NATURAL OIL SEEPS IN THE ALASKAN MARINE ENVIRONMENT

by

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PREFACE

Given our limited understanding of how marine ecosystems function and the causes of their variability, the question of whether chronic low-level petroleum contamination poses a serious threat to life in the sea is particularly difficult to answer. The potential value of using natural petroleum seeps as "laboratories" to investigate some of the questions concerning impacts of chronic petroleum input to coastal areas has been recognized by the National Research Council (1985), based on the results of natural seep studies conducted in southern California.

Anticipating that petroleum seeps might provide future opportunities to address such questions in the Alaskan marine environment, the Outer Continental Shelf Environmental Assessment Program (OCSEAP) reviewed the literature on Alaskan petroleum seeps. The objective of this review was to synthesize all available information on: (1) the marine and coastal oil seeps in Alaska, with emphasis on the arctic, and (2) the effects of chronic oil pollution on arctic marine biotic communities and ecological processes.

The result of this review is the following report which hopefully provides a basis for the development of future studies involving Alaskan marine and coastal oil seeps.

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INTRODUCTION

A petroleum seep is defined as visible evidence at the earth's surface of the present or past leakage of oil, gas, or bitumens from the subsurface (Hunt, 1979). With the increase in the sophistication of instrumentation in subsurface exploration, the importance of surface seeps in oil and gas exploration has been de-emphasized. However, historically surface seeps have been very important in exploration. Hunt (1979) states that, "..many, if not most, of the important oil-producing regions of the world were detected or discovered through surface oil and gas seeps." This is certainly the case in Alaska, where the oil producing potentials of Katalla, Cook Inlet, and the North Slope were first proposed based on the presence of oil seeps.

Oil seeps have been reported from earliest recorded history, dating back to 3,000 BC in the Middle East (Owen, 1975). These reports have not been limited to terrestrial seeps. The oil and gas seeps present in the Dead Sea were responsible for the name the Remans gave to this body of water, "Mare Asphalticum" (Landes, 1973), which can be translated as "Sea of Pitch". Figure 1 in Landes (1973) is a photograph of a block of asphaltic material grounded on the west shore of the Dead Sea. This piece of weathered material originating as seepage has an estimated weight of 20 tons. Offshore seeps were discovered in the mid- to late 19th century during oil and gas explorations in the Red Sea, along the coast of New Zealand, and in the Caspian Sea (Owen, 1975).

Oil seeps in North America were reported as early as the late 18th Century. The best known offshore seeps in North America occur in the Santa Barbara Channel off California. These seeps and the associated tar on the beaches were first reported by the Spanish Franciscan priests in 1776, and additional description of surface oil in the Channel was provided by Vancouver in 1792 (Yerkes et al., 1969 as cited in Landes, 1973).

Hunt (1979) classifies seeps into three categories:

1. Active seeps, composed of gas, light oil, heavy oil, or mounds of sticky black asphalt.
2. Inactive seeps, generally asphaltites or pyrobitumens not connected to any liquid material.
3. False seeps, which appear to be hydrocarbon accumulations, but are actually stains of organic or inorganic origin. For example, accumulations

of manganese dioxide, metallic sulfides, or metallic oxides may be mistaken for oil seeps.

The substance most frequently mistaken in Alaska for oil seepage is the iron oxide film found on the surface of pools or sluggish streams in swampy areas or tidal flats, or found in association with iron-rich springs (Miller et al., 1955) . Oil films and gas derived from decaying vegetation and oily distillation products of burned coal beds can also be mistaken for petroleum (Martin, 1922) .

Documenting and describing land seeps were important in oil and gas exploration during the early years of the petroleum industry. This has resulted in fairly extensive characterization of many of these seeps. Data and information on land seeps is important in documenting and describing marine seepage. Natural seeps from both areas can be expected to behave in a similar manner and to be functions of the same geologic and geochemical parameters (Wilson, et al., 1973).

Wilson et al. (1973, 1974) have used information derived from land seeps plus the limited information on marine seeps to derive geologic criteria for evaluating the seepage potential of offshore areas and to derive an estimate of the amount of petroleum entering the marine environment via natural seepage. Their estimate was 0.6 X 10^6 metric tons per year, with a range estimate of 0.2 to 6.0 X 10^6 metric tons per year. Although it has been argued that this range could vary by at least an order of magnitude both below and above these limits, the estimates made by Wilson et al. (1973, 1974) still remain the best available (National Research Council, 1985) .

The relative importance of natural seeps to the input of petroleum into the marine environment has been discussed in numerous reports including Blumer (1971) , Landes (1973), Wilson, et al. (1973, 1974), National Academy of Sciences (1975), National Research Council (1985). The most recent estimates indicate that natural seepage represents less than 10 percent of the input into the world's oceans. The estimate of the National Academy of Sciences (1975), based on the work of Wilson, et al. (1973), was 9.8 percent. The revised estimate of the National Research Council (1985) is 0.02 - 2.0 X 10^6 metric tons per year, with a best estimate of 0.2 X 10^6 metric tons. This is based on an order of magnitude change in the upper and lower values of the range presented by Wilson, et al. (1973) and results in a value which is 6.25 percent of the total input of petroleum into the marine environment.

Offshore and onshore seepage frequency data are strongly correlated with areas of current tectonic activity and structuring (Wilson et al. (1973) . Margins of basins and sediments that have been folded, faulted, and eroded are areas that are conducive for seepage. Link (1952) categorized seeps into five types based on their origins:

1. Seeps arising from the ends of homoclinal beds exposed at the earth's surface (Figure la) . This type is usually small in volume, but persistently active.

2. Seeps associated with the beds and formations in which the oil was formed (Figure lb) . An example would be asphaltic oil generated by shales feeding into fissures and into sand interbedded with shales (Green River Formation of Utah) .

3. Seeps from large petroleum accumulations that have been uncovered by erosion or the reservoirs ruptured by faulting and folding (Figure 1.c). Seepages originating from the erosion of reservoirs on anticlines are quite common and indicate good prospects for finding oil in nearby anticlines where the same formations have not been eroded. The seeps on the Alaskan North Slope and along the shoreline of the Gulf of Alaska appear to be of this type.

4. Seeps at the outcrops of unconformities (Figure 1.d). An example is the Athabasca oil sands which represents the largest known seep of this type (Hunt, 1979).

5. Seeps associated with intrusions such as mud volcanoes, igneous intrusions, and piercement salt domes (Figure 1.e). Seeps of this type are quite common in Mexico and on the U.S. Gulf Coast.

Petroleum leaking to the earth's surface undergoes a series of weathering processes, regardless of whether it issues from a terrestrial or a submarine seep. There is a loss of volatile and light hydrocarbons up through C_{15} in the earlier stages and continued loss of hydrocarbons up through C_{24} after several months (Hunt, 1970). Water soluble elements and compounds, such as nitrogen, sulfur, and low molecular weight aromatics are leached out in the groundwater. Microbial degradation begins in the groundwater, leading to the oxidation of n-alkanes, isoalkanes and napthalenes. As water, carbon dioxide or hydrogen are eliminated from the seepage, polymerization of intermediate molecules occurs. Sediments are incorporated in submarine seepages. In the presence of sunlight and oxygen, polymers are oxidized and a rigid surface forms on the oil. These processes result in the formation of asphaltic mounds in both submarine and terrestrial seepages.

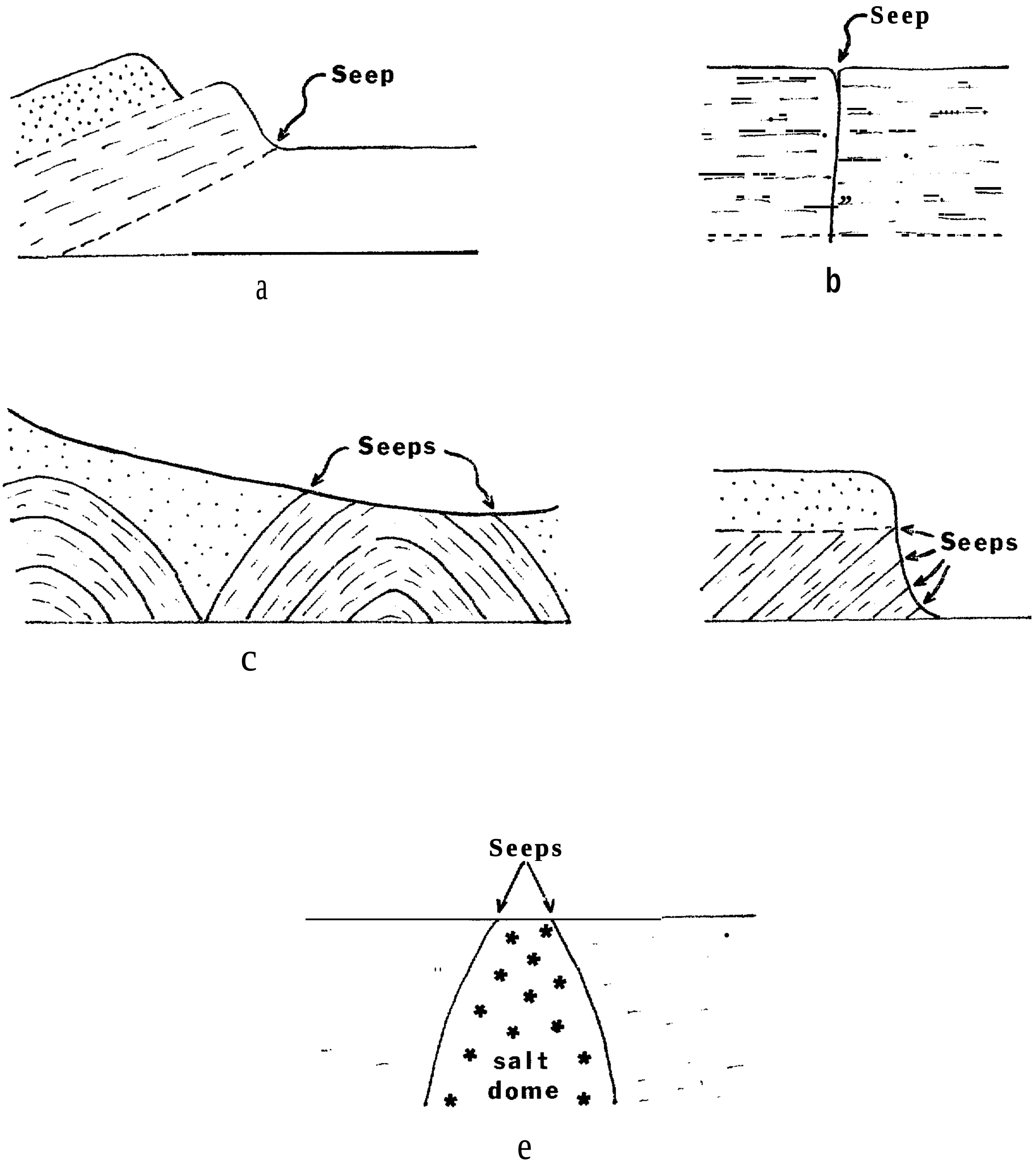

Figure 1. Types of Oil Seeps. Based on the classification of Link (1952).

Enlargement of these mounds depends on a continual supply of fresh oil being released to the surface of the seep.

Although many of the world's oil seeps have histories that go back several centuries, many seeps are intermittent and the volume of released oil 'may vary over time. Seepage can increase, decrease, or stop entirely in response to seismic activity (Rosenburg, 1974). The tapping of the oil source by industrial drilling and production can decrease or stop seep activity. Both industrial and seismic activity may play major roles in the pattern of oil and gas seepage in Alaska.

Wilson et al. (1973, 1974) classified the continental margins of the world into potentially high, medium, and low seepages assuming the following:

1. More seeps exist in offshore basins than have been observed.

2. Factors that determine the total seepage in an area are related to the general geologic structural type of the area and to the stage of sedimentary basin evolution.

3. Within each structural type, seepage depends primarily on the area of exposed rock and not rock volume. This assumption presumes that there is sufficient sediment volume and organic matter for maturation and generation of petroleum.

4. Most marine seeps are clustered within the continental margins where the thickness of sediments exceeds a certain minimum.

5. Seepage rates are lognormally distributed (based on the distribution of known oil field volumes). There are many seeps with low flow rates but only a few with high individual rates; however, the latter probably provide much of the total seepage. The National Research Council (1985) point out that seepage rates might be exponentially distributed, since they probably reflect volumes of all oil accumulations and not just oil field volumes, which are lognormal in distribution.

Using tectonic history, earthquake activity and sediment thickness in their analysis, Wilson et al. (1973, 1974) identified continental areas of high, medium, and low seepage potential based on the following geological criteria:

1. High potential for seepage is characterized by strike-slip faulting associated with high

incidence of earthquakes, tight compressive folding associated with high incidence of earthquakes, igneous activity, and thick geochemically mature Tertiary sediments.

2. Moderate potential for seepage is characterized by strike-slip faulting associated with low incidence of earthquakes, trench associated margins with high incidence of deep earthquakes, early active phase of pull-apart margins, growth faulting associated with giant, river-fed submarine fans, and diapiric or intrusive structures (shale, salt, or igneous rocks).

3. Low potential for seepage is characterized by pull-apart margins, little indication of recent structuring, little or no earthquake activity, and older sediments or geochemically immature young sediments.

The continental margin of greatest petroleum seepage appears to be the circum-Pacific. Wilson, et al. (1973, 1974) estimated that 40 percent of the world's total seepage input to the marine environment originated from this area. Based on the geological criteria presented above, Alaska's continental margins have been classified by Wilson, et al. (1973, 1974) as:

1. High potential- Gulf of Alaska

2. Medium potential- Arctic, northern Bering Sea, Aleutian Chain, and Cook Inlet

3. Low potential- southern Bering Sea

Figure 2 shows the distribution of known coastal seeps in Alaska as related to the classification of Wilson et al. (1973, 1974). The high potential for the Gulf of Alaska is well reflected in the large numbers of seeps that have been identified along the coastline of the central part of this region.

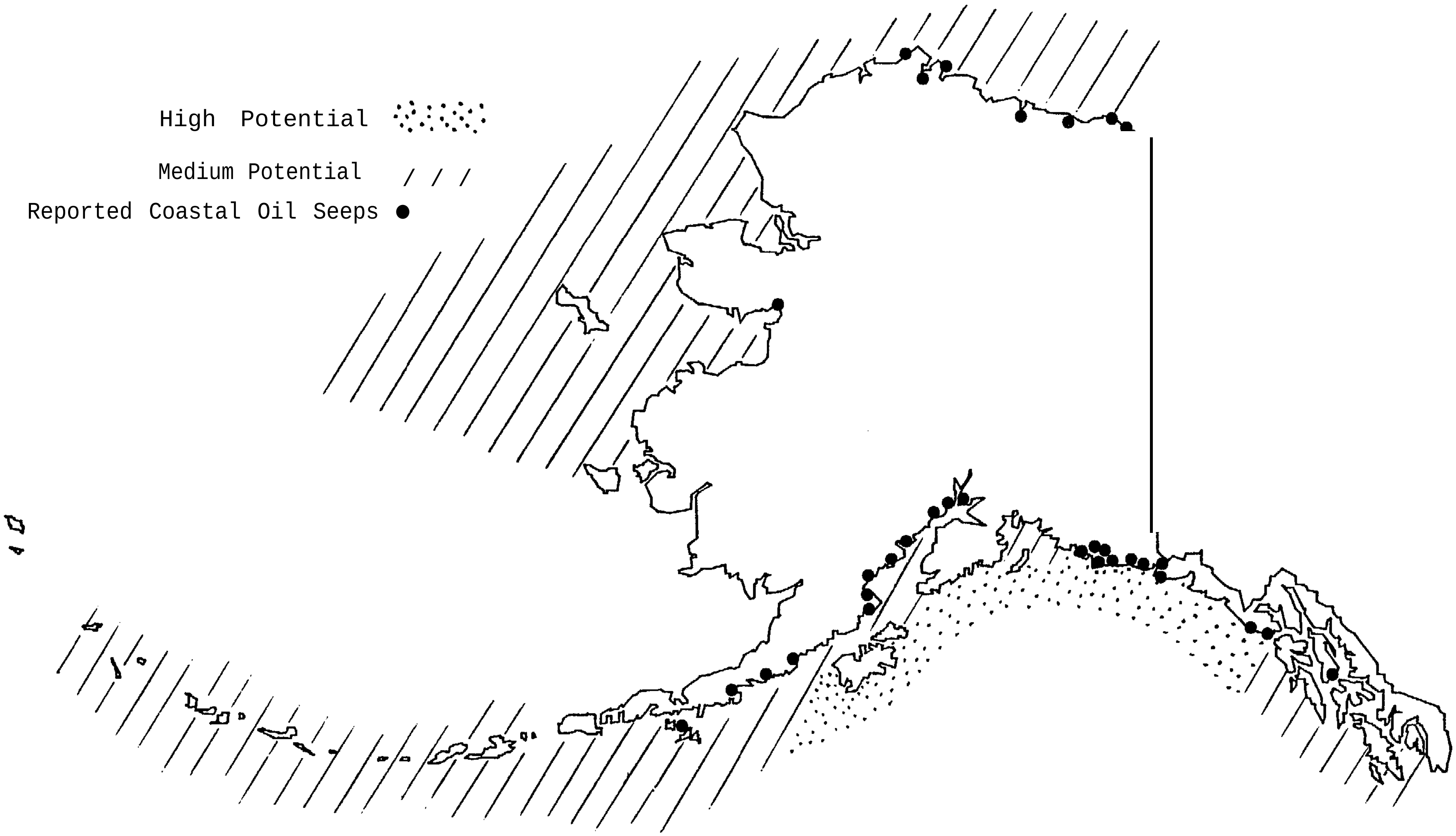

Figure 2. Seepage Potential of the Alaskan OCS. Based on Wilson et al. (1973, 1974) and reported coastal seeps presented in Table 1.

ALASKAN OIL SEEPS

Locations of Coastal Oil Seeps

Based on available information, 29 oil seepage areas have been identified to occur within the coastal regions of Alaska (Figure 3). "Oil seepage area" in this report refers to a geographic area that contains a single seep or any number of seeps that are in proximity to each other and that appear to derive their oil from the same source and through the same mechanism of seepage. Of these 29 areas, 14 are confirmed as containing actual oil seeps and 15 are unconfirmed reports; all of the latter are located in the Gulf of Alaska. None of the confirmed seeps are subtidal, but range in distribution from just above the low tide datum on a beach face, to inland sites that could influence the marine environment through input via freshwater streams. Each of the 29 oil seepage areas are identified by name in Table 1. This table also includes references which either identify the locations of such sites or provide site descriptions, characterizations of oils, etc. The numbers identifying each seepage area in Figure 3 and Table 1 are used throughout this report in reference to specific seeps.

History of Petroleum Seep Studies in Alaska

Since documenting and describing petroleum seeps have been historically important in oil and gas exploration, the study of seeps in Alaska began at the turn of this century primarily through the efforts of the U.S. Geological Survey and the U.S. Bureau of Mines. USGS exploration was started in northern Alaska in 1901 as part of a systematic scientific exploration of the Territory (Miller et al. 1959) . The U.S. Bureau of Mines has been involved in petroleum source evaluation in Alaska since the early 1920's (Blasko, 1975). The emphasis of these agency efforts was to map the geological structures in areas containing indications of the presence of petroleum (seeps and outcrops of oil shale) . Using this geological information, plus physical and chemical characteristics of the petroleum traces, suitable areas for test drilling were identified.

Most of the early discoveries of both coastal and inland oil seeps in Alaska were based on information provided to explorers by local natives. Probably many of these sites had been known for centuries by the local inhabitants, and in some cases native names for geographical locations incorporate characteristics resulting from these seeps. For example, the Inuit name for Griffin Point (Ugsrugtalik) may be translated as, "the place where there is oil on top of the ground" (Jacobson and Wentworth, 1982) and Ungoon

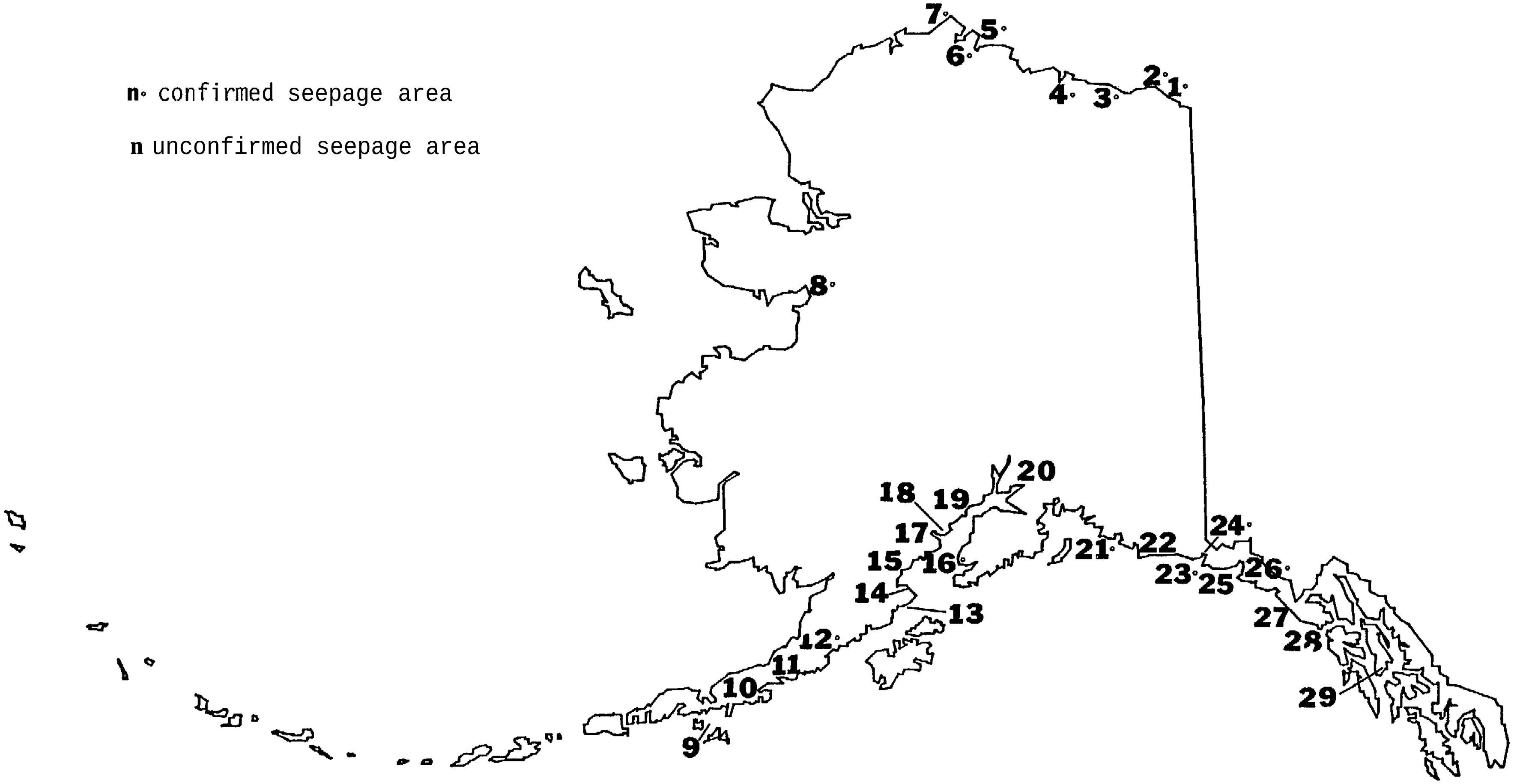

Figure 3. Locations of Alaskan Coastal Oil Seepage Areas

Table 1. Alaskan Coastal Oil Seepages

Site No. & Name	References
1. Angun (Ungoon) Point	Leffingwell (1919)
	Page, et al. (1925)
	Bureau of Mines (1944)
	Miller, et al. (1959)
	Hanna (1963)
	Ball Associates (1965)
	Grantz, et al. (1976)
	Grantz, et al. (1980)
	Magoon & Claypool (1981)
	Alaska Clean Seas (1983)
	Bader (1984)
	Anders and Magoon (1985)
2. Manning Point, Barter Island	Bureau of Mines (1944)
	Miller, et al. (1959)
	Hanna (1963)
	Ball Associates (1965)
	Johnson (1971)
	Grantz, et al. (1976)
	Grantz, et al. (1980)
	Magoon & Claypool (1981)
	Alaska Clean Seas (1983)
	Bader (1984)
	Anders and Magoon (1985)
3. Mouth of Canning R.	Grantz, et al. (1976)
	Grantz, et al. (1980)
4. Oil Lake, Colville River	Grantz, et al. (1976)
	Grantz, et al. (1980)
5. Cape Simpson	Brooks (1909)
	Leffingwell (1919)
	Page, et al. (1925)
	Bureau of Mines (1944)
	Miller, et al. (1959)
	Hanna (1963)
	Ball Associates (1965)
	Johnson (1971)
	Barsdate, et al. (1972)
	McCown, et al. (1972)
	Grantz, et al. (1976)
	Grantz, et al. (1980)
	Magoon & Claypool (1981)
	Alaska Clean Seas (1983)

Table 1. (continued)

Site No. & Name		References
6.	Dease Inlet	Bureau of Mines (1944) Miller, et al. (1959) Hanna (1963) Ball Associates (1965) Johnson (1971) Grantz, et al. (1976) Grantz, et al. (1980) Alaska Clean Seas (1983)
7.	Skull Cliff, Chukchi Sea	Webber (1947) Miller, et al. (1959) Johnson (1971) Grantz, et al. (1976) Grantz, et al. (1980) Magoon & Claypool (1981)
8.	Inglutalik River, Norton Sound	Johnson (1971) Miller et al. (1959)
9.	Andronica Island, Alaska Peninsula (unconfirmed)	Martin (1921) Keller and Cass (1956) Johnson (1971) McGee (1972)
10.	Chignik Bay (unconfirmed)	McGee (1972) Miller, et al. (1959)
11.	Aniakchak Area (unconfirmed)	Martin (1921) Smith and Baker (1924) Miller, et al. (1959) McGee (1972)
12.	Puale Bay (Cold Bay[1], Wide Bay, Oil Creek)	Martin (1905) Martin (1921) Capps (1922) Smith (1926) Miller, et al. (1959) Johnson (1971) McGee (1972) Blasko (1976a) Blasko (1976b) Blasko (1976d)

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[1] Early references to Puale Bay refer to it as "Cold Bay" (Martin, 1905; Martin, 1921; Capps, 1922; Smith, 1926; Miller et al., 1959).

