STRUCTURAL RELATIONSHIPS AND CRUSTAL DEFORMATION IN THE SAINT ELIAS OROGEN, ALASKA

JAMES BENJAMIN CHAPMAN V

Department of Geological Sciences

APPROVED:

Terry L. Pavlis, Ph.D., Chair

Jose Hurtado, Ph.D.

John Walton, Ph.D.

Pablo Arenaz, Ph.D.
Dean of the Graduate School

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by

JAMES BENJAMIN CHAPMAN V, B.S.

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Abstract

The most recent period of orogenesis in southern Alaska began in late Neogene time with the collision of the Yakutat microplate, which is partially accreted to and partially subducted beneath the Alaskan margin to form the St. Elias Mountains. One of the most dynamic areas within the orogen is the Eastern syntaxis where the Dangerous River Zone (DRZ), a significant structural and lithologic boundary, partitions deformation between dextral transpressive structures associated with the Queen Charlotte-Fairweather fault and the Yakutat fold and thrust belt. The DRZ originated as a suture zone between an oceanic plateau and the continental margin or a previously unrecognized structure within the Chugach accretionary complex, which has implications for the crustal structure beneath the western third of the Yakutat microplate.

Neotectonic studies suggest significant spatial and kinematic variation in active deformation during the collision of the Yakutat microplate. The St. Elias orogen experienced a widespread structural reorganization in the Quaternary with oblique convergence accommodated by an en echelon thrust array. The new tectonic configuration also includes the continuing development of an incipient indentor corner, significant retrothrust motion, and shifting deformation fronts. Reorganization is temporally linked to intense glacial erosion in the core of orogen and rapid sedimentation in offshore depocenters during the Pleistocene.

Near the end of the Pleistocene, large tidewater and piedmont glacial complexes began to break up and retreated from the continental shelf resulting in significant isostatic adjustments. Marine to terrestrial sedimentary deposits in the Gulf of Alaska provide constraints on the timing and magnitude of glacial rebound as well as changes in relative sea-level at the end of the Last Glacial Maximum. Drastic ice retreat resulted in rapid isostatic uplift, which was locally exceeded by equally rapid sea-level rise.

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1.1 ABSTRACT

The most recent period of orogenesis in southern Alaska began in late Neogene time with the collision of the Yakutat microplate, which is partially accreted to and partially subducted beneath the Alaskan margin at the easternmost extent of the Aleutian trench. Neotectonic studies suggest significant spatial and kinematic variation in active deformation during the collision of the Yakutat microplate. The Saint Elias orogen experienced a widespread structural reorganization in the Quaternary with oblique convergence partitioned onto an en echelon thrust array. The new tectonic configuration also includes the continuing development of an incipient indentor corner, significant retrothrust motion, and shifting deformation fronts. Reorganization is temporally linked to intense glacial erosion in the core of orogen and rapid sedimentation in offshore depocenters during the Pleistocene. We propose that mass redistribution and modification of orogenic topography played an integral role in the structural and tectonic evolution of the present system. Currently, the spatial deformation front (outboard limit of deformation) and active deformation front are not the same, suggesting deformation swept through the landscape through time, presumably as a result of glaciation, tectonic adjustment, or both. A more complete picture of the complex response of near surface deformation to topographic disruption should improve seismic hazard assessments.

1.2 INTRODUCTION

Southern Alaska is a complex assemblage of accreted terranes and accretionary complexes of which the Yakutat microplate is the latest addition [Plafker et al., 1994]. The Yakutat microplate was excised from the Cordilleran margin in early Tertiary time and transported northward along margin-parallel transform faults, including the Fairweather fault [Plafker et al., 1978; Bruns, 1983; Plafker et al., 1994] (Fig. 1). As transport continued, the microplate encountered the continental margin at the Aleutian trench where the ongoing collision with southern Alaska fundamentally reshaped the northern Cordillera, produced North America's highest mountain range, and the highest coastal mountain range on Earth. The collision is currently driving orogenesis throughout the region and may be responsible for

far-field deformation deep into the Cordilleran interior [Mazzotti and Hyndman, 2002]. As such, any consideration of neotectonics and seismicity in the northern Cordillera cannot ignore the role of the Yakutat collision. However, a poor understanding of the current distribution of deformation within the Yakutat microplate limits the development of successful tectonic models. Recent work as part of the Saint Elias Erosion and tectonics Project (STEEP) is helping to resolve the location of active structures and exploring the role of erosion in the spatiotemporal evolution of deformation within the Yakutat collision.

