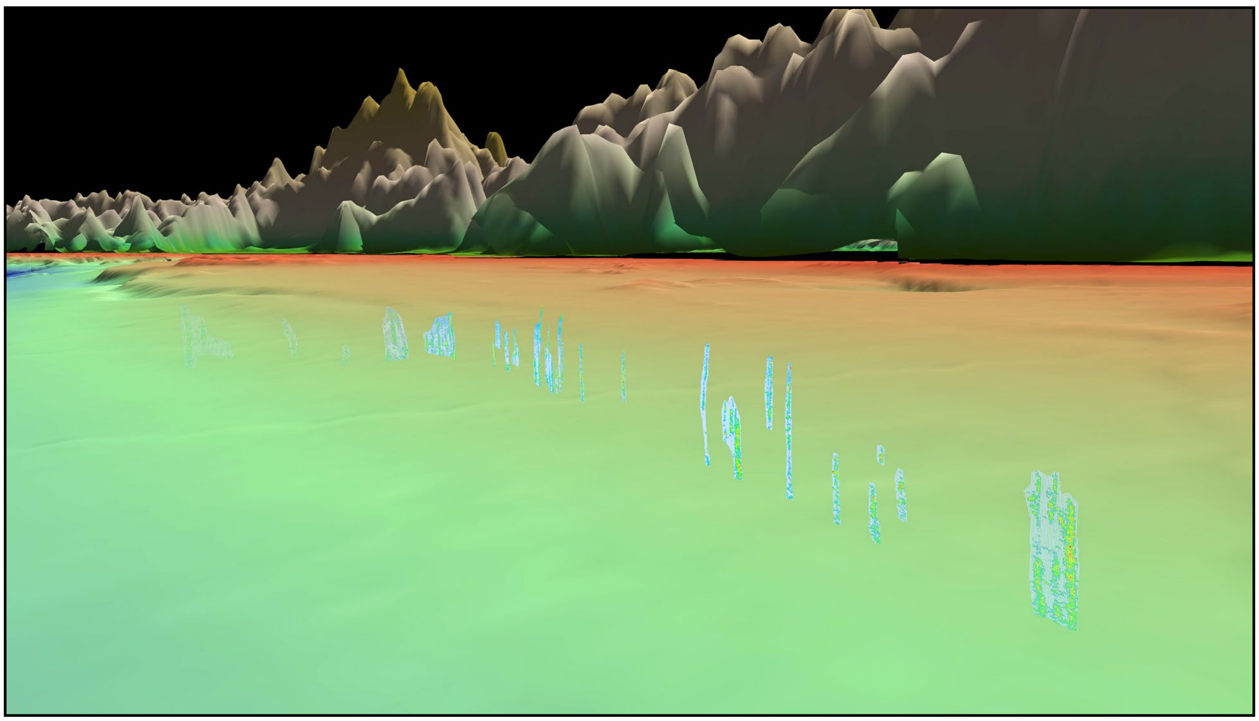
OCS Study
BOEM 2022-057

Hydrocarbon Seeps in the Lower Cook Inlet, Gulf of Alaska, Chukchi Sea and Beaufort Sea OCS Planning Areas



U.S. Department of the Interior
Bureau of Ocean Energy Management
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September 2021

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ABOUT THE COVER

Bubble streams rising from the seafloor along a ship's track in northern Shelikof Strait. The bubbles emerge from the seafloor at cold seeps and gradually dissolve as they rise; they do not necessarily reach the surface. Land topography is shown in brown and green; the seafloor is gray. The bubble streams were imaged using the backscatter signal in EK60 sonar during cruise DY1706 of the NOAA Ship *Oscar Dyson*.

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We are very grateful to **Darin Jones**, Research Fishery Biologist in NOAA's Alaska Fisheries Science Center (Midwater Assessment and Conservation Engineering group) for sharing his database of water column anomalies in the Gulf of Alaska. He had identified these anomalies as "not fish" and recorded them as possible bubble streams during NOAA EK60 fisheries surveys in 2014-2019. We re-investigated hundreds of them and consulted with Darin on interpretation of bubble streams vs fish aggregations. Most of these locations are included in our project database.

We are also pleased to acknowledge contributions by **Mark Zimmermann**, Research Fish Biologist in NOAA's Alaska Fisheries Science Center (Resource Assessment and Conservation Engineering division). Mark has a longstanding interest in seafloor maps and sonar data. He provided both potential and confirmed seep locations from his mapping studies and fisheries research at sea and discussed those sites with us during preparation of our report. The project database and GIS framework were designed by **Brent Dillard**, GIS Data Lead - GeoConsulting Exploration AC, at Fugro U.S.A Marine, Inc. (Houston, TX). It was a pleasure to work with Brent. Our project began as a collaboration between BOEM, the University of Alaska Fairbanks, and Fugro U.S.A Marine. After Fugro dropped out of the project during the Covid-19 pandemic, we continued with the database and GIS framework that Brent had established.

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List of Abbreviations and Acronyms

BOEM	Bureau of Ocean Energy Management
C_1-C_{15}	Carbon isotopes
UAF	University of Alaska Fairbanks
OCS	Outer Continental Shelf
USGS	United States Geological Survey
OCSEAP	Outer Continental Shelf Environmental Assessment Program
GHSZ	Gas Hydrate Stability Zone
NMFS	NOAA Marine Fisheries Service
NOAA	National Ocean and Atmospheric Agency
NCEI	National Centers for Environmental Information
GOA	Gulf of Alaska Planning Area
KOD	Kodiak Planning Area
COK	Cook Inlet
SHU	Shumagin Planning Area
Western OCS	Western Outer Continental Shelf Planning Areas
CHU	Chukchi Sea Planning Area
BFT	Beaufort Sea Planning Area

1 Introduction

Submarine seepage involves the flow of fluids from the seabed into the ocean. These fluids can be groundwater, hot hydrothermal fluids, or hydrocarbon-rich fluids. In the marine realm, fluids "seeping" on the seafloor are now documented along the U.S. continental shelves and slopes (Bernard et al., 1976; L. L. Brothers et al., 2013; A. Judd & Hovland, 2007a; Lorenson et al., 2002; Sager et al., 2004; Skarke et al., 2014). Hydrocarbon fluid flow and associated gas hydrate formations have implications for seafloor geologic features, slope stability, marine biological processes, and the composition of the oceans (A. Judd & Hovland, 2007a).

Hydrocarbon seeps on the seafloor are named cold seeps to distinguish them from hot hydrothermal fluid venting. Cold seeps occur in a variety of seafloor environments from coastal waters to the continental shelf and slope, and into the deep ocean. Seeping hydrocarbons in these environments may be methane or other gaseous hydrocarbons, oil, tar, or mud. The fluid can range from slow and diffuse to effusive flow that releases bubble streams into the water column. Depending on the setting and types of fluids being emitted, seeps may be associated with seafloor features such as pockmark depressions, mud volcanos, or gas hydrate mounds. Seep fluids can also react with shallow pore water and create authigenic carbonate formations that provide hard substrate for cold water corals and sponges, anemones, as well as some species of fish. The hydrocarbons can also directly support communities of endemic chemosynthetic species. The locations of natural seeps may also point to subsurface petroleum deposits. Because hydrocarbon seepage has both benefits and hazards for human activities, it is therefore important to understand the spatial extent of seeps, the setting in which they can be found, as well as volume and type of fluids being emitted.

There are several additional ways in which knowledge of seep locations can help BOEM accomplish its mission of managing development of U.S. Outer Continental Shelf (OCS):

- Distribution and chemical fingerprints of natural seeps may provide an important baseline for monitoring impacts of petroleum exploration and development on the Alaskan environment.
- Seep-associated hazards, such as gas hydrate decomposition and submarine landslides, can affect exploration and infrastructure development in the modern marine environment.
- Hydrocarbon seep emissions can support local chemosynthetic seafloor communities and may impact primary productivity and fisheries. These chemosynthetic seep communities may also include benthic organisms that are capable of metabolizing hydrocarbons for oil spill mitigation and remediation.
- Methane and other fluids emitted by seeps may affect ocean chemistry and physical properties of the ocean.

The primary goal of this desktop study is to help BOEM evaluate the potential for offshore petroleum resources in the Lower Cook Inlet, Gulf of Alaska, Chukchi Sea and Beaufort Sea Outer Continental Shelf. Patterns of seep occurrence on the seafloor provide insights into the geologic history, materials, and subsurface structures, improving our geological understanding of the Alaska offshore region.

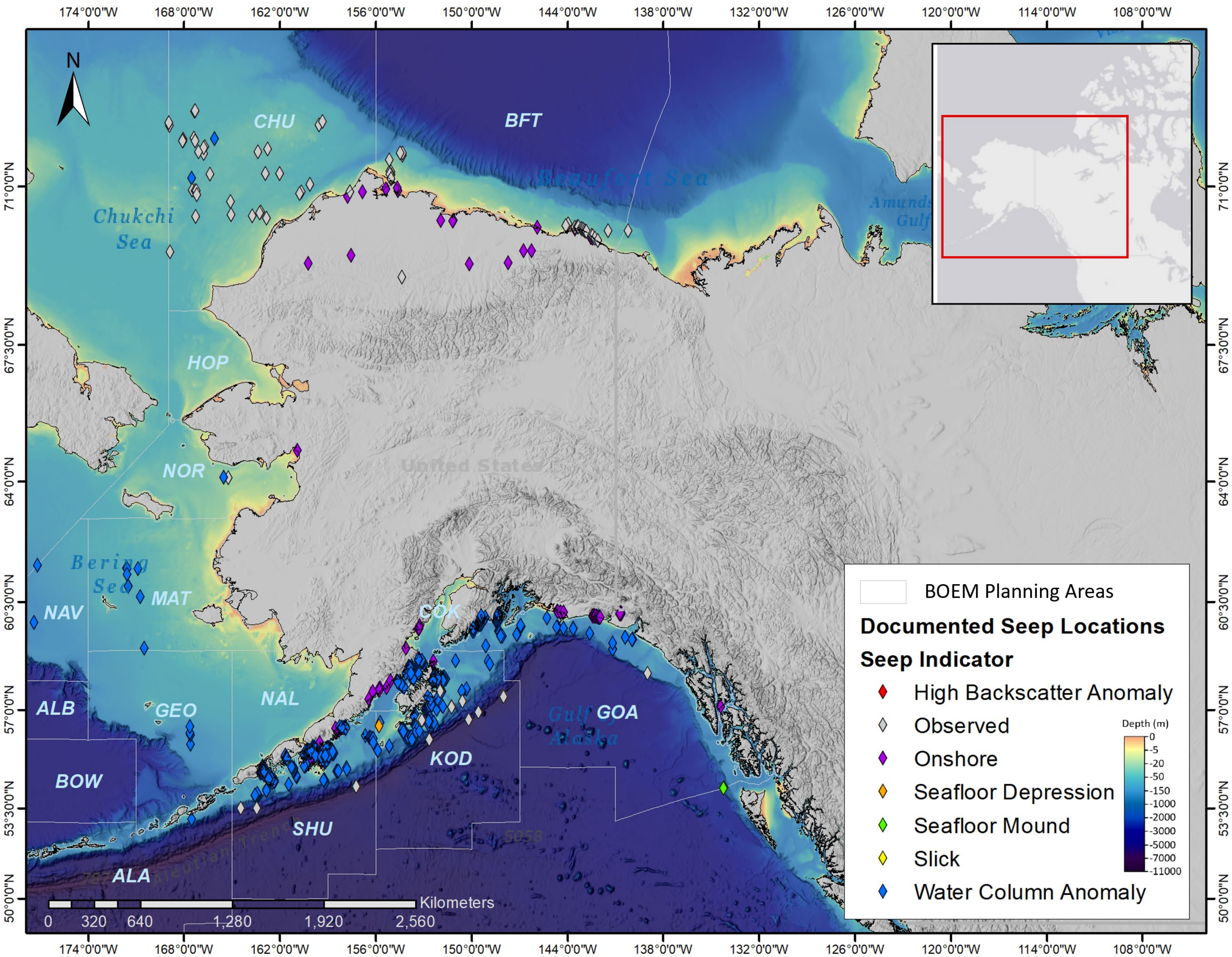

Figure 1. Seep locations discussed in this study (bathymetry from NOAA-NCEI). Categories of seep indicators are described in Section 2. BOEM Planning Areas included in this study are GOA = Gulf of Alaska, KOD = Kodiak, SHU = Shumagin, ALA = Aleutian Arc, CHU = Chukchi Sea, and BFT = Beaufort Sea.

To meet the goals of this desktop study:

- Geographic boundaries of the BOEM Planning Areas for the Alaska region (**Figure 1**) were used to guide data management and provide structure for discussions on seep distribution.

- 1486 seeps have been identified from available literature, publicly available seafloor and water column data, and BOEM documents (which refers to documents from the Bureau of Ocean Energy Management as well as its predecessor agencies).

- A geodatabase is provided with the locations and metadata for the seeps. The geodatabase also includes publicly available geophysical data that were used in interpreting the spatial distribution of the seep locations.

- Where possible, the settings and patterns of seep locations are discussed in geological context.

- Literature sources cited in the database and in this report have been compiled into a bibliography, including “BOEM documents” which refers to the Bureau of Ocean and Energy Management as well as its predecessor agencies.

- This report concludes with recommendations for future field programs aimed at understanding patterns of occurrence, seafloor expression and geochemistry of the hydrocarbon seeps.

In this report, **Section 1** introduces general information about seeps and their importance to offshore development and environmental protection. **Section 2** details methods used to determine seep locations, and outlines where information can be found within the accompanying geodatabase and appendices. **Section 3** discusses seep locations within each relevant BOEM Planning Area region and recommends areas for further study.

2 Sources of Hydrocarbons

Seabed fluid flow occurs in a variety of geologic settings and oceanographic environments. Understanding the context in which hydrocarbon seeps occur can help determine potential distribution of seeps in the Alaska nearshore and OCS regions.

Hydrocarbon gases dissolved in cold seep fluids (Methane (C_1) thru Butane ($C_{4,}$)), are generally discussed as being from either microbial (biogenic) or thermogenic sources. The term microbial refers to hydrocarbons that form at low temperatures (<50°C) in organic-rich sediments through microbially mediated chemical reactions. Thermogenic gas formation occurs through thermocatalytic breakdown of organic matter when burial temperatures are in the range of 80-120°C. Late thermogenic carbon-rich gas is produced at temperatures higher than about 150°C. Fluids formed during each of these processes have characteristic chemical and isotopic compositions (Claypool & Kvenvolden, 1983).

Gases formed in shallow sediments by microbial processes tend to rise through the sediment and be released at the seabed. If rising fluids are trapped under fine-grained sediments, permafrost, or other impermeable geologic formations, the pore pressure can rise until the overburden finally yields and fluid is ejected, forming a pockmark on the seafloor. Pockmarks are found in a variety of sizes from less than one meter to a few hundred meters across (A. G. Judd & Hovland, 1992). Fluid escape and pockmark formation can also occur in shallow water areas with sandy-silty sediments as a result of liquifaction during the large seismic events common around Alaska (Winters et al., 1981).

Deeper sourced thermogenic hydrocarbons require structural migration pathways, such as faults and fractures, to move hydrocarbon fluids to the surface (M. Hovland et al., 2002). Fluid escape features on the seafloor include giant blowout pockmarks, pockmark chains along faults, mud volcanoes, brine pools, oil seeps, and asphalt volcanoes.

Rising methane-rich fluids may encounter subsurface pressure-temperature conditions that are conducive to formation of gas hydrates. When stable, subsurface hydrate deposits sequester methane and inhibit gas migration to the seafloor. Destabilization of hydrates by lowering pressure or raising temperature can release the trapped methane, allowing it to resume its journey to the seafloor. (e.g., Maslin et al. 2010; Ruppel and Kessler 2017; See Section 1.1.4.1**)**. It is important to understand the geologic and tectonic environments that favor or inhibit production, migration, and seepage of hydrocarbon fluids to understand the spatial distribution of seeps on the seafloor.

2.1 Seep Distribution on the Seafloor

In this section we give a short overview of the general seafloor environments and geomorphologic features that have been associated with hydrocarbon seepage worldwide, to provide a context for seeps interpreted within the Alaska OCS.

The location of seeps which are related to modern microbial processes are in areas of sediment accumulations. Thermogenic oil and gas seep locations are related to current tectonic activity and the resulting geologic structures. Sediments that have been folded or faulted provide pathways for fluids to rise to the surface **(Figure 2).** Some seeps are very long-lived, and others are ephemeral, and the amount of fluid seepage can vary over time, depending on the type of fluids, the structure from which it issues, and the size of the reservoir. Documenting and describing the location and character of land seeps can be important to understanding seep locations in the marine environment (Becker & Manen, 1988; Link, 1952a).

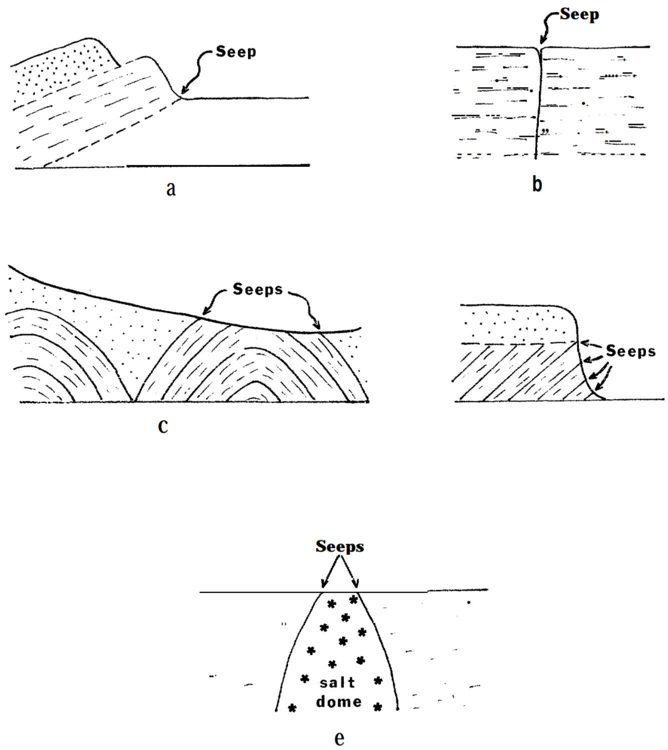

Figure 2. Types of oil seeps (a) fluids utilizing exposed tilted bedding planes (b) fluids feeding into fissures and fault planes (c-d) fluid accumulations exposed through erosion of unconformities (e) seeps associated with intrusions e.g. mud volcanos, salt.
From Becker and Manen 1988 (after Link 1952).

2.1.1 Onshore Seeps

Onshore oil seeps were the location of the first oil leases in Alaska. These oil seeps were found in five districts: the Katalla and Yakataga districts on the northern Gulf of Alaska coast, the Iniskin Bay district in Cook Inlet, the Cold Bay District on the Alaska Peninsula, and the Smith Bay District on the Arctic coast. In an early USGS document on Alaskan petroleum exploration, Martin (1921) reported that oil production occurred exclusively on oil seep sites or within the sedimentary units where seeps were found (**Figure 3**). Athough this study concentrates on offshore seep locations, onshore seeps were included in the seep database accompanying this report because they provide information about geologic formations and structures that may continue offshore into the marine environment. Any mapped faults that continue offshore from seeps observed on land were investigated for evidence of seafloor seepage (see **Section 3.1.3** for details).

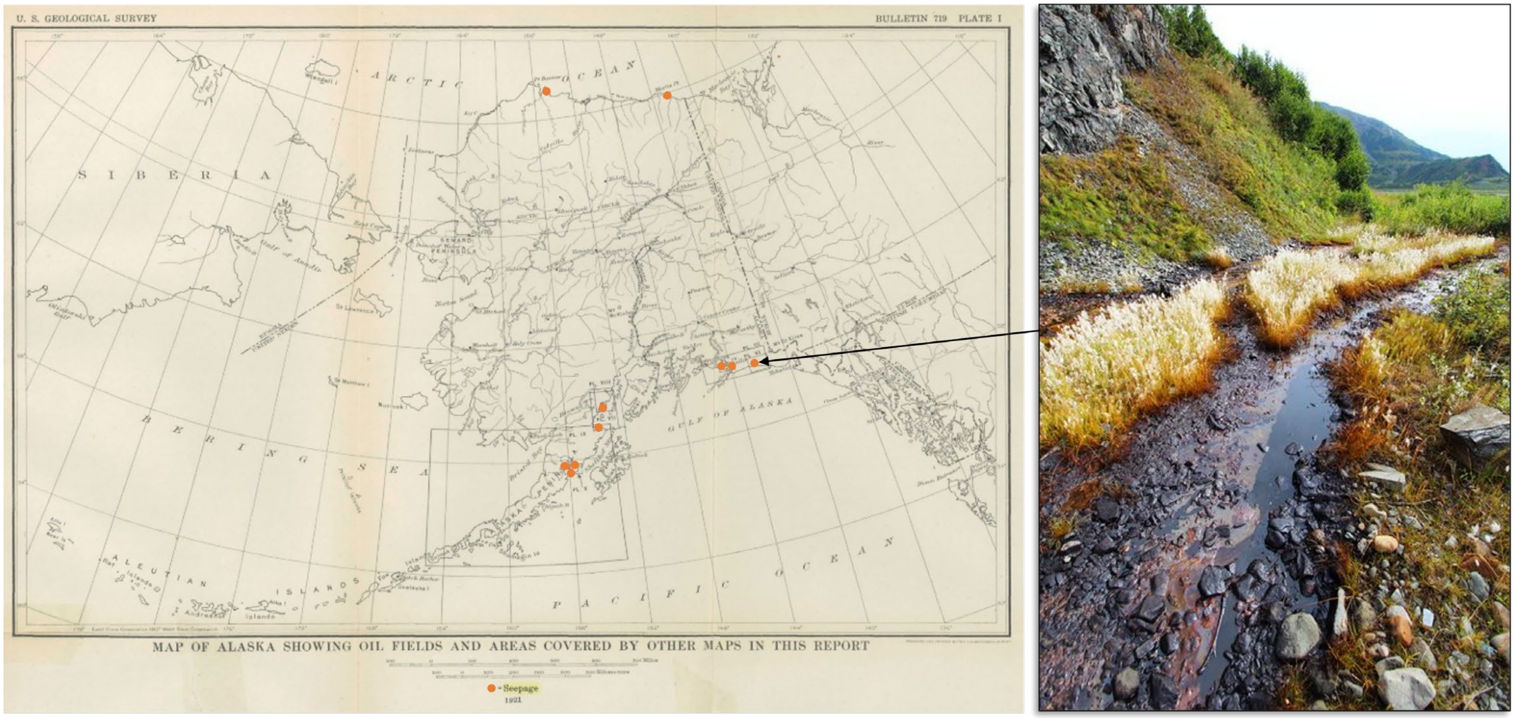

Figure 3. Map from 1921 USGS report showing oil seep locations (orange dots) found during early days of oil exploration in Alaska (from Martin, 1921). (callout) Photograph of oil seep in the Samovar Hills area near the Yakataga district

Photo courtesy of Erin McKittrick, Creative Commons Attribution Non-Commercial license..

2.1.2 Nearshore Seep Environments

Estuaries and shoreline embayments are favorable to microbial methanogenesis due to restricted water movement and deposition of organic-rich sediments from modern rivers. Coastal lagoons, deltas, and drowned coastal plains also have quiet conditions and sediment accumulations rich in organic matter, where methane is generated by microbial processes.

In northern regions, nearshore fluid venting from the seabed may also be related to permafrost or ice. For instance, if microbial methane gas or solid methane hydrate is trapped under permafrost in the nearshore environment, this methane can be released when the permafrost is melted or uncovered. Pockmarks do not necessarily indicate gas release; they can also indicate pore water expulsion from compacted sediments where heavy ice gouges the seafloor forcing pore waters to be expelled. In nearshore areas affected by annual sea ice, pockmarks commonly appear as clusters within ice gouge grooves on the seafloor where the gouging action released shallowly buried microbial methane into the water column.

Glacial valleys and fjords may also contain seeps where sediment-laden glacial runoff along with high rates of organic-rich river sediment deposition creates conditions favorable to microbial methanogenisis (Borges et al., 2016; M. Hovland, 1992; Römer et al., 2014). Fjords often contain shallow water sills that restrict water exchange with deep water basins, creating a stagnant environment and anoxic conditions that leads to production of microbial methane. In glacial valleys after ice retreats, an area isostatically rebounds and the confining pressure of the water column is lessened. Fluids can then be released from the thick sediment within glacial scours and may form pockmarks and bubble plumes in the water column, like those described in Shelikof Strait (**Figure 4;** Hovland and Judd 1992; Römer et al. 2014; Borges et al. 2016; Zimmermann et al. 2019; Daszinnies et al. 2021).

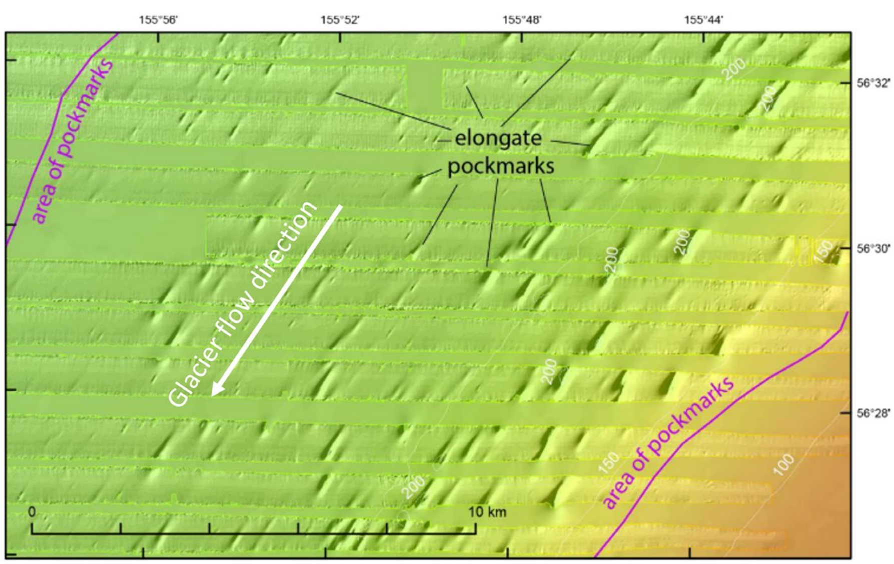

Figure 4. Bathymetry of a glacial trough in Shelikof Strait (see red arrow Figure 9 for location) showing elongate pockmarks in sediment-filled scours aligned with glacial flow direction.

Modified from Zimmermann et al. (2019) and used under Creative Commons license CC BY

2.1.3 Continental Shelf Seeps

Some areas of the continental shelf are more likely than others to be associated with seeps. The most probable areas of seepage are above sedimentary basins where organic matter is degraded by microbial and thermogenic processes (Judd & Hovland, 2007a). Not all basins are petroliferous, but at minimum it is likely that microbial methanogenesis can occur in the organic-rich sediments within these basins.

Studies conducted on continental shelf seeps have indicated that cold seep habitats in water depths <160 m are not generally inhabited by diverse chemosynthetic communities and are instead limited to bacterial mats. Very few symbiont-hosting macrofauna have been identified in shelf seep settings, compared to seeps in water depths greater than 350 m (Martin Hovland & Judd, 1992; Sahling et al., 2003). There are exceptions in situations where fluids are utilizing faults as pathways to the surface at shelfal water depths.

2.1.4 Shelf Break and Continental Slope Seeps

2.1.4.1 Dissociation of Gas Hydrate

In the U.S., cold seeps have been described along the shelf break of the entire Gulf of Mexico (e.g. Teske and Carvalho 2020), the U.S. Atlantic margin (L. L. Brothers et al., 2013; Hornbach et al., 2008; Skarke et al., 2014), on the western Pacific margin, and in the Arctic (e.g. Hovland 1992; Paull et al. 2007; Westbrook et al. 2009). Shelf break and upper slope seeps are usually associated with methane gas release from dissociation of methane hydrates. Solid-solution gas hydrate forms beneath the sea floor from natural gas and water within a stability field determined primarily by temperature and pressure **(Figure 5**). Hydrate dissociation and related methane seepage can occur when changes in temperature, pressure, or salinity at the seafloor alter the depth of the gas hydrate stability zone (GHSZ), and allow free methane to vent on the seafloor (**Figure 6**; Darnell and Flemings 2015). Changes in the stability zone parameters can occur for many reasons, e.g., seasonal, or global changes in water temperature, changes to sea level, or changes in sediment overburden. These changes can force the GHSZ to reach the shelf edge and the unstable methane hydrate dissociates. Fluids are then released to the seafloor and into the water column guided by local lithology and structure. This has impacts on slope stability and canyon morphology.

