Slip partitioning along a continuously curved fault: Quaternary geologic controls on Denali fault system slip partitioning, growth of the Alaska Range, and the tectonics of south-central Alaska

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ABSTRACT

Active transpressional fault systems are typically associated with the development of broad zones of deformation and topographic development; however, the complex geometries typically associated with these systems often make it difficult to isolate the important boundary conditions that control transpressional orogenic growth. The Denali fault system is widely recognized as transpressional due to the presence of the Denali fault, a major, active, right-lateral fault, and subparallel zones of thrust faults and fault-related folding along both the north and south flanks of the Alaska Range. Measured Quaternary and Holocene slip rates exist for the Denali fault system and portions of the adjacent thrust system, but the partitioning of fault slip between contractional and translational components of this transpressional system has not been previously studied in detail. Exploiting the relatively simple geometry of the Denali fault, we analyze the style and distribution of active faulting within the Alaska Range to define patterns of strain accommodation and determine how contractional and translational strain is partitioned across the Denali fault system. As the trace of the Denali fault curves by ~70° across central Alaska, the mean strike of the thrust system to the north remains subparallel to the Denali fault, while to the south, the few faults with known or suspected Quaternary offset are oblique to the Denali fault. This relationship suggests that as the Denali fault system accommodates local fault-parallel strike slip, it partitions the residual part of the regional NW-directed plate motion into NW-SE shortening south of the Denali fault and shortening perpendicular to the Denali fault to the north. The degree of slip partitioning is consistent with a balanced slip budget for the two primary faults that contribute displacement to the Denali fault system (the eastern Denali fault and Totschunda fault). The current obliquity of displacement south of the Denali fault is the result of the late Cenozoic development of the Totschunda fault, which provides a more direct connection for the transfer of strain from the Fairweather transform fault to the Denali fault system. The transmitted strain is partitioned into right-lateral slip on the Denali fault and into Denali fault-normal shortening that is accommodated by thrust faulting in the Alaska Range and distributed left-lateral slip faulting within interior Alaska to the north.

INTRODUCTION

The distribution and geometry of active faults within an orogen provide insights into the processes that control the architecture and evolution of mountain belts and, in particular, can provide a longer view of how strain is accommodated within an orogen than can be deduced from geophysical observations. For transpressional mountain belts, the obliquity of plate motion, erosional processes, crustal rheology, and the ways in which contraction and translation are partitioned between faults work together to control the spatial distribution of rock uplift (e.g., Spotila et al., 2007). Along-strike heterogeneity in these conditions and processes affects the resultant deformation, but the relative importance of these controls is largely unknown and likely varies between fault systems and orogens. In transpressional fault systems with a through-going strike-slip fault, a simple fault geometry reduces one component of the along-strike heterogeneity and facilitates a more straightforward examination of how slip is partitioned between different parts of the system. To demonstrate how the distribution of active faults can constrain the way in which slip is partitioned across a transpressional orogen, we examine the Alaska Range and Denali fault system—a well-defined active mountain belt and associated intracontinental strike-slip fault that spans 70° of a small circle arc across south-central Alaska (Fig. 1). Using current constraints on Quaternary fault slip rates and fault slip orientations, we illustrate the connection between different modes of deformation within this transpressional system and the way in which the Denali fault partitions slip between different components of the Alaska Range orogen. Recognition of the way in which the Denali fault system partitions strain across the Alaska Range presents new implications for how southern Alaska plate-boundary strain is transferred into far-field deformation in south-central Alaska and informs interpretations of crustal blocks and seismicity.

REGIONAL BACKGROUND

The Alaska Range of south-central Alaska is an arcuate mountain belt that extends from near the Alaska-Canada border westward for over 1000 km to where it trends southward and joins the Aleutian volcanic arc (Fig. 1). This active orogen is a prominent topographic element in
the overriding plate of the Aleutian megathrust and a far-field expression of the complex Pacific–North America convergent plate boundary in southern Alaska (Ferris et al., 2003; Eberhart-Phillips et al., 2006; Freymueller et al., 2008; Haeussler, 2008; Jadamec et al., 2013). Much of the complexity of this plate boundary results from the ongoing subduction and accretion of an oceanic plateau known as the Yakutat terrane (Bruns, 1983; Pfafker and Berg, 1994). Recent two-dimensional (2-D) and three-dimensional (3-D) kinematic and geodynamic models have begun to explore the primary forces contributed by the Yakutat terrane and how these forces drive deformation in the overriding North American plate (Soofi and Wu, 2008; Koons et al., 2010; Finzel et al., 2011a; Jadamec et al., 2013). Soofi and Wu (2008) focused primarily on the deformation and stress fields that result when considering just the unsubducted portion of the Yakutat terrane (the Yakutat microplate; Fig. 1), whereas other models have also incorporated forces associated with the flat-slab geometry associated with the subducted portion of the Yakutat terrane (the Yakutat slab; Koons et al., 2010; Jadamec et al., 2013). Furthermore, additional studies have examined the modern deformation field to extract constraints on the kinematics of the Yakutat microplate–related deformation (Mazzotti and Hyndman, 2002; Leonard et al., 2007; Elliott et al., 2010; Finzel et al., 2011a). Regardless of modeling approach, all these studies illustrate far-field deformation across south-central Alaska and northwestern Canada, extending up to 800 km from the Yakutat microplate collision in southeast Alaska.

Although these models for south-central Alaska deformation all include a far-field response to southern Alaska plate-boundary accretion and subduction processes, they differ in how this deformation is accommodated. One distinction is between crustal block models and those that include diffuse deformation. Crustal block models tend to emphasize the role of crustal faults, and given the limited regional geodetic network, these models can provide a good fit to the observed deformation field (e.g., Freymueller et al., 2008; Elliott et al., 2010). However, other studies seek to account for the role of distributed deformation in the upper plate as is suggested by zones of crustal seismicity and strain rate gradients (Mazzotti and Hyndman, 2002; Leonard et al., 2007; Finzel et al., 2011a). Distributed deformation is also accounted for in geodynamic models that seek to establish a 3-D rheological framework that produces the observed crustal deformation patterns across south-central Alaska (Koons et al., 2010; Jadamec et al., 2013). Despite the differences in modeling approaches, most kinematic and geodynamic representations of the southern Alaska tectonics require a counterclockwise rotation of a large portion of south-central Alaska overlying the shallowly subducting Yakutat slab. With a geodynamic model that integrates the 3-D geometry of the subducted Yakutat slab within the southern Alaska plate boundary, Jadamec et al. (2013) examined the contribution of Yakutat slab subduction to deformation of the upper plate and the way in which this deformation is influenced by different crustal viscosity models. A key insight from this study is the requirement of a weak crustal boundary along the modern trace of the Denali fault (Fig. 1) in order to produce the first-order deformation patterns of south-central Alaska. Jadamec et al. (2013) pointed out that this weak crustal boundary acts to decouple south-central Alaska (typically referred to as the Southern Alaska block or Wrangell block; Figs. 1 and 2) from the rest of the North American plate and allows it to rotate counterclockwise.

