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PETROLEUM-RELATED GEOLOGIC STUDIES IN LOWER COOK INLET DURING 2015, INISKIN–TUXEDNI REGION, SOUTH-CENTRAL ALASKA

by
Trystan M. Herriott, editor

Two geologists (sitting, center-right) record observations at the unconformable contact between maroon-brown Upper Jurassic Naknek Formation sandstone (uniform surface in foreground) and a relatively thin wedge of locally oil-bearing orange-brown Maastrichtian(?) strata (middle view; see Gillis, this volume). A relatively thick package of medium gray Paleogene West Foreland Formation conglomerate rests unconformably on the Maastrichtian(?) section; this unconformity surface commonly cuts through the entire thickness of the Maastrichtian(?) section along the Cook Inlet basin margin. Residual oil and oil shows have been encountered in Upper Cretaceous outcrops and well intervals, respectively, throughout the basin, indicating that these strata may be viable reservoir targets in Cook Inlet's underexplored Mesozoic stratigraphy. Photograph by Robert Gillis.

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CONTENTS

FIGURES

CHAPTER 1

INTRODUCTION TO PETROLEUM-RELATED GEOLOGIC STUDIES IN LOWER COOK INLET DURING 2015, INISKIN–TUXEDNI REGION, SOUTH-CENTRAL ALASKA

Trystan M. Herriott[1], editor

INTRODUCTION

Lower Cook Inlet of south-central Alaska has long been recognized to host oil and gas, with hydrocarbon seeps noted on the Iniskin Peninsula as early as the mid-nineteenth century (Martin, 1905) (fig. 1-1). Drilling near these seeps commenced in 1900; continued exploration through 1960 also examined nearby structural culminations (Detterman and Hartsock, 1966). Although no commercial discoveries were made despite oil and gas shows in these wells (Blasko, 1976), the Iniskin–Tuxedni bays region remains important, permitting examination of the basin margin's Mesozoic stratigraphy and structure along an ~80 km outcrop belt (figs. 1-2 and 1-3). These exposures include Middle Jurassic strata that are age-equivalent to probable source rocks for oil produced from fields in upper Cook Inlet (see LePain and others, 2013). Furthermore, this onshore area is important to understanding the potential for commercial accumulations of hydrocarbons in Mesozoic strata of Cook Inlet. Notably, a recent resource estimate indicates significant oil and gas volumes remain likely to be discovered in Cook Inlet (Stanley and others, 2011), and industry-led exploration on the Iniskin Peninsula resumed in 2013 (Nelson, 2014).

Within this context, the Alaska Division of Geological & Geophysical Surveys (DGGS), in collaboration with the Alaska Division of Oil and Gas and U.S. Geological Survey, initiated a lower Cook Inlet research program in 2009. This work aims to further delineate the geology of this economically important region and is ongoing in continued recognition of the critical energy needs of south-central Alaska and the fact that the Cook Inlet forearc basin is underexplored despite a nearly 60 year oil and gas production history. The DGGS-led field investigations in the Iniskin–Tuxedni area build on the seminal study of Detterman and Hartsock (1966) and focus on modern sedimentologic, stratigraphic, and structural analyses, as well as new 1:63:360-scale geologic mapping (see below), to better characterize petroleum potential.

This volume constitutes the fourth annual publication of a collection of short papers regarding our work in lower Cook Inlet (Gillis, 2013, 2014; Wartes, 2015b). Additional standalone papers have also been released recently, including a noteworthy overview of Cook Inlet geology by LePain and others (2013) that incorporates original data from DGGS-led studies conducted throughout Cook Inlet since 2006.

GEOLOGIC MAPPING CAMPAIGNS

Detailed geologic mapping is an integral component of the Iniskin–Tuxedni bays field investigations. Two major mapping campaigns—funded in part by federal STATEMAP grants—were completed during the 2013 (Gillis and others, 2014; Herriott and Wartes, 2014) and 2015 field seasons (for example, Gillis, 2016 [this volume]; Wartes and others, 2016 [this volume]). During 2015 the field crew mapped the geology between Chinitna Bay and the Johnson River (fig. 1-1), including magmatic arc rocks northwest of the Bruin Bay fault system (see fig. 1-2) and extending to the Cook Inlet coast. This map area lies immediately northeast of the Iniskin Peninsula, which was mapped in 2013 (see references above). An important aspect of our lower Cook Inlet work is the recognition of along-strike changes in the stratigraphy and structure and the implications of these changes for depositional systems and deformation along the basin margin through time and space; geologic mapping serves as the cornerstone for documenting these trends in the geology and provides the framework for detailed analyses of the sedimentology, stratigraphy, and structural geology of the Iniskin–Tuxedni area. This information yields insights into basin evolution and petroleum systems.

VOLUME OVERVIEW

Nine topical chapters (2–10) follow this introduction, and address studies carried out during the 2015 field season. Six of these chapters (2–7) report on sedimentologic and stratigraphic investigations and are organized in ascending stratigraphic order (see fig. 1-3 for reference). The final three chapters (8–10) examine the deformational history of the Iniskin–Tuxedni region. Brief context for each chapter is presented below.

- **Chapter 2:** LePain and others (2016a [this volume]) document nonmarine facies in the Horn Mountain Tuff Member of the Lower Jurassic Talkeetna Formation and present a depositional environment interpretation for a 45-m-thick

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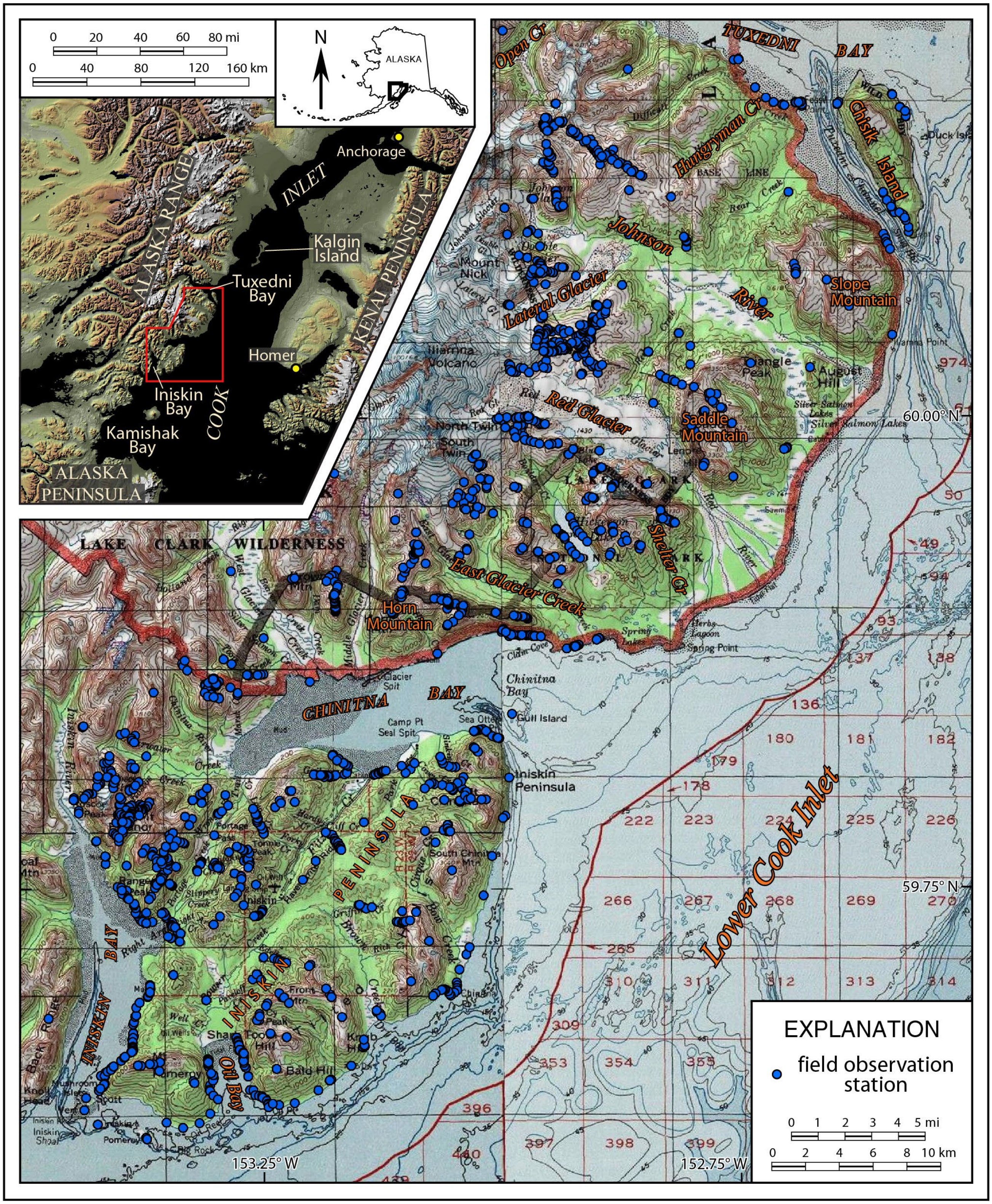

Figure 1-1. Location map for lower Cook Inlet—broadly defined as the forearc region that lies between Kalgin Island and Kamishak Bay (Fisher and Magoon, 1978; LePain and others, 2013)—and the Iniskin–Tuxedni bays study area. Geologic observations were made at ~2,000 field localities by Alaska Department of Natural Resources and U.S. Geological Survey geologists as part of the lower Cook Inlet program during six field seasons in this area. This volume reports on 2015 field studies chiefly focused on the region between Chinitna and Tuxedni bays. Detailed (1:63,360-scale) geologic mapping between Chinitna Bay and the Johnson River was also completed during 2015, building on DGGS-led mapping of the Iniskin Peninsula in 2013. Geographic place names referred to in this chapter are labeled in orange text with black outline. Topographic base map from portions of U.S. Geological Survey Iliamna, Seldovia, Lake Clark, and Kenai 1:250,000-scale quadrangles; shaded-relief image modified after U.S. Geological Survey Elevation Data Set Shaded Relief of Alaska poster (available for download at http://eros.usgs.gov/alaska-0). Abbreviation: Cr = Creek.

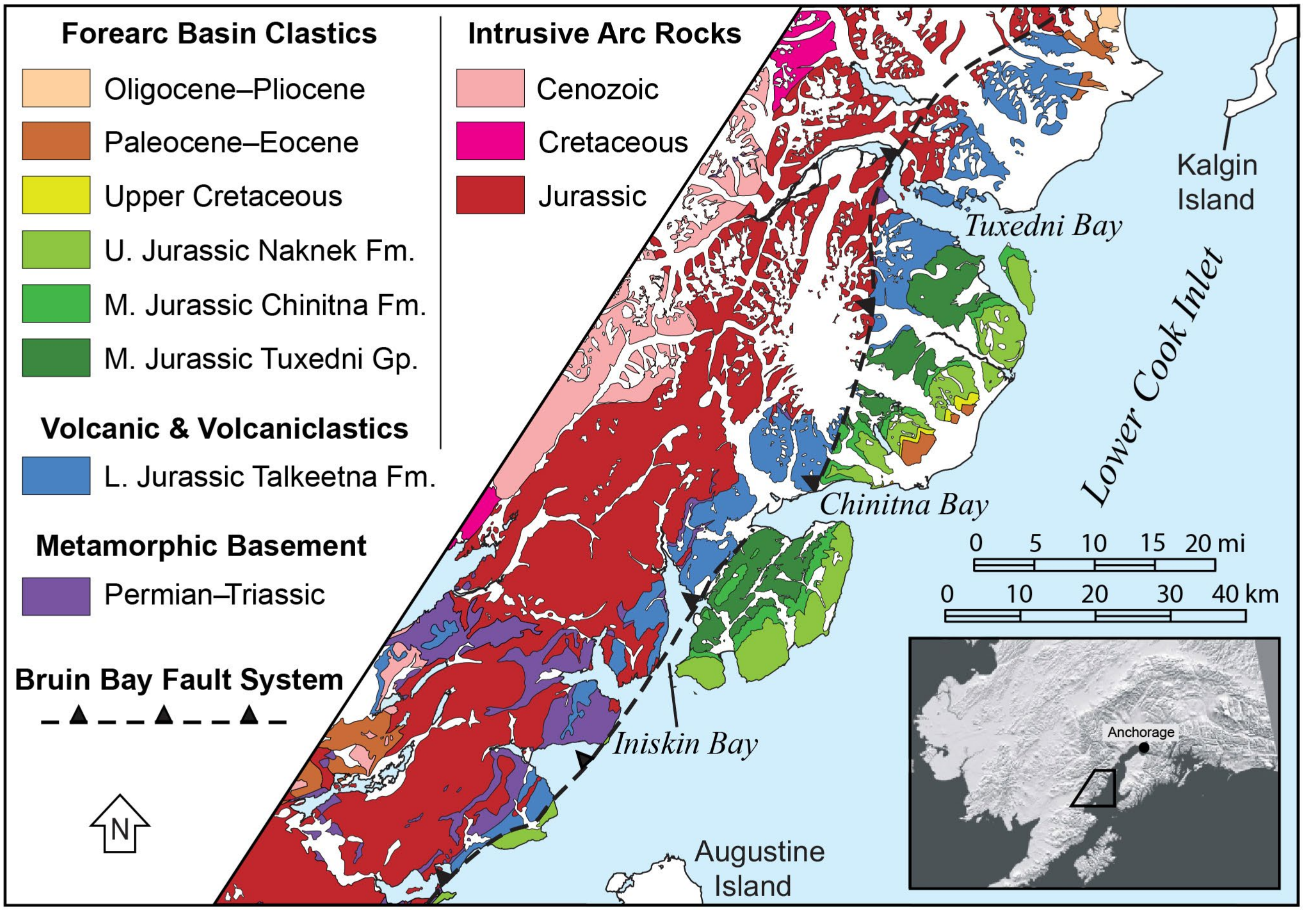

Figure 1-2. Simplified geologic map of lower Cook Inlet. The Bruin Bay fault system in this region is generally regarded as the northwestern margin of the forearc basin, with Middle Jurassic and younger forearc basin strata lying to the southeast and Lower Jurassic and younger arc rocks dominantly to the northwest (see LePain and others, 2013). Figure from Wartes (2015a); geologic mapping modified from regional compilation by Wilson and others (2009; see also Wilson and others, 2012). Abbreviations: Fm. = Formation; Gp. = Group; L. = Lower; M. = Middle; U. = Upper.

interval near Horn Mountain (fig. 1-1). This work provides a better understanding of depositional systems in the Talkeetna Formation as well as additional details regarding local paleogeographic constraints for this early manifestation of the magmatic arc.

- **Chapter 3:** LePain and others (2016b [this volume]) continue an investigation of the Middle Jurassic Red Glacier Formation (see also Stanley and others, 2013; LePain and Stanley, 2015), a stratigraphic unit that is correlative to source rocks for Cook Inlet's oil (see references above). This paper presents a sedimentologic analysis for the lower several hundred meters of the formation south of Hungryman Creek (fig. 1-1). The authors' interpreted depositional setting for this locality contrasts sharply with the Lateral Glacier (fig. 1-1) locality of LePain and Stanley (2015), suggesting along-basin-margin changes in paleo-water depth and depositional setting recorded by this economically significant formation.
- **Chapter 4:** Helmold and others (2016 [this volume]), in a companion study to chapter 3, present preliminary observations and interpretations of petrology and reservoir quality for sandstones in the Red Glacier Formation at the Hungryman Creek (fig. 1-1) locality. Despite the age and volcanogenic composition of these strata, the authors note that comparable facies in the subsurface may serve as tight-gas reservoirs. Furthermore, interfingering of lithologically similar sandstones with oil-prone source rocks could yield continuous oil accumulations in the subsurface.
- **Chapter 5:** Herriott and others (2016a [this volume]) analyze the stratigraphic architecture of the Middle Jurassic Paveloff Siltstone Member (Chinitna Formation) in the Johnson River area, between Slope and Saddle mountains (fig. 1-1). This paper documents sand-prone, channelized depositional systems that likely exported coarse detritus to downdip settings, where such deposits may host oil accumulations in the subsurface of Cook Inlet. Similar sand-rich facies in the Paveloff are oil stained in outcrop at Chinitna Bay (Wartes and Herriott, 2015).

- **Chapter 6:** Herriott and others (2016b [this volume]) continue to examine the stratigraphy of deep-water deposits in the Upper Jurassic Snug Harbor Siltstone and Pomeroy Arkose Members (Naknek Formation) (see also Wartes and others, 2013a; Herriott and Wartes, 2014; Herriott and others, 2015a). This chapter documents a newly discovered paleo-canyon at Chisik Island (fig. 1-1), with implications for bypass and accumulation of sand in deep-water settings as well as the sequence stratigraphic framework of the Naknek Formation (see also Herriott and others, 2015b). Similar deep-water depositional systems known throughout the world are important reservoirs for oil and gas.
- **Chapter 7:** Gillis (2016 [this volume]) documents porosity-hosted residual oil in sandstone of the Shelter Creek area (fig. 1-1). This outcrop lies in a Campanian to Maastrichtian(?) interval that is likely equivalent to Upper Cretaceous strata that are oil stained in outcrop elsewhere in Cook Inlet (for example, LePain and others, 2012; Wartes and others,

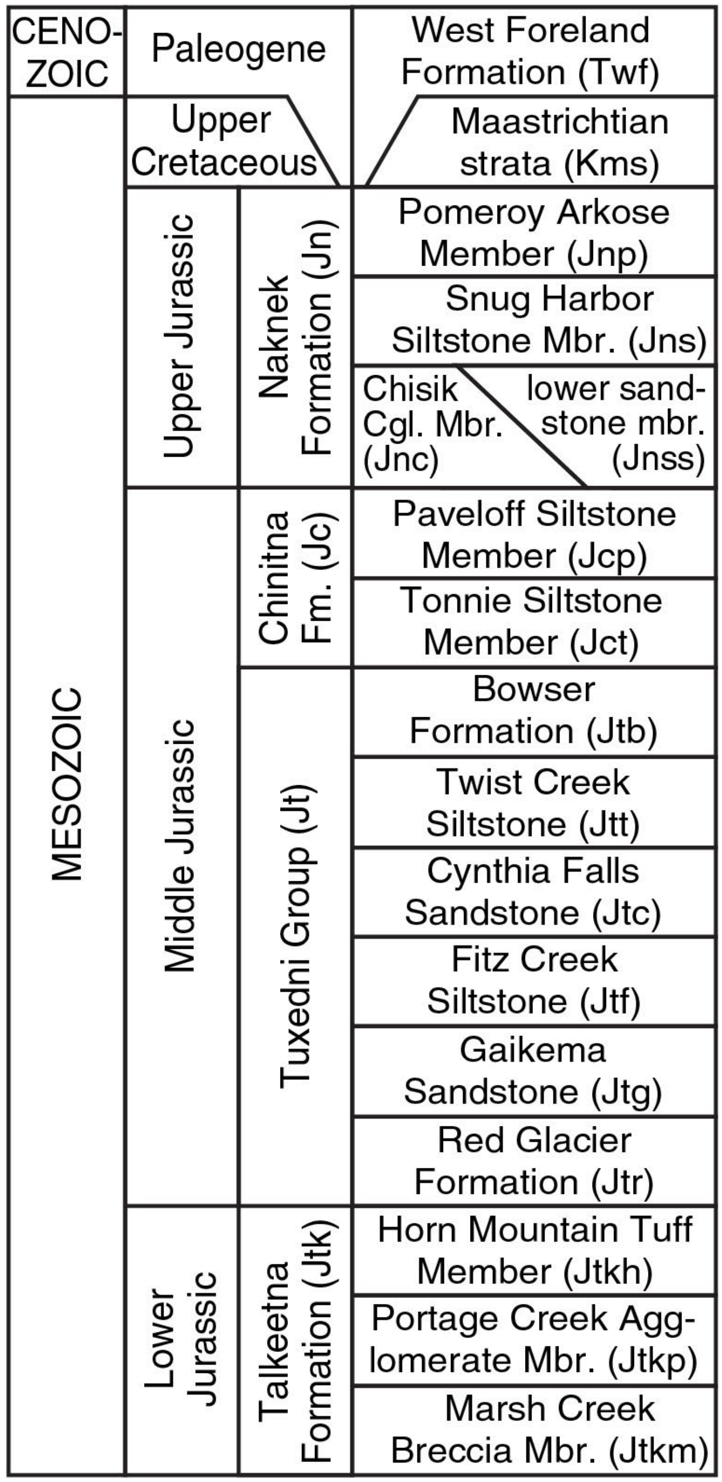

Figure 1-3. Stratigraphic column for the Iniskin–Tuxedni region. Stratigraphy modified from Detterman and Hartsock (1966) and Gillis (2016 [this volume]). Kms from Gillis (2016 [this volume]); all other map unit labels from Detterman and Hartsock (1966) and Wilson and others (2012). Abbreviations: Cgl. = Conglomerate; Fm. = Formation; Mbr. = Member; mbr. = member (informal).

2013b; Herriott and others, 2013) and yield oil shows in wells. The relatively quartz-rich nature of Upper Cretaceous deposits in Cook Inlet and their documented association with porosity-hosted oil suggest the potential for the interval to contain conventional accumulations of oil. This chapter also presents new constraints for timing of deformation in the basin, which is critical to evaluating petroleum migration and trap formation.

- **Chapter 8:** Wartes and others (2016 [this volume]) introduce new geologic mapping of the east-trending ridge between East Glacier Creek and the north shore of Chinitna Bay (fig. 1-1). Their mapping extends across the trace of the Bruin Bay fault system and is immediately north of a kilometer-scale, right-stepping bend, step-over, or offset along this regionally significant structure. The paper proposes several permissible models that may account for the large-scale structural relations across Chinitna Bay that have implications for known fracture-associated occurrences of oil and gas on the Iniskin Peninsula.
- **Chapter 9:** Rosenthal and others (2016 [this volume]) continue a regional fractures study (see also Gillis and others, 2013a; Rosenthal and others, 2015) and present results from two field localities in the Oil Bay area (fig. 1-1). These authors report higher fracture intensities at their Paveloff Siltstone Member (Chinitna Formation) locality than at their Pomeroy Arkose Member (Naknek Formation) locality, inferring that grain size is the primary control of fracture intensity. This work relates to unconventional reservoir prospectivity in the basin and development of effective well stimulation programs for potential reservoirs.
- **Chapter 10:** Betka and Gillis (2016 [this volume]) continue an investigation of the Bruin Bay fault system (see also Gillis and others, 2013b; Betka and Gillis 2014a, 2014b, 2015). New observations from fault exposures near Red Glacier, Johnson River, and Open Creek (fig. 1-1) suggest left transpression along this extent of the fault system. Fault kinematics from the three field localities record a transition from left-reverse-slip in the south to left-strike-slip in the north, probably reflecting the Bruin Bay fault system's change in strike north of the Johnson River. This work aims to constrain the nature and timing of deformation along the basin's northwest margin, which are essential elements to a comprehensive understanding of Cook Inlet petroleum systems.

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Pathfinder Aviation helicopter pilot Merlin "Spanky" Handley skillfully and safely transported field personnel during the 2015 field season. The crew thanks owners and staff of the former cannery on Chisik Island for their hospitality.

Nina Harun compiled station data plotted on figure 1-1 and Marwan Wartes rendered a version of figure 1-2. Paula Davis and Joni Robinson deftly guided this volume through the publication process with timely attention to detail. Steve Masterman carefully reviewed proofs for each of the volume's chapters. David LePain provided instructive comments for this introduction and reviewed all chapters in this volume except those he authored.

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CHAPTER 2

NONMARINE FACIES IN THE LATE TRIASSIC(?) TO EARLY JURASSIC HORN MOUNTAIN TUFF MEMBER OF THE TALKEETNA FORMATION, HORN MOUNTAIN, LOWER COOK INLET BASIN, ALASKA

David L. LePain[1], Richard G. Stanley[2], and Kenneth P. Helmold[3]

INTRODUCTION

The Talkeetna Formation is a prominent lithostratigraphic unit in south-central Alaska. In the Iniskin–Tuxedni area, Detterman and Hartsock (1966) divided the formation into three mappable units including, from oldest to youngest, the Marsh Creek Breccia, the Portage Creek Agglomerate, and the Horn Mountain Tuff Members. The Horn Mountain Tuff Member was thought to include rocks deposited in a nonmarine setting based on the presence of "tree stumps in an upright position" (Detterman and Hartsock, 1966, p. 19) near the top of the type section at Horn Mountain. Bull (2015) recognized possible nonmarine volcaniclastic rocks in the member during the 2014 field season in a saddle on the north side of Horn Mountain (figs. 2-1 and 2-2). The authors visited this location in 2015 and measured a short stratigraphic section to document facies, interpret depositional setting, and constrain age. This report summarizes our field observations and presents preliminary interpretations.

FACIES IN THE HORN MOUNTAIN TUFF MEMBER AT HORN MOUNTAIN

The measured section includes 45 m of interbedded volcaniclastic siltstone, sandstone, and granule conglomerate, and a possible air-fall tuff (fig. 2-2). Chippy, brown- to maroon-weathering, massive siltstone is the dominant facies in the section (fig. 2-3a). This facies includes scattered, irregularly shaped, centimeter-scale masses of pale-green to green-white material that resemble rhizoliths. Small ovoid-shaped patches of silty sandstone up to a few centimeters in maximum diameter are present locally in siltstone (fig. 2-3b). Wavy, slickenside striated surfaces with variable orientations in close proximity are scattered throughout the siltstone (fig. 2-3c). Brown- to maroon-weathering siltstone beds at the base of the measured section include scattered sand- and small-granule-sized crystals of white feldspar, glassy appearing grains of unknown identity, and pistachio-green altered pumice fragments (fig. 2-3d). Silicified pieces of wood up to 40 cm long are associated with siltstone near the top of the measured section (fig. 2-4a); a small log was observed in growth position in siltstone near the same stratigraphic level and rare fragments of poorly-preserved plant fossils are present in the same facies (fig. 2-4b).

Several bodies of medium- to very-coarse-grained, trough cross-bedded sandstone interrupt the siltstone succession and all have sharp bounding contacts (fig. 2-5a). Most of the sandstones are less than a meter thick and have tabular geometries at outcrop scale. However, two of these sand bodies that crop out in the lower to middle part of the measured section are up to 4 m thick and fine upward from granule conglomerate lags to coarse-grained sandstone and thin laterally, suggesting channelized geometries (fig. 2-5b). The erosion surface at the base of the lower channel-fill sand body separates it from an underlying light tan to gray-white colored, well-indurated lithology with abundant sand-sized grains floating in a fine-grained matrix that appears to be an air-fall tuff. Many of these grains appear to be flattened pumice fragments. Well-preserved plant fossils were recovered from near the base of the thick channel-fill sandstone in the middle part of the measured section (figs. 2-4c and 2-4d).

Several tabular bodies of very-poorly-sorted granule to pebble conglomerate are present in the section and two varieties are recognized. One variety of conglomerate is dominated by pumice clasts oriented parallel to bedding (figs. 2-6a and 2-6b) and the other by lithic clasts. Conglomerate beds range from less than 10 cm to more than 4 m thick and both matrix- and clast-supported textures are represented in thin and thick beds. Most beds are structureless, but widely spaced, crudely developed horizontal lamination is visible locally. A well-preserved plant fossil was found on the surface of a thin pumice clast conglomerate near the base of the section (fig. 2-4e). A conglomerate bed greater than 4 m thick caps the measured section (fig. 2-6c). This bed is clast-supported and comprises white, light yellow, and green-white colored pumice clasts up to 6 cm long that are oriented parallel to bedding and subordinate, similarly sized dark brown to black lithic clasts of unknown composition (fig. 2-6d); the matrix is poorly sorted silt and sand. The most striking aspect of this conglomerate bed is the abundance of large, silicified logs that it contains, some more than 1.5 m in diameter and 4 m in apparent length, all oriented parallel to bedding (fig. 2-6e). These logs were clearly visible during our aerial reconnaissance of the section (fig. 2-6c). The smaller silicified logs weathering out of siltstone near the top of the section (see above) come from a stratigraphic level a few meters below this log-bearing conglomerate bed.

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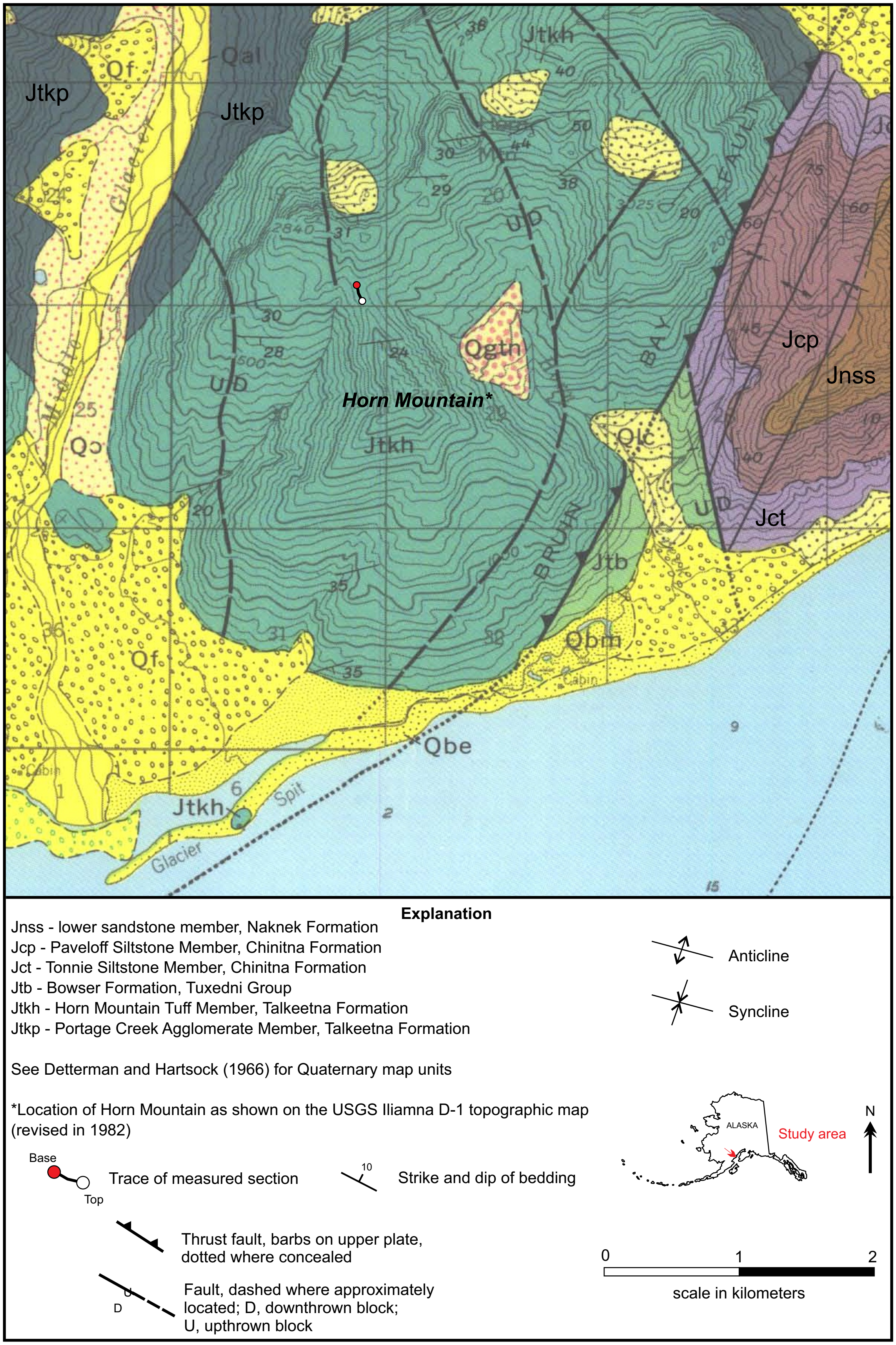

Figure 2-1. Geologic map of the Horn Mountain area, lower Cook Inlet, Alaska, showing the location of the measured section. Modified from Detterman and Hartsock (1966). Note that the location of Horn Mountain shown immediately north of Chinitna Bay corresponds to the location of the feature on the revised version of the 1958 USGS Iliamna D-1 1:63,360-scale topographic map (revised in 1982).