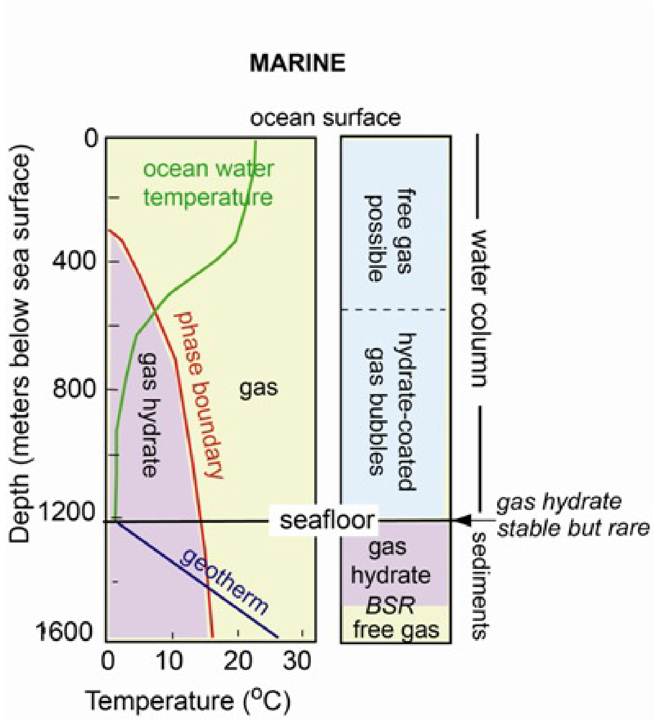

Figure 5. Phase diagram for gas hydrate stability in the marine environment.
From the U.S. Geological Survey web page *Primer on Gas Hydrates*, downloaded Apr 2014

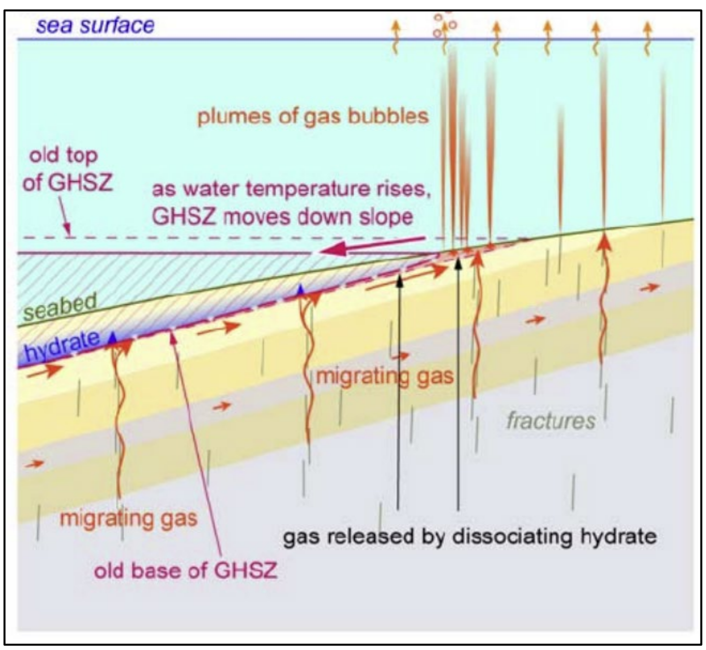

Figure 6. Profile of upper continental slope and location of gas hydrate stability zone (GHSZ) where gas is released on the seafloor at the shelf edge.
Modified from Westbrook et al. 2009, (used under permission policy of the American Geophysical Union)

2.1.4.2 Submarine Channels

The presence of gas hydrate in submarine channels and canyons has implications for slope stability and methane release into the water column. Several circumstances link hydrocarbon gas seepage with submarine channels and canyons on a continental margin. First, minor gas release can occur within submarine canyons where fluids are expelled from microbial methane within the channel fill. Second, the location of some shelf and slope channels is fault controlled, so the same faults that provided accommodation for channel development may also serve as migration pathways for seeping hydrocarbons. Third, submarine canyons can be initiated or enlarged by the collapse of shelf-edge gas hydrate mounds. This collapse and dissociation of the hydrate releases large amounts of sand and mud, causing turbidity currents to initiate down slope channel development (Nakajima et al., 2014).

2.1.5 Deep Sea Seep Environments

2.1.5.1 Deep Sea Fans

Deep sea fans sourced from major river systems are often places where organic-rich sediment accumulates, and hydrocarbons produced from breakdown of this organic matter may vent to the seafloor (A. Judd & Hovland, 2007a). Similarly, thick mass transport deposits on the lower slope and rise are locations of seeping hydrocarbons probably related to hydrate destabilization during slope failure and/or free gas release from disturbed sediment layers (Field, 1990; Saint-Ange et al., 2014). As in other settings, gas can also escape to the seafloor through fractures in shallowly buried rocks on the lower slope (Skarke et al., 2014).

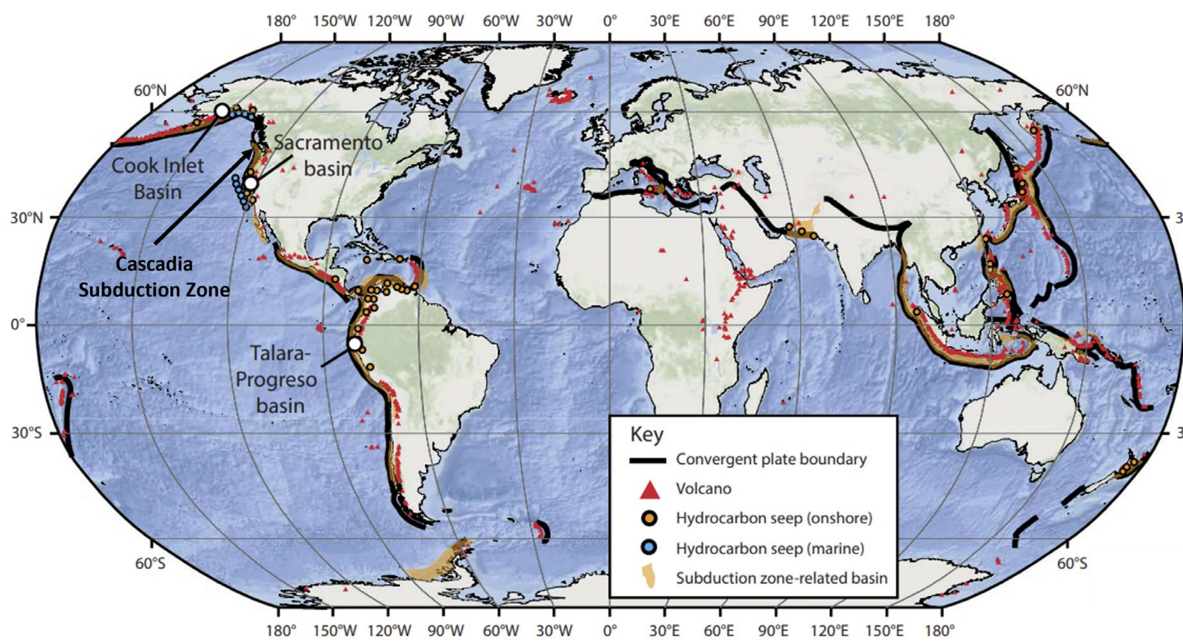

Figure 7. Map of locations of subduction zone basins and subduction related hydrocarbon seeps

From Hessler and Sharman (2018), Creative Commons license DD by NC. .

2.1.5.2 Subduction Zones

Fluids from dewatering of sediments in accretionary prisms are from pore-water expulsion and breakdown of hydrous minerals. Buoyancy drives these fluids upward resulting in mud diapirism and cold seeps (e.g. Suess et al. 1998; Suess 2014; Barrie et al. 2020) Some forearc basins and trench slope basins with thick sedimentary fill and suitable structures, are favorable for hydrocarbon preservation and possibly petroleum production (Hessler & Sharman, 2018).

Cold seeps within subduction zones **(Figure 7**) are usually associated with major faults that facilitate upward migration of fluids (e.g., Sibuet et al. 1988; Suess et al. 1998). For instance, in the Cascadia subduction zone of the Pacific Northwest (see **Figure 7**), hundreds of methane seeps have been observed on the continental slope along the edge of the gas hydrate stability zone, and along extensional faults and ridges (Solomon et al. 2017).

2.2 Seep Hazards and Benefits

Hydrocarbon seepage occurs because of oceanographic and geologic conditions in specific seafloor settings. Understanding seep locations and distribution patterns on the Alaska OCS provides valuable information not only on resource potential but also possible geohazards and habitat characterization that could aid in planning and regulating resource exploration and development.

2.2.1 Oil and Gas Exploration

The occurrence of thermogenic hydrocarbon at the surface can indicate a working petroleum system in terms of the presence of source-rock and migration pathways. Many of the initial giant oil field discoveries, such as in Texas, Iran, Iraq, and Alaska, were made as the direct result of drilling on or near oil seepage areas on shore (Link, 1952b; Martin, 1921). By studying offshore seeps and the reasons for their occurrence, valuable insight into petroleum systems and fluid flow regimes in a marine exploration area can likewise be used to help reduce exploration risk (Dembicki, 2016). Geochemical analysis of associated fluids can provide information on offshore petroleum reservoir quality, maturity, and production potential (Bernard et al., 1976; Dembicki, 2017), further aiding resource evaluation.

2.2.2 Methane Hydrate Exploration

Gas bubble plumes in the water column require a relatively robust supply of methane, and often indicate dissociation of methane hydrate within seafloor sediments. Once assumed to be rare, it is now commonly estimated that 20,000 trillion m^3 of gas occurs in hydrates, and formation thicknesses can be several hundred meters thick (e.g. Boswell, 2009). Methane hydrates are currently being investigated by several countries as a potential energy source (e.g., Collett 2019). Because of their instability at surface pressures and temperatures, the commercial viability of gas hydrate is not yet certain, but the deposit volumes and technical details of production are active areas of study.

2.2.3 Baseline Hydrocarbon Fingerprints

Hydrocarbons can be released into ocean water by anthropogenic sources (e.g., spills) or by natural seepage through the seafloor. A census of seep locations followed by geochemical sampling to characterize them is necessary to distinguish those two sources. This information is important for BOEM's environmental assessment mandate for baselines as well as U.S. environmental management more broadly.

2.2.4 Slope Failure

Gas hydrate dissociation at the shelf edge has been implicated in several large submarine landslides on the U.S. Atlantic margin, such as the Cape Fear Slide and Cape Lookout Slide (Hill et al., 2018; Hornbach et al., 2007), and around the Arctic Ocean (Kayen & Lee, 1993; Wallmann et al., 2018). The cause-and-effect relationship between hydrate dissociation and submarine slope failure can be unclear.

Although methane hydrate itself can stabilizes marine sediments by providing structural support as a type of cement, dissociation of gas hydrate has a negative effect on the stability of submarine slopes. Gas hydrate dissociation can generate considerable excess pore fluid pressure, which changes the mechanical parameters of hydrate-bearing sediments, destabilizes the slope, and contributes to slope failure. (Zhang et al. 2019 and citations therin).

If slopes fail due to other causes such as earthquakes or erosion, hydrate instability may occur as the event unburdens hydrates, exposes them to seawater, and causes dissociation. When this occurs submarine landslide scars where the GHSZ has been disturbed are locations of seeping fluids and mud diapirism (L. L. Brothers et al., 2013; Skarke et al., 2014).

2.2.5 Chemosynthetic communities

Microbially mediated reactions between hydrocarbon-bearing fluids, shallow pore water and seawater can support chemosynthetic communities at cold seeps (e.g., Suess 2014). Location and characterization of chemosynthetic ecosystems associated with hydrocarbon seeps contribute to BOEM environmental assessments of sensitive biological habitats in U.S. Federal waters. Chemosynthetic communities on the continental slope have been studied extensively and are protected as a biological resource, qualifying for avoidance mitigations during oil and gas development in the Gulf of Mexico (U.S. Department of the Interior 2010).

2.2.6 Biotechnology

Understanding how chemosynthetic microbes synthesize and degrade hydrocarbons could provide valuable models and new technologies for oil spill cleanup and other hydrocarbon pollution offshore. The biotechnology industry also uses marine extremophiles found at cold seeps to develop bioactive compounds for industrial, agricultural, environmental, pharmaceutical, and medical uses (e.g., Querellou 2003).

2.2.7 Fisheries

There is some indication that natural seepage of hydrocarbons may be a factor in supporting fisheries (A. Judd & Hovland, 2007a; Levy & Lee, 1988). It is not well understood how primary productivity and various fish species are affected by methane seepage, but there is some evidence that expulsion of hydrocarbon-bearing fluids out of the seafloor can lead to an increase in biomass and an enhanced fishery. Some demersal fish species are associated with rock outcrop habitats, and may benefit from the authigenic carbonate that forms at cold seeps (Orange et al. 2002; Barrie et al. 2020). Therefore, understanding the distribution and fluid volume of seeps on the sea floor, adds to our understanding of the diversity and health of the ocean ecosystem in multiple ways.

3 Methods of seep identification and inventory Data used

3.1 Data used

The purpose of this study is to locate and create a database of known seep sites in Alaskan waters of the Northern Gulf of Alaska, the Chukchi Sea, and the Beaufort Sea. These regions include the following BOEM Planning Areas: Gulf of Alaska, Cook Inlet, Kodiak, Shumagin, Chukchi, and Beaufort (Figure 8). Our database includes a small number of sites in the Bering Sea that were encountered during the study, but we did not deliberately search for seeps outside the target Planning Areas.

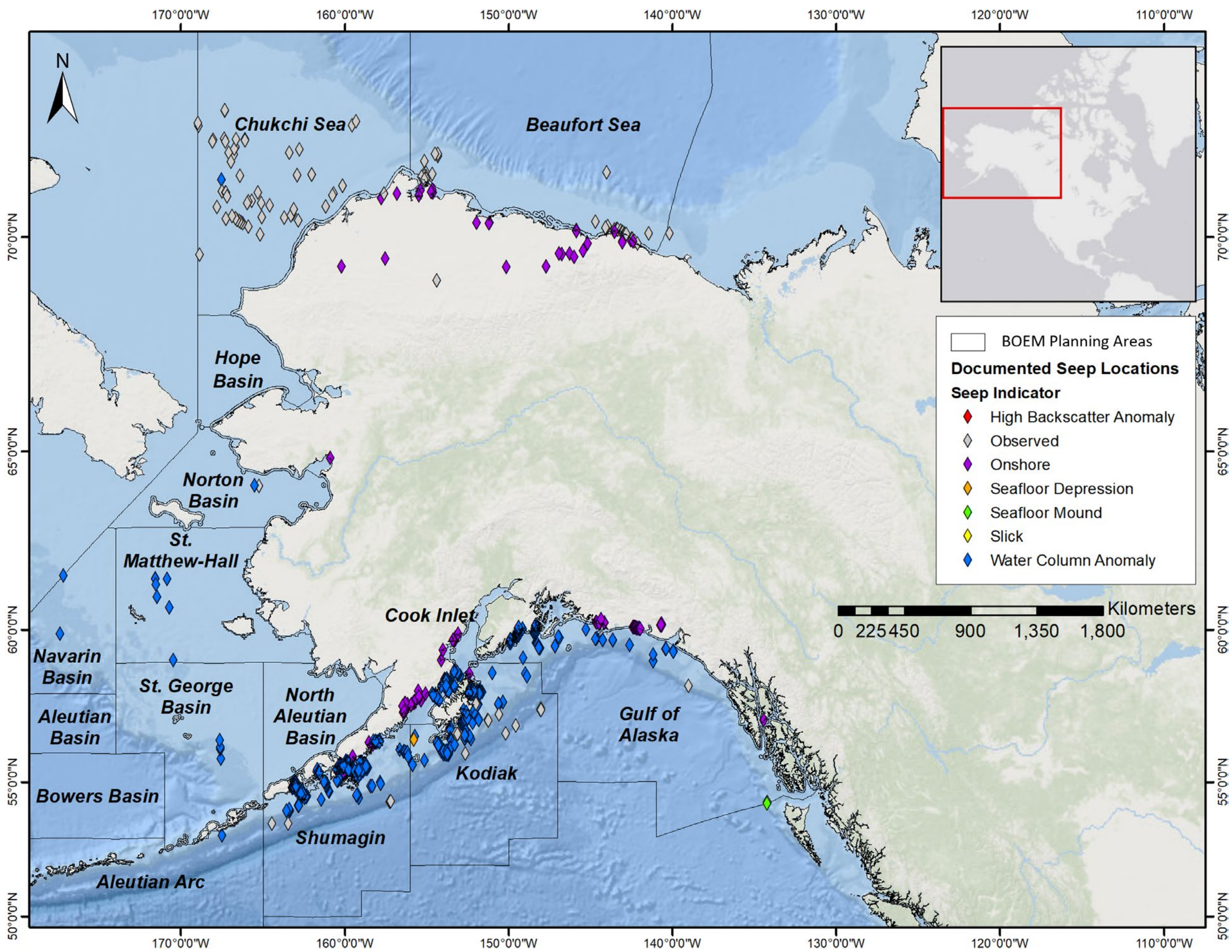

Figure 8. Map of BOEM Planning Areas around Alaska, along with seep locations from this study.
ESRI basemap, WGS84 web Mercator auxiliary sphere.

The following data sources were used to determine seep locations:

- BOEM documents
- Literature search
- Fisheries sonar
- Crowdsourcing (personal communications from scientists, and field spreadsheets)

These sources of geologic information were used to establish context and aid interpretation of the seep locations:

- Geologic map of Alaska (USGS)
- Fault map shapefiles (USGS and literature)
- Seafloor bathymetric rasters (NOAA-NCEI, NMFS smooth sheets, and literature)

The primary product from this study is the database of seep locations. The above-mentioned public datasets were imported into Esri ArcMap (v.10.8) and used to investigate seeps locations. A geodatabase of seep locations accompanies this study. Details of the database entries are provided in project spreadsheets included on the project hard drive. Each entry contains a unique Seep ID, Seep Indicator (method of detection), latitude and longitude in decimal degrees (WGS84), any existing site name, the BOEM Planning Area in which the seep was located, data type (e.g. literature, single beam), data source, date first reported, original coordinate system if available, remarks and confidence level **(Table 1**).

Table 1. Definitions of confidence levels used in seep location database

Confidence Level	Definition	Count in report
1	Report of seep with no precise position given	14
2	Reported seep with accompanying generalized map or photo without precise coordinates	89
3	Coordinates of seep reported utilizing older methods (and converted to WGS84)	49
4	Seeps sites located by modern methods (GPS navigation surveys, sonars, ROV)	1219
5	Seeps sites found or confirmed in this study	93

Confidence levels refer to both the existence and location of the reported seep. Some seeps were originally reported with modern methods (Level 4), but with unknown coordinate systems so were given a lower confidence level (Level 3). If coordinate systems were reported for a seep location, the information appears in the attribute table of geodatabase. All seep locations, and the geodatabase, are reported using World Geodetic System 1984 datum (WGS84). When coordinates systems were reported in literature with geodetic information, the locations were converted to WGS84 using both online conversion tools and ArcMap transformation tools.

3.1.1 BOEM Documents

The Alaska Region Office of the Bureau of Ocean Energy Management provided relevant published and unpublished studies of the Alaska OCS by BOEM and its predecessor agencies. In these studies, seep sites were identified by a range of methods including acoustic water column anomalies, fluorescence mapping, and headspace methane in shallow sediment cores. Seep sites from BOEM (and predecessor agency) unpublished documents are listed as “BOEM documents”, and peer reviewed publications are referenced as formal publications by author.

3.1.2 Literature Search

Although seeps were known and utilized by indigenous people for centuries, the earliest published reports of oil and gas seeps in Alaska came from onshore exploration of the Yakataga and Katalla areas of south-central Alaska in the early 20th century. Because the geological formations and fault structures of south-central Alaska are continuous across the shoreline, evidence of oil and gas seeps on land can help with interpretation of seep patterns offshore. The database contains published reports of seeps on land, dating from 1902 to 1998 (Becker and Manen, 1988; Page et al., 1998).

The locations of onshore seep sites in the literature vary from a reference to topography and landmarks, to highly precise GPS coordinates. Some authors have made an effort to check the existence of seeps at these sites and improve the location information; we have excluded seeps that authors sought and did not find at the reported locations (e.g. Blodgett and Clautice 2005).

Published reports of offshore seeps in the Alaska region are rare. The database contains 25 offshore seep sites from seven publications. Most of these are in the Kodiak or Shumagin Planning Areas.

3.1.3 Fisheries Sonar

Sonar systems used in fisheries to image aggregations of organisms in the water may also be used to image streams of gas bubbles rising from seafloor seeps (e.g. **cover image**). Because the seep gas is dominated by methane, a methane hydrate skin may form on the bubbles (Brewer et al., 1998), increasing the strength of the acoustic backscatter and enhancing their detection (e.g., Heeschen et al. 2003). Because this is a remote sensing method that can image large volumes of water at once, it is a very efficient way of detecting bubbling seeps. In Alaskan waters, NOAA Fisheries vessels make extensive use of EK60 split-beam and ME70 multibeam sonar systems for water column surveys. NOAA Fisheries scientist Darin Jones generously provided logs of acoustic anomalies that he observed during fisheries stock assessment surveys in 2009, 2011, and 2013-2019. These anomalies are narrow, vertical zones of water column reflectors which Jones initially logged as "not fish" due to the relative frequency response. Subsequent acoustic analysis and ground truthing of sites on the Snakehead Bank, near Kodiak, confirmed that these anomalies were bubble streams from seafloor seeps (Jones et al., 2012).

A large majority of the water column anomaly seeps in the seep database come from Jones' spreadsheets. There are over 1200 seep site locations from these spreadsheets with seeps located in the Gulf of Alaska, Cook Inlet, Kodiak, and Shumagin Planning Areas, assigned confidence level 4 **(Table 1**). All seep sites from 2009, 2011, 2013 surveys are listed as being reported in a spreadsheet from 2014, while data from later years are listed as 2019 reports. We reexamined some of the archived sonar data from these fisheries surveys and confirmed Jones' reports from those data.

While the current report is a desktop study to gather information on known seafloor seeps in Alaskan waters, we also conducted a pilot study of single-beam acoustic records to find water column anomalies in the Yakutat region. This area was chosen for the pilot study as (1) an area of interest for oil and gas exploration; and (2) availability of NOAA Fisheries single-beam acoustics data in the NCEI archive. The coastal Katalla field in the Yakutat region was one of the original targets for oil and gas exploration in the early part of the last century due to the presence of onshore seeps (e.g., Martin 1921). In 2019, renewed industry interest in the onshore area resulted in the State of Alaska issuing a single license for onshore oil exploration near Katalla (Brooks, 2019).

Data used for the pilot study near Yakutat were EK60 split-beam and ME70 multibeam sonar data from the NOAA Ship *Oscar Dyson* in 2013, 2015 and 2017 and have a confidence level of 5. Lines near faults, exploratory wells, or known seeps were prioritized for review to greater increase the chance of visualizing a hydrocarbon seep. After converting lines to the QPS Generic Water Column format, the QPS FMMidwater software was used to examine the lines for evidence of seeps. All five frequencies in the EK60 data (18-200 kHz) were reviewed. No down-sampling was applied to the lines. Water column anomalies indicating seep bubble streams were recorded and an image of the sonar record was stored in the accompanying project folder. Also, as part of the pilot study, we examined multibeam sonar data near Yakutat recorded by *the R/V Sikuliaq'*s EM302 and EM710 sonars during transit in the 2015 cruise SKQ201503T. The multibeam data from *Sikuliaq* in this shallow region was very noisy, probably due to the shallow depth (<200 m) and transit speed during data collection, and examination of the *Sikuliaq* data near known seeps did not show indications of seeps. Both single beam and multibeam lines used in this study were imported into the ArcMap project as a feature class in the accompanying geodatabase.

3.1.4 Crowd Sourcing, a.k.a. Personal Communication from Scientists

Some seafloor seep locations came to us by personal communication from marine scientists. The extensive spreadsheets from Darin Jones' fisheries surveys properly belong in this category, but because all his seep detections were done by water column sonar they have been described above. A second important group of seep reports was based on water column sonar observations by Mark Zimmermann, NOAA Research Fish Biologist, who also recorded seep occurrences during stock assessment surveys. Zimmermann seeps are discussed in the Northcentral Gulf of Alaska section below.

3.1.5 Context and Interpretation: Geologic Maps, Fault Maps, Bathymetric Maps

We have used several approaches to understand the context of the seep site locations and their possible relationship to seafloor geological features. Onshore geology is relevant where onshore geologic formations and structures continue offshore; we have used the digital version of the Geologic Map of Alaska published by the U.S. Geological Survey (Wilson et al., 2015). Similarly, the digital version of the U.S. Geological Survey's fault map for Alaska (Bender & Haessler, 2018) allows us to trace the offshore continuation of structures with which onshore seeps are associated.

Finally, we have used regional bathymetric maps to place the seeps in the context of seascape features and to identify seafloor features such as pockmarks and unmapped faults that might act as conduits for seep fluids. Sources of regional bathymetric maps include

- NOAA's National Centers for Environmental Information (NCEI)
- Smooth Sheet maps derived from quality-controlled, full resolution NOAA smooth sheets and updated with available multibeam sonar data. (Zimmermann & Prescott, 2014; Zimmermann & Prescott, 2015; Zimmermann et al., 2019; Zimmermann & Benson, 2013).

4 Seeps on the Alaska OCS

A total of 1486 seeps were interpreted within the Alaska OCS from a variety of sources (see Section 2). This section discusses interpreted seeps per BOEM Planning Area area (**Table 2**) and provides some assessment on seafloor settings within the area where seeps are possible.

Table 2. Number of seeps interpreted per BOEM Planning Areas and onshore regions

BOEM Planning Areas	Number of Seeps (Total)	Interpreted from Literature or BOEM Documentation	Interpreted from Sonar Data (this study)	Interpreted from Sonar Data (crowdsourced)
GOA (Gulf of Alaska)	**109**	55	27	27
KOD (Kodiak)	**739**	16	7	716
COK (Cook Inlet)	**122**	33	65	24
SHU (Shumagin)	**355**	10	0	345
Western OCS	**17**	6	0	11
CHU (Chukchi Sea)	**82**	82	0	0
BFT (Beaufort)	**62**	62	0	0
Total	**1486**	264	99	1123

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4.1 Gulf of Alaska (GOA)

A total of 109 seeps were interpreted within the GOA OCS and nearshore areas adjacent to the GOA Planning Area (**Table 2**). Seep locations came from public documents and various data sources. For the purpose of discussion, the GOA Planning Area was divided into three geographic sections: Southeastern GOA, Yakutat Region, and Northcentral GOA (**Figure 9**). Each section has unique geologic controls on the location of interpreted seeps, and areas where seeps may be found.

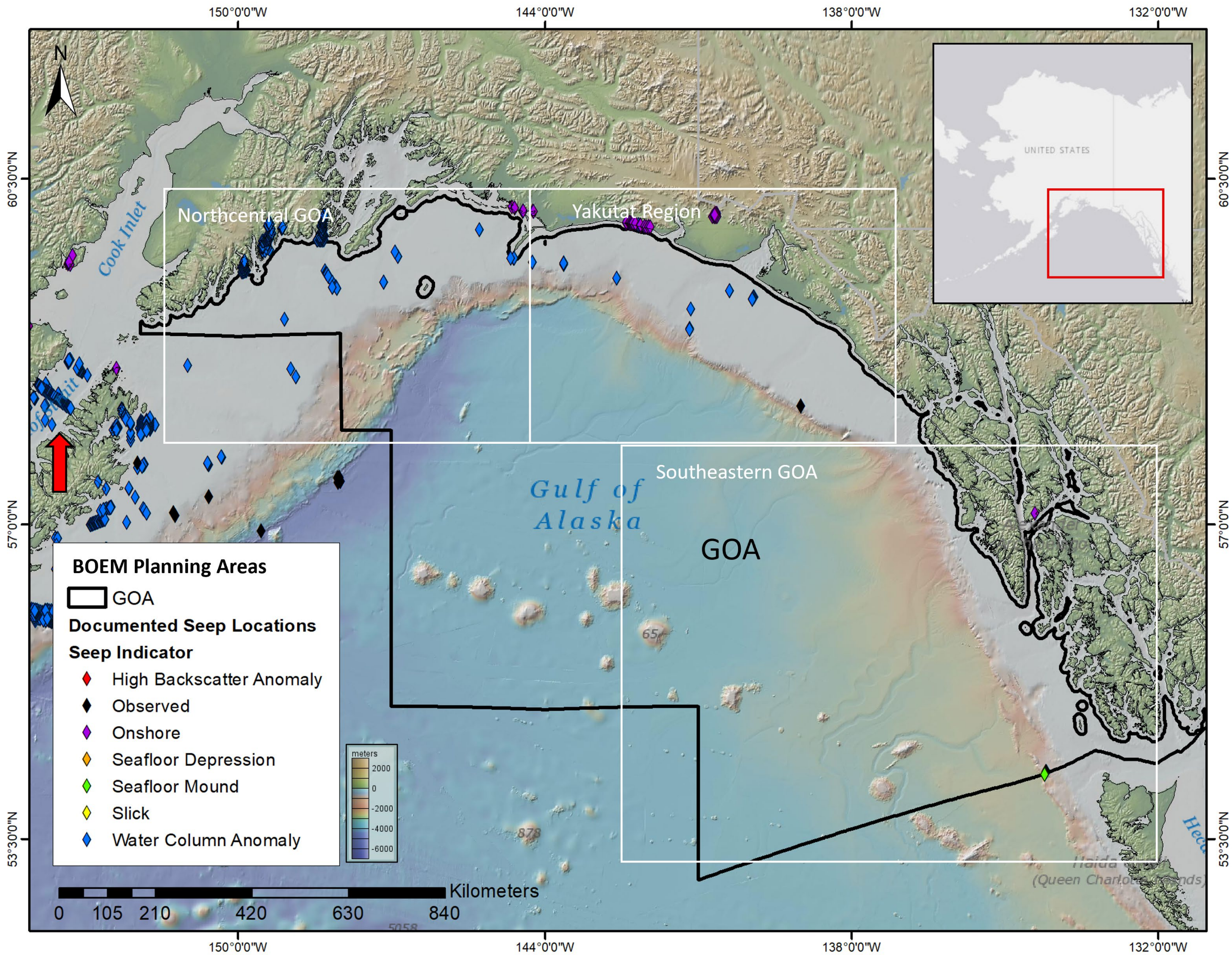

Figure 9. BOEM Gulf of Alaska (GOA) Planning Area with interpreted seep locations. White boxes are locations of overview sections below. Red arrow shows location of Figure 4.

