Chapter FI (Petroleum Occurrence and Timing of Migration)

EVIDENCE FOR PETROLEUM OCCURRENCE AND TIMING OF MIGRATION: PETROLEUM FLUID INCLUSIONS, DEAD OIL, STAINS, AND SEEPS

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ABSTRACT

Geologic constraints on the timing of oil and gas migration are evaluated from evidence of the areal and stratigraphic distribution of hydrocarbons as seeps, stains, dead oil, and fluid inclusions. The petrographic setting and temperature measurements on fluid inclusions combined with apatite fission track analysis of host rocks places additional limits on the timing of migration. The most recent oil migration is documented by seeps of biodegraded oil along the coast of northeastern ANWR at Angun Point and Manning Point. The next oldest stage of hydrocarbon migration is related to the 20 to 25 Ma deformation associated with uplift of the Sadlerochit Mountains and formation of traps at the Kavik and Kemik gas fields where an initial oil charge to Sadlerochit Group sediments was replaced by a gas charge. Oil migration in the Kemik Sandstone in the Ignek Valley occurred at about 33 Ma to possibly as old as 45 Ma. Gas migration is linked to the formation of the Ellesmerian Thrust Belt in eastern ANWR by methane-rich inclusions in crack-seal textures in fractures at Leffingwell Ridge. Gas charged fracture porosity in these rocks at depths of about 7 km. and temperatures of 200 to 220 ^{o}C at about 45 Ma.

The occurrence of dead oil in deformed sandstones exposed at the surface and the presence of gas and condensate fluid inclusions in fracture filling cements in outcrop suggests that petroleum traps were once widespread throughout the frontal outcrops of the Brooks Range in northern ANWR. These traps either lost hydrocarbon charge by remigration in the subsurface during deformation and uplift, or were breached by erosion and the hydrocarbons lost from the petroleum systems by seeps at some time following uplift of the Sadlerochit and Shublik Mountains about 20 Ma.

INTRODUCTION

A key factor in assessing the petroleum resources of frontier areas is the timing of oil and gas migration relative to trap formation. In tectonically deformed areas, the distribution of petroleum as oil stains, dead oil, and oil and gas fluid inclusions can reveal the distribution of oil and gas reservoirs that were uplifted, breached, and presently exposed at the surface. Where thrust tectonics uplifted reservoirs that are breached by erosion, it is possible that detrital sediment grains preserve a record of these earlier petroleum traps as fluid inclusions or dead oil within the grains. Finally, where fracturing and cementation associated with deformation occurs, petroleum fluid inclusions trapped in cements provides direct evidence of the timing of petroleum migration relative to deformation. If there are adequate constraints on the geologic age of diagenesis and deformation, it is possible to place petroleum migration in an absolute geologic time frame (Burruss, Cercone, and Harris, 1983; Burruss, Cercone, and Harris, 1985). In addition, fluid inclusions can yield information the temperature and pressure at the time of entrapment, providing data that can be integrated with other thermal indicators such as vitrinite reflectance, Rock-Eval pyrolysis, and fission track analysis to further refine estimates of the timing of petroleum generation and migration.

The goal of this study is to provide observations that constrain the time of migration of oil and gas in and adjacent to ANWR. These observations, combined with other geologic, geochemical, and geophysical data, form the basis for interpreting the timing of petroleum charge in the petroleum systems within the 1002 area of ANWR.

GEOLOGIC SETTING

The general geologic setting of the 1002 Area of the Arctic National Wildlife Refuge is discussed by Bird (Chap. GG). The general tectonic framework of thrust sheet development in and adjacent to ANWR 1002 is well developed (Wallace and Hanks, 1990). Kinematic modeling of deformation is discussed by Cole and others (Chap. SM). The timing of deformation constrained by seismic stratigraphic and structural analysis is discussed by Houseknecht and Schenk (Chap. BS) and Potter and others (Chap. BD), respectively, and constrained by fission track analysis by O'Sullivan and others, 1993.

METHODS AND SAMPLES

Samples of reported oil seeps, oil stained rocks, and potential reservoir facies in sedimentary rocks within and adjacent to ANWR were collected during the 1995, 1996, and 1997 field seasons. In addition, samples collected during earlier field seasons by C. M. Molenaar (USGS) and R. Carlson (Univ. of Kansas) were utilized where available. Samples from cores in five oil and gas exploration wells drilled in Alaska State lands west of ANWR or in state and Federal offshore waters were also examined. All samples with indications of petroleum as seeps, stains, or fluid inclusions are listed in Table FI1.

Oil seeps occurring as tarry oil in Quaternary alluvium or beach sands, and oil stained Tertiary and Mesozoic sedimentary rocks were characterized by organic geochemical methods and petrographic examination of thin sections. Samples collected for reservoir quality studies, and fractured rocks collected for fluid inclusion observations were thin-sectioned and examined by transmitted, polarized light microscopy, and epi-fluorescence microscopy. A few samples were examined by SEM and SEM-cathodoluminescence microscopy. Samples sectioned since 1995 were prepared as uncovered thin sections or as polished thin sections. Older thin sections with mounted coverslips had the coverslips removed and the Canada balsam cement dissolved with acetone. Where necessary coverslips were reapplied with non-fluorescent immersion oil.

All thin sections were examined with an ultraviolet (UV), epi-fluorescence microscope (long-wave UV, 366 nm, excitation) for the presence of fluorescent, petroleum fluid inclusions (Burruss, 1991). Routine reconnaissance was done at about 100x and the presence of inclusions confirmed at higher magnification, up to 500x. Visible color of fluorescence and number of phases (one phase, or two phase liquid and vapor) were noted. All thin sections contained at least a few fluorescent artifacts in the epoxy mounting media, requiring careful observation to ensure that the fluorescing inclusions occur within the mineral grains of the thin section.

Inclusions of natural gas were identified as one phase, non-fluorescent inclusions that occur on healed microfractures crossing a number of detrital grains or as primary inclusions related to growth zoning or crack-seal textures revealed by cathodoluminescence microscopy. In selected samples, the presence of methane-rich natural gas was confirmed by observations of low temperature phase behavior on a heating and cooling stage microscope (Goldstein and Reynolds, 1994).

RESULTS

Distribution of samples

All localities with samples that contain a direct indication of petroleum are shown on the map in Figure FI1. These occurrences include seeps, oil stained rocks, sandstones with dead oil in porosity, and rocks with oil and gas fluid inclusions. Sample information is summarized in Table FI1.

The seep occurrence at Angun Point, northeastern 1002, is shown in Figure FI2. Unconsolidated, Quaternary sand in a wave-cut bluff is indurated with a tar that is a heavily biodegraded oil (Lillis and others, Chap. OA). Two examples of outcrops of oil stained sandstones are shown in Figure FI3. These oils are biodegraded and their geochemical characteristics are discussed by Lillis and others, (Chap. OA). Examples of the occurrence of dead oil (pyrobitumen) in porosity in Sadlerochit Group sediments in the gas reservoir of the Kavik Gas Field, west of ANWR, are shown in Figure FI4.

Fluid inclusion petrography

Inherited vs. authigenic petroleum fluid inclusions: The petrographic setting or mode of occurrence of fluid inclusions provides the key evidence for determining the time of inclusion trapping. In sedimentary environments, evidence for classically defined primary inclusions is rare and the vast majority of inclusions are secondary (Roedder, 1984). In samples of cemented fractures, a key feature is the presence of crack seal textures, indicating that inclusions were trapped during fracturing (see subsection below "crack-seal textures"). In sandstones without obvious intergrain microfractures, a critical distinction is whether the secondary inclusions are authigenic, formed sometime during the last sedimentary cycle or detrital. Inclusions on healed microfractures in the cores of detrital grains, may or may not be authigenic, but secondary inclusions within authigenic cement phases are by definition authigenic. During reconnaissance observations of thin sections, it was relatively common to find fluorescent inclusions in one or several non-adjacent grains in Canning Formation or Sagavanirktok Formation sandstones. The absence of pervasive, intergrain microfractures made the distinction between authigenic and inherited inclusions difficult. In tectonic environments such as the North Slope where there are multiple cycles of sedimentation, uplift and erosion, the possibility of inherited inclusions is real, but as yet undocumented.