Table 1. (continued)

Site No. & Name	References
13. Shelikof Strait (unconfirmed)	Miller, et al. (1959) McGee (1972)
14. Douglas R. (unconfirmed)	Martin (1905) Miller, et al. (1959)
15. Bruin Bay (unconfirmed)	Martin (1905) Martin (1921) Mather (1925) Miller, et al. (1959) Johnson (1971) McGee (1972)
16. Iniskin Peninsula (Oil Bay)	Martin (1905) Martin (1908) Moffit (1922) Johnson (1971) McGee (1972) Blasko (1976a) Blasko (1976d)
17. Iniskin Bay (unconfirmed)	Moffit (1922) Miller, et al. (1959)
18. Chinitna Bay (unconfirmed)	Moffit (1922) Miller, et al. (1959)
19. Tyonek and Mouth of Little Suisitna River (unconfirmed)	Martin (1921) Miller, et al. (1959) McGee (1972)
20. Anchorage near Knik Arm (no longer active?)	Brooks (1922)
21. Katalla, Controller Bay	Martin (1905) Martin (1908) Miller (1951) Miller, et al. (1959) Johnson (1971) Reimnitz (1970 as cited in Johnson, 1971) McGee (1972) Rosenberg (1974) Blasko (1976c)

Table 1. (continued)

Site No. & Name	References
22. Katalla Area East, Cape Suckling (unconfirmed)	Martin (1908) Miller, et al. (1959) McGee (1972)
23. Yakataga	Martin (1908) Miller, et al. (1959) Palmer (1971) McGee (1972) Rosenberg (1974) Blasko (1976c)
24. Samovar Hills, Malaspina Glacier	Miller, et al. (1959) Johnson (1971) Palmer (1971) McGee (1972) Rosenberg (1974) Blasko (1976c)
25. East Shore of Icy Bay (unconfirmed)	Miller, et al. (1959) McGee (1972)
26. Yakutat	Miller, et al. (1959) Ball & Associates (1965) McGee (1972) Rosenberg (1974)
27. Lituya Bay (unconfirmed)	Miller, et al. (1959) McGee (1972)
28. Cape Spencer (unconfirmed)	Martin (1921) Miller, et al. (1959) McGee (1972)
29. Admiralty Island (unconfirmed)	Martin (1921) Miller, et al. (1959) McGee (1972)

(Angun) Point has been translated to mean, "pitch" point (Bureau of Mines, 1944).

The reports of early surveyors also indicated that some of these seeps were mined for their oil soaked peat by the natives for use as fuel. The seeps on the east shore of Dease Inlet and at Angun Point were reported by Ebbley and Joesting (Bureau of Mines, 1944) to be used by the natives for this purpose.

Oil seeps on the Iniskin Peninsula, west shore of Cook Inlet, were supposedly known to the Russians in 1853 (Martin, 1905). This was probably through the 1850 geological survey of the Cook Inlet area by the Russian mining engineer, Petr Doroshin. The seeps in the Katalla and Yakataga districts, Gulf of Alaska, and Kanatak district (Puale Bay/Cold Bay) were documented by explorers and prospectors in the mid-1890's; those on the Chukchi and Beaufort Sea coasts were probably first documented by non-native explorers at the beginning of the 20th century.

The oil seeps on the Iniskin Peninsula of Cook Inlet resulted in the staking of claims in 1892, a restaking in 1896, and drilling for oil at Oil Bay in 1898 (Martin, 1905). Claims were staked and drilling began at the Katalla-Controller Bay seeps in 1901, and at Puale Bay in 1902. The drilling on the Iniskin Peninsula and Puale Bay was abandoned about 1904, but periodic test drilling continued in both areas through the 1950's.

Drilling continued sporadically at Katalla during the first decade of the 20th century, but was halted during 1910-1920 when the U.S. government withdrew all federal lands from oil and gas leasing. Exploration and development activities at Katalla eventually resulted in the only commercial petroleum production in Alaska (1920 through 1933) up to 1955.

Active exploration began again during the 19201s after the passage of the Oil and Gas Leasing Act of February 25, 1920. In anticipation of this increased activity, the USGS produced a summary of information on petroleum resources and likely areas of petroleum resources in Alaska (Martin, 1921). The location and characteristics of petroleum seepages played a prominent part in this report.

The earliest report of oil seepage in the North American Arctic was by Thomas Simpson of Hudson's Bay Company. During his coastal survey of 1836-37, he reported oil deposits along the Canadian Arctic shore (Hunt, 1970).

The earliest report on the petroleum potential of the Alaskan North Slope was from the year, 1886. Ensign W.L. Howard, a member of the U.S. Navy's exploration expedition headed by Lt. George M. Stoney, explored the head of the

Colville River during the winter of 1886 and brought back a specimen initially believed to have been petroleum residuum (Paige et al. 1925). This sample was later found to be oil shale (Smith and Mertie (1930), which is common along the north front of the Brooks Range.

The first recording of true petroleum seepage on the Alaskan North Slope was by E. deK. Leffingwell as a result of his 1906-1914 explorations. Although he did not personally visit the site, Leffingwell reported the presence of petroleum seeps near the Arctic Coast, 50 miles southeast of Point Barrow, on Dease Inlet (the Cape Simpson Seeps) (Brooks, 1909; Leffingwell, 1919). He obtained a sample of this seepage from C.D. Brewer of Point Barrow which analysis indicated was a petroleum residue. These seeps were visited by A.M. Smith in 1917, whose oral description led to geologists from Standard Oil of California and General Petroleum inspecting and mapping the area in 1921 (Paige et al. 1925; Miller et al., 1959; Hunt, 1970).

Another seep was reported by the natives to Leffingwell as being on the Beaufort Sea coast about 300 miles farther east, or about 35 miles west of the Alaska-Yukon boundary between Humphrey Point and Aichillik River (Leffingwell, 1919) . This was probably the seepage at Angun Point, which has a history of being mined by the Natives for its asphalt.

At about the same time that Leffingwell was being briefed on the presence of the oil seeps at Cape Simpson and Angun Point, William Vanvalin, a teacher with the U.S. Bureau of Education, explored oil seeps on the eastern shore of Smith Bay reported to him by Natives at Wainwright (Hunt, 1970) . He reportedly discovered two springs of oil flowing into a lake 400 by 200 feet in dimension located about one mile from the shore of the Beaufort Sea. Vanvalin staked claim to this deposit, naming it the "Arctic Rim Mineral Oil Claim." The claim was never developed and no additional information was found by the authors relative to this seep.

The major driving force behind the exploration and geological mapping of the western Alaska North Slope during the 1920's was the establishment of the Naval Petroleum Reserve (Pet-4), which encompassed about 37,000 square miles. The establishment of this reserve was part of a national security policy of providing adequate supplies of oil to the U.S. Navy. Pet-4 was established on February 27, 1923, by Executive order of President Warren G. Harding. The selection of this particular area for the reserve was partially due to evidence of the presence of a large oil field here. This evidence consisted of the presence of petroleum seeps coupled with what was known concerning the geology. In fact, oil seeps are actually mentioned in the Executive order (Paige, et al., 1923):

> “Whereas there are large seepages of petroleum along the Arctic coast of Alaska and conditions favorable to the occurrence of valuable petroleum fields on the Arctic coast; ....”

During the period 1923-26, geological surveys of the Pet-4 were conducted by the USGS at the request of the Department of Navy. The results were published in a series of reports, including those of Paige, et al. (1925) and Smith and Mertie (1930) .

In the 1923 USGS expedition to the Pet-4, two oil seeps at Cape Simpson were surveyed. One sample was taken from a surface seepage (weathered oil) and analyzed by the Bureau of Mines. In their report, Paige, et al. (1925) provided maps of the seep locations, photographs of the seeps, plus results of chemical analysis of oil collected from one of the seeps. Page, et al. (1925) also mentioned in their report another oil seep reported by natives, 300 miles east of Point Barrow, near the international boundary. This was probably the same seep reported by Leffingwell. Although Barter Island is a possibility, this was probably the seepage area at Angun Point.

Little additional attention was given to the Alaska North Slope until World War II. In 1943, the Bureau of Mines again examined the Cape Simpson area and continued to search for reported seeps. The results of this exploration were published in Bureau of Mines War Minerals Report 258 (1944). The following additional seeps were described: Umiat Mountain, Fish Creek, Dease Inlet, Manning Point and Angun Point. The latter three seep locations are coastal.

The Navy Department resumed its program of exploration of Pet-4 in 1944 as part of the wartime effort. The USGS resumed its mapping program in northern Alaska and in 1945, at the request of the Navy, it carried out the geologic phases of the Pet-4 exploration (Miller et al. 1959). As part of this effort, two gas seeps (on the upper Meade River and on the Colville River) and the oil seep at Skull Cliff were discovered. The Skull Cliff seepage, which occurs on the Chukchi Sea just north of Peard Bay, was described in a report by Webber (1947) .

Similar to the situation in the Gulf of Alaska, the first test wells on the North Slope were drilled near oil seeps: Cape Simpson (coastal) and Umiat (inland up the Colville River) . The test drillings began in 1945 and continued throughout promising locations in the Pet-4 until 1951. The Umiat oil field was discovered in 1950. The oil reserves at Cape Simpson were found to be small (2.5 million barrels), while the test well at the Fish Creek oil seep (1949) found heavy oil with an asphalt base (Miller et al. 1959). A result of this exploration was the discovery of the small oil and gas fields of Umiat, Cape Simpson, and South Barrow. Exploration of the area between the Pet-4 and the William O. Douglas Arctic Wildlife Range (now known as the Arctic National Wildlife Refuge) was stimulated, in part, by the presence of seepages reported at Kuparuk. This exploration resulted in the 1968 discovery of the Prudhoe Bay oil field.

Additional exploration of Pet-4 was conducted by the Navy during 1974-1977. In 1977, jurisdiction of Pet-4 was reassigned to the Department of Interior and the reserve was renamed the National Petroleum Reserve in Alaska (NPRA) .

The Alaskan North Slope continues to be surveyed and explored for oil and gas deposits. In addition, known oil and gas fields are being delimited. The chemical characterization of oils from test wells, producing wells, and surface seeps for oil/source-rock correlation analyses has been an important part of this exploration and study (Magoon and Claypool, 1981; Anders and Magoon, 1985; Magoon and Claypool, 1985) .

Oil/rock correlation analyses involve the evaluation of source rock for organic matter richness, kerogen type and thermal history and analysis of the oil type to determine:

- API gravity
- carbon isotope ratios
- sulfur and nitrogen content
- relative amounts of odd- and even-numbered n-alkanes
- pristane/phytane ratios
- relative amounts of sulfur and nitrogen isotopes

From a geochemical standpoint the oils from some of the North Slope coastal oil seeps have been relatively well characterized. Surface seepage and more than 25 separate oil-and-gas accumulations have been discovered on the North Slope (Magoon and Bird, 1985) . Analyses of many, but not all, of these seepages and accumulations show that there are several distinguishable types of oil present,

Oil/rock correlation analyses indicate that the oil types of the various coastal seepages are chemically different from and appear to have different sources than the Prudhoe Bay oil (Anders and Magoon,1985; Curiale, 1985; Magoon and Claypool, 1981; Magoon and Claypool, 1985b; Magoon and Anders, 1987) . Prudhoe Bay crude oil originates from the Kingak Shale/Shublik Formation (Figure 4) and is characterized as an isotonically light oil relatively high in vanadium, nickel, sulfur, and tricyclic terpanes (Curiale, 1985). The other oil types are:

> Angun Point Seep, Jago Oil Type- probably originates from type II organic-rich facies of the Cretaceus Hue Shale (Figure 4) based on similarities in carbon

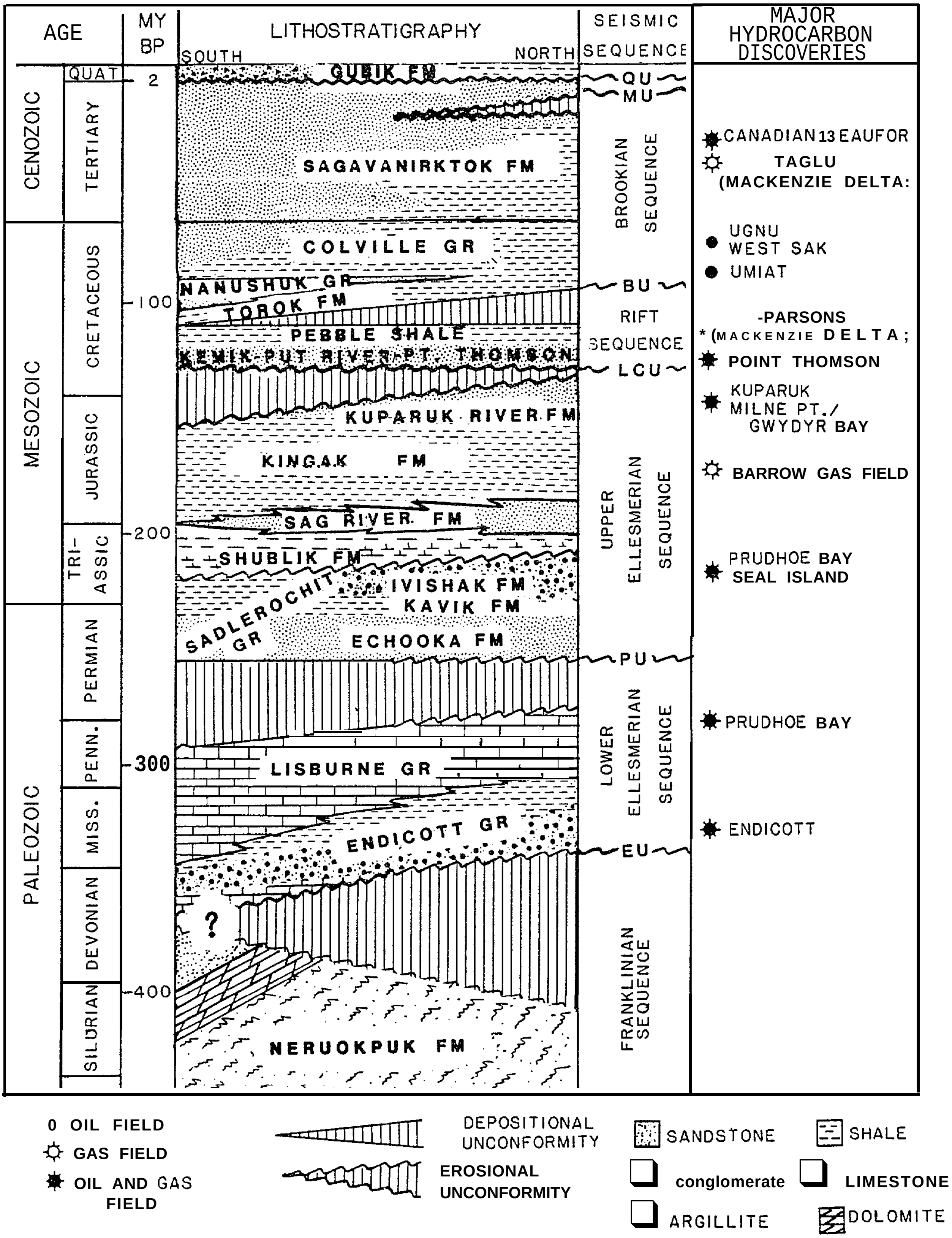


Figure 4. Generalized Lithostratigraphic Column of the Alaskan North Slope (Craig et al. , 1985).

isotope values of the saturate and aromatic hydrocarbon fractions and their C_{19}/C_{23} tricyclic terpane ratios (Anders and Magoon, 1985). It is a high gravity, low sulfur oil, with no or slightly odd-numbered n-alkane predominance. The pristane/phytane ration is greater than 1.5 (Magoon and Claypool (1981).

Manning Point Seep, Manning Oil Type- of unknown source (Anders and Magoon, 1985). This is a high gravity, low sulfur oil, with no or slightly odd-numbered n-alkane predominance. The pristane/phytane ration is greater than 1.5 (Magoon and Claypool (1981).

Cape Simpson and Skull Cliff Seeps, Simpson-Umiat Oil - - appears to be associated with the "pebble-shale"/Torok Formation (Figure 4) (Magoon and Claypool, 1985b). This is a high gravity, low sulfur oil, with no or slightly odd-numbered n-alkane predominance. It is also characterized as being low in vanadium and nickel (Curiale, 1985). The pristane/phytane ratio is greater than 1.5 (Magoon and Claypool, 1981).

Studies of oil seeps in the Alaskan Arctic, beyond geochemical characterization for delimitating petroleum bearing formations, began during the early development of the Trans Alaska Pipeline. Concern for the possible impacts on the tundra biological communities of oil spilled from the proposed pipeline led to a series of ecological studies, some of which used inland and coastal seeps as part of the experimental procedures (Agosti and Agosti,1972; Barsdate et al., 1972; McCown et al., 1972; Zobell and Agosti, 1972).

DESCRIPTIONS OF SELECTED ALASKAN COASTAL SEEPS

Those Alaskan coastal seepage areas that appear to be most closely associated with the marine environment and which have the most background information are described in this section. These descriptions include basic observations (from earliest explorers to present-day observers), maps of the locations, geological sources, chemical characteristics of the oil, and any other pertinent information. Although emphasis is being placed on those seeps located in the Arctic, well known areas in the Gulf of Alaska will also be included in these descriptions. The seeps included are:

Arctic-

Site No. 1,	Angun Point
Site No. 2,	Manning Point
Site No. 5,	Cape Simpson
Site No. 7,	Skull Cliff

Gulf of Alaska -

Site No. 12,	Puale Bay
Site No. 16,	Iniskin Peninsula
Site No. 21,	Katalla
Site No. 23,	Yakataga

A short list of other coastal oil seeps reported in Alaska will also be included at the end of this section.

Angun (Ungoon) Point

This seepage area consists of at least two oil seeps located on the coastal point at the Nuvagapak Entrance to Beaufort Lagoon (Figure 5) (Alaska Clean Seas, 1983). The exposed point is located on scarps 5-10 ft above the narrow beaches. To the east of this point, the exposed beaches consist of gravel and sand, while to the south they are composed of sand-silt (less-exposed) . Based on measurements conducted over a period of 20 years, Hopkins and Hartz (1978) estimated the coastal erosion rate of the area to be 1.5 m/yr.

These seeps were probably reported to explorers by natives at a very early date. Both Leffingwell (1919) and Page, et al. (1925) reported secondhand information on coastal seeps in this general location. The seeps are specifically indicated on maps in Grantz et al. (1976; 1980) , Map 76 of the Alaskan Beaufort Sea Coastal Resources Manual (Alaska Clean Seas, 1983), and USGS Open-File May 84-569 (Bader, 1984) .

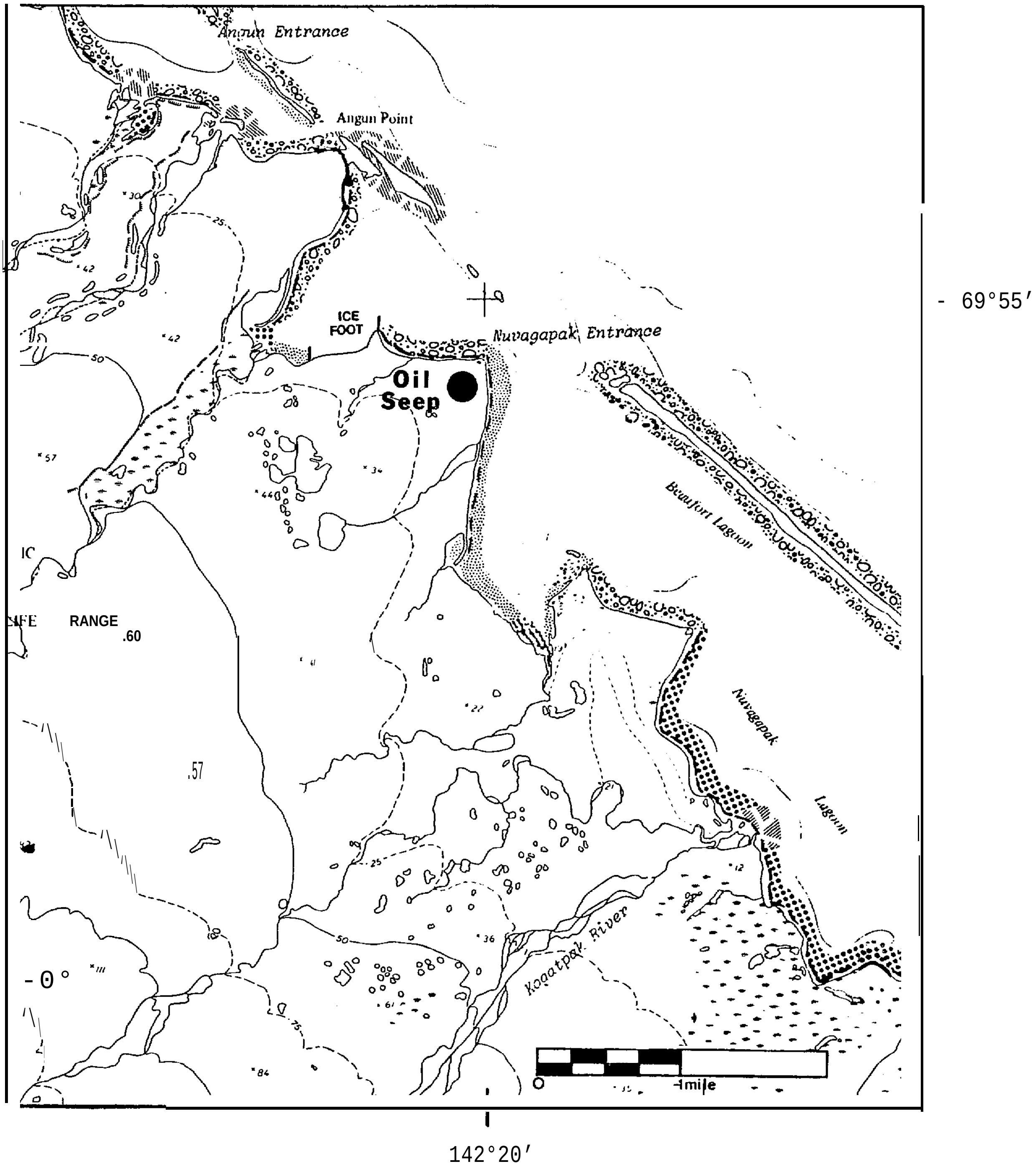


Figure 5 . Angun Point Oil Seepage Area (Alaska Clean Seas, 1983).

The Bureau of Mines (1944) first described this site:

> “Location is 7 miles east of Humphrey Point and about 40 miles west of Demarcation Point. "Ungoon" is the Eskimo term for pitch. Three evidences of petroleum seepages were found on Ungoon Point. The largest of these is mile and a quarter south from the sod house on the Point. The pitch is black and hard and is extremely difficult to dig. A small amount of mining has been carried out and the pitch has appeared in several small holes where the tundra has been removed. The general area is approximately 300 feet north and south and 100 feet east and west.”
>
> “Six hundred yards east and about 250 yards from the east beach a small pool has been excavated in the center of a small hummock. Sample No. 16 was taken from this material which has the same consistency as the larger exposure. On the east side of Ungoon Point and in line with the two seepages mentioned above, an exposure of oil bound sand four feet thick appears along the bank for a distance of about 30 feet. This deposit is located one and one half miles southeasterly from Ungoon Point proper.”

This description from the mid-40’s has been the basis for the Angun seep descriptions produced by Miller et al. (1959) , Hanna (1963) , and Ball Associates, Inc. (1965) .

Samples of this seepage were recently collected by the USGS for oil/source rock correlation analysis. Based on geochemical analysis of this oil, Anders and Magoon (1985) have designated this as Jago Oil Type. It probably originates from type II organic-rich facies of the Hue Shale (Figure 4) and has also been identified as occurring in oil-stained rocks from Katakturuk River and Jago River. Jago Oil Type is a high gravity, low sulfur oil, with no or slightly odd-numbered n-alkane predominance, and has a pristane/phytane ration greater than 1.5 (Magoon and Claypool, 1981).

The oil from the Angun seeps contain biodegraded hydrocarbons and no measurable amounts of n-alkanes or regular chain isoprenoids. The hydrocarbons are dominated by those with boiling points $>n\text{-}C_{20}$. Other characteristics of this oil are presented in Table 2.

Manning Point

This oil seepage is located at tidewater on Manning Point, which is a narrow strip of land lying between Kaktovik and Jago lagoons, 3 km southeast of Barter Island (Figure 6). Manning Point is protected by gravel barrier islands. Both

Table 2. Geochemical Characteristics of Oil from Alaskan Arctic Coastal Seepages. Data are from Magoon and Claypool (1981) and Anders and Magoon (1985).

VARIABLE	ANGUN POINT	MANNING POINT	CAPE SIMPSON #1	CAPE SIMPSON #2	CAPE SIMPSON #3	SKULL CLIFF
‘API Gravity[1]	Solid	26.7	20.2	----	18.8	18.4
‘/0. Sulfur[2]	0.22	0.14	0.34	0.08	0.32	0.32
‘/o. Nitrogen,	0.43	0.02	-----	0.03	0.05	
O/oo delta^{34}S	-10.59	- 4.91	-----	- 5.46	- 6.11	-10.3 - 4.9
°/oo delta^{15}N	1.13	2.75	-----	3.81	2.85	
o/oo delta^{13}C[3] (whole oil)	-28.71	-28.23	-----	-28.94	-29.09	-29.1
°/oo delta^{13}C (C_{15+} Sat. HC)	-29.21	-28.52	-----	-29.31	-27.8 -29.34	
°/oo delta^{13}C (C_{15+} Arom. HC)	-28.57	-27.84	-----	-28.19	-28.48	
Extraction data:						
% Non-HC	73.6	26.8				
% HC	24.4	73.2				
S/A[4]	2.9	5.2				
Biomarker data:						
(C_{19}/C_{23} tricyclic terpane)	0.6	2.1				
Hopane/C_{23} tricyclic terpane	?	15.7				

---

[1] Average for crude oil is 35” API; Prudhoe Bay crude oil is 26.1° API.

[2] Prudhoe Bay crude oil is 0.95% Sulfur.

[3] Prudhoe Bay crude oil is -29.83°/oo delta^{13}C.

[4] Saturate/aromatic hydrocarbon ratio

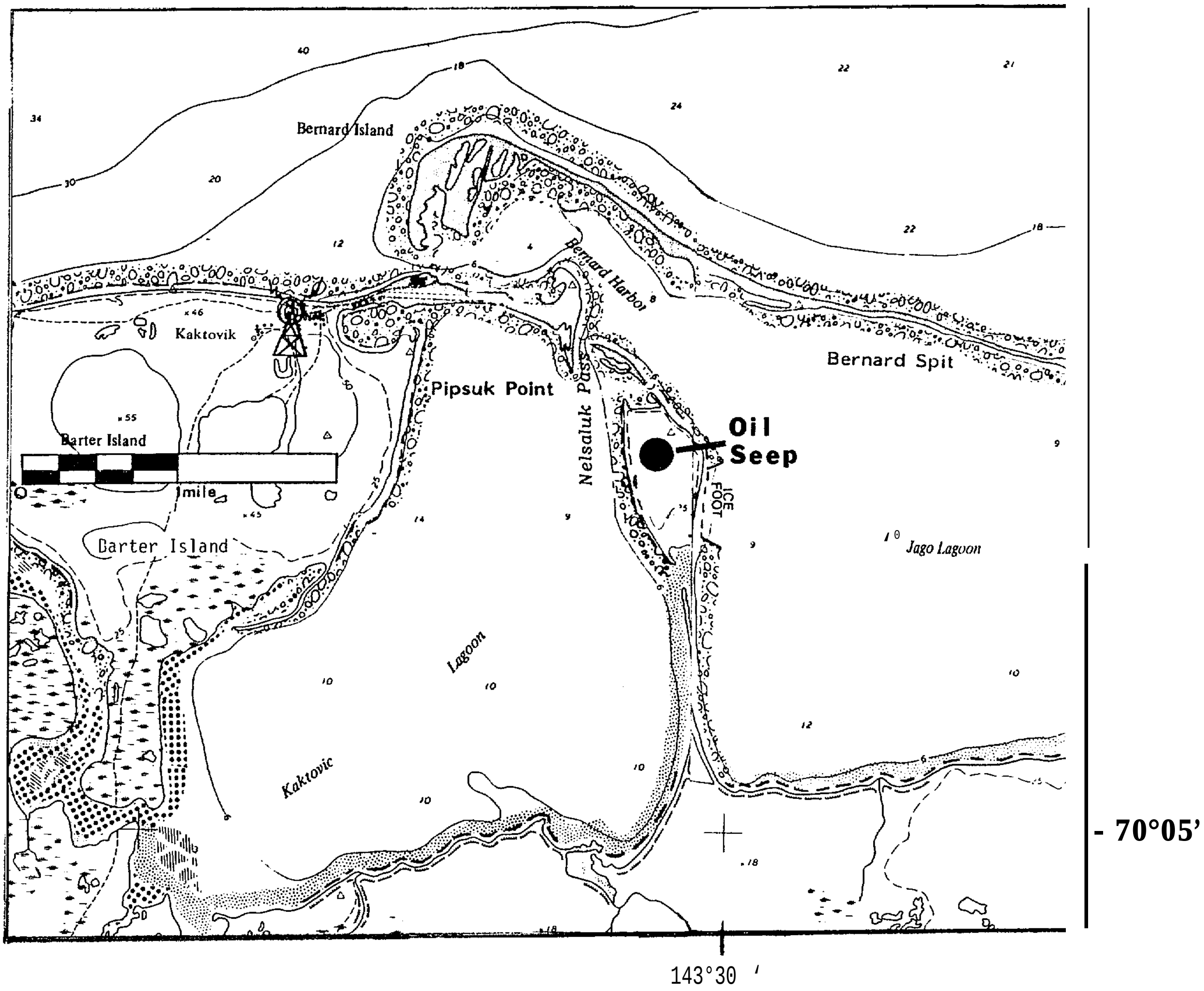


Figure 6 . Manning Point Oil Seepage Area (Alaska Clean Seas, 1983).

