Evolving heavy mineral assemblages reveal changing exhumation and trench tectonics in the Mesozoic Chugach accretionary complex, south-central Alaska

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ABSTRACT

The Gulf of Alaska is one of the largest accretionary complexes on Earth. In this study, we examined the earliest phase of accretion in the Mesozoic McHugh Complex and Valdez Groups, exposed in SE Alaska. The oldest preserved fragment, the Mesomélange assemblage, is Jurassic (ca. 160–140 Ma) and consists of an ~3-km-thick structural package of strongly deformed shaley materials with slices of oceancic shales and basalts. Heavy minerals indicate dominant erosion from a magmatic arc source uplifted after the collision of the Wrangellia and the Talkeetna oceanic arc. A tectonic erosion event affected the forearc just prior to ca. 120 Ma and was likely caused by seamount collision, ridge subduction, or both. This was followed at 105 Ma by mass wasting of sandstone and conglomerates, preserved as the Graywacke-Conglomerate assemblage (ca. 105–83 Ma). Heavy minerals indicate continued flux from arc sources, but with significant changes suggesting a larger, more diverse catchment area. Erosion of deeper crustal sources provided high-Mg diopside and garnets to the area. Erosion of deeper crustal sources provided high-Mg diopside and garnets to the area. Erosion and mass loss (von Huene and Lallemand, 1990; Ranero and von Huene, 2000) but it is less well understood why and how subduction margins begin to accrete (Demétrio et al., 2010). In this study, we examined the earliest accretionary history of the modern Gulf of Alaska. This is one of the largest accretionary complexes on Earth and appears to have been in a state of long-term crustal construction since the Jurassic (Plafker et al., 1994; Amato and Pavlis, 2010). This growth followed a period of tectonic erosion along the southern edge of the Peninsula terrane, which now forms the backstop to the modern accretionary prism (Clift et al., 2005).

In this study, we examined a particularly well-exposed and continuous section of the oldest part of the accretionary body, known as the McHugh Complex, as well as the succeeding Valdez Group. We document the nature of the sedimentology and structural transitions between the different groups and the mineralogy of the sandstones in order to constrain the source of the sediment reaching the trench at any given time. Our working hypothesis was that the switch from erosion to subduction accretion reflected an increase in sediment supply to the trench starting in the Late Jurassic and that this in turn was related to uplift and erosion of source regions onshore caused by accretion of the arc to North America.

INTRODUCTION

Accretionary continental plate margins are believed to be the primary locations where new Phanerozoic crust has been constructed, and although most of that construction has been in the form of magmatism, the accretion of sediments and oceanic volcanic rocks to some plate margins also plays a role in crustal construction (Condie, 2007; Scholl and von Huene, 2007; Cawood et al., 2009; Clift et al., 2009).

The factors that control whether a continental margin experiences long-term accretion or tectonic erosion and mass loss are complex, but it has been recognized that subduction zones where trench sediment thicknesses exceed ~1 km and regions of slower convergence tend to favor development of large-scale accretionary wedges (von Huene and Scholl, 1991; Clift and Vannucchi, 2004). Collisions of seamounts and ridges with trenches are well known to drive tectonic erosion and mass loss (von Huene and Lallemand, 1990; Ranero and von Huene, 2000), but it is less well understood why and how subduction margins begin to accrete (Demétrio et al., 2010). In this study, we examined the earliest accretionary history of the modern Gulf of Alaska. This is one of the largest accretionary complexes on Earth and appears to have been in a state of long-term crustal construction since the Jurassic (Plafker et al., 1994; Amato and Pavlis, 2010). This growth followed a period of tectonic erosion along the southern edge of the Peninsula terrane, which now forms the backstop to the modern accretionary prism (Clift et al., 2005).

GEOLOGICAL SETTING

The McHugh Complex is exposed in SE Alaska and forms the oldest part of the Chugach accretionary terrane, which is the most landward of the tectonic blocks accreted to NW North America since the Late Cretaceous, being succeeded by the Prince William and Yakutat terranes going trenchward (Fig. 1). The McHugh Complex lies south of the Wrangellia-Penin- sular terrane, which is a composite tectonic block (Plafker et al., 1989). The McHugh Complex is directly juxtaposed with the Jurassic Talkeetna Complex, interpreted as an ocean-island arc (DeBarl and Coleman, 1989; Plafker et al., 1994; Greene et al., 2006). The contact between these two blocks is a major fault, known as the Border Ranges fault, which has most recently been active as a high-angle, dextral, strike-slip fault, with several hundred kilometers of offset (Pavlis, 1982; Roeske et al., 2003; Pavlis and Roeske, 2007). In the region of Anchorage, the McHugh Complex is ~35 km in width across strike, compared to ~320 km distance across the entire accretionary wedge.

The McHugh Complex is bounded to the southeast by the Valdez Group across the Eagle River fault, which is a low-angle thrust (Fig. 1B; Clark, 1973; Winkler, 1992). The Valdez Group is an Upper Cretaceous sedimentary sequence...
exposed through much of the eastern part of the Kenai Peninsula and Kodiak Island (Fig. 1). The Valdez Group is interpreted as having been deposed by a system of submarine fans that received sediment derived from active magmatic arcs and an exhumed arc batholith (Nilsen and Zuffa, 1982). This sediment was deposited into and beyond the paleo–Alaskan Trench and was subsequently accreted onto the Alaskan margin by Eocene time (Dumoulin, 1987; Plafker et al., 1989). The Valdez Group is composed of deformed turbidite sandstones and slates that are generally considered to have been offscraped from the subducting plate to form a structural prism at the base of the forearc wedge. The low metamorphic grade does not support this unit or the McHugh Complex having been underthrust deep under the forearc before reexhumation, although some burial has occurred. The moderate degree of deformation of the Valdez Group compared with the oldest parts of the accretionary complex precludes formation along the subduction channel for much of the complex. Only sparse fossil data exist to constrain the maximum depositional age of the Valdez Group (Plafker and Berg, 1994), but recent zircon dating now indicates a maximum age of 85 Ma, continuing until at least 68 Ma (Kochelek et al., 2011).

TECTORIC HISTORY

The Talkeetna Arc appears to be the backstop against which the Chugach accretionary prism was offscraped. The Talkeetna Arc does not have any known basement of either continental or oceanic character that predates subduction (Pavlis et al., 1988), but this block became accreted to the rest of the Wrangellia terrane around 160 Ma (Clift et al., 2005; Rioux et al., 2007). Conversely, observations in southern Canada along the inboard margin of Wrangellia have been interpreted in terms of a Middle Jurassic collision of Wrangellia with North America (Plafker et al., 1994).

