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Structural and Geochronologic History of Southern Alaskan Blueschists

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STRUCTURAL AND GEOCHRONOLOGIC HISTORY OF SOUTHERN ALASKAN BLUESCHISTS

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Chapter 1: Detrital zircon analyses indicate an Early Cretaceous episode of blueschist facies metamorphism in southern Alaska: Implications for the Mesozoic paleogeography of the northern Cordillera

1.1 ABSTRACT

Detrital zircon data are presented from the Liberty Creek blueschist in the central Chugach Mountains which indicate two distinct periods of the preservation of blueschist facies metamorphism along the southern Alaskan margin. A maximum depositional age of ~136 Ma demonstrates that the Liberty Creek schist was deposited long after the Jurassic cooling ages (196-185 Ma; Lopez-Carmona et al., 2011) recorded in western Alaskan blueschist bodies, revealing two blueschist preservation events. This Early Cretaceous depositional age also indicates that there have been major reorganizations within this subduction complex because the Potter Creek assemblage, directly south of the Liberty Creek schist, is an older (maximum depositional ages of 169 Ma - 156 Ma; Amato et al., 2013) but more shallowly exhumed assemblage. Strike-slip motions have rearranged the accretionary complex by carrying the Potter Creek assemblage outboard and south of the Liberty Creek schist. The predominance of 130-140 Ma zircons in the Liberty Creek schist sample and a population of detrital zircons that is distinct from nearby terranes suggest a sedimentary source different from other related accretionary assemblages. Three suggested Cordilleran source terranes are the Chitina Valley batholiths, ~200 km east, the Firvale Suite of the Coast Plutonic Complex, ~1500 km to the southeast near Vancouver, B.C., or the southern Mexican Guerrero terrane, ~3000 km to the southeast. The detrital zircon signature of the Liberty Creek schist and these distances to potential sources support models suggesting thousands of km of strike-slip movement along the western Cordillera since Cretaceous time (e.g. the Baja-BC hypothesis).
1.2 INTRODUCTION

Blueschist facies rocks are among the most difficult rocks to date accurately. Estimation of their maximum age has traditionally been impossible due to mixed source terranes with little or no fossil age control (e.g., Dimitru et al., 2010; Amato et al., 2013) and minimum ages are complicated by difficulties in the K-Ar system within blueschist facies minerals (e.g., Sisson and Onstott, 1986; Baldwin and Harrison, 1989). Increased precision of laser-ablation ICP-MS U-Pb zircon analyses (Gehrels et al., 2008) has led to faster and cheaper dating of single zircon grains. This has led to new insights on forearc assemblages through assessment of detrital zircon ages (e.g., Brown and Gehrels, 2007; Amato and Pavlis, 2010; Snow et al., 2010; Amato et al., 2013), ages of intrusive terranes (e.g., Gehrels et al., 2009; Rusmore et al., 2012), or combinations of both types of analyses (e.g., Willner et al., 2008; Zhu et al., 2011). Less studied in this context are blueschist terranes where pelagic protoliths handicap detrital zircon studies and thermochronologic data are often complicated (e.g., Roeske, 1986; Sisson and Onstott, 1986). Nonetheless, some studies have successfully characterized detrital ages in blueschists and have created insight into the complexities occurring along subduction margins (e.g., Kapp et al., 2003; Brown and Gehrels, 2007; Snow et al., 2010; Zhu et al., 2011). Amato and Pavlis (2010) emphasized that detrital zircon ages in metasandstones of forearc accretionary complexes can be used to approximate the time of accretion due to the short deposition to accretion pathway in subduction zones. Here we apply this relationship to southern Alaskan blueschists.

The southern Alaskan, 2000 km long, Jurassic-Cretaceous paleo-convergent margin contains a series of fault-bounded blueschist bodies that are located either against or in close proximity to the Border Ranges fault (BRF) (Sisson and Onstott, 1986), the crystalline backstop to the accretionary complex (Plafker et al., 1994; Pavlis and Roeske, 2007) (Figure 1.1A). Previous studies have applied K/Ar, \(^{40}\)Ar/\(^{39}\)Ar, Rb/Sr, and P-T pseudo section techniques to these
rocks and have provided a reasonable description of peak blueschist metamorphism for southern Alaskan blueschist terranes (e.g., Decker, 1980; Sisson and Onstott, 1986; Roeske et al., 1989; Plafker et al., 1994; Bradley et al., 1999, Lopez-Carmona et al., 2011) (Fig. 1.1A). Thermochronologic data from these assemblages reveal an ~196–91 Ma range of cooling ages for these blueschist bodies with ages decreasing from west to east along the margin (e.g., Decker, 1980; Sisson and Onstott, 1986; Roeske et al., 1989; Plafker et al., 1994; Bradley et al., 1999; Lopez-Carmona et al., 2011) (Fig. 1.1A). These data have led to three hypotheses regarding the timing of southern Alaskan blueschist metamorphism: 1) the variation in metamorphic cooling ages results from different times of subduction, exhumation, or movement along the subduction interface (Sisson and Onstott, 1986), 2) the varied cooling ages are a result of progressively younger cooling from west to east following an ~210 Ma blueschist metamorphism event (Sisson and Onstott, 1986), and 3) there were two blueschist metamorphism events; one event at ~200 Ma represented by the western and central Alaskan blueschists (K, S, I, L of Fig. 1.1A) and a second blueschist metamorphism event at ~110 Ma represented by the eastern most south Alaskan blueschist (C of Fig. 1.1A) (Plafker et al., 1989). Our goal in this study was to use a detrital zircon approach to test these alternative hypotheses and add detail to the earliest histories of the southern Alaskan blueschist bodies.

Here we report on detrital zircon analyses from the Liberty Creek schist and other nearby rocks of the Chugach accretionary complex in the central Chugach Mountains (Fig. 1.1B and 1.2). These data show that the Liberty Creek blueschist (L, Fig. 1.1A) cannot be related to the Early Jurassic blueschist assemblages of southern Alaska (K, S, and I, Fig. 1.1A), and represents a distinctly younger, Early Cretaceous blueschist assemblage. We show that the detrital zircon signature of the Liberty Creek blueschist is distinct from other detrital signatures yet seen in this
accretionary complex. Based on this distinct detrital signature we speculate that large northward transport of terranes in the North American Cordillera during Late Cretaceous to Paleogene time is responsible for the Liberty Creek schist’s current geographic location both along the paleo-margin and among other terranes of this accretionary complex.
Figure 1.1 A: Map of southern Alaska showing the Wrangellia composite terrane, Chugach accretionary complex, the BorderRanges Fault (BRF), the relative locations of ancient arcs, the Firvale suite, and the extent of the Chitina River drainage basin. The Wrangellia composite terrane is composed of PE-Peninsular terrane, WR-Wrangellia terrane, and AX-Alexander terrane. Dark gray shading is the Chugach accretionary complex, and the light shading shows the position of the Neogene Yakutat terrane. Black squares with letters are the locations of blueschist bodies along the BRF. K, Afognak and Raspberry schist (196 Ma, Rb-Sr), Kodiak Island; S, Seldovia schist (191 Ma, $^{40}$Ar/$^{39}$Ar), Kenai Peninsula; I, Iceberg Lake Schist (185 Ma, $^{40}$Ar/$^{39}$Ar); L, Liberty Creek schist (123-107 Ma, K-Ar), Chitina, AK; H, Hubbard Glacier schist; C, Chichagof Island schist (91-106 Ma, K/Ar), Chichagof Island. After Sisson and Onstott, 1986; Plafker et al., 1989; and Pavlis and Roeske, 2007. B: Geologic map of the central Chugach Mountains showing the Liberty Creek schist and associated Chugach accretionary complex assemblages. Also shown are locations of detrital zircon samples. After Pavlis and Roeske, 2007.

1.3 TECTONIC SETTING
Blueschists along the northernmost Cordilleran margin have been interpreted as exhumed products of a subduction zone with a similar polarity to the present day margin (e.g., Carden et al., 1977; Forbes et. al., 1979; Plafker et al., 1994). Observed structures indicate both the past and current subduction zones are directed to the north (e.g., Carden et al., 1977; Forbes et. al., 1979; Nokleberg et al., 1989; Plafker et al., 1994). Nonetheless, interpretations of the tectonic affinities through time and the subduction histories of these southern Alaskan blueschists remain controversial. Throughout the Mesozoic, the northern Cordillera was characterized by the accretion of arc systems with subsequent strike-slip dispersal of elements of these arc-trench systems leading to the observed terrane mosaic of the modern margin (Plafker et al., 1994). The outer Cordilleran assemblage is comprised of an accreted arc-trench system with the Wrangellia Composite terrane representing the arc-assemblage and the “Chugach terrane” representing the subduction complex (Plafker et al., 1994; Pavlis and Roeske, 2007) (Fig. 1.1B). The Wrangellia Composite terrane was assembled from three late Paleozoic to Early Mesozoic terranes that may represent as many as three distinct oceanic arcs (Israel et al., 2014; Beranek et al., 2014). Overlap assemblages and plutonic ties establish that the Wrangellia Composite terrane was
partially assembled during the late Paleozoic (Israel et al., 2014; Beranek et al., 2014). However, the Peninsular terrane, which is the part of the Wrangellia Composite terrane underlying most of southern Alaska, is a younger oceanic arc that could have been amalgamated with Wrangellia as recently as Late Jurassic time when a cover sequence firmly establishes connections between these terranes (e.g., Coney et al., 1980; Plafker et al., 1994; Trop et al., 2002; Trop et al., 2005). The backstop to the subduction complex is the Border Ranges Fault (BRF) which extends along the entire length of the southern Alaskan margin (MacKevett and Plafker, 1974; Pavlis and Roeske, 2007) (Fig. 1.1A).

The southern Alaskan blueschists are all located south of the BRF (Sisson and Onstott, 1986; Plafker et al., 1994; Pavlis and Roeske 2007) (Fig. 1.1A). The blueschists occur as fault-bounded bodies but juxtapositions with other rocks vary among the isolated bodies. Most lie directly south of the BRF and north of what has traditionally been called the mélange subterrane of the Chugach terrane (e.g., Coney et al., 1980; Plafker et al., 1994). Some of the blueschists, however, occur as large isolated bodies within the Chugach mélange (Sisson and Onstott, 1986); due to this structural relationship the blueschists have loosely been associated with the mélange subterrane of the Chugach terrane.

Recent detrital zircon studies indicate that the mélange subterrane of the Chugach terrane is comprised of at least two elements: (1) a Late Jurassic mélange dominated by pelagic to hemipelagic protoliths and (2) a middle Cretaceous clastic-dominated stratally disrupted assemblage (Amato and Pavlis, 2010; Amato et al., 2013). These data and related studies led Amato et al. (2013) to propose a new nomenclature for these subduction assemblages. They proposed the term Chugach accretionary complex for the Chugach and Prince William terranes, and the terms Potter Creek assemblage and McHugh Creek assemblage for the Jurassic and Cretaceous parts in
the Chugach mélange respectively. The blueschists do not directly fit into this terminology aside from local names for these units; the known cooling ages indicate they may represent older parts of the Potter Creek assemblage or an older undescribed assemblage.

The blueschists are located north of, or sliced into, the Potter Creek assemblage (e.g., Amato et al., 2013) and where undisturbed by younger strike-slip movement the McHugh Creek assemblage lies structurally beneath the Potter Creek assemblage. The McHugh Creek assemblage, in turn, lies structurally above, and is gradational in age to, the Late Cretaceous coherent turbidite assemblage known in the Chugach Mountains as the Valdez group or Chugach flysch (Plafker et al., 1974; Kochelek et al., 2011) and elsewhere termed the Valdez group flysch by Amato et al., (2013). The Chugach flysch comprises the bulk of the “Chugach terrane” (Plafker et al., 1994).

