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The Border Ranges fault system, southern Alaska

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ABSTRACT

The Border Ranges fault system is the arc-forearc boundary of the Alaskan-Aleutian arc and separates a Mesozoic subduction accretionary complex (Chugach terrane) from Paleozoic to middle Mesozoic arc basement that together comprise an oceanic arc system accreted to North America during the Mesozoic. Research during the past 20 years has revealed a history of repeated reactivation of the fault system, such that only scattered vestiges remain of the original subduction-related processes that led to formation of the boundary. Throughout most of the fault trace, reactivations have produced a broad band of deformation from 5 to 30 km in width, involving both the arc basement and the accretionary complex, but the distribution of this deformation varies across the Alaskan orocline, implying much of the reactivation developed after or during the development of the orocline. Along the eastern limb of the orocline the Hanagita fault system typifies the Late Cretaceous to Cenozoic dextral strike slip reactivation of the fault system with two early episodes of strike slip separated by a contractional event, and a third, Neogene strike-slip system locally offsetting the boundary. Through all of these rejuvenations strike slip and contraction were slip partitioned, and all occurred during active subduction along the southern Alaska margin. The resultant deformation was decidedly one-sided with contraction focused on the outboard side of the boundary and strike slip focused along the boundary between crystalline arc basement and accreted sediment. Analogies with the modern Fairweather–St. Elias orogenic system in northern southeast Alaska indicate this one-sided deformation may originate from erosion on the oceanic side of the deformed belt. However, because the strike-slip Hanagita system faithfully follows the arc-forearc contact this characteristic could be a result of rheological contrasts across the rejuvenated boundary.

In the hinge-zone of the Alaskan orocline the smooth fault trace of the Hanagita system is disrupted by cross-cutting faults, and Paleogene dextral slip of the Hanagita system is transferred into a complex cataclastic fault network in the crystalline assemblage that comprises the hanging wall of the fault system. Some of these faults record contraction superimposed on earlier strike-slip systems with a subsequent final strike-slip overprint, a history analogous to the Hanagita system, but with a more significant contractional component. One manifestation of this contraction is the Klanelneechena klippe, a large outlier of a low-angle brittle thrust system in the central Chugach Mountains that places Jurassic lower-crustal gabbros on the Chugach mélange.

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Recognition of unmetamorphosed sedimentary rocks caught up along the earlier strike-slip systems, but beneath the Klanelneechena klippe, provides an important piercing point for this strike-slip system because these sedimentary rocks contain marble clasts with a closest across-strike source more than 120 km to the north and east. Published thermochronology and structural data suggest this dextral slip does not carry through to the western limb of the orocline. Thus, we suggest that the Paleogene strike slip along the Border Ranges fault was transferred to dextral slip on the Castle Mountain fault through a complex fault array in the Matanuska Valley and strike-slip duplex systems in the northern Chugach Mountains. Restoration of this fault system using a strike-slip duplex model together with new piercing lines is consistent with the proposed Paleogene linkage of the Border Ranges and Castle Mountains systems with total dextral offset of ~130 km, which we infer is the Paleogene offset on the paired fault system.

Pre-Tertiary deformation along the Border Ranges fault remains poorly resolved along most of its trace. Because Early Jurassic blueschists occur locally along the Border Ranges fault system in close structural juxtaposition with Early Jurassic plutonic assemblages, the earliest phase of motion on the Border Ranges fault has been widely assumed to be Early Jurassic. Nonetheless, nowhere, to our knowledge, have structures within the fault zone produced dates from that period. This absence of older fabrics within the fault zone probably is due to a major period of subduction erosion, strike-slip truncation, or both, sometime between Middle Jurassic and mid-Early Cretaceous when most, or all, of the Chugach mélange was emplaced beneath the Border Ranges fault. In mid-Early Cretaceous time at least part of the boundary was a high-temperature thrust system with sinistral-oblique thrusting syntectonic to emplacement of near-trench plutons, a relationship best documented in the western Chugach Mountains. Similar left-oblique thrusting is observed along the Kenney Lake fault system, the structural contact beneath the Tonsina ultramafic assemblage in the eastern Chugach Mountains, although the footwall assemblage at Tonsina is a lower-T blueschist-greenschist assemblage with an uncertain metamorphic age. We tentatively correlate the Kenney Lake fault with the Early Cretaceous structures of the western Chugach Mountains as part of a regional Early Cretaceous thrusting event along the boundary. This event could record either reestablishment of convergence after a lull in subduction or a ridge-trench encounter followed by subduction accretion during continuous subduction. By Late Cretaceous time the dextral strike-slip initiated in what is now the eastern Chugach Mountains, but there is no clear evidence for this event in the western limb of the orocline. This observation suggests strike slip in the east may have been transferred westward into the accretionary complex prior to emplacement of the latest Cretaceous Chugach flysch.

Keywords: strike-slip faulting, forearc backstop, Alaskan tectonics, Mesozoic, Cenozoic

INTRODUCTION

A fundamental boundary within all convergent margins is the structural contact between the crystalline basement upon which the magmatic arc is constructed and the forearc accretionary complex(es) developed between the magmatic arc and the trench. This arc-forearc boundary originates during the initiation of subduction and in an ideal world carries a record of that event. Thus, the geologic record along the boundary should carry a record of the thermal and mechanical evolution of the boundary during the initiation of subduction (e.g., Pavlis, 1982, 1986; Cloos, 1985; Platt, 1975).

In the real world, however, the arc-forearc boundary is subjected to complex overprinting because it separates two lithologic assemblages that are mechanically very different: the crystalline massif of the arc and the accreted oceanic assemblages of the forearc accretionary complex. Thus, it is not surprising that the boundary is commonly reactivated. A particularly common reactivation is through the development of strike-slip faults in the hanging wall of a subduction zone during oblique convergence

(Fitch, 1972), and these faults are most common within the arc and at the arc-forearc boundary. Thrust and/or normal fault reactivations also may act to produce large structural relief along the boundary, obscuring the older history. In other cases, partial to complete destruction of the original tectonic join might occur through subduction-erosion processes; for example, in the Andes, Paleozoic and Precambrian basement lie directly above the subduction megathrust due to subduction erosion (Von Huene and Scholl, 1991). Finally, lateral shuffling through forearc slivering, intra-arc collisional events, or ridge subduction could place the original tectonic boundary in a site where metamorphic and plutonic overprinting obscures the early history of the boundary. Collectively, these processes integrated over time act largely to destroy the early record of the arc-forearc boundary in virtually all ancient arc-trench systems.

Our poor understanding of processes that shape the arc-forearc boundary arises partially from the scarcity of on-land exposures of the arc-forearc boundary and the requirement to deduce the nature of the boundary from geophysical data. That is, in most convergent margins this boundary is under water, buried beneath forearc sediments, or both, and thus, it is only in specific cases where forearc uplift has exposed the boundary that we can directly examine the structural evolution of the boundary. Several examples exist worldwide: (1) the Olympic Mountains in western Washington, USA; (2) the Coast Ranges fault in California; (3) the Makran region of Iran; (4) the Median tectonic line of Japan; and (5) several localized exposures in arc-trench systems of the southwestern Pacific. None of these examples, however, expose this boundary on the scale of the arc-forearc boundary in northwestern North America. Here, this boundary is referred to as the Border Ranges fault, and it can be traced more than 2000 km along strike with nearly continuous exposure through more than half of this length (Fig. 1).

The regional significance of this boundary was first pointed out by MacKevett and Plafker (1974). Studies during the last three decades have clarified much of the tectonic history of this boundary well beyond the original concepts presented by MacKevett and Plafker (1974). Summaries in the Decade of North American Geology publications of the Geological Society of America (Plafker et al., 1994; Nokleberg et al., 1994) review some of these concepts, but more recent studies provide important new insights into the nature of this structure. In this paper we review these more recent results and propose regional syntheses of these observations. The key result of all recent studies is that this structure has been subjected to repeated reactivations, primarily through strike-slip systems, but different segments of the structure record very different events due to localized reactivation and variable preservation of older events. Thus, we begin with a review of distinctive characteristics of different segments of the structure and the tectonic significance of those events. We then use those data collectively to synthesize the information to develop a working tectonic model for the history of this boundary. We also propose a specific terminology for the fault system to eliminate genetic implications of the terminology inherited from early studies.

REGIONAL SETTING OF THE BORDER RANGES FAULT

Early Studies and Definition

Figure 1 shows the regional trace of known and projected segments of the Border Ranges fault in southern Alaska. At this scale the structure can generally be treated as a single structure with a known arcuate trace extending over 1300 km from Kodiak Island to Baranof Island, where the structure is truncated by the dextral Denali fault system (Figure 1). The structure continues southwestward from Kodiak Island to at least the Shumagin Islands but is underwater throughout this segment (e.g., Plafker et al., 1994). Geophysical evidence suggests the structure also continues for at least several 100 km to the southwest beyond the Sanak Islands (Fisher and von Huene, 1984), giving a total traceable length of over 2000 km.

When MacKevett and Plafker (1974) first defined the Border Ranges fault, the geology throughout its exposed trace was known only at reconnaissance levels of 1:250,000 and smaller-scale mapping. Thus, their original concept of the structure was a single, regional fault system that “separated upper Paleozoic and lower Mesozoic rocks on the north against upper Mesozoic and Tertiary rocks” (MacKevett and Plafker, 1974, p. 323). Their paper stands as a landmark in that they recognized the structure as marking a convergent plate boundary that developed near the close of the Mesozoic or in the Tertiary. Although they emphasized the primary nature of the structure as a “plate boundary,” they clearly recognized that the structure contained significant overprinting up to Neogene time (e.g., MacKevett and Plafker, 1974, p. 329).

A modification of the original definition of the structure remains a useful generalization. Specifically, at a regional scale the structure is the tectonic contact along which Mesozoic and Paleozoic metamorphic and plutonic rocks on the inboard side are juxtaposed against highly deformed and variably metamorphosed late Paleozoic to late Mesozoic deep-water oceanic assemblages that comprise a late Mesozoic–early Cenozoic forearc accretionary complex accreted under subduction of the same polarity as the present day Aleutian arc. At larger map scales, however, this definition of the fault as a crystalline hanging wall juxtaposed with an accretionary complex obscures some key structural relations, such as the incorporation of younger cover rocks within the fault system, broad ductile deformation zones, and reactivations involving rocks on both sides of the original structural contact. In this paper we try to clarify these relationships, emphasizing the constraints these assemblages place on the history of the structure.

Rock Units along the Fault System

The outboard assemblage (Chugach and Prince William terranes, or the Chugach accretionary complex) is comprised regionally of a two-part structural and lithologic subdivision: an older, generally inboard, mélange assemblage and a younger, coherent

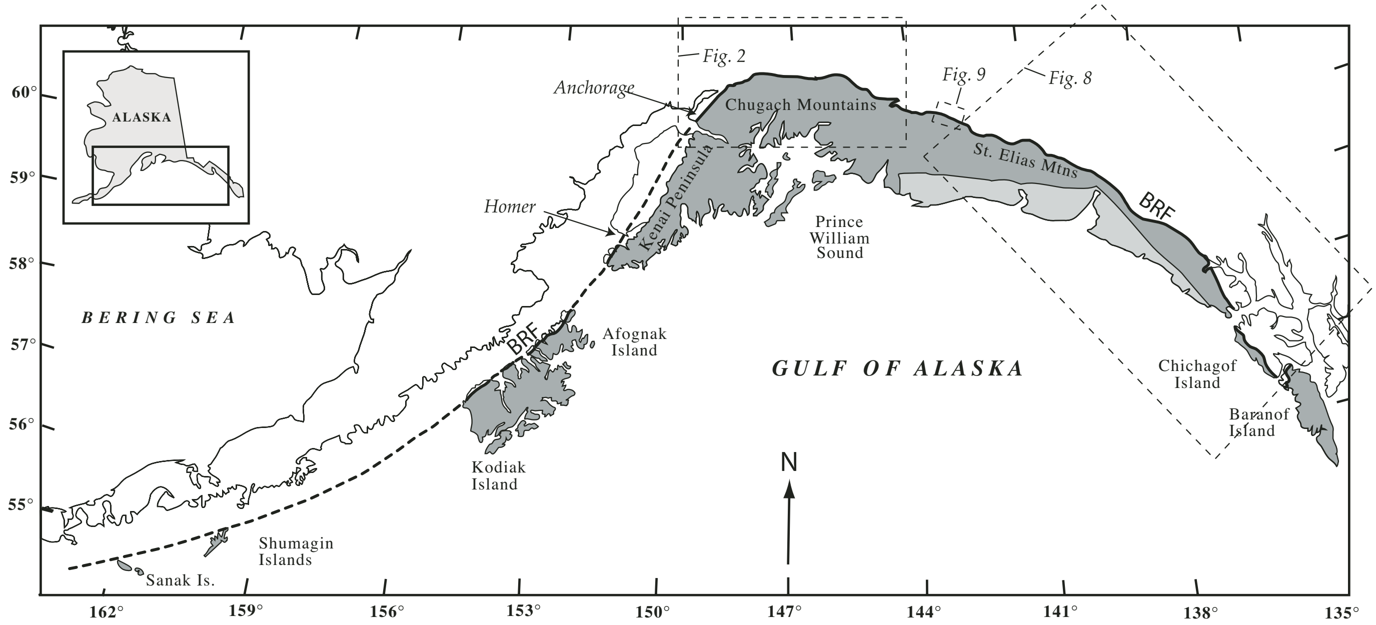

Figure 1. Map of southern Alaska showing Chugach accretionary complex and Border Ranges fault (Border Ranges fault). Dark gray shading is the Chugach terrane (accretionary complex), and the light shading shows the position of the Neogene Yakutat terrane. Adapted from Bradley et al. (2003).

terrane. These rock units have different names regionally, and thus, we refer to them here as the Chugach flysch and Chugach mélange respectively. The Chugach flysch comprises the bulk of the exposed area of the accretionary complex adjacent to the fault system and is characterized by interbedded lithic sandstone (greywacke) and argillite that are generally interpreted as a trench-fill turbidite assemblage that was accreted by subduction in the latest Cretaceous to early Cenozoic (e.g., Moore, 1973; Plafker et al., 1977; Decker et al., 1979; Decker, 1980; Nilsen and Zuffa, 1982; Sample and Reid, 2003). These rocks are coherent and characterized by stratal continuity at outcrop to map scales, with only localized zones of stratal disruption (Sample and Moore, 1987). Structurally, this "flysch" assemblage is characterized by early trench-vergent (toward Pacific) thrust systems (e.g., Sample and Fisher, 1986; Sample and Moore, 1987; Fisher and Byrne, 1987; Nokleberg et al., 1989) that are overprinted by fabrics that vary dramatically along strike (e.g., Kusky et al., 1997; Pavlis, 1982; Little, 1990; Pavlis and Sisson, 1995, 2003; Pavlis et al., 2003; Davis et al., 1998). The structural history of the flysch assemblage is critical to understanding the overprinting relationships recognized along the Border Ranges fault because the assemblage helps constrain the timing of regional structural events that affected the forearc region.

The Chugach mélange is a lithologically heterogeneous unit (Clark, 1973) that generally lies structurally above, or in high-angle contact with, the Chugach flysch, forming a discontinuous outcrop belt along the Border Ranges fault. The mélange is commonly correlated along the entire strike length of the Border Ranges fault (Plafker et al., 1977), but regional fossil ages (e.g., Nelson et al., 1986, 1987) as well as structural relationships strongly suggest that rocks of very different age and structural history are lumped together in this assemblage. Some sections of the mélange have regional map units with distinct protoliths and ages within each unit (Tysdal and Case, 1979; Winkler et al., 1981; Winkler, 1992; Bradley and Kusky, 1992; Bradley et al., 1999). In these regions a clear trenchward-younging progression of protolith ages occurs, which suggests that the progressive accretionary history is at least partially preserved. Other locales appear to contain a more chaotic mixture of ages and lithologies. Many misconceptions about the history of the Border Ranges fault system probably arise from uncertainties in the accretionary and depositional history of this tectonic unit.

The crystalline "backstop" assemblage that lies structurally above, or more inboard of, the Border Ranges fault varies markedly along strike. Moreover, in many areas rocks inboard of the Border Ranges fault sensu stricto include fault slices of greenschist-amphibolite facies rocks derived from the Chugach accretionary complex. These complications blur the description of the fault system on maps but provide the critical information that has led to the present understanding of the fault system.

From southwest Alaska to the central Chugach Mountains (Copper River) the crystalline assemblage is dominated by Jurassic plutonic rocks that comprise the basement of the Peninsular terrane. This assemblage has been interpreted as an upturned, but fragmented, crustal section of the oceanic arc that formed the Early Jurassic Peninsular terrane (e.g., Burns, 1985; DeBari and Coleman, 1989; DeBari and Sleep, 1991). This assemblage locally includes large slabs of ultramafic and mafic rock that formed at pressure of 1 GPa or greater and represent upper mantle and lower crust respectively for an Early Jurassic arc system (e.g., DeBari and Sleep, 1991; Mehl et al., 2003). This assemblage is significant in that it contains marine volcanic rocks and is isotopically primitive, suggesting that this arc system formed in an intraoceanic setting in which recycling of continental material was insignificant in the production of the melts (Hill, 1979; Hudson et al., 1985; DeBari and Coleman, 1989; DeBari and Sleep, 1991; Arth, 1994; Rioux et al., 2004; Clift et al., 2005a).

From the eastern Chugach Mountains to the St. Elias Mountains the "backstop" assemblage is characterized by a broader range of plutonic ages (Pennsylvanian to Cretaceous) and metamorphic rocks comprise a large percentage of the outcrop area (MacKevett, 1978). The pre-Jurassic rocks are lumped together as the Strelna Metamorphic Assemblage, and include late Paleozoic to early Mesozoic sedimentary and volcanic deposits metamorphosed at upper-greenschist to upper-amphibolite facies as well as Paleozoic metaplutonic rocks (Plafker et al., 1985; Plafker et al., 1989, 1992). This metamorphic assemblage is invaded by voluminous Middle to Late Jurassic quartz dioritic to tonalitic plutonic rocks of the Chitina Valley batholith (MacKevett, 1978; Hudson, 1983; Hudson et al., 1985). This Jurassic plutonic assemblage is generally inferred to represent the roots of a magmatic arc with north-dipping subduction (e.g., Plafker et al., 1989), yet like the Peninsular terrane plutonic assemblage, these rocks now lie directly along the Border Ranges fault system. The Strelna Assemblage is typically interpreted as basement to the Wrangellia terrane due to their local overlap by distinctive Triassic volcanic rocks of the Wrangellia terrane (Winkler et al., 1981). Nonetheless, large tracts of this assemblage were strongly overprinted by post-Triassic metamorphism and ductile deformation (e.g., Roeske et al., 1992, 2003) raising questions of why this Triassic cover is not involved in this deformation and metamorphism if these rocks were Wrangellian basement (see details below). In addition, a major Early Cretaceous fault system, the Chitina Valley fault, separates most (or all?) of this assemblage from known pre-Cretaceous Wrangellian cover (MacKevett, 1978; Gardner et al., 1986; Trop et al., 2002). Thus, the tectonic affinity of part of this assemblage remains in doubt, and resolving this affinity ultimately is important to regional interpretations.

