozoic marine and nonmarine clastic strata. Overlying these Paleozoic rocks, there are Upper Triassic to Lower Jurassic mafic volcanic and volcanioclastic rocks (Jones et al., 1981, 1987; Decker et al., 1994; Bundtzen et al., 1997).

The Yukon-Tanana terrane consists of polydeformed and metamorphosed quartz-mica schist, quartzite, gneiss, and metapelite and metavolcanic and mafic rocks (Silberling et al., 1992). Dusel-Bacon et al. (2006) broke down the Yukon-Tanana terrane into two primary parts: Neoproterozoic to lower Paleozoic metasedimentary rocks, thought to have been part of the passive North American continental margin, and widespread Devonian to Mississippian metaigneous and metasedimentary rocks thought to have formed during rifting of the continental margin. The Yukon-Tanana is intruded by Late Triassic to Early Jurassic igneous rocks in the eastern Yukon-Tanana terrane (185–215 Ma; Werdon et al., 2001; Dusel-Bacon et al., 2002; Szumigala et al., 2002). Granitic rocks (85–115 Ma) also intrude the Yukon-Tanana terrane and are cogenetic with regional metamorphism (Aleinikoff, 1984; Nokleberg et al., 1992; Foster et al., 1994).

The Chulitna, West Fork, Susitna, and McKinley terranes (Fig. 1; Jones et al., 1980; Silberling et al., 1992) lie between the Farewell terrane and the Wrangellia composite terrane and, similar to the Mystic subterrane, contain Upper Triassic to Lower Jurassic volcanic rocks. The Chulitna terrane consists of Devonian volcanic and sedimentary rocks overlain by Upper Triassic volcanioclastic red beds, basalt, and limestone, and Upper Triassic to Lower Jurassic volcanioclastic sandstone and basalt (Jones et al., 1980). The presence of Upper Triassic basalts led workers to suggest correlations between the Wrangellia terrane and the Chulitna terrane (e.g., Csejtey et al., 1992; Clautice et al., 2001). However, Jones et al. (1977) originally recognized distinct stratigraphic differences between the Wrangellia and the Chulitna terranes and suggested that a suture must lie between the two terranes. More recent, detailed work on the stratigraphy and geochemistry led Gilman et al. (2009) to reaffirm that the Upper Triassic basalts are not related to the Wrangellia terrane. The West Fork terrane is faulted against the Chulitna terrane and consists of Jurassic crystal tuff, volcanioclastic sandstone, argillite, and chert (Nokleberg et al., 1994). Similar to the younger portions of the Chulitna...
Jurassic and Cretaceous Flysch Units and Their Provenance

There are seven Upper Jurassic to Upper Cretaceous flysch units lying between the terranes of the paleo-Alaskan margin and the Wrangelia composite terrane to the south (Figs. 1 and 2). Units making up the southern belt, from southwest to northeast, are the informally named Koksetna River sequence of Wallace et al. (1989), flysch of the Tordrillo Mountains (informally named herein based on work by Bradley et al. [2009] and Wilson et al. [2012]), informally named graywacke of the Yenlo Hills of Wilson et al. (1998), flysch of the Clearwater Mountains (informally named herein based on mapping by Smith [1981] and Smith et al. [1988]), and the informally named Nutzotin Mountains sequence of the Gravina-Nutzotin belt of Berg et al. (1972). Units making up the northern belt are the Kuskokwim Group and the informally named Kaskelna fl ysch. The contact relationships, paleocurrent indicators, and provenance of these flysch units are discussed individually in the following sections.

Koksetna River Sequence

The Koksetna River sequence was informally defined by Wallace et al. (1989) for deformed Upper Jurassic to Lower Cretaceous volcanic-lithic turbidites in the Lake Clark region (Fig. 1). Only two fossil localities are known that contain Upper Jurassic to Lower Cretaceous bivalves and ammonites (Fig. 2). Based on field relationships and abundance of pyroxene grains in sandstones, Wallace et al. (1989) inferred that the Koksetna River sequence was locally derived from and depositionally overlies the Chilkadotra Greenstone. The unit is locally metamorphosed along the steeply dipping Chilikotna fault where it is faulted against the Kuskokwim Group (Fig. 1; Wallace et al., 1989).

Wallace et al. (1989) interpreted proximal to distal facies trends that suggested northwest-directed paleoflow (Fig. 1). In addition to clasts that match the Chilkadotra Greenstone, they also found clasts of intermediate to felsic volcanic and plutonic rocks, as well as chert and argillite clasts. Flute casts at site A4 (Fig. 1) also suggest a paleocurrent directed to the northwest. Petrographic studies (Fig. 3; Wallace et al., 1989; this study) show that sandstone samples contain predominantly plagioclase grains and volcanic...
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rock fragments, and lesser amounts of monocry staline quartz grains, metamorphic rock fragments, clastic sedimentary rock fragments, and pyroxene grains. Metamorphic rock fragments are predominantly nonfoliated hornfels that appear to be contact-metamorphosed volcanic or volcaniclastic rock fragments (Wallace et al., 1989; this study). Regionally metamorphosed rock fragments and micas are notably absent (Wallace et al., 1989; this study). Point counts of sandstone samples suggest derivation from a magmatic arc (Fig. 3; this study).

Probability plots of four new detrital zircon samples from the Koksetna River sequence are shown in Figure 4. Nearly all of the zircons have U/Th ratios less than 10, suggesting an igneous origin. Three samples contain Early Cretaceous youngest detrital zircon ages (A1, A2, A3) and have similar age distributions; therefore, they are presented together in a composite probability plot in Figure 5. The youngest zircons from these samples are consistent with the Upper Jurassic to Lower Cretaceous fossil ages. The fourth sample (A4) has detrital zircons as young as 85 Ma, which is significantly younger than the fossils identified from the unit (Fig. 2), and this suggests that there are undifferentiated younger

Figure 3. Plots showing modal abundances from point counts of the Upper Jurassic to Cretaceous flysch units along the northern boundary of the Wrangellia composite terrane. Grain types: O—quartz, F—feldspar, L—lithic, Qm—monocrystalline quartz, Lt—total lithics, Qp—polycrystalline quartz, Lv—lithic volcanic-metavolcanic rock fragments, Ls—lithic sedimentary-metasedimentary rock fragments. All point-count data were obtained or reported using the Gazzi-Dickinson method (Dickinson, 1970; Ingersoll et al., 1994). Sources (data from this study shown in red [GSA Data Repository1]): Koksetna River sequence (this study); flysch of the Tordrillo Mountains (this study); graywacke of the Yenlo Hills (this study); flysch of the Clearwater Mountains (Eastham, 2002; this study); Nutzotin Mountains sequence (Manuszak, 2000; this study); Kuskokwim Group (Kalbas, 2006; Miller et al., 2007; this study); Kahiltna flysch (Eastham, 2002; Hampton et al., 2007b; Kalbas et al., 2007; this study). Provenance divisions are from Dickinson et al. (1983) and Dickinson and Suczek (1979).