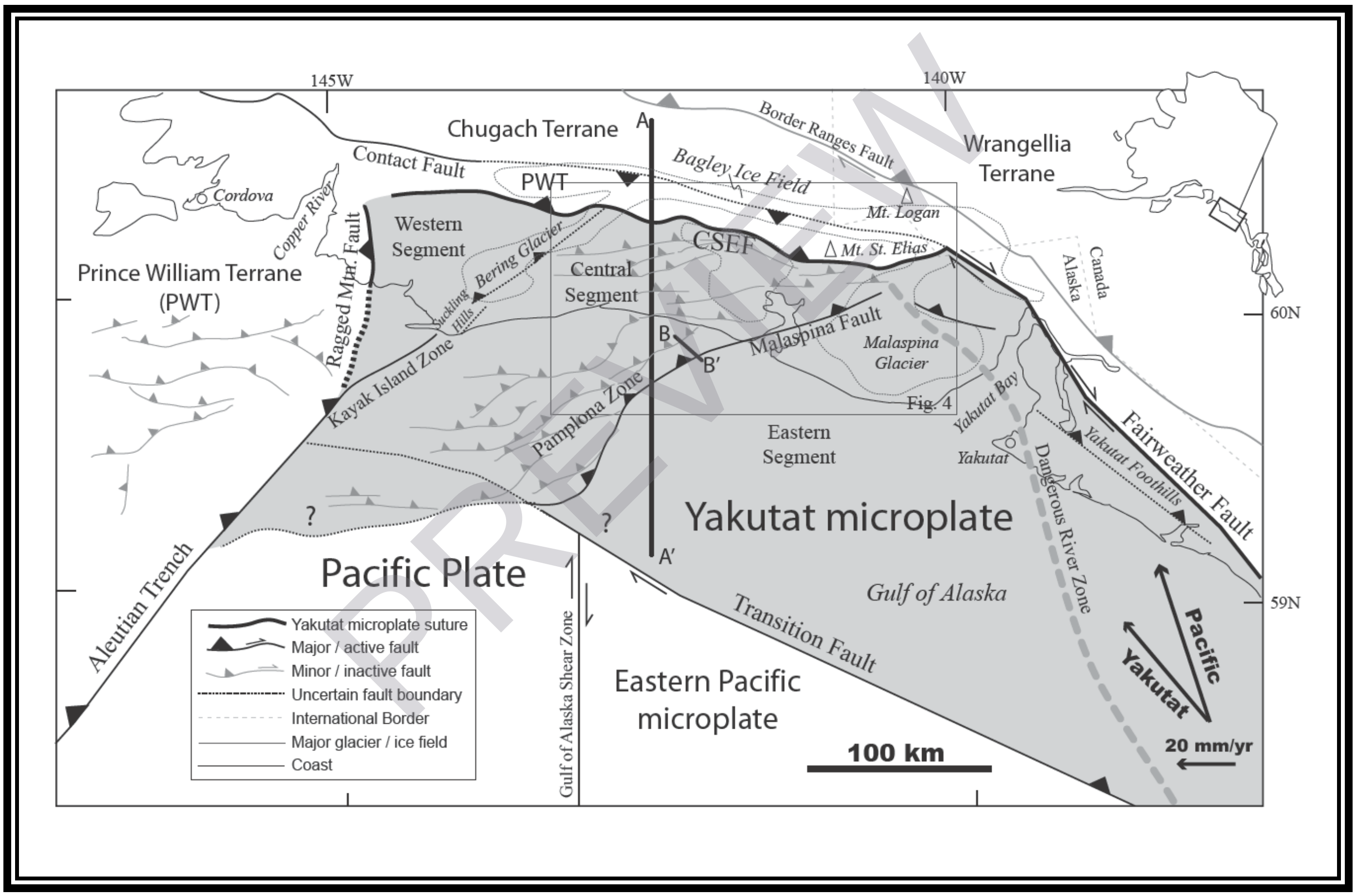

Figure 1.1: Overview map of the Yakutat microplate and surrounding geology after Plafker [1987]. Note the location of cross-section A-A’ across the fold and thrust belt presented in Figure 1.3 and section B-B’ across the Pamplona zone presented in Figure 1.5. CSEF = Chugach Saint Elias Fault (suture). Velocity vectors from Fletcher and Freymueller [2003].