Farther south, from Glacier Bay to Baranof Island, the "backstop" assemblage is even more variable. In the Glacier Bay area the dominant crystalline assemblage is an Early Cretaceous plutonic suite (e.g., Brew and Morrell, 1983; Smart et al., 1996), and the adjacent metamorphic assemblages are probably derived from Paleozoic strata of the Alexander terrane (Berg et al., 1978). Even farther south, however, Triassic cover characteristic of Wrangellia lies directly above the Border Ranges fault (Decker, 1980; Johnson and Karl, 1985). Given the evidence that the pre-Triassic rocks of the Alexander terrane represent basement to at least part of the Wrangellia cover sequence (Gardner et al., 1988) the observations from southeast Alaska indicate this segment of the fault system exposes variable levels of the basement to the Wrangellia terrane. Nonetheless, many structural details in this segment are not well known, and it is possible important details have not been recognized.

These regional relationships support the general concept that the Border Ranges fault initiated in mid-Mesozoic time as a subduction megathrust with the same polarity as the present Alaskan-Aleutian subduction zone. In detail, however, the timing of initiation of subduction is debatable, and this history is strongly overprinted. In particular, a first-order feature of the boundary throughout its exposed length is juxtaposition of mid-Mesozoic arc plutonic assemblages against accretionary complex rocks to the south. That these plutonic rocks originally formed above a deep subduction zone raises an important question on the fate of the intervening older forearc crust that originally must have been outboard of the present fault contact. Below, we consider the state of knowledge on some of these issues by reviewing relationships on different segments of the fault, progressing from southwest (Kodiak Island) to southeast (Baranof Island; Fig. 1).

KODIAK ISLAND TO THE SOUTHERN KENAI PENINSULA

The section of the Border Ranges fault exposed along the northwest side of the Kodiak Islands and the southern Kenai Peninsula is unique from other segments of the fault in that it exposes the oldest and highest-pressure part of the Chugach accretionary complex. Lawsonite-pumpellyite and glaucophane-epidote facies rocks of the Raspberry Schist (Roeske, 1986) and Seldovia schist (Carden et al., 1977; Cowan and Boss, 1978) record pressures ranging from 400 to >700 MPa (Roeske, 1986). The highest-pressure rocks are most inboard, juxtaposed along a brittle, high-angle fault with layered gabbro and quartz diorite that comprise part of the Border Ranges mafic-ultramafic complex, the Early Jurassic arc basement of the Peninsular terrane (Burns, 1985). The fault between the blueschists and plutonic rocks was thought originally to be a minor fault superimposed on an intrusive contact, and the Border Ranges fault was placed outboard of the Raspberry and Seldovia schists (Plafker et al., 1977; Connelly and Moore, 1979). This interpretation was reasonable, based on the geochronology, because the age of the diorite overlaps the metamorphic age of the schist. However, subsequent field work, petrology, and geochronology showed that the Raspberry and Seldovia schists do not have a thermal overprint associated with the pluton, and the ages of the schists are the same whether near or distant from the plutonic rocks, ranging from K-Ar dates of 192–196 to U/Pb and Rb/Sr dates of 196–204 (Carden et al., 1977; Roeske, 1986; Roeske et al., 1989).

These metamorphic ages also overlap the depositional age of the Talkeetna Formation, the extensive volcanic and volcaniclastic section exposed on the Peninsular terrane inboard of the Border Ranges fault in southern Alaska (e.g., Clift et al., 2005a). Thus, the Talkeetna arc and the Kodiak-Seldovia blueschists form an arc/accretionary complex pair with subduction polarity the same as the modern Aleutian subduction zone. The only difficulty with this interpretation is that much of the forearc is missing because the blueschists are adjacent to midcrustal arc plutonic rocks. Roeske et al. (1989) suggest that the juxtaposition could have been by either subduction erosion, a process that has been documented at modern convergent margins (von Huene and Scholl, 1991), or by strike-slip erosion during oblique convergence, also common at modern margins (Jarrard, 1986). One consequence of the latter process is that the subduction complex may have moved laterally some large distance from its original site and thus may not have formed as a "pair" to the now adjacent arc basement.

Regardless of the tectonic process that removed much of the forearc, this event apparently occurred during the Early to Middle Jurassic (Clendenen et al., 2003). Zircon and apatite fission track ages for both the dioritic plutonic rocks and the Raspberry schist are the same; the former are ca. 150 Ma, and the latter are ca. 60–70 Ma (Clendenen et al., 2003), indicating very slow cooling of both the Chugach accretionary complex and Peninsular terrane basement from the middle Jurassic through the Cretaceous. Aside from the case of the coincidental juxtaposition of different rocks with the same cooling history, these data indicate there has been no substantial vertical displacement along this segment of the Border Ranges fault since ca. 150 Ma and that the blueschists and plutonic rocks have been together since Late Jurassic time. In addition, no significant strike slip occurred after ca. 58–62 Ma in this area because granite-granodiorite dikes and plutons of that age are intruded on both sides of the fault (Davies and Moore, 1984). This evidence contrasts markedly with observations along strike where significant Early Cretaceous–early Cenozoic reactivation has occurred (see below).

The Raspberry and Seldovia schists are not continuous, and where they are absent, subgreenschist facies mélange is juxtaposed against plutonic rocks along the Border Ranges fault system. The mélange is called the Uyak Complex on Kodiak Island and the McHugh Complex on the Kenai Peninsula, and both of these units contain a wide range of deep-marine protoliths similar to those found in the schists. Radiolaria ages range from pre-Mesozoic to Early Cretaceous in the Uyak complex (Connelly, 1978) and from Middle Triassic to Early Cretaceous in the McHugh complex (Nelson et al., 1987; Bradley and Kusky, 1992; Bradley et al., 1999). Without a structural and/or stratigraphic context, fossil ages from mélange rocks are often misinterpreted because at best they provide information on the age of subducting lithosphere integrated over the time of mélange formation, which provides only a fuzzy constraint on the age of accretion (e.g., Pavlis, 1982). Thus, these depositional ages allow for the possibility that the oldest parts of the Uyak and McHugh complexes were accreted at approximately the same time as the Raspberry and Seldovia schist. Nonetheless, the presence of mid-Cretaceous fossils indicates that at least part of the mélange is much younger than the blueschists (Pavlis, 1982; Nelson et al., 1987; Winkler, 1992).

KENAI AND WESTERN CHUGACH MOUNTAINS

General

From Homer to Anchorage, the Border Ranges fault system is buried beneath Tertiary to Quaternary sediments. High-angle reverse and thrust faults with east-side up offsets are mapped onland and imaged in seismic data along the Kenai Mountain front (e.g., Pavlis and Bruhn, 1983, and references cited therein; Haeussler et al., 2000). These structures follow the trend of the Border Ranges fault within this segment and indicate significant thrust-reactivation of the boundary. This faulting appears to be late Miocene or younger based on stratigraphic relationships in the Cook Inlet basin (e.g., Pavlis and Bruhn, 1983; Haeussler et al., 2000), but based on relationships to the east there are almost certainly older Cenozoic structures as well (see below). Nonetheless, faulting of late Miocene and younger strata suggests the present forearc highland (Kenai-Chugach Mountains) developed from Late Miocene to recent times. Similar Neogene structures, however, are apparently absent farther east along the Border Ranges fault, suggesting this reactivation is closely tied to the development of the present topographic lowland of Cook Inlet and Susitna basins. This inference is supported by Lahr and Plafker's (1980) suggestion that this basin system may constitute a contractional boundary within southern Alaska and more recently by GPS studies (Fletcher, 2002) and neotectonic studies (Haeussler et al. 2000) that support this model. That is, thrust systems along the east side of the Cook Inlet and Susitna basins led to uplift of the hanging wall (Chugach and Talkeetna Mountains) with subsidence to the west due to downwarping, thrust-loading, or both.

Just north of Anchorage the fault system emerges from beneath the Tertiary sediments that cover it to the south and is well exposed along the northern flank of the Chugach Mountains (Fig. 2). This segment in the western Chugach Mountains was virtually unknown in the early 1970s when MacKevett and Plafker (1974) defined the Border Ranges fault. Now, however, this segment is the most well-known segment due to regional mapping efforts by the Alaska State Geological Survey (Burns, 1982; Burns et al., 1983) and topical studies by T. Pavlis and coworkers (Pavlis, 1982, 1983, 1996; Pavlis and Bruhn, 1983; Pavlis et al., 1988; Barnett et al., 1994), T. Little (Little and Naeser, 1989; Little, 1988, 1990), and L. Burns (Burns, 1985). More recently, U-Pb dating of plutonic assemblages in this belt further clarifies the age relationships (Rioux et al., 2003, 2004).These studies reveal a complex system of brittle faults that are locally superimposed on older ductile structures. These faults affect both plutonic and stratified rocks that range in age from Late Triassic to Early Cenozoic (e.g., Pavlis, 1983; Burns et al., 1991; Little, 1990). Some of the brittle faults can be traced as damage zones—curviplanar zones of intense hydrothermal alteration and cataclasis—that are up to 1500 m in structural thickness (e.g., Pavlis et al., 1988; Pavlis, 1996). In the eastern Anchorage Quadrangle, just east of the Matanuska Glacier, several of these broad fault zones coalesce and form a 3–5 km band of intensely faulted rocks that continues eastward into the Valdez Quadrangle (Fig. 2). Given the scale of this brittle deformation, the slip on many of these structures must be large, but scarcity of cutoff lines or piercing points as well as poor paleo-depth information handicaps reconstruction. Thus, many details of the deformational history may never be resolved. Nonetheless, the detailed studies to date provide a database that clearly establishes a his-

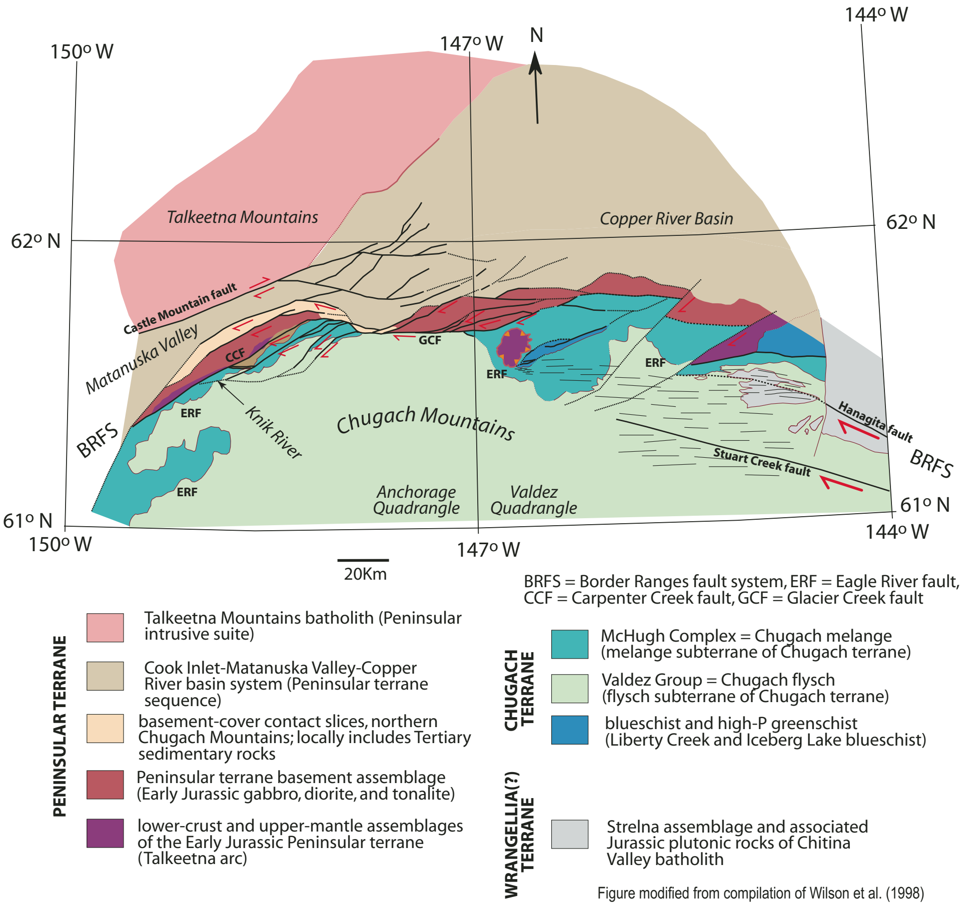

Figure modified from compilation of Wilson et al. (1998)

Figure 2. Tectonic map of the north-central Chugach Mountains, Matanuska Valley, Copper River basin and southern Talkeetna mountains. Figure is generalized from the map compilation by Wilson et al. (1998). Terrane terminology after Plafker et al. (1994).

tory of repeated rejuvenation of the Border Ranges fault since middle Mesozoic time. Key in this interpretation are cross-cutting relationships among structures of different ages, two generations of plutonic rocks of Early Cretaceous and Early Cenozoic age, and sedimentary rocks as young as Eocene (Pavlis, 1982; Pavlis et al., 1988; Little and Naeser, 1989; Little, 1990).

The western Chugach Mountains are an important segment of the Border Ranges fault system because they expose the only segments of the fault system that are demonstrably older than Middle Cretaceous. Resolution of that older history, however, requires looking through an intense late Mesozoic and Cenozoic overprint.

Tertiary Dextral Strike-Slip and Related Structures

Cenozoic deformation along the Border Ranges fault is only part of a broader zone of early Cenozoic deformation that affected not only rocks along the Border Ranges fault in the northern Chugach Mountains but also to the north across the Matanuska River Valley and into the southern Talkeetna Mountains (Fig. 2). Little (1988) and Pavlis et al. (1988) independently recognized that this deformation recorded strike-slip reactivation of the Border Ranges fault system, and Little and Naeser (1989) provided the key data constraining the age to a narrow interval in Eocene time between ca. 55 and 45 Ma. Little's (1990) work provided the key data that constrain this Cenozoic history through documentation of the stratigraphic and structural evolution of Cenozoic sedimentary strata caught up in the deformation. Trop et al. (2003) built on this work and provided important new information on the stratigraphic evolution of the syntectonic-basinal deposits associated with this event, including ties to the motion on the Castle Mountain fault system (Fig. 2).

Two age relationships provide the principal constraints for all of these studies (e.g., Little, 1990; Trop et al., 2003): (1) the syn- to postdepositional history of Paleocene-Eocene cover (Chickaloon and Wishbone Formations) tied to structures as well as sedimentary provenance and (2) Eocene intrusive rocks that cross-cut or are cut by the early Cenozoic structures. Preliminary studies by Barnett et al. (1992) also indicate that many of these faults can be distinguished by hydrogen isotope signatures of fault rocks with a meteoric water signature in the Cenozoic fault rocks, but data are only available for a few faults.

Little (1990, 1992) documented two episodes of fault-related folding in Paleocene–Early Eocene strata that were closely tied to a structural history of folding in the adjacent Chugach terrane. Moreover, he used sedimentary facies and provenance to demonstrate that a southern, uplifted highland along the Border Ranges fault system was the source for these sediments, indicating deformation had begun by the time of deposition of the Paleogene strata. The earlier generation of folds forms an en echelon array, oblique to a major strike-slip fault zone that Little (1990, 1992) referred to as the Glacier Creek fault. In terms of lithologic juxtaposition, the Glacier Creek fault is coincident with the Border Ranges fault along most of its trace, but the fold asymmetries and slickenside data reported by Little (1990, 1992) clearly demonstrate this segment of the fault is a Tertiary dextral fault.

Little (1990, 1992) also documented that a right-stepping bend in the trace of the Glacier Creek fault was an even younger structure that developed after the earlier generation of folds in the Paleogene strata. He documented this history through overprinting relationships in the Paleogene strata in that the early folds were warped into steeply-plunging "megakinks" in the vicinity of these large fault bends. This history was interpreted as a large-scale strike slip analog of a fault bend fold with the fault bend representing a ramp in the strike-slip fault and the "megakinks" equivalent to the fault-bend fold.

We agree with this general interpretation but suggest here that a strike-slip duplex model similar to that shown in Burns et al. (1991) may be a simpler explanation of the observed overprinting (Fig. 3). Specifically, Little (1990, 1992) and Pavlis et al. (1988) collectively documented four significant strike-slip fault systems that form a subparallel array that converge on the fault bend of the Glacier Creek fault (Figs. 2 and 3). The southern three of these faults produce distinctive 5–10 km dextral shifts in the trace of the north-dipping Eagle River fault, which is the local name for Chugach mélange-flysch structural contact (Fig. 3). The northern fault in this array was referred to by Pavlis et al. (1988) as the Carpenter Creek fault, and although it is strongly curved, it can be traced as a continuous structure from the Knik River to the right-stepping bend described by Little (1990, 1992), where it merges with the Glacier Creek fault. Here we infer that the Carpenter Creek fault and Glacier Creek fault are the same structure, which connects eastward into the band of intense cataclasis along the Glacier Creek fault to the east. Moreover, the Carpenter Creek fault almost certainly projects directly across the Knik River to the lithologic break between the Chugach terrane and the Eklutna ultramafic body forming the Border Ranges fault sensu stricto in that area. This structural correlation is important because the strong curvature in the Carpenter Creek–Glacier Creek fault system lies directly north of the three subparallel fault sets that merge with the fault at the eastern end of the fault bend. This geometry is a map view equivalent of an antiformal stack generated by duplex development in the footwall of a thrust; i.e., the Carpenter Creek—Glacier Creek fault system forms the "roof" to the duplex, and the floor would be represented by faults that disappear into the lithologically monotonous Chugach flysch.

Pre-Tertiary Deformation

Pavlis et al. (1988), Pavlis (1982, 1983, 1996), and Barnett et al. (1994) presented data that document the partial preservation of an Early Cretaceous deformational event along the Border Ranges fault. These studies emphasized an interpretation that this event recorded the initiation, or reinitiation, of subduction along the Border Ranges fault. Alternatively, however, this event could be associated with Mesozoic ridge-subduction (see below). The principal evidence for the Early Cretaceous event arises from cross-cutting relationships of Early Cretaceous plutonic rocks, thermochronology, and analysis of metamorphic assemblages in a 5–10-km-wide band of metamorphic and plutonic rocks that lie along the Border Ranges fault from the Knik River to just east of Coal Creek (Fig. 3). The present strike-length of the belt is ~30 km, but restoration of Tertiary dextral faults like the Carpenter Creek fault indicates at least 8–12 km of duplication by dextral strike slip. Given that this dextral slip is likely to be significantly larger (see below), the original pre-Tertiary extent of this belt was probably well in excess of 50 km along strike.