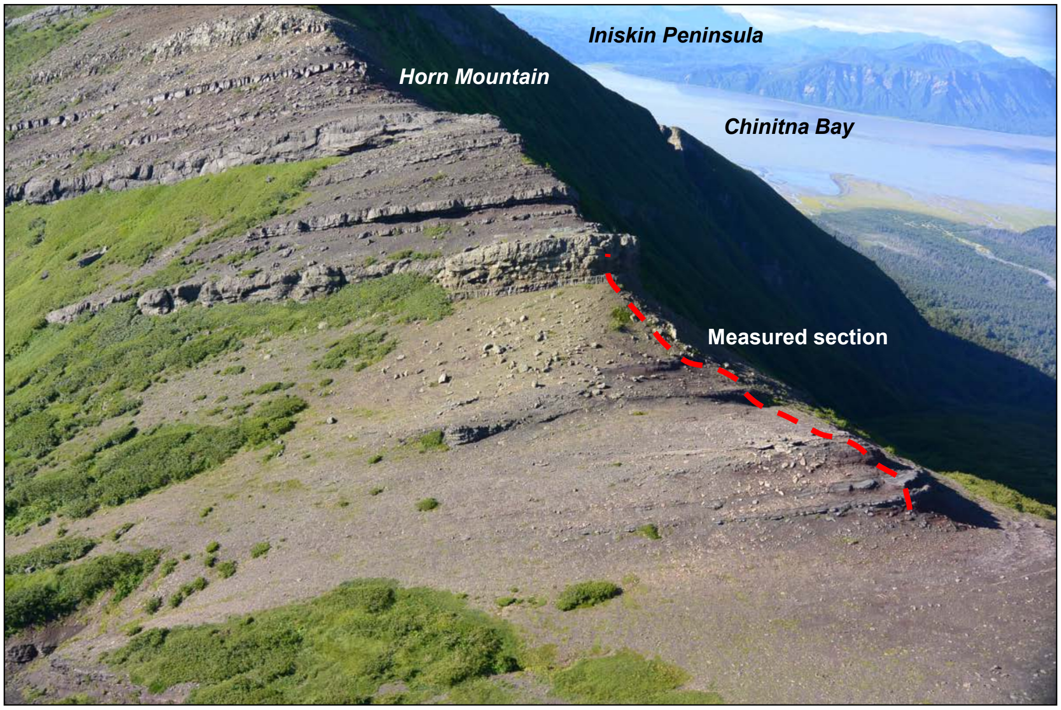

Figure 2-2. Oblique aerial photograph showing the outcrop of Horn Mountain Tuff Member addressed in this report. Note the brown- to maroon-colored strata in the measured section and that rocks of similar appearance continue above and below it. Measured section is 45 m thick, for sense of scale. See figure 2-1 for the location. View is toward the south.

FACIES INTERPRETATION

We interpret the succession in our measured section as the record of deposition on an alluvial plain in a volcanic setting. Siltstone strata record deposition in an overbank environment, and their brown and maroon coloration suggests an oxidized, well-drained setting. The irregularly shaped masses of pale-green and green-white material in siltstone are tentatively interpreted as cement-filled root structures. Ovoid-shaped patches of silty sand in the siltstone facies suggest mixing and destruction of thin sand beds or laminae through soil-forming process or by burrowing organisms. The irregular shape of the slickenside striated surfaces suggests a pedogenic origin, but several high-angle faults and at least one thrust fault have been mapped nearby so a tectonic origin is also possible (fig. 2-1). Small fluvial channels drained the landscape and were ultimately filled with trough-cross stratified sand upon abandonment. Hyperconcentrated flood flows and debris flows transported poorly sorted material across the landscape and deposited siltstones with floating, sand-sized clasts and conglomerates with pebble-sized pumice and lithic clasts. Smaller trees in growth position along with plant fossils suggest the alluvial setting was vegetated. The presence of logs in growth position in the highest conglomerate bed indicates that large trees were growing beyond active channel margins. Although it is unknown how representative our section is of the Horn Mountain Tuff Member overall, aerial reconnaissance in the Horn Mountain area suggests similar brown- to maroon-weathering beds continue for considerable distances above and below our measured section.

AGE CONSTRAINTS AND FUTURE WORK

During the 2014 field season a palynology sample was collected from siltstone immediately below the thick conglomerate bed at the top of our measured section; it yielded a Late Triassic age assignment. It is unclear if this palynomorph assemblage reflects a stratal age or reworking from older sediments. An extensive suite of palynology samples was collected during the 2015 season from siltstones throughout our measured section to verify this age assignment; results will be published in a subsequent report.

Figure 2-3a.

Figure 2-3b.

Figure 2-3. Selected photographs showing key features in siltstones from the study area. ***a.*** *Chippy weathering siltstone. Hammer is 42 cm long.* ***b.*** *Chippy weathering siltstone with ovoid-shaped pocket of silty sandstone.*

Figure 2-3c.

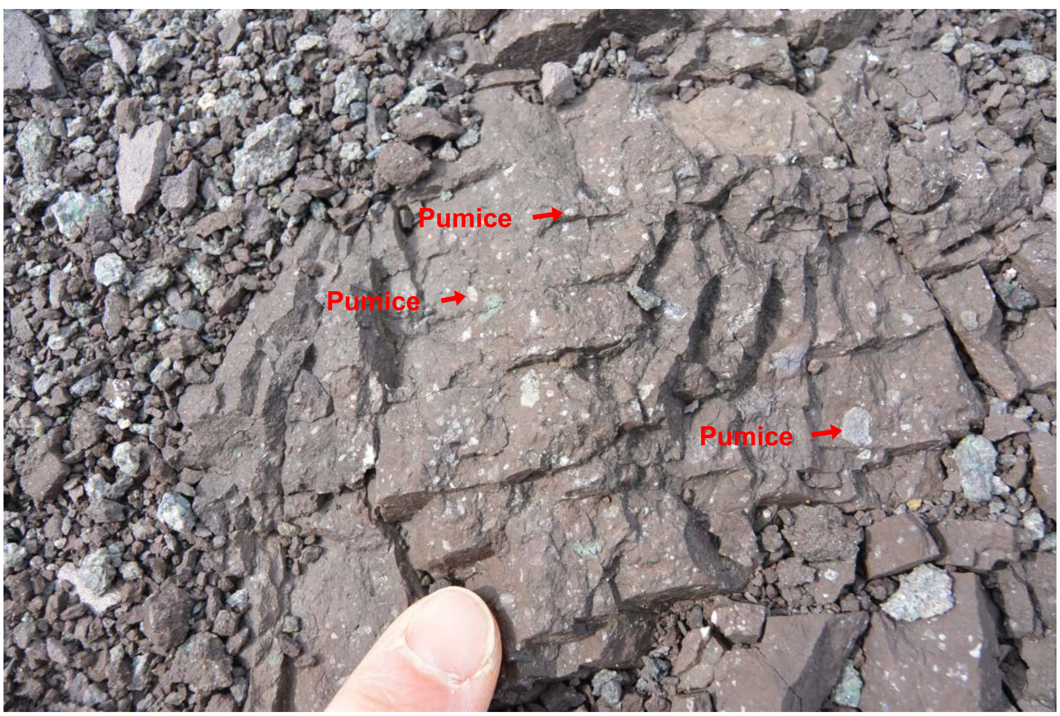

Figure 2-3d.

Figure 2-3 (cont.). Selected photographs showing key features in siltstones from the study area. ***c.*** *Slickenside striae in chippy siltstone.* ***d.*** *Pumice clasts in siltstone.*

Figure 2-4a.

Figure 2-4b.

Figure 2-4. Selected photographs showing plant megafossils from the study area. ***a.*** *Silicified log fragment with well-preserved woody cell structure visible on surface. Log weathered out of siltstone a few meters below the thick conglomerate bed shown in figure 2-6c.* ***b.*** *Cone-like fossil from siltstone.*

Figure 2-4c.

Figure 2-4d.

Figure 2-4 (cont.). Selected photographs showing plant megafossils from the study area. ***c–d.*** *Leaf impressions in silty sandstone. Tip of eraser in d is 2.0 cm long.*

Figure 2-4e.

Figure 2-4 (cont.). Selected photographs showing plant megafossils from the study area. ***e.*** *Leaf impression on surface of pumice clast conglomerate near the base of the measured section. Tip of hammer in e is 2.5 cm long. Note frond-like shape of leaves and the angle between fronds and stems in c–e. Leaves shown in d are oriented nearly perpendicular to stem, whereas those in c and e meet stem at an acute angle. These differences suggest plant fossils may represent at least two different species. Fossils shown in c–e resemble* Otozamites *shown in Knowlton (1916, plates 79 and 81) collected from the Talkeetna Formation on the north side of the Matanuska Valley.*

Figure 2-5a.

Figure 2-5b.

Figure 2-5. Selected photographs showing key features in sandstones from the study area. ***a.*** *Trough cross-bedded, coarse-grained sandstone. Field radio for scale, including yellow/black antenna, is approximately 14 cm long.* ***b.*** *Trough cross-bedded, very coarse-grained sandstone filling a fluvial channel. Pink flag (in red circle) is approximately 1 m above channel base (dotted red line).*

Figure 2-6a.

Figure 2-6b.

Figure 2-6. Selected photographs showing key features in conglomerates from the study area. ***a.*** *Multiple thin beds of pumice clast pebble conglomerate. Rock hammer is 42 cm long.* ***b.*** *Pumice clast pebble conglomerate from the bed shown in figure 2-6a is positioned immediately below rock hammer. Pumice clasts are pistachio green and have altered to clay. Selected pumice clasts are marked with red letter P. Visible part of rock hammer is 17 cm long.*

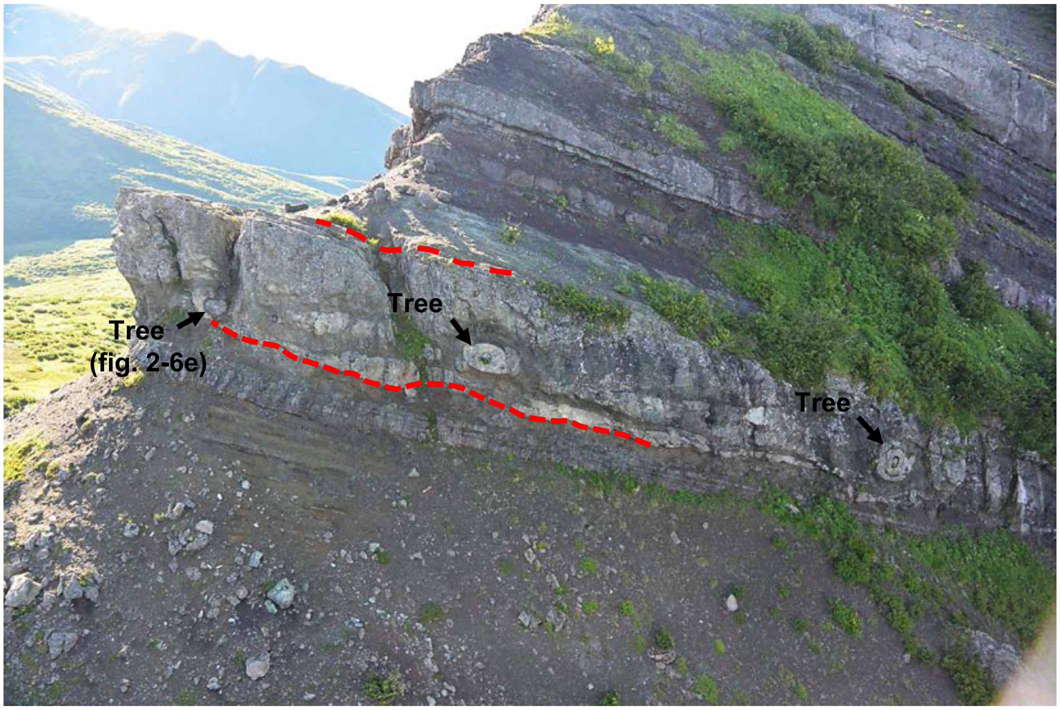

Figure 2-6c.

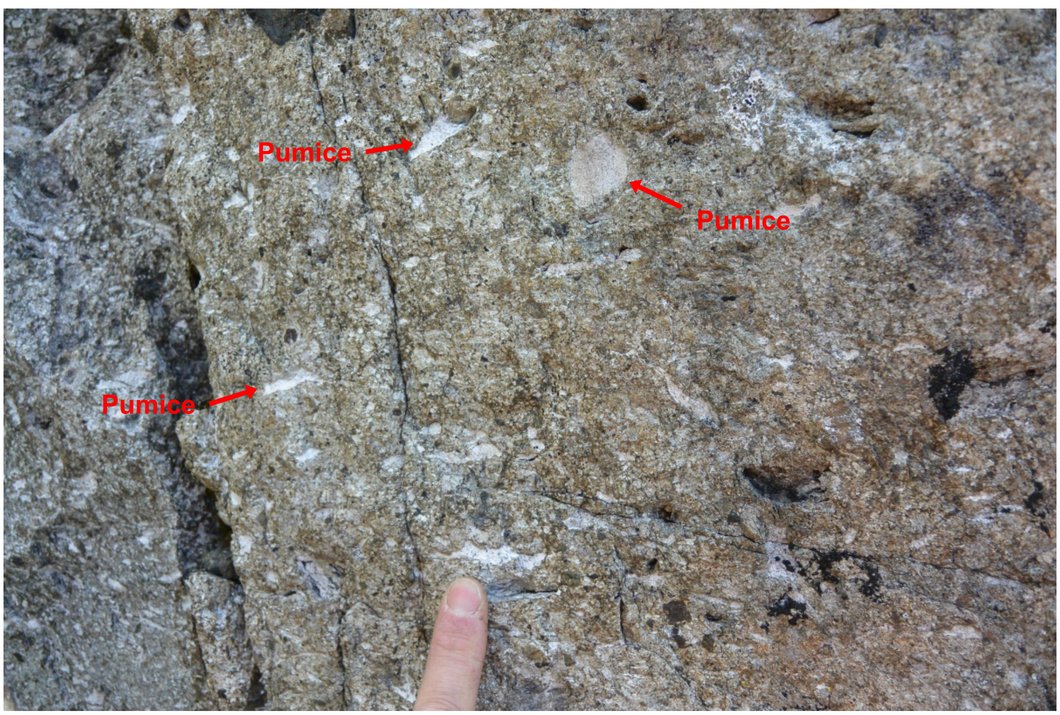

Figure 2-6d.

Figure 2-6 (cont.). Selected photographs showing key features in conglomerates from the study area. ***c.*** *Thick pumice clast conglomerate bed at the top of the measured section. Note the trees in the lower part of the bed. Tree-bearing conglomerate bed is more than 4 m thick, for sense of scale. Photograph taken from helicopter, with view toward southeast.* ***d.*** *Close-up view of pumice clasts in the bed shown in figure 2-6c.*

Figure 2-6e.

Figure 2-6 (cont.). Selected photographs showing key features in conglomerates from the study area. ***e.*** *Transverse cross-sectional view of large log in the bed shown in figure 2-6c. Maximum diameter of log is 1.5 m; larger diameter logs are visible in figure 2-6c.*

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We gratefully acknowledge Kate Bull for showing us the exposure at Horn Mountain during the 2014 field season. Funding for the Alaska DNR Cook Inlet basin analysis program was provided by the State of Alaska, with additional support from Apache Corporation and the U.S. Geological Survey's National Cooperative Geologic Mapping Program through STATEMAP under award numbers G13AC00157 and G15AC00199. We gratefully acknowledge the following organizations for granting land access: Lake Clark National Park & Preserve; Cook Inlet Region, Inc.; and Chickaloon, Knik, Ninilchik, Salamatof, Seldovia, and Tyonek Native village corporations. Merlin "Spanky" Handley provided helicopter transportation for the DNR field crew during the 2015 season. We thank the owners and staff of the Snug Harbor Wilderness Lodge on Chisik Island for their hospitality. We thank Trystan Herriott and Nina Harun for their thorough technical reviews of the manuscript. We thank the 2015 DNR Red Glacier–Iliamna bedrock mapping crew for valuable discussions in the field.

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CHAPTER 3

RECONNAISSANCE STRATIGRAPHY OF THE RED GLACIER FORMATION (MIDDLE JURASSIC) NEAR HUNGRYMAN CREEK, COOK INLET BASIN, ALASKA

David L. LePain[1], Richard G. Stanley[2], and Kenneth P. Helmold[3]

INTRODUCTION

Geochemical data suggest the source of oil in upper Cook Inlet fields is Middle Jurassic organic-rich shales in the Tuxedni Group (Magoon and Anders, 1992; Lillis and Stanley, 2011; LePain and others, 2012, 2013). Of the six formations in the group (Detterman, 1963), the basal Red Glacier Formation is the only unit that includes fine-grained rocks in outcrop that appear to be organic-rich (fig. 3-1). In an effort to better understand the stratigraphy and source-rock potential of the Red Glacier Formation, the Alaska Division of Geological & Geophysical Surveys, in collaboration with the Alaska Division of Oil and Gas and the U.S. Geological Survey, has been investigating the unit in outcrop between Tuxedni Bay and the type section at Lateral and Red glaciers (Stanley and others, 2013; LePain and Stanley, 2015; Helmold and others, 2016 [this volume]). Fieldwork in 2015 focused on a southeast-trending ridge south of Hungryman Creek, where the lower 60–70 percent of the formation (400–500 m) is exposed and accessible, except for the near-vertical faces of three segments near the southeast end of the ridge (figs. 3-2 and 3-3). Three stratigraphic sections were measured along the ridge to document facies and depositional environments (figs. 3-3 and 3-4). Steep terrain precluded study of the upper part of the formation exposed east of the ridge. This report includes a preliminary summary of findings from the 2015 field season.

RED GLACIER FORMATION NEAR HEADWATERS OF HUNGRYMAN CREEK

The Red Glacier Formation unconformably overlies the Talkeetna Formation (Horn Mountain Tuff Member) and the contact is relatively well exposed along the ridgetop south of Hungryman Creek. It is tentatively placed at a color change from light brown and gray volcaniclastic sandstones, siltstones, and tuffs in the Horn Mountain to dark brown and red-brown siltstones, sandstones, and conglomerates of the Red Glacier Formation. Sandstones and siltstones above this contact have a characteristic spheroidal weathering pattern not seen in the underlying Talkeetna (fig. 3-5a).

The lower 154 m of the Red Glacier Formation in section 1 consists of granule and pebble conglomerate, poorly sorted fine- to very-coarse-grained sandstone, and minor siltstone (fig. 3-4). Most beds appear structureless but rare, crudely-developed, horizontal stratification is present. Most finer-grained sandstones and siltstones have a mottled appearance suggesting bioturbation, but discrete trace fossils are absent. Shelly macrofossils appear to be absent from the lower 89 m; belemnites, small *Inoceramus* valves, poorly preserved ammonites, and broken and abraded shell fragments are scattered throughout the remaining part of section 1, but are not abundant (fig. 3-5b). The upper part of section 1 consists of an organized succession of burrow-mottled, very-fine- to fine-grained sandstone with remnant patches of preserved horizontal lamination that grades upsection to medium- to coarse-grained planar(?) and trough cross-bedded sandstone (figs. 3-3, 3-4, and 3-6a).

Facies in the uppermost beds of section 1 and all of sections 2 and 3 record a progradational stack of three coarsening-upward shorezone successions (parasequences) (fig. 3-4). The uppermost 10 m of the lower coarsening-upward succession is accessible at the base of section 2 and consists of interbedded fine-grained, burrow-mottled sandstone and medium- to coarse-grained, planar cross-bedded sandstone in sets up to 80 cm thick (figs. 3-4 and 3-6b). These sandstones are overlain abruptly by burrow-mottled siltstone above an inferred flooding surface. The upper beds in section 2 include burrow-mottled, fine-grained sandstone with scattered interbeds of fossiliferous fine-grained sandstone (figs. 3-4 and 3-6c) and remnant patches of low-angle inclined laminae in fine-grained sandstone that may represent hummocky cross-stratification; these strata lie near the top of the second coarsening-upward succession (fig. 3-4). Section 3 includes a lower burrow-mottled siltstone above an inferred flooding surface with large pieces of silicified logs (figs. 3-4, 3-7a, and 7-b). Siltstones in section 3 grade up to burrowed, fine-grained sandstone with clams in growth position (fig. 3-7c) and rare ammonites (fig. 3-7d). Approximately 20 m above section 3, a 5–6-m-thick bed of cobble and boulder(?) conglomerate interrupts the sandstone succession near the top of the third coarsening-upward succession (figs. 3-4 and 3-7a).

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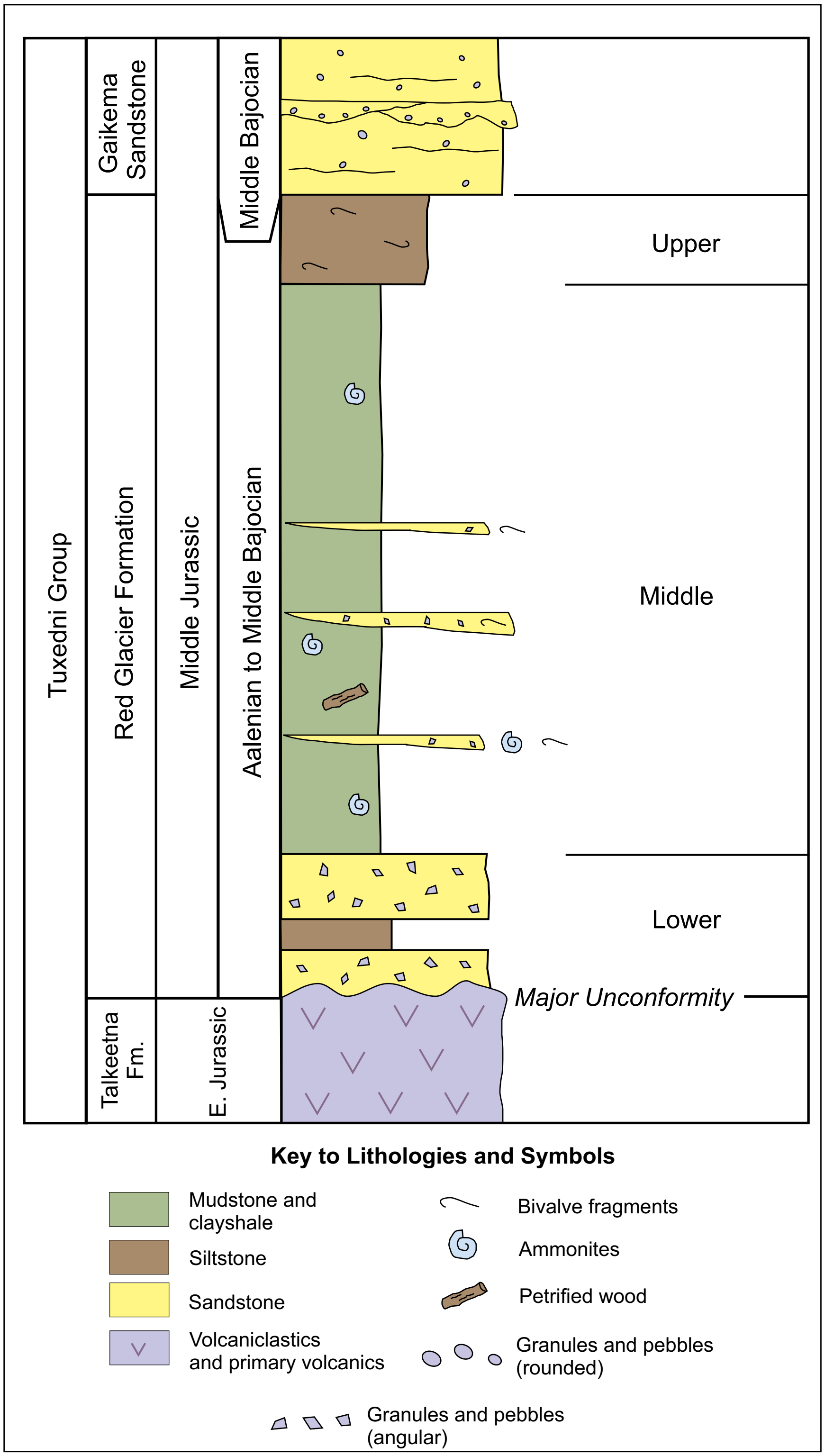

Figure 3-1. Generalized stratigraphic column showing the gross organization of the Red Glacier Formation. Based on fieldwork by the authors at Lateral Glacier in 2014 (LePain and Stanley, 2015).

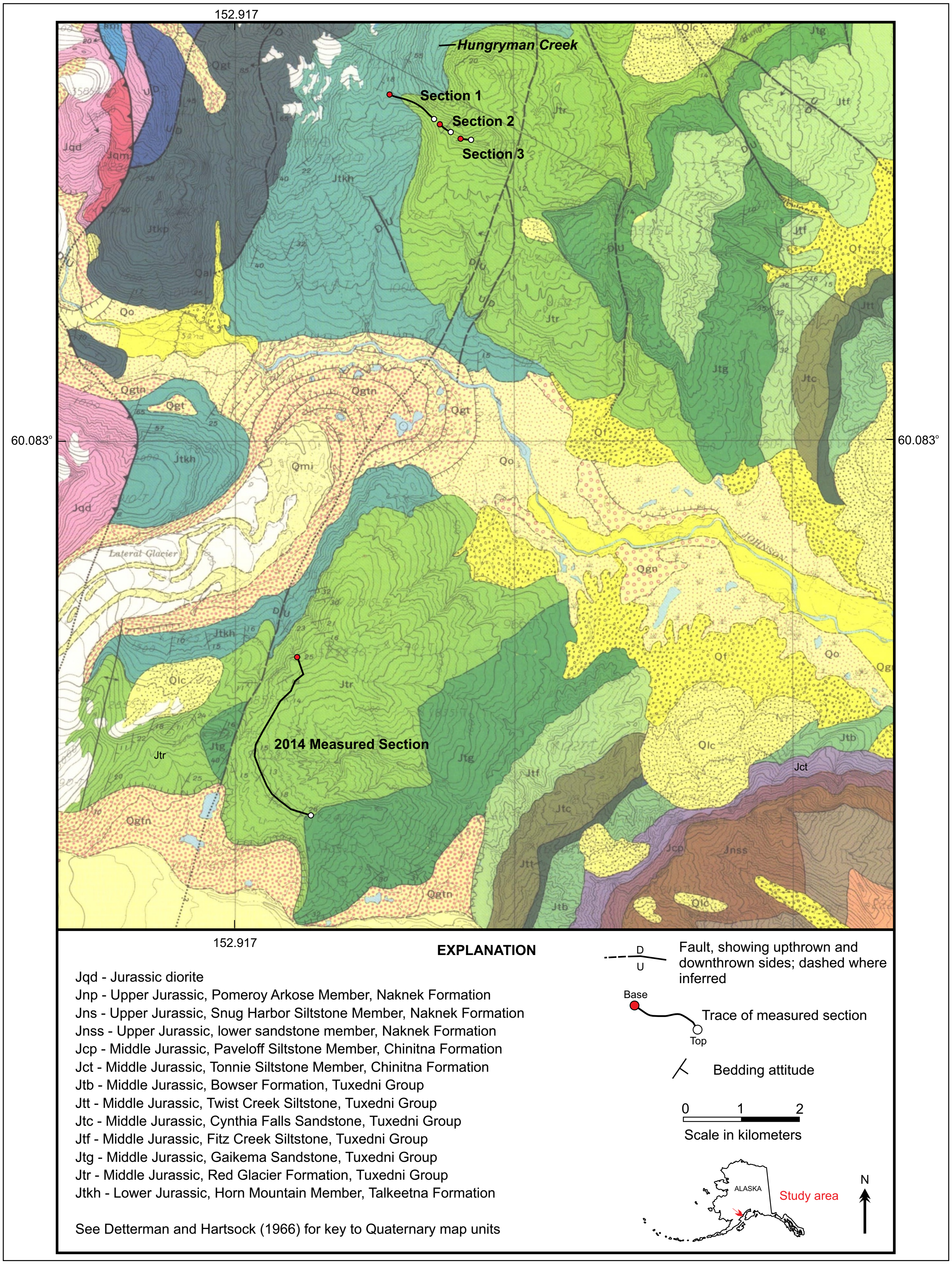

Figure 3-2. Geologic map of the area between Hungryman Creek and Red Glacier (modified from Detterman and Hartsock, 1966). Our 2014 measured section locality is in the type area for the lower part of the Red Glacier Formation.

The facies progression in the upper part of section 1 and basal beds of section 2 record a progradational delta front or shoreface succession, which is separated by a flooding surface from a similar progradational succession in the remainder of section 2 and immediately above; this stacking motif is repeated in and immediately above section 3. The conglomerate bed above section 3 records deposition in a shoreline proximal location, but its significance beyond that is unclear; its presence suggests that each successive progradational package records a successively more proximal position in the depositional profile. Helicopter reconnaissance of Red Glacier exposures east of the ridge shows that facies are dominantly coarse grained (siltstone and coarser) up to, and including, the overlying Gaikema Sandstone.

