Division of Geological & Geophysical Surveys

PRELIMINARY INTERPRETIVE REPORT 2013-1

OVERVIEW OF 2012 FIELD STUDIES: UPPER ALASKA PENINSULA AND WEST SIDE OF LOWER COOK INLET, ALASKA

by
Robert J. Gillis, editor

View southwestward from the eastern flank of Iliamna Volcano, with the headwall of Red Glacier visible along skyline of photo. The resistant rock rib at photo-right is a >5-m-thick sill that intrudes the Red Glacier Formation of the Middle Jurassic Tuxedni Group, which regionally includes organic-rich strata that are widely recognized to be the source rocks of Cook Inlet's oil. However, Red Glacier strata in the vicinity of Red Glacier have yielded high vitrinite reflectance values that indicate significant heating and levels of thermal maturity beyond the oil window. Part of our ongoing work is to assess what factors may have led to this high thermal maturity, and whether the effect is local (for example, associated with magmatic heating by nearby Iliamna Volcano) or reflects regional trends. See Stanley and others (this volume, p. 5) for more information about this project. Photograph by Trystan Herriott.

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OVERVIEW OF 2012 FIELD STUDIES: UPPER ALASKA PENINSULA AND WEST SIDE OF LOWER COOK INLET, ALASKA

by
Robert J. Gillis[1], Editor

Cook Inlet field studies carried out in summer 2012 by the Alaska Division of Geological & Geophysical Surveys (DGGS) and Alaska Division of Oil and Gas (DOG) in collaboration with the U.S. Geological Survey (USGS) focused on Mesozoic forearc basin stratigraphy at selected locations on the western margin of the inlet and the upper Alaska Peninsula (fig. 1). This work builds on similar studies performed by DGGS, DOG, and the USGS in the summers of 2009 and 2010 that were designed to collect baseline geologic data about the greater Cook Inlet Mesozoic petroleum system and develop a better understating of the depositional and structural history of the Mesozoic forearc basin. To date, more than 20 stratigraphic sections have been measured from the Tuxedni Group, and the Chinitna, Naknek, and Kaguyak Formations, as well as unnamed Upper Cretaceous rocks near Saddle Mountain by DGGS (LePain and others, 2011) (fig. 2). Additionally, more than 500 samples have been collected or analyzed for porosity and permeability, sandstone petrography, hydrocarbon seal capacity, organic geochemistry, geochronology, and thermochronology, among others, most of which are tied to measured sections. Results of these studies and analyses will be made available to the public in a series of reports published through DGGS in the coming months. Plans are underway for additional field studies in this area in 2013 and beyond, including new geologic mapping of the Iniskin Peninsula area.

The chapters in this report briefly summarize highlights of our 2012 Cook Inlet field campaign, offering only preliminary impressions of field observations, and serving as precursors to a series of raw data files and detailed interpretive reports about the geologic evolution of Cook Inlet basin and components of its petroleum system. Progress reports such as these will continue to be published to provide timely updates of critical new findings and as supplements to future technical reports.

Topics discussed below first address exposures of petroleum source rocks to Cook Inlet basin, followed by conventional reservoir quality, fracture analyses of Jurassic and Cretaceous strata, occurrences of hydrocarbon saturation of Mesozoic sandstones, and conclude with the tectonic controls for the Mesozoic forearc basin based on preliminary structural and stratigraphic studies:

- Reconnaissance studies of potential petroleum source rocks in the Red Glacier Formation of the Tuxedni Group (Stanley and others)
- Field observations of reservoir quality for the Naknek and Kaguyak Formations (Helmold)
- Fracture studies in Naknek and Kaguyak Formation strata (Gillis and others)
- Observations from a hydrocarbon-bearing sandstone in the Naknek Formation (Stanley and others)
- Preliminary observations about the stratigraphy and occurrence of hydrocarbon in Kaguyak Formation rocks (Wartes and others)
- Observations and preliminary interpretations of the Bruin Bay fault system (Gillis and others)
- Tectonic controls on Naknek Formation deposition (Wartes and others)

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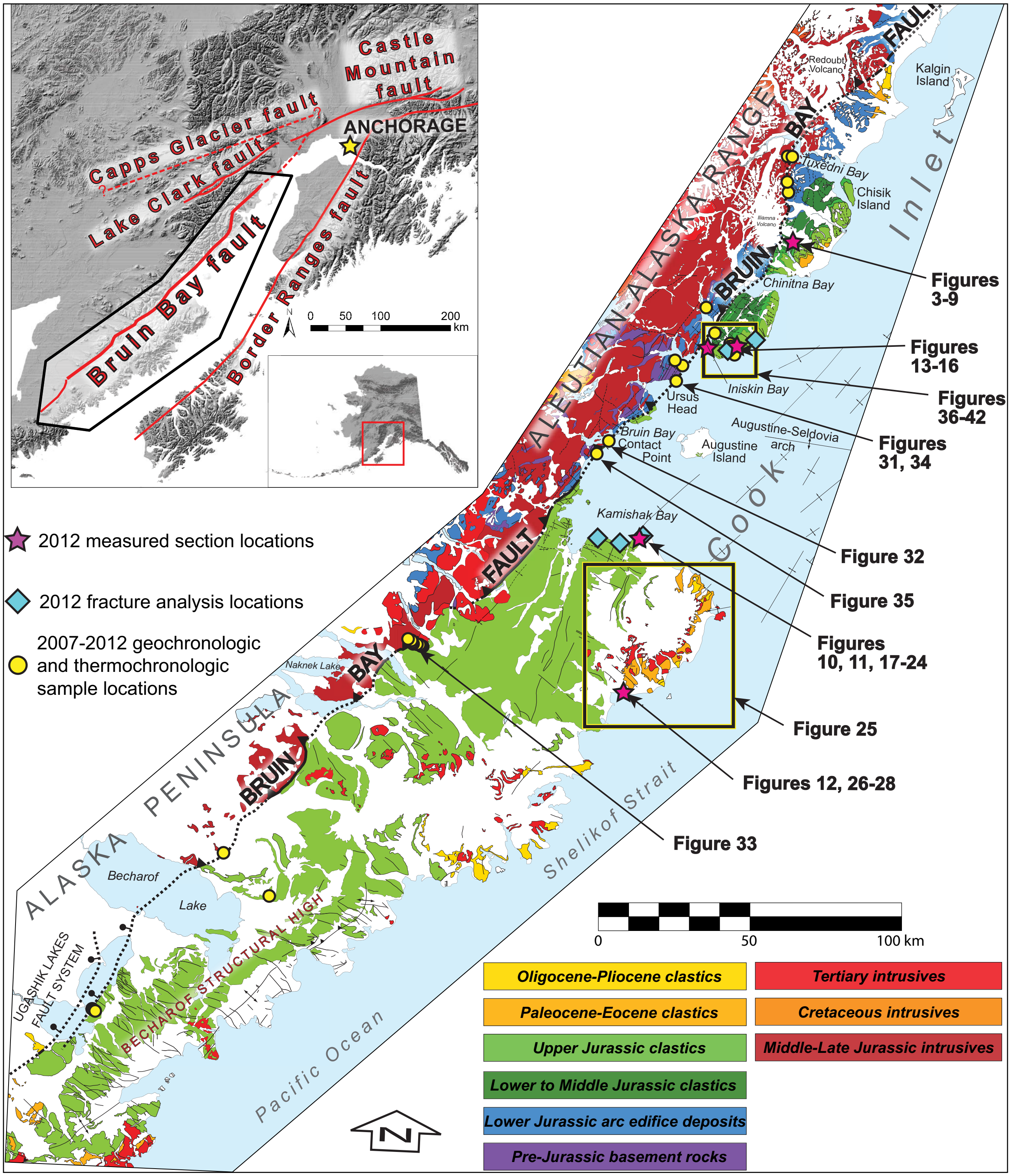

Figure 1. Simplified geologic map of the magmatic arc/forearc margin along the upper Alaska Peninsula and western margin of lower Cook Inlet (adapted from Wilson and others, 1999 and 2009) showing selected field locations discussed in the text that were visited by DGGS from 2007 to 2012.

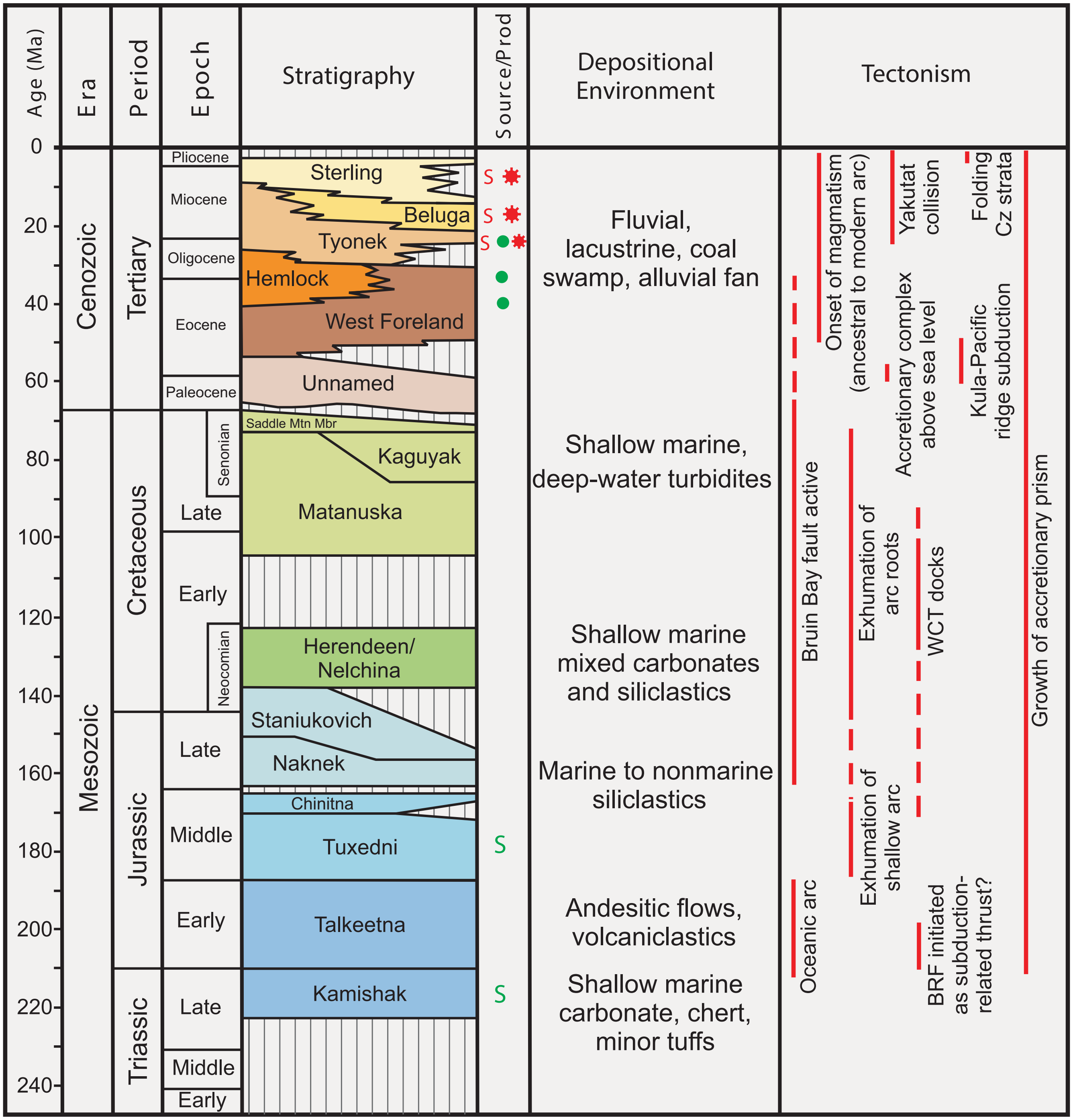

Figure 2. Generalized stratigraphic column of the Cook Inlet region. Redrawn from Swenson (2003); additional information added from Little and Naeser (1989), Nokleberg and others (1994), and Plafker and others (1994).

SIGNIFICANT FINDINGS

- Organic geochemistry results from 19 samples collected from petroleum source rocks to Cook Inlet basin, the Red Glacier Formation of the Tuxedni Group, are overmature near their type locality on the flank of Iliamna Volcano. The high thermal maturity of the rock samples is possibly due to igneous heating related to the ancient or modern volcanic arc, deep burial beneath a thick interval of Mesozoic and Cenozoic strata prior to subsequent exhumation to the surface, or both.
- Naknek Formation samples from the Iniskin Peninsula–Tuxedni Bay region have highly feldspathic compositions and generally poor reservoir quality. However, in at least one location on the south shore of Kamishak Bay on the Upper Alaska Peninsula, hand lens observation of an oil-stained sandstone interval indicates that it has a substantially more quartzose composition. These observations suggest that sandstone composition can vary significantly in the Naknek Formation, and intervals that are more quartzose have the potential to serve as conventional petroleum reservoirs.
- Kilometer- to centimeter-scale systematic fractures found throughout the Mesozoic stratigraphy may represent significant fracture porosity and serve as migration pathways for liquid hydrocarbons into more porous Mesozoic and Cenozoic stratigraphic intervals.
- Two widely separated sandstone intervals in the Naknek and Kaguyak Formations on the upper Alaska Peninsula host oil-bearing strata that indicate past maturation and migration of liquid hydrocarbons in the region. The presence of several other locations in lower Cook Inlet where Upper Cretaceous strata are reported to be oil-bearing suggest that they overlie regionally extensive, thermally mature source rocks and might have potential as conventional reservoirs.
- The leading strand of the Bruin Bay fault is well exposed in coastal bluffs at Ursus Head and near Contact Point on the west side of lower Cook Inlet. Geometries associated with the moderately southwest-dipping fault plane are mostly contractile. However, steeply-dipping structures in the hanging wall arc-ward from the leading strand at these and several other locations exhibit mostly oblique-slip kinematics with mixed senses of motion and may cut lower angle contractile structures, suggesting that the fault system might record a more complicated slip history than previously understood.
- Detailed stratigraphic studies of the Naknek Formation in the Iniskin Peninsula area indicate rapid sedimentary facies changes in its oldest (Chisik Member) and youngest (Pomeroy Member) units that transition from boulder to pebble conglomerates proximal to the Bruin Bay fault to fine-grained sandstone and siltstones within a few kilometers distal to fault. This relationship suggests that the Bruin Bay fault was actively influencing sediment supply and accommodation proximal to the basin margin until latest Jurassic time. Sedimentary facies associations indicate an abrupt deepening of the basin prior to deposition of the Pomeroy Member, marking a major transgressive phase during Late Jurassic time.

RECONNAISSANCE STUDIES OF POTENTIAL PETROLEUM SOURCE ROCKS IN THE MIDDLE JURASSIC TUXEDNI GROUP NEAR RED GLACIER, EASTERN SLOPE OF ILIAMNA VOLCANO

by
Richard G. Stanley[1], Trystan M. Herriott[2], David L. LePain[2], Kenneth P. Helmold[3], and C. Shaun Peterson[3]

Previous geological and organic geochemical studies have concluded that organic-rich marine shale in the Middle Jurassic Tuxedni Group is the principal source rock of oil and associated gas in Cook Inlet (Magoon and Anders, 1992; Magoon, 1994; Lillis and Stanley, 2011; LePain and others, 2012; LePain and others, submitted). During May 2009 helicopter-assisted field studies, 19 samples of dark-colored, fine-grained rocks were collected from exposures of the Red Glacier Formation of the Tuxedni Group near Red Glacier, about 70 km west of Ninilchik on the eastern flank of Iliamna Volcano (figs. 1 and 3). The rock samples were submitted to a commercial laboratory for analysis by Rock-Eval pyrolysis and to the U.S. Geological Survey organic geochemical laboratory in Denver, Colorado, for analysis of vitrinite reflectance. The results show that values of vitrinite reflectance (percent R_o) in our samples average about 2 percent, much higher than the oil window range of 0.6–1.3 percent (Johnsson and others, 1993). The high vitrinite reflectance values indicate that the rock samples experienced significant heating and furthermore suggest that these rocks may have generated oil and gas in the past but no longer have any hydrocarbon source potential. The high thermal maturity of the rock samples may have resulted from (1) the thermal

Figure 3. Outcrop of well stratified, dark-colored silty mudstone in the Middle Jurassic Red Glacier Formation of the Tuxedni Group. This outcrop is on the north side of Red Glacier, about 70 km west of Ninilchik on the west side of Cook Inlet. David LePain (DGGS) for scale. Photo by Rick Stanley (USGS), 2009.

