Oil-stained sandstones of the Upper Jurassic Naknek Formation and Upper Cretaceous Kaguyak Formation, Kamishak Bay area, lower Cook Inlet, Alaska

Trystan M. Herriott[1], Marwan A. Wartes[1], Richard G. Stanley[2], Paul G. Lillis[3], Kenneth P. Helmold[4], Paul L. Decker[4], Robert J. Gillis[1]

[1]Alaska Division of Geological & Geophysical Surveys, Fairbanks, AK (contact: trystan.herriott@alaska.gov)

[2]U.S. Geological Survey, Menlo Park, CA; [3]U.S. Geological Survey, Denver, CO; [4]Alaska Division of Oil & Gas, Anchorage, AK

Our Kamishak Bay work focuses on the Mesozoic stratigraphy and structure of lower Cook Inlet, and is ongoing. Much of the data and interpretations presented here are preliminary and have not yet undergone rigorous technical and peer review. Further information about this project is provided by Gillis (2013), which is available online at http://www.dggs.alaska.gov/publications.

Abstract

The Cook Inlet basin of south-central Alaska hosts a prolific petroleum system that has been producing oil and gas for more than 55 years (e.g., Magoon, 1994). The basin's producing reservoirs are nonmarine sandstone and conglomerate of Tertiary age (e.g., LePain et al., in press), and oil is principally sourced from organic-rich shales in the Middle Jurassic Tuxedni Group (Magoon and Anders, 1992; Lillis and Stanley, 2011). A persistent and as of yet unanswered question is whether the Upper Jurassic through Cretaceous stratigraphy of Cook Inlet hosts conventional oil reservoirs. Limited direct observations have been made in this regard and include fault- and fracture-controlled oil seeps in Jurassic rocks on the Iniskin Peninsula (Detterman and Hartsock, 1966), oil shows in Upper Cretaceous strata of the Raven No. 1 (see LePain et al., 2012) and Anchor Point No. 1 (unpublished industry data) wells, and oil stain in the Maastrichtian Saddle Mountain section (LePain et al., 2012).

During July–August 2012 fieldwork in the Kamishak Bay area of lower Cook Inlet, we studied an oil-stained outcrop in the Upper Jurassic Naknek Formation and discovered, in modern alluvium, oil-stained cobbles and boulders likely derived from nearby outcrops of the Upper Cretaceous Kaguyak Formation. We report our field observations and initial interpretations herein.

The hydrocarbon-bearing outcrop of Naknek Formation lies immediately north of the south shore of Kamishak Bay on a small, unnamed island near the mouth of Douglas River. The oil seep has previously been noted only briefly in published accounts (Magoon et al., 1975 (p. 19); Lyle and Morehouse, 1977 (p. E-1)). In this area, the Naknek Formation chiefly comprises cross-stratified and bioturbated sandstone, with locally abundant molluscan shells and plant debris. Sedimentary facies and an accompanying trace fossil assemblage suggest that these strata were deposited in a moderate to high-energy marine shoreface setting. Freshly-broken surfaces of the hydrocarbon-bearing sandstone have a strong—yet fleeting—kerosene-like odor. Hand-lens observations suggest that the oil-stained sandstone largely consists of quartz and potassium feldspar, with subordinate plagioclase and heavy minerals. Our observation of quartz-rich Naknek strata—and the likely relative abundance of potassium feldspar versus plagioclase—in the Douglas River area starkly contrasts with the quartz-poor and plagioclase-rich Naknek in the Iniskin–Tuxedni region reported by Helmold et al. (2011). The occurrence of quartz-rich and plagioclase-poor Naknek sandstone is significant, because a more mature mineralogy is less susceptible to zeolite cementation and thus more likely to retain primary porosity upon moderate to deep burial (cf. Helmold et al., 2011). Hydrocarbon-stained sandstone at the Douglas River locality indicates that the Naknek Formation, at least locally, may serve as a conventional reservoir of petroleum. Numerous sandstone samples from the Naknek Formation in the Kamishak Bay area are currently being analyzed for reservoir quality, petrology, and organic geochemistry.

During a reconnaissance traverse along an unnamed, north flowing tributary of the Douglas River, we discovered abundant cobbles and small boulders of oil-stained sandstone in the modern stream gravel that were strongly petroliferous, particularly on freshly broken surfaces. The oil-stained rocks largely comprise very fine- to fine-grained sandstone and weather light gray to tan and light greenish-gray. Oil stain occurs 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 hydrocarbons within a small vug. The hydrocarbon-bearing clasts in float are dissimilar to the nearby outcrops of Lower Cretaceous Herendeen Formation, and we infer that the clasts were sourced from outcrops of the overlying Kaguyak Formation that are exposed in small catchments immediately upstream to the east and south. We constrained the likely source of the oil-stained sandstone to a zone within the lower Kaguyak Formation that exhibits a similar weathering color and character, although we were unable to directly access the candidate outcrops due to extremely steep and inaccessible terrain. We collected several oil-stained samples from the alluvial cobbles and boulders to be analyzed for reservoir quality, petrology, and organic geochemistry; analytical results are pending.