Denali Fault System

The Denali fault system is a major intracratonic right-lateral strike-slip system within the upper plate of the Pacific–North America plate boundary (Fig. 1). It has played a prominent role in models of south-central Alaska since the lateral extent of this fault was defined by St. Amand (1957), and the modern tectonic behavior is viewed as being driven predominantly by stresses induced by the collision and flat-slab subduction of the Yakutat microplate in southeast Alaska (e.g., Freymueller et al., 2008; Haeussler, 2008; Jadamec et al., 2013). The Denali fault parallels, and lies within, the active transpressional Alaska Range orogen for much of its length across south-central Alaska (Figs. 1 and 2). Early studies recognized that the Denali fault approximates a small circle arc and that a pole of rotation south of Alaska is required to accommodate the right-lateral strike-slip motion along this fault system (St. Amand, 1957; Stout and Chase, 1980). This arcuate fault geometry is both unique and simple relative to other major continental strike-slip fault systems (e.g., San Andreas fault system—Spotila et al., 2007; the Alpine fault—Norris and Cooper, 2001; Altyn Tagh fault—e.g., Cowgill et al., 2000; also refer to global summary provided by Molnar and Dayem, 2010). The geometric uniqueness of the Denali fault lies in the ~70° of continuous curvature along a small-circle arc spanning 500 km across central Alaska (Fig. 2). The geometric simplicity derives from the continuous curvature and the fact that the Denali fault remains predominantly strike slip for this entire length. For descriptive purposes, we divide the Denali fault by commonly used informal section names, except for our introduction of the “west-central Denali fault” section, which is used to describe the portion of the Denali fault east of Mount McKinley but west of the 2002 earthquake rupture (Fig. 2).

The Totschunda fault is a younger component of the Denali fault system, approaching the eastern Denali fault from the southeast and intersecting it in east-central Alaska near Mentasta Pass (Fig. 2). Richter and Matson (1971) suggested that the Totschunda fault developed after ca. 2 Ma as a more direct connection between the transform portion of the Pacific–North America plate boundary in southeast Alaska (the Fairweather fault) and the Denali fault system, bypassing the eastern Denali fault (Fig. 1). However, no direct geology-based fault connection has been recognized (e.g., Haeussler, 2008). Although the Jadamec et al. (2013) geodynamic model included a weak crustal boundary along
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Despite widespread mapped deformation of late Cenozoic deposits within the Alaska Range, until recently there were few recognized active faults to accommodate this deformation and associated rock uplift of the Alaska Range (Wahrhaftig, 1958; Holmes and Péwé, 1965; Péwé et al., 1966; Nokleberg et al., 1992; Pfafker et al., 1994). There are still limited data on Quaternary faults in the Alaska Range south of the Denali fault, and the Susitna Glacier fault (which ruptured in the 2002 Denali fault earthquake sequence) is the only fault with documented Quaternary displacement (Crone et al., 2004; Persomius et al., 2010). Pfafker et al. (1994) included several additional faults in this region that are classified as "suspicious" in terms of Quaternary activity based on their deformation of Neogene sedimentary rocks. Due to the remoteness of the region and confounded by the inherent difficulty in identifying low-slip-rate thrust faults in geomorphically active environments, the Susitna Glacier fault was unrecognized prior to the 2002 Denali fault earthquake sequence. Furthermore, due to repeated glacial coverage throughout the Quaternary (e.g., Briner and Kaufman, 2008), there are essentially no Quaternary markers older than latest Pleisto-

### TABLE 1. MEAN LATE QUATERNARY SLIP RATES FOR THE DENALI FAULT SYSTEM

| Fault section* | Slip rate (mm/yr) | Source |
|----------------|-------------------|--------|
| Western Denali fault | ~5 | Haeussler et al. (2012) |
| West-central Denali fault, W | 6.7 ± 1.2 | Mériaux et al. (2009) |
| West-central Denali fault, E | 9.4 ± 1.6 | Matmon et al. (2006) |
| Central Denali fault | 12.1 ± 1.7 | Matmon et al. (2006) |
| Central Denali fault | 13.6 ± 3.8 | Mériaux et al. (2009) |
| Eastern Denali fault | 8.4 ± 2.2 | Matmon et al. (2006) |
| Totschunda fault | 6 ± 1.2 | Matmon et al. (2006) |

*Sections labeled on Figure 2.

**Figure 2.** Active faults and shallow seismicity of south-central Alaska. Active fault traces are from the Alaska Quaternary fault and fold database (Koehler et al., 2012), with several smaller fault traces removed for visual clarity. Red dots depict earthquake hypocenters for events >M2, shallower than 30 km, and from the time period 2000–2013. The abundant seismicity along the central Denali fault and Totschunda fault are aftershocks of the 2002 Denali fault earthquake sequence. The Kantishna cluster is a persistent zone of high seismic activity. Ellipses encircle three parallel zones of elevated seismic activity with aligned predominantly left-lateral focal mechanisms (S.Z.—seismic zone). The gray dashed lines depict projections of the seismic zones that form the boundaries of clockwise-rotating crustal blocks, and additional gray dashed lines to the east illustrate bedrock fault zones that could be additional block boundaries that do not display elevated seismicity (Page et al., 1995). Large gray dashed one-sided arrows illustrate the previously proposed mechanism of rotating crustal blocks within a zone of dextral shear between the Denali and Tintina faults. White ellipses containing numbers illustrate documented deformation rates for components of the Alaska Range and Denali fault system. Arrows adjacent to these ellipses indicate whether these are right-lateral slip rates for the Denali fault system (Table 1), or shortening rates across the northern Alaska Range thrust system (Table 2). SGF—Susitna Glacier fault.
 faults with the abrupt range front of the Alaska Range, and additional active faults lying within the foothills south of the range front (Bemis and Wallace, 2007; Carver et al., 2008, 2010). Bemis et al. (2012) synthesized the record of Quaternary faulting in the northern Alaska Range and expanded the previously defined “northern foothills fold-thrust belt” (Bemis and Wallace, 2007) into the northern Alaska Range thrust system (Fig. 2). This thrust system extends as a continuous zone of uplift and shortening on the north side of the Denali fault from Mount McKinley (Denali) eastward for ~500 km (Fig. 2). Along the length of this thrust system, there are four regions that have different structural styles, but in general, each region is dominated by basement-involved thrust faults, has clearly defined late Quaternary faults or folds associated with the northern topographic range front, and contains active faults that are predominantly parallel with the adjacent section of the Denali fault (Fig. 3; Bemis et al., 2012).