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effects of igneous activity (including intrusion by igneous rocks), (2) deep burial beneath Jurassic, Cretaceous, and Tertiary strata that were subsequently removed by uplift and erosion, or (3) the combined effects of igneous activity and burial.

During helicopter-assisted field studies in July 2012, we briefly revisited outcrops of the Red Glacier Formation in the Red Glacier area and found numerous beds of sandstone (fig. 4) as well as several igneous dikes and sills (figs. 5–8) that were hidden by snow during our visit in 2009. In the initial aerial reconnaissance of our 2012 visit, it proved somewhat difficult to differentiate between the sandstone beds and sills because both lithologies are commonly very thick, with resistant weathering profiles and bedding perpendicular joint sets (fig. 8). In laterally persistent exposures, however, field relations serve to aid in clarifying which resistant beds are sills (fig. 8) versus sandstones (fig. 9). We found no evidence of extrusive volcanism (such as lava flows) in the Red Glacier Formation during this work and we directly observed hornfels facies in fine-grained strata immediately overlying the sill at locality 12TMH113 (see fig. 8), demonstrating that the sill is an intrusive rather than an extrusive igneous rock. The appreciable cumulative thickness of Red Glacier Formation-hosted sills north of Red Glacier (fig. 8) is noteworthy from a thermal perspective, and may shed additional light on the origin(s) of the high thermal maturity of the unit in this area. Rock samples from the dikes and sills were collected and will be submitted for isotopic age dating (see figs. 5–8); we anticipate that the results will help constrain the geologic history of the Red Glacier area and perhaps provide insights into the timing of oil generation and expulsion on the west side of Cook Inlet basin.

Figure 4. Outcrop of medium-gray-weathering, coarse sandstone (see inset photograph) in the Red Glacier Formation, north of Red Glacier. This sandstone is composed mainly of lithic volcanogenic particles derived from a volcanic edifice that was uplifted and eroded during the Middle Jurassic. A dark-gray–brown-weathering porphyritic sill immediately overlies the volcaniclastic sandstone (upper right). Trystan Herriott (DGGS) for scale. Photo by Rick Stanley (USGS), 2012.

Figure 5. At right of photo, a prominent igneous dike crosscuts a well layered outcrop of Red Glacier Formation on the south side of Red Glacier. Trystan Herriott (DGGS) for scale. Photo by Rick Stanley (USGS), 2012.

Figure 6. Detail of the light-colored, 35-cm-thick igneous dike in figure 5 that cross-cuts dark-colored silty mudstone of the Red Glacier Formation. We collected a rock sample from this dike for geochronologic analysis. Rock hammer is about 30 cm long. Photo by Rick Stanley (USGS), 2012.

Figure 7. View toward the east of an exposure of the Red Glacier Formation north of Red Glacier. Medium-gray-weathering sandstone of figure 4 lies directly above photo centerline. A sample for geochronologic analysis was collected from the columnar jointed sill along right skyline of photo. Covered intervals largely comprise dark-gray-colored, fine-grained strata (siltstone and mudstone) that, where in close proximity to sills, are altered to hornfels. Rick Stanley (USGS) for scale. Photo by Trystan Herriott (DGGS), 2012.

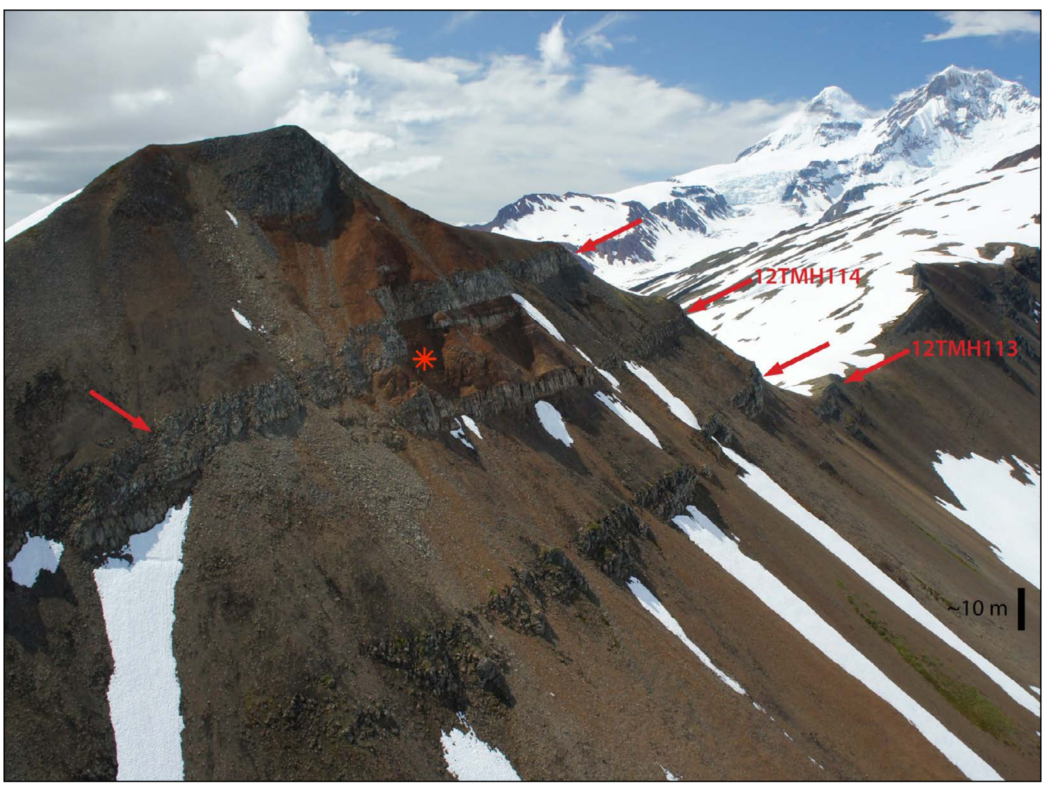

Figure 8. Oblique aerial view toward the southwest of Red Glacier Formation strata that crop out north of Red Glacier. The prominent, resistant weathering, jointed (bedding perpendicular), >5-m-thick, tabular igneous bodies marked by red arrows are porphyritic sills that are locally columnar jointed. Crosscutting relations near the red asterisk are poorly understood and may have resulted from faulting or irregularities in sill geometry during intrusion. The volcaniclastic sandstone of figure 4 lies stratigraphically directly below the sill between stations 12TMH113 and 12TMH114; at both stations, samples were collected from the sills and submitted for geochronologic analyses.

Figure 9. Oblique aerial view toward the southwest of Red Glacier Formation south of Red Glacier. Note that exposures beneath the red asterisk are unreachable because of precipitously steep slopes. The prominent, resistant weathering, jointed (bedding perpendicular), light-colored layer at photo centerline is likely an approximately 8-m-thick sandstone bed that seems to onlap the margins of a deep-water(?) channel (interpreted channel base shown by dashed red line). Sandstones and igneous sills are common in the Red Glacier Formation and have similar outcrop expression; therefore, care must be taken when trying to distinguish sandstones from sills in outcrops such as this that are inaccessible and must be viewed from a distance.

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RESERVOIR QUALITY OF SANDSTONES IN THE NAKNEK AND KAGUYAK FORMATIONS: FIELD OBSERVATIONS

by
Kenneth P. Helmold[1]

During the 2012 Cook Inlet field season we spent seven days (July 14–20) on the Iniskin Peninsula examining outcrops of the Naknek Formation. Twelve additional days (July 24–August 4) were spent in the Katmai–Cape Douglas area surveying outcrops and measuring sections of the Kaguyak and Naknek Formations.

Naknek Formation

Naknek Formation sandstones on the Iniskin Peninsula are very feldspathic, consisting of 40–70 percent (average 50 percent) calcic-plagioclase, with 0–20 percent (average 10 percent) monocrystalline quartz, 5–20 percent (average 15 percent) volcanic rock fragments (VRFs), and 2–45 percent (average 20 percent) accessory detrital minerals, predominantly hornblende, magnetite/ilmenite, and micas. This combination of abundant plagioclase and minor quartz results in a labile framework mineralogy that is highly susceptible to diagenetic alteration. Based on petrographic examinations of previously collected outcrop samples, laumontite is the dominant cement in the majority of samples. It occurs as a replacement of detrital plagioclase grains and as intergranular cement that occludes all primary porosity. In samples containing a higher proportion of VRFs, heulandite cement occurs in addition to, or instead of, laumontite. In either case, primary porosity is almost totally destroyed. Some of the massive sandstone intervals (fig. 10A) display a distinct color zonation with alternations of white- and brown-colored laminae (fig. 10B). My initial hypothesis, based solely on hand lens observations, is that the "white" laminae contain few VRFS and are largely cemented by laumontite, while the "brown" laminae contain a higher proportion of VRFs and are cemented by heulandite. Several samples were collected to test this hypothesis (fig. 10B); they will be plugged for routine core analysis with the plug ends allocated to thin sections. Because of the extensive cementation, Naknek sandstones on the Iniskin Peninsula probably have low potential as conventional reservoirs. If migration of hydrocarbon occurred prior to cementation, it is still feasible that primary porosity may be retained locally, but this was not observed during our field reconnaissance. However, the Naknek in this area is highly fractured and could have potential as an unconventional fractured reservoir (see Gillis and others, this report).

Sandstones of the Naknek Formation were examined in the vicinity of Katmai–Cape Douglas along the southern shore of Kamishak Bay. One stratigraphic section was measured near the mouth of the Douglas River along the southern coast of a small, unnamed island (figs. 1 and 11A; see also Stanley and others *[Observations from a hydrocarbon-bearing sandstone in the Naknek Formation]*, this report). We specifically targeted this outcrop because of previous USGS reports of the existence of a hydrocarbon seep. Based solely on hand-lens observations, this sandstone consists of greater than 50 percent quartz and K-feldspar, with a lesser quantity of plagioclase and heavy minerals. In that respect it has a much

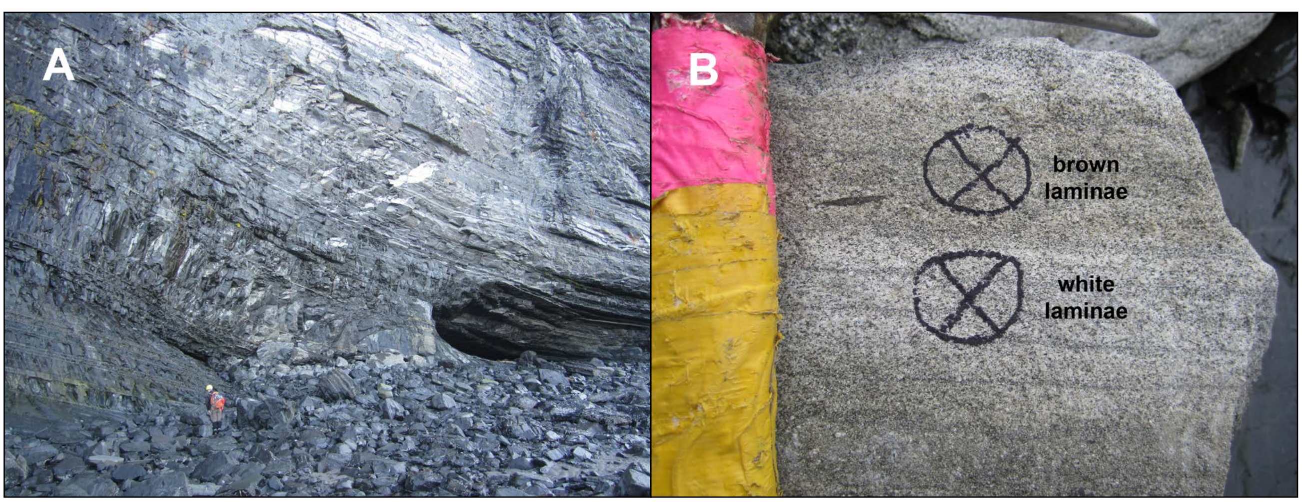

Figure 10. (A) Vertical cliffs of Pomeroy Arkose Member of Naknek Formation exposed along the eastern shore of Oil Bay on the Iniskin Peninsula. (B) Pomeroy arkose with alternating white- and brown-colored laminae that possibly reflect differences in detrital composition (VRF content) and cementation (laumontite versus heulandite).

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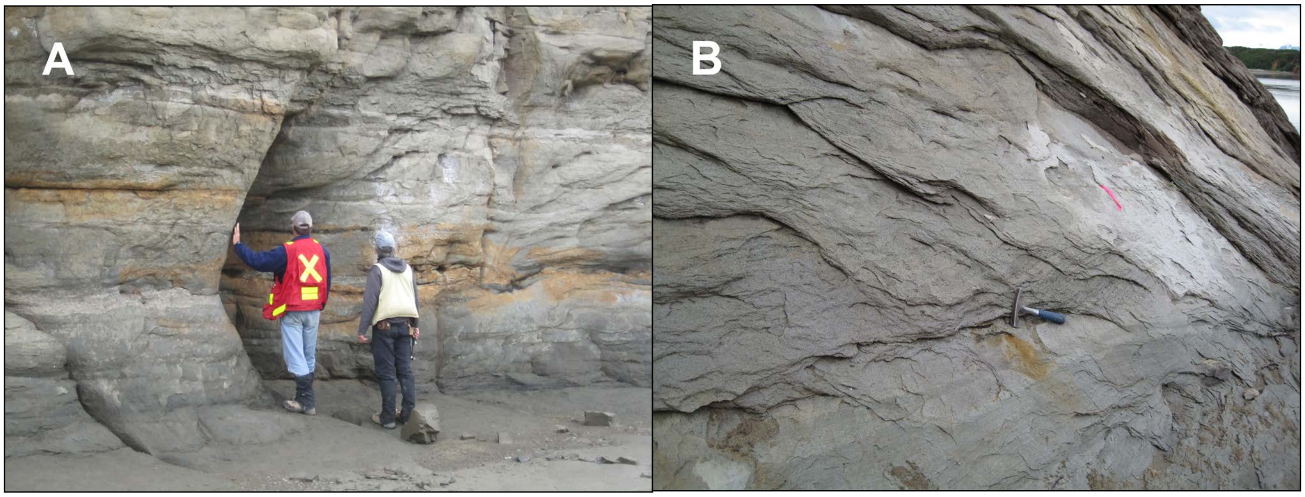

Figure 11. (A) Outcrop of Indecision Creek Sandstone Member of Naknek Formation exposed along the southern shore of Douglas Island. (B) Hydrocarbon-stained sandstone with a compositionally mature (quartz and K-feldspar) mineralogy.

more quartzose composition than sandstones of the Naknek Formation on the Iniskin Peninsula. The hydrocarbon-stained sandstone (33 m in the measured section) is friable with significant intergranular pores visible in hand specimen, indicating it has good to very good reservoir quality. It is not clear if other sandstones in the measured section possess similar reservoir quality. Commonly, sandstones exposed on the outcrop surface were friable and appeared to have intergranular porosity. However, when digging into the outcrop the sandstones were often fairly well lithified. While the porosity in the hydrocarbon-stained sandstone is undoubtedly real, the perceived good reservoir quality of other sandstones may result from surficial outcrop weathering. Detailed analysis of thin sections will help determine the actual reservoir quality of these sandstones. In any case, the presence of relatively quartzose Naknek sandstones is potentially of regional significance. The more mature mineralogy is less susceptible to zeolite cementation and is more likely to retain primary porosity on moderate to deep burial. These sandstones may have the potential to serve as conventional reservoirs.

