The Quaternary thrust system of the northern Alaska Range

Sean P. Bemis¹, Gary A. Carver², and Richard D. Koehler³
¹Department of Earth and Environmental Sciences, University of Kentucky, Lexington, Kentucky 40506, USA
²Carver Geologic, Inc., P.O. Box 52, Kodiak, Alaska 99615, USA
³Alaska Division of Geological and Geophysical Surveys, 3354 College Road, Fairbanks, Alaska 99709, USA

ABSTRACT

The framework of Quaternary faults in Alaska remains poorly constrained. Recent studies in the Alaska Range north of the Denali fault add significantly to the recognition of Quaternary deformation in this active orogen. Faults and folds active during the Quaternary occur over a length of ~500 km along the northern flank of the Alaska Range, extending from Mount McKinley (Denali) eastward to the Tok River valley. These faults exist as a continuous system of active structures, but we divide the system into four regions based on east-west changes in structural style. At the western end, the Kantishna Hills have only two known faults but the highest rate of shallow crustal seismicity. The western northern foothills fold-thrust belt consists of a 50-km-wide zone of subparallel thrust and reverse faults. This broad zone of deformation narrows to the east in a transition zone where the range-bounding fault of the western northern foothills fold-thrust belt terminates and displacement occurs on thrust and/or reverse faults closer to the Denali fault. The eastern northern foothills fold-thrust belt is characterized by ~40-km-long thrust fault segments separated across left-steps by NNE-trending left-lateral faults. Altogether, these faults accommodate much of the topographic growth of the northern flank of the Alaska Range.

Recognition of this thrust fault system represents a significant concern in addition to the Denali fault for infrastructure adjacent to and transecting the Alaska Range. Although additional work is required to characterize these faults sufficiently for seismic hazard analysis, the regional extent and structural character should require the consideration of the northern Alaska Range thrust system in regional tectonic models.

INTRODUCTION

South-central Alaska is a large geographic region characterized by rugged, remote terrain and low population density. Available geologic and elevation data are generally of low resolution, and detailed geologic studies related to Quaternary faults are lacking in many areas. Studies of strain accumulation measured with global positioning system (GPS) (Freymueller et al., 2008) and strain release observed through seismicity (Ruppert, 2008) demonstrate that all of south-central Alaska is actively deforming. However, for the reasons given, many of the structures accommodating this deformation remain elusive. Comparing the three published summaries of Alaskan neotectonics (Brogan et al., 1975; Pfafker et al., 1994; Haeussler, 2008) demonstrates that the number of known active faults has increased significantly over the past 35 years, but the parameters essential for seismic hazard assessments (e.g., slip rate, paleoearthquake timing, and time since the most recent event) are published for only a limited number of these faults. Thus, the current level of fault characterization is insufficient to properly model seismic hazards for the region. Furthering our understanding of these active faults is important for mitigating seismic hazards for several major proposed and planned infrastructure projects crossing interior Alaska.

The 2002 M7.9 Denali fault earthquake sequence (Eberhart-Phillips et al., 2003) initiated a renewed interest in the Quaternary tectonics of central Alaska. While this event provided an opportunity to characterize this major continental strike-slip fault in detail, it also highlighted how little was known about the structures accommodating growth of the Alaska Range. Several studies suggested that deformation of the Alaska Range north of the Denali fault (referred to here as the northern Alaska Range) could help to accommodate the observed westward decrease in slip rate across the Denali fault (Matmon et al., 2006; Mériaux et al., 2009). However, concurrent studies were just beginning to document the widespread nature of Quaternary deformation in the northern Alaska Range (Bemis, 2004; Carver et al., 2006, 2008; Bemis and Wallace, 2007) and these preliminary data were insufficient to constrain the inferences of Matmon et al. (2006) and Mériaux et al. (2009). Therefore, a more systematic understanding of the style and activity of Quaternary faulting in the northern Alaska Range is required to approach the problem of interaction between the dominantly right-lateral strike-slip Denali fault and modern growth of the Alaska Range.

This paper presents the current state of knowledge on Quaternary faulting in the northern Alaska Range, introduces previously undescribed faults in this region, and synthesizes the regional character of this system of Quaternary faults. In addition to our maps, table, and discussion of these Quaternary faults presented here, we have contributed our Quaternary fault database to the development of the Quaternary fault and fold database for Alaska by the Alaska Division of Geological and Geophysical Surveys. Once completed, this database will serve as the repository for access to up-to-date Quaternary fault data for Alaska, including the northern Alaska Range. This paper summarizes major advances in the understanding of central Alaska neotectonics since the last statewide summary by Pfafker et al. (1994). The summary also includes many important contributions beyond Haeussler (2008) and sufficient detail, where available for individual faults, to guide regional interpretations and future studies.

REGIONAL TECTONIC SETTING

Southern Alaska acts as a diffuse plate boundary, where convergence between the Pacific and North American plates is accommodated both along the Aleutian megathrust and by translating strain more than 600 km into central Alaska (Fig. 1). Helping to drive this distributed

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Geosphere; February 2012; v. 8; no. 1; p. 196–205; doi:10.1130/GES00695.1; 6 figures; 1 table.