COMPARISON WITH 2014 MEASURED SECTION AT LATERAL GLACIER

The Red Glacier Formation near Hungryman Creek contrasts sharply with exposures of the formation 9 km to the south, at Lateral Glacier, where two thick sandstone packages separated by a siltstone interval are present near the base of the formation and are overlain by a 573-m-thick succession of dark brown and black mudstone and fissile clayshale (figs. 3-1, 3-2, and 3-4; LePain and Stanley, 2015). Features in sandstones near the base of the unit at Lateral Glacier suggest deposition from concentrated sediment gravity flows below storm wave base, succeeded by deposition of organic-rich mudstones. Comparable fine-grained facies are absent along the ridgetop near Hungryman Creek. The dramatic difference between the Lateral Glacier and Hungryman Creek successions suggests paleobathymetric control on the distribution of facies; the succession near Hungryman Creek records proximity to a coarse-grained deltaic depocenter while the succession at Lateral Glacier records deposition in an off-axis, distal location in deeper water. Results from the 2014 and 2015 field seasons document facies variations in the Red Glacier Formation along the basin margin that have implications for the distribution of oil-prone source rocks in the subsurface.

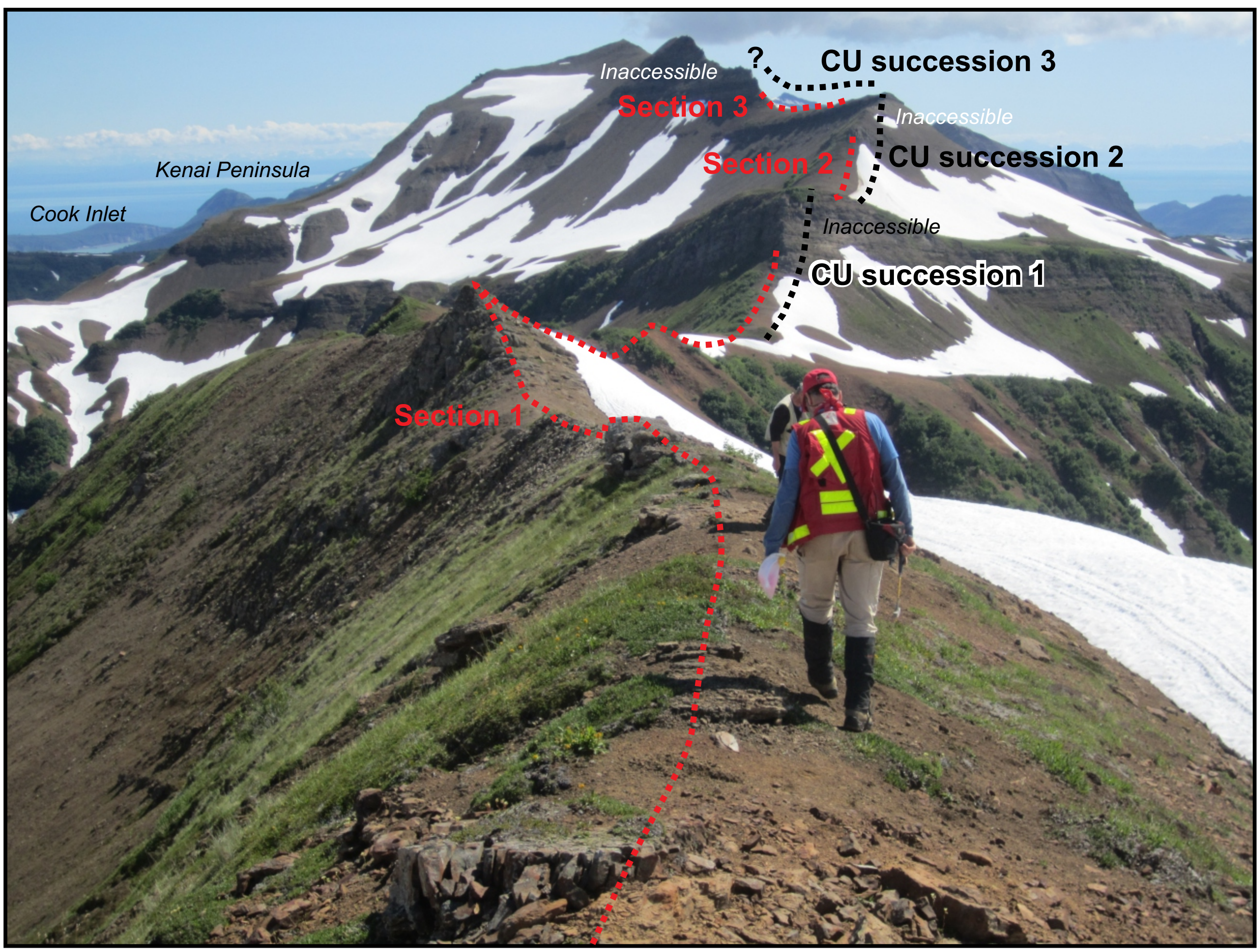

Figure 3-3. Field photograph showing the locations of measured sections 1–3. Note steep, inaccessible slopes separating sections 1 and 2 and sections 2 and 3. The Red Glacier Formation continues above and to the east of section 3, but is inaccessible due to steep topography. CU = coarsening-upward succession. View is toward the southeast.

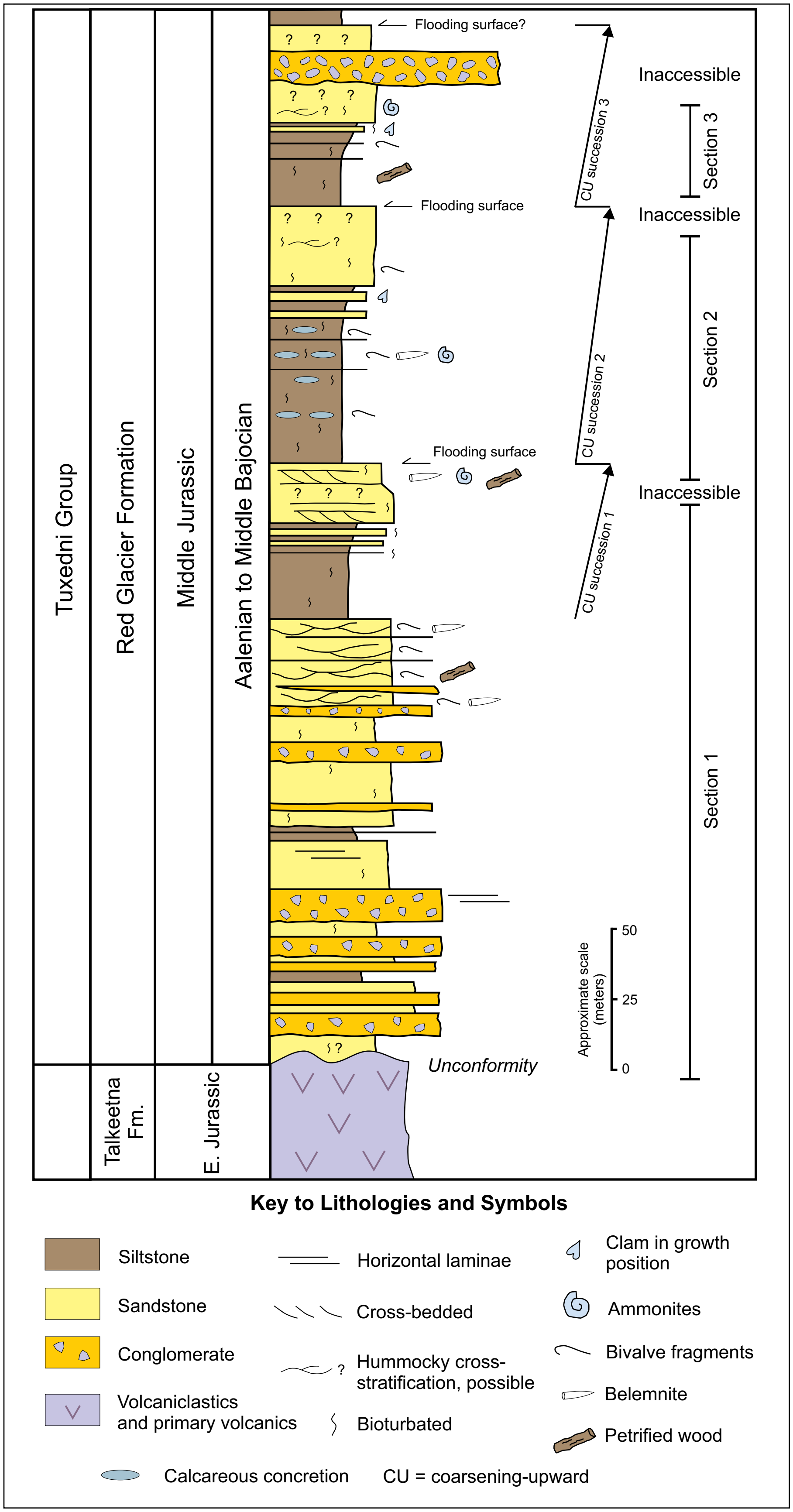

Figure 3-4. Schematic stratigraphic column showing the gross organization of the lower 60–70 percent of the Red Glacier Formation near Hungryman Creek based on fieldwork during the 2015 field season. Each coarsening-upward succession represents a parasequence (Van Wagoner and others, 1990).

Figure 3-5a

Figure 3-5b

Figure 3-5. Photographs showing features in measured section 1. ***a.*** *Spheroidal weathering pattern developed in burrow-mottled, fine-grained sandstone at 7.0 m in section 1. Black and yellow bars on notebook are each 5 cm long.* ***b.*** *Cast of moderately-well-preserved clam,* Inoceramus*, at 91.5 m in section 1. Visible part of gray eraser is 7 cm long.*

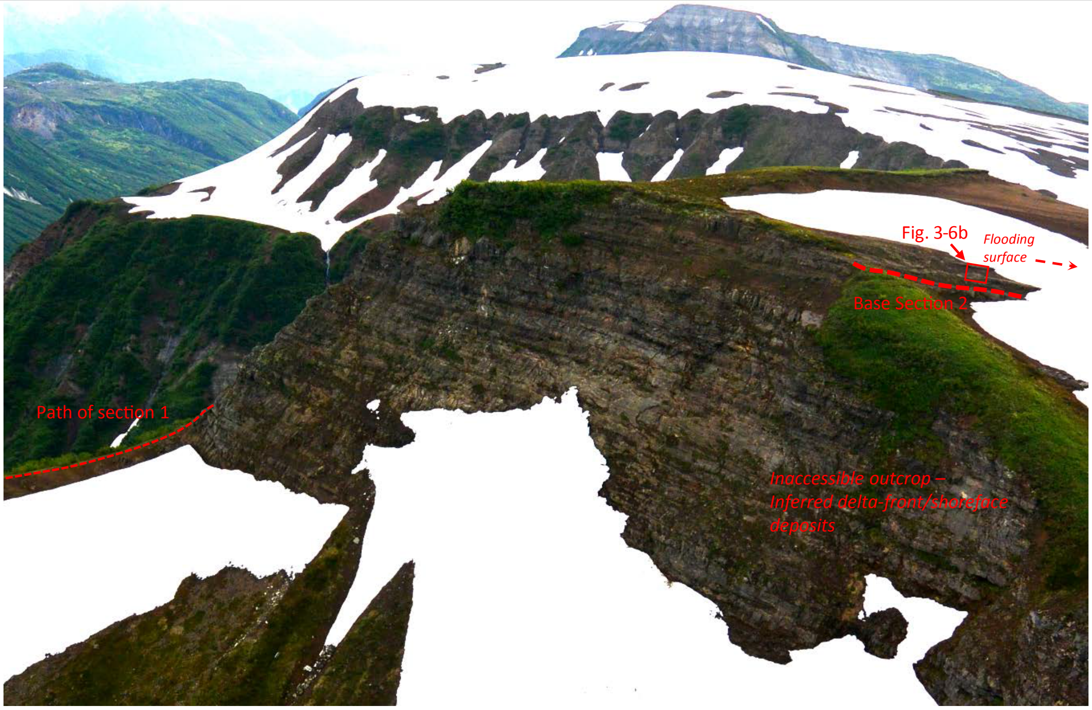

Figure 3-6a

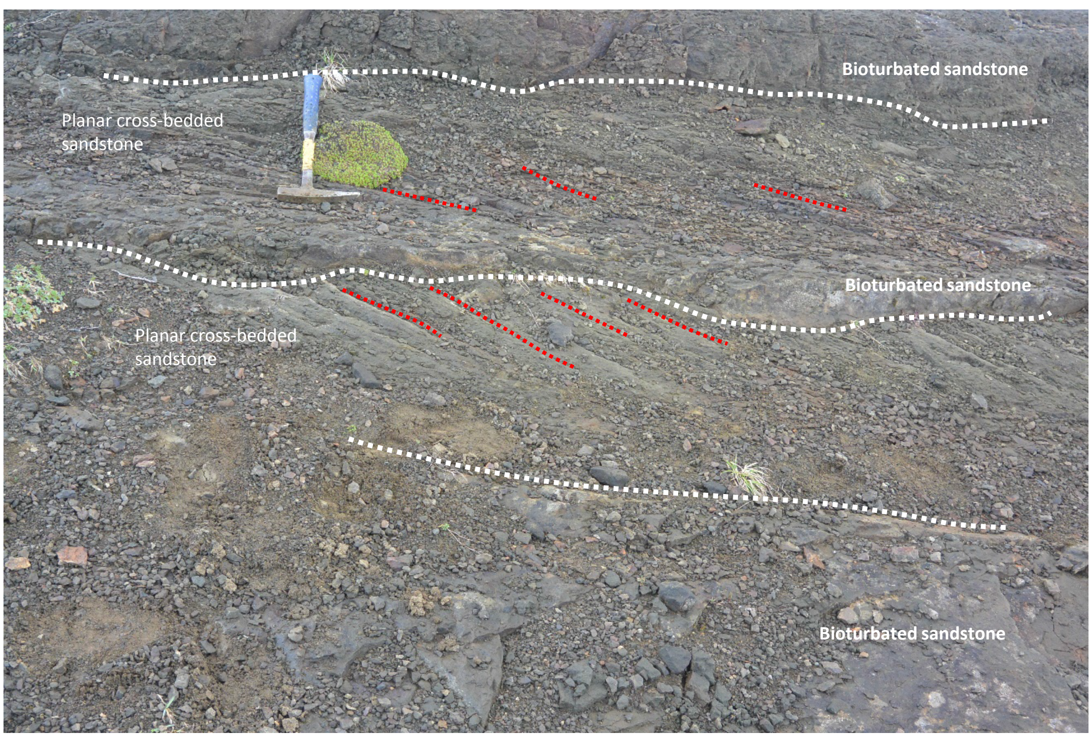

Figure 3-6b

Figure 3-6. Photographs showing features in measured sections 1 and 2. ***a.*** *Aerial view toward the north showing the upper part of section 1 and base of section 2 with an inaccessible slope separating them. The snow patch above the base of section 2 overlies burrow-mottled siltstone, which is also visible above the snow. A marine flooding surface is concealed beneath the snow patch but is exposed beyond it to the right of the field of view (red arrow) at 10.2 m in section 2. Red rectangle shows approximate location of photograph in figure 3-6b. Inaccessible section is thought to be 30–40 m thick.* ***b.*** *Two sets of planar cross-bedded sandstone separated by bioturbated sandstone. The dashed line immediately above the hammer handle is at 4.2 m in section 2. Rock hammer is 42 cm long. The lower 10.2 m of section 2 comprises the uppermost beds of the lower progradational delta-front/shoreface succession discussed in the text.*

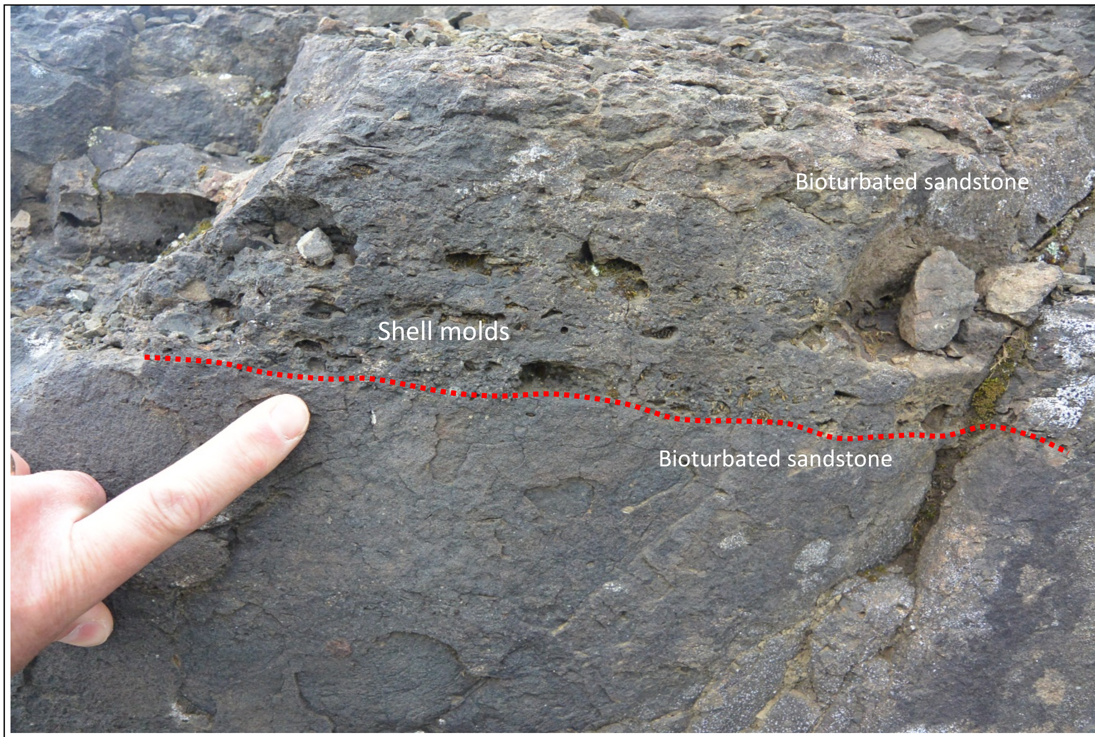

Figure 3-6c

*Figure 3-6 (cont.). Photographs showing features in measured sections 1 and 2. **c.** Fossiliferous sandstone (above finger) separated from bioturbated sandstone (below) by erosion surface (dotted red line). Most voids visible in the fossiliferous sandstone represent shell molds. Bioturbated sandstone overlies the fossiliferous sandstone.*

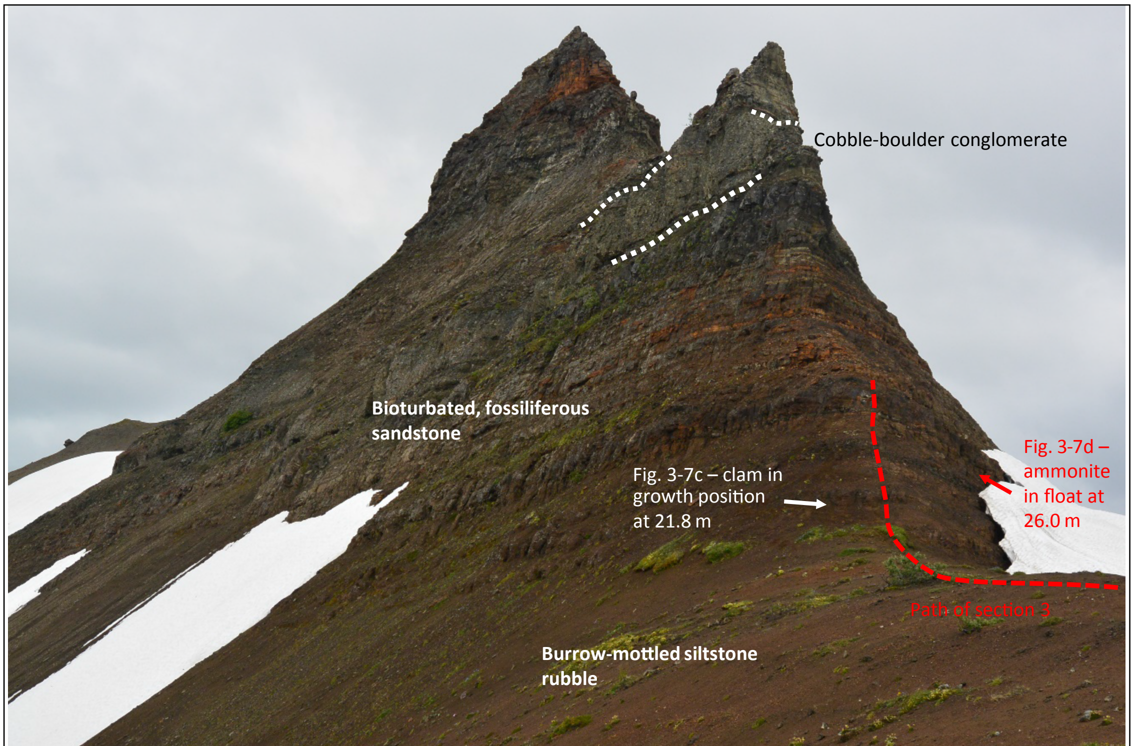

Figure 3-7a

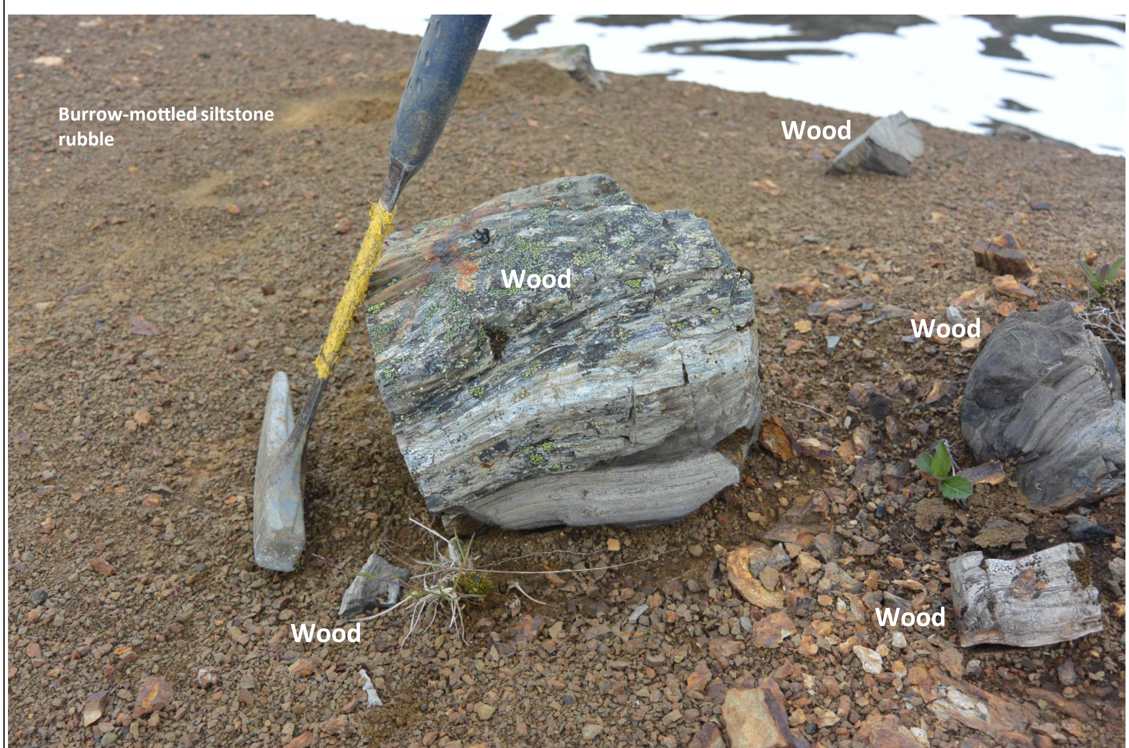

Figure 3-7b

*Figure 3-7. Photographs showing features in measured section 3. **a.** Photograph showing the upper part of section 3 and the inaccessible beds above it. Note the cobble–boulder(?) conglomerate approximately 20 m above the top of section 3. **b.** Silicified wood fragments weathering out of burrow-mottled coarse siltstone at 15.0 m in section 3. Wood was likely transported to the depositional site by flows discharging from a nearby delta distributary channel. Visible part of rock hammer is 30 cm long.*

Figure 3-7c

Figure 3-7d

Figure 3-7. Photographs showing features in measured section 3. ***c.*** *Clam in growth position in bioturbated, very fine sandstone at 21.8 m in section 3.* ***d.*** *Ammonite with well-preserved sutures in float at 26.0 m in section 3.*

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CHAPTER 4

SEDIMENTARY PETROLOGY AND RESERVOIR QUALITY OF THE MIDDLE JURASSIC RED GLACIER FORMATION, COOK INLET FOREARC BASIN: INITIAL IMPRESSIONS

Kenneth P. Helmold[1], David L. LePain[2], and Richard G. Stanley[3]

INTRODUCTION

The Division of Geological & Geophysical Surveys and Division of Oil & Gas are currently conducting a study of the hydrocarbon potential of Cook Inlet forearc basin (Gillis, 2013, 2014; LePain and others, 2013; Wartes, 2015; Herriott, 2016 [this volume]). The Middle Jurassic Tuxedni Group is recognized as a major source of oil in Tertiary reservoirs (Magoon, 1994), although the potential for Tuxedni reservoirs remains largely unknown. As part of this program, five days of the 2015 field season were spent examining outcrops, largely sandstones, of the Middle Jurassic Red Glacier Formation (Tuxedni Group) approximately 6.4 km northeast of Johnson Glacier on the western side of Cook Inlet (fig. 4-1). Three stratigraphic sections (fig. 4-2) totaling approximately 307 m in thickness were measured and described in detail (LePain and others, 2016 [this volume]). Samples were collected for a variety of analyses including palynology, Rock-Eval pyrolysis, vitrinite reflectance, detrital zircon geochronology, and petrology. This report summarizes our initial impressions of the petrology and reservoir quality of sandstones encountered in these measured sections. Interpretations are based largely on hand-lens observations of hand specimens and are augmented by stereomicroscope observations. Detailed petrographic (point-count) analyses and measurement of petrophysical properties (porosity, permeability, and grain density) are currently in progress.

FRAMEWORK MINERALOGY AND PROVENANCE

Red Glacier sandstones are almost exclusively volcanic litharenites that are very-fine- to coarse-grained and moderately to poorly sorted. The rock framework typically consists of 60–80 percent dark grains (figs. 4-3A and 4-B) interpreted to be largely volcanic rock fragments (VRFs). Amphiboles and/or pyroxenes constitute a minor portion of the dark grains. Light-colored grains comprise 20–40 percent of the framework and consist largely of plagioclase as suggested by occasional tabular, lath-shaped crystals. Most of the sandstones contain very little, if any, detrital quartz. The prevalence of VRFs, amphiboles/pyroxenes, and plagioclase suggests the sandstones are volcanogenic and were probably derived from an undissected volcanic arc terrane (Dickinson and Suczek, 1979; Dickinson, 1985). It is hypothesized that the detritus was derived almost exclusively from the erosion of pre-existing volcanic rocks, likely including lava flows, ignimbrites, and tuffs, in close proximity to the depocenter. The source terrane for the Red Glacier sandstones was probably a region of uplifted Lower Jurassic Talkeetna Formation (Bull, 2014; Bull, 2015) west of the Bruin Bay fault (Detterman and Hartsock, 1966).

Sandstones in the lower portion of section 1 (30.4–33.2 m in section) are notably different from the sandstones described above in that they contain a much higher proportion of light-colored grains, largely plagioclase (figs. 4-3C and 4-D). Minor K-feldspar may be present, but it is difficult to distinguish between the two feldspars in hand specimen. Detrital quartz also appears to be present in minor amounts. One possible explanation for the different mineralogy in these samples is that they contain syndepositionally erupted silicic tephra from an active volcanic center in addition to detritus derived from pre-existing volcanic rocks. A more thorough examination of these samples, including the petrographic evaluation of thin sections, should be able to confirm or refute this hypothesis.

RESERVOIR QUALITY

The mixture of abundant VRFs, amphibole/pyroxene, and plagioclase results in a labile framework mineralogy that is highly susceptible to chemical diagenetic alteration. In addition, experimental studies have shown that weathered basaltic detritus becomes extremely ductile and highly susceptible to grain deformation upon even moderate burial (Pittman and Larese, 1991). Due to the high VRF content, authigenic clays (probably chlorite), and zeolites (probably heulandite) are anticipated to be common cements that occlude the primary pore system and result in poor reservoir quality. Examination of hand specimens reveals very little, if any, intergranular porosity and the sporadic occurrence of a white, non-calcareous cement, probably a zeolite (figs. 4-3E and 4-F). Given the Middle Jurassic age of the sandstones (~170 m. y.) and the combination of a chemically and mechanically unstable framework, it is unlikely that significant conventional reservoirs exist in the Red Glacier Formation. However, due to the possibility of extensive authigenic clay cement, the Red Glacier sandstones could

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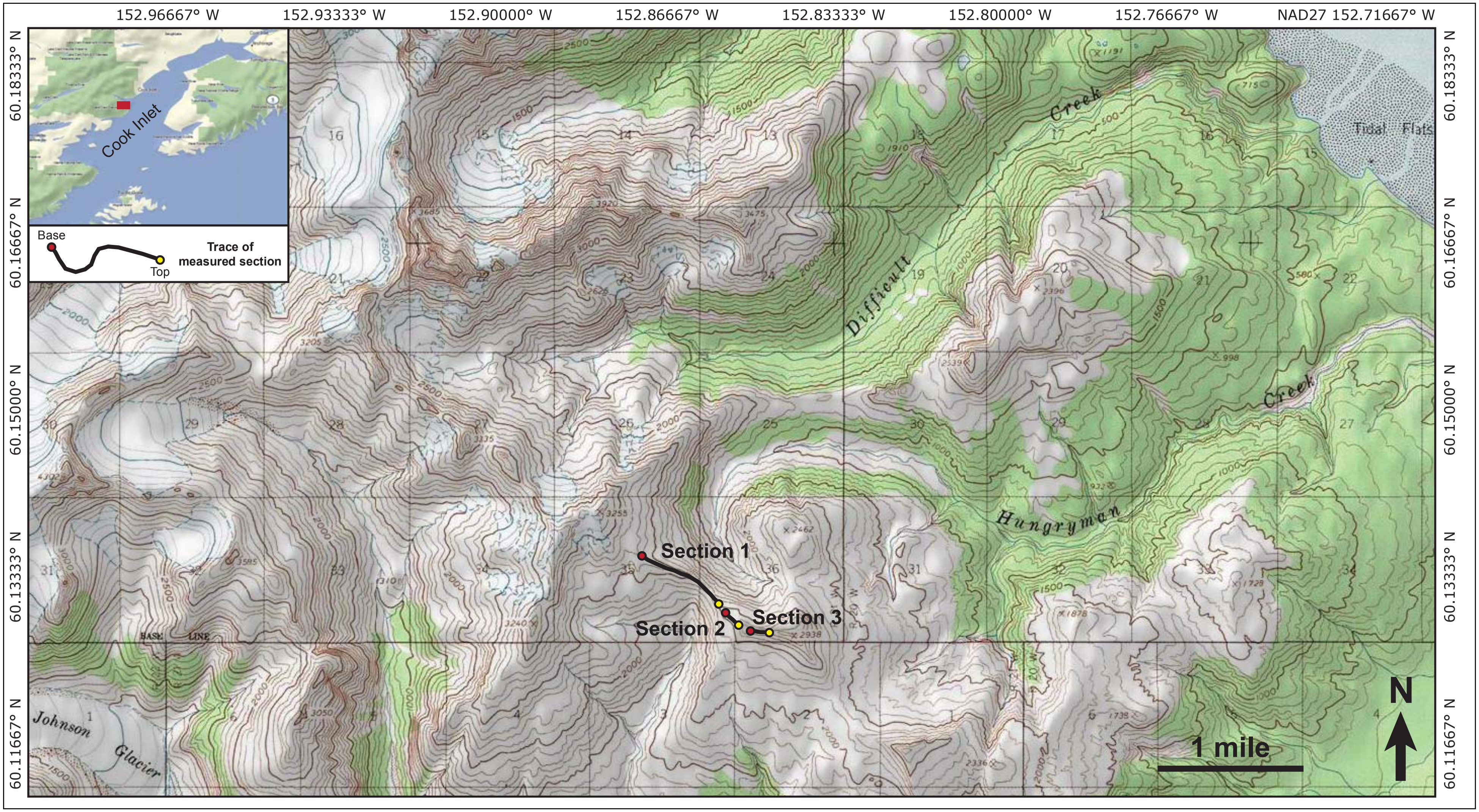

Figure 4-1. Topographic map showing location of measured sections of Red Glacier Formation northeast of Johnson Glacier on the west side of Cook Inlet. Inset is index map with red box showing location of topographic map in Cook Inlet basin.