GSA Data Repository Item 2013360, raw point-count data and a detailed description of samples collected, the equipment, and method used for the U/Pb detrital zircon age analysis, detrital zircon ages, and concordia plots, is available at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

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Figure 4. On this and following two pages.
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Figure 4 (continued). On this and following page.
strata that should be mapped in more detail and separated into a different unit. For the three Early Cretaceous samples, the majority of the detrital zircon ages lie within two populations: 145–170 Ma and 180–220 Ma, but they also contain 5% Paleozoic and Precambrian zircons. The Late Cretaceous sample contains only Mesozoic detrital zircons, with 93% forming a population between 80 and 105 Ma, 6% of the zircons falling between 140 and 165 Ma, and one 193 Ma zircon (Fig. 4, A4). The 140–165 Ma population is similar to the age distribution found in the Early Cretaceous detrital zircon samples.

**Flysch of the Tordrillo Mountains**

To the northeast of the Koksetna River sequence, Wilson et al. (2012) showed a Cretaceous sedimentary and volcanic rock unit (their unit Kes) that is informally referred to here as the flysch of the Tordrillo Mountains (Figs. 1 and 2). The unit consists of turbiditic feldspathic wacke and argillite that is locally contact metamorphosed (Wilson et al., 2012; Bradley et al., 2009). No depositional contacts have been reported. This unit was subdivided from the Kahiltna flysch by Wilson et al. (2012) because of distinct detrital zircon ages and presence of interbedded volcanic rocks. Bradley et al. (2009) reported three fossil localities in this area that contain Jurassic to Lower Cretaceous radiolarians, a Valanginian bivalve, and a Turonian bivalve. Petrographic study of three sandstone samples reveals that they contain predominantly plagioclase grains and volcanic rock fragments (Fig. 3; this study). Minor constituents include contact-metamorphosed volcanic or volcanoclastic rock fragments, quartz grains, siliciclastic sedimentary rock fragments, and rare pyroxene grains. A relatively high abundance of plagioclase grains and volcanic rock fragments suggests derivation from a magmatic arc (Fig. 3).

Four widespread samples (Fig. 1) presented by Bradley et al. (2009) have Early Cretaceous youngest detrital zircon ages (Fig. 2). A compilation of the Early Cretaceous samples shows that 93% of the zircons are Mesozoic, there are no Paleozoic grains, and 7% are Precambrian (Fig. 5; Bradley et al., 2009). Much like the lower Koksetna River sequence, the Mesozoic grains fall between 130 and 200 Ma. The Precambrian grains are not shown in the probability plot in Figure 5, because they are relatively minor, and they do not cluster to define distinct populations.

Like the Koksetna River sequence, Bradley et al. (2009) also found one sample that contained early Late Cretaceous detrital zircons (B* in Fig. 1), which, along with a Turonian fossil, suggests the presence of undifferentiated younger strata that probably should be separated into a different unit. Of the 100 detrital zircon ages, 87 are Mesozoic, 6 are Paleozoic, and 7 are Precambrian (Fig. 5). The detrital zircon ages form a major population that falls between 80 and 110 Ma and a minor population between 130 and 160 Ma.

*Figure 4 (continued).* Histograms and probability plots of detrital zircon U/Pb ages from this study. \( n \) — number of ages used for probability plot; \( n_p \) — number of ages used for histograms after filtering out ages having less than 0.15 probability of concordance (Ludwig, 1998). Letters correspond to sample locations in Figure 1. Samples were crushed, separated, and analyzed for U/Pb detrital zircon ages by Apatite to Zircon, Inc., using the Washington State University laser-ablation—inductively coupled plasma—mass spectrometer (LA-ICP-MS; see text footnote 1). Measured isotopic ratios and their errors were used to calculate ages using Excel® macros developed by Ludwig (2003). The probability plots were created using the probability of concordance weighted method of Nemchin and Cawood (2005) using an Excel® macro provided by A. Nemchin (2010, written commun.) (see supplementary data: Table 2 [see text footnote 1]).
Figure 5. Probability plots of detrital zircon U/Pb ages up to 500 Ma. Shaded areas show age ranges for possible igneous source rocks. Detrital zircon data sources: Kuskokwim Group—combination of samples 09ACH273A and 09ACH277D (this study) and three samples from Kalbas (2006); Kahiltna flysch—samples 09ACH246A and 11ACH037 (this study), and seven samples from Hampton et al. (2007b, 2010) and Kalbas et al. (2007); Mystic subterrane—combination of three samples from Bradley et al. (2007) and four samples from Malkowski (2010); Chulitna terrane—age ranges reported in Hampton et al. (2005, 2007a); upper Koksetna River sequence—sample 09ACH278C (this study), lower—combination of samples 09ACH270, 09ACH274A, and 09ACH275A (this study); upper flysch of the Tordrillo Mountains—sample 05PH105a (Bradley et al., 2009), lower—combination of four Early Cretaceous samples from Bradley et al. (2009); graywacke of the Yenlo Hills—sample 75ANS084A (this study); flysch of the Clearwater Mountains—sample BC-16 from Hampton et al. (2010), and five Early Cretaceous samples from Mooney (2010); Nutzotin Mountains sequence—sample 09ACH150A (this study); Gravina-Nutzotin belt sedimentary rocks of southeast Alaska—combination of thermal ionization mass spectrometry (TIMS) data reported in Gehrels and Kapp (1998) and Gehrels (2001). Probable igneous sources age ranges: Nyac and Ruby terrane plutons (NT/RT)—Wilson et al. (2008) and Patton et al. (2009); Mystic, Chulitna, McKinley, Susitna, and West Fork terranes (MCMSWT)—Jones et al. (1980), Csejtey et al. (1992), Bundtzen et al. (1997), Clautice et al. (2001); Yukon-Tanana terrane (YTT) plutonic and meta-igneous rocks—Dusel-Bacon and Williams (2009), Dusel-Bacon et al. (2006), Colpron et al. (2006), Mortensen et al. (2000), Wilson et al. (1985), and Newberry et al. (1998); Chitina arc—Hudson (1983), Plafker et al. (1989), Roeske et al. (2003); m-IK plutons intruding the Peninsular terrane—Wilson et al. (2006, 2012), Lang et al. (2013); plutons of the Peninsular terrane—Rioux et al. (2007, 2010).
Graywacke of the Yenlo Hills

In the southern Alaska Range, Reed and Nelson (1980) mapped an undivided marine sedimentary rock unit (their unit KS), but in the Yenlo Hills, they noticed that the graywacke was “***significantly different in that the grains are extremely angular, and oscillatory zoned plagioclase, volcanic rock fragments, hornblende, epidote, and calcite grains are more abundant, suggesting that the sandstone may have been derived from the Jurassic magmatic arc***” (p. 6). They also mention occurrences of interbedded tuffs. These distinctions led Wilson et al. (1998) to designate these rocks as a separate unit, which they informally named the graywacke of the Yenlo Hills (Figs. 1 and 2). Thin section analysis of the graywacke of the Yenlo Hills confirms an abundance of plagioclase grains and volcanic rock fragments. Point counts suggest a transitional arc source (Fig. 3).