Here, we present a review of the Yakutat microplate collision and architecture of the Saint Elias orogen with a focus on areas considered candidates for active deformation. Key points of this paper

include evidence for structural reorganization in the Quaternary and the potential effects of erosion on strain localization within the orogen. Specifically, widespread mass redistribution as a result of intense glacial excavation in the Pleistocene may have altered the way in which deformation is partitioned in response to oblique convergence.

1.3 REGIONAL TECTONICS

The Yakutat microplate is readily distinguished from the adjacent Mesozoic and early Cenozoic accretionary complex by a diagnostic Tertiary sedimentary sequence that thins to the east across a composite basement assemblage (Fig. 1.1). To the west, Yakutat microplate basement is inferred to be a Paleogene oceanic assemblage [Plafker, 1987], probably an oceanic plateau [Wells et al., 1984], that is now subducted hundreds of km beneath southern Alaska [Eberhart-Phillips et al., 2006]. To the east, Yakutat basement consists of "continentalized," metamorphosed flysch and accretionary mélange of a late Mesozoic subduction complex that is partially accreted to the North American margin [Plafker, 1987; Bruhn et al., 2004]. The two basement types are separated by a high-angle structural boundary referred to as the Dangerous River Zone [Plafker, 1987; Plafker et al., 1994], which is overlapped offshore by Tertiary strata, but may be a major structural factor for partitioning deformation in the core of the orogen. Overlying this composite basement is a thick sedimentary cover sequence including ~4 km of Paleogene shallow marine to fluvial strata unconformably overlain by up to 5 km of syntectonic glaciomarine strata of the Yakataga Fm. [Plafker, 1987; Eyles and Lagoe, 1990]. The onset of glaciation and deposition of the Yakataga Fm. is coincident with the beginning of mountain building in the late Miocene [Eyles et al., 1991].

After a period of middle Cenozoic margin-parallel transport on the Pacific-North American transform boundary, the Yakutat microplate arrived at the Aleutian trench and initiated orogenesis in the mid-to-late Miocene [e.g. Plafker et al., 1994]. A variety of processes related to the Yakutat collision constructed the present high topography in southern Alaska. First, the indentation of the North American margin by the Yakutat microplate is driving reactivation of structures well inboard of the collision including the Denali fault system [Stout and Chase, 1980; Lahr and Plafker, 1980]. Also, outside the immediate collision zone, underthrusting of the buoyant Yakutat oceanic basement led to flat slab subduction, which appears to be causing regional uplift of much of southern Alaska [e.g. Pavlis et

al., 2004; Eberhart-Phillips, 2006]. On the periphery of the collision, volcanism, previously interpreted as a normal arc complex [Nye, 1983; Richter et al., 1994], assembled the Wrangell Mountains, although recent work suggests magmatism is related to slab-melt associated with plate-edge effects [Preece and Hart, 2004]. Models for Wrangell volcanism not linked to arc systems are consistent with a poorly defined deep seismic zone [Page, 1989; Eberhart-Phillips et al., 2006]. Finally, the Yakutat microplate is driving proximal orogenesis in the Fairweather, St. Elias, and eastern Chugach mountain ranges with basement-involved transpressional systems in the hinterland and a thin-skinned fold and thrust belt in the foreland [Bruhn et al., 2004; Pavlis et al., 2004]. This oblique convergence zone can be loosely described as a three-dimensional orogenic wedge [Koons, 1994] whose character changes along strike as a result of the transition from strike-slip motion to subduction. The transition is manifested as a complex tectonic corner with multiple possible deformation fronts with differing structural styles.

