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ENERGY-RELATED STUDIES DURING THE 2014 FIELD SEASON, WESTERN COOK INLET, ALASKA

by
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June 2015

View toward the southeast of the mountains between Red Glacier and Hickerson Lake. The exposed stratigraphy is more than 2 km (~6,500 ft) thick and comprises Middle Jurassic Tuxedni Group and Chinitna Formation and Upper Jurassic Naknek Formation. These Cook Inlet forearc basin strata are a focus of recent DGGS-led studies in the Iniskin–Tuxedni region that continued during summer 2014 fieldwork, and is the subject of this volume. DNR's energy program in lower Cook Inlet is yielding important insights into the underexplored Mesozoic petroleum system of the basin. Photograph by Trystan Herriott.

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CHAPTER 1

AN INTRODUCTION TO 2014 FIELD STUDIES IN WESTERN COOK INLET, ALASKA

Marwan A. Wartes[1], editor

INTRODUCTION

Resource assessments of the Cook Inlet region in south-central Alaska indicate that significant hydrocarbons likely remain to be discovered in the basin (BOEM, 2011; Stanley and others, 2011). The Alaska Division of Geological & Geophysical Surveys is leading a multi-agency collaborative effort to acquire new geologic data relevant to the petroleum system in Cook Inlet. This type of information is critical to improving the understanding of the basin's evolution and provides new constraints on exploration models.

The Cook Inlet program has resulted in a number of publications to date, most notably a milestone synthesis of the framework geology of the basin, published as a book chapter by the American Association of Petroleum Geologists (LePain and others, 2013). Earlier noteworthy reports stemming from this program include a series of papers on the geology of reservoir analogs exposed in the Kachemak Bay area (LePain, 2009). Investigations along the western margin of Cook Inlet have also produced vital new information on the migration of oil within the basin, including the discovery of several new examples of oil-stained Cretaceous and Jurassic outcrops (LePain and others, 2012; Stanley and others, 2013a; Wartes and others, 2013a; Wartes and Herriott 2014a, 2014b). Petrologic work on newly collected samples has dramatically increased the available data on the reservoir quality of various units around the basin (Helmold and others, 2013). In addition to field geologic studies, the program has also integrated oil and gas well and seismic data to produce an important new map of the depth of the basal Tertiary unconformity in the Cook Inlet subsurface (Shellenbaum and others, 2010).

To provide timely results from ongoing studies, the program has produced an annual series of short reports highlighting noteworthy aspects of the previous year's field studies (Gillis, 2013, 2014). This volume includes preliminary summaries of topical studies undertaken during the 2014 field season in western Cook Inlet. Much of this new information will contribute to a planned geologic mapping effort north of Chinitna Bay in summer 2015 (Gillis and others, 2014).

2014 FIELD STUDIES

This volume includes two papers detailing important aspects of the structural geology of western Cook Inlet. The first examines the complex kinematics of the Bruin Bay fault system, which marks the western boundary between the magmatic arc and the forearc basin (Detterman and Reed, 1980; fig. 1-1). This study examines a key locality at Ursus Head (fig. 1), and builds on prior work reported in Gillis and others (2013b) and Betka and Gillis (2014). The second structural geology paper summarizes new data on the nature of fractures in western Cook Inlet. Due to relatively low bulk porosity and permeability of Mesozoic rocks, fractures may prove to be a key factor controlling a number of potential exploration plays (Detterman and Hartsock, 1966; Blasko, 1976; Gillis and others, 2013a).

- The superposition of strike-slip and reverse-slip faults in the Bruin Bay fault system, Ursus Head, lower Cook Inlet (chapter 2)
- Preliminary investigation of fracture populations in Mesozoic strata of the Cook Inlet forearc basin: Iniskin Peninsula and Lake Clark National Park, Alaska (chapter 3)

The third chapter in this volume summarizes new field data from the volcanic and volcaniclastic rocks that comprise much of the hanging wall of the Bruin Bay fault (fig. 1-1). This report builds on preliminary discussions provided in Bull (2014), and will contribute significantly to criteria used in geologic mapping.

- Preliminary observations: Continued facies analysis of the Lower Jurassic Talkeetna Formation, north Chinitna Bay, Alaska (chapter 4)

The Middle Jurassic Tuxedni Group is the primary source of Cook Inlet oil (Magoon and Anders, 1992) and has been an important target of stratigraphic studies during the Cook Inlet program (LePain and others, 2013; Stanley and others, 2013b). The following three chapters provide new information on the sedimentology and reservoir quality of these rocks.

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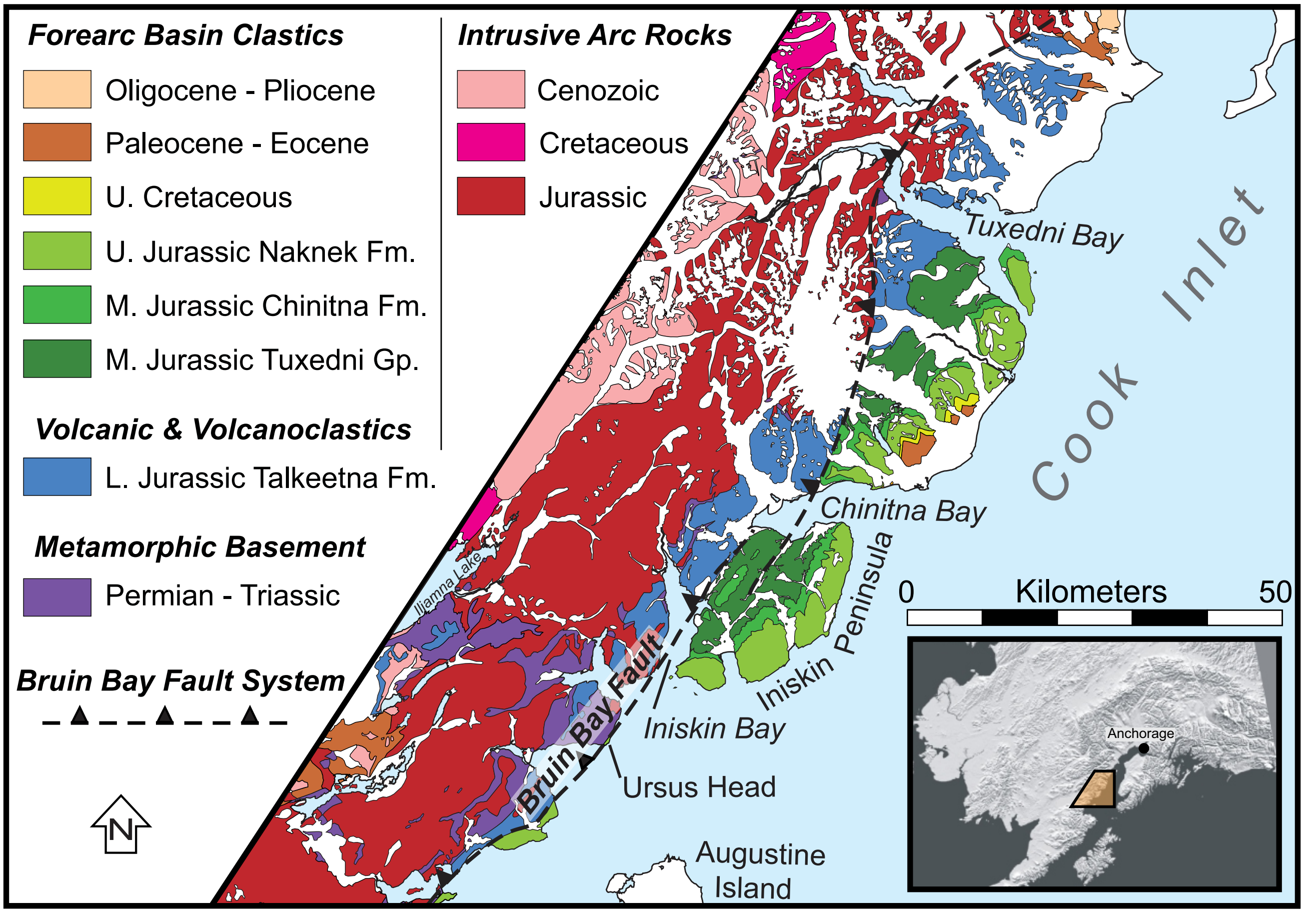

Figure 1-1. Simplified geologic map of western Cook Inlet, modified from compilation by Wilson and others (2009).

- Stratigraphic reconnaissance of the Middle Jurassic Red Glacier Formation, Tuxedni Group, at Red Glacier, Cook Inlet, Alaska (chapter 5)
- Storm-influenced deltaic deposits of the Middle Jurassic Gaikema Sandstone in a measured section on the northern Iniskin Peninsula, Cook Inlet basin, Alaska (chapter 6)
- Petrology and reservoir quality of Gaikema Sandstones: Initial impressions (chapter 7)

The final two chapters discuss ongoing stratigraphic studies of the Upper Jurassic Naknek Formation, building on prior stratigraphic work reported in Wartes and others (2013b) and Herriott and Wartes (2014). Although available data indicate reservoir quality in this unit will be challenging (Helmold and others, 2013), it is locally oil-stained (Stanley and others, 2013a) and may represent an important unconventional tight oil/gas play.

- Preliminary facies analysis of the lower sandstone member of the Upper Jurassic Naknek Formation, northern Chinitna Bay, Alaska (chapter 8)
- Evidence of a submarine canyon in the Snug Harbor Siltstone and Pomeroy Arkose Members, Naknek Formation, south-central Alaska—Implications for the distribution of coarse-grained sediment in Upper Jurassic strata of Cook Inlet (chapter 9)

ACKNOWLEDGMENTS

This work was primarily funded by a State of Alaska Capital Improvement Project. Work on the Iniskin Peninsula was also supported with funding from the National Cooperative Geologic Mapping Program administered by the U.S. Geological Survey (STATEMAP award G13AC00157). DGGS's Cook Inlet basin program also received important funding contributions from Apache Corporation. We thank Jeff Shearer at Lake Clark National Park and Preserve for help with permitting. Critical access to Native lands was provided by Cook Inlet Region, Inc. (CIRI), and the following village corporations: Chickaloon, Knik, Ninilchik, Salamatof, Seldovia, and Tyonek. Helicopter and fuel logistics were ably provided by Pathfinder Aviation.

We thank the staff of Bear Mountain Lodge for their hospitality. We are grateful to Rebekah Tsigonis for providing field assistance, camp support, and patience. Robert Gillis and Paul Betka provided a simplified digital version of the geologic map that is the basis for figure 1-1. James Clough generously provided helpful review comments for this introduction and all the chapter contributions.

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CHAPTER 2

THE SUPERPOSITION OF STRIKE-SLIP AND REVERSE-SLIP FAULTS IN THE BRUIN BAY FAULT SYSTEM, URSUS HEAD, LOWER COOK INLET

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

The Bruin Bay fault system defines a tectonic boundary between Mesozoic–Cenozoic sediments of the Cook Inlet forearc basin and the Mesozoic–Cenozoic Talkeetna–Aleutian arc for most of its exposed length (Detterman and Reed, 1980). It is discontinuously exposed for ~450 km along strike from the upper Alaska Peninsula near Becharof Lake northeastward to upper Cook Inlet. Denudation of the Talkeetna arc in the hanging wall of the fault system sourced Upper Jurassic strata of the Cook Inlet forearc basin that are potential hydrocarbon source and reservoir rocks (LePain and others, 2013; Wartes and others, 2013; compare with Trop and others, 2005). Moreover, the structures that formed in Upper Jurassic strata in the footwall of the fault system impose important geometric and relative timing constraints on the development of the Cook Inlet hydrocarbon system. Here, we report field observations from a well-exposed outcrop of the Bruin Bay fault system near the Iniskin Peninsula at Ursus Head, lower Cook Inlet (fig. 2-1; see also Gillis and others, 2013) to elucidate relative timing relationships between systems of thrust and strike-slip faults that occur regionally in the footwall of the Bruin Bay fault (for example, Detterman and Hartsock, 1966).

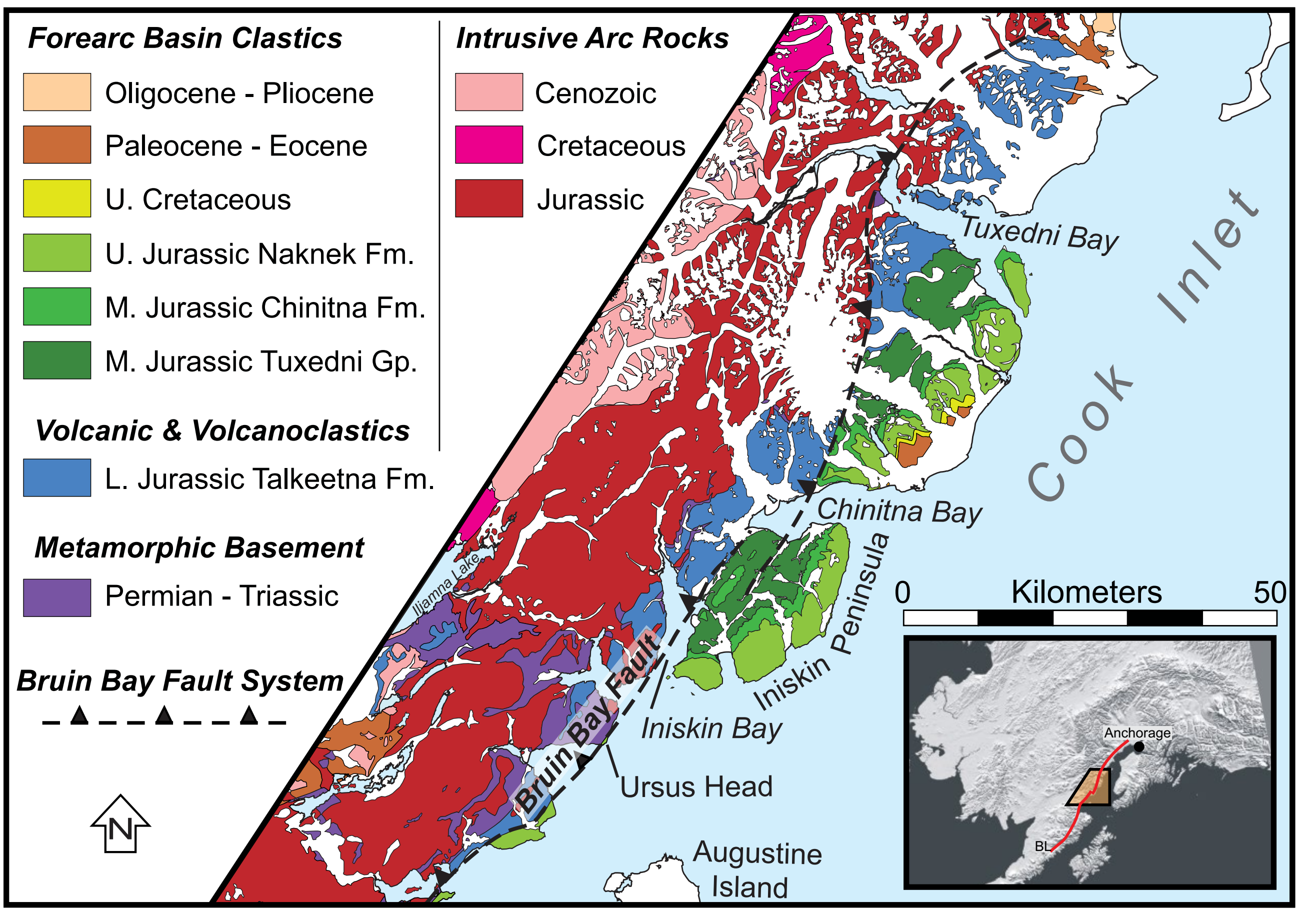

Figure 2-1. Simplified geologic map of the Iniskin Peninsula region, lower Cook Inlet, Alaska, showing the trace of the Bruin Bay fault and distribution of Mesozoic–Cenozoic sedimentary rocks of the Cook Inlet forearc basin, volcanic and plutonic rocks of the Talkeetna–Aleutian arc, and Permian–Triassic metamorphic basement, including the Kamishak Formation referenced in text. Location of the study area at Ursus Head is shown. Inset shows location of geologic map and regional trace of the Bruin Bay fault. BL = Becharof Lake. Map after Wilson and others, 2012.

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Ursus Head (fig. 2-1) is a prominent ~2-km-wide, south-facing sea cliff (fig. 2-2A) southwest of Iniskin Bay and the Iniskin Peninsula. Here, the Bruin Bay fault (BBF, fig. 2-2B) is exposed where it juxtaposes Triassic volcanic rocks and limestone (Kamishak Formation) above Jurassic sandstone (Naknek Formation; fig. 2-2). In the footwall, Jurassic strata of the Naknek Formation are folded into an overturned-to-the-southeast, tight syncline (fig. 2-2B). In the hanging wall, the Kamishak Formation consists of silicic and intermediate composition volcanic rocks and overlying thinly-bedded limestone. Several low-angle thrust faults that commonly form thrust flats subparallel to bedding imbricate and thicken the limestone. Felsic and mafic dikes[3] oriented approximately orthogonal to bedding provide excellent marker units and suggest a top-southeast thrust sense of displacement along the thrusts (fig. 2-2B). Minor folds of bedding in the limestone are commonly breached by small, northwest-dipping thrusts with several centimeters of top-southeast displacement. The minor thrusts confirm the top-southeast sense of slip that is inferred by the separation of the dikes (fig. 2-3A). At the contact between the limestone and underlying volcanic rocks, bedding within the basal ~20 m of the limestone is folded by a train of detachment folds that are detached along the contact and are exposed continuously across the outcrop (pink shading in fig. 2-2B). The detachment fold horizon is imbricated and forms four thrust "horses" (locations I–IV in figs. 2-2B and 2-3B). The low-angle thrusts that imbricate the limestone root into the detachment that formed at the contact with the underlying volcanic rocks, probably reflecting the contrast in competency between the two lithologies.

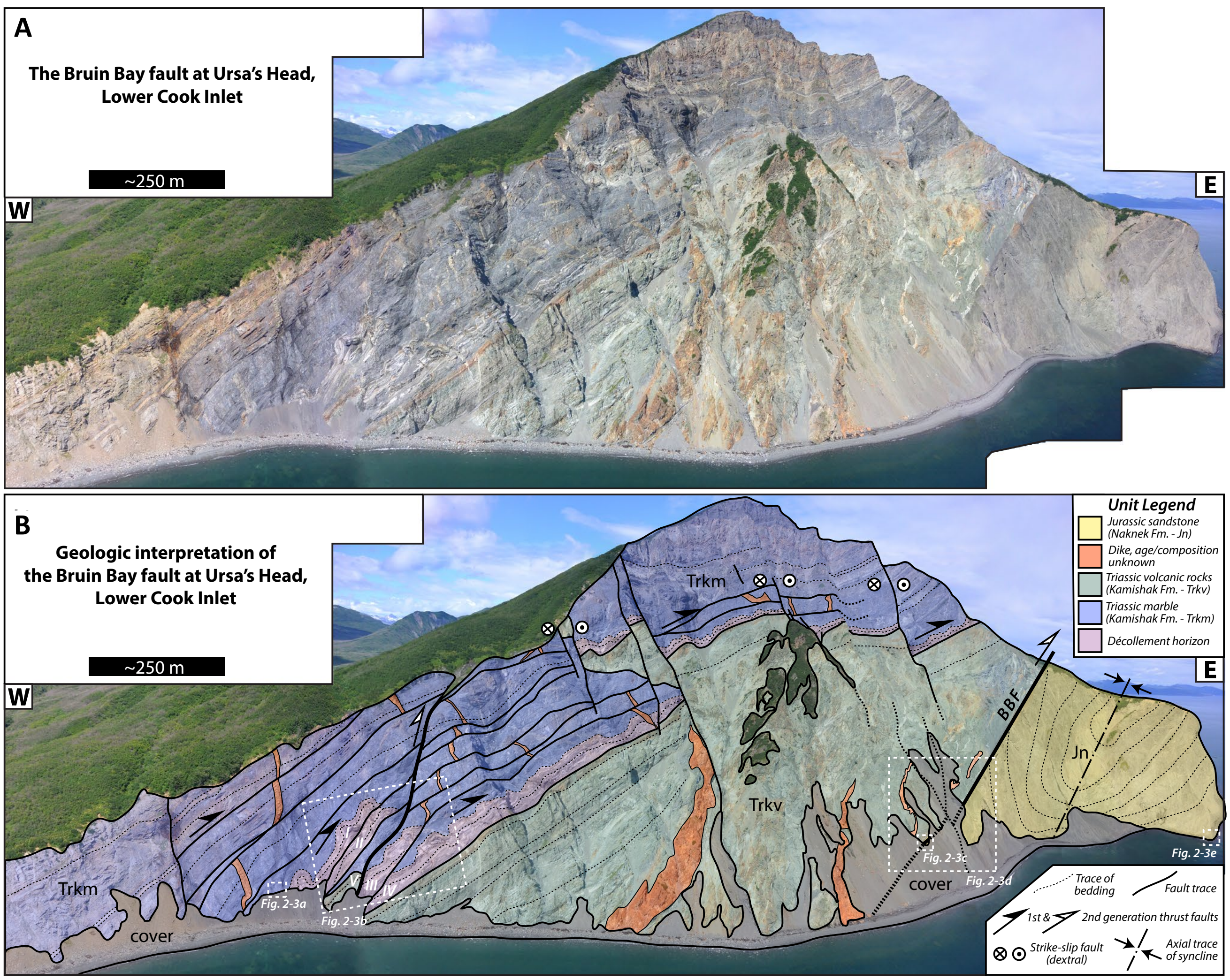

Figure 2-2. Photomosaic (A) and geologic interpretation (B) of the Bruin Bay fault system at Ursus Head, lower Cook Inlet, where Triassic limestone and volcanic rocks of the Kamishak Formation are thrust above Jurassic sandstones of the Naknek Formation. In photo B, unit colors highlight lithology and the detachment horizon discussed in text. Thin dashed lines show trace of bedding, solid lines show fault traces, and heavy solid lines show second-generation reverse faults (dashed where approximately located or inferred). Locations of figures 2-3A–E are shown. Thrust horses I–V are shown in figure 2-3B. BBF = Bruin Bay fault.

[3]Unpublished zircon U-Pb ages are 221 Ma and 225 Ma for two samples.

The Bruin Bay fault crops out in a gully at the top of a talus cone (fig. 2-3C; location in fig. 2-2B), where it dips steeply northwest. Here, the fault zone is ~2 m thick and defined by at least two overlapping thrust surfaces. Fault zone cleavage is subvertical and confirms a top-southeast reverse sense of displacement. In the footwall, bedding in the Naknek Formation is upright and truncated by the fault (fig. 2-3C). At least one other steeply-dipping reverse fault occurs in the hanging wall of the Bruin Bay fault at Ursus Head (fig. 2-2B). The reverse fault is interpreted to truncate the detachment horizon and uplifts volcanic rocks from below the detachment above the limestone (location V, figs. 2-2B and 2-3B). On the basis of similarities in dip and structural style, we infer that the Bruin Bay fault is probably kinematically related to the reverse fault in its hanging wall and thus postdates the low-angle thrusts and the detachment horizon.