An example of the difficulty of distinguishing inherited from authigenic fluid inclusions is shown in Figure FI5. Sample 96DH121 is a carbonate cemented litharenite in the Canning Formation outcropping on the Marsh Creek Anticline. In the epi-fluorescence image, blue fluorescent inclusions are present on a healed microcrack within one quartz grain, but there is no evidence that this microfracture extends through the carbonate cement into adjacent grains. To resolve this type of ambiguity, another sample of a Canning Formation sandstone was examined in fluorescence and cathodoluminescence as shown in Figure FI6. Sample 95DH44, a quartz-rich litharenite in the Canning Formation on Hue Creek, contains three grains with fluorescent inclusions on short, healed microcracks. Whether the inclusions (Figure FI6b) occur within authigenic quartz cement is difficult to determine in transmitted light due to the absence of dust-rims that define the margins of the detrital grains (Figure FI6a). The cathodoluminescence image (Figure FI6c) demonstrates that a large percentage of the field of view including the fluid inclusions is authigenic quartz. This clearly demonstrates that these inclusions were trapped during or after quartz cementation of this sandstone and are not inherited.

Crack-seal textures: Crack-seal textures form in fracture-filling cements when rocks dilate and repeatedly fracture the actively precipitating cement, forming trails of fluid or solid inclusions (Ramsay, 1980). These trails are parallel to the maximum principle stress and their relationships to style and mechanism of deformation are reviewed by Passchier and Trouw (1996). Several examples of studies of fluid inclusions in crack-seal textures are published by Laubach (1989) and Xu (1997). Crack-seal textures are important for constraining the timing of migration of fluids because the repetitive, sequential cracking and sealing of fracture-filling cements traps fluids that are present during deformation. If the time of deformation is well constrained by structural, stratigraphic, and chronologic studies, then the time of migration is well constrained. Although the mode of occurrence of fluid inclusions in crack-seal textures, as decoration on healed microcracks, is "secondary" in the terminology of fluid inclusion studies (Roedder, 1984), these textures are can be overgrown by a generation of inclusion-free cement, classifying them as "pseudo-secondary", as shown in Figures FI7 and FI8.

Both fluorescent oil inclusions and non-fluorescent gas inclusions occur in crack-seal textures in cements in deformed rocks adjacent to the 1002 area of ANWR. Oil inclusions occur in crack-seal microfractures in quartz cement within fractures in overturned Kemik sandstone at Hue Creek illustrated in Figure FI7. The crack-seal texture is overgrown by a relatively inclusion-free generation of quartz.

Extensively fractured outcrops of the Sadlerochit Group at the Aichilik River water-gap in Leffingwell Ridge contain quartz fiber crystals with well developed crack-seal textures. At this locality, all the petroleum inclusions are methane-rich natural gas, as indicated by the low temperature phase behavior (see below), and the complete absence of any fluorescence from the inclusions. Examples of the fractures, quartz fiber crystals, and crack-seal textures are shown in Figure FI8.

Fluid inclusion temperatures

Temperatures of phase changes (microthermometry) in fluid inclusions were measured with standard heating and freezing stage techniques (Roedder, 1984 and Goldstein and Reynolds, 1994). The results are summarized in Table FI2 and Table FI3. Where possible, all measurements were made on fluid inclusion assemblages (FIAs), (Goldstein and Reynolds, 1994) that contain both aqueous and gas (CH_4-rich) inclusions. If the composition of the gas is known or can be estimated, then both trapping temperature and pressure can be estimated from microthermometric measurements.

Fluorescence color of petroleum fluid inclusions

The fluorescence color of petroleum fluid inclusions provides a general indication of the API gravity of fluid trapped in the inclusions (Burruss, 1991 and Goldstein and Reynolds, 1994). The interpretation is similar to that made by a well-site geologist while examining the fluorescence color of solvent cuts of cuttings for oil shows. Inclusions of natural gas are non-fluorescent. A histogram showing the number of occurrences of inclusions with distinctly different fluorescence colors is shown in Figure FI9. There is a distinct bimodal distribution of colors in classes of yellow to orange and white to blue. This is a strong indication that there are two distinct oil gravities in the North Slope of Alaska, within and adjacent to ANWR.

DISCUSSION

General aspects of timing of migration

The map in Figure FI1 shows contours of mean random vitrinite reflectance (%R_o) based on measurements from outcrop samples (Johnsson and others, 1992 and USGS unpublished) and proprietary measurements on samples from the bottom of seismic shotholes (Bird, Chap. VR). The outcrops of oil stained sandstones and fluid inclusion samples containing oil generally fall within the area bounded by the 0.6 % and 1.3% reflectance contours that are considered to bound the oil window (Hunt, 1996). Methane-rich gas inclusions occur in samples located within the area of reflectances greater than 2.0% which is considered to be the top of the gas window. The general correspondence of the fluid type with the level of thermal maturity at the present day surface implies that migration occurred during maximum burial.

Surface seeps document recent migration of oil. Biodegradation of the oils in the seeps at Angun Point and Manning Point (Lillis and others, Chap. OA) make conclusive correlation of these seeps to subsurface samples difficult, but the results indicate that they are part of the Canning-Sagavanirktok(?) petroleum system (Lillis and others, Chap. OA, and Magoon and others, Chap. PS). The presence of biodegraded oil in shallow (approx. 4000 ft. depth) Tertiary age sediments in the Aurora well (Lillis and others, Chap. OA, and Keller and others, Chap. SR) offshore northeastern 1002, suggests at least a spatial relationship to the surface seeps.

The presence of dead oil in porosity indicates that oil was once present but was altered by some geochemical process, leaving an insoluble residue. There are several processes that can cause this phenomenon (Connan, 1984) and the specific process can give important clues to migration history at a particular location. Although initial precipitation may not require high temperatures (for example, gas phase de-asphaltening) the formation of the residue commonly requires higher levels of thermal maturity (deeper burial or hot fluids) than that at the time of initial oil charge. Thus the dead oil in the gas reservoir of the Kavik Gas field (see Figure FI4 and subsection below dealing with Kavik gas field) documents an earlier oil charge to the reservoir. Similarly, dead oil in outcrops of the Kemik Sandstone and sandstones of the Canning Formation in Ignek Valley document oil charge to these rocks prior to reaching maximum thermal maturity and certainly prior to uplift of these rocks at about 25 to 20 Ma during uplift of the Sadlerochit and Shublik Mountains.

Timing of migration in individual plays

The tightest constraints on the timing of oil and gas migration result from combining the mode of occurrence of fluid inclusions and the temperature measurements. The occurrence of oil and gas inclusions in crack-seal textures within vein-filling cements indicates that hydrocarbons were migrating during an episode of continuous deformation that produced the crack-seal texture. The homogenization temperatures of the inclusions and the estimated trapping temperatures constrain the depth of burial during migration. These constraints apply to two plays, the Ellesmerian Thrust Belt Play, and the Thin-Skinned Thrust-Belt Play.

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Ellesmerian Thrust-Belt Play, Eastern ANWR, at Leffingwell Ridge: Methane-rich inclusions and low salinity water inclusions occur in crack-seal textures of quartz and calcite fiber veins in Sadlerochit Group and Kingak Shale outcrops along the Aichilik River downstream from Leffingwell Ridge. The structural relationships of the Ellesmerian strata in outcrop (Wallace and Hanks, 1990, their Figure 11) demonstrate that these outcrops are an excellent example of the Ellesmerian thrust sheets observed in the subsurface of ANWR 1002 on seismic records (Potter and others, Chap. BD).

Quartz fibers were precipitating in dilating vein systems in the presence of methane-rich gas and low salinity water at temperatures of about 220 ^{o}C. Inclusion-rich quartz crystals are overgrown by relatively inclusion free quartz and in some cases calcite. Fission track ages for rocks from these outcrops are in the range of 33 to 45 Ma (O'Sullivan and others, 1993). These ages are the time at which the rocks cooled from temperatures of 120^{o}C to less than 60 ^{o}C. The fact that the fracture systems were forming at temperatures higher than the apatite annealing temperature requires that the time of gas migration and thrusting of the Ellesmerian units be older than the fission track ages. At cooling rates on the order of 10 ^{o}C/my, deformation observed in Leffingwell Ridge at the Aichilik River was at least 10 my older than the measured fission track age.

The depth of burial during thrusting can be estimated using average thermal gradients applicable to the North Slope. Using a gradient of 30 ^{o}C/km (Magoon and others, 1987), gas migration and deformation occurred at depths on the order of 7 km (22,900 ft.).