Pavlis et al. (1988) recognized three distinct structural/lithologic assemblages (terranes/subterranes) within this belt including, from north to south: (1) the northwest-tilted southern edge of the Peninsular terrane including both its cover (Talkeetna Formation and overlying rocks) and Early Jurassic plutonic rocks that invade the coeval cover sequence, (2) a central plutonic complex dominated by highly faulted gabbroic to tonalitic rocks with rare screens of older upper-greenschist to upper-amphibolite facies metamorphic rocks, and (3) a southern, dominantly metamorphic assemblage containing diverse upper greenschist to amphibolite facies metasedimentary and metavolcanic rocks as well as metamorphosed ultramafic bodies. The two northern assemblages are characterized by Early Jurassic cooling ages, extensive brittle deformation but absence of evidence for any post–Middle Jurassic ductile deformation. Peak metamorphic pressures are not well constrained, but Cretaceous assemblages imply conditions <400 MPa for this belt (Barnett et al., 1994). In contrast, the southern assemblage is characterized by several distinctive features (Pavlis, 1982, 1983; Pavlis et al., 1988; Reason, 1990; Barnett et al., 1994): (1) clear evidence of extensive Early Cretaceous ductile deformation constrained in age by syn-tectonic emplacement of several Early Cretaceous leucotonalite-trondhjemite plutons into the metamorphic complex, (2) Early Cretaceous (ca. 120–130 Ma) high-T cooling dates in the metamorphic complex that are indistinguishable from the cooling dates of the syntectonic intrusives, (3) peak metamorphic pressure estimates of 300–400 MPa north of the Carpenter Creek fault but 600–700 MPa south of the fault, and (4) involvement of mafic/ultramafic bodies in the Early Cretaceous metamorphic event. Most significant of all, however, are variations in the cross-cutting relationships of the Early Cretaceous plutonic bodies at different structural levels. Specifically, in the central belt the plutons cut faults, yet in the southern belt the plutons are syntectonic to ductile deformation indicating an exposure of successively deeper structural levels to the south that is consistent with metamorphic pressure estimates. At the lowest structural levels, however, a plutonic body was emplaced across the brittle fault that separates the Early Cretaceous metamorphic rocks from the low-grade mélange of the Chugach terrane, indicating a progression of deformation from ductile to brittle conditions during the deformation at these structural levels of the thrust system.

Pavlis et al. (1988) referred to the central and southern assemblages as the plutonic and metamorphic subterranes respectively

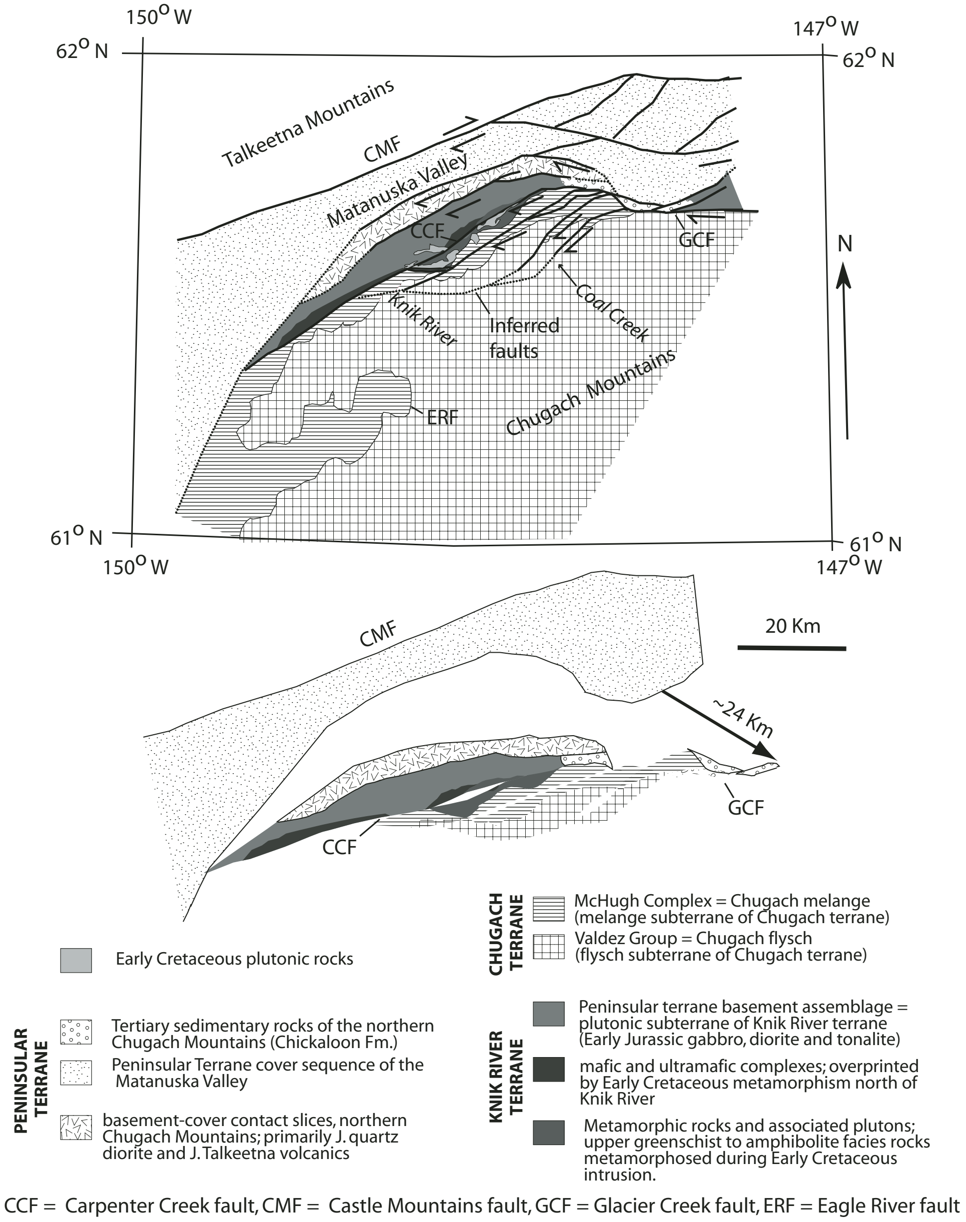

Figure 3. (above) Generalized geologic map of the western Chugach Mountains showing inferred major fault linkages within the western Chugach fault array and connections of that fault array to the Glacier Creek fault system mapped by Little (1990). (below) Map restoration of the Tertiary fault array in the western Chugach Mountains using a strike-slip duplex model. Figure is generalized from Wilson et al.'s. (1998) digitized maps of Winkler's (1992) compilation of the Anchorage quadrangle.

of the Knik River terrane. This tectonic unit arose from 1980s terrane terminology but was used by Pavlis et al. (1988) as an example of a weakness in the classic terrane approach when basement and cover are structurally separated. Specifically, the available data strongly suggest that the central assemblage and parts of the southern belt represent the deformed basement of the Peninsular terrane and the metamorphic rocks in the southern assemblage represent reworked forearc basement, high-grade equivalents of the Chugach terrane, or both (Pavlis et al., 1988 and Barnett et al., 1994). This interpretation was recently supported by fabric studies of ultramafic rocks from the southern belt (Wolverine ultramafic complex) that show high-T crystallographic preferred orientations similar to fabrics in the Tonsina ultramafic complex (Mehl et al., 2003). The Tonsina complex has clear associations to the Early Jurassic Peninsular terrane arc and contains high-P mineral assemblages indicative of lower-crustal to upper-mantle conditions. Thus, by inference the metamorphosed mafic-ultramafic rocks in the southern belt are lower-crustal/upper-mantle basement assemblages of the Peninsular terrane that were caught up in the Early Cretaceous metamorphism and deformation.

Barnett et al. (1994) and Pavlis (1996) modeled the Early Cretaceous deformational history in the context of the initiation, or reinitiation, of a subduction zone. In this model, the Early Cretaceous plutons were generated down-dip in the juvenile subduction zone prior to quenching by subduction refrigeration. The plutons also transported heat and may have been the principal reason for the development of high-T, medium-P metamorphic assemblages recognized within the belt (e.g., Barnett et al., 1994) and the restriction of the metamorphism to the southern part of the belt (Pavlis, 1996). Thermal models of this process (Pavlis, 1996) indicate that the variations in plutonic cross-cutting relationships with structural level can be attributed to plutonic emplacement in an evolving megathrust where the temperature was rapidly cooling due to subduction. In the crystalline rocks of the Knik River terrane, north to south variations from brittle to ductile deformation are consistent with variations in level across a crustal section. The origin of the abrupt boundary in cooling ages within the belt is less clear, but Pavlis (1996) concluded this observation can be attributed to trapping of heat within a zone of inverted thermal gradients along a megathrust. Similarly, the progression from ductile to brittle conditions in the southern belt followed by emplacement of a pluton across the faulted contact with the adjacent Chugach mélange implies a later emplacement of this pluton. Nonetheless, the age span of this process need not have been large due to potential for plate-tectonic rates in an evolving subduction; that is, the entire sequence could have spanned less than 1 m.y. (Pavlis, 1996).

An alternative model for this plutonic and metamorphic event is that it records an Early Cretaceous ridge subduction event (Pavlis, 1982) and recent work lends some support to this alternative hypothesis. A regional lull in magmatic activity from latest Jurassic to mid-Early Cretaceous time and a pre-Albian unconformity in the adjacent forearc basin are recognized (e.g., Armstrong, 1988; Pavlis, 1982; Trop et al., this volume). Events of this type are common in areas of ridge subduction (Sisson et al., 2003a) but are not diagnostic. However, other factors hint more strongly at ridge subduction: (1) the geochemistry and isotopic characters of the Early Cretaceous plutons have similarities to the Paleogene forearc plutons in southern Alaska, which have a clear association with ridge subduction (e.g., Conrad et al., 1988; Pavlis et al., 1988; Harris et al., 1996; Sisson et al., 2003b); (2) the localized high-T metamorphism is similar to, but on a smaller scale than, the Eocene Chugach metamorphic complex, which is widely considered a product of ridge subduction (e.g., Sisson et al., 1989; Sisson et al., 2003a); and (3) there are hints that the belt might be dextrally displaced equivalents of slightly younger, more extensive plutonic rocks found along the Border Ranges fault in the Glacier Bay area (Smart et al., 1996), where the younger age in Glacier Bay could be the product of triple junction migration. More geochronologic and geochemical data on the plutonic system as well as more basic work in the Glacier Bay area is needed to further test this hypothesis. Thus, at present it remains a viable but poorly constrained alternative for the origin of the Early Cretaceous plutonic-metamorphic history.

CENTRAL CHUGACH MOUNTAINS

General

This segment primarily encompasses the region between the Matanuska Glacier and the Richardson Highway. The portion within the Anchorage Quadrangle (west of Nelchina Glacier, Fig. 4) is reasonably well known from the mapping by the Alaska Geological Survey (Burns et al., 1991). The remainder of this segment, however, is poorly understood because the only regional mapping is the 1:250,000 map of the Valdez Quadrangle (Winkler et al., 1981), and topical studies within this segment are spotty. Moreover, our understanding of this segment may remain poor because rock exposure in much of this region is poor relative to adjacent areas. Recent work, however, provides some clarification of the nature of this segment.

Geologic Relationships

In the eastern Anchorage Quadrangle between the Matanuska and Nelchina Glaciers, the Border Ranges fault is the eastward continuation of Little's (1990) Glacier Creek fault. This high-angle fault segment clearly continues eastward into the Valdez Quadrangle at least as far as the Tazlina Glacier and probably continues as the same fault system at least as far as the Klutina River (Fig. 4). This segment is a Tertiary dextral fault based on fault kinematic information and the presence of slices of the Tertiary Chickaloon Formation along the fault (Fig. 4) as far eastward as the Nelchina Glacier (Little, 1990; Burns et al., 1991). The most conspicuous feature of this segment is that a broad band of intense cataclasis parallels the mapped fault trace, but cataclasis is restricted to the deformed crystalline rocks to the north. Regional compilations by Wilson et al. (1998) show part of this cataclastic assemblage (their map unit TKc), but the zone of cataclasis is significantly wider than shown on this compilation. Specifically, although slabs of intact rock up to several km in strike-length are present, a network of steeply dipping cataclastic zones define a broad band of brittle deformation at least 5 km wide throughout this segment. We attribute the bulk of this deformation to Tertiary strike-slip motion on the Glacier Creek segment of the Border Ranges fault system, but other complications are present. Specifically, Winkler et al. (1981) mapped two unusual rock assemblages south of the Glacier Creek fault between Nelchina Glacier and Klutina River (Fig. 4): (1) an area of foliated mafic plutonic rocks with Jurassic K-Ar dates, later confirmed by Ar/Ar geochronology (Sisson and Onstott, 1986; Onstott et al., 1989), that form a crudely circular outcrop area and (2) Jurassic(?) blueschist facies rocks that define an elongate outcrop belt on regional maps. Both of these assemblages lie atop or within a large salient in the Eagle River fault. This salient, however, is also cut off to the north by the Glacier Creek fault, and to the east it shows a complex map pattern with other rock assemblages. Most significantly, however, the plutonic rocks form a klippe atop this salient with a low-angle fault contact on all sides (e.g., Winkler et al., 1981). Because this klippe is centered on the Klanelneechena River, the structural feature is referred to here as Klanelneechena klippe following Rioux et al. (2004). Recent petrologic and geochronologic studies on the Klanelneechena hanging-wall assemblage (Kelemen et al., 2005) confirm that these rocks represent lower-crustal metaplutonic assemblages of the Early Jurassic Peninsular terrane with peak pressures only slightly lower than the Tonsina ultramafic complex where the arc moho is exposed (DeBari and Coleman, 1989).

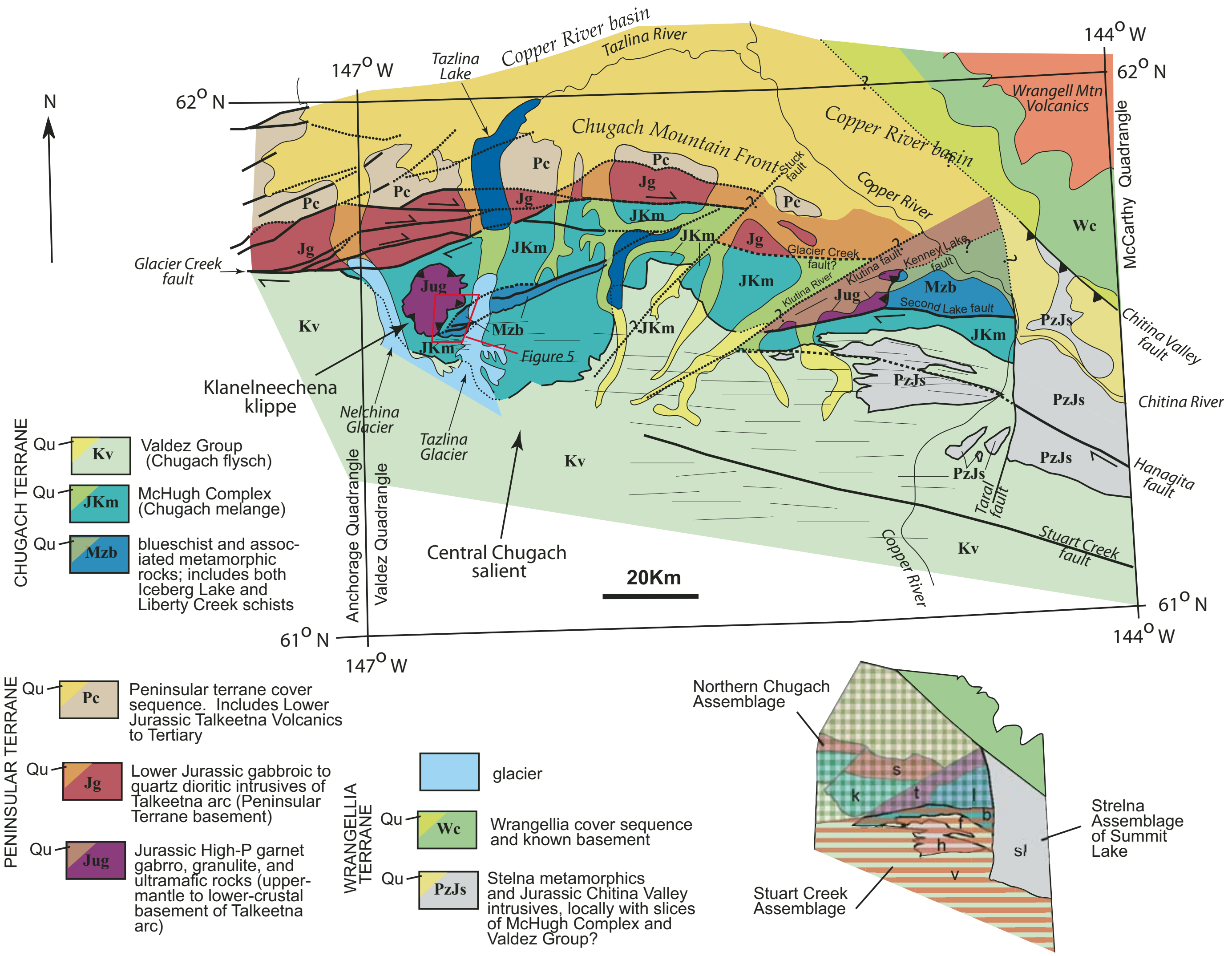

Figure 4. Tectonic map of the Valdez Quadrangle and easternmost Anchorage quadrangle showing our reinterpretation of the major structures in this segment of the Border Ranges fault system. Figure is modified from Wilson et al.'s (1998) compilation map. Note the insert in lower-right corner shows major structural blocks referred to in the text and Table 1. Abbreviations: s = Stuck Mtn Block; k = Klutina Block; t = Tonsina Block; l = Liberty Creek Block; b = Bernard Creek Block; f = Fox Creek Block; h = Haley Creek Block; sl = Summit Lake Block; v = Valdez Group Block.

In 2001 and 2002 one of us (Pavlis) examined a part of this salient and the eastern edge of the Klanelneechena klippe, and detailed mapping revealed some important characteristics about this structural feature. Figure 5 summarizes the results of detailed mapping within this area with three important relationships observed.