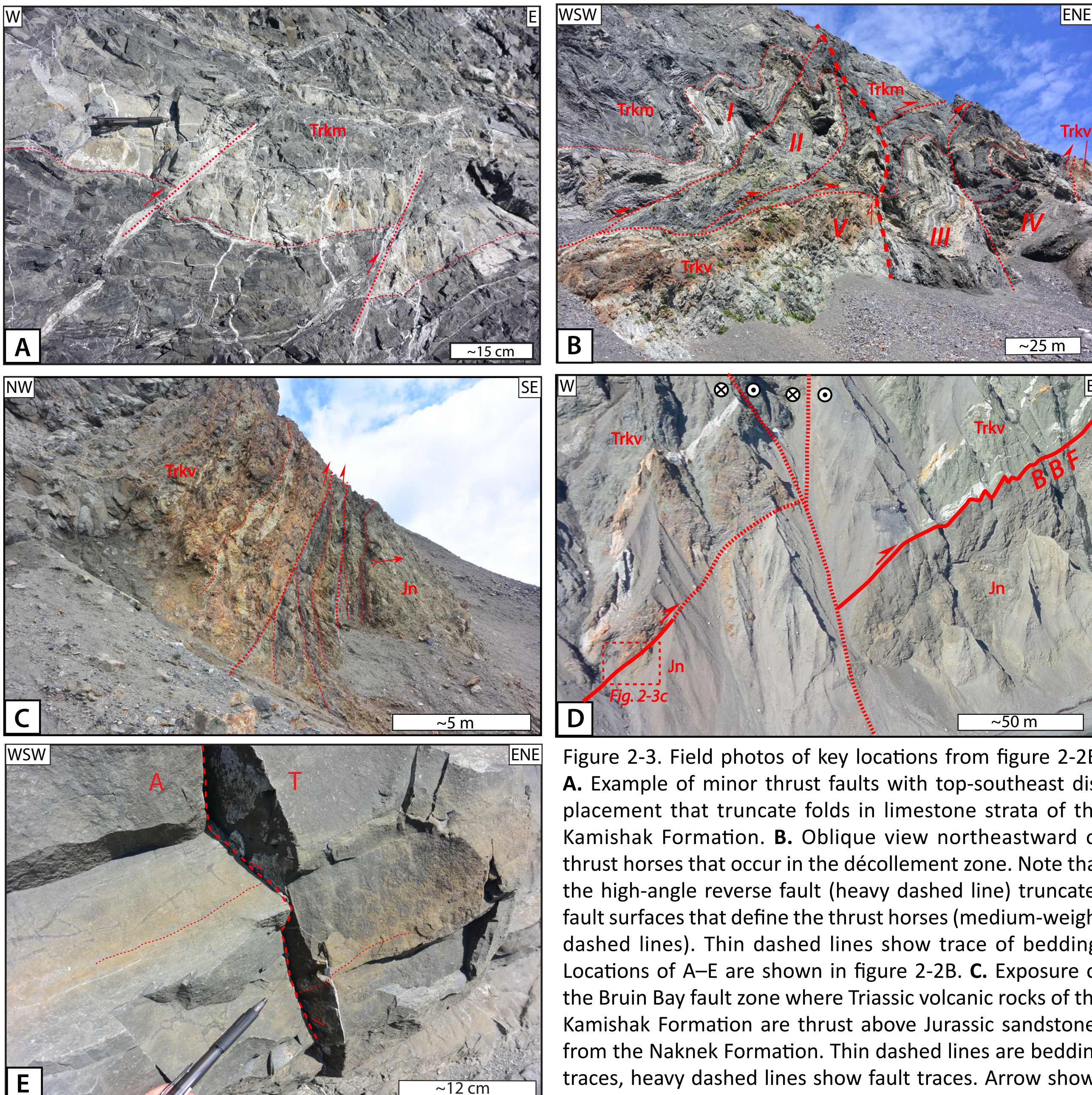

Figure 2-3. Field photos of key locations from figure 2-2B. **A.** Example of minor thrust faults with top-southeast displacement that truncate folds in limestone strata of the Kamishak Formation. **B.** Oblique view northeastward of thrust horses that occur in the décollement zone. Note that the high-angle reverse fault (heavy dashed line) truncates fault surfaces that define the thrust horses (medium-weight dashed lines). Thin dashed lines show trace of bedding. Locations of A–E are shown in figure 2-2B. **C.** Exposure of the Bruin Bay fault zone where Triassic volcanic rocks of the Kamishak Formation are thrust above Jurassic sandstones from the Naknek Formation. Thin dashed lines are bedding traces, heavy dashed lines show fault traces. Arrow shows top-direction in the Naknek Formation on the upright limb of the footwall syncline (see fig. 2-2B). **D.** Aerial view of the Bruin Bay fault offset by an inferred, steeply dipping fault; sense of slip is inferred to be right-lateral. The location of figure 2-3C is shown; see text for details. **E.** Example of minor strike-slip fault surfaces that crosscut the footwall syncline in the Naknek Formation. Thin dashed red line shows base of a medium-grained sand bed that is offset several centimeters by a subvertical fault surface (thicker dashed red line). Short, solid red lines of fault surface show orientation of the slickenline, which plunges shallowly (04°) north. Sense of slip is right-lateral. A = away; T = toward.

Several subvertical, north–northwest-striking faults crosscut contractional structures. These faults are best exposed near the top of the outcrop, where they clearly crosscut the detachment horizon. The apparent sense of displacement is most commonly east-side down (figs. 2-2A–B). A fault of this orientation is inferred to crosscut the Bruin Bay fault where it is covered by talus (figs. 2-2B, 2-3D) because the Bruin Bay fault projects down dip toward the west to a position that is below the exposure of the Bruin Bay fault presented in figure 2-3C (see fig. 2-3D). Thus, we infer that the outcrop in figure 2-3C is in the upthrown block west of the subvertical fault. Minor, subvertical, strike-slip faults with several centimeters of displacement are ubiquitous throughout the outcrop. The strike-slip faults most commonly strike north–northwest and show right-lateral displacements (for example, fig. 2-3E). On the basis of similarities in the attitudes of the minor right-lateral faults and the mesoscale subvertical faults that crosscut the detachment horizon and the Bruin Bay fault, we deduce that the latter set of faults are also right-lateral strike-slip faults. Right-lateral slip is consistent with the apparent east-side-down offset of the northwest-dipping structures and strata that these faults displace.

Crosscutting relationships preserved at Ursus Head record the superposition of three dominant sets of faults. The first faults to form are low-angle thrust faults that imbricate and thicken limestone deposits in the Kamishak Formation. The imbricate thrusts root into a detachment horizon that is defined by a train of detachment folds, and developed along the contact between the limestone and underlying volcanic rocks. The competency contrast between the two lithologies probably influenced the position of the detachment horizon. A second stage of contraction is recorded by two high-angle reverse faults that crosscut the early thrusts and the detachment horizon. At Ursus Head, the Bruin Bay fault is a reverse fault that uplifts and juxtaposes the Kamishak Formation above the Naknek Formation and is inferred to have formed with the second generation of reverse faults and reflect progressive shortening of the thrust wedge. A later stage of deformation is recorded by several subvertical strike-slip faults that strike north–northwest and have right-lateral displacements. The strike-slip faults crosscut both earlier generations of faults, including the Bruin Bay fault, and probably reflect a separate tectonic event. Field relations exposed at Ursus Head provide an important example of the relative timing of structures that formed during the tectonic development of lower Cook Inlet and they can be extrapolated to interpret regional structural evolution of the Cook Inlet hydrocarbon system.

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CHAPTER 3

PRELIMINARY INVESTIGATION OF FRACTURE POPULATIONS IN MESOZOIC STRATA OF THE COOK INLET FOREARC BASIN: INISKIN PENINSULA AND LAKE CLARK NATIONAL PARK, ALASKA

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

INTRODUCTION

Recent investigations by the Alaska Division of Geological & Geophysical Surveys reveal numerous fracture sets exposed in the Mesozoic strata of the Cook Inlet forearc basin on the Iniskin Peninsula, lower Cook Inlet (Betka and Gillis, 2014; Gillis and others, 2013). These fractures are contained in a vast section of potential reservoir rocks and oil source rocks in one of the largest petroleum-producing provinces in Alaska (Magoon and Anders, 1992). Known production areas in Cook Inlet are structurally controlled, fault-cored anticlines (Haeussler and others, 2000; Bruhn and Haeussler, 2006) or en echelon, transpressional anticlines (LePain and others, 2013; Hauessler and Saltus, 2011). Additionally, faults, joints, and fault related fractures control the migration of hydrocarbons through the Mesozoic section (Detterman and Hartsock, 1966; AOGCC, 2015). This ongoing study investigates the possibility of fracture-controlled fluid migration pathways and fractured reservoir resource potential in the Cook Inlet petroleum system.

Middle and Upper Jurassic forearc strata represent important elements of the Cook Inlet petroleum system, including the source of oil in the basin and underexplored potential reservoirs (Magoon and Anders, 1992; Stanley and others, 2011). The Iniskin Peninsula (fig. 3-1) preserves exposures of Middle and Upper Jurassic strata that provide insight into the Cook Inlet subsurface (LePain and others, 2013; Helmold and others, 2013). Here, the Bruin Bay fault system and a northeast-trending, fault-cored anticline–syncline pair deform Mesozoic strata. Detterman and Hartsock (1966) and Detterman and Reed (1980) recognized abundant fracture populations on the Iniskin Peninsula and hypothesized that the fractures were genetically related to the Bruin Bay fault and to regional folds. This ongoing study focuses on understanding the relationship of fractures to these regional structures and considers the field locale as an analog for offshore reservoirs in Cook Inlet. This report contains preliminary field observations for fracture populations from two outcrops that expose fractured strata of the Pomeroy Arkose Member of the Naknek Formation and the Cynthia Falls Sandstone of the Tuxedni Group (fig. 3-1).

FIELD OBSERVATIONS

Three sets of fractures (termed A, B, and C) occur in the Pomeroy Arkose Member of the Naknek Formation, an arkosic sandstone that is well exposed on the Iniskin Peninsula (figs. 3-1 and 3-2A). The fractures dip steeply and form well-defined sets (fig. 3-3A). The mean attitudes of sets A, B, and C are 317°/85°, 204°/83°, and 262°/80°, respectively. Sets A and B form a conjugate geometry (67° angle between mean planes; fig. 3-3A). In some locations, fracture sets A and B terminate against set C (fig. 3-2A), suggesting that set C is older than sets A and B. Fractures in all of the sets have aperture sizes spanning three orders of magnitude (0.05–100 mm) and are commonly cemented with calcite (figs. 3-2C, D, and F). A fourth set of west–northwest-striking open fractures are not mineralized and are interpreted as unloading joints (figs. 3-2A and B). Regionally, fracture set A strikes subparallel to northwest-striking fracture zones that contain minor right-lateral slip surfaces (fig. 3-2B).

Along strike ~50 km toward the northeast (fig. 3-1), the Cynthia Falls Sandstone of the Tuxedni Group also contains three fracture sets that have orientations similar to those in the Pomeroy; thus we use the same naming scheme for the fracture sets. Here the mean orientations of sets A, B, and C are 123°/87°, 204°/83°, and 242°/74°, respectively (fig. 3-3B). Sets A and B in the Cynthia Falls Sandstone cross-cut one another, suggesting contemporaneous deformation (figs. 3-2C and D). Because the fracture sets in the Cynthia Falls have attitudes similar to those of fractures in the Pomeroy (figs. 3-3A and B), we infer that they have a genetically similar origin.

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SUMMARY AND ONGOING WORK

Similarity in fracture orientations in the two widely separated field locations (figs. 3-3C and D) suggests that the three sets are a regional feature. Average strikes of the fracture sets from both field locations are 313°/86° (set A), 204°/83° (set B), and 249°/76° (set C) (figs. 3-3C and D). The cross-cutting and apparent conjugate geometry of fracture sets A and B (angular discordance of 67°) suggest that they formed contemporaneously and are genetically related. Fracture set C is less prominent than sets A and B, and is likely older. Upcoming geochronologic results from felsic and mafic dikes that intrude fractures from sets A and C will help to constrain the ages of deformation.

Ongoing work includes quantifying the fracture intensity (number of fractures per unit length) of the dominant fracture sets and determining the relationships among fracture intensity, geologic formation, and facies. Preliminary observations suggest a relationship between grain size and fracture intensity (figs. 3-2E and F). Fracture intensity in both the Pomeroy and the Cynthia Falls appears to increase with decreasing grain size. Finer-grained units consistently have higher apparent fracture intensity than coarser-grained units (for example, figs. 3-2E and F). Additionally, we will examine a possible relationship between fracture intensity and proximity to regional structures such as the Bruin Bay fault. Upcoming results will help to characterize the unconventional reservoir potential and possible fluid migration pathways in Cook Inlet's hydrocarbon system.

ACKNOWLEDGMENTS

Funding for this work was provided by a State of Alaska Capital Improvement Project. Access to land north of Chinitna Bay was graciously permitted by Lake Clark National Park and Preserve. Permits to work on Native lands were provided by Cook Inlet Region, Inc. (CIRI), and the following village corporations: Chickaloon, Knik, Ninilchik, Salamatof, Seldovia, and Tyonek. Helicopter logistics were ably provided by Pathfinder Aviation. We thank Rebekah Tsigonis for field assistance and camp support, and the staff of Bear Mountain Lodge for their hospitality. An early version of this paper benefited from reviews by James Clough and Marwan Wartes. This work would not have been possible without the support of my advisors Paul, Elisabeth, and Robert.

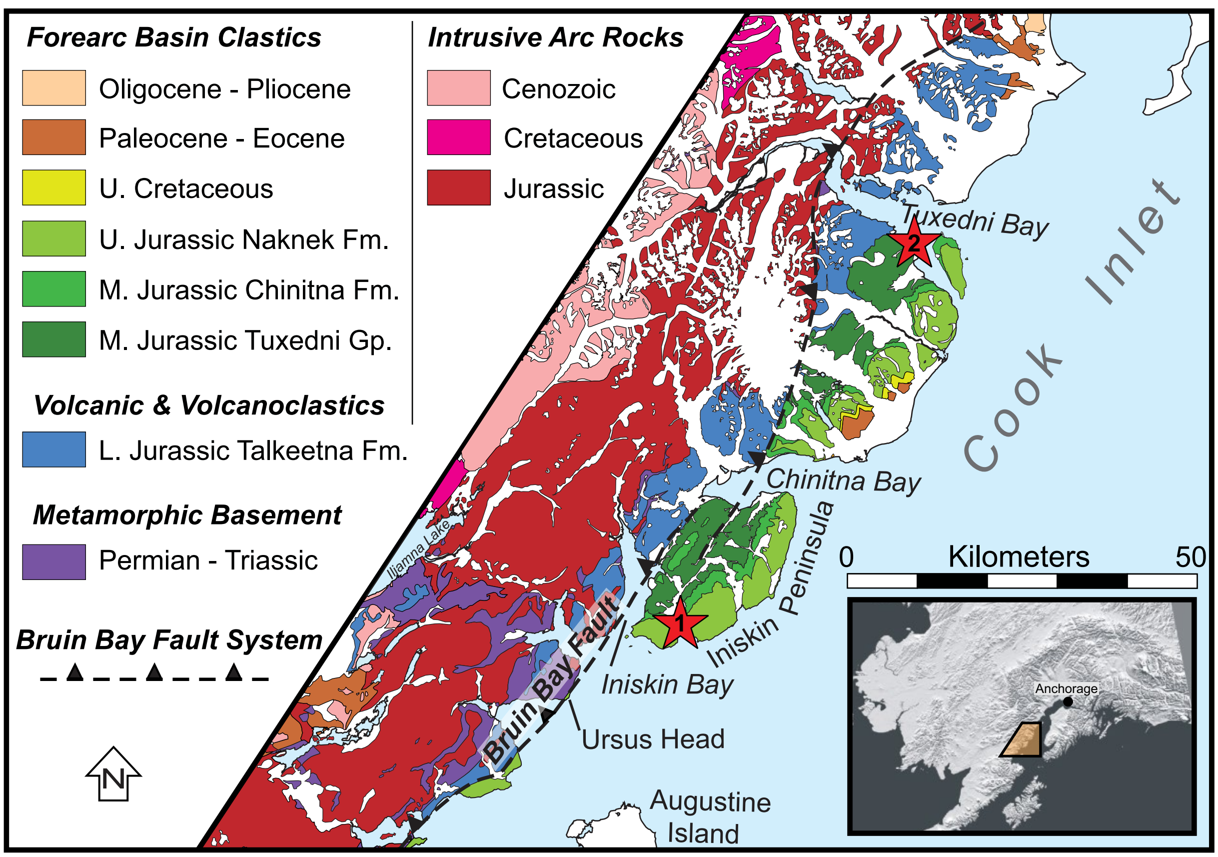

Figure 3-1. Simplified geologic map of the Iniskin Peninsula region, lower Cook Inlet, Alaska, showing the trace of the Bruin Bay fault and distribution of Mesozoic–Cenozoic sedimentary rocks of the Cook Inlet forearc basin, volcanic and plutonic rocks of the Talkeetna–Aleutian arc, and Permian–Triassic metamorphic basement. Large red stars show location of the two study areas discussed in text: 1–Pomeroy Arkose Member of the Naknek Formation, and 2–Cynthia Falls Sandstone of the Tuxedni Group.

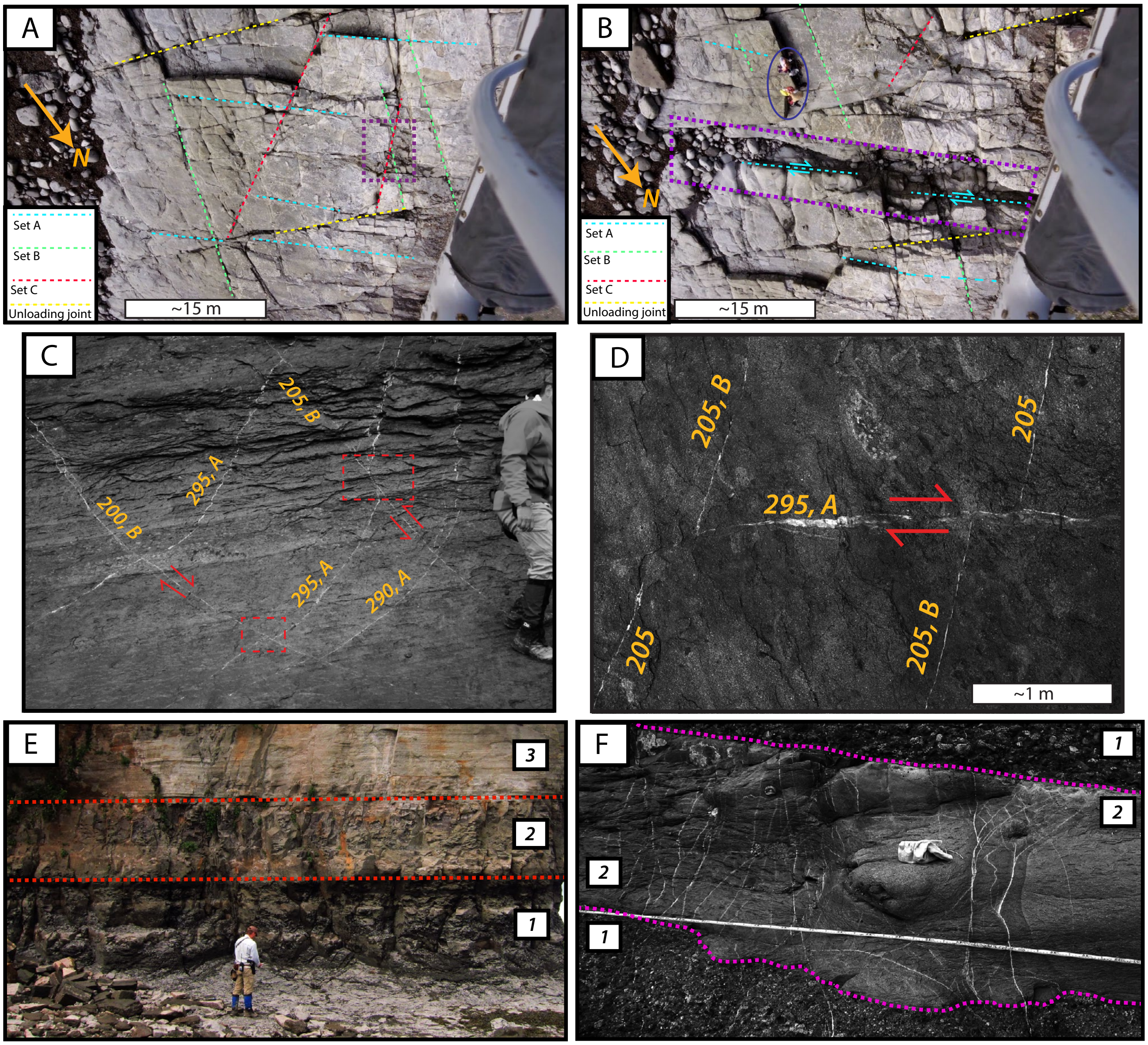

Figure 3-2. **A, B.** Aerial photographs taken from helicopter of the Pomeroy member exposed on the Iniskin Peninsula. **A.** Outcrop orientation relationships between sets A, B, and C. Purple rectangle outlines apparent truncation of fracture set B by fracture set C. In photo **B,** purple rectangle highlights the location of a northwest-striking fracture zone that contains right-lateral slip surfaces. Blue oval indicates geologists for scale. **C, D.** Outcrop of the Cynthia Falls Sandstone of the Tuxedni Group. Fracture strikes and apparent offsets are labeled. In photo **C**, red rectangles highlight piercing points; fracture set B crosscuts fracture set A. In photo **D,** fracture set A crosscuts fracture set B in another location at the same outcrop as in photo C. **E.** Red dotted lines trace bed boundaries, with beds 1–3 comprising a coarsening-upward succession. Bed 3 is coarse- to medium-grained sandstone and has the lowest apparent fracture intensity of the succession. Bed 2 is medium- to fine-grained sandstone and exhibits an increase in fracture intensity relative to bed 3. Bed 1 is fine- to very-fine-grained sandstone and hosts the greatest fracture intensity in this three-bed succession. **F.** Outcrop in the Pomeroy (measuring tape for scale; field of view is 2 m; grayscale to highlight fractures). Fine-grained lenticular sand bed (2) has a higher apparent fracture intensity than the overlying and underlying conglomerate beds (1).