Bathymetry from GMRT Synthesis,(Ryan et al. 2009).

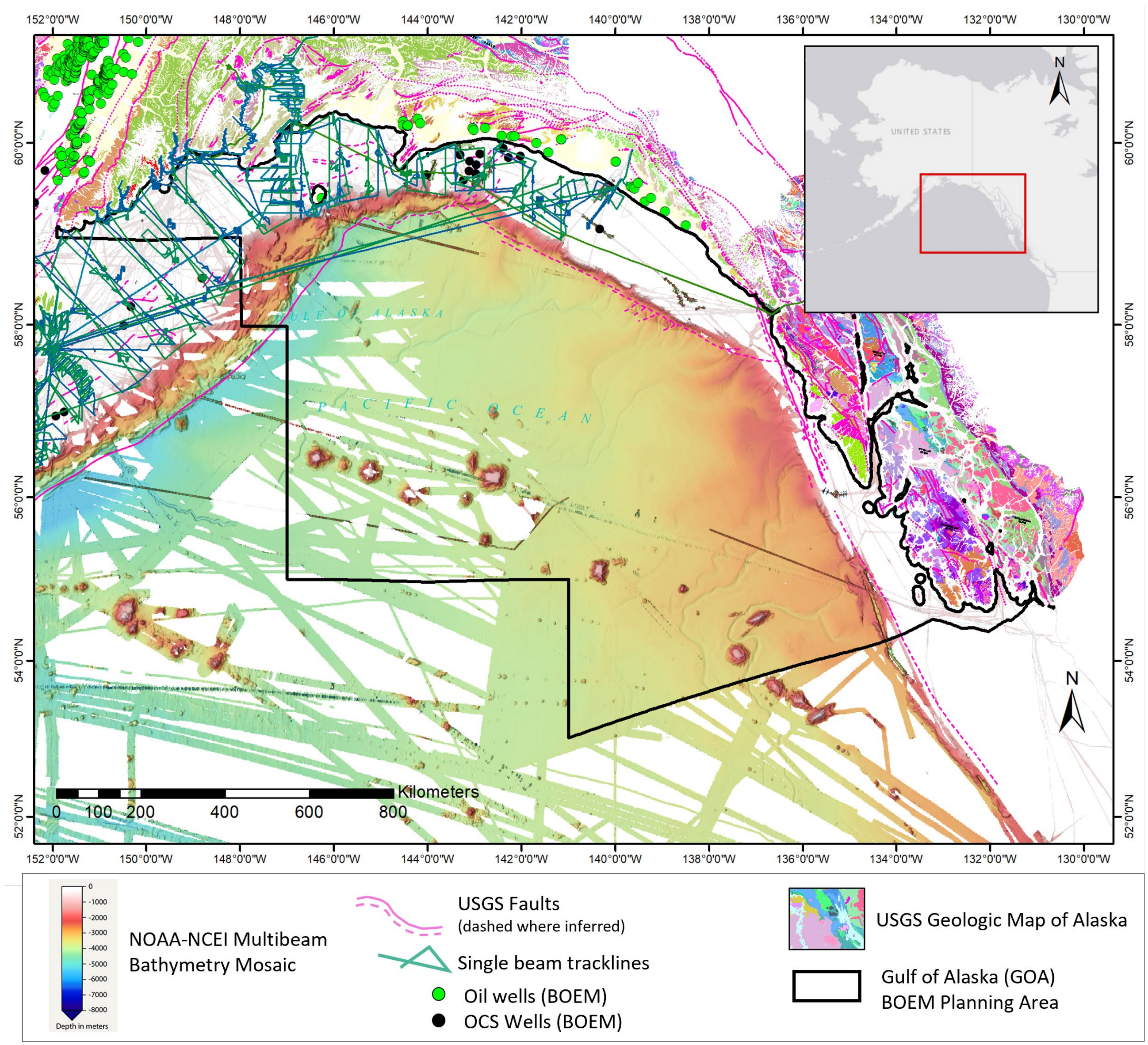

Figure 10. Data used in the GOA for seep interpretation.

4.1.1 Southeastern GOA

Only 5 seeps have been identified in the Southeastern Gulf of Alaska (**Figure 11**), but likely many more exist along the Queen Charlotte Fault, within glacial troughs, and within deep sea fans and channels. Shelf edge seeps are probably also present within Southeastern GOA, like those implicated in slope failures just south of the Alaska-Canada border (D. S. Brothers et al., 2019; Greene et al., 2019).

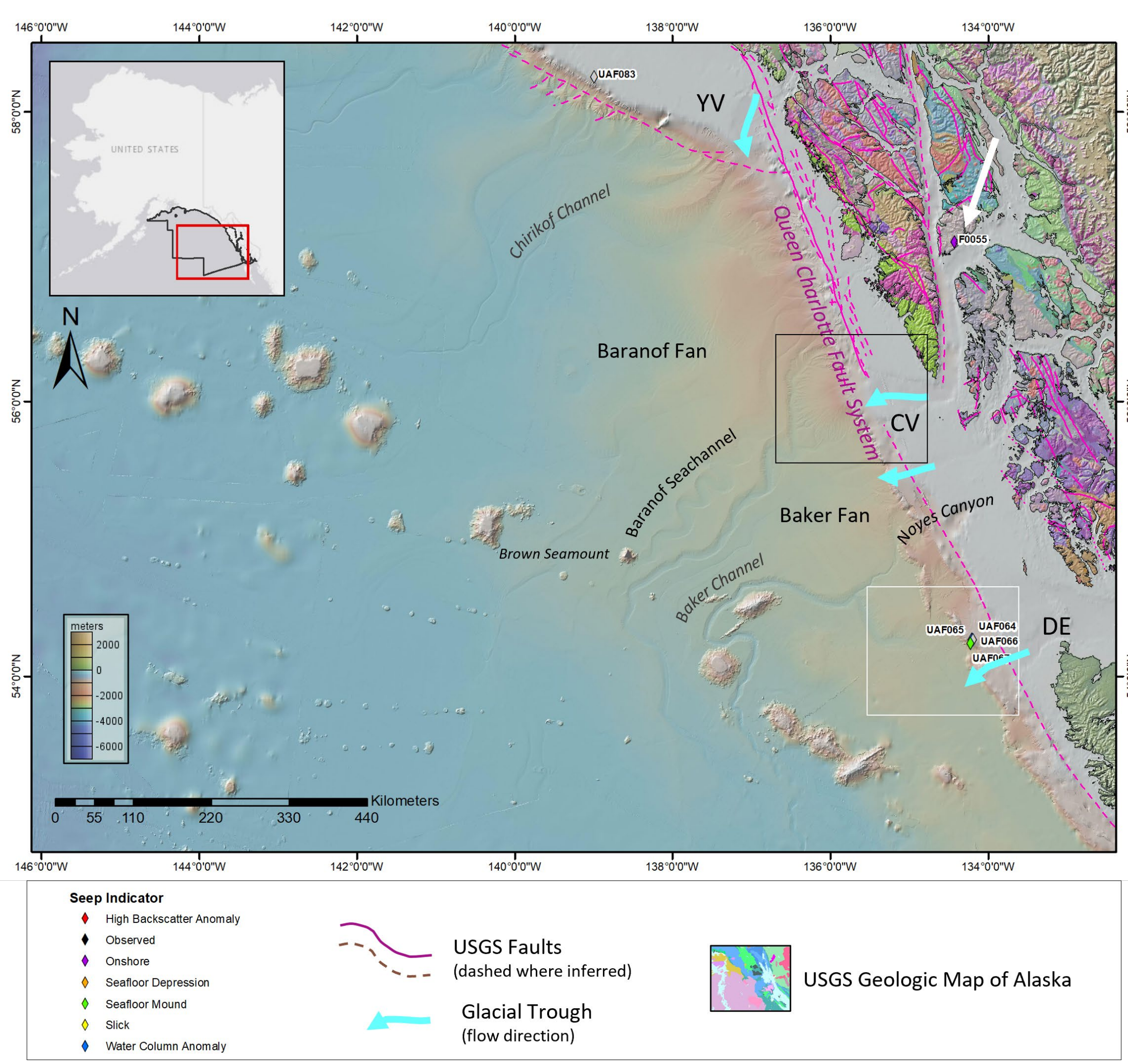

Figure 11. Southeastern Gulf of Alaska showing geomorphological features discussed in text (See Figure 9 for location). Black box is location of Figure 14. White box is location of Figure 12. White arrow points to seep #F0055 discussed in text. Glacier flow direction within troughs to trough mouth fans are indicated with blue arrows; YV=Yakobi Valley, CV=Chatham Valley, DE=Dixon Entrance
Bathymetry from GMRT Synthesis, (Ryan et al. 2009).

4.1.1.1 Onshore Seeps

Reference to only one seep onshore was found in available literature (F0055; white arrow **Figure 11**). Oil saturated black shale and an oil seep was reported at the southern end of Admiralty Island by J.C. Roehm in an unpublished Department of Mines report from 1947 (McGee, 1972). The southern tip of the island is covered by Tertiary volcanic rocks, but older sedimentary rocks outcrop along the shoreline, which could match Roehm's description, however this seep was never verified.

4.1.1.2 Queen Charlotte Fault Seeps

Strike-slip tectonics dominate the southeastern portion of the GOA. The Queen Charlotte/ Fairweather Fault system is a major right lateral transform boundary that separates the Pacific Plate and the North American Plate for about 1200 km between southeastern Alaska and British Colombia (**Figure 11**). Recent studies along the Queen Charlotte Fault in Southeastern GOA and northern British Colombia utilized a 2017 multibeam survey to describe slope processes and mud volcanos and hydrocarbon seeps discovered along the fault (**Figure 12 (a)** ; Brothers et al. 2019; Greene et al. 2019; Barrie et al. 2020).

4.1.1.3 Mud Volcanos and Bubble Plumes

At Dixon Entrance water column anomalies in subbottom profiler and single beam echosounder led to the discovery of a fault-parallel mud volcano that was venting gas at several locations (**Figure 12 (b)**). The valleys along the flanks of the mud volcano contain pockmarks interpreted to be from hydrocarbon expulsion (**Figure 12 (c)).** Bottom camera images on the mud volcano documented the presence of authigenic carbonate slabs and gravel, methanogenic chemosynthetic communities of clams and mussels, tube worms and bacterial mats (**Figure 12 (d)**).

The hard substrate created by the authigenic carbonate provides habitat for anemones, shrimp, sponges and deep sea corals along with deep-water sole and thornyhead rockfish (Barrie et al. 2020). More gas vents were observed along the fault and may be locations of more chemosynthetic communities along this "leaky" transform fault.

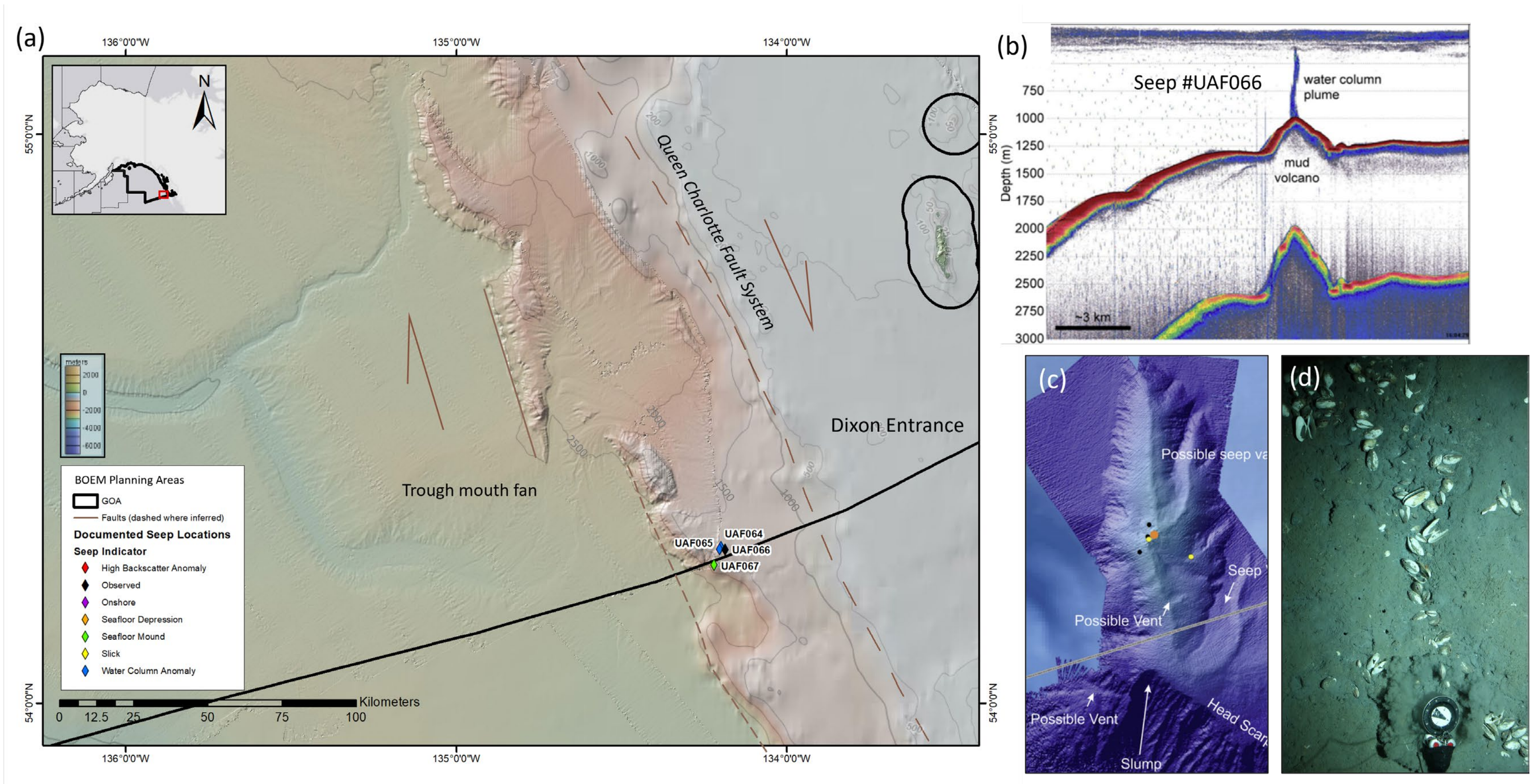

Figure 12. (a) Bathymetry at the Dixon Entrance along the Queen Charlotte Fault showing location of cold seeps and mud volcanos (see white box Figure 11 for location). (b) 18 kHz single beam echosounder and 3.5 kHz subbottom profile image of water column anomalies emanating from a mud volcano (seep #UAF066 in the accompanying data base). (c) multibeam image of the Dixon Entrance mud volcano, dots represent ROV dive locations (c-d modified from Greene et al. 2019). (d) chemosymbiotic clams at the top of the mud volcano.

Modified from Barrie et al. (2020); bathymetry from GMRT synthesis, Ryan et al. (2009).

4.1.1.4 Seeps Implicated in Slope Failure

Slope failure along the Queen Charlotte fault is common. During the same project that discovered the Dixon Entrance mud volcano (D. S. Brothers et al., 2019; Greene et al., 2019), gas bubble plumes were also interpreted within submarine landslide glide planes (**Figure 13**) and along the mouths of gullies just south of the GOA study area. Given the "leaky" nature of the Queen Charlotte fault it is probable that similar seeps exist in association with slope failures within the Southeastern GOA particularly along the steep flanks of ridges and along submarine canyon sidewalls.

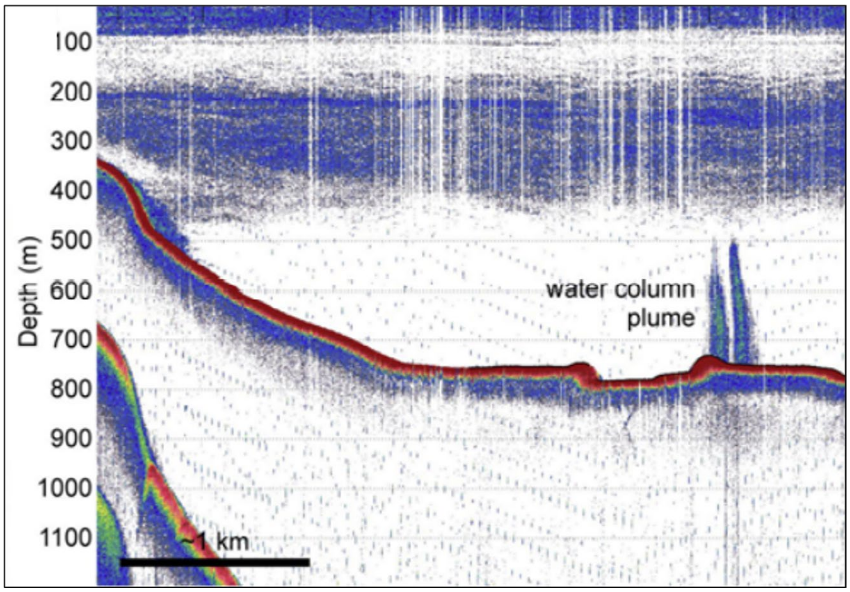

Figure 13. 18 kHz single beam echosounder and 3.5 kHz subbottom profile image of water column anomalies at the base of a submarine landslide glide block in the Southern GOA.
Modified from Greene et al. (2019)

The strength of the bubble streams, and the existence of large chemosynthetic communities associated with the Queen Charlotte fault, suggests that deeply sourced thermogenic hydrocarbons are utilizing the fault as a pathway to the surface, although geochemical analysis of sediment headspace gases is necessary to determine this.

4.1.1.5 Glacial Troughs

The continental shelf, slope, and rise in the Southeastern GOA is characterized by predominantly glaciogenic sediments from erosion of the nearby coastal mountain ranges with one of the largest sediment yields of any continental margin worldwide (D. S. Brothers et al., 2019; Shugar et al., 2014). Within the Southeastern GOA, several glacial troughs cut across the continental shelf and continue to act as sediment traps today. On the continental slope, sedimentary deposits called trough mouth fans are visible at the mouth of Yakobi Valley, Chatham Valley and Dixon Entrance. The continental slope is also incised by numerous canyon systems **(Figure 14**). These post glacial settings receive enormous amounts of sediment, and although glacial outwash is not as organic-rich as river deposited sediment, are still favorable for generation of microbial methane.

As discussed in Section 2.1.2, glacial troughs are locations where pockmarks are often described from dissociation of methane hydrate, fluid flow due to pressure/temperature changes during isostatic rebound, and active microbial methane production within recent soft sediment infill of troughs (A. Judd & Hovland, 2007b). If the locations of glaciers and erosional troughs are fault-controlled, as are the glacial troughs of the southern GOA, thermogenic hydrocarbons from deeper sources could be utilizing the faults as migration pathways and venting on the seafloor as cold seeps. Multibeam mapping and geochemical coring in this area would help determine the extent of this process in the Southeastern GOA.

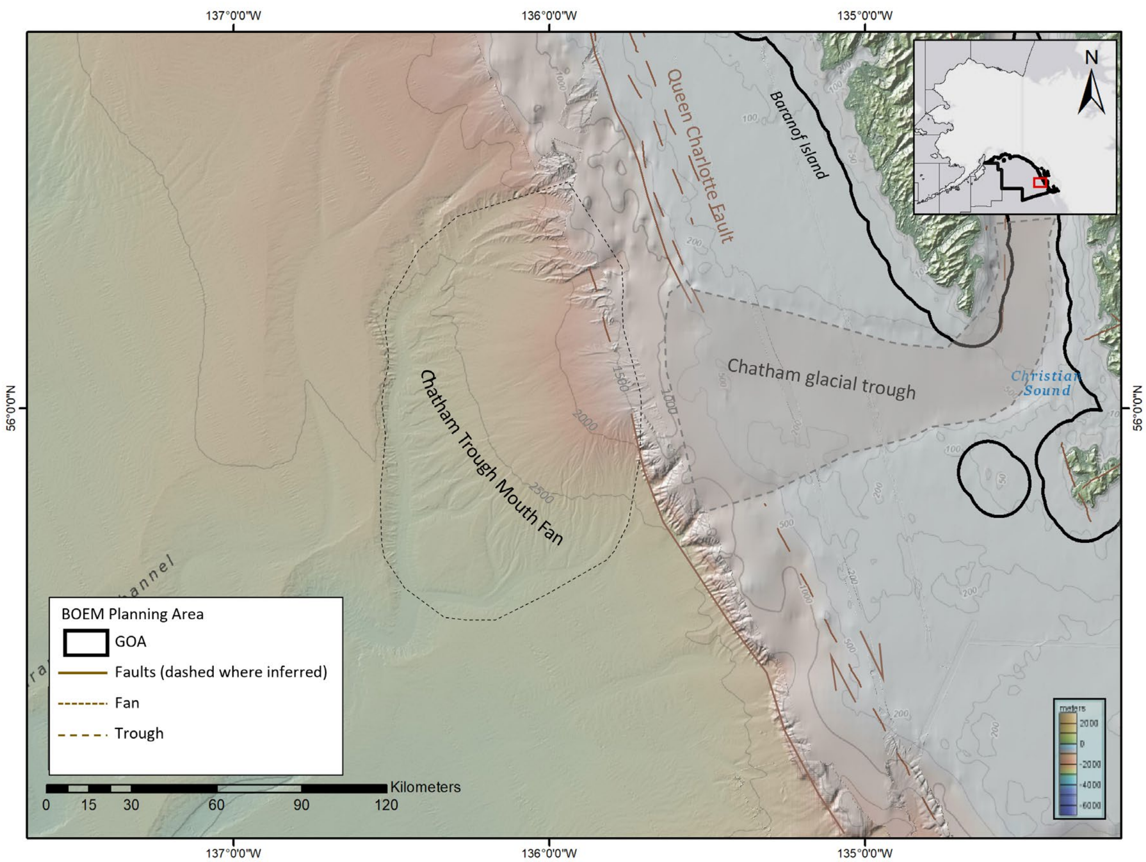

Figure 14. Chatham glacial trough and trough mouth fan along the Queen Charlotte Fault system (see black box Figure 11 for location.

Bathymetry from GMRT Synthesis, (Ryan et al., 2009).

4.1.2 Yakutat Region of GOA

4.1.2.1 Active Faulting

The Yakutat Region of the GOA is a transition region between the strike-slip tectonics along the Queen Charlotte/Fairweather fault system of the Southern GOA to the subduction-controlled setting of the Aleutian Subduction Zone. The right-lateral Transition Fault separates the Yakutat terrane from the oceanic crust of the Pacific plate and merges with the Pamplona fold and thrust belt (**Figure 15**; Gulick et al. 2007). The Yakutat shelf from the Kayak zone to the Pamplona zone is dominated by oblique subduction characterized by northeast-southwest striking thrust faults, compressional folds, and zones of complex faulting. East of the Pamplona Zone, the shelf is much less deformed with low relief anticlines. Deformation in the Yakutat region began less than 2 million years ago (middle to late Pleistocene) and continues into the present (Risley et al., 1992).

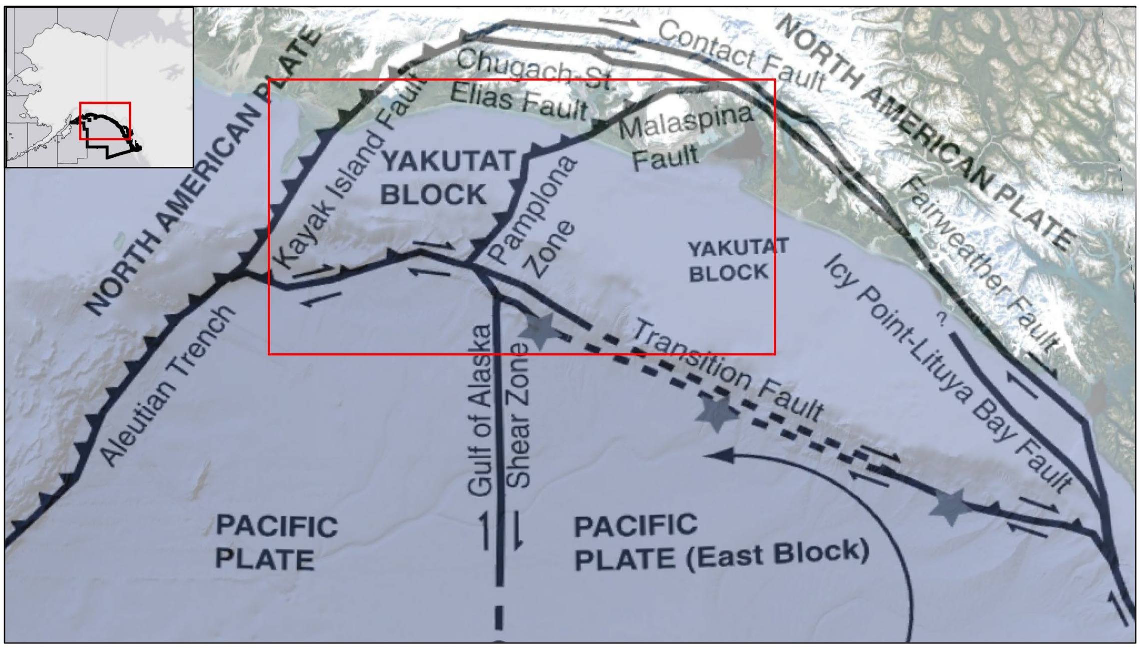

Figure 15. Geologic framework of the Gulf of Alaska, including major faults and regional subdivisions on the continental margin. Red box is location of Figure 18.

Modified from Gulick et al.*(*2007).

4.1.2.2 Following Seeps Offshore

Within the Yakutat Region of GOA study area (**Figure 16**), onshore and offshore oil and gas seeps were interpreted from a variety of sources. Onshore oil seeps were described from various documents and literature sources. Geologic structures associated with these seeps were followed offshore using available USGS fault information. Once possible connections were identified, NMFS archived water column data (tracklines **Figure 16**) were investigated for anomalies consistent with gas bubble plumes across fault locations and near abandoned wells (see Section 2 Methods). Not all available single beam data were interpreted, but the concept proved successful and may be worth further investigation.

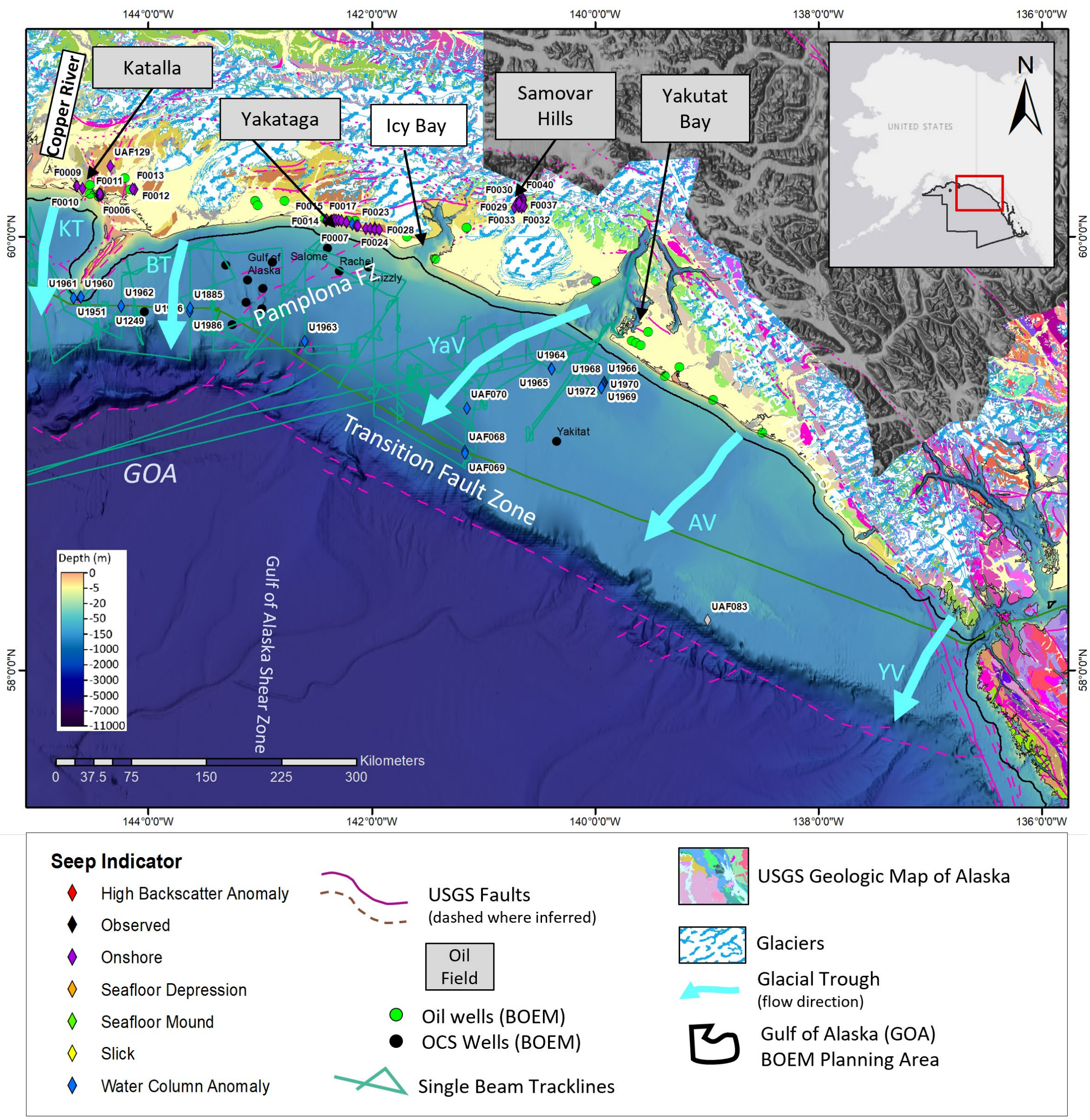

Figure 16. Yakutat Region of Gulf of Alaska showing geomorphological features and oil fields discussed in text. Glacier flow direction within glacial troughs to trough mouth fans are indicated with cyan arrows; YV=Yakobi Valley, AV=Alsek Valley, YaK=Yakutat Valley, BT = Bering Trough, KT = Kayak Trough.