New detrital zircon data for one sample is presented in Figure 4C, which shows that all the detrital zircons are Mesozoic with a nearly unimodal age distribution between 145 and 190 Ma. All of the zircons have U/Th ratios less than 5, suggesting an igneous origin. The youngest detrital zircons are Early Cretaceous (Fig. 2).

Flysch of the Clearwater Mountains

In the Clearwater Mountains, Smith (1981), Smith et al. (1988), and Kline et al. (1990) mapped phylite and biotite schist that represent a metamorphosed sequence of Jurassic to Cretaceous turbidites, which are informally referred to here as the flysch of the Clearwater Mountains (Figs. 1 and 2). The flysch of the Clearwater Mountains overlies the Triassic Amphitheater Group (Smith, 1981), which is part of the Wrangellia terrane (Hillhouse and Gromme, 1981). The flysch contains Upper Jurassic to Lower Cretaceous sedimentary rocks of the informally named Nutzotin Mountains sequence, which is part of the Wrangellia terrane (Csejtey et al., 1992; Smith et al., 1992). The Nutzotin Mountains sequence consists of turbidites that are locally calcareous (Berg et al., 1972; Richter, 1976; Kozinski, 1985; Manuszak et al., 2007). Fossils constrain the unit to the Late Jurassic and earliest Cretaceous, and youngest detrital zircon ages support an Early Cretaceous depositional age for the portion of the unit sampled (Fig. 2).

In the Nutzotin Mountains area, Kozinski (1985) and Manuszak et al. (2007) found northerly and easterly directed paleocurrent indicators (Fig. 1), which suggest a sediment source to the southwest. Conglomerate clasts are dominantly mafic to intermediate volcanic rocks and lesser greenstone, limestone, and granitic rocks (Kozinski, 1985; Manuszak et al., 2007). Point counts of sandstone samples suggest that the unit was derived from an arc (Fig. 3; Manuszak, 2000; this study).

Detrital zircon ages for one new sample from the Nutzotin Mountains sequence (Fig. 4E) fall in a nearly unimodal distribution that ranges between 140 and 170 Ma, contains 6% Paleozoic (385–450 Ma) zircons, and has two Precambrian zircons (Fig. 5). All of the detrital zircons have U/Th ratios less than 6, suggesting an igneous origin.

Kahiltna Flysch

The informally named Kahiltna flysch (Jones et al., 1986) consists of marine turbiditic argillite and graywacke, minor conglomerate, and local limestone (Reed and Nelson, 1980; Csejtey et al., 1992; Hampton et al., 2007b; Kalbas et al., 2007). The Kahiltna flysch has been commonly considered to range from the Late Jurassic to the Late Cretaceous on the basis of sparse fossil collections (e.g., Eastham and Ridgway, 2002; Ridgway et al., 2002; Hampton et al., 2007b, 2010); however, the Jurassic fossils are in the flysch of the Clearwater Mountains (Csejtey et al., 1992). Based on facies and provenance differences between the flysch along the central Alaska Range and the flysch of the Clearwater Mountains, Eastham and Ridgway (2002, p. 51) suggested that “the thousands of meters of Upper Jurassic to Upper Cretaceous strata that have been grouped together as the Kahiltna assemblage in south-central Alaska may actually represent several different sedimentary basins.” Considering the flysch of the Clearwater Mountains as a separate unit, the only Jurassic fossils that may be part of the Kahiltna flysch are from an argillite and chert unit in the Chulitna region, which Clautice et al. (2001) and Hampton et al. (2007b) considered different from the Kahiltna flysch. Based on these differences, we restrict the Kahiltna flysch to the Cretaceous (Fig. 2) and the outcrop extent shown in Figure 1.

The Kahiltna flysch depositionally overlies rocks that made up the paleo-Alaskan margin. In the western Alaska Range, Kalbas et al. (2007) mapped a disconformable contact between the Kahiltna flysch and Upper Triassic pillow basalts of the Mystic subterrane. In the northern Talkeetna Mountains, Hampton et al. (2007b) mapped a depositional contact between the Kahiltna flysch and Lower Jurassic volcanic and volcaniclastic rocks of their informally named Honolulu Pass formation, which is part of the Susitna terrane. In the central Alaska Range, the Kahiltna flysch overlies the McKinley terrane (Csejtey et al., 1992).

In the western Alaska Range, Kalbas (2006) found southwest-directed paleocurrent indicators (Fig. 1). In the central Alaska Range, Eastham and Ridgway (2002) found sparse paleocurrent indicators and interpreted lithofacies relationships to suggest a southwesterly paleoflow direction (Fig. 1). Limestone clasts found in the northeastern portion of the unit contain Ordovician to Devonian fossils, which were correlated with limestone of the Farewell terrane (Csejtey et al., 1992; Ridgway et al., 2002). A half-kilometer-sized limestone olistolith, found in the southwestern part of the Kahiltna flysch near the base of the unit, was interpreted by Kalbas et al. (2007) as lithologically similar to limestone of the Farewell terrane. Conglomerates contain varying proportions of sedimentary, volcanic, and metamorphic clasts (Eastham, 2002; Kalbas, 2006). Sandstone petrography shows that in general, quartz grains and lithic fragments...
predominate (Fig. 3; Eastham, 2002; Hampton et al., 2007b; Kalbas et al., 2007; this study). Quartz grains are evenly divided between monocrystalline and polycrystalline quartz. Metamorphic grains include quartz-mica schist, phyllite, and chert. Point counts of sandstone samples plot in the recycled orogen and arc provenance regions (Fig. 3; Eastham, 2002; Hampton et al., 2007b; Kalbas et al., 2007; this study).

Two new detrital zircon samples were collected from the southern margin of the Kahiltna flysch (locations H1 and H2 in Fig. 1), and the age distribution data are presented in Figure 4. Nearly all the detrital zircons have U/Th ratios less than 10, suggesting a predominantly igneous orogen. The age distributions in these samples are similar to the seven detrital zircon samples from the Kahiltna flysch reported by Hampton et al. (2007b, 2010) and Kalbas et al. (2007). Comparisons of the new data to the previously published data sets result in high similarity and overlap coefficients of 0.87 and 0.85, respectively, so they are presented in composite probability plots in Figures 5 and 6. The composite plots show that the Kahiltna flysch contains a broad range of detrital zircon ages. The unit contains 71% Mesozoic zircons that fall in two populations: 90–135 Ma and 160–250 Ma. Twelve percent of the zircons are Paleozoic, with most forming a population 330–390 Ma. Seventeen percent of the zircons are Precambrian and form two minor populations: 1600–2100 Ma and 2500–2800 Ma (Fig. 6). The youngest detrital zircons from the individual samples of the Kahiltna flysch range from the Early Cretaceous to the Late Cretaceous (Fig. 2). Three of the seven samples contain youngest detrital zircon ages younger than the youngest fossils dated (Reed and Nelson, 1980; Csejtey et al., 1992), which suggest the unit age may extend to the Campanian.