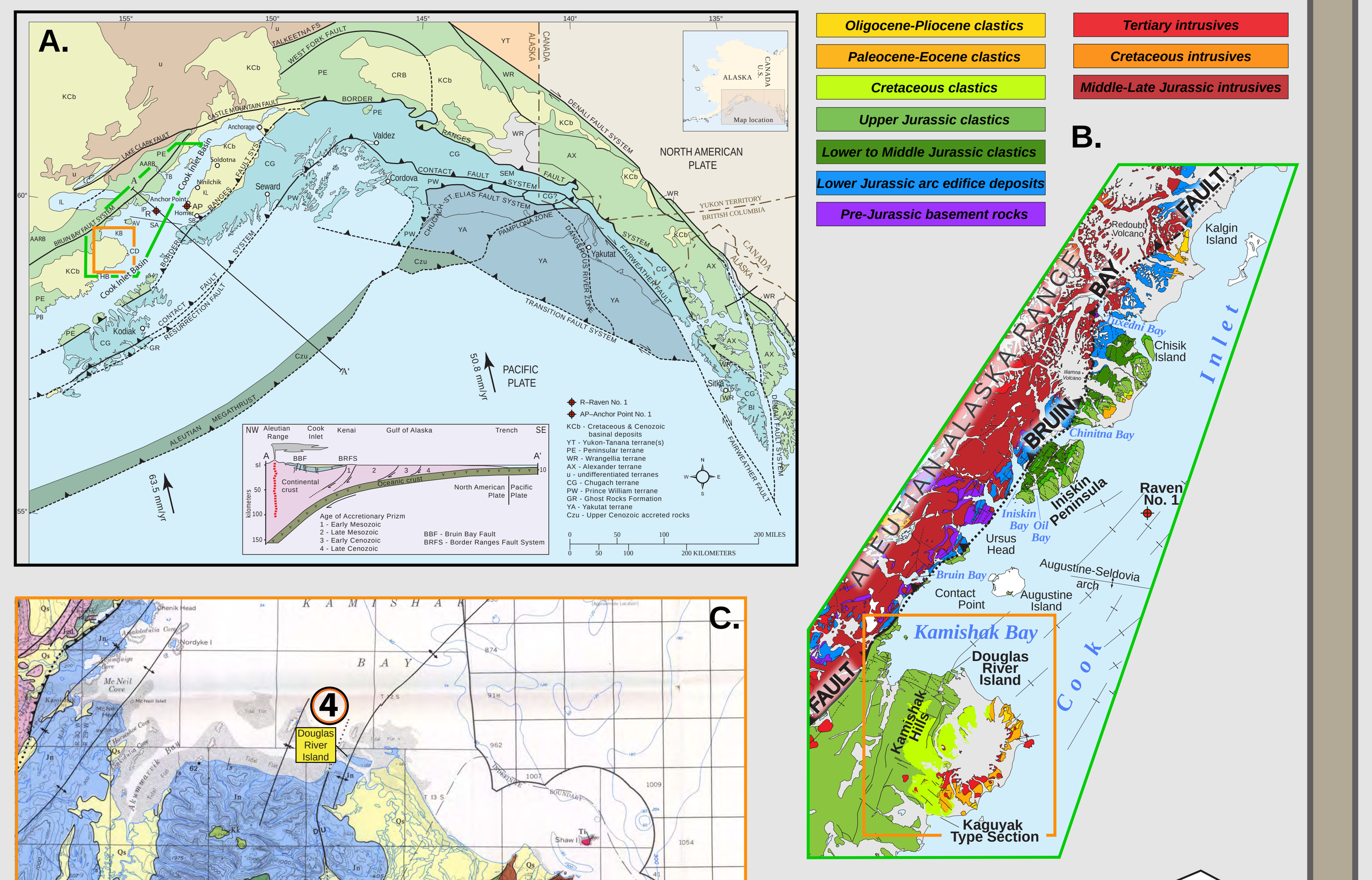
The observations reported herein are consistent with the preliminary hypothesis that an active petroleum system is present in the southern Kamishak Bay area, and that this petroleum system may include oil-generating source rocks in the Middle Jurassic Tuxedni Group as well as potential oil-bearing reservoir rocks in the Upper Jurassic Naknek Formation and Upper Cretaceous Kaguyak Formation. Additionally, the occurrence of oil-stained and apparently more compositionally mature Naknek Formation sandstone in the Douglas River area of Kamishak Bay suggests that sufficient compositional variability exists within the Naknek for it to serve, at least locally, as a conventional reservoir in the Cook Inlet basin. Furthermore, hydrocarbon-bearing Upper Cretaceous sandstones have now been documented in both wells and outcrop in the lower Cook Inlet basin. Therefore, sandstones in the Upper Jurassic through Upper Cretaceous section of Cook Inlet may yet prove to be viable conventional oil exploration targets.