Kaguyak Formation

Sandstones were examined from the type section of the Kaguyak Formation along the western shore of Shelikof Strait north of Hallo Bay (figs. 1, 12A, B, and 25; see also Wartes and others [A], this report). The sandstones ranged from very-fine- to medium-grained and were typically angular to subangular, moderately well sorted, well lithified, and contained greater than 50 percent dark grains, probably chert or volcanic rock fragments (VRFs). No appreciable porosity was noted in any of the samples examined. The sandstones are locally cut by igneous dikes that may be partially responsible for the poor reservoir quality. Additional outcrops should be examined to determine if the type section is representative of regional levels of reservoir quality.

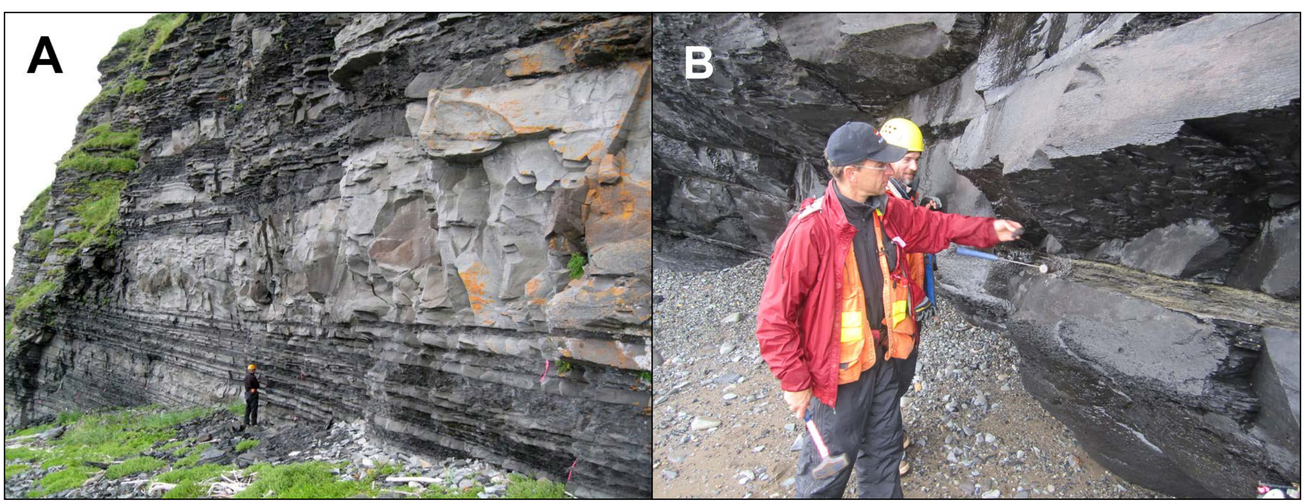

Figure 12. (A) Interbedded sandstones and mudstones exposed at the type section of the Kaguyak Formation north of Hallo Bay. (B) Outcrops of the Kaguyak Formation surveyed during summer 2012 are well indurated with overall poor reservoir quality.

FRACTURE STUDIES IN UPPER CRETACEOUS AND UPPER JURASSIC STRATA ON THE UPPER ALASKA PENINSULA AND LOWER COOK INLET

by
Robert J. Gillis[1], Mary R. Maley[2], Rachel A. Frohman[2], and C. Shaun Peterson[3]

Conventional reservoir quality throughout much of the Cook Inlet Jurassic stratigraphy is commonly believed to be challenged by the effects of authigenic clay and zeolite cementation and compaction (for example, Helmold and others, in press), although there is now evidence for locally good conventional reservoirs as well (Helmold and others, and Stanley and others, this report). To better understand fracture porosity and unconventional reservoir potential within Mesozoic basin fill lithologies, DGGS, in collaboration with the University of Alaska Fairbanks (UAF), has begun field work on a two-year study to characterize systematic fracture sets observed throughout most of the Jurassic and Cretaceous stratigraphy (fig. 2). On the Iniskin Peninsula, the location of active oil seeps is largely controlled by a prominent regional fracture set (for example, Detterman and Hartsock, 1966), and thus understanding fracture persistence and connectivity will also provide insights into hydrocarbon migration pathways between lower source rock intervals and higher potential unconventional and conventional reservoir intervals, including the producing Cenozoic stratigraphy of upper Cook Inlet.

The study is part of a UAF Master's thesis (Maley) that focuses on coastal exposures of mostly Upper Jurassic Naknek Formation strata where a broad tide- and wave-cut terrace abuts against coastal bluffs (figs. 13–16), providing three-dimensional access to fracture sets in targeted stratigraphic intervals. Fracture data is collected with respect to sedimentary facies and tied to measured sections where possible to develop an understanding of how mechanical stratigraphy controls fracture intensity, length, and continuity. Fracture information is also collected with respect to location relative to faults and folds (for example, fold limbs vs. fold crests, proximity to faults) to understand how fracture systematics change with structural position.

During the 2012 field season, we collected data on a total of 1,750 fractures in Naknek Formation strata on the Iniskin Peninsula and south shore of Kamishak Bay, in lower Cook Inlet, and north shore of Hallo Bay on the upper Alaska Peninsula, as well as from the Upper Cretaceous Kaguyak Formation type section near Swikshak Lagoon on the upper Alaska Peninsula (fig. 1). These data, along with those from additional fracture work scheduled for the summer of 2013, will be used to determine the mode and relative timing of fracture set development, and provide baseline information about fracture intensity, connectivity, and fill to aid in the development of fracture reservoir models for the Cook Inlet Mesozoic interval.

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Figure 13. Examples of well developed fracture sets common throughout most of the Mesozoic stratigraphy. Top: Tidal exposure on southeast coast of Iniskin Peninsula (Naknek Formation, Pomeroy Member). Bottom: Oblique plan view of intertidal zone and coastal bluff on east side of Chisik Island (Naknek Formation, Snug Harbor Siltstone Member). Image width approximately 20 m.

Figure 14. Broad tide- and wave-cut terraces abutting against coastal bluffs of gently dipping strata provide excellent three-dimensional access to fracture systems. Such exposures facilitate easy projection of sedimentary facies packages defined in cross section with correlative terrace exposures, where fracture length and intensity are easiest to quantify. Naknek Formation, Indecision Creek Member, Douglas River Island (informal) off the southern coast of Kamishak Bay, upper Alaska Peninsula.

Figure 15. Interface of terrace and bluff exposures showing strata-bound and through-going fracture sets. Chinitna Formation, Paveloff Siltstone Member in Oil Bay on the Iniskin Peninsula (Shaun Peterson for scale).

Figure 16. Bluff exposure of Mode I fractures with well expressed plumose structures (hammer for scale). Chinitna Formation, Paveloff Siltstone Member in Oil Bay on the Iniskin Peninsula.

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HYDROCARBON-BEARING SANDSTONE IN THE UPPER JURASSIC NAKNEK FORMATION ON THE SOUTH SHORE OF KAMISHAK BAY

by
Richard G. Stanley[1], Trystan M. Herriott[2], Kenneth P. Helmold[3], Robert J. Gillis[2], and Paul G. Lillis[1]

The presence of an active petroleum system in Kamishak Bay is demonstrated by an outcrop of hydrocarbon-bearing sandstone in the Upper Jurassic Naknek Formation near the south shore of the bay (fig. 1). The outcrop is about 140 km southwest of Homer on a small, unnamed island near the mouth of the Douglas River (fig. 17). The existence of this outcrop was kindly reported to us by Les Magoon (U.S. Geological Survey, emeritus), who also provided a topographic map showing its exact position. The outcrop was mentioned very briefly in publications by Magoon and others (1975, p. 19) and by Lyle and Morehouse (1977, p. E-1), but to our knowledge there are no detailed descriptions of this outcrop or its hydrocarbons in the published scientific literature.

The Naknek Formation at this locality consists mainly of quartz-bearing, cross-stratified, and bioturbated sandstone with locally abundant molluscan shells, and plant debris (figs. 19–24). Discrete trace fossils include *Macaronichnus* (fig. 23), *Planolites* (fig. 24), *Fugichnia*, and probable *Skolithos*. Based on sedimentary facies and ichnofauna, we interpret this section as moderate- to high-energy marine shoreface deposits. The quartzose sand may have been derived from erosion of uplifted granitic rocks in the vicinity of the modern Aleutian Range. Freshly broken pieces of the hydrocarbon-bearing sandstone have a strong—yet fleeting—kerosene-like odor. Samples of the hydrocarbons were collected during helicopter-assisted fieldwork in 2012 and submitted to the U.S. Geological Survey organic geochemical laboratory in Denver, Colorado, for analysis. The results of these analyses will be used to evaluate the hypothesis that the hydrocarbons were derived from petroleum source rocks in the Middle Jurassic Tuxedni Group, the principal source of oil and associated gas in the Cook Inlet basin (Magoon and Anders, 1992; Magoon, 1994; Lillis and Stanley, 2011; LePain and others, 2012). We also measured and described a detailed 45-m-thick stratigraphic section (figs. 17 and 18) and collected numerous photographs and rock samples for use in analyzing the sedimentology, sedimentary petrology, and reservoir characteristics of the Naknek Formation at this location. A detailed report regarding this work is planned for publication during 2013.

Figure 17. View to the east across the mouth of the Douglas River toward an unnamed island, with Kamishak Bay in the distance. On the island, light-colored sandstone beds of the Upper Jurassic Naknek Formation dip gently upstream (toward right of photo) in low cliffs along the Douglas River, which here is about 500 m wide. Our detailed, 45-m-thick measured section lies between the two red arrows. The stratigraphically highest beds in these cliffs (tan-colored interval near red arrow at right) are hydrocarbon bearing and have a strong, kerosene-like odor. Photo by Rick Stanley (USGS), 2012.

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Figure 18. View to the east of hydrocarbon-bearing sandstone outcrop in the Naknek Formation. The top of the cliff is 12–15 m above the beach. A rock sample (approximately 33 m stratigraphically above the base of the measured section) was collected near the location of the four geologists in photo and submitted to the U.S. Geological Survey organic geochemical laboratory in Denver, Colorado, for analysis of the hydrocarbons.

Figure 19. Detail of hydrocarbon-bearing sandstone outcrop, showing coarse, granular texture and cross-stratification. Rock hammer is about 30 cm long. Photo by Rick Stanley (USGS), 2012.

Figure 20. Detail of outcrop about 20–25 m stratigraphically below the hydrocarbon-bearing sandstone in figure 3. Orange–brown-weathering bioturbated sandstone with mottled texture and color is overlain by darker colored, well laminated sandstone. Shiny black fragments are coalified plant material; white molluscan shells and shell fragments are also visible. Photo by Rick Stanley (USGS), 2012.

Figure 21. Detail of outcrop about 30 m stratigraphically below the hydrocarbon-bearing sandstone in figure 3, showing a coquina bed of molluscan shells and shell fragments. Photo by Rick Stanley (USGS), 2012.

Figure 22. Fragment of flattened log in sandstone about 28 m stratigraphically below the hydrocarbon-bearing sandstone in figure 3. Rock hammer is about 30 cm long. Photo by Rick Stanley (USGS), 2012.

Figure 23. Ichnofossils in sandstone, possibly Macaronichnus segregatis, in a float block about 20 m stratigraphically below the hydrocarbon-bearing sandstone in figure 3. Barrel of pencil is about 1 cm diameter. Photo by Rick Stanley (USGS), 2012.

Figure 24. Ichnofossils in sandstone, probably Planolites, in a float block about 2 m stratigraphically below the hydrocarbon-bearing sandstone in figure 3. Pencil is about 14 cm long. Photo by Rick Stanley (USGS), 2012.

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PRELIMINARY STRATIGRAPHY AND FACIES ANALYSIS OF THE UPPER CRETACEOUS KAGUYAK FORMATION, INCLUDING A BRIEF SUMMARY OF NEWLY DISCOVERED OIL STAIN, UPPER ALASKA PENINSULA

by
Marwan A. Wartes[1], Paul L. Decker[2], Richard G. Stanley[3], Trystan M. Herriott[1], Kenneth P. Helmold[2], and Robert J. Gillis[1]

The Alaska Division of Geological and Geophysical Surveys has an ongoing program aimed at evaluating the Mesozoic forearc stratigraphy, structure, and petroleum systems of lower Cook Inlet. Most of our field studies have focused on the Jurassic component of the petroleum system (this report). However, in late July and early August of 2012, we initiated a study of the stratigraphy and reservoir potential of the Upper Cretaceous Kaguyak Formation.

The Kaguyak Formation is locally well exposed on the upper Alaska Peninsula (fig. 25) and was named by Keller and Reiser (1959) for a sequence of interbedded siltstone and sandstone of upper Campanian to Maastrichtian age that they estimated to be 1,450 m thick. Subsequent work by Detterman and Miller (1985) examined 900 m of section and interpreted the unit as the record of a prograding submarine fan. This interpretation of deep-water deposition contrasts with other Upper Cretaceous rocks exposed along the Alaska Peninsula and lower Cook Inlet that are generally described as nonmarine to shallow marine (Detterman and others, 1996; LePain and others, 2012). Based on foraminifera and palynomorphs from the COST No. 1 well, Magoon (1986) concluded that the Upper Cretaceous rocks were deposited in a variety of water depths and environments ranging from upper bathyal to nonmarine. During our recent fieldwork west and south of Fourpeaked Mountain, we similarly encountered markedly varying lithofacies in the Kaguyak Formation (fig. 25), and we also found oil-stained rocks that are consistent with the existence of an active petroleum system in Upper Cretaceous rocks on the upper Alaska Peninsula and in lower Cook Inlet. These field observations are summarized below.

Type Section

The most completely exposed section of Kaguyak stratigraphy crops out along coastal cliffs near Swikshak Lagoon (fig. 25; Keller and Reiser, 1959; Detterman and Miller, 1985). We conducted reconnaissance traverses of the entire east-dipping type section as well as a narrow peninsula approximately 5 km to the south that is mapped as the lower part of the Kaguyak Formation (Riehle and others, 1993; fig. 25). We subsequently focused our efforts on measuring two detailed stratigraphic sections from the unit's type section—a 75 m section in the middle of the unit and another 210 m section capturing the uppermost part of the formation (see fig. 25 for location of sections). For reservoir quality and provenance data, we collected a comprehensive suite of samples tied to these sections. Final reports summarizing the stratigraphic and analytical work are in progress; below is a preliminary summary of our observations and interpretations.

The lowermost stratigraphy exposed at the type section and in neighboring outcrops is dominated by dark-gray-weathering, medium- to thick-bedded, very-fine-grained sandstone and lesser siltstone. Ovoid tan-weathering calcareous concretions are locally common and help define bedding. We observed numerous fossils, including small pelecypods, inoceramids, and ammonites. This part of the unit notably included a diverse and abundant trace fossil assemblage, including possible *Helminthopsis* or *Phycosiphon*, *Schaubcylindrichnus*, *Terebellina*, *Teichichnus*, and *Thalassinoides* (fig. 26). Primary sedimentary structures are rare, likely reflecting a combination of deposition below wave base and thorough disruption of lamination by bioturbation. We interpret this part of the unit as offshore transition to shelfal.

