Plate margin deformation and active tectonics along the northern edge of the Yakutat Terrane in the Saint Elias Orogen, Alaska, and Yukon, Canada

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ABSTRACT

Structural syntaxes, tectonic aneurysms, and fault-bounded fore-arc slivers are important tectonic elements of orogenic belts worldwide. In this study we used high-resolution topography, geodetic imaging, seismic, and geologic data to advance understanding of how these features evolved during accretion of the Yakutat Terrane to North America. Because glaciers extend over much of the orogen, the topography and dynamics of the glaciers were analyzed to infer the location and nature of faults and shear zones that lie buried beneath the ice. The Fairweather transform fault system terminates by oblique-extensional splay faulting within a structural syntaxis, where thrust faulting and contractional strain drive rapid tectonic uplift and rock exhumation beneath the upper Seward Glacier. West of the syntaxis, oblique plate convergence created a dextral shear zone beneath the Bagley Ice Valley that may have been reactivated by reverse faulting when the subduction megathrust stepped eastward during the last 5–6 Ma. The Bagley fault zone dips steeply through the upper plate to intersect the subduction megathrust at depth, forming a fault-bounded crustal sliver capable of partitioning oblique convergence into strike-slip and thrust motion. Since ca. 20 Ma the Bagley fault accommodated more than 50 km of dextral shearing and several kilometers of reverse motion along its southern flank during terrane accretion. The fault is considered capable of generating earthquakes because it is suitably oriented for reactivation in the contemporary stress field, links to faults that generated large historic earthquakes, and is locally marked by seismicity.

INTRODUCTION

The Saint Elias and eastern Chugach Mountains of Alaska, USA, and the Yukon, Canada provide a classic locality to study relationships between glaciation, tectonics, and landscape evolution (Fig. 1; Worthington et al., 2010; Enkelmann et al., 2010; Berger and Spotila, 2008; Meigs et al., 2008; Jaeger et al., 2001; Meigs and Sauber, 2000). Glaciers mask the structural geology where they...
flow over folds and faults that form the tectonic framework of the Saint Elias orogen (Bruhn et al., 2004, 2010), erode and transfer large volumes of rock detritus between the mountains and offshore realm (Hallet et al., 1996; Jaeger et al., 2001), and modulate the tectonic stress field by creating transient loads on the lithosphere (Sauber et al., 2000; Sauber and Molnia, 2004; Doser et al., 2007; Sauber and Ruppert, 2008). Regional faults that are mostly buried by glaciers include the Fairweather fault, the Malaspina and Bering glacier faults, and the Bagley fault. The Bagley fault cuts through the spine of the main range of the Saint Elias Mountains, where it lies beneath the Bagley Ice Valley, which is one of the most spectacular geomorphic features of the orogen (Fig. 2). The Bagley Ice Valley was previously mapped as part of the Bagley Ice Field. However, the U.S. Board of Geographic Names officially changed the name to Bagley Ice Valley in 1997.

Although the Saint Elias orogen is cited as a classic example of where climatic conditions have strongly affected tectonics (e.g., Spotila et al., 2004; Berger et al., 2008a, 2008b), it is also an important example for the study of complex deformation and tectonic exhumation within a plate boundary syntaxis and oblique collision zone (Plafker, 1987; Bruhn et al., 2004; Berger et al., 2008a, 2008b; Berger and Spotila, 2008; Koons et al., 2010) where transform motion of the Yakutat microplate relative to the North American Plate transitions from the Fairweather fault–Queen Charlotte transform system to tectonic accretion and subduction to the west. That is, the Yakutat microplate provides a contemporary example of terrane accretion that is a common process during mountain building, while also providing insight into the manner in which structural syntaxes, tectonic aneurysms, and plate boundary strain partitioning evolve both in space and time. In this study, we focus on the system of faults that accommodate deformation within the orogen, refining and extending work on the structural geology (Plafker, 1987; Bruhn et al., 2004; Chapman et al., 2008, 2011, 2012; Wallace, 2008; Pavlis et al., 2012), while integrating recently published work on the thermochronology (Berger et al., 2008a, 2008b; Enkelmann et al., 2008; Enkelmann et al., 2009; Enkelmann et al., 2010) and geodynamics (Koons et al., 2010). In doing so, we also demonstrate how modern remote sensing and geodetic data may be used to document the surface morphology and dynamics of large glaciers, which provide insight into the topography and structural geology at the base of the ice.

**TECTONIC SETTING OF THE YAKUTAT BLOCK**

The Yakutat microplate is colliding into southern Alaska at a rate of ~43–50 mm/yr (Fig. 1; Plafker, 1987; Plafker et al., 1994; Sauber et al., 1997; Elliott et al., 2010). The microplate is a fragment of an oceanic plateau with thick basaltic crust that is structurally overlain partly by Cretaceous flysch and mélange, and blanketed by Tertiary and Quaternary strata (Christeson et al., 2010; Worthington et al., 2012). The tectonically off-scraped and deformed rocks of the microplate form the “Yakutat Terrane” within the Saint Elias orogen, while the basaltic crust and mantle of the microplate is subducted beneath the North American Plate margin.

The rise of the Saint Elias orogen overlapped in time with the onset of glaciation, resulting in deposition of the coarse-grained glacial till and glacial marine deposits of the late Miocene to Quaternary Yakataga Formation (Eyles et al., 1991), much of which is uplifted and deformed by faulting and folding (Plafker, 1987). Offshore in the Gulf of Alaska, the Yakutat microplate abuts the Pacific Plate along the Transition fault, a prominent submarine escarpment created by transform motion between the tectonic plates (Bruns, 1983; Gulick et al., 2007). Subduction of the Yakutat lithosphere beneath southern Alaska occurs along a gently dipping megathrust with profound and far-reaching effects on the tectonics and landscape of interior Alaska (Ferris et al., 2003; Eberhart-Phillips et al., 2006; Bruhn and Haeussler, 2006; Haeussler, 2008; Abers, 2008; Benowitz et al., 2011).

The arcuate geometry of the plate margin in southern Alaska together with the NNW-directed relative motion causes a marked change in the obliquity of convergence within the Saint Elias orogen. Deformation in the eastern part is dominated by dextral strike-slip faulting along the Fairweather fault and by crustal contraction in a narrow coastal thrust belt that is developed within the edge of the Yakutat microplate (Plafker, 1987; Bruhn et al., 2004). Peaks of the Fairweather Range tower above the eastern side of the Fairweather fault reflecting slow and diffuse deformation that extends far into the continental interior to the east and north of the transform fault boundary (Mazzotti et al., 2003; Elliott et al., 2010). The plate boundary bends abruptly westward at the northern end of the Fairweather fault creating a structural syntaxis that is a locus of rapid tectonic uplift and exhumation (Plafker, 1987; Bruhn et al., 2004; Spotila and Berger, 2010; Enkelmann et al., 2008, 2009; Koons et al., 2010; Chapman et al., 2012).

West of this syntaxis, the Chugach–Saint Elias fault is the north-dipping suture between tectonically accreted rocks of the Yakutat terrane and the overlying metamorphic and igneous rocks of the Early Tertiary plate margin of southern Alaska (Fig. 2; Plafker, 1987). The Bagley fault cuts through the upper plate creating a narrow sliver of crust that is bounded to the south by the Chugach–Saint Elias fault and to the north by the Bagley fault. Tectonic accretion of the Yakutat terrane together with southward and eastward propagation of the subduction décollement created the wide foreland fold and thrust belt within this central segment of the orogen, as well as the offshore folds and thrusts of the Pamplona zone (Plafker, 1987; Bruhn et al., 2004; Chapman et al., 2008; Wallace, 2008; Worthington et al., 2010; Pavlis et al., 2012).

Structures curve southwestward toward the Aleutian Trench in the westernmost part of the Saint Elias orogen (Figs. 1 and 2) resulting in complex reworking and faulting that affects both the tectonic sliver of the upper plate and the orogen more generally.