Kaktovik and Jago lagoons are relatively shallow, not exceeding 4 in in depth; tidal range is less than 20 cm (Johnson, 1971). The shoreline of Manning Point is steep, 3-4 m high, and consists primarily of coarse gravel (Alaska Clean Seas, 1985). The shoreline of Kaktovik Lagoon extending along the spit from the oil seepage to the mainland (about a mile in length) is composed of sand-silt.

The Manning Point seep is specifically indicated on maps in Grantz et al. (1976; 1980), on Map 71 of the Alaskan Beaufort Sea Coastal Resources Manual (Alaska Clean Seas, 1983), and on USGS Open-File Map 84-569 (Bader, 1984).

The Manning Point seep was first described by Ebbley and Joesting (Bureau of Mines 1944):

> "No actual pitch residue was noted; however, the northwest and northeast beaches which form the point are lined with oil froth for a mile and a half. A considerable portion of the beach particularly on the northwest side, consists of an oil bound silt and numerous boulders of soft oil bound reddish-brown sand were observed. Several trickles of water-carrying oil film cross the narrow beach. Oil soaked peat was noted at several places along the sloughed bank."

Samples were collected by Ebbley and Joesting from this seepage and their API gravity determined (Bureau of Mines, 1944):

17.3° API- Oil bound silt found in layers along the northwest beach

19.0° API- Sample skimmed from the several small streams of water flowing from the bank to the ocean

2.6° API- Exposures of an unconsolidated oil bound brownish-red sand which appeared in places along the bank

21.3° API- Oil soaked vegetable debris found along the bank throughout the entire mile and a half distance

The above information from Bureau of Mines (1944) is the basis for descriptions presented in Miller et al. (1959), Hanna (1963), Ball Associates, Ltd. (1965), and Johnson (1971).

Based on carbon isotope values of the saturate and aromatic hydrocarbon fractions, saturate/aromatic hydrocarbon ratios, C_{19}/C_{23} tricyclic terpane ratios, and hopane/C_{23} tricyclic terpane ratios, the oil from this seep has been designated as a separate oil type ("Manning Oil Type") sufficiently different geochemically to suggest a source that has not been evaluated as yet (Anders and Magoon, 1985) . Manning Oil Type is a high gravity, low sulfur oil, and has a pristane/phytane ratio greater than 1.5 (Magoon and Claypool, 1981) . The hydrocarbons are biodegraded, containing no measurable amounts of n-alkanes or regular chain isoprenoids; it is dominated by hydrocarbons with boiling points $<n\text{-}C_{20}$.

Other characteristics of this oil are presented in Table 2.

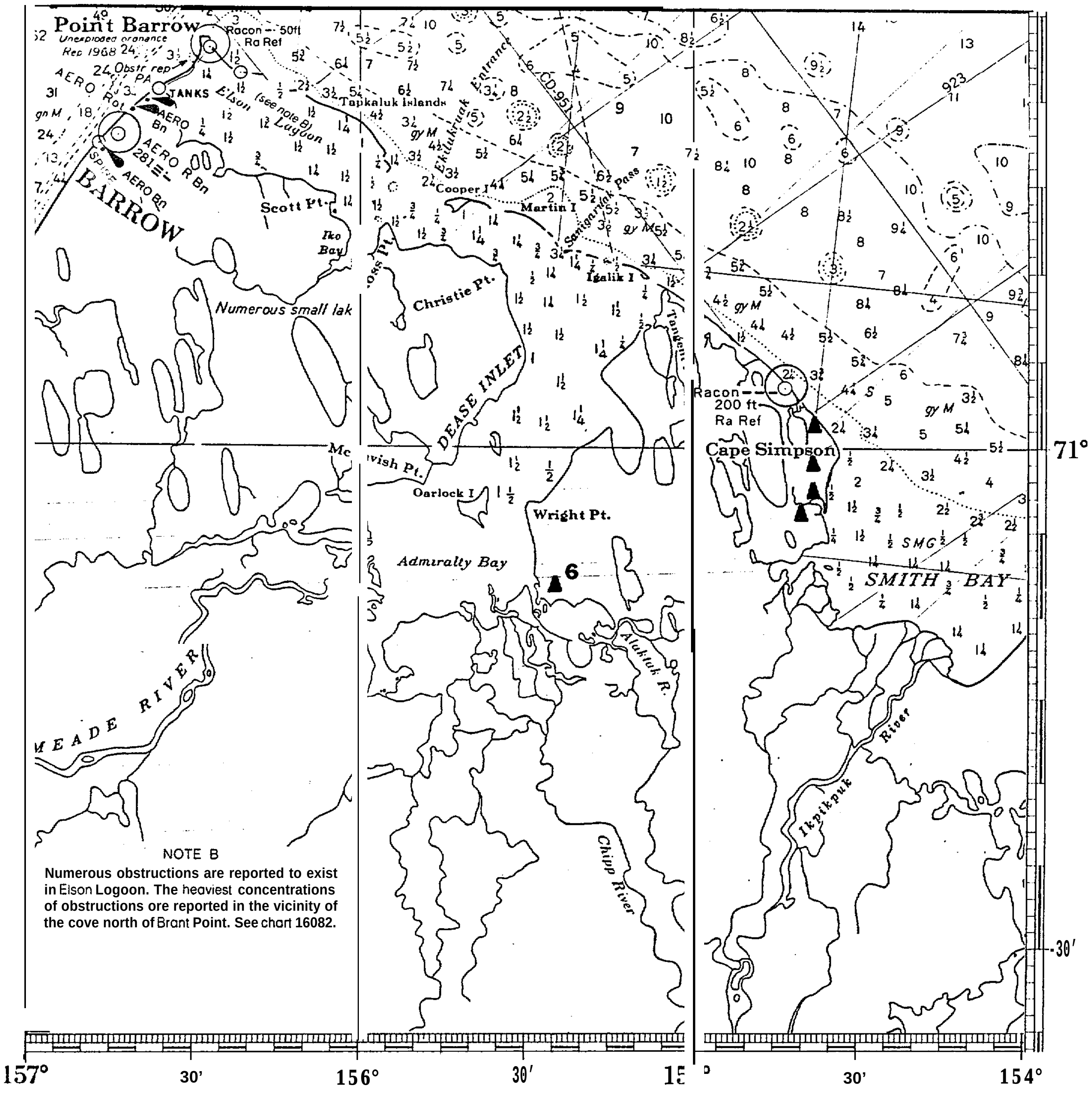
Cape Simpson

The best known oil seepage area on the North Slope of Alaska consists of those seeps located on the west shore of Smith Bay at Cape Simpson (Figure 7). Sylar (1987) mentions that this is one place where one can see oil bubbling from the ground in subzero weather. Eyewitness descriptions have been provided by Leffingwell (1919), Page et al. (1925), Bureau of Mines (1944), Hanna (1963), Agosti and Agosti (1972) , Barsdate et al. (1972) , and McCown et al. (1972) . The seepage area is specifically indicated on maps in Grantz et al. (1976; 1980) and on Map 17 of "Alaskan Beaufort Sea Coastal Resources Manual" (Alaska Clean Seas, 1983) .

The earliest description of this site is provided by Leffingwell (1919):

> "At Cape Simpson on the west side of Smith Bay, there are two conspicuous mounds. The writer has been informed by natives that the northern mound contained a petroleum residue, but , according to information furnished by Stefansson, this residue is contained in a pool a few hundred yards from the mound. A sample was secured from a keg of the material collected by natives in the employ of Mr. C.D. Brewer, of Barrow. It resembles axle grease. An analysis by David T. Day is given below. The deposit is near the seashore, and the natives say that a considerable amount could easily be dug out with spades."

"Water and soluble matter	22 %
Alcoholic extract (resins and some oil)	8 %
Naphtha extract:	
Light oil	12 %
Heavy oil	16 %
Benzol extract (asphaltic material)	11 %
Clay and vegetable fiber	29 %"



NOTE B
Numerous obstructions are reported to exist in Elson Logoon. The heaviest concentrations of obstructions ore reported in the vicinity of the cove north of Bront Point. See chort 16082.

Figure 7 . Cape Simpson Oil Seepage Area. Seeps - ▲

The earliest map showing the seepage mounds were published in Page, et al. (1925) (Figure 8). According to Page:

> "A low moss-covered ridge of irregular shape stretches for 2 miles along the Arctic Ocean, its southeast terminal about a mile north-west of Cape Simpson. Its highest point is about 50 feet above the sea . . . ..Seepage No. 1 occurs near the inland base of this ridge, a third of a mile from the ocean and 20 feet above tidewater, from which it is visible. Here in an irregular area several hundred feet in diameter the moss is soaked with petroleum which also slowly seeps from the gentle slope.
>
> Seepage No. 2 is on the southern top, 40 feet high, of a small double knob 3 miles almost due south of seepage No. 1 and 1 1/4 miles west of Smith Bay. Here the residue from the seepage covers several acres. . .
>
> The main petroleum flow moves southward down the slope for 600 or 700 feet to a lake; this active channel is 6 to 10 feet wide, though the area covered by residue is several hundred square feet and indicates that a considerable flow is coming from this seepage. The ridge at these two seepages is covered with moss and muck, and there are no surface indications that it is made up of hard rock. . ."

Analysis of samples collected from the seeps cited above resulted in the following:

API gravity-	18.6°
Sulphur-	0.36%
Water-	7.5%
Pourpoint-	< 5°F

Later descriptions are provided by Ebbley and Joesting (Bureau of Mines, 1944), Hanna (1963) and McCown et al. (1972) .

The area of seepage at Cape Simpson is located between Sinclair Lake and Smith Bay, and extends approximately 10 mi along the coast with Cape Simpson, itself, in the center of the eastern boundary (Figure 9). Shoreline erosion rates in the Beaufort Sea are quite high, the shoreline at Cape Simpson being the highest (Craig et al., 1985). Leffingwell (1919) reported that the rate of erosion was 30 m/yr at Cape Simpson. Based on measurements conducted over a period of 20 years, Hopkins and Hartz (1978) estimate the erosion rate at Cape Simpson to be 11.4 m/yr. Quite possibly, significant amounts of petroleum hydrocarbon may be entering the Beaufort Sea via coastal erosion in this seepage area.

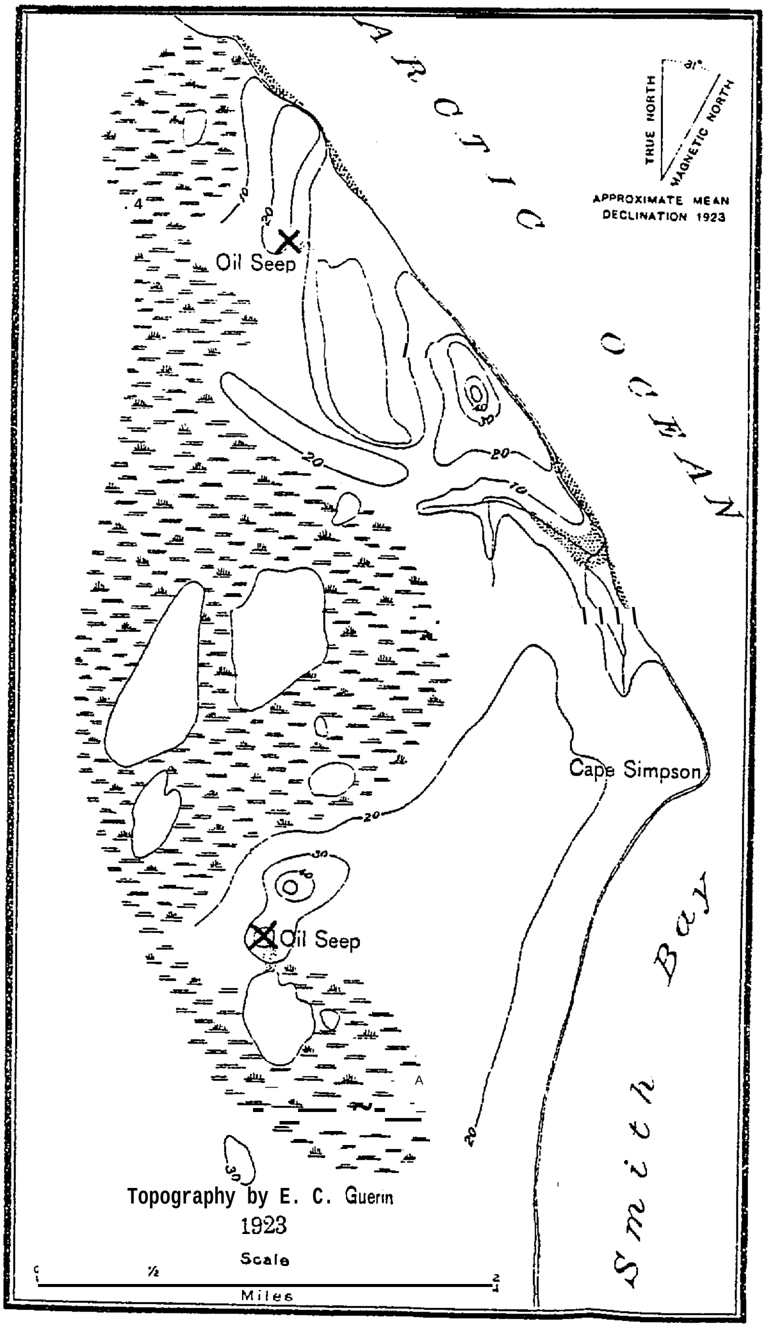


Figure 8 . Cape Simpson Oil Seeps from Page et al. (1925),

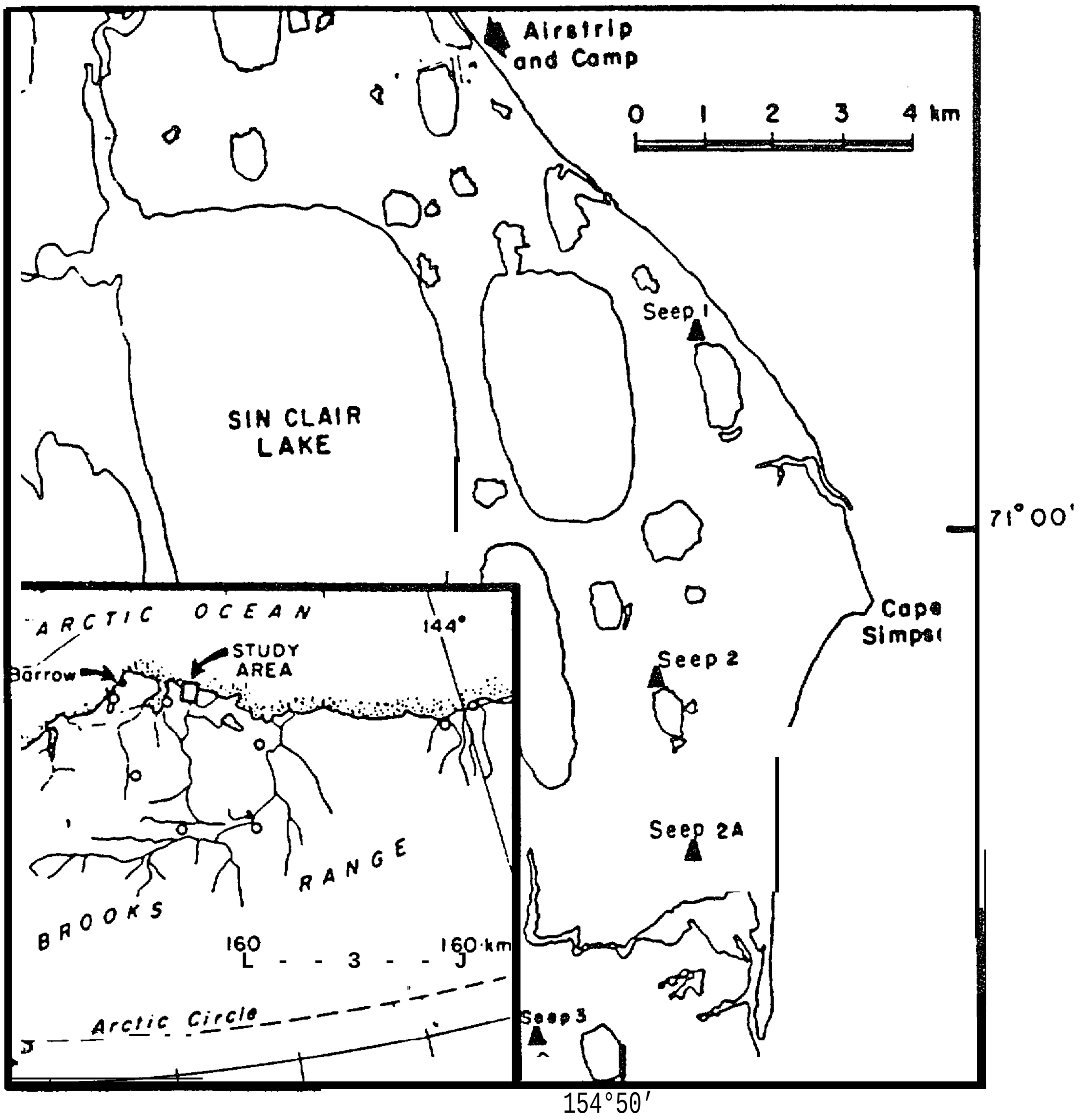


Figure 9. Cape Simpson Oil Seeps from McCown et al. (1972)

Although evidence of seepage is found throughout the area, four seeps are the best known and have been repeatedly referred to as seeps 1, 2, 2A, and 3 (Bureau of Mines, 1944; Hanna, 1963; Barsdate et al., 1972; McCown et al., 1972). Seep 1 is located about 3 mi northwest of Cape Simpson and 500 yds from the shore of Smith Bay. The beach here consists of high energy, narrow sand-gravel shores less than 20 ft wide and scarpes 2-6 ft in height (Alaska Clean Seas, 1985) .

Seep 2 is on a prominent hill 3.5 mi south of No. 1. It is about 1.25 mi west of the Bay. The viscous oil flows down hill and eventually reaches a lake which covers several acres. At times it covers the surface of the water; this led to early reports of "a lake of Oil". Ebbley and Joesting reported evidence of removal of residue from this seepage by Natives for fuel (Bureau of Mines, 1944) .

Seep 2A is located north of the outlet to Sinclair Lake and slightly less than 1 mi west of the shore of Smith Bay. The shoreline south of the outlet is vegetated and is generally a complex subsiding tundra area with submerged ponds and a river channel (Alaska Clean Seas, 1985) .

Seep 3 is about 2 mi southwest 2A and about 2 mi from the ocean. Ebbley and Joesting reported that the residue at this seep covered an area about 800 feet x 1000 feet (Bureau of Mines, 1944) . The API gravity of oil samples collected by the Bureau of Mines from seeps 1, 2, and 3 ranged from 13.6″ to 17.6° (Bureau of Mines, 1944).

The oil issuing from these seepages is relatively viscous (13.6° - 20.2° API) . It tends to creep downslope in elongated streams from its point of issue. Fresh oil flows most often in the centers of the asphalitic areas, along contraction cracks, and sometimes along the periphery of the seepages (McCown et al., 1972) . All observers have noted that the evaporation of volatiles appears to be quite rapid. Remnants of inactive seeps are found scattered among the active sites. At dry sites, these remnants have weathered to a dry, oxidized,crumbly material. This evidence, plus the occurrence of tar deposits within the tundra soil at various depths, indicates that the center of seepage activity might change with time. Revegetation of inactive seepage sites was noted by McCown et al., (1972) .

McCown et al. (1972) found that the relatively higher temperatures of the oil flows (3-5°C warmer during the day and 1-2°C warmer during the night than the undisturbed tundra at 10 cm depth) affected permafrost integrity. Depressions along the margins of the seeps appeared to be themokarst features which formed ponded water. Ponds covered by floating oil were found to be 0.6-1.6°c warmer than unaffected ponds.

In all four of the seeps studied by McCown et al. (1972), plants were found growing in close association, both on the periphery and when encompassed by flows. Eriophorum scheuchzeri (Alaska cotton) and Carex aquatilis (a sedge) occurred in the wet areas while Arctagrostis latifolia (a grass) was dominant in the drier sites. A more detailed study of Seep 1 showed that plants growing near the edge of the seep (C. aquatilis) were larger and more advanced phonologically in flower and fruiting than those a few meters away (McCown et al., 1972). The authors suggested that this is due to stimulation of growth by the warmer microclimate at the seep. Oil content of the soils adjacent to the seep was <0.1 mg/g wet soil except where tar was encountered in the profile.

Lakes and ponds in the seepage area are variously affected by oil from the seeps. The oil forms the characteristic mousse emulsion when in contact with the water with white floating paraffin deposits and associated bacterial flora.

Barsdate et al. (1972) found that phytoplankton productivity and abundance and bacterial numbers were higher in waters in contact with old tars and asphalts at the Cape Simpson seeps than those in either oil-free ponds or ponds recently impacted by fresh oil. The seeps appeared to have little effect on the ionic composition of the ponds, although elevated phosphate levels were recorded for the most heavily affected pond (Table 3) . They suggested that the higher productivity at the moderately affected ponds might be due to reduced grazing pressure. The affected ponds were dominated by very small forms of zooplankton and relatively sensitive filter feeders, such as Brachinecta sp. and Polyartemia sp. (both fairy shrimp characteristic of tundra ponds), were absent.

The Cape Simpson seeps appear to be in line with the known horst structure (Ball Associates, Inc., 1965). The oil apparently migrates up along the fault planes and fissures into the overlying Pleistocene Gubik Formation. The Cape Simpson seep mechanism appears similar to that of the oil seeps on the east shore of Dease Inlet (Figure 7) where similar faulting may be responsible for the latter seepage (Ball Associates, Inc., 1965).

Magoon & Claypool (1981) indentified the oil from these seeps as Simpson-Umiat Type. The source rock appears to be from the "pebble shale"/Torok Formation (Magoon and Claypool, 1985b) (Figure 4). This is a high gravity, low sulfur oil, with no or slightly odd-numbered n-alkane predominance. The Pristane/phytane ratio , greater than 1.5. Delta ^{13}C are -29.1 to -27.8 ^{o}/oo and Delta ^{34}S are -10.3 to -4.9 0/OO. Additional characteristics of the oil are presented in Table 2.

Table 3. Limnological factors in arctic ponds at Barrow and Cape Simpson from Barsdate et al. (1972) Values given for Barrow Control Ponds B and C are means of determinations on samples taken at five intervals throughout **July, 1970.** The oil seep ponds were sampled **July 19-20, 1970.**

	BARROW CONTROLS		CAPE SIMPSON OIL SEEPS				
Parameter*	B	C	2-2	2-1	3-1	2-3	3-2
Potential oil stress	None	None	None	Light	Light	Medium	Heavy
Bacteria (cells/ml)	$6.1x10^4$	$4.5x10^4$	--	--	$1.0x10^7$	3.0X109	6.8X105
Plankton algae (cells/liter)	$1 .7x10^6$	$2 ,6x10^6$	--	--	3.3X10'3	$I.8x10^7$	$4.8x10^5$
^{14}C productivity (µg C/liter-day)	2.3	5.6	3,0	67	57	69	7.8
Conductivity (µmho/cm, 25" C)	131	131	178	141	--	135	--
Calcium (mg/liter)	6.1	4.9	4.8	6.1	--	4.5	--
Magnesium (mg/liter)	3.8	3.7	2.4	2.3	--	2.0	--
Potassium (mg/liter)	0.82	0,66	0.92	0.80	--	0.66	--
Sodium (mg/liter)	11.7	11.3	19.5	15.9	--	13.8	--
Dissolved reactive phosphorus (µg/liter)	2.3	2.2	0.6	1.7	1.4	1.0	30
Particulate phosphorus (µg/liter)	S.8	11	12	19	10	22	43

● Potential oil stress was evaluated subjectively (see text); direct cell counts were made on samples preserved in Lugol's solution using a Carl Zeiss 5 cc counting cell; productivity and chemical analyses were done by routine methods (8).

Skull Cliff

Skull Cliff is located on the Chukchi coast, northeast of Peard Bay (Figure 10). It consists of a steep sandstone cliff exposed to high wave energy. The cliff slopes are greater than 45° and the fringing beach is composed of sand, gravel and shells (Robilliard et al, 1985). The sea bottom deepens gradually to 20 meters at 6.5 km offshore.

The oil seep at Skull Cliff was first described by Webber (1947) as part of the 1945 geological mapping program of the USGS . It is specifically indicated on maps in Grantz et al. (1976 and 1980). The seepage occurs as a light petroleum slowly dripping from a bed of fine-grained Tertiary sandstone. The area of seepage is only a few inches across. The thickness of the exposed sandstone is eight feet. The coastline here is exposed to the open sea and erosional. The comparatively high wave exposure and the substrate of the fringing beach probably prevents oil penetration (Robilliard et al., 1985). The small amount of oil released here is probably rapidly flushed away from the site (Johnson, 1971).

Based on geochemical analyses by Magoon & Claypool (1981) the oil from this seep has been identified as Simpson-Umiat Type. The source rock appears to be from the “pebble shale"/Torok Formation (Magoon and Claypool, 1985b) (Figure 4) . It is a high gravity, low sulfur oil, with no or slightly odd-numbered n-alkane predominance. The pristane/phytane ratio is greater than 1.5. Other characteristics of this oil are presented in Table 2.

Puale Bav

The Alaska Peninsula from Wide Bay to Puale Bay (Figure 11) contains numerous terrestrial oil and gas seeps, that have been known since the beginning of the 20th century. Some of these seeps have an associated paraffin residue accumulation covering up to two acres (Johnson, 1971). The best known seeps occur on the Bear Creek and Oil Creek anticlines, and south of Becharof Lake on the Ugashik Anticline (McGee, 1972) . Gas seeps have also been reported in the lake (Blasko, 1976b).