First, the metaplutonic rocks in the hanging wall of the Klanelneechena klippe are intensely faulted in a zone up to 600 m in structural thickness. This brittle fault zone is marked by anastamosing cataclastic zones from 1 to 200 m thick separating more intact slices of rock up to 1–2 km along strike and up to 200 m in thickness. Mineral assemblages within these fault rocks are indistinct chlorite-zeolite assemblages indicating subgreenschist conditions. These very low-grade mineral assemblages contrast markedly with the high-P granulite facies assemblages recognized in the metagabbro of the Klanelneechena klippe and indicate that these metaplutonic rocks had been deeply exhumed prior to the development of these fault rocks (e.g., Clift et al., 2005b; Kelemen et al., 2005). This conclusion is also consistent with Jurassic hornblende Ar/Ar cooling ages obtained from the complex (Sisson and Onstott, 1986; Onstott et al., 1989) and with Paleogene U-Th-He zircon ages obtained from the complex (M. Rioux, personal commun. to T. Pavlis, 2004). The basal thrust of the klippe and most of the faults are gently dipping structures that cut across more steeply dipping granulite facies foliations. In the Tonsina area, equivalent high-T fabrics are parallel to the ultramafic-gabbro contact, the presumed moho of the exhumed Talkeetna arc section (e.g., Burns, 1985, and DeBari and Coleman, 1989), suggesting this fabric was originally approximately flat-lying. This inference is important because the fault

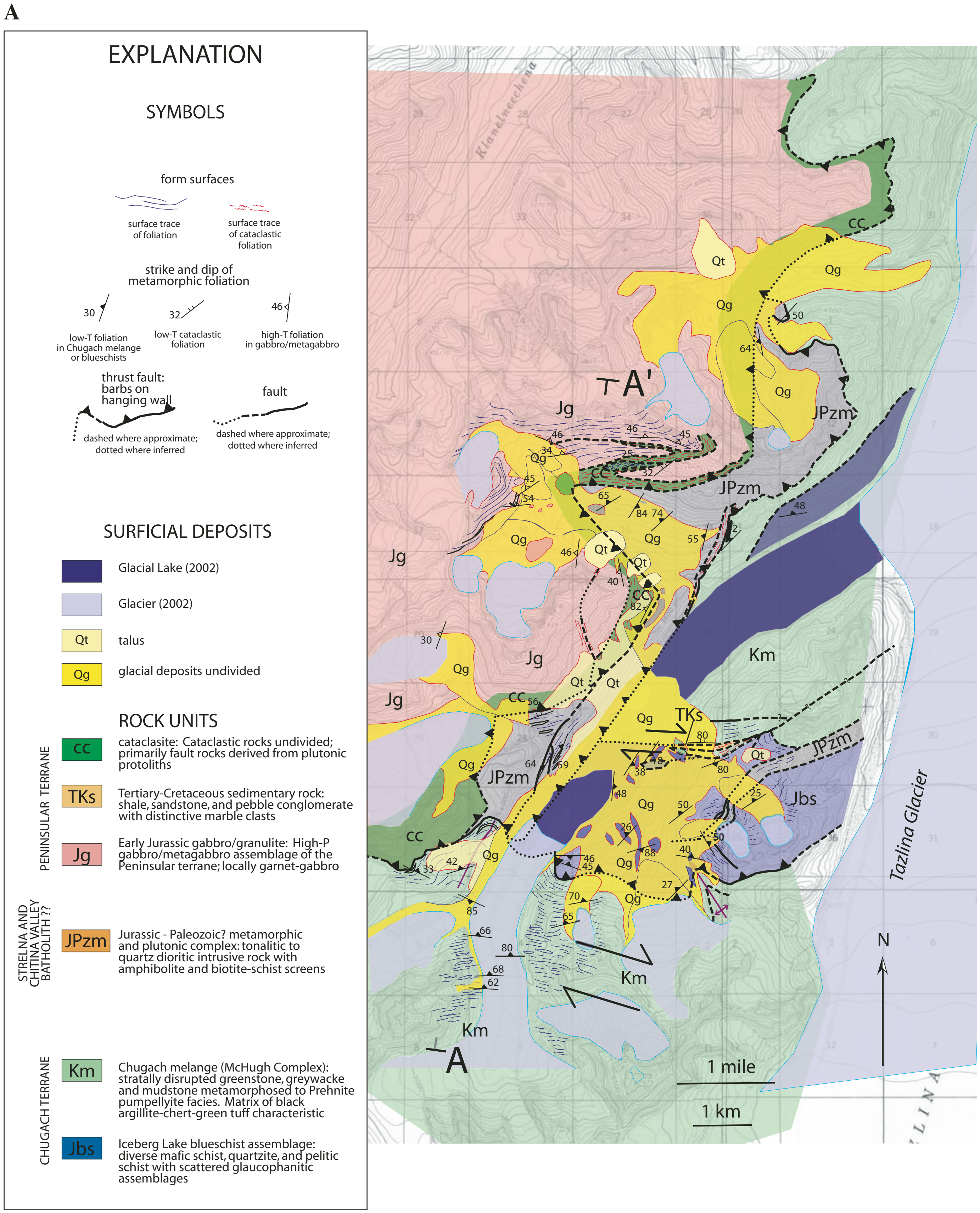

Figure 5. (*continued on the next page*) Geologic map (A) and cross section (B) of the eastern part of the Klanelneechena klippe just west of the Tazlina Glacier.

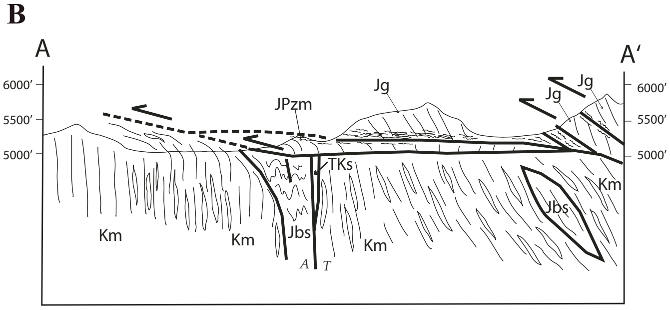

Figure 5. (*continued*)

cutoff relationships with these high-T fabrics are incompatible with a south-directed thrust system that nucleated across a flat fabric. That is, a south-directed thrust ramping upward through flat layering would show either layer parallel faults (hanging wall flat) or south-dipping layering above a flat fault (hanging wall cutoff), and instead layering dips steeply north and is truncated against a flat fault. The simplest solution to this observation is that the fabric had already been tilted northward prior to faulting, and faults cut across that layering to carry the klippe atop the footwall assemblage.

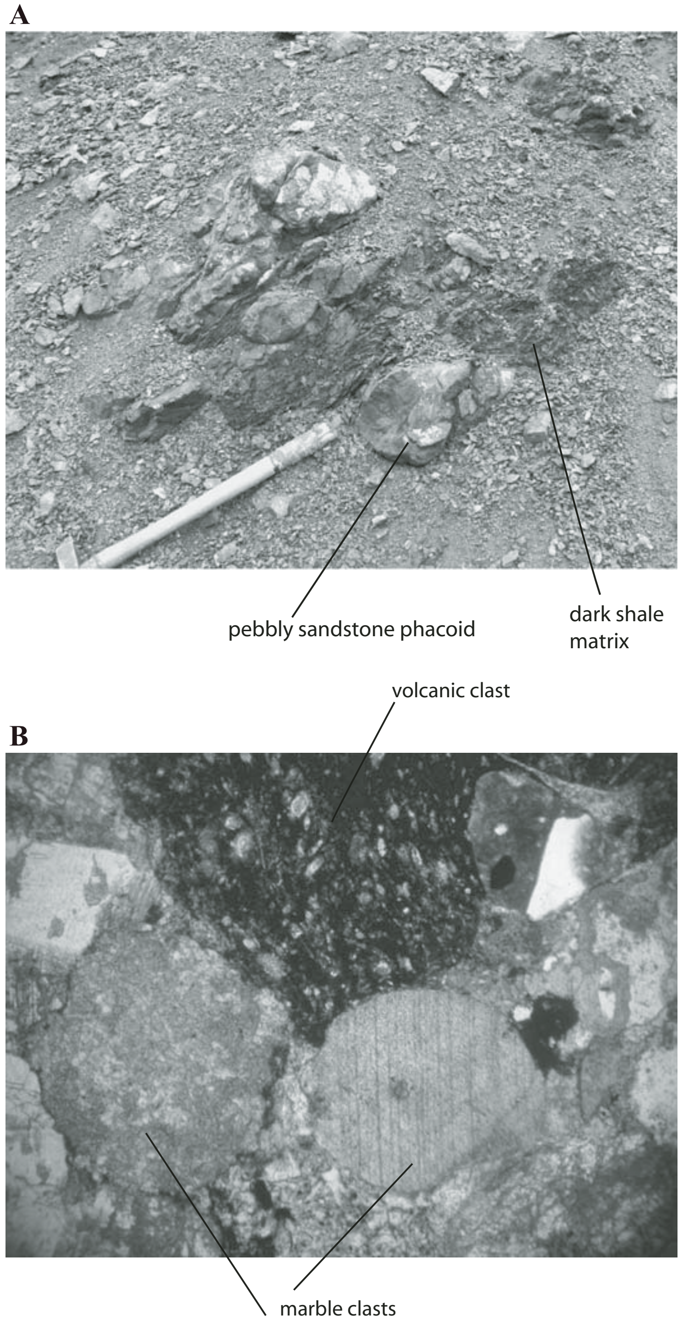

Figure 6. Field exposure (A) and photomicrograph (B) of unmetamorphosed sedimentary rocks sliced together with Chugach mélange and blueschists in the area of Figure 5 (map unit TKs). In Figure 6A, note the stratal disruption of the sedimentary rocks with a dark mudstone matrix surrounding sandstone phacoids, indicating brittle fault disruption of the stratified rocks. Figure 6B shows a low-magnification photomicrograph of the sandstone (field of view is ~8 mm across) of the unmetamorphosed sandstone dominated by marble and volcanic clasts in this coarse sandstone. The marble clasts have no known source nearby.

Second, the low-angle basal thrust system of the Klanelneechena klippe truncates steeply dipping, low-grade metamorphic fabrics in the Chugach mélange that lie directly beneath the klippe, indicating this fault is younger than that fabric. More importantly, however, a system of brittle faults in the footwall of the Klanelneechena klippe are subparallel to this steeply dipping fabric, and these faults also appear to be truncated by the basal thrust of the klippe. These footwall faults have produced a shuffling of large slices of blueschist, graphitic-biotite schist, high-P barrositic amphibolite, and metaplutonic rocks incorporated as structural blocks into the Chugach terrane mélange and as fault slices below the klippe (Fig. 5). Most importantly, however, these footwall faults have also incorporated slices of unmetamorphosed sedimentary rocks that range from dark carbonaceous mudstone to pebble conglomerate (Figs. 6A and 6B). These sedimentary rocks have been stratally disrupted by faulting but probably represent the same stratigraphic assemblage. The mudstone is superficially similar to the Chickaloon Formation, which is exposed only a few kilometers to the west along the Nelchina Glacier but in a different structural position (Fig. 4). The coarse sandstones and conglomerates in these rocks are similar in grain size to the southern facies of Chickaloon Formation described by Little (1988, 1990) but are petrologically distinct. Specifically, in the Klanelneechena rocks, the dominant clasts are marble and volcanic rock fragments (Fig. 6B). This contrasts markedly with the mixture of volcanic and plutonic clasts typical of the bulk of the Chickaloon Formation (e.g., Trop et al., 2003) and is distinct from Little's (1988, 1990) southern facies, which is dominated by local, southerly derived sources from the Peninsular and Chugach terranes. This petrologic distinction is important because there are no local sources for the extensive marble clasts that comprise the Klanelneechena conglomerates. The closest extensive source for these marble clasts exposed today lies over 100 km to the east in the Summit Lake area just east of the Taral fault (Fig. 4). This association therefore places constraints on the strike-slip history of the Border Ranges fault system (e.g., Pavlis and Roeske, 2003, and below).

Third, the regional map pattern of the Eagle River fault may be misleading in light of structural relationships at the base of the Klanelneechena klippe. The large salient in the fault between the Nelchina and Klutina Rivers suggests that this segment locally preserves the low-angle Mesozoic thrust contact of the Eagle River fault. The observation of steeply dipping to vertical fabrics and faults within this salient and the emplacement of the Klanelneechena klippe after these steep fabrics were developed indicate that the apparent low-angle contact beneath this salient may be, like the Klanelneechena klippe, a younger thrust system that postdates the steep fabrics and faults within the salient. Alternatively, the basal contact of the salient may be more complex, similar to the Haley Creek klippe (see below), where overprinting of ductile strike-slip shear and faulting produce a complex, composite structural contact.

Synthesis

These observations strongly suggest that the thrust emplacement of the Klanelneechena klippe, and possibly the salient in the Eagle River fault, represents a relatively late structural event within the central Chugach Mountains segment of the Border Ranges fault. The observation that blueschists, plutonic rocks, and unmetamorphosed sediments are structurally interleaved with low-grade Chugach mélange along systems of high-angle faults, some with strike-slip slickensides, suggests that this structural shuffling is a local manifestation of the extensive dextral strike-slip history recognized immediately to the west and north along the Glacier Creek fault segment of the Border Ranges fault system. More importantly, however, the observation that these high-angle fabrics and faults are truncated by the basal thrust of the klippe indicates the emplacement of the klippe postdates most, or all, of the strike-slip deformation recognized in the footwall assemblage.

Thus, we conclude that the strike-slip–related deformation that is well documented in the western Chugach Mountains continues through the central Chugach Mountains. Unlike the western Chugach Mountains, however, the strike slip was not concentrated in the crystalline assemblages north of Border Ranges fault but instead was dispersed into faults and shear zone that cut into the subduction assemblages to the south (Chugach terrane). Late in this deformation, the Klanelneechena klippe was apparently expelled from the strike-slip system along a low-angle fault and emplaced atop the faults and fabrics of this earlier strike-slip system. The Eagle River fault may have moved during the same interval, but more field work is needed to test that hypothesis.

EAST-CENTRAL CHUGACH MOUNTAINS, COPPER RIVER AREA

General

The most complex map pattern along the Border Ranges fault system occurs in a short segment of the fault system between 144° and 146° W, in the vicinity of the Copper River and the Richardson Highway (Fig. 4). This area has been the focus of some of the most intense studies along the fault system, beginning with the Ph.D. work of Wallace (1981) and the regional map produced by Winkler et al. (1981), through the TACT studies of the USGS (Nokleberg et al., 1989; Pavlis and Crouse, 1989; DeBari and Coleman, 1989; Plafker et al., 1992, and more recent work by the authors and colleagues (e.g., Roeske et al., 2003; Pavlis and Sisson, 2003; Pavlis et al., 2003). These studies reveal that the complex map pattern is a composite effect of multiple structural overprints that include thrusting and folding as well as both brittle and ductile strike-slip deformation. Although complex, this segment is, in many respects, a Rosetta stone for the Cenozoic deformational history of the Border Ranges fault system because several cross-cutting relationships between fault strands are preserved. Despite the complexity, we propose a fault displacement history that provides a potential link between the dextral strike-slip reactivation along the Border Ranges fault system in the eastern and western Chugach mountains.

Within this segment the Taral and Second Lake faults (Fig. 4) separate three structural blocks with very different structural-metamorphic histories. This basic map relationship requires significant postmetamorphic shuffling by brittle faults. Although the history and kinematics of that shuffling are not well resolved, the following observations (below) from detailed mapping provide constraints on the kinematics and relative timing. Two major changes in interpretation from previous work are important to reconstructing the fault history. First, Nokleberg et al. (1989) inferred that the Second Lake fault was a thrust fault warped to vertical dips. Our examination of this structure revealed, however, that extensive strike-slip slickensided surfaces parallel the fault, indicating the structure is part of the Tertiary dextral fault system of the northern Chugach Mountains. Second, this dextral slip must be older than the last motion on the Taral fault because the Second Lake fault terminates at the Taral fault (Fig. 4). The Taral fault is thought to be a tear fault associated with south-directed thrusting (Plafker et al., 1989), but there are no kinematic data constraining its motion. To link the Second Lake fault with a known strike-slip fault to the east, the Hanagita fault, we propose a reconstruction (Fig. 7) that has the Taral fault forming as a dextral-oblique tear fault associated with north-verging thrusting, one of the final penetrative deformation events to affect the region.

Northern Chugach Assemblage

To the north of the Second Lake fault (Fig. 4 and Table 1) four structural units define a fragmented assemblage that is analogous to the Peninsular and Chugach terranes exposed to the west along the northern Chugach Mountains. Thus, we refer to this composite structural block as the northern Chugach assemblage. Similar to areas to the west, this assemblage lacks clear evidence of ductile strike-slip overprints, and Tertiary overprinting is limited to brittle faulting.

Most significant within this assemblage is the paired structural association of the Tonsina and Liberty Creek blocks (Fig. 4 and

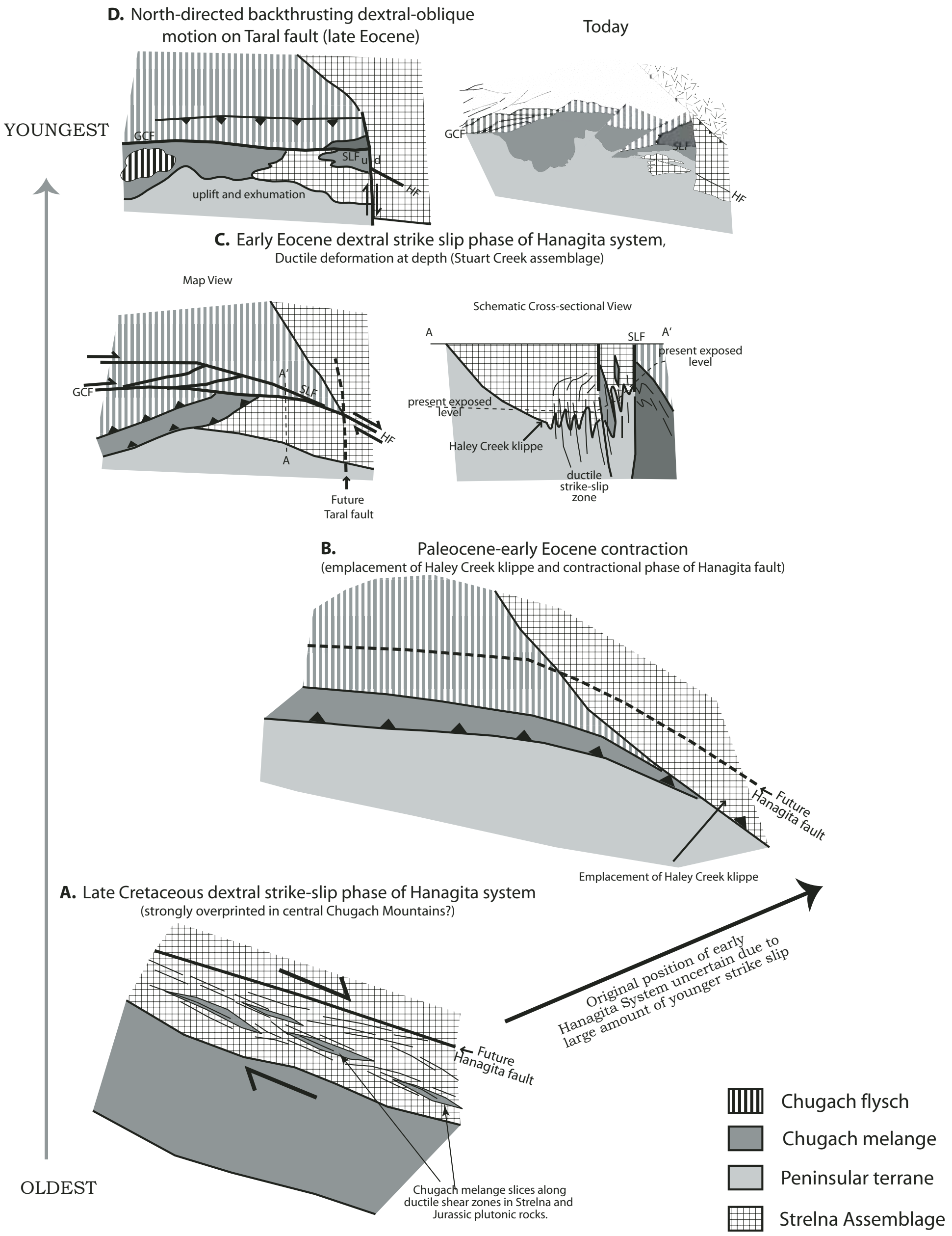

Figure 7. Scenario showing interpreted sequence of fault displacements in the central Chugach section of the Border Ranges fault system. Abbreviations: GCF = Glacier Creek fault, HF = Hanagita fault, and SLF = Second Lake fault.