The depositional ages of protoliths to the southern Alaskan blueschist bodies were previously unknown other than minimum ages provided by cooling dates. Based on cooling ages as old as the earliest Jurassic and structural position, these blueschists are widely cited as evidence for the initiation of subduction and the earliest accretion of the Chugach accretionary complex (e.g., Plafker et al., 1994; Pavlis and Roeske, 2007). Detrital zircons from the other members of the Chugach accretionary complex, however, are much younger than the available blueschist cooling ages (Amato et al., 2013). This observation, together with relationships in the adjacent arc on the Wrangellia composite terrane, is the principal evidence that a prolonged period of subduction erosion followed Early Jurassic accretion of the blueschists (Clift et al., 2005; Amato and Pavlis, 2010).

The source of the clastic rocks that formed the protolith to the Potter Creek assemblage was the Early to Middle Jurassic Talkeetna-Bonanza arc or another coeval mid-Jurassic arc on
the Wrangellia composite terrane, but the Potter Creek clastic rocks are mixed with pelagic to hemipelagic rocks that include radiolarian cherts with a wide range of depositional ages (e.g. Plafker et al., 1994; Amato et al., 2013). In contrast, the younger McHugh Creek assemblage and the Valdez Group indicate a source primarily from the Coast Mountains Batholith near SE Alaska and British Columbia, which is consistent with younger dextral strike slip transport of these rocks to their present position in southern Alaska (Kochelek et al., 2011; Amato et al., 2013). These source terranes are important for this study because they provide tectonic context for time windows that surround the blueschist accretion.

1.3.1 Geology of the central Chugach Mountains blueschists

The southern Alaska blueschists are scattered along the margin from Kodiak Island in the west to Chichagof Island in the east (Figure 1.1A). The rocks have been most extensively studied in the far west on Kodiak Island (K, Figure 1.1A, including the Raspberry schist of Raspberry Island and Afognak Island schist of Carden et al., 1977; Roeske, 1986; and Roeske et al., 1989) and the southwestern tip of the Kenai Peninsula (Seldovia schist, S, Figure 1.1A). Less well known are the blueschists of the central Chugach Mountains which include the Iceberg Lake (I, Figure 1.1A) and the Liberty Creek schist (L, Figure 1.1A) as well as southeastern Alaskan blueschists (Hubbard Glacier locality, H, Figure 1a and Chichagof Island, C, Figure 1.1A). In this study we concentrate on the two central Chugach Mountains localities (Figure 1b).

The Iceberg Lake schist was first recognized by Winkler et al. (1981a, 1981b, 1981c) during reconnaissance mapping but has received little attention because of its remote setting. They recognized that the assemblage was surrounded by lower-grade mélange rocks of the McHugh complex, and showed the assemblage as a large, elongate slab bounded by high-angle
faults. Later work by Pavlis and Roeske (2007) and Day (Chapter 2, this dissertation) showed that the structure of the Iceberg Lake schist is more complex, with the assemblage comprised of multiple faulted slices of rock of varying scale. The structural history of the faulting is poorly understood but clearly included Cenozoic faulting (Pavlis and Roeske, 2007) suggesting a complex structural history. Where we have observed the Iceberg Lake schist, it is lithologically diverse and comprised of rocks with variably developed metamorphic fabrics. The most abundant rocks are mafic glaucophane +/- lawsonite schists derived from both volcanic and plutonic protoliths with highly variable fabric development. Other rock types are diverse metasedimentary rocks including dark phyllites and fine- to medium-grained micaceous schists associated with quartzites and minor amounts of marble. We interpret the mafic rocks as disrupted fragments of oceanic crust and the metasediments as associated pelagic sedimentary rocks.

Sisson and Onstott (1986) dated the Iceberg Lake blueschists with $^{40}\text{Ar}/^{39}\text{Ar}$ techniques applied to blue amphiboles and white mica separates and recognized that the blue amphiboles were essentially dating fine-grained white mica inclusions in the amphiboles. Their study provides the only age constraint on the Iceberg Lake blueschists, a clear Early Jurassic cooling date of 186 Ma which indicates a likely correlation to the Kodiak and Seldovia blueschists which have similar Early Jurassic (~190 Ma) cooling dates (Roeske et al., 1986; Bradley et al., 1999).

The second blueschist assemblage of the central Chugach Mountains is the Liberty Creek schist (L, Figure 1a and detail in 1b). The blueschist assemblage was first recognized by Metz (1976). These early studies concentrated on the petrology of the assemblage. Later studies (e.g., Nokleberg et al., 1989) described the basic structure, which was further refined by Pavlis and
Roeske (2007). Most recently Lopez-Carmona (2011) analyzed samples for thermobarometry and estimate peak pressures of 15 kb or a depth of ~50 km for the Liberty Creek schist.

The Liberty Creek blueschist is lithologically distinct from the Iceberg Lake blueschist both in mineralogy and apparent protolith. The Liberty Creek schist is comprised predominantly of metasedimentary rocks with a prominent, relatively uniform continuous cleavage defined by a pronounced mica foliation. In outcrop the Liberty Creek schist appears superficially similar to the Potter Creek assemblage in that it is typically comprised of thin laminae of mafic greenschist interleaved with dark phyllite and minor quartzite; compositions suggestive of the green tuff, black argillite, chert association characteristic of the Potter Creek assemblage. The Liberty Creek schist is different, however, with a characteristic penetrative, continuous cleavage suggesting a more pronounced ductile finite strain than other parts of the Chugach mélangé. Nokleberg et al. (1989) noted this fabric and its parallelism with fabrics in adjacent rocks, although Pavlis and Roeske (2007) considered it a distinctly different fabric. The Liberty Creek schist is also structurally distinct on a large scale, bounded by two prominent, but distinctly different fault systems. To the north and west the Liberty Creek schist is in fault contact with the Tonsina ultramafic complex, the assemblage widely recognized as the upper mantle basement to the Early Jurassic Talkeetna arc of the Peninsular terrane (Burns, 1985; Debari and Coleman, 1989; Rioux, et al., 2007; Hacker et al., 2008; Rioux et al., 2010). To the south of the Liberty Creek schist is the Second-Lake fault, a high-angle strike-slip fault that is clearly a younger strike-slip structure (Pavlis and Roeske, 2007). Rocks south of the Second Lake fault were originally mapped as a different assemblage (Winkler et al., 1981b). Later work (Plafker et al., 1994) correlated these rocks to the McHugh Complex and our work reported here supports this conclusion.
The age of the Liberty Creek blueschist has been debated since its discovery. Winkler et al. (1981b), made initial attempts to date the complex using conventional K-Ar dating and later work by Plafker et al. (1989) produced additional conventional K-Ar dates. All of these dates were on whole rocks and scatter from 107-123 Ma, suggesting a middle Cretaceous minimum age. Nonetheless, these ages are difficult to interpret because with conventional K-Ar, particularly whole-rock ages, these dates could be too old from extraneous argon or excessively young due to partial argon loss during later events. For example, the region experienced a well known Paleogene thermal event (e.g., Sisson et al., 1989) which could easily have produced partial argon loss from rocks the cooled originally in the Jurassic. Although we had similar problems producing clean mineral separations in these fine-grained rocks, the detrital signature of these rocks confirms they are distinct from the blueschists exposed to the west.

1.4 GEOCHRONOLOGY

1.4.1 Methods

We analyzed U-Pb ages of detrital zircons using the Nu Plasma HR laser ablation–multicollector–inductively coupled plasma–mass spectrometer (LA-MC-ICP-MS) at the University of Arizona (See Gehrels et al. (2008) for LA-MC-ICP-MS methods, and Amato and Pavlis (2010) for detrital zircon sample preparation methods). Maximum depositional ages were determined from the weighted mean of the youngest population of grains with overlapping uncertainties with a MSWD (mean square of the weighted deviates) as close to 1 as possible (Fig. 2). This procedure produces a maximum age that this population of zircons could have been derived from a common source. Relative probability plots in Figure 1.2 have been normalized, where peaks in the probability plots are placed on an equal scale relative to the number of grains.
of each age. This allows for comparison of one sample to another despite varying numbers of zircons analyzed in different sample sets.

Figure 1.2 Normalized probability plot of detrital zircon populations from this study. 10CED14, Liberty Creek schist; 09CED02 and 09DED09, greenschist from the Second Lake shear zone south of the Liberty Creek schist; 10CHITINA-1, sands from the Chitina River valley. Valdez group flysch, McHugh Creek assemblage, and Potter Creek assemblage detrital zircon populations from the Chugach accretionary complex assemblages of Amato et al., (2013) provided for comparison.
1.4.2 Results: Central Chugach Mountains Blueschists

We sampled the Iceberg Lake blueschist for detrital zircons and none of the 11 samples we processed yielded zircons. Amato et al. (2013) reported similar problems with the Seldovia blueschists. The absence of zircons from both assemblages is consistent with the hypothesis that these blueschists were formed from a deep sea pelagic sedimentary and mid-ocean ridge basalt type volcanic assemblage.

Of 20 samples we examined for detrital zircons in the Liberty Creek schist, three samples yielded detrital zircons (Figs. 1.1B, 1.2). Sample 10CED14 is demonstrably part of the blueschist assemblage. In hand sample 10CED14 is a fine-grained medium-dark green color with a phyllitic texture and ferruginous chert layers. In thin section (Fig. 1.3) this sample has blue Na-amphibole confirming that 10CED14 is a blueschist facies rock. Lopez-Carmona et al. (2011) analyzed similar Na-amphiboles from a nearby locality and showed a variety of Na-amphibole compositions ranging from glaucophane to magnesio-riebeckite for this assemblage. The matrix of the sample is a mix of fine-grained chlorite and white mica. Na-amphiboles are partially replaced by chlorite, and the presence of multiple cross cutting generations of prehnite, stipnomelane, laumontite, and calcite veins indicate low temperature retrograde conditions after blueschist metamorphism. The MDA of sample 10CED14 is $136 \pm 2$ Ma with half of the zircon ages between 130 and 140 Ma (Fig. 1.2, Table 1.1). Multiple peaks are visible in the probability plot of 10CED14, located at 137 Ma, 159 Ma, 170 Ma, and 173 Ma.
Samples 09CED02 and 09CED09 were collected in rocks originally mapped as the Liberty Creek schist (Plafker et al., 1989). The samples were collected just north of the southern strand of the Second Lake fault which separates the Liberty Creek schist and the McHugh complex (Fig. 1.1B). Our work (Day, Chapter 2, this dissertation) indicates that the Second Lake fault is a complex, ~600 m wide shear zone where rock units are shuffled and difficult to recognize because of lithologic similarities between the McHugh complex and Liberty Creek schist (e.g., Pavlis and Roeske, 2007). In hand sample 09CED02 is a light green to gray meta-greywacke with minor visible sand sized grains and clear evidence of cleavage development similar to cleavages in the Liberty Creek schist. Petrographic observations confirm the sand sized grains as quartz and cryptocrystalline quartz (chert) in a very fine-grained matrix of cryptocrystalline quartz, and recrystallized, very-fine grained micaceous matrix (chlorite and white mica). Sample 09CED09 is a gray, coarse grained meta-greywacke; petrographic
observations reveal the presence of mud rip-up clasts and deformed quartz grains in a matrix of very fine grained micaceous matrix (chlorite and white mica) and cryptocrystalline quartz. The MDA of 09CED02 is 149 ± 2 Ma with zircon population peaks at 153 Ma and 203 Ma (Fig. 1.2). Sample 09CED09 has an MDA of 159 ± 2 Ma with zircon population peaks at 159 Ma, 190 Ma, and 208 Ma (Fig. 1.2, Table 1.1). These MDA and zircon population peaks are different from 10CED14 but similar to the Potter Creek assemblage of the McHugh complex in the Anchorage area (Amato et al., 2013) (Fig. 1.2).