Because of the surface evidence, the area was the site of early exploratory drilling (1903-1904). Early references to these seeps (Martin, 1905; Martin, 1921; Capps, 1922: Smith, 1926; Miller, et al., 1959) refer to "Cold Bay", now known as Puale Bay. In addition to the activity at the beginning of this century, exploratory drilling was also conducted in

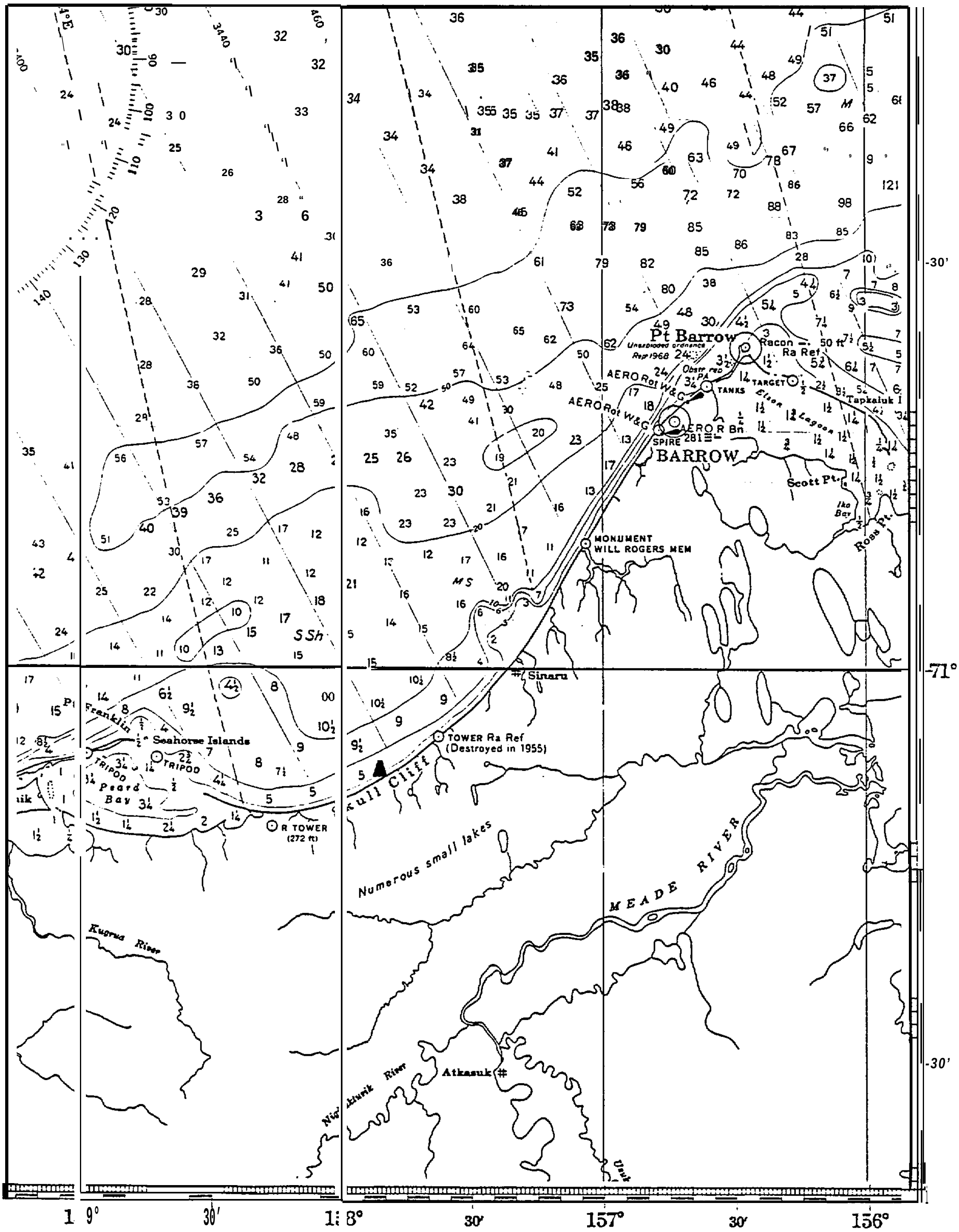


Figure 10. Skull Cliff Oil Seep A.

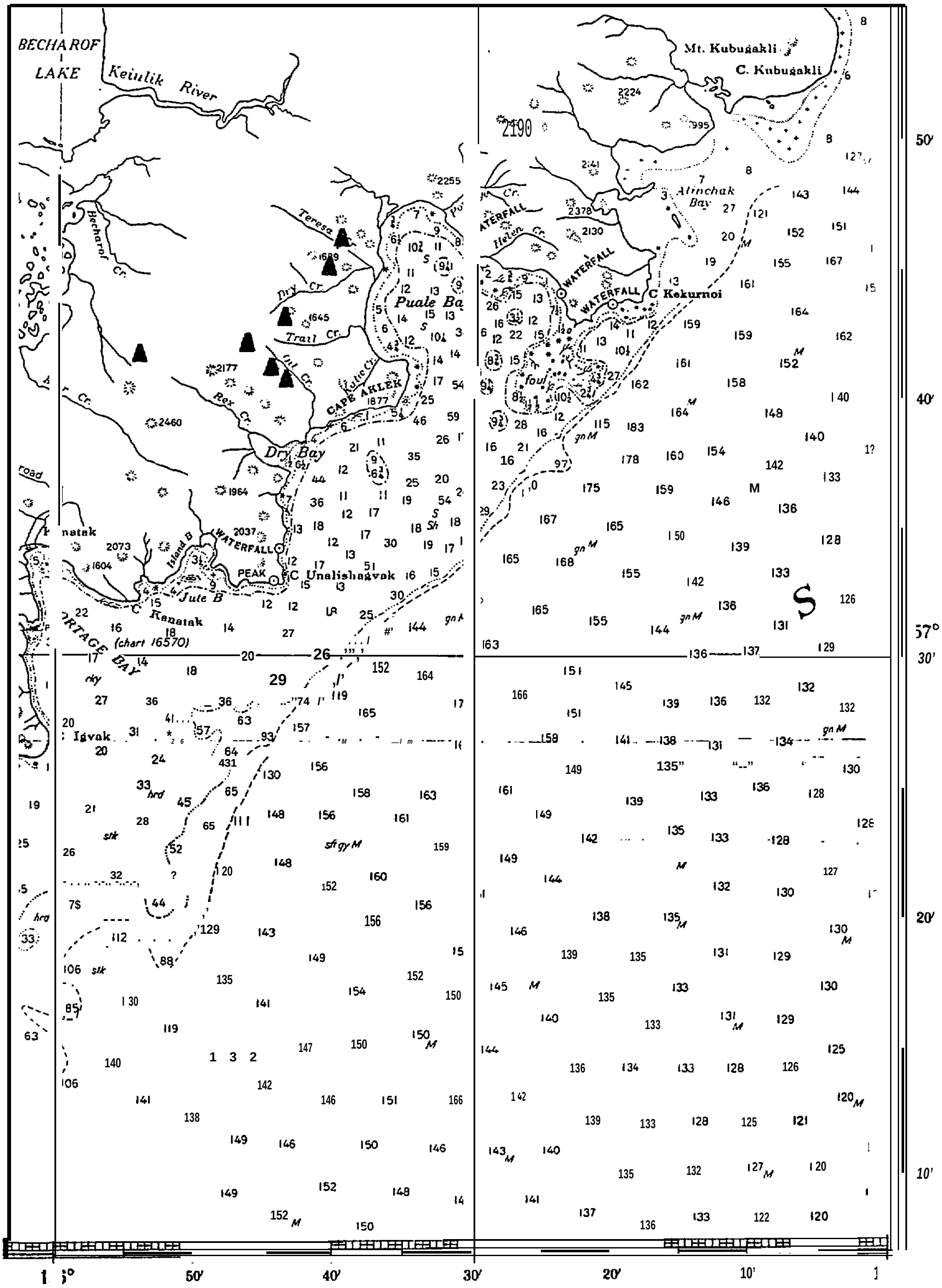


Figure 11. Puale Bay Oil Seepage Area, Alaskan Peninsula.

1938-1940 and 1957-1959, none of which resulted in commercial finds (Blasko, 1976b) .

The most prolific seeps occur at the head of Oil Creek (Figure 12). This appears to have been the situation from earliest reports and also appears to be the case today. The earliest estimate of seepage from the head of Oil Creek was 0.5 bbl/day (21 gal/day) (Capps, 1922). McGee (1972) estimates that the total quantity of oil from all the seeps in the area (Wide Bay to Puale Bay) does not exceed 0.75 bbl/day (31.5 gal/day), emphasizing the relatively greater size of the Oil Creek seeps as compared to others in the area.

The seepages at the head of Oil Creek originate from two separate springs located at the foot of a small knoll on the south side of the creek (Blasko, 1976b) . These seeps issue from the upper part of the Shelikof Formation (McGee, 1972). The descriptions provided by Capps (1922) and Blasko, 1976b) are very similar even though their visits to the seepages were 50 years apart. Seep A is act ive, bubbling intermittently. Oil collected from this seepage was 15.7″ API with 0.58 % sulfur (Blasko, 1976b). The water and oil from this seep flow into a pond with dimensions of about 20 feet by 40 feet, which is lined with tar. The water and oil continue flowing over the grassy slope and into Oil Creek. The vegetation here appears to act as a filter, trapping the heavier portions. Blasko (1976b) stated that:

> " Lush, green growth at the seep sites often obscured the seep itself. In particular, the growth of grass through and on top of the asphalt deposit at Oil Creek was a stark and colorful contradiction to the barren surroundings. No attempt was made to determine whether the resultant growth on or near the seeps was because of or spite of the bitumen escaping.″

Stimulation of vegetative growth in areas of oil seepages is not unusual and has been documented by McCown et al. (1972) at the Cape Simpson seeps. Such a response might be related to environmental temperature moderation by the warm seepage or to possible growth stimulation from associated trace elements.

The second seep (Seep B) is located 45 feet west of seep A. Blasko (1976b) reports it as originating from a series of five trickles that cover an area with a radius of 4 feet and collect at one point, forming a pool. This pool flows into a stream that discharges into Oil Creek. Oil collected from this seepage was 21.4″ API with 0.21% sulfur (Blasko, 1976b) . Oil staining and paraffin deposits were evident in the creekbed and adjacent vegetation.

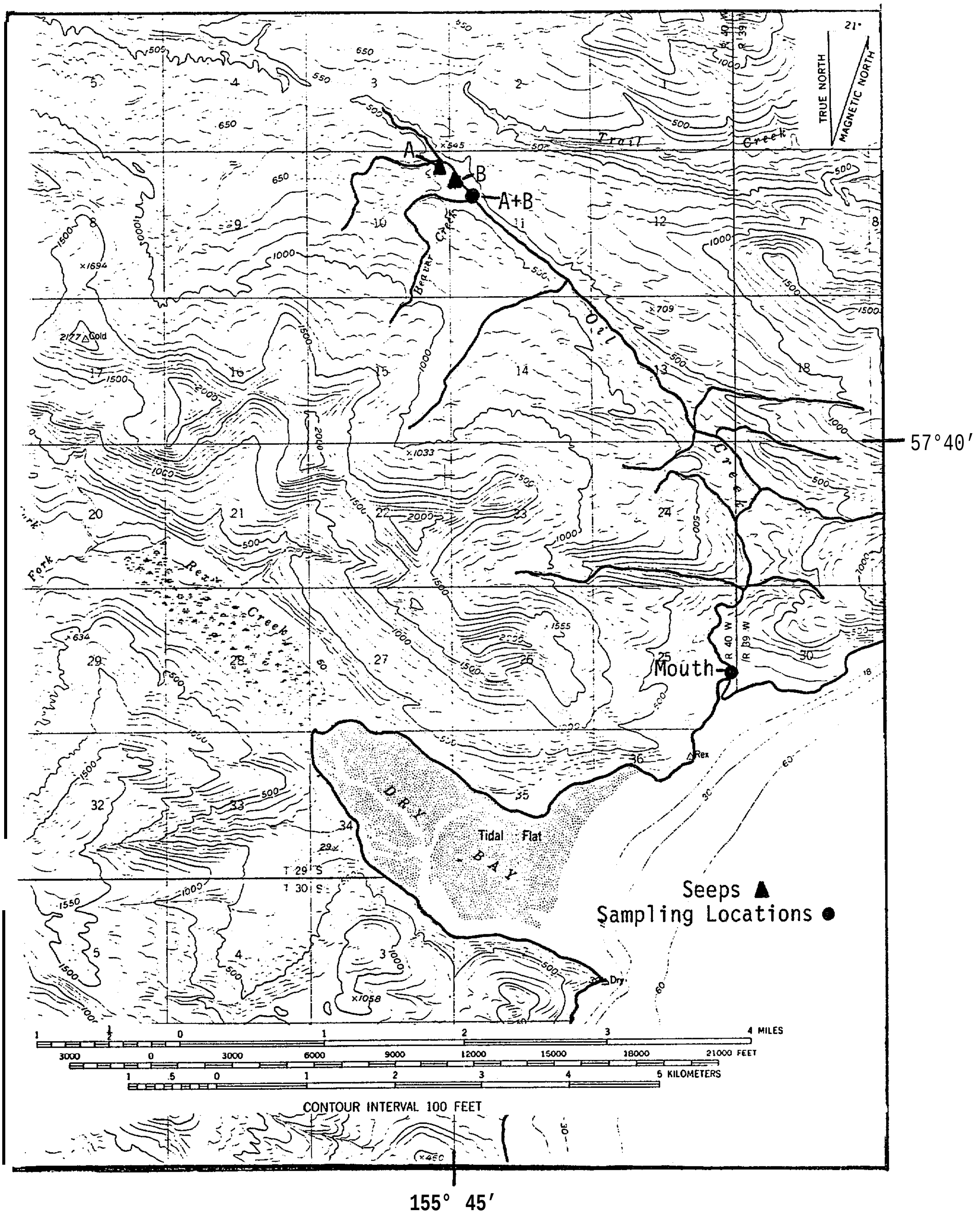


Figure 12. Oil Creek Oil Seeps, Puale Bay. (From Blasko, 1976b)

Although no recent estimates of seepage rates have been made, the area was resurveyed and samples collected by the Bureau of Mines for chemical analysis in 1973-1974 (Blasko, 1976a) . Blasko (1976b) reported that the only seeps between the Gulf of Alaska and Becharof Lake that were active enough to be deemed significant were at the head of Oil Creek (Seeps A and B). Although the oil content of the water collected at the head of the creek was relatively high (Table 4), water samples collected from the mouth of Oil Creek in Puale Bay did not indicate very much oil being carried to the Bay (Blasko, 1976b) . No oil was found on the beach of Puale Bay; however, the flow of oil from the seeps into the creek and from the creek into the bay could vary depending upon rainfall and runoff. Blasko (1976b) noted that at the time he sampled, the creek was running at a low level and little rainfall had been received. He speculated that runoff could possibly flush more oil into the creek and intermittently increase oil discharge to the bay.

Iniskin Peninsula

The Iniskin Peninsula is located on the west shore of Cook Inlet about 150 miles southwest of Anchorage (Figure 13). The peninsula is formed by the indentation of Chinitna Bay on the north and Iniskin Bay on the South. The peninsula' principal shoreline embayments are Oil Bay and Dry Bay, both of which have been known to contain oil and gas seepages in their drainages. The seeps are located on the eastern limb of a faulted anticline and are from fine-grained sandstones and claystones of the Tuxedni Formation (Middle Jurassic) . McGee (1972) estimated that the oil released from these seeps amounts to no more than 1-2 gal/day.

Evidence of early oil well drilling and oil and gas seeps is present in the Well - Bowser Creek drainage of Oil Bay, the Brown Creek drainage of Dry Bay, and the Fritz Creek drainage of Chinitna Bay (Figure 14). The Bureau of Mines surveyed these areas in 1973 to determine if the seeps were still active and if they were introducing any significant amounts of oil into the coastal environment (Blasko, 1976d) .

Two abandoned wells and four intermittently active seeps were identified on Well Creek (Figure 15) . These ponds were located at the base of a northeast-trending ridge. The oil, which occurred on pools of water, appeared to be thick and weathered; it clung to the edges of the pools and adhered to the vegetation (Blasko, 1976d). These pools drained into Well Creek and produced a floating sheen.

Stream samples indicated discharge of oil into Bowser Creek from the Well Creek drainage (Table 5) (Blasko, 1976d). Levels of 377 mg oil per liter water was measured 100 ft downstream of the junction of the two creeks. Levels

Table 4. **Chemical characteristics of** Stream Water at Oil Creek, Puale Bay, **June 1973** (Blasko, 1976b). Concentrations are in mg/l.

Variable	Seep A[1]	Seep B[2]	Seeps A + B[3]	Creek Mouth
pH	6.3	6.8	6.9	6.7
Oil	3.3	3.6	0.2	<0.1
TDS[4]	68	68	91	44
Na	26	26	37	18
K	Trace	Trace	Trace	Trace
Mg	Trace	Trace	Trace	Trace
Ca	2	1	1	Trace
CO_3	0	0	0	0
HCO_3	37	31	67	24
SO_4	5	10	Trace	Trace
Cl	17	16	20	14

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[1] Sample from drainage creek about 100 yd downstream from Seep A at head of Oil Creek.

[2] Sample from creek about 300 yd downstream from Seep B at head of Gil Creek.

[3] Sample from about 50 ft below juncture of drainages from Seeps A and B at head of Oil Creek.

[4] Total dissolved solids.

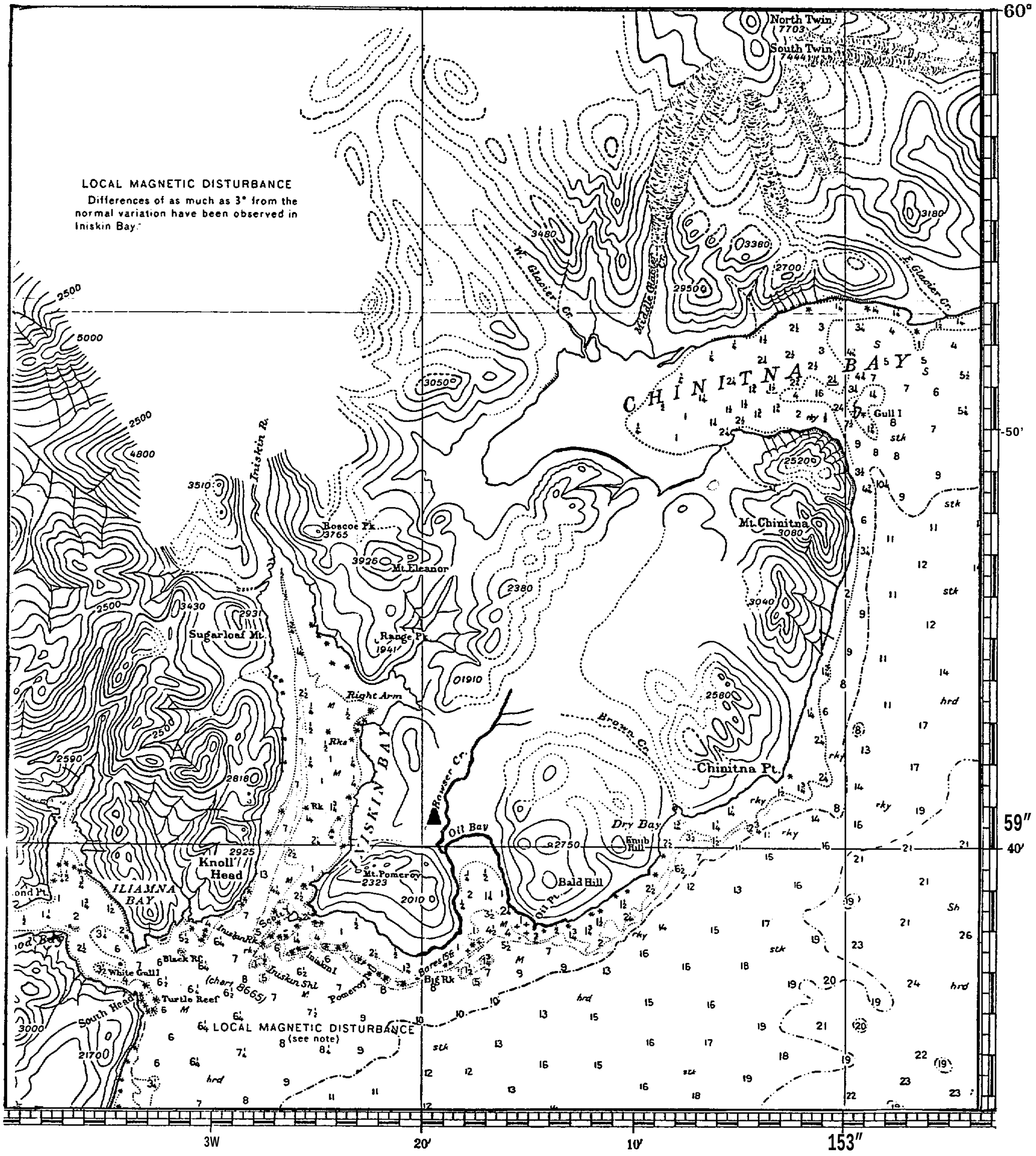

Figure 13. Iniskin Peninsula Oil Seepage Area.

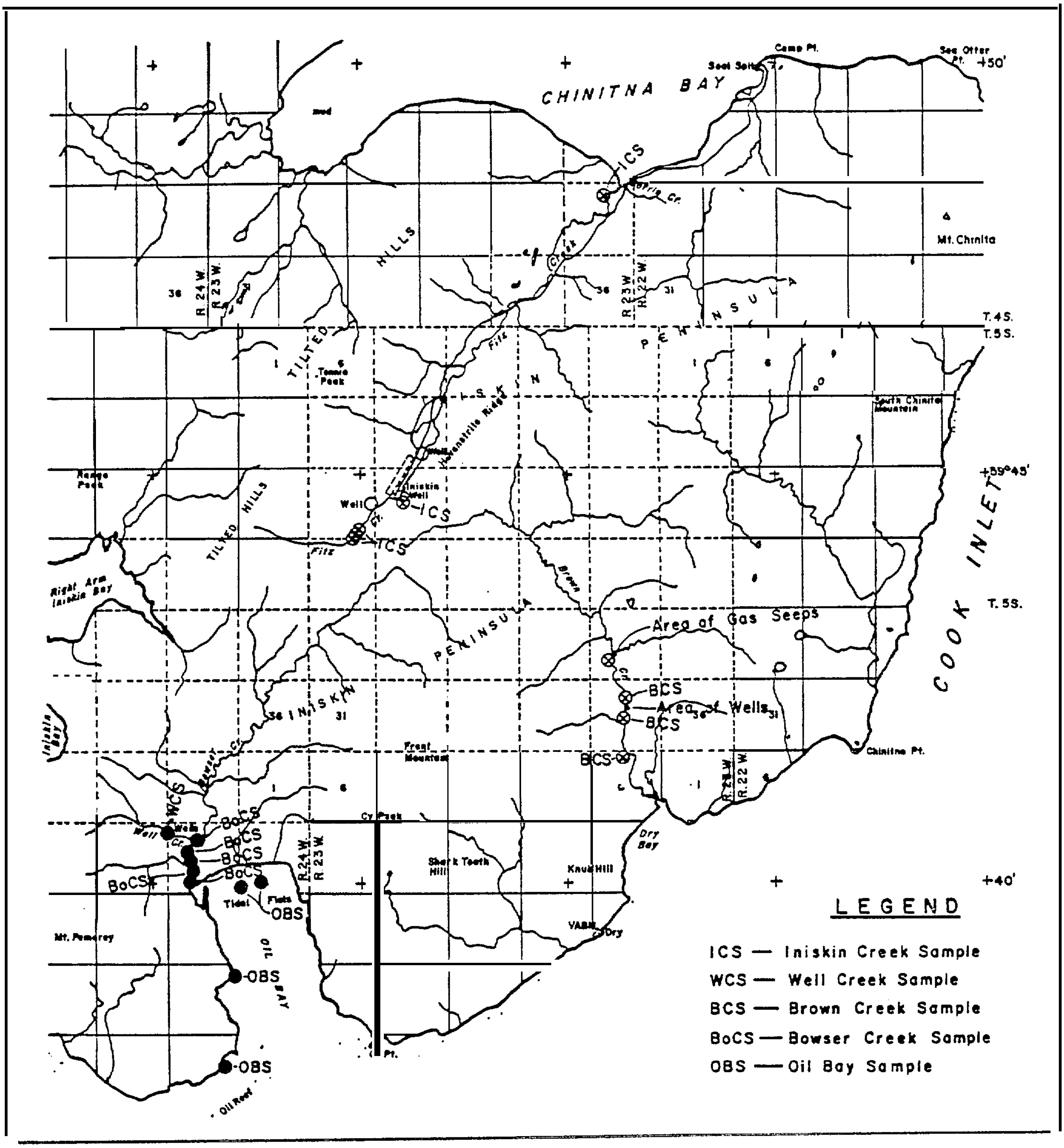

Figure 14. Oil Bay Oil Seeps, Iniskin Peninsula. (From Blasko, 1976d)

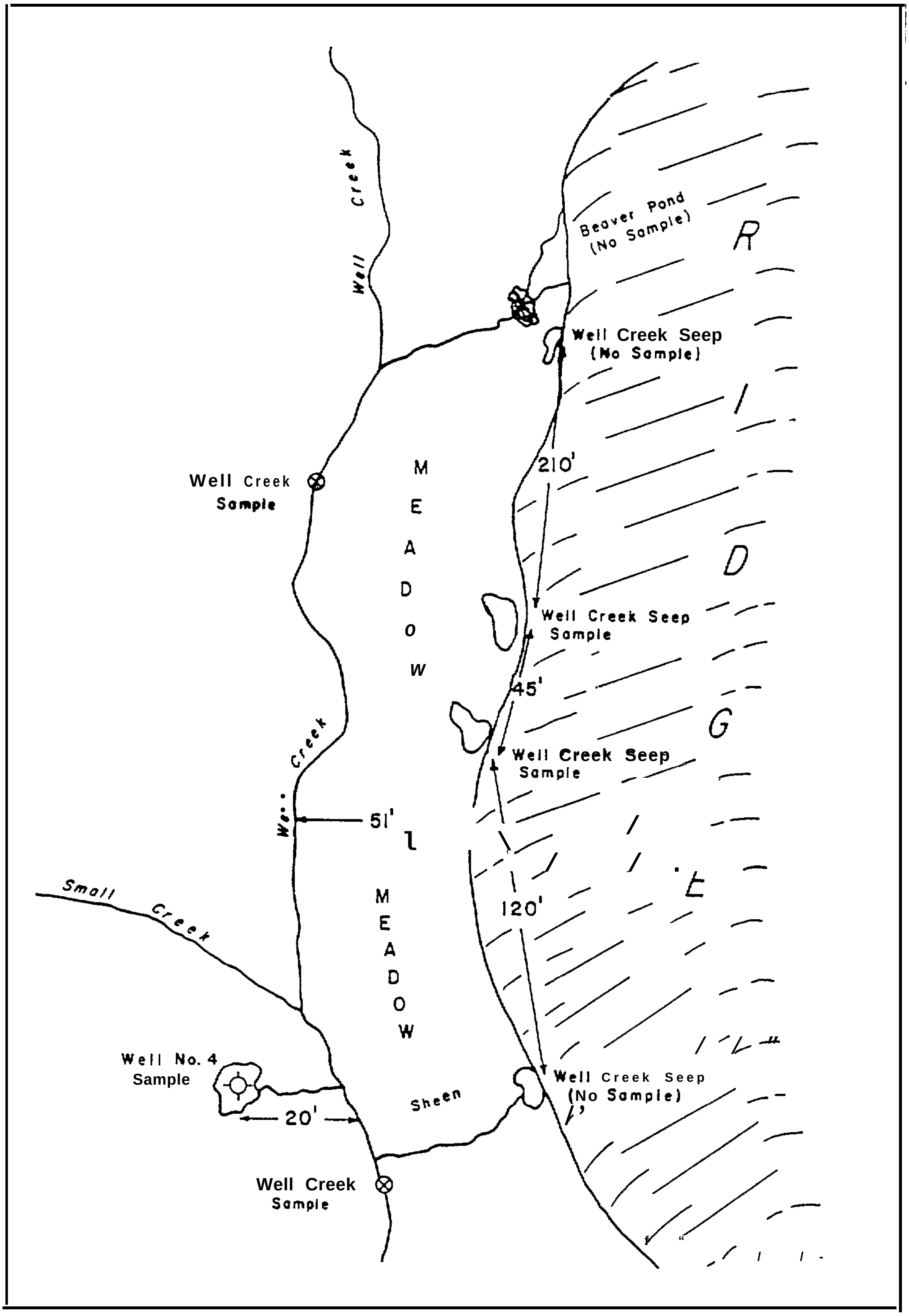

Figure 15. Oil Seeps on Well Creek, In"skin Peninsula, (From Blasko, 1976d)

Table 5. Chemical characteristics of stream water at Iniskin Peninsula, June 1973 (Blaska, 1976b). Concentrations are in mg/l.