The active continental margin experienced a number of tectonic events before the onset of McHugh accretion. A major change in tectonic regime in the Talkeetna Arc is shown by the cessation of magmatism, tilting of the section, and erosion and deposition of the Upper Jurassic Taxedni Formation, followed by the more conglomeratic Naknek Formation within basins overlying the arc (Trop et al., 2002). This series of events is interpreted to reflect collision of the backarc northern side of the Talkeetna Arc with the south-facing active margin of the Wrangellia-Peninsular terrane. However, at this stage, the entire assemblage was still remote from North America, as shown by evidence for a Late Jurassic to late Early Cretaceous (ca. 110–105 Ma) “Gravina-Kahiltna Ocean” between the Wrangellia-Peninsular and Yukon composite terranes (van der Heyden, 1992; Trop and Ridgway, 2007). Conversely, observations in southern Canada along the inboard margin of Wrangellia have been interpreted in terms of a Middle Jurassic collision of Wrangellia with North America, followed by a backarc opening in the Late Jurassic (van der Heyden, 1992). In any case, there is widespread agreement that
a Late Jurassic to Early Cretaceous ocean, the Gravina-Kahiltna Ocean, separated the Wrangellia composite terrane from North America, and this ocean basin did not close until Middle Cretaceous time (Trop and Ridgway, 2007).

Other Mesozoic arc terranes are known from SE Alaska and may have provided sediment to the McHugh Complex. The Chitina Arc was active mainly in the Late Jurassic and spans the margin of the northern Wrangellia and Alexander terranes (Plafker et al., 1989; Trop et al., 2002, 2005). The Chisana Arc was active in Early Cretaceous time and is also located on the margins of the Alexander and Wrangellia terranes (Berg et al., 1972; Trop et al., 2002). Because of the significant margin-parallel tectonic displacements, it is necessary to consider possible sediment sources along strike to the SE when identifying the origin of sediment deposited into the paleo–Alaskan Trench. The Coast Mountains Batholith, located in southeastern Alaska and southwestern British Columbia (Fig. 1A), is a Middle Jurassic to Eocene body interpreted to have likely contributed sediment to the paleotrench from the Middle Jurassic to Paleocene (Dumoulin, 1988; Monger et al., 1994; Gehrels et al., 2009). Not all the eroded arc material was delivered to the trench axis, and some is preserved in the Mesozoic forearc in the Matanuska Valley–Talkeetna Mountains Basin (Trop and Ridgway, 2007; Trop, 2008).

Subduction accretion is believed to have commenced between 157 and 146 Ma based on the age of detrital zircon sand grains extracted from the oldest parts of the McHugh Complex close to Anchorage (Amato and Pavlis, 2010). This age shortly postdates accretion of Talkeetna to Wrangellia, but predates the closure of the Gravina-Kahiltna Ocean, ca. 105 Ma. The start of accretion is also somewhat younger than Early Jurassic blueschists exposed along the Border Ranges Fault (e.g., 185–179 Ma and 204–190 Ma, respectively, for Iceberg Lake schists near Talkeetna and Raspberry schists of Kodiak Island; Sisson and Onstott, 1986; Roeske et al., 1989; Bradley et al., 1999). Although these older ages suggest an earlier onset to accretion, these have been interpreted to represent subduction and recycling of small volumes of material within a subduction channel prior to the start of large-scale permanent accretion (Clift et al., 2005).

In this study, we follow the division of the McHugh Complex into a Jurassic–Early Cretaceous “Mesomélange” assemblage and a Cretaceous “Graywacke-Conglomerate” assemblage, as defined by Amato and Pavlis (2010), on the basis of their character at exposures and established differences in the U-Pb age of zircon grains. There is a distinct separation in the U-Pb ages of detrital zircons between the two McHugh Complex assemblages, with a period of forearc magmatic activity (ca. 125 Ma) separating the units in time. This gap in zircon ages suggests an Early Cretaceous subduction erosion event probably driven by a ridge subduction event (Amato and Pavlis, 2010). Kochelek et al. (2011) performed U-Pb dating of detrital zircons from the Valdez Group and demonstrated that there is no significant time gap between the sedimentation of the Valdez Group and the adjacent Graywacke-Conglomerate assemblage. They interpreted the onset of accretion of the Valdez Group as representing the filling of the paleotrench and sedimentation on the abyssal seafloor.

METHODS

The sedimentary rocks of the McHugh Complex and adjacent Valdez Group were described at outcrop and examined in microscope thin section in order to determine their mode of sedimentation and origin of the sediment particles. Our main focus was a series of outcrops along the northern coast of Turnagain Arm, east of Anchorage (Figs. 1B and 2). This was done because of the readily accessible road cuts and nearby shore outcrops that provide semi-continuous exposure across the entire width of the McHugh Complex along Route 1, Seward Highway. This allowed the structural boundaries between the different units to be documented. Samples were taken at representative outcrops along this section and at additional locations along strike in Seldovia to the south and on the Knik River and Eklutna to the north (Fig. 1B). This was done in order to test the degree of lateral homogeneity in the units. A list of the sampled locations and their coordinates is provided in Table DR1 (see GSA Data Repository).

In order to better define the provenance of sediment in the accretionary wedge, we conducted a heavy mineral study, because these phases have an established record of being able to resolve erosion from contrasting source regions based on the premise that heavy minerals from the source bedrock are transferred to the sediments and are not destroyed during sediment transport (Morton, 1985; Prestdon et al., 1998; Mange and Morton, 2007). Moreover, heavy minerals have an established track record in arc and convergent margin settings, not only in active systems but also in older sequences that have been affected by low-grade metamorphism (Cawood, 1991a). Composition of mineral phases is directly related to the composition of the host rocks, and thus is a function of the exposed convergent plate-margin magmatic series.

While we recognize that burial and diagenesis may result in the chemical breakdown of some minerals, the metamorphic grades of the McHugh Complex and Valdez Groups are similar, i.e., subgreenschist-facies, prehnite-pumpellyite assemblages throughout the study area. Both units were exhumed in two pulses starting after 20 and 11 Ma (Spotila et al., 2004; Enkelmann et al., 2008; McAleer et al., 2009). As a result, any diagenetic changes should have equally affected both the McHugh Complex and Valdez Group so that systematic differences between the heavy mineral assemblages can be interpreted to reflect changes in source rather than postdepositional changes. The metamorphism has resulted in common alteration offeldspars and the total loss of all volcanic glass. Cawood (1991a) has argued from Paleozoic volcanoclastic sedimentary rock series from SE Australia that only Fe-Ti oxides, clinopyroxene, and hornblende are original in sequences with the same metamorphic grade as the McHugh Complex and that the zeolites, epidote, prehnite, and pumpellyite seen are linked to alteration of primary ferromagnesian phases.