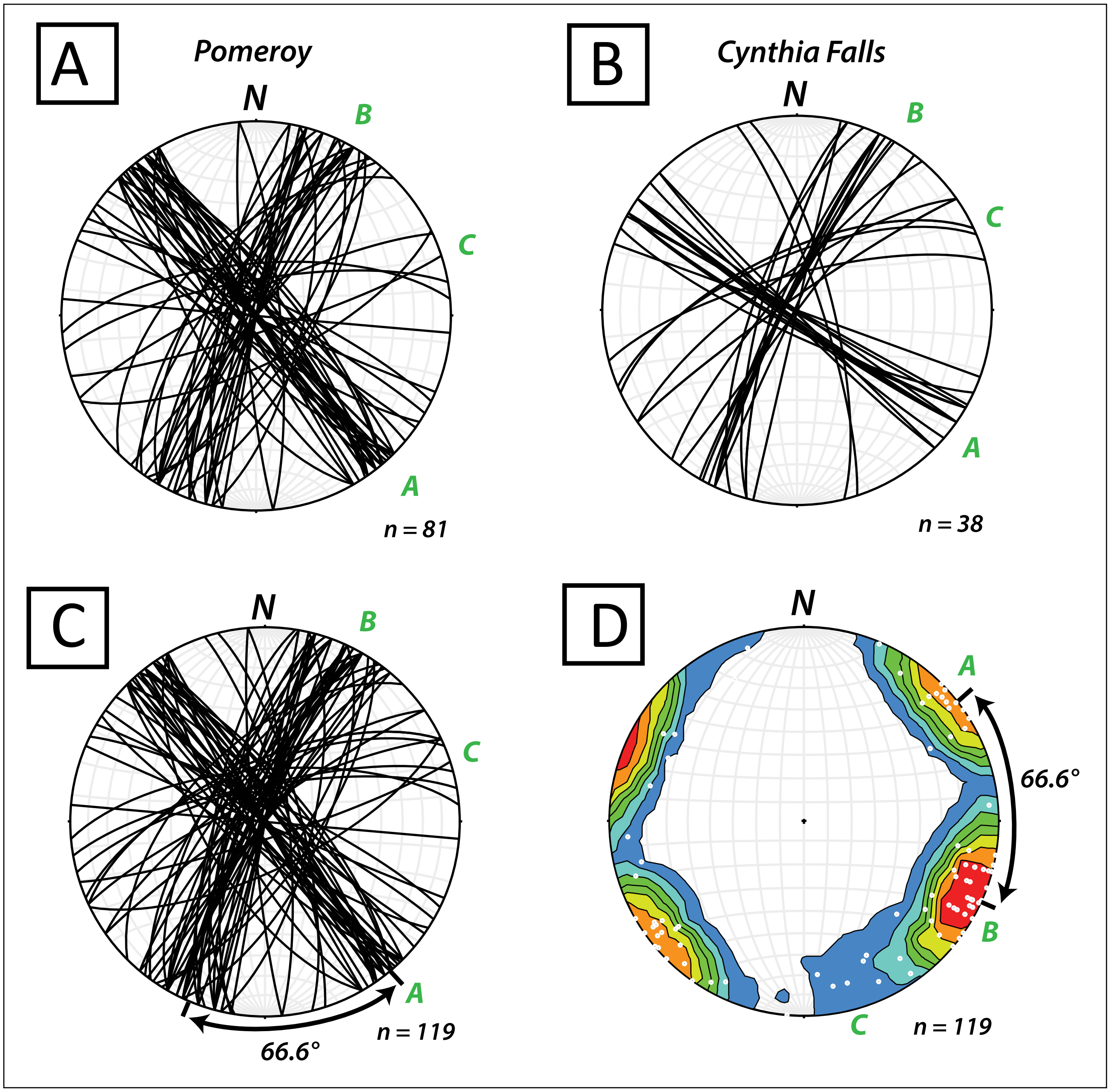

Figure 3-3. Stereograms showing similarity in orientations of three fracture sets (A, B, and C) of both the Cynthia Falls Sandstone of Tuxedni Group and the Pomeroy Arkose Member of Naknek Formation. **A.** Fracture populations of the Pomeroy near Dry Bay. **B.** Fracture populations from the Cynthia Falls in Tuxedni Bay. **C.** Combined fracture populations from stereograms A and B. **D.** Poles to the planes from C. The angle between mean planes from populations A and B is 67°

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CHAPTER 4

PRELIMINARY OBSERVATIONS: CONTINUED FACIES ANALYSIS OF THE LOWER JURASSIC TALKEETNA FORMATION, NORTH CHINITNA BAY, ALASKA

Katharine F. Bull[1]

Field studies in 2014 continued the detailed, 1:63,360-scale geologic mapping associated with the Cook Inlet basin analysis program. In 2013, the focus was on inch-to-mile mapping of the Iniskin Peninsula, lower Cook Inlet, and included mapping of the Lower Jurassic Talkeetna Formation (Martin, 1926; Detterman and Reed, 1980; Bull, 2013, 2014). The mapping area in 2014 extended from Chinitna Bay to Tuxedni Bay, with the main focus on the area from Chinitna River to Red Glacier, north of Chinitna Bay (fig. 4-1). This short report is intended as a continued discussion of preliminary observations reported in Bull (2014).

North of Chinitna Bay, the Talkeetna Formation forms a northeast-trending belt of volcaniclastic sediments, lava flows, lava domes, and possible sills. These facies have been identified between Iliamna Volcano and its Quaternary deposits to the north and west, and the Bruin Bay fault to the east. Prior to 2013, detailed stratigraphic analysis of the Talkeetna Formation had been limited to facies in the Talkeetna Mountains, north of Anchorage (for example, Draut and Clift, 2006). In 2013 a high concentration of very thick lavas was identified around Roscoe Peak and Mt. Eleanor on the Iniskin Peninsula, which suggests one or more effusive eruption centers (Bull, 2013, 2014). The facies north of Chinitna Bay do not include such a concentration of lavas; effusive eruptive centers are not apparent. Instead, ridges running north from the bay are underlain

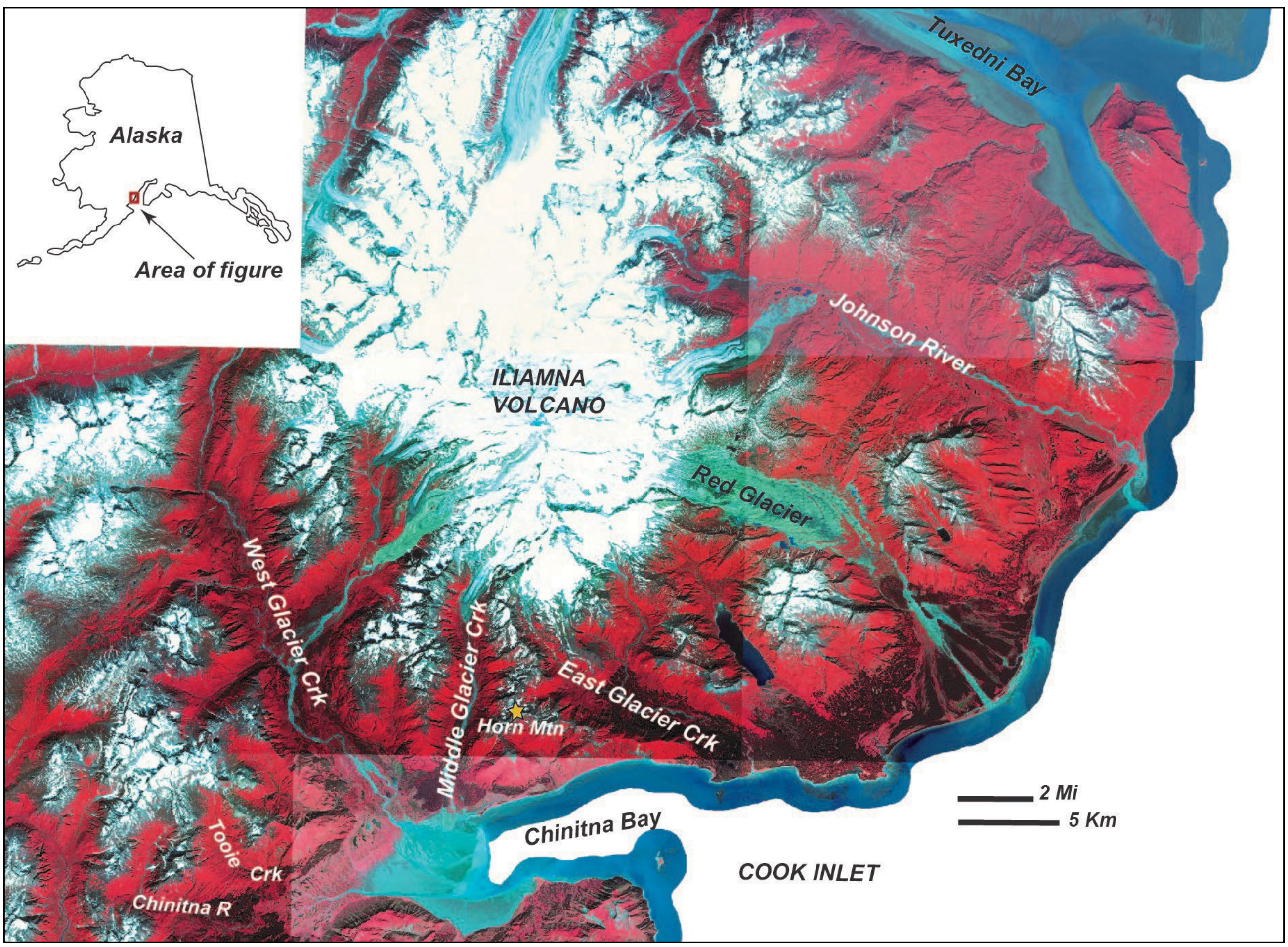

Figure 4-1. Location of Iniskin–Tuxedni map area.

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by lavas interbedded with internally structureless volcaniclastic pebble breccias and poorly sorted, angular, volcaniclastic sandstones. The volcaniclastic deposits are full of angular, intermediate to mafic, porphyritic to aphanitic lava clasts, suggesting the beds represent mass flow deposits transported relatively short distances on volcanic slopes, likely from the north. In addition, the frequency of lavas increases northward, suggesting the source vents may be covered by the younger deposits of Iliamna Volcano and its associated vents (Waythomas and Miller, 1999).

Explosive volcanism also occurred in the map area, clearly evident in thin sections made from samples collected in 2013 and 2014 (fig. 4-2). The sections reveal shard- and pumice-bearing pyroclastic deposits preserved in thinly bedded deposits in several areas, including south of Roscoe Peak, on Horn Mountain ridge, Chinitna ridge, and possibly in Tuxedni Bay. Preservation of the delicate bubble-wall shards and pumice fragments provides evidence not only of explosive volcanism, but also of the directly eruption-fed, non-transported nature of some of the deposits.

Additional volcaniclastic facies in the 2014 map area provide evidence of deposition in shallow marine and possibly fluvial environments. A somewhat discrete zone (southern Horn Mountain ridge) of thinly bedded, laterally continuous beds locally exhibits cross-laminations, channel fills, normal grading, and lenticular beds (fig. 4-3). The units also show characteristics such as subrounded clasts and oxidative coloring of the beds that together are possibly indicative of subaerial–alluvial and perhaps even lacustrine deposition. In addition, in the southern Horn Mountain ridge package, approximately 800 m (0.5 mi) north of Horn Mountain, we observed a cliff-forming, altered, 8–10-m-thick, brown, very-coarse-grained volcaniclastic sandstone to pebble breccia that is structureless to weakly laminated and contains flattened, altered, white–pink pumice and polymictic coherent clasts. The breccia also contains approximately 10 percent fossilized logs, 10 cm to 1 m in diameter at the base of the unit (fig.4-4). The logs are elongate parallel to bedding, as if lying down. Immediately underlying the pumice breccia is a 1–2-m-thick bed with brown siltstone to very-fine-grained sandstone matrix and 10–25 percent white–pink

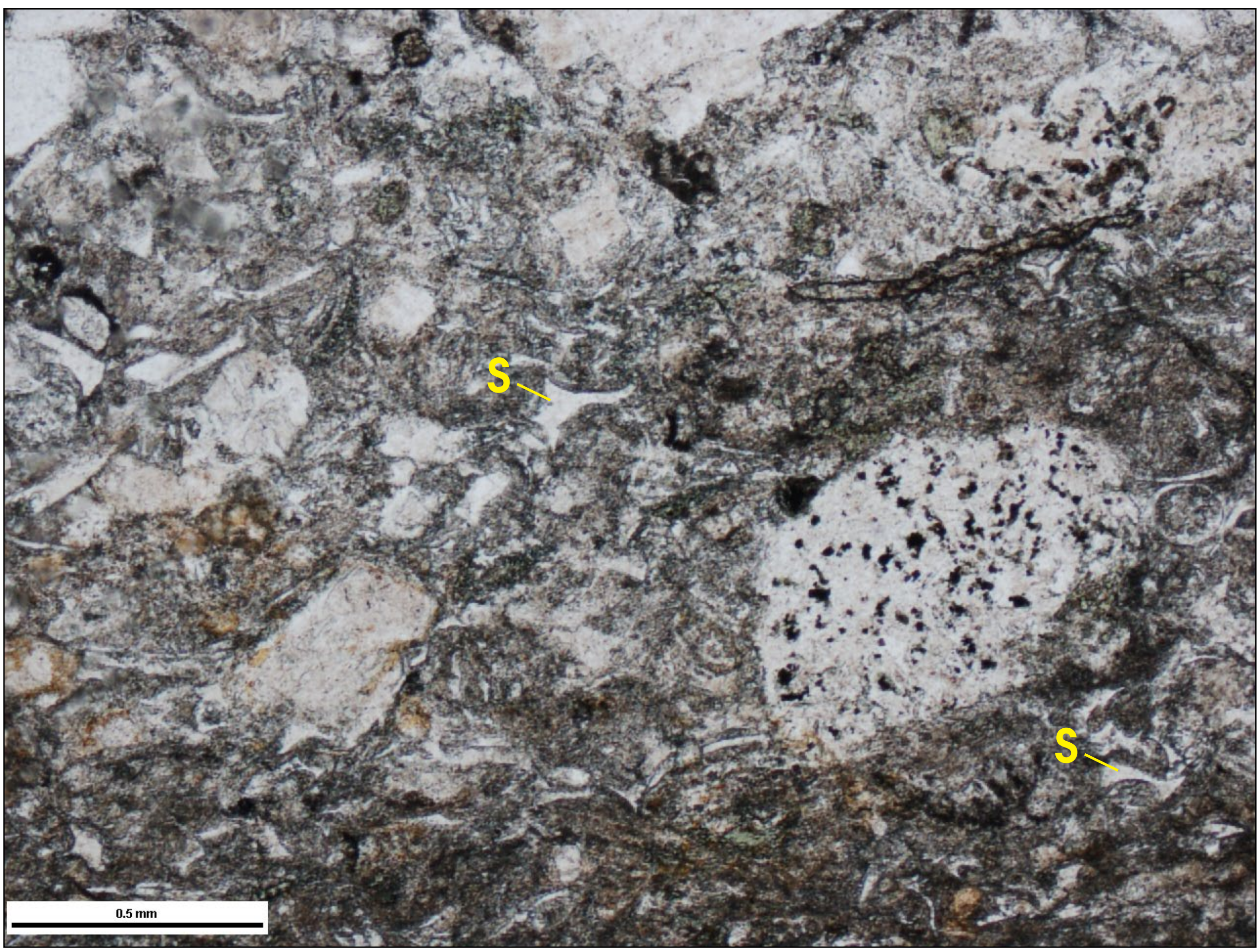

Figure 4-2. Bubble-wall shards (white, curvilinear shapes, S) in volcaniclastic sandstone. The shard clasts are the result of pulverization of magma during explosive eruption in predominantly intermediate to silicic magmas. Preservation of these delicate features suggests eruption-fed (pyroclastic) deposits laid down in quiet water.

pumice and/or aphanitic coherent clasts, and 1–3 percent, 4 mm to 2 cm, black, angular, lithic (siliciclastic?) clasts. The bed is weakly laminated. Together, these two units—the log-bearing pumice breccia and the lithic-bearing laminated basal unit—likely represent a pyroclastic density current (PDC) deposited in a subaerial or shallow aqueous environment. Underlying the PDC deposit are several 20–50-cm-thick maroon and olive green volcaniclastic fine-grained sandstone and siltstone beds (fig. 4-5). These beds contain sedimentary structures such as channel fills, crossbeds and lenticular beds (fig. 4-6).

Thinly bedded and laterally continuous volcaniclastic beds are also exposed along the ridge west of Horn Mountain ridge, and are folded into an east–west-striking syncline. The facies in this area, however, include siliciclastic black siltstone and gray cherty layers not indicative of fluvial deposition. High-angle faults displace units with varying offset on both ridges (Gillis, 2014), and the relationship between the thinly bedded facies on the neighboring ridges is not clear.

Marbles are exposed in the Iniskin–Tuxedni map area in a number of locations, the majority of which lie in the contact zone between the intrusions of Alaska–Aleutian Batholith and the Talkeetna Formation. The marbles were previously mapped as part of the Triassic Kamishak Formation (Trm; Detterman and Hartsock, 1966); however, mapping completed during this study suggests their stratigraphic position may be within the Talkeetna Formation. One marble exposure not previously mapped is immediately northeast of the Chinitna River, proximal to the batholith but not in contact with it. The marble is interbedded with poorly sorted volcaniclastic sandstones and pebble breccias (fig. 4-7). Beds overlying the marble are ≤10-cm- to 2-m-thick, pumice-bearing volcaniclastic granule to pebble breccia and medium- to coarse-grained, poorly sorted volcaniclastic sandstone. Overlying and along strike with these pumice-bearing units are internally structureless to laminated and cross-bedded, crystal-rich, moderately-well-sorted volcaniclastic sandstones and conglomerate–breccias with subangular to subrounded clasts (fig. 4-8). Underlying the marble are thickly- to moderately-bedded, internally structureless, chlorite+epidote-altered, mafic to intermediate, volcaniclastic siltstone, sandstone, and pebble breccia.

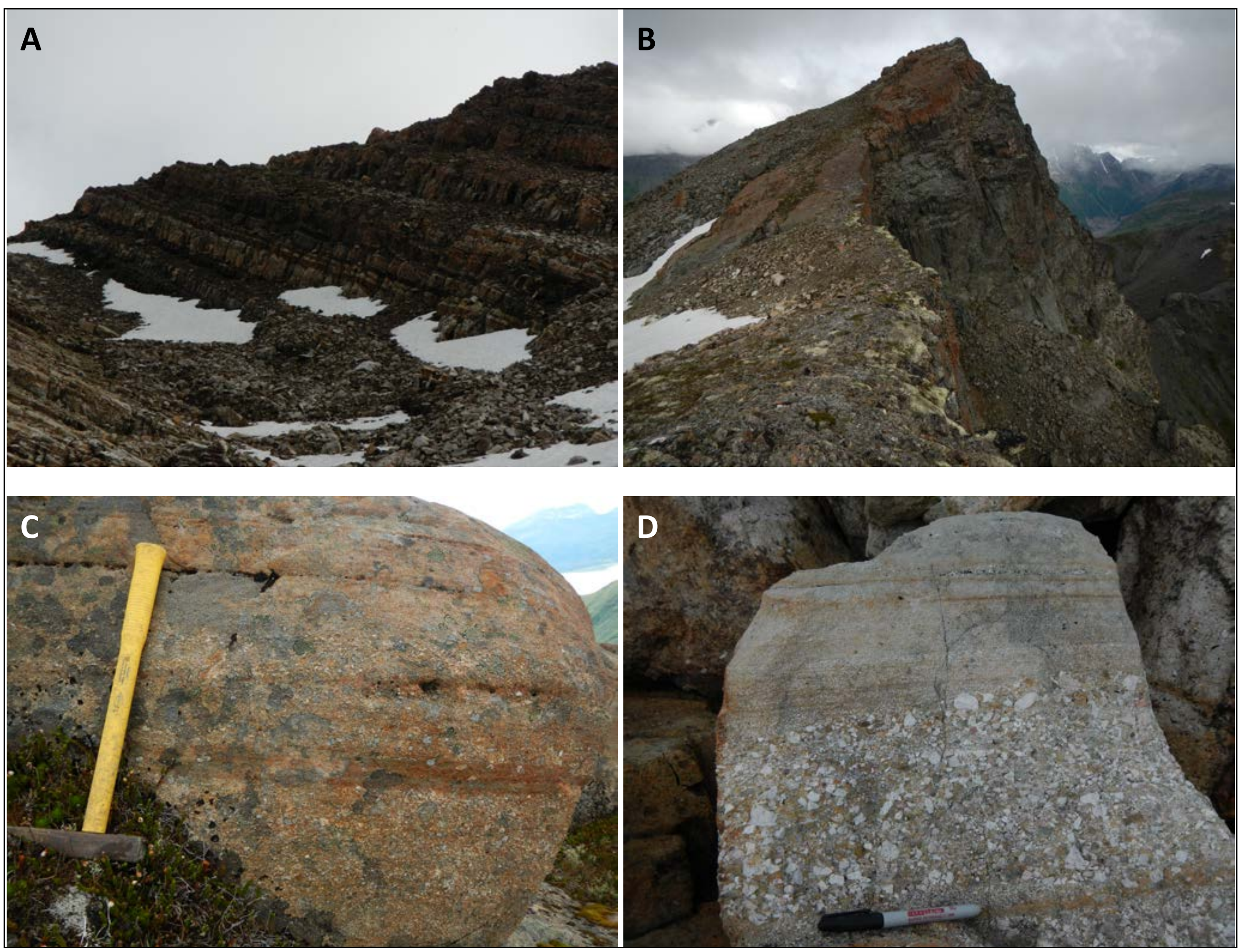

Figure 4-3 A–D. South-dipping, thinly-bedded, laterally continuous outcrops of volcaniclastic siltstone, sandstone, and pebble breccia along southern Horn Mountain ridge. Some beds are laminated (image C), normally graded (image D), and exhibit structures such as cross-laminations and lenticular bedding.

The volcaniclastic facies associated with the marble do not exhibit unique characteristics that distinguish them as part of the Triassic package. Field observations made during a half-day investigation of the Triassic Cottonwood Bay Greenstone yielded few revelations either; the exposures along the north and west shores of Cottonwood Bay comprise chlorite+epidote-altered lower fine- to upper medium-grained volcaniclastic sandstone, and mafic autoclastic breccia, including hyaloclastite (fig. 4-9). Similar facies were observed in the Roscoe Glacier area in the Iniskin–Tuxedni map area (Bull, 2013). In hopes of determining the age of the carbonates exposed in the map area, multiple samples were taken of the carbonates and/or the volcaniclastic rocks above and below the carbonate for possible conodonts, and U-Pb and $^{40}Ar/^{39}Ar$ dating; results are pending.

Detterman and Hartsock (1966) split the Talkeetna Formation into three members: in ascending order, the Marsh Creek Breccia Member, Portage Creek Agglomerate Member, and the Horn Mountain Tuff Member. In 2013, due to similarities in the facies of the Marsh Creek and Portage Creek Members on the Iniskin Peninsula, and the inability to separate these along regional strike, the two members were combined into one member, and the Horn Mountain Member remained separate (Bull, 2013, 2014). However, rapid facies changes and complex stratigraphy render volcanic successions difficult to subdivide into continuous mappable units along strike, and the facies of the Horn Mountain Tuff Member vary markedly from Iniskin Bay to Chinitna Bay to Tuxedni Bay. Overall preliminary observations presented here suggest the arc may have become shallower, and even subaerial, locally, but the facies included in the Horn Mountain Tuff Member do not reflect common characteristics consistent enough to define a distinctive member. Further work may allow subdivisions of the Talkeetna Formation into groups of facies, or facies associations, but these will likely vary across the regional strike.

Figure 4-4 A–C. Fossilized logs (marked by arrows) in crystal pumice lithic breccia (see fig. 4-6). The logs are elongate parallel to bedding. Images **B** and **C** are enlargements of fossilized logs denoted as X and Y in image A. Rock hammer is 50 cm long.

Figure 4-5. Maroon and olive green fine-grained volcaniclastic sandstone and siltstone beds underlying log-bearing, crystal pumice lithic breccia.

Figure 4-6. Cross-laminations (A and B) and lenticular beds (C) in strata underlying log-bearing, crystal pumice lithic breccia interpreted to be a pyroclastic density current (PDC) deposit. Hammer is 50 cm long.