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deformation is the subduction and accretion of the eastern and central Yukutat terrane (Fig. 1), which began in the late Miocene to Pliocene (e.g., Bruns, 1983; Plafker and Berg, 1994; Chapman et al., 2008). The strain from this collision is transferred into central Alaska through the translation and counterclockwise rotation of south-central Alaska (Freymueller et al., 2008; Haeussler, 2008). The Denali fault system defines the northern margin of the south-central Alaska rotation and accommodates a large proportion of the strain translated into central Alaska (Fig. 1).

Deformation related to the modern Alaska Range was probably under way by the early Miocene as indicated by the formations of the Oligocene–Miocene Usibelli Group (Wahrhaftig et al., 1969; Ridgway et al., 1999, 2007) and thermochronologic exhumation ages (Haeussler, 2008; Benowitz et al., 2009). Stratigraphy, paleoflow directions, and unconformities within the Usibelli Group indicate minor syndepositional foreland deformation (Ridgway et al., 2007). As the locus of Alaska Range deformation migrated northward, this foreland deformation was overwhelmed by the deposition of the Nenana Gravel, a thick sequence of coarse alluvial fan and coalescing braidedplain deposits. This unit signals a major drainage reversal after 6.7 Ma (Wahrhaftig, 1958, 1987; Triplehorn et al., 2000). The Nenana Gravel filled the former foreland basin of the Alaska Range until widespread deformation propagated northward, and motion across thrust and/or reverse faults uplifted these deposits above local base level (Thoms, 2000; Bemis and Wallace, 2007). As the former basin surface, the upper surface of the Nenana Gravel forms a distinct geomorphic surface of possibly early Quaternary age (Wahrhaftig, 1987; Bemis, 2010) and is an important marker for determining cumulative uplift and deformation since that time. Where the Neogene sedimentary sequence has been stripped in the northern Alaska Range, the topography of the more resistant crystalline basement rocks of the Yukon-Tanana terrane often exhibits a subplanar surface representing the exhumed unconformity between the bedrock and Usibelli Group and/or Nenana Gravel. Prior to the 2002 Denali fault earthquake sequence, most of the shallow crustal seismicity of interior Alaska occurred in a broad zone between the Denali and Tintina faults and between 152° W and 146° W (Ruppert et al., 2008). In this area, prominent NNE-trending lineaments of seismicity with predominantly left-lateral focal mechanisms (Page et al., 1995; Ruppert et al., 2008) are associated with the Salcha, Fairbanks, Minto Flats, Rampart, and Dall City seismic zones. However, these lineaments have no known surface traces, despite the occurrence of three Ms>7 earthquakes associated with these seismic zones since 1900 (Page et al., 1995; Ratchkovski and Hansen, 2002).

**QUATERNARY FAULTS OF THE NORTHERN ALASKA RANGE**

Most of our current understanding of Quaternary tectonics in the northern Alaska Range is derived from the following studies: (1) Wahrhaftig’s geologic mapping and related studies in the western northern foothills (Fig. 2) (Wahrhaftig, 1958, 1968, 1970a–1970h; Wahrhaftig et al., 1969); (2) active faulting investigations for the Trans-Alaska pipeline system (TAPS) prior to development (Woodward-Lundgren and Associates, 1974; Brogan et al., 1975); (3) post–2002 Denali fault earthquake investigations (Carver et al., 2006); (4) synthesis of published and unpublished neotectonic data for Alaska (Plafker et al., 1994); (5) structural and geomorphic studies in the western northern foothills (Bemis, 2004, 2010; Bemis and Wallace, 2007); and (6) the Alaska Division of Geological and Geophysical Surveys geologic framework studies for the Alaska Highway corridor between the Delta River and Canadian border (Carver et al., 2008, 2010). Taken together, these studies define a system of Quaternary faults in the northern Alaska Range extending from Denali in the west, to near the town of Tok in the east (Fig. 2). For most of this distance, the topographic range front is defined by active faults or folds. These structures form the boundary between the actively uplifting Alaska Range and the subsiding Tanana Basin. To describe the Quaternary faulting of the northern Alaska Range, we divide it into regions based on along-strike structural changes, which essentially correspond with the manner in which each region has been previously described. For each region, we describe the major faults and style of deformation and introduce new observations from previously unpublished studies. Additional data for each fault are contained in Table 1.