Bathymetry and NMFS tracklines from NOAA-NCEI.

4.1.2.3 Onshore Seeps

The Pacific coast of Alaska between the Copper River and Yakutat Bay was the location of the first oil wells in Alaska at the beginning of the 20th century. Seepages were discovered in Yakataga, Katalla, Samovar Hills, and Yakutat Bay areas around 1896 (**Figure 16**). A discovery well was drilled in Katalla field in 1902 and oil was produced commercially from 44 wells that were drilled around surface oil seeps

(**Figure 17)**. A small oil refinery at the mouth of the Katalla River provided refined products for the local fishing fleet. Although oil production ceased in 1933 when the refinery burned down (Blasko, 1976b), an early USGS preliminary report on petroleum in Alaska stated:

> *"The widespread and copious seepages indicate that large areas may be regarded as possible oil land. The results obtained in the wells on the patented claim near Katalla probably give a fair indication of what may be expected near the other seepages" –* Martin, 1921

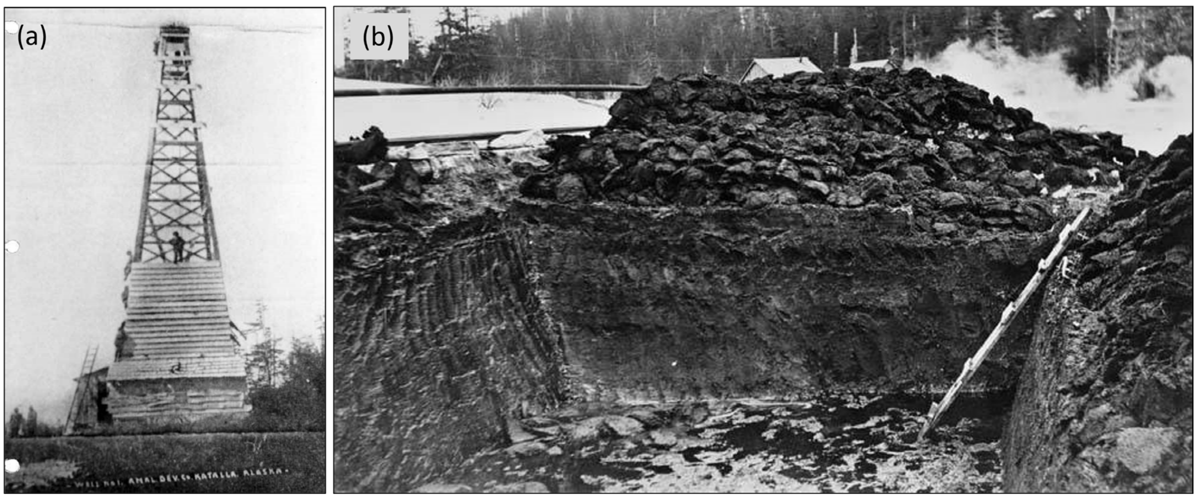

Figure 17. (a) Well #1 drilled in 1902 in the Katalla Field. (b) First oil tank in Alaska cut into peat bog near an oil seep

Photographs c. 1910, courtesy of Alaska State Library historical collection.

Most of the natural oil seepages reported onshore in the Yakutat region were still active in the early 1970s (Blasko, 1976b). In the late 1970's several exploratory wells were drilled offshore between the Copper River and Icy Bay, and one well offshore of Yakutat Bay in 1983 (**Figure 18**). Although none of the exploratory wells encountered significant quantities of pooled hydrocarbons (BOEM, 2006), the faults within the Kayak, Paplona, and Transition fault zones appear to be locations of active seepage.

4.1.2.4 Fault Zone Seeps

In this study, NMFS single beam water column data, and multibeam data collected by the *R/V Sikuliaq*, were investigated in fault zones across the Yakutat Shelf, and near exploratory wells. Within the Kayak Fault Zone several water column anomalies were interpreted as gas bubble plumes near the southern tip of Kayak Island in very shallow water depths (between about 45-100 m; **Figure 18 (1)**). Within the Pamplona Fault Zone **(Figure 18 (2))** single beam lines crossed anticlinal folds with apparent bubble plumes emanating from them. Several seepages were also interpreted from a single beam line situated within the Transition Fault zone at the mouth of Yakutat Bay **(Figure 18 (3)),** about 60 km north of the Arco exploration well. This suggests fluids are utilizing structures in this heavily faulted region to reach the seafloor.

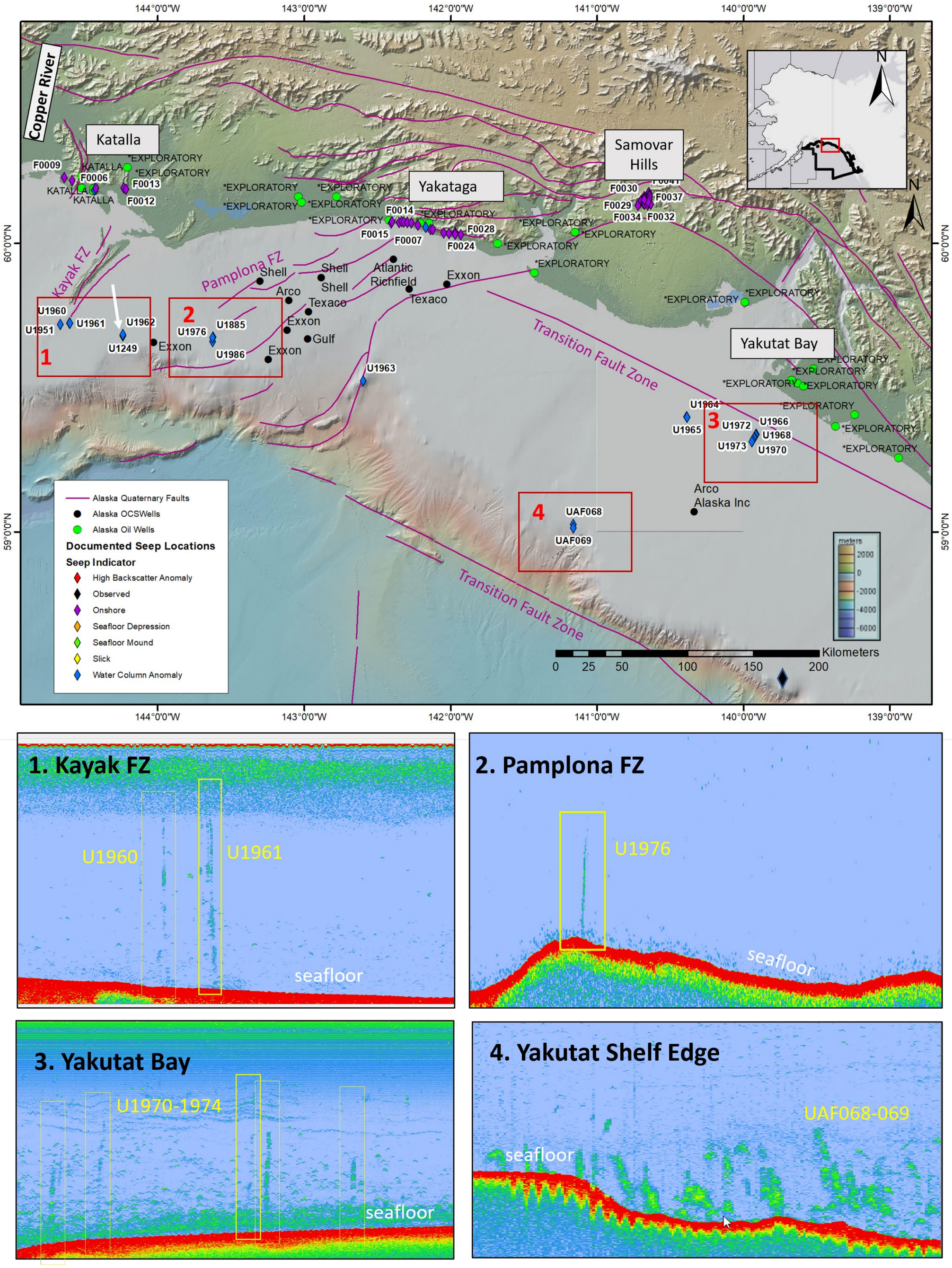

Figure 18. (Top) Fault zones related to onshore oil fields and OCS exploratory wells in the Yakutat Region of GOA. Red boxes correspond to single beam records of representative seep areas 1-4. (bottom). White arrow in Box 1 is location of seep #1962 discussed in text. (Bottom 1-4) identified in single beam records. Each image is a screen grab of NOAA Fisheries single beam water column data, showing water column anomalies interpreted as gas bubble plumes.

Background bathymetry from GMRT v. 3.9 (Ryan et al., 2009), screen shots of Fledermaus MidWater ® software.

4.1.2.5 Shelf Edge Seeps

As discussed in Section 2.1.4 , seeps are common along continental shelf edges and often are caused by dissociation of gas hydrates where the limits of the gas hydrate stability zone reach the seafloor at the upper slope and shelf break. In two locations within the Yakutat Region of GOA, single beam lines were investigated for seeps along the shelf edge (see **Figure 16** for line locations). At the Yakutat shelf edge, gas bubble plumes appear within canyons at the shelf break in water depths around 145 m and could be related to gas hydrate dissociation **(Figure 18 (4)).** However, given the proximity of the Transition Fault Zone, the seeps could also be from deeper sourced hydrocarbons utilizing the fault plane to reach the surface. Geochemical sediment core analysis in that area could provide insight to the source of the seeping hydrocarbons along the Yakutat shelf edge. Near the shelf edge at the Fairweather Ground, an ROV transect through a field of volcanic cones crossed a cold seep (UAF083) marked by chemosynthetic bacteria and (dead) mussels (Rooper et al., 2017). This seep may be utilizing fluid pathways related to the shelf edge, which follows the Transition Fault, or pathways related to the volcanic cones.

4.1.2.6 Glacial Troughs

The continental shelf in the Yakutat Region of GOA is cut by several glacial valleys. From west to east, these are the Kayak Trough, Bering Trough, Yakutat Valle, Alsek Valley and Yakobi Valley **(Figure 16)**. The walls of the valleys have as much as 100 m of relief and the floors have been partially filled in with recent Holocene glacial silts and gravels with sedimentation rates as high as 15 mm/yr (Carlson et al., 1982). These thick sedimentary deposits may be favorable to methanogenesis. Probably due to sparse bathymetric data on the shelf, no seeps or pockmarks have yet been described within the troughs. One NMFS single beam line that crosses Bering Trough was investigated in this study (DY1506_EK60-D20150810) and gas bubble plumes were interpreted within the glacial valley (**Figure 19**). The location of the glacial troughs in the Yakutat Region of GOA have been influenced by the same fault zones discussed in Section 4.1.2.4 where seeps have been found thereby increasing the likelihood of pockmarks or other fluid escape features being present within the glacial troughs in this section of the continental shelf

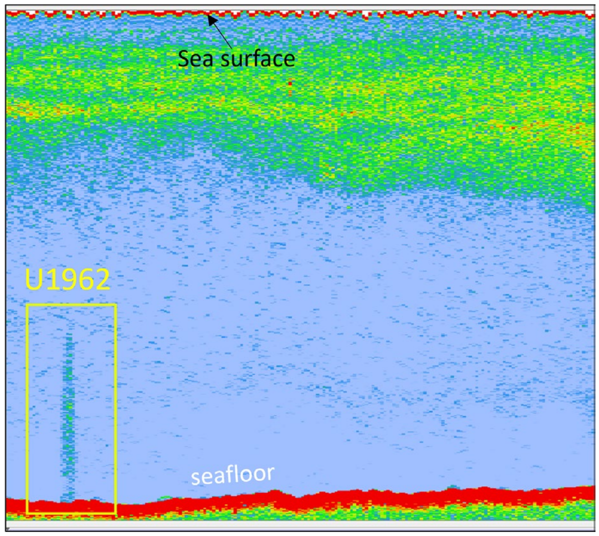

Figure 19. NOAA Fisheries single beam water column data (line DY1506_EK60-D20150810), showing water column anomalies interpreted as gas bubble plumes *within the Bering Trough glacial valley* (yellow box with associated seep number, see white arrow Figure 18 for seep location)
Water column anomalies interpreted with Fledermaus MidWater ® software.

4.1.3 Northcentral Gulf of Alaska

Within the Northcentral GOA, seeps were interpreted from various sources (**Figure 20)**. Gas bubble plumes were inferred from NMFS single beam data within Resurrection Bay, Day Harbor, Port Bainbridge, and Harris Bay. Several seeps were identified in glacial troughs and along mapped faults.

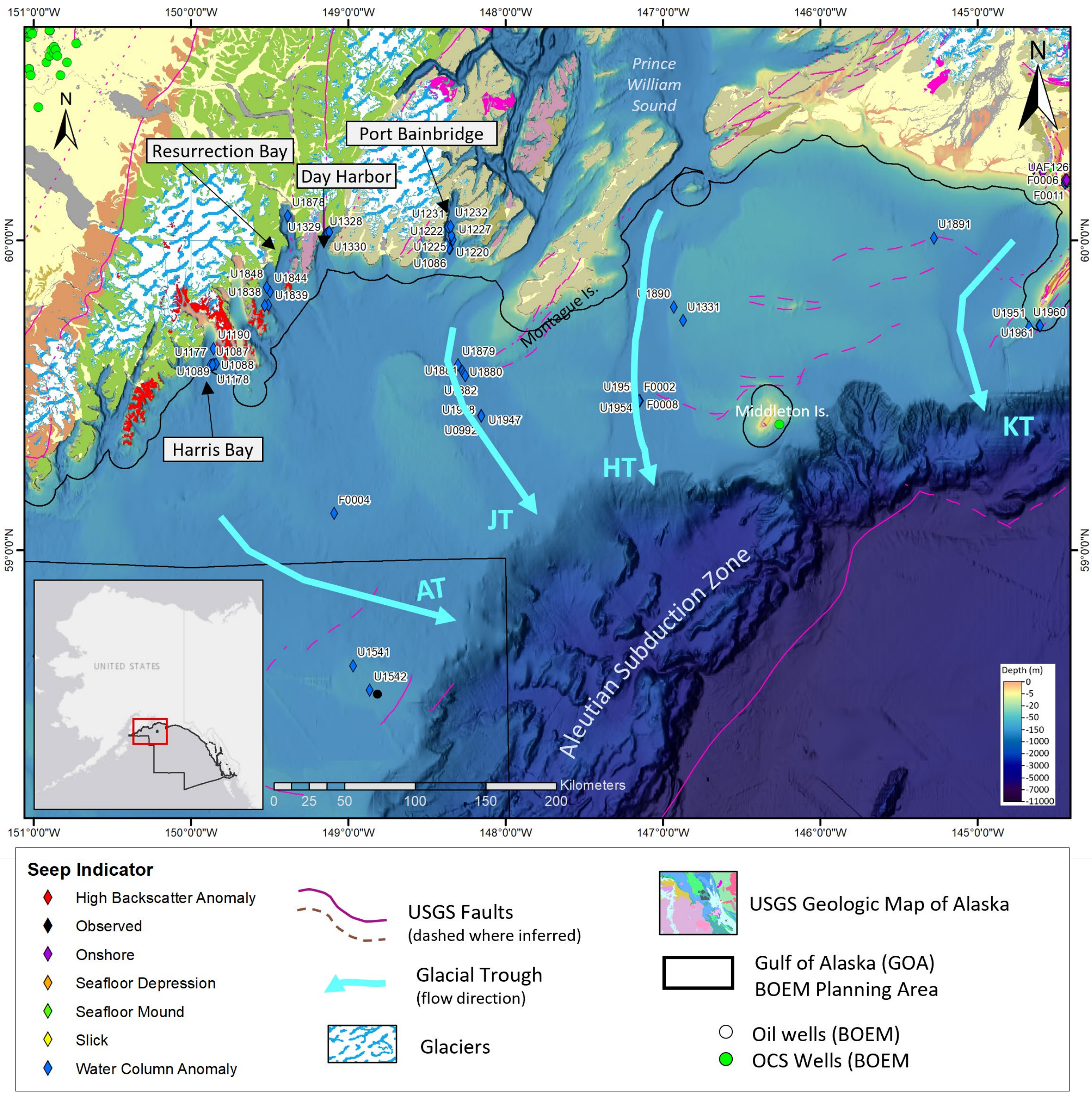

Figure 20. Northcentral Gulf of Alaska showing geomorphological features discussed in text. Glacier flow directions within glacial troughs are indicated with blue arrows in AT= Amatuli Bay, JT=Junken Trough, HT= Hinchinbrook Trough and KT=Kayak Trough.

Bathymetry from NOAA-NCEI.

4.1.4 Seeps in Nearshore Glacial Fjords

Many gas bubble plumes were interpreted within glacial fjords bordering the Northcentral GOA by NMFS Biologist Darin Jones using EK60 echosounder data collected during acoustic-trawl stock assessment surveys aboard the NOAA Ship *Oscar Dyson* (DY1702). Plumes were documented in Harris Bay, Resurrection Bay, Day Harbor and Port Bainbridge (**Figure 21**). It is unknown whether bubble plumes were not observed in other glacial fjords during this survey, or whether those lines were not monitored for bubble plumes. The data, however, are available and could also be investigated for water column anomalies.

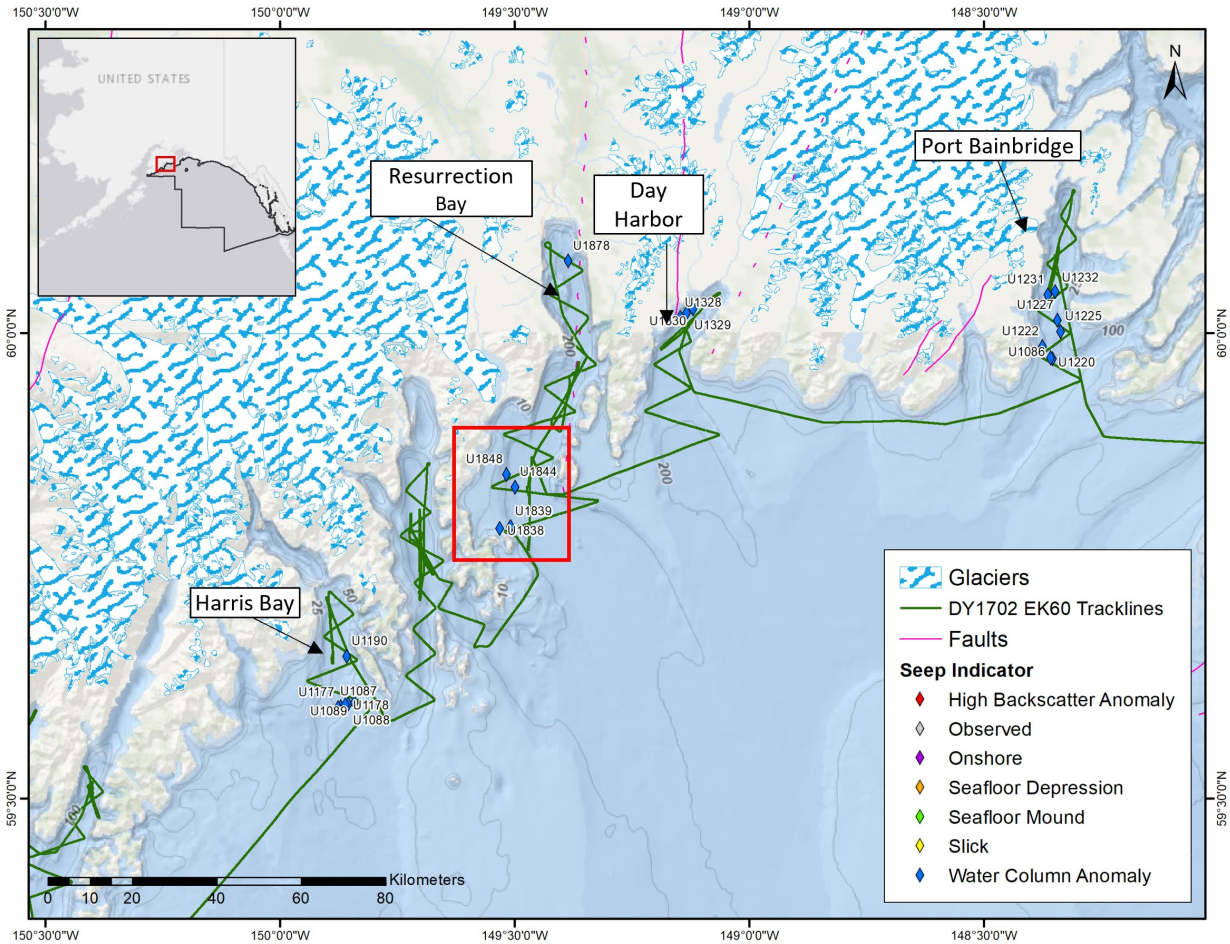

Figure 21. Seeps located within glacial fjords interpreted from EK60 water column data. Red box is location of Figure 22

ESRI Oceans basemap, GEBCO 2020 bathymetric contours.

Pockmarks are often described on the seafloor of glacial fjords probably due to release of fluids in sediments due to microbial methane production. It is also possible that the underlying geologic structures that control the location of the fjords could be providing pathways to the seafloor for fluids sourced from deeper gas reservoirs, creating seafloor pockmarks (See **Section 2.1.2**). An example of this is observed in Resurrection Bay where pockmarked seafloor corresponds to areas where bubble plumes were interpreted in single beam water column data **(Figure 22**). The imaged pockmarks create chains that roughly parallel visible fault scarps suggesting a possible use of faults as fluid migration pathways in this area.

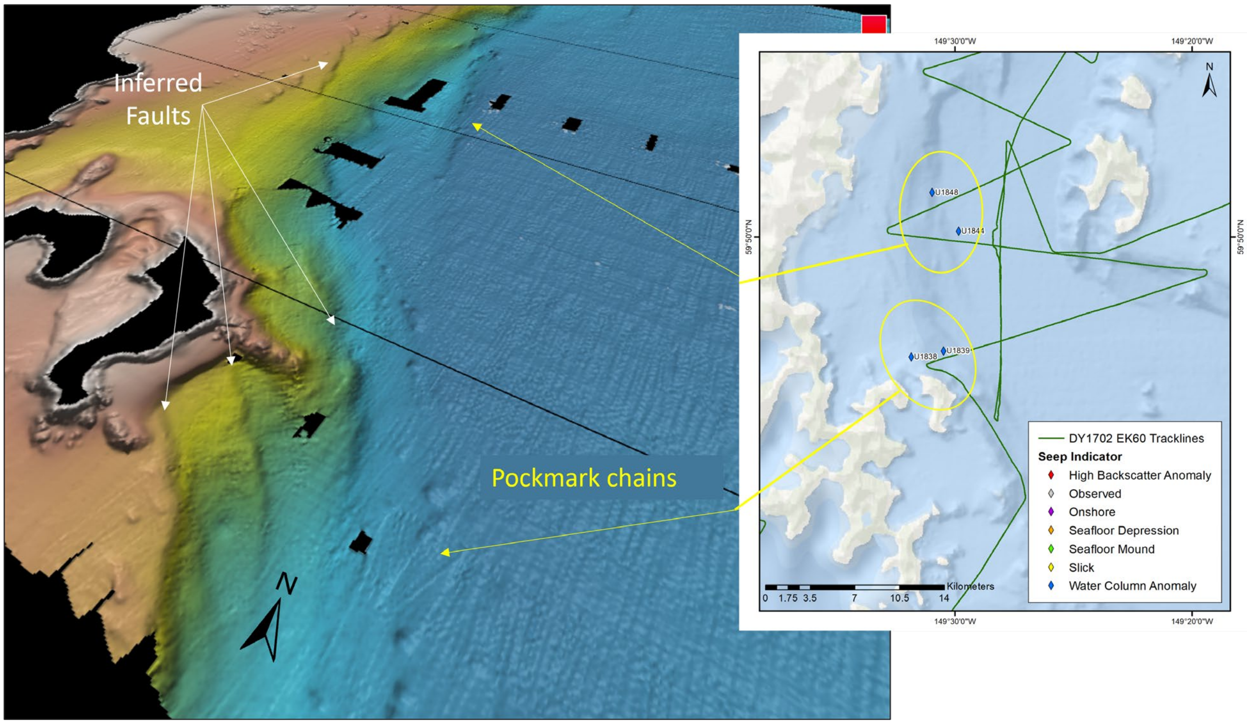

Figure 22. perspective view of bathymetry at the southern end of Resurrection Bay (see red box Figure 21 for location) showing pockmarked seafloor corresponding to gas bubble plumes interpreted from NMFS single beam data (yellow outlined areas on callout map).
Bathymetry from *NOAA Ship Rainer* (H11074) visualized in Fledermaus® Viewer 8.4.1. Single beam lines from NMFS survey DY1702.

4.1.5 Seeps in Glacial Troughs

Gas bubble plumes were interpreted within all the glacial troughs on the Northcentral GOA shelf from NMFS single beam data, and the locations were contributed to this project by Darin Jones (personal communication and spreadsheets, 2020 from DY1706), and Mark Zimmermann (personal communication and spread sheets, 2017) during stock assessment surveys from various platforms. Additional single beam data from NMFS were also investigated as part of this study. In this "pilot study" described in Section 3.1.3, we found evidence of active seepage surveys in Hinchinbrook Trough (DY1506) and Junken Trough (DY1307) (**Figure 23**). The strong vertical water column anomalies seem to represent high flux seepage, (**Figure 23 (B-C)**) which suggests they are sourced from a hydrocarbon reservoir and are not simply due to low-volume microbial methanogenesis in glacial trough sediments. These seeps also fall within a region where subduction zone related splay faults have ruptured the seafloor during several earthquake cycles, including fault offset during the M_w9.2 Great Alaska Earthquake of 1964 (Liberty et al., 2019). These active faults could be providing pathways to the surface for deeply sourced hydrocarbons.

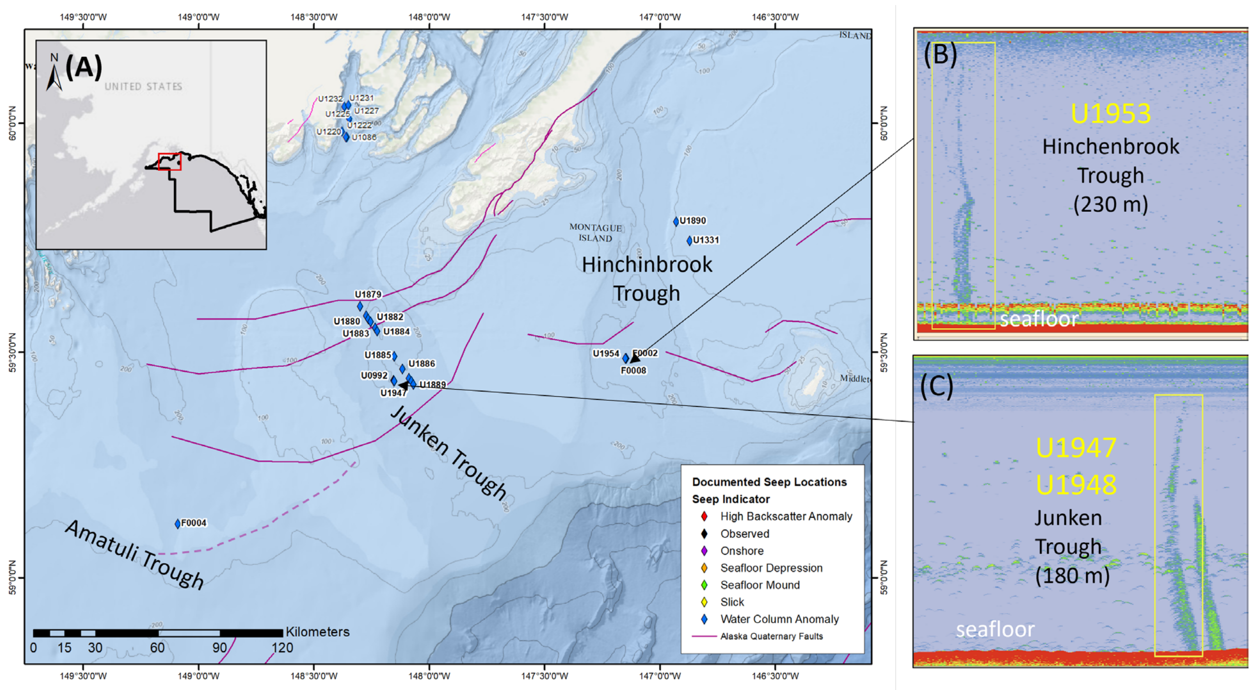

Figure 23. (A) Bathymetry of glacial troughs on the Northcentral GOA shelf showing fault locations (purple lines, dashed where inferred) interpreted by Liberty et al., 2019. (B-C) ME70 multibeam water column data (DY1307), showing water column anomalies interpreted as gas bubble plumes in Hinchinbrook and Junken Troughs (yellow boxes with seep numbers).