Both detailed measured sections along the coast west of Swikshak Lagoon are notably different than the basal part of the formation and are dominated by a well bedded, rhythmic stratigraphy of alternating siltstone and very-fine- to medium-grained sandstone (fig. 27). Spherical to ovoid calcareous concretions are common and locally reach several meters in diameter. Individual sandstone units commonly exhibit partial Bouma sequences with a sharp base overlain by an upward-fining massive to plane laminated zone that is typically capped by a rippled facies (fig. 28). Sandstone beds locally amalgamate to form bedsets up to 10 m thick, although 10–40-cm-thick beds separated by thin, recessive mudstone are more common. Evidence for sediment instability is common and includes convolute lamination, load marks, flame and ball and pillow structures, and sandstone dikes. Sole marks are locally abundant and are typically bidirectional grooves; rare flutes and longitudinal scours suggest dominantly east-directed sediment transport. Most beds are very tabular and laterally continuous, although one 8-m-thick zone of highly disrupted and discontinuous bedding suggests the development of a mass transport complex or similar gravitational slumping (fig. 27). Fossils are conspicuously rare, although *Inoceramus* prism fragments and ammonite debris were observed. Trace fossils and bioturbation are also uncommon in the type section, although we did observe one excellent example of tiered *Rhizocorallium* (fig. 28). The totality of sedimentary facies is consistent with deposition via sediment gravity flows, ranging from high-density flows to more dilute, turbulent flows. Based on the sedimentary facies, the lack of wave-generated structures, and the dearth of bioturbation, we interpret the upper half of the

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type Kaguyak Formation as deposited in deep water, beyond the shelf edge. The abundance of sandstone favors deposition in a high-accommodation, high-sediment delivery zone such as the base of slope or basin floor, although it is possible that part of the section represents slope facies. The parts of the section with thick amalgamated sandstone packages may reflect low-stand deposition when abundant coarse-grained material is exported off the shelf.

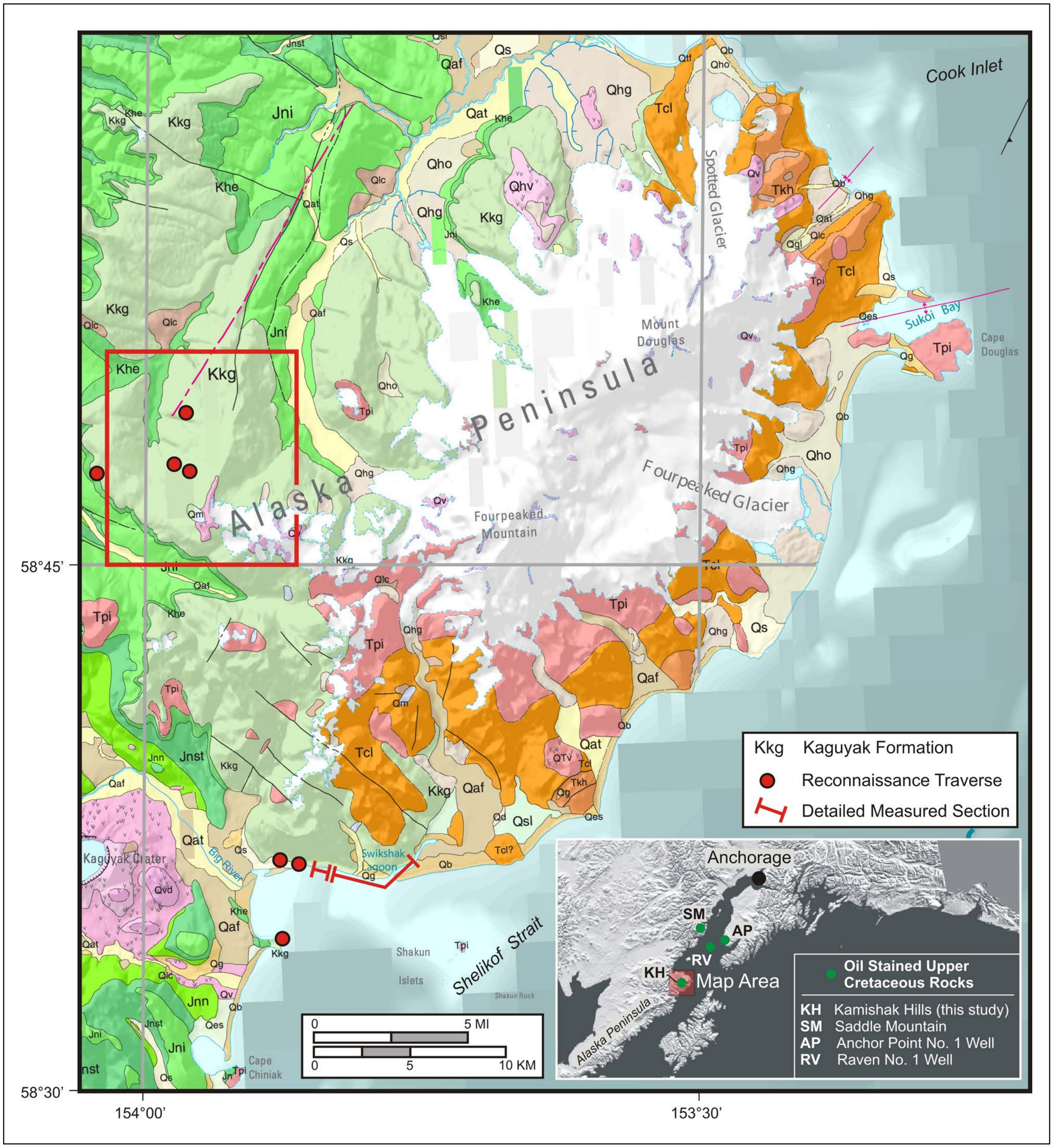

Figure 25. Geologic map of the upper Alaska Peninsula (modified from Wilson and others, 2009), showing the Kaguyak Formation localities inspected in 2012. The red box outlines the location for figure 29 in the eastern Kamishak Hills. Inset map highlights generalized locations of reported oil staining in outcrop, and wells with significant oil shows.

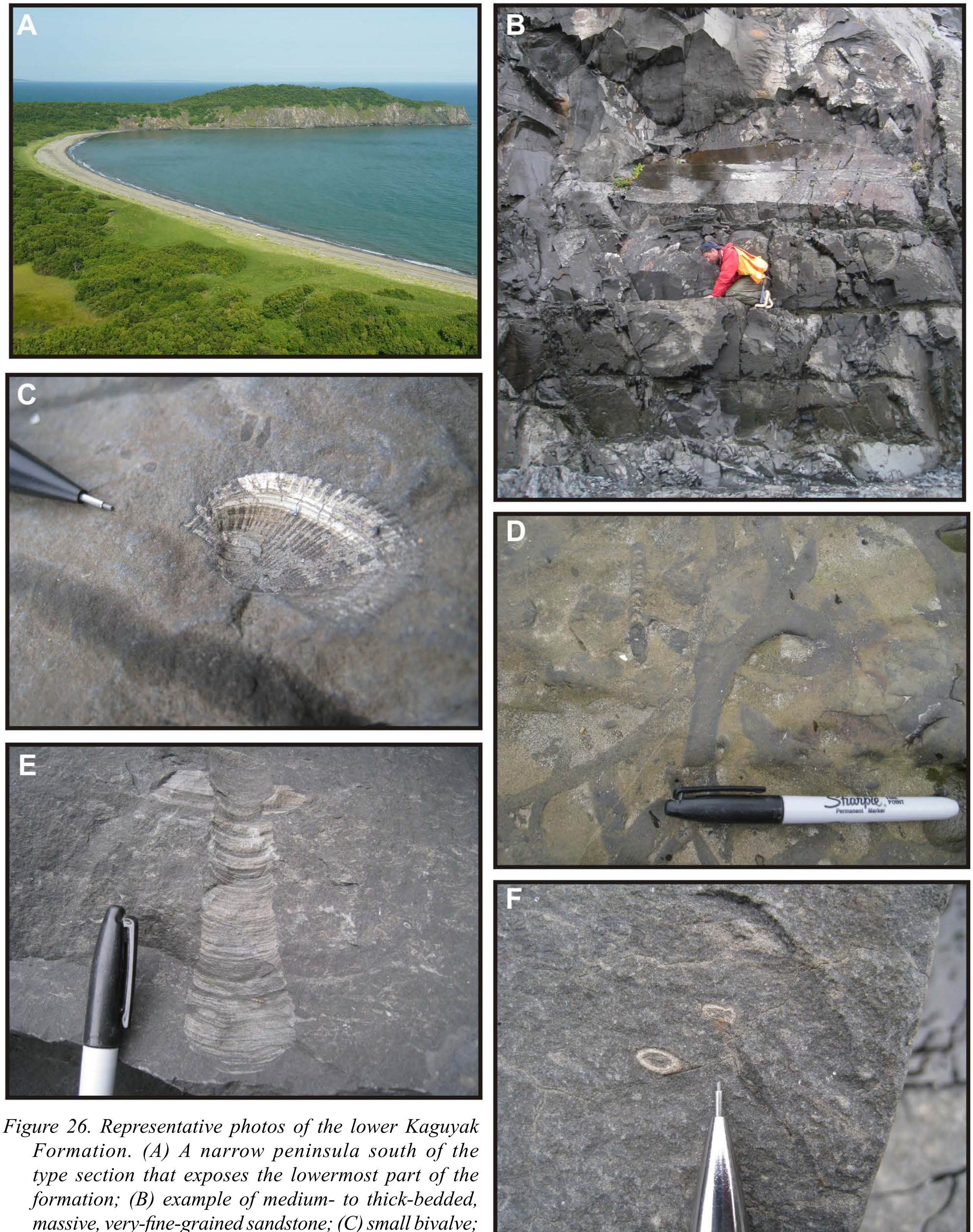

Figure 26. Representative photos of the lower Kaguyak Formation. (A) A narrow peninsula south of the type section that exposes the lowermost part of the formation; (B) example of medium- to thick-bedded, massive, very-fine-grained sandstone; (C) small bivalve; (D) Thalassinoides burrows; (E) Teichichnus burrow; (F) Schaubcylindrichnus trace fossil.

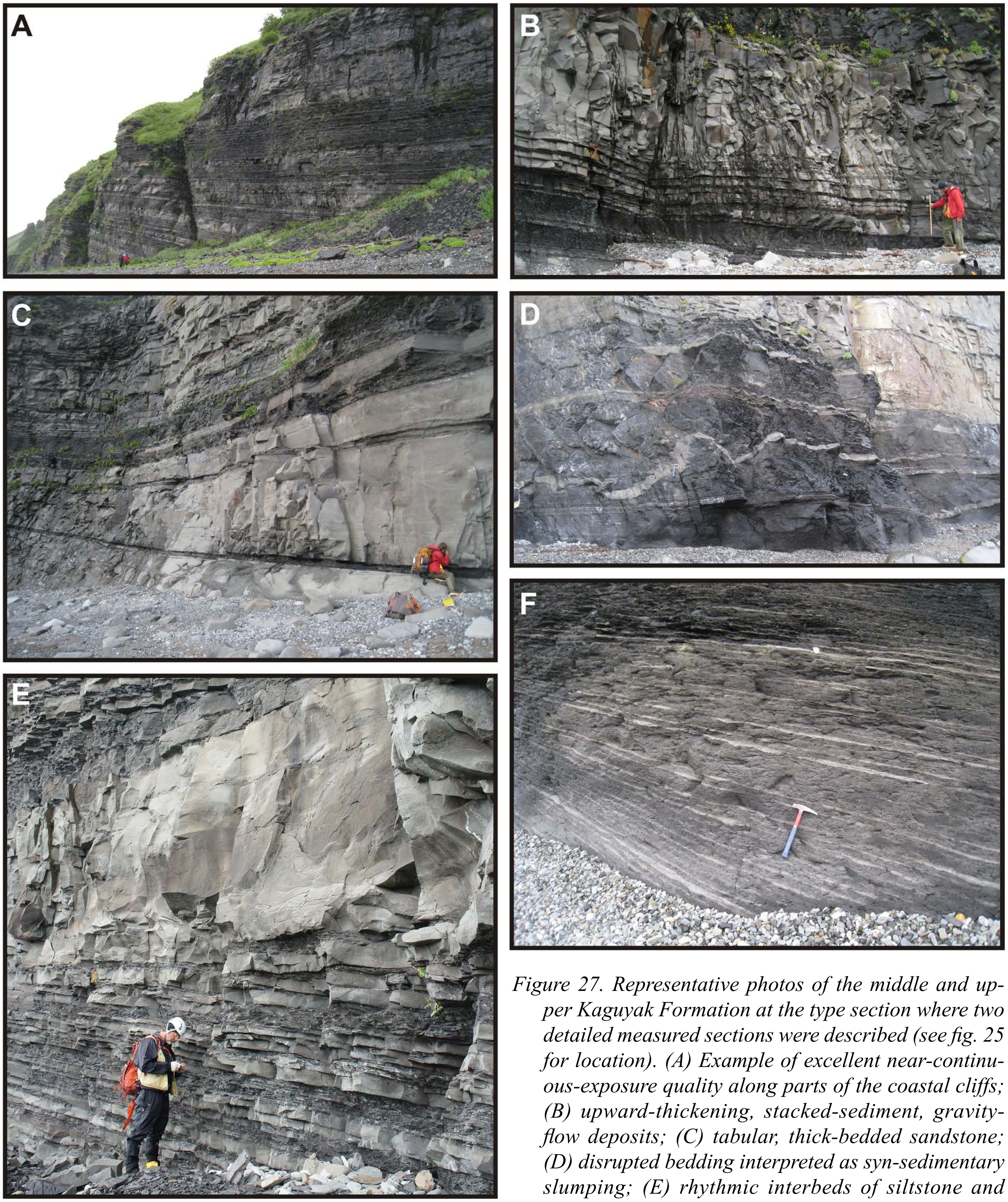

Figure 27. Representative photos of the middle and upper Kaguyak Formation at the type section where two detailed measured sections were described (see fig. 25 for location). (A) Example of excellent near-continuous-exposure quality along parts of the coastal cliffs; (B) upward-thickening, stacked-sediment, gravity-flow deposits; (C) tabular, thick-bedded sandstone; (D) disrupted bedding interpreted as syn-sedimentary slumping; (E) rhythmic interbeds of siltstone and very-fine-grained sandstone overlain by a thick, amalgamated fine-grained sandstone bed; (F) example of heterolithic facies comprising siltstone and very-thin-bedded, rippled, very-fine-grained sandstone.