**Kantishna Hills**

The Kantishna Hills region (Fig. 3) is the least studied in terms of Quaternary deformation despite the high rate of instrumental seismicity...
Figure 2. Quaternary faults of the northern Alaska Range. Map shows the extent of known Quaternary faults north of the Denali fault discussed in this paper and the direct relationship of these faults with the topographic extent of the northern Alaska Range. Regions noted in text are shown in all-caps, towns and other locations shown in title case, rivers labeled with white italicized letters, and major crustal faults labeled with black italicized letters. Faults shown here with simplified traces. NFFTB—northern foothills fold-thrust belt; TF—Totschunda fault. Base imagery is a slope map (black—steep, white—flat) overlain with the U.S. Geological Survey 30-m digital elevation model (elevation gradient from green [low] to white [high]). The white portion of the elevation scale roughly corresponds with the glaciated high peaks along the axis of the Alaska Range. Figures 3 through 6 use the same base image and will show each major region of the northern Alaska Range deformation from west to east.

associated with the Kantishna cluster (Ruppert et al., 2008). Seismicity here does not clearly correspond with known faults, although cumulative deformation results in two primary topographic elements, the Kantishna Hills proper, and a band of mountains immediately north of the Denali fault. Occurrences of the Nenana Gravel on the flanks of the Kantishna Hills (Reed, 1961) demonstrate the antclinal origin of this landform. Geomorphic evidence of late Quaternary faulting at the southwest end of the Kantishna Hills and convex profiles of an antecedent stream (Lesh and Ridgway, 2007) indicate that the anticline is active and propagating to the southwest. Based on the presence of uplifted Nenana Gravel-like sediments near the Denali fault (Reed, 1961) and our reconnaissance mapping on air photos and satellite images north of Mount McKinley, we infer the existence of a thrust fault that accommodates uplift along the range front (herein named the Peters Dome fault; Fig. 3). Although field investigations have not examined this fault, late Pleistocene activity of the Peters Dome fault is inferred from the presence of apparent scarp in moraine deposits along the fault trace.

Also within these mountains is the East Fork fault, which is only documented by Plafker et al. (1994) and displays an unvegetated, 4-m-tall, late Holocene fault scarp with open fissures that are visible on recent satellite images. Based on the style of bedrock deformation (Reed, 1961) and topographic trends, we suspect that additional Quaternary faults occur adjacent to the East Fork fault, as well as along the Minto Flats seismic zone, but the resolution and focus of our mapping has not been sufficient to recognize late Quaternary deformation. The zone of deformation north of the Denali fault becomes narrower west of the Kantishna Hills as indicated by the relatively narrow band of hills between the Denali fault and the basin to the north.

Western Northern Foothills

An abrupt change in topographic grain between the broad, NE-SW-trending antclinal ridge of the Kantishna Hills (Fig. 3) and the E-W-trending ridges and broad, plateau-like uplift to the east (Fig. 4) constitutes the boundary (Fig. 2) between the Kantishna Hills and the western northern foothills fold-thrust belt. This boundary also corresponds with the NNE alignment of earthquakes associated with the southern end of the Minto Flats seismic zone. The western northern foothills fold-thrust belt is also bound by the Tanana basin to the north, the Hines Creek fault to the south, and the Wood River to the east (Fig. 4). The general bedrock geology and Quaternary stratigraphy are documented in a series of eight geologic maps (Wahrhaftig, 1970a–1970h) and a number of related papers (Wahrhaftig, 1958, 1968; Wahrhaftig et al., 1969). Subsequent workers have revised and refined the understanding of the Neogene stratigraphic record (e.g., Ridgway et al., 1999, 2007; Thoms, 2000) and recently developed the framework of faults that accommodates the Quaternary uplift and deformation of this region (Bemis and Wallace, 2007; Bemis, 2010).