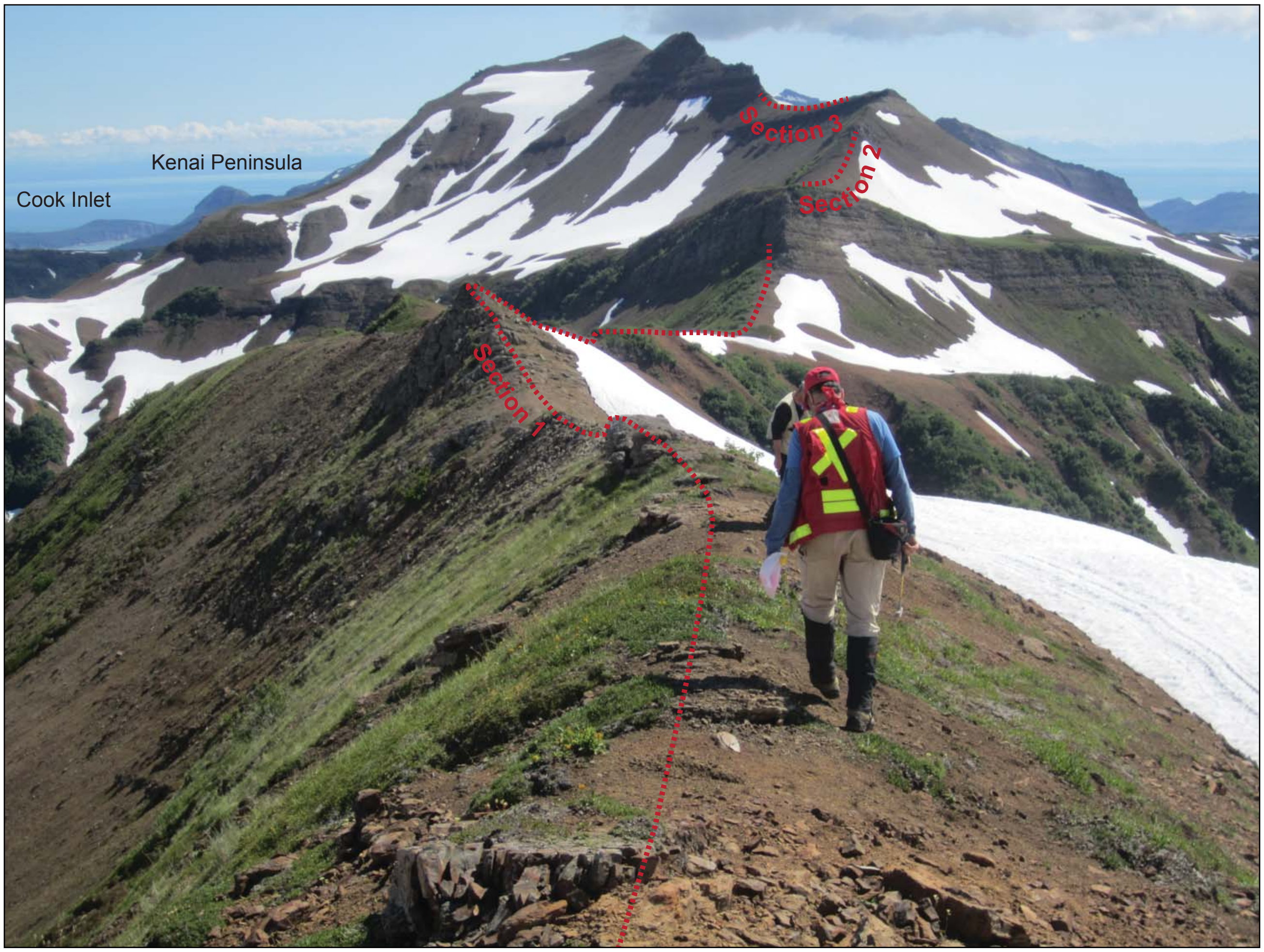

Figure 4-2. View southeastward of the three measured sections of Red Glacier Formation along ridge crest. Lithologies consist largely of fine- to coarse-grained sandstone with minor interbedded siltstone. Geologists for scale.

have potential as tight-gas reservoirs. The interfingering of tight sandstones and potential source rocks of the Red Glacier Formation (LePain and Stanley, 2015) also suggests the possibility of this formation to host continuous oil accumulations, perhaps analogous to those in the Late Devonian and Early Mississippian Bakken Formation of North Dakota (Nordeng, 2009). A similar possibility has been suggested for the overlying Gaikema Sandstone (Helmold and Stanley, 2015). Additional analyses from a larger geographic area are needed before making sweeping conclusions regarding the regional reservoir potential of the Red Glacier Formation.

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Funding for this work was provided by the State of Alaska, with additional financial support from Apache Corporation. Field work was partly funded by the National Cooperative Geologic Mapping Program, administered by the U.S. Geological Survey (STATEMAP awards G13AC00157 and G15AC00199). We gratefully acknowledge the following organizations for granting land access: Lake Clark National Park & Preserve; Cook Inlet Region, Inc; and Chickaloon, Knik, Ninilchik, Salamatof, Seldovia, and Tyonek Native village corporations. We are grateful to Merlin "Spanky" Handley of Pathfinder Aviation for safely transporting us in the field. We thank the owners and staff of the Snug Harbor Wilderness Lodge on Chisik Island for their hospitality and making us feel welcome during our stay. We thank Trystan M. Herriott and Nina T. Harun for helpful reviews of the manuscript.

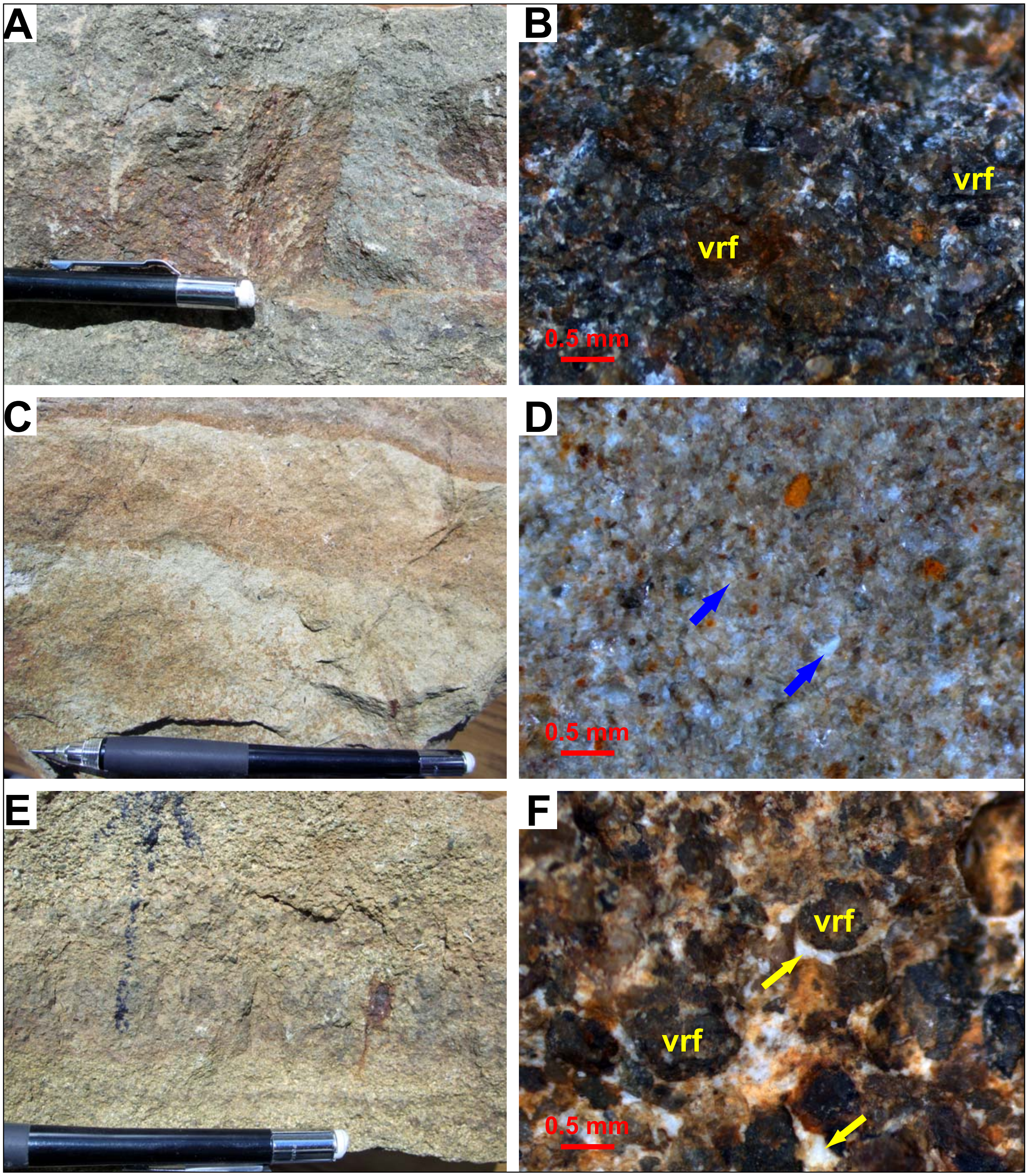

Figure 4-3. Photographs of Red Glacier sandstones from measured section 1. ***A.*** *Upper fine- to lower medium-grained, poorly-sorted, gray-green-colored sandstone consisting largely of volcanic rock fragments (VRFs). Hand specimen photograph; 187.5 m in section.* ***B.*** *Same sample as A, showing rock framework consisting predominantly of dark-colored, subangular to subrounded VRFs. Stereomicrograph; 187.5 m in section.* ***C.*** *Upper very-fine-grained, moderately-well-sorted, tan-colored sandstone consisting largely of euhedral to subhedral plagioclase crystals and minor detrital quartz. Hand specimen photograph; 30.4 m in section.* ***D.*** *Same sample as C, showing rock framework consisting predominantly of light-colored, angular to subangular, plagioclase grains (arrows). Orange grains are oxidized mafic components. Stereomicrograph; 30.4 m in section.* ***E.*** *Lower to upper medium-grained, poorly-sorted, tan-green-colored sandstone consisting largely of VRFs. Hand specimen photograph; 196.6 m in section.* ***F.*** *Same sample as E, showing white, non-calcareous, probably zeolite cement (arrows) filling intergranular pores between subrounded VRFs. Stereomicrograph; 196.6 m in section.*

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CHAPTER 5

PRELIMINARY STRATIGRAPHIC ARCHITECTURE OF THE MIDDLE JURASSIC PAVELOFF SILTSTONE MEMBER, CHINITNA FORMATION, TUXEDNI BAY AREA, COOK INLET, ALASKA

Trystan M. Herriott[1], Marwan A. Wartes[1], Paul L. Decker[2], and Nina T. Harun[1]

INTRODUCTION

Field studies of the Chinitna Formation are being conducted by the Alaska Department of Natural Resources to better understand the Middle Jurassic stratigraphy in the hydrocarbon-bearing Cook Inlet forearc basin. The Chinitna Formation crops out in lower Cook Inlet along the northwest basin margin between Iniskin and Tuxedni bays (fig. 5-1), where the formation is ~700 m thick and comprises two members: Tonnie Siltstone and Paveloff Siltstone (Detterman and Hartsock, 1966). Although it remains unclear what role the Chinitna Formation may play in Cook Inlet petroleum systems, Wartes and Herriott (2015) documented an oil-stained locality in the lower Paveloff at Chinitna Bay (fig. 5-1), demonstrating that the formation at least locally hosts migrated oil.

LePain and others (2013) interpreted the Chinitna Formation as a shelfal unit and proposed that sand-rich basal successions reported by Detterman and Hartsock (1966) in each of the members mark onset of regressive–transgressive sedimentation cycles. Detterman and Hartsock (1966) also noted that the Tonnie and Paveloff sand-prone intervals are thicker and locally coarser grained to the northeast, which is consistent with our observations. This short paper presents a preliminary stratigraphic architecture analysis of the Callovian-age Paveloff in the Johnson River area south of Tuxedni Bay (fig. 5-1), where the member's sandy basal unit is well developed and a series of large-scale incisions and their fills are observed. We propose that sand-choked, channelized depositional systems recorded in part by the outcrops described below bypassed coarse detritus to more distal settings that may host hydrocarbons in the subsurface of Cook Inlet.

OBSERVATIONS—STRATIGRAPHIC ARCHITECTURE

The Paveloff is a chiefly fine-grained, dark-gray-brown/green-weathering unit overlying the medium-brown-weathering Tonnie (fig. 5-2; Herriott and Wartes, 2014). However, the lower Paveloff in the Johnson River area is a sharp-based, tan- to gray-weathering, ~95–105-m-thick interval (Jcp_1 of this study) that renders an especially conspicuous Tonnie–Paveloff contact (figs. 5-2 and 5-3). Jcp_1 largely comprises sandstone and subordinate conglomerate that transition up-section from dominantly tabular to dominantly channelized stratal geometries (figs. 5-2 and 5-3); convolute stratification is also common to Jcp_1 (fig. 5-4). Channelized successions in Jcp_1 are very thick bedded and typically amalgamated, with channel fills stacked up to ~75 m thick; an ~15-m-thick, channelized conglomerate is observed near Triangle Peak (figs. 5-1 and 5-4). Jcp_1 is overlain by a thinner- and tabular-bedded, finer-grained succession (Jcp_2) that is ~160 m thick and consistent with the regional lithostratigraphic character of the Paveloff. Large-scale incisions cut Jcp_2, forming concave-up surfaces with up to ~140 m of stratigraphic relief (fig. 5-2). Channel-form sediment bodies of Jcp_3 that fill these containers are locally thicker bedded and more resistant than the host strata of Jcp_2, but are similar in their weathering color. Chaotic stratification and apparent convex-up stratal surfaces are observed within and proximal to the largest Jcp_3 incision-fill succession of figure 5-2. Finally, an uppermost Paveloff subunit, Jcp_4, caps the Chinitna Formation and is overlain by the Naknek Formation (fig. 5-2); the lithostratigraphy of Jcp_4 is generally similar to that of Jcp_2.

INTERPRETATIONS AND DISCUSSION

The stratigraphic architecture of the Paveloff reflects the interplay of numerous factors that influenced forearc basin sedimentation during the Callovian. We concur with LePain and others (2013) that the base of the Paveloff records regression, terminating Tonnie deposition. We infer that high sedimentation rates prevailed during accumulation of thick, sandy beds in the basal Paveloff interval (see also Wartes and Herriott, 2015), likely creating the requisite conditions for rapid dewatering and establishment of convolute stratification in Jcp_1. The channelized Jcp_1 succession is interpreted to record a marine-shoreline-proximal depositional system that prograded over the lowermost Jcp_1 package of chiefly tabular-bedded sandstone. The caliber of sediment and thickness of channel-fill sandstones and the conglomerate of figure 5-4 is suggestive of a high-energy deltaic environment of deposition or possibly nonmarine sedimentation during continued regression. Maximum regression probably corresponds to the end of Jcp_1 deposition; the shoreline is inferred to have stepped landward at onset

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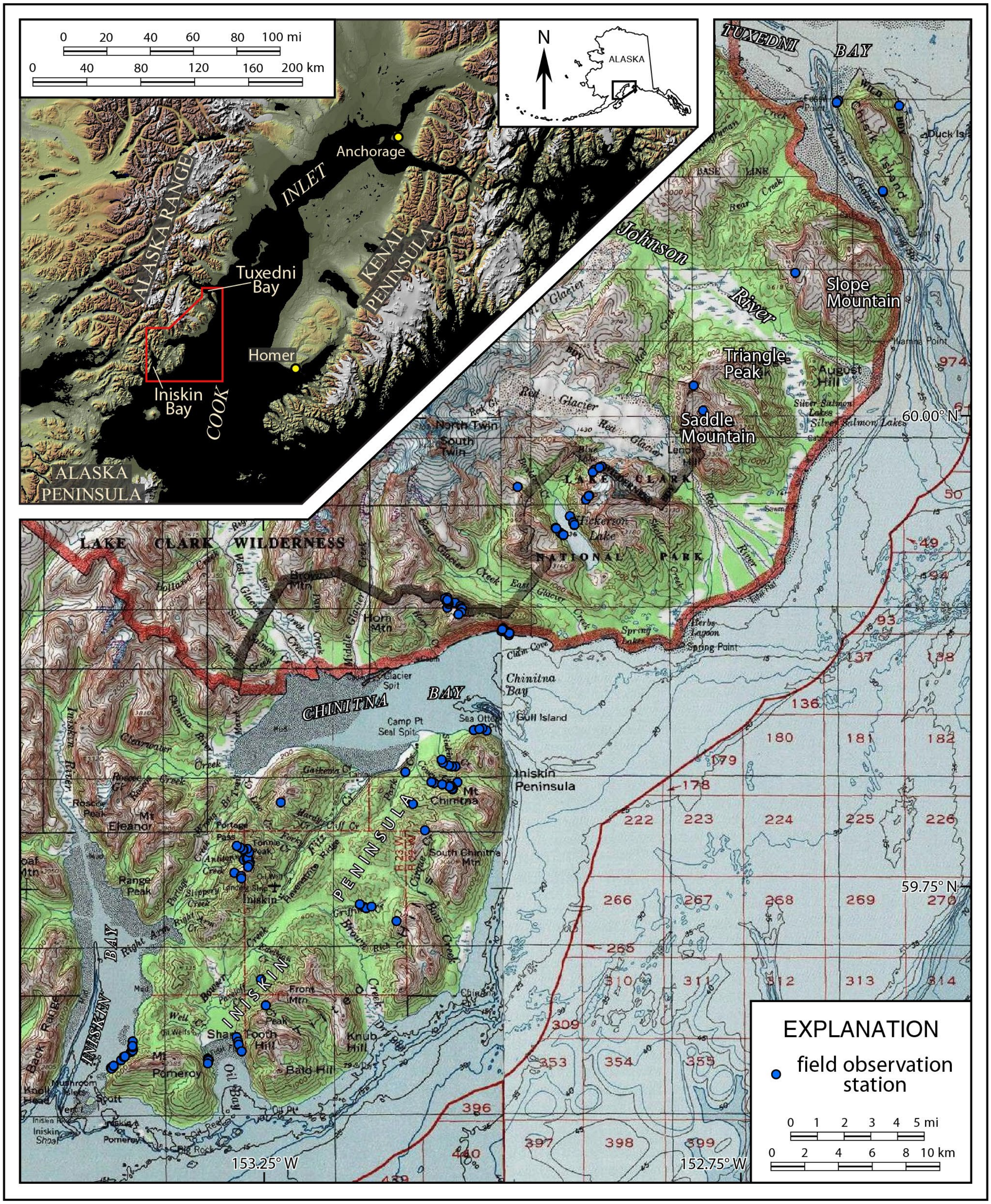

Figure 5-1. Location map of the Iniskin–Tuxedni bays area. Detailed observations of the Chinitna Formation were made by the authors at more than 150 localities during six field seasons and supplemented by geologic mapping of precipitously steep and inaccessible slopes and cliff faces where the unit's two members commonly crop out. This paper focuses on the stratigraphic architecture of the Paveloff Siltstone Member in the Johnson River area south of Tuxedni Bay. Topographic base map from portions of U.S. Geological Survey Iliamna, Seldovia, Lake Clark, and Kenai 1:250,000-scale quadrangles; shaded-relief image modified after U.S. Geological Survey Elevation Data Set Shaded Relief of Alaska poster (available for download at http://eros.usgs.gov/alaska-0).

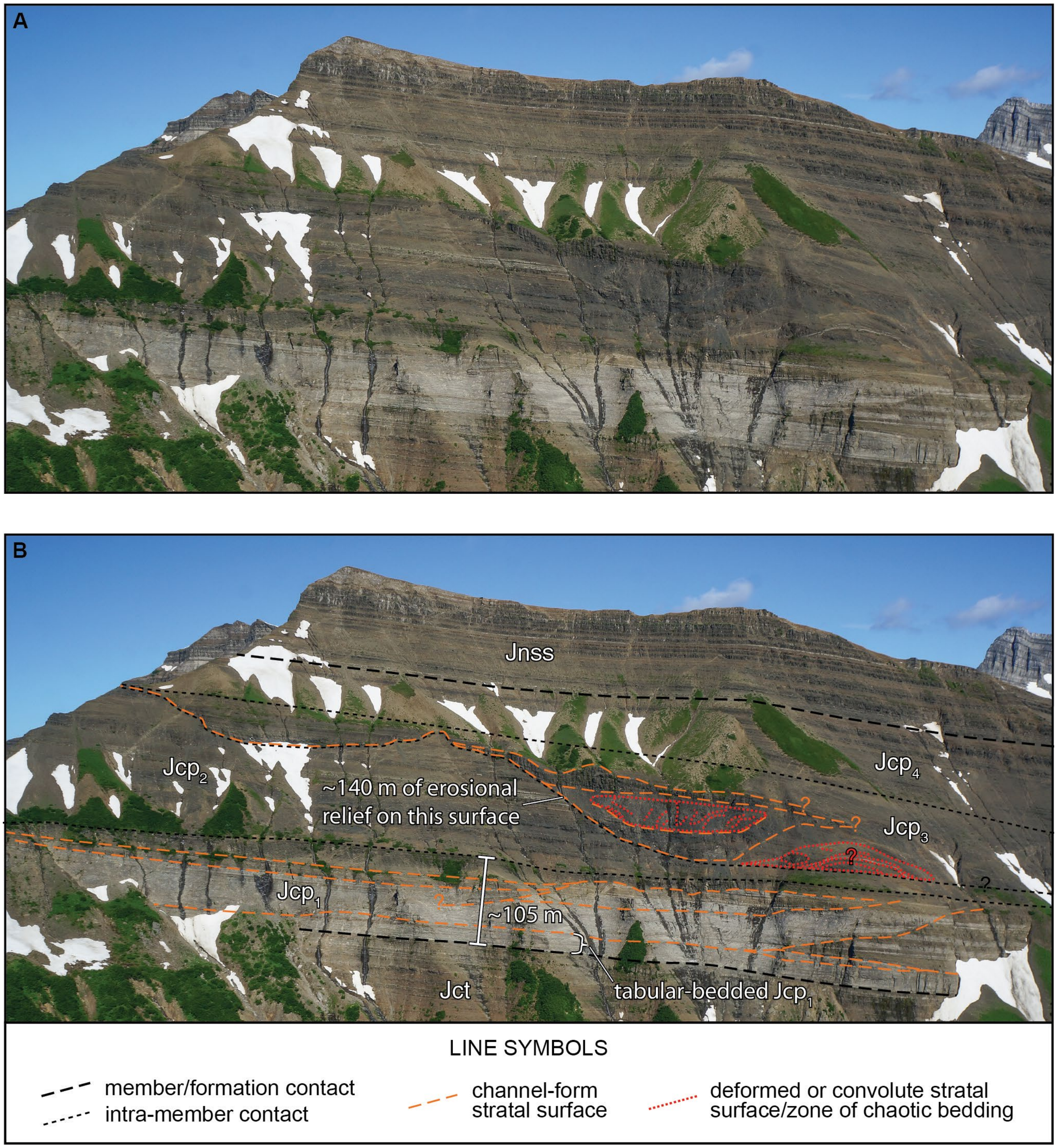

Figure 5-2. Oblique aerial view eastward of mountainside exposure of the Paveloff Siltstone Member and associated stratigraphic units ~3 km northwest of Slope Mountain (fig. 5-1). ***A.*** *Noninterpreted photograph.* ***B.*** *Photogeologic interpretation of photograph. See the text for discussion of the stratigraphic architecture in the Paveloff. Abbreviations:* Jct *= Tonnie Siltstone Member, Chinitna Formation;* Jcp *= Paveloff Siltstone Member, Chinitna Formation (subscripted divisions of this study are discussed in the text);* Jnss *= lower sandstone member, Naknek Formation. Photograph by M.A. Wartes.*

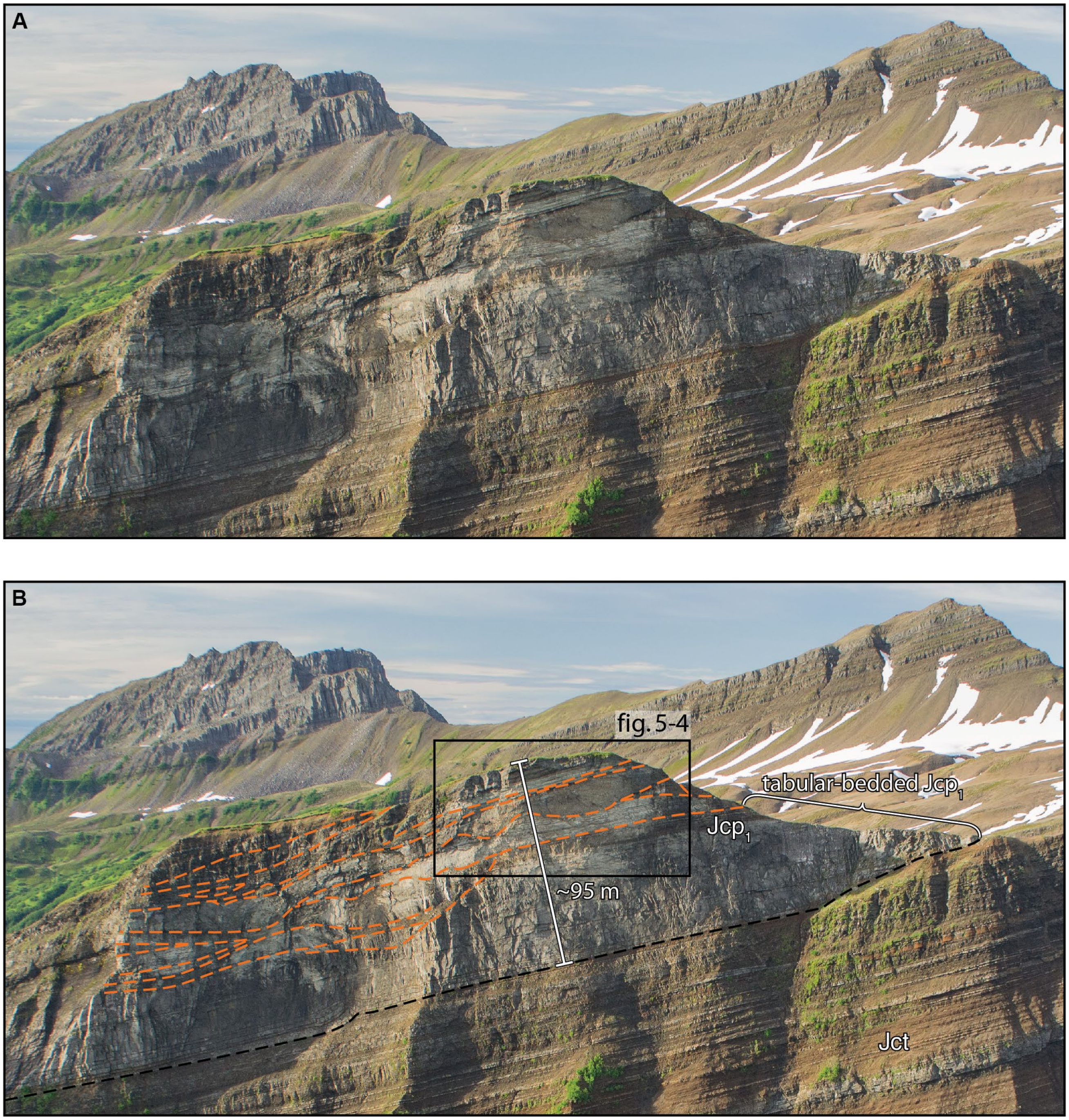

Figure 5-3. Oblique aerial view southward of a cliff-face exposure of upper Tonnie Siltstone and lower Paveloff Siltstone Members ~1.5 km west of Triangle Peak (fig. 5-1). ***A.*** *Noninterpreted photograph.* ***B.*** *Photogeologic interpretation of photograph. Peak at skyline-left is Saddle Mountain (fig. 5-1). See figure 5-2 for line symbol and abbreviation explanations. Photograph by T.M. Herriott.*