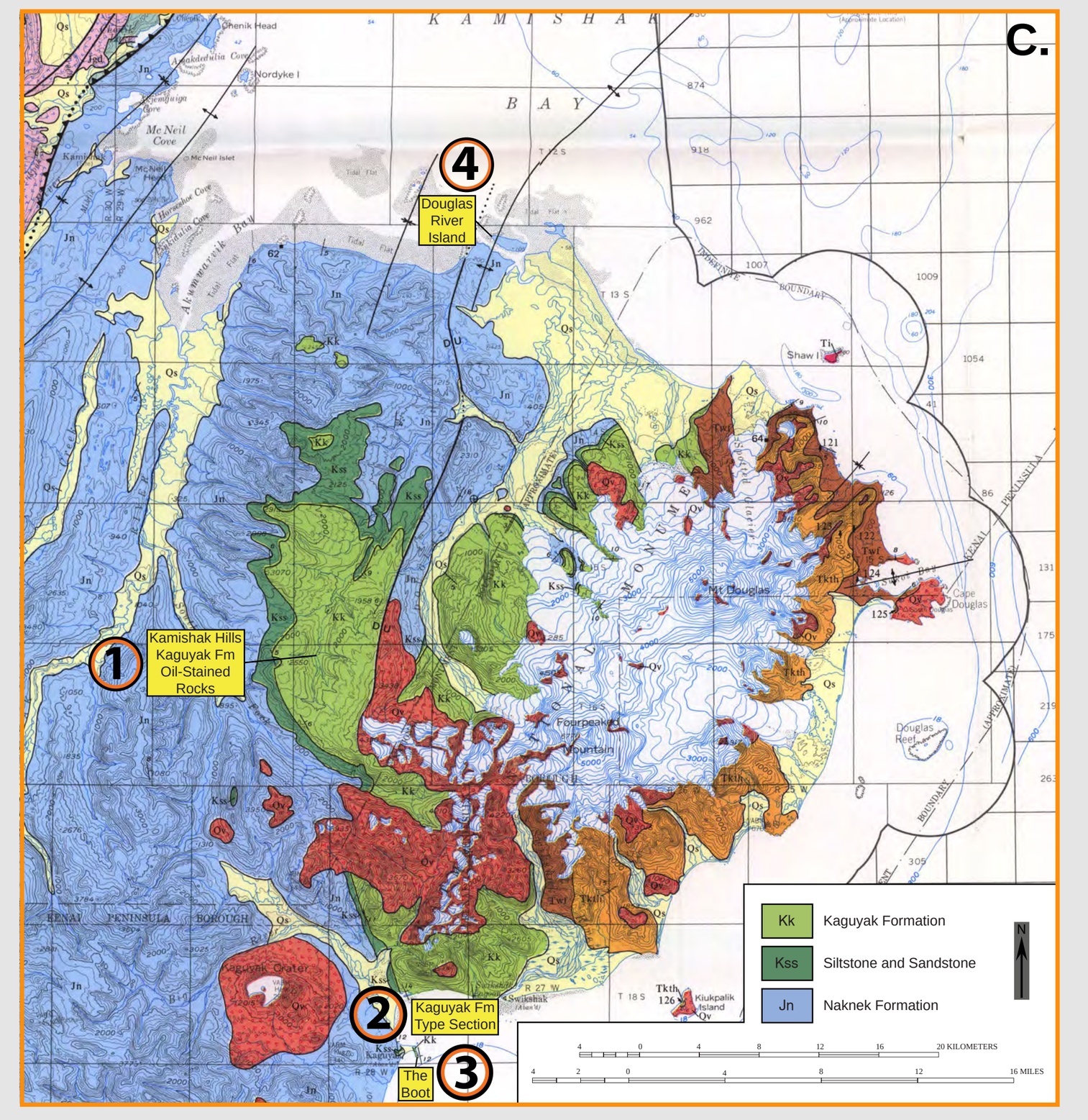
Key Highlights and Observations

- Current oil production in Cook Inlet is limited to Tertiary-age reservoirs
- Oil source rocks of Cook Inlet principally occur in the Middle Jurassic Tuxedni Group
- ***Do Jurassic through Cretaceous strata in Cook Inlet host conventional oil reservoirs?***
- We examined two localities in the Kamishak Bay area where oil-stained Upper Jurassic Naknek Formation and Upper Cretaceous Kaguyak Formation sandstones occur; the Kaguyak oil-stained locality is newly discovered, and the Naknek locality has heretofore only be briefly described
- Kaguyak lithofacies and detrital composition vary significantly throughout the Kamishak Bay area and undoubtedly influence potential reservoir quality
- Hydrocarbon-bearing Upper Cretaceous sandstones have now been documented in both wells and outcrop in the lower Cook Inlet basin
- In contrast to the Naknek of the Iniskin Peninsula area, more compositionally mature Naknek sandstones in the Douglas River area suggest sufficient regional compositional variability may exist within the Naknek for it to serve, at least locally, as a conventional oil reservoir
- An active petroleum system is present in the southern Kamishak Bay area of lower Cook Inlet, and may include oil-generating source rocks in the Middle Jurassic Tuxedni Group and potential reservoir rocks in the Naknek and Kaguyak formations
- Organic geochemistry results for the oil-stained rocks are pending
- Our work in lower Cook Inlet is ongoing, with additional fieldwork scheduled for summer 2013

Regional Context

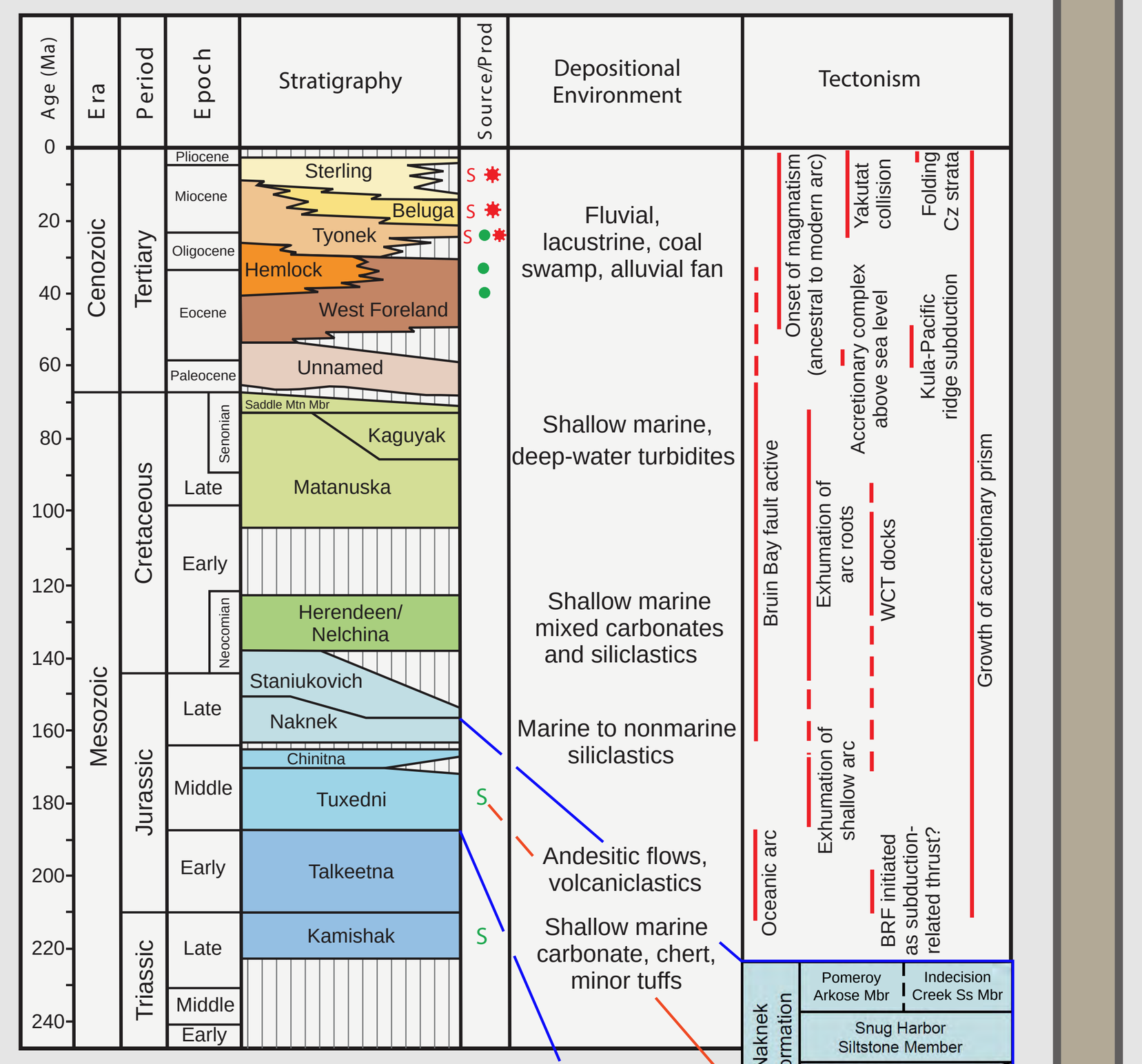
Location Maps





The long-lived Cook Inlet forearc basin hosts sediments as old as Middle Jurassic (see right) and lies between the Bruin Bay and Border Ranges fault systems that are bordered, respectively, by the Aleutian-Alaska Range batholith (AARB) to the northwest and an emergent accretionary prism comprising the Chugach and Kenai mountains (CG) to the southeast (see A). Our most recent work in the region has focused on Middle Jurassic through Cretaceous strata exposed from Tuxedni Bay to south of Kamishak Bay along the basin's northwestern margin (see B). During fieldwork in the Kamishak Bay area in 2012, we examined occurrences of oil-stained sandstones in the Upper Jurassic Naknek Formation ("Douglas River island") and Upper Cretaceous Kaguyak Formation (Kamishak Hills) (see C). We also described two detailed measured sections in the upper part of the Kaguyak Formation type section, and conducted a detailed traverse of the lowermost Kaguyak at an exposure we informally refer to as "the boot." Figure A modified after Winkler (2000); figure B modified after Gillis (2013); figure C modified after Magoon et al. (1976)