Figure 2. Fault map of the Saint Elias orogen superimposed on a MODIS (Moderate Resolution Imaging Spectroradiometer) image background. See dashed red rectangle in Figure 1 for location. Faults with incontrovertible evidence for Late Pleistocene and younger displacement are shown in red. Those faults that are suspected to have been active, or at least partially reactivated, during the same time period are shown in purple. The orogen is divided into three segments, an eastern segment marked by the Fairweather transform fault and coastal mountains thrust and fold belt, a central segment containing the Chugach–Saint Elias fault suture and broad foreland fold and thrust belt, and a western segment where the Yakutat Terrane is molded into the syntaxis of southern Alaska at the northeastern end of the Aleutian megathrust. Onshore faults are located primarily from mapping by Plafker (1987), Bruhn et al. (2004), Chapman et al. (2008), and Chapman et al. (2011). Offshore structures are located from marine geophysical surveying reported by Worthington et al. (2008, 2012). The Chugach–Saint Elias fault (brown line) is the original suture between the Yakutat Terrane and North America. The upper part of the fault may now be abandoned because thrust faulting migrated southward over time into the foreland fold and thrust belt. Fault numbers are as given in Tables 1 and 2. The light yellow areas marked Barkley Ridge and Steller Ridge are prominent geomorphic features noted in the text.
Upper Seward Glacier

Eastern Bagley Ice Valley

Western Bagley Ice

Bering Glacier

Tana Glacier

Steller Glacier

Martin River Glacier

Miles Glacier

Agassiz Glacier

Valerie Glacier

Hubbard Glacier

Yahtse Glacier

Guyot Glacier

Malaspina Glacier

Chugach - St. Elias fault

Pamplona Formation Front

Chugach - St. Elias fault

Active faults (L. Pleistocene - Holocene slip.)
1: Fairweather fault
2: Fairweather Boundary fault
3: A. Yakutat thrust fault, B. Omeloi thrust fault
4: Bancas - Esker Creek dextral-thrust fault
5: Yana Stream thrust fault
6: Malaspina thrust fault
7: Pamplona fold and thrust fault zone
8: Bering Glacier - thrust &/or strike-slip fault
9: Kayak Island thrust fault zone
10: Ragged Mountain normal fault scarp

Major faults, possibly active along partial or total length
1: Art Lewis strike-slip fault
2: Chaix Hills thrust fault
3: Cascade Glacier thrust fault
4: Sullivan fault
5: Leeper thrust fault
6: Hope Creek thrust fault
7: Bagley fault zone

Active tectonic welt superimposed upon earlier foreland fold and thrust belt structure. Forms a broad antiform with N trending fold axis superimposed on east-trending folds.

Active faults (red), Possibly active faults (purple)
Thrust or oblique-slip thrust fault, barb on hanging wall
Normal or oblique-slip normal fault, hatch mark on hanging wall
Strike-slip fault

Orogen segments
Eastern - Fairweather fault and coastal thrust belt
Central - Central foreland fold and thrust belt
Western - Refolding & secondary faulting where Yakutat terrane is intruded and molded into the Alaskan syntaxis

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Table 1. Faults with known Quaternary or historical displacement

<table>
<thead>
<tr>
<th>Fault</th>
<th>Rationale for displacement interpretations</th>
<th>Reference</th>
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<tbody>
<tr>
<td>3a: Yakutat thrust fault</td>
<td>M 8.1 on September 10, 1899 (coast uplift)</td>
<td>Pfafker and Thatcher (2008)</td>
</tr>
<tr>
<td>3b: Olowi thrust fault</td>
<td>M 8.1 on September 10, 1899 (coastal deformation)</td>
<td>Pfafker and Thatcher (2008)</td>
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<tr>
<td>4. Esker and Bancas thrust fault(s)</td>
<td>M 8.1 on September 10, 1899 (coastal uplift), dextral offset subglacier drainage valley</td>
<td>Pfafker and Thatcher (2008); Cotton (2011)</td>
</tr>
<tr>
<td>5. Malaspina foreland fault</td>
<td>Geodetic modeling, uplift of a beach benm ca. 1899 (tentative correlation)</td>
<td>Savage and Lisowski (1986); Estabrook et al. (1992); Elliott (2011)</td>
</tr>
<tr>
<td>6. Malaspina fault</td>
<td>Geodetic measurements and aftershocks to ( M \geq 7.4 ) Saint Elias earthquake</td>
<td></td>
</tr>
<tr>
<td>7. Pamplona zone thrust faults</td>
<td>Earthquakes up to ( M \geq 6.1 )</td>
<td></td>
</tr>
<tr>
<td>10: Ragged Mountain</td>
<td>Normal (a) and thrust faulting (b)</td>
<td>(a) Tysdal et al. (1976)</td>
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<td></td>
<td></td>
<td>(b) Bruhn et al. (2004)</td>
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Table 2. Faults that may have Quaternary displacement (purple color)

<table>
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<tr>
<th>Fault</th>
<th>Rationale for displacement interpretations</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Art Lewis Glacier fault</td>
<td>Link to Fairweather fault</td>
<td>G. Pfafker (2009, personal commun.)</td>
</tr>
<tr>
<td>2: Chaix Hills fault (western part)</td>
<td>May link to Fairweather boundary fault</td>
<td>Geological mapping (Richter et al., 2005)</td>
</tr>
<tr>
<td>4: Sullivan fault (thrust?)</td>
<td>Marked by uphill facing scarp on mountainside of Sullivan anticline</td>
<td>R.L. Bruhn (2011, personal observ)</td>
</tr>
<tr>
<td>5: Miller Creek thrust fault</td>
<td>Mountain front and stream channel geomorphology</td>
<td>Chapman et al. (2012)</td>
</tr>
<tr>
<td>6: Leeper fault (thrust)</td>
<td>Geodetic measurements</td>
<td>Elliott (2011)</td>
</tr>
<tr>
<td>7: Bagley fault</td>
<td>South flank geomorphology, thermochnology</td>
<td>This study; Berger and Spotila (2008); Enkelmann et al. (2009)</td>
</tr>
</tbody>
</table>
Figure 3. Topographic profiles of the northern (A) and southern (B) mountain crests bordering the Bagley fault along the length of the Saint Elias and Eastern Chugach Mountains. Rock exhumation ages are marked in red and based on published results by Berger and Spotila (2008), Spotila and Berger (2010), Enkelmann et al. (2009, 2010), and O’Sullivan and Currie (1996). The blue line marks the surface elevation along the centerline of the glaciers. Notice that the rock exhumation ages are older along the northern side of the Bagley Ice Valley than along the southern side, and that this pattern also applies to the region of the Miles Glacier west of Mount Tom White. See Figure 2 for locations of major geographic features. Elevation data are from the ASTER GDEM global elevation model.

Figure 4. Earthquake epicenters (M > 1.5) and first motion focal mechanisms (M > 2.5) from Alaska Earthquake Information Center earthquake catalog (July 2005–June 2011, depth < 30 km). In the STEEP seismograph station network core area, best-located events (M ≥ 2) have errors on the order of 2–3 km or less. There are two major regions with high background seismicity; one in the Icy Bay/Malaspina region and the other west of Bering Glacier that have been observed over the last several decades, even prior to the 1979 Saint Elias earthquake. Double couple focal mechanisms contain two possible fault planes oriented normal to one another, of which one is the actual fault. Keeping this ambiguity in mind, there are mechanisms consistent with dextral shearing along or near the Art Lewis Glacier and Fairweather faults, at the eastern end of the Bagley fault in the upper Seward Glacier basin, along the western part of the Bagley fault, including one event near the intersection of the Bagley and Martin faults, and at the southwestern end of the Martin River fault. Focal mechanisms in the foreland of the orogen indicate a mixture of thrust and strike-slip fault motion, with only a few normal faulting events.
Plate margin deformation, Saint Elias Orogen

thermochronology data reveal that the pluton was uplifted and exhumed by several kilometers within the last 5 Ma to 10 Ma, during collision and accretion of the Yakutat terrane (Fig. 3; Berger et al., 2008b). Farther east the mountains along the southern side of the Bagley fault were also uplifted and exhumed during the last several million years, possibly by reverse faulting (Chapman et al., 2008; Berger and Spotila, 2008; Spotila and Berger, 2010; Enkelmann et al., 2010).