1.4.3 Chitina River Valley Sediment

Sample 10Chitina-1 was collected from modern sediments of the Chitina River near the Ultima Thule Lodge (Fig. 1.4). This sample was collected because a potential source for the Liberty Creek Schist and McHugh Complex is the Jurassic Chitina arc exposed for more than 400 km along the BRF from the Copper River into SE Alaska (Plafker et al., 1989; Roeske et al., 2003) (Fig. 1.1A). However, the Chitina arc is not well dated with the bulk of the geochronology from conventional K-Ar dates (Hudson, 1983; Dodds and Campbell, 1988; Plafker et al., 1989) and a few modern $^{40}$Ar/$^{39}$Ar cooling ages (Roeske et al., 2003), all of which scatter from 130–171 Ma. Thus, the modern sediment sample was collected as a proxy for the age of the Chitina Valley batholith which makes up a significant part of Chitina arc (Plafker et al., 1994). Figure 1.4 shows the drainage basin of the Chitina River and the sample locality indicating this sample should be sampling ~150km of the strike-length of the Chitina Valley batholith (Jc and PzJs of Fig. 1.4) plus rocks of Wrangellia (Wc of Fig. 1.4). The sands of sample 10Chitina-1 were analyzed following the same procedures as the other samples from the Chugach accretionary complex. Treating the Chitina sand like the metasedimentary samples, it shows an MDA of 143 ± 2 Ma (Fig. 1.2), with observable peaks at 146 Ma, 156 Ma and 305 Ma.
Figure 1.4  Geologic map showing the extent of the Chitina River drainage basin. The location of sample 10Chitina-1 shows that the sands of this part of the Chitina River mostly sample rocks related to the Wrangellia terrane or the Chitina Valley intrusives (batholith).

1.5  DISCUSSION

1.5.1 Two Distinct Blueschist Assemblages in Southern Alaska

The MDA of 136 Ma from the Liberty Creek blueschist confirms the hypothesis of Plafker et al. (1989) that there are two distinct blueschist assemblages along the southern Alaskan margin. Prior to this study robust geochronologic data only existed for the three western blueschist bodies (K, S, and I, Figure 1.1A) and these cooling ages indicate an Early Jurassic blueschist assemblage. Our 136 ± 2 Ma MDA (Fig. 1.2, Table 1.1) for the Liberty Creek schist unequivocally shows that it cannot be a part of the Early Jurassic blueschist assemblage because the protolith for the Liberty Creek schist was deposited at least 50 Ma after the Early Jurassic blueschists had cooled through their \(^{40}\text{Ar}/^{39}\text{Ar}\) and Rb-Sr (white mica) closure temperatures. Thus, the Liberty Creek schist must represent a distinctly younger blueschist metamorphic event.
Possible correlations for the Liberty Creek blueschists are blueschists from the Hubbard Glacier (H, Fig. 1.1A) and Chichagof Island (C, Fig. 1.1A). There is little geologic and thermochronologic data available for the Chichagof Island blueschists (e.g., Decker, 1980) and even less for the Hubbard Glacier schist (C and H, Fig. 1.1A). The latter is known only from glacial float (Forbes et al., 1979; and Pavlis, unpublished field observations). The Chichagof blueschists have lithologic similarities with the Liberty Creek schist (Decker, 1980), but the Chichagof blueschists occur as blocks in a mélange suggesting structural affinities with other southern Alaskan blueschists (Decker, 1980). Decker (1980) considered the associated mélange, the Kelp Bay Group, as an equivalent of the McHugh complex, which led to widespread correlation of these blueschists with the Kodiak Island blueschists. Nonetheless, Decker (1980) reported conventional K-Ar cooling ages from actinolite and white mica from greenschist and blueschist facies rocks of the Kelp Bay group that range from 109 Ma to 91 Ma; three of the white mica cooling ages from blueschists range from 98 Ma to 95 Ma. These cooling ages are similar to the conventional K-Ar ages reported from the Liberty Creek schist (Plafker et al., 1994), suggesting a possible related blueschist preservation event. Nonetheless, until more reliable cooling ages from both assemblages are available, this correlation should be considered tentative.

1.5.2 Paleogeography of the Liberty Creek Schist: Central Chugach Mountains

The location of the Liberty Creek schist within the complex geology of the central Chugach Mountains has implications for subduction zone processes that produced this system, particularly the role of strike-slip overprinting during oblique subduction. The Liberty Creek schist now lies to the south of, and structurally beneath, the Tonsina ultramafic complex but to the north of a dextral-strike-slip fault system that transported these rocks at least 130 km along
strike in the latest Cretaceous-Paleogene (Pavlis and Roeske, 2007) (Fig. 1.1B). The mantle rocks of the Tonsina complex in juxtaposition with blueschists formed at pressures comparable to mantle depths (Lopez-Carmona et al., 2011) suggests the Liberty Creek schist preserves a vestige of the mantle-level megathrust but that younger events both to the north and south have isolated this deeply exhumed fragment relative to adjacent areas. The northern limits of both the Tonsina complex and the Liberty Creek schist are not exposed (Fig. 1.1B). Thus, the structures responsible for the exhumation of these assemblages are poorly constrained. The northwest-dipping thrust contact between the Tonsina complex and the Liberty Creek schist, the Kenney Lake fault, is truncated by the Second Lake shear zone, a major strike-slip fault system that forms the southern contact of these assemblages (Pavlis and Roeske, 2007) (Fig. 1.1B). This pattern suggests that strike-slip faulting along the Second Lake fault occurred after the thrusting of the Kenney Lake fault. However, the geometry of these and other nearby structures strongly suggests that the deep exhumation of the assemblages in this area is at least in part related to strike-slip and or oblique motions (e.g., Fig. 7 of Pavlis and Roeske, 2007).

This interpretation may explain the location of the Liberty Creek blueschist along this segment of the BRF. The classic 2D, north directed, trench perpendicular subduction model, creates an age progression from older to younger accreted rocks as one moves from the backstop south toward the trench. This ideal south directed age progression within an accretionary complex is clearly violated in this area with the Cretaceous Liberty Creek blueschists (MDA ~136 Ma, Fig. 1.1B and 1.2) being located inboard of the Jurassic Potter Creek assemblage represented by samples 09CED02 and 09CED09 with MDA of ~149 Ma and ~159 Ma respectively (Fig. 1.1B and 1.2). This progression is consistent with a 3D view of the system. That is, the Liberty Creek and Tonsina assemblage presumably were both at upper mantle depths
in the Early Cretaceous but later strike-slip systems juxtaposed these rocks with younger and older rocks that had been accreted at shallower depths and 100's of km along strike. Thus, strike-slip motions have rearranged the accretionary complex by carrying the Potter Creek assemblage laterally along strike, outboard and south of the Tonsina complex and the Liberty Creek schist. The missing McHugh Creek assemblage rocks and the presence of the much younger Valdez group flysch structurally below and south of the Potter Creek strengthen the argument for strike-slip motions reorganizing the Chugach accretionary complex during late Cretaceous dextral oblique subduction (Pavlis and Roeske, 2007).

1.5.3 Paleogeography of the Liberty Creek schist: southeastern Alaska to British Columbia

Our initial hypothesis based on the detrital zircon analysis of the Liberty Creek schist was that the nearby Chitina Valley batholith, part of the Chitina arc, was the source for the assemblage because cooling ages as young as 130 Ma have been reported from this belt (Hudson, 1983; Dodds and Campbell, 1988). Pavlis and Roeske (2007) showed that clasts in sedimentary cover deposited unconformably on the Chugach terrane were derived from Chitina Valley metamorphic rocks now lying 150 km to the east, indicating at least 150 km of dextral slip and a paleogeography adjacent to the Chitina Valley batholith. Our sample from the Chitina River sands (10Chitina-1) shows, however, that the Chitina Valley batholith is an unlikely source for the Liberty Creek schist. Assuming these modern sands are a good proxy for the age of the batholith, the maximum depositional age (143 Ma) and the main peak on the probability distribution curve for the Chitina Valley batholith (146 Ma), are ~10 million years older than the main peak (137 Ma) and the calculated maximum depositional age of the Liberty Creek schist (136 Ma) (Fig. 1.2). Further, 50 out of 96 zircons, 52% of analyzed grains from the Liberty Creek blueschist (10CED14) have an age (±2 sigma errors) between 140 and 130 Ma, indicating
the Liberty Creek schist was sourced from an area dominated by Early Cretaceous rocks with zircon ages primarily in the 140–130 Ma range. In contrast, for the Chitina River sands, only 25 out of 83 zircons, 30% of analyzed grains, have ages within this range (Table 1.1). Finally, the population of detrital zircons in the Liberty Creek blueschist sample (10CED14, Fig. 1.2) is distinct from the population of zircons collected from the Chitina River sands, and all other samples analyzed from the Chugach accretionary complex to date (Fig. 1.2). Thus, unless our sampling of the Chitina Valley batholith is a poor proxy for the true age of the batholith, it is not the source for Liberty Creek sand in 10CED14. Moreover, the distinct population of zircons collected from the Liberty Creek schist could have a source different from the other rock assemblages within the Chugach accretionary complex.

The time interval between 140-120 Ma lies within a well-known magmatic gap in the northern Cordillera (e.g., Armstrong et al., 1988). This gap has been confirmed in the Canadian Cordillera (Gehrels et al., 2009) as well as within the Wrangellia Composite terrane (Hudson, 1983; Rioux et al., 2007) and sedimentary debris derived from it (Hampton et al., 2007; Amato et al., 2013). Thus, the predominance of 140-130 Ma zircons in the Liberty Creek schist raises the question of what was the source for these zircons.

Because igneous rocks of these ages in the northern Cordillera are rare, the simplest assumption is to use reasonable post-mid Cretaceous right lateral motions along the margin to infer a paleogeography. Estimates are variable for different structures but if the Liberty Creek schist was transported as much as 600 km along the BRF system (e.g. Pavlis and Roeske, 2007) as well as ~350 km along the Denali system (e.g., Lanphere, 1978; Lowey, 1998) offsets on the order of 1000 km are reasonable. This translation distance would point to a source in western Canada or southeast Alaska in what is now the Coast Plutonic complex; a reasonable source
location for the Liberty Creek schist given evidence that the Coast Plutonic complex was likely the source of the McHugh Creek assemblage a few million years later (Amato et al., 2013; Garver et al., 2013). Like most of the northern Cordillera the Coast Plutonic complex experienced a magmatic lull from Late Jurassic to Early Cretaceous time (~140-110 Ma) but that lull varies spatially (e.g., Gehrels et al., 2009). In particular, the lull is prominent to the west of the Coast Shear zone in rocks of the Wrangellia composite terrane, yet intrusive rocks to the east, which invade older basement rocks, are known to have been active during this magmatic lull (Gehrels et al., 2009; Mahoney et al., 2009). Particularly notable is the Firvale suite near Bella Coola, British Columbia (Fig. 1.1A) which was an active magmatic belt from 140–130 Ma (Gehrels et al. 2009; Mahoney et al. 2009). Nonetheless, although this belt is the right age to source the Liberty Creek schist, the plutons in this region are emplaced into Stikine and Yukon-Tanana basement which not only contain older rocks than we see in the detrital zircons of the Liberty Creek schist, but also lie on the wrong side of the Coast Shear Zone, which is widely recognized as a mid-Cretaceous suture (Rubin and Saleeby, 1992). That is, an ocean basin separated these rocks in the Early Cretaceous, prior to mid-Cretaceous closure of the suture. One solution to this issue is the tectonic model of Gehrels et al. (2009) that proposed a diachronous closure of the basin associated with a left-lateral strike-slip system along what is now the Coast Shear zone, allowing for open ocean basins at the same time the Bella Coola area was a magmatic arc source to the Early Cretaceous trench (Fig. 5). Nonetheless, that model may be too simplistic to accommodate these new data.
Figure 1.5  Schematic model of the Northern Cordillera in the Late Cretaceous. This model illustrates one hypothesis of how the eastern Coast Plutonic complex could have supplied sediments to the Chugach terrane. Modified from Gehrels et al. 2009.