Stratigraphy



Stratigraphy
Depositional Environment
Tectonism
Fluvial, lacustrine, coal swamp, alluvial fan
Shallow marine, deep-water turbidites
Shallow marine mixed carbonates and siliciclastics
Marine to nonmarine siliciclastics
Andesitic flows, volcaniclastics
Shallow marine carbonate, chert, minor tuffs
Kaguyak
Matanuska
Herendeen/ Nelchina
Naknek
Tuxedni
Talkeetna
Kamishak
Paveloff Siltstone Member
TonnieSiltstone Member
Chinitna Formation
Bowser Formation
Twist Creek Siltstone
Cynthia Falls Sandstone
Fitz Creek Siltstone
Gaikema Sandstone
Red Glacier Formation
Tuxedni Group

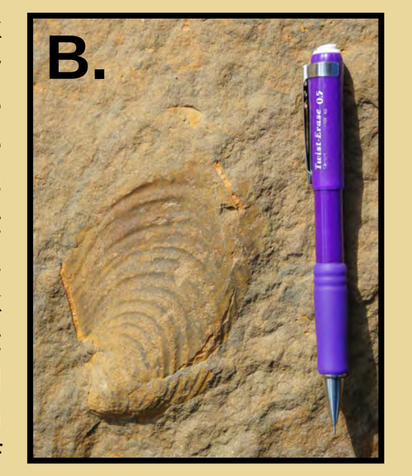
The nearly 190 million year stratigraphic record of the Cook Inlet forearc basin comprises more than 35,000 feet of Middle Jurassic through Cretaceous marine strata and up to 25,000 feet of nonmarine Tertiary deposits. Oil and gas are produced from sandstones within the Tertiary section; however, the oil is chiefly sourced from the underlying Middle Jurassic Tuxendi Group, while the gas—of biogenic origin—is sourced from Tertiary coals. Red S indicates gas source rock; green S indicates oil source rock; red asterisk represents gas production; green circle represents oil production. Figure modified after Gillis (2013).

A. Exposure of dark-gray silty mudstone in the Middle Jurassic Red Glacier Formation along the north side of Red Glacier between Tuxedni and Chinitna bays; organic-rich marine shales of the Tuxedni Group are the principal source of oil in the producing, Tertiary-age reservoirs of Cook Inlet. See Stanley et al. (2013a) for further information about the Red Glacier Formation. Photo by Rick Stanley.

Kaguyak Formation—Kkg

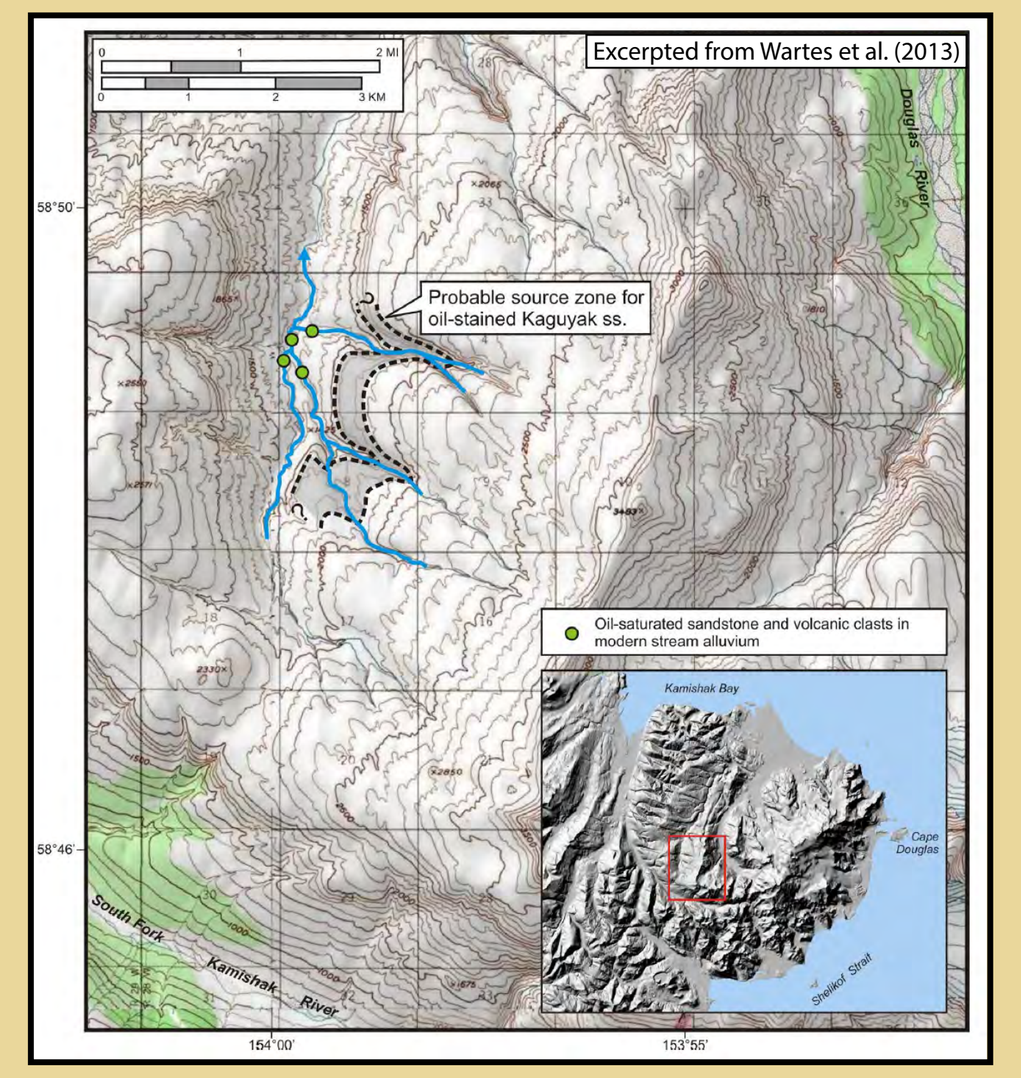
① Kamishak Hills Oil-Stained Rocks

Although the Kaguyak Formation locally crops out prominently within the Kamishak Hills, most of the exposures are extremely steep and inaccessible, with limited helicopter access. Nevertheless, we examined several outcrops in the area. The thick-bedded, major cliff-former of this photo is suspected to be the source interval for oil-stained sandstone boulders and cobbles discovered downstream (see map below). Photo by Trystan Herriott.