1.4 DEFORMATION FRONTS

The Yakutat microplate can be structurally divided into the western, central and eastern segments as defined by Bruhn et al. [2004] (Fig. 1.1). The eastern segment is internally undeformed, but bounded to the east by the Fairweather fault and associated transpressive structures that locally comprise the suture between the Yakutat microplate and North America. The central segment is separated from the eastern segment by the Pamplona zone offshore and its onshore equivalent, the Malaspina fault, which form the outboard limit to fold and thrust deformation typical of the central segment (Fig. 1.1). The Chugach Saint Elias fault (CSEF) is the suture for the central segment, although the mechanical backstop for the orogen occurs to the north of the suture along the Bagley Ice Field [Berger et al., in press]. Deformational style becomes more complex west of the Bering Glacier in the western segment, where the original fold and thrust belt of the central segment appears to be complexly refolded [Bruhn et al., 2004; Pavlis et al., 2004]. Deformation may be more diffuse in the western segment, but is at least partially concentrated along the Ragged Mountain fault, which forms the suture in that locality. All three segments share a southern boundary offshore at the contact between the Yakutat microplate and the Pacific plate at the Transition fault (Fig. 1.1).

We present a review of neotectonic activity in these segments and at their boundaries below. A key observation, arising from recent work, is that the "accretionary complex" style of deformation in the

past is no longer characteristic of the orogen and a new tectonic model is required that integrates spatial and temporal changes in deformation fronts.

1.4.1 Eastern Boundary: Fairweather Fault

To the east, GPS estimates suggest the Yakutat microplate is being transported north along the dextral Fairweather fault at 40-49 mm/yr with a transport direction nearly parallel to the plate-bounding fault [Plafker et al., 1978; Fletcher and Freymueller, 1999; 2003; Leonard et al., 2007]. However, recent studies hint that glacial rebound may be obscuring a margin-normal component of motion [Larsen, 2006]. The present geomorphology of the area, uplift in the 1899 Yakutat Bay earthquakes [Tarr and Martin, 1912; Thatcher and Plafker, 1982; this volume], and young (< 3Ma) apatite [U-Th]/He (AHe) ages near Mt. Fairweather [McAleer et al., in review.] also support a slip-partitioned, transpressional fault system with convergence accommodated by a narrow thrust belt forming the Yakutat foothills within the microplate [Bruhn et al., 2004] (Fig. 1.1). The Fairweather fault last ruptured in the 1958 Lituya Bay event with ~3.5m of nearly pure right-lateral offset [Tocher, 1960; Page, 1969; Doser and Lomas, 2000] and paleoseismic work confirms continued deformation through the Quaternary [Plafker et al., 1978]. The Fairweather fault disappears beneath ice fields to the north of Yakutat Bay where the Saint Elias orogen assumes an ~E-W strike and other structures presumably take up the increased convergence.

1.4.2 Western Boundary of the Central Segment

To the west, the Aleutian trench absorbs 50-60 mm/yr of Pacific Plate motion [DeMets et al., 1994], although it is unclear how this boundary links to structures within the Yakutat microplate. The trench is roughly coincident with the strike of the Kayak Island zone, an onshore structure uplifting the Suckling Hills [Chapman and Vorkink, 2006], and the Bering Glacier structure proposed by Bruhn et al. [2004; in press] (Fig. 1.2). These structures all cut obliquely across the bathymetric and topographic grain, including the onshore fold and thrust belt.