Variable	Bowser[1] Creek 1	Bowser[2] Creek 2	Bowser[3] Creek 3	Head of Oil Bay	Mouth of Oil Bay
pH	7.2	6.9	6.7	6.9	7.2
Oil	<0.1	377	14	0.1	<0.1
TDS[4]	122	103	835	7888	27,716
Na	43	36	285	2584	9,754
K	Trace	Trace	11	187	430
Mg	Trace	Trace	16	230	498
Ca	5	5	5	25	56
HCO_3	48	41	49	111	134
SO_4	12	8	66	7	12
cl	38	34	428	4800	16,900

[1] 100 ft upstream of juncture of Well Creek and Bowser Creek.

[2] 100 ft downstream of juncture of Well Creek and Bowser Creek.

[3] 200 ft upstream at mouth of Bowser Creek at low tide.

[4] Total dissolved solids.

dropped to 14 mg/l near the mouth of Bowser Creek and 0.1 mg/l at the head of Oil Bay at the mouth of the creek. Sediments collected at the head of Oil Bay, about 100 yds east of the mouth of the creek had an oil content of 8.0 mg/ kg. Reconnaissance of the beaches from Oil reef to Oil Point at high and low tides did not reveal any seeps or evidence of oil.

Although gas seeps were observed and sampled during the 1973 survey of the Bureau of Mines, no oil seeps were found in the Brown Creek drainage or in Dry Bay (Blasko, 1976d). The Fritz Creek drainage contains several abandoned exploratory wells but no oil or gas seeps. Blasko (1976d) indicated that, although some oil appears to be entering the creek from these abandoned wells, no significant amounts were reaching Chinitna Bay during the Bureau of Mines survey. The author also noted that the amount of release appears to be directly related to the amount of rainfall and the runoff through the drainage system.

Katalla, Controller Bay

This coastal seepage area extends along an eastward-trending belt about 25 mi long and 4-8 mi wide (Figure 16). This zone lies along the north shore of Controller Bay, extends to the east into the alluvial flats of the Bering River and to the west into the Copper River flats (McGee, 1972). Miller et al. (1959) reported that at least 75 oil seeps and 11 gas seeps have been observed in this area. Martin (1908) reported several large oils seeps on the banks of Mirror Slough near the mouth of the Martin River and had seen oil on the north beach of Strawberry Harbor. He also indicated surface accumulations of oil on the tide flats between Burls Creek and the mouth of the Bering river. Rosenberg (1974) pointed out that the nine-foot shoreline uplift during the 1964 earthquake has removed all of these sources to well above tidal influence.

Reimnitz (personal communication as cited in Johnson, 1971) indicated personal observations of a possible oil seep at tide level. This was in the vicinity of the Copper River Delta where oil was observed to be seeping near the level of mean higher high water in a salt marsh. This oil appeared to be flushed out of the marsh during the outgoing tide.

Nearly all of the reported seeps are located in the outcrop of the middle part of the Katalla Formation of Middle Oligocene to Middle Miocene age (Miller et al. (1956). The largest seeps are associated with sandstones or conglomerates and usually with depositional or structural features (joints and bedding planes) (McGee, 1972).

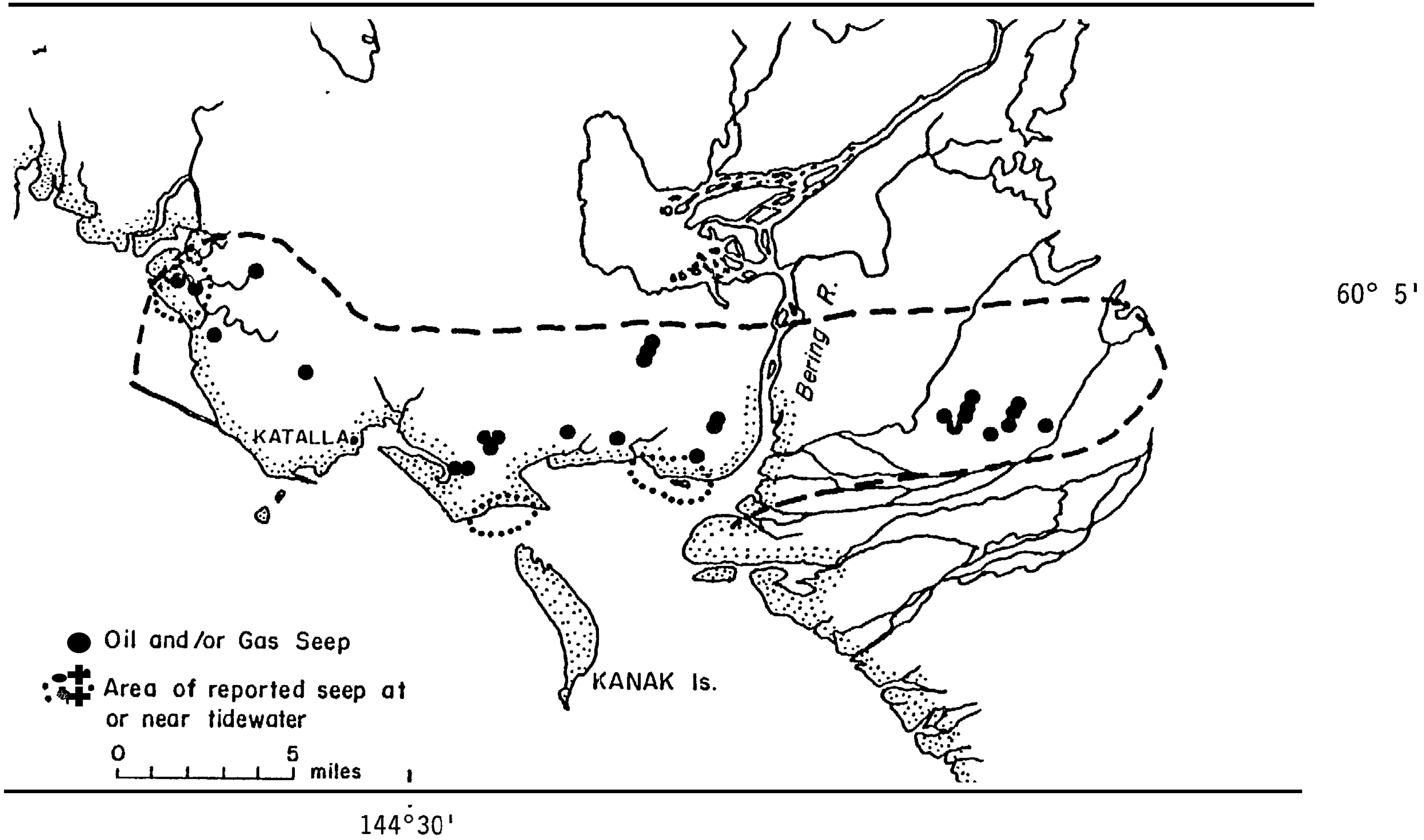

Figure 16. Katalla, Controller Bay Oil and Gas Seepage Area (From berg, 1974)

According to McGee (1972), the abandoned oil wells in the Katalla area do not appear to be contributing oil to the coastal waters. The total quantity of oil issuing from the seeps in the area is 0.5-1.0 bbl/day (21-42 gal/day). Much of the light fraction of the 40°-45° API oil evaporates from the surfaces of the sloughs and ponds and the remainder appears to be absorbed into the soil. McGee (1972) estimated that <10% reaches the marine environment.

Most of the natural seeps in the Katalla area that have been reported in the literature were found to be active during the Bureau of Mines field surveys of 1973-1974 (Blasko, 1976c). The degree of activity varied from seep to seep. Some appeared to be dormant but showed some indications of past sporadic activity. Blasko found that determining seep activity in the Katalla oil field was very difficult because of past oil production there. The oil field had ponded water and most of the time these ponds were covered with an oil sheen. Analyses by the Bureau of Mines of streams draining the Katalla oil field indicated very small amounts of oil entering Katalla Bay via Katalla Slough (Figure 17) (Blasko, 1976c).

Mitcher Creek is located east of the Katalla oil field. It begins on the east side of Mount Hazelet and flows into Redwood Creek and then into Redwood Bay (Figure 18). An active seep was observed here by Blasko (1976c). Fresh oil was trapped by rocks near the edge of the creek; however, no oil was observed escaping from the creek bottom. Water collected downstream of the seep contained 7,130 mg/1 of oil (Table 6). About 200 ft downstream of the site, the concentrations were found to have dropped to 10.7 mg/l, and at the mouth of Redwood Creek the levels were <0.1 mg/l.

Active oil seeps were also observed by Blasko (1976c) on Chilkat Creek. This creek drains a narrow valley west of the Bering River and discharges into Controller Bay (Figure 19). One seep was observed 0.5 mi upstream from the mouth of the creek. It was found to discharge into the creek and produce a sheen over an area of about 15 ft^2 immediately below the seep. The creek bottom from the seep downstream to its mouth was covered with a waxy precipitate. Oil concentrations in the water ranged from 73.9 mg/1 at the seepage to 6.5 mg/l at the creek mouth (Table 6).

Yakataga

This area, which extends from Cape Yakataga to Icy Bay (Figure 20), contains probably the most extensive development of oil and gas seeps on the Gulf of Alaska coast. The surface evidence of petroleum in this area led to exploratory drilling during the periods 1926-1927, 1954-

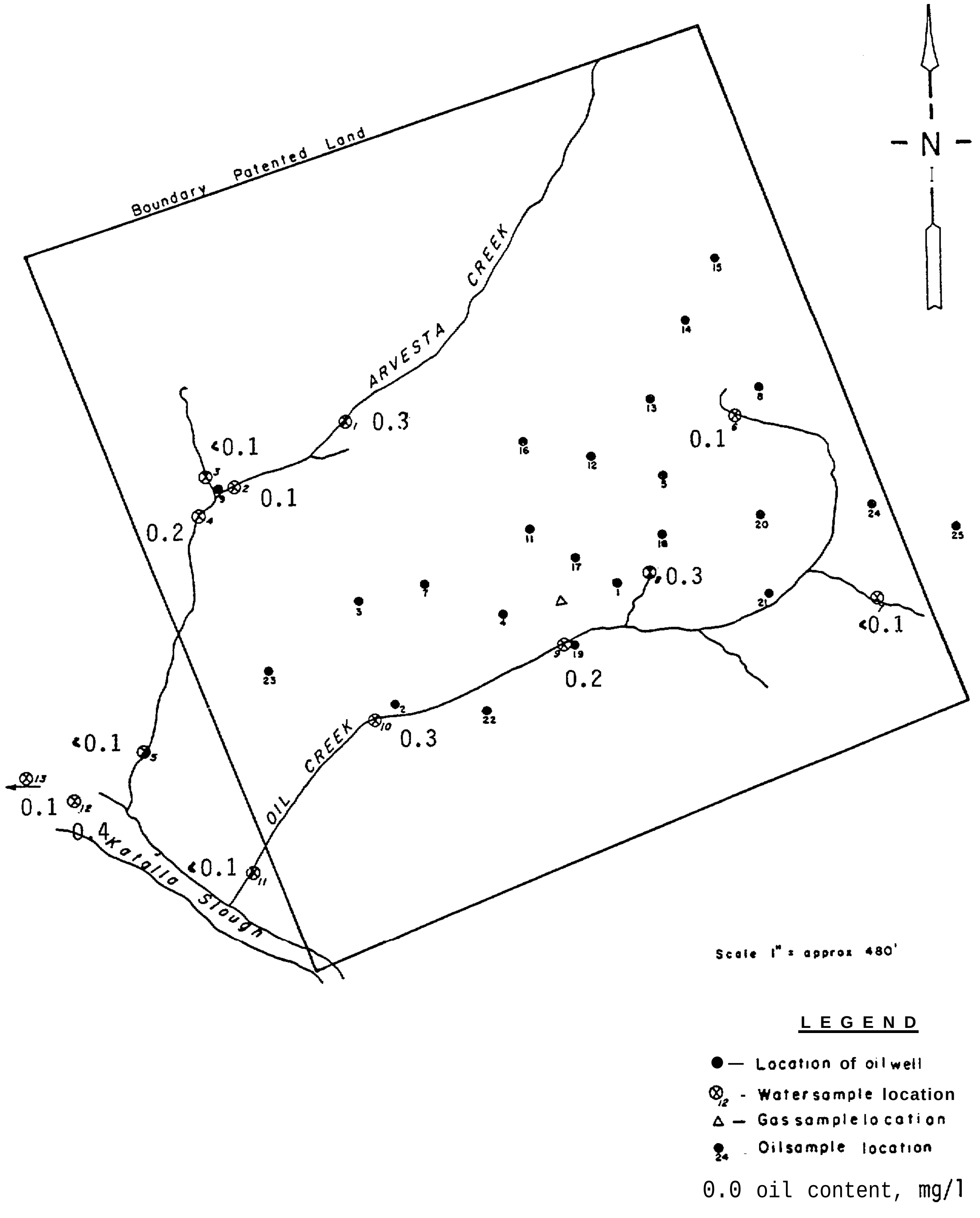

Figure 17. Stream Sampling Locations and Oil Concentrations, Katalla Oil Field. (From Blasko, 1976c)

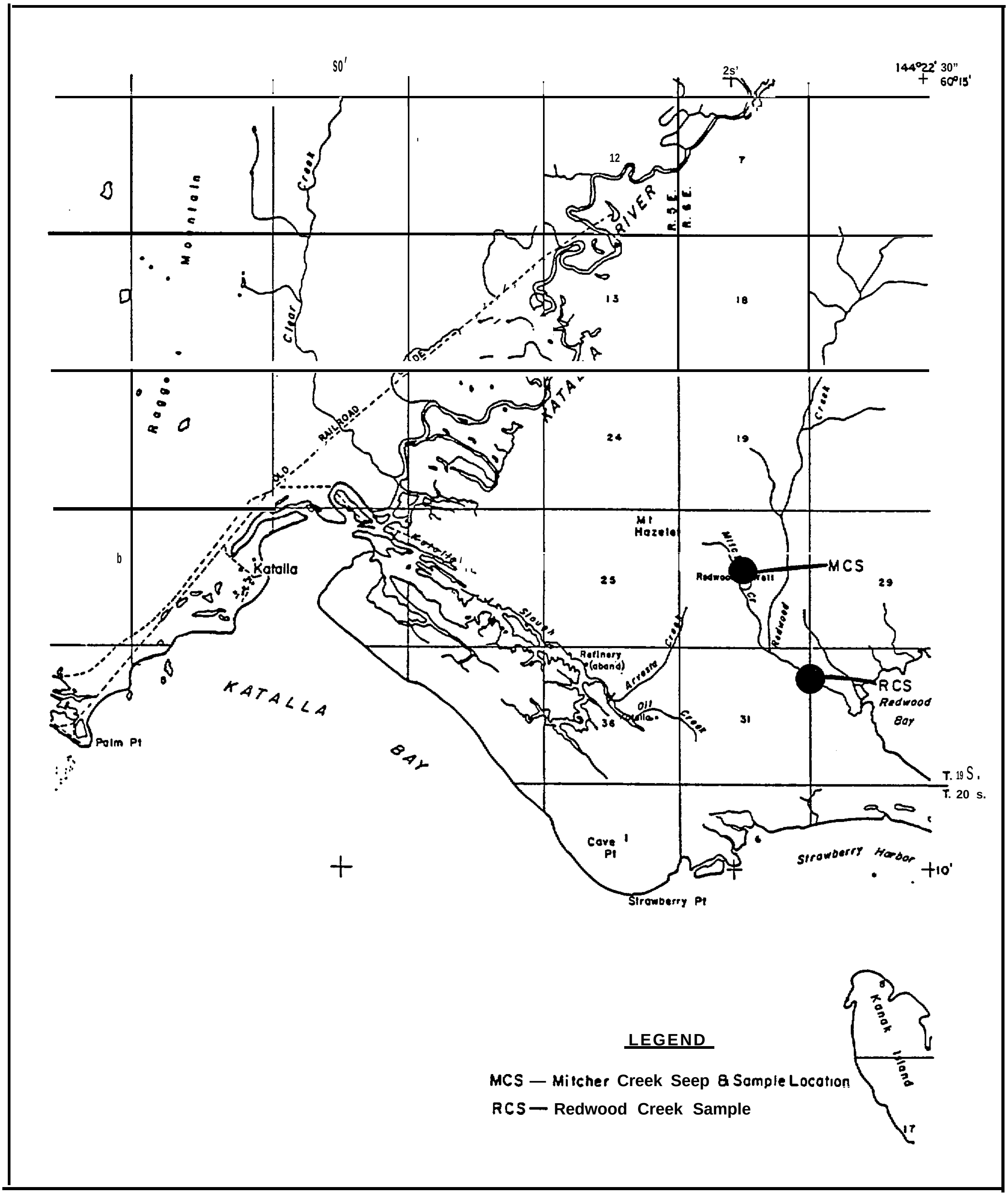

Figure 18. Mitcher Creek, Katalla Oil Seepage Area. (From Blasko, 1976c)

Table 6. Chemical characteristics of Streams in the Katalla, Controller Bay Oil Seepage Area, Sept. 1972 (Baska, 1976c). Concentrations are in mg/l.

Variable	Mitcher Creek 1[1]	Mitcher Creek 2[2]	Mitcher Creek 3[3]	Mitcher Creek 4[4]	Chilkat Creek[5]	Chilkat Creek 1[6]	Chilkat Creek Mouth
pH	6.7	6.6	6.7	7.1	7.0	6.5	7.0
Oil	7,310	<0.1	10.7	<0.1	73.9	182	6.5
TDS[7]	97	67	48	53	97	97	92
Na	25	15	7	14	17	20	19
K	1	1	trace	1	2	2	1
Mg	2	3	2	1	3	3	3
Ca	11	5	8	5	14	11	11
HCO_3	90	37	29	37	62	62	62
SO_4	8	17	11	8	18	18	15
Cl	6	8	6	6	12	12	12

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[1] Below seep.
[2] Above seep.
[3] 300 ft downstream of Site 1.
[4] Mouth of Redwood Creek before draining into Redwood Bay
[5] At seepage 0.5 mi upstream from mouth
[6] 1,000 ft downstream of seepage
[7] Total dissolved solids

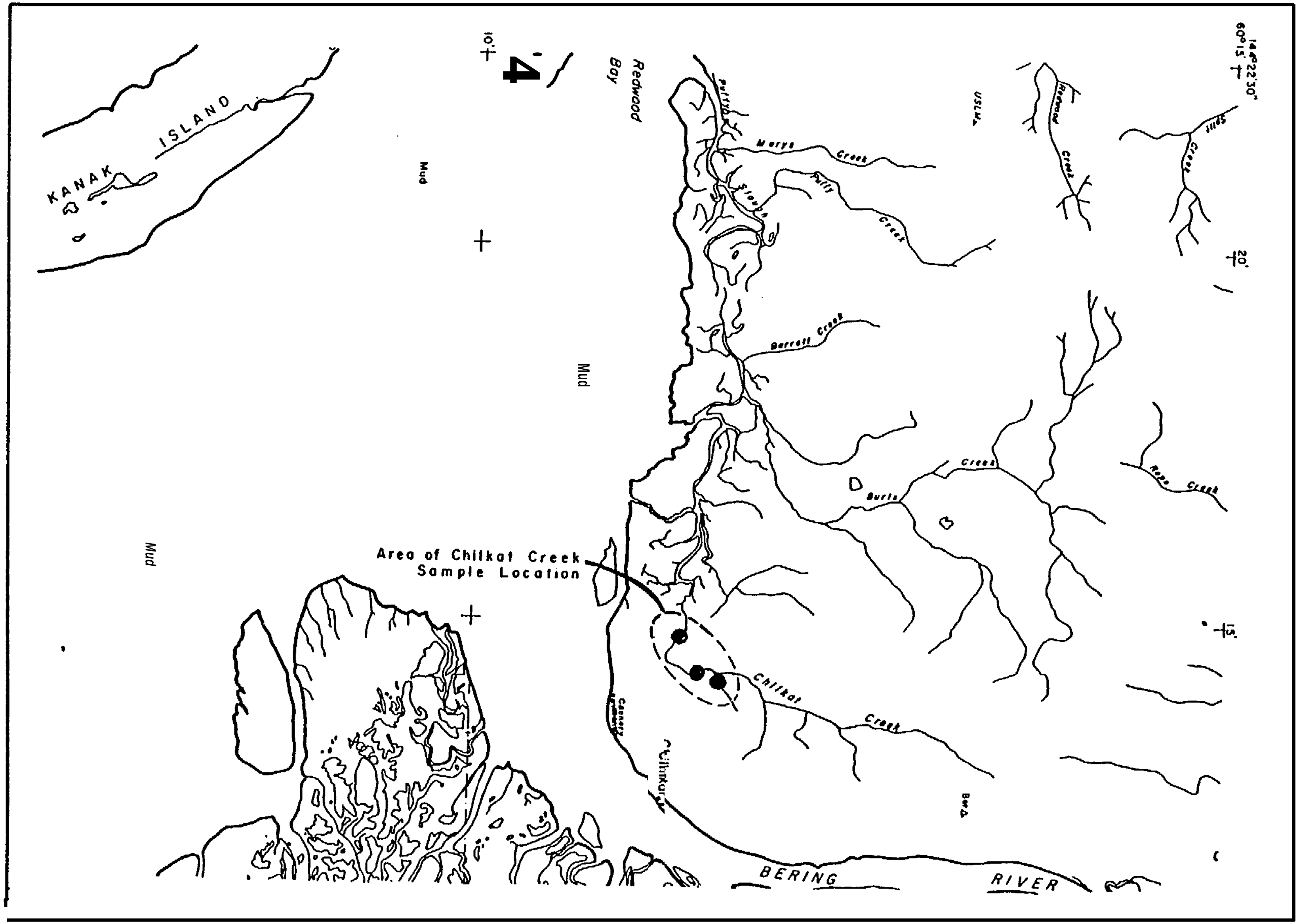

Figure 19. Chilkat Creek, Kataa Oil Seepage Area. (From Blasko, 1976c)

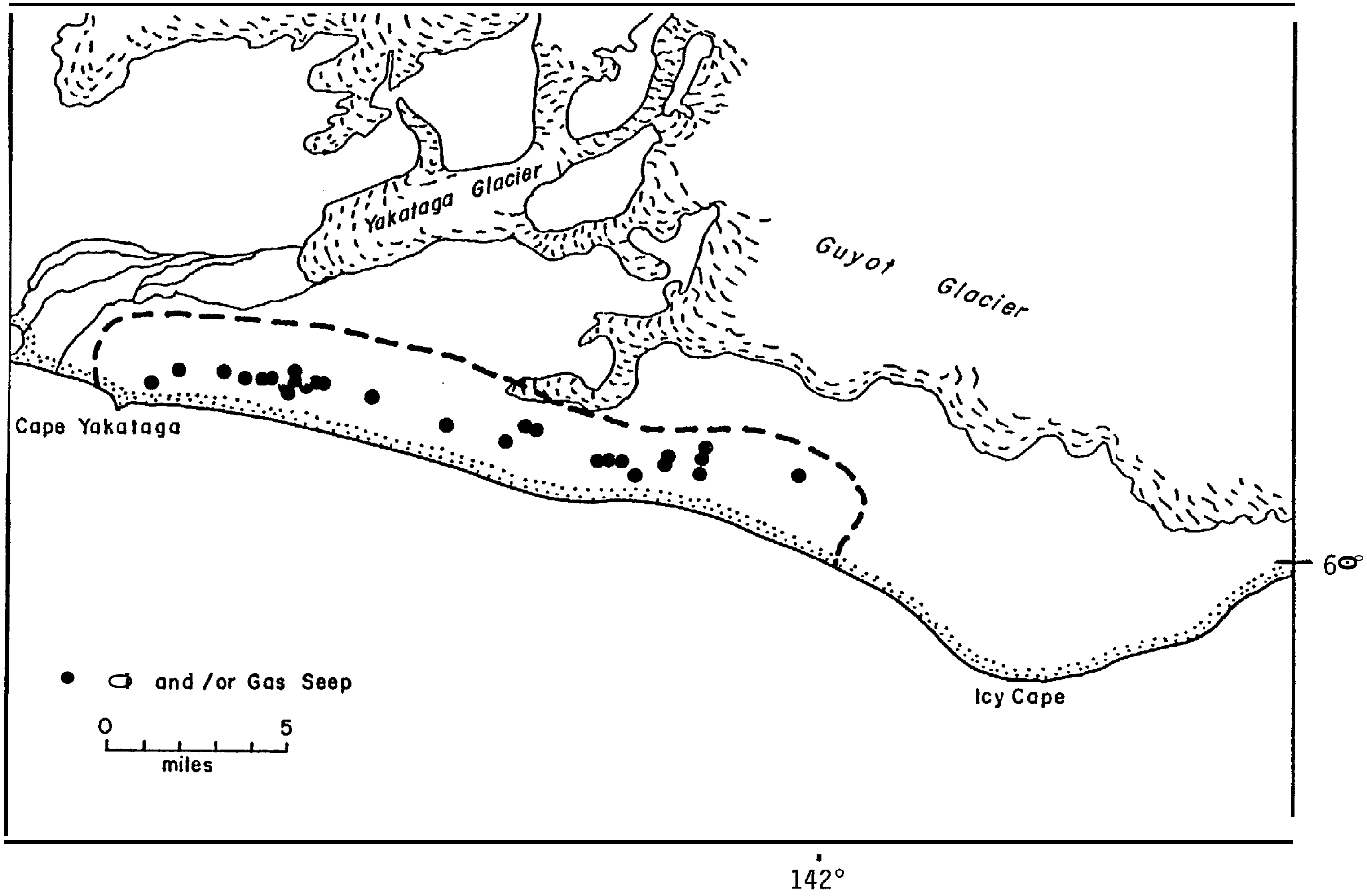

Figure 20. Yakataga Oil and Gas Seepage Area. (From Rosenberg, 1974)

1955, and 1959-1962 (Blasko et al. , 1976c) . There were no commercial finds.

Oil and gas seeps have been found on almost all of the rivers draining the Sullivan anticline (Blasko, 1976c) . The Sullivan anticline runs parallel to the shoreline and all of the seeps have been reported to occur on the crest of the fault plane of this anticline, 0.5-2 mi inland. They are in areas of outcrops of the Poul Creek Formation (Miocene) and the lower part of the Yakataga Formation (Miocene - Lower Pliocene) .

The map of Martin (1921) identifies 10 seeps in this area. He indicated that the most prolific seep was on Johnston Creek and resulted in:

> "...appreciable quantities of oil are carried down its course to the ocean. A scum of oil residue also occurs on the cobble bars of Johnston Creek from its mouth up to the seepage. Probably a barrel or more of petroleum a day escapes from this seepage."