Water column anomalies in B-C visualized with Fledermaus MidWater ® software

The seeps interpreted in Hinchinbrook Trough (See **Figure 23** for location) are long lived, and have been active since at least 1976, which also suggests more than an ephemeral microbial methane source. A National Ocean Service smooth sheet from 1976 contains a seemingly anomalous sounding that is 12 m deeper than the surrounding seafloor (red circle **Figure 24(A)**). During a bottom trawl survey in 2017, NMFS Research Fishery Biologist Mark Zimmermann made 4 passes over the bathymetric "anomaly" (ship track blue line Figure 24 (A)) observed seafloor depressions in the same location as the 1976 smooth sheet anomaly. The single beam sonar also recorded water column anomalies issuing from the depressions at each consecutive pass (**Figure 24 (B)).** Two years later in 2019, Zimmerman crossed the region again, and observed that bubble plumes were still visible in the same location (**Figure 24 (C)).** In this study we investigated publicly available EK60 single beam data as well as ME70 multibeam water column data from a different 2013 NMFS survey in the same location (DY1307), which also imaged this seep (**Figure 23 (B)).**

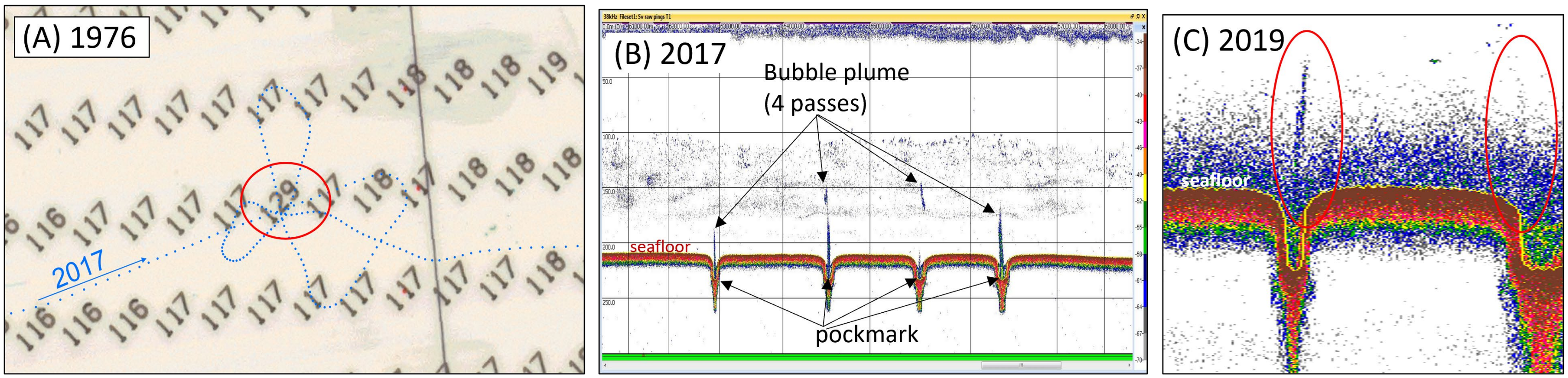

Figure 24 (A) NOS smooth sheet #H09626 showing "anomalous" sounding (red circle). Blue line represents the shiptrack from a 2017 NMFS survey that passed over the anomaly 4 times. (B) Single beam read out during an NMFS bottom trawl survey in 2017 aboard the *F/V Ocean Explorer* showing imaged bubble plume along shiptrack in (A). (C) Closeup of sonar readout with water column anomalies still active in 2019 (red circles)

Mark Zimmerman personal communication, 2019, horizontal scale not available.

4.2 Kodiak (KOD)

A total of 739 seeps were interpreted within the KOD Planning Area (**Table 2; Figure 25**) from scientific literature, BOEM documents, and various data sources (**Figure 26)**

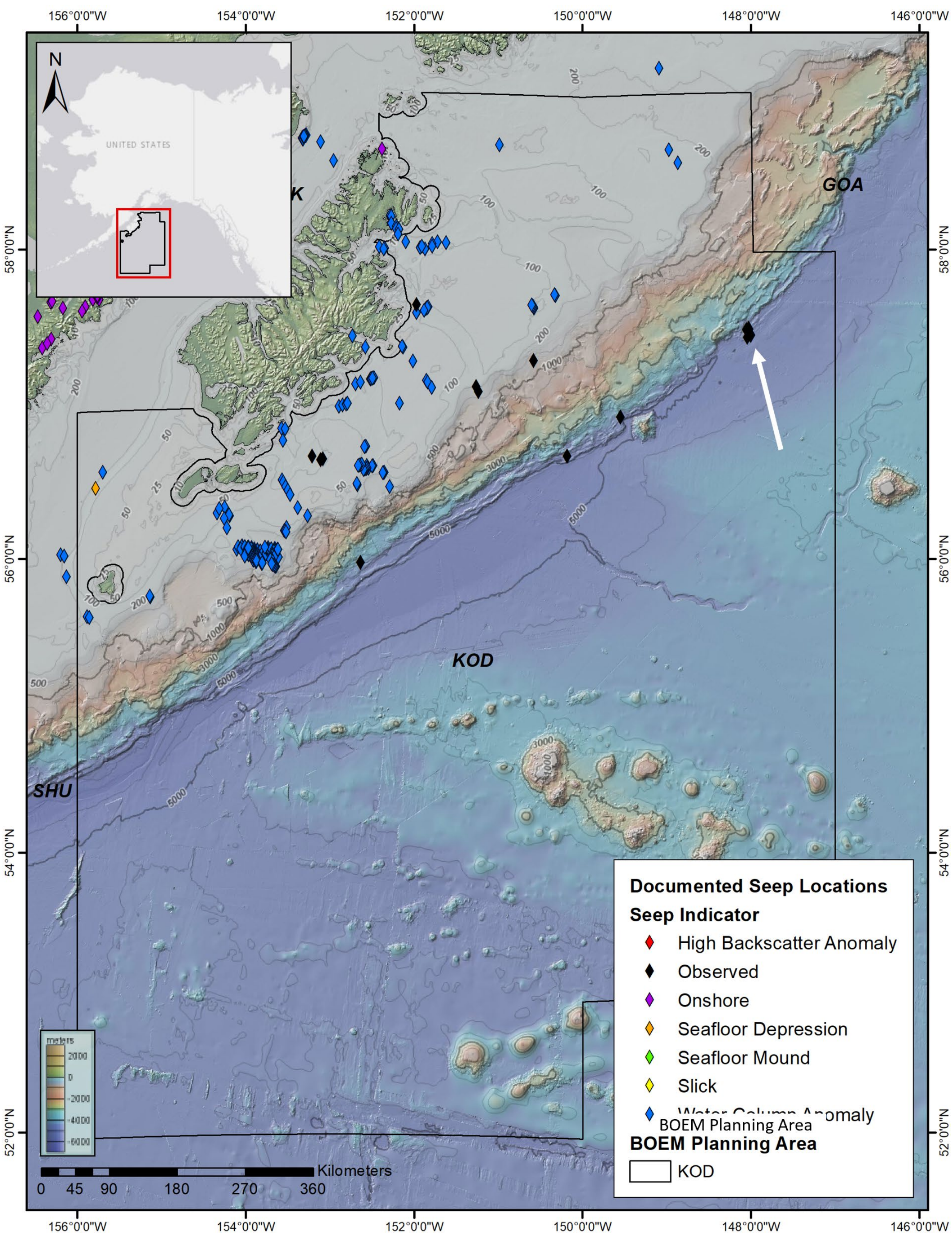

Figure 25. BOEM Kodiak (KOD) Planning Area with interpreted seep locations. White arrow shows location of seep #UAF073 discussed in text

Bathymetry grid from GMRT Synthesis, Ryan et al. (2009); GEBCO 2020 bathymetric contours)

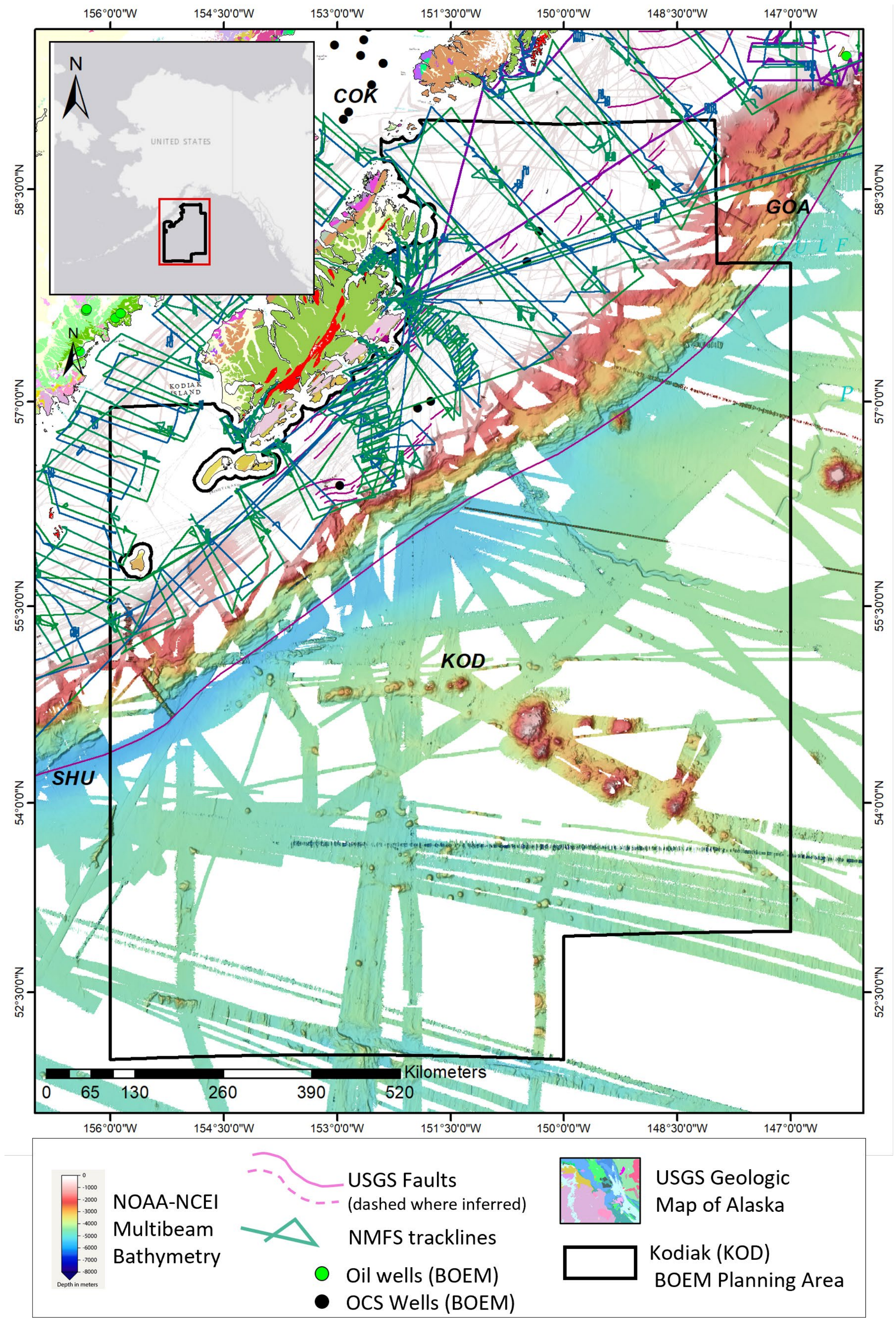

Figure 26. Data used in KOD for seep interpretation.

4.2.1 Kodiak Shelf

The bathymetry of the Kodiak Shelf is characterized by shallow banks cut by glacial erosional troughs (**Figure 27)**. Major faults in the area are related to subduction and trend northeast-southwest generally following the trend of the Aleutian Trench **(Figure 27**).

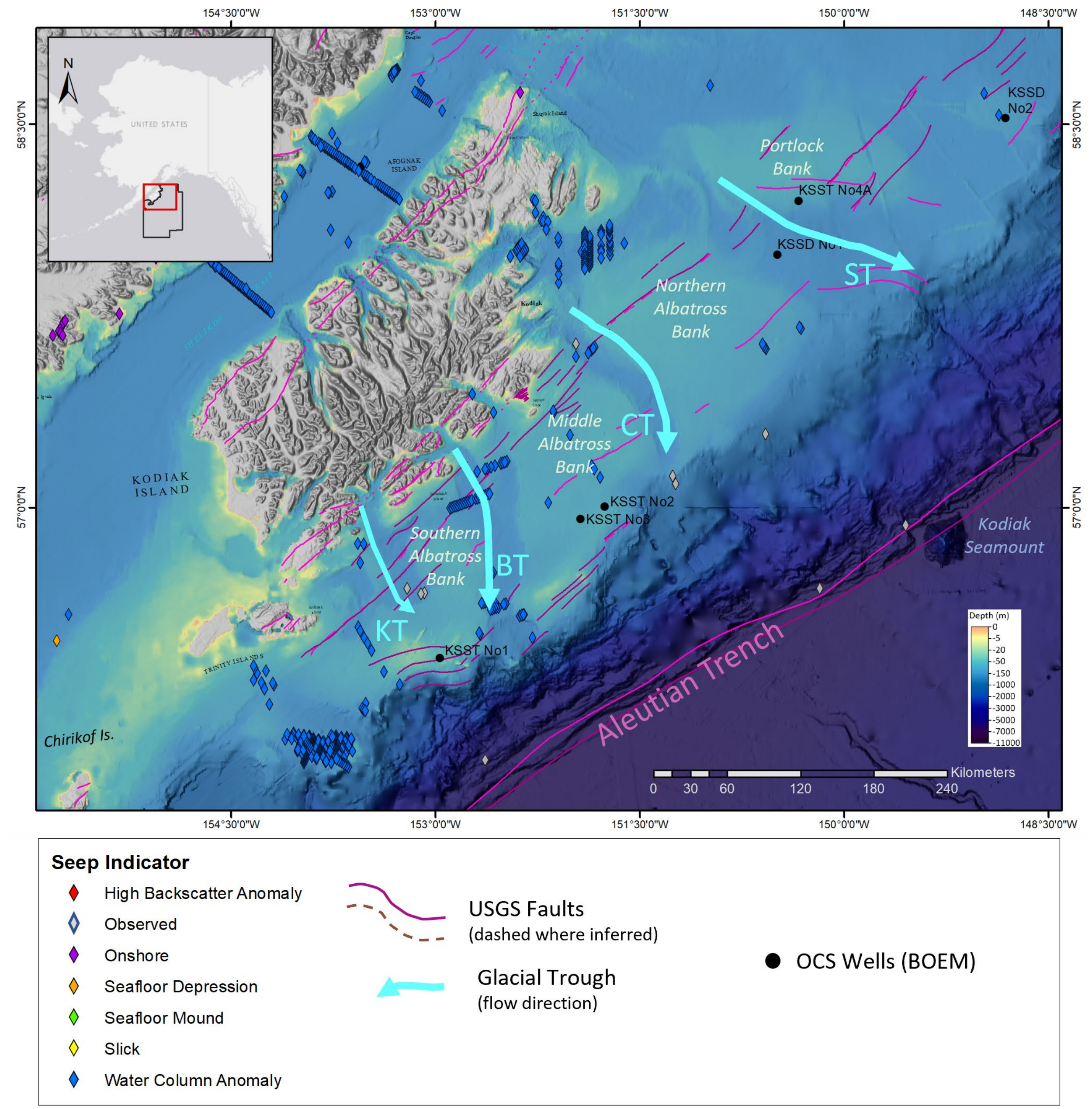

Figure 27. Bathymetry of Kodiak Shelf showing geomorphologic features discussed in text. Glacial troughs include ST=Stevenson Trough, CT=Chiniak Trough, BT= Barnabas Trough, KT=Kiluda Trough. Bathymetry from NOAA-NCEI.

4.2.1.1 Seeps on Kodiak Shelf

Interpreted seeps on the Kodiak shelf were observed as water column anomalies in NMFS single beam data during acoustic stock assessment surveys. Several seeps were also described as part of the Outer Continental Shelf Environmental Assessment Program (OCSEAP) that were imaged as water column anomalies along a fault interpreted from seismic reflection profiles (**Figure 28**; Hampton 1982). Also as part of the OCSEAP study, sediment cores were collected that contained head-space gasses with very high C_1-C_4 concentrations database (M A Hampton & Kvenvolden, 1981), and were interpreted here as seep locations and added to the database. Gas charged sediments in the collected cores were most abundant in the Kiliuda Trough. Hydrocarbon concentrations (C_1-C_4) were generally higher in the glacial troughs on the Kodiak shelf than on the continental slope (Monty A Hampton, 1982).

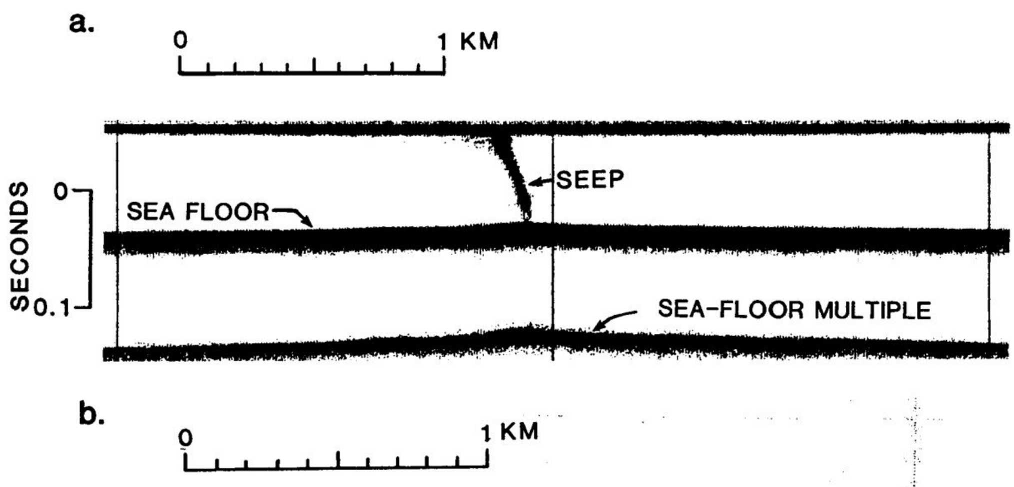

Figure 28. Seismic reflection image from Middle Albatross Bank showing water column anomaly interpreted as a gas seep.
Modified from Hampton, (1982); courtesy of USGS.

The organic-rich sedimentary environments and high sedimentation rates within glacial troughs on the Kodiak Shelf, are suitable for the microbial production of gas, and may be the source of the interpreted seeps (M A Hampton & Kvenvolden, 1981). Another possibility is that the methane-rich fluids have a deeper source that is focused within the troughs along faults that underlie the Kodiak shelf.
Oil and gas assessments on Kodiak Island determined that the area had limited potential for accumulation of oil and gas due to a basement of metamorphic and deformed volcanic rocks which offer little hydrocarbon potential (Bascle et al. 1993; Sherwood et al., 1998). The large quantities of sediments being subducted beneath the Kodiak margin may have potential for generating a large volume of gas (von Huene et al., 1987). However, deep stratigraphic test wells drilled in the mid-1970s (see **Figure 27** for KSST and KSSD well locations) and geochemical analysis (Chapter 8 in Turner et al., 1987) found no evidence of gas charged sediments or structural traps that may indicate oil and gas reservoirs.

4.2.2 Subduction Zone Seeps

At least 9 seep locations were documented along the Aleutian subduction zone in the KOD Planning Area region and several more in SHU region during the third leg of a GEOMAR "Hydrotrace" expedition aboard the *R/V Sonne* in 1996 (SO110- 2; Suess et al. 1998). Venting sites were located along faults and/or exposed bedding planes produced from subduction zone deformation, and expelled either methane or sulfide dominated fluids consistent with tectonic induced fluid flow from the accretionary prism (Suess et al., 1998). Features at the vent sites along the Aleutian subduction zone included methane plumes in the water column, as well as authigenic carbonates, and cold seep megafauna (**Figure 29)**. The source of the methane is unknown (i.e. microbial or thermogenic), but the quantity of hydrocarbons available to support chemosynthetic communities and authigenic carbonate production seem to be similar to cold seeps found along other convergent margins (Suess et al., 1998).

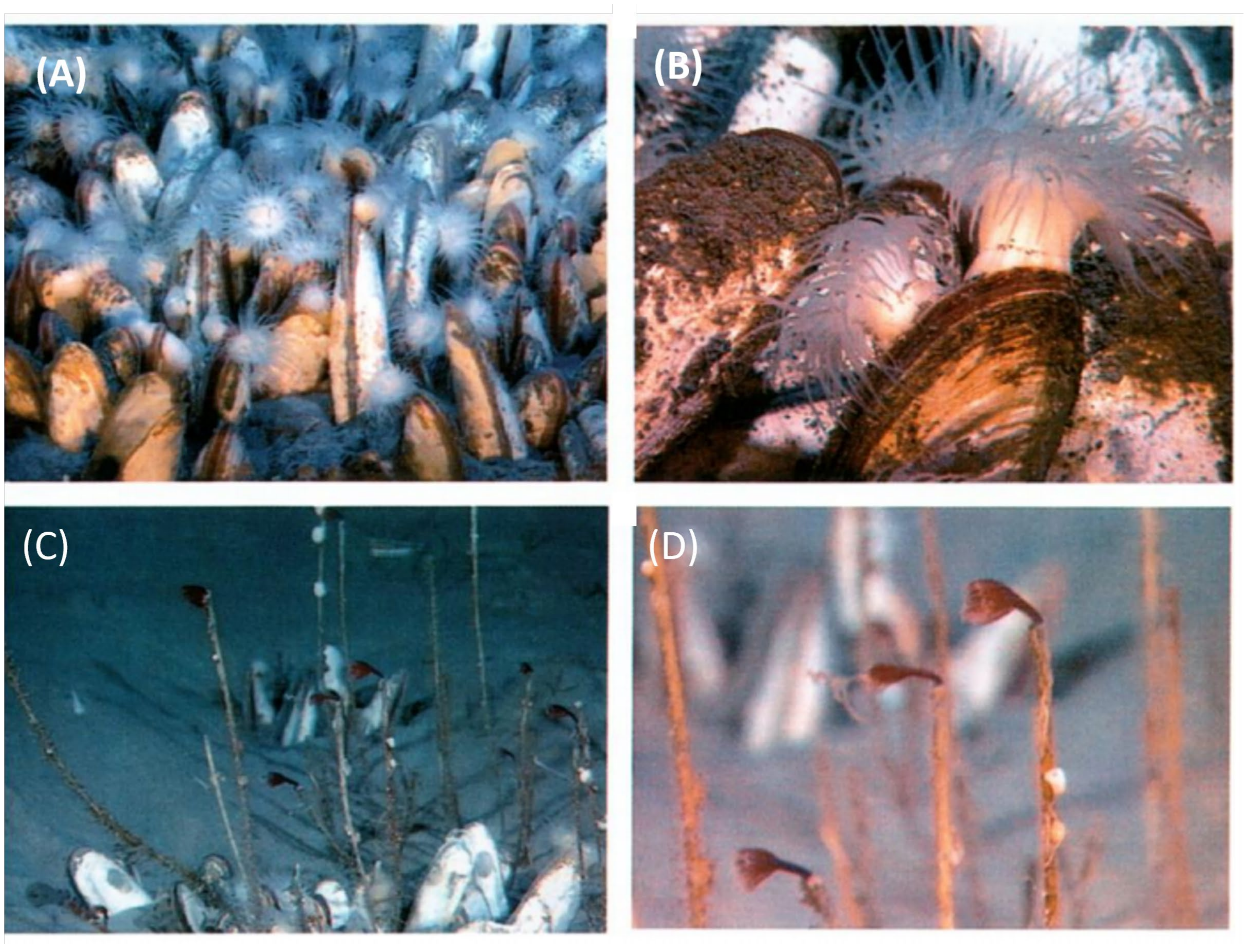

Figure 29. Drop camera photographs from Seep UAF073 showing (A-B) vesicomyid clams and (C-D) Pogonophoran tube worms (see white arrow Figure 25 for location).

Modified from Suess et al., (1998) used by permission under AGU policy.

4.3 Shumagin (SHU)

A total of 355 seeps were investigated in the SHU Planning Area (**Table 2; Figure 30**) from scientific literature, BOEM documents and various data sources (**Figure 31).** Interpreted oil and gas seeps are distributed onshore and within shallow bays of the Alaska Peninsula. Water column anomalies consistent with gas bubble plumes were interpreted on the continental shelf. Several vent locations with chemosynthetic communities are described on the upper and lower slope within the Aleutian accretionary prism.

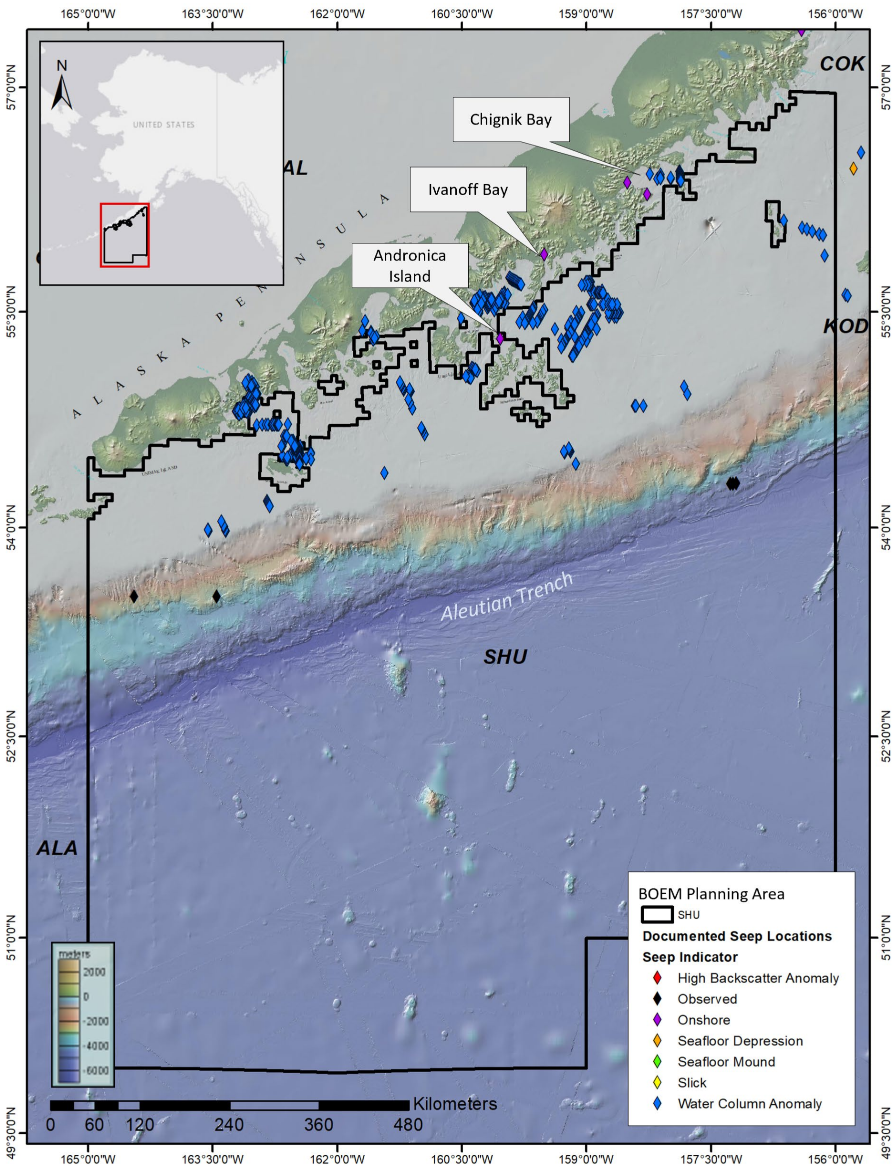

Figure 30. . Bathymetry within the BOEM Shumagin (SHU) Planning Area with interpreted seep locations

Bathymetry from GMRT Synthesis,(Ryan et al. 2009)

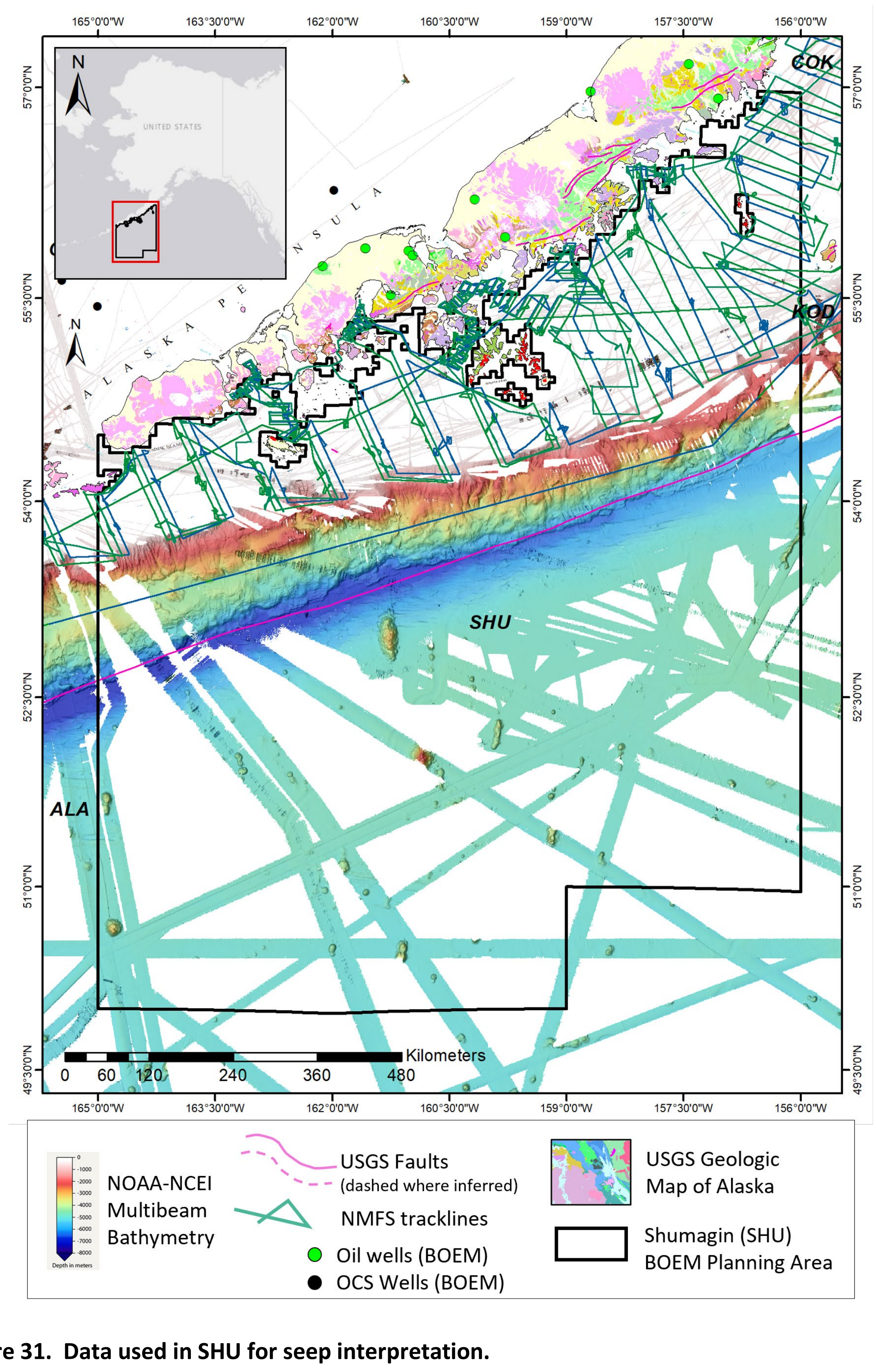

Figure 31. Data used in SHU for seep interpretation.