Faults and folds of the western northern foothills fold-thrust belt trend approximately east-west, with both north- and south-vergent structures. Additional faults occur oblique to this trend, and these appear to be subvertical faults that correspond with lateral changes in the structural style of the fold-thrust belt (Fig. 4; Bemis and Wallace, 2007; Bemis, 2010). The Northern Foothills thrust extends the entire length of the western northern foothills fold-thrust belt,
<table>
<thead>
<tr>
<th>Fault name</th>
<th>Activity*</th>
<th>Youngest offset unit</th>
<th>Geomorphic expression</th>
<th>Dip direction</th>
<th>Dip (°)§</th>
<th>Relative motion#</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Billy Creek fault</td>
<td>Holocene</td>
<td>Holocene colluvium</td>
<td>Fault scarps</td>
<td>?</td>
<td>&gt;60</td>
<td>LL, NW-up</td>
<td>Carver et al. (2008)</td>
</tr>
<tr>
<td>Canteen fault</td>
<td>Holocene</td>
<td>Holocene loess, pond</td>
<td>Scars, offset moraines</td>
<td>?</td>
<td>&gt;60</td>
<td>LL, NW-up</td>
<td>Carver et al. (2008)</td>
</tr>
<tr>
<td>Cathedral Rapids fault</td>
<td>Holocene</td>
<td>Holocene alluvium</td>
<td>Scars</td>
<td>S</td>
<td>15–60?</td>
<td>S-up</td>
<td>Carver et al. (2010)</td>
</tr>
<tr>
<td>Ditch Creek fault</td>
<td>Quaternary</td>
<td>Nenana Gravel</td>
<td>Long-term scarp on Nenana Gravel surface</td>
<td>SW?</td>
<td>&gt;60?</td>
<td>SW-up</td>
<td>Modified from Carver et al. (2006)</td>
</tr>
<tr>
<td>East Fork fault</td>
<td>Holocene</td>
<td>Modern surface</td>
<td>Fresh scarp, open fissures in tundra</td>
<td>S?</td>
<td>&gt;60?</td>
<td>N-up</td>
<td>Reed (1961), Pfafker et al. (1994)</td>
</tr>
<tr>
<td>Eva Creek fault</td>
<td>Quaternary</td>
<td>Nenana Gravel</td>
<td>Topographic lineaments</td>
<td>?</td>
<td>&gt;60?</td>
<td>N-up</td>
<td>Allen et al. (2006)</td>
</tr>
<tr>
<td>Gold King fault – Section A</td>
<td>Late Pleistocene</td>
<td>Late Pleistocene fluvial terraces</td>
<td>Scarp across multiple terraces</td>
<td>S</td>
<td>15–30</td>
<td>S-up</td>
<td>Bemis (2010)</td>
</tr>
<tr>
<td>Granite Mountain fault – Section A</td>
<td>Holocene</td>
<td>Alluvial fans, modern surface</td>
<td>Open fissures, offset moraines</td>
<td>?</td>
<td>&gt;60?</td>
<td>LL, NE-up</td>
<td>Holmes and Péwé (1965), Brogan et al. (1975), Nokleberg et al. (1992)</td>
</tr>
<tr>
<td>Granite Mountain fault – Section B</td>
<td>Quaternary</td>
<td>Nenana Gravel</td>
<td>Topographic breaks-in-slope</td>
<td>SW</td>
<td>30–60?</td>
<td>S-up</td>
<td>Nokleberg et al. (1992)</td>
</tr>
<tr>
<td>Healy Creek fault</td>
<td>Late Pleistocene</td>
<td>Mid/late Pleistocene fluvial terrace</td>
<td>Scarp on terrace surface</td>
<td>N</td>
<td>60–90?</td>
<td>N-up</td>
<td>Wahrhaftig (1970g), Bemis and Wallace (2007), Bemis (2010)</td>
</tr>
<tr>
<td>Kantishna Hills anticline</td>
<td>Quaternary</td>
<td>Pleistocene(?) alluvial surface</td>
<td>Folded alluvial surfaces</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>Lesh and Ridgway (2007)</td>
</tr>
<tr>
<td>Macomb Plateau fault</td>
<td>Quaternary</td>
<td>Erosion surface</td>
<td>Long-term scarp on erosion surface</td>
<td>S</td>
<td>15–60?</td>
<td>S-up</td>
<td>This study</td>
</tr>
<tr>
<td>McGinnis Glacier fault</td>
<td>Holocene</td>
<td>Modern surface</td>
<td>Tension gashes in modern surface</td>
<td>SW?</td>
<td>&gt;45?</td>
<td>SW-up</td>
<td>Brogan et al. (1975), Nokleberg et al. (1992)</td>
</tr>
<tr>
<td>Molybdenum Ridge</td>
<td>Holocene</td>
<td>Alluvial/colluvial deposits</td>
<td>Steep scarp facet at base of older scarp</td>
<td>S</td>
<td>15–45</td>
<td>S-up</td>
<td>Carver et al. (2006)</td>
</tr>
<tr>
<td>Northern Foothills thrust</td>
<td>Late Pleistocene</td>
<td>Late Pleistocene fluvial terrace</td>
<td>Scarp, range front monocline</td>
<td>S</td>
<td>15–45?</td>
<td>S-up</td>
<td>Bemis and Wallace (2007), Bemis (2010)</td>
</tr>
<tr>
<td>Panoramic fault</td>
<td>Late Pleistocene</td>
<td>Alluvial surface</td>
<td>Surface offset across Panoramic Creek</td>
<td>S</td>
<td>&gt;60?</td>
<td>NE-up</td>
<td>Carver et al. (2008)</td>
</tr>
<tr>
<td>Park Road fault</td>
<td>Late Pleistocene</td>
<td>Alluvial fans</td>
<td>Lineaments and intermittent scarps</td>
<td>N</td>
<td>30–90?</td>
<td>N-up</td>
<td>Bemis and Wallace (2007)</td>
</tr>
<tr>
<td>Peters Dome fault</td>
<td>Quaternary</td>
<td>Nenana Gravel, moraines?</td>
<td>Long-term scarp uplifting Nenana Gravel</td>
<td>S</td>
<td>15–45?</td>
<td>S-up</td>
<td>This study</td>
</tr>
<tr>
<td>Potts fault</td>
<td>Quaternary</td>
<td>Alluvial surface</td>
<td>Lineaments, disrupted drainage</td>
<td>?</td>
<td>&gt;60?</td>
<td>NE-up</td>
<td>Bemis (2010)</td>
</tr>
<tr>
<td>Rex fault</td>
<td>Late Pleistocene</td>
<td>Late Pleistocene outwash</td>
<td>Surface offset across large drainage</td>
<td>S</td>
<td>&gt;30</td>
<td>S-up</td>
<td>Carver et al. (2006)</td>
</tr>
<tr>
<td>Stampede fault</td>
<td>Late Pleistocene</td>
<td>Late Pleistocene fluvial terraces</td>
<td>Fold scarps in multiple terraces</td>
<td>N</td>
<td>15–30</td>
<td>N-up</td>
<td>Bemis and Wallace (2007), Bemis (2010)</td>
</tr>
<tr>
<td>Trident Glacier fault</td>
<td>Quaternary</td>
<td>Nenana Gravel</td>
<td>Topographic breaks-in-slope</td>
<td>S</td>
<td>30–60?</td>
<td>S-up</td>
<td>Nokleberg et al. (1992)</td>
</tr>
</tbody>
</table>