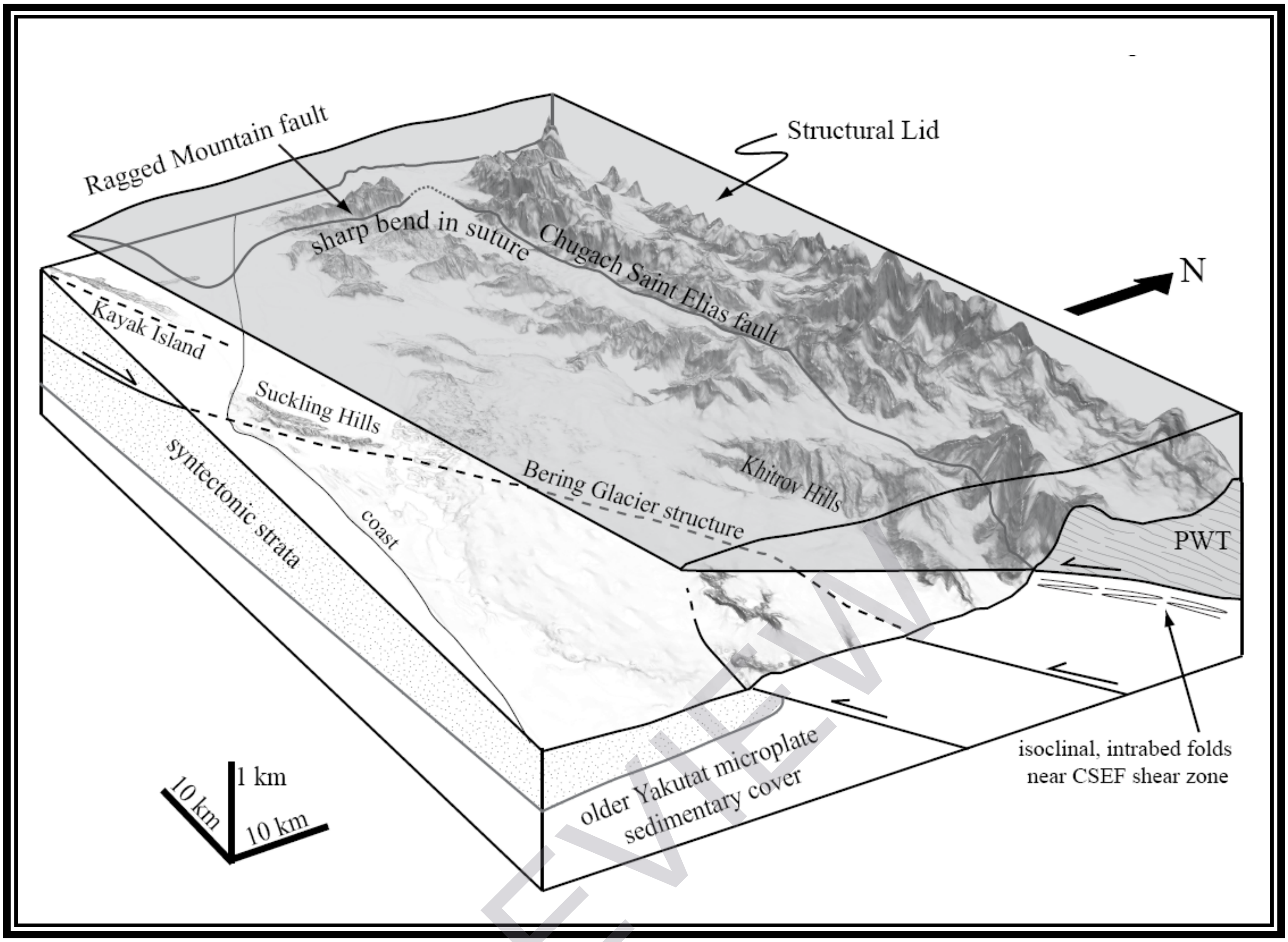

Figure 1.2: 3D block model looking northwest into the western segment. The outcrop pattern of the Prince William terrane (PWT), trace of the Yakutat suture, localized deformation in the Khitrov Hills in the projection of the Chugach Saint Elias fault (CSEF), and a small klippe (not shown) near the Bering Glacier all suggest the PWT extended out across the landscape at a low angle on the CSEF creating a structural lid, which was subsequently exhumed and eroded.

The Kayak Island zone was uplifted 2-3m during the M9.2 1964 Great Alaskan earthquake along what is interpreted to be a splay off the Aleutian Megathrust [Plafker, 1965; 1974]. Despite recent motion, many workers believe the Kayak Island zone is inactive based on a USGS seismic line that clearly shows flat-lying reflectors overlapping relatively high-angle thrust structures [Lowe et al., this volume; Bayer et al., 1977]. Deposition rates in the area are very high (~ 1 cm/yr) because of the close proximity of the Copper River delta and a small local gyre that acts as a sediment trap [Jaeger et al.,

1998], which opens the possibility that the undeformed sediment package may be too young to record deformation.

Onshore, the Suckling Hills preserve an erosional surface cut into syntectonic strata that is tilted ~5 degrees to the west, likely along a west-dipping thrust fault [Chapman and Vorkink, 2006]. The Bering Glacier structure is obscured by ice, but is probably also a west-dipping thrust that intersects the Suckling Hills fault and Aleutian Megathrust at depth [Bruhn et al., 2006; in review] (Fig. 1.2). The Bering Glacier is located at a major structural boundary that separates the ~E-W-striking fold and thrust belt in the central segment of the orogen from the complexly refolded western segment [Bruhn et al., 2004]. The arrangement practically requires a mechanical discontinuity between the two regions [Bruhn et al., 2006] and AHe ages decrease from east to west across the Bering Glacier structure, possibly suggestive of differential exhumation [Berger and Spotila, in review].