Geodetic data in the region of Figure 2 include trilateration (Savage and Lisowski, 1986, 1988), VLBI (very long baseline interferometry), and GPS campaign-style measurements (Sauber and Molnia, 2004) obtained between 1979 and 2000, and a regional network of GPS campaign-style measurements completed during the Saint Elias Erosion and Tectonics project in the period 2005–2009 (Elliott et al., 2007; Elliott, 2011). The results of the most recent study differ from earlier ones that postulated dextral shearing along or surrounding the Bagley fault in the Bagley Ice Valley (Savage and Lisowski, 1986; Sauber and Molnia, 2004). Elliott’s (2011) tectonic block model of the orogen requires no contemporary motion along the Bagley fault within the limits of resolution of several mm/yr, but it does place the northeastern boundary of a small Bagley Glacier tectonic block near the intersection between the Bering Glacier and Bagley fault. The Bering Glacier block is moving southwest relative to other parts of the orogen and relative to the newly defined Elias tectonic block that is located to the north and west of the Saint Elias Mountains. Although the conclusions of the various geodetic studies differ with respect to strike-slip motion on the Bagley fault, all identify active deformation near the intersection of the Bering Glacier and Bagley faults.

RESEARCH DATA AND PROCEDURES

Our research goal is to infer the role of the Bagley fault in accommodating deformation during collision and accretion of the Yakutat terrane. Given that glaciers blanket much of the landscape, we rely primarily upon remote sensing techniques that augment available data from published structural (e.g., Pfafker, 1987; Bruhn et al., 2004; Chapman et al., 2008) and thermochronology studies (O’Sullivan and Currie, 1996; Berger and Spotila, 2008; Berger et al., 2008a, 2008b; Enkelmann et al., 2009, 2010; Spotila and Berger, 2010; Meigs et al., 2008).

Elevation data for analysis of the topography was obtained from the Ice, Sea and Land Satellite (ICESat; Schutz, 2001; Schutz et al., 2005), Airborne Terrain Mapper (ATM; Krabill et al., 2002), Shuttle Radar Topographic Mission (SRTM; Farr and Kobrick, 2000; Rodriguez et al., 2005; Musket et al., 2003, 2008, 2009), and the Advanced Spaceborne Thermal Emission and Reflectance Spectrometer (ASTER) Global Digital Elevation Model (GDEM; ASTER GDEM Validation Team, 2009). Elevation posting is 30 m for the ASTER GDEM and SRTM data. A 10 m posted digital elevation model over the eastern Bagley Ice Valley and western part of the upper Seward Glacier by Intermap Technologies was the highest resolution DEM (Musket et al., 2009), and it is used to investigate the surface topography of the eastern Bagley Ice Valley.

Ice surface velocity was measured with offset tracking methods using both optical and synthetic aperture radar (SAR) data. Optical feature tracking was performed using normalized image cross correlation (COISI-CORR) software (Leprince et al., 2007) on pairs of Landsat images acquired over intervals of 1 month to several years (Cotton, 2011). SAR offset feature tracking was performed using normalized cross correlation (GAMMA Software [Strozzi et al., 2002]) on RADARSAT-1 Fine Beam, ALOS PALSAR Fine Beam, and ERS1/2 data over intervals of 24–45 days (Burgess et al., 2012).

Optical imagery from the KH-9 satellite, Landsat 7 and 5, and ASTER data were used to map rock type and structure in selected areas, as well as to map spatial patterns of crevasses and folds on glaciers. Ice and rock structures were visualized by draping optical imagery over digital elevation models. Orientations of tectonic faults and folds that project beneath glaciers were determined by three-point and linear least-squared calculations to determine strike and dip where field measurements were not available.

GLACIOLOGY AND STRUCTURE OF BAGLEY FAULT

The Eastern Syntaxis–Fairweather and Bagley Fault Interaction

The topography and structure of the orogen rises abruptly where the plate boundary bends from a regional strike of ~319° along the Fairweather fault to roughly east–west (270°) parallel to the Chugach–Saint Elias and Bagley faults (Fig. 2). This bend or “syntaxis” increases the ratio of convergence to strike-slip motion within the central part of the Saint Elias orogen relative to that along the Fairweather fault (e.g., see also fig. 7 of Sauber et al., 1993). The resulting increase in transpressional strain drives uplift of the mountains creating some of the highest peaks in North America. Understanding the structural geology of the syntaxis is crucial to our goal of evaluating the role of the Bagley fault in regional tectonics. The eastern end of the fault must interact with the Fairweather strike-slip fault that extends into the spine of the Saint Elias Mountains, and also with the underlying thrust faults that drive uplift of the range.

The syntaxis begins at a 10° counterclockwise bend in structural and topographic grain at Disenchantment Bay and culminates at the terminus of the Fairweather fault, where the mountains rotate an additional 30° toward the west into alignment with the Bagley and Chugach–Saint Elias faults (Fig. 5). The low-lying foreland beneath the Malaspina Glacier is thrust obliquely beneath the mountains along the Bancas–Esker Creek and Malaspina faults in this region (Bruhn et al., 2004; Pfafker and Thatcher, 2008; Chapman et al., 2012) and the Fairweather fault terminates by splaying beneath the upper Seward Glacier (Fig. 5; Ford et al., 2003). Most, if not all, of these faults ruptured during large to great magnitude earthquakes in the past 110 yr but the evidence is limited in some cases by the lack of instrumental records. Thrust faults formed parts of the seismic source zones of two Ms 8.1 earthquakes in 1899 (Pfafker and Thatcher, 2008). Rupturing along the length of the Fairweather fault in 1958 terminated to the north beneath the upper Seward Glacier, creating an Ms 7.9 earthquake (Tocher, 1960; McCann et al., 1980; Doser, 2010). The Ms 7.4 Saint Elias earthquake in 1979 initiated beneath the mountains north of the Bagley fault and ruptured up to the south and laterally toward the east before arresting along the northern side of the Bagley fault and near the terminus of the Fairweather fault (Estabrook et al., 1992).

Faults in Disenchantment Bay and Russell Fiord form a complex structural system (Fig. 5). The Fairweather fault is the primary plate boundary fault that accommodates much of the dextral relative plate motion. The Fairweather boundary fault is a subsidiary structure that parallels the Fairweather fault. The southeastern part of the Fairweather boundary fault outcrops in a stream cut where the fault dips steeply and sicken-lines indicate dextral shearing. The presence of the fault beneath the northern side of Russell Fiord is indicated by an abrupt increase in vertical uplift along the northeastern edge of the Fiord that occurred during the Ms 8.1 earthquake of September 10, 1899 (Tarr and Martin, 1912; Bruhn et al., 2004; Pfafker and Thatcher, 2008). The Yakutat and Bancas–Esker Creek faults do not crop out, but are inferred from dislocation modeling of shoreline uplift during the September 10, 1899 earthquake (Pfafker and Thatcher; 2008).

Bruhn et al. (2004) considered the Yakutat fault as a part of an asymmetrical or “one-sided”
flower structure that emanates from the side of the Fairweather fault because of transpressional deformation (Fig. 5). The Fairweather boundary fault may be truncated at depth by the Yakutat thrust fault as proposed by Bruhn et al. (2004). GPS displacements modeled by Elliott et al. (2010) suggest that the mountain block bounded by the Fairweather and Fairweather boundary faults is a transpressional sliver, which is also consistent with the interpretation of the structural geology. The Hubbard Glacier thrust crops out along the mountain front where the Hubbard Glacier enters Disenchantment Bay, and the Art Lewis Glacier fault splays off the northeastern side of the Fairweather fault and extends beneath the Art Lewis Glacier into the mountains north of Mount Vancouver (Fig. 5). Evidence for contemporary activity on the Art Lewis Glacier fault consists of two earthquake focal mechanisms that indicate dextral shearing parallel to the trace of the fault (Fig. 4). We do not know if the Hubbard Glacier thrust is currently active.

The uplifted shorelines surrounding Disenchantment Bay and Russell Fiord, together with an abrupt right-handed jog of the mountain front where the Fairweather fault extends beneath the terminus of the Valerie Glacier, reflects cumulative displacement on the Fairweather fault during the last ca. 100 ka given slip rate estimates between 43 mm/yr and 50 mm/yr (Fig. 6; Elliott et al., 2010; Plafker et al., 1978). This amount of displacement is ~1 km less than the lateral offset and deflection of a stream channel along the Fairweather fault just south of the Hubbard Glacier, suggesting that some of Fairweather fault displacement is transferred onto the Fairweather

Figure 5. Shaded relief image viewed toward the west of the structural syntaxis formed at the transition from dominantly strike-slip to intense transpression along the plate boundary in the central segment of the orogen. This transition is marked by two bends in the plate boundary. The boundary first bends ~10° westward at Disenchantment Bay where the terrain rises abruptly to the west. The second and more prominent bend is located beneath the upper Seward Glacier where the plate boundary rotates an additional 25° westward parallel to the Chugach–Saint Elias and Bagley faults. The shaded relief image is created from the ASTER Global Digital Elevation Model (GDEM). Refer to Figure 2 for locations of major geographic and structural features depicted in this scene.
boundary and Bancas–Esker Creek faults within the syntaxis.