Ellesmerian Thrust-Belt Play, Kemik and Kavik Gas Field analogs: The Kemik and Kavik Gas Fields west of the ANWR 1002 area are analogs of prospects that may occur in the Ellesmerian Thrust Belt play (Grow and others, Chap. P9). Fractures healed with quartz and calcite cements containing petroleum fluid inclusions in crack-seal textures are present in the Shublik Formation in the Kemik field and in Sadlerochit Group sediments in the Kavik Gas Field. Measured homogenization temperatures of aqueous inclusions in calcite in the Kemik field (maximum of 220 ^{o}C) are comparable to temperatures measured in samples from the Aichilik River outcrops. The homogenization behavior of the methane-rich gas inclusions allows estimates of pressure during fracturing. However, these yield a wide range of pressures from about 475 to 700 bars. The highest pressures converted to depths with a

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hydrostatic gradient of 100 bars/km are give depths of burial of 7km (22,900 ft.) during deformation and gas migration.

Temperatures measured on aqueous inclusions in samples from the Kavik gas field are lower (maximum of 185 °C) than those in the Kemik field samples. In addition to methane-rich gas inclusions in FIAs with the aqueous inclusions, Kavik field samples contain blue fluorescent, liquid and vapor inclusions. The blue color of the fluorescence of these inclusions indicates that they contain a high API gravity, gas-rich petroleum.

The Sadlerochit Group samples also contain pyrobitumen in the pore space, indicating that these reservoir rocks were once charged with oil (Figure FI4). This suggests a history of hydrocarbon charge that started as crude oil, the oil was replaced by gas-rich, volatile oil or the reservoir was charged with gas and the oil displaced up-dip. Late gas charge could cause de-asphaltening of the oil and formation of the pyrobitumen now present in the pore space.

The relationship between the timing of deformation and petroleum migration in the Ellesmerian thrust structures of these gas fields is not as well constrained as it is at the Aichilik River outcrops. Based on the general model of Ellesmerian thrust sheet development (Wallace and Hanks, 1990) and the kinematic modeling by Cole and others (Chap. SM), I infer an age of deformation, and therefore oil and gas migration, of 45 to 33 mypb. However, according to the seismic data available for the Kavik gas field (Potter and others, Chap. BD), the fault that forms the trap extends to basement as a high angle fault, analogous to the high angle faults that uplift the Sadlerochit and Shublik Mountains. The AFTA results for uplift of these mountain ranges indicate an age of trap formation at about 25 to 20 Ma (O'Sullivan and others, 1993). Also, AFTA of subsurface samples of Sadlerochit Group sediments in the Kemik Unit 2 well (O'Sullivan, 1990) yields ages at three depths of 13 to 22 mypb for the deepest to shallowest samples, respectively. These young ages indicate relatively recent uplift of these sediments to temperatures less than 120 °C. This age presents some challanges for modeling the history of hydrocarbon charge because it requires that an initial oil charge and the latest gas charge be younger than trap formation.

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Thin-skinned Thrust-Belt Play

Surface exposures of potential reservoir units within the Brookian Thin-skinned Thrust-Belt Play occur along the Marsh Creek anticline where broadly folded Canning and Sagavanirktok Formations crop out. These rocks contain small numbers of grains with yellow and blue fluorescent oil inclusions as shown in Figure FI5. South of the 1002 area, the more intensely deformed Kemik sandstone is also part of this play. The thrust duplexes and tight folds in the Kemik are uncoupled from deformation in the younger Brookian rocks and underlying Ellesmerian rocks through the detachment surfaces in the Pebble Shale unit and Kingak Shale, respectively. Because deformation of the Kemik is mechanically uncoupled from deformation in the younger Canning and Sagavanirktok Formations, it may have occurred at a different time and possibly be older than deformation in the younger strata.

The occurrence of oil inclusions in small numbers of grains in samples of Tertiary age sediments on the Marsh Creek Anticline does not place tight constraints on the timing of migration of oil through these rocks. The only constraint is that trapping occurred in the subsurface, prior to uplift. Seismic evidence presented by Potter and others (Chap. BD) demonstrates that uplift of the Marsh Creek Anticline began about 20 Ma, but in the absence of temperature measurements, there is no way to constrain the time of trapping relative to uplift.

Fluid inclusions of gas and oil occur in crack-seal textures in fracture-filling cements within deformed Kemik sandstone at several locations listed in Table FI2 and shown on Figure FI1. Temperature measurements on three samples indicate that oil migration occurred in the temperature range 120 to 160 °C and gas migration occurred during deformation at temperatures up to 195 °C. Blue fluorescence and homogenization at lower temperatures, in some cases to vapor, indicate that some of the migrating petroleum was condensate-like.

Petroleum inclusions in crack-seal textures at the Hue Creek locality are shown in Figure FI7. A separate sample from the same locality, 95FC14B (Table FI2), contains aqueous inclusions with a maximum homogenization temperature of 125 °C. This temperature is consistent with complete resetting of apatite fission track ages to a 33 Ma age of uplift for this location in the Ignek Valley (O'Sullivan and others, 1993). This fission track age requires that oil migration occurred at or before 33 Ma. The crack-seal occurrence of oil inclusions demonstrates that oil was present in fracture porosity during deformation. The timing of deformation appears to be consistent with the age of uplift documented by fission track analysis and kinematic modeling of deformation of the Shublik and Sadlerochit Mountains (Cole and others, Chap. SM).

CONCLUSIONS

The occurrence of petroleum as fluid inclusions, dead oil, oil stains, and seeps within and adjacent to the 1002 area of ANWR demonstrates that migration of oil and gas has occurred in the past and continues to the present day. Oil and gas fluid inclusions in crack-seal textures in deformed Ellesmerian and Brookian rocks show that petroleum was migrating during deformation that is constrained by fission track ages to be in the range of 45 to 33 Ma. The presence of dead oil in porosity of folded rocks suggests that extensive re-migration of reservoired oil occurred in the geologic past and may indicate extensive loss of petroleum from the systems that charged reservoirs in ANWR, especially the older, thrust-belt related plays.

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Table FI1. ANWR localities with indications of petroleum as fluid inclusions, stains, seeps, and dead oil