Knowledge of slip rates for the faults of the northern Alaska Range thrust system is currently limited by poor age control of deformed Quaternary landforms and from having few direct constraints on subsurface fault dip. However, there are three corridors across portions of the thrust system where we documented shortening rates based upon offset and deformed Quaternary markers. The westernmost transect (Figs. 2 and 3) crosses the full thrust system where each active thrust fault offsets and deforms Quaternary glaciofluvial terraces. Using the regional geology and progressive deformation of the terraces, Bemis (2010) derived subsurface fault geometries along this transect and, utilizing correlations of the terraces with the regional glacial sequence, determined a shortening rate of 1–3 mm/yr (Table 2; Figs. 2 and 3). The easternmost transect also appears to capture most of the shortening across the thrust system, but most of this deformation occurs across a single fault (Figs. 2 and 3). The structural style for this portion of the thrust system is characterized by left-stepping thrust fault segments connected by NE-trending strike-slip faults. These strike-slip faults do not extend significantly beyond the thrust faults to which they connect, and thus they appear to be tear faults within the larger thrust sheet (Bemis et al., 2012). Carver et al. (2008) determined the slip rate for one of these NE-trending faults, the Canteen fault, based upon offsets of late Pleistocene moraines (Table 2; Fig. 3). The thrust fault that connects to the Canteen fault from the west, the Granite Mountain fault, deforms deposits tentatively correlated to early Quaternary glacial deposits (Carter, 1980) and is known to overlie an extensive bedrock unconformity. This unconformity is preserved in the hanging wall of the

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**Figure 3. Quaternary faults of the Alaska Range with kinematic information for the Southern Alaska block based on our model of slip partitioning.** Brown vectors are sums of the fault-parallel slip rates (Table 1) and our estimated fault-normal shortening rate of 3 mm/yr, providing a geologic estimate of the local magnitude and orientation of Southern Alaska block motion (Table 3). Multiple vectors at each site result from calculating the sum vectors individually for offset landforms at sites where multiple offset landforms were used to derive the mean slip rate, thus illustrating a portion of the uncertainty in our calculations. Slip rate sites are labeled with names from Table 3 (BC—Bull Creek; SC—Slate Creek; DFSC, DFWC, DFCR, DFMF). Thick gray dashed lines approximate the Minto Flats (MFSZ), Fairbanks (FSZ), and Salcha (SSZ) seismic zones. The irregular white pattern delineates the modern glacial extents and highlights the regions of high average elevation. Faults traces are from Bemis et al. (2012). CF—Canteen fault; DF—Denali fault; GMF—Granite Mountain fault; JH—Japan Hills; SGF—Susitna Glacier fault.
TABLE 2. SHORTENING RATE CONTROLS IN THE NORTHERN ALASKA RANGE

| Slip rate site          | Slip rate (mm/yr) | Fault dip (°) | Shortening rate (mm/yr) | Time period for slip rate | Comments                                                                 |
|-------------------------|-------------------|---------------|-------------------------|---------------------------|--------------------------------------------------------------------------|
| Hokitika thrust         | 0.3–1             | 21–35         | 0.2–0.9                 | Quaternary                | Multiple surfaces with inferred age correlations offset across fault (Bemis, 2010). |
| Northern Foothills thrust | 0.2–1           | 15–25         | 0.2–0.9                 | Quaternary                | Multiple surfaces with inferred age correlations offset across fault (Bemis, 2010). |
| Japan Hills transect†   | 0.3–1             | –30           | 0.4                     | Late Pleistocene          | Offset late Pleistocene terraces. Additional small scarp recently discovered nearby suggest a slightly higher slip rate. |
| Haines thrust           | 0.3               | 0.3–0.9       |                         | Quaternary                | Minimum offset of a widespread early Quaternary surface.                |
| granite Mountain Fault  | 1.6               | 90            | 1.6                     | Late Pleistocene          | Offset Pliocene/early Quaternary deposits and surface (Bemis et al., 2012). |
| Canteen fault           | 1.6               | 90            | 1.6                     | Late Pleistocene          | Offset late Pleistocene moraines (Carver et al., 2008).                  |

*Additional Quaternary faults exist along this transect but lack offset features of a known age.
†NFFTB—northern foothills fold-thrust belt.

Granite Mountain fault, and Bemis et al. (2012) used this marker to derive a slip rate estimate of 1–4 mm/yr. In between these transects, Bemis (2010) also used a sequence of progressively deformed fluvial terraces and offset early Quaternary deposits near the Japan Hills (Fig. 3) to interpret the subsurface geometry and displacement across two faults at the range front of the thrust system (Fig. 2; Table 2).

The tectonic growth of the Alaska Range recorded by the deformation of late Cenozoic deposits and geomorphic surfaces (Wahrhaftig, 1958; Bemis and Wallace, 2007; Bemis et al., 2012) is complemented by records from syn- orogenic sediments (e.g., Ridgway et al., 2002, 2007) and thermochronology (Fitzgerald et al., 1995; Haeussler, 2008; Benowitz et al., 2011). The correspondence of topography and active faults in the Alaska Range (Fig. 3) was established during the Quaternary and is viewed as a response to flat-slab subduction processes (Finzel et al., 2011b), local structural conditions of the Denali fault (Benowitz et al., 2011), and inherited crustal structures (Fitzgerald et al., 2014). Early low-temperature thermochronologic data in conjunction with the onset of widespread deposition of a coarse-grained foreland basin sequence on the north side of the Alaska Range have been interpreted to represent an orogen-wide pulse of exhumation at ca. 6 Ma (Fitzgerald et al., 1995). However, new thermochronologic data demonstrate a heterogeneous and asymmetric pattern of exhumation along the Alaska Range–Denali fault system (Benowitz et al., 2011). In general, the regions of high topography in the Alaska Range (glaciated regions on Fig. 3) are associated with younger cooling ages, whereas areas of lower average topography have low—temperature cooling ages that reflect pluton cooling and not exhumation-related cooling (Fitzgerald et al., 1995; Benowitz et al., 2011, 2013). Exhumation in the Alaska Range is neither synchronous nor evenly distributed about the arc of the Denali fault, suggesting that the rock uplift is primarily controlled by local structures rather than far-field processes.