1.4.3 Western Segment and Ragged Mountain Fault

The western segment is characterized by subdued topography with numerous (~103) small to mid-sized scarps that may be sackung (gravitational slope collapse features resulting from seismic shaking), flexural slip planes along active folds, faults, or other features [Pavlis and Bruhn, 2005; Vorkink et al., 2007]. Trenching suggests that some of the scarps are tectonic in origin and could theoretically accommodate a large amount of deformation on a diffuse array of small structures [Bruhn et al., 2006]. Current investigation of recently acquired light detection and ranging (LIDAR) data will help resolve the nature of the swarms of scarps [Vorkink et al., 2007]. The unique pattern of deformation is likely related to the development of an incipient syntaxis that involves a combination of constriction, lateral extrusion and folding about steeply plunging axes [Pavlis et al. 2004; Bruhn et al., 2004].

One of the most prominent features of the western segment is an ~90 degree bend in the suture between the Yakutat microplate and the Prince William terrane (PWT) (Fig. 1.1, 1.2), whose orientation is interpreted as a consequence of the indentation of the Alaskan margin by the Yakutat microplate and continued vertical-axis folding [Bruhn et al., 2004; Pavlis et al., 2004]. The suture is locally referred to as the Ragged Mountain fault in the western segment and the CSEF elsewhere. Early workers interpreted a large fault scarp at the base of Ragged Mountain as a low-angle normal fault [Tysdal et al.,

1975]; however, recent field work revealed that the suture may be an active thrust fault with secondary extensional deformation localized in the hangingwall [Bruhn et al., 2006]. Final conclusions are pending results of ongoing analysis.

The N-S strike of the suture (i.e. Ragged Mountain fault) in the western segment is an important structural marker that records post-collisional deformation of the backstop. Immediately west of the collision zone, the PWT (i.e. the backstop assemblage) is >150 km wide, but decreases abruptly to a narrow strip <10 km across within the core of the orogen. Although the presence of the PWT gradually decreases to the east regionally, the sharp change in map pattern implies that the Yakutat microplate indented the margin by a minimum of 100 km (Fig. 1.1, 1.2). The fate of the missing PWT rocks is unknown, but may involve subduction erosion of the hangingwall assemblage [e.g. Von Huene and Scholl, 1991] or exhumation of a structural lid; as Brandon [2004] suggested for the Cascadia and Alpine orogenic wedges (Fig. 1.3). Although an additional ~50 km of the mid-Cenozoic accretionary complex of the eastern Aleutian trench was likely destroyed by subduction erosion since the Yakutat collision initiated [Fruehn et al. 1999], we propose that the thick sedimentary cover of the Yakutat microplate continues to be accreted to the margin and the overlying PWT "lid" was exhumed by a combination of uplift as a result of structural thickening at depth and rapid glacial erosion. Evidence for a structural lid in the past includes apparent klippen near the suture [M. Vorkink and R. Bruhn, unpub. obs., 2005; Chapman et al., 2007] and localized deformation in the area along the projection of the CSEF shear zone (Fig. 1.2). Structural reorganization in the backstop, including the shutdown of the CSEF, may have accelerated uplift and removal of the lid.

1.4.4 Backstop

The CSEF lies at the base of a large topographic escarpment along most of its length, suggesting the structures could be active. However, new AHe ages obtained across the CSEF show no differential exhumation, suggesting that it was inactive at least since 1 Ma [Berger et al., in press]). Furthermore, new zircon [U-Th]/He (ZHe) ages across the fault (which have a higher closing temperature) suggest that the CSEF was actively exhuming its hanging-wall around 5 Ma [Berger et al., in press].