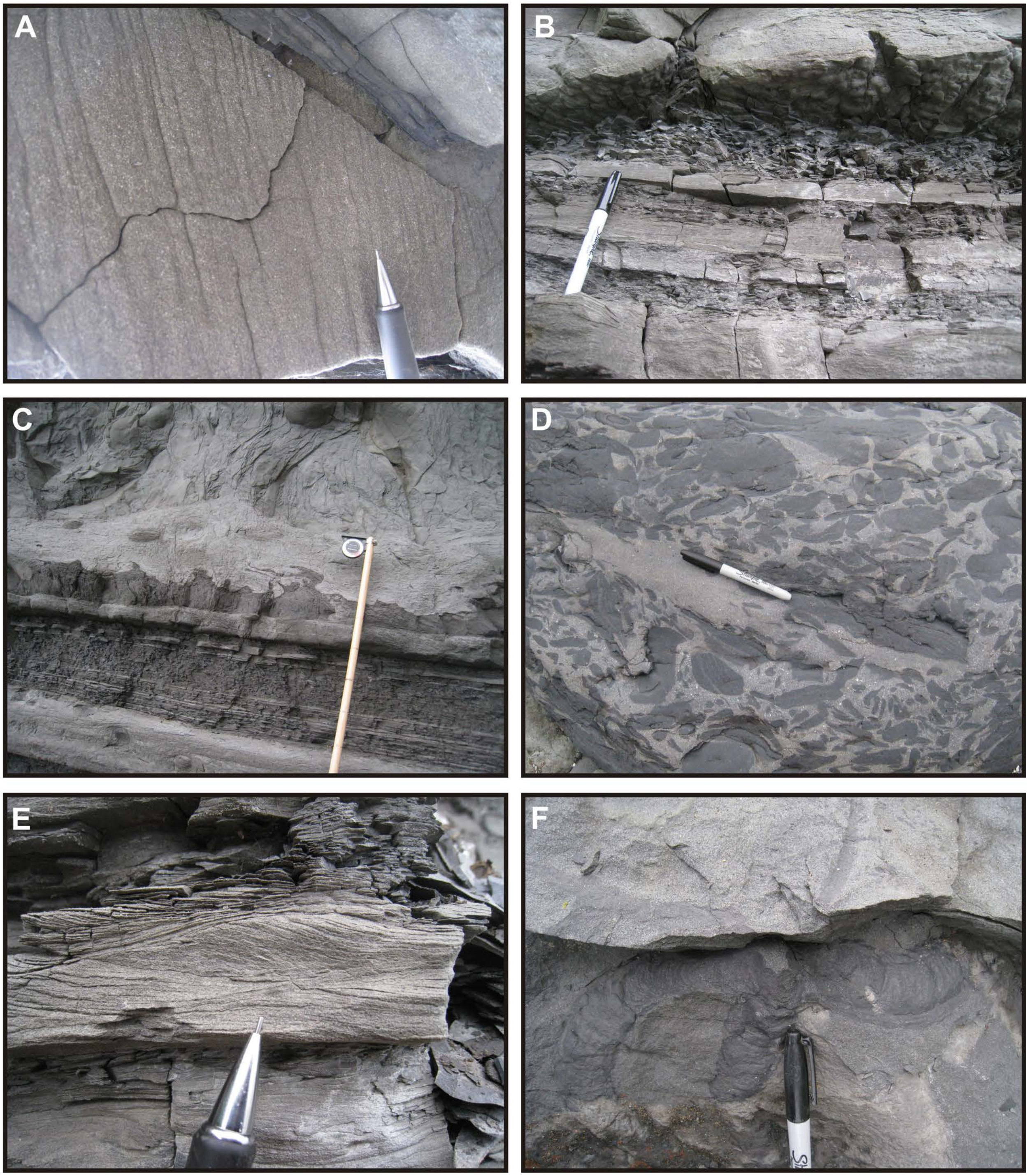

Figure 28. Representative photos of sedimentary structures and facies from measured sections of the middle and upper Kaguyak Formation at its type locality (see fig. 25 for location). (A) Longitudinal scour sole marks provide paleocurrent information; (B) load marks along the base of the sandstone at photo top; (C) flame structures; (D) intraformational mud rip-up conglomerate; (E) climbing ripple cross lamination; (F) unusual Rhizocorralium burrow showing tiered, propeller-shaped structure with branches projecting from a central shaft.

Kamishak Hills Reconnaissance

We spent part of two days examining exposures mapped as Kaguyak Formation in the Kamishak Hills (fig. 25; Riehle and others, 1993; see also Jones and Detterman, 1966). Outcrop is extensive, but most of the well exposed sections are extremely steep and inaccessible. Dense vegetation and deep, narrow gorges limited helicopter landings near outcrops. Nevertheless, we examined several outcrops that were distinctly different than the type section of the Kaguyak Formation described above. We did not observe any features that suggested sediment gravity flows. Instead, the rocks included abundant evidence for shelfal water depths, including thick sections of bioturbated siltstone and very fine sandstone and discrete traces such as *Paleophycos*, *Thalassinoides, Planolites*, and possible *Terrebellina*. Inoceramids are locally abundant, as is coalified woody debris. A fairly well exposed channel with 1.5 m of visible erosional relief and filled with 2.5 m very-fine- to fine-grained argillaceous sandstone may record an episode of lowered base level and delivery of sediment to the outer shelf or deeper environments.

Hydrocarbon Occurrence

During a reconnaissance traverse along an unnamed tributary of the Douglas River (fig. 29), we discovered abundant cobbles and small boulders of sandstone in the modern stream gravel that were strongly petroliferous, particularly on freshly broken surfaces (fig. 30). The oil-stained float blocks were dominantly very-fine- to fine-grained sandstone and weather light gray to tan and light greenish-gray. The oil stain occurred as both matrix and fracture fill, with the latter commonly healed. One small boulder of porphyritic andesite was also strongly oil stained along a fracture plane and included visible hydrocarbon within a small vug. The sandstone is dissimilar to the nearby outcrops of Lower Cretaceous Herendeen Formation, and we infer that the clasts were sourced from outcrops of the overlying gently east–southeast-dipping Kaguyak Formation exposed immediately upstream to the east and south. We spent most of one day attempting to locate the origin of these clasts, but were not successful, in part due to the rugged terrain. However, select observations throughout the unit allowed us to reasonably constrain the source of the oil-stained sandstone to a zone within the lower Kaguyak (fig. 29). Several oil-stained samples were collected and will be analyzed for reservoir quality, petrology, and organic geochemistry; results will be published when the analytical data become available.

Summary

Initial examination of the Kaguyak Formation confirms some of the prior interpretations for this unit, particularly the deep-water depositional environment emphasized by previous workers (Detterman and Miller, 1985). However, our preliminary observations from the type section suggest that the lower part of the formation was likely deposited on the shelf and subsequently witnessed a relative deepening sufficient to transition into basin floor, sediment gravity flow-dominated deposition for the remainder of the unit. Future work will aim to evaluate the cause and regional significance of this stratigraphic change.

The lack of evidence for deep-water deposition in the Kamishak Hills suggests this area may have been more proximal than the type section further southeast. This conclusion is broadly consistent with our preliminary paleocurrent data and suggests the axis of the basin developed east or southeast of the present outcrop belt (see also Hastings and others, 1983; Magoon, 1986). However, additional work is required to better constrain the paleogeography of the Late Cretaceous forearc basin.

The newly discovered oil-stained sandstone cobbles and boulders from the Kaguyak Formation indicate that the unit can preserve sufficient porosity and permeability to serve as an oil reservoir and that viable migration pathways must, at least locally, connect with probable source rocks of the Middle Jurassic Tuxedni Group. Significant oil staining has also been documented elsewhere in Upper Cretaceous rocks in lower Cook Inlet (see inset map in figure 25), such as the nonmarine facies near Saddle Mountain (LePain and others, 2012; Magoon and others, 1980) and reported oil shows in the Raven No. 1 well (LePain and others, 2012) and the Anchor Point No. 1 well (unpublished industry reports). These widespread occurrences in lower Cook Inlet suggest that Upper Cretaceous rocks overlie a regionally extensive, mature, oil-generating source rock and represent a viable oil exploration target in Cook Inlet.

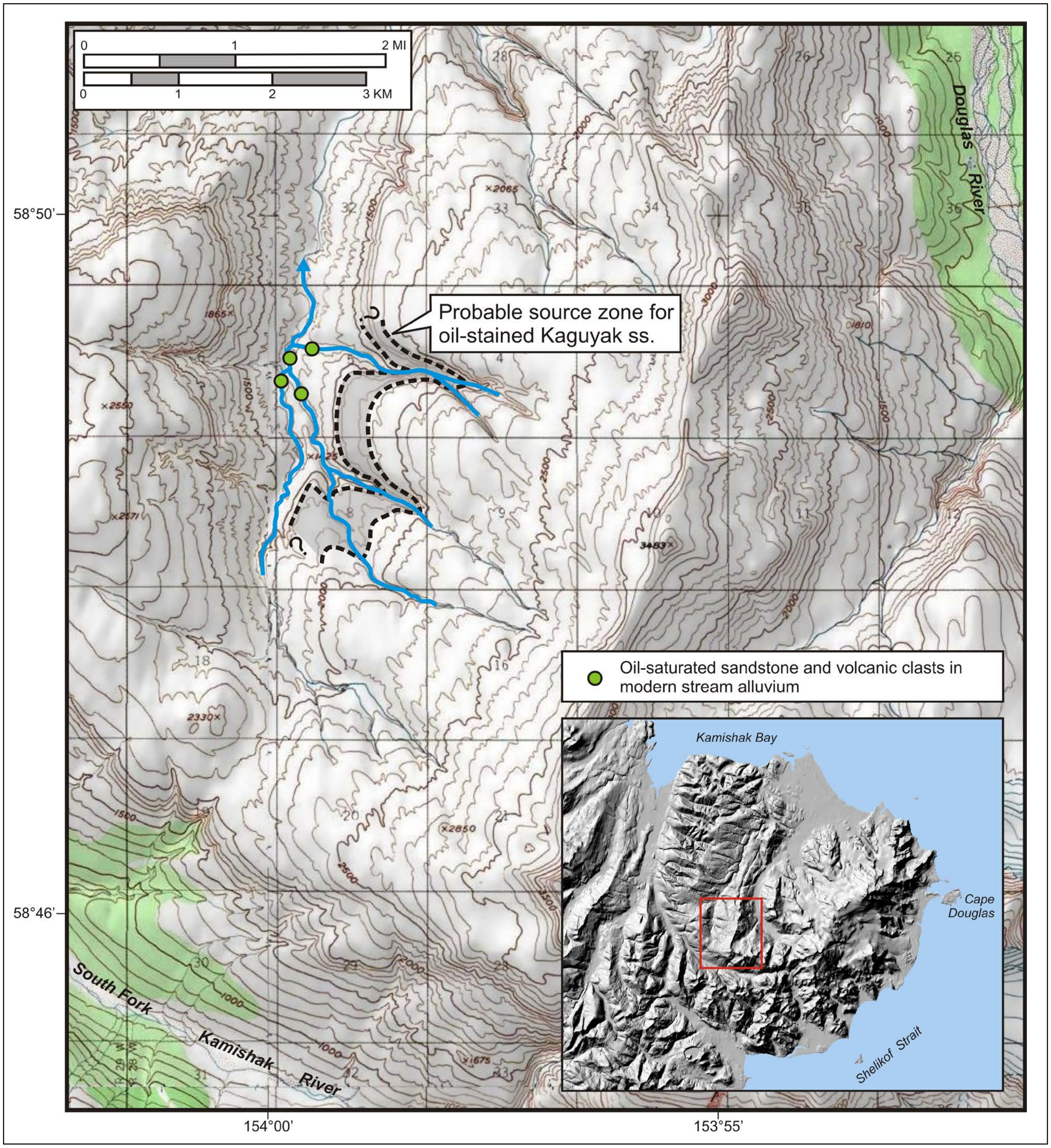

Figure 29. Location map of unnamed tributary of the Douglas River in the Kamishak Hills (see fig. 25 for location and geologic map context). Green dots indicate locations where oil-saturated cobbles and boulders were discovered in modern stream gravel. Gray-shaded area indicates likely source region for these clasts.

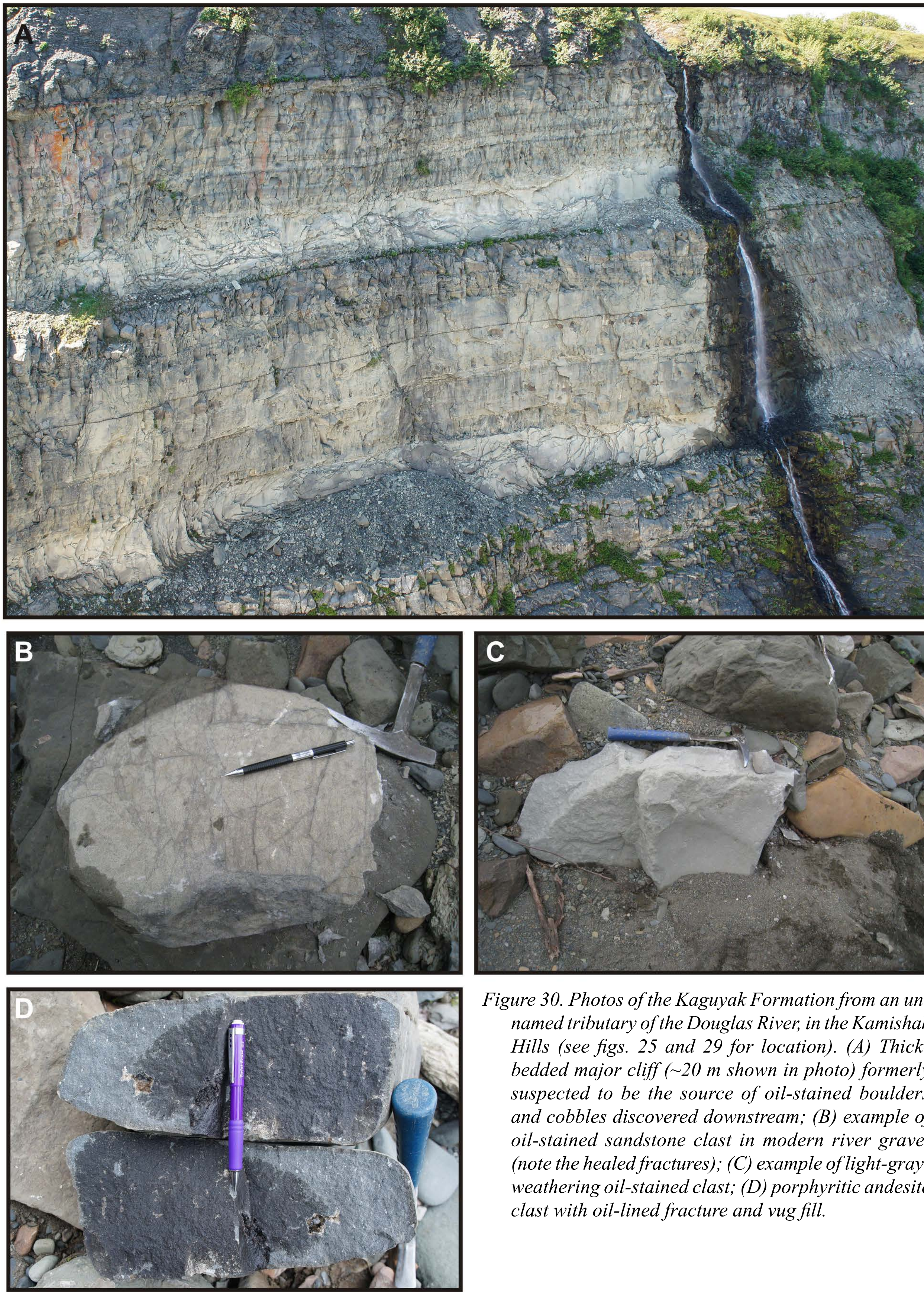

Figure 30. Photos of the Kaguyak Formation from an unnamed tributary of the Douglas River, in the Kamishak Hills (see figs. 25 and 29 for location). (A) Thick-bedded major cliff (~20 m shown in photo) formerly suspected to be the source of oil-stained boulders and cobbles discovered downstream; (B) example of oil-stained sandstone clast in modern river gravel (note the healed fractures); (C) example of light-gray-weathering oil-stained clast; (D) porphyritic andesite clast with oil-lined fracture and vug fill.

RECONNAISSANCE INVESTIGATIONS OF THE BRUIN BAY FAULT SYSTEM ALONG THE WESTERN MARGIN OF LOWER COOK INLET AND UPPER ALASKA PENINSULA, ALASKA

by
Robert J. Gillis[1], Robert Swenson[1], Marwan A. Wartes[1], and Rachel Frohman[2]

The Bruin Bay fault is discontinuously exposed for about 400 km from Becharof Lake on the upper Alaska Peninsula northeastward to near the east flank of Redoubt Volcano on the west side of upper Cook Inlet (fig. 1). The fault separates the roots of an Early–Middle Jurassic magmatic arc to the northwest, including parts of its volcanic edifice and Triassic-age metamorphic country rocks(Detterman and Hartsock, 1966; Detterman and Reed, 1980; Riehle and others, 1993; Iliamna subterrane of Wilson and others, 1999), from Middle and Upper Jurassic forearc basin strata (Detterman and Reed, 1980; Trop and others, 2005) to the southeast that were derived from the arc complex (Detterman and Hartsock, 1966; Detterman and others, 1996; Trop and others, 2005; Chignik subterrane of Wilson and others, 1999). The Bruin Bay fault was likely a principal control of exhumation of the Jurassic arc and sediment accommodation for the Mesozoic forearc basin (for example, Trop and others, 2005), and is thought to have been active until as recently as late Oligocene time (Detterman and Reed, 1980). However, little work has focused on understanding the fault's geometry, kinematics, and slip history.