Additional constraints on the modern tectonic framework of south-central Alaska come from the abundant shallow crustal seismicity of the region. Major features of the current patterns of seismicity include aseismicshocks of the 2002 Denali fault earthquake, the Kantishna cluster, diffuse seismicity in the Alaska Range foothills, and three NE-trending linear zones of seismicity, with predominantly left-lateral focal mechanisms (Fig. 2). Five >M7 earthquakes have occurred in this region during the past 100 yr, including two on the Denali fault (2002—Eberhart-Phillips et al., 2003; 1912—Carver et al., 2004) and three associated with the NE-trending seismic zones (Fletcher and Christensen, 1996). Page et al. (1995) proposed that the NE-trending left-lateral seismic zones separate clockwise-rotating crustal blocks within a broad dextral shear zone between the Denali fault and the Tintina fault to the north (Fig. 2). The westernmost seismic zone (Minto Flats seismic zone) cuts across the Tanana Basin and across the foothills of the Alaska Range. Although this seismic zone does not have a clear fault surface trace, it does correspond with an E-W change in the structural style and topographic fabric of the Alaska Range foothills (Fig. 3; Bemis et al., 2012). The two seismic zones to the east (Fairbanks seismic zone and Salcha seismic zone) also cut across the Tanana Basin, but the seismicity lineaments end at the northern range front of the Alaska Range, and there are no structural or topographic trends to suggest that the deformation associated with these zones extends into the foothills (Figs. 2 and 3; Bemis et al., 2012).

The stress map of Alaska by Ruppert (2008) was derived from historical earthquake focal mechanisms and provides a means by which to compare the stress tensor inversion results for individual crustal volumes with the observed regional active faulting patterns. For the Denali fault system, this analysis shows stresses consistent with the observed right-lateral strike-slip faulting. Stress tensor inversion results for the northern foothills of the Alaska Range show predominantly reverse faulting with a N-S–oriented maximum compressive stress, and the NE-trending seismic zones immediately north of the foothills have the same maximum compressive stress orientation but with strike-slip mechanisms (Ruppert, 2008).

PROBLEM AND OBJECTIVES

The typical view of the modern Denali fault system is that it separates the relatively rigid counterclockwise rotation of south-central Alaska (the Southern Alaska block; e.g., Freymueller et al., 2008) from the distributed deformation of central Alaska (e.g., Ruppert et al., 2008; Haeussler, 2008). In a simple kinematic sense, rigid rotation of the Southern Alaska block is not consistent with the observed westward decrease in slip rate on the Denali fault. Furthermore, to drive shortening across the northern Alaska Range thrust system, the Denali fault appears to be migrating northward. To accommodate the westward decrease in Denali fault slip rate, strain must be accommodated by the SE-striking thrust faults within the Southern Alaska block (south of the Denali fault; Hae-
ussler, 2008) or transferred across the Denali fault into the northern Alaska Range thrust system (Matmon et al., 2006; Mériaux et al., 2009). Haeussler (2008) provided a descriptive model that includes the key aspects of a westward decrease in the Denali fault slip rate and rotation and northwestward migration of the Southern Alaska block but did not attempt to balance relative or absolute motions. Mériaux et al. (2009) proposed a simple model that fully accommodates the westward Denali fault slip rate decrease through pure northwestward indentation of the Southern Alaska block. In this model, the westward slip rate decrease occurs due to the progressive westward increase in obliquity of the Denali fault relative to the plate motion direction of the Southern Alaska block. As a result, their model predicts that the 12–14 mm/yr slip rate for the Denali fault east of the Delta River (Fig. 3) is balanced by ~4 mm/yr of fault-normal shortening north of the Denali fault, whereas near the Nenana River, the ~7 mm/yr Denali fault slip rate is balanced by ~12 mm/yr of fault-normal shortening north of the Denali fault (Mériaux et al., 2009). Although this model provides a quantifiable explanation for the westward decrease in Denali fault slip rate, it does not account for the counterclockwise rotation of the Southern Alaska block recognized by most models of southern Alaska tectonics. However, this model provides a testable conclusion that can be addressed through documentation of the shortening rates across the Alaska Range near the Nenana River (Table 2).

The simple, arcuate geometry of the Denali fault system should result in an along-strike trend in the relative crustal motion across the fault, regardless of whether a predominantly indentation model (Mériaux et al., 2009) or a block rotation model (e.g., Freymueller et al., 2008; Haeussler, 2008) is invoked for the crustal motion of south-central Alaska. The presence of this strike-slip fault with a continuous map-view curvature within the Alaska Range transpressional system simplifies the isolation of slip partitioning between different structural components of the system. The Alaska Range follows the same curvature as the Denali fault, and, if active deformation is driven by the contractional component of slip that is partitioned across the Denali fault system, the primary Alaska Range faults that accommodate deformation within the orogen should vary systematically with this curvature. We use Quaternary geologic data from the Alaska Range in the form of fault orientation and sense of displacement for Quaternary-active faults to show that the Denali fault completely partitions slip into fault-parallel and fault-normal components. We test this complete slip-partitioned relationship at the eastern end of the Denali fault system arc, where the Totschunda fault provides a conduit for slip that is oblique to the main trace of the Denali fault. In this configuration, we use the complete slip-partitioned model and the geologically determined fault-parallel and fault-normal slip rates for the central Denali fault to predict the slip rates for the Totschunda and eastern Denali faults and test the viability of this model by comparing the predicted results to the geologically observed slip rates. Finally, we assess the likely far-field contributions of strain to the Denali fault system from the southern Alaska plate boundary, as well as implications for the remnant components of strain to the north in regional tectonic models.