Whole-rock samples of 5–10 kg were crushed to sand size and then sieved through a <40 mesh (<0.4 mm). Sand was separated by density on a Gemini water table, and the heavy fraction, consisting of ~10% of the total sample, was dried. Strongly magnetic grains and iron particles from grinding plates were removed with a hand magnet. Further magnetic separations were conducted with the Frantz® Magnetic Barrier Laboratory Separator Model LB-1 at New Mexico State University. Samples for this study were collected using all of the minerals that were magnetic at settings of 0.9–1.4 A. Through this process, all quartz and feldspar were removed from the sample, and although some of the high-density minerals could have been washed into the light fraction on the water table, it is more likely that these minerals are also present in the dense fraction, given the inefficiency of the water table. Other nonmagnetic, dense minerals such as zircon, barite, and apatite would not be present in the magnetic fraction and are therefore underrepresented in this study.

After mounting in epoxy and polishing using aluminum-oxide powder, the heavy minerals were analyzed for a standard suite of major elements using the JXA-733 Superprobe electron probe micro-analyzer (EPMA) at the Massachusetts Institute of Technology. Where possible >100 grains were analyzed in order to yield a statistically representative sample of the grains in each sample. The probe was equipped with

GSA Data Repository item 2012107, online supplement (Tables DR1 and DR2), is available at http://www.geosociety.org/pubs/2012.htm or by request to editing@geosociety.org.
five wavelength-dispersive spectrometers, and a JEOL (e2v/Gresham) silicon-drift energy-dispersive spectrometer. Backscattered electron (BSE) images, wavelength dispersive elemental X-ray maps, and chemical compositions of minerals were acquired using JEOL analysis software. The compositional analyses were performed using an accelerating voltage of 15 kV, a beam current of 10 nA, beam diameter of ~1 μm, and 40–60 ms counting times per element. Typical 1σ standard deviation of counts was between 0.5% and 1%. Results are provided in Table DR2 (see footnote 1). Backscatter images were generated using the ISI-ABT55 scanning electron microscope (SEM) at the University of Aberdeen with image capture using an ISS I-SCAN 2000 Digital Image Acquisition System. The SEM was operated with an accelerating voltage of 15 kV.

**STRATIGRAPHY**

The three sedimentary units considered in this project are all readily distinguished at outcrop because of their sedimentary facies and structural condition. The oldest, westernmost unit is the Mesomélange assemblage, which is exposed over ~3 km across strike along Turnagain Arm (Figs. 2 and 3). The unit is dominated by shale with a well-developed scaly cleavage. Tuffaceous fine sandstones and siltstones are interbedded within the shale, with beds typically just millimeters thick, although rarely ranging up to tens of centimeters across in the case of the thicker beds. The rock has experienced strong shearing deformation and associated stratigraphic disruption so that the sandstones are pulled apart in a series of blocks that float in the shale matrix and are easily recognized by their green-gray weathering (Fig. 4C). This rock was described as “argillite-tuff” in the earlier literature (Connelly, 1978). In addition to argillite-tuff, the Mesomélange assemblage contains numerous tectonic slices of centimeter-scale, bedded, red and black cherts together with altered, massive, basaltic lavas. At a small number of outcrops, pillow forms are present in the basalts. Even more rarely massive, light-gray, recrystallized limestone blocks up to 2 m across are described, although these account for <1% of the total outcrop observed. Figure 3 shows a typical cross section of the Mesomélange assemblage showing the subvertical sheared fabric and the slices of basalt that comprise up to ~30% of the total outcrop locally. The larger slices range up to 15 m thick, but smaller fragments of lava floating in the argillite-tuff matrix are also present. The lava is generally aphyric and weathered greenish.

The Mesomélange assemblage has a sharp boundary with the younger Graywacke-Conglomerate assemblage. Figure 5 shows that there is a rapid transition from sheared argillite-tuff with a steep NW-dipping cleavage to massive sandstones with effectively no interbedded fine-grained rocks. There is an ~18-m-thick sandstone layer at the boundary interleaved between slates, but this may be a tectonic slice rather than original interbedding. Internally, the structure of the Graywacke-Conglomerate assemblage is often hard to discern because most of the unit consists of apparently unbedded, medium- or coarse-grained sandstone cut by a series of joints, fractures, and faults (Fig. 6). Where visible, there is a preferential dip of the jointing to the NW, although faults are seen to be both high and low angle, dipping both to the NW and SE, but with a majority dipping NW. The sandstones themselves are typically massive but have a clear cleavage that penetrates the entire unit (Fig. 4D). Over long sections of outcrop, the sandstones are interbedded with conglomerates, which can comprise more than half the total exposed rock. Individual conglomerate layers are typically 2–3 m thick, but they can range up to 20 m or more. The conglomerates have sharp contacts with the sandstones, which do not show any grading toward the conglomerates against either top or bottom surfaces. The conglomerates are poorly sorted, with larger blocks floating in a coarse sandy matrix. Clasts are generally <10 cm across, but they can range up to 100 cm across. The clasts are subrounded to rounded in character and include a variety of different clast types (Figs. 4E and 4F), discussed later herein.

The Valdez Group is the youngest accretionary unit considered in this study and differs from the McHugh Complex by the general absence of stratigraphic disruption aside from narrow shear zones with deformation restricted to folding and thrust-faulting of a coherently interbedded sequence of sandstones and slates interpreted as deep-water turbidites (Fig. 4A). The sandstones are well sorted and typically graded with sharp bases. Proportions of sandstone versus shale vary, but sandstone is commonly >60%, suggestive of a relatively proximal location. Bedding is likewise quite thick, with individual sandstones >1 m and often >30 cm thick. More than 95% of the Valdez Group is either sandstone or shale, and although coarser units are present, they are rare. Figure 4B shows an example of a conglomeratic unit containing rounded cobbles of light-gray to pink feldspar-phyric volcanic rocks, suspended
Tectonics of the Chugach accretionary complex

in a coarse sandstone matrix. Nonetheless, such units are rare, and the vast majority of the clasts in conglomerate are intraformational shales that were likely locally reworked during deposition of the turbidite sandstones. The transition between the Graywacke-Conglomerate assemblage and the Valdez Group is quite sharp. After the last exposure of massive sandstone, the lithologies are seen to become much finer and shale-dominated across the Eagle River fault, but stratal disruption continues for several tens of meters structurally beneath the contact. The slates are well cleaved and dip steeply to the SE, although they overturn to dip to the NW further into the Valdez outcrop (Fig. 7). Blocks of coherent, well-sorted sandstone are common but comprise <10% of the outcrop. Locally, the noses of small folds were identified, but with the sandstones not continuous over long distances, suggestive of large amounts of bedding-parallel shear within the vicinity of the fault. Bedded, black cherts were also observed in zones 3–4 m across, but comprising <5% of the total observed outcrop. This strongly sheared contact zone is ~200 m thick, before grading into the more normal, well-bedded, and unsheared Valdez Group.