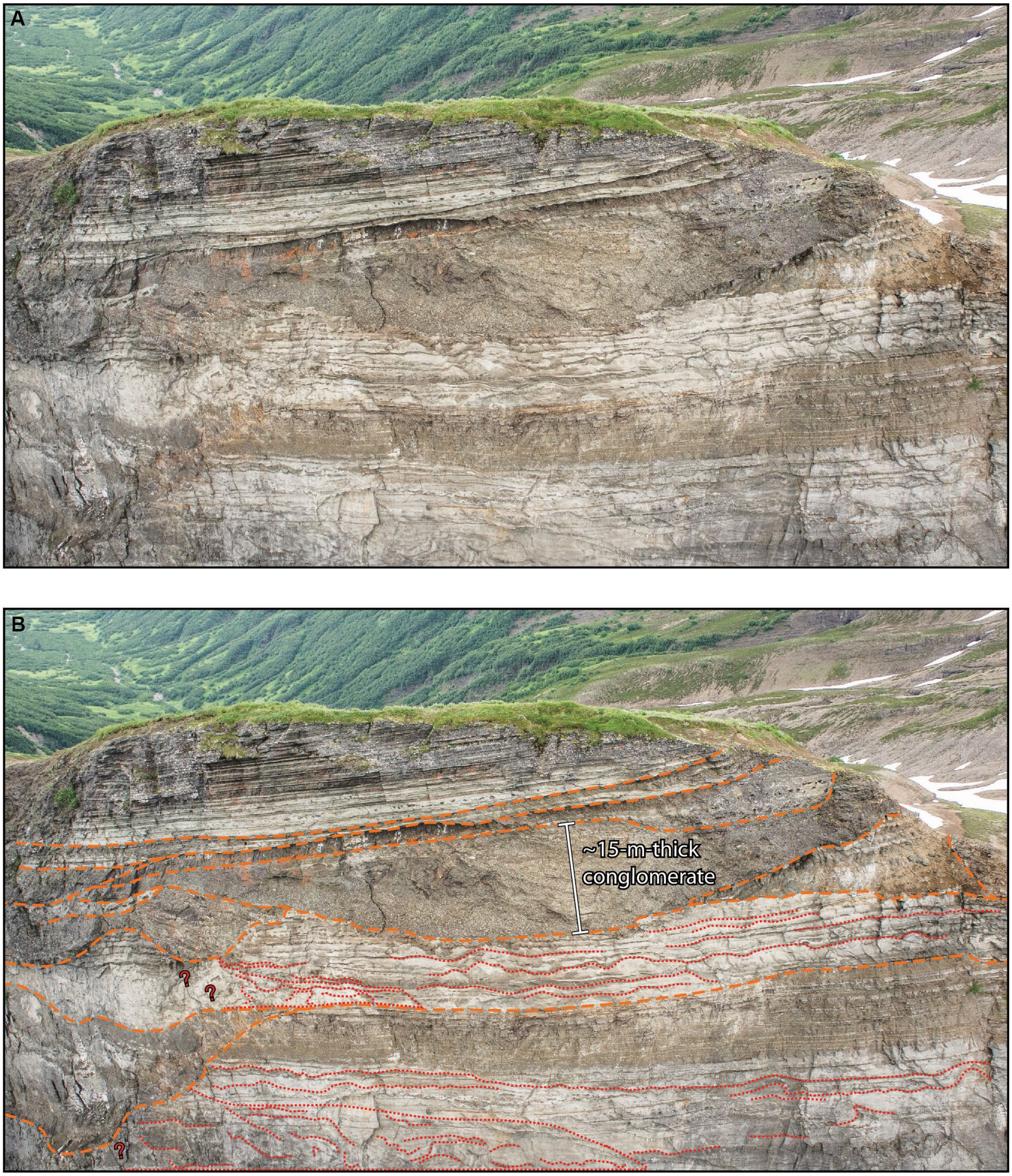

*Figure 5-4. Detailed oblique aerial view southward of the cliff-face exposure in figure 5-3. **A.** Noninterpreted photograph. **B.** Photogeologic interpretation of photograph. Note zones of convolute stratification and ~15-m-thick, channel-form conglomerate discussed in the text. See figure 5-2 for line symbol and abbreviation explanations. Photograph by T.M. Herriott.*

of Jcp_2, which is likely the record of lower-energy shelfal sedimentation. The deep incisions of Jcp_3 may be associated with gravitationally driven submarine mass-wasting processes, as suggested by the deformed strata associated with the largest of these channel forms; a candidate setting for mass-wasting inception of these features is a shelf edge immediately inboard of a steeper gradient slope (compare with Posamentier and Allen, 1999). Although coarser grained and thicker bedded in part, the dark weathering color of the fill in Jcp_3 incisions suggests compositional similarity to the host strata and may in part be recycled sediment from Jcp_2 up-dip. Fine-grained, non-channelized sedimentation (Jcp_4) resumed after the Jcp_3 incisions were healed. Deposition of the Paveloff ceased during establishment of a regional unconformity that Herriott and others (2015) identify as a sequence boundary at the base of the Naknek Formation.

An important aspect of this architectural analysis is the likelihood that significant volumes of coarse detritus associated with Jcp_1 were exported to depositional settings beyond the modern outcrop belt. Furthermore, the incisions of Jcp_3 may indicate proximity to a shelf–slope break, and coarse-grained sediment that reached a shelf edge may have accumulated in slope channels or bypassed to a basin floor (compare with Hubbard and others, 2014). This study thus presents viable scenarios where Paveloff reservoir facies could have been deposited in shallow- to deep-marine environments that today lie in the subsurface of Cook Inlet and may be prospective for oil and/or gas.

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CHAPTER 6

RECORD OF A LATE JURASSIC DEEP-WATER CANYON AT CHISIK ISLAND, SOUTH-CENTRAL ALASKA: FURTHER DELINEATION OF NAKNEK FORMATION DEPOSITIONAL SYSTEMS IN LOWER COOK INLET

Trystan M. Herriott[1], Marwan A. Wartes[1], and Paul L. Decker[2]

INTRODUCTION

Sedimentologic, stratigraphic, and geologic mapping-based studies of the Upper Jurassic Naknek Formation are part of a Department of Natural Resources-led project to examine the Mesozoic stratigraphy and structure of lower Cook Inlet (Gillis, 2013, 2014; Wartes, 2015; Herriott, 2016 [this volume]). This ongoing research aims to elucidate geologic relations that are relevant to the petroleum systems in the Cook Inlet forearc basin, a producing yet underexplored hydrocarbon province (LePain and others, 2013). Our recent Naknek Formation work focuses on an ~80 km trend exposed parallel to the basin margin between Iniskin and Tuxedni bays (fig. 6-1), building on the geologic framework established by Detterman and Hartsock (1966).

In this brief paper, we continue to document stratigraphic relations between the Snug Harbor Siltstone and Pomeroy Arkose Members (Naknek Formation), which are interpreted chiefly as marine slope and base-of-slope/basin floor units, respectively (LePain and others, 2013; Wartes and others, 2013). The Snug Harbor–Pomeroy contact is typically sharp and conformable and is mapped at the base of amalgamated, tabular packages of light-gray-weathering arkose (Detterman and Hartsock, 1966; Herriott and Wartes, 2014). However, during field investigations in 2013 and 2014, atypical stacking relations between the Snug Harbor and Pomeroy were recognized in the Mount Pomeroy and Hickerson Lake areas (fig. 6-1), where lithofacies, stratal geometries, and seismic-scale stratigraphic architecture were interpreted to record processes associated with two deep-water canyons (Herriott and others, 2015a, 2015b). Presented below are new field observations from Chisik Island (fig. 6-1) that suggest establishment and filling of a third canyon in the Snug Harbor–Pomeroy interval, further delineating the stratigraphic framework of Cook Inlet during the Late Jurassic.

STRATIGRAPHIC OBSERVATIONS AT CHISIK ISLAND

Aerial reconnaissance of a superb mountainside exposure at the north end of Chisik Island revealed prominent concave-up erosional surfaces in the Snug Harbor–lower Pomeroy that are overlain by channel-form sediment bodies (fig. 6-2). A basal erosional surface is identified as the master channel margin. This surface cuts across ~100 m of stratigraphy, marking the Snug Harbor–Pomeroy contact to the northeast, separating two architecturally distinct packages of Snug Harbor (the lower denoted here as Jns_1 and the upper as Jns_2) in the central area of figure 6-2, and juxtaposing the lower sandstone member (Naknek Formation) and Jns_2 to the southwest, where Jns_1 is entirely truncated. Jns_1 comprises relatively thin, tabular beds of siltstone and very-fine-grained sandstone typical of Snug Harbor (Herriott and Wartes, 2014). Jns_2 is distinguished from Jns_1 in that it lies within the master channel, hosts abundant channel-form stratal geometries, and is sandier. The contact between Snug Harbor and lower Pomeroy (Jnp_1) is mapped at the base of very thick successions of amalgamated arkoses that are tabular to locally channelized, although channel margins are less steep than those observed in Jns_2 (fig. 6-2); siltstone intercalations in Jnp_1 are only a minor constituent. Finally, an upper Pomeroy unit (Jnp_2) contains thicker amalgamated arkosic packages than are observed in Jnp_1, is dominantly tabular-bedded at the scale of exposure, lacks siltstone interbeds, and is lithostratigraphically consistent with Pomeroy successions that typically crop out conformably above Snug Harbor of Jns_1 affinity (Herriott and Wartes, 2014).

INTERPRETATIONS AND DISCUSSION

The lithostratigraphic relations and large-scale stratal architecture described above and in figure 6-2 are interpreted as the record of a deep-water canyon. This Chisik Island canyon association consists of pre-, intra-, and beyond-canyon facies—Jns_1, Jns_2–Jnp_1, and Jnp_2, respectively—permitting insights into trends in Naknek Formation deep-water depositional systems. Deposition of Jns_1 (slope facies) was terminated by canyon incision and establishment of intra-canyon channel belts (Jns_2) with relatively steep channel margins during an early canyon-fill episode that was likely dominated by erosional processes and sediment bypass. Jnp_1 marks a transition to widening channel belts with relatively gentle channel margins, increasing

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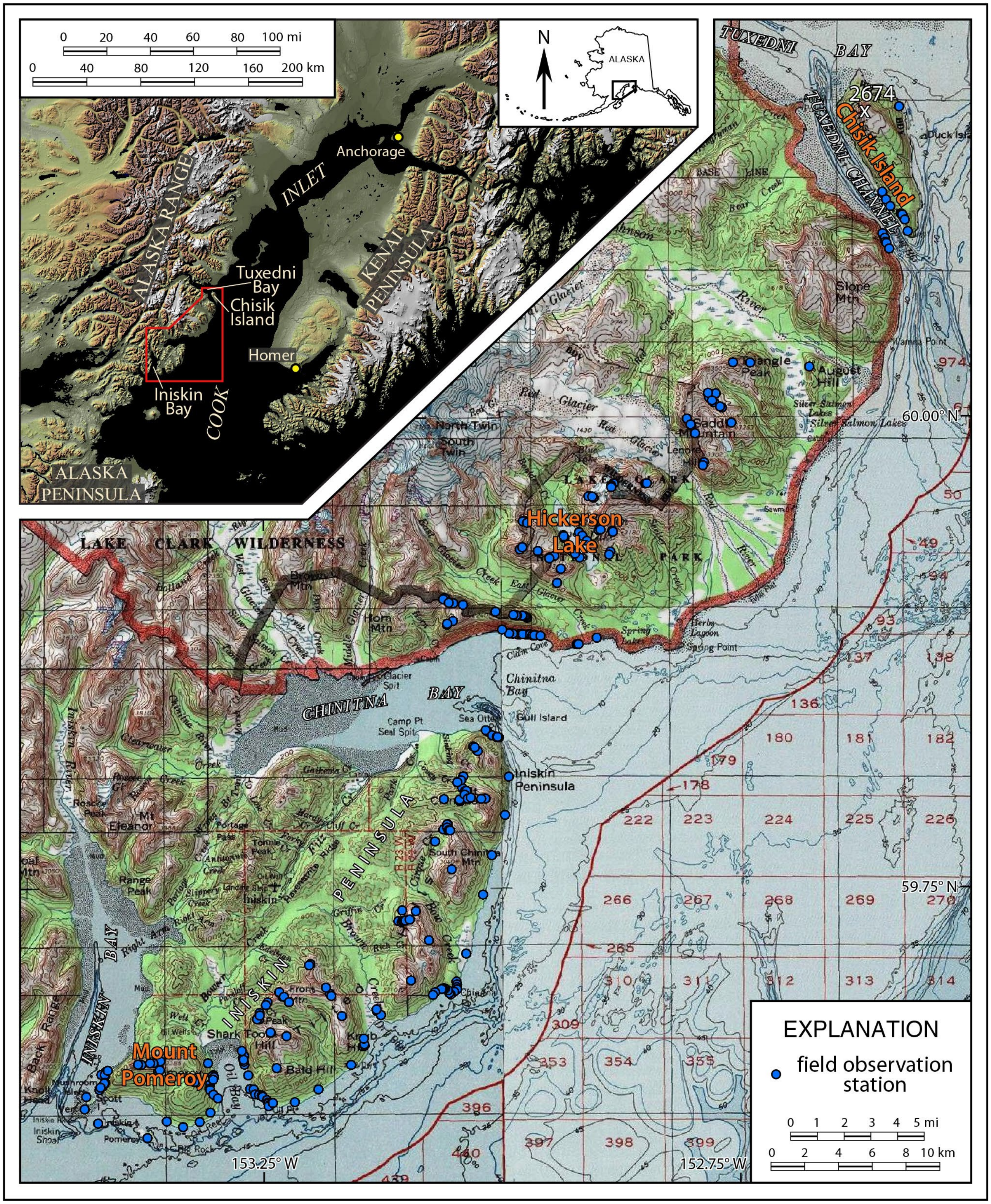

Figure 6-1. Location map of the Iniskin–Tuxedni bays study area. Detailed observations of the Naknek Formation were made by the authors at more than 325 localities during six field seasons. Evidence of deep-water canyon and associated processes in the Snug Harbor Siltstone–lower Pomeroy Arkose Members interval have been documented in three areas (see orange labels with black outlines and text for discussion). Topographic base map from portions of U.S. Geological Survey Iliamna, Seldovia, Lake Clark, and Kenai 1:250,000-scale quadrangles; shaded-relief image modified after U.S. Geological Survey Elevation Data Set Shaded Relief of Alaska poster (available for download at http://eros.usgs.gov/alaska-0).

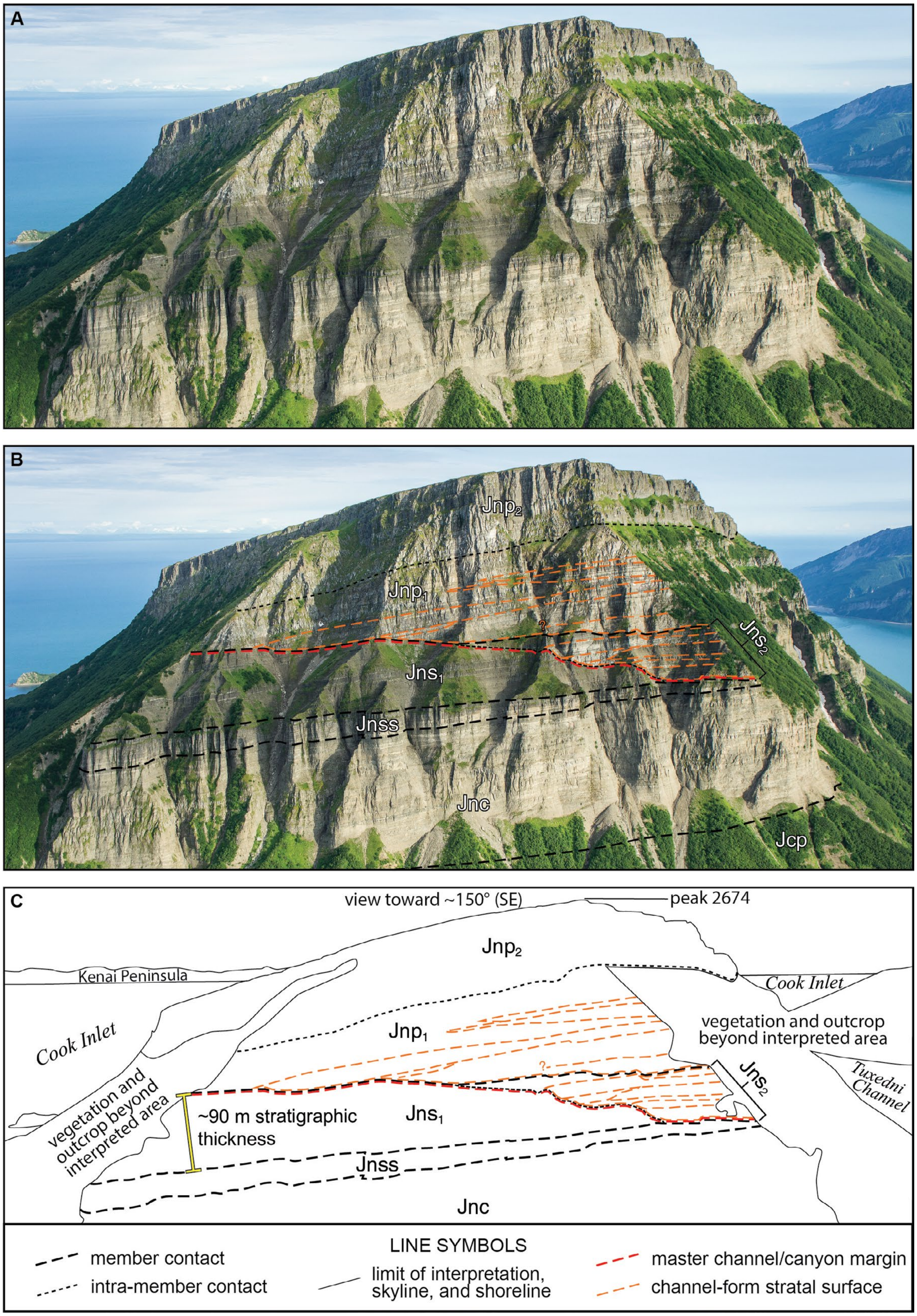

*Figure 6-2. Oblique aerial view southeastward of the northern extent of Chisik Island (fig. 6-1). Key stratigraphic relations in the Snug Harbor Siltstone (*Jns$_1$ *and* Jns$_2$*) and Pomeroy Arkose (*Jnp$_1$ *and* Jnp$_2$*) Members are discussed in the text and include the distribution of lithofacies and stratigraphic architecture.* ***A.*** *Noninterpreted photograph.* ***B.*** *Photogeologic interpretation.* ***C.*** *Line drawing interpretation. Approximately 400 m (~1,300 ft) of topographic relief lie between peak 2674 (fig. 6-1) and the base-of-cliff exposures of Chisik Conglomerate Member (*Jnc*; Naknek Formation), for sense of scale. Additional abbreviations:* Jcp *= Paveloff Siltstone Member, Chinitna Formation;* Jnss *= lower sandstone member, Naknek Formation; SE = southeast. Photograph by T.M. Herriott.*

occurrence of tabular beds, and increasing sandstone-to-siltstone ratios. These Jns_2 to Jnp_1 trends may in part reflect a reduction in gradient along the canyon axis and reduced bypass at this site, potentially as a result of canyon-associated depositional systems trending toward equilibrium grade as the base-of-slope environment accumulated sediment and the basin-floor depositional elements of the Pomeroy onlapped the inherited paleobathymetric profile of the Snug Harbor slope (Herriott and others, 2015a). Jnp_2 is interpreted to record distributary lobe sedimentation beyond the canyon mouth, which retreated farther upslope as arkosic sediment continued to debouch onto the basin floor (compare with Mutti and Normark, 1987).

These observations and interpretations are consistent with: (1) our prior work (see references above), (2) the tendency of deep-water channelized depositional systems to evolve in space and time (for example, Posamentier and Kolla, 2003; Hubbard and others, 2014), with erosional processes and bypass dominant in steeper gradient settings and channelized-aggradational to distributary-aggradational processes dominant in lower gradient settings, and (3) deep-water canyons commonly serving as conduits to route coarse-grained sediment to basin floors (for example, Miall, 1990). The Chisik Island canyon—in conjunction with our observations in the Mount Pomeroy and Hickerson Lake areas—also establishes a maximum canyon spacing of ~30–40 km along the Iniskin–Tuxedni bays outcrop belt (fig. 6-1). This study thus further constrains depositional systems evolution, sediment routing pathways, and location of paleobathymetric elements during Snug Harbor and Pomeroy deposition, yielding insights into the distribution of coarse-grained strata that may host oil and gas in Cook Inlet.

ACKNOWLEDGMENTS

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CHAPTER 7

DISCOVERY OF A NEW SANDSTONE WITH RESIDUAL OIL IN MAASTRICHTIAN(?) STRATA AT SHELTER CREEK, LOWER COOK INLET, ALASKA

Robert J. Gillis[1]

INTRODUCTION

Mesozoic sandstones in Cook Inlet basin are commonly thought to possess insufficient primary porosity and permeability (for example, Helmold, 2013; Helmold and others, 2013; Helmold and Stanley, 2015) to host commercial hydrocarbon reservoirs, which has negatively impacted exploration efforts that target these intervals. Nevertheless, local incidences of porosity-hosted oil in Mesozoic strata have been identified in outcrop (for example, Stanley and others, 2013; LePain and others, 2012; Wartes and others, 2013; Wartes and Herriott, 2014, 2015) and in wells (Magoon and Anders, 1992), but controls of their distribution are poorly understood. Most of these occurrences are in more quartz-rich Upper Cretaceous strata found throughout Cook Inlet basin (fig. 7-1; Magoon and others, 1980; Magoon and Anders, 1992; Magoon and Egbert, 1986; LePain and others, 2012; Wartes and others, 2013). This report documents a newly discovered oil-bearing sandstone locality in probable Upper Cretaceous (Maastrichtian[?]) strata on the west side of lower Cook Inlet that was encountered during geologic mapping by the Alaska Division of Geological & Geophysical Surveys (DGGS) in summer 2015 (see Herriott, 2016 [this volume]). Presented below is a description of this locality at Shelter Creek on the west side of Cook Inlet (figs. 7-2 and 7-3), followed by a brief discussion of the regional distribution and significance of porosity-hosted hydrocarbons in Upper Cretaceous strata of Cook Inlet.

BRIEF DESCRIPTION OF MAASTRICHTIAN(?) STRATA AT SHELTER CREEK

A thin, newly-identified wedge of conglomerate, sandstone with residual oil, siltstone, and silty coal observed at Shelter Creek has characteristics similar to a well-studied nonmarine Maastrichtian interval hosting oil-bearing sandstones near Saddle Mountain (sometimes informally referred to as the Saddle Mountain member or Saddle Mountain section [Magoon and others, 1980; LePain and others, 2012]). The section likely composes part of a thin belt of strata that is discontinuously exposed for about 9.5 km from east of Hickerson Lake to southeast of Saddle Mountain (fig. 7-2; see also Wilson and others, 2012). The entire Maastrichtian(?) interval at Shelter Creek is only about 7 m thick (fig. 7-4a) and overlies Upper Jurassic Naknek Formation marine sandstone. An up-to-5-m-thick succession at the base of the interval is composed of clast-supported cobble conglomerate (fig. 7-4b). The upper portion of the Maastrichtian(?) interval consists of an approximately 80-cm-thick, light tan- to buff-colored, tabular, fine-grained, arkosic sandstone that is overlain by an approximately 80-cm-thick succession of siltstone. The Maastrichtian(?) interval is capped by a 5–10-cm-thick, highly carbonaceous siltstone to bony coal (figs. 7-4b and 7-4c). The upper several centimeters of the undisturbed sandstone bed emits a faint, fleeting petroliferous odor that is strong and persistent from freshly broken surfaces. The sandstone is mostly massive, but includes weakly expressed, very thin, concave-up partings in the upper 35 cm consistent with preferentially weathered ripple laminations. This sandstone is moderately well indurated, contrasting with other occurrences of Maastrichtian sandstones with residual oil that are friable, presumably because hydrocarbon migration preceded cementation (LePain and others, 2012). The Maastrichtian(?) strata are overlain by more than 100 m of poorly organized cobble conglomerate of the Paleogene West Foreland Formation (figs. 7-3 and 7-4). Although the two conglomeratic units have similar volcanic and volcaniclastic clast compositions, the Maastrichtian(?) conglomerate contains a higher percentage of plutonic clasts (~20% vs. ~10%, respectively), perhaps suggesting a more quartz-rich, dissected arc provenance for the former.

STRATIGRAPHIC RELATIONSHIP BETWEEN MAASTRICHTIAN(?) STRATA AND OVERLYING/UNDERLYING UNITS

Upper Cretaceous strata in Cook Inlet basin are bounded by regional unconformities that are locally well expressed in the study area (see fig. 7-2 for location). Here, Maastrichtian(?) strata unconformably overlie a uniform dip panel of well-indurated Naknek Formation sandstone and are separated from overlying West Foreland Formation conglomerate by a complex, undulating unconformity (figs. 7-5a and 7-5b). The unconformity often erosionally removes the Maastrichtian(?) rocks altogether and places West Foreland conglomerates directly on the Naknek strata (fig. 7-5a), forming thin, tapering lenses of Upper Cretaceous rocks (fig. 7-2). Magoon and others (1980) reported 14 degrees of fanning bedding discordance between Naknek and Maastrichtian strata and 10 degrees of discordance between Maastrichtian strata and West Foreland

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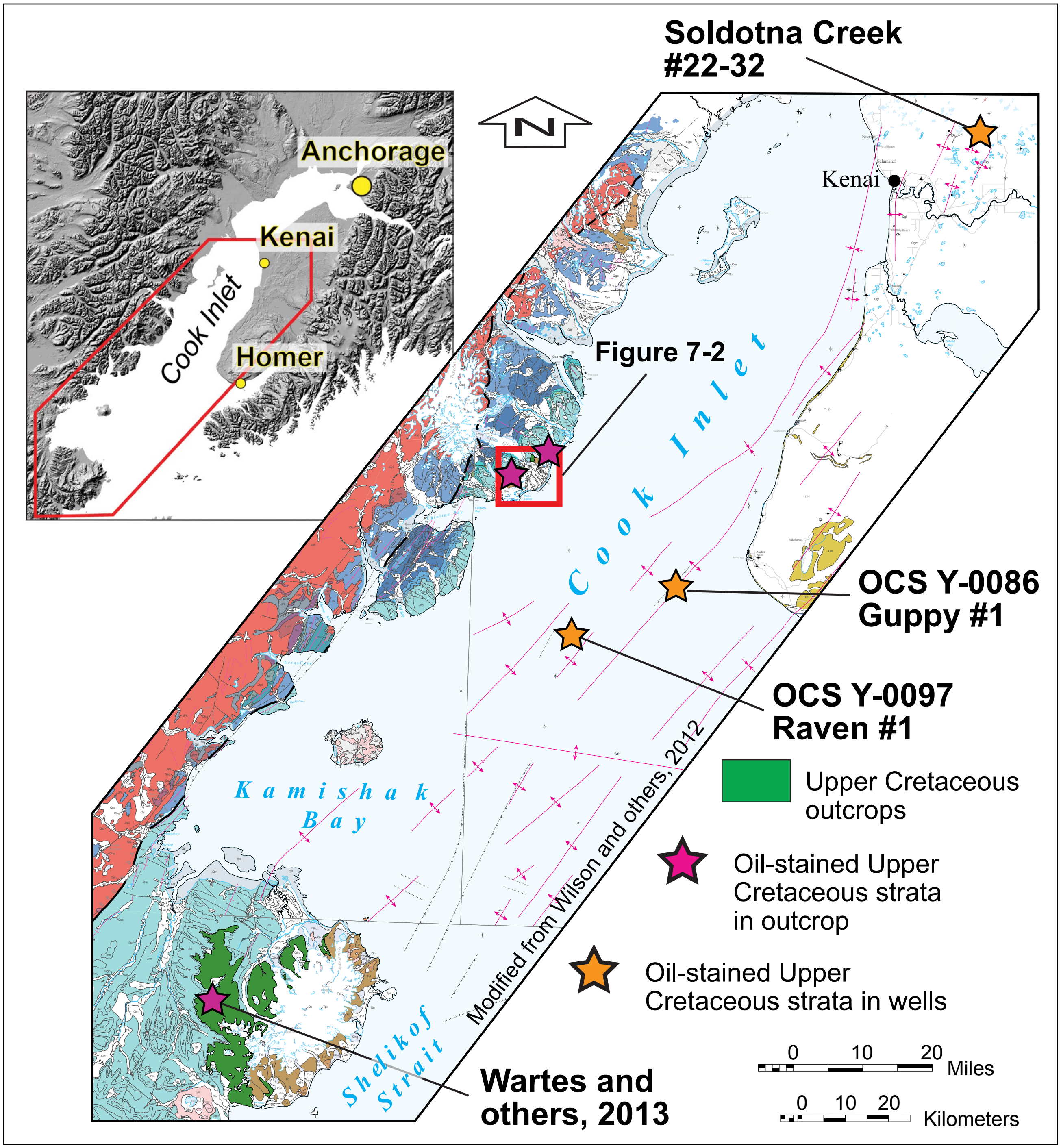

Figure 7-1. Simplified geologic map of lower Cook Inlet, modified from Wilson and others (2012), showing distribution of Upper Cretaceous rock outcrops (dark green polygons), distribution of known oil-saturated Upper Cretaceous sandstones in outcrop (magenta stars), and distribution of Cook Inlet wells in which oil-saturated sandstones and liquid hydrocarbons were encountered in Upper Cretaceous rocks (orange stars). Note the broad distribution of Upper Cretaceous sandstones throughout the basin that possess porosity-hosted hydrocarbons. Field study area defined by red box.