**CHARACTERISTICS OF ALASKA RANGE AND DENALI FAULT SYSTEM DEFORMATION**

Quaternary faults in and adjacent to the Alaska Range display characteristic trends on their respective sides of the Denali fault. The thrust faults south of the Denali fault, including those with suspected Quaternary activity (Plafker et al., 1994; Figs. 2 and 3), all have an approximately NE-SW strike and appear to obliquely intersect the Denali fault, whereas the thrust faults to the north are subparallel to the Denali fault (Fig. 3). The geomorphology of fault scarps and structural geometry of fault-related folding indicate that these thrust faults of the northern Alaska Range thrust system are predominantly pure dip-slip faults (Fig. 4). Despite natural variability in the mapped traces of these thrust faults, due to the interaction of a dipping plane with topography, the influence of preexisting structures and rheological variations, and decreasing displacement at fault tips, the map-view parallelism between these thrust faults and the Denali fault for ~500 km and through 70° degrees of Denali fault curvature is clear (Figs. 2 and 3). Additional strike-slip and oblique-slip faults exist in portions of the northern Alaska Range thrust system, and these are typically oblique to the thrust fault traces and connect adjacent segments of these faults (Fig. 3). These lateral-slip faults correspond with along-strike changes in architecture of the thrust system and are interpreted as tear faults within the hanging wall of the thrust system (Bemis and Wallace, 2007; Carver et al., 2008). To provide a graphical assessment of the relationship between the orientation of thrust and lateral-slip faults of the northern Alaska Range thrust system and the Denali fault, we plotted the orientations of the faults in the northern Alaska Range thrust system relative to the orientation of the adjacent portion of the Denali fault between 143°W to 152°W. To average out small-scale variability in the mapped surface traces, we divided the Denali fault into 10 km segments and each of the Alaska Range faults into 5 km segments. The average strike was calculated for each fault segment, and the Alaska Range fault segments lying within a perpendicular 10-km-wide swath were plotted against the orientation of that Denali fault segment (Fig. 5).

As shown in map view (Fig. 3) and graphically (Fig. 5), the surface traces of active faults north of the Denali fault are dominantly parallel to subparallel to the strike of the Denali fault, despite an ~70° change in the strike of the Denali fault over the 400 km between the intersection with the Totschunda fault in the east and Denali to the west. This trend is clearly shown by the orientation of thrust faults (Figs. 5A and 5B), whereas the subvertical lateral-slip faults tend to cluster around an orientation of 30°–60° from the strike of the Denali fault (Fig. 5C). The predominantly dip-slip nature of thrust faults within the northern Alaska Range thrust system combined with the parallelism with the Denali fault demonstrate that this thrust system is accommodating shortening orthogonal to the Denali fault throughout the broad arcuate trace across southern Alaska. Furthermore, the sense of slip on the lateral-slip faults (left-lateral for NE-striking; right-lateral for NW-striking) and their highly oblique orientation relative to the Denali fault show that these faults are well aligned to also accommodate shortening orthogonal to the Denali fault. Therefore, the principal shortening direction defined by the orientations of these Quaternary-active faults remains perpendicular to the Denali fault through the ~70° curve, indicating the nearly complete partitioning of slip between the strike-slip Denali fault and the northern Alaska Range thrust system.

**Slip Budget of the Totschunda-Denali Intersection**

To test our model of a completely slip-partitioned Denali fault, we analyzed the slip budget for the Totschunda-Denali fault intersection (Fig. 6), utilizing the late Quaternary slip rates (Table 1) and mapped fault orientations to isolate the contributions to Denali fault system and Alaska Range deformation. If the central Denali fault is completely slip partitioned, and the deformation is driven by strain transferred into the system from the southeast, then we should be able to show that (1) the Southern Alaska block motion vector adjacent to the central Denali fault decomposes to equal the slip rate of the Denali fault and the shortening rate across faults to the north, (2) the slip rates of the Totschunda fault and eastern Denali fault should sum to the Southern Alaska block motion vec-
Neotectonic controls on Denali fault system slip partitioning

Figure 4. Examples of fault scarps from the northern Alaska Range thrust system illustrating evidence for sense of slip. In mapping much of this fault system, no clear evidence of appreciable oblique slip on thrust faults has been observed (e.g., Bemis et al., 2012), and examples A, B, C, D, and F illustrate a variety of geomorphic clues for no appreciable lateral slip. (A) Satellite image of an ~15-m-tall thrust fault scarp displaying a swath of bending moment grabens parallel to the fault scarp, suggesting pure dip-slip displacement (e.g., McCalpin, 2009). (B) Light detection and ranging (LiDAR) shaded-relief view of the Hines Creek fault trace across late Pleistocene glaciofluvial outwash deposits. The fault scarp is 10–12 m tall, and numerous linear features show no apparent lateral displacement across the scarp (Federschmidt, 2014). (C) LiDAR shaded-relief image reveals multiple small (~1 m tall) south-vergent fault scarps that offset a late Pleistocene fluvial terrace and numerous linear features that lack evidence of lateral offset. (D) Interferometric synthetic aperture radar (IfSAR) shaded-relief topography showing a south-vergent thrust fault scarp with antecedent streams that are not laterally displaced across the fault. (E) IfSAR shaded-relief showing right-lateral displacement of terrace margins and stream channels along with southwest-side-up oblique slip. This fault has a highly oblique strike relative to the Denali fault and correspondingly displays oblique-slip consistent with N-S shortening. (F) LiDAR-derived shaded-relief image of large anticlinal fault scarps that are transected by alluvial-fan deposits. The alluvial-fan morphology and the along-strike sinuosity of the fault scarp do not support an interpretation of appreciable lateral slip.