Active seeps have been reported through the years on One Mile Creek, Oil Creek, Hamilton Creek, Crooked Creek, Lawrence Creek, Poul Creek, Munday Creek, and Johnson Creek (Miller et al., 1959). Most of this oil discharges from joint cracks in sandstone and the quantity released is relatively small (McGee, 1972) . Rosenberg (1974) also lists this area in his compilation of Gulf of Alaska petroleum seeps, citing 32 reported seeps based on Palmer (1971) .

Known oil seeps were visited by the Bureau of Mines in 1973-1974 and samples were collected from seepages and stream water in order to characterize the oil and to determine how much is being discharged into the Gulf of Alaska (Blasko, 1976c) . The following streams were included in this survey: Oil Creek, Crooked Creek, Lawrence Creek, Munday Creek, Poul Creek, Johnston Creek, Little River, yakataga River, White River, Felton Creek, and Duktoth River (Figure 21) . All of these creeks were walked from head to mouth, and the entire beachline from Yakataga to Icy Bay was observed in segments on foot several times.

Blasko (1976c) found that most of the seeps previously reported in the area were still active (Crooked Creek, Lawrence Creek, Munday Creek, Poul Creek, and Johnston Creek), but the amount of oil actually reaching the Gulf of Alaska was relatively small (Table 7). Descriptions of the seeps are presented below:

<u>Crooked Creek</u>- active oil and gas seeps are located 1.5 mi upstream on the west side of the creek about 30 ft from the creek bank. Blasko (1976c) observed light-green oil

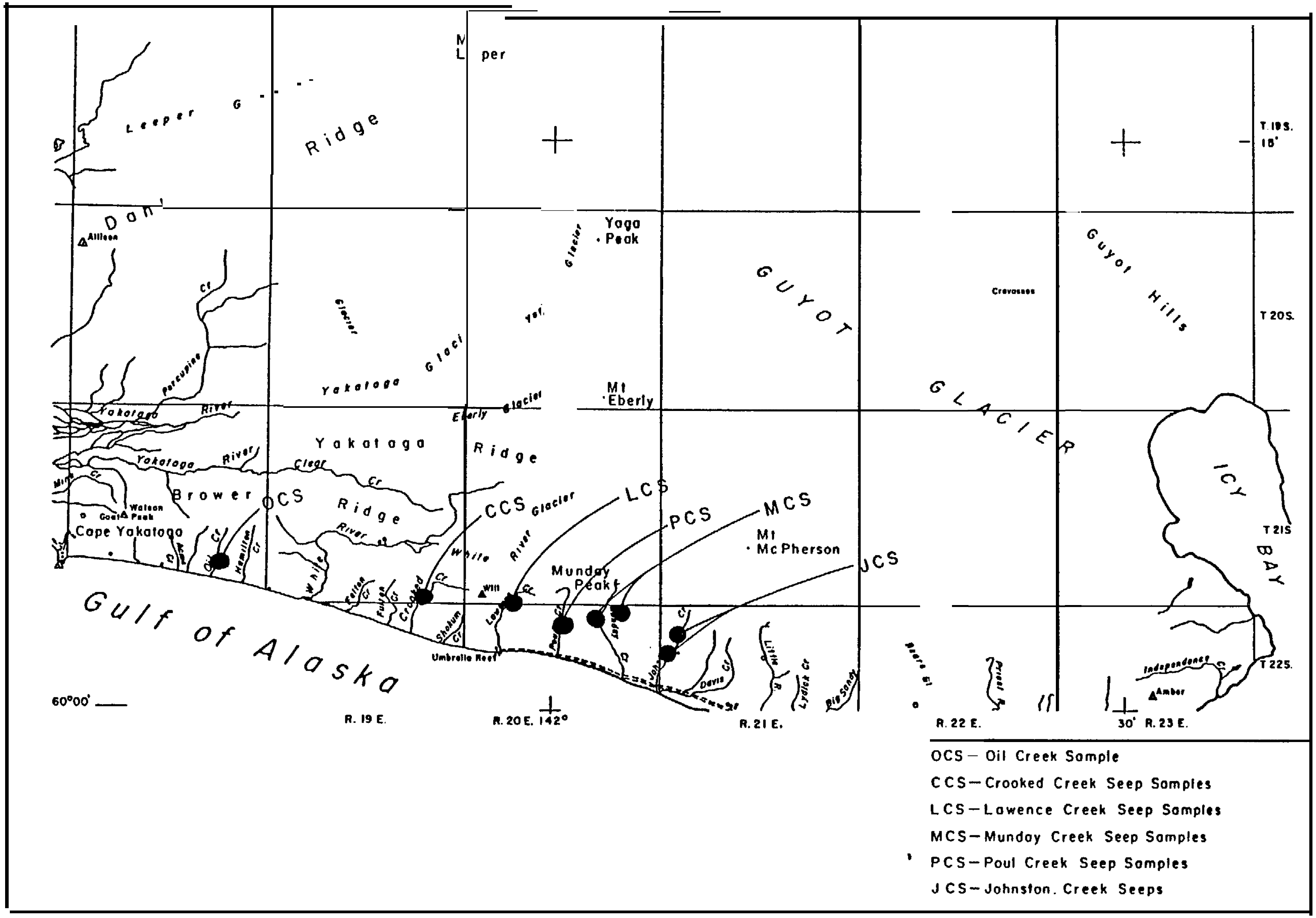

Figure 21. Stream Sampling Locations, Yakataga Oil Seepage Area. (From Blasko, 1976c)

Table 7a. Chemical Characterization of Streams in the Yakataga Seepage Area, July 1974. (Blaska 1976c) Concentrations are in mg/l.

Variable	Oil[1] Creek	Crooked[2] Creek 1	Crooked[3] Creek 2	Crooked* Creek Mouth	Lawrence[5] Creek 1	Lawrence[6] Creek 2	Lawrence[7] Creek Mouth
pH	7.6	6.7	7.2	7.1	7.8	7.4	7.5
Oil	0.1	3.2	1.6	<0.1	18.0	1.6	0.1
TDS[8]	204	595	91	82	213	76	73
Na	46	139	21	19	60	14	12
K	3	6	1	1	3	1	2
Mg	5	11	4	2	3	2	3
Ca	20	71	8	9	21	11	10
HCO_3	98	110	54	37	183	49	49
SO_4	56	2	11	9	4	14	12
CI	26	312	19	24	32	10	10

[1] 0.5 mi. upstream from beach

[2] 21.0” API; 0.90% S; sample from small stream that drains seep into Crooked Creek

[3] 200 ft below point where oil seep drainage enters Crooked Creek

[4] Mouth of Crooked Creek above entrance to Gulf of Alaska

[5] 12.9° API; 0.82% S; sample from small stream that drains oil seep into Lawrence Creek

[6] Below falls downstream of seep on Lawrence Creek

[7] Mouth of Lawrence Creek above entrance to Gulf of Alaska

[8] Total dissolved solids

Table 7b. Chemical Characterization of Streams in the Yakataga Seepage Area July 1974. (Blaska 1976c) Concentrations are in mg/1.

Variable	Munday[1] Creek 1	Munday[2] Creek 2	Munday[3] Creek 3	Munday[4] Creek Mouth	Poul[5] Creek 1	Poul[6] Creek 2	Poul[7] Creek Mouth
pH	6.8	7.0	7.2	7.2	7.7	6.9	7.1
Oil	3.7	1,336	0.1	0.1	114,800	8.3	0.1
TDS[8]	183	63	70	201	322	91	94
Na	47	12	16	44	78	20	15
K	2	1	1	12	7	2	3
Mg	4	2	2	4	10	2	3
Ca	19	9	8	17	29	10	13
HCO_3	98	48	49	73	256	49	49
S04	3	7	9	36	50	23	22
cl	60	8	10	52	22	10	14

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[1] 17.2° API; 0.96% S; 100 ft downstream of seep on Mundy Creek
[2] Oil seep on east fork of Mundy Creek
[3] At mouth of east fork of Mundy Creek
[4] Mouth of Mundy Creek above its entrance to Gulf of Alaska
[5] 24.8° API; 0.68% S; at oil seep on Poul Creek
[6] 200 ft downstream of seep
[7] Mouth of Poul Creek above its entrance to Gulf of Alaska
[8] Total dissolved solids

Table 7c. Chemical Concentrations of Streams in the Yakataga Seepage Area July 1974. (Blaska 1976c) Concentrations are in mg/1.

Variable	Johnston[1] Creek 1	Johnston[2] Creek 2	Johnston[3] Creek 3	Johnston Creek Mouth	Johnston[4] Creek 4	Johnston[5] Creek 5	Johnston[6] Creek 6
pH	6.7	7.2	6.9	7.1	6.8	6.9	7.0
Oil	2,341	92.0	1.0	0.1	246,000	8.5	1.6
TDS[7]	162	91	67	118	705	72	874
Na	25	20	14	27	179	17	247
K	1	1	2	6	10	2	8
Mg	4	3	1	2	10	1	12
Ca	13	11	9	1	74	8	75
HCO_3	88	62	43	49	207	24	268
SO_4	10	3	11	18	20	2	trace
c1	16	22	9	30	310	30	400

[1] Lower seep - 15.4° API; 0.73% S; seep pond at discharge point
[2] Stream draining Johnston Creek from seep pond
[3] 300 yd above Johnston Creek Mouth
[4] Upper seep - 19.0° API; 0.70% S; sample from seep pond
[5] Stream draining from upper seep pond into Johnston Creek
[6] Johnston Creek, 100 ft below drainage stream
[7] Total dissolved solids

with gas bubbles emerging from the seep spring. A gas seep is located in a dry creekbed 10 ft east of the oil seepage.

Lawrence Creek- Several active and inactive oil seeps occur in a 600 ft^2 area of talus rubble on the east side of Lawrence Creek about 1.5 mi upstream from the mouth. Blasko (1976c) observed the sides of the creek and the creek banks downstream of the seeps to be oily with brown bitumen deposits occurring down to the creek mouth. Sheens were observed on the surface of the stream water. Blasko (1976c) stated that this area shows more evidence of oil seepage and transportation than any other between Cape Yakataga and Johnston Creek.

Munday Creek- An intermittent oil and gas seep is located 2 mi upstream from the creek mouth on the west side. Blasko (1976c) reported several greenish-black oil pools spread over a 50 ft^2 area. An active oil seep is located 0.25 mi upstream of the east fork of Munday Creek. Here Blasko (1976c) observed bubbles of oil emerging from the stream bed. A sheen was observed on the creek, although the stream was swift at the time with numerous riffles.

Poule Creek- numerous oil seepages (but no gas seeps) were observed in an area 1.75 mi upstream from the creek mouth. The seeps discharge oil directly into the creek at the water's edge.

Johnston Creek- two seepage areas were observed by Blasko (1976c) on Johnston Creek, which is a rapid, turbulent glacial stream. One seepage is located 1.5 mi from the mouth of the creek on the west side. It is in a marshy area of about an acre, 16 feet above the creek bed and consists of two ponds separated by meadows. Both oil and gas were reported by Blasko (1976c) to be released from this seep. For several hundred feet downstream from where the oil entered the creek, the rocks of the creek bed were observed to be covered with a thick layer of light-brown paraffin and a cover of black oil. Other seepages on Johnston Creek occur 0.25 mi upstream from the above seeps on the west bank of the creek.

Blasko (1976c) reported seeing oil on the beach only once and that was at the mouth of Johnston Creek. Blasko also observed that precipitation influenced the amount of oil entering the drainage from the seepage. Since the seeps on this creek are located in a pond about 15 ft above the creekbed, during heavy precipitation the water level rises and the oil accumulated on top of the water spills over the lip of the pond and into the creek. A sheen of oil at the mouth of the creek was most evident during heavy rainfall. The apparent heavy vegetative growth at the seepages observed by McCown et al. (1972 at Cape Simpson, Blasko

(1976b) at Puale Bay, and Blasko (1976b) at Katalla was also observed here.

Other Seepage Areas

A list of other oil seepages reported in Alaskan coastal areas is presented below:

Dease Inlet [Site 6- Figure 3; Table 1)
This seepage, commonly known as the "Admiralty Oil Seep," was first described by Ebbley and Joesting (Bureau of Mines, 1944) as being located on the east side of Dease Inlet, near the mouth of Chipp River, about 4.5 mi northeast of Thomas Brewer's warehouse. The latter is indicated on U.S Geological Survey Map E of Alaska, 1954. This seepage area is also described in Miller, et al. (1959), Hanna (1963), Ball Associates, Inc. (1965), and Johnson (1971) and is indicated on the maps of Grantz et al. (1976; 1980) and Alaska Clean Seas (1983).

The seepage is a heavy black oil issuing from a low mound similar to that at Cape Simpson. Most of the oil has been exposed to the air and is hard enough to walk on. The API gravity was determined by Ebbley and Joesting to be 11.6° - 14.8° (Bureau of Mines, 1944). They also reported that, during their surveys, several hundred sackfuls had been mined by the local inhabitants for fuel.

Inglutalik River (Site 8- Figure 3; Table 1)
This seepage was reported by Miller et al. (1959) as being located in the Norton Sound region upstream of the Inglutalik River mouth. It is also listed in Johnson (1971).

Andronica Island (Site 9- Figure 3; Table 1)
This seep was reported by the USCG in 1913 to be in Cenozoic volcanic material on the eastern shore of Andronica Island (Johnson, 1971). The seepage is unconfirmed.

Chignik Bay (Site 10- Figure 3; Table 1)
Cited by Miller et al. (1959) and McGee (1972), but unconfirmed.

Aniakchak Area [Site 11- Figure 3; Table 1)
Cited by Martin (1921), Smith and Baker (1924), Miller et al. (1959) and McGee (1972), but unconfirmed.

Shelikof Strait (Site 13- Figure 3; Table 1)
This seep was reported to be located on the north shore of Shelikof Strait, 20 mi. southwest of Cape Douglas (Miller et al., 1959; McGee, 1972); however, the sighting is unconfirmed.

Douglas River (Site 14- Figure 3; Table 1)

A seep was reported by Martin (1905) from the upper Triassic Naknek Formation at the mouth of the Douglas River, Kamishak Bay; however, the sighting is unconfirmed (Miller et al., 1959) .

Bruin Bay (Site 15- Figure 3; Table 1)

Oil seeps were reported by Martin (1905) at the entrance to Bruin Bay on the south side of Kamishak Bay. The sighting is unconfirmed (Johnson, 1972; McGee, 1972) .

Iniskin Bay (Site 17- Figure 3; Table 1)

Oil seeps reported in Iniskin Bay by Moffit (1922) are unconfirmed (Miller et al., 1959).

Chinitna Bay (Site 18- Figure 3; Table 1)

Oil seeps reported in Iniskin Bay by Moffit (1922) are unconfirmed (Miller et al., 1959) .

Tyonek and Mouth of Little Susitna River (Site 19- Figure 3; Table 1)

Oil seeps reported near Tyonek and at the mouth of the Little Susitna River (Martin (1921) are unconfirmed (McGee (1972) .

Anchorage near Knik Arm (Site 20- Figure 3; Table 1)

Oil seepage was located near Knik Arm by Brooks (1922). A sample of this petroleum was collected and analyzed. No additional information is available. The seepage is probably no longer active.

Katalla Area East (Site 22- Figure 3; Table 1)

Seeps have been reported east of Katalla, but these have not been verified (McGee, 1972)

Samovar Hills (Site 24- Figure 3; Table 1)

Oil seeps exist on the north and west sides of Malaspina Glacier, the largest seep being on the northern margin of the glacier in the Eocene and Cretaceus strata of the Samovar Hills (Johnson, 1971). McGee (1972) estimated the total volume released from these seeps to be 2.5 bbl/day. This seepage area is documented by Rosenberg (1974) and Blasko (1976c) included it in his oil seep surveys and sample collections.

East Shore of Icy Bay (Site 25- Figure 3; Table 1)

These oil seeps have not been verified. McGee (1972) failed to find them during his surveys.

Lituya Bay (Site 27- Figure 3; Table 1)

A possible seep reported by Miller et al. (1959) to be associated with Tertiary sandstone on Topsy Creek is unconfirmed (McGee, 1972) .

Cape Spencer [Site 28- Figure 3; Table 1)

McGee (1972) indicated that, although oil films have been reported near Cape Spencer, there is no reliable information indicating seeps are present in this area.

Admiralty Island (Site 29- Figure 3; Table 1)

In 1944 a prospector reported to the USGS that he had seen an oil seep near the southwest end of Admiralty Island, at a locality several miles inland from the head of Herring Bay. J.C. Roehm, in an unpublished report of the Territory of Alaska Department of Mines (1947) referred to oil-saturated black shale and an oil seep near the southwest end of Admiralty Island and to bituminous matter in limestone of Permian age on the Keku Islands (Miller, et al., 1955). These seeps are unconfirmed.

THE EVIDENCE FOR SUBMARINE OIL SEEPS IN ALASKA

The authors of this report found a limited amount of data in the available public record on the presence of submarine seeps in Alaska. All of the seeps described in the literature as associated with the Alaskan marine environment (Ball Associates, 1965; Johnson, 1971; McGee, 1972; Wilson, 1973; Landes, 1973; Rosenberg, 1974) are not subtidal but are associated with the coastal terrestrial environment, either not flowing into the sea (Angun Point) , entering the sea through freshwater streams (Katalla, Yakataga) or located on a supratidal beach face (Skull Cliff). According to McGee (1972):

> "There are only four known active seep areas in proximity to Gulf of Alaska marine waters. The total amount of oil emitted by these areas is estimated to be 296 + or - gallons per day, most of which is evaporated or degraded by oxidation with the formation of hydrocarbon soils. The total amount of oil reaching the Gulf of Alaska marine waters is estimated at 10% of the total amount, or about 30 gallons a day. There are no known seeps within the Gulf of Alaska marine waters and there have been no reports of visual observations of oil films or tarry material that would indicate underwater oil seeps."

A statement quite similar to that of McGee's relative to the absence of reported submarine oil seeps in the Gulf of Alaska is also found in Rosenberg (1974).

Review of the literature, plus conversations with numerous agency and oil industry geologists indicates that, except for a possible site in the southeastern Bering Sea, there is no information available in the public sector identifying submarine oil seeps in the Alaskan OCS, including the Alaskan Arctic. All of the subtidal seeps that have been discovered in the World's oceans so far have been the result of observing obvious surface-floating oil globules and slicks. So far, none have been seen in the Alaskan Beaufort and Chukchi seas. Twenty-eight months of observations by USGS scientists in the Alaskan Arctic have recorded no obvious surface evidence of submarine oil seeps (Erk Reimnitz, Pers. Comm., 1988).

Hydrocarbon gases (C_1-C_4) have been found to be quite common in the surface sediments of the Beaufort Sea (Sandstrom et al., 1983) . It is also believed that shallow gas (19-35 m depth) occurs quite extensively in this region (Craig et al., 1985) . Shallow gas may be found in isolated pockets beneath permafrost, in association with faults that cut Brookian strata, and as isolated concentrations in the Pleistocene coastal plain deposits. Much of this gas may be biogenic in origin. Carbon isotope analysis of shallow gas collected from sediments at Flaxman Island indicated biogenic methane (Reimnitz, pers. Comm., 1988).

Of the several kinds of shallow faults identified on the Beaufort Sea Shelf, the shallow gas seems to be most commonly identified adjacent to high-angle faults along the Barrow Arch (Figure 22) which may act as conduits for gas migration (Craig et al. 1985) . Such faults might also act as conduits for petroleum seepage.

Ventkatesan and Kaplan (1982) and Ventkatesan et al. (1983) in their review of the distribution and transport of hydrocarbons in surface sediments of the Alaskan outer continental shelf, found little evidence of surface or subsurface oil seepage. The exceptions were in Cook Inlet, north of Kalgin Island, and in the southeastern Bering Sea.

In the case of Cook Inlet, bottom sediments at a location north of Kalgin Island (60°34'N: 151°49'W) (Figure 23) contained an alkane distribution with a broad UCM over the entire boiling point range which is typical of weathered petroleum. In addition, an anthropogenic source of hydrocarbons was also indicated by the presence of a triterpenoid suite similar in pattern to Cook Inlet crude oil. Although the presence of an oil seep was not excluded by the authors, Ventkatesan and Kaplan (1982) suggested that these compounds could have originated from petroleum production in the upper Cook Inlet. Considering the relatively long history of oil production in the upper inlet, the latter source is very likely. Interestingly, this site is at the same location as the most western tidal rip which was observed to trap the crude oil spilled during the GLACIER BAY incident of July 1987.

Although no submarine oil seeps have been reported from the Bering Sea, sediment geochemical studies have indicated the presence of weathered crude oil from sediments at one location in the southeastern Bering Sea (station 35 - 56°12'N: 168°20'W, Figure 24) (Ventkatesan et al., 1981; Ventkatesan and Kaplan, 1982; Ventkatesan et al., 1983). Gas chromatograms of the hexane extract from these sediments, sediments from two other locations in the Bering Sea, as well as weathered oil contaminated sediments from the San Pedro Basin of California are presented in Figure 25. The n-alkane distribution with a broad UCM over the entire boiling point range is typical of microbial degraded petroleum. In addition, the titerpenoid distribution (Figure 26) and the delta ^{34}S value for the organic sulfur (about 10% more positive than the other samples from the eastern Bering Sea) are consistent with the n-alkane distribution in these sediments and suggest the presence of thermogenic hydrocarbons.

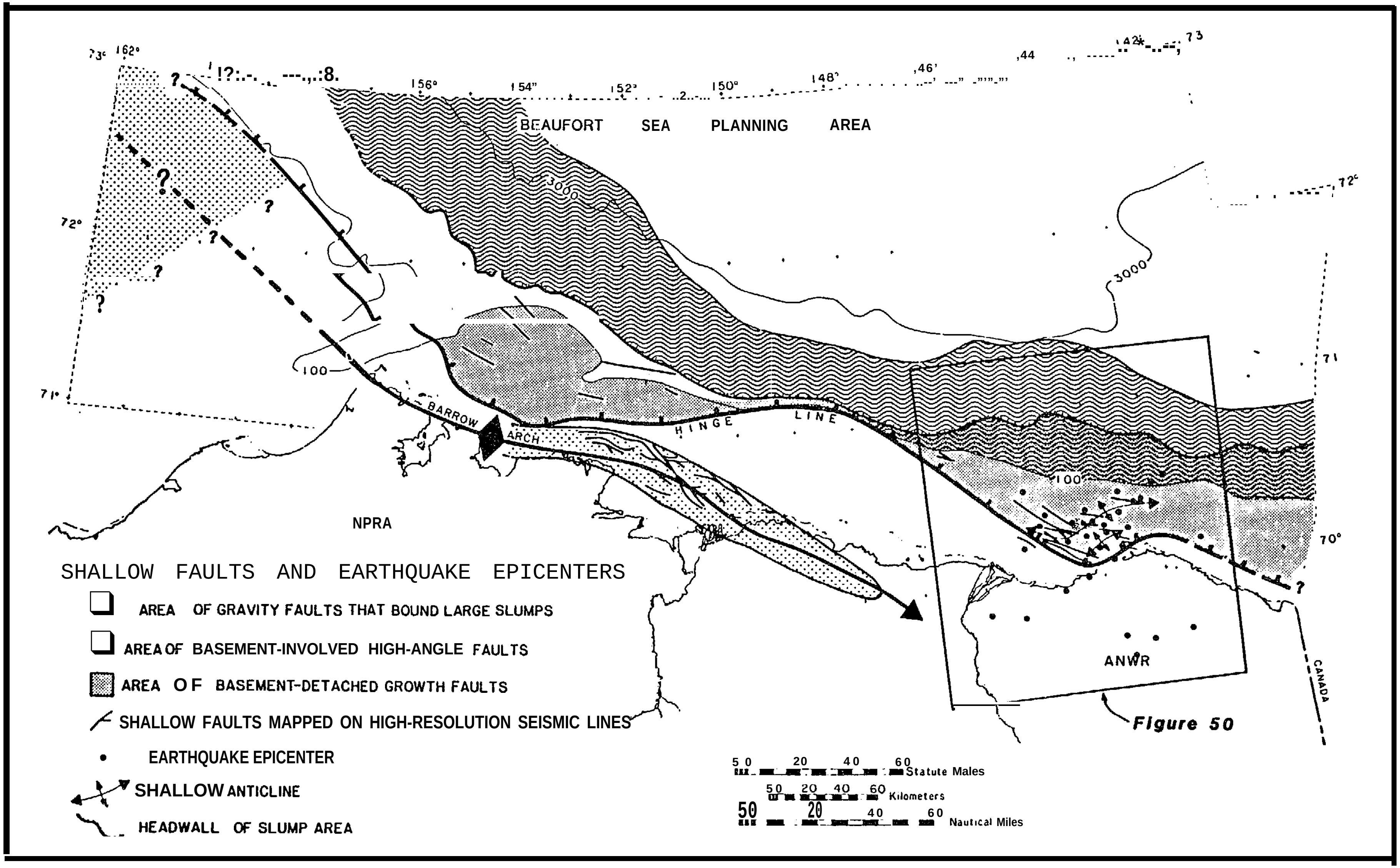

Figure **22.** Shallow Faults, Mapped or Expected in the Beaufort Sea. From Craig et al. (1985)

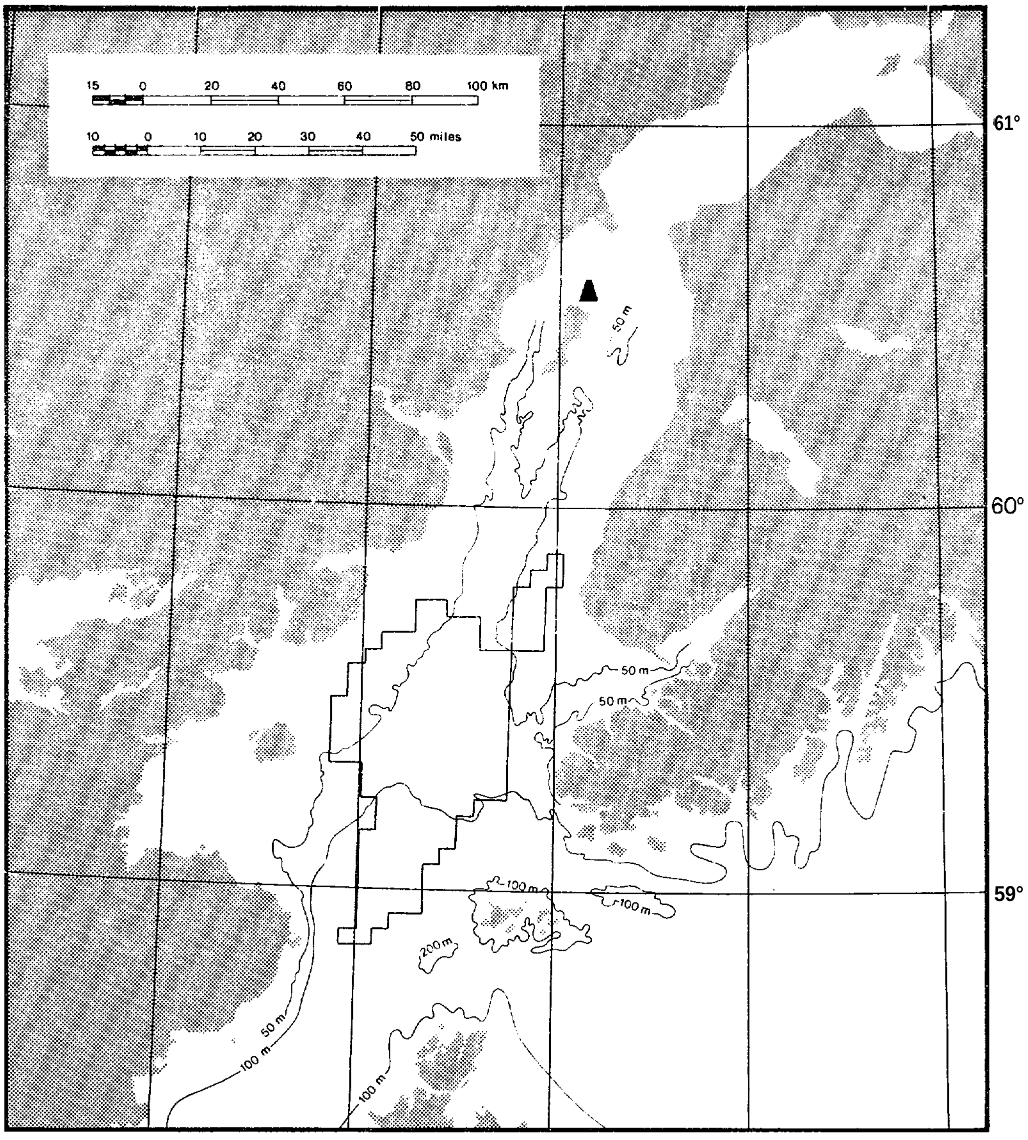

Figure 23. Locations of Elevated **Levels of** Anthropogenic **Hydrocarbons** in **Sediments (A) of Cook Inlet** (Venkatesan and **Kaplan,** 1982).