*Time period during which the most recent displacement of the fault is constrained. Use of Quaternary indicates that significant displacement has occurred, but recent offset geologic markers or detailed field studies do not exist. Late Pleistocene indicates offset or deformation of landforms/deposits within the past ~130,000 yr. Holocene indicates that geomorphic evidence or paleoseismic studies establish surface offset within the past ~12,000 yr.

§Queried dip values indicate that these were estimated based on geomorphic expression and the mapped trace of the fault.

#LL—left-lateral motion, RL—right-lateral motion, n/a—not applicable.
Figure 3. Quaternary faults and deformation of the Kantishna Hills area. The large dotted line is along the Minto Flats seismic zone, which separates the Kantishna Hills from the western northern foothills fold-thrust belt. Incised meanders of the McKinley River where it crosses the axis of the Kantishna Hills anticline demonstrate recent activity of this structure (Lesh and Ridgway, 2007). HCF—Hines Creek fault; SF—Stampede fault. This and subsequent figures use the following typical fault symbology: solid—certain, long dashes—inferred, dotted—concealed, and queries indicate existence is uncertain.

typically occurring near the base of a large monocline that marks the northern margin of the Alaska Range. Studies of this fault near the Nenana and Wood rivers (Fig. 4; Bemis, 2010) suggest that these parts of the Northern Foothills thrust have not produced a surface rupture during the Holocene, although late Pleistocene activity is apparent due to offsets of fluvial terraces. The Stampede fault is clearly defined by the steep forelimb of a bedrock-cored anticline and a fold scarp that progressively offsets several middle and late Pleistocene fluvial terraces (Bemis and Wallace, 2007; Bemis, 2010). The Park Road fault also occurs on the south flank of a bedrock-cored anticline, with the trace of the fault defined by intermittent scarp in alluvial fans, deformed Nenana Gravel, and mapped bedrock offsets (Sherwood and Craddock, 1979; Bemis and Wallace, 2007). The Healy fault has a well-defined scarp where it offsets several fluvial terraces. Paleoseismic trenching demonstrates that the most recent rupture was between 500 and 1600 yr ago (Bemis, 2010). The Healy Creek fault has a distinct scarp where it offsets older fluvial terraces, but latest Pleistocene terraces are not offset (Wahrhaftig, 1970g; Brogan et al., 1975; Bemis, 2010). Cumulative displacement across the Healy Creek fault appears to decrease significantly west of the Nenana River, presumably transferring slip onto the adjacent Stampede fault (Bemis and Wallace, 2007). The Eva Creek fault is mapped by Athey et al. (2006) to offset the Nenana Gravel and corresponds with a topographic lineament, but the recent activity of this fault is unknown. The Mystic Mountain, Kansas Creek, and Ditch Creek faults appear to be a complex system of NW-striking, SW-side-up oblique-slip faults connected by east-west striking thrust and/or reverse faults (Bemis and Wallace, 2007). All three faults are associated with deformation of the Nenana Gravel, and Carver et al. (2006) indicate the presence of late Pleistocene scarp. The Gold King fault and related structures accommodate the uplift and deformation of the Japan Hills anticline north of the Northern Foothills thrust (Fig. 4).

The western part of the Gold King fault is a north-vergent thrust fault that progressively offsets a sequence of late Pleistocene terraces. The eastern portion of this fault has a south-vergent surface trace and is clearly defined at the surface by monoclinal folding of the uppermost beds of the Nenana Gravel (Bemis, 2010).

Because the individual faults and folds within this zone are superimposed on the uplift of the entire region, Bemis and Wallace (2007) interpreted that the Northern Foothills thrust is the surface trace of a basal detachment that extends underneath this region at least to the Hines Creek fault. Therefore, the smaller-wavelength folds within this zone (such as the folds associated with the Stampede and Park Road faults; Fig. 4) are the expression of shortening within the hanging wall of the Northern Foothills thrust. Based on slip rates inferred from the deformation of Pleistocene fluvial terraces by Bemis (2010), we estimate a maximum value of ~3 mm/yr of horizontal shortening across the northern foothills fold-thrust belt west of the Nenana River.