Kaguyak in the Kamishak Hills area is distinctly different than at the type section (see right), with the latter exhibiting ubiquitous evidence of sediment gravity flow deposition. Kamishak Hills Kaguyak strata yield abundant evidence of shelfal sedimentation, including thick sections of bioturbated siltstone and sandstone with discrete traces such as *Paleophycos*, *Thalassinoides* (A), *Planolites*, and possible *Terebellina*. Inoceramids (B) and coalified woody debris are locally abundant. Photos by Trystan Herriott.

We discovered abundant cobbles and small boulders of Kaguyak sandstone in the modern stream gravel that are strongly petroliferous, particularly on freshly broken surfaces (Wartes et al., 2013). A. Oil-stained sandstone clast in modern river gravel. B. Light-gray-weathering oil-stained clast with healed fractures. C. Porphyritic, Tertiary-age andesite boulder with oil-lined fracture and vug fill. Photos by Marwan Wartes (A and B) and Trystan Herriott (C).

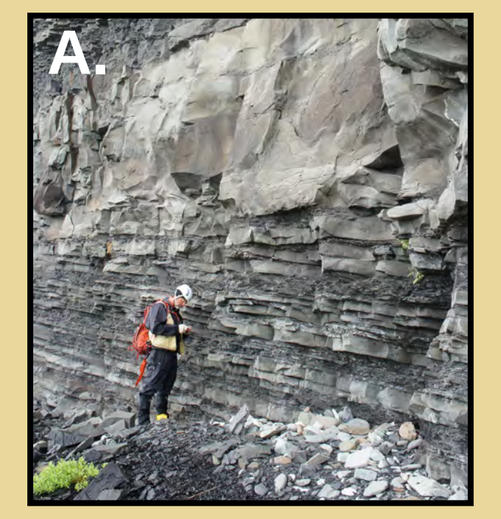


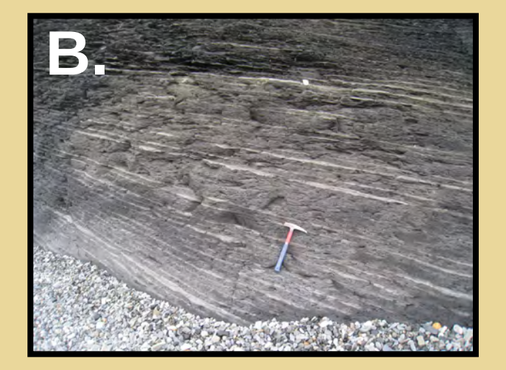
Excerpted from Wartes et al. (2013)
Probable source zone for oil-stained Kaguyak ss.
Oil-saturated sandstone and volcanic clasts in modern stream alluvium
Kamishak Bay
Cape Douglas
Shelikof Strait
South Fork Kamishak River
58°50'
58°46'
154°00'
153°55'

② Kkg Type Section

We measured two detailed stratigraphic sections (see right for one of these) within the upper ~300 m of the Kaguyak type section. These sections are dominated by a well-bedded, rhythmic stratigraphy of alternating siltstone and very-fine- to medium-grained sandstone. Photo by Marwan Wartes.

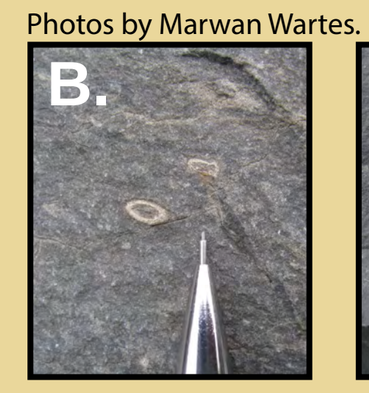
Our observations, including lithofacies, sedimentary structures, and dearth of trace and body fossils, are consistent with deposition via sediment gravity flows beyond the shelf edge (i.e., basin floor to toe-of slope, and possibly slope). A. Rhythmic interbeds of siltstone and very-fine-grained sandstone overlain by an amalgamated, fine-grained sandstone bed. B. Heterolithic facies comprising siltstone and rippled, very-fine-grained sandstone. C. Dark-gray-weathering, siltstone-dominated package abruptly overlain by tens of meters of light-gray-brown-weathering, amalgamated sandstone. Orange backpack for scale. Photos by Trystan Herriott (A) and Marwan Wartes (B and C).