Within the hanging wall of the CSEF, the PWT is separated from the Chugach terrane by the Contact fault, but this structure is buried in a deep glacial trough, the Bagley Ice Field. The Contact

fault was originally a north-dipping suture between the PWT and Chugach terrane and represented a thrust within the Aleutian subduction complex [Plafker et al., 1994]. Remnants of the original Paleogene fault are still preserved along the western edge of the orogen where an undeformed Eocene pluton intrudes the Contact fault [Plafker et al., 1994], but that observation is only applicable to a short segment of the fault [Bruhn et al., 2004]. Geodetic data suggests that right-lateral slip, convergence, or both could occur across the structure [Savage and Lisowaki, 1988; Sauber et al., 1997]. Low-temperature cooling ages to the north of the Bagley Ice Field suggest limited exhumation (≤ 2.5 km) within the Chugach terrane for most of the history of the Saint Elias orogen, yet ages to the south of the Bagley Ice Field are significantly younger, indicative of sustained south-side up motion across the Contact fault boundary [Berger et al., in press; Berger and Spotila, in review; Spotila et al., 2004; Johnston et al., 2004]. Recent earthquake locations by Doser et al. (2007) reveal a prominent south-dipping seismicity trend in the vicinity of the Bagley Ice Field that Berger et al. [in press] interpret as a previously unrecognized backthrust to explain the AHe ages. The development and initiation of significant motion on the backthrust may coincide with the shutdown of the CSEF and formation of a new mechanical backstop.

Metamorphic grade within the hanging wall of the CSEF increases markedly from west to east, reaching upper amphibolite facies near Mt. Saint Elias [Dusel-Bacon et al., 1994]. The field gradient along the Yakutat suture (i.e. CSEF) probably reflects an increase in total exhumation, consistent with high topography to the east [Sisson et al., 1989]. The relative activity and interactions between the CSEF, Contact fault, proposed backthrust and Fairweather fault to produce the high topography at this eastern junction is poorly understood [Chapman et al., 2007]. The region experienced a complex rupture pattern during the 1979 Saint Elias earthquake (7.4 Mw), which included thrust and strike-slip motion in the backstop and numerous thrust-related aftershocks in the foreland [Estabrook et al., 1992].

1.4.5 Central Segment: Fold and Thrust Belt

Outboard of the CSEF are a series of stacked thrust sheets that young toward the offshore deformation front in the Pamplona zone [Plafker, 1987]. Synorogenic deposits of the Yakataga Formation are absent in the structurally highest thrust sheets, progressively young toward the coast, and

are actively deforming offshore [Plafker, 1987; Plafker et al., 1994]. These observations are broadly consistent with the general stacking succession recognized in most fold and thrust belts, accretionary complexes, and orogenic wedges where surface morphology and structure are closely correlated [e.g. Elliot, 1976; Davis et al., 1983]. Figure 1.3 presents a schematic cross-section across the central segment in line with these more traditional interpretations of an accretionary style orogen and previous cross-section constructions [Plafker, 1987; 1994]. This interpretation differs from that of Wallace (this volume) by the inclusion of the retrothrust beneath the Bagley Ice Field [Berger et al., in press] and significant internal shortening and duplexing within the sedimentary cover rather than a regional detachment at moderate depth above basement horses. Ongoing and planned geophysical work may help to resolve the role of basement in the orogen [Bauer et al., 2007]. Line length restoration of just the Yakataga Formation and a reasonable restoration of the Bagley Ice Field backthrust suggests ~25 km shortening since 3-5 Ma (corresponding to 5-8.5 mm/yr) comparable to the total shortening proposed by Wallace [this volume]. In our interpretation, area balance restoration of all the sedimentary cover suggest a minimum of 75 km shortening, which is still well short of the 120-250 km convergence estimated for that period of time based on plate motion reconstructions [Pavlis et al., 2004]. Much of that deformation was likely taken up on thrusts higher in the structural succession and subsequently eroded. Assuming limited surface uplift, inclusion of exhumation estimates from Berger et al. [in review] since 3-5 Ma results in ~200-300 km shortening. Other possibilities for missing shortening include strike-slip motion and sediment subduction along the CSEF.