4.3.1 Oil Seeps on Western Alaska Peninsula

Several oil seeps have been reported along the banks of Chignik and Ivanoff Bays **(Figure 32**), however, none have been confirmed (McGee, 1972; Page et al., 1998a).

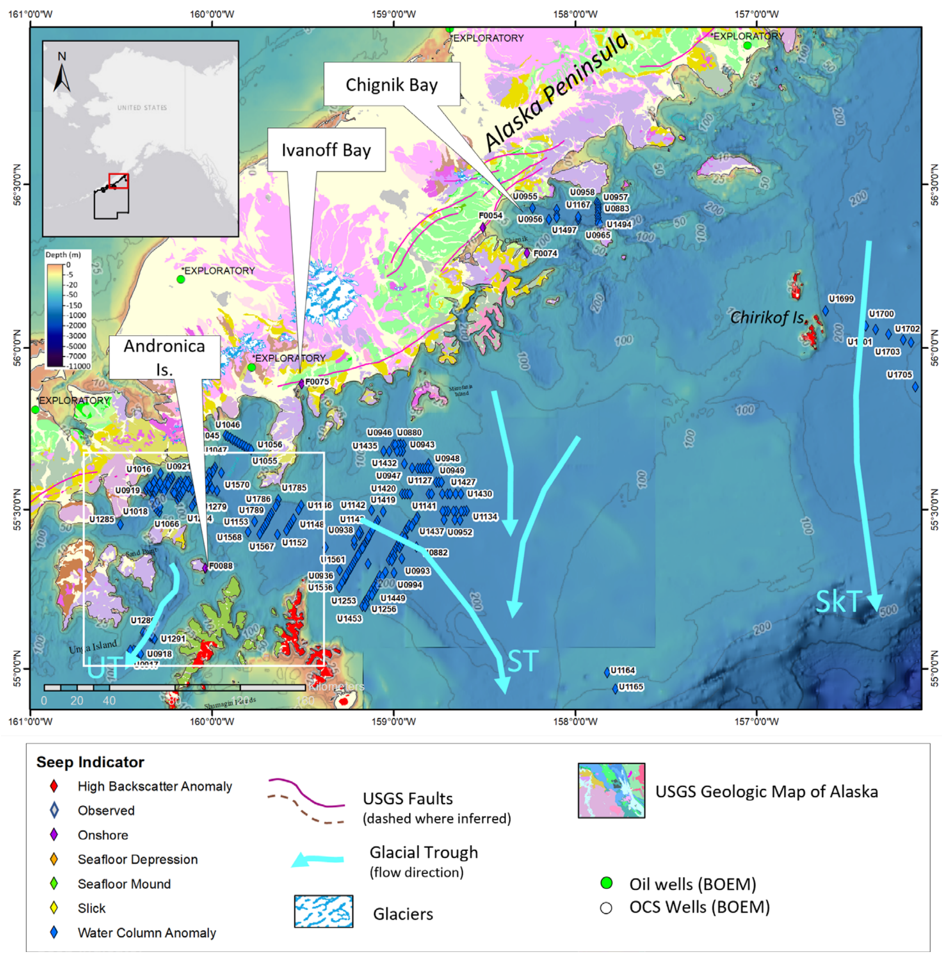

Figure 32. Bathymetry around Alaska Peninsula showing glacial troughs and flow directions; ST=Shumagin Trough; SkT=Shelikof Trough; UT=Unga Trough. White box is location of Figure 34.
Bathymetry from NOAA-NCEI.

Early geologic exploration in the southern Alaska Peninsula (e.g. Atwood 1911; Smith 1925) found significant coal deposits in this area, but no oil seeps were reported (**Figure 33**). Analysis of nearshore sediments in Chignik and Ivanoff Bays showed detectable concentrations of compounds consistent with petrogenic hydrocarbon sources (Page et al., 1998b), but the study also noted the boat and seaplane activities within the bays could be the source of the hydrocarbons in the sediment. NMFS EK60 data showed water column anomalies in Chignik Bay, interpreted as gas bubble plumes but it is impossible to assign any relationship to the unconfirmed seeps around the bay.

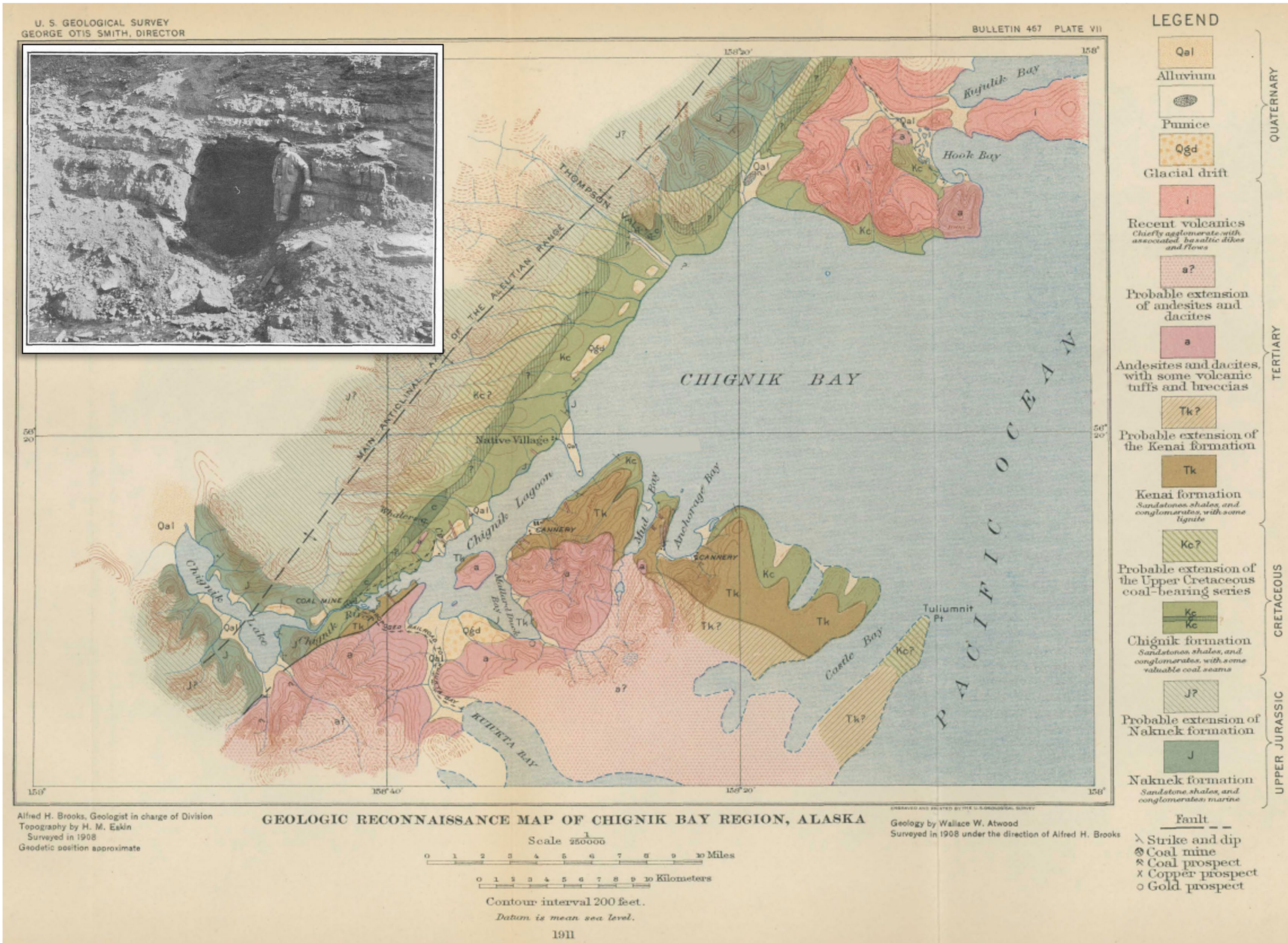

Figure 33. Geologic map of Chignik Bay Region from 1911 . Photograph (inset) shows a miner at the tunnel opening in Whalers Creek Coal Seam.

Map and photograph modified from Atwood, (1911).

Oil exploration wells drilled in the western Alaska Peninsula (see **Figure 32** for locations) did not yield any oil or gas shows as most reached bedrock of volcanic derived deposits, or batholithic rocks, that cannot be considered a source or a potential reservoir for petroleum. The younger sedimentary deposits above the volcanics were considered immature and nonproductive (Detterman, 1990). .

A seep was reported by the U.S. Coast Guard in 1913 to be in Cenozoic volcanic material on the eastern shore of Andronica Island, but is also unconfirmed (Becker and Manen 1988; Johnson, 1971)**.** As part of this study, numerous bubble plumes were interpreted from NMFS surveys (DY1307, DY1706) in troughs in an around the Shumagins **(Figure 34)**.

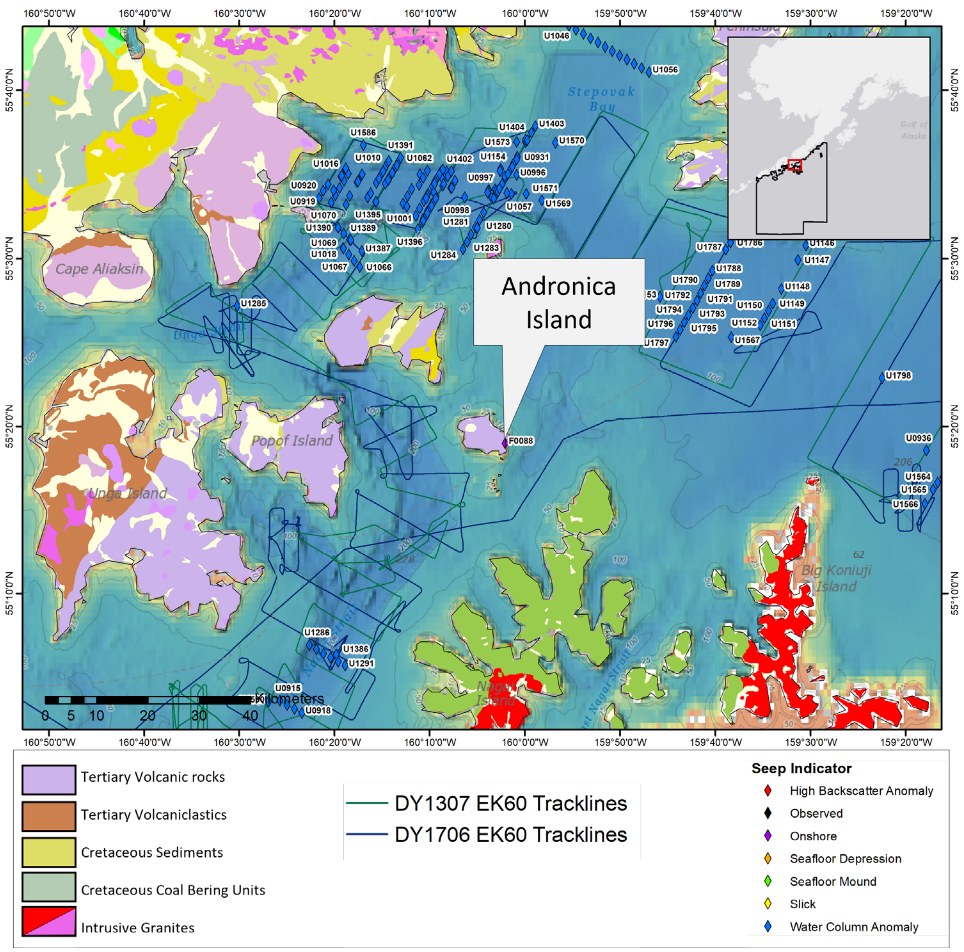

Figure 34. Bathymetry and geologic units around Shumagin Islands with NMFS survey track lines discussed in text. Bathymetry from NOAA NCEI, geologic map from USGS.

4.3.2 Subduction Zone Seeps

Active methane venting, chemosynthetic communities, and authigenic carbonates were observed and documented along the lower slope near the Aleutian Trench in water depths over 5000 m (Suess et al., 1998), and midslope between 3200- 4500 m **(Figure 35**; Levin and Mendoza 2007; Rathburn et al. 2009)

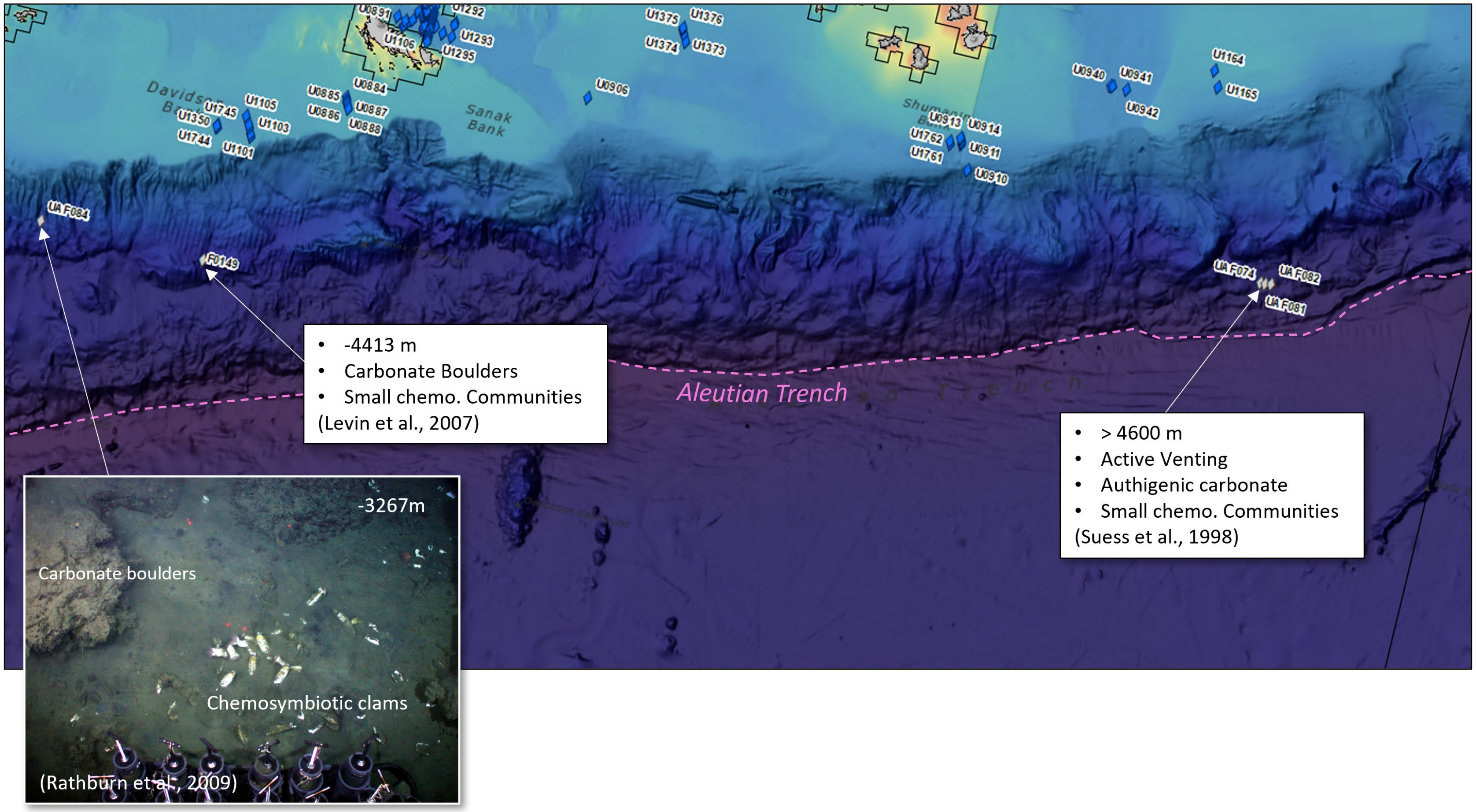

Figure 35. Seeps within the Aleutian subduction zone within the Shumagin Planning Area. Tow camera image . (Callout) from ROV Jason II aboard the R/V Revelle, July 2004.

At all of the seeps sites within the Shumagin portion of the Aleutian subduction zone, authigenic carbonates and chemosynthetic communities including clams, mussels and tubeworms were observed **(Figure 35**). Fluid vents expelled either methane or sulfide-dominated fluids that differ from other fluids examined along the Aleutian Trench, and may have migrated from greater depths along vertical shear faults (Suess et al., 1998).

4.4 Cook Inlet (COK)

A total of 122 seeps were investigated in the COK Planning Area (**Table 2; Figure 36)** from scientific literature, BOEM documents and various data sources **(Figure 37).** Interpreted oil and gas seeps are distributed onshore and in shallow bays. Water column anomalies consistent with gas bubble plumes were interpreted in Shelikof Strait.

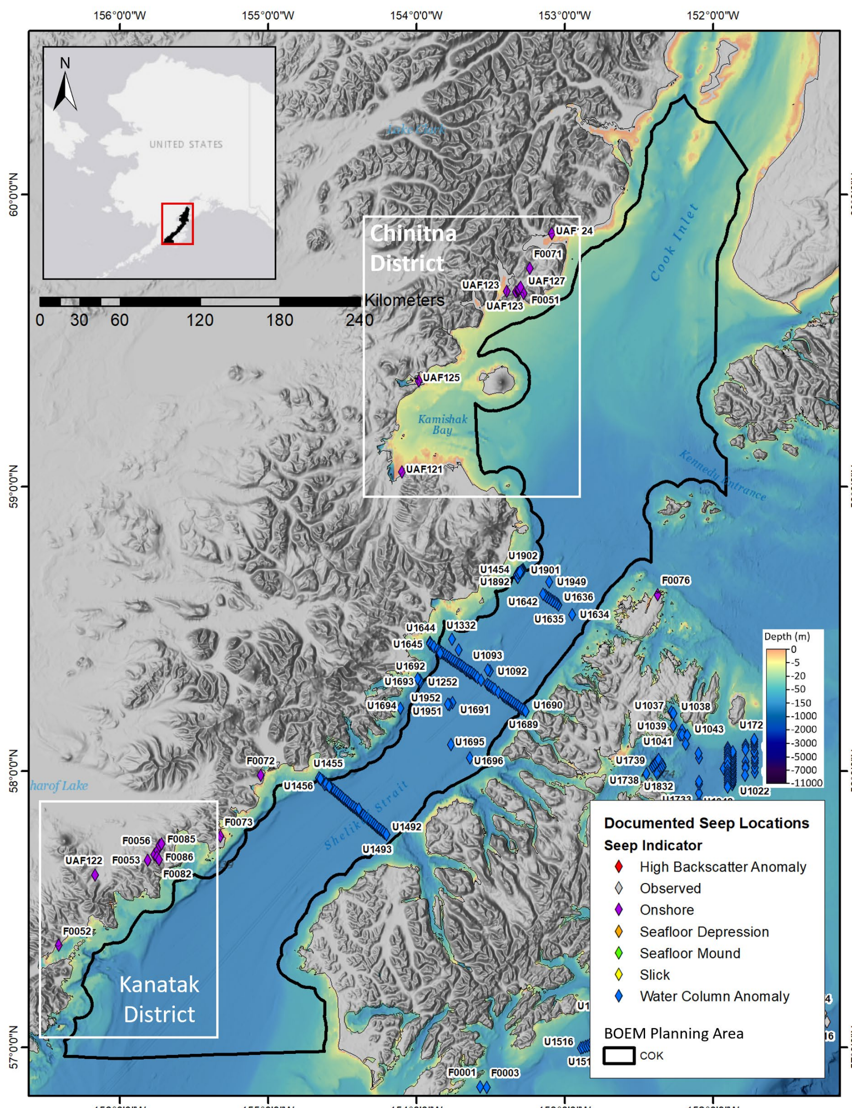

Figure 36. Bathymetry within the BOEM Cook Inlet (COK) Planning Area with interpreted seep locations

Bathymetry from NOAA NCEI.

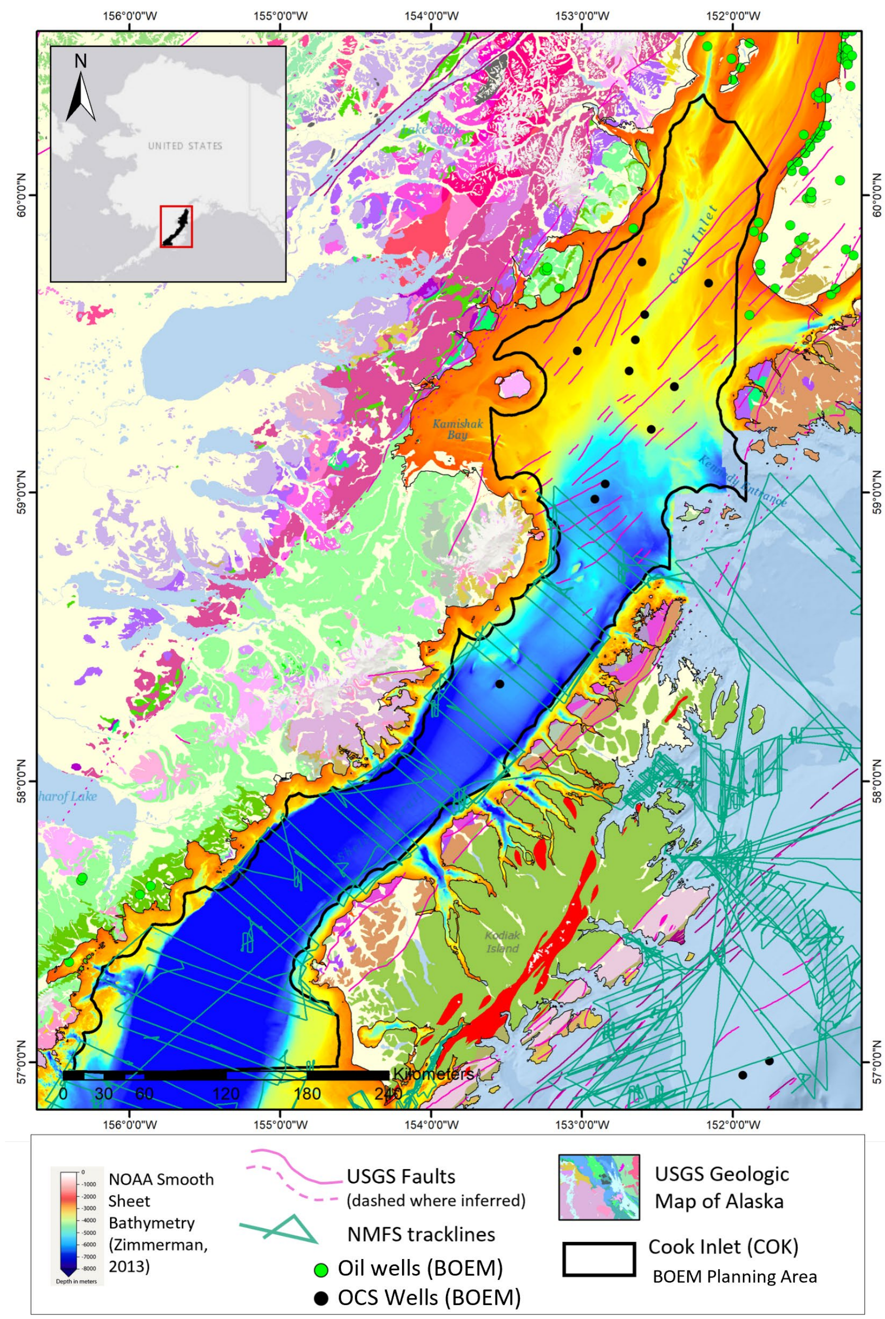

Figure 37. Data used for seep interpretation in COK region.

4.4.1 Chinitna District (Iniskin Peninsula)

Oil seeps in lower Cook Inlet were first described in 1853 by Russian named Paveloff, and initial exploratory drilling began around 1898 concluding in 1904 (Martin, 1921). Six wells were drilled on the Iniskin Peninsula between 1900-1906 at Oil Bay and Dry Bay (**Figure 38**). These wells encountered oil but not in commercial quantities (Blasko, 1976a). Exploration in the area resumed in the 1920s in the areas around seepages, all of which were sourced from the lower part of the Tuxedni sandstone at the crest of the Fritz Creek anticline extending from Iniskin Bay to Chinitna Bay (**Figure 39**). Historically, north of Tuxedni Bay was not considered favorable for oil occurrence, as the oil sand was too deep for drilling with 1920s technology. Although most of the seeps were reported around Oil Bay, seeps were described within the Tuxedni sandstone as far south as Kamishak Bay.

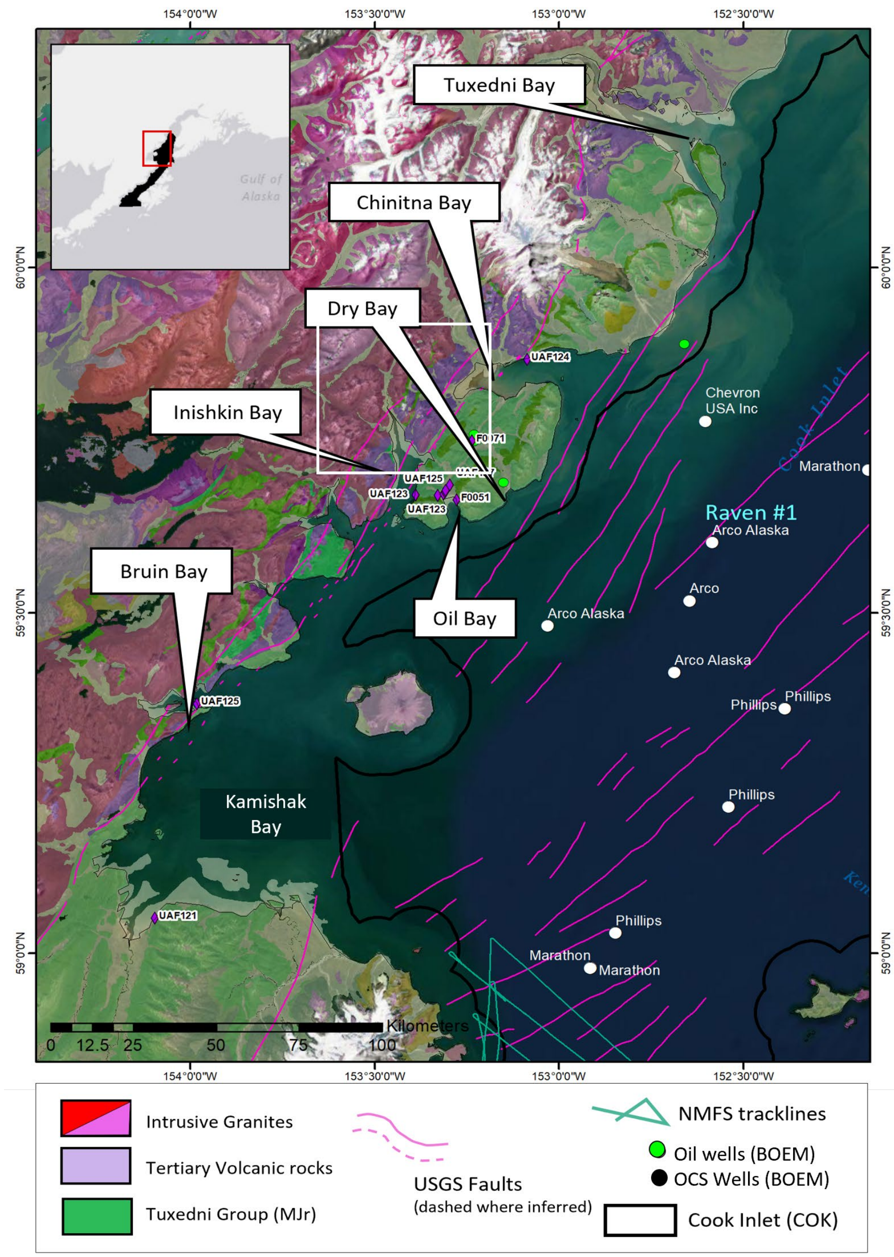

Figure 38. Satellite image of Chinitna District showing geologic units and exploratory wells. Numbered diamonds are seep locations from this study, white box is location of Figure 39.