Sample ID	Latitude	Longitude	Formation	Locality	Petroleum indications
97RCB13	69.50500	-143.38830	Arctic Creek	Ridge west of Okerokovik River, Arctic Creek facies	one phase (ph.) gas inclusions
96RCB10	69.56950	-145.81217	Canning	Hue Creek	Rare blue fluorescent (fl.) inclusions (incl.)
96RCB13	69.71583	-145.43333	Canning	Katakturuk River South	Blue fluorescent incl.
95DH44	69.56950	-145.81217	Canning	Hue Creek	Dead oil and 2 grains (grn.) with yellow fl. incl.
96DH121	69.93167	-144.66517	Canning	Marsh Creek anticline (MCA2)	a few grains with yellow fluorescent inclusions
96DH146	69.71467	-145.43583	Canning	Katakturuk #1	yellow fluorescent inclusions
96DH149	69.71533	-145.32783	Canning	Katakturuk #2	one grain with 2-phase yellow fl. incl.
96RCB14B	69.65367	-146.24250	Sagavanirktok	Canning River, Ken Bird oil stain locality	oil stain, no fluorescent inclusions
80AMK-26	69.57100	-145.80000	Canning?	Brookian turbidites - Ignek Valley	one grain with blue fluorescent 2-phase inclusions
80AMK-41D	69.71500	-145.43333	Canning?	Cret-Paleoc turb section – along Katakturuk River north of Sadlerochit Mtns	yellow fl. 1 +2 ph. incl., 1 ph. blue fl. incl.
82AMK-20	69.58317	-146.30333	Canning?	Paleocene turbidites - W bank of Canning River	one grn. / 2 ph. yellow fl. incl.
82AMK-78	69.54500	-146.29167	Canning?	Oil-stained UK(?) turbs – West side Canning River	abundant 2 ph. yellow fl. incl.
DH95-29	69.53219	-145.20667	Fire Creek	Fire Creek, Shublik Mtns.	secondary, 1-phase methane-rich gas inclusions
95FC-01C	69.39683	-146.41800	Kemik	Kavik River south !!!	Yellow, white, blue fluorescent inclusions
95FC-14B	69.55555	-145.83333	Kemik	Hue Creek	Blue and Yellow fluorescent inclusions
96RCB5	69.69167	-144.85000	Kemik	Marsh Creek at Kelley's footwall cutoff	Yellow and blue fl. inclusions, possible 1-phase gas
96RCB12	69.55667	-145.83500	Kemik	Hue Creek	Blue fluorescent inclusions
96RCB15B	69.46417	-146.34083	Kemik	Canning River, Kemik duplexes	Rare blue fluorescent inclusions
96RCB15D	69.46417	-146.34083	Kemik	Canning River, Kemik duplexes	Yellow and blue fluorescent inclusions
96DH34	69.55650	-145.45767	Kemik	Horseshoe, Ignek Valley	dead oil
96DH35	69.55650	-145.45767	Kemik	Horseshoe, Ignek Valley	dead oil in clasts as detrital component
96DH37	69.55650	-145.45767	Kemik	Horseshoe, Ignek Valley	dead oil
96DH39	69.55650	-145.45767	Kemik	Horseshoe, Ignek Valley	trace dead oil
96DH42	69.55650	-145.45767	Kemik	Horseshoe, Ignek Valley	dead oil
96DH18	69.63200	-144.44817	Kemik	Last Creek	gas inclusions in quartz+calcite cement in breccia
96DH84	69.61350	-144.46250	Kemik	Sadlerochit #2 Section	possible dead oil
80AMK-18H	69.49733	-146.31133	Kemik	120' Kemik Ss Section - W bank Canning River	blue fluorescent inclusions
80AMK-23A	69.41050	-146.91667	Kemik	117' Kemik Ss Section – Fin Creek	1 and 2-phase blue fluorescent inclusions
80AMK-49B	69.63067	-144.42817	Kemik	Kemik Ss - Last Creek, E end of Sadlerochit Mtns	dead oil??
82AMK-55C	69.58617	-145.97000	Kemik	Kemik Ss-Kps - Ignek Creek Section	dead oil
83AMK-40D	69.69567	-144.85983	Kemik	Kemik Ss - E fork Marsh Creek	Dead oil
83AMK-40F	69.69567	-144.85983	Kemik	Kemik Ss - E fork Marsh Creek	Dead oil
95DLG-7A	69.49950	-146.30933	Kemik	Repeated Kemik Ss, Canning River	1 grain with blue fl. 2 ph. incl., possible dead oil
95FC-17	69.55833	-145.83333	Kemik	Kemik Ss, Hue Creek, Ignek Valley	blue-white fl. 2 ph. in matrix and pebbles, dead oil
97RCB11	69.53000	-143.06950	Kingak	Aichilik R. section, deformed Kingak	one phase gas inclusions
DH95-14	69.68658	-144.84267	Kingak?	Marsh Creek	one phase methane-rich gas
96DH81	69.34267	-147.20933	Kingak?	Peregrine Nest	one phase methane-rich gas
CarlsonMS	69.68030	-144.85000	Lisburne	Marsh Creek measured section	2 phase yellow fluorescent inclusions and dead oil
83AMK-1	69.81117	-145.57567	Sagavanirktok	Sag. Fm. - E side of Tamiariak River	2 ph. yellow fl. incl, 1 ph. blue fl. incl.
95DLG-2C	69.87100	-145.17933	Sagavanirktok	Fluvial Sag. Fm., Bluff on east side of Kat. Riv.	2 phase yellow fluorescent inclusions
96RCB2	69.65317	-146.72067	Sagavanirktok?	Kavik oil stained SS	oil stain and no fluorescent inclusions
96DH122	69.94567	-144.66433	Sagavanirktok?	Marsh Creek Anticline (MCA3)	rare yellow fluorescent inclusions
DH95-34	69.53583	-145.20167	Shublik	Fire Creek, Shublik Mtns.	Secondary aqueous and 1 phase methane-rich incl.
95FC-15B	69.55555	-145.83333	Shublik	Hue Creek	Possible one-phase methane-rich inclusions
95DLG-MP1	70.11666	-143.51666	Quaternary	Manning Point oil Seep	oil saturated unconsolidated sand
97RCB17	69.91800	-142.39500	Quaternary	Angun Point oil seep	oil saturated unconsolidated sand

Table FI2. Fluid inclusion temperature measurements, outcrop samples

1. Location: Fire Creek, 95DH34 Formation: Fire Creek
Inclusions: water and CH_4-rich gas
FIA: Aq. T_h: 185-190°C, 195-200°C
CH_4-rich gas T_h: -76 to -75°C to L and V
salinity: approx. 10,000 ppm TDS
max. obs. aq. T_h: 225-230°C

2. Location: Hue Creek, 95FC14B Formation: Kemik
Inclusions: water and oil (yellow and blue fluorescent), crack seal texture
Blue fluorescence T_h: 40-45°C
Yellow fluorescence T_h: 115-120°C
max. obs. aq. T_h: 125°C (minimum trapping temp.)

3. Location: Kavik R. south, 95FC01C Formation: Kemik
Inclusions: water and fluorescent oil
FIA: Aq. T_h: 150-160°C
Salinity: approx. 10,000 ppm TDS
Blue fluorescence T_h: 65-70°C to V
Fluorescent inclusions
Min. T_h: 65-70°C to V
Max. T_h: 130-135°C to L

4. Location: Aichillik R., 97RCB11 Formation: Kingak
Inclusions: water and CH_4-rich gas, crack-seal texture
FIA: Aq. T_h: max. 210-215°C
salinity: approx. 10,000 ppm TDS
CH_4-rich gas T_h: approx. -80°C

5. Location: Leffingwell Ridge, 97RCB13 Formation: Arctic Creek facies
Inclusions: water and CH_4-rich gas, crack-seal texture
FIA: Aq. T_h: max. 200-215°C
salinity: approx. 10,000 ppm TDS
CH_4-rich gas T_h: approx. -80°C

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Table FI2. Fluid inclusion temperature measurements, outcrop samples (continued)

6. Location: Peregrine Nest, 96DH81 Formation: Kingak?/Kemik

Inclusions: water and CH_4-rich gas, crack-seal texture

FIA, crack-seal: Aq. T_h: 185-195 °C
salinity: approx. 10,000 ppm TDS
Th: CH_4: -80 °C to L

FIA, post crack-seal: Aq. Th: 175-185 °C
salinity: approx. 10,000 ppm TDS
CH_4-rich gas T_h: -80 °C to L

Table FI3. Fluid inclusion temperature measurements, subsurface core samples

1. Well: Kemik Unit 1 Formation: Shublik, 8669 ft.

Inclusions: water and CH_4-rich gas in quartz (qtz.-calcite frac.)
FIA: Aq. T_h: 210-220°C
salinity: approx. 10,000 ppm TDS
CH_4-rich gas T_h: -81.7 to -74.6°C to L, V, and critical

Pressure estimate: 700 bars to 475 bars
Depth estimate:
Temperature gradient:

2. Well: Kavik Unit 3 Formations: Sag River: 4946.2 ft.
Shublik: 5035.7 ft.
5069.3 ft.

Inclusions: water and blue fluorescent oil in quartz (qtz.-calcite frac.)
FIA in qtz: Aq. T_h: 175-180°C
salinity: approx. 10,000 ppm TDS
CH_4-rich gas T_h : -64 to -48°C to L and V

FIA in calc.: Aq. T_h: 180-185°C
salinity: approx. 10,000 ppm TDS
Blue fluorescent oil: T_h: 35 to 50 °C

Depth estimate: 185°C/48°C /km: 3.85 km (12,600 ft)