Table 1). The Tonsina block is a large slab of ultramafic rock and mafic granulite that has been interpreted as the upper-mantle to lower-crustal basement of the Peninsular terrane arc (e.g., Burns, 1985; DeBari and Coleman, 1989). The Tonsina block lies structurally atop the transitional greenschist-blueschist assemblages (Plafker et al., 1992) of the Liberty Creek block along a moderately northwest-dipping fault contact shown on Figure 4 as the Kenney Lake fault. Although previous studies generally lumped the structural contacts that surround the Tonsina Block as a single structure (e.g., Nokleberg et al., 1989; Plafker et al., 1992) our examination of this structure indicates that the Kenney Lake fault is an older structure that is truncated along the vertical Second Lake fault. Indeed, the Kenney Lake fault may be a modestly overprinted vestige of an original Mesozoic thrust contact similar to, but at lower temperatures, than the metamorphic assemblages of the western Chugach Mountains (see below). Evidence for this interpretation is twofold. First, the metamorphism of the transitional blueschist-greenschist assemblage below the fault is broadly consistent with the high-P conditions of the structurally overlying rocks. That is, although metamorphic temperatures are clearly very different, the likely pressures in the blueschist assemblage would be consistent with rock thrust beneath a thick hanging-wall assemblage indicated

TABLE 1. CENTRAL CHUGACH MOUNTAINS STRUCTURAL ASSEMBLAGES

Block (Abbrev.)	Dominant Lithology	Bounding Structures	Structural History
Stuck Mtn. (s)	BRUMA plutonics and Jtk cover	Glacier Creek fault to south; north side buried in Quat.; east and west bounded by inferred faults (referred to as Tonsina and Stuck faults in Fig. 4)	North tilting of overlying stratified rocks (Mesozoic?); bounding faults and most internal faults dominantly Tertiary
Klutina (k)	McHugh Complex (Chugach mélange)	Glacier Creek fault to north; Eagle River fault to south; east and west bounded by inferred faults (referred to as Tonsina and Stuck faults in Fig. 4)	Sub-greenschist facies grade metamorphism; bounding fault dominantly Tertiary with possible older (late Mesozoic) motion on Eagle River fault; Mesozoic mélange fabric preserved in McHugh Complex
Tonsina (t)	Tonsina Ultramafic and Mafic complex	Dextral Second Lake fault to south; west-dipping thrust to the east; inferred Tonsina fault to northwest	Upper-mantle to lower-crustal section partially exhumed by Middle Jurassic (no post-Early Jurassic ductile structure), Jura-Cretaceous(?) thrusting to east, Cenozoic Second Lake fault
Liberty Creek (l)	Liberty Creek schist (Chugach mélange)	Dextral Second Lake fault to north; thrust beneath Tonsina block to northwest; high-angle Taral fault to the east (not exposed)	Transitional blueschist-greenschist metamorphism in late Mesozoic with associated gently northwest-dipping continuous cleavage and north-trending lineation superimposed on mélange fabric; F2 upright folds trend ∼EW with crenulation cleavage; Cenozoic brittle fault truncations to east and south
Bernard Creek (b)	McHugh Complex (Chugach mélange)	Dextral Second Lake fault to north; complex ductilely modified fault contact to south; high-angle Taral fault contact to east (not exposed)	Lower-greenschist facies steeply dipping continuous cleavage with subhorizontal lineation superimposed on mélange fabric; younger brittle faults to north and east; southern contact poorly understood but probably ductilely modified thrust
Fox Creek (f)	Valdez Group (?) (Chugach flysch assemblage)	Ductilely modified older faults on all sides except eastern high-angle Taral fault	Early lower-greenschist facies continuous cleavage overprinted by upright to steeply included, horizontal to gently plunging folds with EW-trending axes; fabrics similar to Valdez Group assemblage exposed south of block
Haley Creek (h)	Pz Strelna metamorphics, Jurassic granitoids, Chugach(?) rocks	Ductilely modified thrust contact at the base of a large klippe	Vertical to steeply dipping mylonitic to ultramylonitic foliation with subhorizontal extension lineation overprints older high-T fabrics in Strelna and J. plutonic rocks, with abundant dextral shear sense indicators in mylonitic fabric; fabric also developed in interleaved black argillite and marble (Valdez Group?) and greenschists (McHugh Complex?)
Summit Lake (sl)	Pz Strelna, Jurassic granitoids, McHugh Complex, and cover	Low- to moderate-angle thrust to south; high-angle Taral fault to west; Hanagita fault system to north	High-T amphibolite facies fabrics and associated plutonism overprinted by subgreenschist facies ductile dextral shear zones, overprinted by north-directed thrusts, overprinted by Cenozoic dextral brittle faults of the Hanagita system
Valdez Group (v)	Valdez Group (Chugach flysch)	Structural domain beneath Haley Creek klippe bounded to south by dextral Stuart Creek fault	Lower-greenschist facies metamorphism associated with early layer parallel continuous cleavage overprinted by two younger crenulation cleavages. S2 associated locally with upright folds of basal thrust is probably coeval with mylonitic fabrics of Haley Creek block; S3 is late backfolding with north-directed thrust systems

by the Tonsina block. Second, structural fabrics below the fault show a main continuous cleavage that is characterized by relatively low dips, subparallel to the fault and a north-northeast-trending extension lineation. This lineation orientation is similar to lineation orientations in the Mesozoic ductilely deformed rocks of the western Chugach Mountains but trends nearly 90° from lineations in Tertiary mylonitic rocks to the south. Thus, we tentatively conclude that the Tonsina and Liberty Creek blocks represent a deep-seated vestige of the Mesozoic megathrust system, with the Liberty Creek assemblage representing the underthrust assemblage. Thus, as inferred by others (e.g., Plafker et al., 1992) we assume the Liberty Creek block is the greenschist-blueschist facies equivalent of the Chugach mélange that was underthrust below the Tonsina assemblage, but the Kenney Lake fault is the only vestige of that original contact relationship.

The Tonsina and Liberty Creek blocks are distinct from the remainder of the northern Chugach assemblage, which is shown on Figure 4 as the Stuck Mountain and Klutina blocks. These rocks are direct equivalents of rocks exposed to the west, including Early Jurassic volcanic cover and fragmented plutonic rocks that intrude them (Stuck Mountain block, Table 1) as well as low-grade mélange and deformed flysch of the Chugach terrane (Klutina block, Table 1). All previous studies recognized these main lithologic assemblages (e.g., Winkler et al., 1981; Nokleberg et al., 1989; Plafker et al., 1992), but our interpretation of the structural contacts is very different. We infer that the contact between the Stuck Mountain and Klutina blocks is an eastward continuation of Little's Glacier Creek fault and is, therefore, a major dextral fault. We also infer a significant younger fault along the Klutina River valley, the Klutina fault, that truncates the Glacier Creek fault and possibly the Second Lake fault (Fig. 4). The existence of the Klutina fault is indicated by the disappearance eastward of a major strike-slip fault (Glacier Creek fault), and the structural relief of as much as 20 km between the Tonsina block and the Stuck Mountain block.

Strelna Assemblage of Summit Lake

Most of the rocks east of the Taral fault represent the Strelna metamorphic assemblage (Winkler et al., 1981; Plafker et al., 1989) and associated Jurassic plutonic rocks (Fig. 4 and Table 1). South of the Hanagita fault (Fig. 4) the assemblage also includes large fault-bounded slices of the Chugach mélange—McHugh Complex; (Roeske et al., 2003). The protolith of the Strelna has no known correlatives in the northern Chugach assemblage or Peninsular terrane, but the Late Cretaceous and Cenozoic structural history of this region can be correlated across the Taral fault through reconstructing the cross-cutting relations. The structure of this region was described in detail by Roeske et al. (2003) and is summarized below.

Our mapping (Roeske et al., 2003) identified a major dextral-brittle fault system, the Hanagita fault system, which overprints two earlier periods of deformation in this segment, a ductile dextral strike-slip movement recorded in rocks within and south of the Hanagita fault system and a south-vergent thrust event. The relative timing of these three events is well constrained by cross-cutting field relations of distinctive fabrics associated with each event. The absolute age of south-vergent thrusting must be post-85 Ma, the oldest possible age of initiation of the dextral mylonitization (Roeske et al., 2003). The youngest structures are brittle normal faults, subparallel to and locally reactivating strands of the Hanagita fault system, with south-side up displacement. The combination of these fault motions exposes deeper structural levels progressively to the south. The Hanagita fault system appears to continue across the Taral fault because along strike, in the Haley Creek block, a mylonitic shear zone referred to as the Haley Creek tectonic zone (Wallace, 1981) contains subvertical fabric with the same orientation of foliation and lineation as the fabrics in the Hanagita fault system. The continuity of dextral slip across the Taral fault appears to contradict the idea that the Second Lake fault is an offset equivalent to the Hanagita fault system, but other alternatives present greater problems (see below). Our preferred interpretation is that the Haley Creek tectonic zone and Hanagita fault system are a coincidental juxtaposition that produces an appearance of continuity of structure, but it is also possible that there was more than one phase of slip on the Taral fault and the final stage was as a dip-slip structure with a slip vector coincidentally parallel to its intersection with the Hanagita system, or that other, unrecognized structural relationships complicate the problem.

Stuart Creek Assemblage

South of the Second Lake fault and west of the Taral fault is a large area of intense ductile deformation that contains a similar structural history for at least the late phases of the deformation (e.g., Nokleberg et al., 1989). We recognize this structural continuity as far southward as the Stuart Creek fault (Fig. 4), a late brittle fault that separates distinct structural domains in the Chugach terrane (Pavlis et al., 2003).

Following Winkler et al.'s (1981) regional mapping this structural assemblage consists of four litho-tectonic blocks (Fig. 4 and Table 1): (1) Bernard Creek, (2) Fox Creek, (3) Haley Creek, and (4) the main Valdez Group. Blocks 1, 2, and 4 comprise different portions of the Chugach terrane (Plafker et al., 1989 and Table 1), but the Haley Creek block is derived from a variety of protoliths. In particular, the Haley Creek block is comprised primarily of reworked Strelna and associated Jurassic plutonic rocks (Plafker et al., 1989), but it also contains black phyllites of uncertain protolith and metavolcanic/metasedimentary assemblages that are probably reworked equivalents of the Chugach mélange (McHugh Complex). Most important, however, are clear field relationships that demonstrate the Haley Creek block lies structurally atop the Chugach terrane assemblages and forms a large klippe (e.g., Plafker et al., 1989, 1992).

The distinctive feature of the Stuart Creek assemblage is a surprisingly constant deformational history for the latest phases of ductile deformation, regardless of primary protolith (e.g., Nokleberg et al., 1989). The last two fabrics in all four blocks include a prominent continuous cleavage that is generally a mylonitic fabric overprinted by a moderately to steeply south-dipping crenulation cleavage (Nokleberg et al., 1989). The crenulation cleavage appears to record a late-phase, north-directed backthrusting, but the overprint geometry is different from south to north (Nokleberg et al., 1989, and Pavlis et al., 2003). Specifically, in the main Valdez Group block the crenulation cleavage is superimposed on folded layers that form moderately north-dipping enveloping surfaces, suggesting original north-dipping units overprinted by the cleavage. Farther north, however, the older continuous cleavage and layering are typically vertical, and the moderately south-dipping crenulation cleavage intersects the older steep foliation at a low angle. Most importantly, however, crystalline rocks of the Haley Creek block show that this older fabric is a retrograde, crystal-plastic (mylonitic) fabric with a vertical foliation and a subhorizontal elongation lineation. In the Chugach terrane assemblages to the north (Bernard Creek and Fox Creek blocks, Fig. 4) this vertical fabric is a phyllitic cleavage with a subhorizontal stretching lineation parallel to a prominent intersection lineation. Wallace (1981) and Nokleberg et al. (1989) emphasized the intersection lineation in this area and inferred a superimposed thrust-backthrust history to account for these fabric overprints. Pavlis and Crouse (1989) showed, however, that mylonitic foliation in the Haley Creek block recorded strike-slip related motion superimposed on older high-grade fabrics, but they assumed that the fabric was Mesozoic and predated emplacement of the Haley Creek block atop the Chugach terrane. An Ar/Ar date of 51.9 ± 0.3 on biotite from a metadiorite in the Haley Creek block is a minimum age for the penetrative deformation events (Plafker et al., 1989). Later work (Roeske et al., 2003) demonstrated that equivalent mylonitic fabrics along the Hanagita fault system are late Mesozoic to early Cenozoic in age and are clearly the product of dextral shear. Thus, we interpret all of the steep fabrics as broadly of the same generation, and infer that the fabrics record a significant Late Cretaceous to Paleogene ductile strike-slip event that produced intense, distributed deformation in a zone between the Second Lake fault and the southern edge of the Haley Creek block. The exact correlation of ductile to brittle fabrics is more speculative, but a feasible scenario can be worked out by correlating events across the Taral fault.

Synthesis

Figure 7 summarizes our interpretation of the deformational history of this segment of the fault system. This synthesis emphasizes known relationships along this and adjacent fault segments (described above and below) but is based on several underlying assumptions and interpretations that are subject to change as new data become available.

Assumption 1, correlation across Taral fault. Although the deformational sequence is well known on both sides of the Taral fault, and these sequences are undoubtedly linked, the exact correlation of deformational phases across the fault is unclear. Here we correlate the steeply dipping, mylonitic foliations in the Stuart Creek block (the Haley Creek tectonic zone) with the brittle strike-slip phase of the Hanagita system and assume deeper structural levels of this event are exposed west of the Taral fault to produce the distinction in structural style.

Assumption 2, nature of Taral fault. Although there are virtually no kinematic constraints on the motion of the Taral fault, we infer that the latest phase was dextral-oblique slip that truncated the dextral Second Lake fault and separated it from an assumed correlative fault, the Hanagita fault system. We further assume that this dextral motion occurred during the late, north-directed backthrusting to superimpose the south-dipping cleavage on foliations west of the Taral fault. In this interpretation the Taral fault served as a tear fault between north-directed back thrusting to the west and S-side up brittle faulting to the east, with differential uplift exhuming deeper structural levels to the west and south.

Assumption 3, fault contact beneath Haley Creek klippe. We correlate emplacement of the Haley Creek klippe atop the Chugach flysch with the south-directed thrusting recognized to the east along the Hanagita system. This further implies that the earlier dextral slip recorded on the Hanagita system is cryptic within the Haley Creek assemblage due to intense younger overprints.

Assumption 4, nature of lithologic contacts in the Stuart Creek assemblage. The preservation of low-angle structural contacts like the base of the Haley Creek klippe within a strike-slip system is counterintuitive given the intense, mylonitic deformation associated with the event and the typical association of steeply dipping structural contacts in strike-slip systems. We suggest that a low-angle contact is preserved here because of a distinction between rocks deformed by distributed flow in a deep strike-slip shear zone vs. slip along a fault. In flow the presence of a low-angle structural contact (e.g., thrust at the base of the Haley Creek block) is simply a subhorizontal marker horizon within the crust, which is subject to the details of the flow. A horizontal layer deformed in strike-slip shear might buckle to form folds, with axes parallel to elongation (e.g., Grujic and Mancktelow, 1995), but unless the bulk shear were oblique, there need not be significant structural relief across the shear zone. Indeed, this is precisely the geometry of the Haley Creek block with prominent folds parallel to the maximum elongation direction but only modest structural relief associated primarily with folds of this crustal layer.

Evaluation of assumptions and alternative hypotheses. These assumptions are allowable but nonunique because our correlation of ductile and brittle events could be in error. The Ar/Ar date of 51.9 Ma from a metaplutonic rock in the Haley Creek tectonic zone (above) certainly permits that this fabric developed simultaneously with the younger brittle phase of strike slip on the Hanagita fault. If we have miscorrelated events (e.g., brittle vs. ductile strike-slip phases), however, then the inferred sequence is incorrect.

Assumption 2 contains perhaps the greatest uncertainty of the three because there are virtually no constraints on the kinematics of the Taral fault, and the inferred history is the key tie in relative chronologies across the fault. We prefer the interpretation in Figure 7 because it provides a simple explanation for the out-of-sequence thrust that produced the Haley Creek klippe. Moreover, although it requires a coincidental juxtaposition of fabrics and faults along the trace of the Hanagita fault system, it can explain the restriction of the superimposed south-dipping cleavage to the Stuart Creek block. Other scenarios require even more complex coincidences. For example, the older ductile strike-slip phase of the Hanagita system could correlate to the ductile deformation in the Haley Creek block, but in this scenario both a contractional event and a second strike-slip event would have been superimposed on the ductile fabrics. In this scenario, it is difficult to rationalize how a brittle strike-slip fault (Hanagita system) could pass through the Haley Creek block with little disturbance of the low-angle basal contact (Fig. 4).

Despite this rationale, we recognize that other hypotheses are allowable, particularly models with alternative slip histories for the Taral fault or models calling on cryptic faults hidden beneath Quaternary deposits. Thus, further work, particularly kinematic studies of the Taral fault, geochronological work and detailed work on the Strelna assemblage are needed in this critical segment of the fault system.

Working model for the local system. A general cartoon representation of the deformational sequence (Fig. 7) illustrates our inferred history of this segment. In this model we infer that the Border Ranges fault system was rejuvenated as a dextral strike-slip system sometime in the late Mesozoic (Fig. 7A). During this period Chugach terrane mélange was structurally interleaved with Strelna metamorphics and Chitina Valley batholith rocks in a complex network of ductile to brittle shear zones. This event is well recorded in the eastern Chugach Mountains but would be cryptic in the central Chugach Mountains in this scenario due to Tertiary overprints.

In the early Cenozoic, following underthrusting and accretion of the Chugach flysch, we infer a contractional event that placed deformed Chugach and Strelna assemblages atop the Chugach flysch (Fig. 7B). This event was quickly followed by, and may have been broadly coeval with, renewed dextral motion on the Hanagita system (Fig. 7C). Here we infer that the brittle fault phase of the Hanagita system transferred westward across the Taral fault as ductile deformation recorded as the steep fabrics in the Stuart Creek block. We infer that this distinction is due to differential structural levels now exposed across the Taral fault (Fig. 7D). This deformation presumably also included brittle deformation, which we infer is the Second Lake fault and Glacier Creek faults that formed a continuous fault system during this interval. Finally, during this interval we also infer that the strike slip in this segment transferred westward into thrust systems, one of which generated the Klanelneechena klippe in central Chugach Mountains.

The last phase of the deformational history is inferred to be the north-directed backthrusting recorded as the south-dipping fabrics in the rocks west of the Taral fault. In this model we presume that this thrusting produced differential uplift and exhumation to the west of the Taral fault at the same time as dextral slip displaced contacts like the Second Lake fault northward toward their present positions.

COPPER RIVER (TARAL FAULT) TO LONGITUDE 141°

The Border Ranges fault east of the Taral fault to the Canadian border (longitude 141° W) is a fault zone with different strands clearly recording different phases of displacement (Figs. 8 and 9). A recent publication presents the data documenting these different phases (Roeske et al., 2003); thus, only a summary of the main points is presented here.