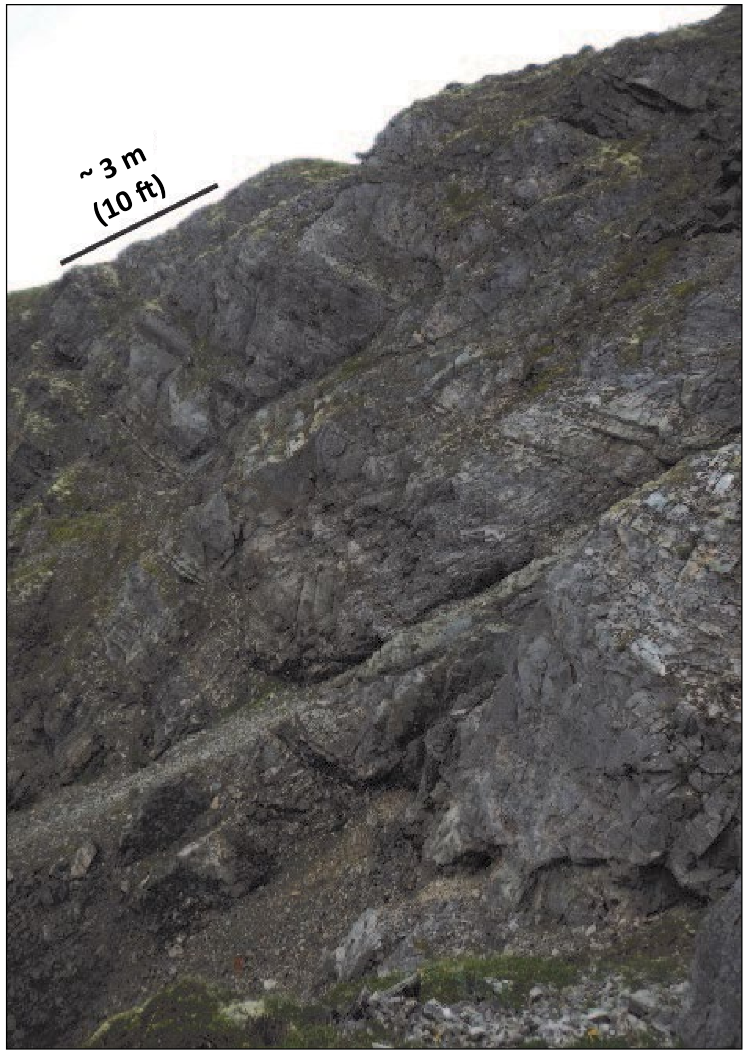

Figure 4-7. Bedded marble on Chinitna ridge, ~3 m wide, intercalated with volcaniclastic sandstone and pebble breccia.

ACKNOWLEDGMENTS

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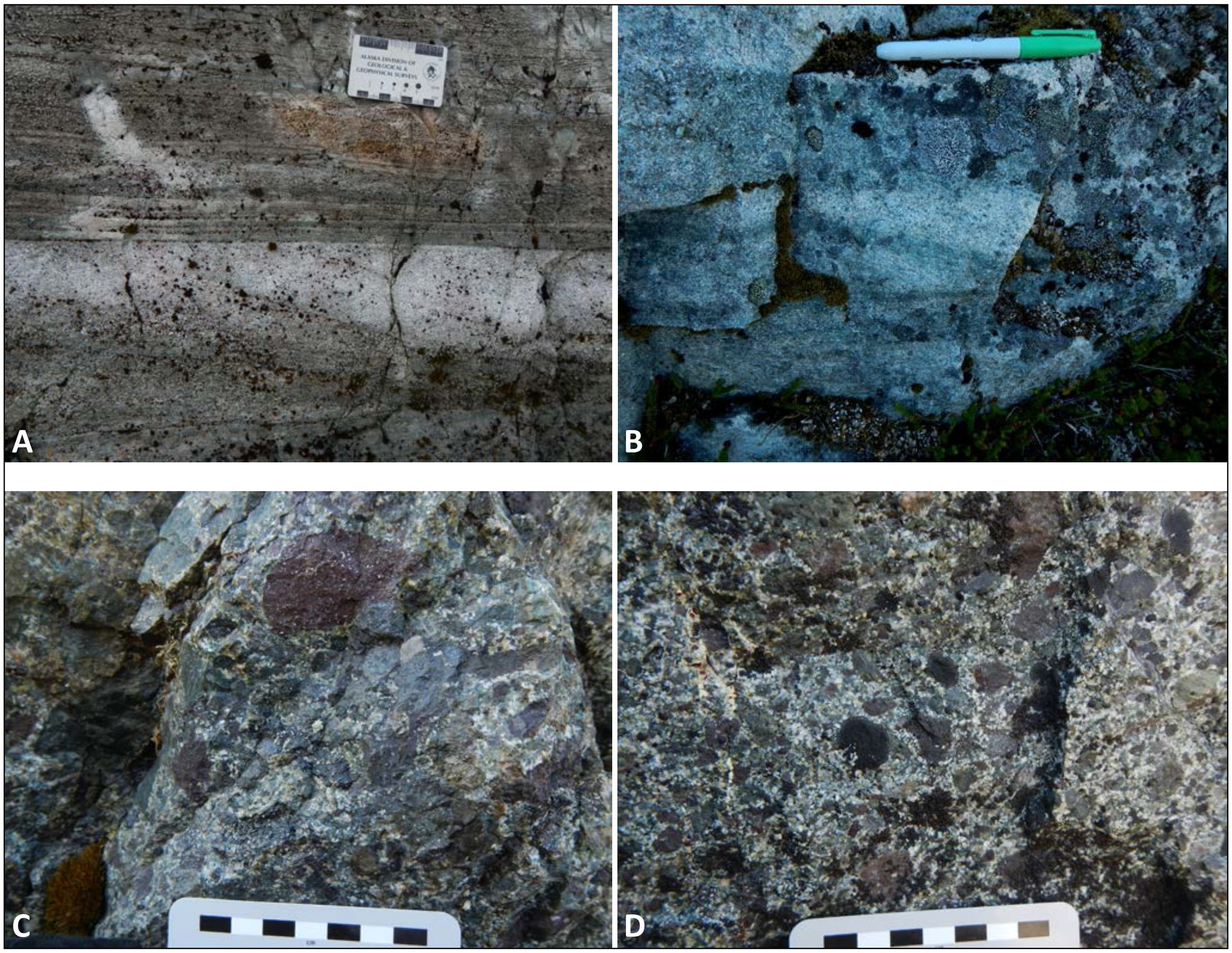

Figure 4-8. Crystal-rich volcaniclastic sandstones and conglomerate-breccias on Chinitna ridge, along strike from beds overlying the marble seen in figure 4-7. **A, B.** Cross-laminated medium- to coarse-grained volcaniclastic sandstone. **C, D.** Polymictic volcaniclastic pebble-conglomerate–breccia.

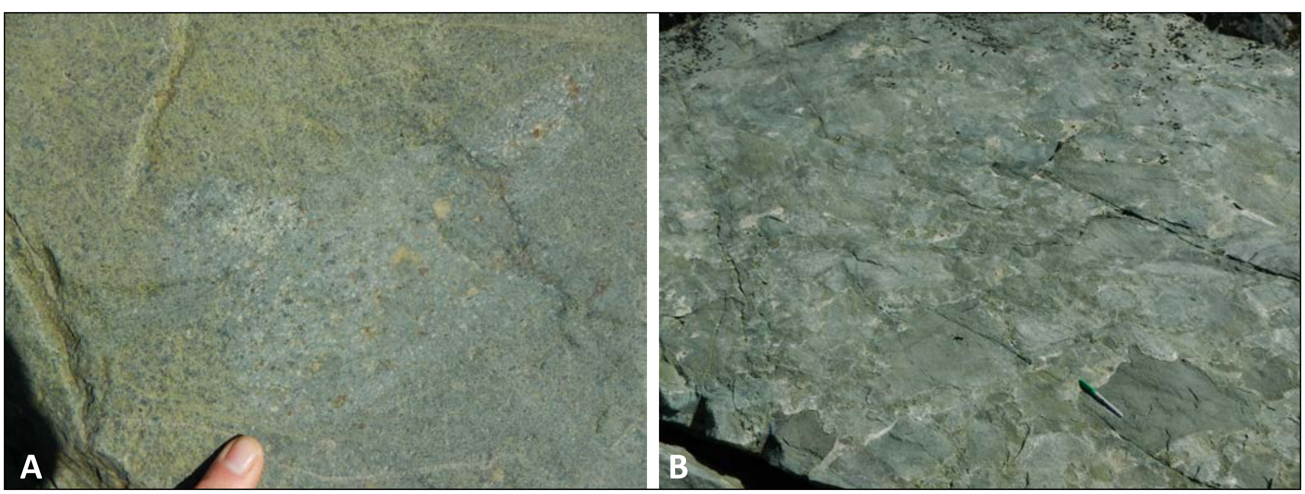

Figure 4-9. Triassic Cottonwood Bay Greenstone facies, Cottonwood Bay. **A.** Porphyritic clast within chlorite–epidote-altered, medium- to coarse-grained volcaniclastic sandstone. **B.** Chlorite–epidote-altered autoclastic breccia with tightly packed blocky clasts and hyaloclasts. Clasts with cuspate and curvilinear margins are likely quench-fragmented hyaloclasts, such as the clast to the right of the green marking pen (lower right corner of photo).

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CHAPTER 5

STRATIGRAPHIC RECONNAISSANCE OF THE MIDDLE JURASSIC RED GLACIER FORMATION, TUXEDNI GROUP, AT RED GLACIER, COOK INLET, ALASKA

By David L. LePain[1] and Richard G. Stanley[2]

INTRODUCTION

The Alaska Division of Geological & Geophysical Surveys (DGGS) and U.S. Geological Survey (USGS) are implementing ongoing programs to characterize the petroleum potential of Cook Inlet basin. Since 2009 this program has included work on the Mesozoic stratigraphy of lower Cook Inlet, including the Middle Jurassic Tuxedni Group between Tuxedni and Iniskin bays (LePain and others, 2013; Stanley and others, 2013; fig. 5-1). The basal unit in the group, the Red Glacier Formation (fig. 5-2), is thought to be the principal source rock for oil produced in upper Cook Inlet, and available geochemical data support this contention (Magoon and Anders, 1992; Magoon, 1994). Despite its economic significance very little has been published on the formation since Detterman and Hartsock's (1966) seminal contribution on the geology of the Iniskin–Tuxedni area nearly 50 years ago. Consequently its stratigraphy, contact relations with bounding formations, and source rock characteristics are poorly known. During the 2014 field season, a nearly continuous stratigraphic section through the Red Glacier Formation in its type area at Red Glacier was located and measured to characterize sedimentary facies and to collect a suite of samples for analyses of biostratigraphy, Rock-Eval pyrolysis, vitrinite reflectance, and sandstone composition (fig. 5-3).

The poorly known nature of the Red Glacier Formation is likely due to its remote location, steep terrain, and the fact that the type section is split into two segments that are more than 3 km apart. The lower 375 m segment of the formation is on the ridge between Red Glacier and Lateral Glacier and the upper 1,009 m segment is on the ridge between Red Glacier and Boulder Creek (fig. 5-3). Structural complications in the area add to the difficulty in understanding how these two segments fit together.

STRATIGRAPHIC RECONNAISSANCE OF THE RED GLACIER FORMATION

Our section, on the ridge between Red and Lateral glaciers, includes part of the lower 375 m of Detterman and Hartsock's (1966) type section, and continues southeast along this same ridge to the contact with the overlying Gaikema Sandstone, for a total measured Red Glacier thickness of 681 m (fig. 5-3). The lower 150 to 200 m of Red Glacier is not accessible for measurement due to the steep terrain. Assuming the true thickness of this inaccessible part lies in this range, the total thickness of the formation is between 831 and 881 m. Many faults with minor offsets (few decimeters to a meter) cut the section but do not complicate measurement, as marker beds can be traced with high confidence across these structures.

The lower part of our measured section includes a 178-m-thick lower succession that consists of two thick packages (each 20–40 m thick) of amalgamated, fine- to very-coarse-grained sandstone separated by recessive-weathering mudstone with many interbeds of fine- to very-coarse-grained sandstone (figs. 5-4A and B). Only the upper 20 m or so of the lower amalgamated package was accessible. Sandstones in the amalgamated packages consist of a variety of volcanolithic grains, including dark-colored volcanic rock fragments and abundant light gray and white plagioclase grains. Most sandstones are medium to very thick bedded and appear internally massive, but crudely developed horizontal stratification and well-developed plane-parallel lamination are locally common as is ripple cross-lamination in fine-grained sandstones; graded bedding is not common and, where present, is limited to the upper few centimeters of beds. Mudstone rip-ups are locally prominent as well-defined clast-rich layers, but they also occur widely scattered throughout many sandstone beds. Most sandstone beds lack trace fossils but a few include possible *Phycosiphon* and/or *Helminthopsis*. Belemnites are rare. Recessive-weathering mudstone with many individual beds of sandstone separates the amalgamated sandstone packages. Mudstone consists largely of argillaceous siltstone with undisturbed plane-parallel lamination. Some mudstones are bioturbated and have a mottled appearance and either lack lamination or include disrupted lamina. Mudstone successions include decimeter- to multi-meter-thick beds of coarse-grained sandstone similar to the sandstones in the amalgamated sandstone packages. Massive sandstones and crudely laminated sandstones record deposition from high-density flows, whereas sandstones with well-developed traction structures record deposition from lower-density flows (Lowe, 1982; Mulder and Alexander, 2001; Talling and others, 2012). Mudstones record deposition from dilute, low-density flows (Potter and others, 2005; Talling and others, 2012). Bioturbated mudstones and rare body fossils indicate deposition in a marine setting. The entire package is inferred to have been deposited below maximum storm wave-base.

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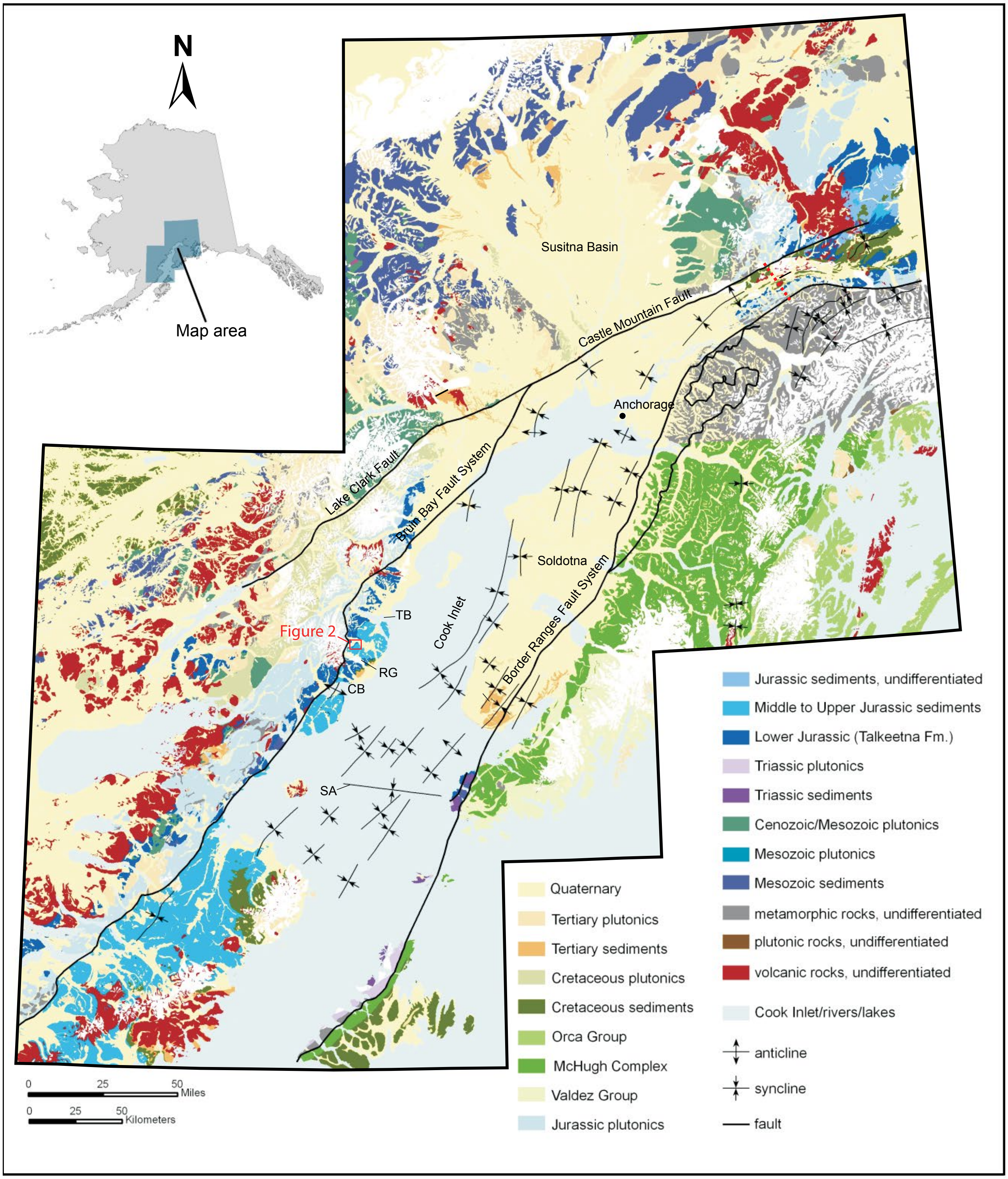


Figure 5-1. Bedrock geologic map of the Cook Inlet region. CB = Chinitna Bay; SA = Seldovia arch; RG = Red Glacier; TB = Tuxedni Bay. Modified from Wilson and others (2009).

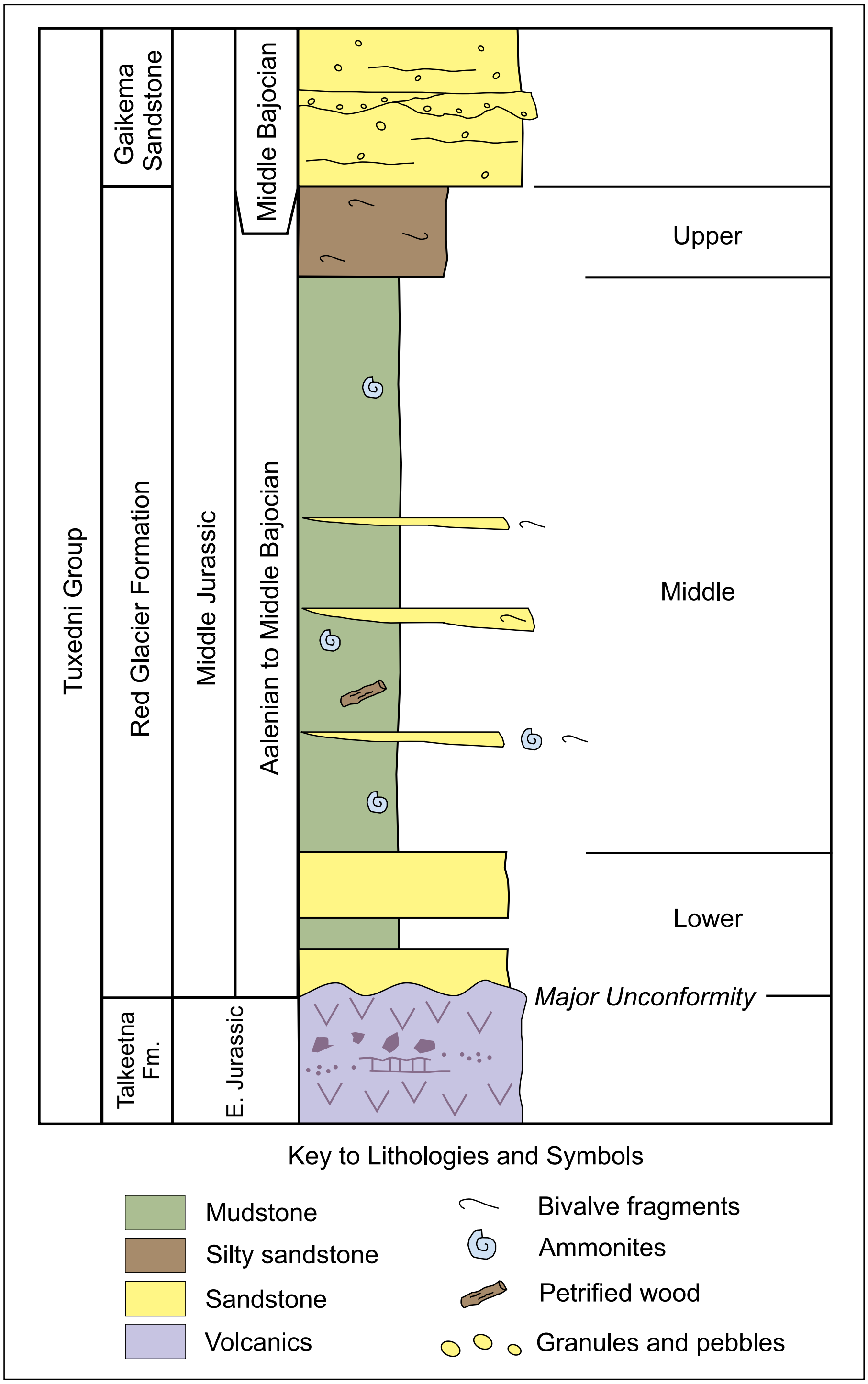


Figure 5-2. Generalized stratigraphic column showing the Red Glacier Formation and Gaikema Sandstone. Compiled from Detterman and Hartsock (1966) and modified based on the author's experience.

The middle part of our section includes 573 m of dark gray, dark brown, and black mudstone with thin laminae up to 1 mm thick of siltstone and very-fine-grained sandstone (fig. 5-4C). Beds of fine- to coarse-grained sandstone up to 0.5 m thick punctuate this part of the section but are not abundant (fig. 5-4D). Dark brown mudstone is commonly soft and fissile. Dark gray mudstone appears moderately bioturbated in the lower 100 m of the package, and bioturbation fabrics are not apparent in the upper part. Ammonites, belemnites, and bivalves are scattered throughout and are most conspicuous when incorporated in beds of coarser material (silt and fine sand; fig. 5-4E). Several discrete horizons include pieces of petrified logs up to 30 cm long and 20 cm diameter (fig. 5-4F). Well-developed quartz crystals up to 5 cm long are scattered along the ground surface at several locations. Thin sheet-like accumulations of a fibrous zeolite(?) mineral are present as dike-like features that cut across stratigraphy and as sill-like features that are concordant with stratigraphy. Prominent clastic dikes filled with fine-grained sandstone are common and are oriented at high angles to bedding. Sandstone composition is similar to sandstones in the lower part of the section, and most beds are massive or normally graded; mudstone rip-up clasts are present locally but are not abundant. Mudstone records deposition in relatively deep water from suspension and from low-energy, dilute muddy flows (Potter and others, 2005; Talling and others, 2012). These conditions were interrupted occasionally by more energetic low- and high-density sediment gravity flows that transported fine- to coarse-grained sand. The appearance of the dark gray and brown mudstones suggests that marine organic material was an abundant component in sediment at the time of deposition. Rock-Eval pyrolysis results, underway at the time of this writing, will test this supposition and add to a limited dataset collected in 2009 (LePain and others, 2013).