The Fairweather fault is marked by several significant structural and geomorphic features where it enters the syntaxis and cuts through the mountains into the basin of the upper Seward Glacier. These include: (1) A 2.5-km-long south-facing cliff where the Fairweather fault extends beneath the terminus of the Valerie Glacier (Fig. 6). The height of the cliff increases northward from a south-facing monocline on the surface of the Hubbard Glacier to a steep south-facing icefall on the lowermost Valerie Glacier that is up to 200 m high (Fig. 6). (2) The northeast-dipping thrust fault that crosses the mouth of the Hubbard Glacier presumably represents crustal contraction created by transpression east of the Fairweather fault. This thrust may emanate off the southern side of the Art Lewis Glacier fault forming a one-sided flower structure. There is no geological evidence to demonstrate that the fault is active, but it does form a prominent monoclinic flexure on the surface of the ice where it crosses beneath the Hubbard Glacier, and there is a band of enhanced seismicity beneath the mountains that form its hanging wall (Fig. 4). (3) The Valerie Glacier trough necks down in width between an elevation of 970 m and 1830 m where the Fairweather fault rotates several degrees counterclockwise between two restraining bends (Fig. 5; Supplemental Fig. 1). Narrowing of the trough is caused by enhanced contraction because of the greater misalignment of the fault with respect to plate motion. The dome of bedrock that protrudes into the fault zone at 1830 m is then a transpressional “pop-up” structure. (4) The Fairweather fault extends through the mountain pass at the head of the Valerie Glacier and into a west-plunging glacial trough before terminating beneath the upper Seward Glacier. The fault termination is marked by a northwest-trending splay fault that extends toward the southern flank of Mount Logan (Ford et al., 2003) and by the Cascade Glacier thrust fault that lies beneath the outlet valley of the lower Seward Glacier (Fig. 5).

The Fairweather and Bagley Faults beneath the Upper Seward Glacier

Geological information concerning the structural geology of this region relies on mapping of outcrops in the surrounding mountains and the nunataks that lie within the basin of the upper Seward Glacier (Campbell and Dodds, 1982; Richter et al., 2005). However, much of the deformed terrain lies beneath glaciers that occupy alpine basins and valleys. Herein we attempt to locate geologic structures that lie beneath the glaciers based upon theoretical concepts and experimental observations that predict how ice flow on the surface of a glacier is perturbed by the topography and rheology at its base (Gudmundsson, 2003; Bruhn et al., 2004).

The directions of the glacier velocity field determined by optical feature tracking of Landsat V scenes acquired 1 yr apart (Fig. 7) are similar to those reported by Ford et al. (2003) who
Figure 7. (A) Velocity of ice flow measured on the surface of the upper Seward Glacier by optical tracking of offset features using two Landsat images acquired 1 yr apart. The small arrows indicate direction and velocity of ice flow at points on a grid where the optical tracking algorithm is able to resolve displacement on the surface of the glacier. The thick blue lines with arrowheads represent generalized direction of flow in various parts of the basin summarized from the underlying optical tracking vectors. A subtle topographic welt or rise affects flow near the center of the glacier (7B). (B) Close-up of the ice velocity field shown in A (dashed rectangle) focusing on the areas surrounding the ice-covered ridge of bedrock that affects ice flow in the western part of the basin (also see Supplemental Figs. 2 and 3 [see footnotes 2 and 3], which show more details of deformed moraine bands and crevasses and several topographic profiles across the glacier’s basin).
used 24 hr repeat-pass SAR scenes and interferometry techniques (InSAR). The velocity magnitudes obtained by optical feature tracking are significantly larger, however, than those reported by Ford et al. (2003); we hypothesize that the higher rate is due to a glacier surge during the period of Landsat scene acquisition in 1986–1987 (Muskett et al., 2008). The surging state of the Seward Glacier caused large changes in flow speeds; flow direction, however, was not affected significantly.

West of the Fairweather fault ice flow velocities in the southern part of the upper Seward Glacier are 100 m/yr to 400 m/yr and significantly faster than in the northern part, where the flow is generally less than 100 m/yr. Rapid ice flow along the southern side of the basin deforms rock debris that originates from cirque glaciers and rock slides into tightly curved and narrow moraine bands that point downslope to glaciers and rock slides into tightly curved and narrow moraine bands that point downslope to the east (Supplemental Figure 2). Moraine bands of higher shear strain rate are bounded on one or more sides by reverse-oblique strike-slip faults (Currie, 1996). Alternatively, the glacier may flow above the outcrop of the reverse-oblique slip fault that was activated during the M_{ws} 7.4 St. Elias earthquake in 1979, an idea that we explore further.

The St. Elias earthquake initiated on a gently west-northwest–dipping thrust fault (Fig. 8, fault 1a) at a depth of ~22.4 (±3) km beneath the mountains north of the eastern Bagley Ice Valley (Estabrook et al., 1992). The rupture then propagated updip and to the east, initiating slip at a depth of roughly 26 (±3) km on a dextral-oblique slip fault located beneath Mount Logan (Fig. 8, fault 1b). Rupturing terminated updip along the north side of the Bagley fault and immediately west of the terminus of the Fairweather fault. The fault map in Figure 8 is constructed by locating the hypocenters and using fault plane orientations preferred by Estabrook et al. (table 3, 1992), with the fault surfaces extended upwards to intersect beneath the upper Seward Glacier. Variability in the dip angles and directions of the faults are noted on the figure based on estimates of uncertainty in the earthquake source parameters. We speculate that a third fault (fault surface 1c) links the earthquake source faults 1a and 1b in the subsurface. Key features include: (1) Faults 1a and 1b intersect at a depth of several kilometers near the ice flow divide that separates the Seward Glacier and Bagley Ice Valley. Fault surface 1a is part of the regional décollement or plate boundary megathrust (Estabrook et al., 1992) and presumably continues updip as part of the Malaspina and perhaps Bancas–Esker Creek faults. (2) Fault 1b abuts the terminus of the Fairweather fault, providing a structural linkage with the décollement (fault 1a) to the west as originally proposed by Estabrook et al. (1992). (3) Reactivation of uplift and exhumation at Mount Logan (O’Sullivan et al., 1996) may be driven by reverse motion on faults 1b and/or 1c, which dip northward as “flower-structure” faults that emanate from the side of the Art Lewis Glacier strike-slip fault zone (Figs. 2 and 5).

The Bagley Fault within the Bagley Ice Valley

The Bagley Ice Valley is divided into eastern and western arms that meet in a topographic saddle above the Bering piedmont lobe and the Tana Glacier (Figs. 2 and 3). West of the Tana Glacier the northern flank of the ice valley has undergone younger uplift and exhumation than in the region to the east, and the spatial pattern of exhumation ages suggests that the structure is characterized by uplifted mountain blocks that are bounded on one or more sides by reverse faults (Spotila and Berger, 2010; Berger et al., 2008b). To the west of the Bering piedmont lobe and Tana Glacier outliers the region is also marked by frequent earthquakes with a mixture of reverse and strike-slip focal mechanisms (Fig. 4; Doser et al., 2007).

Geology of the ice valley flanks.

Mountains that flank the Bagley Ice Valley contain crystalline and sedimentary rocks that were incorporated into the plate margin of southern Alaska prior to collision of the Yakutat microplate (Fig. 9; Pfafker, 1987; Pfafker et al., 1994; Gasser et al., 2011). These rocks were metamorphosed ca. 50 Ma, and subsequently thrust over the Yakutat margin deformation, Saint Elias Orogen

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Footnote 1: Supplemental Figure 2. PDF file of supplement for Figure 7. Binary black and white segmentation image of a Landsat scene showing ice crevassing and flow-deformed traces of moraine on the surface of the upper Seward Glacier. Note en echelon crevasses along the southern flank of the ice-covered ridge of bedrock that is outlined in the dashed brown polygon. Red polygons are outcrops of bedrock that poke through the snow and ice on the southern and northern flanks of the basin. The image is derived from a Landsat scene with bedrock mapped by band 7. The binary black and white image is constructed by segmentation of a false color composite image created with bands 7,4,1. Refer to Figure 7 for location of the image by comparing geographic features listed in each figure. The location of the figure is also indicated in Universal Transverse Mercator (UTM) coordinates that are marked around its borders. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00807.S2 or the full-text article online at www.gsapubs.org to view Supplemental Figure 2.