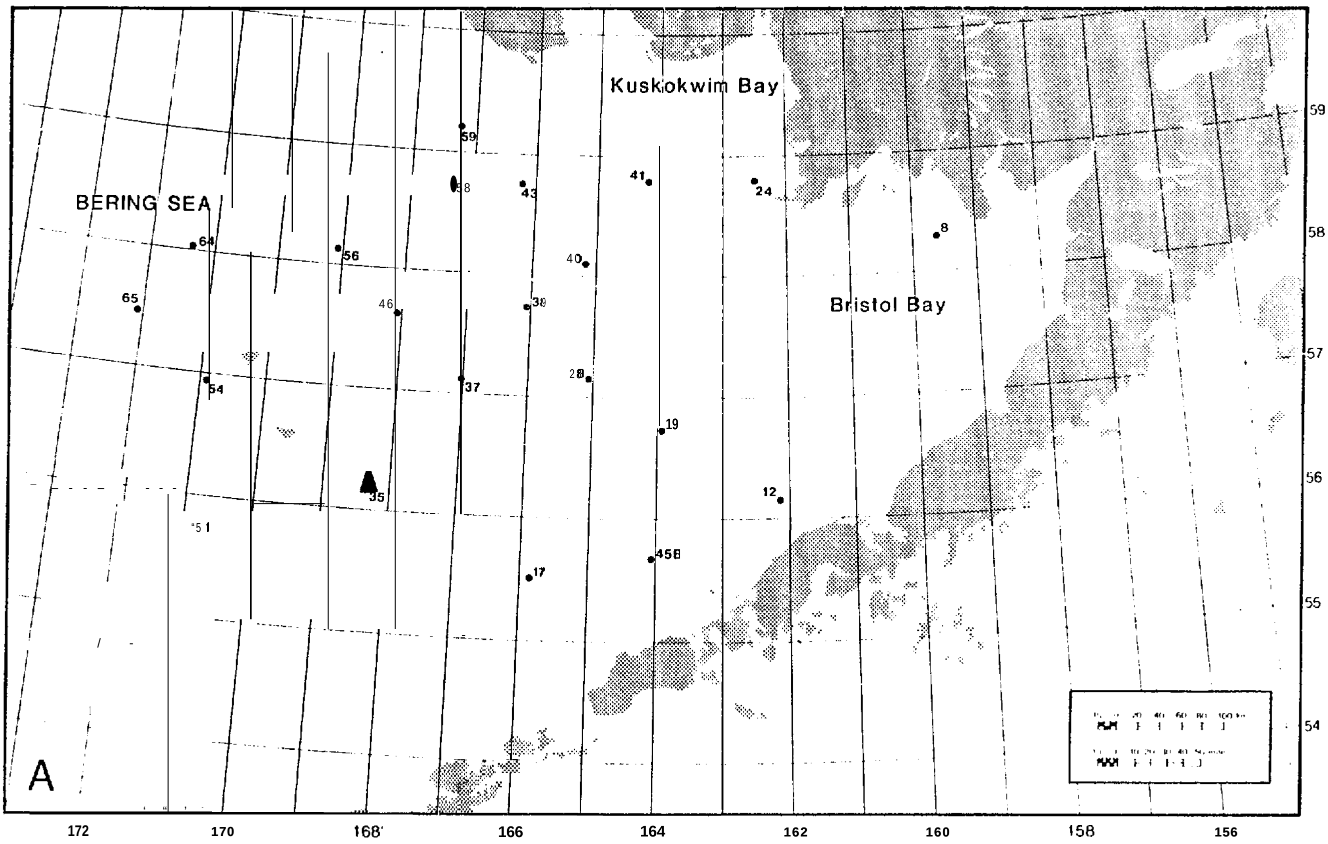

Figure 24. Locations of Elevated Levels of Anthropogenic Hydrocarbons in Sediments (A)ofthe Bering Sea(Venkatesan and Kaplan, 1982).

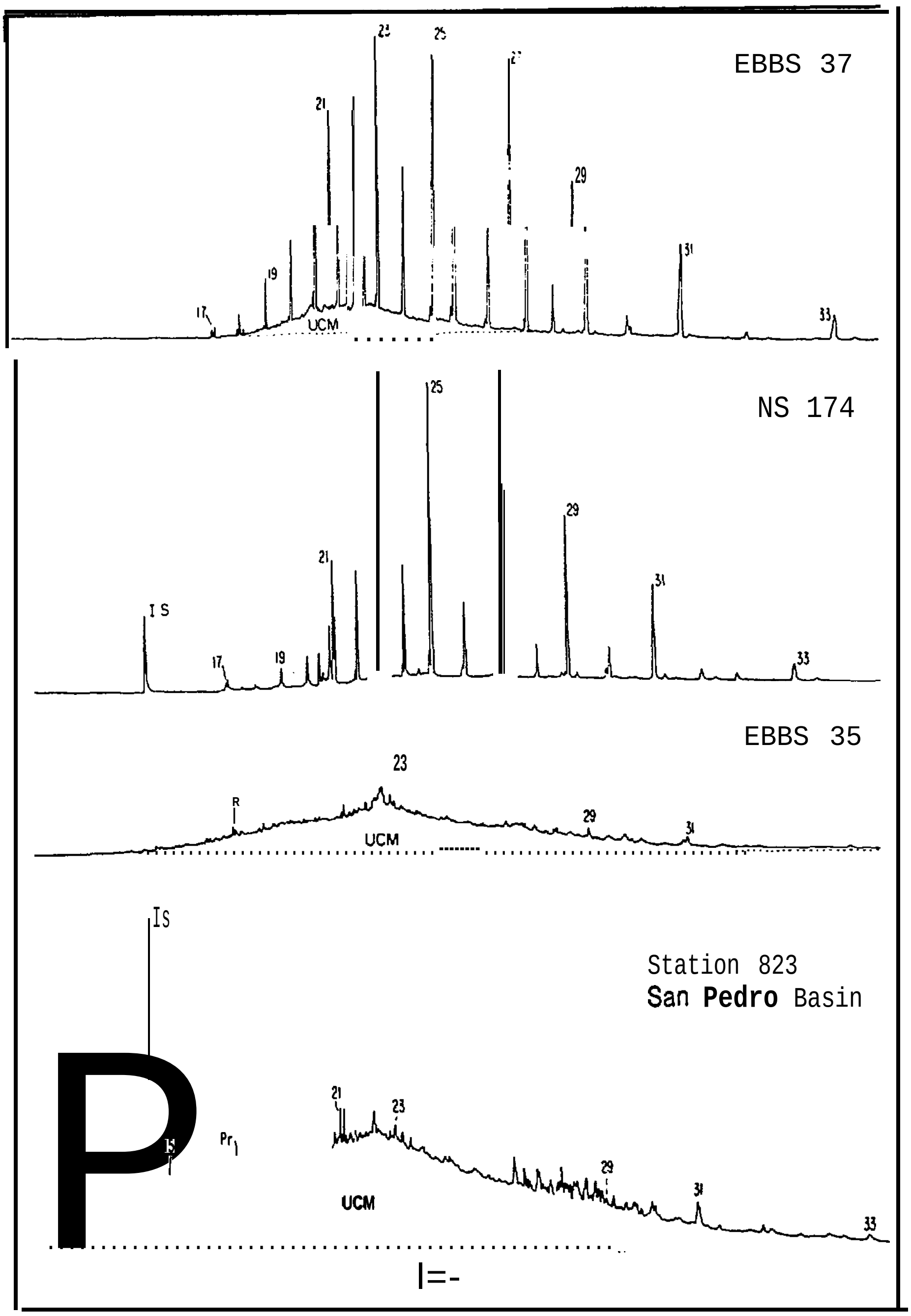

Figure 25. n-Alkane Distribution in Sediments from the Bering Sea and California (from Venkatesan et al, 1981). Gas chromatograms of hexan fraction from southeastern Bering Sea (EBBS) and Norton Sound (NS) sediments. Station 823 contaminated with weathered petroleum (Venkatesan et al., 1980). Numbers 15-33 refer to carbon-chain length of n-alkanes. Pr: pristane. UCM: unresolved complex mixture. LS: Internal Standard hexa-methyl benzene.

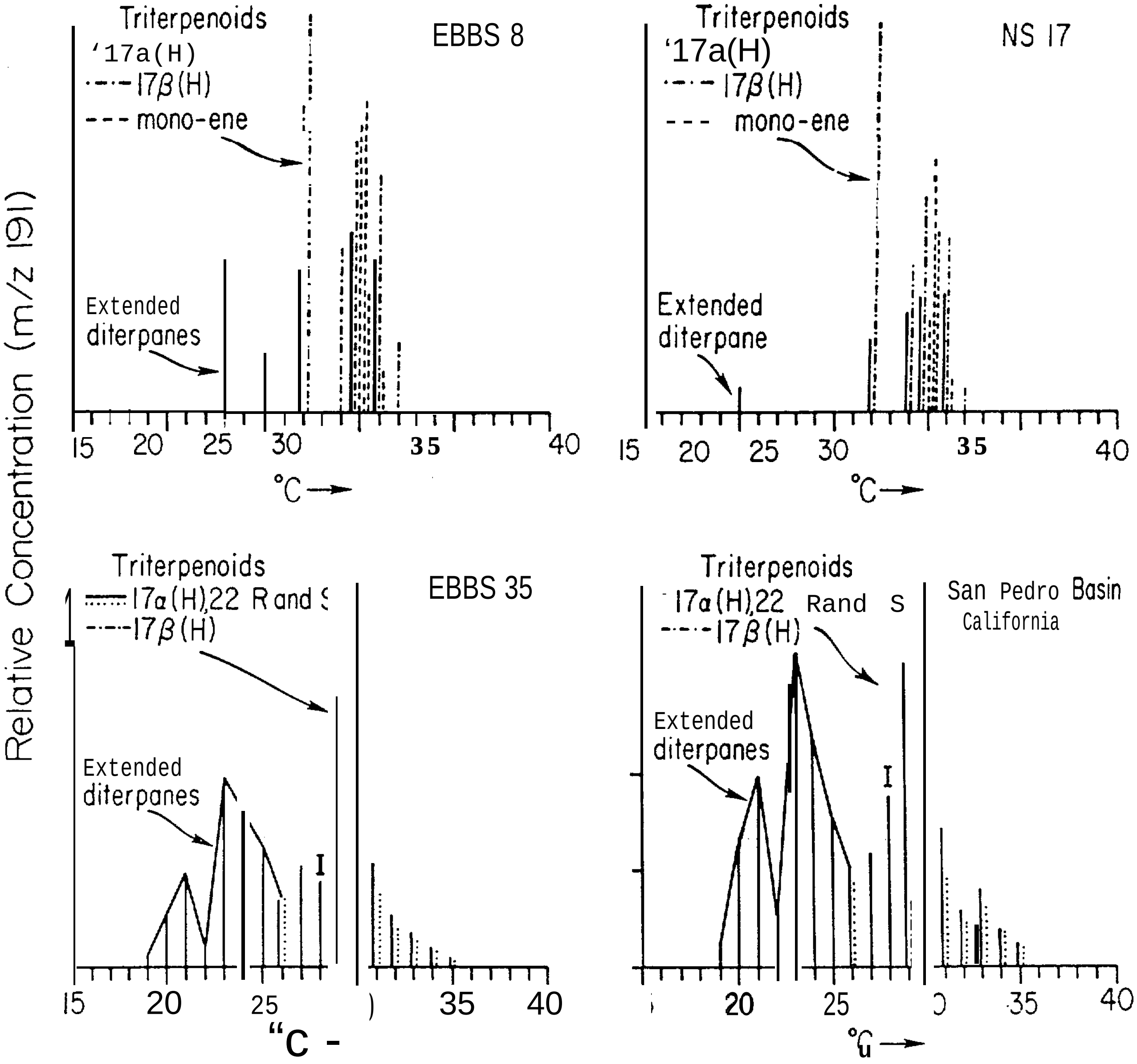

Figure 26. Diterpenoid and Triterpenoid Distributions in Sediments from the Bering Sea (from Venkatesan et al., 1981). Relative distribution histograms based upon m/z 191 mass chromatograms. EBBS = southeastern Bering Sea; NS = Norton Sound; San Pedro Basin = 20-25 mm core, Venkatesan et al., 1980. Diastereomers indicated by dotted and continuous lines. I is 17a(H), 18a(H), 21b(H)-28, 30-bisnorhopane.

It is possible that petroleum is being released from faults that occur in this area. Thermogenic gas was reported by Kvenvolden and Redden (1980) and Kvenvolden et al. (1981) from two locations near Station 35 (56°17.8'N: 168°14.28'W and 56°11.95'N: 168°20.01'W). However, there was no correlation between hydrocarbon gas and C_{15+} hydrocarbon content in those sediments from this site (Sandstrom et al., 1983).

Site 35 occurs at about the 200-m depth contour, in the Outer Shelf Domain at about the Shelfbreak Front (Kinder and Schumacher, 1981). Sediments from the area have been characterized as predominately sand (70 %) (Haflinger, 1981). Annual bottom-water temperature fluctuations are probably not as great here as occurs within the Middle Shelf and Coastal Domains due to the influence of the northwesterly flowing Bering/Alaska Stream water on the Outer Shelf Domain. Haflinger (1981) suggests that the benthic community associations in this area probably consist of stenothermal, Arctic-Boreal species. Multivariate statistical analysis of benthic species associations indicate that the area near Station 35 contains relatively small group (3-5 species) associations of ampeliscid amphipods, bivalves, and polychaetes (Haflinger, 1981). Infaunal standing biomass also appears to be relatively low (<75 g/m^2, wet weight; <4 g/m^2, infaunal organic carbon; Haflinger, 1981). If the Station 35 vicinity eventually proves to contain oil seeps, this site may prove useful in addressing the hypothesis of "organic enrichment" which is discussed in "Effects of Low Level Chronic Releases of Petroleum Hydrocarbons on Components of the Marine Ecosystem," this volume.

Based on anomalous levels of C_1 - C_2 gases measured by Cline and Holmes (1977) in Norton Sound (Figure 27), it was suspected that petroleum seepages were present south of Nome. Although of thermogenic origin, additional investigation (Venkatesan et al. 1981; Kvenvolden et al., 1979; Kvenvolden et al., 1981) indicated that the major compound in this seepage was CO_2. There was little hydrocarbon accumulation in the sediments, which was probably due to discrete gas vents piping hydrocarbons directly into the water column (Kvenvolden et al., 1981).

Several studies have been conducted on the distribution of hydrocarbons in the sediments of the Alaskan Arctic OCS (Shaw et al., 1979; Shaw, 1981; Kaplan and Venkatesan, 1981; Venkatesan and Kaplan, 1982; Venkatesan et al., 1983; Boehm et al., 1987) From these studies it is apparent that hydrocarbon concentrations in Beaufort Sea sediments are somewhat elevated over other outer continental shelf sediments. The compositions of the hydrocarbons are largely fossil derived (peat, coal and petroleum) and, therefore differ from most other shelf sediments.

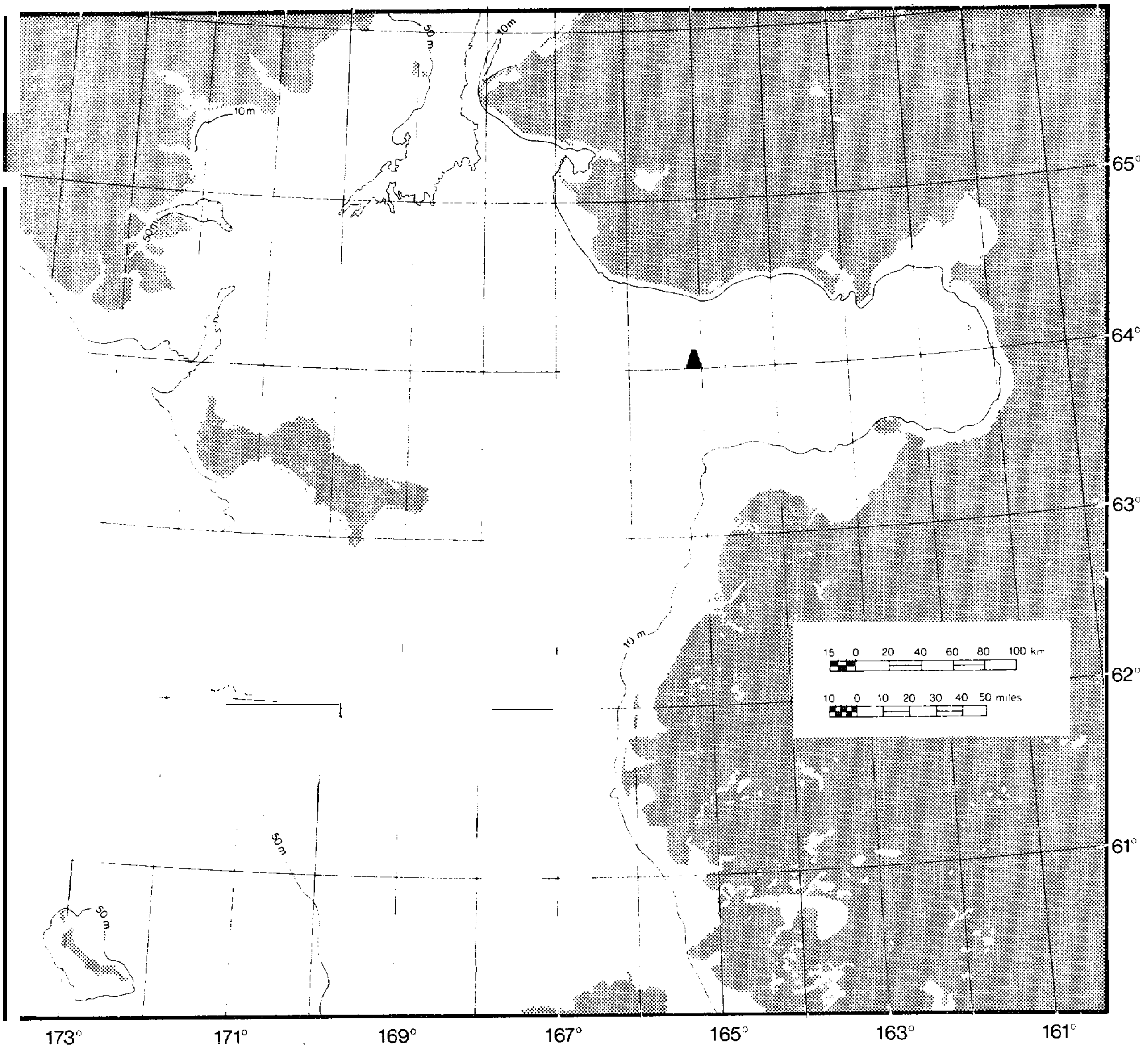

Figure 27. Location of Gas Seeps (A) in Norton Sound (Kvenvolden, 1981).

Shaw, et al. (1979) examined the hydrocarbons in the nearshore sediments from Point Barrow to Barter Island and identified a suite of nearshore arctic sediments whose alkane composition suggested only biogenic sources. The saturated hydrocarbons were dominated by n-alkanes ranging in chain length of 23-31 C with strong odd-even preference and no UCM. Total hydrocarbon concentration in the nearshore area was 0.3-20 ug/g dry sediment. The range of total hydrocarbon concentrations in the offshore areas was reported by Kaplan and Venkatesan (1981) and Venkatesan and Kaplan (1982) to be 20-50 ug/g dry sediment. These differences in nearshore vs. offshore areas could possibly have been due to the differences in the methods used or to a greater abundance of fine-grained, organic-rich sediments in the offshore area.

In both nearshore (Shaw et al., 1979) and offshore (Kaplan and Venkatesan, 1981; Venkatesan and Kaplan, 1982) sediments, the distribution of saturated hydrocarbons indicated a prevalent biogenic input of terrigenous plant material, most likely resulting from transport of riverine materials. Some marine biogenic sources were indicated by the occurrence of pristane and n-heptadecane in the offshore sediments (Kaplan and Venkatesan, 1981; Venkatesan and Kaplan, 1982).

Measurable amounts of aromatic hydrocarbons have been found in almost all Beaufort Sea sediments examined so far. Ventkatesan and Kaplan (1982) indicated that Beaufort Sea sediments contain the highest PAH levels in the Alaskan outer continental shelf (200-300 rig/g), an order of magnitude above that of the Bering Sea and also higher than the Gulf of Alaska and Cook Inlet. Complex mixtures of aromatics (including PAH) have been found with distributions characteristic of both pyrolytic and fossil sources (Shaw, et al., 1979; Kaplan and Venkatesan, 1981; Venkatesan and Kaplan, 1982)). This was suggested by the distribution of akylated homologies determined by GC/MS.

Shaw et al. (1979) found that fossil aromatic distribution was most obvious at Smith Bay, Cape Halkett, Egg Island and Stockton Island (Figure 28). Pyrolytic signatures were most evident in the sediments of the Hulahula Delta, Anderson Point and Pitt Point. Those aromatics recognizable as of fossil origin were cadalene, retene and simonellite, products of minor diagenic alteration of terpenes. Only retene was a member of one of the homologous series investigated. It appeared in anomalous abundances in sediments of Smith Bay, Cape Halkett, Atigaru Point, Colville Delta, Oliktok, Simpson Lagoon, Egg Island, Stump Island, Cross Island, and Hulahula Delta. In their analysis, it was unclear to what extent diterpenoid aromatics were being produced from precursors supplied by

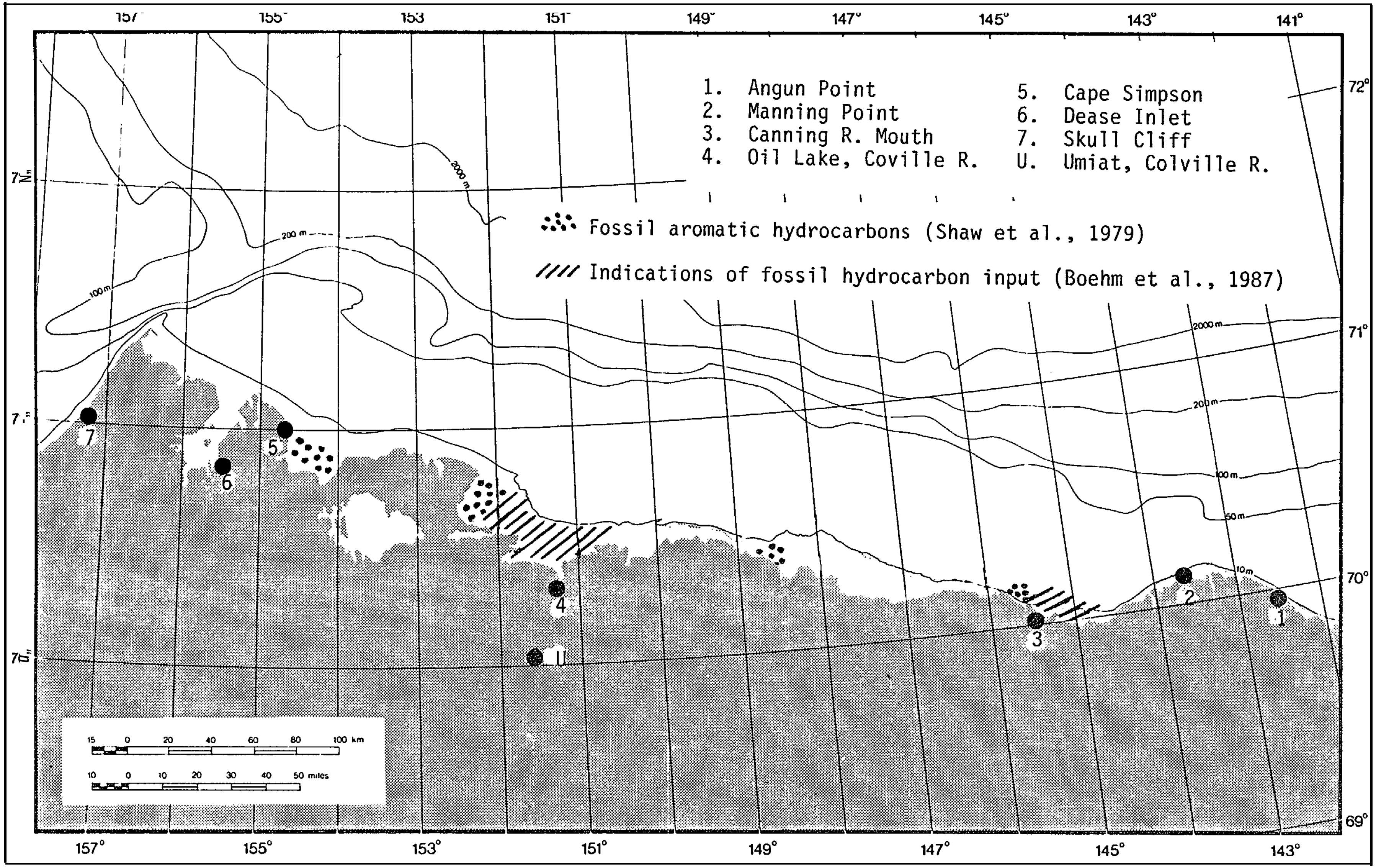

Figure 28. Coastal Seepage Areas on the Alaskan North Slope.

contemporary plants or were derived from sedimentary fossil hydrocarbons, such as peat, coal, and oil (seeps) .

In a two year study of the hydrocarbons and metals of the Beaufort Sea, Boehm et al. (1987) found that the saturated hydrocarbon composition (determined by GC-FID analysis) was composed of an n-alkane distribution from n-C_{10} to n-C_{20} with no odd-to-even carbon dominance and and n-alkane distribution from n-C_{21} to n-C_{33} with a distinct odd-to-even dominance. The n-C_{10} to n-C_{20} alkanes appeared to originate in the rivers, possibly due to upstream fossil inputs, while the coastal peat samples contributed to the sediments throughout the study area and were rich in the higher molecular weight alkanes. There appeared to be no relationship between the distribution patterns of the PAH compounds and the saturated hydrocarbons.