The upper part of our section is 41 m thick and consists of light-brown-weathering sandy siltstone and silty sandstone (figs. 5-4G and H). Although not perfectly exposed, the contact between the middle and upper parts of the section appears to

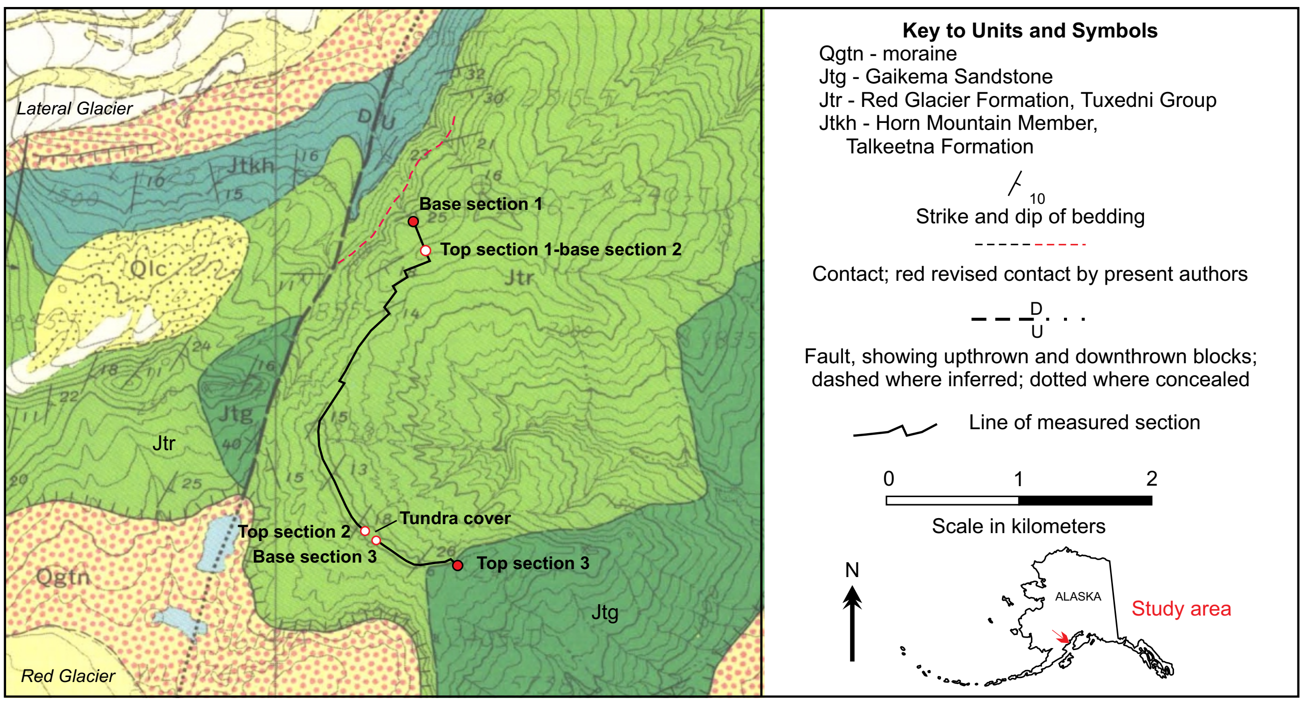
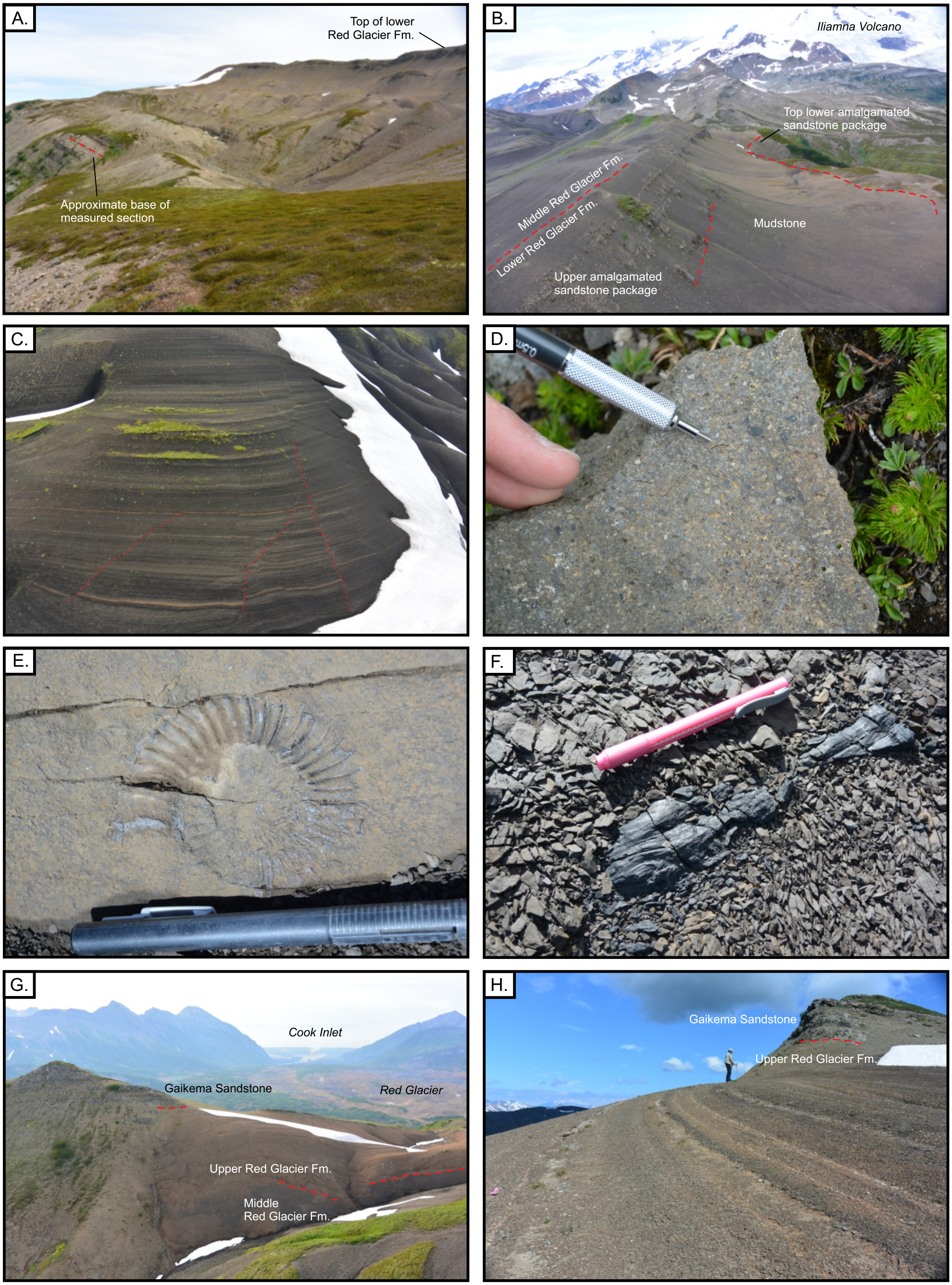


Figure 5-3 (above). Geology of the Red Glacier type area modified from Detterman and Hartsock (1966) and showing the line of the measured section from figure 5-2. Red dashed line shows our revised location of the contact between the Talkeetna Formation and Red Glacier Formation.

Figure 5-4 (right). **A.** View to the north, showing the lower Red Glacier Formation. Area shown in photo is immediately north of Lateral Glacier. **B.** View to the south–southwest, showing the contact between the lower and middle Red Glacier Formation. **C.** View from the air toward the east, showing well-stratified mudstones of the middle Red Glacier Formation. Note the minor faults (shown with dotted red lines). **D.** Coarse-grained volcanolithic sandstone from the middle Red Glacier Formation. **E.** Ammonite preserved in a silty sandstone bed in middle Red Glacier Formation. **F.** Fragment of petrified wood in siltstone from the middle Red Glacier Formation. Eraser is 12 cm long. **G.** View to the east–southeast, showing the contact between middle and upper Red Glacier Formation (lower red dashed line) and the upper Red Glacier Formation and Gaikema Sandstone. Note the sharp contact between the middle and upper Red Glacier Formation. **H.** View to the north, showing stratified siltstone and silty sandstone of the upper Red Glacier Formation. The dashed red line marks the contact between the upper Red Glacier Formation and Gaikema Sandstone.


A.
Top of lower
Red Glacier Fm.
Approximate base of
measured section
B.
Iliamna Volcano
Top lower amalgamated
sandstone package
Middle Red Glacier Fm.
Lower Red Glacier Fm.
Mudstone
Upper amalgamated
sandstone package
C.
D.
E.
F.
G.
Cook Inlet
Gaikema Sandstone
Red Glacier
Upper Red Glacier Fm.
Middle
Red Glacier Fm.
H.
Gaikema Sandstone
Upper Red Glacier Fm.

be conformable but sharp, and corresponds to a prominent color change from dark gray and brown mudstones to light brown coarser-grained lithologies (fig. 5-4G). The contact with the overlying Gaikema Sandstone also appears to be conformable and is placed at the base of first thick sandstone succession with abundant trough cross-stratification (fig. 5-4H). Siltstones and silty sandstones include prominent plane-parallel (horizontal) lamination. The upper part of the section is interpreted as a prodeltaic succession transitional to the overlying shallow marine (deltaic) Gaikema Sandstone.

A suite of samples was collected throughout the accessible part of the formation for analyses of Rock-Eval pyrolysis, vitrinite reflectance, palynology, and sandstone composition. These samples will help in evaluating the source rock characteristics and thermal maturity of the formation and assist in correlation to subsurface locations throughout the basin. Analytical results will be summarized in a subsequent report.

ACKNOWLEDGMENTS

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CHAPTER 6

STORM-INFLUENCED DELTAIC DEPOSITS OF THE MIDDLE JURASSIC GAIKEMA SANDSTONE IN A MEASURED SECTION ON THE NORTHERN INISKIN PENINSULA, COOK INLET BASIN, ALASKA

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

Middle Jurassic strata of the Gaikema Sandstone were deposited about 170 million years ago on a delta that was located on the western shoreline of the Cook Inlet basin (Detterman and Hartsock, 1966; LePain and others, 2011, 2013). The delta was built by swift, sediment-laden rivers that flowed southeastward from a mountainous volcanic terrane west of the Bruin Bay fault (fig. 6-1). Upon reaching the edge of the Jurassic sea, the rivers dumped abundant sand, gravel, and mud into a depocenter on the northern Iniskin Peninsula, about 240 km southwest of Anchorage (figs. 6-1, 6-2).

This report provides a preliminary description and interpretation of a detailed, 34-m-thick measured section in the Gaikema Sandstone on the south shore of Chinitna Bay at latitude 59.816°N, longitude 153.168°W (figs. 6-1–6-3). The sandstone in this measured section exhibits hummocky cross lamination and other features suggestive of storm-influenced deposition on the shallow-marine, seaward margin of the Gaikema delta.

Our field studies of the Gaikema Sandstone were conducted during 2013 and 2014 as part of a collaborative effort by the Alaska Division of Geological & Geophysical Surveys (DGGS), Alaska Division of Oil and Gas (DOG), and U.S. Geological Survey (USGS) to provide the public with reliable information on the geologic framework and petroleum resource potential of Cook Inlet basin (Gillis, 2013, 2014). Jurassic rocks in Cook Inlet, including the Gaikema Sandstone, are of economic interest because they could contain significant undiscovered petroleum resources (Bureau of Ocean Energy Management, 2011; Stanley and others, 2011a, 2011b, 2013a; LePain and others, 2013).

STRATIGRAPHIC SETTING, AGE, AND THICKNESS OF THE GAIKEMA SANDSTONE

The Gaikema Sandstone is one of six formations that make up the Middle Jurassic Tuxedni Group (fig. 6-4; Detterman and Hartsock, 1966; Detterman and Westermann, 1992). The Tuxedni Group was deposited in a spectrum of deep-marine, shallow-marine, and nonmarine environments and records a complicated history of relative rises and falls of sea level (LePain and others, 2013). In the lowermost part of the Tuxedni Group, the Red Glacier Formation consists mainly of mudstone, siltstone, and sandstone that were deposited in prodeltaic and relatively deeper-water marine environments (LePain and Stanley, 2015). The Gaikema Sandstone, Cynthia Falls Sandstone, and Bowser Formation are richly fossiliferous and represent coarse-grained deltas that prograded eastward and southeastward into the Jurassic sea (fig. 6-4). The Fitz Creek Siltstone and Twist Creek Siltstone are fine-grained units that were deposited during episodes of marine flooding. The mineralogical composition of sandstones in the Tuxedni Group indicates that the principal sources of sediment were Early Jurassic volcanic and plutonic rocks that were uplifted and eroded during the Middle and Late Jurassic (Helmold and others, 2013; Helmold and Stanley, 2015). Evidence from field investigations by DGGS and USGS suggests that the uplifted volcanic and plutonic rocks were located on the western, upthrown side of the Bruin Bay fault (fig. 6-1; LePain and others, 2011, 2013; Wartes and others, 2013).

In its type section along Gaikema Creek (figs. 6-1, 6-2), the Gaikema Sandstone conformably and gradationally overlies the Red Glacier Formation and is overlain conformably and abruptly by the Fitz Creek Siltstone. The Bajocian (Middle Jurassic) age of the Gaikema Sandstone is based on studies of abundant ammonites and other marine fossils (Detterman and Hartsock, 1966, p. 28; Imlay, 1984, p. 10; Detterman and Westermann, 1992, p. 53).

On the northern Iniskin Peninsula, the Gaikema Sandstone ranges in thickness from 150 to 260 m and consists of resistant, cliff-forming, green to gray sandstone with subordinate conglomerate, siltstone, and shale. Using the geologic map of Detterman and Hartsock (1966) we estimate that the base of our detailed measured section (fig. 6-5) is stratigraphically about 30–40 m above the covered contact between the Gaikema Sandstone and the underlying Red Glacier Formation.

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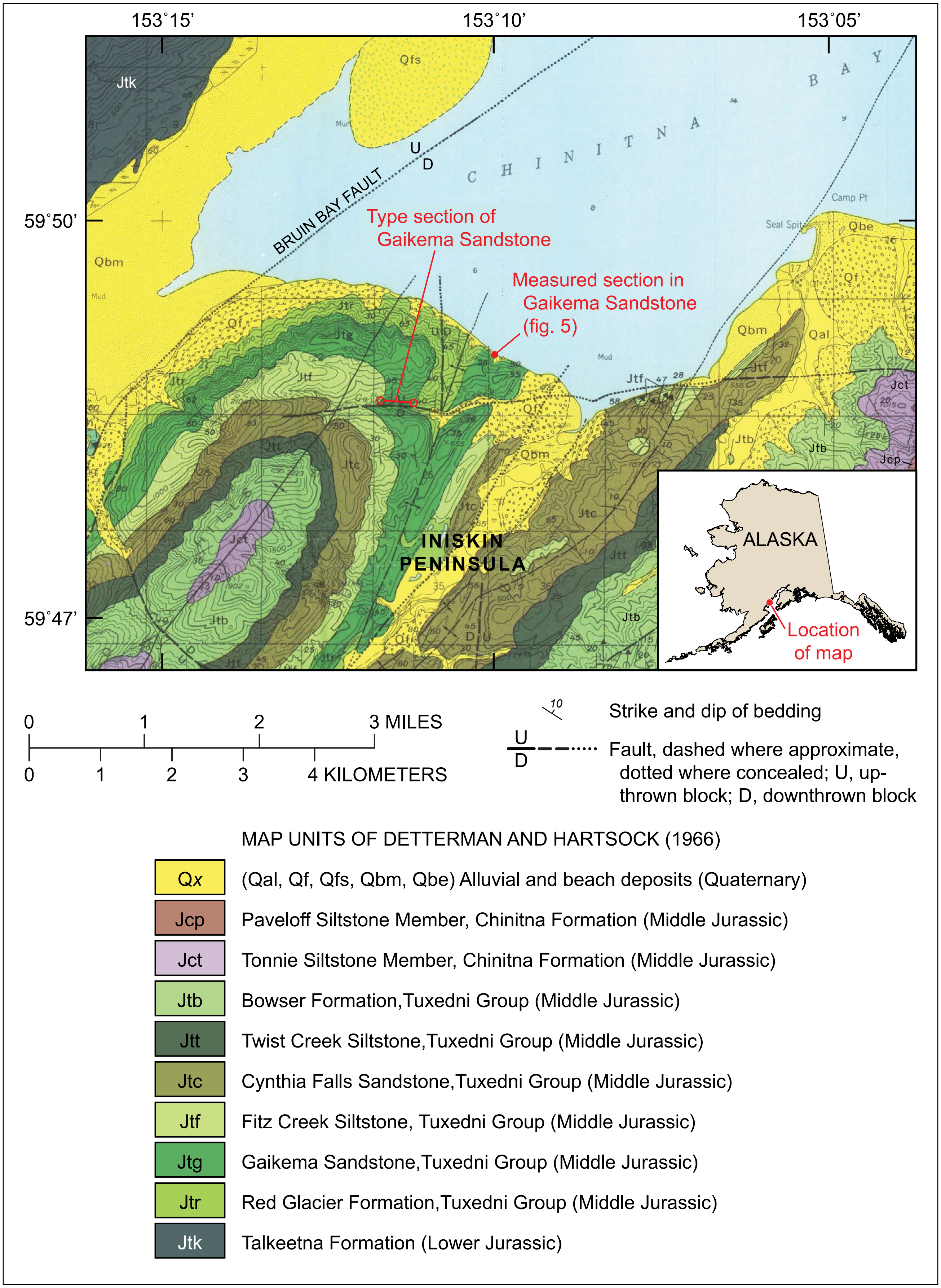

Figure 6-1. Map showing the northern Iniskin Peninsula, the location of the type section of the Gaikema Sandstone, and the location of our detailed measured section in the Gaikema Sandstone. Geologic map from Detterman and Hartsock (1966).

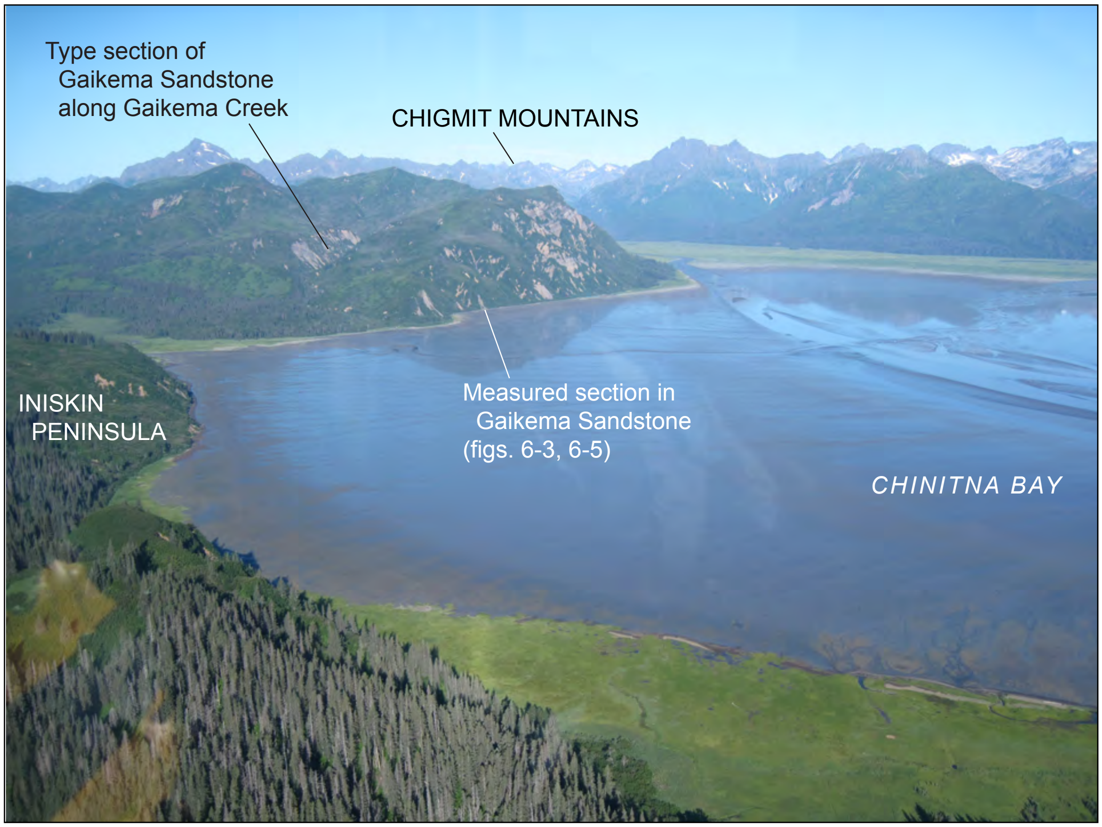

Figure 6-2. View to the west across Chinitna Bay and the northern Iniskin Peninsula toward the Chigmit Mountains, showing the type section of the Gaikema Sandstone along Gaikema Creek at photo left and our detailed measured section in the Gaikema Sandstone on the south shore of Chinitna Bay at photo center.

Figure 6-3. View, looking south from helicopter, of the south shore of Chinitna Bay and an outcrop of the Gaikema Sandstone; our detailed, 34-m-thick measured section is between the two white arrows. Bedding in this outcrop is upright, strikes N50°E to N60°E, and dips about 65° to the southeast (photo left). See figures 6-1 and 6-2 for location.

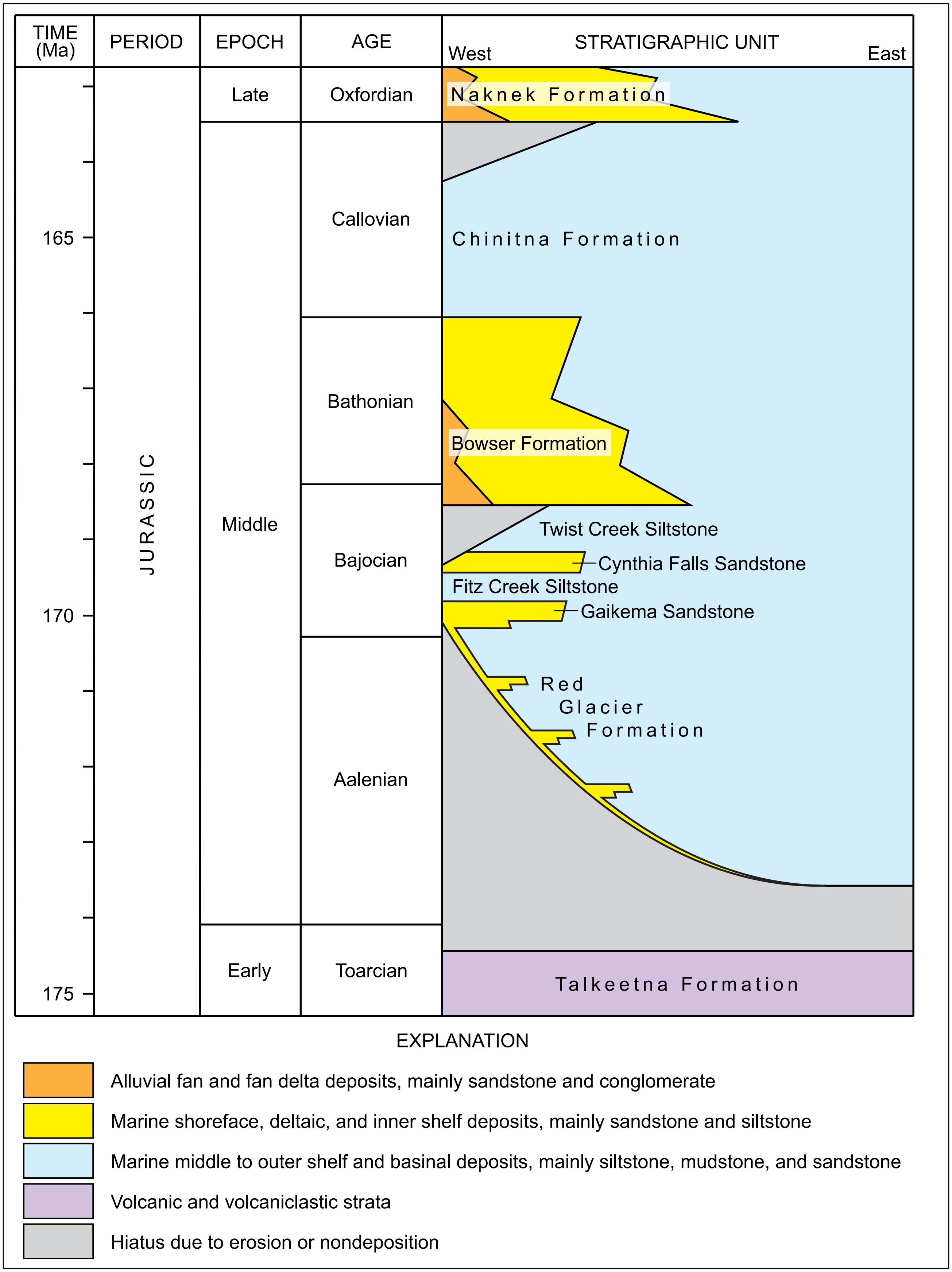

Figure 6-4. Schematic chronostratigraphic diagram showing Middle Jurassic stratigraphic units in the lower Cook Inlet basin, modified from LePain and others (2013, p. 44) using formation ages reported by Detterman and Westermann (1992), the geologic time scale of Cohen and others (2014), and field observations by the authors. The Tuxedni Group comprises the Bowser Formation, Twist Creek Siltstone, Cynthia Falls Sandstone, Fitz Creek Siltstone, Gaikema Sandstone, and Red Glacier Formation (Detterman and Hartsock, 1966).