The Hines Creek fault juxtaposes rocks of the Yukon-Tanana terrane (a Cretaceous metamorphic assemblage of Precambrian–Paleozoic metamorphic rocks and Mesozoic plutons [e.g., Pavlis et al., 1993; Hansen and Dusel-Bacon, 1998; Dusel-Bacon et al., 2004]) to the north, with Paleozoic to Paleogene rocks representative of marine environments to the south (Wahrhaftig et al., 1975). This fault also approximates a boundary between the rugged, recently glaciated terrain of the main axis of the Alaska Range and the northern foothills of the Alaska Range, which contain widespread Neogene deposits and landforms that span Quaternary time. Locally the Hines Creek fault is described as deforming Neogene deposits, although different workers have mapped this fault in different locations (e.g., Wahrhaftig, 1958; Sherwood and Craddock, 1979; Csejty et al., 1992).

Bemis and Wallace (2007) reinterpreted some of this previous mapping to suggest that this late Cenozoic deformation results from motion on adjacent contractual faults. At one location, a short segment of the fault mapped near the Nenana River and Denali Park headquarters offsets late Pleistocene glacial outwash deposits ~6 m down to the south (Wahrhaftig, 1958; Wahrhaftig et al., 1975).

Plafker et al. (1994) document several faults between the Denali and Hines Creek faults as “suspicious” and two as being active during the Quaternary. Subsequent reconnaissance work in the region has not identified additional evidence for Quaternary activity of these suspi-
Transition Zone between the Western and Eastern Northern Foothills

Most geologic mapping of the northern foothills between the Wood and Delta rivers of the Alaska Range has been published at 1:250,000 scale (Csejty et al., 1992; Nokleberg et al., 1992), and as a result, only captured some of the basic details of possible Quaternary deformation. What is clear from this previous mapping is that the major east-west–trending anticlines of the western northern foothills fold-thrust belt (Fig. 4), as defined by the deformed Nenana Gravel, transition to structures of the eastern northern foothills fold-thrust belt coincident with a southerly step in the topographic range front and a narrowing of the Alaska Range north of the Denali fault (Fig. 5).

Active faulting investigations performed prior to the development of the Trans-Alaska pipeline system (Woodward-Lundgren and Associates, 1974; Brogan et al., 1975) identified the McGinnis Glacier fault as an active fault. These studies describe evidence suggestive of a Holocene surface rupture including north-south-oriented, en echelon tension cracks across glaciofluvial deposits in several valleys. However, the tectonic history and structural relation to the northern foothills fold-thrust belt and/or the Denali fault system remain unclear. Nokleberg et al. (1992) provide additional map documentation of the McGinnis Glacier fault, and also map the Trident Glacier fault as displacing Nenana Gravel–like deposits, indicating Quaternary activity of this fault.

Post–2002 Denali fault earthquake investigations for the Alyeska Pipeline Service Company identified evidence for additional Quaternary faults. The results of these studies are only presented in an abstract by Carver et al. (2006), and thus Table 1 and Figure 5 summarize the evidence for these faults from their mapping. Although Carver et al. (2006) did not include detailed fieldwork west of the Delta River, their regional reconnaissance identified late Pleistocene and Holocene fault scarps associated with several previously mapped faults, including the Red Mountain fault (Csejty et al., 1992), Glacier Creek fault (Wahrhaftig 1970e; Bemis and Wallace, 2007), and the eastern end of the Northern Foothills thrust (Bemis and Wallace, 2007). In addition to late Quaternary fault scarps, the Red Mountain and Glacier Creek faults bound the north side of bedrock uplifts and are closely associated with folded Neogene deposits. The eastern end of the Northern Foothills thrust is associated with a large anticline, under which the fault becomes a blind thrust as the anticline begins to plunge to the east. Carver et al. (2006)
Dome fault was originally defined as a normal and Dot “T” Johnson faults. The Donnelly to east, the Donnelly Dome, Granite Mountain, Eastern Northern Foothills Fold-Thrust Belt glacial deposits. Nenana Gravel–equivalent and late Pleistocene cumulative displacements, and appear to offset (Fig. 5). The Rex and Trident faults have low disturbed surface drainage across the anticlinal axis, which has dis- subtle folding of the landscape, which has dis- 

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also document several previously unknown Quaternary faults, including the Molybdenum Ridge fault, the Rex fault, and the Trident fault (Fig. 5). The Molybdenum Ridge fault is clearly defined by fault scarps for ~30 km. Farther east, surface deformation from this fault appears as subtle folding of the landscape, which has disturbed surface drainage across the anticlinal axis (Fig. 5). The Rex and Trident faults have low cumulative displacements, and appear to offset Nenana Gravel–equivalent and late Pleistocene glacial deposits.