We concur with earlier work on these units in terms of depositional setting (Nilsen and Zuffa, 1982; Dumoulin, 1987). The Valdez Group is a deep-water, clastic deposit likely laid down by turbidity currents in a submarine fan setting. This contrasts with the much more massive Graywacke-Conglomerate assemblage. Ignoring the stronger deformation of the Graywacke-Conglomerate assemblage, we note that the lack of bedding or grading and the coarse grain sizes are consistent with a mass-wasting origin in a proximal setting. Debris-flow or landsliding processes are most likely responsible for the sediment preserved in this unit. The lack of slates or siltstones indicates sedimentation close to source, with the finer material presumably advected by turbidity currents or in buoyant plumes deeper into the basin.

Both these units contrast with the much more distal Mesomélange assemblage. Shale dominance and interbedded cherts point to a deep-water basin setting, although the common thin tuffs and volcanic sandstones require a volcanic source to have been located not too far distant. While some of the volcanic sediment may be air-fall tuffs, the majority was likely delivered as distal turbidites. The trench during sedimentation of the Mesomélange assemblage must have been relatively starved compared to the abundance of the coarse sediment in the Graywacke-Conglomerate assemblage. The fine-grained facies does not require that sedimentation occurred far offshore on the subducting Pacific Ocean floor, because coarser sediment could have been ponded on the Alaskan continental margin in trench slope and other forearc basins (Trop, 2008). The large coherent limestone
blocks, like the slices of lava, are exotic to the sedimentary regime. Whereas the volcanic rocks were interleaved by thrusting after sedimentation, the limestones are rarer and are interpreted to have been emplaced into the muddy sediment as olistoliths during mass-wasting events. Clearly, the source of the limestones was isolated from the volcanic sediments, and we suggest that they were deposited from collapsing carbonate-topped seamounts colliding with the trench, analogous, for example, to the Capricorn Seamount, which is presently in collision with the Tonga Trench (Ballance et al., 1989a, 1989b; Cawood, 1990). Such limestone blocks are common features in ophiolitic and subduction mélanges worldwide (Blake et al., 1988; Taira et al., 1988; Collins and Robertson, 1997). In this respect, the Mesomélange assemblage is a typical subduction zone product.

MICROSCOPIC ANALYSIS

Further clues to the origin of the paleotrench sediments can be derived from microscopic examination of sedimentary rock thin sections. The strongly sheared character of the Mesomélange assemblage is apparent at microscopic scales, where clay-rich bands cut across the silty-shale fabric that comprises the bulk of the rock (Fig. 8C). The sorting of the sediment is poor, and the individual clasts are relatively angular. No well-defined sedimentary fabric is visible beyond the cleavage. Most of the larger clasts are of a volcanic lithic character, with some fragments of volcanic rock having feldspar phenocrysts visible within the groundmass. Very common cloudy, altered plagioclase grains dominate over quartz (Fig. 8D). The Graywacke-Conglomerate assemblage shares the strongly lithic character and abundance of volcanic clasts (Figs. 8A and 8B). Again, sorting tends to be poor, and the grains are held in a clay-rich matrix, although the degree of shearing at the microscopic level is less than seen in the Mesomélange assemblage. In both units, quartz is present but not common in most samples, giving an impression of sediment that is both compositionally and texturally immature. Much of the quartz that is present is in the form of chert, and in some samples, this can be abundant. Heavy minerals are very much in the minority in both units and mostly represent optically opaque iron oxides. The Valdez Group sandstones are also poorly sorted and rich in volcanic clasts and feldspar grains. Microscopic evidence from all three units points to erosion from a nearby volcanic source terrane and a limited degree of weathering between source and sink.

We assessed the general character of both McHugh and Valdez sandstones by point counting of the bulk mineralogy using the divisions of Dickinson et al. (1983) (Fig. 9). Here, we plot data from the McHugh Complex Graywacke-Conglomerate from Worthman and Amato (2010) and from the Valdez Group from Kochekle et al. (2011). Most of the McHugh sandstone shows slightly more lithic material than the Valdez sandstone and overlaps between the “transitional arc” and “undissected arc” fields of Dickinson et al. (1983). In contrast, the Valdez sedimentary rocks plot firmly within the “transitional arc” field, indicative of erosion from a magmatic arc that has been partially exhumed and is eroding material from both the volcanic carapace and from deeper intrusions that were only starting to be exposed and eroded at the time of sedimentation. Two samples from the McHugh Complex plot toward the quartz end member, but this is because of high chert content rather than reflecting a more continental provenance. The point counting data suggest progressive exhumation of an arc terrane between McHugh and Valdez times.

Figure 4. Field photographs showing the characteristics of the sediments considered in this study. (A) Turbidite sandstones and shale from the Valdez Group close to the boundary with the McHugh Complex (sample J6). (B) Rounded cobbles of feldspar-phyric lavas and mudstone rip-up clasts in coarse sandstone debris flow, Valdez Group. (C) Typical exposure of “tuff-argillite” from the Mesomélange assemblage showing strong pull-apart deformation of the volcaniclastic silt and sandstones. (D) Coarse sandstones of the Graywacke-Conglomerate assemblage showing development of weak cleavage. (E) Conglomerates of the Graywacke-Conglomerate assemblage at Beluga Point (see Fig. 2) showing clasts of granite, lavas, and black cherts. (F) Large clasts of brown sandstone and white granites from the Graywacke-Conglomerate assemblage.
PROVENANCE OF CONGLOMERATES

The changing provenance of the McHugh and Valdez Groups can be partially constrained by looking at the composition of pebbles in conglomerates in different parts of the stratigraphy. As noted already, the range of clast types in the Mesomélange assemblage is restricted, mostly being mafic lavas, red and black cherts, ultramafic rocks, and altered volcanic sandstones with rare limestones. The Graywacke-Conglomerate assemblage shows a large change, not least in the much greater proportion of conglomerate in the sediment. The largest outcrops seen are at Beluga Point (Fig. 2), and these were described to constrain the variety of lithologies seen there. Black argillite is the most common type of clast (Fig. 10), and although there are no shale interbeds in the Graywacke-Conglomerate assemblage, this material may well have been reworked from elsewhere in the sedimentary system. Figure 10 shows the breakdown of 165 clasts counted at Beluga Point, confirming the presence of both oceanic and continental rock types (Fischietto et al., 2006). Cherts, mostly black in color, are common, as are mafic volcanic rocks, gabbros, and ultramafic clasts.