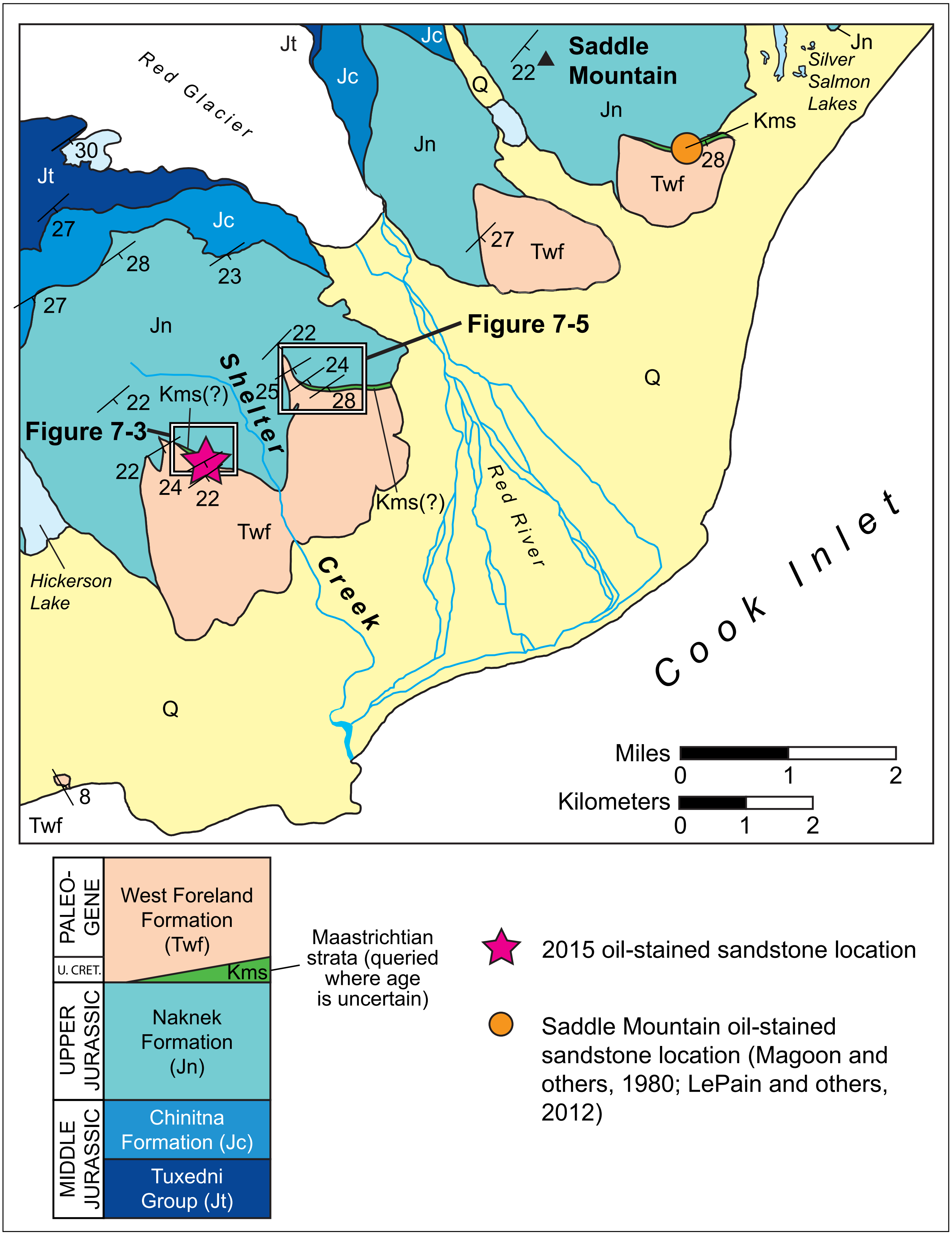

Figure 7-2. Geologic map showing the distribution of Upper Cretaceous strata on the west side of lower Cook Inlet. Map simplified from new 1:63,360-scale field mapping by DGGS in summer 2015. Magenta star indicates the location of a newly identified occurrence of oil-saturated sandstone in Maastrichtian(?)-age strata. The orange circle indicates the location of an occurrence of Maastrichtian rocks hosting residual oil previously identified by LePain and others (2012). These strata are interpreted to represent a once continuous succession of Upper Cretaceous strata that was erosionally dissected prior to Cenozoic nonmarine deposition.

Formation, suggesting progressive tilting of the basin margin since Late Jurassic. However, this study documents that over the length of outcrops that extend several tens to hundreds of meters, depositional surfaces are commonly subparallel between units (fig. 7-5a). This is supported by 69 bedding orientation measurements from all three units that indicate relatively uniform attitudes, implying that southeast tilting of the entire stratigraphic package by about 22–24 degrees occurred after Paleogene time.

SIGNIFICANCE OF WIDESPREAD OCCURRENCE OF OIL IN UPPER CRETACEOUS ROCKS OF COOK INLET

Maastrichtian(?) rocks at Shelter Creek and near Saddle Mountain represent the northernmost outcrops of Upper Cretaceous strata known in the Cook Inlet basin. The nearest sedimentary outcrops of equivalent age are marine Kaguyak Formation strata on the upper Alaska Peninsula (Riehle and others, 1993) approximately 130 km due southwest of the study area (fig. 7-1), which are also locally oil bearing (Wartes and others, 2013). Despite being only discontinuously exposed at the surface, Upper Cretaceous strata occur in the offshore subsurface throughout much of the Cook Inlet basin (Boss and others, 1976; Magoon and Egbert, 1986; Magoon and Anders, 1992; Gregerson and Shellenbaum, in press). Although relatively few Cook Inlet wells penetrate Mesozoic strata, drill stem tests of three such wells (fig. 7-1) produced non-commercial amounts of oil from Upper Cretaceous rocks (Magoon and Anders, 1992). The wide distribution of Upper Cretaceous sandstones with oil shows in Cook Inlet basin suggests that these strata might be viable conventional reservoir rocks in the underexplored Mesozoic stratigraphy.

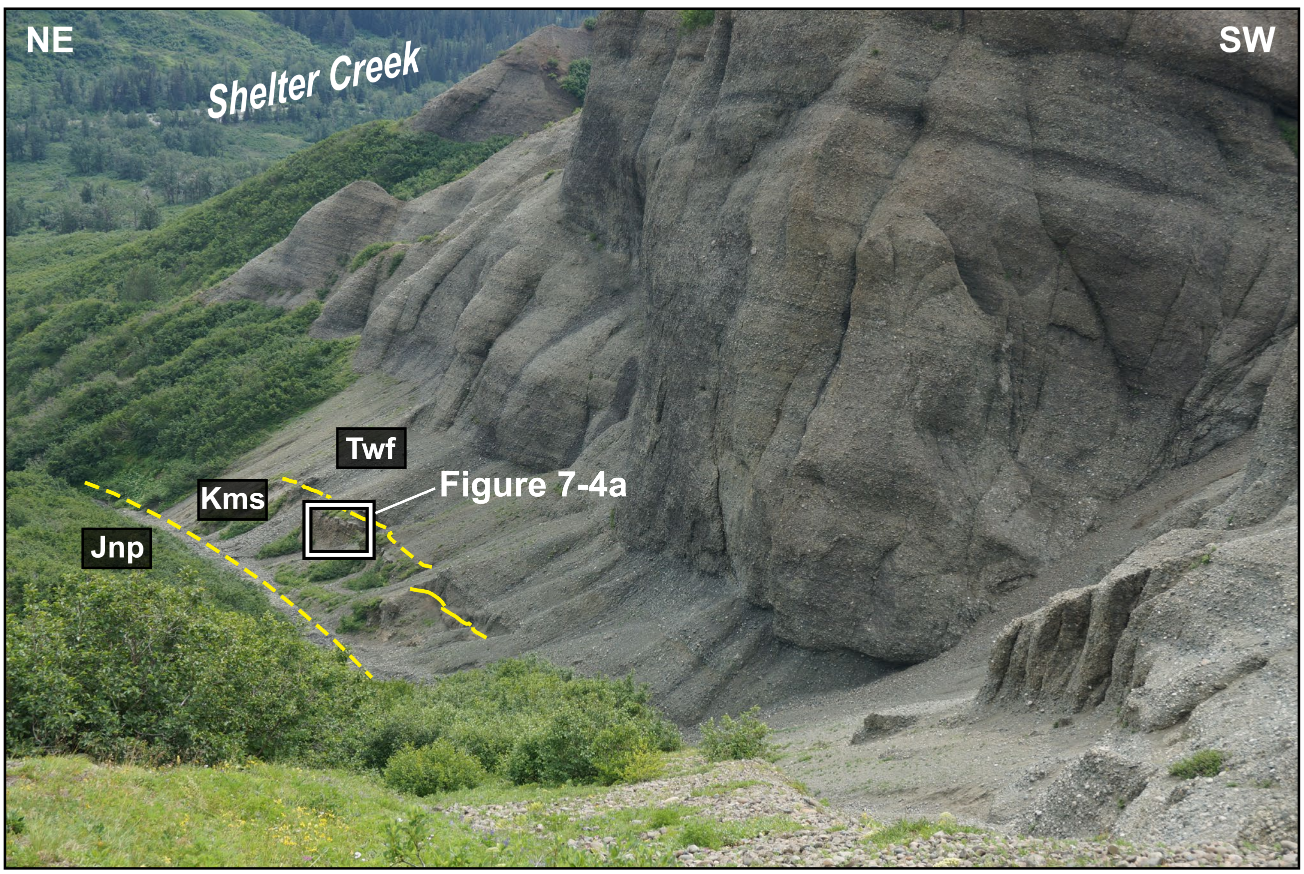

Figure 7-3. View, looking due southeast, from near the headwaters of Shelter Creek toward Cook Inlet. A thin succession of Maastrichtian(?) strata unconformably overlies Upper Jurassic Naknek Formation marine sandstone and unconformably underlies a thick succession of Paleogene West Foreland Formation nonmarine conglomerate. White box frames area of detailed images of a Maastrichtian(?) sandstone interval hosting residual oil (fig. 7-4). Jnp *= Naknek Formation (Pomeroy Arkose Member),* Kms *= Maastrichtian(?) strata,* Twf *= West Foreland Formation. Yellow lines (dashed where inferred) represent formation contacts. See figure 7-2 for location context.*

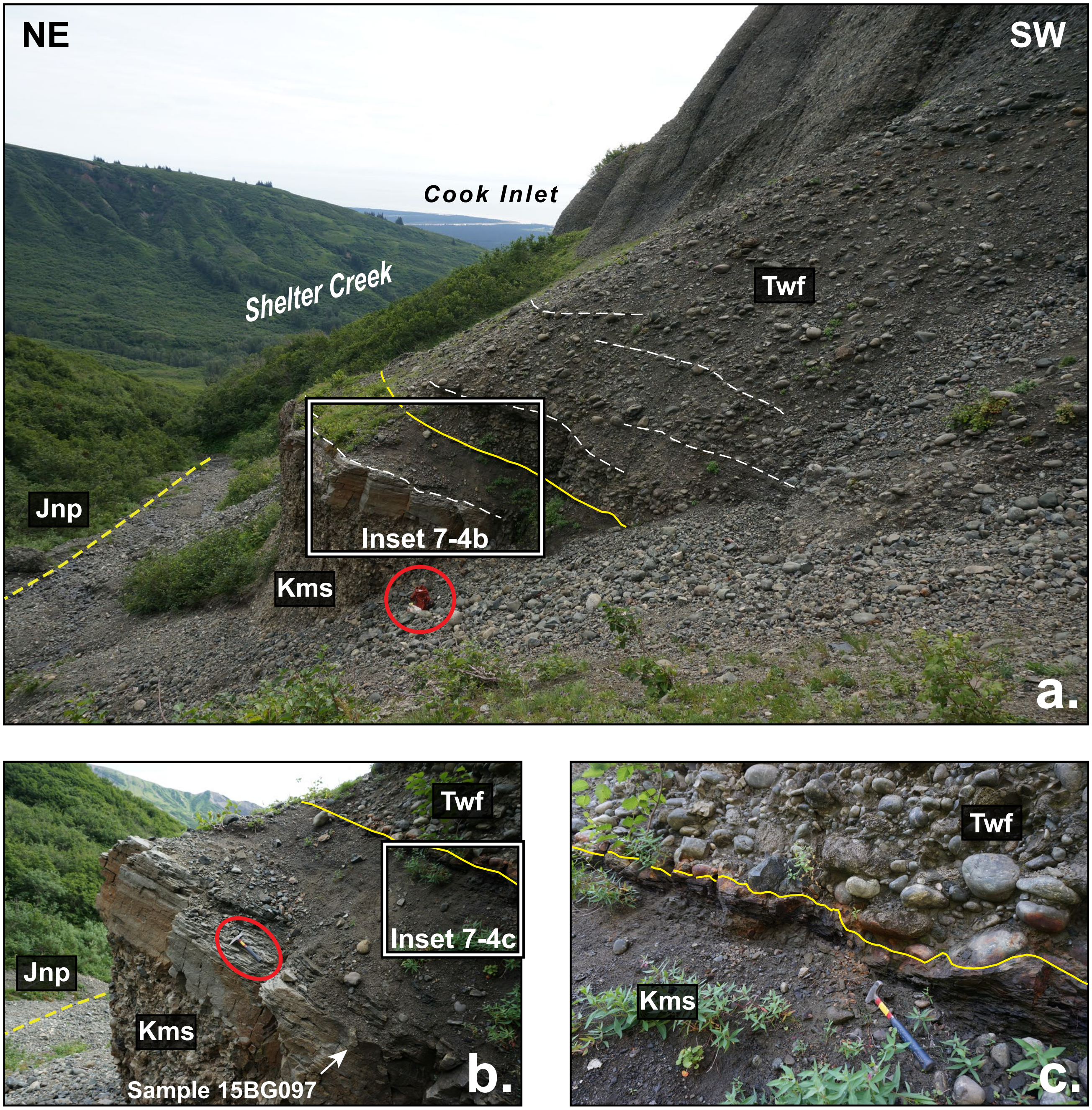

Figure 7-4. Detailed views, looking due southeast, at the Shelter Creek Maastrichtian(?) section. Yellow lines represent formation contacts and white lines represent traceable bedding surfaces; dashed lines are inferred. Jnp = *Upper Jurassic Naknek Formation (Pomeroy Arkose Member),* Kms = *Maastrichtian(?) strata,* Twf = *West Foreland Formation. See figure 7-2 for location context.* ***a.*** *An up-to-5-m-thick succession of conglomerate overlying a uniform Naknek Formation dip slope is capped by an approximately 80-cm-thick sandstone bed that emits a faint petroliferous odor. Backpack (in red circle) for scale.* ***b.*** *A sample (15BG097) for organic geochemical analysis was collected near the top of the sandstone bed, from the interval where a petroliferous odor is most strongly emitted. Sandstone bed transitions from massive to ripple cross-laminated in the upper 35 cm. The sandstone bed is moderately well indurated throughout, unlike other reported occurrences of remnant oil-bearing Upper Cretaceous sandstones that are friable (LePain and others, 2012), possibly suggesting that cementation occurred prior to hydrocarbon migration at this location. Hammer (in red oval) for scale.* ***c.*** *Uppermost Maastrichtian(?) interval and contact with overlying West Foreland Formation. Highly carbonaceous siltstone and bony coal compose the upper 5–10 cm of the Maastrichtian(?) succession. The irregular contact with the overlying West Foreland Formation at this location is non- or minimally erosive and appears to be concordant with overlying and underlying bedding surfaces.*

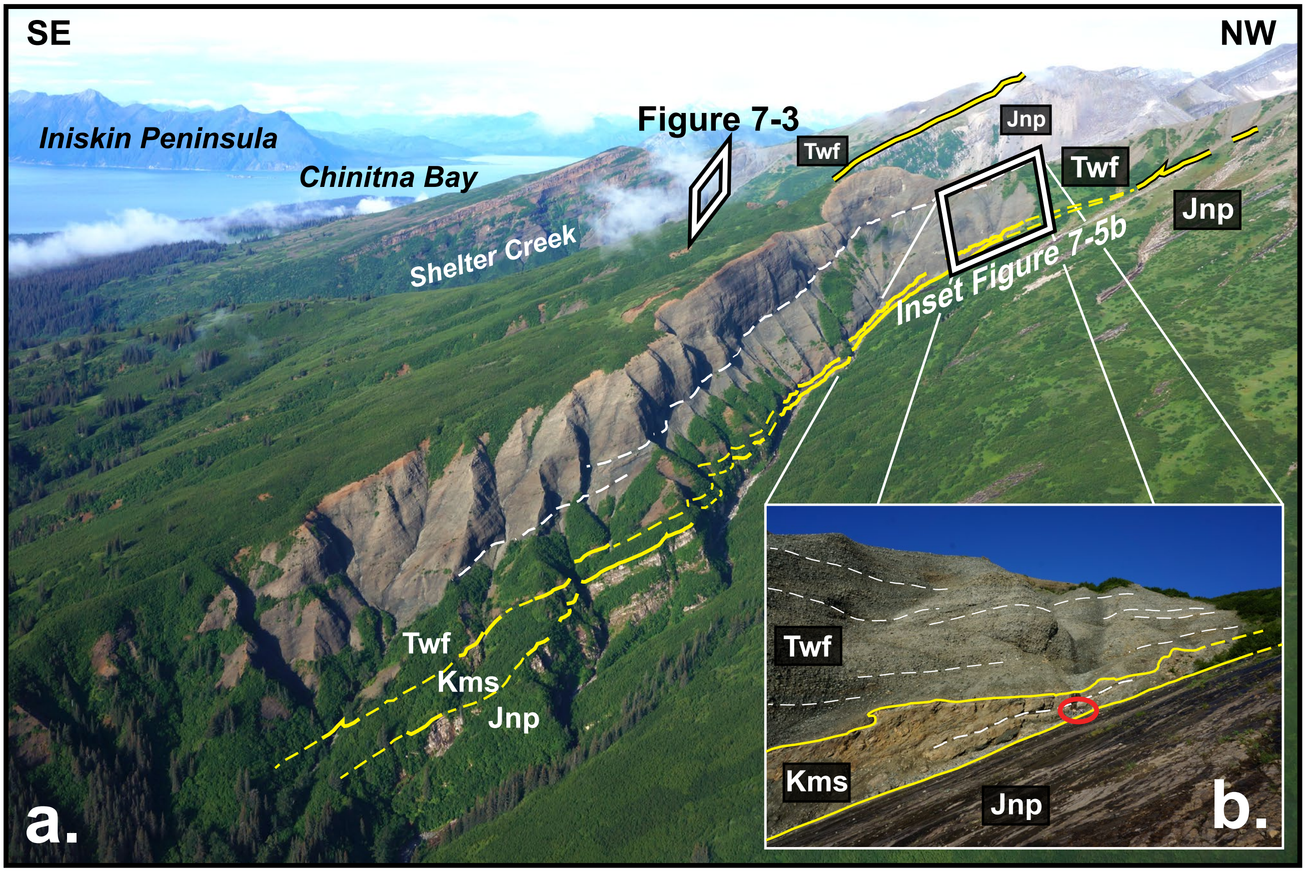

Figure 7-5. ***a.*** *View, looking due southwest toward Chinitna Bay, across two flatirons of southeast-tilted Naknek Formation, Maastrichtian(?), and West Foreland Formation strata. Unnamed creek in the foreground drains into the Red River (see fig. 7-2); Shelter Creek appears in the middle ground. Formation contacts represented as yellow lines (dashed where inferred). Major stratigraphic horizons in West Foreland Formation conglomerates are marked with heavy dashed white lines.* Jnp *= Upper Jurassic Naknek Formation (Pomeroy Arkose Member),* Kms *= Maastrichtian(?) strata,* Twf *= Paleocene(?) to Eocene West Foreland Formation. In both creeks,* Jnp *forms a remarkably uniform dip slope, and* Twf *cuts downsection upslope, removing* Kms *and directly juxtaposing* Twf *and* Jnp*. A well-defined* Twf *stratal surface parallels Jnp for hundreds of meters, indicating that both were subhorizontal during* Twf *deposition. Sixty-eight bedding orientations measured from all three units in this view suggest little regional bedding angularity between the formations.* ***b.*** *Detailed view of* Jnp/Kms/Twf *contacts, highlighting the uniform* Jnp *dip slope, concordant* Jnp/Kms *contact and subparallel deposition of* Kms*, and erosive* Kms/Twf *contact that thins* Kms *upslope to the northwest. Thin dashed white lines in represent traceable bedding surfaces. Two geologists (sitting, in red oval) for scale. See figure 7-2 for location context.*

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CHAPTER 8

REVISED MAPPING OF THE UPPER JURASSIC NAKNEK FORMATION IN A FOOTWALL SYNCLINE ASSOCIATED WITH THE BRUIN BAY FAULT SYSTEM, CHINITNA BAY REGION, WESTERN COOK INLET, ALASKA

Marwan A. Wartes[1], Robert J. Gillis[1], and Nina T. Harun[1]

INTRODUCTION

The Alaska Division of Geological & Geophysical Surveys (DGGS) is engaged in a multi-year investigation of the petroleum geology of the Cook Inlet region in southern Alaska. The Cook Inlet forearc basin has a long history of oil and gas production, and resource assessments indicate that significant potential remains for additional hydrocarbon discoveries (Stanley and others, 2011; LePain and others, 2013). Recent DGGS-led work includes detailed 1:63,360-scale geologic mapping as well as topical structural and stratigraphic studies (Gillis, 2013, 2014; Wartes, 2015; Herriott, 2016 [this volume]). These types of data provide important constraints on the evolution of the petroleum system and reduce exploration risk. This brief report summarizes new geologic mapping of Jurassic rocks in the Chinitna Bay region of western Cook Inlet (figs. 8-1 and 8-2) and offers additional insight into the structural evolution of the basin margin.

PREVIOUS WORK

The Bruin Bay fault system is a major structural boundary in western Cook Inlet, separating Jurassic magmatic arc and associated rocks from Middle to Upper Jurassic forearc basin strata (fig. 8-1; Detterman and Hartsock, 1966). Earlier mapping noted equivocal piercing points, suggesting the fault system was dominated by sinistral strike-slip motion with estimates of offset ranging from ~20 to 65 km (Detterman and Reed, 1980). More recent reconnaissance studies by DGGS recorded slip indicators on faults suggesting a complex mix of strike-slip and dip-slip motion (Gillis and others, 2013). Subsequent detailed studies provided robust kinematic analysis of fault surfaces, documenting at least two fault populations that record reverse and strike-slip deformation; the apparent oblique polyphase slip history may partly reflect variations in the strike of the fault (Betka and Gillis, 2016 [this volume]) and/or discrete episodes of faulting under different regional stress orientations (Betka and Gillis, 2014).

NEW MAPPING

During summer 2015 DGGS conducted detailed geologic mapping of the region between Chinitna Bay and the Johnson River (fig. 8-1). The southern part of the map area between Chinitna Bay and East Glacier Creek was recognized as important due to the potential to resolve understanding of structural and stratigraphic details in the immediate footwall of the Bruin Bay fault. The new mapping (fig. 8-2A) shares a broadly similar pattern with Detterman and Hartsock (1966), although the mapped stratigraphy and structures in the footwall of the fault are different in several notable aspects (fig. 8-2). We did not recognize the three folds (anticline–syncline–anticline) depicted in the earlier mapping (fig. 8-2B). Instead, aerial reconnaissance and several mapping traverses established the presence of a single, large overturned footwall syncline (figs. 8-2A and 8-3). Small-displacement, out-of-syncline backthrusts are present near the core of the fold (fig. 8-4), consistent with space problems associated with an increase in bed curvature during progressive folding (Mitra, 2002). Approximately 3 km east of the syncline our mapping defined a broad, relatively symmetric anticline (figs. 8-2A and 8-5), generally in agreement with Detterman and Hartsock (1966).

Three members of the Upper Jurassic Naknek Formation are present in the footwall syncline; the basal unit (lower sandstone member) has distinctive light-gray-weathering lithofacies that can be readily mapped southeastward to well-exposed coastal cliffs overlooking Chinitna Bay (fig. 8-3; Wartes and others, 2015). The overlying Snug Harbor Siltstone Member forms much of the exposed stratigraphy outlining the syncline (figs. 8-2 and 8-3). This unit is heterolithic, typical of the Snug Harbor in the region, including interbedded tabular, very-fine sandstone and siltstone with rare beds of poorly organized pebble conglomerate (see also Herriott and Wartes, 2014). Sole marks and ripple cross-lamination are uncommon, but provide useful stratigraphic top indicators, confirming the locally overturned nature of the western limb of the syncline. The Pomeroy Arkose Member is limited to a few tens of meters of very poorly organized boulder conglomerate preserved in the core of the syncline (figs. 8-2, 8-3, and 8-4). Similar anomalously coarse-grained facies are present in the Pomeroy on the southwestern Iniskin Peninsula (Wartes and others, 2013; Detterman and Hartsock, 1966).

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CORRELATION WITH OTHER STRUCTURES IN THE REGION

The asymmetry of the footwall syncline strongly suggests it formed in response to top-to-the-east reverse motion on the Bruin Bay fault. This geometry is very similar to a prominent footwall syncline documented south of the Iniskin Peninsula, at Ursus Head (fig. 8-1; Gillis and others, 2013; Betka and Gillis, 2015), as well as other newly mapped east-vergent footwall synclines to the north near Red Glacier and the upper Johnson River areas (fig. 8-1; Betka and Gillis, 2016). Footwall shortening appears to be principally concentrated adjacent to the Bruin Bay fault at each of these locations, with relatively gentle dips basinward of the tight footwall synclines (for example, fig. 8-2A).

The Fitz Creek anticline on the Iniskin Peninsula (figs. 8-1 and 8-6) has long been recognized as an exploration target due to several oil and gas seeps along the crest of the structure (Detterman and Hartsock, 1966). This fold is in a broadly similar position to the anticline mapped in this study, north of Chinitna Bay. However, the trace of the Bruin Bay fault cannot be correlated in a simple linear fashion between the two regions. Figure 8-6 presents five alternative models to account for the structural linkages across Chinitna Bay. This segment of the Bruin Bay fault may exhibit either a right-stepping bend (fig. 8-6A; see also Detterman and Hartsock, 1966), or a right-stepping stepover (fig. 8-6B) associated with sinistral

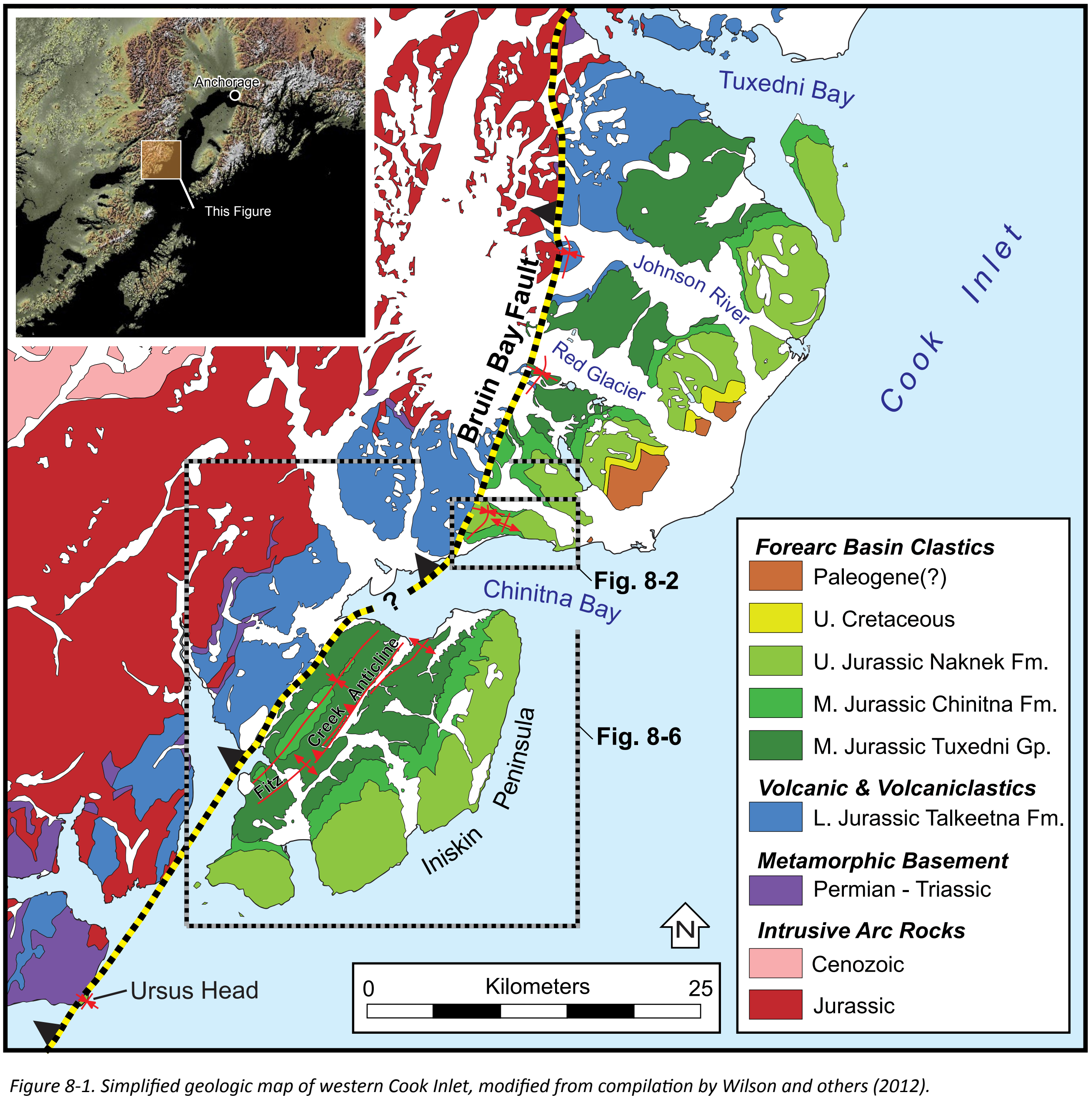

Figure 8-1. Simplified geologic map of western Cook Inlet, modified from compilation by Wilson and others (2012).