140-130 Ma rocks are also present within the western North American Cordillera. The rocks that now comprise the Guerrero terrane of western Mexico carry the signature of a well-known Jura-Cretaceous arc terrane that was active during this 140-130 Ma interval (Talavera-
It has long been thought that the Wrangellia composite terrane was an offshore arc system in Late Jurassic-earliest Cretaceous time, and paleomagnetic data have consistently shown low paleolatitudes for the Wrangellia composite terrane in this time period (Coney et al., 1980; Oldow et al., 1989; Irving et al., 1996; Stamatakos et al., 2001). Indeed, these conclusions are at the heart of the Baja-BC controversy which includes the paleogeography of Wrangellia composite terrane. We suggest that the results from the Liberty Creek terrane reopen this issue because a paleogeographic scenario by Umhofer (2003) places the Wrangellia composite terrane in close proximity to the Guerrero terrane, currently in southwestern Mexico, in latest Jurassic time. This paleogeography would allow a Guerrero arc source for the Liberty Creek schist protolith. More work is needed to confirm this speculation, but the results here may be the first real support beyond paleomagnetic data for such large-scale, post-early Cretaceous northward transport of the Wrangellia composite terrane.

1.6 CONCLUSIONS

At least two examples of blueschist metamorphic events are preserved along the south Alaskan margin. The first blueschist event was in the Early Jurassic and produced the blueschist bodies on the Kodiak Islands, the Seldovia schist, and the Iceberg Lake schist. The second blueschist event produced the Liberty Creek schist after ~136 Ma and probably before the 123-107 Ma K/Ar whole rock ages from the Liberty Creek schist. The Hubbard Glacier schist and Chichagof Island schist probably were produced during this second blueschist metamorphism event but further work is needed on the cooling history of all of the eastern blueschists. A 2-dimensional subduction margin perpendicular accretionary model cannot account for the present distribution of subduction assemblages in the central Chugach Mountains. The presence of a younger accretionary assemblage, the Liberty Creek schist, inboard of an older assemblage, the
Potter Creek assemblage, points to a 3-dimensional process including the well-known record of forearc strike-slip within the system. The unusual detrital zircon signature of the Liberty Creek blueschist with a predominance of 140-130 Ma zircons points to a sedimentary source that is atypical of the northern Cordillera but consistent with a more southerly Cordilleran source, particularly the Guerrero terrane of western Mexico. Thus, future work should address far-traveled scenarios for the Wrangellia composite terrane.

1.7 ACKNOWLEDGMENTS
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1.8 WORKS CITED


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1.9 SUPPLEMENTARY DATA

Table 1.1 Complete U-Pb Zircon Data Collected by LA-MC-ICPMS

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1001041: Liberty Credit: solid (WV, 02/27/00, 02/27/01)
100104: Liberty Credit: solid (WV, 02/27/00, 02/27/01)
Chapter 2: Structural History of the Iceberg Lake and Liberty Creek blueschist bodies of the central Chugach Mountains, southern Alaska

2.1 Abstract

Structural data collected from the Iceberg Lake schist, the Liberty Creek schist, and the surrounding Potter Creek assemblage suggest these rocks have recorded a similar strain history. The Iceberg Lake schist, the Liberty Creek schist, and the Potter Creek assemblage have different lithologies, cooling ages, and ages of accretion that span 50 million years. Similar strain patterns include a shallow southerly dipping cleavage (S2) which folds (F2) previous layering, a vertical N-S striking cleavage (S3) which folds F2 folds, and variably cross-cutting low temperature mineral veins that follow these cleavages. Two hypotheses could explain these similar strain patterns. 1) These rock assemblages underwent accretion, metamorphism, and exhumation at the respective times indicated by thermochronologic analyses and observed similarities in recorded strain are caused by a similarly-oriented subduction zone. In this scenario the current geographic locations of these assemblages are a result of latest Cretaceous to Paleogene strike-slip motion on the Border Ranges fault. 2) A regionally complex, time transgressive, three dimensional model of both margin perpendicular and margin parallel motion accounting for accretion, erosion, and dextral transpression has been recorded in this section of the Jurassic-Cretaceous paleo-subduction wedge. After individual earliest histories of accretion, underplating, and metamorphic cooling, central Chugach Mountain assemblages were incrementally moved vertically and horizontally through the subduction wedge at sub-greenschist temperatures. These incremental motions were recorded as shortening perpendicular to the relative direction of motion, S2 and S3 cleavages, and low temperature veins intruding along cleavage planes perpendicular to that shortening.
2.2 Introduction

Subduction complexes record extensive and complex kinematic histories of deformation (e.g., Freehan and Brandon, 1999; Platt, 2000), reworking of wedge materials (e.g., Karig, 1980; Wakabayashi, 2012), and changes in subduction style from erosion to accretion (e.g., Clift and Vannucci, 2004; Schemmann et al., 2008; Amato and Pavlis, 2010; Amato et al., 2013) throughout their active histories. Reactivation of a paleo-margin can reorganize an already complex geochronologic history (Wakabayashi, 1992; Roeske et al., 2003; Pavlis and Roeske, 2007). Any combination of these processes can make deciphering the history of assemblages within a subduction complex a difficult structural problem.

Understanding how these complexities interact through time is integral to unraveling the workings of subduction zones. Investigators of subduction complexes utilize various thermochronologic techniques (e.g., $^{40}$Ar/$^{39}$Ar, Rb-Sr, U-Pb, and U/Th-He systems in various minerals) in conjunction with strain markers (e.g., crenulation cleavages, S-C fabrics, mineral and intersection lineations, porphyroblasts, slickenfibers, and GPS measurements in modern systems etc.) to clarify the temporal record of deformation along a subduction margin. The geologic record along a short (~100 km) section of a subduction margin can be obscured by the occurrence of multiple accretion and erosion events driven by an uneven subducting plate surface and subduction orientation (e.g., Cloos and Shreve, 1988; Bourgois et al., 2000; Clift and Vannucci, 2004; Amato and Pavlis, 2010; Wakabayashi, 2012; Amato et al., 2013). Changes in stress orientations within a subduction complex can cause variations in recorded strain and exhumation histories (e.g., Platt 2000; Miller et al., 2001; Nicol et al., 2007; Schemmann et al., 2008). These variations during the history of a subduction margin can result in the true kinematic histories of recorded deformations unclear, as strain markers can be overprinted and thus mis-interpreted or even unrecognized (e.g., Ferguson, 1984; Platt, 2000; Lebit et al., 2002).
The arrangement of the assemblages of the central Chugach Mountains of southern Alaska has long been known to exhibit evidence of multiple deformations and subsequent reactivations (e.g., Carden et al., 1977; Forbes et al., 1979; Decker, 1980; Plafker et al., 1989; Plafker et al., 1994; Pavlis and Roeske, 2007). The geochronologic history of these assemblages continues to be refined as new data are described (e.g., Pavlis and Roeske, 2007; Amato et al., 2013; Day, Chapter 1, this dissertation). We present structural data from the Iceberg Lake and Liberty Creek blueschists together with structurally adjacent rocks in the central Chugach Mountains that shows that these two separate tectonic assemblages and surrounding rocks record similar strain histories, despite the blueschist metamorphism of the Iceberg Lake and Liberty Creek blueschists having occurred over 50 million years apart (Day, Chapter 1, this dissertation). We propose two hypotheses to explain these relationships: 1) The Iceberg Lake schist was subducted to blueschist facies and exhumed through white mica closure temperature (~400°C) at ~186 Ma (Sisson and Onstott, 1986). The Iceberg Lake schist then sat at or above these mid-crustal depths until the Liberty Creek blueschist protolith was deposited at ~136 Ma (Day, Chapter 1, this dissertation), subducted, and then cooled through white mica closure (~400°C) at ~123-107 Ma (Plafker et al., 1994). After the Liberty Creek schist passed through the ~107 Ma white mica closure temperature (~400°C), both blueschist bodies were moved through the subduction wedge at lower greenschist to sub-greenschist facies, under the same kinematic regime, thus recording the same youngest generation of strain. 2) The Iceberg Lake and Liberty Creek blueschist bodies were subducted through blueschist facies and cooled through white mica closure temperatures and lower-grade metamorphic facies at their respective times, tens of millions of years apart from one another. The similarity in recorded strain is a result of these blueschist bodies experiencing the same stress regimes while being deformed along a similarly-
oriented subduction margin 50 million years apart from one another. We conclude that the first hypothesis better explains the strain record of these blueschists based on our observations and a thermochronologic record established by these and other assemblages in the central Chugach Mountains.

Figure 2.1  Geologic map of the Valdez Quadrangle and easternmost Anchorage Quadrangle showing major structures and geology along this segment of the Border Ranges Fault system. Figure is after Pavlis and Roeske, 2007.

### 2.3 Tectonic Setting

The Valdez Quadrangle in the central Chugach Mountains contains some of the most complicated geology related to the long history of southern Alaskan subduction. This segment of the Border Ranges Fault (BRF) megathrust is poorly understood because previous work has been done at smaller scales of 1:250,000 and 1:100,000. Much of the area has poor rock exposure, and minimal topical studies have been done across the Quadrangle (Pavlis and Roeske, 2007).
The oldest rocks in the central Chugach Mountains are present in the Peninsular and Wrangellia terranes (Coney et al., 1980; Plafker et al., 1994) (Fig. 2.1). The Peninsular terrane is composed of the basement, upper mantle to lower crust, and volcanic rocks of the Lower Jurassic Talkeetna arc (Burns et al., 1991; Clift et al., 2005; Rioux et al., 2007; 2010). These rocks were intermittently exhumed but are overlain by younger forearc basin strata that preserve at least two angular unconformities in what are now the Chugach Mountains (e.g., Fisher and Magoon, 1978; Trop et al., 2005; Hacker et al., 2011). In the central Chugach Mountains the upper mantle to lower crustal rocks are represented by the Klanelneechna klippe and Tonsina ultramafic complex (Burns, 1985; Rioux, et al., 2007 and 2010; Hacker et al., 2008) (Fig. 2.1). The Klanelneechna klippe was exhumed from depths ranging from 19-29 km (Hacker et al., 2008) and has cooling ages that range from 201 Ma (U-Pb, zircon), 188 Ma (40Ar/39Ar on hornblende),...
to 59 Ma (U-Th/He, zircon) (Hacker et al., 2011). The Tonsina ultramafic complex was exhumed from depths ranging from 23-44 km (Debari and Coleman 1989; Hacker et al., 2008) and has cooling ages that range from 204-159 Ma ($^{40}$Ar/$^{39}$Ar on hornblende) to 9 Ma (U-Th/He, apatite) (Hacker et al., 2011).

The Wrangellia terrane includes variably metamorphosed andesitic arc basement rocks of the Skolai arc (Beard and Barker, 1989); Late Pennsylvanian intrusives indicate that the aforementioned Wrangellia terrane basement rocks are at least Middle Pennsylvanian in age (Gardner et al., 1988; Plafker et al., 1989). Sillimanite-bearing metapelites and other metamorphosed sedimentary and mafic igneous rocks are a part of this basement sequence which is covered by non schistose greenschist facies upper Paleozoic andesitic and sedimentary rocks of the Skolai Group (Smith and MacKevett, 1970; Plafker et al., 1989). The Strelna metamorphic rocks (Fig. 2.1) are thought to be equivalent to these Skolai Group metamorphic rocks (Plafker et al., 1989; Pavlis and Roeske, 2007).

The Late Jurassic Chitina arc is limited to intrusive rocks along and immediately north of the BRF (Plafker et al., 1989; Roeske et al., 2003) and the Cretaceous Chisana arc (Short et al., 2005; Snyder and Hart, 2007) is developed across the older arc assemblages as both intrusive rocks and volcanic cover on the Peninsular and Wrangellia arc terranes. Isotopic signatures from the Chitina arc indicate that it was generated in either an intraoceanic island arc or an "immature" (proto-) continental arc setting indicating that it may have been transitional between the Talkeetna island arc and the Chisana continental arc (Snyder and Hart, 2007). These various arc sequences were fully accreted to North America by the middle Cretaceous and are currently referred to as the Wrangellia composite terrane (e.g., Gardner et al., 1988; Burns et al., 1991;
Plafker et al., 1994; Pavlis and Roeske, 2007; Hacker et al., 2008; Beranek et al., 2014; Israel et al., 2014).