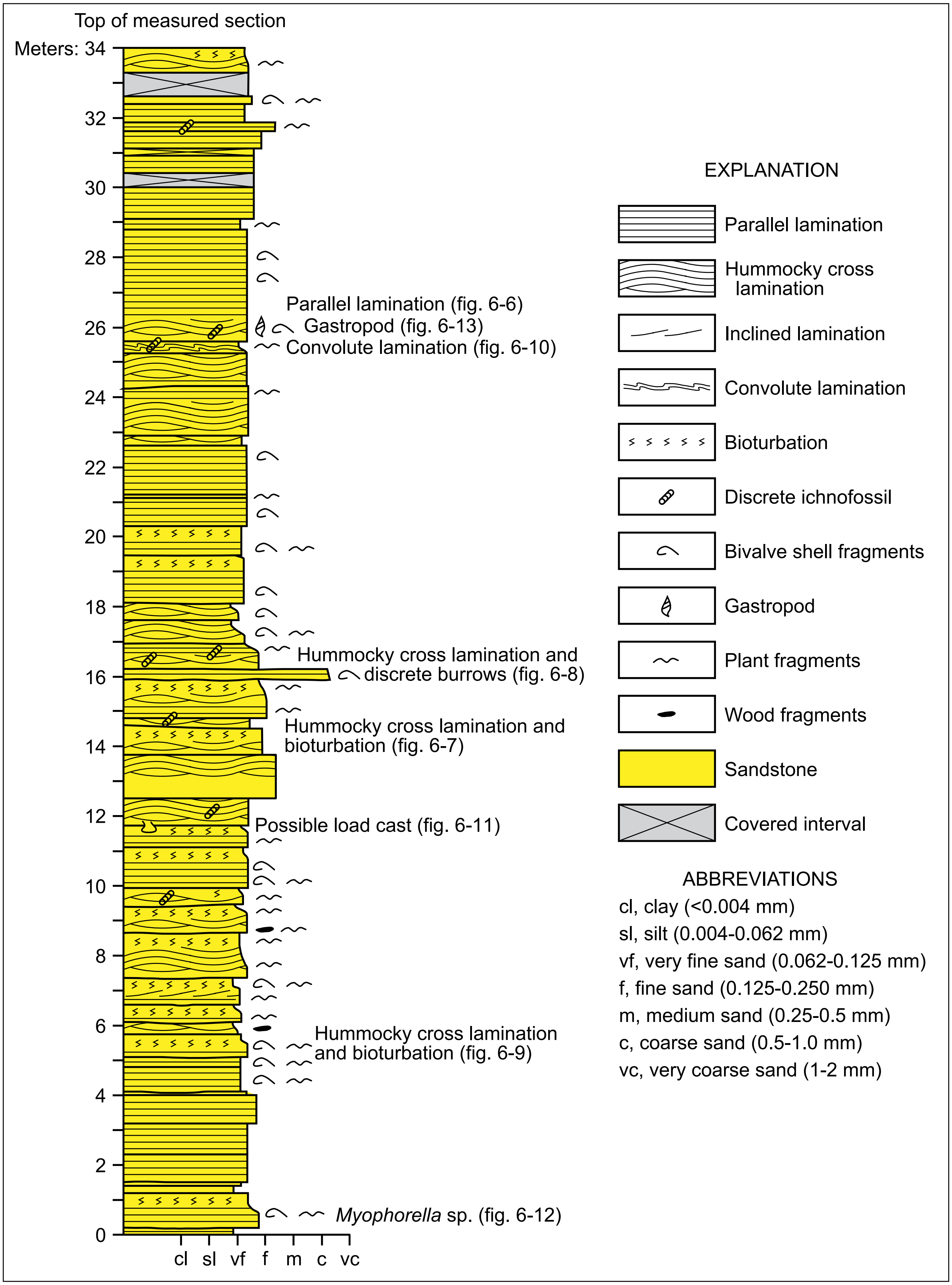

Figure 6-5. Detailed, 34-m-thick measured section of part of the Gaikema Sandstone. See figures 6-1–6-3 for location.

BRIEF DESCRIPTION OF THE DETAILED MEASURED SECTION

Sandstone in our detailed measured section (fig. 6-5) ranges in texture from very fine to coarse grained but is predominantly fine grained. The sandstone is medium to light gray-green on freshly broken surfaces, and weathers to gray-brown, orange-brown, and red-brown. The sandstone is hard and readily breaks apart into small blocks and slabs along fractures and planes of stratification (fig. 6-6).

The sandstone beds range in thickness from 10 cm to about 300 cm but most beds are in the range of 30–100 cm thick. Nearly all of the sandstone beds have sharp, erosional lower contacts that are immediately overlain by parallel laminated and/or hummocky cross-laminated sandstone (figs. 6-6–6-8). The laminated sandstone grades upward into bioturbated sandstone that exhibits color and textural mottling and is abruptly truncated by a sharp, erosional contact with laminated sandstone belonging to the next overlying bed (fig. 6-9). In some sandstone beds, lamination is cut by discrete ichnofossils (figs. 6-7, 6-8) that we tentatively identify as *Thalassinoides* on the basis of their resemblance to illustrations in Pemberton (1992, p. 188, 325, 391), Gerard and Bromley (2008, p. 39), and Pemberton and others (undated, p. 143–145). Convolute lamination is prominent in a bed about 25.5 m above the base of the measured section (fig. 6-10). A load cast was observed at about 11.75 m in the section (fig. 6-11).

Molluscan shell fragments are common in our measured section, but we found no unbroken, well-preserved fossils. However, about 0.4 m above the base of the section we found a fragment of a trigoniid bivalve that resembles *Myophorella* sp. and is suggestive of shallow, inner shelf water depths (fig. 6-12; Robert Blodgett, written communication, November 19, 2014). A poorly preserved, unidentified gastropod was found about 26 m above the base of the section (fig. 6-13). In some sandstone beds abundant disarticulated valves and broken pieces of small, unidentified bivalve mollusks are concentrated along laminations (fig. 6-14). Finely comminuted plant fragments, mostly smaller than 2 mm diameter and gray to black in color, are abundant throughout our measured section and in places are concentrated along certain laminae (fig. 6-15). Wood fragments up to 22 cm long and dark gray to black in color were observed at several horizons in the measured section (fig. 6-5).

PRELIMINARY INTERPRETATION OF THE DETAILED MEASURED SECTION

Parallel lamination and hummocky cross lamination are commonly found in the sandy deposits of ancient shallow marine settings that were influenced by periodic, intense storms (Plint, 2010). Plane lamination is formed by high-velocity unidirectional flow along a flat bed (Collinson and others, 2006), whereas the mechanism of formation of hummocky cross lamination appears to involve a combination of unidirectional and oscillatory flow generated by large storm waves (Cheel, 1978; Collinson and others, 2006; Dumas and Arnott, 2006).

Storm deposits, sometimes termed tempestites or event beds, are common in the geologic record and have been recognized at many locations throughout the world (for example, Dott and Bourgeois, 1982; Myrow and Southard, 1996; Plint, 2010). Drawing on plentiful published scientific literature on storm deposits, we suggest the following preliminary interpretation for the sandstone in our detailed measured section. Sand carried by rivers to the margins of the Gaikema delta was mobilized by storms and redeposited on the shallow offshore flank of the delta as layers with parallel lamination and hummocky cross lamination. During spells of fair weather between storms, the upper part of each laminated bed was reworked by sediment-churning organisms to form horizons of bioturbated sand. As the next storm started, the bioturbated horizon was eroded by waves and currents and then sharply overlain by a new layer of storm-deposited, laminated sand.

The detailed sedimentology and paleogeography of the Gaikema Sandstone are mostly unstudied and poorly understood. As a testable hypothesis to guide future work, we suggest that our detailed measured section may have been located on the northeastern flank of a sand- and gravel-dominated delta that was centered on the northern Iniskin Peninsula, as suggested by Detterman and Hartsock (1966).

PETROLEUM RESOURCE POTENTIAL

The potential of the Gaikema Sandstone to be a reservoir rock for petroleum is of interest because the Gaikema Sandstone directly and conformably overlies the Red Glacier Formation (fig. 6-4), which is thought to contain the principal source rocks of oil and associated gas in Cook Inlet basin (Magoon and Anders, 1992; Magoon, 1994; Lillis and Stanley, 2011; LePain and others, 2013; Stanley and others, 2013b; LePain and Stanley, 2015). About 8 km southwest of our detailed measured section a wildcat exploration well—the Iniskin Unit Beal 1—was drilled during 1954–1955 on the Fitz Creek anticline and tested minor shows of gas but no oil in the Gaikema Sandstone at depths of 748–788 m (Detterman and Hartsock, 1966, p. 74).

To facilitate better understanding of the oil and gas reservoir potential of the Gaikema Sandstone, during the 2013 and 2014 field seasons we collected rock samples for petrographic studies and analyses of porosity and permeability; preliminary results are reported by Helmold and Stanley (2015). In addition, three rock samples from our detailed measured section

Figure 6-6. Detail of sandstone outcrop about 26.5–27.0 m above the base of the measured section in figure 6-5, showing parallel lamination and fracturing. Hammer is about 30 cm long.

Figure 6-7. Detail of sandstone outcrop about 14.6 m above the base of the measured section in figure 6-5, showing dark, bioturbated sandstone at photo right overlain by lighter-colored sandstone with hummocky cross lamination and discrete ichnofossils tentatively identified as *Thalassinoides*. Hammer is about 30 cm long.

Figure 6-8. Detail of sandstone outcrop about 16.5–17.0 m above the base of the measured section in figure 6-5, showing hummocky cross lamination and discrete ichnofossils tentatively identified as *Thalassinoides*. Barrel of pencil is about 1 cm diameter.

Figure 6-9. Detail of sandstone outcrop about 5.75 m above the base of the measured section in figure 6-5, showing sharp, erosional contact at pencil point between light-colored, bioturbated sandstone at photo right and overlying dark-colored, possible hummocky cross-laminated sandstone at photo left. Barrel of pencil is about 1 cm diameter.

Figure 6-10. Detail of sandstone outcrop about 25.5 m above the base of the measured section in figure 6-5, showing convolute lamination; red arrow points to a discrete ichnofossil. Hammer is about 30 cm long. The mode of origin of the convolute lamination is unknown but may have entailed liquefaction and deformation of the sand in response to a trigger mechanism such as rapid deposition and sediment loading, downslope movement, or shaking by a Middle Jurassic earthquake.

Figure 6-11. Detail of sandstone outcrop about 11.75 m above the base of the measured section in figure 6-5, showing a load cast above and to photo left of pencil point. Red-brown, bioturbated sandstone at photo right is sharply overlain by light-colored, hummocky cross-laminated sandstone at photo left. Barrel of pencil is about 1 cm diameter.

Figure 6-12. Detail of sandstone outcrop and fossil bivalve at about 0.4 m above the base of the measured section in figure 6-5. The bivalve appears to be a trigoniid, possibly *Myophorella* sp. (Robert Blodgett, written commun., November 19, 2014). Barrel of pencil is about 1 cm diameter.

Figure 6-13. Detail of sandstone outcrop, showing poorly-preserved fossil gastropod about 26 m above the base of the measured section in figure 6-5. Barrel of pencil is about 1 cm diameter.

Figure 6-14. Detail of sandstone block from float recovered from near the 15–25 m interval in the measured section shown in figure 6-5. The sandstone is broken along a flat surface nearly parallel to lamination, revealing numerous bivalve shell fragments. Barrel of pencil is about 1 cm diameter.

Figure 6-15. Detail of sandstone block from float recovered from near the 10–15 m interval in the measured section shown in figure 6-5. The sandstone is broken along a flat surface nearly parallel to lamination and shows abundant dark plant fragments, mostly smaller than 2 mm diameter.

were analyzed for vitrinite reflectance by Mark J. Pawlewicz (U.S. Geological Survey, Denver, Colorado) and yielded values of 0.8–1.0 percent R_o, which are Mature I in the thermal maturity scheme of Johnsson and others (1993). These vitrinite reflectance values suggest maximum burial depths of about 4.5–7.7 km, using an equation that relates percent R_o to maximum burial temperature (Barker and Pawlewicz, 1986; Barker, 1988) and modern Cook Inlet geothermal gradients of 19–27°C/km (Lillis and Stanley, 2011), and assuming no significant variations in geothermal gradient from the Middle Jurassic to the present. The results of these and future investigations are expected to provide useful information for evaluation of the Gaikema Sandstone as a possible exploration target for commercial accumulations of hydrocarbons.

ACKNOWLEDGMENTS

We thank Mark J. Pawlewicz for his many years of work on vitrinite reflectance samples from Alaska and wish him a long and happy retirement. Robert B. Blodgett kindly helped with fossil identification. We thank Marwan A. Wartes and James G. Clough for helpful reviews of earlier drafts of the manuscript. We are grateful to helicopter pilots Roger Hinsdale and Merlin “Spanky” Handley for safely transporting us in the field. Generous permits to access Native lands were provided by Cook Inlet Region, Inc. (CIRI), and the following village corporations: Chickaloon, Knik, Ninilchik, Salamatof, Seldovia, and Tyonek. Funding for field work was provided by the Alaska Division of Geological & Geophysical Surveys and by the U.S. Geological Survey. Field work on the Iniskin Peninsula during 2013 was also supported by funding from the National Cooperative Geologic Mapping Program administered by the U.S. Geological Survey (STATEMAP award G13AC00157).

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CHAPTER 7

PETROLOGY AND RESERVOIR QUALITY OF THE GAIKEMA SANDSTONE: INITIAL IMPRESSIONS

Kenneth P. Helmold[1] and Richard G. Stanley[2]

INTRODUCTION

The Division of Geological & Geophysical Surveys (DGGS) and Division of Oil & Gas (DOG) are currently conducting a study of the hydrocarbon potential of Cook Inlet basin (LePain and others, 2011). The Tertiary stratigraphic section of the basin includes coal-bearing units that are prolific gas reservoirs, particularly the Neogene sandstones. The Paleogene sandstones are locally prolific oil reservoirs that are sourced largely from the underlying Middle Jurassic Tuxedni Group. Several large structures act as hydrocarbon traps and the possibility exists for stratigraphic traps although this potential has not been fully exploited. As part of this study a significant number of Tertiary sandstones from the basin have been already collected and analyzed (Helmold and others, 2013). Recent field programs have shifted attention to the Mesozoic stratigraphic section to ascertain whether it contains potential hydrocarbon reservoirs. During the 2013 Cook Inlet field season, two days were spent on the Iniskin Peninsula examining outcrops of the Middle Jurassic Gaikema Sandstone along the south shore of Chinitna Bay (fig. 7-1). A stratigraphic section approximately 34 m in thickness was measured and a detailed description was initiated (Stanley and others, 2015), but due to deteriorating weather it was not possible to complete the description. During the 2014 field season two additional days were spent completing work on the Gaikema section. Analyses of thin sections from six of the samples collected in 2013 are available for incorporation in this report (table 7-1). Data from samples collected during the 2014 field season will be included in future reports.

Table 7-1. Samples of Gaikema Sandstone collected during the 2013 Cook Inlet field season that are included in this report.

Sample Number	General Location	Specific Location	Latitude	Longitude	Unit
13A017-006.0A	Iniskin Peninsula	South shore Chinitna Bay	N 59.81702	W 153.16617	Gaikema
13A017-006.15A	Iniskin Peninsula	South shore Chinitna Bay	N 59.81702	W 153.16617	Gaikema
13A017-006.8A	Iniskin Peninsula	South shore Chinitna Bay	N 59.81702	W 153.16617	Gaikema
13A017-008.2A	Iniskin Peninsula	South shore Chinitna Bay	N 59.81702	W 153.16617	Gaikema
13A017-008.3A	Iniskin Peninsula	South shore Chinitna Bay	N 59.81702	W 153.16617	Gaikema
13A017-012.7A	Iniskin Peninsula	South shore Chinitna Bay	N 59.81702	W 153.16617	Gaikema

FRAMEWORK MINERALOGY AND PROVENANCE

Petrographic analyses indicate that Gaikema sandstones on the Iniskin Peninsula are largely feldspatholithic with an average modal composition of $Qt_{33}F_{34}L_{33}$, $Qm_{11}F_{33}Lt_{56}$, $Qm_{25}P_{73}K_{2}$, $Qp_{41}Lvm_{52}Lsm_{7}$ (figs. 7-2 and 7-3) and a plagioclase/feldspar (P/F) ratio of 0.97 (see table 7-2 for explanation of grain parameters). The average grain size is 0.09 mm (upper very-fine) with an average Folk sorting of 0.52 (moderate). The rock framework consists predominantly of plagioclase (range 30–50 percent, average 21 percent) and volcanic rock fragments (VRFs; range 26–43 percent, average 15 percent). Additional components include monocrystalline quartz (average 10 percent), polycrystalline quartz (average 9 percent), chert (average 11 percent), sedimentary rock fragments (SRFs, average 3 percent), and heavy minerals (average 3 percent). Accessory grains include plutonic rock fragments (PRFs), K-feldspar, and micas. One sample (13A13-12.7A) is distinctive in that it consists almost exclusively of euhedral to subhedral plagioclase crystals, with virtually no detrital quartz or other lithic grains. It remains to be determined if this variability in detrital mineralogy is related to differences in depositional environment.

The prevalence of plagioclase and VRFs, along with the dearth of K-feldspar, suggests the sandstones were derived from an undissected volcanic arc terrane. The most likely provenance is volcanic flows, ignimbrites, and tuffs that comprise the Lower Jurassic Talkeetna Formation that underlies the Tuxedni Group (Bull, 2014; Bull, 2015). The source terrane was probably a region of uplifted Talkeetna Formation west of the Bruin Bay fault (Detterman and Hartsock, 1966).

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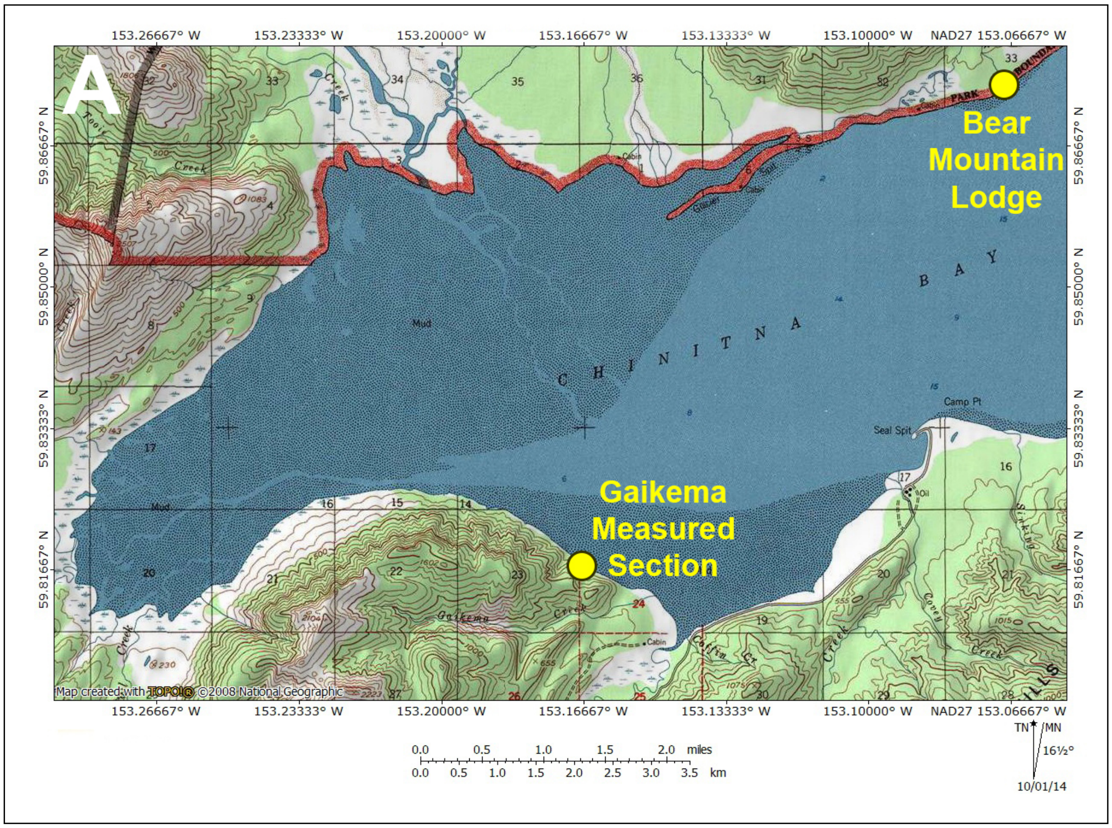

Figure 7-1. **A.** Topographic map showing location of measured section of Gaikema sandstone along the northern shore of Chinitna Bay on the Iniskin Peninsula. **B.** Measured section of Gaikema sandstone consists largely of very-fine- to fine-grained sandstone and siltstone. Distance between flags represents a stratigraphic thickness of 1 m.