Footnote 2: Supplemental Figure 3. PDF file of supplement for Figure 7. Three topographic profiles across the basin of the upper Seward Glacier extracted from ICESat laser profiling tracks. Track locations are shown in the satellite image in the upper right corner of the figure, with the profiles marked in black on each track. The tracks are also marked and labeled by number on Figure 7. The location of a high-resolution laser data swath obtained by aircraft (ATM) that was used to verify features observed in Supplemental Figure 2 (see footnote 2) is marked in purple. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00807.S3 or the full-text article online at www.gsapubs.org to view Supplemental Figure 3.
Terrane along the Chugach–Saint Elias fault (Figs. 1 and 2). The shallow southern edge of the Chugach–Saint Elias fault was subsequently uplifted and deformed as the Yakutat Terrane continued to accrete and deform into a broad foreland fold and thrust belt in the last 10 Ma to 20 Ma. The uppermost part of the Chugach–Saint Elias fault that underlies the mountains immediately south of the Bagley Ice Valley is probably now an inactive imbricate fault that is truncated at depth by the basal décollement of the foreland thrust belt (megathrust) and perhaps by reverse displacement along the southern side of the Bagley fault (Chapman et al., 2008; Pavlis et al., 2012).

The Bagley fault dips steeply where it cuts through the hanging wall of the Chugach–Saint Elias fault (Campbell et al., 1986), presumably penetrates the deeper-seated part of the underthrust Yakutat Terrane, and abuts the décollement that marks the subduction megathrust within the Yakutat lithosphere (e.g., Chapman et al., 2008; Meigs et al., 2008; Wallace, 2008; Pavlis et al., 2012). The structural configuration of the Bagley fault and underlying subduction thrust is ideal for partitioning oblique plate convergence into strike-slip and thrust-type displacement (e.g., Haq and Davis, 2010). Structural studies of foreland thrust kinematics by Bruhn et al. (2004) demonstrated that slip along the Chugach–Saint Elias fault and east-trending foreland thrusts was dominantly thrust motion with little or no strike-slip motion. This result suggested that dextral shearing was possibly focused along the Bagley fault.

The steep slopes along the southern flank of the Bagley Ice Valley may reflect tectonic uplift that is keeping pace with erosion of the ice valley wall. Topographic relief of the mountains on both sides of the eastern Bagley Ice Valley generally decreases to the west from Mount Logan and Mount Saint Elias, but the southern range flank is generally steeper and higher than the northern flank, consistent with thermochronology data that indicate more rapid rock uplift.

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**Figure 8.** Shaded relief map of the Saint Elias Mountains showing the mapped projections of faults 1a and 1b that ruptured during the Mw 7.4 Saint Elias earthquake in 1979 (Estabrook et al., 1992). The main shock of the Saint Elias earthquake nucleated at the large red star in the northwest corner of fault 1a and the fault then ruptured updip toward the Bagley fault and along strike to the east, where rupturing then spread onto fault surface 1b. The aftershock zone of the 1979 earthquake spread southward from beneath the main range into the foreland beneath the Malaspina Glacier and Icy Bay (shaded orange polygon). Fault 1b projects upwards toward the east-west–trending mid-basin ridge of bedrock that affects ice flow and is marked by the light brown polygon within the western part of the Seward Glacier Basin in Figure 7.
rate with greater exhumation of the southern mountain range (Figs. 10C-1 and 10D-1; Berger and Spotila, 2008; Berger et al., 2008b; Enkelmann et al., 2010). Steepness of the mountain flanks above the ice valley is expressed as the average slope index (R/W), which is the ratio of mountain flank relief above the glacier (R) to mountain flank width (W) in Figure 10 (C-2 and D-2). The steeper slopes along the southern range flanks do not correlate with erosional resistance related to rock composition because the rocks along the northern flanks of the ice valley are of equal, and in most areas higher, metamorphic grade than those on the southern flank. The azimuth or “aspect” of the flanks is also poorly correlated with slope angle based on inspection of the topography of other range fronts throughout the region.

Small cirque basins that are elongated north to north-northeast embay the southern flanks of the ice valley (Fig. 9). The geometry of the basins is partly if not wholly controlled by the structure of the underlying rock, which is characterized by east-trending folds that are overturned toward the south, and cut by large fracture or “joint zones” that dip steeply and strike north-northeast across the fold axes (Supplemental Figure 4). Failure along planar discontinuities in the rock mass created by the structural geology creates rockslides that cascade northwards down the mountain front and onto the glaciers below (Huggel, 2009). This leads to cirque basins that are elongated and point slightly up the topographic slope of the trunk valley glacier instead of normal or downslope as might be expected without a strong control of erosion by rock structure.

Three linear mountain front segments that are offset by right-handed jogs at the Quintino Sella and Jefferies glaciers form the northern margin of the eastern Bagley Ice Valley (Fig. 9). The ice valley widens from ~5 km to 7.5 km on either side of the Quintino Sella Glacier, and then to ~10 km below the Jefferies Glacier. The increased ice flux at the Quintino and Jefferies glaciers must enhance erosion along the northern mountain flank, causing the valley to widen below each tributary glacier. However, the linear
mountain fronts and right-handed jogs are also characteristic of dextral strike-slip fault systems, where the jogs mark pull-apart basins (Aydin and Nur, 1982). The ice valley is significantly narrower west of the Tana and Bering Glacier piedmont lobe outlets, where the northern edge of the ice valley steps left several kilometers between the eastern and western arms. A left-stepping jog in a dextral fault system is contractual, which fits the structural map prepared by Berger and Spotila (2008) and Berger et al. (2008b) to account for the younger exhumation ages obtained from the mountain block located on the western side of the Tana Glacier (see Figs. 2 and 3). One other piece of circumstantial evidence supports the dextral fault interpretation: Several NW-trending glaciated valleys are located within the mountain block between the Jeffries and Tana glaciers (Fig. 9). The longitudinal axis of each valley projects out of the mountain front up and over the Bagley Ice Valley as though the head of each valley is truncated by faulting.

The glacier in the eastern Bagley Ice Valley. The topography and dynamics of the glacier in the eastern arm of the Bagley Ice Valley is evaluated using the STAR3i DEM (Fig. 11), speckle tracking of SAR images (Fig. 12), and ICESat topographic profiles (Fig. 13). The glacier slopes 1° west between its head and the topographic saddle where the eastern and western arms of the Bagley Ice Valley join together (Figs. 2 and 3). The thickness of the ice is 800 m to 1000 m thick in the Bering–Tana region and most of the base of the Bering Glacier piedmont lobe is near sea-level elevation (Molnia and Post, 1995; Conway et al., 2009).

Both persistent and transient features mark the surface of the glacier in the eastern Bagley Ice Valley. Transient topographic features include circular to elliptical hillocks and depressions above migrating englacial fluids, and “kinematic waves” that propagate along the length of the glacier in response to variations in ice flux (e.g., Lingle et al., 1997; Lingle and Fatland, 2003; Fatland and Lingle, 2002). These transient features are related to ice dynamics and not necessarily direct consequences of bed topography. Here, we focus on persistent features that reflect ice flow over and around undulations at the base of the glacier. These features persist over decades and are observed on images acquired by different sensors and on elevation models and maps constructed by different techniques.

North to north-northeast–trending ridges and troughs are the most prominent features on the surface of the glacier (Fig. 11A). The topographic relief between ridges and troughs is on the order of several tens of meters, and crest-to-crest spacing varies from roughly 1 km to 10 km (Fig. 11B). The ridge crests are curved or sigmoidal in shape, several kilometers long, and appear to be laterally offset at several localities (Fig. 11C). Glacier strain rates determined from the ice surface velocity field in Figure 12A also show coincident north-northeast–oriented bands of longitudinal contraction downstream of the Jeffries confluence (Fig. 12B), a strain-rate pattern that is expected where ice slows on the upslope side of a basal ridge and then accelerates over the downslope side of the ridge (e.g., Reeh, 1987; Gudmundsson, 2003). The west-northwest–facing monocline that extends across the glacier in the eastern arm of the Bagley Ice Valley from just below the mouth of the Jeffries Glacier to near the head of the Bering Glacier is exceptional because of its continuity and relatively linear crest (Fig. 11A). These ridges and troughs are relatively stationary in location and persist over decades, thus implying irregular topography at the base of the glacier (Reeh, 1987). The boundary between left-lateral (Fig. 12C, red pattern) and right-lateral (blue pattern) shear is also of interest. Rather than occurring within the center of the glacier, the boundary between the two dextral and sinistral shear strain zones extends along the southern side of the glacier in the eastern ice valley, where the glacier is presumably flowing along an asymmetric valley that is deepest along its southern margin.