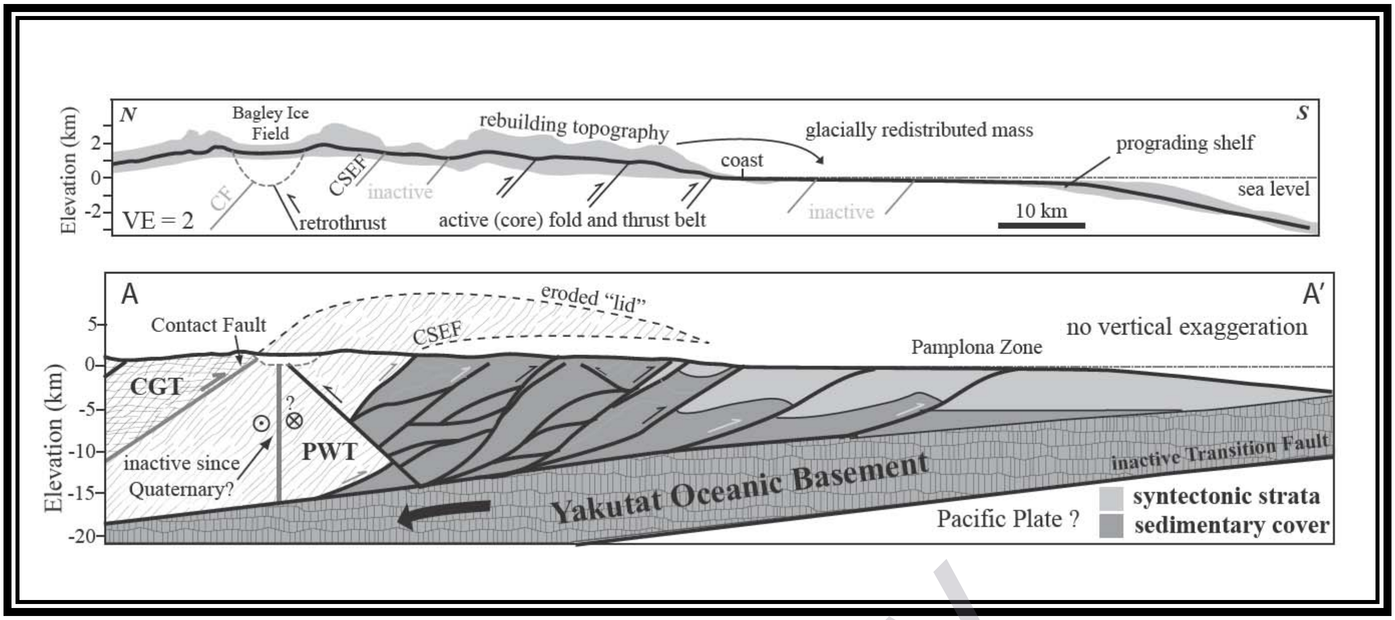

Figure 1.3: Top) Average topography from a 50 km swath across the central fold and thrust belt. The area between the maximum and minimum elevations is shaded. Mass is removed from the Bagley Ice Field and southern flank of the orogen and deposited offshore to create a broad shelf. Uplift from active thrust structures in the core of the fold and thrust belt kept close pace with erosion. Bottom) Schematic cross-section across the fold and thrust belt showing general architecture of the orogen, modified from Berger et al. [in press]. Duplexing at depth may have deformed the Prince William terrane (PWT) structural lid and led to the development of the retrothrust. Wallace [this volume] presents an alternative interpretation for a similar section line. CSEF = Chugach Saint Elias fault, CGT = Chugach terrane. Position of section shown in Fig. 1.1.

AHe age distributions and river channel analyses suggest that deformation is focused within the core of the fold and thrust belt and not directly linked to orogenic topography (Fig. 1.3) [Berger et al., in press; Chapman and Vorkink, 2006]. The spatial distribution of high exhumation rates (~ 5 mm/yr) is roughly coincident with the intersection between topography and the glacial equilibrium line altitude (ELA) [Berger et al., in press; Berger and Spotila, in review; Spotila et al., 2004]. In temperate (warm-based) glacial systems, erosion is thought to be greatest at the ELA where the basal sliding velocity is the highest [Hallet, 1979; Meigs and Sauber, 2000]. Thus, focused glacial erosion and tectonics should be coupled whereby the mean topographic slope of the orogenic wedge is preserved by enhanced exhumation at the ELA [Berger et al. in press; Berger and Spotila, in review; Tomkin, 2007]. An important consequence of this arrangement is that active deformation migrated away from the outboard