By middle Cretaceous time the BRF was clearly the backstop to subduction beneath the Wrangellia composite terrane and an ocean-continent subduction zone was fully established (Plafker et al., 1994; Pavlis and Roeske, 2007). It is unclear if prior to this time strike-slip systems disrupted the system, subduction erosion modified the forearc, or both. The forearc accretionary complex that would normally be associated with such a subduction zone is missing and the forearc basin carries a complex history of uplift and erosion during the latest Jurassic to middle Cretaceous (Pavlis and Crouse, 1989; Roeske et al., 1989; Clift et al, 2005; Trop et al., 2002; Trop et al., 2005; Pavlis and Roeske, 2007).

The Chugach accretionary complex associated with this convergent margin is located south of the BRF (Amato et al., 2013). The Chugach accretionary complex has traditionally been divided into two subterraneas, including a mélange unit and a coherently deformed turbidite assemblage (Plafker et al., 1994). Scattered blueschists along the margin have typically been lumped with the mélange unit because of their spatial association with that unit. There are now five distinct assemblages recognized in the Chugach accretionary complex (Amato et al., 2013; Day, Chapter 1, this dissertation) from oldest to youngest: 1) Early Jurassic blueschists; 2) the Late Jurassic Potter Creek assemblage; 3) the Early Cretaceous Liberty Creek blueschist; 4) the middle Cretaceous McHugh Creek assemblage; and 5) the Chugach flysch/Prince William assemblage. The first four are subdivisions of the mélange unit whereas the last is a composite Late Cretaceous to Paleogene subduction assemblage that systematically youngs toward the modern trench (Kochelek et al., 2011; Amato et al., 2013; Garver and Davidson, 2013). Either during or after their accretion, the five assemblages of the Chugach accretionary complex were
structurally reorganized via strike-slip motions and no longer match the typical 2D accretion model with accretionary assemblages younging from arc to trench (Pavlis and Roeske, 2007; Day, Chapter 1, this dissertation). These strike-slip motions are thought to be a result of either slip-partitioned transpressional subduction during accretion of the Chugach accretionary complex or Cenozoic reactivation of the margin (Pavlis and Roeske, 2007).

All five assemblages of the Chugach accretionary complex record ductile fabrics of varying metamorphic grade which show variable amounts of overprinting reflecting kinematic changes over time. Wallace (1981) and Nokleberg et al. (1989) first described these relationships in the central Chugach Mountains but interpreted the structural history in a 2D thrust overprinting scenario. Pavlis and Crouse (1989) proposed an alternative 3D kinematic history that included strike-slip overprints and later work supported this interpretation in the context of a major Late Cretaceous strike-slip overprint (e.g., Pavlis et al., 2003; Roeske et al., 2003; Pavlis and Roeske, 2007). These studies demonstrate that the complex fabric overprints vary in age and kinematics, but the details remain poorly resolved (Pavlis and Roeske, 2007).

2.4 METHODS
Prior to this study geologic mapping carried out in the central Chugach Mountains describing the Iceberg Lake schist, Liberty Creek schist, and surrounding assemblages had been carried out at smaller scales of 1:250,000 and 1:100,000 (e.g., Nokleberg et al. 1989; Plafker et al., 1989; Plafker et al., 1994). Pavlis and Roeske (2007) presented a 1:36,000 map of the western edge of the Iceberg Lake schist but that small area comprised a fraction of the exposed blueschist assemblages. Thus, a goal of this study was to map both central Chugach blueschist bodies at larger scales (1:12,000-1:24,000) and evaluate their structural history relative to the regional chronology. The 2009 and 2010 field seasons were spent mapping within the Iceberg
Lake and Liberty Creek schists with access limited by road and trail access (Liberty Creek schist) and fixed-wing aircraft access to the Iceberg Lake schist (Figs. 2.2 and 2.3).

This study reports the results field based data collection in the central Chugach Mountains focused on the structure of the Iceberg Lake and Liberty Creek blueschist assemblages. The study also incorporates earlier work carried out in the early 2000’s by T. Pavlis on the Iceberg Lake blueschists, partially reported in Pavlis and Roeske (2007). Aside from the earlier work by Pavlis, all of the field data were acquired with a digital mapping procedure described by Pavlis et al. (2007) with most orientation data collected using Geoclino automated compass devices (see http://www.gsinet.co.jp/english/geoclino/geoclino-g.html). These devices showed considerable compass drift during field days at these high latitude sites, which we attempted to compensate for with frequent recalibration. Nonetheless, some of our orientation data may be contaminated by erroneous compass errors as large as 10-15 degrees, which may account for some of the scatter in our orientation data. These errant data account for a small fraction of the large number of measurements collected and are unlikely to modify average orientations. Despite this potential for error, these data are consistent with previous observations within this region, though individual interpretations may vary (e.g., Nokleberg et al., 1989; Bol and Roeske, 1993; Roeske et al., 2003; Pavlis and Roeske, 2007).

2.5 GEOLOGY OF THE CENTRAL CHUGACH MOUNTAINS ACCRETIONARY ASSEMBLAGES

The geologic maps produced during this work (Figs. 2.2 and 2.3) show both lithologic distributions and surface trace form lines for the major fabrics in the field sites.
2.5.1 Rock Units

2.5.1.1 Iceberg Lake schist

The oldest assemblage of the Chugach accretionary complex in the central Chugach Mountains is the Iceberg Lake schist. We examined this unit at three localities: two localities along the western edge of the Tazlina glacier, described previously by Pavlis and Roeske (2007), and the area of Fig. 2.2, east of the Tazlina glacier. The Iceberg Lake schist was originally mapped as a large 10 x 30 km body within the McHugh complex (Winkler et al., 1981c) but the work by Pavlis and Roeske (2007) and this study show that the mapped assemblage is a series of fault-bounded bodies within the younger mélange.

![Figure 2.2](image_url)

Figure 2.2 1:36:000 scale geologic map of the Iceberg Lake schist showing dominant lithologies and structures.
The dominant rock type in the Iceberg Lake schist is variably deformed mafic schist, which appears to represent both metagabbros and metavolcanic rocks. The rocks of the Iceberg Lake schist contain a variably developed continuous cleavage and mineral lineation. The mafic schists show variable mineral assemblages indicative of blueschist to epidote-amphibolite facies conditions. The blueschist facies mineral suite lawsonite-crossite-albite-chlorite is common (Winkler et al., 1981a, b) but the greenschist facies assemblage actinolite-chlorite-albite-epidote is also ubiquitous. In a few of our samples higher temperature conditions are suggested by epidote amphibolites in mafic rocks and garnet-white mica-chlorite bearing assemblages in pelitic rocks. Collectively, the mineralogy suggests variable metamorphic conditions among the fragments of the assemblage. In hand sample the mafic schists display a continuous cleavage that is variably developed and commonly weak. Occasionally these rocks show a microcrystalline matrix with 0.5 mm - 4 mm plagioclase porphyroblasts. In thin section these minerals are crystallographically aligned to form the main fabric (e.g., Fig. 7e).

In addition to the mafic schists, the Iceberg Lake schist also contains: 1) highly deformed quartzites with a strong LS tectonite fabric, which almost certainly represent deformed chert because these rocks do not yield detrital zircon; 2) pelitic schists, which presumably originated as argillites and mafic tuffs based on the lack of detrital zircons (Day, Chapter 1, this dissertation) and carry the most complete fabric overprint record due to their prominent mica foliation; 3) meta-greywacke, which are coarser-grained than the pelitic schists, but are also devoid of detrital zircons; and 4) minor blocks and lenses of weathered dark colored marble. Iceberg Lake assemblages are demonstrably of a higher metamorphic grade than the surrounding sub-greenschist to greenschist facies Potter Creek assemblage, based on both grain size and mineralogy.
Sisson and Onstott (1986) showed that the Iceberg Lake schist is an Early Jurassic blueschist assemblage that underwent peak blueschist metamorphism at approximately 185 Ma. Lithologic descriptions (e.g., Winkler et al., 1981a, b) and geochemical analyses presented by Plafker et al., (1994) indicate that the Iceberg Lake schist has an N-type MORB affinity which is common of many blueschists (e.g., Agard et al., 2009). The peak metamorphic assemblage is consistent with exhumation from depths of approximately 20 km (Sisson and Onstott, 1986) and emplacement within the Potter Creek assemblage may or may not be related to the nearby Klanelneecheena klippe (e.g., Sisson and Onstott, 1986; Pavlis and Roeske, 2007) (Fig. 2.1).
2.5.1.2 Potter Creek assemblage

Amato et al., (2013) proposed the name Potter Creek assemblage for the older parts of the McHugh complex that are characterized by the lithologic association of black argillite-green tuff-chert that is stratally disrupted to form a mélange. In the two mapped areas of this study, the rocks previously shown as McHugh complex all appear to be Potter Creek assemblage based on lithology and from detrital zircon signatures described below. These rocks typically vary from light gray to dark green in color. Where chert or argillite-rich layers are present these phyllitic rocks contain white and red or black laminaitions, respectively. Structural fabrics are more clearly visible in argillite rich rocks, whereas more sand-rich meta-greywacke rocks tend to have a more massive appearance. Both of these assemblages from the Potter Creek assemblage were sampled for detrital zircons and two lithic sandstone samples yielded detrital zircons with maximum depositional ages of 149 Ma and 159 Ma (Day, Chapter 1, this dissertation).

2.5.1.3 Liberty Creek schist

Day (Chapter 1, this dissertation) showed that the Liberty Creek schist has a maximum depositional age of 136 Ma and was accreted during a regional gap in accretion that Amato et al. (2013) ascribe to a period of subduction erosion. The blueschist facies mineral assemblage of the Liberty Creek schist reveals that the Liberty Creek schist may have reached depths as deep as 50 km (Lopez-Carmona, 2011), and conventional K-Ar whole rock cooling ages are scattered but suggest blueschist metamorphism occurred sometime between 123–107 Ma (Plafker et al., 1989; Plafker et al., 1994). Currently the Liberty Creek schist is in-board and north of the older Potter Creek assemblage separated by a major strike-slip fault (Day, Chapter 1, this dissertation) (Fig. 2.1). The timing of this structural reorganization is unclear, though it has been attributed to strike-slip motion related to Late Cretaceous transpressional subduction or Cenozoic strike-slip reactivation of the BRF (Pavlis and Roeske, 2007).
The Liberty Creek schist is composed of layers and slices of pelitic schists and metagreywacke. Similar to the rocks of the Iceberg Lake schist the pelitic schists probably originated as pelagic mud and tuff based on the scarcity of detrital zircons. Similarly, lithic sandstones sampled in this study were devoid of detrital zircons suggesting a mafic source or other source lacking zircons. Liberty Creek schist rocks vary from light gray or green, to dark green, to a light steel blue in color. Most outcrops carry a phyllitic to schistose texture which becomes pronounced in more argillite rich layers. Layers that are more chert or argillite rich can carry white and red or black laminations respectively.

2.5.1.4 McHugh Creek assemblage and Valdez group flysch

Following Liberty Creek schist emplacement, accretion resumed in the latest Early Cretaceous and is represented by the McHugh Creek assemblage and the Valdez group flysch (Amato and Pavlis, 2010; Amato et al., 2013). We have not found any rocks diagnostic of the McHugh Creek assemblage in the central Chugach Mountains. Because the Iceberg Lake schist is contained within Potter Creek assemblage rocks and the Liberty Creek schist, a younger tectonic unit (Day, Chapter 1, this dissertation), lies structurally inboard of the Potter Creek assemblage (Figures 2.1 and 2.3), the blueschist units of the Chugach terrane are out-of-sequence in the normal stacking succession typically seen in accretionary complexes. Thus, structural overprinting must have shuffled these rocks from their original structural positions; a problem that is considered below through an analysis of the structure in these rocks.
2.6 Structural Data

2.6.1 Iceberg Lake schist

2.6.1.1 Bounding faults

The Iceberg Lake schist is a series of fault-bounded slivers of mafic schists, meta-psammites, and meta-pelites (Fig. 2.2). Although the rocks are highly variable across the area with lithologic variations at outcrop scale, the rocks can be broadly divided into two lithotypes: a predominantly metasedimentary assemblage comprised of quartz-bearing, layered rocks (unit Jbs, Figure 2.2) and a predominantly metaigneous assemblage comprised of mafic schists (unit JPzm, Figure 2.2). All of the metamorphosed rocks are distinguished from the adjacent Potter Creek assemblage by recrystallization producing new mineral growth visible in hand specimen and by a variably developed tectonite fabric with overprinting cleavages that were a focus of this study.