Kuskokwim Group

The Upper Cretaceous Kuskokwim Group (Cady et al., 1955) covers a large portion of southwestern Alaska (Fig. 1) and consists of marine turbiditic argillite, graywacke, and conglomerate, as well as marginal marine and nonmarine sandstone and conglomerate, which locally contains coal (Hoare and Coonrad, 1959; Box et al., 1993; Miller and Bundtzen, 1994; Kalbas, 2006; Wilson et al., 2006, 2008). Based on fossil ages and geologic relationships, the age of the Kuskokwim Group is well constrained to early Late Cretaceous (Fig. 2; Miller and Bundtzen, 1994; Elder and Box, 1992). The Kuskokwim Group overlies a number of terranes that made up the paleo-Alaskan margin (Fig. 1): the Farewell terrane (Wallace et al., 1989; Bundtzen et al., 1994; Wilson et al., 1998, 2008; Kalbas, 2006; Patton et al., 2009); the Ruby, Innoko, and Nyac terranes (Wallace et al., 1989; Wilson et al., 1998, 2008); and the Togiak, Goodnews, and Kilbuck terranes (Box et al., 1993).

The lithofacies distributions and palaeocurrent indicators presented by Wallace et al. (1989), Elder and Box (1992), and Kalbas (2006) suggest that the paleocurrent flowed from shallower northern and western (present-day) part of the basin to a deeper part to the southeast (Fig. 1). Elder and Box (1992) also suggested that the coarse nearshore facies and nonmarine deposits on the margins of the basin indicated that the surrounding terranes were subaerially exposed at the time of deposition. Elder and Box (1992) and Miller and Bundtzen (1994) noted metamorphic rock, volcanic rock, and chert conglomerate clasts, which they interpreted were probably derived from the Innoko and Ruby terranes. Box et al. (1993) attributed locally abundant volcanic, volcaniclastic, and plutonic rock clasts to the adjacent Togiak terrane. Patton et al. (2009) referred to a limestone clast conglomerate that they suggested was derived from the Farewell terrane.

Petrographic analysis of sandstone samples shows that the Kuskokwim Group contains grains of a diverse origin. Framework grains in sandstone include sedimentary rock fragments, metamorphic rock fragments, polycrystalline...
quartz, plagioclase, and monocrystalline quartz (Kalbas, 2006; Miller et al., 2007; this study). Kalbas (2006, Chapter 4, p. 232) stated, “meta-
morphic lithic grains include biotite- and white
mica-schist, argillaceous to phyllitic mudstone,
weak to strongly foliated argillaceous mud-
stone, and tectonized, sometimes radiolarian-
bearing chert.” Point counts suggest the unit was
derived predominantly from a recycled orogen
with some input from arc sources (Fig. 3; Kal-
bas, 2006; Miller et al., 2007; this study).

Two new detrital zircon samples were col-
lected from the southeastern margin of the Kus-
kokwim Group (locations G1 and G2 in Fig.
1), and the age distribution data are presented
in Figure 4. These data are very similar to the
detrital zircon distributions from the central and
northwestern portions of the basin (three sam-
pies in Kalbas [2006], locations marked by F
in Fig. 1; 11 samples presented by Miller et al.,
2007). Comparison of the new data to the Kalbas
(2006) data results in high similarity and over-
apl coefficients of 0.76 and 0.80, respectively.
The two new samples were combined with the
three Kalbas (2006) samples for the probability
plot shown in Figures 5 and 6. Nearly all the
detrital zircons have U/Ta ratios less than 10,
suggesting an igneous origin. The age distribu-
tion of zircons is 34% Mesozoic, 16% Paleo-
zoic, and 50% Precambrian. The unit contains
Cretaceous youngest detrital zircon ages (Fig. 2;
Kalbas, 2006). The Mesozoic zircons primarily
form two populations, 90–145 Ma and 160–230
Ma. Paleozoic zircons of all periods are found
in the unit, but most fall in a range between 340
and 440 Ma. Proterozoic zircons are relatively
evenly distributed throughout the time period
but form a minor population between 1600 and
1900 Ma (Fig. 6). The samples also contained a
few Archean zircons (Fig. 6).

**DISCUSSION**

**Provenance Interpretation of the Southern Flysch Belt**

The flysch units of the southern flysch belt have similar provenance, are similar in age, and
overlie (or are inferred to overlie) rocks of the
Wrangellia composite terrane. Although fos-
sil control and other age constraints are sparse,
the available data are consistent and suggest
that the bulk of units range from latest Jurassic
to early Early Cretaceous in age (Fig. 2). The
Koksetna River sequence and flysch of the Tor-
drillo Mountains apparently contain undifferen-
tiated Upper Cretaceous strata that have not yet
been mapped separately and probably should be
considered different units. Paleocurrent indi-
cators suggest that sediment was derived from the
direction of the Wrangellia composite terrane
(Fig. 1). The units contain conglomerate clasts
that are predominantly volcanic and plutonic,
which is consistent with derivation from the
abundant volcanic and plutonic rocks of the
Wrangellia composite terrane. Minor constitu-
teurs include greenstone, limestone, and argil-
ligt clasts, which are also consistent with deriv-
ation from the rocks of the Wrangellia composite
terrane (Kozinski, 1985; Wallace et al., 1989;
Eastham and Ridgway, 2002; Manuszk et al.,
2007). The sandstone samples have a high per-
centage of plagioclase grains and volcanic rock
fragments, and point counts suggest the units
were derived from an arc (Fig. 3). Interbedded
volcanic rocks in the lower flysch of the Tor-
drillo Mountains, graywacke of the Yenlo Hills,
and flysch of the Clearwater Mountains indicate
the arc was active.

**Detrital Zircon population age ranges are sim-
similar in the Lower Cretaceous units of the
southern belt (Fig. 5). Similarity coefficients
among the units are high (0.73–0.90; Table
1), suggesting they shared a similar source. The
overlap coefficients are low (0.18–0.46; Table
1), but the overlap coefficient is strongly influ-
enced by the presence of minor amounts of
older zircons found in some units.