Satellite imagery from Esri, 2021

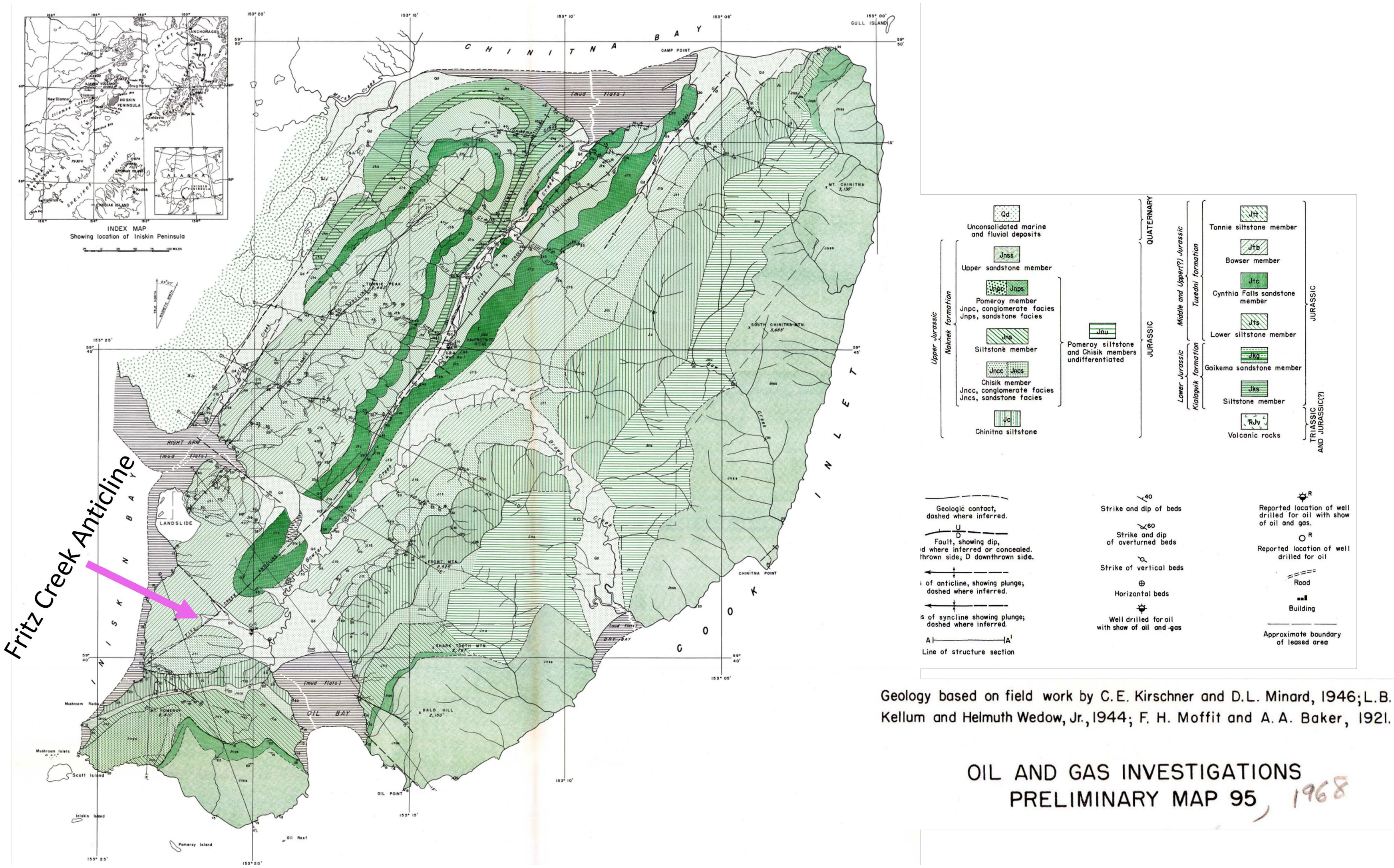

Figure 39. Geology of the Iniskin Peninsula showing Fritz Creek Anticline and folded Tuxedni sandstone (solid dark green unit).

Modified from C.E. Kirschner and D.L. Minard (1949)

Offshore exploratory wells were drilled within anticlinal structures in the late 1970s and early 1980s in lower Cook Inlet. The Raven #1 well (Arco Alaska**; Figure 38**) encountered oil-stained sandstone, possibly in Upper Cretaceous strata but evaluation of the accumulation did not encounter flowable hydrocarbons, and the well was abandoned (Lepain et al., 2012).

Although no seeps were interpreted during NMFS acoustic stock assessment surveys offshore of the Iniskin Peninsula seeps, single beam lines archived at NCEI do exist in this area and could be investigated for gas bubble plumes.

4.4.2 Kanatak District (Cold Bay/ Puale Bay)

Early exploration on the Alaska Peninsula from Wide Bay to "Cold Bay" (now Puale Bay) found copious seeps, both oil and gas. The best known seeps occur on the Bear Creek and Oil Creek anticlines, around Wide Bay, and south of Becharof Lake on the Ugashik Creek Anticline (**Figure 40**; McGee, 1972) .

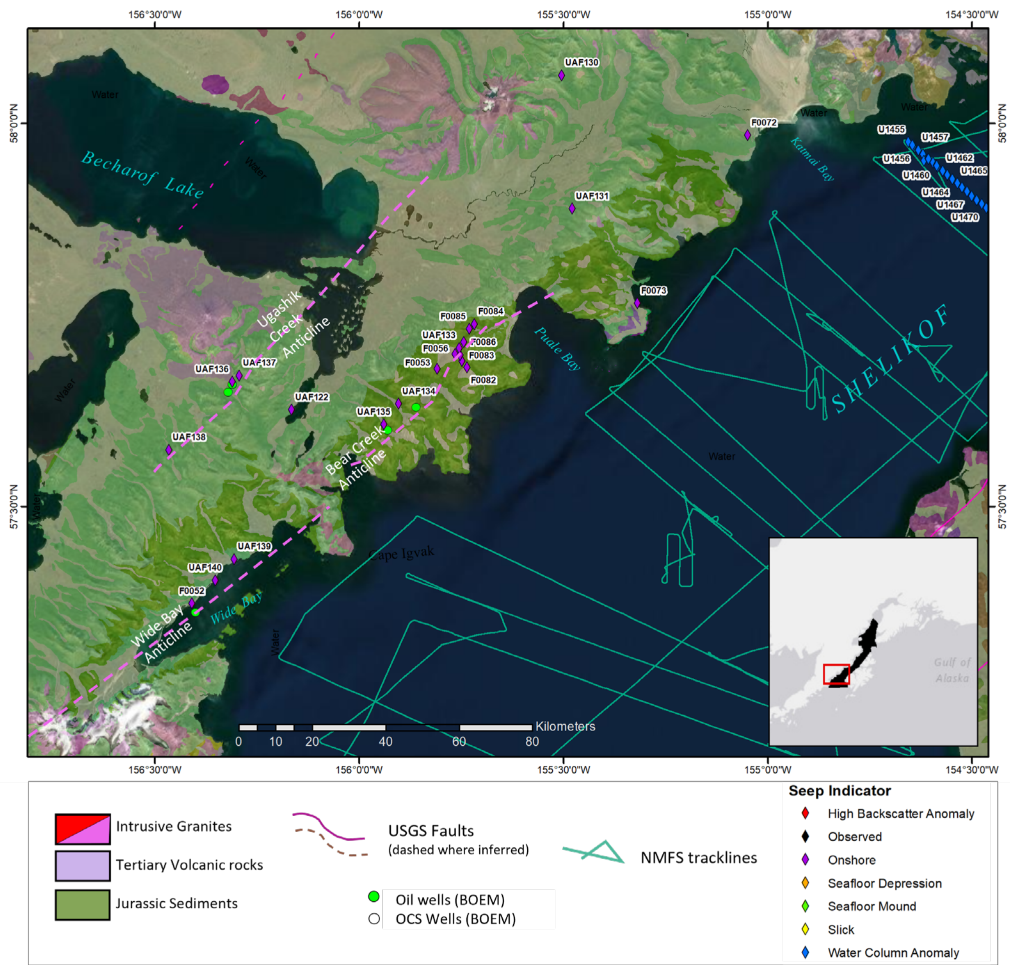

Figure 40. Satellite image of the Kanatak District with geologic units and exploratory wells.
Esri satellite imagery

All of these seeps issued from Middle and Upper Jurassic strata belonging to the Kialagvik, Shelikof, and Naknek formations (Blodgett, 2014). Gas seeps have also been reported in Becharof Lake (Blasko, 1976b). Seep locations in the Kanatak area were described in literature, maps, and field reports between 1902 and 2005, and were compiled and field-checked by Blodgett and Clautice (2005). These locations were added to the database for this study.

Exploratory drilling occurred at seep locations between 1902 and 1926, and again in the 1950s, but most wells were abandoned due to no commercial production and recovery of large volumes of salt water (Blodgett & Sralla, 2006). The few shallow wells drilled were not conclusive and it was assumed that the most promising prospects in the Jurassic rocks were just not reached (Becker & Manen, 1988).

Seeps were not interpreted from NMFS single beam surveys in the Shelikof Strait adjacent to either the Kantak or Chinitna districts, but many were interpreted during NMFS surveys within the Shelikof Strait on lines that lie between these two regions where oil seeps were reported on land (**see Figure 36** for locations and cover image). However, the many single beam lines that are publicly available within the Shelikof Strait were not investigated for gas bubble plumes during this study.

4.5 Western Alaska OCS

Although this study is focused on Lower Cook Inlet, Gulf of Alaska, Chukchi Sea and Beaufort Sea OCS Planning Areas, 17 seeps were found in the St. George Basin, Navaro Basin, St. Matthew-Hall region, and in Norton Sound Planning Areas **(Figure 41**). Many studies investigated the hydrocarbon potential of this region in the 1980s, and dozens of stratigraphic test wells were drilled.

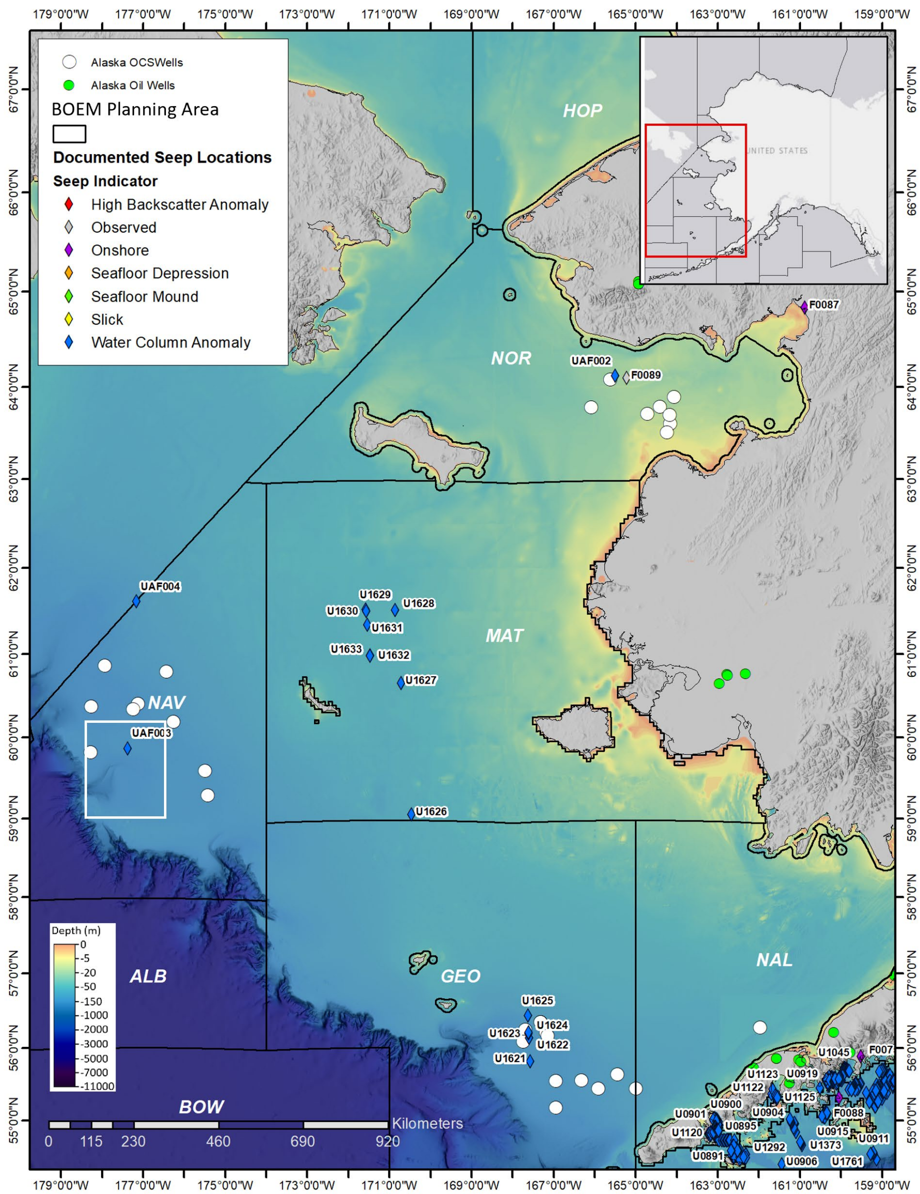

Figure 41. Bathymetry within the western Alaska OCS planning areas including Navaro (NAV), St. George Basin (GEO), North Aleutian Basin (NAL), Bowers Basin (BOW), Aleutian Basin (ALB), Norton Basin (NOR), St. Matthew-Hall (MAT) with interpreted seep locations. White box is general location of Figure 42.

Bathymetry from NOAA NCEI .

A study by Woodward-Clyde-Oceaneering (1984) in the Norton Basin (white box **Figure 41**) found an area with high methane and elevated ethane concentrations **(Figure 42**). This area correlated to recent sediments deposited in a graben which suggested that most of the is methane is derived biogenically from recent sediment. The seeps added to the database for this study were derived from the locations of bubble plumes in the water column interpreted from multichannel seismic images (Carlson, 1989; Woodward-Clyde-Oceaneering, 1984).

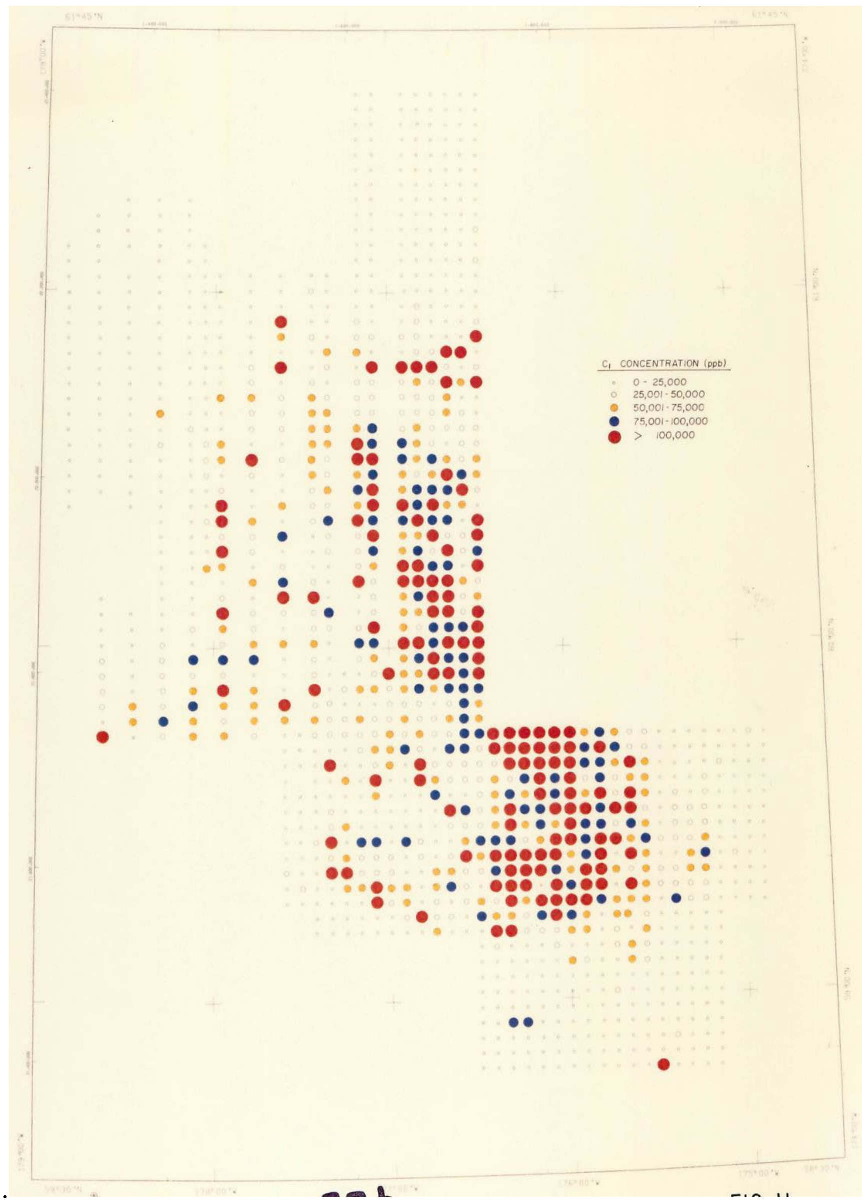

Figure 42 Map of methane concentrations in area of a Woodward Clyde Oceaneering report from 1984 (general area of white box in Figure 41).

No reference map with bathymetry or location was provided other that coordinate grid (unknown datum).

One particularly well-studied seep occurs in Norton Sound (Atlas et al., 1983; Cline & Holmes, 1977; Kvenvolden et al., 1979; Nelson et al., 1979; Venkatesan & Kaplan, 1982). The fluids were determined to be from thermogenic hydrocarbon sources and may be mixed with hydrothermal fluids (**Figure 43**).

The rest of the seeps included in the database in Western Alaska OCS were interpreted by Darin Jones during NMFS acoustic stock assessment surveys.

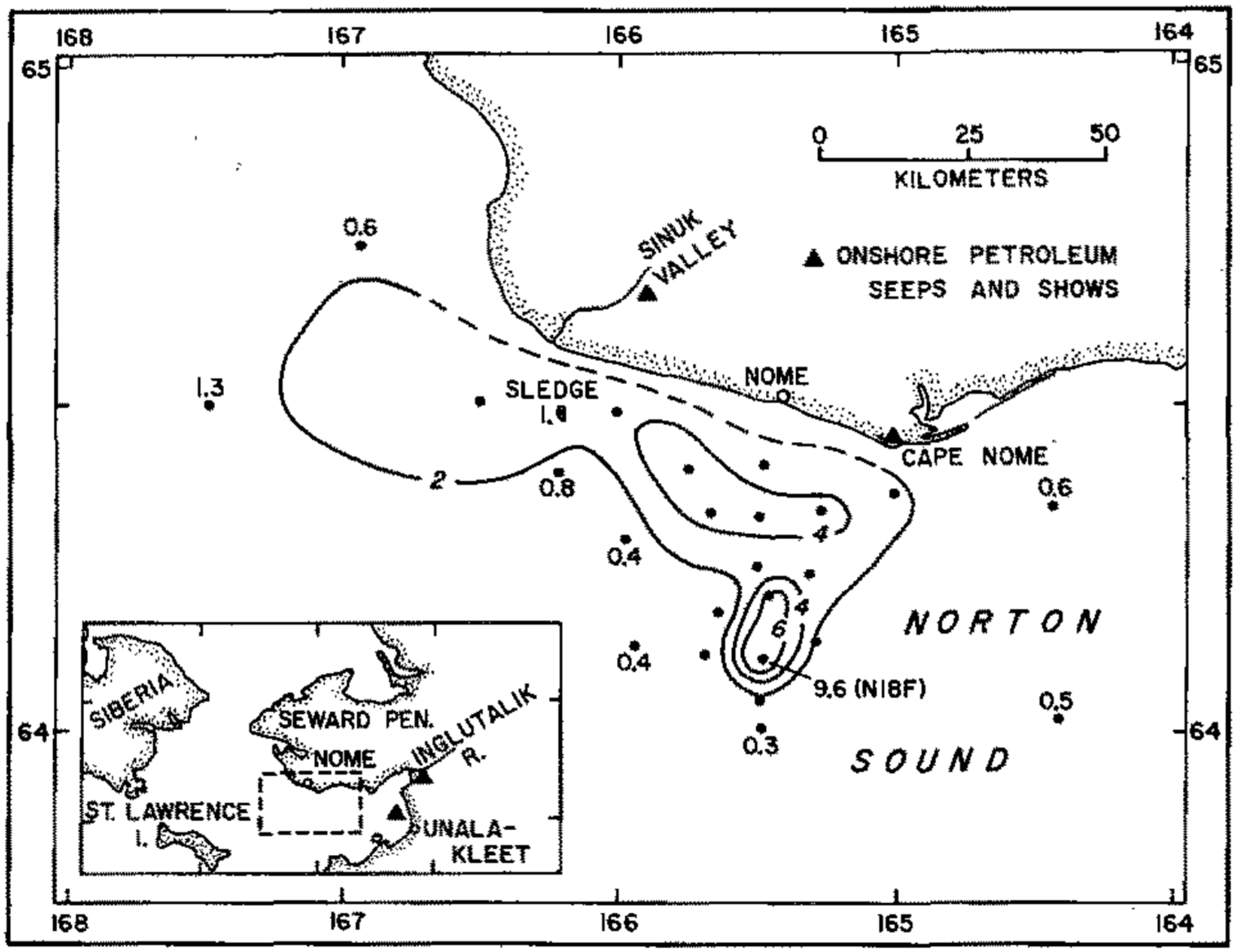

Figure 43 Location of seep in Norton Sound and contoured ethane concentration (10^{-9} dm^3/cm^3) within 5 m of seafloor.

Image from *Cline and Holmes (1977)*

4.6 Chukchi (CHU)

A total of 82 seeps were recorded in the Chukchi Planning Area **(Figure 44)**. Onshore oil and gas seeps in northwest Alaska have been described in literature since 1909 (AMAP, 2010), some of which were verified (and included in the database), such as the Skull Cliff seeps described in a report by Webber in 1947, and others that were never found again after the initial early reports (Becker & Manen, 1988).

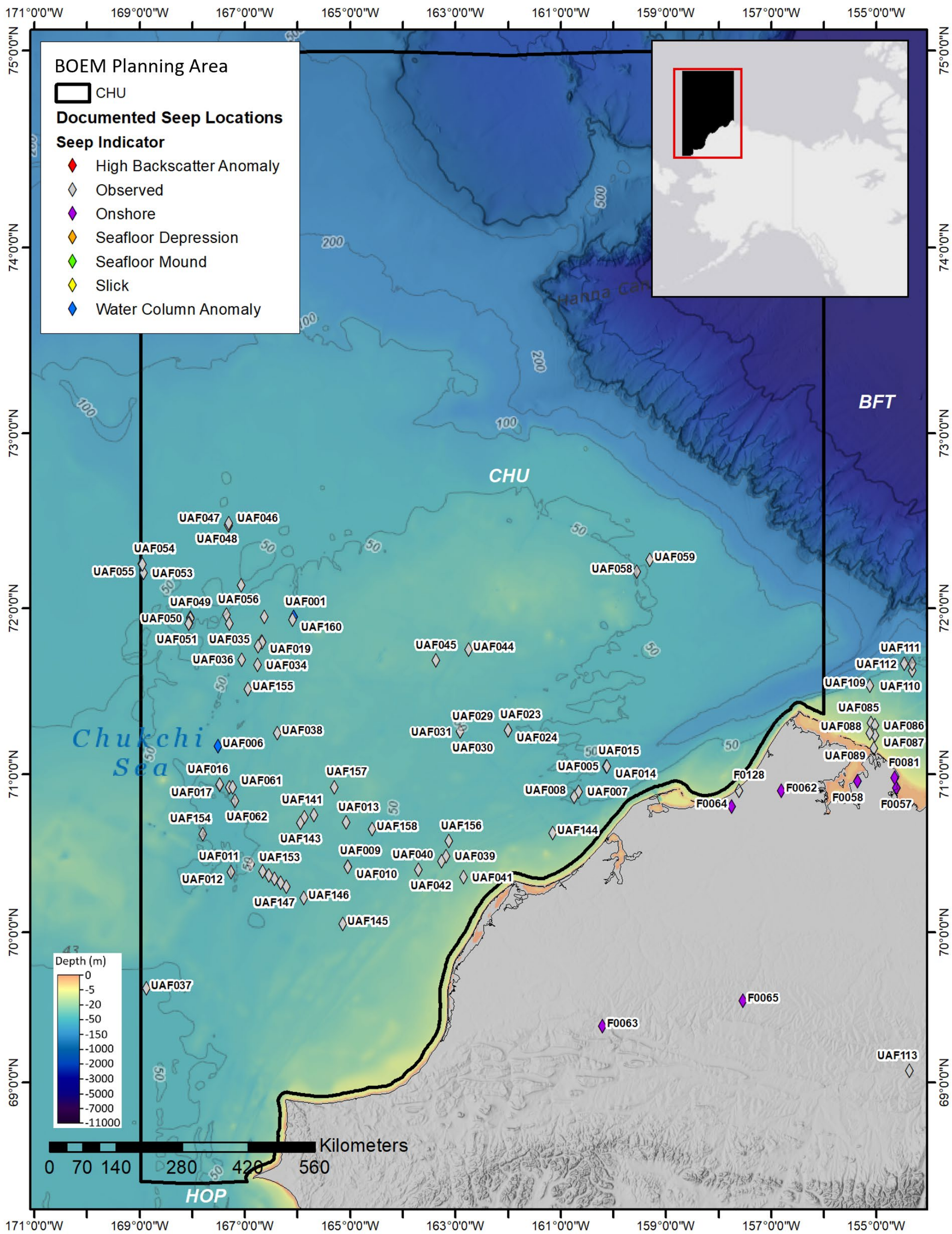

Figure 44. . Bathymetry within the BOEM Chukchi (CHU) Planning Area with interpreted seep locations

Bathymetry from NOAA NCEI.

Offshore seep locations within the Chukchi Planning Area were mostly compiled from various coring and geochemical surveys contracted by BOEM in the 1980s, from sniffer data and analysis of headspace gases in sediment core samples as well as from sampling clathrates. (**Figure 44**). Because microbial methane is so common in the shallow sediments tested in the Chukchi Sea, the locations included had methane concentrations were >100 ppm and C_2-C_5 concentrations above trace values.