These rocks bear the most resemblance to lithologies in the Mesomélange assemblage. However, new rock types are also seen at this level, most notably brown and green sandstones, feldsparphyric volcanic rocks, and leucogranites. The green sandstones may be more volcaniclastic, but the brown sandstones and granites have more continental compositions, with significant volumes of quartz grains compared to the clasts from the Mesomélange assemblage. Moreover, the clasts of both these rock types are quite large, often >30 cm across, implying that they were deposited close to source. The rounded character of the clasts requires some transport, but in view of the grain size, this cannot be hundreds of kilometers (Paola et al., 1992). Except for a few granites in the western Chugach Mountains, such rock types are not known close to the exposures today, but this is consistent with the large-scale strike slip on the Border Ranges fault since that time.

HEAVY MINERALS

We examined the heavy mineral assemblages in a series of sandstones from all three units considered in this study. Imaging of heavy minerals with a scanning electron microscope allows the range of heavy minerals to be assessed. Erosion from igneous and higher-grade metamorphic source regions is shown by the presence of amphiboles in the sandstones of the Graywacke-Conglomerate assemblage (Fig. 11A). However, veining of the amphibole by chlorite is evidence of a lower-grade, retrograde overprint that developed as the source rock was being exhumed, or it may have developed during greenschist metamorphism of the McHugh Complex itself. The presence of fine-grained volcanic lithic grains along with the amphiboles is evidence of both shallow- and deeper-level magmatic arc rocks in the drainage basin feeding sediment to the margin. A volcanic source is further consistent with the presence of large numbers of pyroxenes, some surrounding high-temperature titanomagnetite inclusions (Fig. 11E). These grains were mostly likely derived from erosion of a coarse-grained plutonic gabbro or ultramafic rock, similar to those known from the Talkeetna Arc (DeBari and Coleman, 1989; Greene et al., 2006).

Titane is a common Ti-bearing accessory mineral in basic maetaigneous rocks, especially in chlorite-bearing greenschist (Itaya.
Figure 6. Representative section of the Graywacke-Conglomerate unit showing the dominance of the massive sandstones and lesser amount of conglomerate. Bedding is either not apparent or only weakly developed. Vertical scale equals horizontal scale. See Figure 2 for location of section.

Figure 7. Structural section across the Eagle River fault zone showing the transition between the McHugh Complex and the Valdez Group. Note the presence of bedded cherts and mélanges that are not common in either the Graywacke-Conglomerate assemblage or the Valdez Group. Vertical scale equals horizontal scale. See Figure 2 for location of section.
and Banno, 1980), and is widely seen as detrital grains in the McHugh Complex. Figures 11B and 11D show large titanite grains with networks of ilmenite within them. Such assemblages are known from prograde metamorphic reactions within biotite-zone greenschist-facies rocks, with the chlorite representing a retrograde overprint (Miyashiro, 1994).

Other heavy minerals are secondary and were formed during metamorphism of the McHugh Complex after accretion, e.g., epidote. Because of their wide range of pressure-temperature stability, epidote group minerals of variable composition may form in a single rock during several stages of metamorphic reequilibration (Grapes and Hoskin, 2004). Although epidotes are typical of hydrothermal alteration in oceanic and arc-type settings (Cann and Gillis, 2004) and could have been eroded from an exhuming mafic arc source, the low-grade metamorphism is likely the origin of the grains found here. Similarly, Figure 11F shows a grain of pumpellyite with a network of titanite replacement. Pumpellyite is typically associated with lower metamorphic grades and is transitional between zeolite facies and greenschist facies (~250–350 °C), with a pressure range of approximately 2 to 7 kbar (Blatt and Tracy, 1995). This mineral likely grew in situ within the sediment after burial and within the greenschist facies.

The overall character of the heavy mineral suite in each tectonic unit is shown in Figure 12, with mineral identification based on electron probe analyses. Each unit is unique, although both parts of the McHugh Complex show dominance in titanite, pyroxene, and chlorite compared to the Valdez Group, which has no pyroxene identified (N = 149), but instead abundant titanite and epidote. The number of analyses from the Valdez Group is somewhat less than in the other units, and the results are less statistically reliable as a result. Within the McHugh Complex, we note that amphibole and pyroxene are much more abundant in the Graywacke-Conglomerate compared to the Mesomélange assemblage, whereas epidote is less common.

Within individual units, there are significant degrees of variability between different sedimentary rock samples. Heavy mineral assemblages from four representative samples from each of the Mesomélange and the Graywacke-Conglomerate assemblages are shown in Figure 13. We note that whereas garnet is totally absent from the Mesomélange assemblage, it is found in sedimentary rocks from the Graywacke-Conglomerate assemblage, most notably sample 08AnMS-08.

In an attempt to see if the two McHugh assemblages can be separated using their heavy mineral suites, we considered the chemistry of the pyroxenes in each. We did this because there...
are relatively high numbers of these minerals in both units and because pyroxenes are known to have a variable chemistry and to have been successfully used as provenance tools in the past (Cawood, 1990; Morton, 1991; Mange and Morton, 2007). Figure 14 shows the Ca$_2$Si$_2$O$_6$-Mg$_2$Si$_2$O$_6$-Fe$_2$Si$_2$O$_6$ composition plot of Deer et al. (1992) with the McHugh Complex detrital pyroxenes plotted. The two populations plot in a similar part of the diagram, but with the Graywacke-Conglomerate pyroxenes having higher Mg contents, i.e., more diopside rich in their range.

Further discrimination is possible through use of the SiO$_2$ versus Al$_2$O$_3$ diagram for pyroxene coupled with the subalkaline, alkaline, and peralkaline divisions from LeBas (1962) (Fig. 15). The great majority of the grains plot within the subalkaline field, consistent with erosion from a tholeiitic magmatic arc. This is especially true of the Mesomélange assemblage, while grains in the Graywacke-Conglomerate assemblage tend to scatter to higher Al$_2$O$_3$ and lower SiO$_2$ values, suggesting a more diverse source terrain. Even within the higher SiO$_2$ grains, we note that Mesomélange pyroxenes tend to have lower Al$_2$O$_3$ values compared to the Graywacke-Conglomerate assemblage.

Further provenance information is available from other mineral groups, and in Figure 16 we consider the range of compositions for amphiboles, exploiting changes in the alkali content (Na + K) and the Mg/(Mg + Fe) ratios. Amphiboles are much more abundant in the Graywacke-Conglomerate compared to the Mesomélange assemblage. These plots show that the composition of amphibole changed between sedimentation of the two units. While Figure 16A shows that high–(Na + K) grains are present in both McHugh units, there is a large population of amphiboles in the Graywacke-Conglomerate assemblage with low SiO$_2$ values, suggesting a more diverse source terrain. Even within the higher SiO$_2$ grains, we note that Mesomélange pyroxenes tend to have lower Al$_2$O$_3$ values compared to the Graywacke-Conglomerate assemblage.