In the mapped area the blueschists are contained within the Potter Creek assemblage primarily as a large fault-bounded block, but also occurring as smaller fragments north and south of the main outcrop belt (Figs. 2.1 and 2.2). The Jurassic mafic granulites of the Klanelneechena klippe lie structurally above, and west-northwest of the Iceberg Lake schist (Fig. 2.1). Pavlis and Roeske (2007) showed that the basal thrust in the Klanelneechena klippe was a Cenozoic structure, because the thrust cross-cut strike-slip faults that involved Tertiary rocks. Thus, the area contains a complex Cenozoic fault history that is difficult to distinguish from older structures, which handicaps detailed reconstruction of the assemblage.
The contacts between the Iceberg Lake schist and adjacent mélange to the north and south were originally mapped as vertical faults (Fig. 2.1). Our mapping confirms a vertical northern fault boundary to the main body of the Iceberg Lake schist. However, this fault is not
the northern limit of the blueschist assemblage because at least one blueschist fragment lies north of this large fault in the northwest corner of the mapped area (Fig. 2.2). The northern fault is marked by a broad damage zone up to 400 m wide with steeply north-plunging quartz rods along this fault boundary. Based on the cross-cutting relationships recognized by Pavlis and Roeske (2007) across the Tazlina Glacier to the west, we infer that this structure is probably an Eocene strike-slip fault that is part of the complex array of Eocene structures in this segment of the BRF.

The southern boundary of the Iceberg Lake schist is distinctly different than the northern boundary. In the mapped area this structure is a ~30° north-dipping fault surface that is a relatively discrete fault. That is, although a damage zone follows the fault, the faulting is less conspicuous within the crystalline rocks of the blueschist assemblage with enveloping mélange fabrics to the south subparallel to the fault boundary. This suggests the boundary is a remnant, Mesozoic structure generated during emplacement of the blueschist assemblage within the mélange, although a more regional mapping effort would be required to fully test this hypothesis. An isolated klippe ~2km to the south of the main fault trace (Fig. 2.2) may be a low-angle fault equivalent of the southern boundary fault, but it could also represent a younger, isolated fault block similar to the Klanelneechema klippe.

Numerous faults also occur in the interior of the Iceberg Lake schist, typically separating the major mappable units within the blueschist assemblage (Fig. 2.2). Many of these fault systems contain highly polished surfaces. Many fault traces also show evidence of iron rich fluids migrating along the faults as evidenced by hematitic staining in fault rocks and fault boundaries.
2.6.1.2 Ductile structures, blueschist units

The different slivers of rock within the blueschist assemblage reveal a variable record of finite strain. The metasedimentary units (unit Jbs, Fig. 2.2), particularly pelitic rocks within the assemblage, show the main tectonite fabric and overprints most clearly. Mafic schists (unit JPzm, Fig. 2.2) display equivalent structures but the main fabric and overprinting structures are less conspicuous.

The main tectonite fabric in the Iceberg Lake schist is a continuous cleavage, S1, which is parallel to layering. The cleavage is a composite fabric formed by both crystallographic and dimensional preferred orientation of minerals. We interpret layering as transposed bedding, layering inherited from an early mélangé fabric, or both. The S0=S1 fabric dips steeply to moderately to the north-northwest, subparallel to the southern bounding fault but locally ranges to steep southerly dips due to fold overprints (Fig. 2.4a-1, 2.7a). A prominent intersection lineation, S1-S0, trends east-northeast to west-southwest but can be observed to fan 10°-20° to the north and south (Fig. 2.4a-4).

S1 is overprinted by a second cleavage, S2. S2 is a shallow, south to southeast dipping crenulation cleavage that is axial planar to open to close F2 folds (Fig. 2.4a-2, 2.7a). L2, an S2-S1 intersection lineation (Fig. 2.4a-5), is subhorizontal and trends east-northeast to west-southwest, parallel to F2 fold axes. F2 folding disperses S0=S1 foliation from moderately north dipping through steeply south dipping orientations (Figure 2.4a-1).

A third cleavage, S3, is a north-south to north-northwest striking vertical crenulation cleavage that is axial planar to a third fold generation, F3 (Fig. 2.4a-3, 2.7c). F3 form open to close folds of S1 and S2 cleavage planes. F3 fold wavelengths vary from 2-20 cm, with fold axes (L3 of Fig. 2.4a-6) plunging moderately to steeply north, down dip along S1, and moderately to shallowly south down dip along S2 cleavage planes (e.g., Fig. 2.6a, b, and c). The three fold
generations produce type 1 interference patterns of Ramsay (1967) leading to dome and basin structures observable along S1 and S2 cleavage planes (Fig. 2.6a, b, and c). The cross-cutting relationships between D2 and D3 structures are generally cryptic in hand specimen, but we infer that that N-S cleavage is younger because the folds are more open and the fabric is weaker, consistent with formation during falling temperature conditions during later overprints in the rock.

2.6.1.3 Ductile structures, Potter Creek assemblage

In the mapped area, the blueschist units are enveloped by mélange rocks of the Potter Creek assemblage. Correlation to the Potter Creek assemblage is confirmed by a sample collected just north of the Iceberg Lake blueschist which yielded detrital zircons with a maximum depositional age of 160 Ma and a detrital zircon age distribution indistinguishable from Amato et al.’s (2013) type Potter Creek assemblage in the Anchorage area (C. Worthman, unpublished data). The mélange assemblage has relatively indistinct mineral assemblages but ubiquitous chlorite-white mica-epidote with abundant prehnite veins suggests greenschist to subgreenschist facies conditions. The structural fabrics developed in these rocks, however, show apparent correlations to the history of the blueschists and are a major focus of this study.

The Potter Creek assemblage contains a conspicuous lensoidal mélange that shows a prominent cleavage, S1 that is subparallel to the stratal disruption of the mélange fabric. S1 is marked by a very fine-grained micaceous mineral growth (primarily chlorite and white mica) producing a phyllitic cleavage. S1 is subparallel to the southern bounding fault of the Iceberg Lake schist and the S1 Fabric of the Iceberg Lake schist (Figure 2.4). That is, S1 is characterized by northeast strikes and dips steeply to moderately to the north-northwest but locally ranges to steep southerly dips due to overprinting folds (Fig. 2.4b-1).
S1 is overprinted by a prominent crenulation cleavage, S2. S2 is moderately south dipping (Fig. 2.4b-2) and axial planar to open to close folds in S0-S1, giving S0-S1 the observed variation of dips (Fig. 2.4b-1). L2, S2-S1 intersection lineation, is locally present but indistinct such that only a few measurements were possible (Fig. 2.4b-5) but given the geometry of the cleavage and S1 the intersections, like the F2 folds, must have NE-SW trends with shallow plunges.

A third cleavage, S3, is a second crenulation cleavage in the Potter Creek assemblage but shows more variability than S2 (Fig. 2.4b-2 and 2.3). Strikes vary from north-south to northwest-southeast and have a range of vertical to more moderate dips (Fig. 2.4b-3). Basin and dome structures potentially created by F2 and F3 fold interference patterns were less clearly conspicuous than equivalent structures in the schist, but presumably are present.

2.6.2 Liberty Creek schist

2.6.2.1 Bounding faults

Unlike the Iceberg Lake schist, the Liberty Creek schist is relatively intact internally with few conspicuous faults other than faults that bound the main outcrop belt. In addition, the blueschist assemblage lies structurally adjacent to the crystalline backstop, rather than as blocks within the Potter Creek mélange. The northern and eastern boundaries of the Liberty Creek schist are obscured by Quaternary sediments of the Copper River (Plafker et al., 1994; Pavlis and Roeske, 2007). The western boundary of the Liberty Creek schist is a west dipping thrust fault (Plafker et al., 1994; Pavlis and Roeske, 2007) placing older Talkeetna arc ultramafic rocks (Hacker et al., 2011) structurally on top of the younger Liberty Creek schist (Day, Chapter 1, this dissertation). The southern boundary of the Liberty Creek schist, however, is a younger, vertical fault, the Second Lake fault (Figure 2.3).
Although the Second Lake fault was shown on regional maps (e.g. Plafker et al., 1994) as a single fault, our mapping reveals that the structure is a complex fault zone up to 1 km wide. Slickensided surfaces and fault geometry strongly suggest that the Second Lake fault is a strike-slip fault, but the zone displays mixing of Liberty Creek type blueschist and greenschist with mélangé rocks that are demonstrably part of the Potter Creek assemblage (Day, Chapter 1, this dissertation).

2.6.2.2 Ductile structures, blueschist units
Our field observations indicate the earliest foliation in these rocks, S1, is overprinted by two younger crenulation cleavages, S2 and S3, in agreement with previously published observations of south verging folds overprinted by north verging folds consistent with the first two foliations observed in this study (e.g., Plafker et al., 1989; Nokleberg et al., 1989; Plafker et al., 1994). The oldest foliation, S1, has transposed S0, which is a layering or pseudo-layering representing an even earlier mélangé fabric. The absence of distinct, mappable layers showing folding and general mesoscopic lensoidal lithologic bodies within the assemblage suggest an original mélangé fabric, but the ductile overprint is sufficiently intense that this conclusion is uncertain. S1 itself is marked by a pronounced mica foliation and dimensional preferred orientation of minerals and objects, many of which may be primary sedimentary clasts or volcanic clasts. Mineral and stretching lineations are indistinct in the assemblage, suggesting flattening strains during D1. S1=S0 dips moderately to the north-northwest but locally ranges to steep southerly dips due being overprinted by younger fold generations (Fig. 2.5a-1, 2.7b). L1 lineations, defined by S1-S0 intersections trend east-northeast to west-southwest and fan out as a result of folding around younger generations of D2 and D3 folds (Fig. 2.5a-4).
Figure 2.5  Stereonet representation of crenulation cleavage and intersection lineation data collected within the blueschist rocks of the Liberty Creek schist. b. Stereonet representation of crenulation cleavage and intersection lineation data collected within the Potter Creek assemblage south of the Liberty Creek schist. Detailed descriptions of cleavage and lineation interactions are in the text.

S1 is overprinted by a prominent crenulation cleavage S2. S2 is a shallow, south dipping, crenulation cleavage, (Fig. 2.5a-2) that is axial planar to open to tight F2 folds (Fig. 2.5a-1, 2.6c, 2.7b). L2, the S2-S1 intersection lineation, (Fig. 2.5a-5), has a sub-horizontal plunge and east-
northeast to west-southwest trends. These variable trends are due to folding around a third
generation of folds, F3 (Fig. 2.5a-6).

The youngest cleavage, S3, is a north to south striking, vertical crenulation cleavage that
is axial planar to open, upright F2 folds in S1 (Fig. 2.5a-3, 2.7d). L3, the S1/S2-S3 intersection
lineation, intersects both S1 and S2 but the overprint on S2 is not conspicuous (Fig. 2.5a-6).
Observations in thin section reveal lower grade veins, stipnomelane, prehnite, laumontite, and or
calcite, filling and following cleavages and remnant layering. Figure 2.7f is a photomicrograph
of veins observed in the Liberty Creek schist, forming parallel to horizontal the S1/S2 cleavages
and vertical S3 cleavages. S1/S2 parallel veins can be observed to cross-cut and offset S3 parallel
veins and in the same slide S3 parallel veins can be seen to cross-cut and offset S2 parallel veins.
This suggests both generations are relatively young, and used the planar anisotropy from the
fabrics during generation of the veins.