Most of what has been published about the Bruin Bay fault is the result of work performed by the U.S. Geological Survey spanning the 1960s to early 1980s, which continues to be recycled through subsequent literature. Detterman and Reed (1980) recognized that the Bruin Bay fault is not defined by a single plane, but rather is a system of steeply dipping faults up to 6–8 km wide. Motion along the fault system is inferred to be mostly strike-slip and sinistral, with perhaps 19 km (Detterman and Hartsock, 1966) to as much as 65 km (Detterman and Reed 1980) of left-lateral separation from equivocal offset stratigraphic markers, yet only about 3.5–4 km of stratigraphic separation is estimated from units juxtaposed across the fault system (Detterman and Hartsock, 1966).

Reconnaissance investigations by DGGS in 2007, 2009, 2010, and 2012 at several locations along the fault system (fig. 1) were aimed at developing a better understanding of the fault geometry, sense of motion from observations of meso- and macro-scale structures associated with the fault, and kinematic indicators in fault zones. New geochronology of cross-cutting igneous features and thermochronology of hangingwall and footwall blocks are helping to constrain the timing of deformation and exhumation associated with fault slip. Preliminary field observations indicate that the frontal fault plane separating Jurassic forearc deposits from the arc complex dips moderately northwestward at approximately 45°–50° where measured, with proximal hangingwall and footwall deformation characterized by decimeter- to hectometer-scale contractile folds (figs. 31–35) indicative of primarily dip-slip, reverse motion. Hangingwall rocks are intensely brittlely deformed in zones up to approximately 1 km wide, especially in Triassic Kamishak Formation limestones and locally in Early Jurassic Talkeetna Formation volcanic and volcaniclastic rocks. Conversely, deformation of Tuxedni Group and Naknek Formation footwall strata is most often expressed as large-scale folds sometimes restricted to within a few hundred meters of the fault. Faults arc-ward of the main strand tend to dip steeply and might cut lower angle contractile structures. Bi-, and uni-directional slip indicators on surfaces of more steeply dipping faults indicate mostly oblique slip, however the slip sense often varies between components of reverse, normal, dextral, and sinistral motion, suggesting the fault system has evolved over time within different states of stress, accommodated space problems in a complex manner, or both. Anticipated work at key locations along the fault in 2013 and 2014 and geochronologic and thermochronologic analyses in progress should provide a clearer picture of the role of the Bruin Bay fault in the development of the Mesozoic and modern Cook Inlet forearc basin.

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Figure 31. Bruin Bay fault contact at Ursus Head on the northeastern shore of Ursus Cove (see fig. 1 for location). Highly deformed Triassic carbonate strata (Trk) placed over Late Jurassic forearc basin strata (Jn) along a moderately northwest-dipping plane. Jn deformed by a footwall syncline with overturned forelimb. Arcward-dipping backlimb suggests the existence of an additional basinward structure. Trk = Kamishak Formation; Jn = Naknek Formation. Faults shown as red lines; selected marker beds by yellow lines; fold axis by white line.

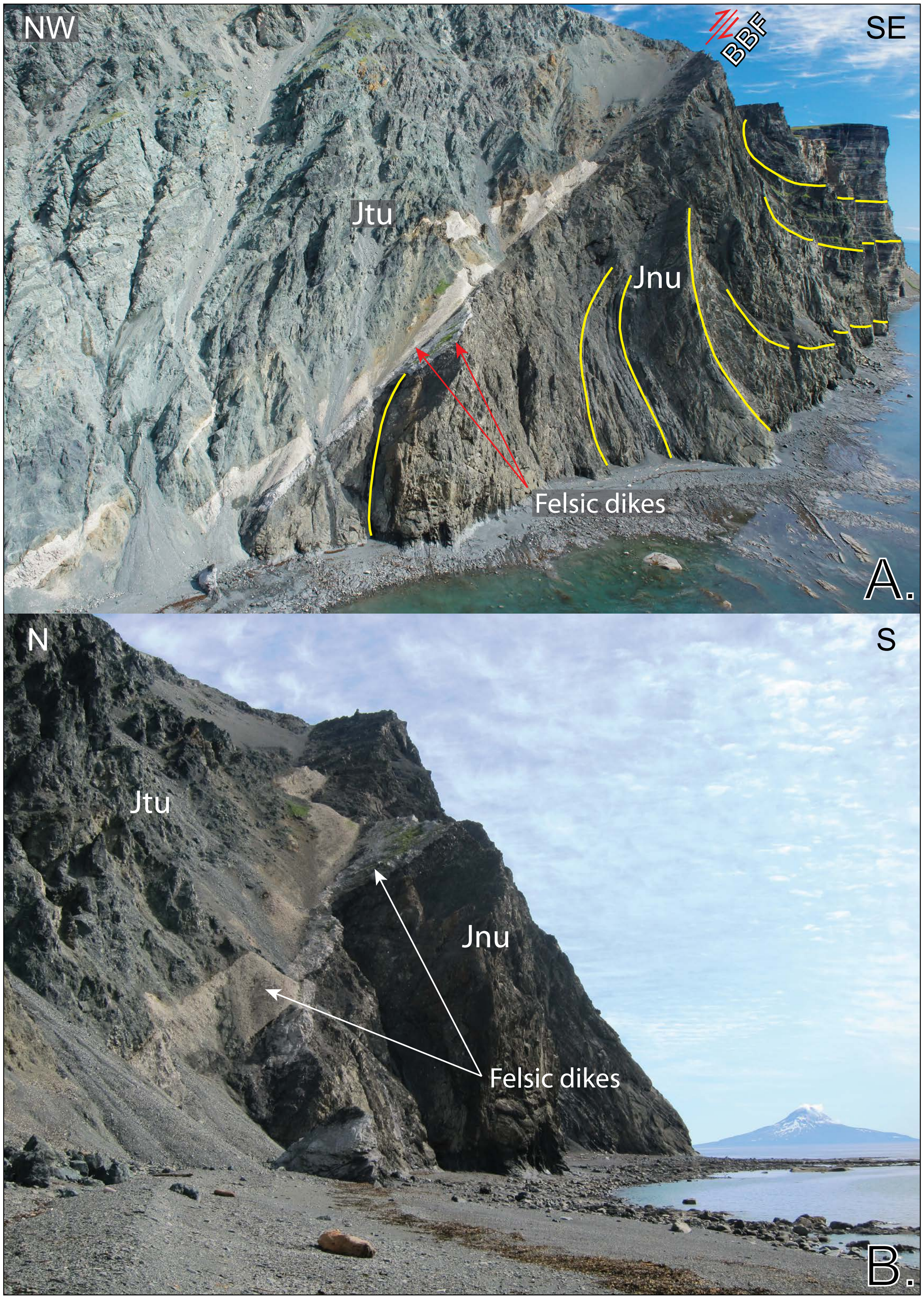

Figure 32. Bruin Bay fault contact southwest of Contact Point (see fig. 1 for location). Highly deformed mafic volcanic rocks of the Jurassic arc edifice placed over Late Jurassic forearc basin strata (Jnu) along a moderately northwest-dipping plane. (A) Jnu deformed by a footwall syncline with an overturned forelimb, similar to the geometry observed at Ursus Head. Two felsic dikes of different composition intruded along fault plane are virtually undeformed, and thus suture the hangingwall to the footwall. (B) Same exposure looking eastward. Differential weathering of hangingwall and footwall rocks exposes the Bruin Bay fault plane and felsic dikes intruded along the plane. Both dikes were sampled for age dating (in progress), and the results should provide a minimum age before which significant motion along the fault ceased. Selected marker beds shown with yellow lines. Jtu = Early Jurassic Talkeetna Formation; Jnu = Late Jurassic Naknek Formation; BBF = Bruin Bay fault.

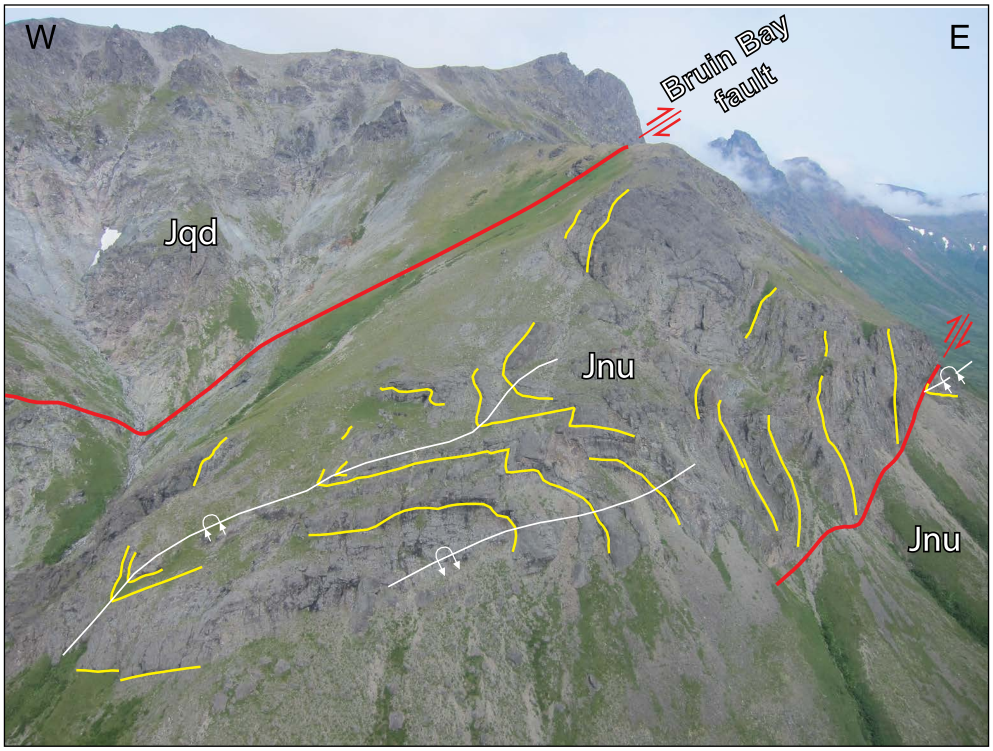

Figure 33. Bruin Bay fault contact northeast of Lake Grosvenor, Katmai National Park and Preserve (see fig. 1 for location). Highly fractured Jurassic arc intrusives placed over Late Jurassic forearc basin strata (Jnu) along a moderately steeply northwest-dipping plane. The larger-scale footwall structure is an overturned syncline with a local breaching fault. Disharmonic folding locally thickens the backlimb of the syncline. Jqd = Middle Jurassic quartz diorite; Jnu = Late Jurassic Naknek Formation. Faults shown as red lines; selected marker beds as yellow lines; fold axes as white lines.

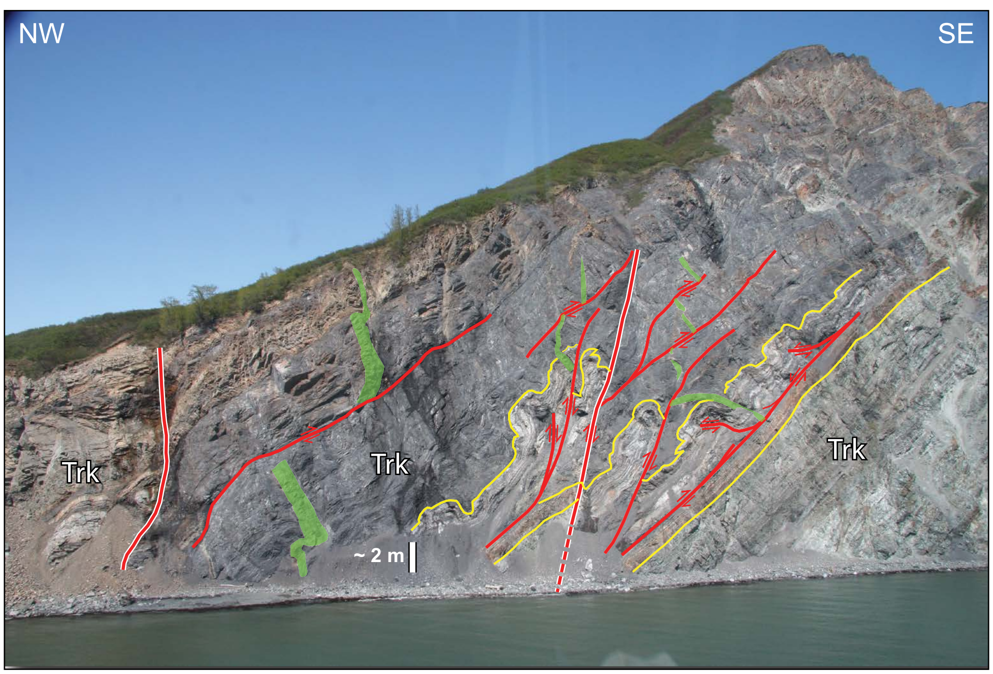

Figure 34. Hinterland-dipping panel in hangingwall of the Bruin Bay fault at Ursus Head (see fig. 1 for location) Triassic carbonate strata (Trk) deformed by an imbricate fan that detaches in a mechanically less competent interval. Imbricate fan later cut by high-angle(?) reverse fault. Trk = Kamishak Formation. Selected marker beds marked with yellow lines; earlier faults with red lines; and later faults as red lines with white outlines. Offset dikes shown with green shading.

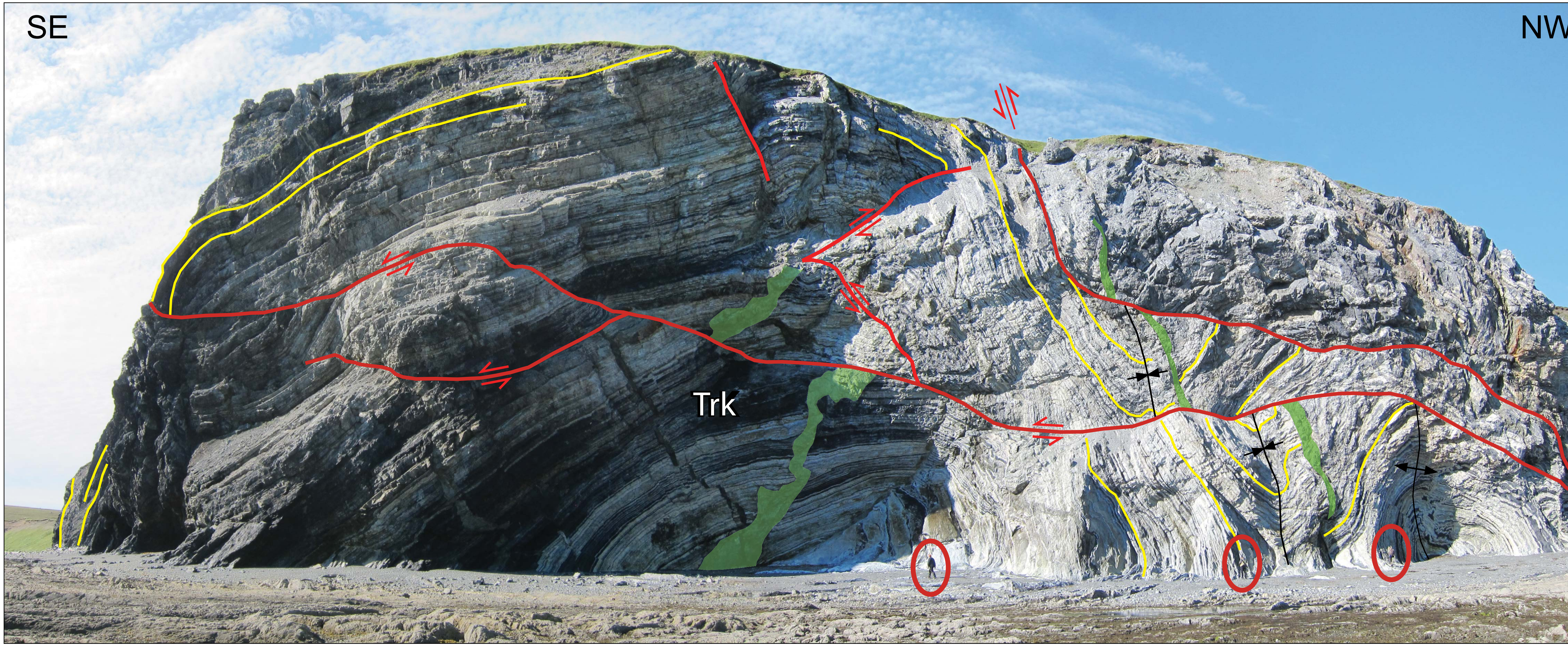

Figure 35. Anticline with overturned forelimb in hangingwall of Bruin Bay fault deforming Kamishak Formation limestone (Trk) near Contact Point (see fig. 1 for location). Tight detachment folds in backlimb of anticline cut by out-of-sequence thrust faults. Trk = Kamishak Formation. Selected marker beds shown by yellow lines; out-of sequence thrust faults shown by red lines; fold axes shown by black lines. Offset dikes shown as green shading. Geologists for scale (red ovals).