Garnet is only present in the Graywacke-Conglomerate, not the Mesomélange assemblage, and although these grains are not numerous, their affinity can be determined using the discrimination diagrams from Mange and Morton (2007) (Fig. 17). Garnets in the Graywacke-Conglomerate assemblage are all high-Ca, grossular in composition, which are generally associated with metasomatic, altered metasomatic, altered metabasalt and metacarbonate rocks (Miyashiro, 1994). In the Valdez Group, another garnet of this type was noted, but there is also appearance of high-Mg garnets, which Mange and Morton (2007) associated with erosion of ultramafic rocks, such as pyroxenites and peridotites.
DISCUSSION

Significance of Heavy Minerals for Provenance

The heavy mineral assemblage in any given sediment can be quite variable (Fig. 13), possibly because of changing erosion patterns, but also likely linked to hydraulic sorting of grains during the sediment transport process in the case of the primary, detrital phases. In the case of the secondary phases, heterogeneity within a single stratigraphic unit may be explained in terms of variable growth of these phases within the metamorphosed section. It is thus not practical to define a typical heavy mineral assemblage for each assemblage that could be used to distinguish a given sample affinity independent of additional information.

Garnet is significant in being present in the Graywacke-Conglomerate assemblage. Within southern Alaska, there are few potential sources for such minerals, although garnet-bearing granulites are known from the lower parts of the Talkeetna Arc section (DeBari and Coleman, 1989) and garnet-bearing assemblages in Early Cretaceous metamorphic rocks along the Border Ranges fault (Pavlis, 1983; Barnett et al., 1994). Metamorphosed carbonate rocks are known from the Alexander terrane (Plafker et al., 1994) and the Strelna assemblage in the eastern Chugach Mountains (Roeske et al., 2003). This change may imply deeper exhumation of source terrains during the sedimentation of the Graywacke-Conglomerate assemblage.

Further insight into source regions can be gained by comparing pyroxene compositions with published bedrock values from the region available from the GEOROC database. Although erosion directly from the Talkeetna Arc north of the exposures is impossible, this does not preclude erosion from the Talkeetna Arc or its equivalents along strike (e.g., the Bonanza Arc). The Talkeetna Arc is better studied than most potential sources in SE Alaska and at least provides some indication of the potential compositions of midcrustal arc rocks. Modern arc volcanic rocks from Augustine volcano and the Alaska Peninsula (Fig. 1) plot close to the range measured from the Talkeetna lower and midcrustal gabbros (Fig. 15). We infer that most of the pyroxenes in the Mesomélange assemblage could have been eroded from a source similar in composition to the modern volcanoes on the Alaskan Peninsula. The higher-Al$_2$O$_3$ pyroxenes are hard to match with known sources, but we note that pyroxenes from lower-crustal Talkeetna pyroxenites and gabbronorites do have such higher values (Greene et al., 2006), as do the small number of pyroxenes analyzed from the Wrangellia terrane. A volcanic source is moreover supported by the presence of rare millosevichite, a sulfate mineral usually associated with volcanic fumaroles (Palache et al., 1951). Whether this is original and detrital, or secondary, is unknown, although the latter is more likely given the weak character of the phase.

The tectonic setting of the source rocks from which the pyroxenes were eroded can be constrained through use of the discriminant diagram of Nisbet and Pearce (1977), which was primarily developed to differentiate clinopyroxenes from mafic magmas, although the volcanic arc basalt field does include clinopyroxene compositions from arc andesites (Cawood, 1991b). In this method, two eigenvectors are calculated based on the chemical composition and cross-plotted against one another (Fig. 18). Nisbet and Pearce (1977) chose values that allowed pyroxenes from different tectonic regimes to plot in different parts of the diagram and thus allow tectonic setting to be determined for old pyroxenes where the original location was unclear.

Our figure shows that only one pyroxene plots in each of the within-plate alkaline and within-plate tholeiitic fields. Most of the grains from both McHugh units plot in the volcanic arc basalt (VAB) or ocean-floor basalt (OFB) fields, as might be expected in an active margin setting including accreted oceanic arcs. There are no significant differences between the two units plotted on this diagram. It is noteworthy that...
some of the grains plot with lower eigenvector F2 and within the field for within-plate tholeiite or ocean-floor basalts. This is unlikely to reflect erosion of oceanic crust sensu stricto, but probably shows input from intra-oceanic-arc rocks. It is noteworthy that Cawood (1991b) also identified grains with these values in the Neogene Tonga forearc, where their provenance is not ambiguous. A less likely but possible alternative is erosion from the oceanic plateau rocks of the Wrangellia terrane, and there is a Mid-Cretaceous angular unconformity within the Wrangellia stratigraphy, at least in the Chitina area (Fig. 1), that would be consistent with erosion into the McHugh Trench (Trop et al., 2002).

However, grains from the Wrangellia terrane would be expected to overlap into the within-plate tholeiite field, which is not seen. We conclude that the pyroxenes to both McHugh units are derived from a mixed continental and oce-

Amphiboles show a range of compositions comparable to both amphiboles from the Talkeetna Arc midcrust (Greene et al., 2006) and from modern Alaska Peninsula volcanoes, although the low-grade metamorphism of the McHugh units may have affected the chemistry of the original detrital grains (Fig. 16), which may make this less robust as a provenance tool. If arc sources provided the younger amphiboles, then the other compositional grouping found in the older Mesomélange assemblage is more enigmatic, although it is clear that there was an increase in source diversity between the Jurassic and the Cretaceous. No source has been analyzed as having the same amphibole compositions as this second group of detrital grains, although the Coast Mountains Batholith must be a potential candidate, if they are detrital.

Sedimentation within the McHugh Complex and oldest parts of the Valdez Group underwent important changes in style and source during the start of subduction accretion in SE Alaska. The fine-grained sediments of the argillite tuff and the accreted oceanic basalts and cherts give the impression of a subduction zone with little sediment in the trench. The décollement in most accretionary prisms is controlled by hydrology and is often located at the base of the rapidly de-

Figure 13. Pie diagrams showing the differences in heavy mineral assemblages between selected different samples from the Mesomélange and the Graywacke-Conglomerate assemblages, highlighting the significant amount of variability within each unit.