Two samples in the southern belt contain
Late Cretaceous detrital zircons: the upper
Koksetna River sequence, and the upper flysch
of the Tordrillo Mountains (Fig. 5). The nearly
unimodal mid-Cretaceous and Late Cretaceous
populations match the age of mid-Cretaceous
and Late Cretaceous plutons intruding the Pen-
insular terrane including: the Older Granite
(97–109 Ma) of Wilson et al. (2012); the Peb-
ble Deposit intrusions (90–96 Ma; Lang et al.,
2013), and the Late Cretaceous plutons (75–85
Ma) described in Wilson et al. (2006). These
undifferentiated strata are probably related to the
volcaniclastic sedimentary rocks that con-
tain similar-age volcanic and plutonic clasts
that were dated by Layer and Solie (2008).

Detrital zircon distributions of the southern
belt all contain a population that matches the age
of the Chitina arc (135–175 Ma) and the plutons
of the Peninsular terrane (Fig. 5). The presence
of the 135–175 Ma detrital zircon population,
abundant volcanic and plutonic clasts, and interbeds of similar-age volcanic rocks suggest
that the Lower Cretaceous units were deposited
adjacent to the active Chitina arc, or possibly,
volumism associated with the Middle to Late
Jurassic plutons in the Peninsular terrane (mJ-
eK plutons in Fig. 1). The lower Koksetna River
sequence and the lower flysch of the Tordrillo
Mountains contain an additional latest Triassic
Middle Jurassic population that could have
originated from the older plutons of the Penin-
sular terrane (Fig. 5). Rioux et al. (2007, 2010)
proposed two episodes of plutonism in the Pen-
insular terrane, latest Triassic to Middle Jurassic
and Middle to Late Jurassic, which appear to be
reflected in the detrital zircon age distributions
of these two units (Fig. 5). The minor Paleozoic
and Precambrian zircons in the two units could
have been recycled from the Kakkonak com-
plex and Titakakila complex, which are base-
ment rocks of the Peninsular terrane (Dettelman
and Reed, 1980) and contain a significant pro-
portion of Paleozoic and Precambrian zircons
(Atm et al., 2007a, 2007b). The detrital zircon
sample from the Nutzotin Mountains sequence
also contains 8% early Paleozoic zircons (Fig.
4), which match well with the age of Ordovic-
ian to Silurian plutonic rocks and interbedded
volcanic rocks of the Karheen Formation in the
Alexender terrane (Gehrels, 1992). The ages
are also present in detrital zircon samples from
Paleozoic rocks of the Alexander terrane (Geh-
rels et al., 1996).

The presence of the 135–175 Ma zircon pop-
ulation in the units of the southern belt (Fig. 3)
suggests that this age range may be a signature of the sedimentary units shed from the Wrangellia composite terrane. In addition to the detrital zircon distributions presented herein, there are other Jurassic to Cretaceous sedimentary units shed from the Wrangellia composite terrane that contain detrital zircons and igneous clasts that fall in this age range. The undivided Tuxedni and Chinitna Formations, in the Talkeetna Mountains, contain detrital zircons ranging in age from 160 to 190 Ma (Amato et al., 2007b). The Upper Jurassic Naknek Formation on the southern margin of the Peninsular terrane contains plutonic clasts that range in age from 157 to 168 Ma (Trop et al., 2005). In the Yukon, the Dezadeash Formation, considered a distal equivalent to the Nutzotin Mountains sequence, contains 144–149 Ma detrital zircon ages (Lowey, 2006) and 149 Ma volcaniclastic rock interbeds (Lowey, 2011). In the Nutzotin Mountains sequence, Manuszak et al. (2007) dated zircons in granitic clasts ranging from 148 to 159 Ma. The conglomerate of the Gravina-Nutzotin belt in southern southeast Alaska also contains 154–158 Ma granitic clasts (Rubin and Saleeby, 1991b). The 135–175 Ma zircon population found in sedimentary rocks that were derived from the Wrangellia composite terrane reflects the ages expected from erosion of the plutons intruding the Peninsular terrane or from the Chitina arc and coeval plutonic rocks, and it defines a distinctive age range that can be used for identifying sedimentary rocks sourced from the Wrangellia composite terrane.

The similarity of age and provenance of the Lower Cretaceous units of the southern belt to the Gravina-Nutzotin belt of southeast Alaska (Fig. 5) suggests that they may be a continuation of the Gravina-Nutzotin belt of Berg et al. (1972). Previous researchers’ suggested that the flysch of the Clearwater Mountains may be correlative to the Gravina-Nutzotin belt (Stout, 1976; Csejtey et al., 1978, 1992; Smith et al., 1988; Klime et al., 1990). The Gravina-Nutzotin sequence in southeast Alaska is similar to the southern flysch belt in that it contains the dominant 135–175 Ma detrital zircon population, but it is different in that it contains a significant proportion (41%) of Paleozoic and older zircons (Fig. 5; Gehrels and Kapp, 1998; Gehrels, 2001). Gehrels (2001) and Gehrels and Kapp (1998) suggested that these older detrital zircons were derived from the Alexander terrane and the Yukon-Tanana terrane. Specifically, they suggested that the Late Devonian to Mississippian zircons were shed from the Yukon-Tanana terrane, because igneous rocks of this age are uncommon in the Wrangellia composite terrane. Although uncommon, igneous rocks of this age are found in the Alexander terrane and southern portions of the Wrangellia terrane. In the Alexander terrane, the Middle Devonian Freshwater Bay Formation and Upper Devonian Port Refugio Formation are volcanic sequences that could have produced zircons of this age. In fact, the Pennsylvanian Klawan Formation (of the Alexander terrane) contains four detrital zircons with ages between 357 and 375 Ma that are less than 20% discordant. Of the 13 zircon ages reported, 12 are less than 20% discordant, so the four Late Devonian detrital zircons make up 33% of the concordant zircons from the unit (Gehrels et al., 1996). In addition, the Sicker Group, which is basement to the Wrangellia terrane on Vancouver Island in Canada, also contains igneous rocks that produced 360–395 Ma U/Pb age zircons (Brandon et al., 1986; Parrish and McNicoll, 1992). A greater proportion of Paleozoic and older zircons is expected in the Gravina-Nutzotin belt of southeast Alaska, because the Alexander terrane contains older rocks than the rest of the Wrangellia composite terrane and the older sedimentary rocks contain detrital zircons of this age (Gehrels et al., 1996).

We suggest that the Paleozoic and older zircons have possible sources in the Wrangellia composite terrane, so that it is not necessary to call upon the Yukon-Tanana terrane for a source of these detrital zircons.

Provenance Interpretation of the Northern Flysch Belt

Provenance indicators suggest that the northern flysch belt was derived from the rocks of the paleo-Alaskan margin. Paleocurrent directions show that the Kuskokwim Group and Kahlitna flysch were derived from the northeast, north, and west (Fig. 1). The units contain conglomerate clasts similar in composition and age to rocks of the Yukon-Tanana terrane and Farewell terrane (Csejtey et al., 1992; Eastham and Ridgway, 2002; Ridgway et al., 2002; Kalbas, 2006; Kalbas et al., 2007; Patton et al., 2009). Point counts show that the sandstone samples contain abundant quartz and lithic grains and plot in the recycled orogen and arc provenance zones (Fig. 3). These data are consistent with derivation from the predominantly metamorphic and sedimentary rocks of the Yukon-Tanana terrane and Farewell terranes mixed with the adjacent and underlying volcanic rocks of the McKinley, Chulitna, Susitna, and Mystic terranes.