Additional information concerning the morphology of the ice valley is provided by the dynamics of ice flow depicted in Figure 12. The Quintino Sella Glacier flows into the ice valley as the primary ice stream, suggesting that the uppermost section of the Bagley Ice Valley is a hanging valley, forming a subsidiary rather than a main trunk glacier flow channel. However, above the confluence, the shear strain rate boundary between left and right lateral shearing remains along the southern side of the ice valley, similar to the situation on the Bagley Glacier below the confluence. Below the confluence with the Jeffries Glacier, the rate of rapid ice flow is also concentrated along the southern side of the ice valley and is then deflected primarily into the head of the Bering piedmont lobe, rather than Tana Glacier. Southward curvature of the main trunk channel into the Bering Glacier piedmont lobe may reflect deeper erosion along the major fault that lies beneath the top of the Bering Glacier piedmont lobe and the intersection with the Bagley fault (Fig. 2). Uplift of the mountains and the eastward slope of the western arm of the Bagley Ice Valley presumably reflect movement on the Bering Glacier fault and also crustal contraction at the left-stepping jog in the northern wall of the Bagley Ice Valley, which occurs across the head of the Tana Glacier. Continuing deformation beneath the western Bagley Ice Valley and surrounding mountains is indicated by a cluster of intense crustal seismicity (Doser et al., 2007), and also by geodetic data which indicates active deformation in this region (Savage and Lisowski, 1986, 1988; Sauber and Molnia, 2004; Elliott, 2011).

Additional details concerning the elevation of the glacier’s surface were provided by ICESat profiles that cross the eastern Bagley Ice Valley between its upper section and the Tana and Berg glaciers (Fig. 13). There is a broad rise or “bulge” in the ice along the southern side of the glacier in the central area between Mount Saint Elias and Mount Miller, which is not present on ICESat profiles that cross both higher and lower sections of the valley. The bulge may simply reflect additional snow and ice accumulation along the southern edge of the glacier where the mountain crest is lower between Mount Saint Elias and Mount Miller, providing a pathway for storms to move over the ice valley (Figs. 2 and 3). However, the bulge is also located where the tectonic highland that is capped by the Guyot and Yathise glaciers extends beneath and warps the Chugach–Saint Elias fault upwards (Fig. 13).
Figure 10. (A) Perspective view of the eastern Bagley Ice Valley and Seward Glacier basin created by draping a false-color Landsat scene (bands 5,4,1) over the ASTER GDEM. (B) Schematic illustration of the mountainside relief (R) to width (W) geomorphic index, and symbols for thermochronology dates summarized by Enkelmann et al. (2010). The colored symbols indicate the age at which bedrock samples passed below the thermal closing temperature (Tc) for apatite and zircon. Approximate closing temperatures associated with various minerals and methods are: (1) apatite - ap He (U-Th/He) = 60 °C, (2) apatite fission track (ap FT) = 110 °C, and (3) zircon fission track (Zr FT) = 250 °C. (C) and (D) Plots of the ridge-line topography on the north (C-1) and south (D-1) sides of the eastern Bagley Ice Valley, with associated plots of the geometric ratio R/W for each mountainside (C-2, D-2), respectively. The surface of the glacier is shown as a blue line on both C-1 and D-1 plots. Locations of bedrock samples collected for thermochronology analyses are indicated on profiles in C-1 and D-1, with the age color coded as indicated in B.
DISCUSSION

The structure and tectonics of the collisional plate boundary is discussed proceeding from the syntaxis in the east to the terminus of the Bagley fault in the west. This format allows us to begin by describing the terminus of the Fairweather fault, where plate motion is best constrained by both geologic (Plafker et al., 1978; Plafker and Thatcher, 2008) and geodetic data (Elliott et al., 2010). The structural geology of the syntaxis surrounding the Fairweather fault also provides insight into how deformation was transferred onto the Bagley fault and the underlying mega-thrust. We subsequently focus on the role of the Bagley fault in accommodating plate boundary motion throughout the history of terrane accretion, followed by a discussion of the seismic potential of the Bagley fault.

Structural Geology of Seward Glacier Basin

Surprisingly, the most rapid upward advective and exhumation of deeply seated rock (rates up ~7 mm/yr) is located beneath the upper Seward Glacier rather than in the surrounding mountains where the exhumation rates are significantly less (~4 mm/yr) (Enkelmann et al., 2009). Dilatational strain and splay faulting at the terminus of the Fairweather fault may play an important role in tectonic exhumation by providing a local zone of extension into which rocks are forced by thrust faulting and transpressional strain at depth (Fig. 7; Ford et al., 2003). Consider a conceptual experiment, where one squeezes a tube of paste (Bancas–Esker Creek and Malaspina thrust faults driving mechanism—Figs. 5 and 7) and removes the lid from the tube (i.e., the Fairweather extensional splay fault). The paste flows rapidly upwards and out of the tube upon removing the cap. In the case of the upper Seward Glacier, broad tectonic upwelling driven by transpression and thrust faulting at depth creates the topographic welt encircled by 5000+ m alpine peaks, but the center of the welt is tectonically denuded by crustal dilatation at the end of the Fairweather fault. This process creates the “tectonic aneurysm” (Koons, 1995) where upwelling rock is eroded as quickly as it arrives at the base of the upper Seward Glacier. Subglacial rivers that extend beneath the lower Seward and Malaspina glaciers transport the detritus out of the alpine basin.
The geometry of the splay fault within the Seward Glacier's basin is consistent with fault growth into a lobe of dilatational strain that develops adjacent to the tip of a strike-slip fault, or "mode II" shear crack in the parlance of fracture mechanics theory (e.g., Pollard and Segall, 1987). Extensional splay faults or "wing cracks" propagate outward at 70° from the surface of the primary strike-slip fault; the fault in the Seward Glacier basin splays at an angle of ~60°, consistent with dextral-oblique normal slip in the more complex natural strain field that must exist within the transpressional syntaxis (e.g., Koons et al., 2010). We also expect to find a zone of intensified contraction along the southern side of the Fairweather fault where the lower Seward Glacier descends the southern range front.

The persistence of the relatively narrow valley of the lower Seward Glacier is puzzling to glaciologists given that the ice flows into the outlet valley at a rate in excess of several hundred m/yr during surging (Fig. 7; Headley et al., 2007). Competition between contraction of the outlet valley by reactivation of the Cascade Glacier fault and widening of the valley by glacier erosion may account for the relatively narrow width given rapid glacier flow which must widen the valley by several millimeters to possibly more than 1 cm each year (e.g., Hallet, 1979; Headley et al., 2007; Headley et al., 2008; Headley and Enkelmann, 2009). Displacement along the Cascade Glacier fault may constrict the upper part of the outlet valley because it is preferentially oriented for reactivation by thrust faulting within the contractional strain lobe at the Fairweather fault's terminus (Figs. 5 and 7). This process may be limited to the upper reaches of the glacier valley where the thrust fault is located. At lower elevation the Chaix Hills and Dome Pass thrust faults extend across the valley of the lower Seward Glacier and are not truncated by younger faulting.

The late stage uplift and exhumation of Mount Logan within the last 5 Ma presents a fundamental problem when attempting to understand the structural geology of the eastern syntaxis (O’Sullivan and Currie, 1996; Spotila and Berger, 2010). Geodynamic modeling by Hooks (2009) and Koons et al. (2010) implies a south-dipping reverse fault or shear zone may lie beneath the northern side of the Saint Elias Mountains. However, this type of structure has not been mapped (Campbell and Dodds, 1982).

Alternatively, the uplift of Mount Logan may be driven by displacement on faults 1b and/or 1c (Fig. 8) that dip to the northeast and splay off of the Art Lewis Glacier strike-slip fault. The Art Lewis Glacier fault occupies a linear ice-filled valley that branches off of the Fairweather fault and extends around the northeastern sides of Mount Vancouver and projects toward the northern side of the Mount Logan massif (Figs. 2 and 3).
Evidence for Strike-Slip Faulting in the Bagley Ice Valley

Our interpretations of faulting beneath the eastern arm of the Bagley Ice Valley are based on several observations.