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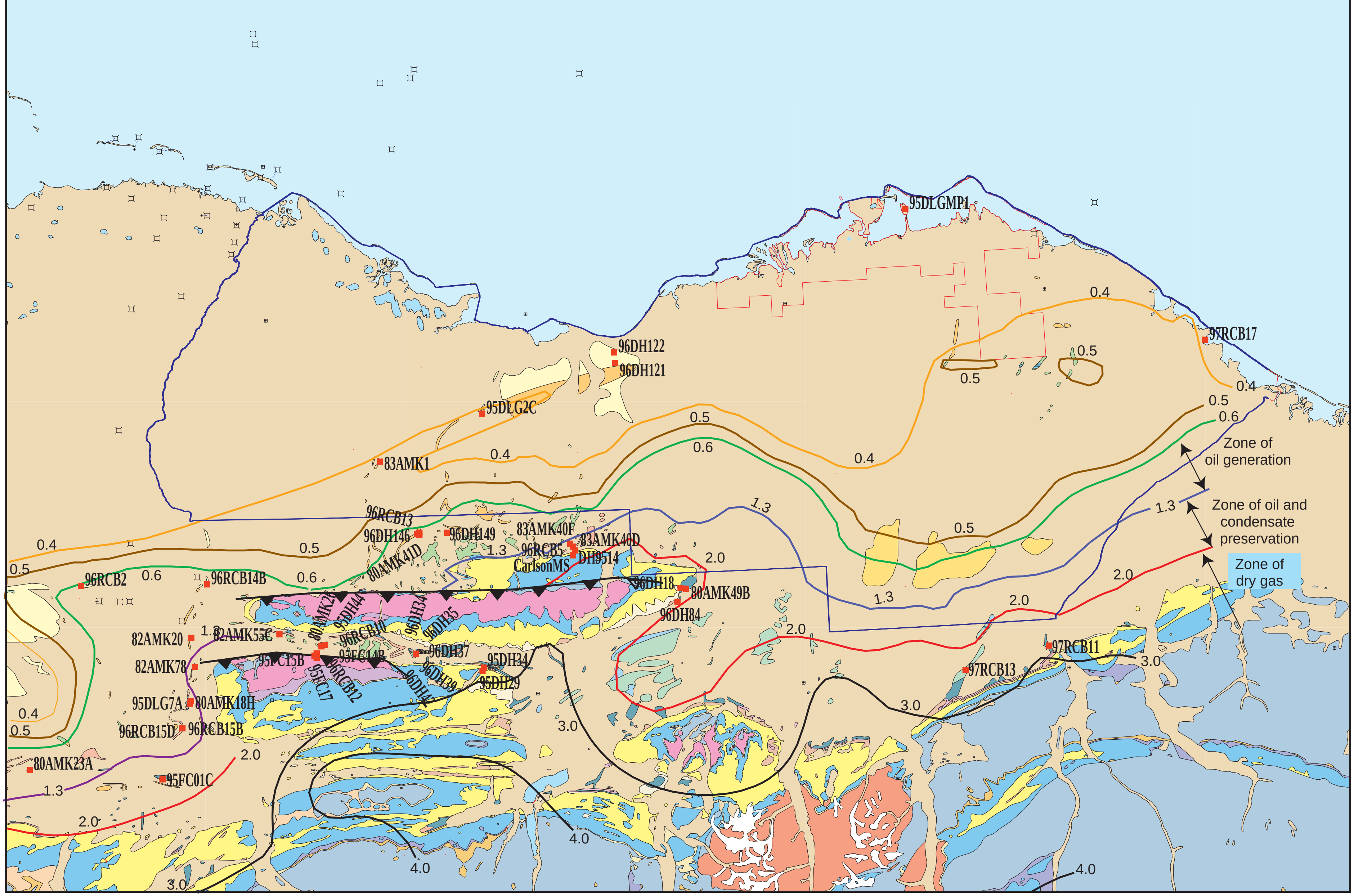
Figure FI1: Locations of samples with indications of oil and gas as seeps, stains, dead oil, and oil and gas fluid inclusions. Also shown are selected contours of vitrinite reflectance at the surface. Samples are listed Table FI1.



USGS
science for a changing world

The Oil and Gas Resource Potential of the Arctic National Wildlife Refuge 1002 Area, Alaska
Open File Report 98-34

Figure FI2: Oil Seep at Angun Point, within the 1002 area of ANWR. Quaternary sand indurated with tar occurs at the base of a low, wave-cut bluff on the northwestern shore of Beaufort Lagoon. Sample 97RCB17 was analyzed geochemically (Lillis and others, Chap. OA) and the tar is extremely biodegraded. This sample location is about the same as C. M. Molenaar's sample 83AMK-6 (Appendix CM). USGS field notes by Detterman and Brosge' indicate that other occurrences of tar were observed in the tundra within a mile to the west of this site.

A. Sand indurated with tar with the consistency of asphalt.

B. View of the outcrop, looking to the northeast. Tom Moore for scale, Beaufort Lagoon in the background.

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Figure FI3: Examples of oil stained outcrops adjacent to the 1002 area of ANWR.

A. Oil stained, massive sandstone with hummocky crossbedding, Canning Formation, east bank, Canning River. Shelley Orth (taking photograph) for scale. View to south. Location of sample 96RCB14 analyzed for geochemical characteristics of oil. This location is at the north end of the panorama used to illustrate the sequence stratigraphic interpretation of the Canning Formation presented by Houseknecht and Schenk, Chap. BS.

B. "Outcrop" of oil stained rocks, possibly the Sagavanirktok Formation, known as the "Kavik" locality. Blocks of sandstone on the tundra, humans and helicopter for scale. View to the south.

C. Close-up of oil stained sand in B. Sample 96RCB2 analyzed for geochemical characteristics of oil.

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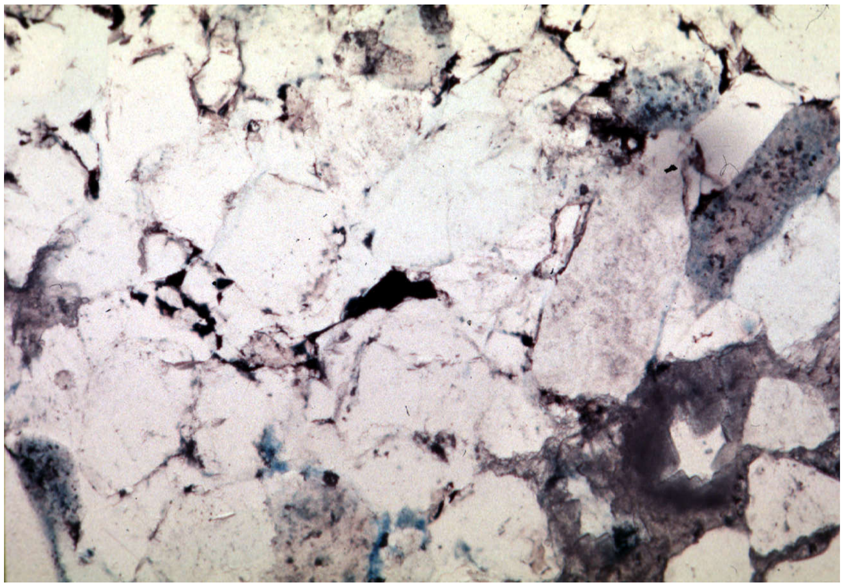
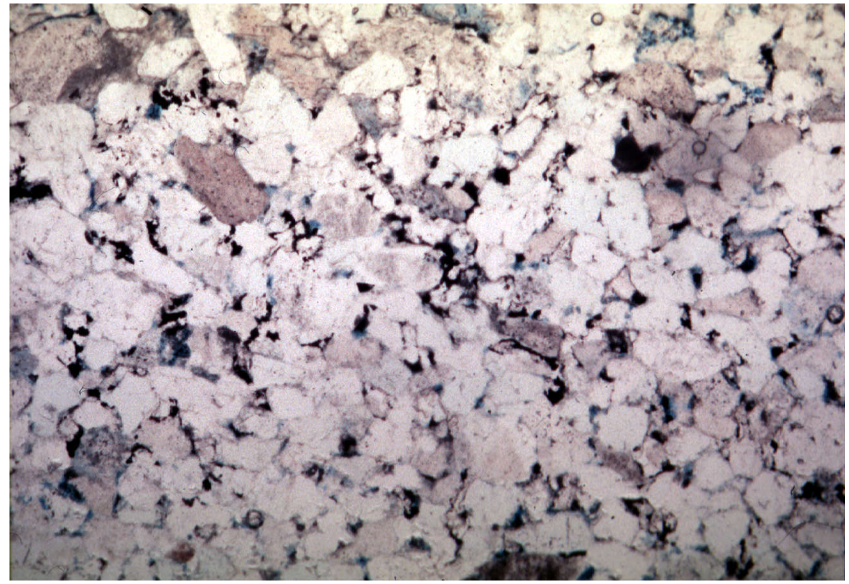
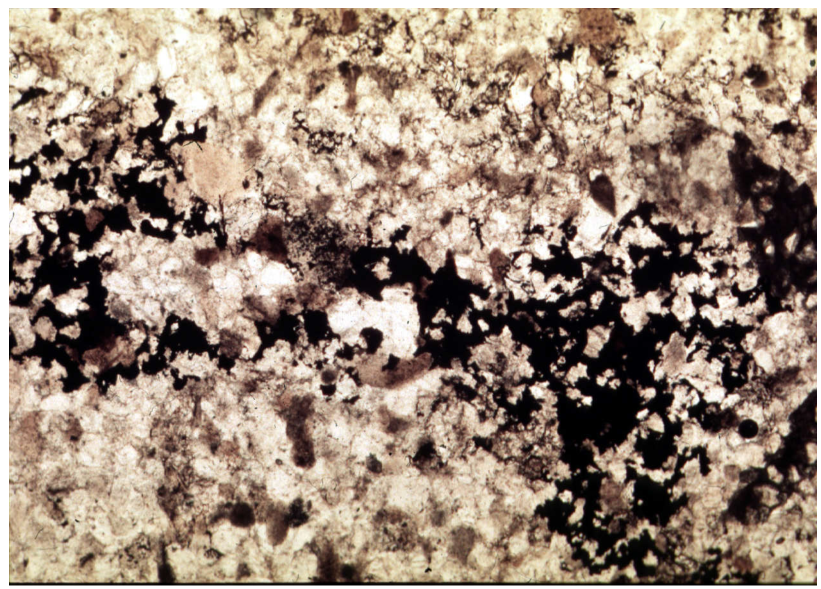
Figure FI4: Examples of dead oil (pyrobitumen) in porosity in Sadlerochit Group sediments in wells in the Kavik Gas Field. Dead oil is an indicator of the former presence of liquid oil in this fault trap. The Kavik and Kemik Gas Fields are analogs for traps in the Ellesmerian Thrust Belt Play of the 1002 area of ANWR.