The Kuskokwim Group and Kahlitna flysch detrital zircon age distributions are similar and contain a wide assortment of ages that match well with the expected ages from terranes making up the paleo-Alaskan margin. High similarity and overlap coefficients (0.76 and 0.82 respectively; Table 1) suggest these two units were derived from a similar source. They both contain a significant 90–145 Ma population, a prominent 160–250 Ma population, a 330–440 Ma population, and a wide span of Proterozoic zircons, all of which match the age of paleo-Alaskan margin igneous sources (Figs. 5 and 6). The 90–145 Ma populations of detrital zircons in the Kahlitna flysch and Kuskokwim Group match the age of regional metamorphism and magmatism in the Yukon-Tanana terrane and western Alaska terranes that occurred from 85 to 135 Ma (Aleinikoff, 1984; Wilson et al., 1985; Nokleberg et al., 1992; Foster et al., 1994; Hansen and Dusel-Bacon, 1998; Dusel-Bacon et al., 1995, 2002, 2003; Day et al., 2003), and the Early Cretaceous plutonic rocks in the Nyac and Ruby terranes (Wilson et al., 2008; Patton et al., 2009). The 160–250 Ma detrital zircon ages (Fig. 5) could have been derived from the Upper Triassic to Lower Jurassic volcanic and volcaniclastic rocks found in the Mystic, Chulitna, McKinley, West Fork, and Susitna terranes; however, no reliable radiometric ages have been determined for these rocks (e.g., Clautice et al., 2001). They also could have been derived from the Late Triassic to Early Jurassic igneous rocks in the eastern Yukon-Tanana terrane (Werdon et al., 2001; Dusel-Bacon et al., 2002; Szumigala et al., 2002). The 330–390 Ma detrital zircons match Devonian to Mississippian U/Pb zircon ages from meta-igneous rocks of the Yukon-Tanana terrane (Fig. 5; Dusel-Bacon et al., 2006; Dusel-Bacon and Williams, 2009). The Precambrian ages match with the detrital zircon age populations found in the Yukon-Tanana, Farewell, and Ruby terranes (Fig. 6; Bradley et al., 2007; Nelson and Gehrels, 2007; Dusel-Bacon and Williams, 2009). A detrital zircon sample from the southwestern portion of the Ruby terrane (Bradley et al., 2007) contains a wide distribution of zircons yielding ages between 1000 and 2000 Ma, similar to the Kuskokwim Group distribution (Fig. 6). The Triassic and older detrital zircon populations in the Kuskokwim Group and Kahlitna flysch match well with detrital zircon ages in the Mystic subterrane and Chulitna terrane (Figs. 5 and 6). Detrital zircon age distributions for the Chulitna terrane and Mystic subterrane are very similar to each other (Figs. 5 and 6; Hampton et al., 2005, 2007a; Bradley et al., 2007; Malkowski, 2010). Comparison of the pre-Triassic detrital zircon ages from the Kahlitna flysch with the detrital zircon ages from the Mystic subterrane results in high similarity (0.80) and overlap (0.84) coefficients. The generally younger Kuskokwim Group contains a higher proportion of Precambrian zircons (49%) relative to the Kahlitna flysch (17%), which suggests either: (1) the more western source area for the Kuskokwim Group
contains a higher proportion of older rocks; or (2) the older rocks of central Alaska were exposed more during deposition of the younger Kuskokwim Group.

**Discrete Provenance versus Mixed Provenance**

Although the provenance indicators in the two flysch belts can be matched to rocks on their respective sides, there are some similarities between the two belts. For example, the lower Kuskokwim River sequence and the lower flysch of the Tordrillo Mountains contain latest Triassic to Early Jurassic detrital zircons that overlap in part with detrital zircon populations in the flysch of the northern belt (Fig. 5). However, the northern flysch belt contains more Late Triassic zircons, which may reflect the generally older age of the volcanic rocks in the Chulitna, Mystic, McKinley, Susitna, and West Fork terranes, whereas the lower Kuskokwim River sequence and lower flysch of the Tordrillo Mountains contain only a few latest Triassic detrital zircons, which match well with the age of the latest Triassic to Early Jurassic plutons of the Peninsula terrane (Fig. 5). The mid-Cretaceous and Late Cretaceous detrital zircon populations in the upper Kuskokwim River sequence and upper flysch of the Tordrillo Mountains overlap the youngest detrital zircon population in the northern belt (Fig. 5); however, the mid-Cretaceous age range is a nonunique age, because there are similar age rocks in both the Wrangellia composite terrane and the paleo-Alaskan margin.

Numerous workers have proposed that the Wrangellia composite terrane started accreting to the paleo-Alaskan margin in the Late Jurassic and that during a protracted accretion, last up to 100 m.y., sediment in an intervening basin was derived from both the paleo-Alaskan margin and the Wrangellia composite terrane (Ridgway et al., 2002; Eastham and Ridgway, 2002; Kalbas et al., 2007; Hampton et al., 2007b, 2010; Trop and Ridgway, 2007). For example, Hampton et al. (2007b) suggested that the volcanic grains and Mesozoic detrital zircons in the Kahlita flysch of the northern Talkeetna Mountains were derived from the arc portions of the Wrangellia composite terrane. However, as discussed earlier herein, the detrital zircon age populations in the Kahlita flysch match age ranges of Mesozoic igneous rocks that made up the paleo-Alaskan margin, so it is not necessary to call upon the Wrangellia composite terrane as a source of these zircons. Also, the Kahlita flysch locally overlies or is adjacent to the volcanic-rich Chulitna, Mystic, McKinley, Susitna, and West Fork terranes (Fig. 1), so the paleo-Alaskan margin contained widespread sources of volcanic detritus. Overall, the Kahlita flysch is quartz rich and contains variable proportions of sedimentary and volcanic lithic grains (Fig. 3), which are consistent with derivation from the pericratonic and volcanic terranes that made up the paleo-Alaskan margin.

The differences between the northern and southern belts are greater than their similarities (Fig. 5): (1) The northern units contain significant proportions of Paleozoic and Precambrian zircons (29%–66%) that are minor in the southern units (0%–7%). (2) The predominant population with 135–175 Ma detrital zircon ages in the southern belt is insignificant in the northern belt (Fig. 5). (3) The similarity and overlap coefficients between the northern belt and southern belt are very low (0.14–0.62 and 0.06–0.46, respectively; Table 1). (4) The southern belt is dominated by plagioclase and lithic volcanic grains as compared to the northern belt, which is dominated by quartz and mixed lithic grains (Fig. 3). These differences support the hypothesis that the two flysch belts were derived from different sources.