Eastern Northern Foothills Fold-Thrust Belt

Along the northern margin of the Alaska Range east of the Delta River, the range front defines a series of left steps, including from west to east, the Donnelly Dome, Granite Mountain, and Dot “T” Johnson faults. The Donnelly Dome fault was originally defined as a normal fault (Péwé and Holmes, 1964), but was subsequently redefined as a reverse fault (Nokleberg et al., 1992). Moraines of the late Pleistocene Donnelly Dome glacial advance are offset 3–9 m (Brogan et al., 1975), and trenching demonstrates that this fault has ruptured during the Holocene (Carver et al., 2006; Table 1). Directly east of the Donnelly Dome fault, the northeast-striking portion of the Granite Mountain fault displays SE-side-up, left-lateral slip where it offsets late Pleistocene glacial deposits. Here, the northeast-trending Panoramic fault offsets Holocene alluvium on the south side of the Tanana River valley and, together with the Granite Mountain fault, may be kinematically linked to the Donnelly Dome fault (Fig. 6). The Granite Mountain fault follows the range front around an ~90° bend to the southeast, and becomes a predominantly reverse-slip fault (Carver et al., 2008). The predominantly left-lateral Canteen fault forms a link between the Granite Mountain fault and the Dot “T” Johnson fault across another left step in the range front. The Canteen fault is delineated by left-laterally offset latest Pleistocene glacial moraines (Carver et al., 2008). The previously unknown Dot “T” Johnson fault is nearly continuous along the range front for the next ~40 km between the Canteen fault and the town of Dot Lake (Fig. 6). Geomorphic mapping and trench studies indicate that the Dot “T” Johnson fault is a Holocene-active thrust fault (Carver et al., 2008, 2010). East of Dot Lake, the range front steps to the south, and evidence for active faulting is absent in the late Pleistocene glacial deposits of the Robertson River.

East of the Robertson River, the Cathedral Rapids fault extends for ~40 km near the Tok River valley (Fig. 6). The western half of this fault is characterized by well-developed triangular facets on the range front and three sub-parallel, sinuous, south-dipping thrust splays. These fault splays offset late Pleistocene glacial deposits and Holocene alluvium (Koechler et al., 2010). The eastern half of this fault is characterized by an anticline that progressively deforms alluvial fan deposits along the northern range front. Offset and folded terraces as well as paleoseismic excavations indicate late Pleistocene and Holocene displacement of the Cathedral Rapids fault (Carver et al., 2010). Although Plafker et al. (1994) noted numerous suspect lineaments in the Tok River valley and to the northeast as potential Quaternary faults, investigations by Carver et al. (2010) did not find evidence for Quaternary activity on any of these features.

Outside of the range-bounding faults, there are two additional Quaternary faults in this portion of the northern Alaska Range. Carver et al. (2008, 2010) investigated geophysical and geomorphic lineaments north of the Tanana River, and only documented evidence for Quaternary displacement on the Billy Creek fault (Fig. 6). Within the Alaska Range, we infer the Mcambo Plateau fault based on the large (100–200 m) sinuous scarp that appears to offset the broad Mcambo Plateau surface (Fig. 6).

Slip-rate information for the eastern northern foothills fold-thrust belt is limited to measurements on offset late Pleistocene moraines cut by the Canteen fault, part of the Dot “T” Johnson fault system that suggests a left-lateral slip rate of 1.6 mm/yr (Carver et al., 2008). We can also estimate a slip rate for the adjacent, and likely kinematically connected Granite Mountain fault. Carter (1980) measured a 1000 m section of tilted Nenana Gravel on the footwall of the Granite Mountain fault, which has uplifted a bedrock unconformity containing relict patches of Nenana Gravel (Homes and Péwé, 1965) on its hanging wall ~1 km above the exposure. This suggests up to 2 km of vertical separation on the upper surface of the Nenana Gravel. Therefore, assuming a 30° dip for the Granite Mountain fault and allowing for generous uncertainties in the early Quaternary age of the upper Nenana

![Figure 5. Quaternary faults and deformation of the transitional zone between the western and eastern northern foothills fold-thrust belt (NFFTB). The Northern Foothills thrust, which is continuous along the entire range front of the western NFFTB, terminates into large, east-plunging Rex anticline. This anticline deforms late Pleistocene terraces along the Little Delta River. Beyond this to the east, the range-bounding faults step southward, closer to the Denali fault. The Molybdenum Ridge fault forms a link between the Granite Mountain fault and the Dot “T” Johnson fault across another left step in the range front. The Canteen fault and the Dot “T” Johnson fault across a relict patches of the Nenana Gravel (Homes and Péwé, 1965) on its hanging wall ~1 km above the exposure. This suggests up to 2 km of vertical separation on the upper surface of the Nenana Gravel. Therefore, assuming a 30° dip for the Granite Mountain fault and allowing for generous uncertainties in the early Quaternary age of the upper Nenana...](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/8/1/196/3341856/196.pdf)
Gravel and the fault dip, we suggest a horizontal shortening rate of 1–4 mm/yr. This range is consistent with the slip rate for the Canteen fault, and suggests that either the Granite Mountain fault has a similar slip rate or, if faster, that the Canteen fault accommodates only a portion of the shortening across this portion of the northern Alaska Range.