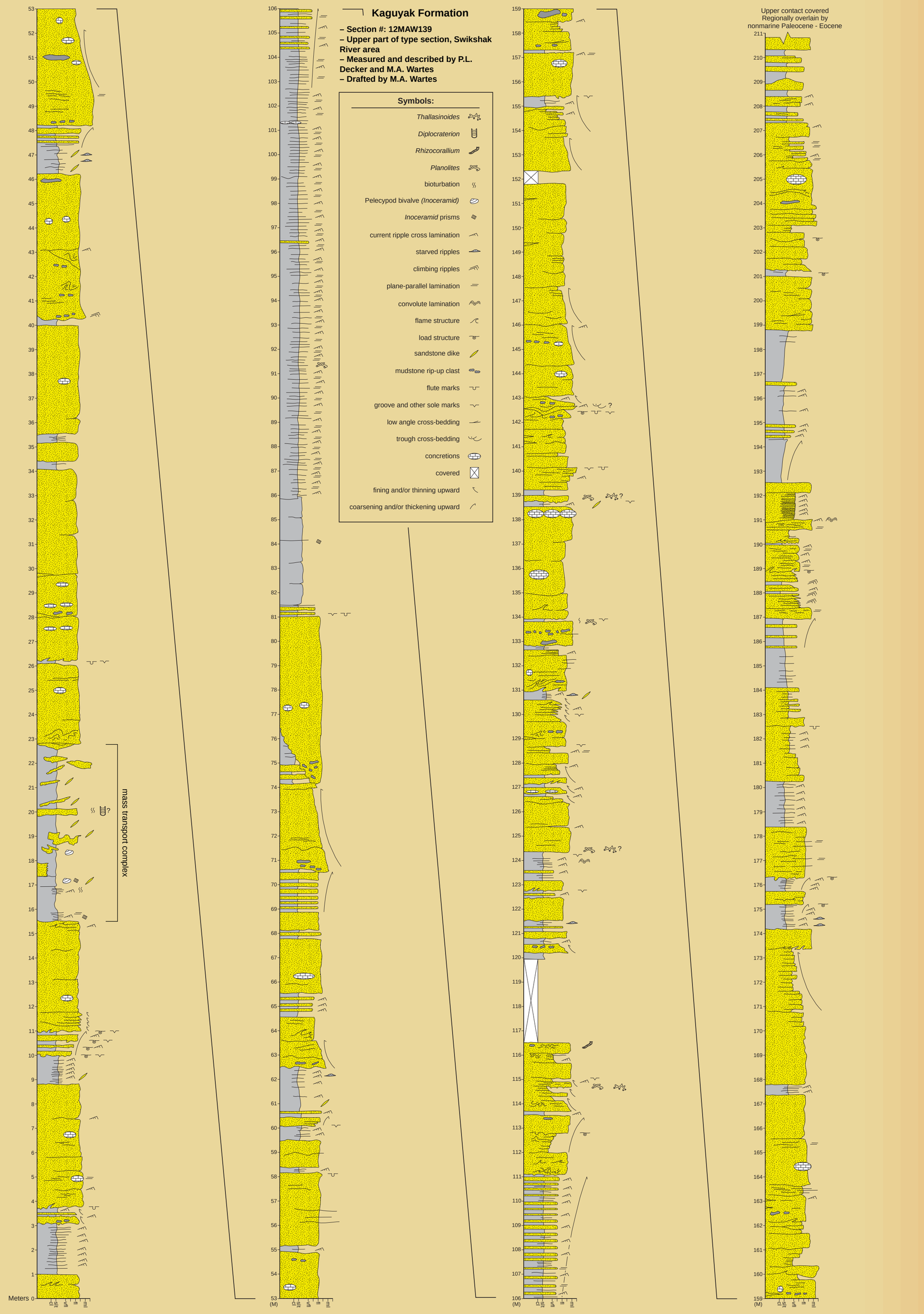




③ Lowermost Kkg–"The Boot"

The lowermost Kaguyak comprises medium- to thick-bedded, structureless, very-fine-grained sandstone and lesser siltstone (A). A diverse and abundant trace fossil assemblage (e.g., *Schaubcylindrichnus* (B), *Teichichnus* (C), and *Thalassinoides* (D)), thorough bioturbation, and rarely observed sedimentary structures are consistent with offshore transition to shelfal deposition at least in part below wave base. Photos by Marwan Wartes.





Naknek Formation—Jn

④ "Douglas River Island" Oil-Stained Locality

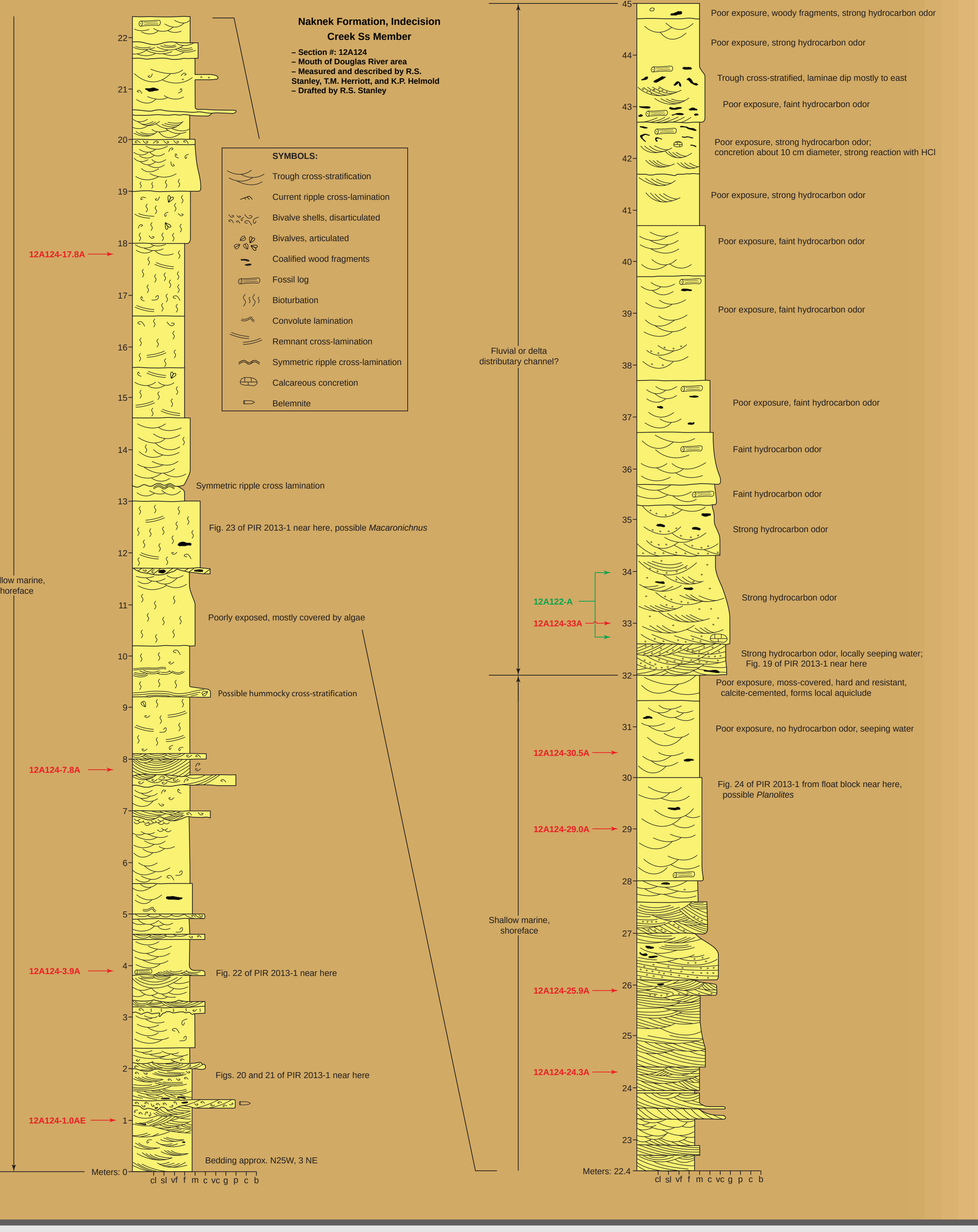
Eastward view across the mouth of Douglas River toward "Douglas River island," with Kamishak Bay and Cook Inlet in the background. Light-colored sandstone beds of the Naknek Formation dip gently upstream (toward photo-right) in low cliffs along the Douglas River, which here is about 500 m wide. Our detailed, 45-m-thick measured section (see right) lies between the two red arrows. The stratigraphically highest beds (tan-colored interval near red arrow at right; see photo at right) are hydrocarbon bearing and have a strong, kerosene-like odor (Stanley et al., 2013a). Photo by Rick Stanley.

Eastward view of hydrocarbon-bearing Naknek sandstone. 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 this photo and submitted to the USGS organic geochemical laboratory in Denver, Colorado, for analysis of the hydrocarbons; results are pending. Photo by Trystan Herriott.