A third interpretation is that the Lower Cretaceous units of the southern belt (Fig. 2) are overlain by the generally younger flysch units of the northern belt. However, nowhere has it been demonstrated that the flysch of the northern belt overlies flysch of the southern belt, and, so far, the only documented contact between the northern and southern belts is along the Chilchitna fault (Fig. 1; Wallace et al., 1989). Also, the Late Cretaceous detrital zircon samples from the Kuskokwim River sequence and the flysch of the Tordrillo Mountains do not contain significant proportions of the Paleozoic and Precambrian zircons that are present in the Kuskokwim Group and the Kahlita flysch (Figs. 4, 5, and 6). If accretion of the Wrangellia composite terrane lasted up to 100 m.y., then there should be abundant syndepositional compressional structures (e.g., growth strata) in the intervening flysch beds. No structures of this type have yet been reported. In fact, as outlined next, deformation of the flysch units along the margin is constrained to the Late Cretaceous.

**Northern Boundary of the Wrangellia Composite Terrane**

Structural and geophysical data suggest that a major tectonic boundary lies between the two flysch belts, and deformation is constrained to the Late Cretaceous. In the Lake Clark region, Bedrosian et al. (2010) modeled a first-order, sinuous, north-dipping discontinuity along the Chilchitna fault (Fig. 1). The Chilchitna fault is coincident with a change from high aeromagnetic intensities on the south, which Saltus et al. (2007) called the southern Alaska aeromagnetic high, to weakly magnetic rocks on the north, which Saltus et al. (2007) called the western southern Alaska magnetic trough (Fig. 7). These geophysical data, in conjunction with the provenance differences between the Kuskokwim Group and the Koksetna River sequence, suggest that the northern boundary of the Wrangellia composite terrane is coincident with the Chilchitna fault.

Structural and stratigraphic relationships constrain the timing of deformation along Chilchitna fault to Late Cretaceous time. The fold axes in both the Kuskokwim Group and the Koksetna River sequence are oriented parallel to the Chilchitna fault (Eakins et al., 1978), which suggests that they were folded during the faulting event (Wallace et al., 1989). Folding of the units and the motion of the Chilchitna fault are constrained to the Late Cretaceous, because along the fault both the Kuskokwim Group and the Koksetna River sequence contain Upper Cretaceous strata (Fig. 2), and Paleocene to Eocene (Thrupp and Coe, 1986) volcanic rocks unconformably overlie both units (Eakins et al., 1978).

Along the Skwentna River (near sample H2 in Fig. 1), Solle et al. (1991) recognized an extensive shear zone. The detrital zircon data and sandstone framework grains from the Kahlita flysch on the north side of this shear zone are different from the detrital zircon distributions from the flysch of the Tordrillo Mountains south of the shear zone (Fig. 5; Table 1). The strata in the area are steeply dipping, and both the Kahlita flysch and the flysch of the Tordrillo Mountains contain Upper Cretaceous strata in the Skwentna area (Fig. 2), so the timing of deformation is constrained to the Late Cretaceous. There is also an abrupt change in geophysical character in this area that is continuous with the Chilchitna fault and continues to the northeast into the Talkeetna Mountains (Fig. 7).

In the northern Talkeetna Mountains, Glen et al. (2007) presented gravity, aeromagnetic, and magnetotelluric modeling that suggested there is a deep, first-order crustal discontinuity, which they called the Talkeetna suture zone. Using receiver functions, Brennan et al. (2011) modeled a sharp transition in the depth of the Moho coincident with the Talkeetna suture zone of Glen et al. (2007). They found that the depth of the crust in the southern Alaska Range and the northern Talkeetna Mountains (35–40 km) is significantly greater than the depth of the crust south of the Talkeetna suture zone (28–31 km). However, identification of the surface expression of this suture zone has been elusive; for
Flysch provenance and the accretion of the Wrangellia composite terrane, Alaska | RESEARCH

example, Glen et al. (2007, p. 37) stated that “no one structure at the surface is continuous with the deep crustal break.” The aeromagnetic map of south-central Alaska shows the change in aeromagnetic intensities that occurs in the Clearwater Mountains (Fig. 7).

The differences between the provenance indicators of the Kahiltna flysch and the flysch of the Clearwater Mountains (Figs. 3, 5, and 6) suggest that the northern boundary of the Wrangellia composite terrane lies between these units (Fig. 1). Although the precise location of the northern boundary of the Wrangellia composite terrane in the Talkeetna Mountains is not clear, some previously proposed locations can be ruled out. Next, we list some of the proposed candidates that may or may not be the surface expression of the Talkeetna suture zone.

**Serpentinized Rocks and Mélange**

The Broad Pass area contains serpentinized rocks and mélangé, which led Eastham and Ridgway (2001) and Roeske et al. (2005) to postulate that it may be the location of a suture zone. However, detrital zircon age distributions for the Kahiltna flysch are similar on both sides of Broad Pass (Hampton et al., 2010). In addition, Hampton et al. (2009) suggested that the rocks of the Susitna terrane south of Broad Pass are lithologically similar to the rocks of the Chulitna terrane north of Broad Pass. The pre-Triassic detrital zircon distributions from the Kahiltna flysch (both north and south of Broad Pass) are very similar to the underlying Chulitna and Mystic terranes (Figs. 5 and 6), suggesting they were the sources of detrital zircons to the Kahiltna flysch. In addition, there is no significant intensity gradient of the aeromagnetic character along Broad Pass (Fig. 7). Based on this evidence, it is not likely that the Broad Pass area is the northern boundary of the Wrangellia composite terrane.

**The Talkeetna Fault**

This fault in the Clearwater Mountains (Fig. 1) was originally thought to be a major suture between the Wrangellia composite terrane and the paleo-Alaskan margin (Csejty et al., 1978, 1982, 1992; Coney et al., 1981). However, Smith (1981) mapped the flysch of the Clearwater Mountains north and south of the Talkeetna fault and depositionally overlying the rocks of the Wrangellia terrane. In addition, the flysch of the Clearwater Mountains contains clast compositions and detrital zircons.
that match the Wrangellia terrane (Fig. 5; Eastham and Ridgway, 2002; Hampton et al., 2010; Mooney, 2010). Based on this evidence, it appears that the Talkeetna fault has only modest offset and is not the northern boundary of the Wrangellia composite terrane.