Figure 5. Plots illustrating the orientations of Quaternary faults on the north side of the Alaska Range vs. the orientation of the Denali fault. (A) Quaternary thrust faults are shown as gray triangles, with range-bounding thrust faults illustrated as outlined triangles. Additional Denali fault-parallel thrust faults exist in the vicinity of 240° that would strengthen this trend, but these unpublished data are not shown here. (B) Same source data as A, but with the mean and standard deviation of thrust fault orientations calculated for 10 km bins of the Denali fault orientations. (C) Only the steeply dipping, predominantly lateral-slip faults (black dots). The least squares best-fit regression is a poor fit to the naturally scattered data shown in A but provides a better fit to the mean values of the binned data (B). The regression line from A is shown in C to illustrate how these faults have orientations oblique to the Denali fault (30°–60°). Oblique-slip faults at this orientation relative to the Denali fault system accommodate the same principal shortening direction as the thrust faults.
Figure 6. Map of the simplified fault geometry of the Totschunda fault–Denali fault system intersection. The solid black lines illustrate the straight section approximations for the central Denali fault (CDF), eastern Denali fault (EDF), and the Totschunda fault (TF) used in the relative velocity analysis (shown below the maps). The thin blue line on the maps is the 2002 Denali fault earthquake rupture sequence as mapped by Haessler (2009), and it illustrates that the straight segment approximations are representative of the fault trace. These line segment orientations were used to construct the model geometry of the relative velocity diagram, with gray lines representing fault orientations, black lines representing slip rates for strike-slip faults, the red arrow illustrating the orientation and rate of shortening required by a lack of closure, and the blue line representing the predicted motion of the Southern Alaska block relative to stable North America. Base map topography shows higher elevations in darker grays to illustrate the localization of higher topography between the active thrust faults and the central Denali fault. White dots indicate the locations of slip rate determinations from Matmon et al. (2006) and Mériaux et al. (2009). NAe—North America–east (approximation of stable North America), NAw—North America–west (crust north of the Denali and west of the Totschunda–Denali fault triple junction), SA—Southern Alaska block, T—Totschunda block. Map projection is based on NAD83 UTM.
The model of complete slip partitioning also predicts that the shortening north of the Denali fault should be restricted to the area west of the Totschunda fault intersection (Figs. 3 and 6). Carver et al. (2010) and Koehler and Carver (2012) demonstrated that there is no evidence for late Quaternary faulting north of the eastern Denali fault, and this transition between active and inactive faults corresponds with the location of the Totschunda-Denali fault intersection. A factor supporting active faulting patterns is the matching trend of decreasing elevations and relief from the northwest to southeast across the same area. Considering that the fault intersection is migrating northwestward effectively at the eastern Denali fault slip rate, the eastern extent of active faulting north of the Denali fault is likely migrating at a similar rate, and thus the hills immediately east of the fault intersection (Fig. 6) are remnant topography from active deformation in the recent past, which is now abandoned and is being lowered by erosion and buried by aggrading sediment.

Recognition of the completely slip-partitioned nature of the Denali fault system and the continued parallelism between the Denali fault and the northern Alaska Range thrust system to the west places important constraints on the possible mechanisms that could be accommodating the westward decrease in Denali fault slip rate. This progressive westward decrease in the geologic slip rate of the Denali fault (Fig. 2; Table 1) suggests an increase in fault-normal shortening rate north of the Denali fault (e.g., Mériaux et al., 2009), a component of shortening south of, and parallel to, the Denali fault, or some combination of the two. The shortening rate constraint for the northern Alaska Range thrust system near the Nenana River (~1–3 mm/yr) does not support a shortening rate of the magnitude that the Mériaux et al. (2009) model would require across the Alaska Range (~12 mm/yr; Table 2). The other mechanism to accommodate a westward decrease in Denali fault slip rate for which we have first-order geologic observations is the possibility that active shortening across the SW-trending thrust faults south of the Denali fault absorbs some of the relative strike-slip motion on the Denali fault itself. These faults south of the Denali fault are oriented oblique to, and appear to intersect with, the Denali fault, making them well aligned to accommodate shortening within the Southern Alaska block south of the Denali fault. Only the Susitna Glacier has documented Quaternary deformation, with an estimated slip rate of 1–5 mm/yr (Koehler et al., 2012). Similarly, the proportion of lateral slip on the thrust faults with suspected Quaternary fault activity (Pfaffer et al., 1994; Koehler et al., 2012) is unknown, except for the lack of lateral slip during the 2002 rupture of the Susitna Glacier (Crone et al., 2004). Regardless of the magnitude/style of slip or the driving mechanism, the result of active shortening across these thrust faults would be to create a westward decrease in rotation rate of the Southern Alaska block adjacent to the Denali fault, and as a result, produce a westward decrease in relative motion across the Denali fault.

As an estimate for crustal velocity vectors for the Southern Alaska block and how they vary with the Denali fault curvature and the westward decrease in slip rate, we used the geologically determined Denali fault-parallel slip rates (Table 1) and fault-normal shortening rates (Table 2) across the Alaska Range to derive the rate and orientation of Southern Alaska block motion that drives Alaska Range deformation (Table 3; Fig. 4). In particular, we inferred a constant fault-normal shortening rate of 3 mm/yr (Table 2), because this is the best fit for the fault-normal shortening rate derived from our slip budget calculations at the Totschunda-Denali fault intersection, and this value is consistent with the limited geology-based shortening rates available for the northern Alaska Range thrust system (Table 2). The resulting vector sum (Table 3; Fig. 4) illustrates the counterclockwise rotation of the Southern Alaska block and the westward decrease in this rotation. This decrease in rotation is related to the decrease in Denali fault-parallel slip rate, because as the ratio of fault-parallel slip rate to fault-parallel shortening rate gets smaller to the west, the vector sum orientation does not change as fast as the curvature of the Denali fault trace (Fig. 4). The obliquity of these Southern Alaska block vectors also illustrates the northward migration of the Denali fault. Overall, these crustal velocity vectors for the Southern Alaska block adjacent to the Denali fault illustrate that, similar to the framework proposed in a regional neotectonic summary by Haeussler (2008), the Southern Alaska block is rotating counterclockwise and migrating northwestward. Additionally, the westward changes in the orientation and magnitude of the crustal velocity between the Denali fault slip rate sites correspond with the occurrence of the active and suspected active thrust faults south of the Denali fault, supporting the importance of these faults in accommodating the westward decrease in Denali fault slip rate.

**CONSTRAINTS ON REGIONAL TECTONICS**

Parallelism between the northern Alaska Range thrust system and the Denali fault shows that the principal shortening direction has been perpendicular to the Denali fault during the Quaternary growth of these faults. This is supported by the study of Ruppert (2008), who used stress tensors derived from regional earthquake focal mechanisms to show that maximum compressive stresses in the Alaska Range north of the Denali fault are predominantly fault-normal to the Denali fault. These geologic and geophysical data indicate that the style of Quaternary Alaska Range growth is fundamentally due to the strain partitioning of the NW-directed motion of the Southern Alaska block into fault-parallel and fault-normal components. The difference in general thrust fault orientation and corresponding shortening directions north versus south of the Denali fault provides important insight into how south-central Alaska is responding to far-field plate-boundary–imposed strain.