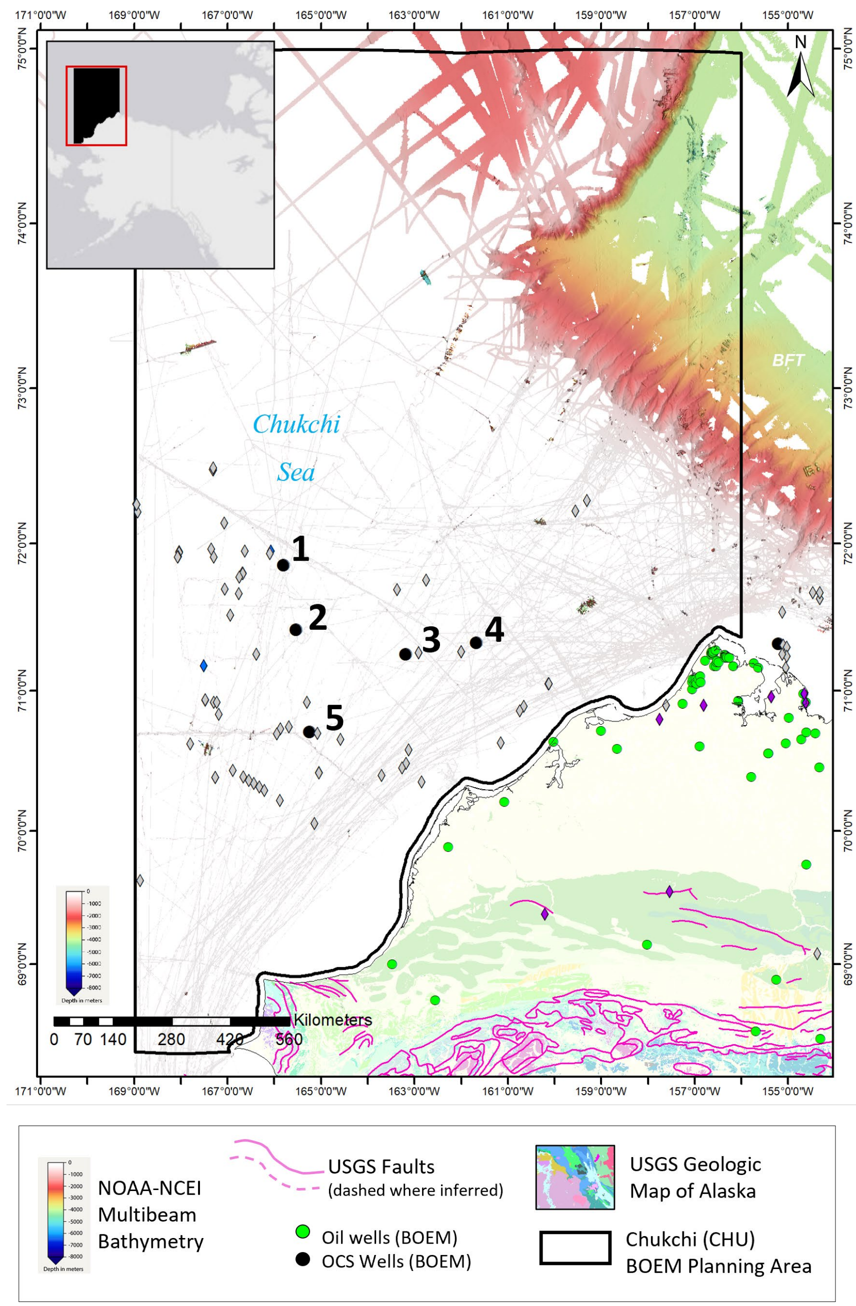

Figure 45. Data used for seep interpretation in CHU planning area region. Numbered wells correspond to Table 3

Results from the various geochemical surveys showed that oil seeps were more common in the southeastern portions of the surveys, whereas gas seeps were more common north of about 71° N. From an internal BOEM memo on a 1985 Fugro geochemical survey, Sherwood, (1992) noted:

> *"The geographic trends inferred from shallow geochemical data are confirmed by recoveries from exploratory wells. Medium- to high-gravity oil was recovered from Klondike well in the south but high-gravity oil, condensate, and gas dominate recoveries from exploratory wells in the north (Burger, Popcorn). These observations suggest that prospects south of 71° N are generally more likely to contain oil, while those to the north are more likely to contain higher-gravity oil or a greater share of gas*."

BOEM estimates the Chukchi Sea planning area may hold more "technically recoverable" oil and natural gas than any other OCS planning area except for Gulf of Mexico's Central planning area (Bureau of Ocean Energy Management, 2021). However federal waters in the Chukchi Sea have a limited history of leasing and exploration with only 5 test wells drilled between 1989 and 1991 **(Figure 45 and Table 3**). All of the very shallow wells resulted in the discovery of hydrocarbons, although none were considered commercial (National Research Council, 1994).

Table 3 . Exploratory wells in the Chukchi Sea

Well #	Prospect	Operator	End	Water Depth (ft)
1	Popcorn	Shell Western E&P Inc.	1990	143
2	Crackerjack	Shell Western E&P Inc.	1991	137
3	Burger	Shell Western E&P Inc.	1990	149
4	Klondike	Shell Western E&P Inc.	1989	141
5	Diamond	Chevron U.S.A Inc.	1991	152

Note: not included are Shell tophole wells of 2012 and 2015 within the Burger Prospect.

In 2012, Shell succeeded in drilling a top hole at Burger A well site, which is located about 137 km northwest of Wainwright, AK in approximately 140 m water depth. Because of the significant problems that occurred during the 2012 exploration season, Shell paused its Alaska offshore program until 2015, when Shell resumed drilling to test the Burger prospect, with disappointing results. President Obama in January 2015 designated portions of the Beaufort and Chukchi Seas off limits from consideration for future oil and gas leasing to protect the area's sensitive environmental resources, and in 2017 the Chukchi planning area was not included in the BOEM's Proposed Final Program (BOEM, 2016).

4.7 Beaufort (BFT)

A total of 62 seeps were interpreted in and around the BFT region (**Table 2; Figure 46**) from a variety of data sources (**Figure 47**).

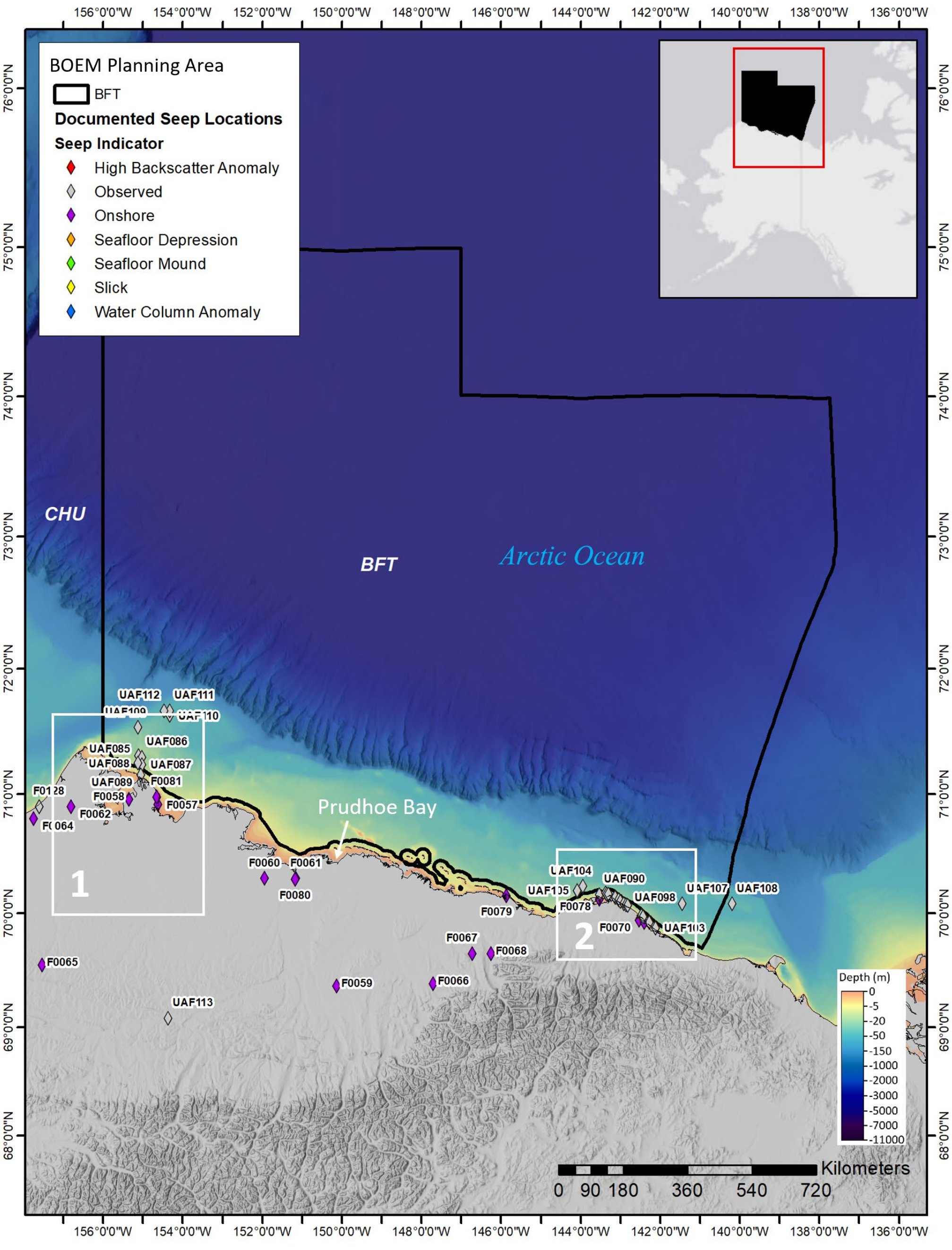

Figure 46. Bathymetry within the BOEM Beaufort (BFT) Planning Area with interpreted seep locations White boxes correspond to 1. Smith Bay area and 2. Agun/Manning Point area.
Bathymetry from NOAA NCEI.

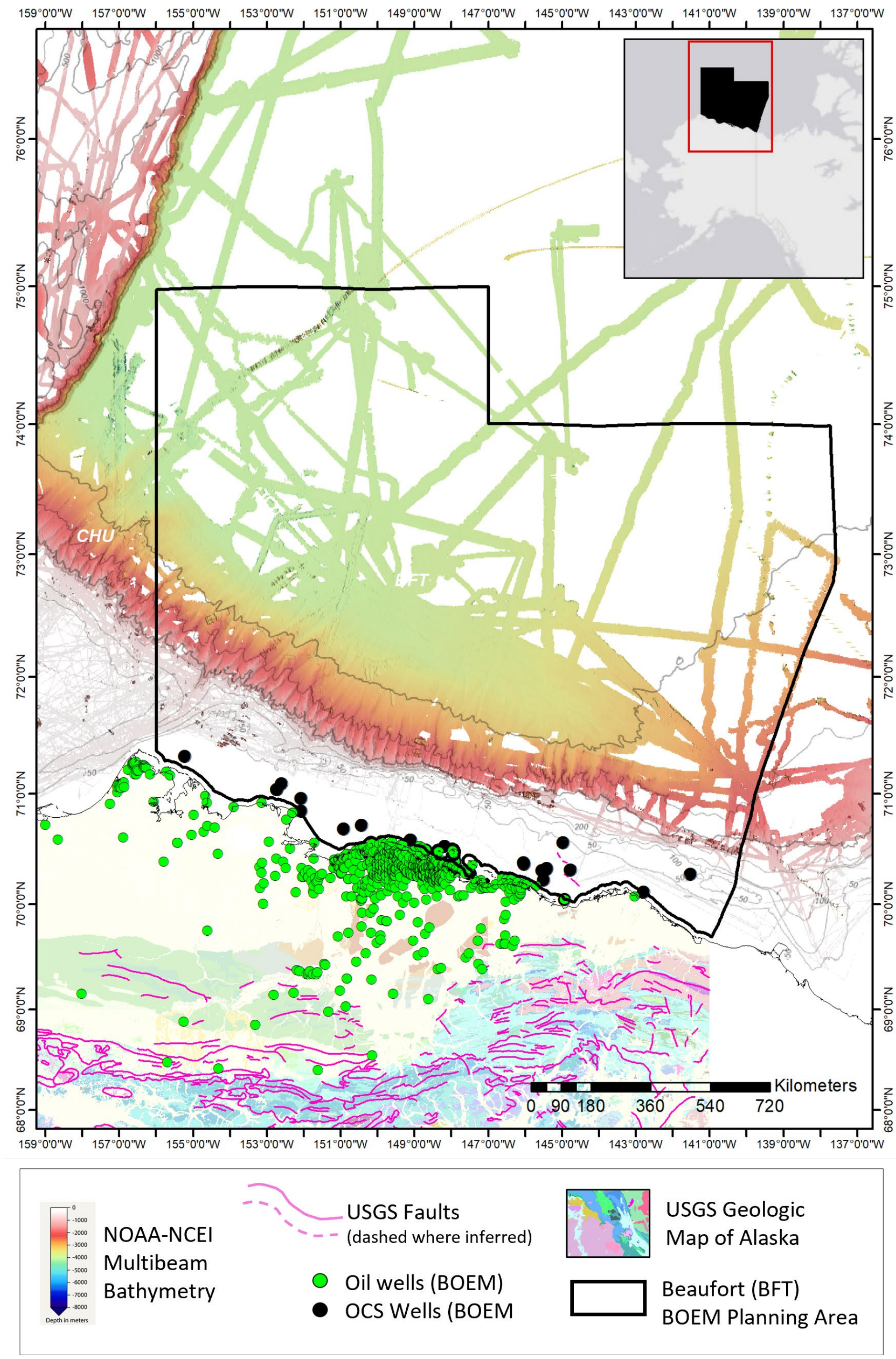

Figure 47. Data used for seep interpretation in BFT region

Early discoveries of oil seeps in Alaska were by local Inupiat who used oil-soaked peat for fuel, as noted in an early USGS document by A.H. Brooks (1909). Ensign W. Howard of the U.S. Navy reported that:

“Here they found on the surface rather abundantly scattered masses of a brown material resembling powerfully compressed peat, recalling pitch in hardness and weight, but not brilliant nor disposed to melt with heat, but making a clean cut, like "plug" tobacco, when whittled with a knife. This material was sufficiently flammable to ignite and burn with a steady flame on applying a match to a corner of it, so that in their cold and weary journey it formed a most welcome substitute for wood or other fuel for the campfire”.

The earliest written report of petroleum on the Alaskan north slope was in 1886 by a U.S. Navy expedition at the head of the Colville River (Becker & Manen, 1988). The first real petroleum seepage in North Slope was recorded by E. Leffingwell in the Smith Bay area between 1906-1914 (**Figure 46 box 1**; Leffingwell 1919). H.A. Campbell examined oil seepages near Cape Simpson in 1921, and the oil seeps were later visited by the Paige expedition of the Point Barrow region in 1923 (**Figure 48;** Paige et al. , 1925). The Inupiuat People of Barrow (Utqiagvik) Alsaka reported to Leffingwell information about another seepage near Angun Point. (White box 2. **Figure 46)**. Soon afterward President Warren G. Harding established the Naval Petroleum Reserve No. 4, which covered most of the northern coast of Alaska.

A. OIL SEEPAGE NO. 1, CAPE SIMPSON

Arctic Ocean on the right

Figure 48 Photograph of “oil seepage No.1” near Cape Simpson.
From *Paige et al. (1925)*.

.

The first test wells were drilled in the 1940s near oil seeps at Cape Simpson, up the Coville River, and South Barrow. A seep at Manning Point was reported in 1944 and appears on maps by Art Grantz in 1976 and 1980, and again by Bader in 1986 (**Figure 49**). Another oil seep reported at Kuparuk, resulted in the 1968 discovery of the Prudhoe Bay oil field (Becker & Manen, 1988)

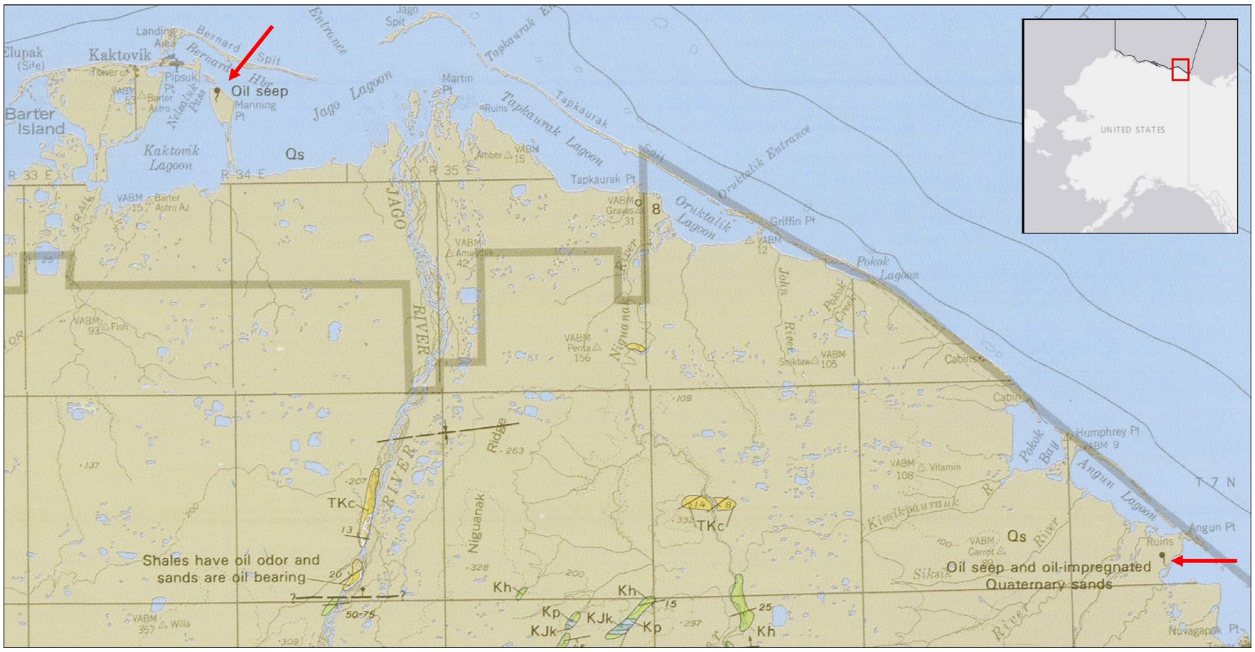

Figure 49 Manning Point and Angun Point seeps (red arrows)
From *Bader and Bird (1986)*.

As in the Chukchi, BOEM contracted and/or permitted a series of geochemical surveys of the nearshore Beaufort shelf in the 1980s. These surveys interpreted oil and gas seeps offshore, most of which were added to the database. However, many "seeps" were recorded by contractors where methane concentration of only 30 ppm was reported as "elevated" with only trace amounts of C_2-C_5 . These locations were included in the database, although modern geochemical coring may be necessary to determine if such low concentrations of methane do indeed indicate hydrocarbon seepage, or just background microbial methane within modern sediments.

5 Recommendations

This study has pulled together a database of known seafloor cold seeps in four areas of interest around Alaska: Gulf of Alaska, Cook Inlet, Chukchi Sea, and Beaufort Sea. The study is not exhaustive in the sense that we have not used all established methods for locating cold seeps and we have not examined archived data (e.g. single beam and multibeam backscatter), except for the pilot study between Copper River and Yakutat. Here we recommend approaches to expanding this desktop study, and field work for addressing open questions about the extent, nature, and characteristics of the Alaska cold seeps.

5.1 Methods for Extending the Desktop Study

Locating cold seeps in the ocean is most efficiently done by methods of remote sensing rather than direct visual examination of the seafloor. The two established methods are water column surveying for bubble streams; and seafloor backscatter mapping to locate authigenic carbonate deposits on the seafloor or under very shallow sediment. Further application of these methods in the region around Alaska would provide a more comprehensive database of seafloor seeps, and a better basis for understanding their relationship to underlying geological features.

5.1.1 Water column Data Analysis

The bubble stream identifications from water column anomalies, by Darin Jones, Mark Zimmermann and ourselves, provide ample evidence of the value of this approach. Utilizing sonar data which has already been collected, is a rapid way of surveying for active seeps, those which are expelling streams of methane-rich gas bubbles into the ocean. Given the number of seeps identified so far with this method, seeps appear to be widespread in the Gulf of Alaska. Furthermore, the approach is efficient because of the availability of public water column data collected and archived by NOAA, as we have successfully shown.

Other sources of water column data are also available, e.g., NSF research vessels including R/V *Sikuliaq*, but those data are of unknown quality. We tested a transit portion of the *Sikuliaq* line that runs through our “pilot study” region (green lines in **Figure 50 callout**) and found that the water column data were very noisy and not suitable for imaging bubble streams.

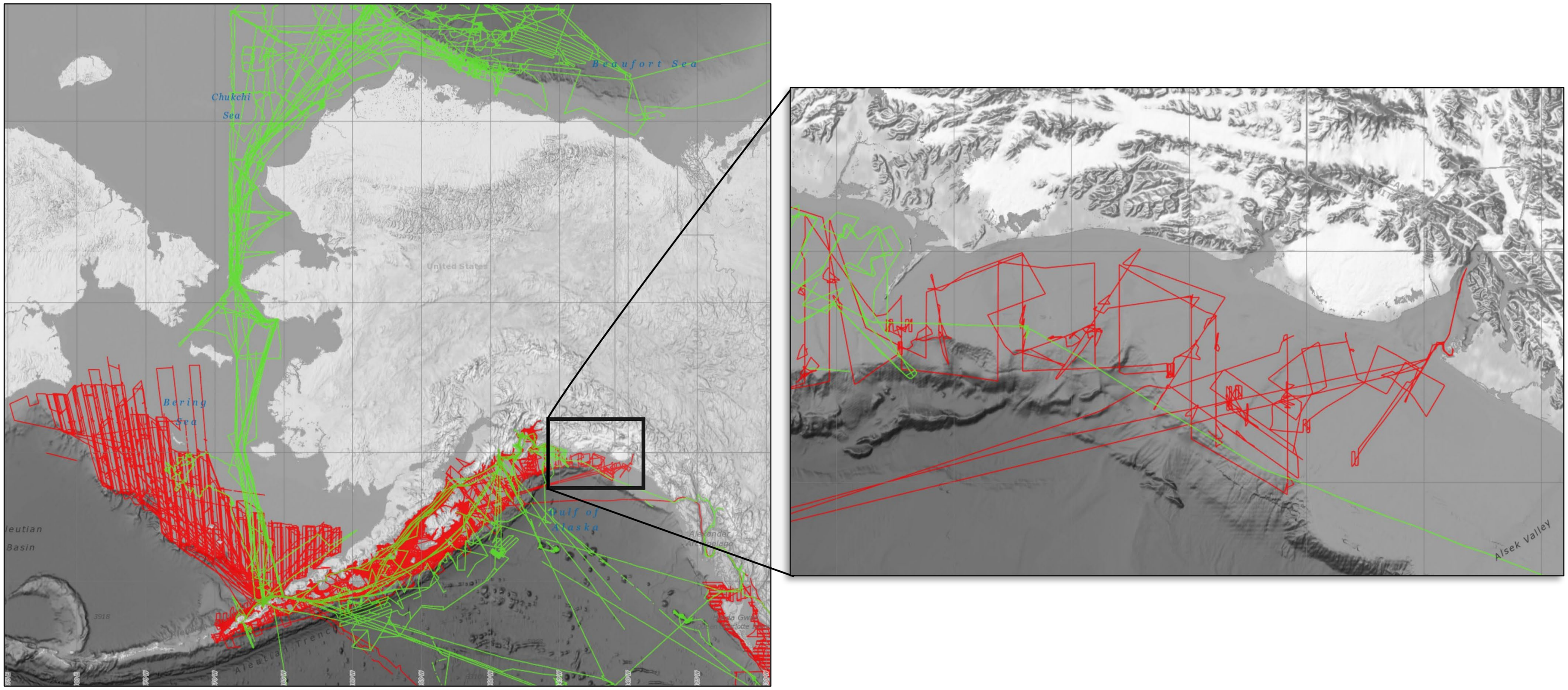

Figure 50. Examples of tracklines of surveys with water column data that are archived in NCEI https://www.ncei.noaa.gov/maps/water-column-sonar/ Callout shows our "pilot study" region from Copper River to Yakutat Bay, discussed in Section 2.1.3 . Red (NOAA NOS). Green = NSF research vessels.

Latitude-longitude grid lines are at 1 degree intervals. Basemap is the NOAA NCEI visualization of GEBCO 2020 bathymetry, in grayscale.

5.1.1.1 Collaboration with NMFS

One of the results of this study has been a collaboration with Mark Zimmerman and Darin Jones (NMFS seep-finding biologists discussed above) on a manuscript for a peer reviewed journal, where we investigate single beam water column data, to not only locate seeps, but to determine if the distribution and habitat of fish populations such as walleye pollock (*Gadus chalcogrammus*) are influenced by seeps. Funding continued processing and interpretation of single beam data for seep locations and fish habitat studies in collaboration with NMFS has several possible applications relevant to BOEM:

- Investigating fish abundance around seeps is a novel application of the BOEM seep database and may lead to further notation of seep locations during stock assessment surveys that could be added to this database.
- Continued collaborative single beam studies could provide baseline information and greater understanding of how hydrocarbon seeps provide not only habitat for chemosynthetic communities, but also for broader regional fisheries. If seeps are shown to influence pollock distribution, then the BOEM seep database will be used to describe pollock Essential Fish Habitat (EFH) and may be used to stratify the acoustic survey for pollock.
- Continued collaborative single beam interpretation with NMFS provides an opportunity of multi-agency and interdisciplinary studies that, if funded, could increase understanding of marine processes and enhance ecosystem knowledge for conservation.

5.1.2 Seafloor backscatter data

Chemical reactions between rising seep fluids and shallow sediment pore waters can cause precipitation of authigenic carbonate in the shallow sediment, centimeters below the seafloor. This authigenic carbonate may be exposed by subsequent sediment erosion, particularly if the seep has a bathymetric expression. These patches of carbonate can be imaged with multibeam backscatter data, which shows where the seafloor is hard and/or rough (high backscatter) or smooth and/or soft (low backscatter). Authigenic carbonate at seep sites has a very strong acoustic response and stands out as high-backscatter spots on seafloor maps (**Figure 51)**.

Interpretation of high-backscatter regions on the seafloor can be ambiguous and requires additional geological information or ground truthing. Nevertheless, seafloor backscatter is often used as a tool for locating cold seeps because it is an efficient, remote method and because backscatter data are relatively widely available. The ideal system is a multibeam sonar at moderate to high frequency (30-100 kHz), as this can produce co-registered bathymetry and backscatter data at a resolution suitable for “seeing” authigenic carbonate deposits.

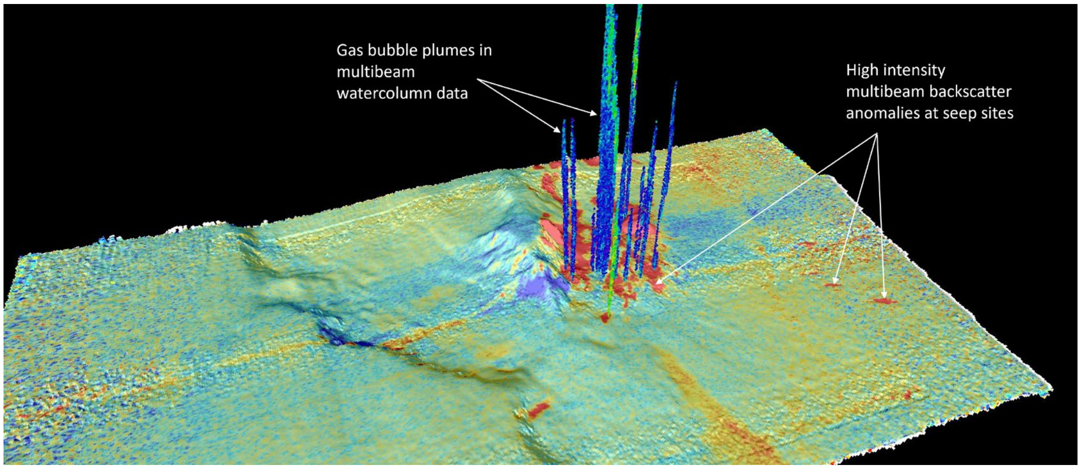

Figure 51. Perspective view of multibeam bathymetry draped with water column and seafloor backscatter data. Warm colors represent high backscatter intensities, cool colors represent low backscatter intensities.

From *Millar et al. 2019* used by permission of the author.

An important point about backscatter identification of possible seep sites is that this method does not require effusive fluid venting (bubble streams) which is not always occurring at seep sites (**Figure 51**). Multibeam seafloor backscatter can therefore detect a wider range of seep activity including low-level, diffusive flow or inactive seeps. Thus, this method is complementary to water column acoustic surveys.

Analyzing backscatter data was beyond the scope of this study, but these data are available from multiple Alaskan NOS multibeam surveys starting in 2013 along with a few earlier ones. Typically, the bathymetry data are processed for charting, while backscatter data are sent to the NCEI archive in unprocessed form because they are not necessary for charting. Availability of backscatter data for a given region needs to be checked by survey.

5.2 Recommended Field Work

The presence and patterns of seafloor seeps around Alaska reflect both the subsurface fluid sources and the geological structures and pathways that allow fluids access to the seafloor. The sources and the surface expression of seeps (morphology, biology) may be related. A better understanding of the seep fluid compositions would be important for identifying sources of hydrocarbons in seawater and provide a baseline geochemical fingerprint of seafloor locations.

Several goals could be addressed through field work at Alaskan seafloor seeps:

- High-resolution bathymetric and backscatter maps to characterize type examples or specific seeps of interest
- Seafloor imaging (video) to determine presence of chemosynthetic communities and their general characteristics, e.g., presence of microbial mats and macrofauna

- Geochemical sampling and analysis
    - for geochemical fingerprinting of the hydrocarbons
    - to investigate possible relationships between seafloor expression of seeps and their geochemical characteristics

Some of these, especially geochemical fingerprinting of hydrocarbons, would be advisable in all regions where seeps occur and there is potential for industrial oil spills.

The goals listed above could be addressed in a region with favorable logistics for field work, such as the Northcentral GOA. There, the field work could focus on characterizing a range of seeps in order to investigate possible relationships among physical, chemical and biological characteristics.

A specific site of interest is the large seep (or seeps) in Hinchinbrook Trough as discussed in Section 3.1.5. This site has been active since at least 1976 and any authigenic carbonate, chemosynthetic communities, and geochemical fluid compositions should be mature and well established. It may be an end member in some characteristics, and information from this site could be compared with well-sampled seafloor seeps in the KOD and SHU Planning Areas of the Alaska subduction zone (e.g. **Figure 24** and **Figure 29**) (Seuss et al. 1998; Levin and Mendoza 2007; Rathburn et al. 2008).

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