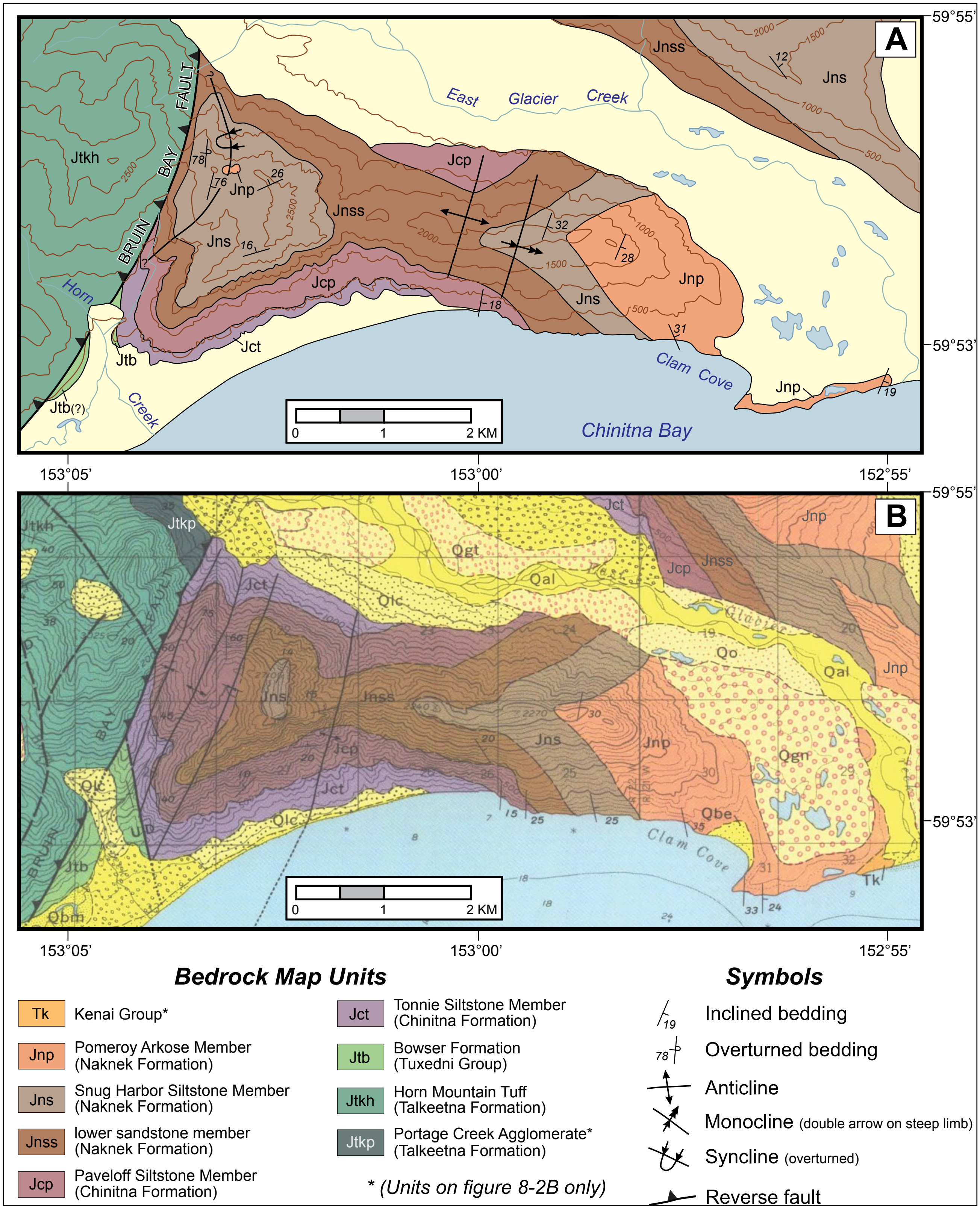

Figure 8-2. Geologic maps of the upland region between Chinitna Bay and East Glacier Creek. ***A.*** *Simplified version of new mapping completed in this study;* ***B.*** *snippet of equivalent map area from Detterman and Hartsock (1966). See figure 8-1 for map location and Detterman and Hartsock (1966) for explanation of Quaternary units and other symbols and line styles not utilized in figure 8-2A.*

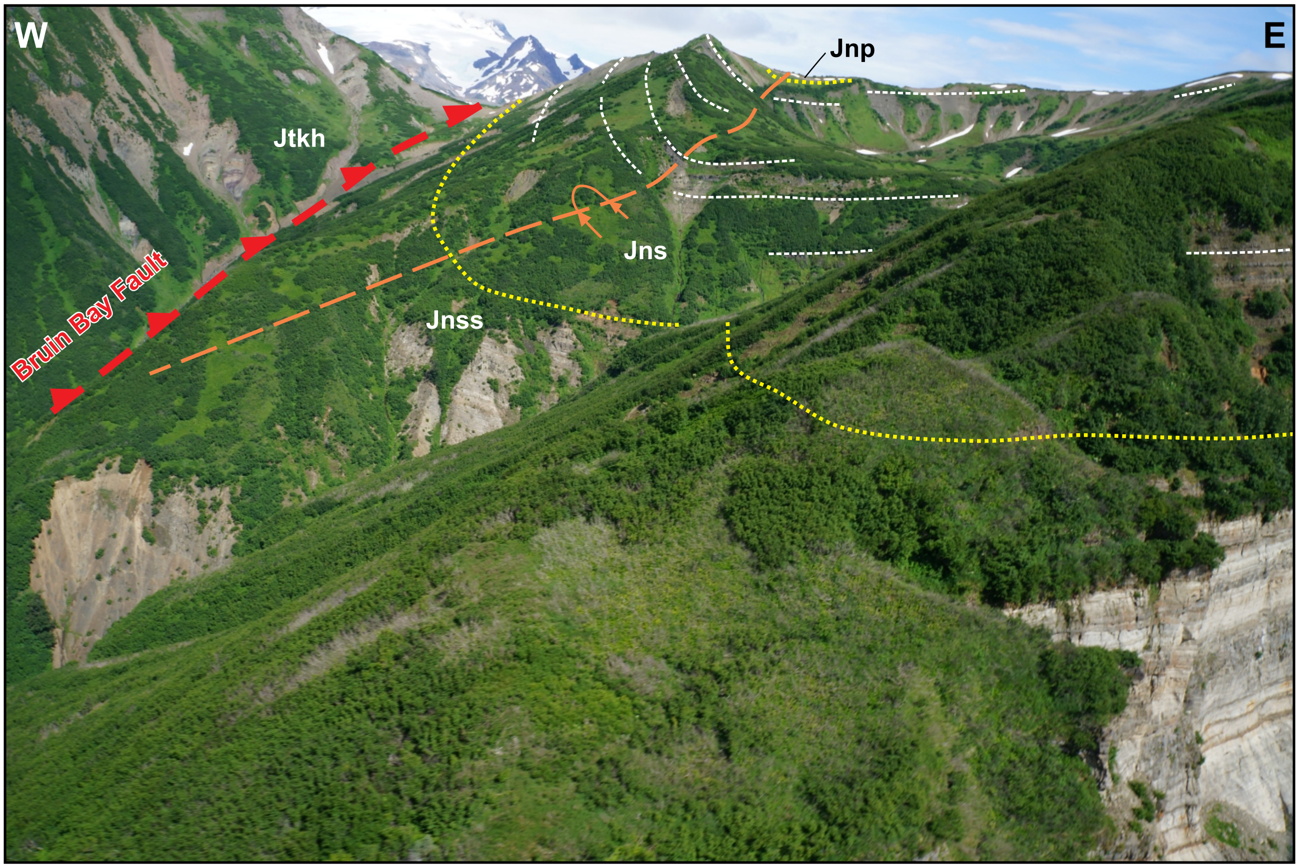

Figure 8-3. Aerial view to the north illustrating the mapped syncline in the footwall of the Bruin Bay fault. Key to line colors: Mapped fold axis shown in orange, map unit contacts in yellow, and selected bed traces in white to highlight the structure. See figure 8-2 for explanation of map unit abbreviations.

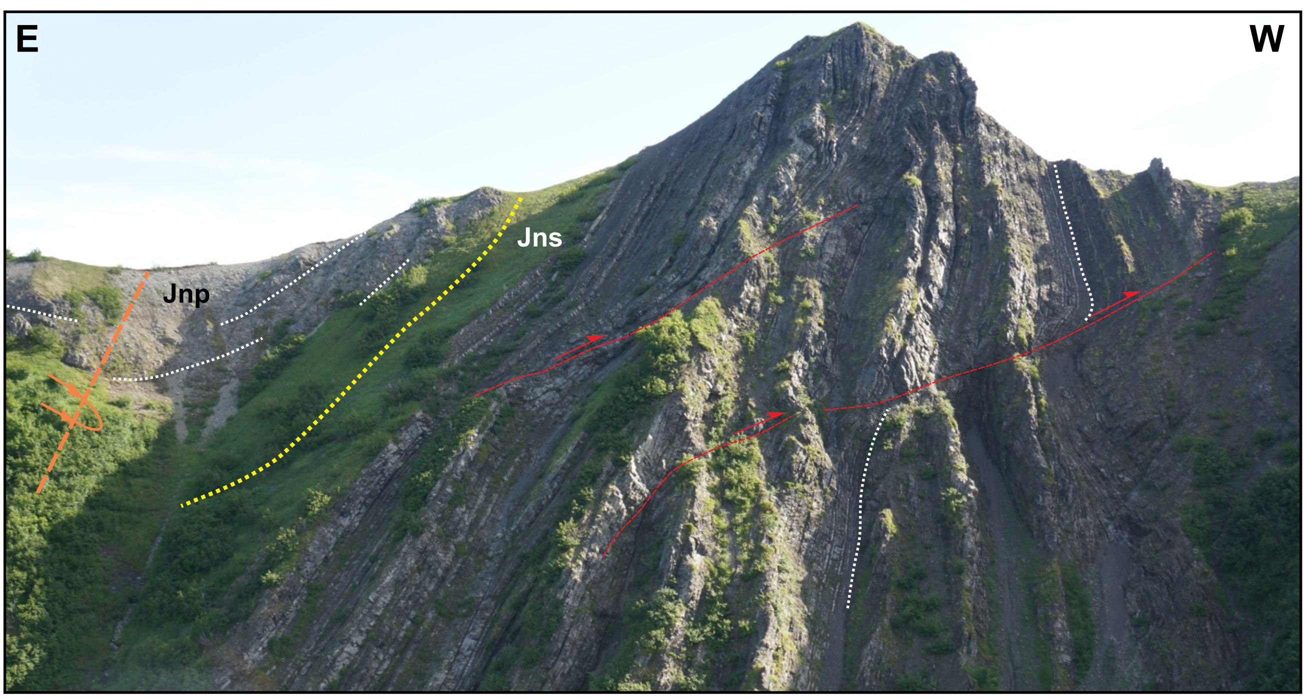

Figure 8-4. View to the south showing out-of-syncline thrust faults (dashed red lines) accommodating the "space problem" near the core of the tight fold. Key to line colors: Mapped fold axis shown in orange, map unit contacts in yellow, and selected bed traces in white to highlight the structure. See figure 8-2 for explanation of map unit abbreviations.

Figure 8-5. View to the south depicting a pseudo-cross-sectional view of the mapped area of figure 8-2. Key to line colors: Mapped fold axis shown in orange, map unit contacts in yellow, and selected bed traces in white to highlight the structure. See figure 8-2 for explanation of map unit abbreviations.

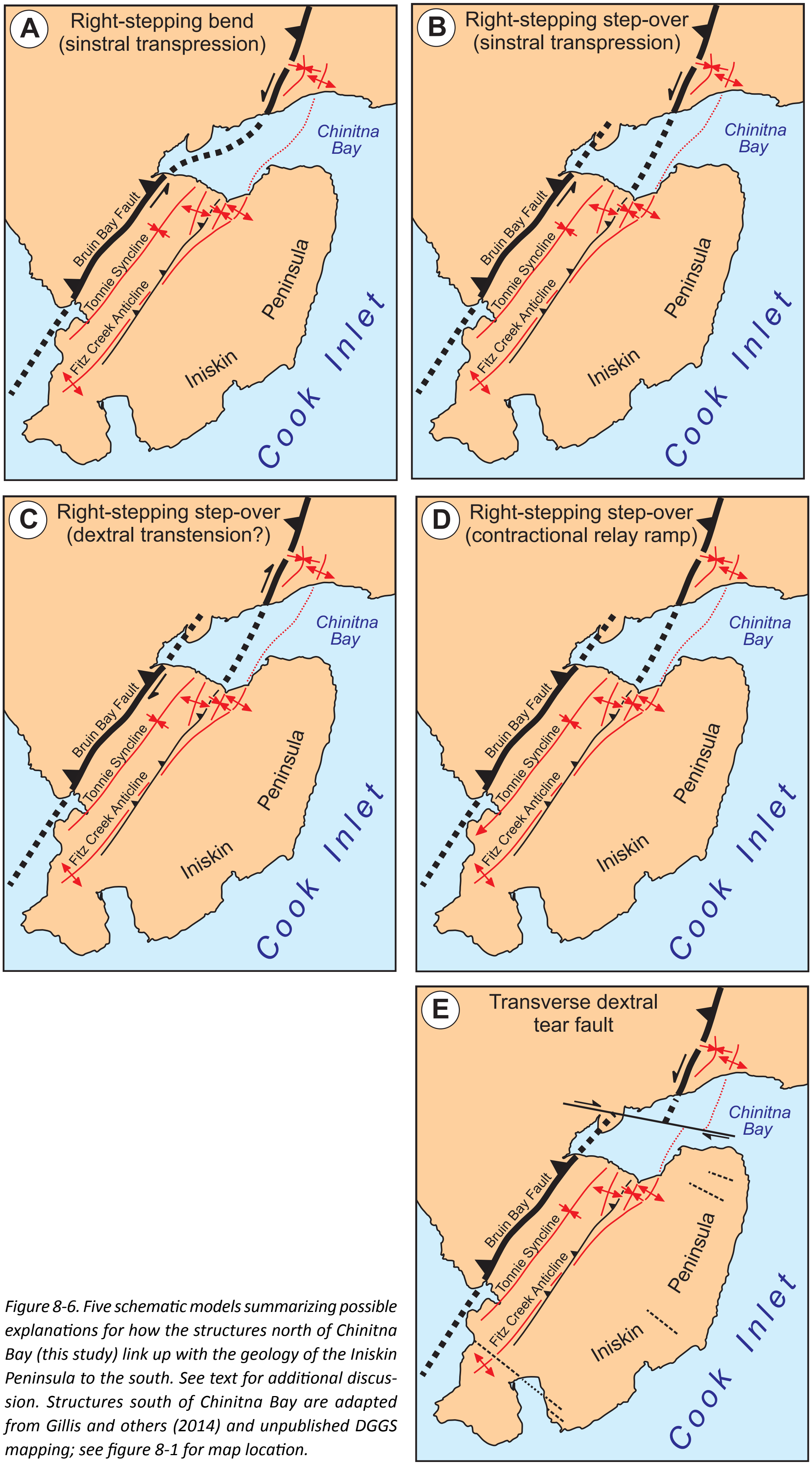

Figure 8-6. Five schematic models summarizing possible explanations for how the structures north of Chinitna Bay (this study) link up with the geology of the Iniskin Peninsula to the south. See text for additional discussion. Structures south of Chinitna Bay are adapted from Gillis and others (2014) and unpublished DGGS mapping; see figure 8-1 for map location.

transpressional motion. These two scenarios predict the development of an en echelon array of contractional structures oblique to the strands—a pattern that is not readily apparent in available mapping. Alternatively, a right-stepping bend or stepover could have developed during overall dextral transpression (fig. 8-6C), although the strike-slip component in this geometry would favor extension between the strands, which is not observed. Figure 8-6D illustrates a scenario where the fault is dominantly dip-slip (contractional), with a relay ramp between overlapping strands (see also Hartsock, 1954). This type of transfer zone may be consistent with the southwest plunge of the footwall Tonnie syncline. A final speculative model involves a transverse dextral tear fault offsetting the Bruin Bay fault and projecting beneath Chinitna Bay (fig. 8-6E). Although no direct evidence for such a fault has been observed, several fracture swarms and small-displacement faults of a similar orientation occur on the Iniskin Peninsula, some of which are associated with oil and gas seeps (Detterman and Hartsock, 1966).

ACKNOWLEDGMENTS

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CHAPTER 9

FRACTURE INTENSITY IN THE PAVELOFF SILTSTONE MEMBER (CHINITNA FORMATION) AND POMEROY ARKOSE MEMBER (NAKNEK FORMATION), INISKIN PENINSULA, ALASKA: IMPLICATIONS FOR HYDROCARBON MIGRATION IN COOK INLET BASIN

Jacob L. Rosenthal[1, 2], Paul M. Betka[1, 3], Robert J. Gillis[1], and Elisabeth S. Nadin[2]

INTRODUCTION

Recent field studies in the Iniskin–Tuxedni bays area of lower Cook Inlet, Alaska, seek to document the nature of fractures hosted in deformed forearc basin strata of Jurassic age (Rosenthal and others, 2015a, 2015b; fig. 9-1). This outcrop-based work relates to our understanding of petroleum systems in the underexplored hydrocarbon province of Cook Inlet and may serve as an analog for fracture intensity in the basin's subsurface. In this short paper we present preliminary results from two field localities, with one each in the Pomeroy Arkose Member of the Naknek Formation and the Paveloff Siltstone Member of the Chinitna Formation (fig. 9-1).

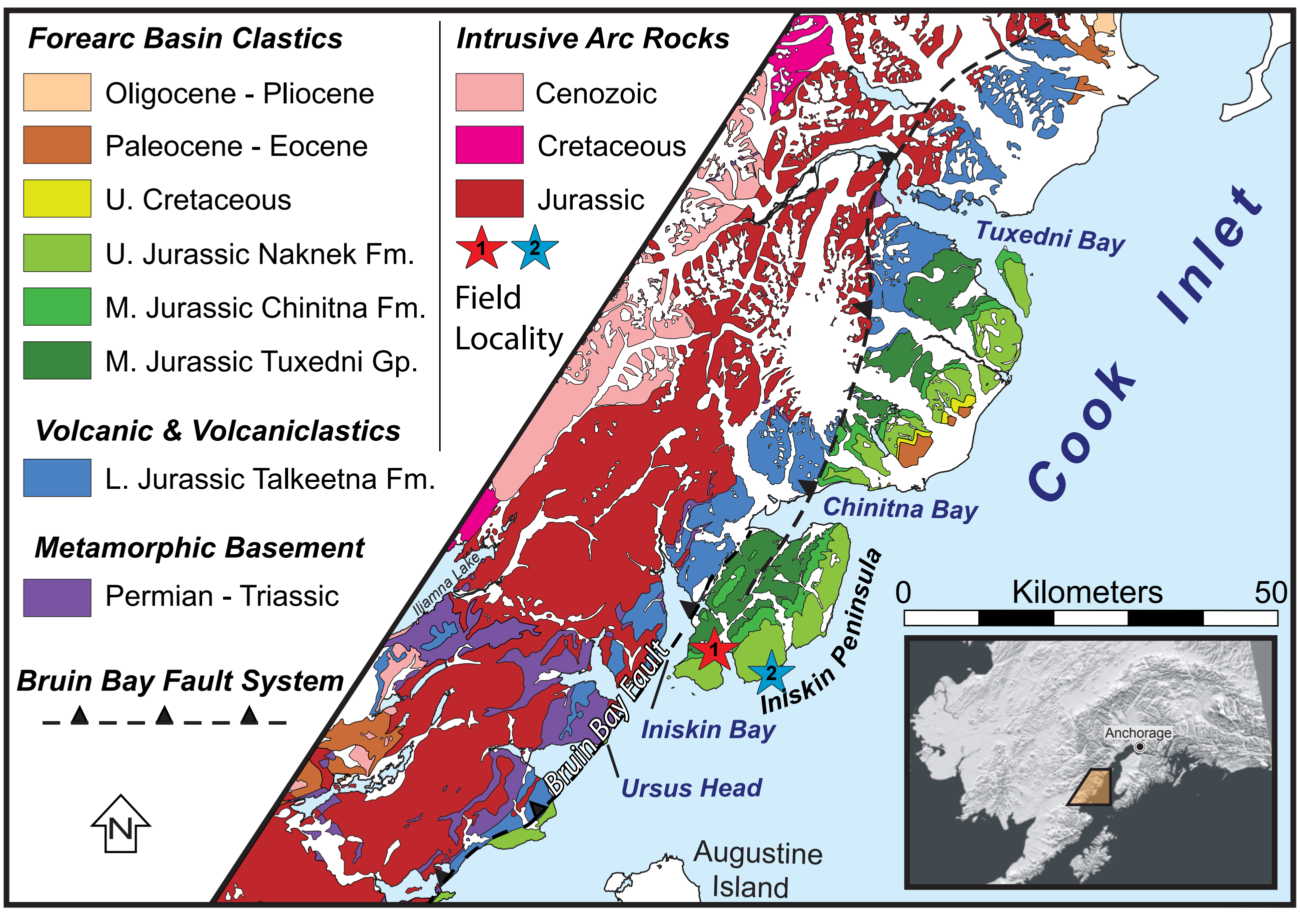

Figure 9-1. Simplified geologic map of the Iniskin–Tuxedni Bays region, lower Cook Inlet, Alaska, showing the trace of the Bruin Bay fault and distribution of Mesozoic–Cenozoic sedimentary rocks in the Cook Inlet forearc basin, volcanic and plutonic rocks of the Talkeetna arc and Alaska–Aleutian Range batholith, and Permian–Triassic metamorphic basement. Red and blue stars show locations of the two localities discussed in text: 1 = Paveloff Siltstone Member of the Chinitna Formation; 2 = Pomeroy Arkose Member of the Naknek Formation. Modified from Wilson and others (2012).

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BACKGROUND

Fractures serve as fluid conduits and control the migration of basinal fluids in strata where primary porosity and permeability were reduced during diagenesis (Engelder and others, 2009; Zeng and Li, 2009; Ortega and others, 2010), with large fractures (≥ 0.5 mm aperture) playing an especially important role in fluid migration (Laubach, 1997). Helmold (2013) demonstrated that Jurassic sandstones in lower Cook Inlet exhibit diminished primary porosity and permeability as a result of diagenesis, and oil shows and seeps in the region are often associated with major fractures that likely control the migration of hydrocarbons in the basin (Detterman and Hartsock, 1966; LePain and others, 2013; Wartes and Herriott, 2014; Alaska Oil and Gas Conservation Commission, 2015). Quantifying lithologic controls (for example, grain size) on the size and density of regionally mapped fracture sets is important for the development of tight sandstones in unconventional hydrocarbon plays. Understanding which parameters correlate with fracture size and density could enhance the economic potential of low permeability and porosity reservoirs in Jurassic strata of Cook Inlet.

METHODS

This study employs the size-normalized fracture intensity (number of fractures of a given size or larger) measurement scheme of Ortega and others (2006). We identified fracture sets at the two localities on the basis of fracture orientations, placed scan lines perpendicular to each set, and then measured the position and aperture (width) of every cement-filled fracture encountered along each scan line using a tape measure and logarithmically graduated fracture aperture comparator (figs. 9-2A, 9-2B, and 9-2C; Ortega and others, 2006).

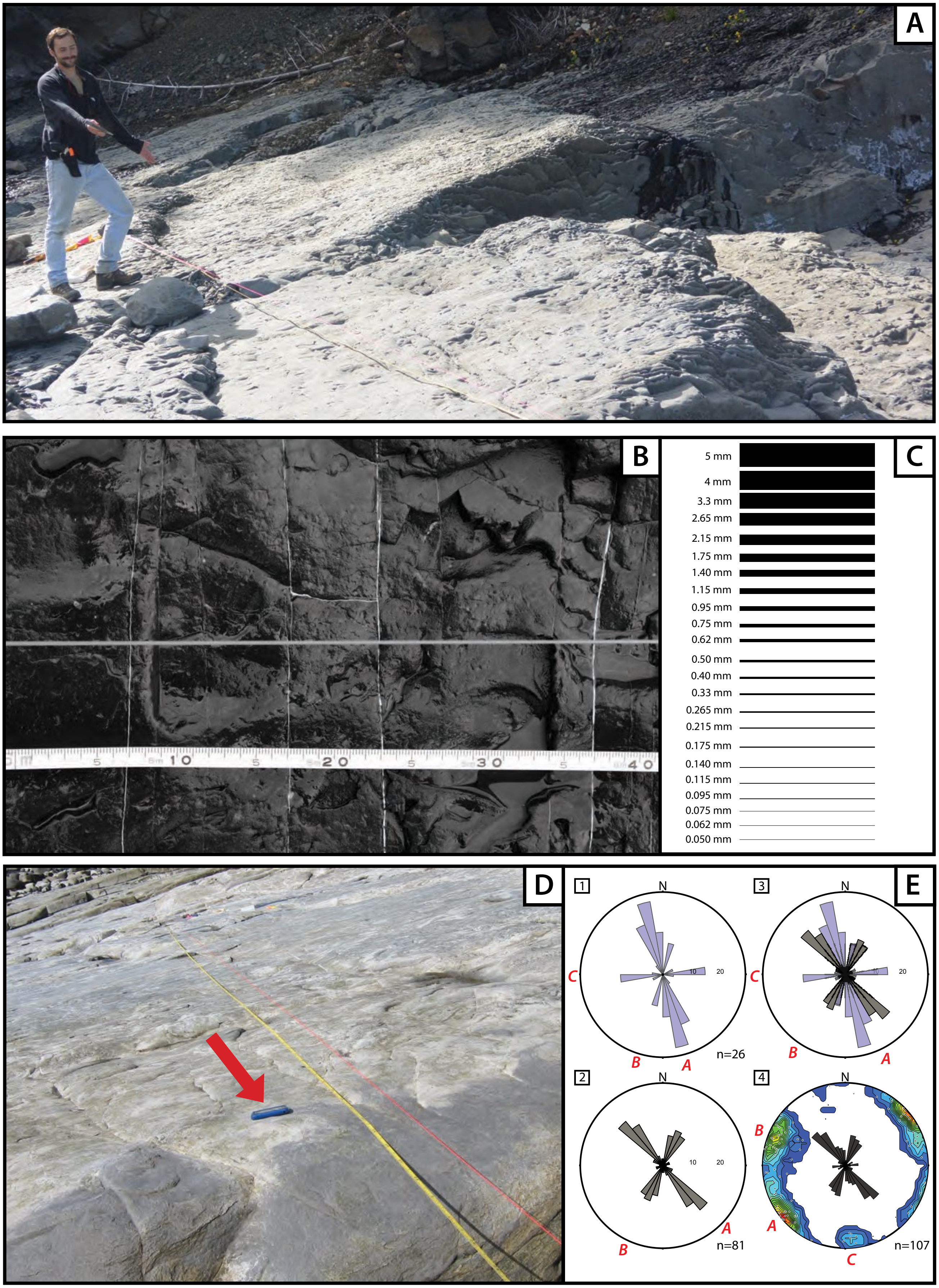
The method of Ortega and others (2006) is a scale-independent approach to quantify fracture aperture distributions because it normalizes the cumulative number of fractures by the length of observation. Fracture aperture measurements for each scan line are sorted in descending order, starting with the largest. The cumulative number of fractures in each interval of measure (graduations on the comparator) are counted and normalized by the length of the scan line to determine the cumulative frequency per meter. Cumulative frequency versus aperture distributions fit power-law scaling relationships across three orders of magnitude (for example, Marrett and others, 1999). The power-law coefficient and exponent are determined by a least-squares regression; the coefficient represents the predicted number of fractures 1 mm or larger and the exponent is the slope of the regression, reflecting the abundance and range of fracture sizes (Ortega and others, 2006). We use the regression equation to compare fracture intensities from fracture sets at the two sampling locations to determine how fracture intensity correlates with lithology.

RESULTS

Three scan lines at locality 1 (fig. 9-1) were used to document the fracture intensity of three fracture sets (A, B, and C after Rosenthal and others, 2015a) in the Paveloff Siltstone Member (figs. 9-2A, 9-2B, and 9-3A). Scan line lengths were 14.98 m (number of fractures [n] = 449), 4.75 m (n = 72), and 15.81 m (n = 62) for sets A, B, and C, respectively. The mean strike and dip for each set is 340°/88° (set A), 015°/88° (set B), and 260°/82° (set C) (fig. 9-2E). Fracture apertures ranged from 0.05 to 10 mm in all three sets. The fracture intensity coefficients for sets A, B, and C are 1.21, 0.36, and 0.29, respectively. Fracture set A is the most intense at this location, followed by fracture set B, and then set C.

Two scan lines at locality 2 (fig. 9-1) document the fracture intensity of two fracture sets (A and B) in the Pomeroy Arkose Member (figs. 9-2D and 9-3B); fracture set C was present but was not measured at this locality due to extremely low fracture intensity and outcrop area. Scan line lengths were 35.48 m (n = 208) and 19.44 m (n = 103) for sets A and B, respectively. The mean strike and dip for each set is 320°/89° (set A) and 025°/83° (set B) (fig. 9-2E). Fracture apertures ranged from 0.05 to 2.65 mm in both sets. The fracture intensity coefficients for sets A and B are 0.33 and 0.14, respectively. Fracture set A has the highest intensity of fracture sets at this location, consistent with our observations at locality 1.