A. Kavik No. 2, 6231.9 ft. depth, Ledge Sandstone. Transmitted light photomicrograph. Black pore-filling material is dead oil. Blue areas are porosity filled with blue-dyed epoxy. Width of field of view: 1.1 mm.



B. Kavik No. 3, 5436.9 ft. depth, Ledge Sandstone. Transmitted light photomicrograph. Black objects are dead oil. Blue areas are porosity filled with blue-dyed epoxy. Width: 2.2 mm.



C. Kavik No. 3, 5426.2 ft. depth, Ledge Sandstone. Transmitted light photomicrograph. Black mass is dead oil. Width: 4.4 mm.

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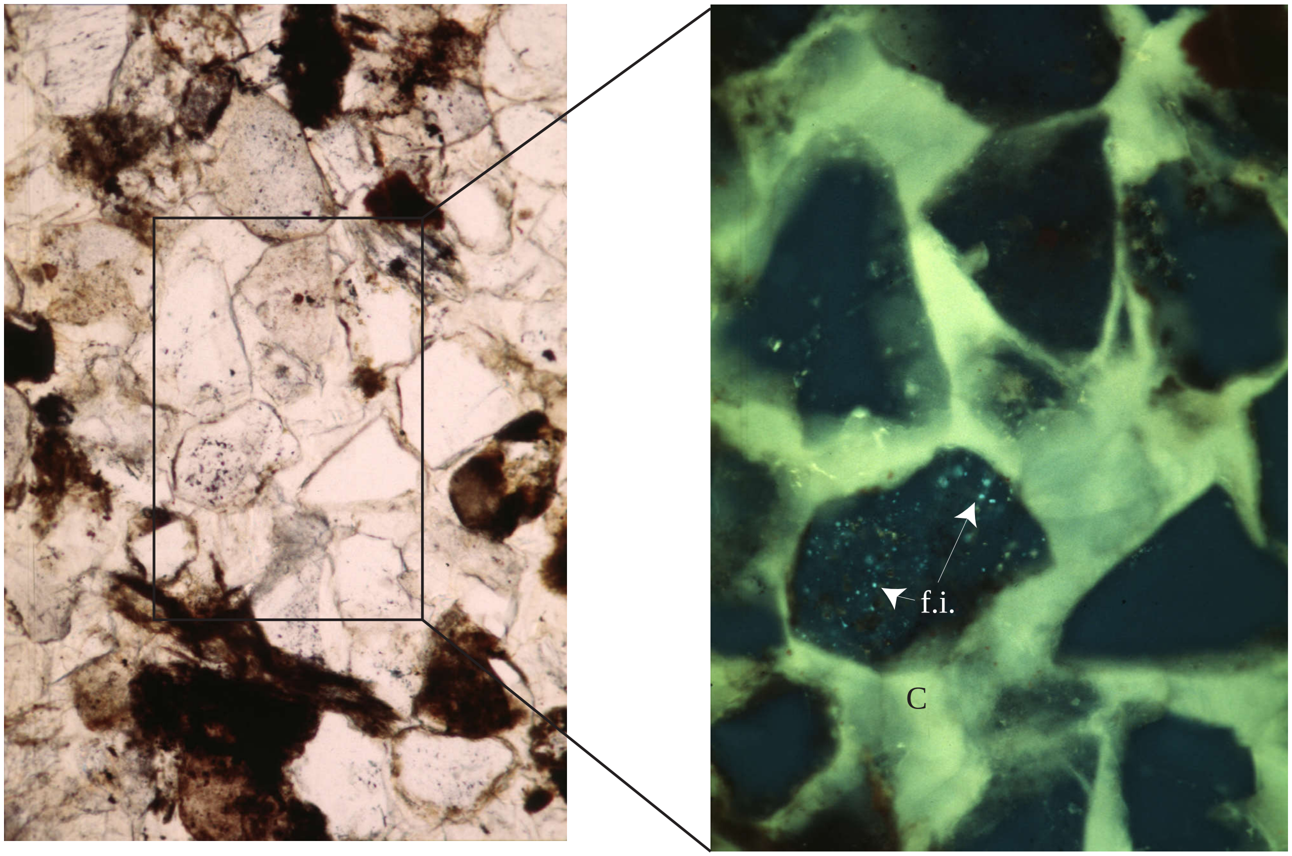
Figure FI5: Photomicrographs illustrating the difficulty of determining whether oil inclusions in isolated grains in a thinsection are authigenic or inherited. See text and Figure FI.6 for further discussion. Sample: 96DH121, Canning Formation at Marsh Creek Anticline.



A. Transmitted light, quartz litharenite cemented with calcite. Long axis of field of view 2.2 mm.

B. Epi-fluorescence image of part of field of view in A. Blue fluorescent oil inclusions (f.i.) occur in a single quartz grain surrounded with fluorescent carbonate cement (C). Long axis of field of view 1.1 mm.