This section of the fault is where it was first identified as an ancient plate boundary (MacKevett and Plafker, 1974), and indeed

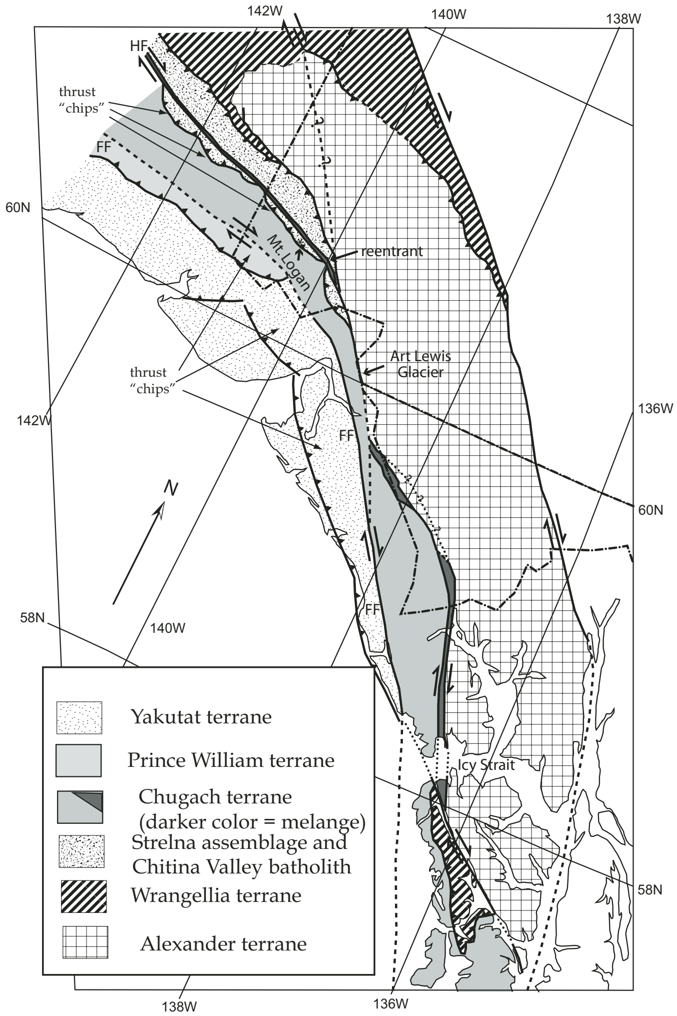

Figure 8. Terrane map of northern southeast Alaska showing the trace of the Border Ranges fault system through this region. Note the development of the linear Hanagita fault system along the trace of the fault through the eastern Chugach and into the St. Elias mountains. Map redrawn from base map of Tipper et al., 1981. Abbreviations: HF = Hanagita fault, and FF = Fairweather fault.

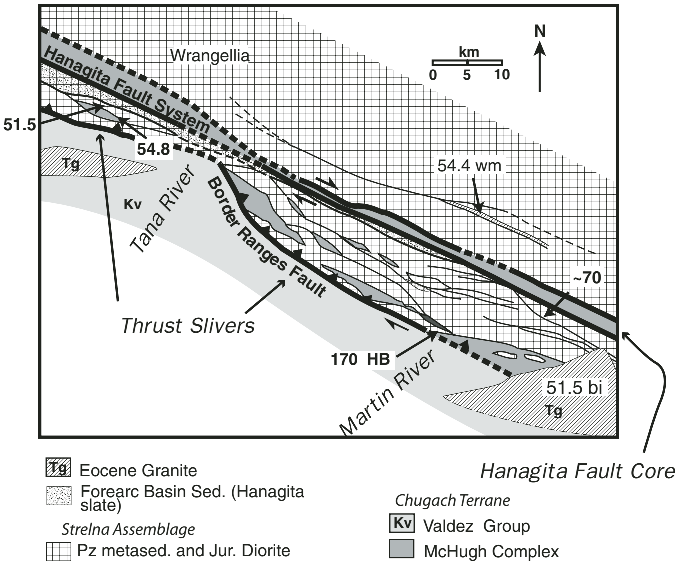

Figure 9. Geologic map of part of the eastern Chugach Mountains showing the position of the Hanagita fault system as the Late Mesozoic–Early Cenozoic reactivation of the Border Ranges fault system. Note the complex slicing of crystalline rocks with the Chugach mélange (McHugh Complex) along the Hanagita system but no involvement of the younger Valdez Group suggesting significant pre-Valdez movement. Also note that some fault strands are cut by a pluton with a minimum age of 51.5 Ma. Figure is modified from Roeske et al. (2003).

crystalline rocks, including diorite, amphibolite schist, and marble, are juxtaposed along a north-dipping thrust over low-grade greywacke of the Valdez Group (Fig. 1b, Roeske et al., 2003, and Fig. 9). We retain the name Border Ranges fault for the fault between the southernmost extent of the crystalline rocks and the Valdez Group but interpret that fault to be an early Tertiary out-of-sequence thrust formed during oblique convergence. North of this thrust, slices of the mélange unit of the accretionary prism are juxtaposed with crystalline rocks along both thrust and dextral-slip contacts.

The zone of high- and low-angle faults inboard of the Border Ranges fault that shuffle the accretionary prism and crystalline rocks together is the Hanagita fault zone (Fig. 9), and we identify at least three phases of displacement along it. An early phase of dextral-slip faulting may have begun as early as 85 Ma and certainly was active by 70 Ma, based on Ar/Ar ages from white mica within hornblende deformed in a dextral fault zone. The faults formed near the brittle-ductile transition and are best identified in the abundant Late Jurassic diorite that intrudes the crystalline basement. This phase coincided with, or is locally older than, a period of thrust displacement that caused both north- and south-directed displacement. Dextral slip continued along the Hanagita fault system from 70 to ca. 52 Ma, based on direct ages of white mica formed during alteration associated with faulting and the biotite Ar/Ar age of a pluton that crosscuts most of the fault zone (Roeske et al., 2003). An absolute minimum age is not known because no crosscutting relationship exists across the through-going brittle strands that produce the profound topographic lineament associated with the fault zone. However, the presence of a 54 Ma dike north of the Hanagita fault zone, the same age as abundant plutons in the Valdez group south of the fault zone (Fig. 9), suggests no significant dextral slip through this region since early Eocene (Roeske et al., 2003).

Several lines of evidence suggest that the total amount of displacement prior to 54 Ma along the Hanagita fault zone could be quite large (>500 km). First, the scale and longevity of the dextral fault zone argue for significant displacement. The fault zone was active as a dextral-slip system for over 20 million years, from the Late Cretaceous into the early Eocene. Based on ages from fauna in the accretionary prism, accretion was also continuous during this time; thus the Border Ranges fault was being reactivated as a dextral-slip system to accommodate oblique convergence. The result was a fault zone that is locally over 10 km wide with distinct shear zones within it varying from 10s of m to several 100 m wide. Second, the fault zone can be mapped continuously for over 250 km before disappearing under the icefields of the St. Elias Range and probably extends as a continuous structure for at least another 100 km into the central St. Elias Range (Fig. 8). The main through-going strands of the Hanagita fault have very few steps or evidence of anastamosing strands. For other large-scale continental strike-slip faults, this "smoothing" is associated with faults that have the greatest amounts of total displacement (Wesnousky, 1990).

The direct evidence for significant displacement comes from the age of a plutonic rock within the outer part of the Hanagita fault zone which does not match the age of any plutonic rocks in the region. All of the U-Pb zircon and hornblende Ar/Ar ages of diorites and tonalites in the region range from 155 to 144 Ma, yet this one diorite has a hornblende plateau age of 170 Ma. Diorites with similar ages do exist in the in the Peninsular terrane in the Talkeetna Mountains to the northwest, but none occur near the Border Ranges fault (Rioux et al., 2004). If one assumes this mid-Jurassic diorite was incorporated during dextral slip, then the closest plutonic rocks with similar ages are on Chichagof Island over 600 km to the southeast on strike. Much greater displacements, over 1000 km, would potentially juxtapose this plutonic rock and associated rocks with a very similar suite on the western coast of Vancouver Island. Although this magnitude of strike slip seems difficult to reconcile with the geology along strike, it is supported by paleomagnetic data from rocks outboard in the accretionary prism (Plumley et al., 1983; Bol et al., 1992).

SOUTHERN ST. ELIAS MOUNTAINS TO ICY STRAIT

Mt. Logan to Glacier Bay

In the St. Elias Mountains the Border Ranges fault system is largely buried beneath glacial ice, but the exposures that do exist provide clear evidence that the general structural style recognized in the eastern Chugach Mountains (e.g., Roeske et al., 2003) continues throughout this segment. The principal regional mapping for this segment is reconnaissance scale (1:250,000) work by Campbell and Dodds (1983a, 1983b, 1983c) and Plafker, (2005), but more detailed mapping by Mihalynuk et al. (1993) and Smith et al. (1993) and topical studies (Decker and Plafker, 1982; Roeske et al., 1992; Smart et al., 1996; Sisson et al., 2003b; Roeske et al., 2003; T. Pavlis, and our field observations, 1998) provides important local constraints.

In the central St. Elias Mountains the Border Ranges fault system is spectacularly exposed on the south-face of Mt. Logan (Fig. 10), where it juxtaposes brittlely deformed Jurassic dioritic-plutonic rocks against variably metamorphosed rocks of the Chugach terrane (Campbell and Dodds, 1983b). The latter comprise part of the Chugach metamorphic complex of Hudson and Plafker (1982) with Eocene high-grade metamorphism of the Chugach terrane assemblage. Campbell and Dodds (1983b) did not differentiate protolith assemblages in Chugach metamorphic complex, but our work (T. Pavlis, V. Sisson, and K. Stuwe, and our field observations, 1998) indicates that both the Chugach mélange assemblage and flysch assemblage are present in the ridges south of Mt. Logan. As in the eastern Chugach Mountains, the mélange lies adjacent to the structural contact with Jurassic plutonic rocks, and is locally structurally interleaved with slices of plutonic rock, suggesting similar structural complexities. Although we have not seen the contact between the mélange and metamorphosed flysch assemblages, it is presumably a fault because the mélange is relatively low-grade (greenschist facies) at Mt. Logan, whereas the adjacent metamorphosed flysch is an upper-amphibolite facies gneiss. The fault contact between the mélange and the Jurassic plutonic rocks is a moderately to steeply north-dipping contact.

Insights from the eastern Chugach Mountains and Mt. Logan allow one important reinterpretation of map relationships in the central St. Elias Mountains. Campbell and Dodds (1983b) recognized exposures of Chugach flysch at the northeastern end of the Logan Massif between MacArthur Peak and Mt. King George, well north of the trace of the Border Ranges fault on the south side of Mt. Logan (labeled reentrant, Fig. 8). From this observation they inferred a lasso-shaped map pattern for the Border Ranges fault, yet the inferred fault connecting the lasso to the fault system on the south side of Mt. Logan was a projection beneath the Hubbard Glacier. We suggest that a more likely geometry is that shown in Figure 8, where the Chugach terrane rocks to the north are slices along a high-angle fault representing the eastern projection of the Hanagita fault system. Thus, the Mt. Logan block probably represents a transpressional slice south of the Hanagita system similar to analogous structures in the eastern Chugach Mountains.

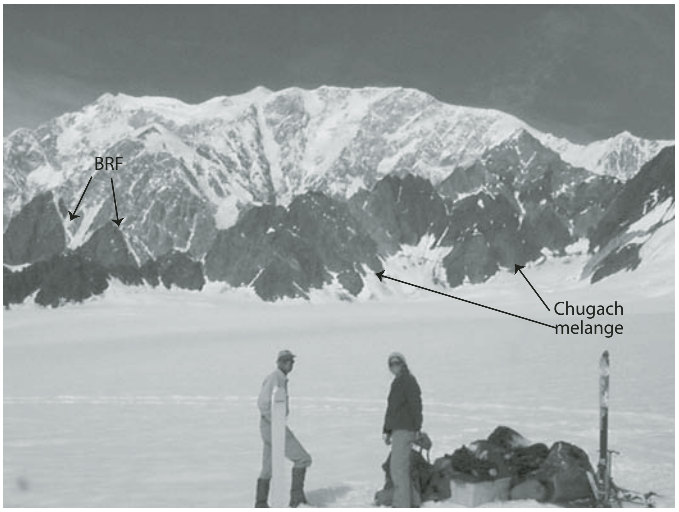

Figure 10. Field photograph of the Border Ranges fault exposed along the south face of Mt. Logan in the St. Elias Mountains (see Figure 8 for general location). Note the involvement of the Chugach mélange in fault slices along the Border Ranges fault system analogous to observations in the eastern Chugach Mountains.

In the southern St. Elias Mountains the Border Ranges fault system is largely buried in glacial ice, but some important features are recognized. Plafker (oral presentation, 2003) proposed that an active strike-slip fault may be present along the Art Lewis Glacier and could represent the southern extension of the Totshunda fault. If this hypothesis is true, then this segment of the Border Ranges fault is actually an active Neogene fault with several 10s of km of slip. This hypothesis is attractive because Mihalynuk et al. (1993) and Smith et al. (1993) recognized a more northwesterly trending segment of the Border Ranges fault in the northwest corner of British Columbia with a structural style similar to that seen farther south in Glacier Bay rather than the narrow, discrete fault along the Art Lewis Glacier. Smith et al.'s (1993) description of the Border Ranges fault system in this region also suggests that the structure at this latitude possesses a similar large-scale slicing of Chugach mélange rocks together with metamorphic basement assemblages of the Alexander terrane as well as slices of Triassic cover of the Wrangellia sequence. Although the fault zone trace (Fig. 8) is curved, both Campell and Dodds' (1983a, 1983b, 1983c) and Mihalynuk et al.'s (1993) mapping indicate this segment is a high-angle shear zone analogous to more well documented regions farther south.

Farther south in Glacier Bay is perhaps the most spectacular exposure of the Border Ranges fault system anywhere along its trace. The deep fiords of John Hopkins and Tarr Inlets provide an unusually clear natural cross section across this segment of the structure. Smart et al. (1996) described this cross section in detail, and Roeske et al. (1992) and Sisson et al. (2003b) provided new data constraining the age of deformation along this segment. This area contains a relatively simple structural geometry indicative of its origin as a structure dominated by the effects of early Cenozoic dextral-slip motion across the zone (Smart et al., 1996). Specifically, the zone is characterized by a system of high-angle faults and ductile shear zones ~10 km in structural thickness. The fault/shear zone itself is comprised largely of Chugach mélange rocks with slices of plutonic rock and metamorphic rocks of uncertain affinity. Abundant shear sense indicators show clear evidence of dextral-ductile shear that progressed to brittle faulting (Smart et al., 1996). This area is also significant in that it contains some of the most clear crosscutting relationships defining the age of the dextral reactivation of the system. As in most areas, dextral faults cut the contact between the mélange and flysch assemblages of the Chugach terrane, but faults and fabrics of the shear zone are cut by a gabbroic pluton with a U/Pb date of 42 Ma (Sisson et al., 2003b).

SOUTHEAST ALASKA SECTION OF THE BORDER RANGES FAULT, SOUTH OF ICY STRAIT

The southernmost exposure of the Border Ranges fault exhibits much of the same complexity seen farther north, and observations on Chichagof and northern Baranof Islands pose many of the same questions. Tertiary to recent dextral-slip faults are abundant in this region; the Border Ranges fault lies between two active dextral-slip faults, the Chatham Strait fault and the plate boundary transform, the Fairweather fault (Fig. 8). The southern terminus of the fault occurs on northern Baranof Island, where the Border Ranges fault is cut by the younger, dextral Peril Strait fault, which in turn is cut by the Chatham Strait fault, the southern extent of the Denali fault system. Another prominent dextral fault, the Neva Strait fault, strikes subparallel to the Border Ranges fault and offsets locally the contact between the mélange and coherent units in the Chugach terrane (Loney et al., 1975) (Figs. 11 and 12). Because of the abundant evidence of Tertiary dextral fault displacement on these islands, the question of

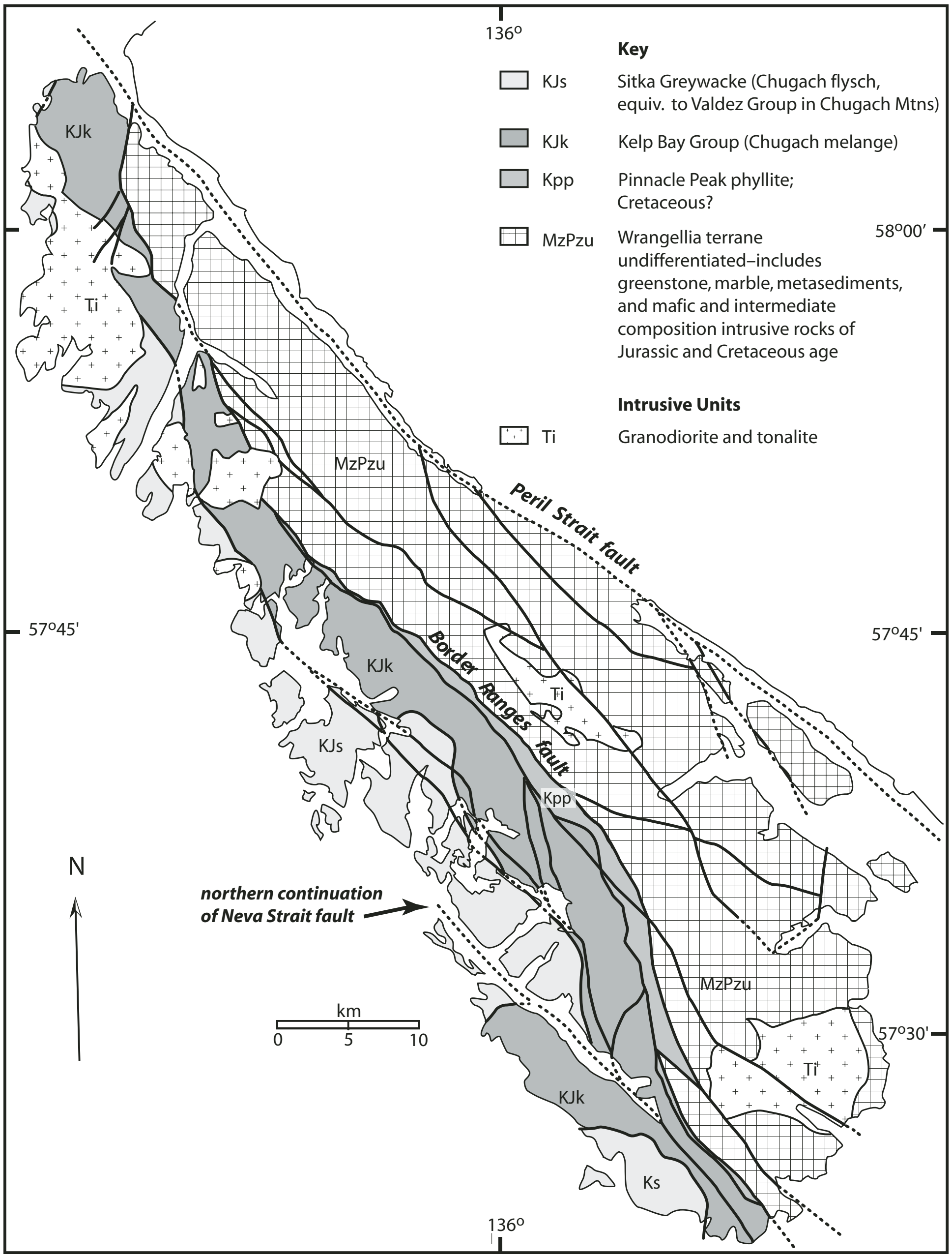

Figure 11. Geologic map of western Chichagof Island and Yakobi Islands, southeastern Alaska. Adapted from Johnson and Karl (1985).