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PRELIMINARY STRATIGRAPHIC INTERPRETATION OF THE NAKNEK FORMATION: EVIDENCE FOR LATE JURASSIC ACTIVITY ON THE BRUIN BAY FAULT, INISKIN PENINSULA, LOWER COOK INLET

by
Marwan A. Wartes[1], Trystan M. Herriott[1], Kenneth P. Helmold[2], Robert J. Gillis[1]

The northeast-trending Bruin Bay fault is a major structure bounding the western side of Cook Inlet where it generally separates Early Jurassic plutonic and volcanic rocks of the Talkeetna arc on the northwest side from Middle and Late Jurassic forearc sedimentary rocks on the southeast side (Detterman and Reed, 1980). Despite the significance and size of this fault system, which can be traced for >400 km, its history remains poorly understood (fig. 1, see Bruin Bay fault section, this paper). To evaluate the possibility of Jurassic activity on the fault, we conducted stratigraphic studies of the Middle and Upper Jurassic units exposed on the southwestern Iniskin Peninsula, nearest the mapped trace of the fault system (fig. 36). LePain and others (2011) reported stratigraphic evidence from the upper Tuxedni Group that suggested that activity on the Bruin Bay fault was likely initiated by late Middle Jurassic time. The following discussion focuses on our observations from the Upper Jurassic Naknek Formation (fig. 37).

We measured detailed stratigraphic sections along the shores of Iniskin and Oil bays (fig. 36), focusing specifically on the Chisik Conglomerate Member and the Northeast Creek Sandstone Member (formerly called the "lower sandstone member"; Detterman and Hartsock, 1966; Detterman and others, 1996). This work has led to an improved understanding of the map-scale distribution of the coarse-grained Chisik, restricting the unit to exposures along Iniskin Bay (fig. 36) where it is dominated by approximately 100 m of poorly organized pebble, cobble, and boulder conglomerate (fig. 38), interpreted as fan delta deposits. In sharp contrast, this conglomeratic package is not present just 7 km to the east in Oil Bay (fig. 36). Instead, the Chisik transitions into >230 m of the age-equivalent Northeast Creek Sandstone Member (fig. 37), which is characterized by bioturbated siltstone and arkosic fine-grained sandstone (fig. 39) interpreted as a storm-influenced shelfal assemblage. The eastward thickening and marked fining of the Chisik–Northeast Creek stratigraphic interval reflects the eastward paleoslope of this part of the basin margin and strongly suggests deposition was driven by activity on the nearby Bruin Bay fault.

The Snug Harbor Siltstone Member occupies a generally recessive zone overlying the Chisik–Northeast Creek interval (fig. 37; Detterman and Hartsock, 1966). Reconnaissance examination indicates Snug Harbor is dominated by tabular, thin bedded, fossiliferous very-fine-grained sandstone and siltstone (fig. 40). Although the depositional environment is poorly constrained, interpretations of the bounding units above and below supports an outer shelf to slope depositional setting. If correct, this would suggest the unit records an important transgressive episode of abrupt deepening along the basin margin. The increase in accommodation may be related to ongoing activity along the Bruin Bay Fault, although the lack of coarse-grained detritus suggests limited exhumation from the nearby hangingwall.

In the Iniskin Peninsula area, the Pomeroy Arkose Member is the youngest preserved member of the Naknek Formation (fig. 37; Detterman and Hartsock, 1966) and typically forms resistant cuestas with southeastward-dipping flat-irons. Similar to the Chisik Conglomerate, our measured sections (fig. 36) and supplementary reconnaissance observations indicate the Pomeroy is considerably coarser grained in the Iniskin Bay area, nearest the Bruin Bay fault. In this area, clast sizes exceeding 2 m in diameter were observed (fig. 41), indicating substantial flow competence and gradient. In contrast, the Pomeroy exposures to the east in Oil Bay (basinward) host almost no conglomerate and are dominated by siltstone and very-fine- to fine-grained sandstone (fig. 42). The facies in Oil Bay include abundant indications of sediment gravity-flow deposition, including sole marks, mudstone intraclasts, and graded beds with rippled tops (fig. 42). Bedding is typically very tabular, although local lenticular channel geometries were also observed. Unlike the underlying Chisik facies, the Pomeroy is nearly devoid of any bioturbation. The balance of observations from Oil Bay support an interpretation of lower slope to basin floor deposition for the Pomeroy, which indicates a marked deepening relative to the Northeast Creek Sandstone Member, further supporting the inference that the intervening Snug Harbor interval records a significant transgression. The very-coarse-grained proximal facies of Pomeroy in Iniskin Bay, near the Bruin Bay fault, suggest basin margin deposition continued to be influenced by activity along this structure into the latest Jurassic.

Volcanic and plutonic clast composition and preliminary detrital zircon age data indicate that the sediment source region on the hangingwall block of the Bruin Bay fault was principally composed of the Jurassic Talkeetna arc, although occasional

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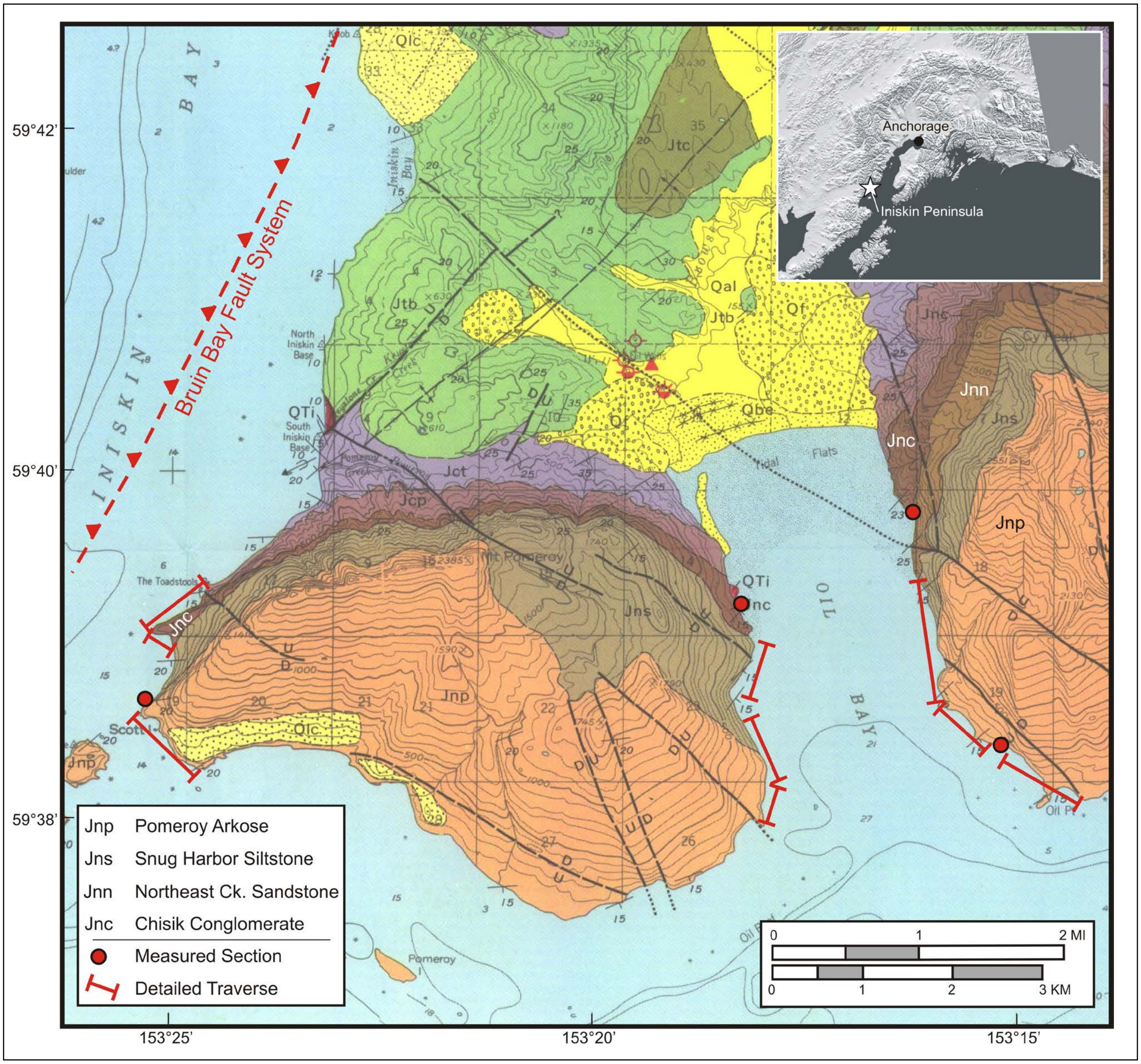

Figure 36. Geologic map of the southwestern Iniskin Peninsula, modified from Detterman and Hartsock (1966) to illustrate approximate trace of the Bruin Bay fault system and the location of Naknek Formation outcrops investigated in this study. Notably, Detterman and Hartsock (1966) recognized that the Chisik Conglomerate (Jnc) and Northeast Creek Sandstone (Jnn) members were lateral equivalents, but in their mapping shown here, they incorrectly depict the Chisik as present along both sides of Oil bay. Our work indicates that only the Northeast Creek Sandstone is present at this stratigraphic position in Oil Bay and the actual pinch-out of Chisik facies must occur in the uplands between Iniskin and Oil bays. See text for additional discussion of stratigraphic changes in the Naknek Formation.

sedimentary clasts suggest that rocks of the Middle Jurassic Chinitna Formation and/or Tuxedni Group were also unroofed (fig. 37). The observed relationship between the Naknek Formation and the Bruin Bay fault is remarkably similar to that described along the Little Oshetna fault in the Talkeetna Mountains (fig. 36; Trop and others, 2005), likely indicating syn-depositional tectonism controlled the evolution of much of the Late Jurassic forearc basin margin.

Future stratigraphic studies and detailed geologic mapping will aim to further document these facies changes in the Iniskin Peninsula area. These data will allow for an improved model for development of the basin margin and provide new constraints on the broader evolution of the Jurassic forearc basin. Furthermore, this stratigraphic work will be combined with detailed analysis of reservoir quality in the Naknek Formation, which remains a viable, albeit poorly tested, target for conventional and unconventional hydrocarbon exploration (Stanley and others, 2011).

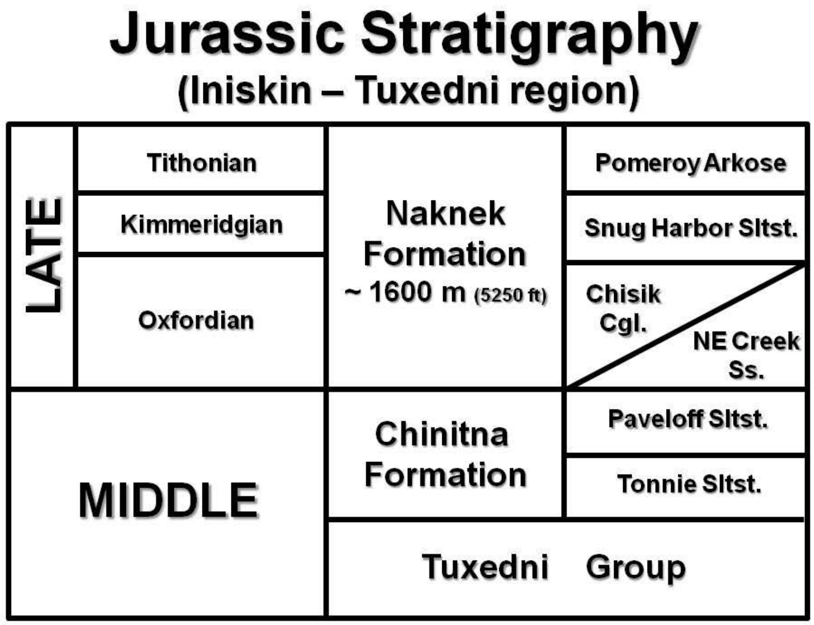

Figure 37. Simplified stratigraphic chart of Jurassic forearc basin units in the Iniskin Bay area, based on Detterman and Hartsock (1966) and Detterman and others (1996).

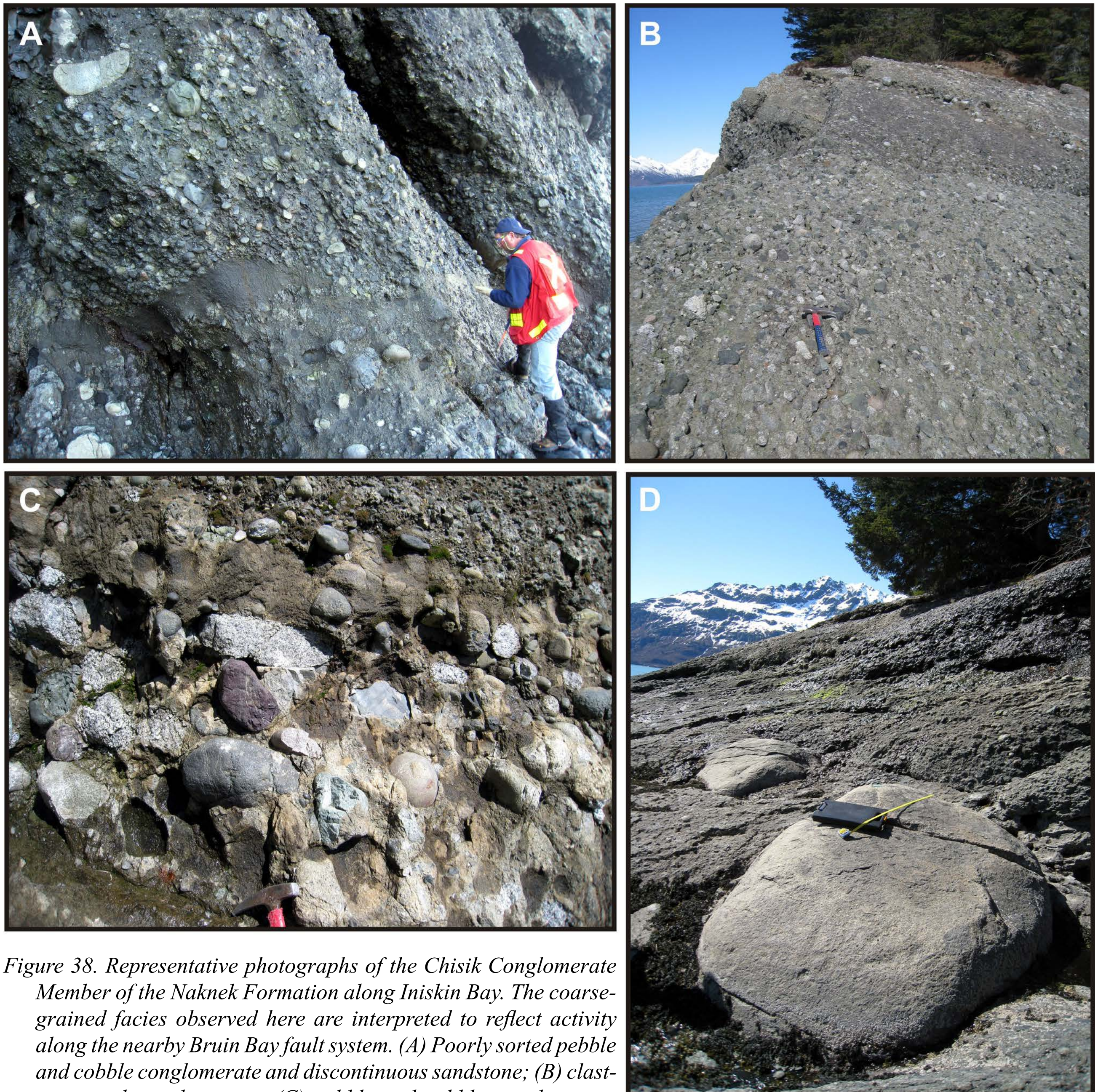

Figure 38. Representative photographs of the Chisik Conglomerate Member of the Naknek Formation along Iniskin Bay. The coarse-grained facies observed here are interpreted to reflect activity along the nearby Bruin Bay fault system. (A) Poorly sorted pebble and cobble conglomerate and discontinuous sandstone; (B) clast-supported conglomerate; (C) pebble and cobble conglomerate illustrating mix of volcanic and plutonic clast types; (D) example of largest observed clast (2.8 × 1.9 m).