1. Topographic features at a glacier’s base perturb the surface of the ice where they appear as “muted” undulations that persist over time (Fowler, 1982; Gudmundsson, 2003). The surface undulations may change in wavelength and amplitude and shift laterally by a limited amount because of temporal fluctuations in ice velocity, but the features persist on the surface of the glacier over decades.

2. Valley glaciers erode the bedrock into a repetitive series of steep down-glacier-facing steps (cliffs) that are separated by longer tracts of abraded and till-mantled bedrock that slope gently either down or up-valley, e.g., large-scale “roche moutonnee” landforms in glaciated terrain (Fig. 14A; Hooke, 1991). Cliffs are created by ice plucking out the bedrock as it flows downslope, and the intervening treads are created where the debris-laden ice abrades the underlying bedrock. When this “step and tread” topography is offset by strike-slip faulting at the base of the glacier, the surface of the glacier will develop low-amplitude ridges and swales that are aligned along their axes (Figs. 14B and 14C).

3. Large strike-slip fault zones are characterized by distinctive patterns of subsidiary faulting and related topography (Tchalenko, 1970). Pull-apart basins and thrust-faulted ridges form at jogs and bends within the fault zone, and subsidiary strike-slip faults are inclined to the regional boundaries of the fault zone (Tchalenko, 1970). These subsidiary faults are clearly displayed in arid landscapes where rates of tectonic activity outpace erosion, but beneath temperate glaciers the smaller-scale features may be quickly removed by erosion, or mantled by till. Pull-apart basins and large thrust-faulted ridges that form at jogs and bends in a strike-slip fault system persist because of greater original topographic relief compared to lower-relief features developed by lateral displacement along strike-slip faults.

Features that may be partly preserved structures associated with dextral faulting along the northern edge of the Bagley Glacier include pull-apart depressions at the right-stepping jogs where the Quintino Sella and Jefferies glaciers enter the ice valley. Contractional jogs and bends occur (1) where the northern margin of the Bagley Ice Valley steps several kilometers south (left-handed step) across the head of the Tana Glacier, and (2) where the Bagley and Martin River Glacier faults join in a restraining fault bend (Fig. 2). Some dextral shearing along the Bagley Fault extends at least 40 km west of this latter restraining bend, where the fault lies beneath the linear Miles Glacier. The 4 km offset of the mountain front where the Miles Glacier enters the Copper River indicates dextral shearing, and the pattern of rock exhumation ages reflects uplift along the southern side of the fault (e.g., Berger et al., 2008a, 2008b).

We interpret the low-amplitude sigmoidal ridges on the surface of the glacier in the eastern arm of the Bagley Ice Valley as a subdued topographic expression of dextrally faulted “step and tread glacier valley” topography at the base of the glacier (Figs. 11 and 14). The sigmoidal shape of the ridges reflects erosional smoothing of the bedrock and possibly clockwise rotation of the faulted blocks in the dextral shear zone. Longitudinal ice strain rates derived from ice flow velocity data confirm the presence of north-northeast elongated ridges at the glacier’s base (Fig. 12B). The large northwest-facing monocline flexure on the surface of the glacier located just below the inlet of the Jefferies tributary glacier may reflect the presence of a large

Figure 13. Topographic profiles across the eastern Bagley Ice Valley extracted from ICESat tracks (A) 1279 and (B) 416 (see Fig. 9 for locations). Note higher terrain on the southern part of the glacier.

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reverse-fault cored fold that trends obliquely across the dextral shear zone at the base of the Bagley Ice Valley.

Uplift along the southern side of the Bagley fault is required during the last several Ma based upon the results of regional thermochronology studies that indicate much younger uplift and exhumation along the southern sides of the fault zone between Mount Saint Elias and the Bering Glacier, and also along the southern side of the Miles Glacier (e.g., Berger and Spotila, 2008; Berger et al., 2008a, 2008b; Spotila and Berger, 2010). The region between the western Bagley Ice Valley and Martin River fault system has been uplifted and exhumed over a broader area, including the mountains on both the northern and southern side of the Bagley fault. Hypotheses concerning the structure responsible for uplift of the southern mountain flanks include a south-dipping reverse fault (Berger and Spotila, 2008; Chapman et al., 2008; Wallace, 2008), up-warping of the mountains where active east-northeast–trending foreland thrust faults project beneath the mountains along the southern edge of the Bagley Ice Valley (Enkelmann et al., 2010), and uplift and “back-rotation” of the entire mountain block above a north-dipping fault ramp that connects foreland thrusts to the subduction zone beneath southern Alaska (Pavlis et al., 2012).

Although our work on the Bagley fault and the geomorphology of its mountain flanks does not distinguish between the various hypotheses for uplift along the southern side of the Bagley Ice Valley, we note that the southern flank of the eastern ice valley is steep and embayed by a number of small cirque basins. This suggests that the southern flank is rejuvenated by tectonic activity rather than an old mountain front that is worn down by erosion. The most likely locus of reverse faulting is along the southern side of the Seward Glacier basin and eastern Bagley Ice Valley, where the glaciers flow most rapidly leading us to infer the presence of a linear fault strand at depth. In this scenario, Pliocene and younger deformation is partitioned between dextral shearing beneath the central and northern edge of the ice valley, and uplift by reverse faulting along the southern edge. We postulate that the more complex pattern of deformation and uplift surrounding the western part of the Bagley fault is related to (1) the intersection of the Bering Glacier fault, (2) crustal contraction and “pop-up” mountain blocks created by the left-stepping fault jog in the northern wall where the Tana Glacier exits the ice valley (Berger et al., 2008b), and (3) the restraining bend formed where the Bagley and Martin River Glacier faults meet (Fig. 2). This region is also one of the most seismically active areas within the Saint Elias orogen, which is consistent with this conclusion (Fig. 4; Doser et al., 2007).

Role of Bagley Fault in Plate Boundary Deformation

Our analysis of remote sensing and geological data provides a better foundation for integrating the Bagley fault into the tectonic framework of the Saint Elias orogen. Structurally, the configuration of the plate boundary created by the foreland fold and thrust belt and the Bagley fault is

Figure 14. (A) Sketch of the step and tread topography that evolves by erosion at the base of valley glaciers (Hooke, 1991). (B) Illustration of offset in the step and tread topography caused by dextral strike-slip faulting. (C) Map view of part of the shaded relief image of residual topography on the surface of the lower Bagley Ice Valley in Figure 9. Note sigmoidal-shaped ridges on the surface of the glacier that may be caused by dextral shearing of bedrock beneath the ice. The illumination angle is from an azimuth of 150° and elevation of 20°. Northwest facing slopes are darker and southeast facing slopes are brighter grayscale.
ideal to partition oblique plate convergence into thrust and strike-slip motion (Bruhn et al., 2004; Haq and Davis, 2010). Bruhn et al. (2004) specifically searched for evidence of oblique thrust faulting versus plate boundary slip-partitioning during their structural study of the Chugach–Saint Elias fault and east-trending foreland thrust faults in the central part of the Saint Elias orogen. They concluded that the requisite strike-slip motion was accommodated along the Bagley fault rather than by oblique thrust faulting (they used old Contact fault terminology) prior to the progressive eastward steps of the mega-thrust décollement from the Kayak Island zone to the eastern Pamplona zone and Malaspina fault from the Late Miocene to Late Pleistocene (Worthington et al., 2010). However, the Bagley fault remained active since the Pliocene (e.g., Berger and Spotila, 2008; Chapman et al., 2008; Spotila and Berger, 2010), although vertical motion may have become most important as the leading edge of subduction migrated ~200 km eastward (e.g., Bruhn et al., 2004; Worthington et al., 2010). Doser et al. (2007) speculate that a linear south-dipping band of earthquakes beneath the mountains on the south side of the Bagley Ice Valley may mark the reverse fault first proposed by Berger et al. (2008a).