The Valdez Creek Shear Zone

This shear zone (Fig. 1; Davidson et al., 1992) is a likely candidate for the northern boundary of the Wrangellia composite terrane. The flysch of the Clearwater Mountains overlies and was derived from the rocks of the Wrangellia terrane, so the boundary of the Wrangellia composite terrane must lie to the north of the unit. The Valdez Creek shear zone has a reverse metamorphic gradient, placing amphibolite-facies gneissic rocks on the north over lower-greenschist-facies rocks of the flysch of the Clearwater Mountains on the south (Davidson et al., 1992). Along the shear zone, Davidson et al. (1992) described a steeply to moderately dipping foliation with near-vertical lineations, and a syntectonic intrusion of a Late Cretaceous tonalite sill. U/Pb and Ar/Ar geochronology and geologic relationships along the Valdez Creek shear zone suggest that metamorphism occurred in the Late Cretaceous (Conen et al., 1981; Ridgway et al., 2002). The fold axes and metamorphic fabrics affecting the flysch of the Clearwater Mountains are parallel with the metamorphic fabrics in the Valdez Creek shear zone (Smith, 1981; Davidson et al., 1992). Davidson et al. (1992) and Davidson and McPhillips (2007) suggested that deformation of the flysch of the Clearwater Mountains was coeval with the accretion of the Wrangellia composite terrane in the Late Cretaceous.

However, detrital zircon and εNd isotope data presented by Huff et al. (2011) suggest that the northern boundary of the Wrangellia composite terrane may lie north of the Valdez Creek shear zone, or has been displaced by subsequent faulting. They reported detrital zircon data from metamorphosed strata in the Alaska Range north of the McKinley strand of the Denali fault system that are mapped as thrust over Devonian metamorphic rocks of the Yukon-Tanana terrane (Csejtey et al., 1992). The detrital zircon ages fall primarily in two populations 140–153 Ma and 190–220 Ma, and contain some Paleozoic and Precambrian zircons. They also presented εNd isotope values for the detrital zircons for their sample in the Alaska Range and a sample from the flysch of the Clearwater Mountains. They suggested that the high values (+8 to +12) for the 140–153 Ma detrital zircons indicate the zircons were derived from a juvenile source, such as the plutons of the Chitina arc. The 190–220 Ma zircons from the Alaska Range sample had a wider range of εNd values (−4 to +12.8). The presence of lower εNd values led them to suggest that the age and isotopic composition “are incompatible with a sole derivation from outboard terranes...” (Huff et al., 2011, p. 552). However, the two age ranges reported are the same age ranges in the lower Koksetna River sequence and the lower flysch of the Tordrillo Mountains (Fig. 3). The 190–220 age range is found in flysch units on the north and the south (Fig. 5), so it is not an age range exclusive to northern or southern sources. The low εNd values for the zircons in the 190–220 age range are suggestive of an evolved magmatic source or magma that incorporated older crustal sources, which led them to suggest the Yukon-Tanana terrane was the source of the zircons. However, Rioux et al. (2007) found that the plutons of the Peninsular terrane contain inherited zircons, and the ca. 190 Ma plutons in the Talkeetna Mountains contain lower εNd values (4.0–5.5) and 87Sr/86Sr ratios between 0.703656 and 0.706252, which they interpreted to represent assimilation of older crustal material. Also, as demonstrated already, the 140–153 Ma population is a distinct feature of flysch units derived from the Wrangellia composite terrane. We suggest that these strata may represent a faulted sliver of Wrangellia composite terrane–derived flysch that was displaced during thrusting associated with accretion or later strike-slip faulting.

We suggest that the evidence for a Late Cretaceous deformation event along the northern boundary of the Wrangellia composite terrane and the lack of a distinct provenance link between the Wrangellia composite terrane and the paleo-Alaskan margin are consistent with derivation from the terranes of the Wrangellia composite terrane. We suggest that the Valdez Creek shear zone extends from southwest Alaska through the Talkeetna Mountains to southeast Alaska.

In contrast, the provenance data from the Kuskokwim Group and Kahiltna flysch suggest that they were derived from the terranes making up the paleo-Alaskan margin. The units overlie rocks of the paleo-Alaskan margin, contain clasts that match the rocks of the paleo-Alaskan margin, and have provenance indicators that are consistent with derivation from the terranes of the paleo-Alaskan margin. Detrital zircon age populations in both units match with igneous and metamorphic sources in the terranes of the paleo-Alaskan margin. Pre-Triassic detrital zircon age distributions from these units are very similar to the detrital zircon distributions from the Mystic and Chulitna terranes. The Kahiltna flysch and Kuskokwim Group detrital zircon distributions are very similar, suggesting they were derived from a similar source. The detrital zircon age distributions for units overlying the paleo-Alaskan margin do not contain the distinctive 135–175 Ma population found in the southern flysch belt.

The provenances of the northern and southern flysch belts match rocks on their respective sides. As such, there is no unambiguous provenance relationship between the two belts. The boundary between the two flysch belts is coincident with a large, deep geophysical gradient. The southwestern part of this geophysical gradient is coincident with the Chilchita fault. It continues to the northeast through the Susitna Basin and traverses through the Talkeetna Mountains, where the geophysical gradient is called the Talkeetna suture zone. The surface expression of the Talkeetna suture zone is not clear, but it most likely lies between the northern Talkeetna Mountains and the Clearwater Mountains. The lack of

CONCLUSIONS

Provenance data for the southern flysch belt suggest that it was derived from rocks of the Wrangellia composite terrane. The sedimentary rocks contain conglomerate clast types and detrital zircon ages that are attributed to the Wrangellia composite terrane. All the units contain a distinctive 135–175 Ma population of detrital zircons, matching the age of the Chitina arc in the Wrangellia terrane and the Middle to Late Jurassic plutons in the Peninsular terrane. Also, most of the Lower Cretaceous units contain interbedded volcanic rocks, suggesting deposition proximal to the active Chitina arc and coeval igneous rocks. The detrital zircon age distributions differ along the boundary, but the differences reflect changes along strike of the three underlying terranes that make up the Wrangellia composite terrane. The flysch units form a coeval and nearly continuous belt that extends from southwest Alaska through the Talkeetna Mountains to southeast Alaska.
a provenance link in the Jurassic to Cretaceous flysch between the Wrangellia composite terrane and the paleo-Alaskan margin, geophysical evidence of a major crustal boundary, and evidence for a Late Cretaceous deformation event along the northern boundary of the Wrangellia composite terrane are consistent with arrival of the Wrangellia composite terrane to the paleo-Alaskan margin in the Late Cretaceous.

ACKNOWLEDGMENTS

The authors want to thank the following reviewers for the thoughtful and detailed suggestions and comments on this and earlier versions of the manuscript: Darrel Cowan, Robert Blodgett, Dwight Bradley, George Gehrels, Marti Miller, Ken Ridgway, Jeff Trop, and two anonymous reviewers. Although some of the reviewers did not agree with the conclusions presented in this manuscript, we appreciated their objective and constructive reviews. Initial funding for this project was provided by the Alaska Division of Geological and Geophysical Surveys as the result of a collaborative mapping project with the lead author.

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MANUSCRIPT RECEIVED 19 JULY 2013
REvised MANUSCRIPT RECEIVED 12 OCTOBER 2013
MANUSCRIPT ACCEPTED 4 NOVEMBER 2013
Printed in the USA