**EXTENT AND CHARACTER OF THE NORTHERN ALASKA RANGE THRUST SYSTEM**

Active faults exist in an essentially continuous system as part of the northern Alaska Range for ~500 km, from Denali to the town of Tok (Fig. 2). Faults or folds that exhibit late Pleistocene to Holocene activity define the range front for essentially this entire distance. The relatively persistent style of plateau-like uplift suggests that much of the uplift occurs over a south-dipping basal thrust fault that underlies much of the northern Alaska Range. In the western northern foothills fold-thrust belt, the widespread preservation of the upper surface of the Nenana Gravel defines this uplift (Fig. 4). Along the eastern northern foothills fold-thrust belt, bedrock surfaces with local remnants of Nenana Gravel-like deposits (Holmes and Péwé, 1965; Holmes and Foster, 1968) define a similar style of regional uplift. Within the hanging wall of the basal thrust are additional thrust faults that superimpose localized zones of deformation upon the regional uplift. Long-term subsidence of the foreland basin to the north is indicated in the Tanana basin (Fig. 2) by the thick sequence of sedimentary fill (Hanson et al., 1968).

The mapped western and eastern extents of Quaternary faulting in the northern Alaska Range correspond with significant geometric complexities of the Denali fault system. The Peters Dome fault occurs immediately north of an abrupt ~17° bend in the Denali fault, inside of which is the high topography of Denali (Figs. 2 and 3). West of this fault bend, the Denali fault displays Quaternary activity (Reed and Landerhore, 1974; Pfaffker et al., 1994; Bundtzen et al., 1997), but significant topography north of the fault is absent. At the eastern end of the northern Alaska Range, Carver et al. (2010) did not identify any evidence for Quaternary faulting east of Tok, and the topography immediately north of the Denali fault is subdued relative to the rugged mountains of the eastern northern foothills fold-thrust belt. This eastern termination of the northern foothills fold-thrust belt near the Tok River valley (Fig. 6) lies immediately north of the intersection between the Totschunda and Denali faults (Fig. 2), suggesting that the angular difference between these two faults may play a role in the occurrence of shortening north of the Denali fault.

The NNE-trending faults of the eastern northern foothills fold-thrust belt, the Granite Mountain fault, Canteen fault, and perhaps a similarly oriented portion of the Dot “T” Johnson fault (Fig. 6), are aligned with faults and geophysical lineaments mapped in the Yukon-Tanana Uplands well to the north of the Alaska Range (e.g., Foster, 1970; Carver et al., 2008). A widely accepted regional model proposed by Page et al. (1995) suggests that the NNE-trending faults could be throughgoing active structures accommodating clockwise block rotations and offsetting the range front of the Alaska Range. However, because the Quaternary displacement across the NNE-trending faults appears to be mostly restricted to between thrust fault segments (Carver et al., 2008, 2010), we argue that these NNE-trending faults are older bedrock structures that have been reactivated locally as lateral tears in the Dot “T” Johnson fault thrust sheet. This would suggest that, although active, the NNE-trending faults may not rupture independent of the adjacent thrust fault segments.

Figure 6. Quaternary faults of the Dot “T” Johnson fault system. Note the left-stepping pattern of faulting between Dot Lake and the Delta River. PF—Panoramic fault. (A) and (B) refer to sections A and B of the Granite Mountain fault, with their individual characteristics described in Table 1.
CONCLUSIONS

Although only basic characteristics are known for most faults in the northern Alaska Range, the pattern of uplift and regional continuity of structures demonstrates the presence of a system of Quaternary faults that accommodate recent uplift north of the Denali fault. This system is contractual in nature, with most of the major, topography-building faults being thrust and reverse faults. The strike-slip and oblique-slip faults are oriented to accommodate the same shortening direction as defined by the thrust and reverse faults. Faults are active both at the range front and within the range and, in general, the system exhibits the characteristics of being a basement-involved fold-thrust belt.

The occurrence of this 500-km-long zone of Quaternary faults represents a regional, and poorly understood, seismic hazard. Each individual fault in the northern Alaska Range presumably has a relatively low seismic hazard due to relatively low slip rates; however, when viewed as a system, the seismic hazard should be much more significant. We hope this summary will be a foundation for improvements in the understanding of central Alaska tectonics by providing a geologic context for regional seismicity and geodetically determined crustal strain.

Forthcoming improvements to the coverage of high-resolution orthoimagery and modern digital elevation models will facilitate more accurate mapping of regional faults and help target field sites for fault characterization studies. Many opportunities also exist for refining the glacial chronologies and the ages of related landforms, which would provide key constraints for fault slip rates. In addition to improving our understanding of these known faults, with the rate at which new Quaternary faults have been identified in recent years, we expect more faults to be found during future detailed studies. In particular, an important complement to our current understanding of the northern Alaska Range will be to address the potential for unknown Quaternary faults south of the Denali fault, such as the Susitna Glacier fault, which was unknown prior to being the initiation point of the 2002 M7.9 Denali fault earthquake sequence (Eberhart-Phillips et al., 2003).

ACKNOWLEDGMENTS

Studies contributing to this manuscript were partially supported by the Alaska Division of Geological and Geophysical Surveys and U.S. Geological Survey National Earthquake Hazards Reduction Program external grants 07HQGR0018 and 08HQGR0074. This manuscript benefited significantly from reviews by T. Pavlis, A. Cyr, and G. Pfirken.

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