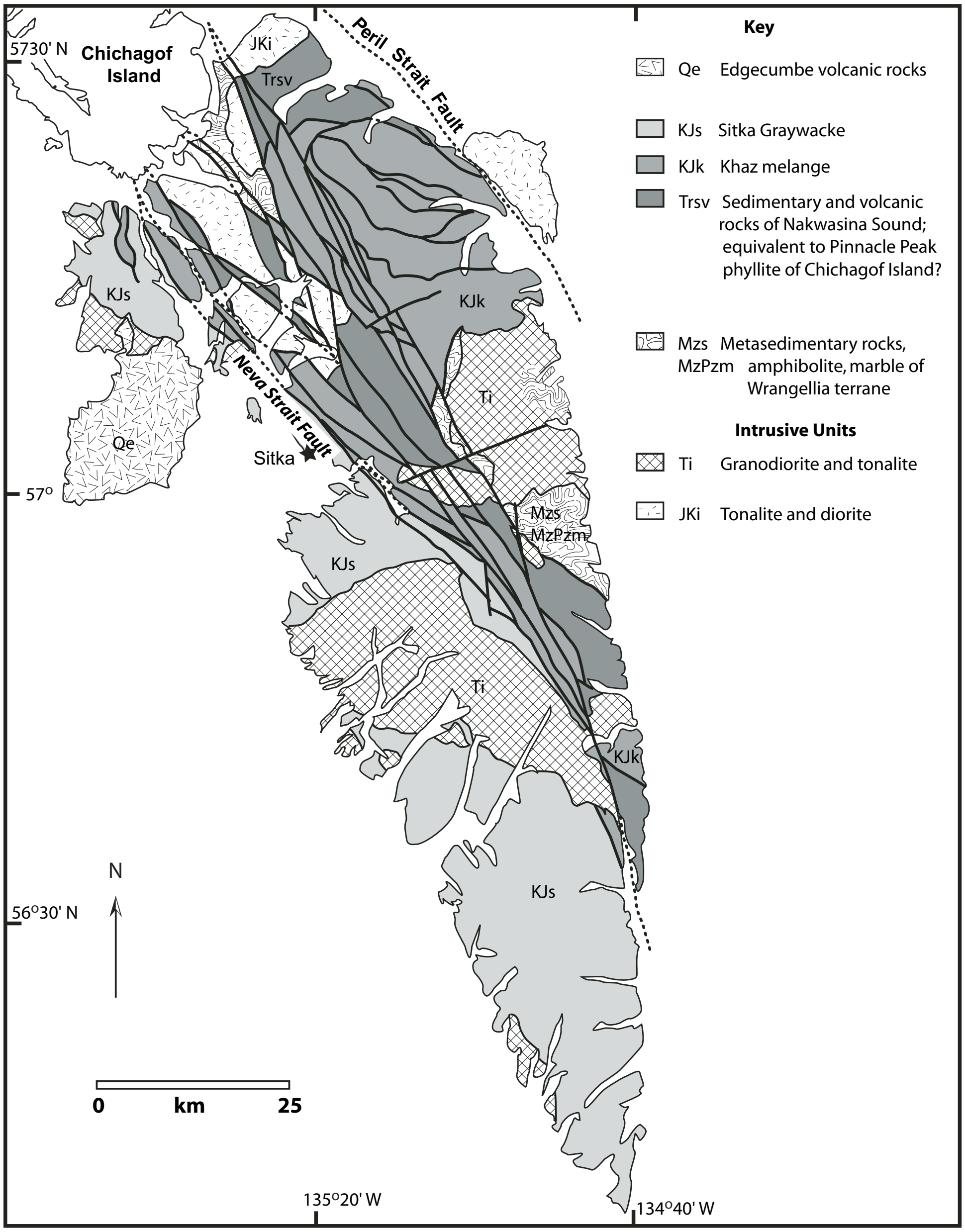

Figure 12. Geologic map of Baranof Island, southeastern Alaska. Border Ranges fault is the complex system of faults between the Neva Strait fault and the Peril Strait fault (see text for discussion of this problem). Adapted from Zumsteg et al. (2003).

whether any part of the Border Ranges fault in this region preserves the primary subduction zone geometry is debatable. The Border Ranges fault is overall linear, subvertical, and north-northwest striking in this area. Decker and Johnson (1981) ascribe the subvertical section of the fault to rotation of an original thrust boundary. Others have suggested that strike-slip faults have extensively overprinted any primary thrust fault relationship (Karl et al., 1990). All of the north-northwest striking faults have dominantly dextral motion based on slickenline data, and minor east-northeast faults are sinistral (Haeussler et al., 1994, 2003; Roeske, unpub. data).

Rocks east and north of the fault are typically plutonic rocks, associated schists and gneisses, and greenstone and carbonate of the Wrangellia terrane (Plafker et al., 1976), except at the farthest north end of Chichagof Island, where Paleozoic metasedimentary rock of the Alexander terrane and Cretaceous granitoids occur on the inboard side of the fault (not shown on Fig. 11; Loney et al., 1975; Karl, 1999). Rocks west and south of the fault include a highly diverse suite of rocks of oceanic affinity. They have been correlated to the two subdivisions of the Chugach accretionary prism, with the mélange unit referred to as the Kelp Bay Group and the flysch unit referred to as the Sitka Greywacke (Plafker et al., 1977). All workers in this region note the many exotic blocks in the Kelp Bay Group, and some are recognized as likely derived from the Wrangellia terrane, the inboard portion of the fault (Decker, 1980; Karl et al., 1990; S. Karl, personal commun., 2004). These exotic blocks have subvertical boundaries and lie in a zone of dextral strike-slip faults (Haeussler et al., 1994), suggesting that their incorporation in the mélange occurred during strike-slip faulting rather than as klippe of an original low-angle boundary (Karl et al., 1990).

The interpretation of which units fall into hanging-wall and footwall packages has varied through the years, and consequently the location of the Border Ranges fault trace on regional maps has shifted. Loney et al. (1975) included Triassic(?) greenstone and marble in the Kelp Bay Group, but subsequent authors interpret these units as part of Wrangellia and distinct from greenstone within the Kelp Bay Group (Plafker et al., 1976). Decker (1980) and Johnson and Karl (1985) placed the Border Ranges fault on Chichagof Island at the most profound break in metamorphism, structure, and composition. Using this criterion, the rocks immediately outboard of the Border Ranges fault include a unit unlike that seen typically in the mélange complex of the Chugach terrane. Phyllite and chlorite-epidote-albite schist of the Pinnacle Peak phyllite (Fig. 11) occurs adjacent to the Border Ranges fault (Decker, 1980; Johnson and Karl, 1985) along much of Chichagof and Baranof Island, and an Ar/Ar age of white mica from this unit on Baranof Island is 155 Ma (Snee, written communication, cited in Zumsteg et al., 2003). The tectonic significance of this age is unclear because it is the same as K-Ar ages from plutonic rocks within a few kilometers of the sample location (Loney et al., 1975). The metamorphic grade of the rocks sampled for Ar/Ar is upper-greenschist to lower-amphibolite facies with biotite, garnet, and epidote. Thus the muscovite age is probably a cooling age and may represent a minimum age for accretion of the coherent part of the Pinnacle Peak phyllite along this section of the Border Ranges fault.

Most of the development of the accretionary complex is probably significantly younger than 155 Ma. The mélange part of the accretionary complex contains blocks of clastic rocks with Buchia bivalve fossils as old as Tithonian (Brew et al., 1988) and as young as Berriasian age (Johnson and Karl, 1985), and radiolaria as young as Valanginian occur in chert blocks in the mélange. No fauna have been identified in the matrix; thus, these ages are maximum ages of accretion for local segments. K-Ar dates of 91–106 Ma are reported from phyllite blocks in the mélange on Chichagof Island (Decker, 1980). Nearby, scattered occurrences of sodic amphibole in greenschist blocks indicate this part of the mélange experienced high-P/T metamorphism and thus, the K-Ar ages are presumably cooling dates from that metamorphic event suggesting those dates record a minimum age for accretion. Taken together, the faunal and K-Ar dates suggest an Early Cretaceous age for the accretion (Decker, 1980). A minimum age of accretion for all of the mélange assemblage is Late Cretaceous, on the basis of the inferred age of the Sitka Greywacke that is thrust beneath it.

Although dextral faults clearly were active in the Tertiary in southeast Alaska, it is uncertain how much dextral slip occurred and when, along the southern extent of the Border Ranges fault system. Answering this question raises the same issues as seen along strike, namely that there are many strands to the fault, and a pin across one strand does not necessarily apply to all of the strands. Davis et al. (1998) interpret the fabrics in the Sitka Greywacke as developing during oblique convergence in the latest Cretaceous–early Tertiary, which is consistent with evidence farther west. Mineralization in the fault zones yields ages of ca. 50 Ma, and Haeussler et al. (2003) attribute this period of brittle deformation to the Eocene ridge subduction event recorded throughout the margin. A small Oligocene pluton crosscuts the Border Ranges fault on northern Chichagof Island (Fig. 11); thus, strike slip on this strand ceased by that time. Elsewhere a 50 Ma pluton crosscuts the southernmost strand of the Border Ranges fault (Haeussler et al., 2003).

Synthesis

Data from this segment of the fault system are more scarce than from other segments of the fault, and thus, any generalizations are preliminary. Nonetheless, available data suggest collectively that the fault system throughout this segment is similar to the section immediately to the north, with Cenozoic strike slip dominating the structural architecture. Evidence strongly suggests that at least two segments of the fault in this region have been rejuvenated as recently as Neogene time, displacing and truncating older segments of the fault. One of the most difficult problems along this segment of the fault remains a problem of distinguishing the hanging-wall assemblage from footwall assemblage in the context of the "original" thrust contact. Throughout this segment large slices derived from the hanging wall, including metamorphosed rocks of the Alexander and Wrangellia terranes, are sliced together with Chugach mélange along a broad band of strike-slip related deformation. The greatest difficulty with this lithologic association is that highly faulted, low-grade assemblages derived from Wrangellia can be very difficult to distinguish from blocks of Mesozoic ocean crust incorporated in the Chugach mélange; thus, the character of the fault throughout this zone remains contentious.

DISCUSSION

Redefinition of the Border Ranges fault

When the Border Ranges fault was defined in the early 1970s, concepts of forearc accretionary complexes were in their infancy, and large-scale tectonic maps of Alaska—for example, "terrane" maps of Jones et al. (1981)—had not yet been developed. Terrane terminology initially seemed to clarify the usage of the term *Border Ranges fault*. However, in light of recent work in the eastern Chugach Mountains (see above), where there are literally hundreds of Border Ranges faults if the original definition is used, definitions of the fault based on terrane terminology also fail to portray the nature of the structure. Similarly, where the structure is ductile, such as the western Chugach Mountains, all terminology is inadequate to describe the structure. Thus, although

MacKevett and Plafker's (1974) definition of the structure was a critical regional synthesis, it is too vague in the context of modern geology and our increased understanding of the regional geology of the fault system.

We propose the following terminology be used in the context of the Border Ranges fault. First, from the descriptions above, it is clear the fault system includes many different structural features representing a time-integrated history that varies radically along strike. Nonetheless, the structural boundary remains a readily recognizable regional feature that can be shown at various map scales. Thus, we propose that the term *Border Ranges fault* should be maintained but should always be used in a nongenetic sense to describe the regional structural contact between forearc accretionary complex assemblages of the Chugach terrane and crystalline assemblages on the continental side of the structure. This definition maintains the regional map definition of MacKevett and Plafker (1974) but removes assumed genetic modifiers commonly linked to the structure.

Second, we propose that the term *Border Ranges fault* be restricted to descriptions of the structure at small map scales with a suggested maximum scale of 1:1,000,000. At this scale the structure can generally be shown as a single line or group of lines that clarify its regional geometry. At larger map scales, the terms *Border Ranges fault system* or *fault zone* should be used for the entire system of brittle faults and ductile shear zones that comprise the zone of deformed rocks along the regional structure. By this definition the Border Ranges fault system in the western and central Chugach Mountains comprises an ~20-km-wide swatch of deformed rocks along the Chugach Mountain front extending southward to include the southernmost of the known strike-slip faults in the Tertiary fault array, some of which occur exclusively within the Chugach terrane (Fig. 2). In the eastern Chugach Mountains, however, the deformed zone is generally narrower, from 2 to 10 km wide, with the bulk of the deformation concentrated along the core of the Late Cretaceous–Tertiary Hanagita fault, southward to the fault contact with the Chugach flysch.

Third, where timing, kinematics, or both are well constrained, descriptive modifiers, such as *the Eocene right-lateral Border Ranges fault system* should be used, although this terminology could become cumbersome. Alternatively, a local name could be used for a distinct phase or system of faults; for example, as in Roeske et al.'s (1992, 2003) terminology of the Hanagita phase of the Border Ranges fault system.

Finally, at more local scales, we suggest that individual major structures within the fault system be given local names for clarity, but these names need not be carried to regional scales. Thus, the faults can be interpreted in the broader context of the history of the fault system, but the local name preserves the nongenetic character of a distinct structure in the array. For example, here we preserved the terminology of Little (1990) describing the Glacier Creek fault as the major Tertiary strike-slip strand of the Border Ranges fault system in the central Chugach Mountains, and we extended this terminology to a larger scale, as far as we could reasonably trace the fault as a continuous structure. Similarly, we use the name *Hanagita fault,* after Roeske et al. (2003), for the major strike-slip system in the eastern Chugach Mountains but do not correlate this structure directly to the Glacier Creek fault, which is clearly similar in age and kinematics, because there is no unequivocal link between the structures.

Tertiary Faulting History and Inferred Fault Geometry

Although the Border Ranges fault was originally described as a subduction zone megathrust, the fault only locally preserves this history, and throughout most of its trace the fault system is dominated by the effects of Paleogene strike-slip that rejuvenated the structure. This is particularly true in the eastern Chugach Mountains where, to our knowledge, there are no vestiges of the original Mesozoic boundary with all of the major structural contacts strongly overprinted by the effects of latest Mesozoic to Tertiary strike-slip. Indeed, this rejuvenation process probably continues to the present day where Neogene strike-slip appears to have reactivated the boundary in the Art Lewis Glacier area (G. Plafker, oral presentation, Austin, Texas, [TS4]2003) and on Chichagof and Baranof Islands.

From just east of the Copper River through the St. Elias Mountains to Chichagof Island, the structural style of the Tertiary deformation is relatively uniform with a distinct 2–5-km-wide fault core occupied by steeply dipping, anastomosing networks of faults and ductile shear zones. Following Roeske et al. (1992) we refer to this strike-slip system as the Hanagita phase of the Border Ranges system. Along most of this trace there is a conspicuous 1–2-km-wide band in the core of the fault occupied by the Chugach mélange and dark phyllites (forearc basin sedimentary cover, Chugach flysch, or both) with steep lithologic contacts on both sides. Typically on the inboard side deformation falls off sharply toward the continental side with little evidence of the fault within 10 km of the fault core. Outboard, however, are fault-bounded blocks comprised of ductilely sheared and faulted rocks lying in low- to moderate-angle fault contact on the ductilely deformed Chugach flysch. Most of these fault bounded blocks are isolated, and the thrusts typically merge with or are crosscut by the strike-slip core, indicating these fault blocks are essentially fault-bounded chips with a strike-slip fault on the inboard side and an underlying thrust. Thus, the structural style in this segment is that of a typical positive "transpressional flower structure" (terminology of Sylvester, 1988) that has been moderately deeply exhumed. However, the structure is strongly one-sided with little thrusting toward the arc/continent side of the boundary.

The structural geometry along this segment of the fault system is remarkably similar to structures along the Neogene Fairweather fault system, which is an active dextral fault just outboard of the Border Ranges fault system (Fig. 8). Specifically, the Fairweather system is transpressional but is strongly slip partitioned with the strike-slip component taken up on the Fairweather fault and thrusting taken up on thrust systems at the base of the low foothills between the strike-slip fault and an undeformed foreland (e.g., Doser et al., 1997; Bruhn et al., 2004; Pavlis et al., 2004). This fault system is essentially a one-sided strike-slip flower structure (Bruhn et al., 2004). Were this modern fault system exhumed to depths of 5–10 km, the structure would be indistinguishable from the Hanagita system with coeval slip on a strike-slip core (Hanagita system) and thrusting on the southern edge of the fault-bounded chips. It is of note that this structure is distinct from two-sided transpressional systems like the San Andreas (e.g., Namson and Davis, 1988), and by analogy with the Fairweather system, the one-sided character of the Hanagita system may originate from a similar effect where extreme erosion on the outboard side facilitated the concentration of deformation on the outboard side (e.g., Bruhn et al., 2004). Alternatively, this geometry could result from a mechanical contrast between accretionary prism assemblages and older crystalline basement, which is a characteristic of both the Fairweather and Border Ranges fault systems.

In the central Chugach Mountains the transpressional strike slip of the Hanagita system transfers into a much broader zone of distributed deformation, and the deformation appears to be concentrated on the inboard side of the fault system. We suggest here that this deformation was not limited to the conspicuous deformation along the northern Chugach Mountains but instead is part of a regional deformation that also affected rocks through the Matanuska Valley and into the Talkeetna Mountains. In particular, following a suggestion by Pavlis et al. (1988) we suggest that the strike slip along the Border Ranges fault system was linked to dextral strike slip along the Castle Mountains system (Figs. 2 and 13).

Figures 7 and 13 illustrate this interpretation through a possible reconstruction of the dextral slip on the Border Ranges fault system. This reconstruction (Fig. 13) emphasizes the apparent strike-slip duplex in the western Chugach Mountains (Fig. 3) and the assumption that the contraction in the Matanuska Valley is directly linked to the strike-slip event. In this reconstruction, we show only inferred positions of larger crustal blocks developed within the fault system, and to avoid confusion we have only shown ductile deformation as affecting the Haley Creek klippe, where the most extreme Paleogene ductile deformation is recognized.

In this reconstruction we began by arbitrarily dividing the Matanuska-Copper River basin system along a line extending eastward along the northern Chugach mountain front from the southernmost branch of the Castle Mountains system and then restoring ~130 km of dextral slip on the Castle Mountains system. This division of blocks is not meant to describe any real structures because most of this region is buried by thick Neogene-Quaternary cover. Instead its division is meant to illustrate how slip between the Castle Mountains and Border Ranges systems could be linked. The 130 km of dextral slip is inferred both from recent work by Trop et al. (2005) that correlated the Little Oshetna Fault with the Bruin Bay Fault and from earlier studies (Grantz, 1966; Hackett, 1976) that correlated sedimentary and intrusive assemblages across the fault.

We then used all of the major Tertiary fault blocks mapped by ADGGS workers (e.g., Burns et al., 1991) and carried the strike-slip duplex model (Fig. 13) through the central Chugach Mountains, assuming this approach provided a minimum estimate of the strike-slip motion. Finally, we carried this approach farther east into the more poorly understood assemblages of the east-central Chugach Mountains using three principal constraints: (1) we restored the Klanelneechena klippe to a position near the other high-P lower-crustal assemblages of the Talkeetna arc—Tonsina block—assuming that these rocks were probably rooted near the same position as this deeply exhumed assemblage; (2) we restored the Iceberg Lake blueschists and the unmetamorphosed sedimentary rocks sliced together with them to a position where both lay in close proximity to either similar rocks (Liberty Creek blueschist) or a reasonable source for the marble clasts that are characteristic of the sedimentary deposits (Fig. 6).