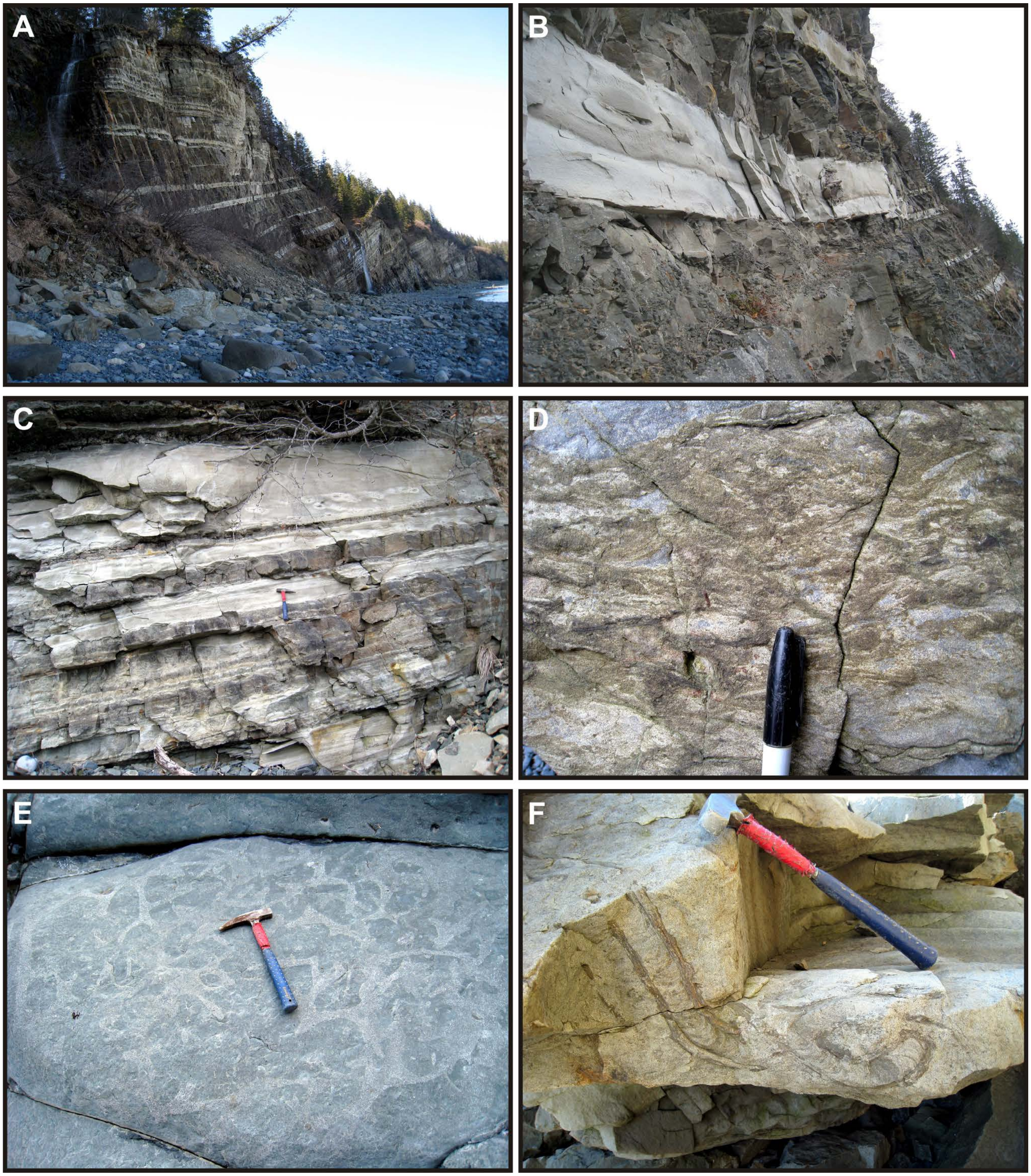

Figure 39. Representative photographs of the Northeast Creek Sandstone Member of the Naknek Formation in Oil Bay. This interval is interpreted as the basinward equivalent of the Chisik Conglomerate. (A) Banded appearance typical of this unit aids differentiation from bounding units above and below, which lack this characteristic; (B) light-colored, arkosic, tabular-bedded, very-fine- to fine-grained, laumontite-cemented sandstone interbedded with brown-colored, hackly weathering, very-fine-grained, bioturbated sandstone; (C) cyclic stacking of laminated, rippled sandstone interbedded with bioturbated siltstone interval is interpreted as stacked tempestites; (D) moderate bioturbation fabric where original lamination is still partly preserved; (E) robust Thalassinoides burrows filled with coarse-grained sand; (F) nested Rhizocorallium trace fossils.

Figure 40. Annotated photograph of the interpreted contact between the Northeast Creek Sandstone Member (Jnn) and the Snug Harbor Siltstone Member (Jns) of the Naknek Formation, western Oil Bay. Note the transition upward to the more recessive Snug Harbor, here interpreted as a significant transgressive unit.

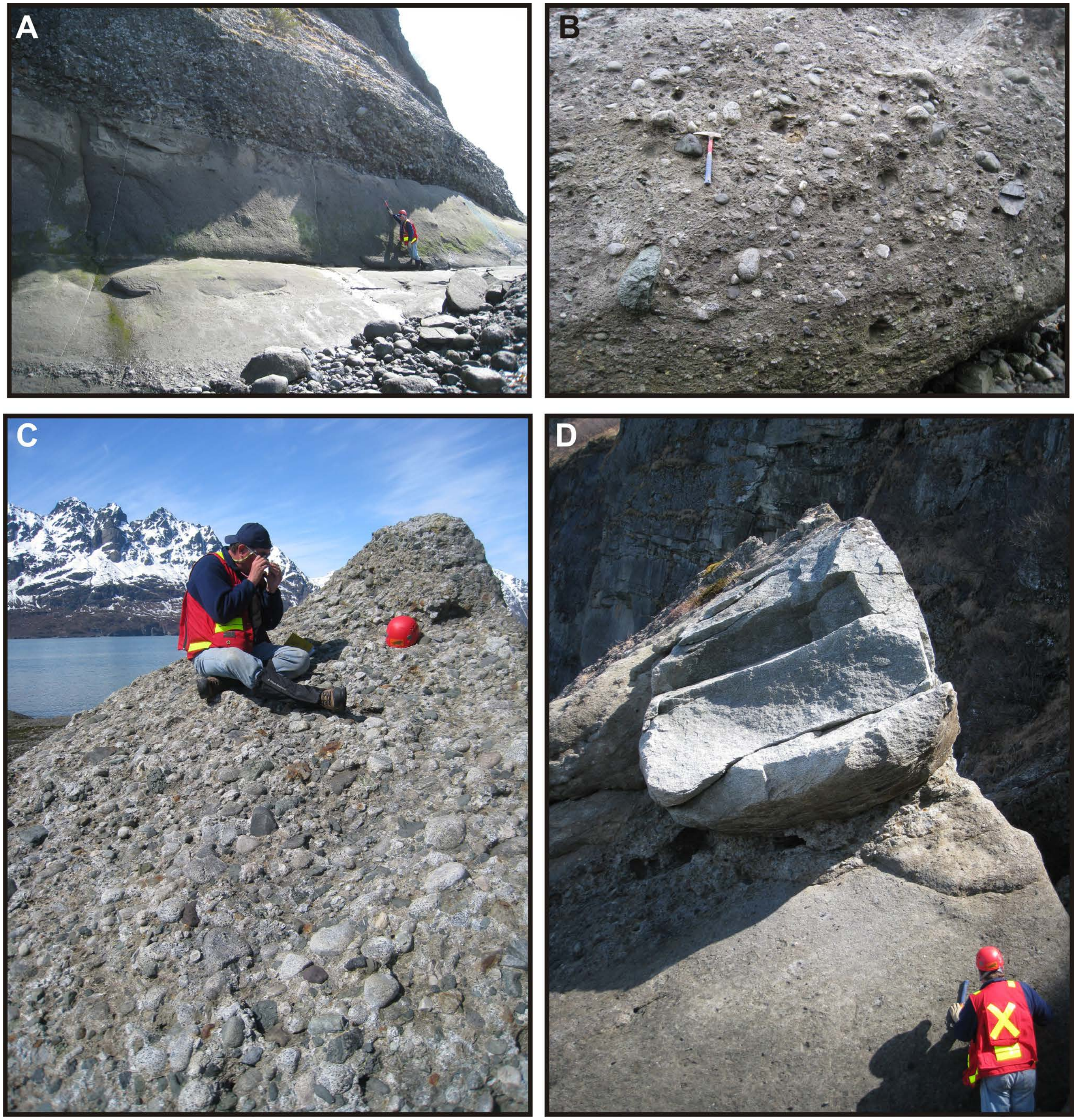

Figure 41. Representative photographs of the Pomeroy Arkose Member of the Naknek Formation along Iniskin Bay. Similar to the Chisik Conglomerate, the coarse-grained facies observed here are interpreted to reflect activity along the nearby Bruin Bay fault system. (A) Thick, amalgamated beds of medium- to coarse-grained sandstone and moderately sorted pebble conglomerate; (B) poorly sorted conglomerate; (C) clast-supported conglomerate illustrating the abundance of diorite pebbles and cobbles derived from the unroofing Talkeetna arc; (D) example of largest observed clast (~3 m diameter).

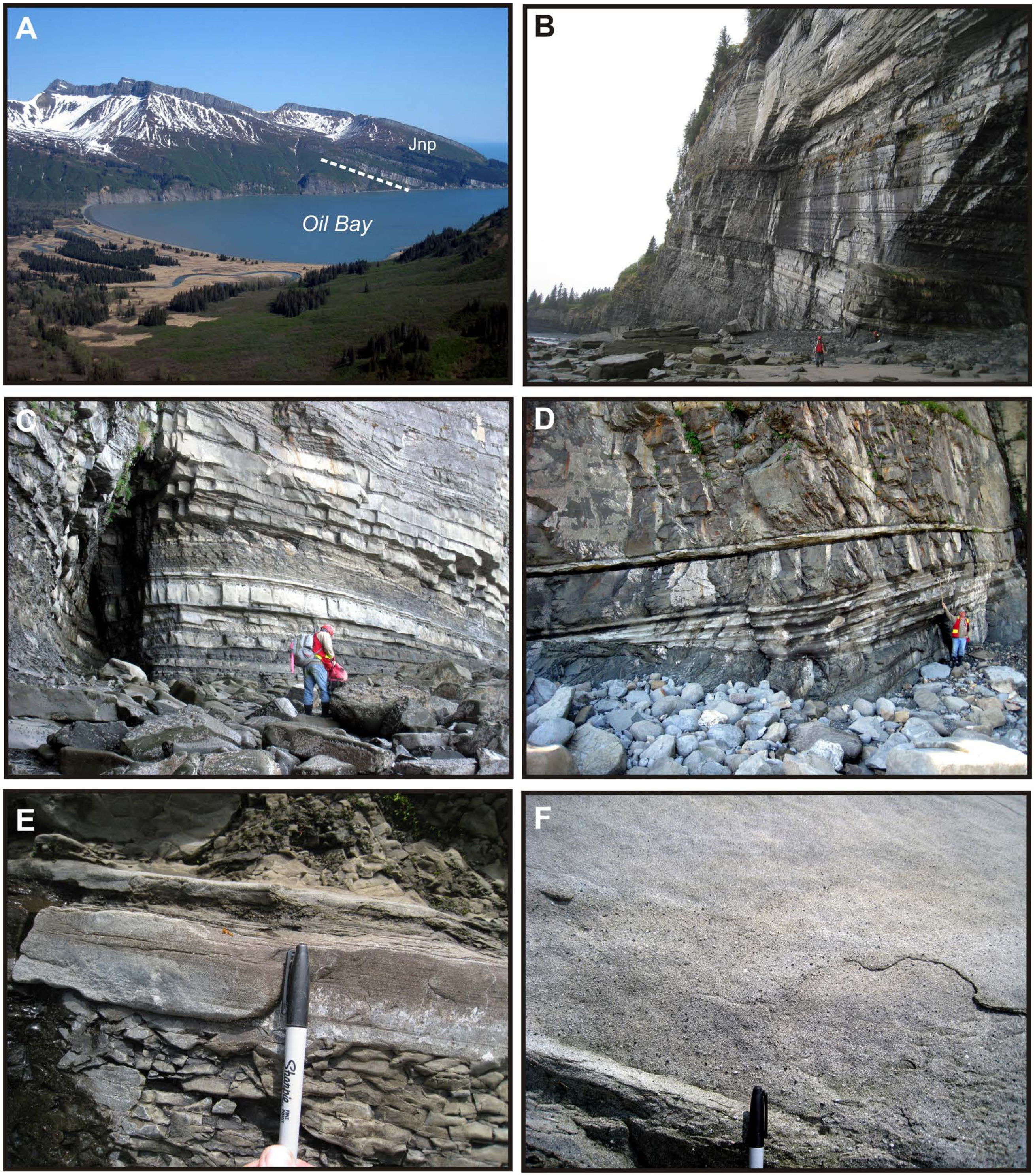

Figure 42. Representative photographs of the Pomeroy Arkose Member of the Naknek Formation along Oil Bay. (A) View to the southeast across Oil Bay showing the resistant Pomeroy (Jnp), which forms prominent cuestas with flat-irons dipping southeastward into Cook Inlet; (B) example of rugged coastal exposures of laterally continuous, tabular-bedded sandstone and siltstone; (C) upward-thickening packages of sandstone and siltstone interpreted as stacked sediment gravity-flow deposits; (D) incision along the margin of a submarine channel; (E) normally graded fine- to very-fine sandstone with massive to laminated internal structure and capped by weakly developed current ripples—interpreted as partial Bouma sequence associated with turbidite deposition; (F) upward-fining, poorly sorted, structureless sandstone interpreted as high concentration mass flow deposit.

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