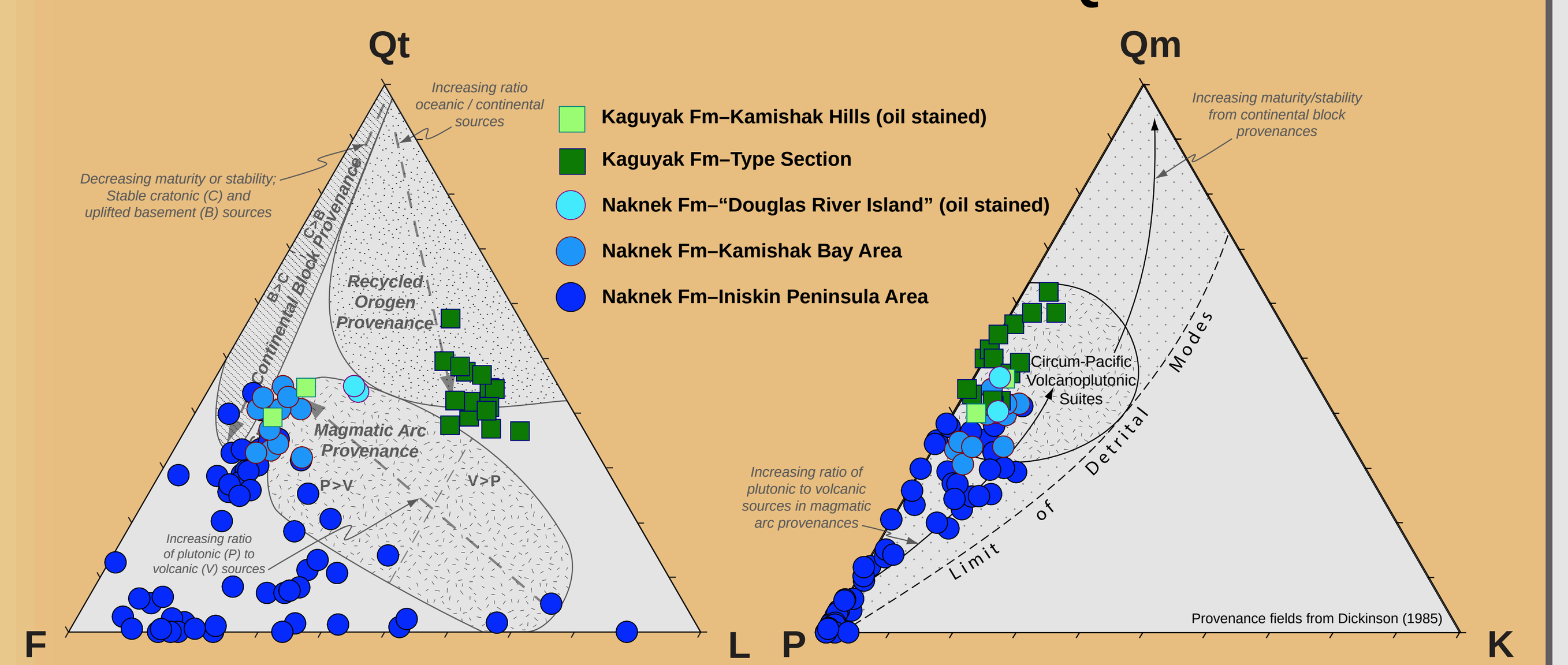
A. Northeastward view of petroliferous sandstone that extends from where geologists stand at photo-lower left to vegetative cover at photo-lower right (corresponds to 32–45 m interval of measured section). Photo by Trystan Herriott.

Our observations of the oil-stained interval and underlying strata are consistent with deposition in shallow marine (shoreface) and fluvial or delta distributary channel(?) environments. B. Coquina bed of molluscan shells and shell fragments near the base of the measured section. C. Detail of outcrop about 20–25 m stratigraphically below the hydrocarbon-bearing sandstone. 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. D. Fragment of flattened log in sandstone about 28 m stratigraphically below the hydrocarbon-bearing sandstone. Rock hammer is ~ 30 cm long. E. Ichnofossils in sandstone, probably *Planolites*, in a float block about 2 m stratigraphically below the hydrocarbon-bearing interval. Barrel of pencil ~1 cm diameter. Photos by Rick Stanley.

Detail of hydrocarbon-bearing sandstone, with coarse, granular texture and cross-stratification. Rock hammer is ~30 cm long. Photo by Rick Stanley.

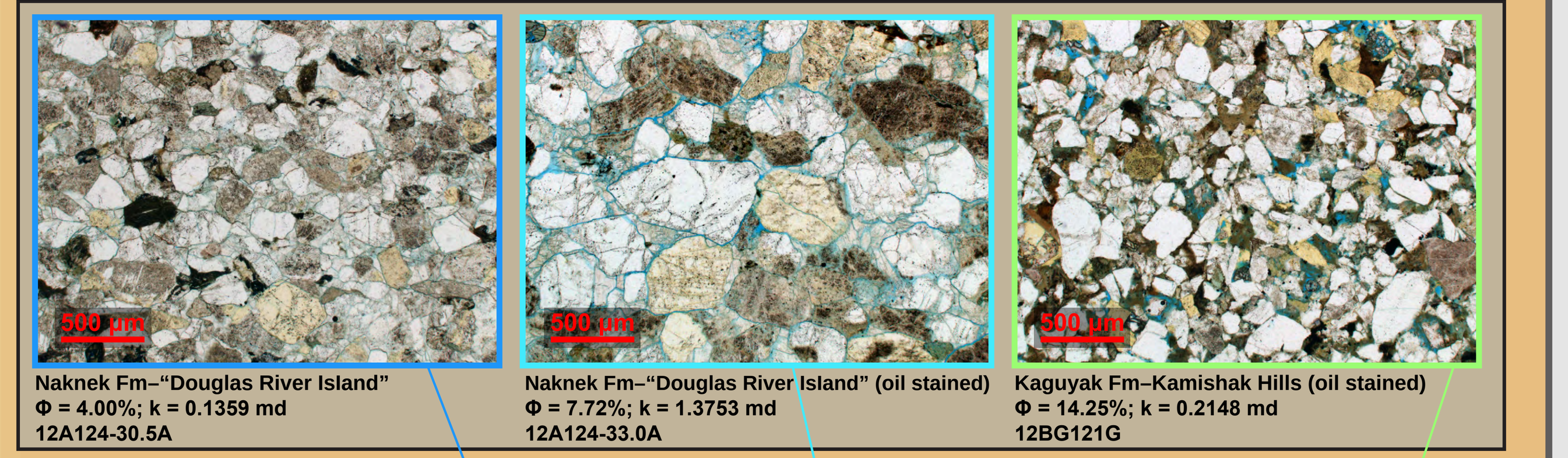


Petrology and Reservoir Quality



Qt
Qm
F
L
P
K
Recycled Orogen Provenance
Magmatic Arc Provenance
Increasing ratio of plutonic (P) to volcanic (V) sources
P>V
V>P
Increasing ratio of plutonic to volcanic sources in magmatic arc provenances
Limit of
Provenance fields from Dickinson (1985)
Kaguyak Fm–Kamishak Hills (oil stained)
Kaguyak Fm–Type Section
Naknek Fm–"Douglas River Island" (oil stained)
Naknek Fm–Kamishak Bay Area
Naknek Fm–Iniskin Peninsula Area