The method used in this restoration allows a large range of solutions, and thus, this restoration should be considered preliminary. Nonetheless, it is of note that the restoration is consistent with the hypothesis that strike slip on the Border Ranges system transferred to the Castle Mountain system because the ~130 km of slip on the Castle Mountain system—shown as the offset of the arbitrary cut along the northern Chugach Mountain front—is well matched by the restoration of the strike-slip duplexes within the Tertiary fault arrays of the Border Ranges fault system.

It is of note that the 130 km of restored slip in this scenario does not mean that this slip estimate is a maximum; rather, this slip estimate is only the magnitude of slip that is likely to have been dispersed onto the Castle Mountain system and accounts only for the latest period of dextral slip, which almost certainly corresponds to the late "brittle" phase of the Hanagita fault system. This brittle slip apparently transferred westward into brittle and ductile shear in the Stuart Creek assemblage and involved both basement and the Chugach flysch. This shear system connecting through complex fault and shear zone arrays with the central Chugach fault complex where coeval thrusting and strike slip fully involved Paleogene sedimentary rocks (e.g., Little, 1990). Finally, other strike-slip systems developed outboard of the Border Ranges system during this same time interval including the brittle Stuart Creek fault (Fig. 4) and the Bremner shear zone, which emanates from the Chugach metamorphic complex (e.g., Pavlis and Sisson, 2003; O'Driscoll et al., 2004). Thus, we presume the ~130 km of displacement is post-65 Ma, and was primarily manifest as brittle faults with ductile deformation limited to the Stuart Creek assemblage and deformation within the Chugach terrane.

Larger magnitudes of strike slip are possible if the earlier dextral slip recorded on the Hanagita fault zone was transferred into the subduction megathrust. An analogous process is occurring today where the Fairweather fault (Fig. 8) transfers dextral slip into thrust systems of the St. Elias orogen that merge with the Aleutian megathrust. If true, this period would have predated emplacement of the Chugach flysch, and this phase of strike slip would have been strongly overprinted during accretion of the Chugach flysch. One piece of evidence for this presumed chronology is a simple field relationship: in the eastern Chugach Mountains the earlier ductile strike-slip phase of the Hanagita system involved only the

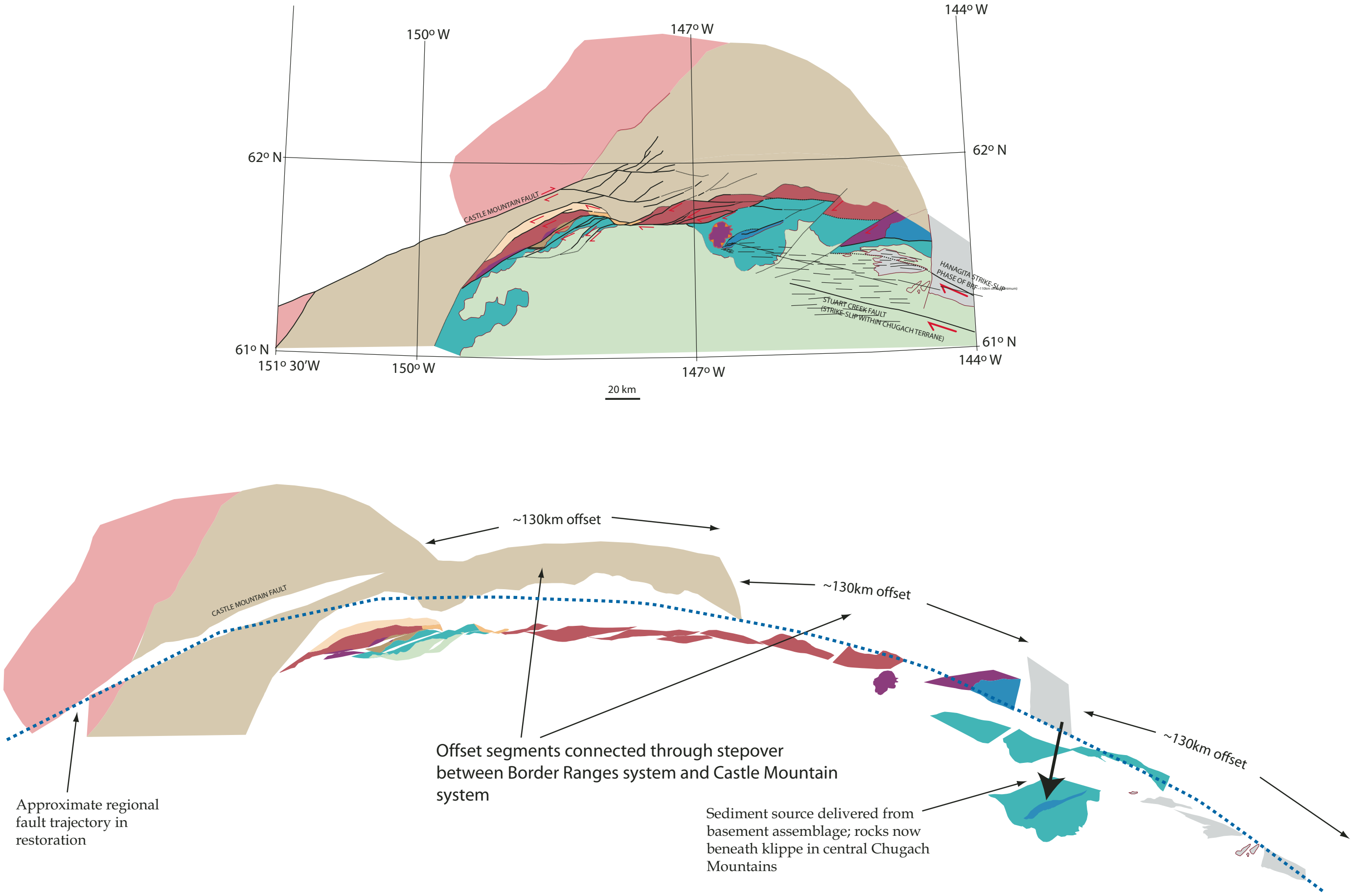

Figure 13. Present geology (above) and map reconstruction (below) of the Border Ranges fault illustrating the potential linkage of Cenozoic strike slip from the northern Chugach fault system, across the Matanuska Valley, and linking to the Castle Mountains system. Key result is the restoration of major fault arrays in the northern Chugach Mountains, assuming a strike-slip duplex model, can account for the ~130 km offset of the Castle Mountains system.

Chugach mélange and older crystalline assemblages and was followed by contraction (e.g., Fig. 7). It is possible that the lack of involvement of Chugach flysch in the deformation is due to strike slip localized exclusively along the fault contact between the Chugach mélange and older rocks. Nonetheless, in light of the geochronological data (e.g., Roeske et al., 2003), this relationship strongly suggests deformation prior to emplacement of the Chugach flysch. Available data also indicate, however, that large-magnitude dextral slip almost certainly did not stay on the Border Ranges fault as far west as the Kodiak Islands. The results of Clendenen et al. (2003) and Davies and Moore 1984 (see above) indicate little vertical slip across the Border Ranges fault in the Kodiak Islands since 150 Ma and little strike-slip displacement since 58–62 Ma. Thus if large (i.e., >500 km) displacement occurred on the Border Ranges fault system in eastern Alaska, it must have been transferred to some fault system other than the Border Ranges or Castle Mountain faults. As a speculation we suggest that that the Alaskan orocline may be older than previously thought (Paleogene) and the latest Mesozoic plate tectonic setting could have been somewhat similar to today with a strike-slip eastern limb and a convergent western limb. If this configuration existed in the time interval between the latest known accretion age for the Chugach mélange (ca. 100 Ma) and earliest accretionary age for the Chugach flysch ca. 75 Ma), then strike slip on the eastern limb would account for the observations of the early phase of the Hanagita system while subduction erosion or nonaccretion along the western limb of the orocline could account for the lack of strike-slip overprinting in the Kodiak Islands.

Mesozoic History of the Border Ranges fault system

Although a simple view of the history of a convergent margin would suggest that boundaries like the Border Ranges fault system contain a record of initiation of the subduction megathrust (e.g., MacKevett and Plafker, 1974; Pavlis, 1982) it now appears that overprinting along the Border Ranges fault system has destroyed virtually all of this record. Although small pockets of the Mesozoic boundary may be preserved elsewhere, it appears that the only vestiges of this older history are preserved in three general localities: the Knik River terrane in the western Chugach Mountains, the Tonsina area of the central Chugach Mountains, and Kodiak Island. On Kodiak Island, however, this deformation is more cryptic as brittle faults with a complex geometry (Roeske, 1988; Clendenen, 1991) and minor structures in the Chugach mélange (e.g., Connelly, 1978).

Of these localities, probably the best documented Mesozoic history is recorded in the western Chugach Mountains, where crosscutting plutons provide a geochronological and kinematic constraint on the record. In that area Pavlis et al. (1988), Pavlis (1996), and Barnett et al. (1994) documented a ductile deformational event associated with syntectonic plutonism that is clearly linked to a period of sinistral-oblique thrusting. The exact duration of this event is uncertain, but available geochronology (Barnett et al., 1994) suggests the event was short-lived, between 125 and 130 Ma. In this early work these investigators generally emphasized a tectonic model for this event that linked the high-T metamorphism and plutonism to a reinitiation of subduction along the boundary in the Early Cretaceous. This inference was based primarily on regional relationships that linked this event to: (1) a preceding lull in arc magmatism, which is consistent with an absence of subduction prior to the event; (2) interpretation of regional stratigraphy in the adjacent forearc basin; and (3) an association in time to the early phase of mid-Cretaceous deformation along the suture between outer Cordilleran terranes (Peninsular-Alexander-Wrangellia composite) and North America, which is consistent with nucleation of a subduction zone on the trailing edge as the collision proceeded. This model has been largely ignored in other regional syntheses for Alaska (e.g., Plafker et al., 1994; Nokleberg et al., 1994) and in the long-standing Baja BC controversy (e.g., Cowan et al., 1997), but it is important to realize that, regardless of model, the basic data demonstrate that sinistral-oblique convergence along the Border Ranges fault system was established by ca.120 Ma and the subduction cycle has continued to the present day.

Some insight into this problem may lie in the short segment of the Border Ranges fault system that we refer to here as the Kenney Lake fault (Fig. 4). Although this contact is clearly a brittle fault, it has important similarities to the western Chugach Mountains including: (1) upper-mantle ultramafic rocks emplaced atop ductilely deformed Chugach mélange—amphibolite facies in the western Chugach Mountains and transitional greenschist-blueschist facies in the Tonsina area, (2) approximately equivalent structural depths based on mineral assemblages—assuming the blueschist facies assemblages at Tonsina were developed during Mesozoic thrusting at the same time as the western Chugach, and (3) similar kinematics—lineations in the Liberty Creek schist trend NE on a low-angle foliation, which is consistent with development during sinistral-oblique thrusting. Thus, although the Liberty Creek schist is undated, it is conceivable it developed at the same time as the Knik River schist but under different thermal conditions.

An intriguing feature of the Mesozoic record of the Border Ranges fault system arises by examining the pre-Cretaceous record along the boundary. In its simplest sense, this boundary is inconsistent with a simple model of forearc accretion in an oceanic arc because the rocks that lie directly above the fault system are generally mid- to lower-crustal plutonic rocks and, at several localities (Red Mountain, Eklutna, Wolverine, and Tonsina), contain upper-mantle assemblages that formed the basement to the plutonic assemblages in the Early Jurassic (Mehl et al., 2003). A critical feature of these ultramafic and mafic hanging-wall assemblages is that throughout the northern Chugach Mountains these rocks clearly cooled to hornblende closure temperatures by late-Early Jurassic (~175–195 Ma) time (e.g., Winkler et al., 1981; Pavlis, 1983; Burns et al., 1983; Barnett et al., 1994). This cooling indicates that the Early Jurassic arc either shut down, was uplifted and exhumed, or was cooled by subduction refrigeration or that some combination of all three effects occurred. Of the three, we suggest that only erosional exhumation can be rejected because there is no sedimentary record of Early Jurassic uplift and erosion within the Peninsular terrane arc (e.g., Clift et al., 2005a). Recent geochronologic work (Clift et al., 2005b) indicates that at least part of the record is the result of the arc shutting down and migrating inboard to the late Early to Middle Jurassic Alaska Range–Talkeetna Mountains plutonic belt, but tectonic events associated with that event are unclear. This cooling event could record an episode of tectonic erosion along the subduction interface or an episode of strike-slip truncation that drove a forearc sliver laterally, rapidly placing the arc assemblages adjacent to the subduction interface (e.g., Roeske et al., 1989; Clift et al., 2005b). At present we believe these two alternatives cannot be clearly separated, but in either case it is clear from relationships in the western Chugach Mountains that lower-crustal to upper mantle rocks (ultramafic rocks and high-P mafic rocks) had been exhumed to mid-crustal levels by Early Cretaceous time and possibly much earlier. That is, in the western Chugach Mountains, the ultramafic bodies are metamorphosed together with surrounding rocks at upper greenschist to amphibolite facies conditions and pressures of ca. 400–600 MPa (e.g., Barnett et al., 1994), or about half the Jurassic pressure conditions of equivalent rocks at Tonsina (e.g., DeBari and Coleman, 1989). We suggest that this observation is more easily explained by a forearc sliver model, which would readily allow for localized uplift of slabs along the strike-slip system but is not exclusive to this model. For example, forearc normal faulting, coeval with subduction erosion, would produce localized uplift of formerly deep-seated rocks and could explain the exhumation history of the ultramafic assemblages. Thus, more study is needed on the high-T history of the mafic-ultramafic assemblages of the northern Chugach Mountains before these questions can begin to be addressed.

Mechanical Backstops in Forearcs

A surprising feature of the Border Ranges fault is its continuity for more than 1500 km around the north Pacific rim despite the clear evidence for repeated reactivations of the boundary. Indeed, it was this continuity that originally led to the regional correlation of the structure by MacKevett and Plafker (1974) and continued usage of the term today. This continuity is surprising because other equivalent structures, such as the Coast Range Fault in California, have been reactivated by normal faulting and strike-slip, but the strike-slip reactivations have not faithfully followed the tectonic join between the subduction assemblages and the older basement terranes. For example, in California the San Andreas Fault dismembered the Coast Range thrust by cutting obliquely across the boundary and transported the Salinian block laterally, juxtaposing it against accretionary complex assemblages of the Franciscan. This raises an issue of why younger structures appear to have followed this older structural contact so faithfully, with only small-scale slicing and shuffling along the contact.

We suggest that there are probably at least two explanations that account for this observation. First, the boundary may have already been partially "predisposed" to this configuration long before latest Mesozoic to Paleogene strike slip rejuvenated the boundary. Specifically, in the Jurassic, major structural events had already shaped the boundary including development of fault arrays (e.g., Pavlis, 1982) and large amounts of exhumation—either due to Jurassic strike-slip truncation or subduction erosion (Roeske et al., 1989; Clift et al., 2005b). These preceding events may have developed a mechanical boundary within the forearc lithosphere that was easily reactivated by later deformation, which allowed for a persistence of a relatively narrow boundary. Second, this observation may be a quirk of the structural level of present-day exposure. Large slabs of crystalline rock lie atop the accretionary complex in several areas, like the Klanelneechena klippe or the Haley Creek klippe. This observation implies that in the past much of what is now the northern Chugach Mountains was underlain by upper-crustal equivalents of these crystalline hanging-wall assemblages. Neogene uplift has removed most of this hanging wall, but in the Paleogene, the paleogeology would have looked quite different; for example, there would have been Salinian-like slabs of crystalline rocks outboard of the strike-slip systems, and erosion has simply stripped those rocks away, exposing the deeper levels of the strike-slip system. Indeed, this hypothesis is supported by the similarity in structural style between the modern Fairweather fault and the Paleogene structures of the Border Ranges fault system. That is, slip partitioning produces a strike-slip fault along the structural contact, carrying thrust "chips" on the outboard side but not cutting deeply across the boundary.

Ultimately resolution of these issues has important broader implications for forearc tectonics. The Border Ranges fault is the fundamental compositional break in the Alaskan-Aleutian forearc, but as a mechanical boundary it has acted as a different feature at different times. Early in its history it undoubtedly evolved from an initial break that formed the subduction zone into a backstop against which the accretionary complex ultimately formed. During that interval the boundary almost certainly experienced a cycle (or cycles) of subduction erosion along the thrust interface, but ultimately it became the "backstop." Oblique subduction intervals ultimately destroyed the boundary as this "simple" thrust interface and generated the present boundary, which is dominated by the affects of Tertiary strike slip. Moreover, the nature of the boundary as a mechanical backstop almost certainly evolved during its history. That is, early Cenozoic ridge subduction, which was coeval with the strike-slip event on the Border Ranges fault system, essentially welded the forearc accretionary complex into a coherent slab of continental crust in the Chugach metamorphic complex and probably throughout the margin (e.g., Pavlis et al., 2003). Subsequent evolution of the forearc records a system where the mechanical backstop to the accretionary complex jumped far outboard of the Border Ranges fault by late Eocene time, and consequently no significant vertical or lateral displacement has occurred along the Border Ranges fault since that time.

CONCLUSIONS

In the 30+ years since MacKevett and Plafker (1974) first recognized the Border Ranges fault as a Mesozoic subduction megathrust in southern Alaska, the research community has made large strides in understanding the development of the structure. MacKevett and Plafker (1974) recognized the importance of younger overprints, but more recent work has demonstrated that these overprints dominate the present geology with only a few vestigates of older, Mesozoic tectonics. Foremost among these overprints is latest Mesozoic to early Cenozoic dextral reactivation of the fault, particularly in the central and eastern segments. Total slip magnitudes of the different phases of this overprint remain elusive, but it is now clear that the Border Ranges fault stands along with the Denali and Tintina Faults as one of the great northern Cordilleran strike-slip systems that reshaped the Cordillera during late Mesozoic and Cenozoic time. The relatively recent recognition of this structure as a major strike-slip fault is conceptually significant because its role in Cordilleran strike-slip tectonics has not been included in tectonic syntheses of the Cordillera. Thus, these early syntheses need some reevaluation in light of the evidence that the structure was a major player in the Late Cretaceous–Paleogene tectonics of North America.

Despite recent work, the Border Ranges fault system remains one of the most enigmatic structures within the Cordillera. Large segments remain poorly known, with geologic mapping in several segments limited to 1:250,000 or smaller scales. New data from some of these poorly understood segments will undoubtedly provide key information to address some of the questions raised in this paper. The Border Ranges fault remains one of the best, if not the best, exposures of an arc-forearc boundary on earth and, thus, should serve as an important natural laboratory for study of these systems. The dramatic differences in exposed structural levels along the fault provide important potential for future studies of strike-slip fault systems at different crustal levels. Moreover, although strike-slip fabrics are intense in the eastern segments, opportunities still remain for further understanding of subduction megathrust systems through studies of the fault in scattered segments where the older history of the boundary is partially preserved.

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