Cumulative strike-slip motion along the Bagley fault is difficult to resolve because there are no unambiguous piercing points to match on either side of the fault zone. Restoring the sliver of the relict plate boundary preserved at Ragged Mountain back to a location near the head of the Martin River Glacier requires roughly 50 km of dextral shearing along the Martin River and Bagley faults (Fig. 15). This restoration follows the tectonic displacement pattern suggested by Bruhn et al. (2004) and Pavlis et al. (2004) for

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**Figure 15.** Landsat V false-color image of the west-central and western part of the Saint Elias orogen showing part of the foreland fold and thrust belt east of the Bering Glacier, and the multiple-phase deformed region of tectonic accretion and extrusion in the structural syntaxis west of the Bering Glacier. The red two dashed rectangles enclose remnants of NW-trending valleys that may have once been continuous across the Bagley fault. Restoration of the valleys by removing 50 km of dextral slip along the Bagley fault is illustrated in the lower right part of the figure with each valley marked by a dashed line with the arrowhead pointing down-valley. The prominent peak of Mount Tom White rises abruptly from the restraining bend where the Bagley fault links to the Martin River Glacier fault. Bering Glacier fault is marked in red.
deformation by tectonic extrusion and indentation in the region west of the Bering Glacier. It is interesting, albeit speculative, to note that this restoration aligns the several northwest-trending glacier-filled valleys in the mountains along the southeastern side of the Steller Glacier with the “headless” valleys located on the northern side of the Bagley Ice Valley between the Jefferies and Tana glaciers (Fig. 15, inset image). This restored valley alignment could simply be fortuitous given that glaciation can reset the landscape within a period of a few hundred thousand years, but it is not outrageous given the long and protracted history of oblique convergence along the plate boundary (Pfafker et al., 1994).

The cause of the progressive eastward steps in the megathrust décollement remains speculative, but the timing coincides with an increase in oblique transpression along the transform plate boundary created by an ~20° clockwise rotation of relative motion between the Pacific and North America plates. The ratio of crustal shortening to dextral shearing increased within the orogen at that time, which would have inhibited lateral motion and enhanced vertical motion along the Bagley fault. The proposed decrease in the rate of lateral shearing together with initiation of reverse slip on the Bagley fault following plate motion reorganization ca. 5 Ma is certainly consistent with plate margin structures and displacements inferred from geodynamic models of “fore-arc slivers” presented by Haq and Davis (2010).

This change in fault behavior may be captured by the thermochronology data, which indicates young uplift and rock exhumation along the southern side of the Bagley fault (Berger et al., 2008a; Chapman et al., 2008), although the authors of those studies prefer a model in which glacial erosion on the windward side of the mountain range triggered “back-thrusting” along the Bagley fault. The structural style and exhumation history (e.g., Enkelmann et al., 2009) of the region surrounding the upper Seward Glacier is broadly consistent with geodynamic models of tectonic aneurysms developed in general by Koons (1995) and Koons et al. (2010), and for the Saint Elias origin specifically (Koons et al., 2010). That is, tectonic upwelling to create high topography and rapid exhumation of rocks is a fundamental physical response of deformation in a tectonic “corner” like that formed where the plate boundary develops a cusp. In the case of the Yakutat microplate the spatial variations in the thickness of the underthrust crust may also be in play (Worthington et al., 2012). The crust of the microplate thickens to the south-east, which in turn increases the buoyancy of the microplate approaching the syntaxis at the northwestern end of the Fairweather fault. Worthington et al. (2012) propose that driving this wedge-shaped “door stopper” beneath the syntaxis may have triggered much of the uplift and exhumation in the syntaxis. If so, then this process overlapped in time with the ~20° clockwise rotation in relative motion between the Pacific and North American plates, which triggered oblique thrusting along the Queen Charlotte part of the transform boundary south of the Saint Elias region (Smith et al., 2003), and presumably increased the amount of transpression in the Saint Elias orogen (Bruhn et al., 2004).

As noted by Bruhn et al. (2004), collision and subduction of the Yakutat microplate into North America provides a case study of terrane accretion that is the hallmark of mountain building worldwide. When studying ancient orogens, structural studies in the Saint Elias Orogen provide a number of caveats to consider when making interpretations of plate motions and causes of deformation. Within the last several million years deformation within the Saint Elias orogen has been affected by climate-related erosion and deformation focusing, by plate boundary geometry, and perhaps lateral variations in the crustal structure of the microplate and globally induced changes in relative motions between the interacting tectonic plates. In a more optimistic vein, our work, when integrated with that of others, provides considerable insight into how a major transform fault terminates and partially controls tectonic uplift and rock exhumation in a structural syntaxis. Additionally, we are able to better elucidate the underlying structure and tectonic significance of the Bagley Ice Valley, which is one of the most significant geomorphic features in the plate margin of southern Alaska.

Seismic Potential of the Bagley Fault

Estabrook et al. (1992) noted that the Bagley fault is at the very least an important structural and mechanical boundary in the orogen. The Bagley fault blocked updip rupture propagation on faults 1a and 1b (Fig. 8) during the Mw 7.4 Saint Elias earthquake, and also bounded an offset or step in the hypocenter depths of aftershocks. We add that the Bagley fault also marks the terminus of several active thrust faults that cut across the foreland of the Yakutat microplate and project beneath the western Seward Glacier basin and Bagley Ice Valley (Figs. 2 and 16).

Although recent geodetic results across the Bagley Ice Valley suggest minimal strain accumulation rates (Elliott, 2011), there is a strong rationale for considering the Bagley fault capable of generating earthquakes. The fault is structurally linked to major seismogenic faults in the orogen (Fig. 16); it is marked by both diffuse and spatially clustered seismicity with focal mechanisms that indicate dextral shearing in some areas, but more complex deformation with both normal and reverse faulting in others (Fig. 4; Doser and Lomas, 2000; Doser et al., 2007; Ruppert, 2008); and the fault is favorably oriented for reactivation in the contemporary stress field (e.g., see regional stress map of Ruppert, 2008). The fault is capable of generating Mw ≥ 8.0 earthquakes were it to rupture along the 125-km-long section extending between the upper Seward and Bering glaciers according to earthquake moment magnitude versus surface rupture length equations of Wells and Coppersmith (1994). This section of the fault zone is relatively linear and bounded by clusters of earthquake activity where the Malaspina and Bering Glacier foreland thrust faults project toward and intersect the Bagley fault at depth. Admittedly, the fault is a complex structural zone that contains several strike-slip and presumably one or more reverse fault strands that may rupture independently to generate small to modest magnitude earthquakes, or alternatively, link together to form a complex seismic source zone for larger earthquakes.

CONCLUSIONS

(1) Collision and accretion of the Yakutat Terrane to North America provides a modern analog for the geodynamics of mountain building at cusp-like plate boundaries where deformation transitions from dominantly transform motion to more intense transpression within the orogen. In the Saint Elias orogen, the plate boundary cusp causes termination of the Fairweather transform fault and formation of a tectonic crustal sliver where the Bagley fault cuts through the southern edge of the North American plate to intersect the megathrust at depth. This fault bounded “sliver” has a complex history of strike-slip and transpressional deformation created by temporal changes in plate motion and underthrusting of microplate lithosphere with spatially variable crustal thickness.

(2) Rapid uplift and exhumation surrounding the Seward Glacier is caused by crustal contraction related to thrust faulting and transpressional strain beneath the mountains and localized extension high in the crust surrounding the terminus of the Fairweather transform fault. Evidence for dextral shearing along the Bagley fault includes a series of NNE-trending ridges and swales on the surface of the Bagley Glacier that are offset in a dextral sense and right-handed jogs in the northern wall of the eastern Bagley Ice Valley at the Quintino Sella and Jeffries glaciers. A tentative correlation of NW-trending valleys that are truncated by the Bagley

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fault indicates 50 km of dextral displacement, which is probably a minimum value.

(3) The Bagley fault has a protracted history of deformation caused by collision of the Yakutat microplate. This includes both dextral shearing as part of the slip-partitioned plate margin, and vertical uplift of the mountains along the southern side of the Bagley Ice Valley. The vertical component of motion was presumably enhanced during the last ca. 5 Ma when the subduction front migrated eastward to its present position near the eastern syntaxis, partly bypassing the slip-partitioned and structurally linked Chugach–Saint Elias–Bagley fault system.

(4) The Bagley fault is considered active and a potential earthquake source because it is directly linked to strike-slip and thrust faults that have undergone Quaternary displacements and generated historical earthquakes. The largest earthquake of M ≤ 8.0 may occur on the section of fault zone between the upper Seward Glacier and the outlet of the Bering Glacier piedmont lobe, which is demarcated by clusters of earthquake activity at its ends.

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