Table 7-2. Classification of grain parameters

A. Quartzose grains
Qm = Monocrystalline quartz
Qp = Polycrystalline quartz (including chert)
Qt = Total quartzose grains (Qm + Qp)

B. Feldspar grains
P = Plagioclase
K = Potassium feldspar
F = Total feldspar grains (P + K)

C. Lithic grains
Ls^+ = Sedimentary rock fragments (including chert)
Lv = Volcanic rock fragments
Lm = Metamorphic rock fragments
Lp = Plutonic rock fragments
Lsm = Sedimentary and metasedimentary rock fragments
Lvm = Volcanic and metavolcanic rock fragments
L = Lithic grains (Ls^+ + Lv + Lm + Lp)
Lt = Total lithic grains (L + Qp)

RESERVOIR QUALITY

The combination of abundant plagioclase and VRFs results in a labile framework mineralogy that is highly susceptible to diagenetic alteration. Authigenic chlorite and/or mixed-layer chlorite/smectite is the dominant cement in the majority of samples. Laumontite is a significant cement in a few samples, where it occurs as a replacement of detrital plagioclase grains and as intergranular cement that occludes primary porosity. Due to the high VRF content, heulandite is anticipated to be a common cement in Gaikema sandstones, although it has not been observed in the few samples analyzed to date. The combination of authigenic clay and zeolite occludes virtually all primary porosity, resulting in overall poor reservoir quality with porosities typically less than 8 percent and permeabilities less than 1 millidarcy (md) (figs. 7-3 and 7-4). The two samples with the lowest permeabilities (<0.1 md) contain significant laumontite cement. Based on this limited dataset, it appears laumontite has a greater impact on permeability than porosity. Because of the extensive cementation, Gaikema sandstones on the Iniskin Peninsula probably have minimal potential as conventional reservoirs. However, due to the extensive authigenic clay cement, the Gaikema in this area could have potential for tight-gas reservoirs. The superposition of tight Gaikema sandstones and potential source rocks of the underlying Red Glacier Formation (LePain and Stanley, 2015)

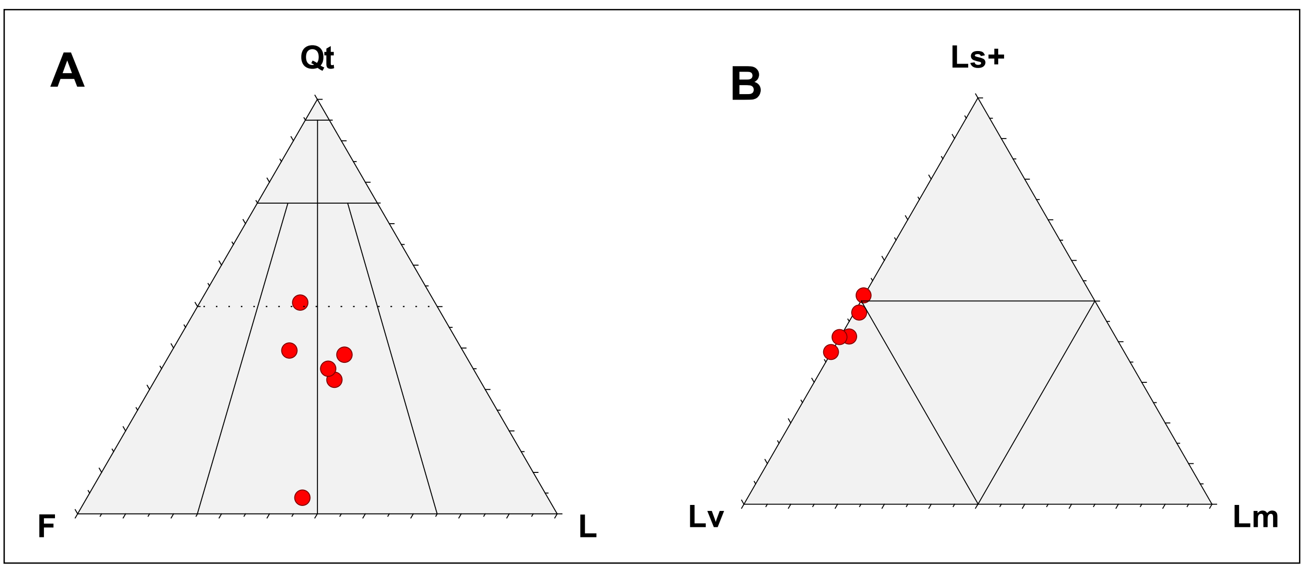

Figure 7-2. **A.** QtFL ternary diagram of total quartz (Qt), feldspar (F), and lithic grains (L), showing the feldspatholithic nature (<50% total quartz) of the Gaikema sandstones. **B.** Ls+LvLm ternary diagram of sedimentary lithic grains including chert (Ls^+), volcanic lithic grains (Lv), and metamorphic lithic grains (Lm), showing that the lithic population consists almost exclusively of VRFs and chert.

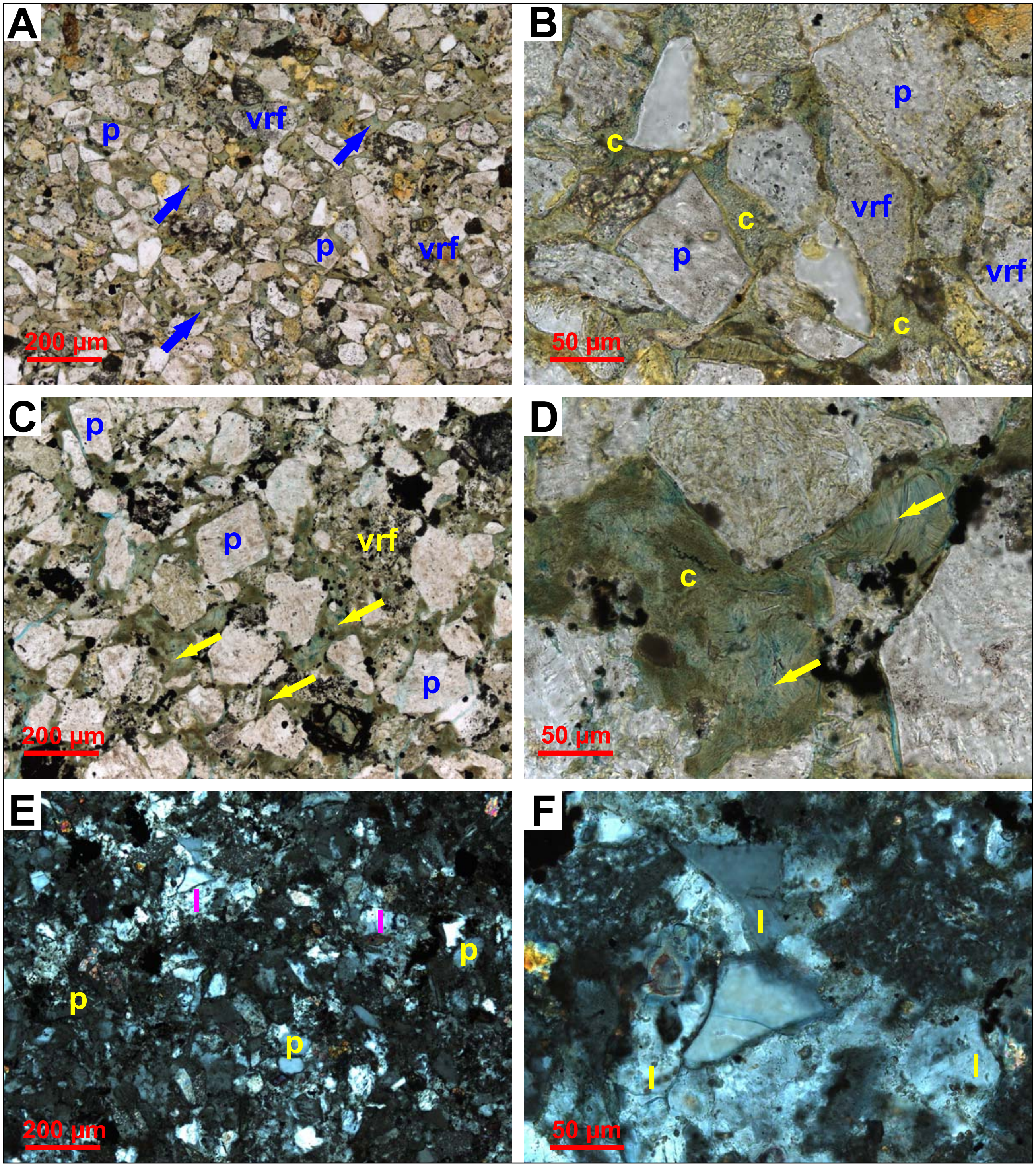

Figure 7-3. Photomicrographs of Gaikema sandstones from the measured section. **A.** Very-fine-grained (upper), well-sorted sandstone consisting largely of plagioclase (p) and volcanic rock fragments (vrf). Primary intergranular porosity is almost completely occluded by authigenic clay (arrows). Sample 13A17-6.0A; plane-polarized light. **B.** Plagioclase (p) and VRFs (vrf) comprise the majority of the rock framework. Intergranular pores are totally occluded by authigenic clay cement (c). Sample 13A17-6.0A; plane-polarized light. **C.** Fine-grained (lower), moderately-sorted sandstone consisting largely of euhedral to subhedral plagioclase crystals (p) and VRFs (vrf), with virtually no detrital quartz. Primary intergranular porosity is almost completely occluded by authigenic clay (arrows). Sample 13A17-12.7A; plane-polarized light. **D.** Authigenic chlorite (c) with well-developed medial sutures (arrows) filling large intergranular pore. Sample 13A17-12.7A; plane-polarized light. **E.** Very-fine-grained (upper), well-sorted sandstone consisting largely of plagioclase (p). Laumontite cement (l) has patchy distribution throughout the rock. Sample 13A17-8.3A; crossed polarizers. **F.** Laumontite cement (l) replacing detrital plagioclase and filling intergranular pores. Sample 13A17-8.3A; crossed polarizers.

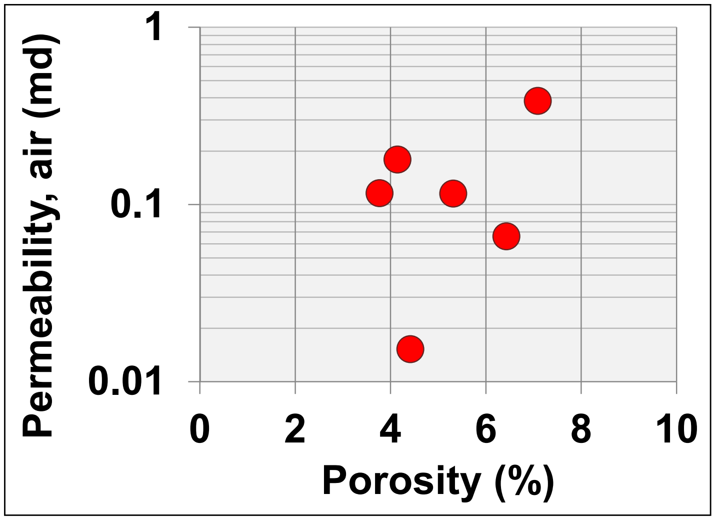

Figure 7-4. Porosity–permeability cross plot shows the relatively poor reservoir quality (φ <8 percent, k <1 md) of Gaikema sandstones from the measured section.

also suggest the alluring possibility of continuous oil accumulations in the Tuxedni Group, perhaps analogous to those in the Late Devonian and Early Mississippian Bakken Formation of North Dakota (Nordeng, 2009). Additional analyses from a larger geographic area are needed before making sweeping conclusions regarding the regional reservoir potential of the Gaikema Sandstone.

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CHAPTER 8

PRELIMINARY FACIES ANALYSIS OF THE LOWER SANDSTONE MEMBER OF THE UPPER JURASSIC NAKNEK FORMATION, NORTHERN CHINITNA BAY, ALASKA

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INTRODUCTION

Nearly all oil and gas in the Cook Inlet region of southern Alaska is produced from Cenozoic reservoirs (Magoon, 1994). However, a number of plays involving Mesozoic strata are still underexplored and the potential for discovery of new hydrocarbon accumulations remains significant (Stanley and others, 2011). New geologic information is necessary to constrain the nature of the Mesozoic petroleum system. Relatively few wells penetrate below the Cenozoic section; however, excellent exposures of Mesozoic strata are present along the western margin of Cook Inlet and have been the focus of recent stratigraphic and structural studies led by the Alaska Division of Geological & Geophysical Surveys (DGGS; LePain and others, 2013; Gillis, 2013, 2014). New stratigraphic studies of potential Upper Jurassic reservoirs were conducted during the summer of 2014. This brief report summarizes our preliminary observations from one of these units, the lower sandstone member of the Naknek Formation, which is well exposed along the north side of Chinitna Bay (fig. 8-1). This information will lead to an improved depositional model for this formation, and ultimately assist in the assessment of the region's petroleum potential. These data also provide a robust framework for planned geologic mapping in upcoming years, including criteria for map unit identification (Gillis and others, 2014).

LOWER SANDSTONE MEMBER OF THE NAKNEK FORMATION

The presently accepted stratigraphic subdivision of the Upper Jurassic Naknek Formation in the study area was established by Detterman and Hartsock (1966). The Chisik Conglomerate Member marks the base of the formation regionally, but is absent in the Chinitna Bay area (fig. 8-1); instead the basal position is occupied by the laterally equivalent lower sandstone member. The lower sandstone member remains an informal designation; our recent stratigraphic studies (Wartes and others, 2013) and geologic mapping (Herriott and Wartes, 2014) suggest that the unit is widespread in the region and likely warrants formal member status. Robust collections of ammonite and bivalve fossils from the lower sandstone indicate the unit is entirely Oxfordian in age (Detterman and Hartsock, 1966; Imlay, 1981) and likely equivalent in part to the Northeast Creek Sandstone Member of the lower Naknek Formation exposed farther south, along the Alaska Peninsula (Detterman and others, 1996).

CHINITNA BAY SECTION

The lower sandstone member was examined along the north shore of Chinitna Bay, where it forms light gray weathering coastal cliffs (fig. 8-2). The southern part of the exposure lies in the footwall of the Bruin Bay fault, where the unit is subhorizontally dipping and exposed high on the cliff face. Dips increase eastward, rolling over to ~30 degree east dips, bringing the unit down to more accessible exposures at beach level (figs. 8-1, 8-2, 8-3). A detailed measured section indicates the lower sandstone member is approximately 317 m thick at this location.

The base of the lower sandstone member was chosen at a notable change in weathering style, marked principally by an increase in grain size from the underlying Paveloff Siltstone Member of the Chinitna Formation. Similarly, the top of the lower sandstone was picked at a mappable change in outcrop resistance from the cliff-forming sandstone bodies upward into the more recessive, finer-grained facies of the overlying Snug Harbor Siltstone Member of the Naknek Formation. The criteria for formation designation used in this measured section followed the lithostratigraphic characteristics outlined by Herriott and Wartes (2014) for the Iniskin Peninsula region immediately south of Chinitna Bay.

The grain size of the lower sandstone member is dominantly upper very fine to lower fine. Two principal lithofacies are observed: (1) light gray to white weathering arkose, and (2) olive-gray to gray-brown weathering argillaceous sandstone (fig. 8-3). These two facies are interbedded at a variety of scales, often giving the outcrop a banded appearance (fig. 8-4A); where they are finely interbedded, they occasionally preserve partial Bouma sequences dominated by plane-parallel lamination grading up into rippled facies with silty caps.

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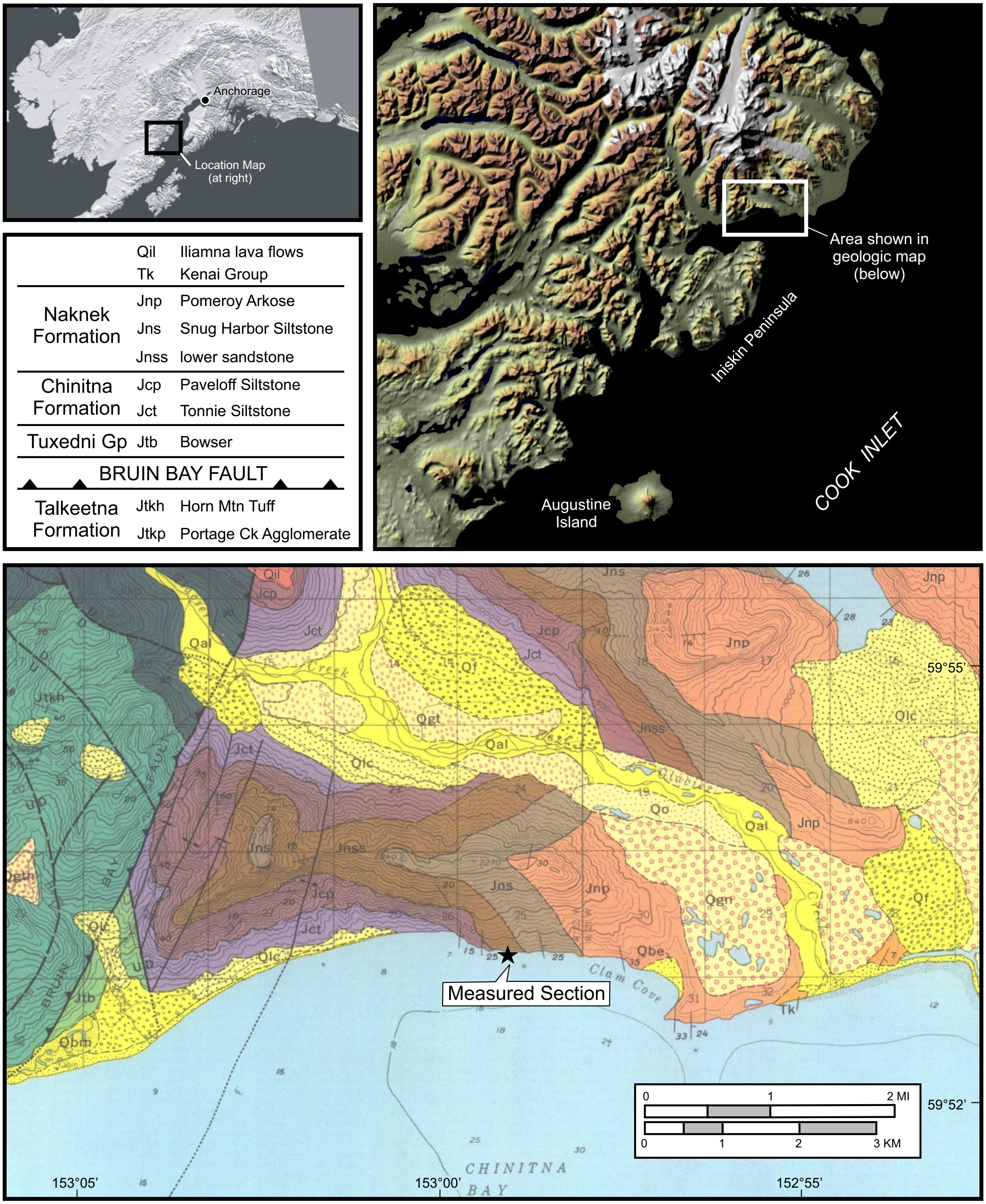

Figure 8-1. Geologic map of the area north of Chinitna Bay (Detterman and Hartsock, 1966), showing the location of detailed measured section.

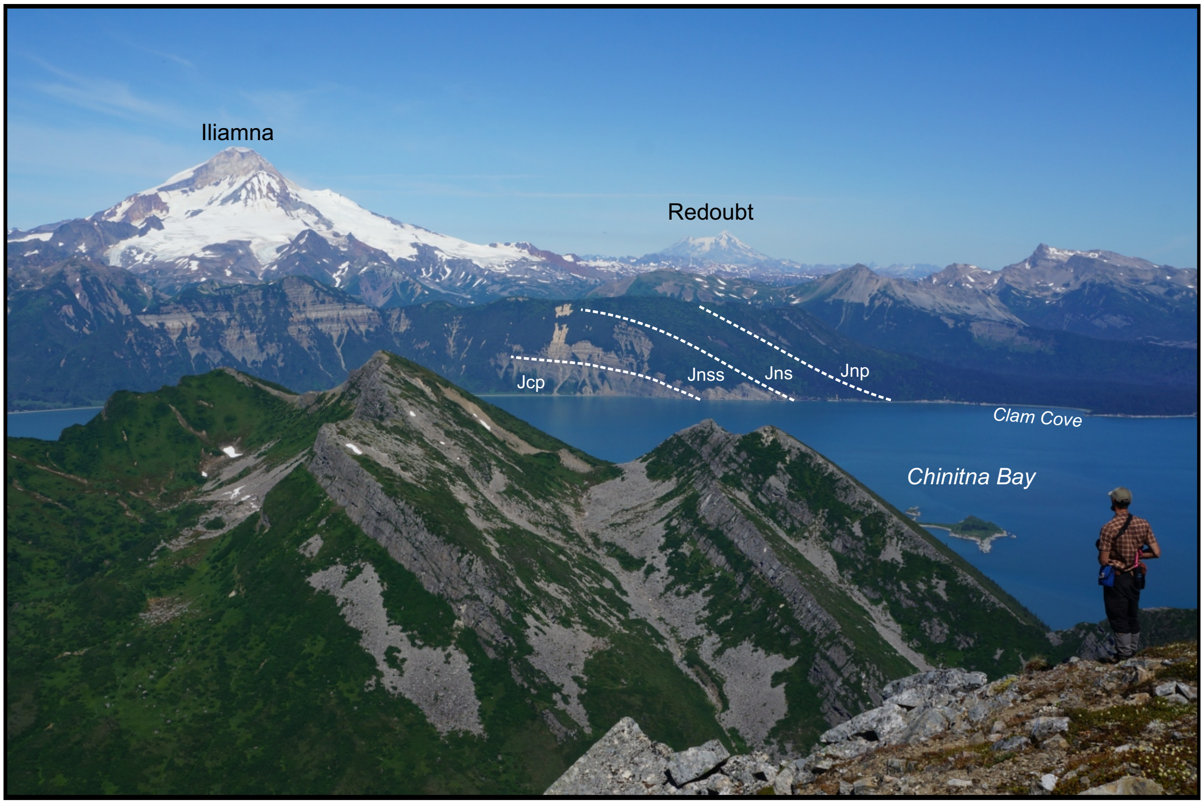

Figure 8-2. View to the north, looking across Chinitna Bay. Jcp = Paveloff Siltstone of the Chinitna Formation; Jnss = lower sandstone member of the Naknek Formation; Jns = Snug Harbor Siltstone of the Naknek Formation; Jnp = Pomeroy Arkose of the Naknek Formation.

Figure 8-3. Representative view of exposure quality along the north shore of Chinitna Bay. The banded appearance of parts of the outcrop is a common feature of the lower sandstone member in this region.

The lighter colored arkose is typically more resistant, with tabular bedding ranging from thin and flaggy to massive. The arkose often preserves sedimentary structures, including trough and low-angle cross-stratification, and locally hummocky and swaley bedforms (fig. 8-4B). Trains of mudstone intraformational rip-up clasts are common, particularly above through-going scour surfaces. Evidence for soft-sediment deformation ranges from diffuse zones of dewatering (fig. 8-4C) to meter-scale disrupted beds with ball and pillow structures.

The argillaceous sandstone is often structureless, although remnant textures (fig. 8-4D) indicate the unit has been disrupted by burrowing organisms. A variety of bioturbation was observed, ranging from cryptic and wispy fabrics to zones with well-expressed, complexly churned facies (fig. 8-4E). Discrete trace fossils recognized include *helminthopsis*(?), *phycosiphon, thalassinoides, paleophycus, diplocraterion, fugichnia*(?), *teichichnus*, and *rhizocorralium*.

Figure 8-4. Representative photographs of the lower sandstone member along the north side of Chinitna Bay. **A.** View of rhythmically interbedded argillaceous sandstone and arkose; B. Hummocky cross-stratification; **C.** Convolute bedding; **D.** Example of locally intense bioturbation, with only wispy remnants of less disturbed zones; **E.** Bioturbation fabric; **F.** Coarse-grained sandstone with mud rip-up clasts and internal truncation surface.

A less common lithofacies is medium gray to reddish brown, medium- to very-coarse-grained sandstone (fig. 8-4F). This facies typically exhibits a sharp, erosive base with up to 2 m of relief. Internally, these coarser zones are moderately to poorly sorted and locally include thin gravel stringers, carbonaceous and woody debris, and belemnite and bivalve fossils (figs. 8-4F and 8-5).