The type 1 interference patterns (Ramsay, 1967) formed by folds associated with the
three cleavage generations create basin and dome structures observable along the S1 cleavage
planes (Fig. 2.6a and c). The wavelengths of these basin and dome structures vary from 1-2 cm
to ~20 cm locally (Fig. 2.6b and c). S3 and L3 extend into the Potter Creek assemblage rocks to
the south, across the Second Lake fault zone (Figure 3). However, S3 spacing and the intensity
of the crenulation fall off rapidly to the south and is absent in the larger exposures of Potter
Creek assemblage just south of the Second Lake fault.

2.6.2.3 Ductile structures, Potter Creek assemblage

Lower greenschist facies meta-psammites and meta-pelites with interleaved
metamorphosed chert and tuffaceous layers are exposed just south of the Liberty Creek schists,
from the Second Lake fault southward to exposures of metasedimentary rocks that comprise
fragments of the younger Valdez Group (Figure 2.3). Winkler et al. (1981b) initially considered these rocks as a separate terrane, but later work by Plafker et al. (1989 and 1994) correlated this assemblage with the McHugh Complex. Two samples collected in the Second Lake shear zone confirm Plafker et al.’s (1994) correlation with detrital zircons showing a maximum depositional age of 149 Ma and 159 Ma (Day, Chapter 1, this dissertation), consistent with the Potter Creek assemblage of Amato et al., 2013. These rocks record a strain history similar to the blueschist and greenschist facies rocks in the Liberty Creek schist, which accounts for their initial confusion in correlation as well as placement of the Second Lake fault relative to this study.

The oldest generation of cleavages in the Potter Creek assemblage in this area is a mica foliation defined by chlorite and white mica, similar to the Liberty Creek schist but devoid of blueschist minerals. S1 dips steeply to moderately to the north-northwest but locally ranges to steep southerly dips due to overprinting folds (Fig. 2.5b-1). Like fabrics in the adjacent Liberty Creek schist, this foliation overprints what appears to be a stratally disrupted, mélange fabric typical of the Potter Creek assemblage and a shallowly-plunging intersection lineation (S0-S1) trends NE-SW, with scattering trends caused by younger fold overprints (Fig. 2.5b-4).

A crenulation cleavage, S2, overprints S1. S2 is a shallow, south-dipping cleavage (Fig. 2.5b-2) axial planar to open to close folds in S0-S1, giving S0-S1 the observed variation of dips (Fig. 2.5b-1). L2, S2-S1 intersection lineations (Fig. 2.5b-5) trend east-northeast to west-southwest and scatter due to folding around a third generation of folds, F3.

The youngest generation of cleavage, S3, is a north to south striking, vertical axial planar crenulation cleavage (Fig. 2.5b-3). The interactions of these three cleavage generations create basin and dome structures observable along the S1 cleavage planes, due to type 1 interference
patterns (Ramsay, 1967) of F2 and F3 folds (Fig. 2.6a, b, and c). The wavelengths of these basin and dome structures vary from 1-2 cm to ~20 cm locally (Fig. 2.6b and c).

Figure 2.6  a. Diagrammatic illustration showing the interaction of S1, S2, and S3 axial planar cleavages. Note basin and dome structures formed by interaction of F2 and F3 along S1 planes. b. Photograph of Iceberg Lake schist looking at the underside of a S1 cleavage plane. c. Photograph of Liberty Creek schist looking down on an S1 cleavage plane.

2.7  DISCUSSION

2.7.1  Formation of Arc Basement, Blueschist Bodies, and the Earliest Generations of Deformation

Despite differences in the timing of accretion and of metamorphism of the Iceberg Lake schist, Liberty Creek schist, and Potter Creek assemblage, these rocks share similar metamorphic fabrics. That is, S0 layering (bedding or pseudo-layering inherited from mélange formation) has been transposed by D1 folds (F1) that are close to isoclinal folds with S1 axial planar cleavage dipping steeply to moderately to the north (Figs. 2.4a-1, 2.4b-1, 2.5a-1, 2.5b-1and 2.6a). This
transposed layering S1, has been folded (F2) around S2 a moderate to shallow south dipping axial planar cleavage (Figs. 2.4a-2, 2.4b-2, 2.5a-2, 2.5b-2, and 2.6a). These interactions have formed shallow east-west plunging intersection lineations, L1 and L2 (Figs. 2.4a-4, 2.4b-4, 2.4a-5, 2.4b-5, 2.5a-4, 2.5a-5, 2.5b-4, 2.5b-5). The formation of F1 folds and S1 cleavages has been attributed to the previously described north directed subduction (e.g., Nokleberg et al., 1989; Plafker et al., 1994; Pavlis and Roeske, 2007), yet the evidence that all these assemblages represent at least 3 different protoliths of varying ages (Day, Chapter 1, this dissertation) leads to the questions of how and why they preserve such similar strain.

Both the Iceberg Lake and Liberty Creek blueschist bodies are adjacent to large bodies of arc basement material and each of these basement-blueschist pairings are adjacent to the BRF or included within the Potter Creek assemblage sub-greenschist to green schist facies accretionary material (Fig. 2.1). The Klanelneechnena Klippe, northwest of the Iceberg Lake schist (Fig. 2.1), was exhumed from ~19-29 km depth (Hacker et al., 2011) with cooling ages that range from ~201 Ma (U-Pb, zircon), to 188 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$, hornblende), to 59 Ma (He, zircon) (Hacker et al., 2011). The Tonsina ultramafic complex, west of the Liberty Creek schist (Fig. 2.1), was exhumed from even greater depths of 44-23 km (Hacker et al., 2008) and has cooling ages that range from 204-154 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$, hornblende) to ~9 Ma (He, Apatite) (Hacker et al., 2011).

The Jurassic high-T cooling ages of the Klanelneechnena Klippe, Tonsina ultramafic complex, and Iceberg Lake schist are consistent with the hypothesis that the Early Jurassic Talkeetna arc was shifting northward as a result of a shallowing of the subducting slab (Plafker et al., 1989) or tectonic erosion of the forearc (Clift et al., 2005; Rioux et al., 2007). Hacker et al., (2011) described two periods of cooling at the base of the Talkeetna arc with shorter periods, of rapid cooling within these longer cooling events. The first cooling event recorded at the base
of the Talkeetna arc was described as the cooling from zircon U-Pb closure temperatures (~700°C) through biotite $^{40}$Ar/$^{39}$Ar closure temperatures (~350°C) between ~200-150 Ma (Hacker et al., 2011). There was a period of more rapid cooling within this longer event from ~191 Ma to 162 Ma (Hacker et al., 2011). There is a period of inferred magmatism at ~150 Ma in the western Chugach Mountains due to a lack of biotite cooling ages from this time period (Hacker et al., 2011), followed by the second cooling event which cools from hornblende $^{40}$Ar/$^{39}$Ar closure (~550°C) through zircon He closure (~200°C) from ~141 Ma to ~119 Ma (Hacker et al., 2011). There is a period of rapid cooling within this second longer event between ~128 Ma and ~119 Ma (Hacker et al., 2011) that is associated with cooling from a forearc metamorphic event represented by near trench plutons in the western Chugach Mountains (e.g. Pavlis and Roeske, 2007; Amato et al., 2013).

The timing of peak blueschist metamorphism for the Iceberg Lake schist (186 Ma, $^{40}$Ar/$^{39}$Ar on white mica) and the Liberty Creek schist (123-107 Ma, K-Ar whole rock) match the first and second cooling events described by Hacker et al., (2011). We suggest that the blueschist metamorphism of the Iceberg Lake schist is a result of underplating of oceanic material within a reduced geotherm created during the Early Jurassic subduction erosion event described by Clift et al. (2005) and Rioux et al. (2007). The Iceberg Lake schist was accreted and cooled through white mica $^{40}$Ar/$^{39}$Ar closure (~400°C) at ~186 Ma (Sisson and Onstott, 1986); this timing is synonymous with the Earliest Jurassic cooling of the Klanelneechena Klippe and Tonsina ultramafic complex through hornblende $^{40}$Ar/$^{39}$Ar closure (~550°C) (Hacker et al., 2011). This orogen-perpendicular underplating is interpreted as the event that formed the north-dipping cleavage, S1, observed in the Iceberg lake schist. This period was apparently a period of subduction erosion (Clift et al., 2005); we infer that cooling was driven by the removal of large
amounts of forearc material and the blueschists are the only preserved rocks representing this erosion event.
By ~169 Ma accretion had resumed (Amato et al., 2013) and the Klanelneechena Klippe, Tonsina ultramafic complex, and Iceberg Lake schist were incorporated into the subduction complex deformation zone between the subduction backstop and the Potter Creek assemblage. During this time period the Potter Creek assemblage was stratally disrupted as a mélange, carried to moderate depths, and the main phyllitic cleavage, S1, was imprinted on the rocks at greenschist to sub-greenschist conditions of less than ~400° C and moderate pressures (Fig. 2.8). If these motions were a single event, or diachronous along the margin is not clear from available cooling data, but geochronology from the Liberty Creek schist strongly suggests a diachronous event(s).

Accretion of the pelagic and oceanic crustal material that was the protolith of the Liberty Creek schist occurred after ~136 Ma (Day, Chapter 1, this dissertation). We infer that the underplating of Liberty Creek schist material formed the main cleavage, S1, observed in the Liberty Creek rocks. Although the maximum age for the Liberty Creek blueschist metamorphism is well constrained, the minimum age is not. Available cooling ages are poor-quality conventional K-Ar ages that range from ~123-107 Ma (Plafker et al., 1994) which suggests a mid-Cretaceous age but little beyond this broad swath of geologic time. Amato and Pavlis (2010) and Amato et al., (2013) inferred a late Early Cretaceous (~125-104 Ma) subduction erosion event based on the absence of detrital zircon age across the subduction complex in this age range. We suggest that the Liberty Creek schist rocks were exposed to high-pressure low-temperature conditions under a reduced geothermal gradient created by this event, in a process
similar to the event that accreted the older, Iceberg Lake blueschist. The Liberty Creek schist presumably remained at lower greenschist to sub-greenschist conditions of moderate pressures and temperatures less than ~400° C following this event (Fig. 2.9). After ~104 Ma, accretion had resumed and the McHugh Creek assemblage was added to the base of the accretionary wedge (Amato et al., 2013) (Fig. 2.9).

Figure 2.8  Diagrammatic model illustrating the timing of cooling of the Tonsina ultramafic complex, Iceberg Lake schist, and Klanelneechna klippe. T, I, and K respectively. Structures represented in this diagram are that of S1 formed in the Iceberg Lake schist via accretion and underplating.
2.7.2 Formation of Youngest Strain History

F2 folds (Figs. 2.6a, 2.7a, and 2.7b) and S2 axial planar cleavages (Figs. 2.4a-2, 2.4b-2, 2.5a-2, 2.5b-2 and 2.6a) observed in rocks of the Chugach accretionary complex have been described as resulting from latest Cretaceous to Early Cenozoic transpressional subduction (e.g., Plafker et al., 1989; Pavlis and Roeske, 2007). Nokleberg et al. (1989) observed shallow south dipping cleavages, equivalent to our S2 cleavages (G3 structures in their manuscript) and described them as conjugate folds formed during late stage accretion of the northern margin of the Prince William terrane. Nokleberg et al. (1989) also observed vertical N-S cleavages, similar to our S3 cleavages (G4 structures in their manuscript) and described them as a result of Cenozoic relaxation of north-south directed compressional stresses that formed older structures.

Our observations suggest a more complex history for the formation of the main foliation across the region because that fabric must be different ages in different segments of the belt. For example, the Iceberg Lake schist had cooled through muscovite argon closure temperatures (~350° C) long before the Liberty Creek schist or the Potter Creek assemblage were even deposited as sediments. Thus, the similarity in fabric orientations among these three distinct assemblages is presumably an imprint of the margin geometry, orogen-perpendicular shortening that spanned millions of years along the subduction zone interface. Because most of these rocks also show evidence of having originated as mélange, prior to the formation of the main mica foliation, S1, it is possible that part of the fabric development is coeval, particularly between the Potter Creek and Liberty Creek assemblage. Nonetheless, the simplest explanation is that these rocks record similar processes, over an extended period of time, of ductile deformation following accretion along the subduction interface.