Figure 14. Ca$_2$Si$_2$O$_6$-Mg$_2$Si$_2$O$_6$-Fe$_2$Si$_2$O$_6$ composition plot of McHugh Complex detrital pyroxenes (after Deer et al., 1992). Note that both units have pyroxenes of a similar range but with more diopside compositions found in the Graywacke-Conglomerate assemblage.
of sheared material within a subduction channel, the recognized zone between the underthrusting oceanic plate and the overriding forearc (Cloos and Shreve, 1988) (Fig. 19). This would be consistent with the oceanic rocks found in the Mesomélange assemblage and lack of sandy turbidites. The 3 km thickness is more than the 0.9 km global average for subduction channels estimated by Scholl and von Huene (2007) and significantly more than the 500-m-thick zone mapped in the Apennines by Vannucchi et al. (2008), but it is comparable to seismically imaged zones in active systems, such as the Nankai Trough (Park et al., 2002) or Cascadia (Calvert, 2004). The structural thickness may also have been affected by later deformation along the Border Ranges fault. At the time of formation, the proto–Border Ranges fault would have been a low-angle structure, effectively the base of the overriding forearc wedge, against which the Mesomélange assemblage was accreted. The depth of this accretion could not have been too deep based on the low metamorphic grade, but it would not have been right at the toe of the forearc.

This phase of slow sedimentation and accretion occurred after the collision of Talkeetna Arc and Wrangellia at ca. 160 Ma (Figs. 19 and 20). Sedimentation of the coarse Naknek Formation is known from forearc basins of this age (Trop et al., 2005), and it is likely that this basin captured much of the clastic material generated by erosion of the collisional orogen. Some sediment overspilled the basin and was deposited into the trench, which coincided with the end of the long-lived phase of tectonic erosion that preceded the Mesomélange assemblage. We suggest that it is the collision that tipped the margin into the accretionary mode.

Amato and Pavlis (2010) documented a truncation of the McHugh Complex between the Mesomélange and Graywacke-Conglomerate assemblages that is most easily interpreted as a phase of tectonic erosion, probably caused by collision by a ridge or seamount with the trench. Our observations are consistent with a sharp tectonic contact between the two (Fig. 5). This implies a period of accretion between the Mesomélange and Graywacke-Conglomerate assemblages that has been lost. An erosion-inducing collision would thus be dated as preceding the start of accretion of the Graywacke-Conglomerate assemblage. The presence of a synchronous Early Cretaceous (Neocomian, ca. 144–121 Ma) unconformity in the Matanuska forearc basin, located between the Chugach and Talkeetna Mountains (Fig. 1A), is further evidence of tectonic disruption of the forearc at this time (Trop and Ridgway, 2007). Evidence of unconformity in the basin along strike from our study area would be more consistent with subduction of a ridge rather than an individual seamount.

Comparison with modern collision zones would suggest that accretion began again soon after the seamount-trench collision, partly fed by the mass wasting in the wake of the subducting seamount as the oversteepened forearc began to collapse (Ranero and von Huene, 2000). This may explain the common occurrence of debris-flow sediments in the Graywacke-Conglomerate assemblage, although we note that debris-flow sedimentation is also found on the trench slope of accretionary prisms now in a state of active construction (Expedition 333 Scientists, 2011). The occurrence of exotic lithologies, such as brown sandstones, and new mineral species, such as diopside and garnets, in the Graywacke-Conglomerate assemblage also shows that the fast sedimentation does not simply reflect reworking of the older accretionary prism because
these sandstones are not turbidite facies and are quartzose continental type. Nonetheless, the presence of 180 Ma zircons in the brown sandstone suggests an arc-proximal location for sedimentation (Bradley et al., 2009). Zircon dating of the Graywacke-Conglomerate assemblage shows the presence of older grains dating to 440–422 Ma and very rare >2000 Ma ages that require some limited erosional flux from older terrains in the continental interior (Amato and Pavlis, 2010). The rapid influx of sediment to the trench and the accretion of the Graywacke-Conglomerate would explain the preservation of the Mesomélange subduction channel material because its location in the subduction channel would make it vulnerable to tectonic erosion. Emplacement of the Graywacke-Conglomerate provided a barrier between the Mesomélange assemblage and the subduction interface. The rapid emplacement of the Graywacke-Conglomerate as a tectonically imbricated package of sediment at or close to the toe of the forearc would shield the Mesomélange assemblage from the subduction interface and result in the formation of a new subduction channel at a lower structural level (Fig. 19C). The moderate metamorphic grade of the Graywacke-Conglomerate assemblage argues against this having been deeply overthrusted by the forearc and suggests that this is a body accreted close to the trench, albeit on the underside of the forearc wedge.

It is clear that by Graywacke-Conglomerate times (<105 Ma) and into the period when the Valdez Group was accreted, the rate of sediment supply to the trench axis had sharply increased, and true subduction accretion had begun in earnest. The bulk of that sediment was coming from magmatic arc sources, which zircon dating attributes largely to the Coast Mountains Batholith (Amato and Pavlis, 2010; Kochelek et al., 2011). The granite boulders seen in the Beluga Point conglomerate have generally younger ages of 180–200 Ma (Bradley et al., 2009) and suggest erosion from either the Talkeetna Arc or similar arc terrane. In that location, the sandstone boulders could have been the sedimentary cover of the batholith, but they could have been eroded from any exposed continental sedimentary basin. These data imply an important change in the source of sediment supply to the trench between Mesomélange and Graywacke-Conglomerate assemblages times away from purely oceanic rock types. We link this change to the collision of an amalgamated Talkeetna-Wrangellia block with the mainland of North America in the form of the Yukon composite terrane. The timing of this collision at ca. 105 Ma lies close to a period of major tectonic reorganization around the Pacific region, most notably the termination of subduction along the Gondwana margin prior to the subsequent opening of the Tasman Sea (Mortimer, 2004; Tulloch et al., 2009). Whether the change of plate motion following arc collision precipitated some of these other events is unclear but should be considered as a possible trigger.

The age of the McHugh Complex is broadly comparable with the start of other major accretionary prisms around the Pacific Rim. Accretion of the Shimanto Complex is loosely defined by radiolarians in the oldest units as being Alban to Cenomanian (93–112 Ma; Ishii and Takahashi, 1993). In the Kanto Mountains of central Japan, the oldest part of the Shimanto Complex, the Ogochi Group, is dated at having been deposited from late Alban to Campanian, ca. 105–71 Ma (Hara and Hisada, 2007). In contrast, on the California margin, sedimentation of the first Franciscan turbidites is dated as ca. 145–132 Ma (Isozaki and Blake, 1994), but the onset of rapid accretion is constrained at around 123 Ma, somewhat before the offscraping of the Graywacke-Conglomerate assemblage (Dumitrut et al., 2010). Nonetheless, radiometric dating of the Franciscan rocks indicates a phase of imbrication and high-pressure metamorphism ca. 105–90 Ma (Blake et al., 1988), suggesting tectonic changes in that margin around that time.