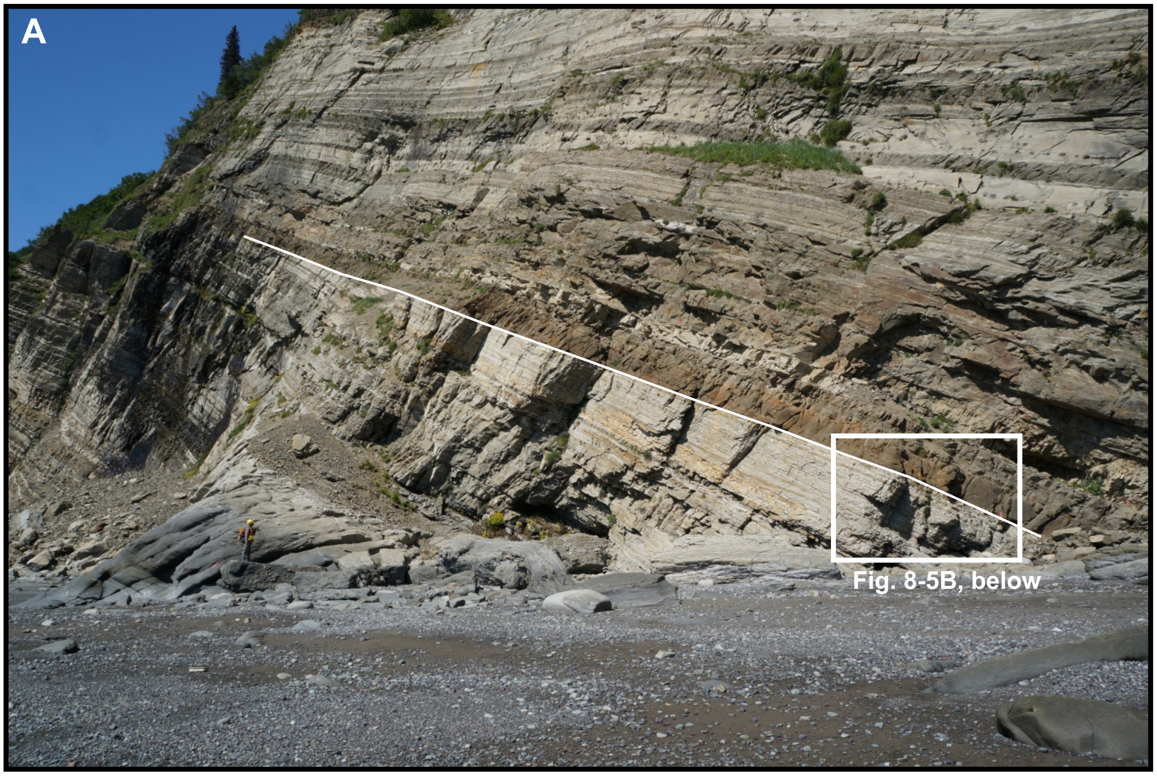

Figure 8-5. Photographs of angular unconformity in the lower sandstone member along northern Chinitna Bay. **A.** Annotated view of angular unconformity, illustrating the westward (toward the upper left) increase in the amount of section removed beneath the surface. **B.** Close-up view of the unconformity, including the conglomeratic base of the reddish-brown weathering bed.

The unit displays occasional upward-coarsening trends, but the vertical stacking of facies is otherwise not organized into a clear repeating pattern or motif. Most bed sets appear generally tabular at the scale of the exposure. However, in at least two positions in the measured sections there are subtle truncations running more than 100 m across the outcrop (fig. 8-5). These local(?) angular unconformities both cut downsection toward the west.

PRELIMINARY INTERPRETATION

Many of the facies observed in the lower sandstone member along northern Chinitna Bay are very similar to those reported from elsewhere on the Iniskin Peninsula to the south (Wartes and others, 2013; Herriott and Wartes, 2014). The evidence for well-developed and locally diverse burrowing infauna is consistent with a shelfal setting. The occasional preservation of hummocky cross-stratification provides further evidence that deposition was influenced by waves, likely in a lower shoreface setting (Dott and Bourgeois, 1982). The relative role of a deltaic influence is unclear, although the weakly-expressed upward-coarsening motif is consistent with progradational character of delta-front settings. In addition, the coarser-grained facies may represent distributary channels and mouth bars. Further assessment of the detailed measured section will seek to refine this interpretation.

Our measured thickness of 317 m is considerably thicker than estimates for the lower sandstone member on the south side of Chinitna Bay (Detterman and Hartsock [1966] reported a thickness of 256 m, while Herriott and Wartes [2014] calculated 253 m). This difference may reflect differing mapping criteria, leading to variable placement of formation contacts. However, our mapping in the Hickerson Lake area (Herriott and others, 2015), only a few miles north of Chinitna Bay, indicated a thickness of 322 m for the lower sandstone member in that area. Thus, we tentatively suggest that the unit thickens markedly northward, perhaps indicating variations in accommodation along the margin.

The angular unconformities in the lower sandstone member suggest possible uplift of more proximal parts of the depositional system. The cause of these intraformational surfaces is unclear, but may be related to syndepositional activity on the nearby Bruin Bay fault (Wartes and others, 2013; Trop and others, 2005). Alternatively, the Late Jurassic growth of the batholith may have promoted magmatic inflation(?) and subtle tilting of the forearc basin.

ACKNOWLEDGMENTS

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CHAPTER 9

EVIDENCE OF A SUBMARINE CANYON IN THE SNUG HARBOR SILTSTONE AND POMEROY ARKOSE MEMBERS, NAKNEK FORMATION, SOUTH-CENTRAL ALASKA—IMPLICATIONS FOR THE DISTRIBUTION OF COARSE-GRAINED SEDIMENT IN UPPER JURASSIC STRATA OF COOK INLET

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

INTRODUCTION

The Alaska Division of Geological & Geophysical Surveys (DGGS) is continuing research it began in 2009 to study the stratigraphy and sedimentology of lower Cook Inlet's Upper Jurassic Naknek Formation (Wartes and others, 2011, 2013, 2015; Herriott and others, 2013; Stanley and others, 2013; Herriott and Wartes, 2014). This work has been complemented by recent geologic mapping of the Naknek Formation on the Iniskin Peninsula (fig. 9-1), which yielded numerous insights into lithostratigraphic relations among the mappable members of the unit (Herriott and Wartes, 2014; Gillis and others, 2014). During July 2014 we continued field investigations of the Naknek Formation northeastward along the northwest margin of the Cook Inlet forearc basin to the area north of Chinitna Bay (Wartes, ed., 2015). In this brief paper, we present preliminary geologic mapping of the Hickerson Lake area (fig. 9-1) and highlight field observations that indicate establishment and filling of a submarine canyon in the Snug Harbor Siltstone and Pomeroy Arkose Members of the Naknek Formation.

Hickerson Lake lies in a landslide-dammed glacial valley (Detterman and Hartsock, 1966) ~5 km north of Chinitna Bay, with nearby topographic relief locally exceeding 1,000 m. Naknek Formation strata in the area dip gently southeastward and are discontinuously exposed along the lake's northeast and southwest shores as well as in the ridges and peaks surrounding the lake. During this study we mapped the geology near the lake (fig. 9-2), employing the lithostratigraphic mapping criteria of Herriott and Wartes (2014).

LITHOFACIES AND GEOLOGIC MAP RELATIONS

A traverse along the southwest shore of Hickerson Lake revealed a >5-m-thick, boulder-bearing, cobble conglomerate (figs. 9-3A and 9-4) with outsized clasts to ~80 cm. This conglomerate comprises a channel-form sediment body with a sharp, erosional base (fig. 9-3B) that immediately overlies 98 m of thin- to medium-bedded, sandy siltstone and subordinate sandstone of the Snug Harbor; the conglomerate is overlain by thin- to very-thick-bedded sandstone and siltstone. Approximately 200 m above the cobble conglomerate lies a cliff-forming, tens-of-meters-thick, amalgamated, arkosic sandstone succession with prominent, sharp-based, channel-form stratal geometries (fig. 9-4).

Following Detterman and Hartsock (1966) and Herriott and Wartes (2014), we mapped the Snug Harbor–Pomeroy contact at the base of the thick, amalgamated arkose beds described above, thus including the conglomerate and overlying thin- to very-thick-bedded sandstone and siltstone with the Snug Harbor (see fig. 9-4). Extending this contact westward from the lake's shore suggests that this readily mappable lithostratigraphic surface is in a stratigraphically higher position near peak 3140, where an appreciably thicker (~500 m) Snug Harbor section occurs than is observed along the southwest shore of Hickerson Lake, where the unit is ~300 m thick (fig. 9-4C). The difference between these Snug Harbor thicknesses indicates ~200 m of stratigraphic relief along the top of the unit. This relief is in turn occupied by the arkosic, channel-form strata of the lower Pomeroy that onlap the underlying Snug Harbor (fig. 9-4). Aerial reconnaissance suggests the thick Snug Harbor section below peak 3140 is dominantly tabular bodied and finer grained than strata exposed above the conglomerate at the lake shore.

INTERPRETATIONS AND DISCUSSION

Recent sedimentologic and stratigraphic studies suggest that the Snug Harbor–Pomeroy transition records a shift from slope to toe-of-slope or basin-floor sedimentation (Wartes and others, 2013; Herriott and Wartes, 2014). Within this framework, the channel-form stratal geometries, lithofacies, along-strike changes in unit thicknesses, and overall stratigraphic architecture reported above and evident in figure 9-4 strongly suggest a broad (kilometer-scale) "container" with marked negative relief (hectometer scale) that we interpret as a submarine canyon. The boulder-bearing conglomerate locally defines the lowermost

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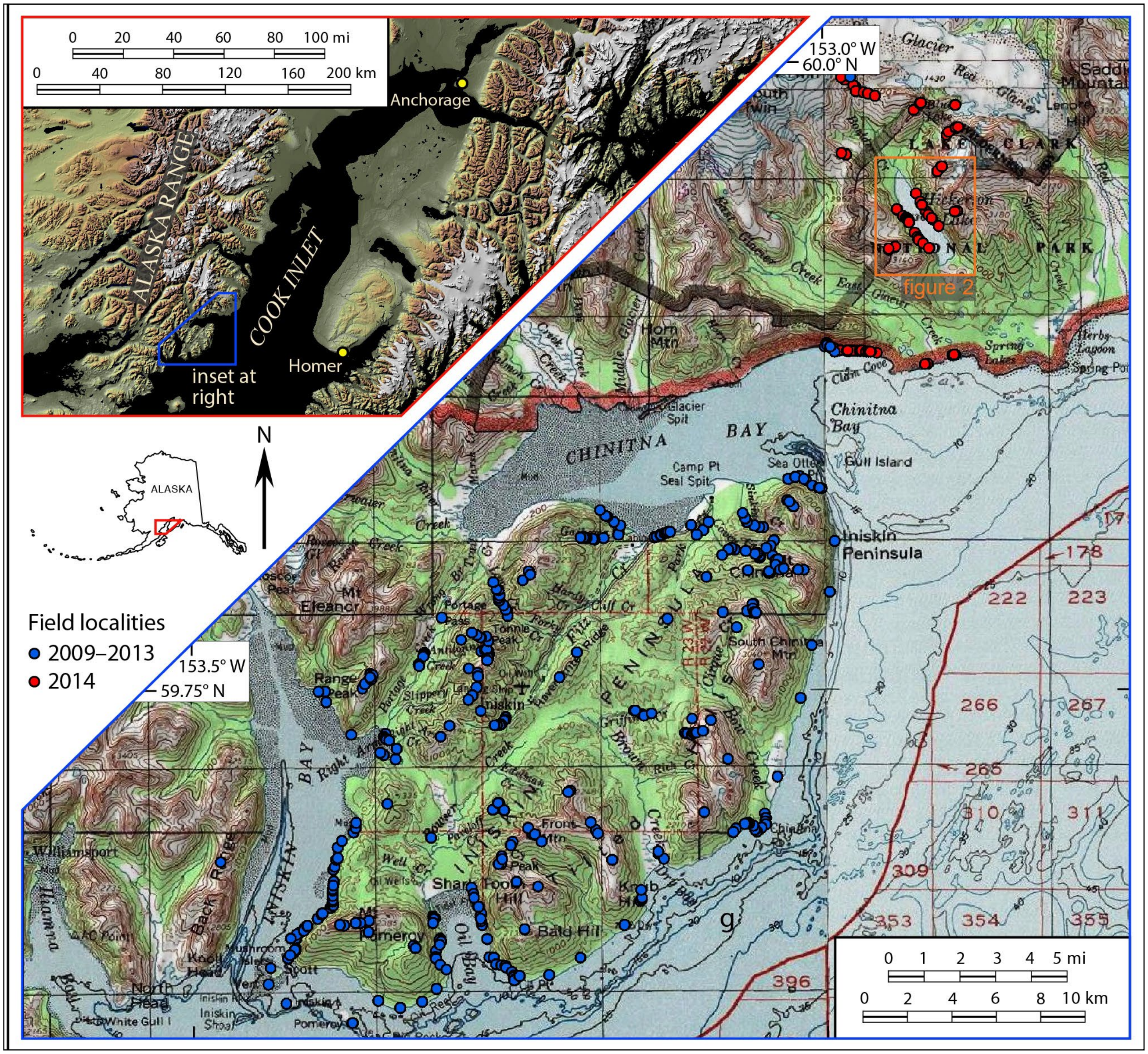


Figure 9-1. Index map of the study area. Detailed observations were made by the authors at more than 400 localities during five field seasons. During 2014, our focus shifted northeastward from the Iniskin Peninsula to the area north of Chinitna Bay. Topographic base map from portions of U.S. Geological 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

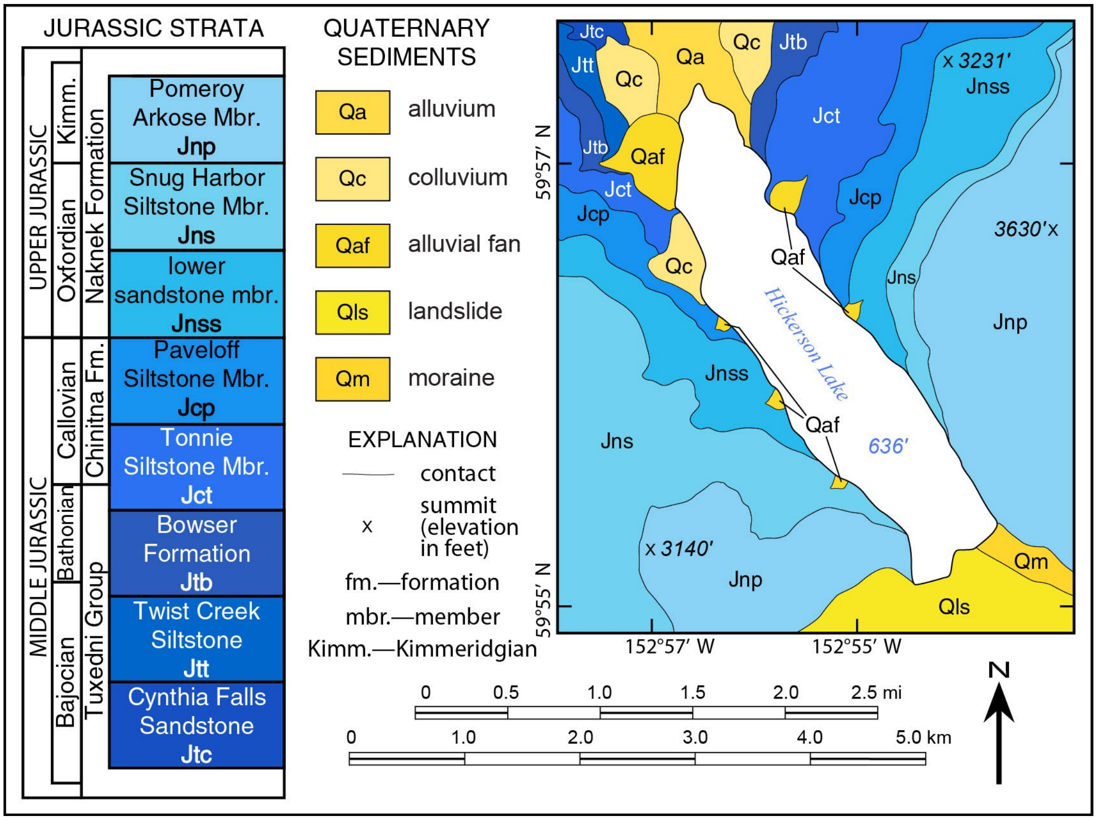
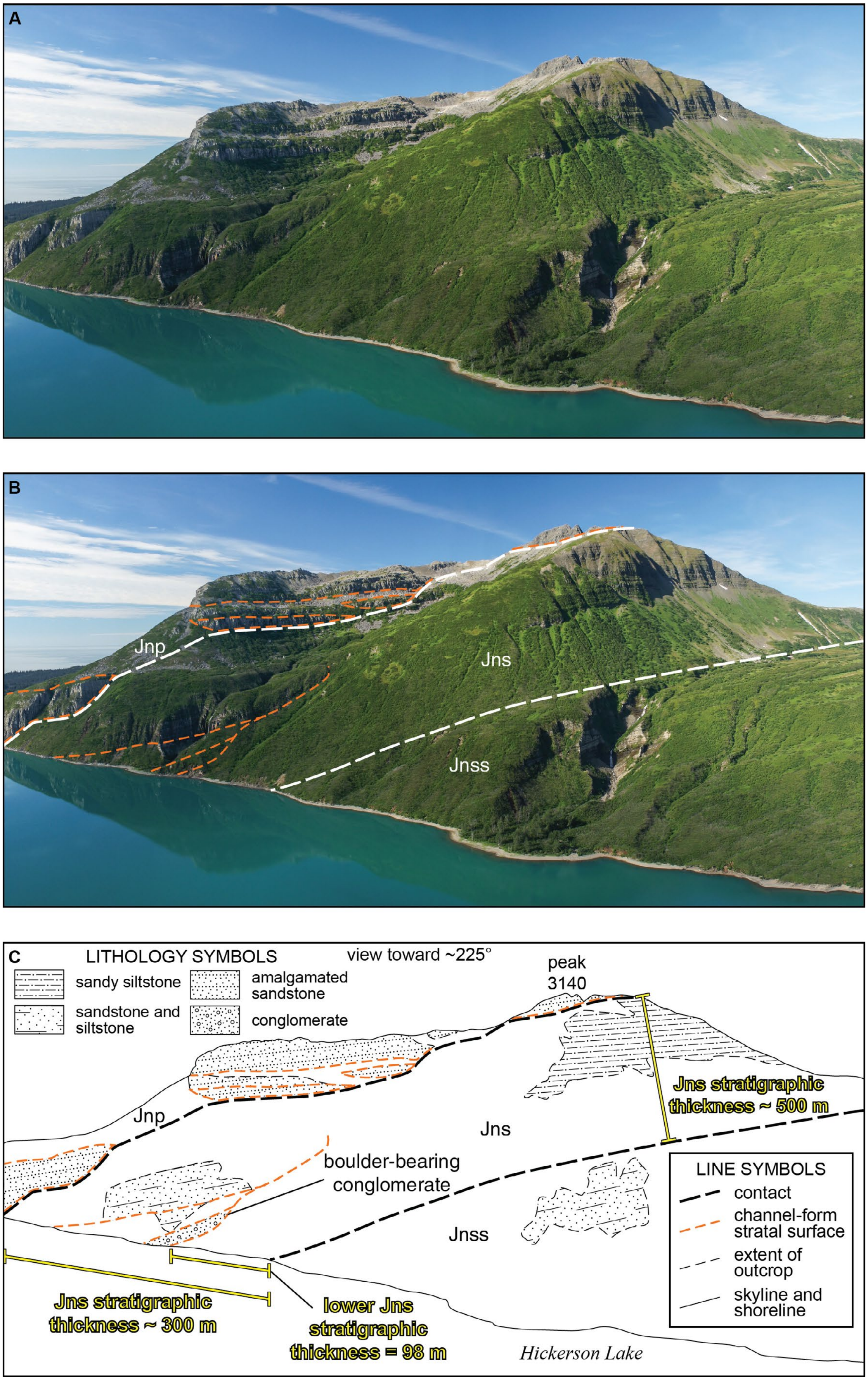


Figure 9-2. Simplified geologic map of the Hickerson Lake area. This preliminary sketch map is based on 1:63,360-scale mapping completed during July 2014 and is part of a larger project focused on mapping the northwest margin of the Cook Inlet forearc basin between Chinitna Bay and Red Glacier (Wartes, ed., this volume). Schematic stratigraphic column (modified after Detterman and Hartsock [1966] and Herriott and Wartes [2014]) is not scaled to time or thickness, nor does it reflect known depositional hiatuses. See figure 9-1 for location index map.

Figure 9-3. Outcrop photographs of the boulder-bearing cobble conglomerate in the Snug Harbor Siltstone Member, southwest shore of Hickerson Lake. **A.** The cobble conglomerate is clast supported and lacks evidence of internal stratification. Rounded cobbles are common and subangular, intra-basinal, siltstone rip-up clasts are also observed. Geologist for scale. Photograph by M.A. Wartes. **B.** Sharp, erosional base (dashed orange line) of channel-form cobble conglomerate bed. Notebook (12 x 19 cm) for scale. Photograph by P.L. Decker.


A
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view toward ~225°
sandy siltstone
amalgamated sandstone
sandstone and siltstone
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peak 3140
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Jnp
Jns
boulder-bearing conglomerate
LINE SYMBOLS
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channel-form stratal surface
extent of outcrop
skyline and shoreline
Jnss
Jns stratigraphic thickness ~ 300 m
lower Jns stratigraphic thickness = 98 m
Hickerson Lake

part of the canyon fill succession, with the overlying, upper part of the Snug Harbor at Hickerson Lake comprising a continued early filling history. This proposed canyon is hosted at least in part by the dominantly tabular-bodied Snug Harbor strata below peak 3140. The amalgamated, channel-form arkosic beds of the lower Pomeroy mark a later, continued filling phase of the canyon. The intra-canyon contact between these Naknek Formation members may record back-stepping and onlapping of the Pomeroy depositional system onto the Snug Harbor slope as toe-of-slope accommodation filled with arkosic sand.

Channelized depositional systems on slopes are recognized as pathways for turbidity currents and associated processes to transport coarse-grained sediment (sand and gravel) into deep-marine settings (for example, Hubbard and others, 2014), commonly yielding deposits with high net (sand+gravel) to gross (mud+sand+gravel) ratios (for example, Mayall and others, 2006). In fact, the submarine canyon reported here is consistent with this part of the Naknek depositional system, as sediment supplied to the immensely thick, sand-rich, deep-water Pomeroy must have bypassed the Snug Harbor slope environment, and it has been suggested that most coarse-grained sediment that reaches basin floors is transported through submarine canyons (Miall, 1990). Notably, deep-water canyon fill and basin-floor deposits (commonly comprising fans) constitute significant hydrocarbon reservoirs throughout the world (for example, Richards and others, 1998; Weimer and Slatt, 2006; Macauley and Hubbard, 2013), rendering our observations and interpretations presented here as the basis for a new predictive model for the distribution of potential reservoir facies in the Naknek Formation that includes locally coarse-grained, channelized facies belts hosted in submarine canyons.

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Figure 9-4 (left). Oblique aerial view southwestward of peak 3140, with Hickerson Lake in the foreground. **A.** Noninterpreted photograph. **B.** Photogeologic interpretation of photograph. **C.** Line drawing interpretation. View toward center of photograph is approximately strike parallel. Approximately 760 m (~2,500 ft) of topographic relief is present between Hickerson Lake and peak 3140, for sense of scale.

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