Figure 9-2 (right). ***A.*** *Scan line from the Paveloff Siltstone Member of the Chinitna Formation. Scan line oriented normal to the dominant fracture trending 340° (set A). Geologist for scale.* ***B.*** *Detailed photograph of scan line from A, showing scanline oriented normal to prominent calcite-filled fractures of set A.* ***C.*** *Logarithmically gauged fracture aperture comparator used for quickly and accurately measuring fracture apertures in the field. Note: Not to scale.* ***D.*** *Scan line from the Pomeroy Arkose Member of the Naknek Formation. Scan line oriented normal to the dominant fracture set trending 320° (set A). Cell phone (10 cm long; see red arrow) for scale.* ***E.*** *Rose diagrams representing the strike of fracture planes and contoured poles to fracture planes.* ***1.*** *Rose diagram of fracture planes from the Paveloff Siltstone Member (locality 1).* **2.** *Rose diagram of fracture planes from the Pomeroy Arkose Member (locality 2).* ***3.*** *Overlay of the rose diagrams of 1 and 2, showing similarities between observed fracture sets at both locations (see fig. 9-1).* ***4.*** *Poles to planes and rose diagrams for fracture data from both localities shown with Kamb contours in two standard deviation intervals. Note distribution of fracture poles to planes into well clustered fracture sets A, B, and C.*


A
B
C
5 mm
4 mm
3.3 mm
2.65 mm
2.15 mm
1.75 mm
1.40 mm
1.15 mm
0.95 mm
0.75 mm
0.62 mm
0.50 mm
0.40 mm
0.33 mm
0.265 mm
0.215 mm
0.175 mm
0.140 mm
0.115 mm
0.095 mm
0.075 mm
0.062 mm
0.050 mm
10
20
30
40
D
E
1
N
C
B
A
n=26
2
N
B
A
n=81
3
N
C
B
A
4
N
B
A
C
n=107

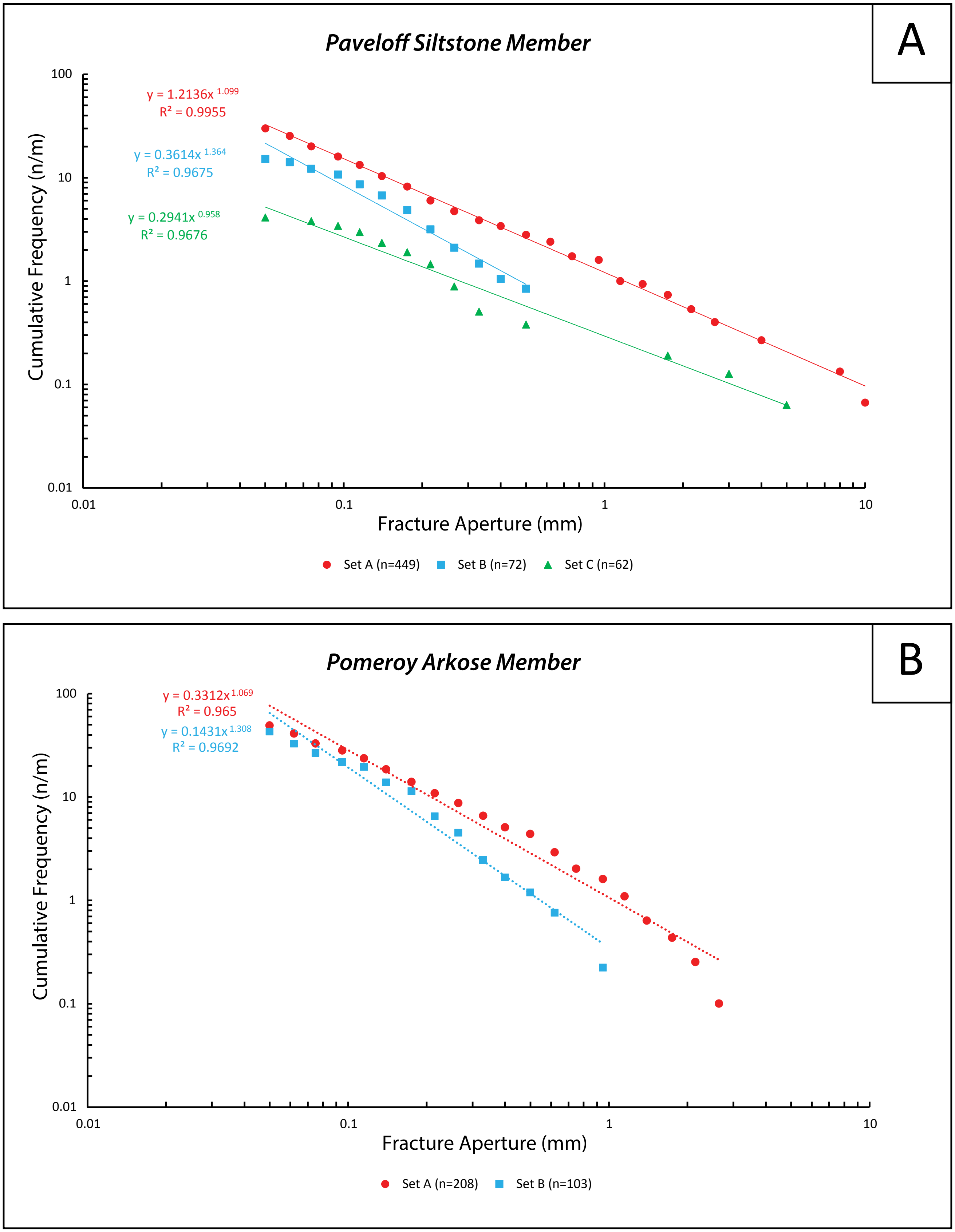


Figure 9-3. Fracture intensity data from scan lines at localities 1 and 2. ***A and B.*** *Fracture set A (red) has the highest fracture intensity at both field sites discussed in the text, as shown by the higher coefficient reflecting a higher predicted number of fractures of 1 mm or larger per meter. Fracture set B (blue) hosts the second highest fracture intensity at both locations. Fracture set C (green) was only measured in the Paveloff Siltstone Member, and therefore no comparison can be made except to note that it is the least intense fracture set measured. Overall, the finer-grained Paveloff Siltstone has a higher fracture intensity than the coarser-grained Pomeroy Arkose.*

SUMMARY AND CONCLUSIONS

Fracture set A at both sampling localities is the most intense fracture set, followed by set B and then set C (measured only at locality 1). The Paveloff Siltstone hosts higher fracture intensities for each equivalent fracture set than does the Pomeroy Arkose. The Paveloff Siltstone is a finer-grained unit than the Pomeroy Arkose (Detterman and Hartsock, 1966) and we postulate that grain size is a primary control of fracture intensity variance between fracture sets of similar orientation at the two locations (compare with Nelson, 1985; Sinclair, 1980).

Rosenthal and others (2015b) establish that fractures trending 320° ± 10° (set A) are the most pervasive and were observed from Tuxedni Bay to Iniskin Bay. Fracture set A has the largest fracture intensity documented by this study, and we suggest that these fractures may serve as important fluid migration pathways in the basin. Furthermore, the modern-day maximum principal stress—determined from stress tensor inversions of crustal earthquakes in the Cook Inlet region—trends southeast, approximately subparallel to set A (Ruppert, 2008). These data indicate that set A fractures would thus be the most likely to have served as natural fluid conduits under the modern stress regime in Cook Inlet. These observations also suggest that fracture set A would be the easiest to stimulate during drilling operations. Rosenthal and others (2015b) suggest that these fractures could have opened during Eocene ridge subduction, and therefore could have allowed for petroleum migration for the past 50 million years.

ACKNOWLEDGMENTS

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CHAPTER 10

OBSERVATIONS ON THE BRUIN BAY FAULT SYSTEM BETWEEN CHINITNA AND TUXEDNI BAYS, COOK INLET, ALASKA

Paul M. Betka[1,2] and Robert J. Gillis[2]

INTRODUCTION

The Alaska Division of Geological & Geophysical Surveys (DGGS) is conducting an ongoing study to understand the structural geology and deformational history of western Cook Inlet. The Bruin Bay fault (BBF) system defines a structural boundary between Mesozoic–Cenozoic sediments of the Cook Inlet forearc basin and the Mesozoic–Cenozoic Talkeetna–Aleutian arc for most of its exposed length between the upper Alaska Peninsula near Becharof Lake northeastward to upper Cook Inlet (fig. 10-1). Recent work conducted along the BBF on the Iniskin Peninsula and at Ursus Head (fig. 10-1A) indicates that the fault system experienced a polyphase slip history characterized by both strike-slip and reverse fault-slip kinematics (Gillis and others, 2013; Betka and Gillis, 2014a, 2014b, 2015). This report presents new field observations made along the BBF near Johnson River, Red Glacier, and Open Creek pass between Chinitna and Tuxedni bays of western Cook Inlet to evaluate along-strike change in the structure of the BBF system (fig. 10-1).

FIELD OBSERVATIONS

The BBF is well exposed immediately south of the Johnson River (fig. 10-2A; location on fig. 10-1B). Here, the fault strikes north and branches to form two thrust splay faults that dip moderately to the west. The lower (easterly in map view) splay uplifts lavas and volcanic breccia of the lower informal member of the Talkeetna Formation (Jtkl; Bull, 2014, 2015) above the well-bedded lavas and volcaniclastic deposits that define the upper informal member of the Talkeetna Formation (Jtku; Bull, 2014, 2015). In the footwall, Jtku strata are folded into a top-easterly-verging, gently inclined, overturned syncline (fig. 10-2A). The upper splay (westerly in map view) juxtaposes Jurassic quartz diorite (Jqd) in the hanging wall above Jtkl in the footwall (fig. 10-2A); this splay forms an ~5-m-thick fault zone that contains cataclasite and forms a distinct red–orange-weathering band, probably resulting from oxidation of iron-sulfide minerals (figs. 10-2A and 10-2B). The stratigraphic separation across both splays of the fault zone indicates a component of top-to-the east reverse motion. However, minor fault-slip surfaces preserved in the fault zone cataclasite (fig. 10-2C; example shown in fig. 10-2B) preserve slickenlines with moderate to shallow rakes on the fault surface and indicate that the sense of slip was oblique, left-reverse. Several minor, dextral-slip surfaces strike northwest and are antithetic to the strike of the fault zone cataclasite (fig. 10-2D; example shown in fig. 10-2B). The upper fault splay was observed at a second location down-dip from the cataclasite (location E shown in fig. 10-2A). Here, the fault zone also contains cataclasite and several northeast-striking slip surfaces that record sinistral-reverse motion (fig. 10-2E; location shown in fig. 10-2A); northwest-striking right-lateral slip surfaces also occur at this outcrop (fig. 10-2E).

The BBF is also well exposed near Red Glacier, approximately 10 km south of the Johnson River locality (fig. 10-3A; location in fig. 10-1B). Here, the fault strikes north–northwest and uplifts Jtkl in the hanging wall above Jtku. Jtku strata are folded into an east-vergent footwall syncline, similar to the syncline preserved near Johnson River, but at this locality the fold is not overturned. In the hanging wall, the strata of Jtkl are also folded and form an east-vergent hanging wall anticline. The stratigraphic separation across the BBF and geometry of the footwall and hanging wall folds suggest a component of top-to-the east reverse motion. However, similar to our observations of the fault near the Johnson River, fault striations preserved on minor fault surfaces in the immediate footwall of the fault (location B in fig. 10-3A) have shallow plunges and suggest the sense of slip was oblique left-lateral (fig. 10-3B). One minor northwest-striking dextral fault also occurs at this location.

We also examined a well-preserved exposure of the BBF at a high pass above the headwaters of Open Creek, approximately 8 km north of the Johnson River locality (fig. 10-4A; location on fig. 10-1B). The fault zone separates Jurassic quartz diorite to the west from Jtkl exposed to the east for much of its length. However, granitic rocks occur in hanging wall and footwall settings north of the pass (fig. 10-4A). Here, the fault zone is subvertical, more than 100 m wide, and composed principally of intensely deformed Jtlk strata. Also found in the fault zone are common lenses of limestone that were interpreted by Detterman and Hartsock (1966) to be part of the Late Triassic(?) Kamishak Formation that are tectonically interleaved with volcanic and volcaniclastic rocks of Jtkl, suggesting the fault cuts the contact between Late Triassic carbonate rocks and overlying volcanic deposits. Cataclasite and tectonic breccia are pervasive throughout the fault zone and contain numerous subvertical slipsurfaces (for example, figs. 10-4B and 10-4C). Minor slip surfaces record predominantly strike-slip fault

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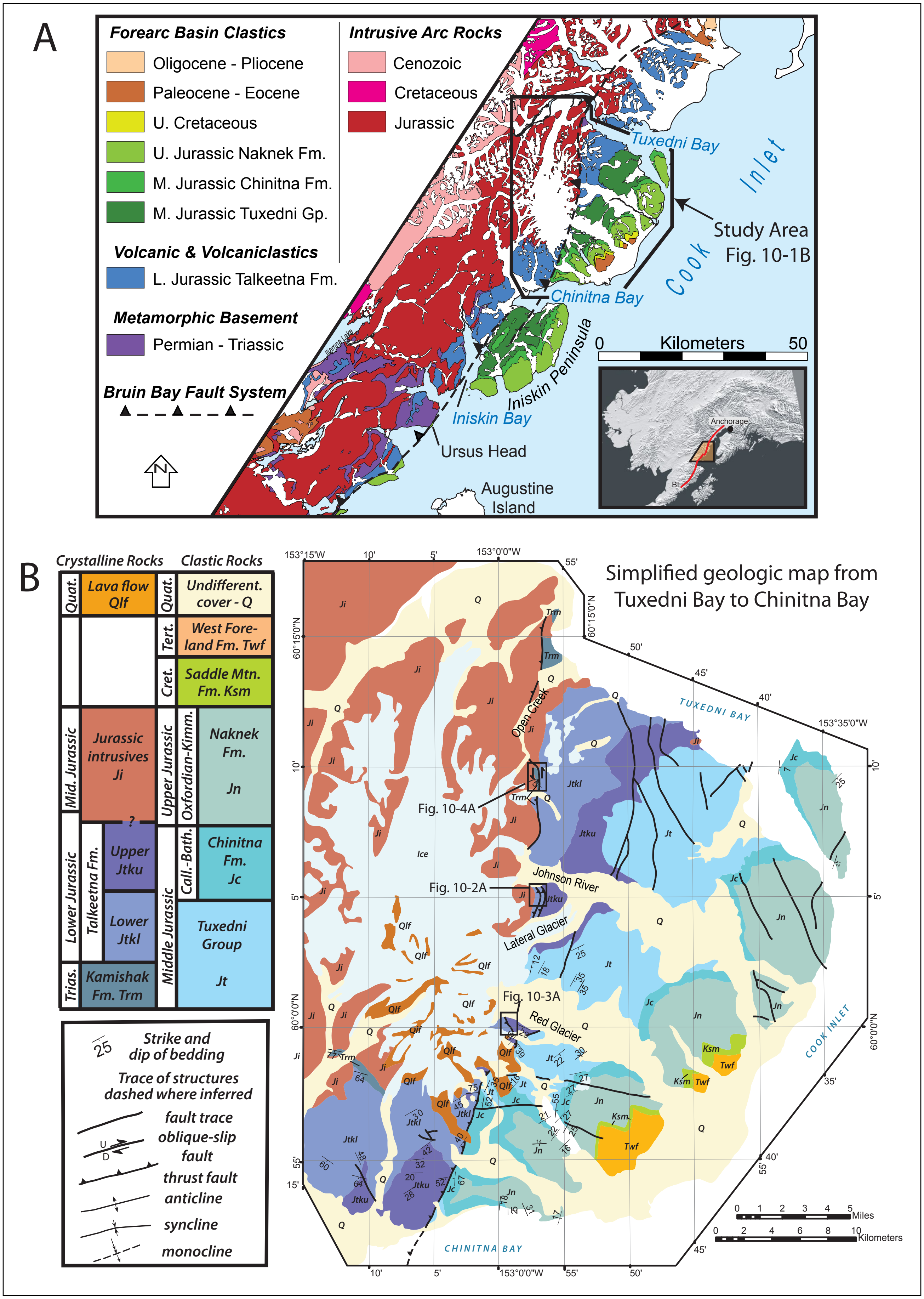
A
Forearc Basin Clastics
Oligocene - Pliocene
Paleocene - Eocene
U. Cretaceous
U. Jurassic Naknek Fm.
M. Jurassic Chinitna Fm.
M. Jurassic Tuxedni Gp.
Volcanic & Volcaniclastics
L. Jurassic Talkeetna Fm.
Metamorphic Basement
Permian - Triassic
Bruin Bay Fault System
Intrusive Arc Rocks
Cenozoic
Cretaceous
Jurassic
Tuxedni Bay
Cook Inlet
Study Area Fig. 10-1B
Chinitna Bay
Iniskin Peninsula
Iniskin Bay
Ursus Head
Augustine Island
0 Kilometers 50
Anchorage
B
Crystalline Rocks
Clastic Rocks
Quat.
Lava flow Qlf
Undifferent. cover - Q
Tert.
West Fore-land Fm. Twf
Cret.
Saddle Mtn. Fm. Ksm
Mid. Jurassic
Jurassic intrusives Ji
Upper Jurassic
Oxfordian-Kimm.
Naknek Fm. Jn
Lower Jurassic
Talkeetna Fm.
Upper Jtku
Lower Jtkl
Middle Jurassic
Call.-Bath.
Chinitna Fm. Jc
Tuxedni Group Jt
Trias.
Kamishak Fm. Trm
Strike and dip of bedding
Trace of structures dashed where inferred
fault trace
oblique-slip fault
thrust fault
anticline
syncline
monocline
Simplified geologic map from Tuxedni Bay to Chinitna Bay
TUXEDNI BAY
COOK INLET
CHINITNA BAY
Open Creek
Johnson River
Lateral Glacier
Red Glacier
Fig. 10-4A
Fig. 10-2A
Fig. 10-3A
Ice
153°15'W
153°0'0"W
153°35'0"W
60°15'0"N
60°0'0"N
0 1 2 3 4 5 Miles
0 2 4 6 8 10 Kilometers

Figure 10-1 (left). ***A.*** *Simplified geologic map of western Cook Inlet modified from compilation by Wilson and others (2012).* ***B.*** *Simplified geologic map of the study area modified after Detterman and Hartsock (1966), Detterman and Reed (1980), Wilson and others (2012), and new mapping by the Alaska Division of Geological & Geophysical Surveys. Location is shown in figure 10-1A. Locations of figures 10-2A, 10-3A, and 10-4A and field localities discussed in this report are shown. BL—Becharof Lake.*

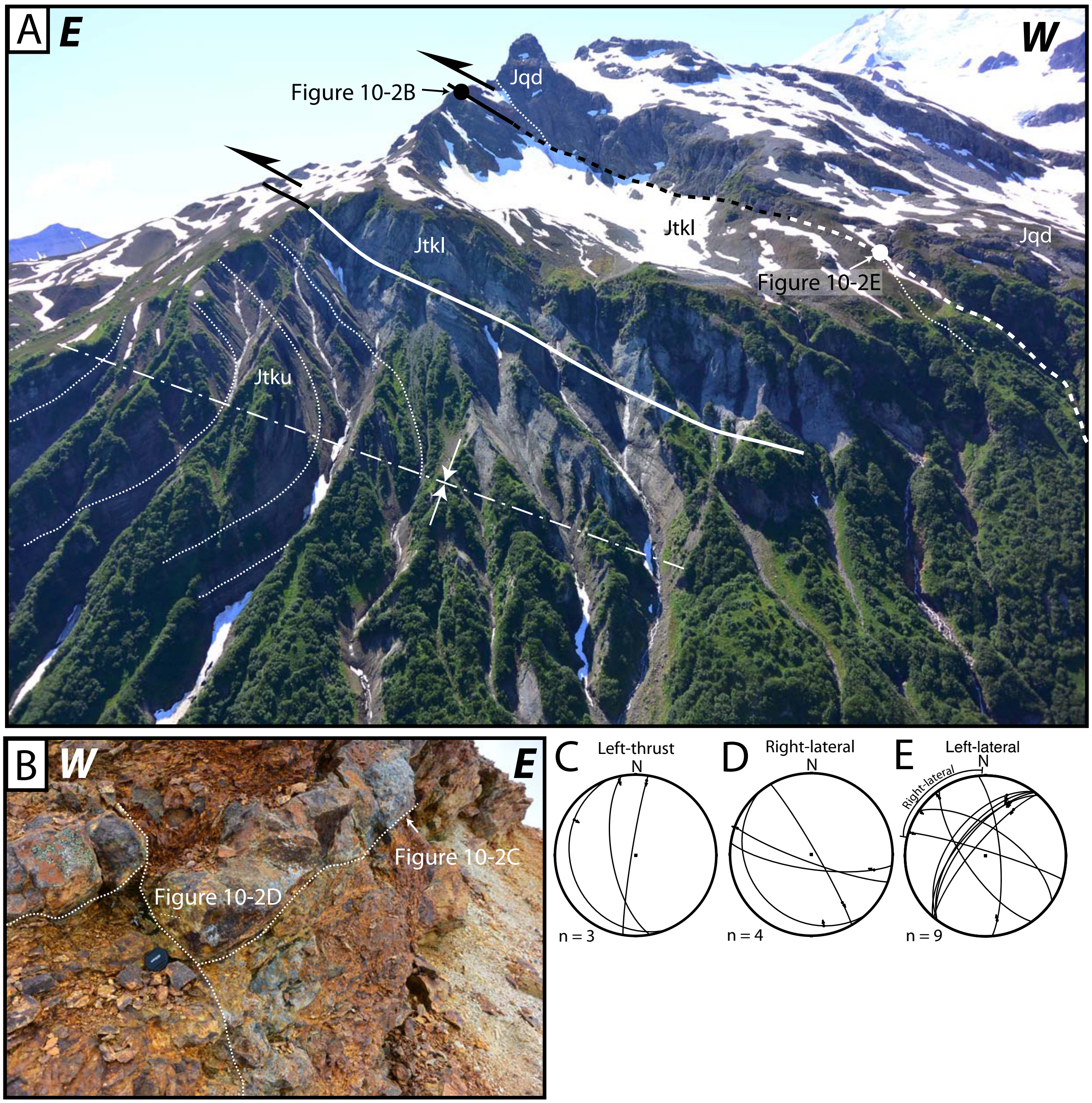

Figure 10-2 (above). Field photographs and stereograms of the Johnson River and Red Glacier localities. ***A.*** *Aerial photograph, viewed toward the south, of the Bruin Bay fault south of the Johnson Glacier (location on fig. 10-1B; locations of figs. 10-2B and 10-2E are shown); field of view is approximately 1 mile. The fault (thick white/black line, dashed where inferred) uplifts the lower member of the Talkeetna Formation* (Jtkl) *above the upper member* (Jtku) *of the Talkeetna Formation; trace of bedding shown with thin dotted lines (see Bull, 2014, 2015, for informal member designations). Note strata of* Jtku *are folded into an overturned-to-the-east footwall syncline.* Jqd*—Jurassic quartz diorite.* ***B.*** *Photograph of oxidized fault zone cataclasite contained in the upper ramp (location shown in A); field of view is ~3 m. A competent sandy, volcaniclastic layer preserves minor slip surfaces (locations B and D) that indicate both thrust and strike-slip sense of shear. Fault-slip data from locations C and D are shown in figures 10-2C and 10-2D. Lens cap in lower left of photo for sense of scale.* ***C–E.*** *Stereograms showing fault slip data from minor fault surfaces in the fault zone cataclasite (C, D) and in the immediate footwall of the Bruin Bay fault (E); data locations shown in A and B. Arrows show attitude of striations and motion of the hanging wall; see text for discussion of fault-slip kinematics.*

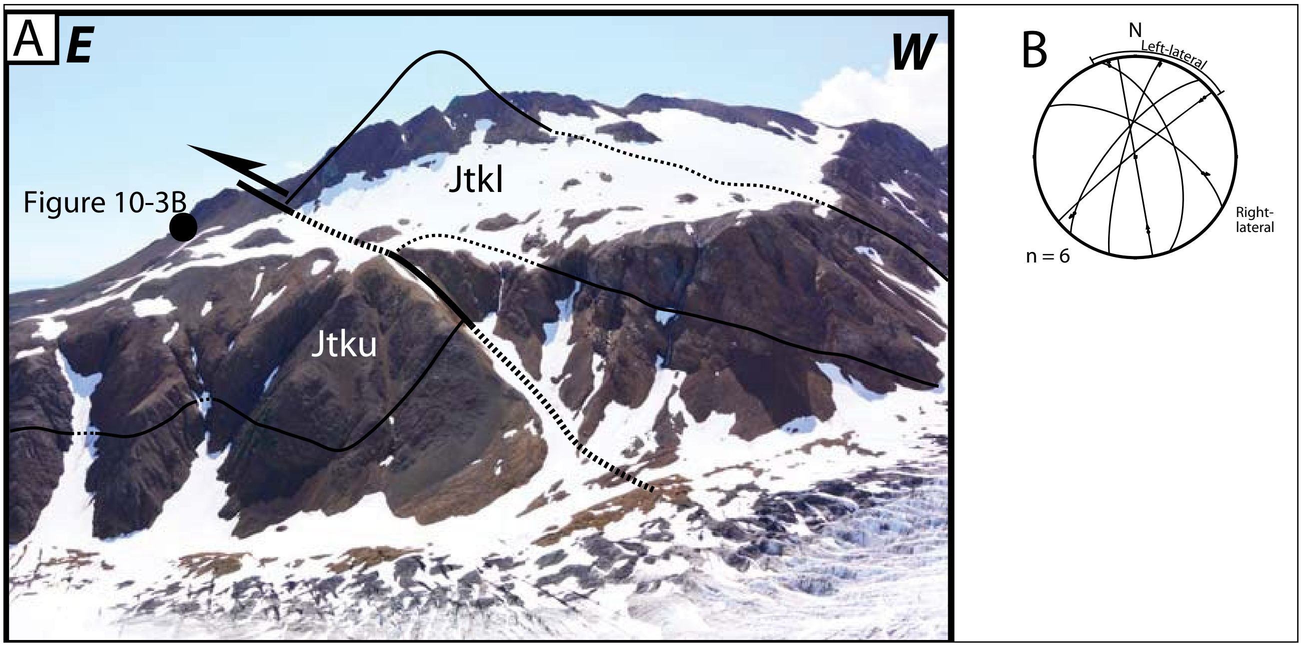

*Figure 10-3. **A.** Aerial view, looking toward the south, of the Bruin Bay fault south of Red Glacier (location on fig. 10-1); field of view is approximately 1 mile. The fault uplifts* Jtkl *above* Jtku *along a thrust ramp that dips moderately to the west. Thick dashed lines show trace of fault; thinner dashed lines show trace of bedding; dashed where inferred. **B.** Stereogram showing fault slip data from minor fault surfaces in the fault zone; location of figure 10-3B is shown in figure 10-3A. Arrows show attitude of striations and motion of the hanging wall; see text for discussion of fault-slip kinematics.*

kinematics. Sinistral faults strike dominantly northeast and have subhorizontal striations. A set of north–northwest-striking sinistral faults have an orientation that is consistent with synthetic Riedel shears (fig. 10-4D). Right-lateral faults strike northwest or west and are interpreted to be antithetic to the north–northeast strike of the fault zone (fig. 10-4D).

CONCLUSIONS

Observations along the BBF system between Chinitna and Tuxedni bays indicate that the fault kinematics record left-transpressional movement. Near the Johnson River and Red Glacier the fault strikes northeast and dips moderately to steeply northwest; at these localities, the BBF accommodates oblique, left-reverse slip. Fault-slip kinematics preserved to the north at Open Creek are dominated by sinistral strike-slip deformation along a subvertical fault zone, contrasting somewhat with the sinistral-reverse fault-slip kinematics observed at the two localities to the south. The change of fault-slip kinematics probably reflects the change in strike of the BBF zone from north–northeast near Chinitna Bay and Red Glacier to a more northerly strike north of the Johnson River. Fault-slip kinematics of the BBF reported in this study are consistent with thrust and left-reverse sense of slip previously reported south of the study area on the Iniskin Peninsula and at Ursus Head (fig. 10-1; Betka and Gillis, 2014a, 2014b, 2015). Altogether, new data collected by DGGS from 2013 through 2015 suggest that the BBF dominantly accommodated sinistral transpression. Ongoing work and companion studies will attempt to resolve the timing and tectonic setting of deformation along the BBF system.

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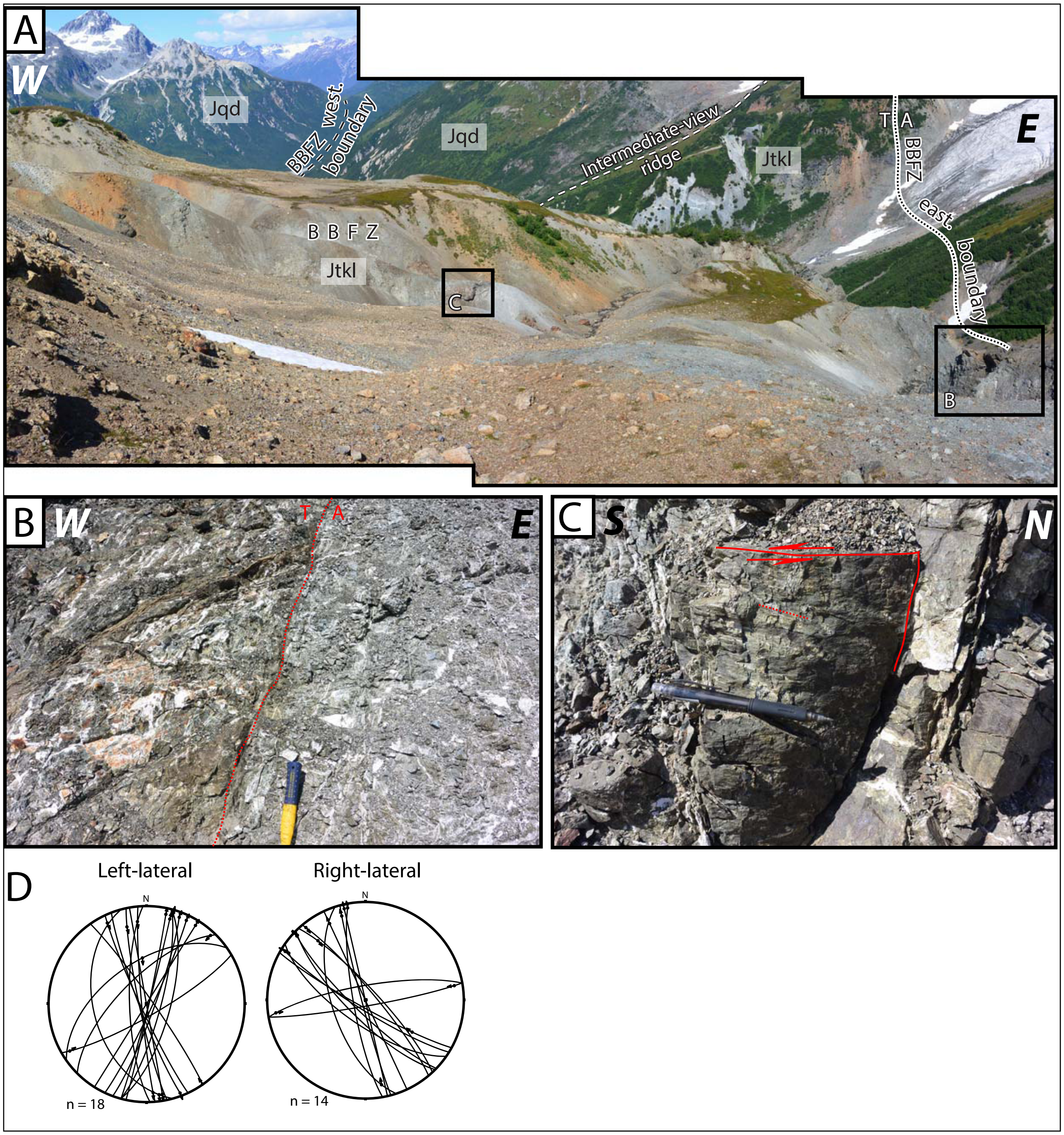

Figure 10-4. Field photographs and stereograms of the Open Creek locality. ***A.*** *Panoramic view toward the north of the Bruin Bay fault zone (BBFZ) at the pass south of the headwaters of Open Creek (location on fig. 10-1A); field of view is approximately 0.5 miles. Here, the fault zone is defined by cataclasite contained dominantly within steeply dipping strata of the Talkeetna Formation (subvertical layering in fig. 10-4A) and is hundreds of meters wide (western boundary of the BBFZ out of view in foreground). Locations of figures 10-4B and 10-4C are shown. T–toward; A–away.* ***B.*** *Example of fault zone cataclasite in the Talkeetna Formation; dashed red line shows trace of a fault surface with sinistral sense of slip. Hammer handle for sense of scale.* ***C.*** *Example of a minor slip surface, showing quartz slickenfibers and steps indicative of left-lateral slip. Red line shows trace of fault surface and short dashed line shows attitude of the slip lineation. Pencil for sense of scale.* ***D.*** *Stereograms showing attitudes of left- and right-lateral faults measured at locations B and C. Arrows show attitude of striations and motion of the hanging wall; see text for discussion of fault-slip kinematics.*

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