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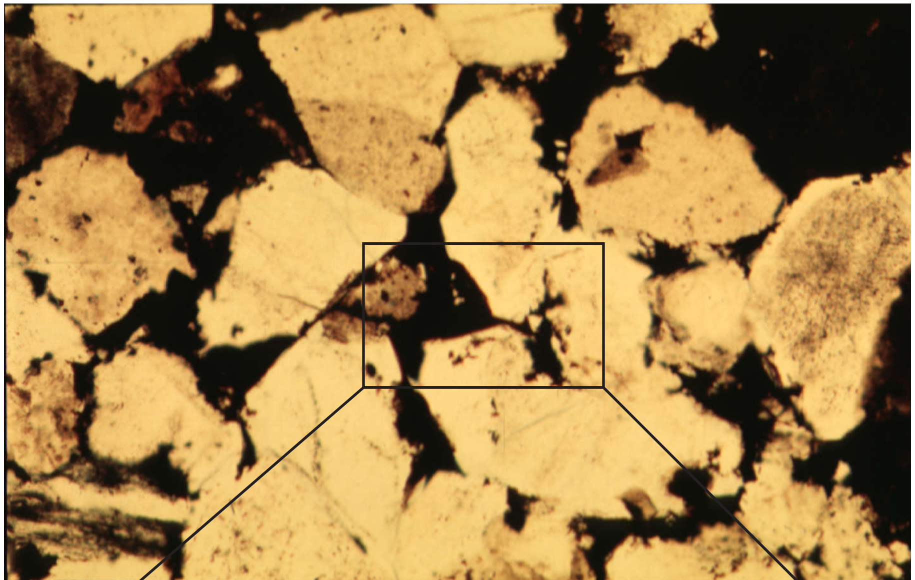
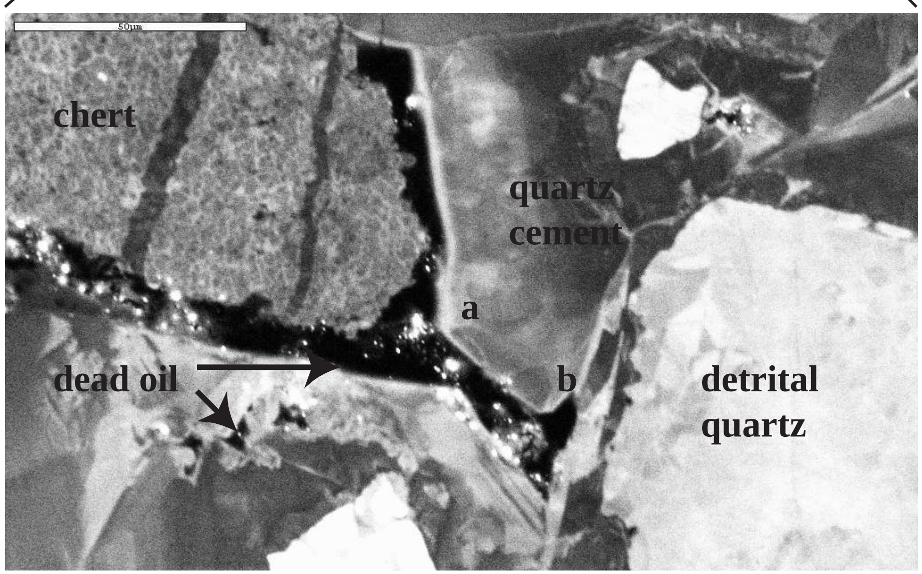
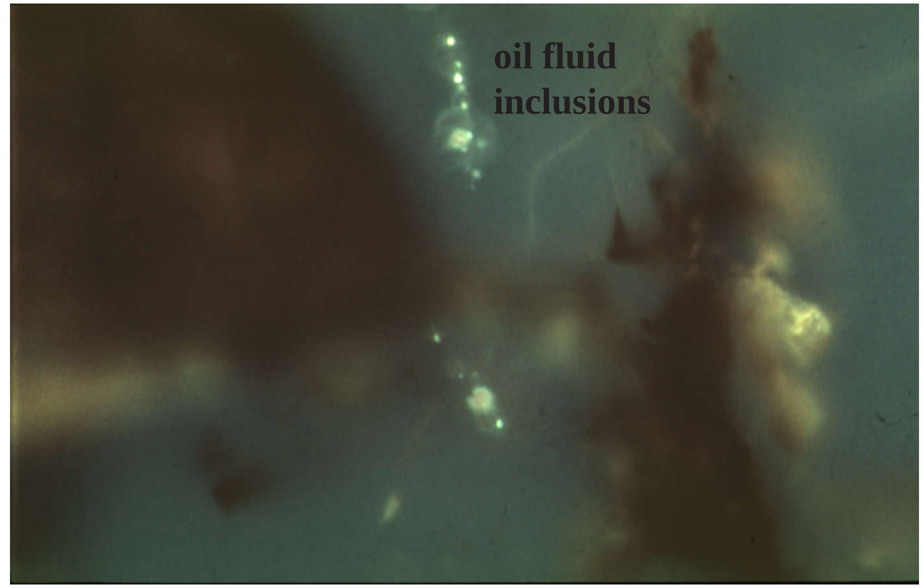
Figure FI6: Photomicrographs demonstrating the occurrence of oil fluid inclusions in authigenic quartz cement. Sample 95DH44, Canning Formation, Ignek Valley, along Hue Creek.



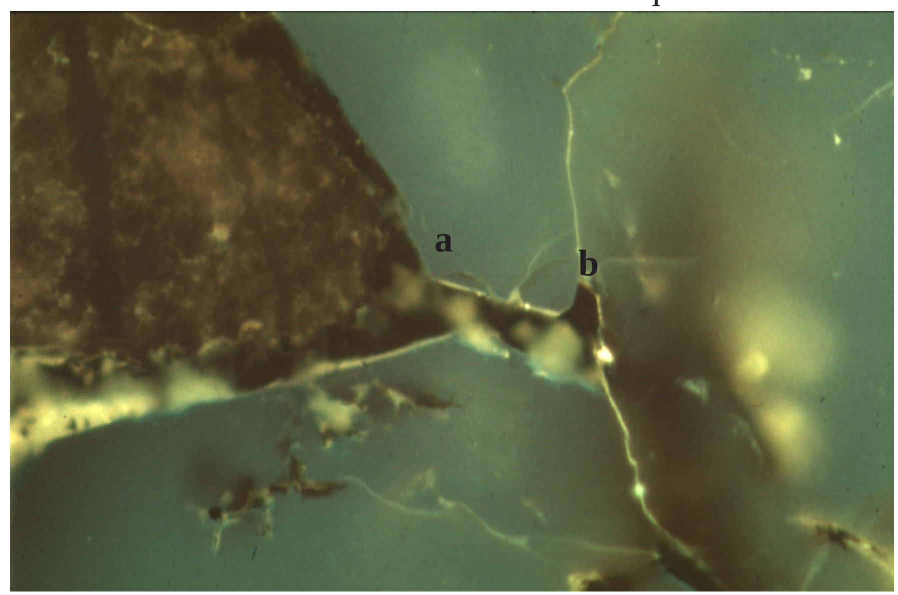
A. Transmitted light, chert litharenite, field of view 1.1 mm.



B. Cathodoluminescence (SEM) image showing distinction between authigenic (gray) and detrital quartz (white) and chert. Field of view 0.25 mm.



D. Same field of view as C, focused into section to show fluorescence of oil fluid inclusions within quartz cement.



C. Epi-fluorescence image of field of view in B. focused on surface of polished section. Points a and b correspond to labelled points in B. Field of view 0.2 mm.

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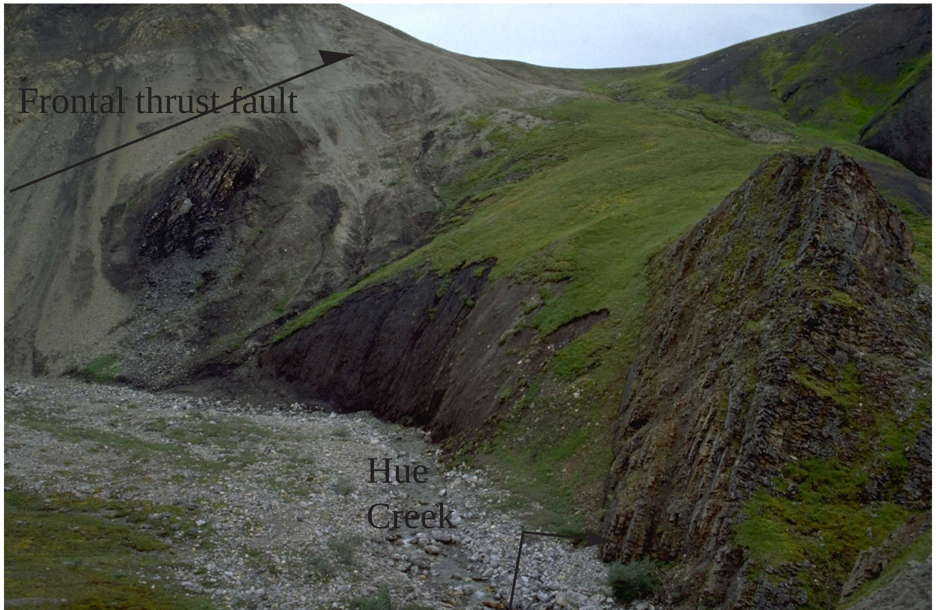
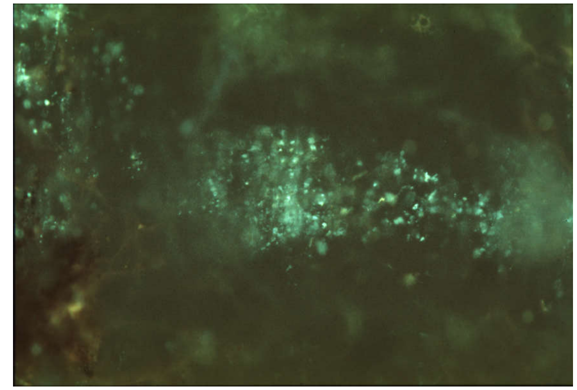
Figure FI7: Oil inclusions in crack-seal texture in fracture filling quartz cement in overturned Kemik sandstone along Hue Creek at the Shublik Mountain front. Sample 96RCB12.