**TABLE 3. ESTIMATES FOR DISPLACEMENT VECTORS DERIVED FROM GEOLoGIC SLIP RATES**

| Slip rate site* | Slip rate (mm/yr) | Denali fault orientation (°) | Denali fault-normal rate (mm/yr) | Denali fault-normal orientation (°) | Sum vector magnitude (mm/yr) | Sum vector orientation (°) |
|-----------------|-------------------|-----------------------------|---------------------------------|----------------------------------|-----------------------------|---------------------------|
| West-central Denali fault | | | | | | |
| Bull Creek | 6.7 ± 1.2 | 260 | 3 | 350 | 7.3 | 284 |
| Bull Creek | -8.7 | 260 | 3 | 350 | 9.2 | 279 |
| DFSC | 9.4 ± 1.3 | 266 | 3 | 356 | 9.9 | 284 |
| DFSC | 7.5 ± 1 | 266 | 3 | 356 | 8.1 | 288 |
| DFSC | 9.2 ± 1.1 | 266 | 3 | 356 | 9.7 | 284 |
| DFWC | 9.3 ± 2.3 | 265 | 3 | 355 | 9.8 | 283 |
| DFWC | 11.7 ± 1.8 | 265 | 3 | 355 | 12.1 | 279 |

| Central Denali fault | | | | | | |
| Slate Creek | 13.3 ± 3.6 | 294 | 3 | 024 | 13.6 | 307 |
| DFCR | 12.0 ± 1.8 | 294 | 3 | 024 | 12.4 | 308 |
| DFCR | 12.1 ± 1.8 | 294 | 3 | 024 | 12.5 | 308 |
| DFMF | 10.9 ± 1.4 | 296 | 3 | 026 | 11.3 | 311 |
| DFMF | 13.3 ± 1.7 | 296 | 3 | 026 | 13.6 | 309 |

*Site names reflect the names used in the original publication (acronyms from Matmon et al., 2006) and creek names from Mériaux et al. (2009) and Haeussler et al. (2012).
Totschunda Fault and the Quaternary Thrust System

We propose that the eastern extent of active faulting in the northern Alaska Range thrust system is directly related to the proximity of the intersection of the Totschunda fault with the Denali fault near Mentasta Pass (Figs. 3 and 6). The inherent instability of this triple junction is mitigated by the addition of a N-directed fault-normal translation of the central Denali fault to accommodate the oblique motion contributed by the Totschunda fault. Therefore, because the triple junction migrates westward along the Denali fault at the rate of the eastern Denali fault slip rate, we predict that the eastern extent of active faulting north of the Denali fault is migrating westward at the same rate. Furthermore, because of this geometry, Richter and Matson’s (1971) evidence that the Totschunda fault formed in the last 2 m.y. provides an explanation for Bemis et al.’s (2012) conclusion that the northern Alaska Range thrust system expanded in the Quaternary. Specifically, activation of this fault forced the contraction west of the intersection (Fig. 6), and, accordingly, the link-up of this fault to the plate-boundary Fairweather system suggests direct ties between these events. By providing a shortcut for strain transfer from the plate boundary in southeast Alaska that bypasses the eastern Denali fault, the Totschunda fault creates a more oblique and narrow indenter into central Alaska. This would essentially have the effect of changing the pole of rotation for the Southern Alaska block and perhaps causing an increase in strain oblique to the Denali fault that instigated the current phase of widespread contraction and uplift of the northern Alaska Range thrust system.

Motion of the Southern Alaska Block

Although a majority of recent studies of southern Alaska tectonics have invoked a model of crustal deformation that includes a counterclockwise-rotating Southern Alaska block, several studies either proposed or adopted a model of pure northwestward indentation of the Southern Alaska block into south-central Alaska (Taylor et al., 2008; Mériaux et al., 2009; Vallage et al., 2014). Despite limited constraints on Denali fault-normal shortening across the northern Alaska Range, our analysis of fault orientations and slip rates illustrates a clear pattern of Southern Alaska block rotation, internal shortening, and northwestward migration (Fig. 3), supporting the complex model proposed by Haeussler (2008). In particular, the progressive counterclockwise rotation of our geologically derived velocities for the Southern Alaska block adjacent to the Denali fault supports geodetic data demonstrating this rotation (e.g., Freymueller et al., 2008) and the geodynamic models that produce rotation of the Southern Alaska block (Jadamec et al., 2013). This specifically counters the model presented by Mériaux et al. (2009), in which the westward decrease in Denali fault slip rate is accommodated by simple northwestward migration of the Southern Alaska block, which would require no rotation and higher fault-normal shortening rates than is geologically supported. The occurrence of shortening within the Southern Alaska block supports the kinematic modeling of Finzel et al. (2011a) and their argument for diffuse deformation, as well as highlighting discrete faults that accommodate shortening (Fig. 3).