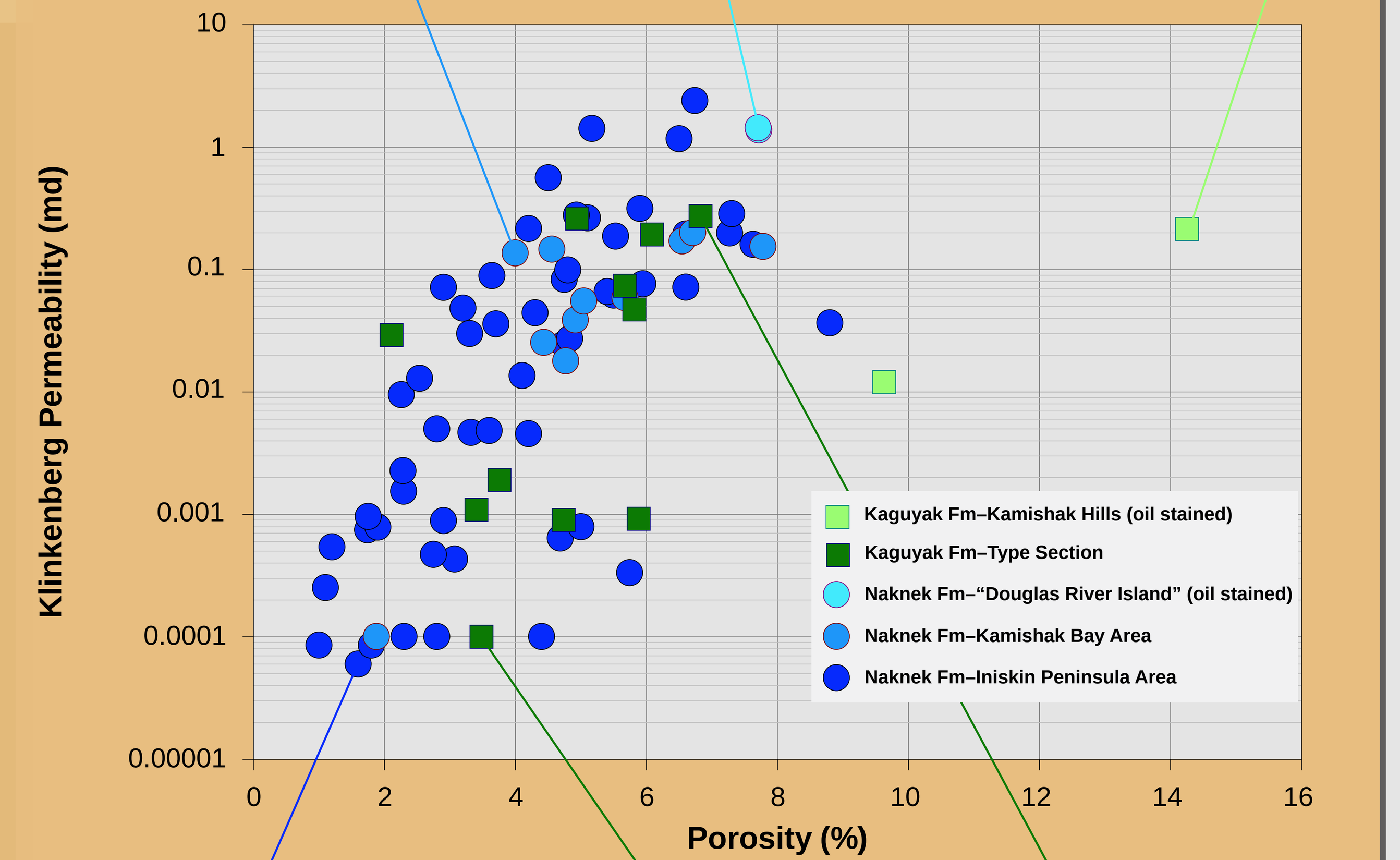
Naknek Formation sandstones from the Iniskin Peninsula area consist largely of calcic plagioclase with variable amounts of volcanic rock fragments and are typically cemented by laumontite, resulting in reduced reservoir quality. In contrast, Naknek sandstones from the Kamishak Bay area contain greater proportions of both quartz and K-feldspar, but are also cemented by laumontite. The oil-stained Naknek sandstones of Douglas River island are the most quartzose of the Naknek samples collected from throughout the Kamishak Bay area; interestingly, the oil-stained Naknek contains numerous micro-fractures, which may be partially responsible for the significant (blue) staining (see photomicrograph below). Kaguyak Formation sandstone samples collected from the type section are distinctly different from the Naknek in that they contain a high proportion of chert, mudstone and phyllite rock fragments. Due to the abundance of ductile argillaceous grains, these Kaguyak sandstones are susceptible to porosity loss through compaction. Cobbles and boulders of Kaguyak sandstone collected from stream beds in the Kamishak Hills have a detrital composition more similar to the quartzose Naknek sandstones from the Kamishak Bay area, although they lack laumontite cement and thus exhibit increased reservoir quality parameters (see porosity–permeability plot below). Ternary diagrams, photomicrographs, and porosity–permeability plot by Ken Helmold.



Naknek Fm–"Douglas River Island" Φ = 4.00%; k = 0.1359 md 12A124-30.5A

Naknek Fm–"Douglas River Island" (oil stained) Φ = 7.72%; k = 1.3753 md 12A124-33.0A

Kaguyak Fm–Kamishak Hills (oil stained) Φ = 14.25%; k = 0.2148 md 12BG121G



Klinkenberg Permeability (md)
Porosity (%)
10
1
0.1
0.01
0.001
0.0001
0.00001
0
2
4
6
8
10
12
14
16
Kaguyak Fm–Kamishak Hills (oil stained)
Kaguyak Fm–Type Section
Naknek Fm–"Douglas River Island" (oil stained)
Naknek Fm–Kamishak Bay Area
Naknek Fm–Iniskin Peninsula Area

Naknek Fm–Iniskin Peninsula Area Φ = 1.60%; k = 0.00006 md 10DL007-0.8A

Kaguyak Fm–Type Section Φ = 3.48%; k = 0.0001 md 12A149-10.8A

Kaguyak Fm–Type Section Φ = 6.82%; k = 0.2742 md 12MAW139-155.4A

References Cited