Collectively there seems to be little evidence for a climatically triggered intensified flux of sediment to the trench at 105 Ma, comparable to...
what has been seen in the last 3–4 m.y. (Zhang et al., 2001). The climate of the Albian is generally considered to have been warm, although conditions may have varied strongly during that period (Bice and Norris, 2002; Erbacher et al., 2011). The major oceanic anoxic events that characterize this period bracket the onset of subduction accretion at 99 Ma (OAE-1d) and 121 Ma (OAE-1b; Wilson and Norris, 2001), but there is not any event close to the 105 Ma start of rapid accretion. We therefore favor a dominantly tectonic trigger for the start of major accretion.

History of Margin Exhumation

Subduction accretion was able to start because of the supply of sediment from a progressively unroofing arc complex onshore. Our geochemical data show that at least some of the pyroxenes are derived from midcrustal mafic and ultramafic rocks comparable to the Talkeetna Arc, and the range of detrital zircons is compatible with some erosion from sources of that age (ca. 200–160 Ma). Change in pyroxene composition to more diopside-rich values in the Graywacke-Conglomerate assemblage indicates erosion of deeper crustal levels compared to the Mesomélangé assemblage because diopside is a mineral typical of ultramafic rocks, such as peridotites, although diopside-rich augites are also known from some basaltic lavas (Deer et al., 1992). The garnets are of grossular compositions that imply erosion of metacarbonate rocks, most likely from the Alexander terrane or the eastern Chugach Mountains. Mg-rich garnets only appear in the Valdez Group, and these are most likely eroded from mafic or ultramafic igneous rocks. Garnet-bearing gabbros of this variety are exposed in the Talkeetna Arc and could be the source of these grains (DeBari and Coleman, 1989). Thus, we interpret the Graywacke-Conglomerate assemblage to represent erosion from deeper arc structural levels and from tectonic units located further inboard within the North American margin compared to the Mesomélangé assemblage, consistent with the report of Paleozoic limestone clasts derived from Wrangellia in the Beluga Point conglomerates of the Graywacke-Conglomerate assemblage (Fischietto et al., 2006). Erosion continued to deepen further in Valdez times.

In the case of southern Alaska, a mixture of shallow and deep arc rock types could reflect erosion from the active arc and from an exhuming accreted arc (e.g., Chitina or Talkeetna). While the plutonic units of the Talkeetna Arc are exposed immediately to the north of the McHugh Complex, these outcrops are unlikely to be the source of these grains because of the lateral motion on the Border Ranges fault since sedimentation. Moreover, if the McHugh sandstones were deposited in the trench, then the adjacent rocks of the backstop would be in the forearc and in deep water on the continental margin, where they could not be eroded by subaerial processes (Figs. 19B and 19C). The Talkeetna Arc is directly juxtaposed with the McHugh Complex and measures ~110 km across strike east of Anchorage. Nonaccretionary forearc is often ~150 km wide between the trench and the coast. Thus, even if the forearc taper was steeper than average, only the northernmost part of the Talkeetna Arc would be expected to be exposed on land when the McHugh sediments were being deposited. Those parts located more oceanward would be under water and unavailable to be

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**Figure 19**. Tectonic model showing the way in which trench tectonics are believed to have evolved along with the changing nature of the source terrains onshore. Two collision events drove bedrock uplift and provided more material to the trench, allowing the start of major subduction accretion. The Mesomélange represents a paleosubduction channel preserved above the newly accreting wedge of trench sediments.
eroded. The northernmost part of the arc is dominated by volcanic rocks, granites, and trondhjemitic rocks (Beikman, 1992; Rioux et al., 2010). The uplift and exhumation of the southern, deeper structural level of the Talkeetna Arc occurred much later than accretion of the McHugh Complex (Enkelmann et al., 2008), largely during the Paleocene–Eocene (Little and Naeser, 1989). However, erosion of 180–200 Ma plutonic rocks into the Graywacke-Conglomerate assemblage favors erosion from the Talkeetna or laterally equivalent Bonanza Arc along strike. The provenance data require erosion from some lower arc crust. Either this was another accreted arc of similar age to the Talkeetna, or the forearc had a much steeper taper than normal (such as seen in the Osa Peninsula of Costa Rica), and the Talkeetna Arc was wider across strike along the margin in the place where the Graywacke-Conglomerate assemblage was accreted.

A major influx of sediment, especially from a coastal orogen, would likely require some degree of bedrock uplift, as well as a moist climate. Uplift of the terrestrial forearc could imply large-scale mass wasting of the type that typifies the Graywacke-Conglomerate assemblage. The start of subduction accretion in southern Alaska is recorded in the sedimentary rocks of the McHugh Complex and Valdez Group. Zircon dating has shown that the sediment was largely derived from the magmatic arcs of NW North America, especially the Coast Mountains Batholith; however, our heavy mineral study shows that accreted oceanic arc rocks were also important to the sediment flux to the trench. We suggest that the initial moderate increase in sediment flux to the trench followed collision of the Talkeetna Arc and Wrangellia ca. 160 Ma resulted in the end of long-term subduction erosion, although much of the sediment was captured in forearc basins to the north at that time. Following the collision of a seamount with the trench, or ridge subduction, significant subduction accretion began at ca. 105 Ma. Sedimentation switched to dominantly debris flows, some of which were linked to mass wasting from the oversteepened forearc in the wake of the collision event.

Changing provenance of sandstones and conglomerates shows that the drainage basin widened after accretion of the Mesomélange assemblage. The appearance of garnets and more Mg-rich diopside pyroxene grains in the sandstones indicates erosion of progressively deeper levels of a mafic magmatic arc section, similar to the Talkeetna Arc, against which the McHugh Complex is now juxtaposed. We suggest that changing degrees of coupling across the plate boundary, together with uplift and erosion triggered by collision of the Wrangellia-Peninsular terrane with the Yukon composite terrane, caused uplift of the terrestrial forearc and increased sediment flux to the trench, which in turn caused an acceleration of subduction accretion. Thus, the history of subduction accretion is linked to sediment supply controlled by the progressive accretion of exotic blocks to the western margin of North America. If the McHugh Complex is representative of accretionary margins worldwide, then it appears that the onset of large-scale subduction accretion is mostly linked to large-scale collisional events and especially to the accretion of oceanic arc systems to large continental blocks.

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REFERENCES CITED


Erbacher, J., and Hecker, J.A., 1994, Paleotemperature of the ancient Cascadia subduction zone: Tonga-Trench–Louisville Ridge col-


Hara, H., and Hisada, K., 2007, Tectono-metamorphic evo-


Jackson, R.E.P., 1984, Subduction-channel model of prism accretion, melange formation, sedimen