NNE-Trending Seismic Zones in Central Alaska

Widespread shallow crustal seismicity in central Alaska is dominated by three NE-trending, left-lateral seismic zones, which are generally interpreted as boundaries of crustal blocks undergoing counterclockwise vertical-axis rotation within a broad dextral shear zone between the Denali fault and the subparallel Tintina fault to the north (e.g., Page et al., 1995; Ruppert et al., 2008; Finzel et al., 2011a; Fig. 2). Although it is difficult to isolate young transrotational effects within a broader transcurrent/transpressional system, the slip-partitioned nature of the Denali fault system and the principal shortening direction across the northern Alaska Range thrust system do not provide Quaternary geologic evidence of deformation within a dextral shear-dominated system. For example, two seismic zones end at the northern range front of the Alaska Range, contrary to predictions made by the previous models (e.g., Page et al., 1995), and there is no seismological or geologic evidence for the continuation of these zones into the Alaska Range (Figs. 2 and 3). The agreement between the seismologically determined maximum compressive stress for the thrust system and the NE-trending seismic zones (Ruppert, 2008) and our geologically derived principal shortening direction north of the Denali fault indicates that interior Alaska is experiencing N-S shortening. Given the orientation of the NE-trending seismic zones, the crustal blocks between the seismic zones can accommodate N-S shortening through clockwise rotation. Therefore, we propose that the left-lateral displacement across the Fairbanks and Salcha seismic zones and associated crustal block rotation are operating within the same Denali fault-normal maximum compressive stress that drives the active thrust faults of the northern Alaska Range thrust system. Previously mapped NE-trending, steeply dipping bedrock fault zones east of and parallel to the seismic zones were proposed as additional block boundaries (Fig. 2; Page et al., 1995) but perhaps are not seismically active because the principal shortening direction north of the central Denali fault is subparallel to the preexisting NE-trending bedrock fault zones. Therefore, where the principal shortening direction is near-parallel to the preexisting bedrock faults, it should be difficult to drive relative displacement across the fault, whereas in the west, the principal shortening direction is favorably aligned to drive left-lateral slip on steeply dipping, NE-trending faults. Our model, taken together with the seismological evidence, shows that a broad zone of dextral shear between the Denali and Tintina faults is not required to drive the seismicity lineaments and proposed block rotation and alternatively can be driven by N-S shortening induced by the northward migration of the Southern Alaska block.

IMPLICATIONS FOR FAR-FIELD STRAIN TRANSFER

Modern activity of the Denali fault system, the growth of the Alaska Range, and widespread seismicity in interior Alaska and the Yukon Territory are typically viewed as far-field crustal deformation resulting from the collision and subduction of the Yakutat microplate. Recent tectonic models of southern Alaska crustal deformation argue for the importance of coupling between the buoyant, subducted Yakutat slab underneath south-central Alaska and the overriding plate in driving this far-field deformation (Abers, 2008; Haeussler, 2008; Finzel et al., 2011a; Jadamec et al., 2013). This flat-slab contribution should act upon a broad swath of the overriding plate, presumably corresponding to the area of the subducted slab (Fig. 1). Despite the smaller area, the accretion of the Yakutat microplate has been shown to contribute an additional and significant component of far-field strain (e.g., Mazzotti and Hyndman, 2002; Soofi and Wu, 2008). The potential role of the Totschunda fault in realigning the Southern Alaska block and the alignment of this fault with the Fairweather fault (which is the eastern margin of the Yakutat microplate) support the significance of this accretionary contribution to far-field deformation.

The contributions to far-field deformation from coupling of the subducted Yakutat slab and Yakutat microplate accretion in southeast Alaska should be influenced by the strength of the lithosphere—both the vertical strength profile and horizontal strength variability. For one, horizontal variations in lithospheric strength are likely
what localizes the trace of the Denali fault due to the contrast between the relatively strong Southern Alaska block and the crustal-scale weakness associated with the Alaska Range suture zone to the north. Furthermore, Fitzgerald et al. (2014) argued that significant contrasts in lithospheric strength in the Alaska Range allowed for the formation of asymmetric topography across the Denali fault. These strength contrasts potentially have multiple effects in both localizing the development of zones of high exhumation and extreme topography within the Alaska Range orogeny, as well as essentially dictating the side of the Denali fault on which the axis of deformation will occur. In order to transmit deformation into central Alaska and beyond, a weak lower-crustal detachment appears to be accommodating the decoupling of the upper crust and allowing it to translate away from the southern Alaska plate boundary while simultaneously allowing it to deform internally (e.g., Oldow et al., 1990; Mazzotti and Hyndman, 2002).

CONCLUSIONS

Outside of natural variability, major thrust fault segments should be responding to the regional stress field, and the strike of these faults should be perpendicular to the maximum compressive stress. We integrate the results of recent neotectonic studies that document the distribution and orientation of Quaternary faults along 500 km of the Alaska Range to establish constraints on the way in which far-field strain transmitted from the southern Alaska plate boundary is partitioned by the Denali fault and associated Alaska Range deformation. The rates and orientations of Quaternary fault displacement along the strike-slip Denali fault system and the associated thrust fault–dominated Alaska Range illustrate the persistent pattern of Denali fault–parallel thrust faults that accommodate Denali fault-normal shortening across ~70° of curvature across south-central Alaska. Thus, it appears that the Denali fault completely partitions oblique strain imposed from the southeast into fault-parallel slip on the Denali fault itself and fault-normal slip within the northern Alaska Range thrust system. Available geologic data on shortening rates across the northern Alaska Range provide only broad constraints, but in our slip partition model, the predicted central Denali fault-normal shortening rates are consistent with the shortening rates known for this system. Furthermore, these shortening rates provide critical constraints on potential regional tectonic models for the contribution of regional strain into the Denali fault system. Low shortening rates across the Nenana River corridor adjacent to the west-central Denali fault show that there is not a significant westward decrease in northern Alaska Range shortening rates that corresponds with the westward decrease in Denali fault slip rate. This counters the model of Mériaux et al. (2009) of a northwestward–translating Southern Alaska block with the requirement of internal shortening and rotation of the Southern Alaska block in order to balance the observed slip rates. Complete slip partitioning across the Denali fault supports observations from the patterns of deformation in the northern Alaska Range, which illustrate that significant right-lateral shear is not transmitted north of the Alaska Range. Therefore, the model of rotating crustal blocks in interior Alaska appears to operate within a larger field of predominantly pure shear accommodating the northwestward indentation of the Southern Alaska block as opposed to the model of simple shear between the Denali and Tintina faults as proposed by Page et al. (1995). Also, the distribution of active faults north of the Denali fault system shows that shortening to the north of the Denali fault is related to the angular difference and displacement of the Totschunda fault relative to the through-going Denali fault. With the Totschunda fault as a connection for partial strain transfer from the Fairweather fault into central Alaska, we suggest that the collision of the Yakutat microplate provides an important contribution to far-field upper-plate deformation in addition to the long-lived flat-slab subduction processes. The decoupled pattern of strain accommodation across the Denali fault along with the well-documented westward decrease in Denali fault slip rates require rotation, northward migration, and internal shortening of the Southern Alaska block. Our results provide an example of the use of geologic data to constrain the nature of strain partitioning in a tectonically active fault system and emphasize the potential contributions of active fault studies to the development of regional tectonic models.

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Lithosphere

Slip partitioning along a continuously curved fault: Quaternary geologic controls on Denali fault system slip partitioning, growth of the Alaska Range, and the tectonics of south-central Alaska

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