Despite evidence for a diachronous accretionary history and the formation of the main structural fabric in the different accreted rocks, the similarity in overprint history across all of the
assemblages implies a close connection between these events. It is possible that a detailed thermochronology study could separate the overprint generations into distinct time windows, but at present available data allow two, rather different scenarios, for the origin of the fabric overprints.

Figure 2.9  Diagrammatic model illustrating the timing of cooling of the Liberty Creek schist. Structure represented in this model is that of S1 formed in the Liberty Creek schist via accretion and underplating. It should be noted that the Tonsina ultramafic complex, Iceberg Lake schist, and Klanelneechena klippe (T, I, and K respectively) remain at depths above their relative cooling temperatures.

2.7.2.1 Varied ages of accretion, metamorphism, and exhumation

The first hypothesis is that the overprints and cleavage parallel veining were recorded in the Iceberg Lake schist and Liberty Creek schist independently at different times and are similar in orientation by coincidence. This scenario requires a process that is constant over time, but of
different ages in different segments. In this scenario F2 in the Iceberg Lake schist would most likely have occurred during the ~125-104 Ma subduction erosion event which was hypothesized to have been driven by subduction of a spreading ridge (Amato and Pavlis, 2010; Amato et al., 2013). F2 in the Liberty Creek would be a result of transpressional subduction during the accretion of the Valdez group flysch (Plafker et al., 1994; Pavlis and Roeske, 2007). F3 folding within the Iceberg Lake schist and Liberty Creek schist would be a result of early Cenozoic relaxation of north directed compressional stresses and the resulting east-west shortening of the margin (Nokleberg et al., 1989). In this hypothesis map scale reorganization of these rock bodies is a result of Late Cretaceous to early Paleogene strike-slip motions (Pavlis and Roeske, 2007) and reorganization of the accretionary wedge is not related to the accretion or internal deformation of these rocks. Our observations of varied generations and cross cutting relationships of sub-greenschist facies veining would be interpreted as low grade metamorphism overprinting previously existing cleavage planes and are not indicative of any similarity between deformation and sub-greenschist facies veining within these blueschists.

2.7.2.2 Internal deformation of translating blocks

An alternative hypothesis is that our observations of axial planar cleavages and varying cross cutting relationships of sub-greenschist veining of both blueschist bodies records the same younger deformational overprint at a regional scale. S2 axial planar cleavages, S3 axial planar cleavages, and these varying cross cutting generations of sub-greenschists veins were all formed contemporaneously during the long time periods spent moving through the subduction interface at sub-greenschist facies.

Both the Iceberg Lake and Liberty Creek schists have a tectonic history where they would be located within the subduction wedge for protracted periods of time at lower greenschist
to sub-greenschist facies (<400° C), the Iceberg Lake schist from ~185 Ma to less than ~60 Ma(?), and the Liberty Creek schist from ~107 Ma - 60 Ma. Petrographic observations reveal generations of stipnomelane, phehnite, laumontite, and calcite veining which follow S2 and S3 cleavages. Cross cutting relationships of these veins reveal no preferred pattern of mineral veins to either generation of cleavage. S3 parallel veins cut and off set S2 parallel veins, and S2 parallel veins cross cut and off set S3 parallel veins in the same sample.

Figure 2.10 Diagrammatic model illustrating the incremental stepwise motions of the Liberty Creek schist, Tonsina ultramafic complex, Iceberg Lake schist, and Klanelneechena klippe (L, T, I, and K respectively) through the accretionary wedge from ~107 Ma to ~59 Ma. Horizontal motions create horizontal compression, forming S3, and vertical tension, forming S2 parallel veining. Vertical motions create a vertical compression, forming S2, and horizontal tension, forming S3 parallel veining. See text for a more detailed description.
These observations of cross cutting relationships on sub-greenschist veins parallel to S2 and S3 cleavages suggest that the 2 generations of cleavages and sub-greenschist veining may all be contemporaneous. Here we suggest that F2 folds, S2 axial planar cleavages, F3 folds, and S3 axial planar cleavages are a result of perpendicular compressional stresses associated with Late Cretaceous transpression (e.g., Pavlis and Roeske, 2007) or Eocene transtension (e.g., Cole, 2014). We suggest that these F2 and F3 folds and S2 and S3 cleavages are a result of internal ductile deformation (e.g., Freehan and Brandon, 1999) within blocks moving incrementally horizontally and vertically through the subduction wedge in a regional scale process (Fig. 2.10).

In this model, S2 crenulations are formed perpendicular to the direction of motion as a block moved vertically through the subduction wedge under vertical compression; at the same time S3 planes would become tensional allowing for the opening and filling of the sub-greenschist veins. In the next increment of motion the block would move horizontally, switching the orientations of compressional and tensional forces. The horizontal compressional forces strengthen S3 cleavages, while S2 cleavages become tensional spaces for low temperature veining. As the process continues we create the observed overprints and random cross-cutting pattern of the low grade veining.

The observed cleavages have remained separate because of their nearly perpendicular orientations and the repetitive incremental horizontal and vertical motions as shown by the varying generations of veining (Figs. 2.7e and 2.7f). Periodic incremental motion at sub-greenschist facies over long time periods, tens of millions of years, prevent S2 and S3 from becoming a record of cumulative strain (e.g., Lebit et al., 2002) and or one fabric overprinting and obliterating the other (e.g. Ferguson, 1984; Lebit et al., 2002) resulting in the distinct strain history we observe today.
Although available data do not firmly establish hypothesis 1 vs. hypothesis 2, we suggest here that hypothesis 2 is most consistent with the available data. During and following the accretion of the Chugach accretionary complex there has been anywhere from 200-1000 km of strike-slip translation along the BRF in the central Chugach Mountains. It has been suggested that these younger strike-slip motions are related to oblique subduction in the latest Cretaceous and early Cenozoic pure strike-slip reactivation of the BRF along the Hanagita fault system (Roeske et al., 2003; Pavlis and Roeske, 2007). Cole (2014) suggests a period of transtension in the Matanuska basin in response to dextral-oblique subduction at ~46 Ma. We suggest that it is these dextral transpression, and potentially transtension, related strike-slip motions that created S2 and S3 in the Iceberg Lake and Liberty Creek schists. These dextral strike-slip motions are also responsible for the map scale reorganization of the members of the Chugach accretionary complex in the central Chugach Mountains (Figs. 2.1, 2.8, 2.9, 2.10). The Liberty Creek schist was moved north of the Potter Creek assemblage and east of and below the Tonsina ultramafic complex during this latest Cretaceous to early Paleogene time period (Fig. 2.1, 2.10).

2.8 SUMMARY AND CONCLUSIONS

The Iceberg Lake blueschist is bounded to the north by a vertical, northeast striking fault, bounded to the south by a shallow 30° north dipping southwest to northeast trending fault, and is internally faulted at a variety of scales (Fig. 2.1 and 2.2). The Iceberg Lake schist is composed of smaller fault-bounded blueschist and greenschist facies slivers of ultramafic, mafic, psammitic, and pelitic schistose rocks (Fig. 2.2). In contrast the Liberty Creek blueschist occurs in a relatively coherent mass with little internal faulting but intense ductile deformation. The eastern and northern boundaries of the Liberty Creek schist are obscured by Quaternary deposits but the western boundary is a northwest-dipping thrust, placing Talkeetna Arc ultramafic basement
rocks above the Liberty Creek schist (Plafker et al., 1994; Pavlis and Roeske 2007) (Fig 2.1 and 2.3). The southern boundary of the Liberty Creek schist is a broad ~0.5-1 km wide shear zone (Fig. 2.3).

The Iceberg Lake schist, the Liberty Creek schist, and the surrounding Potter Creek assemblage rocks record similar structural histories despite great differences in age and local geology. The first cleavage, S1, has transposed bedding and pseudo-bedding from early mélange fabrics creating tight to isoclinal folds (F1). S1 trends east-northeast and dips moderately to steeply north (Figs. 2.4a-1, 2.4b-1, 2.5a-1, 2.5a-2). The next cleavage, S2, trends east-northeast and dips moderately to shallowly south (Figs. 2.4a-2, 2.4b-2, 2.5a-2, 2.5a-2). S2 is a crenulation cleavage that creates gentle to open folds (F2) in S1. The third cleavage, S3, is a north-south trending vertical cleavage (Figs. 2.4a-3, 2.4b-3, 2.5a-3, 2.5a-3). S3 cleavages fold F1 and F2 folds, forming open to close F3 folds that are expressed as basin and dome type 1 interference patterns (Ramsay, 1967) (Fig. 2.6a, 2.6b, and 2.6c). Microscopic observations reveal diverse low grade veins parallel to and filling S1/S2 and S3 cleavages. These veins had no temporal preference to S1/S2 or S3 cleavages and show mutually cross-cutting relationships (Fig. 2.7e and 2.7f).

A maximum depositional age for the Liberty Creek schist of 136 Ma (Day, Chapter 1, this dissertation), indicates that the Iceberg Lake schist and the Liberty Creek schist could not have undergone blueschist metamorphism at the same time yet both blueschists, as well as associated lower grade mélange, show a similar strain history. Two hypotheses could explain these similar patterns. 1) The Iceberg Lake schist, the Liberty Creek schist, and the surrounding rocks underwent accretion, metamorphism, and exhumation at their own respective times as revealed by thermochronologic analyses (e.g., Hacker et al. 2011; Day, Chapter 1, this
dissertation). Any similarity in recorded strain is a result of a similarly oriented subduction margin over time and the current geographic locations of these rocks is a result of latest Cretaceous strike-slip motions along the Border Ranges fault. 2) The similar strain history recorded in the Iceberg Lake schist, the Liberty Creek schist, and the surrounding rocks is a result of a complex three dimensional subduction wedge history of accretion, erosion, and dextral transpression that is regional in scope. In this hypothesis, despite different timings of accretion and metamorphic cooling, the Iceberg Lake schist, the Liberty Creek schist, and the surrounding rocks, including the Tonsina ultramafic complex and Klanelneechena klippe, were all moved vertically and horizontally through the subduction wedge along the crystalline backstop. These incremental motions through sub-greenschist facies conditions were recorded as a shallow south dipping crenulation cleavage, S2, a vertical north-south trending cleavage, S3, and cross cutting generations of low grade veins filling these cleavages. It is these motions through the subduction column along with dextral transpressional (transtensional?) motions that result in the modern day locations and similar strain histories recorded in these rocks. More detailed thermochronology is necessary to distinguish these hypotheses although the available data are most consistent with the second hypothesis.

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2.10 WORKS CITED


Vita

Erik Day earned his Bachelor of Arts in Geological Sciences from Occidental College in 2003. He received his Master of Science in Geological Sciences from the University of New Orleans in 2007. In 2007 he joined the doctoral program of the Department of Geological Sciences at The University of Texas at El Paso.

Dr. Day has been awarded numerous honors and awards including the Vernon G. and Joy Hunt Endowed Scholarship Fund. Dr. Day was selected by his peers to receive the UTEP Department of Geological Sciences Bruce Davidson Memorial Graduate Student Award. Dr. Day was a member of UTEP’s Department of Geological Sciences’ first team sent to the American Association of Petroleum Geologists Imperial Barrel Award (IBA) competition. This team won the IBA Southwest Section competition, and traveled to Denver, CO to compete against eleven other teams in the IBA international competition.

While pursuing his degree, Dr. Day worked as a research associate and assistant instructor for the Department of Geological Sciences at UTEP. During his time at UTEP Dr. Day also spent time as a lecturer for the Department of Geological Sciences at El Paso Community College, and as a 12th grade Physics and 7th grade Science and Technology instructor for the Radford School in El Paso. Dr. Day has also been involved in geologic contract work for MiraTek, a service company on Fort Bliss, MexMetals, an El Paso based junior mining company, and CEMEX, a global leader in the building materials industry.

Dr. Day has presented this research at international conference meetings including the Geological Society of America Annual Meeting and the American Geophysical Union Fall Meeting. Dr. Day is currently reviewing manuscripts of this research for publication in peer reviewed journals.

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