A.



B. Quartz filled fracture in Kemik Sandstone. View of bedding surface indicated, above.

E.

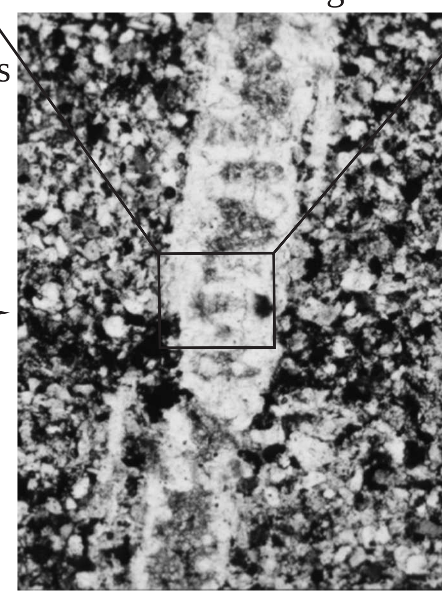


Epi-fluorescence

D.

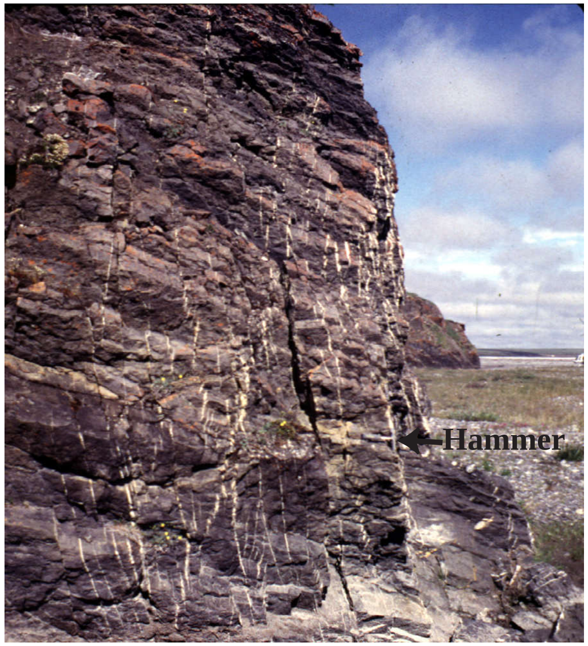
Transmitted light

Photomicrographs of crack-seal textures in quartz cement.



C.

Figure FI8: Quartz fiber veins with gas-rich fluid inclusions in crack-seal textures and later cross-cutting microfractures, documenting gas migration during deformation, Leffingwell Ridge at the Aichilik River.



A. Outcrop of extensively fractured sandstone, Sadlerochit Group, possibly Fire Creek Sandstone, sample 97RCB7. Note hammer for scale.

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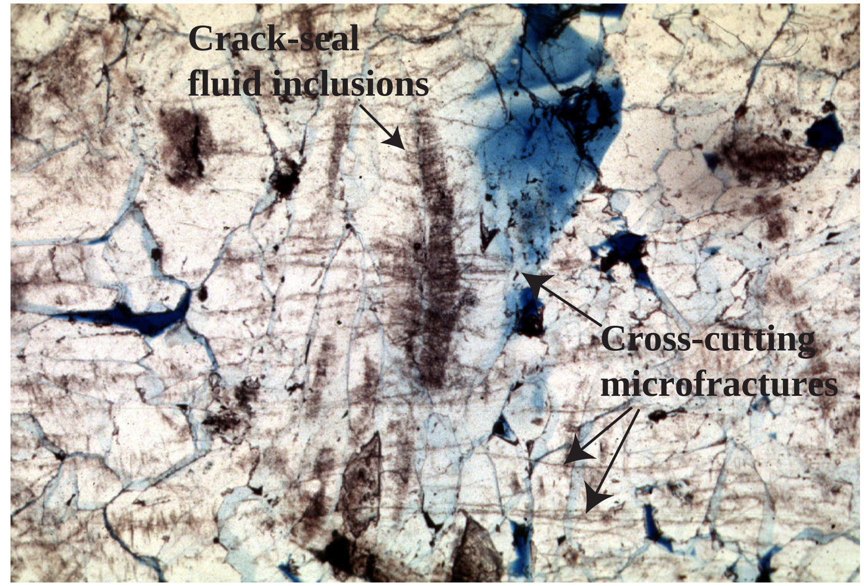
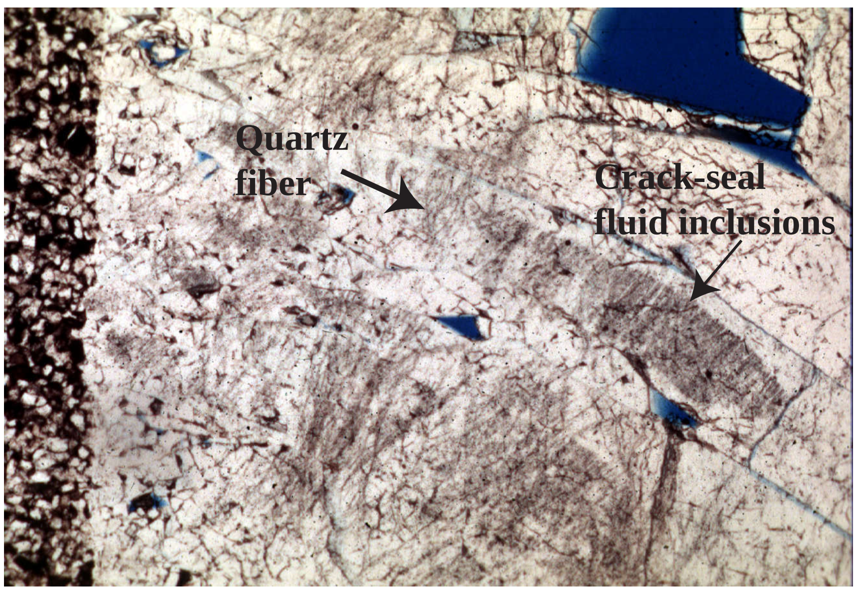
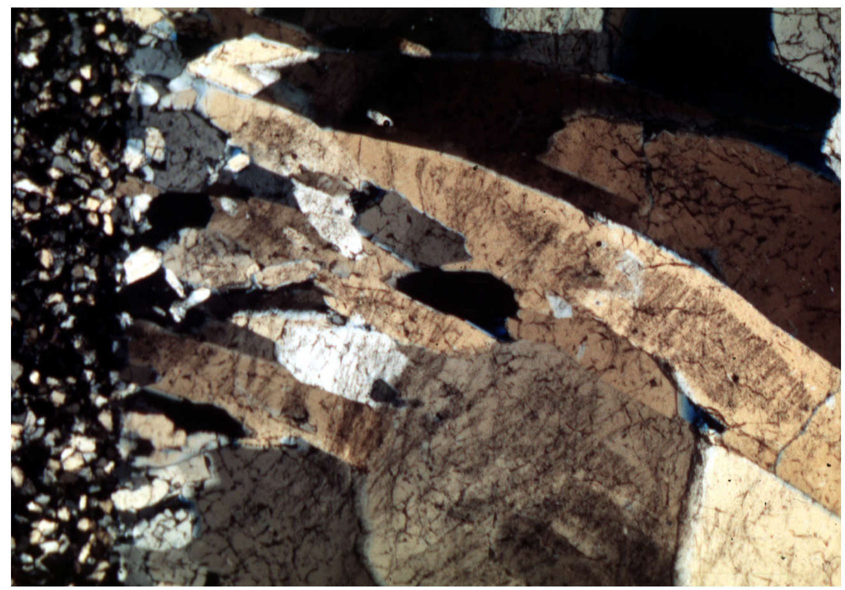


D. Transmitted light image showing crack-seal texture gas inclusions cross-cut by later generation of micro-fractures. Field of view 4.4 mm.

Fracture edge



B. Transmitted light image of quartz fiber vein, with internal crack-seal texture in curved fiber, overgrown with clear quartz. Field of view, 4.4 mm.



C. Same field of view as B with crossed polarizers, emphasizing fibrous nature of quartz crystals.

Figure FI9: API gravity inferred from fluorescence color of fluid inclusions in samples from outcrops within and adjacent to 1002 area, ANWR.