The aromatic hydrocarbon distributions were fairly uniform with the 2- and 3-ringed naphthalene and phenanthrene series dominant (Boehm et al., 1987). In other continental shelf sediments not impacted by petroleum, the 4- and 5-ringed PAH usually dominate. It appears that this lower molecular weight PAH originates from river discharge (introducing fractions from peat, coal beds and oil seeps) .

Sediment samples from Harrison Bay contained the strongest signals for fossil hydrocarbon input - PAH and lower molecular weight alkanes (Figure 8) (Boehm et al. , 1987) . This was attributed to input from the Colville River drainage basin, which contains numerous outcrops of coal and oil shale as well as oil seeps. For example, Oil Lake is located slightly west of the Colville and 5 mi from the coast (70°18'N: 151°09'W). This 1.5-mile-long lake is named for the natural seep oil that forms a slick on its surface. The organic material carried by the Colville River includes fractions of peat, coal, and oil.

Stations in the Harrison Bay region contained the greatest concentrations of hydrocarbons, with those in east Harrison Bay area, nearest the Colville River, having the highest values. This was also reflected in the PAH concentrations (2-3 ringed PAH). Unfortunately, no samples were collected in Smith Bay, therefore, indications of fossil hydrocarbon input presented by Shaw (1979) could not be confirmed with data from Boehm et al. (1987) . The lower molecular weight n-alkanes characteristic of petroleum were found to be relatively high in the sediments discharged from both the Canning and the Colville rivers.

The general conclusion from this review is that the existing data base on the hydrocarbon constituents of the sediments in the Beaufort Sea can not be used to any great extent to locate areas of probable submarine seepage. This is basically due to the limitation in areal coverage of sampling stations, plus the fact that all areas of elevated fossil derived hydrocarbons which have been identified by this limited data base can be attributed to either known coastal terrestrial seepages or freshwater stream input from a variety of sources (known oil seeps in the river system, coal deposits, and peat) .

DISCHARGE OF OIL FROM NATURAL SEEPS INTO THE ALASKAN MARINE ENVIRONMENT

It is difficult to estimate the volume of oil that might be entering the Alaskan marine waters via natural oil seepage. For the seepages located on the Arctic coast, only those at Skull Cliff and Manning Point appear to be directly entering the marine environment. The volumes of those discharges have not been determined.

Terrestrial erosion undoubtedly provides petroleum hydrocarbons to the Arctic marine waters through transport via freshwater streams, but no estimate of the magnitude of this input is available. Much of the oil is probably altered and oxidized during erosion and transport. It might also be difficult to distinguish petroleum hydrocarbons from coal-bed sources. Kvenvolden and Harbough (1981) estimated that, on a world-wide basis, only 10 percent of the erosional petroleum hydrocarbons actually reach the ocean.

McGee (1972) estimated the amount of natural oil seepage discharge to the marine waters of the Gulf of Alaska. His estimates for individual seeps were usually <1.0 bbl/day. His estimate of total discharge to the Gulf of Alaska from all known seeps was 7 bbl/day. This value is an order of magnitude less than the estimated 70-90 bbl/day released from the Coal Oil Point submarine seep off the California coast (Hunt, 1979) .

EFFECTS OF LOW LEVEL CHRONIC RELEASES OF PETROLEUM HYDROCARBONS ON COMPONENTS OF THE MARINE ECOSYSTEM

The low level, chronic release of oil into the marine environment, such as may occur with oil and gas development and production activities, has been postulated to exert effects on the marine community ranging from organic enrichment to environmental toxicity (Spies, 1985). The resolution of this question is difficult as pertinent laboratory research requires a major long-term commitment from the researcher and the funding agency. The use of marine seeps as "natural laboratories", although replete with the problems typical of field studies, is a viable alternative to laboratory research.

A group of easily accessible, very active seeps near Coal Oil Point in the Santa Barbara Channel, California are the most extensively studied marine seeps in the world. Of this group, the Isla Vista seep, shaped like a rough oval approximately 10,000 m^2 in area, releases 50 to 100 bbl per day of petroleum into the Pacific Ocean, has been the focus of a series of long-term observations and field experiments (See Montagna et al., 1986 for references). Seepage within the oval is variable. There are many loci, ranging from approximately 0.25 - 2.0 m^2, of very active seepage. Between these loci are larger areas of less active but observable seepage. Gas bubbles are common and are often associated with the oil droplets. The seepage differs from the production oil pumped from similar formations farther offshore by virtue of its extremely low levels of n-alkanes and high levels of low-molecular-weight naphthenic compounds, suggesting bacterial degradation of the oil before it reaches the sediment-water interface (Reed and Kaplan, 1977; Figure 29).

The total extractable hydrocarbons in the sediments around the seep range from nearly 100% in source sediments to less than 1 ppt several kilometers "upstream", with an apparent median concentration (within 2 kilometers) of between 5,000 and 10,000 ppm. Total extractable hydrocarbons as well as the proportion of fresh petroleum can be quite variable in close-set samples depending on how many lumps of tar or oil droplets are included in the sample. Every core (0.019 m^2) taken at the seep station during a 28 month study of community structure by Davis & Spies (1980) contained at least a few drops of fresh oil, evidence that benthic organisms are brought into close contact with large amounts of petroleum. Most of the exposure however, appears to be to highly weathered asphaltic compounds and, except in heavy seepage areas or chance encounters with droplets in areas of moderate seepage, the exposure to the most acutely toxic and water soluble, mono- and di-aromatic petroleum compounds is in the low parts-per -billion range. The concentrations of

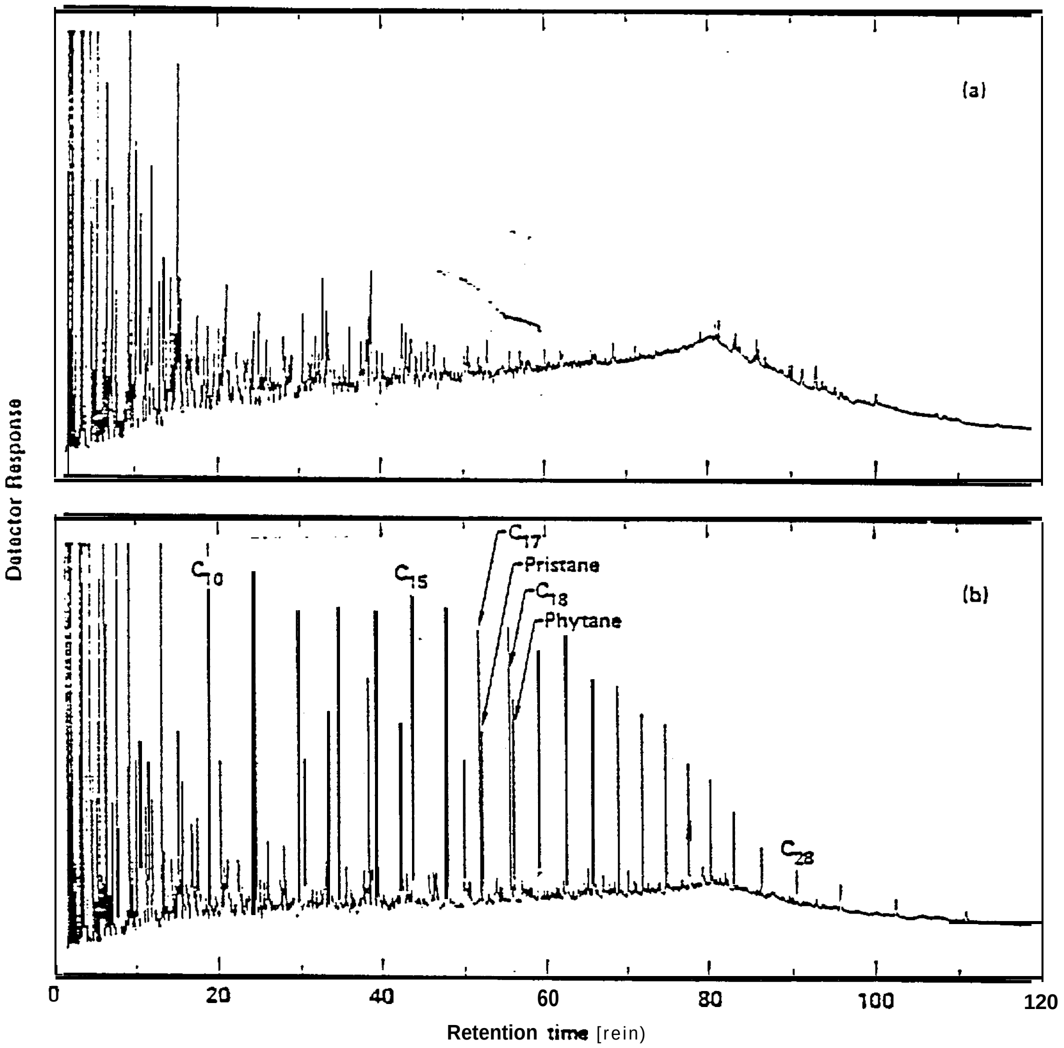

Figure 29. Gas chromatograms of crude oils: a) Isla Vista seep and b) Platform Holly, Monterey Zone. Note the large hump of the Unresolved Complex Mixture (UCM) that is indicative of microbially degraded oils in the Isla Vista seep oil. (from Spies et al. 1980)

these hydrocarbons are usually below 10 ppb in waters around the Coal Oil Point seep and are often in the <1 ppb range. The concentrations in interstitial water are more variable: in an area of intense seepage, an interstitial water sample had a concentration of 1.3 ppm (these limited areas are generally depauperate in numbers of individuals and species, Spies et al. 1980); in areas of moderate seepage, concentrations ranged from 45 to 117 ppb and in a non-seepage area, concentrations of 0.2 to 5.0 ppb have been observed (Stuermer et al. 1982) .

The benthic community of the Isla Vista seep is well developed, with a typical structure and faunal composition for that region of the California coast. Comparisons of the seep community with a nearby non-seep community (Spies & Davis, 1979; Davis & Spies, 1980), however, demonstrated consistently higher numbers of individuals at the seep station than the non-seep station, even though the number of species at the seep station was only slightly higher. The dominant species, listed in Table 8, contributed a total of 58 and 52% of the individuals to the seep and comparison stations, respectively. Both sites had in common 72% of the 320 species collected, representing over 90% of the individuals. The remaining (site-specific) 28% or 90 species represented only 10% of the total number of individuals collected. Both areas had, on the average, similar values for diversity (H') although small scale fluctuations of Shannon-Weiner diversity were apparent; evenness was fairly constant and the differences seen were not consistent. Measures of skewness and kurtosis of the dominance-diversity curves were also quite similar, despite the density differences between stations and pronounced seasonal fluctuations (Davis and Spies, 1980) .

Other, less striking differences between the two stations were:

1. An abundance of surface-deposit feeders at the seep station (14 of the 15 species considered). The seep station had one carnivore and 14 deposit-feeders (11 surface); the comparison station supported 3 carnivores, 1 herbivore, 6 surface-deposit feeders and 5 sub-surface feeders (Table 8) .

2. The extreme dominance of oligochaetes, both individuals and populations, at the seep station.

3. Significantly fewer numbers of amphipods (5.9% of total) at the seep station as compared to the non-seep station (11.5%) .

Spies et al. (1980) suggested that the differences in density and the numbers of surface deposit feeders at the

Table 8. Fifteen most abundant taxa from each station during study period (December 1975 - March 1978) near Santa Barbara, California. Abbreviations in parentheses denot A, amphipod; An, anthozoan; E, echinoderm; O, ostracod; Pe, pelecypod; Po, polychaete. (Davis and Spies, 1980)

Taxa	Density per core ($\bar{X} \pm S_{\bar{X}}$)	[a]
Seep Station:		
Oligochaetes	14.0 ± 7.3	
Tellina modesta (Pe)	12.1 ± 7.0	(1)
Mediomastus californiensis (Po)	11.1 ± 7.6	(2)
Euphilomedes sp. (0)	9.4 ± 2.1	(3)
Prinospio pygmea (Po)	9.0 ± 4.2	(4)
Nematodes	8.5 ± 4.7	(5)
Chaetozone setosa (Po)	7.5 ± 4.9	(6)
Tharyx nr tesselata (Po)	6.7 ± 3.4	(7)
Tellina nuculoides (Pe)	4.2 ± 2.8	(8)
Nepthys caecoides (Po)	3.9 ± 3.4	(9)
Parvilucina approximata (Pe)	3.4 ± 3.3	
Ophiuroid	3.4 ± 2.6	
Edwardsia sp. (An)	2.8 ± 3.7	(lo)
Neries procera (Po)	2.8 ± 1.5	
Pista disjuncta (Po)	2.6 ± 4.2	(11)
Comparison station:		
Nematodes	8.5 ± 5.4	
Euphilomedes sp. (0)	6.7 ± 1.7	
Prinospio pygmea (Po)	6.6 ± 4.7	
Chaetozone setosa (Po)	4.0 ± 3.2	
Tellina modesta (Pe)	3.4 ± 3.1	
Mediomastus acutus (Po)	3.4 ± 1.4	(15)
Paraphoxus abronius (A)	3.2 ± 2.4	
Typosyllis sp. (Po)	2.8 ± 0.8	
Mediomastus californiensis (Po)	2.7 ± 2.0	
Lytechinus pictus (E)	2.4 ± 4.2	
Thaianessa spinosa (Po)	1.9 ± 0.7	
Edwardsia sp. (An)	1.8 ± 2.9	
Exogone uniformis (Po)	1.7 ± 0.8	(13)
Megaiona piteikai (Po)	1.6 ± 1.9	
Tharyx nr tesseilata (Po)	1.6 ± 0.8	

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[a] Thirteen of the 15 most abundant taxa common to both stations; not listed are No. 12, Hemilamprops sp. (cumacean) and No. 14, Hemicordata.

two stations were a reflection of microbially-mediated organic enrichment occurring as a result of the seepage. This hypothesis of increased microbial biomass associated with the H_2S and oil-laden seep sediments was based on gas chromatography indicating extensive bacterial degradation of the n-alkanes in the seep oil (Reed & Kaplan, 1977) and the presence of extensive mats of the sulfide-reducing bacterium, *Beggiatoa sp*., in areas of intense seepage. Experimental evidence for a gradient of increasing sediment ATP with increasing amounts of fresh oil also supports this hypothesis (Davis & Spies, 1980). More recent work (Montagna et al., 1986; Montagna et al., pers. comm.) has correlated bacterial abundance (as number of cells) and measurements of microbially-mediated benthic metabolism, e.g. rates of hydrocarbon degradation and sulfate reduction, with total extracted hydrocarbons (Table 9) .

Evidence for the utilization of the seeping petroleum by the benthic community was provided by examination of the isotopic ratios of sulfur and carbon in the tissues of infaunal invertebrates from seep and non-seep stations (Spies & DesMarais, 1983). The seepage constituents are isotonically light with respect to carbonate: g^{13}C = -24% for whole oil and -38% for the gasses (Reed & Kaplan, 1977). Other sources of carbon in the marine environment are quite variable but generally consist of isotopically heavier carbon with less negative values of g^{13}C. So if the consistently denser populations in the seep truly result from trophic enrichment by petroleum that is isotonically light in carbon, then one would expect a shift in the g^{13}C values of the seep organisms towards more negative values. The stable carbon-isotope abundances in *Beggiatoa sp*. and 12 infaunal invertebrates common to both the seep and comparison stations displayed g^{13}C shifts ranging from - 0.22% for the cirratulid polychaete *Tharyx tesselata* to -4.5% for the maldanid polychaete *Axiothella rubrocinta* (Table 10). The mean shift for all species was -1.32% towards the petroleum g^{13}C value. Interestingly, the development of a carbon budget for the maldanid polychaete, *Praxillella affinis pacifica*, indicated that the lighter hydrocarbons and gases, e.g. methane, were utilized more readily than the liquid oil (Spies & DesMarais, 1983) .

Similarly, the presence of large amounts of isotopically light H_2S (g^{34}S=1.7%) as compared to the heavier (g^{34}S=20%) sulfur found in seawater and most marine organisms (Kaplan et al., 1960) provides a tracer of energy derived from the petroleum seepage. Sulfate reducers favor $^{32}SO_4^{-2}$ and low sulfur isotope ratios are indicative of biologically derived H_2S. The sulfur isotope ratios for *P. affinis pacifica* are lower at the seep station (12.27 compared to 14.11). The sulfur isotope ratio in the interstitial H_2S at the seep station is lower yet (1.69) and lowest in *Beggiatoa* mat (-0.37) at this station (Spies & DesMarais, 1983).

Table 9. Grand averages of bacterial abundances, metabolic rates and total hydrocarbon concentrates in the sediments at Seep and Comparison sites in and near the Isla Vista petroleum seep in the Santa Barbara Channel. (modified from Montagna et al., 1986)

Process	Station	
	Seep	**Comparison**
O_2 Flux (mmol M'^{2} d^{-1})	-41	-12
Sulfate reduction[1] (mmol M^{-2} d-l)	4.1	0.66
Hydrocarbon mineralization[2] (%d^{-1})	10	5.1
Total hydrocarbons (mg g-l sediments)	4.8	1.1
Mean cells[3] (millions cm '^{1} sediment)	58	47

[1] To a depth of 5cm

[2] Average of alltests

[3] Data from Montagna et al. unpubl.

Table 10. Stable carbon isotope abundances and $\delta^{13}C$ shifts in samples of benthic organisms from petroleum seep area of Santa Barbara Channel. Numbers of samples are given in parentheses. am: amphipod; bi: bivalve; po: polychaete. nd: no data. (Spies and DesMarais, 1983)

Organism	Mean $\delta^{13}C$				$\Delta\delta^{13}C$
	Comparison		Seep		
Praxillella affinis pacifica (po)	-17.97 ± 1.12	(4)	-20.7 ± 0.58	(3)	-2.73
Axiothella rubrocinta (po)	-16.9	(1)	-21.4	(2)	-4.5
Mediomastus californiensis (po)	-16.6	(1)	-17.5	(2)	-0.9
Hemichordate	15.9	(1)	16.3	(1)	-0.4
Tellina modesta (hi)	-16.18 ± 0.49	(4)	-16.65	(2)	-0.47
Tharyx tesselata (po)	-17.05	(2)	-17.27	(1)	-0.22
Pista disjuncta (po)	-17.35	(2)	-18.13	(2)	-0.78
Nematodes	-17.4	(1)	-18.45	(2)	-1.05
Nereis procera (po)	-17.4	(1)	-19.1	(2)	-1.7
Paraphoxus spp. (am)	-14.27 ± 1.7	(3)	-13.8	(1)	-0.47
Nepthys caecoides (po)	-16.15	(2)	-18.07	(1)	-1.93
Glycera branchiopoda (po)	-16.05		-16.75	(2)	-0.7
Beggiatoa sp.	nd		-20.7		nd
			Mean = - 1.32±1.24		

In summary, benthic metabolism at the Isla Vista seep is similar to that described for other organically enriched systems such as salt marshes (Howarth & Teal, 1980) and abyssal hydrothermal vents (Karl et al., 1980) . When the enrichment is derived from seeping petroleum, aerobic heterotrophs metabolize petroleum to supply chemoautotrophs with carbon; the energy source is H_2S, originally at least partially derived from the oxidation of petroleum (Figure 30) . Meiofauna feed on both the heterotrophs and the chemoautotrophs as well as the chlorophyllous microbes (either microalagae or cyanobacteria) and are in turn fed upon by macroinfauna and larval fish.

Enrichment is not the only observed effect of the seeping petroleum. Even at low levels, oil released in the marine environment may cause changes in community structure as the result of the mortality, decreased reproduction or avoidance of sensitive or vulnerable species. Amphipods, in particular, seem to be sensitive to low levels of petroleum hydrocarbons. Davis & Spies (1980) reported significantly fewer numbers of amphipods (5.9% of total) at the seep station than at the comparison station (11.5% of total individuals) . Immediate and almost total mortality of amphipods followed the Florida, Tsesis and Amoco Cadiz oil spills (Sanders et al., 1980; Elmgren et al., 1983; Gundlach et al. 1983) . Also , the winter after the Tsesis spill, Elmgren et al. (1983) reported an increase in the frequency of abnormally developed eggs in Pontoporeia femorata females. Length-frequency data for P. femorata, Gammarus setosus, and Anonyx sp., from the Baffin Island Oil Spill (BIOS) Experiment also indicate possible reproductive anomalies in amphipods chronically exposed to low level petroleum contamination (Cross et al., 1987) . Alternatively, the changes in population structures observed for these species may have been due to the active avoidance of the oil by the animals, such as has been reported previously (Percy, 1976; 1977). Echinoderms also seem to be sensitive water quality indicators. Decreases in the densities of the urchin, Strongylocentrotus droebachiensis, in the experimental bays following the BIOS oil releases were very probably the result of avoidance behavior (Cross et al. 1987) .

Sublethal acute and chronic exposures to petroleum compounds such as aromatic hydrocarbons will induce the enzymes of the cytochrome P-450 or mixed function oxygenase (MFO) system (see review by Stegeman, 1984 for induction in marine species) . These enzymes catalyze the metabolism of organic pollutants and endogenous steroids. There is increasing evidence that the induction of the enzymes of the P-450 system may adversely affect reproduction. For example, in starry flounder, Platichthys stellatus, increased maternal hepatic aryl hydrocarbon hydroxylase (AHH) activity has been

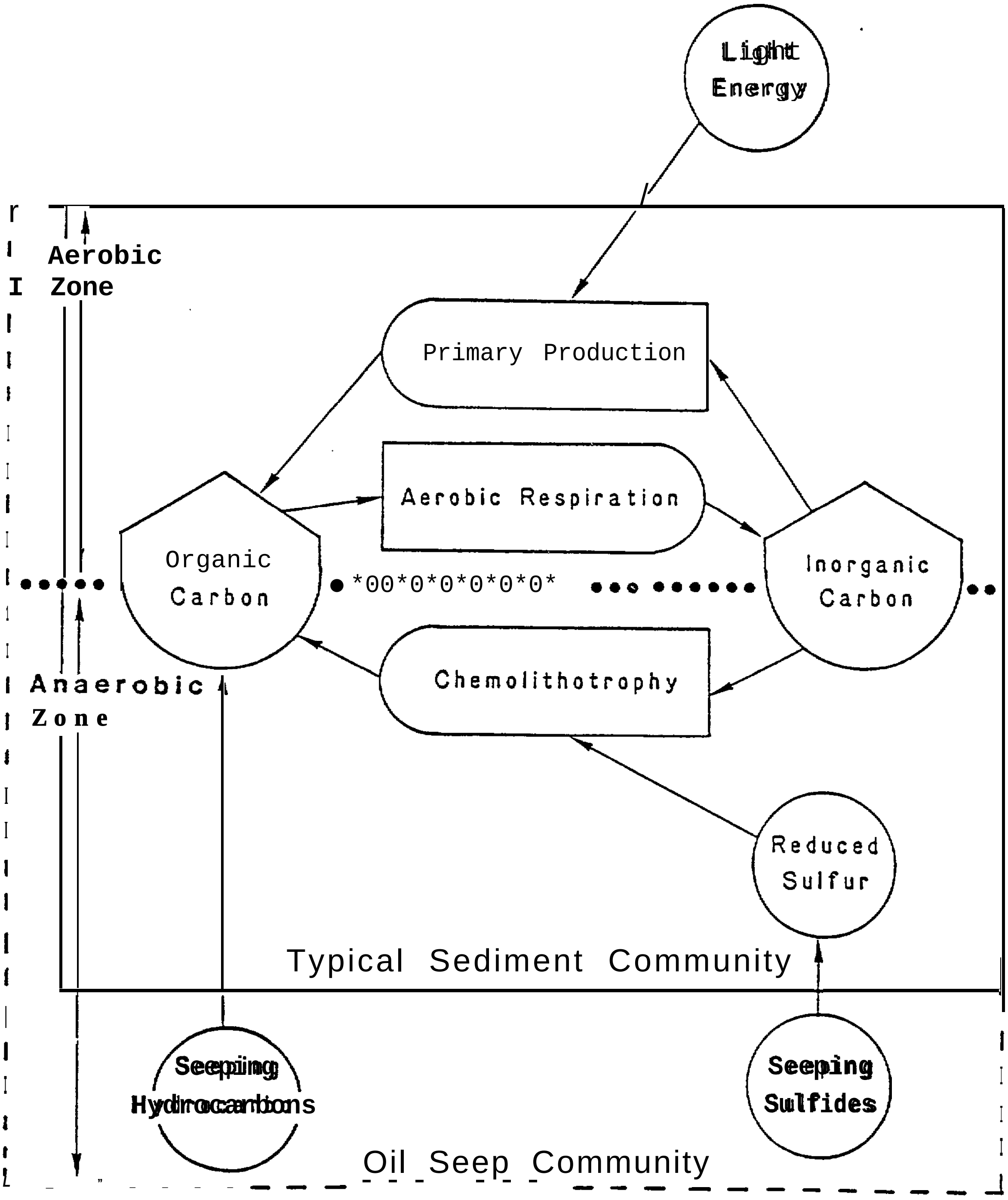

Figure 30. Model of sediment trophic-dynamics. The model demonstrates trophic enrichment by carbon and sulfide additions, via seepage, to the benthic community. The vertical zonation of oxygen and sulfide gulates decoupling of carbon and energy fdmflow in anaerobic zone. (Montagna et al. , personal communication)

associated with subsequent reductions in gamete viability, fertilization success and embryo survival (Figure 31, Spies et al., 1985; 1986) .

Induction of the P-45o system may have direct effects on reproduction through the catalytic activity of this system. All lipophilic organic molecules present in an animal must undergo biotransformation through the enzymes of the P-450 system to more polar derivatives before they can be excreted. Upon oxidation, however, some compounds form reactive intermediates which are capable of binding with macromolecules including deoxyribonucleic acid (DNA) . Specifically, benzo(a)pyrene, polynuclear aromatic hydrocarbon, is metabolized by^{a} AHH to a bay-region dihydrodiol-epoxide, which binds closely to available DNA (Dipple et al., 1984). If this reaction occurs in the liver or gonads of a sexually mature organism, the resulting lesion may affect either the synthesis and storage of necessary lipids or proteins, e.g. vitellogenin, or be transferred directly to the gamete (Varanasi et al., 1981, 1982) . In either case, the lesion may be expressed through the abnormal development or mortality of the gamete and embryo. The potential for such toxicity is indicated in a study where female flathead sole, *Hippoglossoides elassodon*, fed 4 mg of benzo(a)pyrene 5 h before spawning produced eggs with significantly lower hatching success and a higher incidence of embryological abnormalities than controls (Hose et al., 1981) .

Alternatively, induction of the P-450 system may have indirect effects on reproduction, through interference with the synthesis and degradation of steroid hormones. As all the steps in steroidogenesis from cholesterol to estradiol, as well as steroid metabolism, are mediated by P-450 enzymatic function, there are multiple opportunities for contaminant-induced P-450 activity to interfere in steroid balance and normal reproductive function. For example, a P-450 isozyme (P-450E) has been isolated from the hepatic microsomes of induced Scup , *Stenotomus chrysops*, that hydroxylates both benzo(a)pyrene, for which it is the major catalyst and testosterone (Klotz et al., 1986) , the immediate precursor of estradiol. Because of this surprisingly broad substrate specificity, P-450E might be expected *in vivo* to accelerate testosterone clearance rates in contaminant-induced fish. Indeed, a series of short-term exposures of salmon and winter flounder to petroleum did result in lower total plasma and bile titers of testosterone, 11-ketotestosterone and 17b-hydroxytestosterone in sexually mature males (Truscott et al., 1983) .

Elevated levels of AHH activity have been reported in fish collected from areas with low-level chronic petroleum contamination. Spies et al. (1982) measured increased

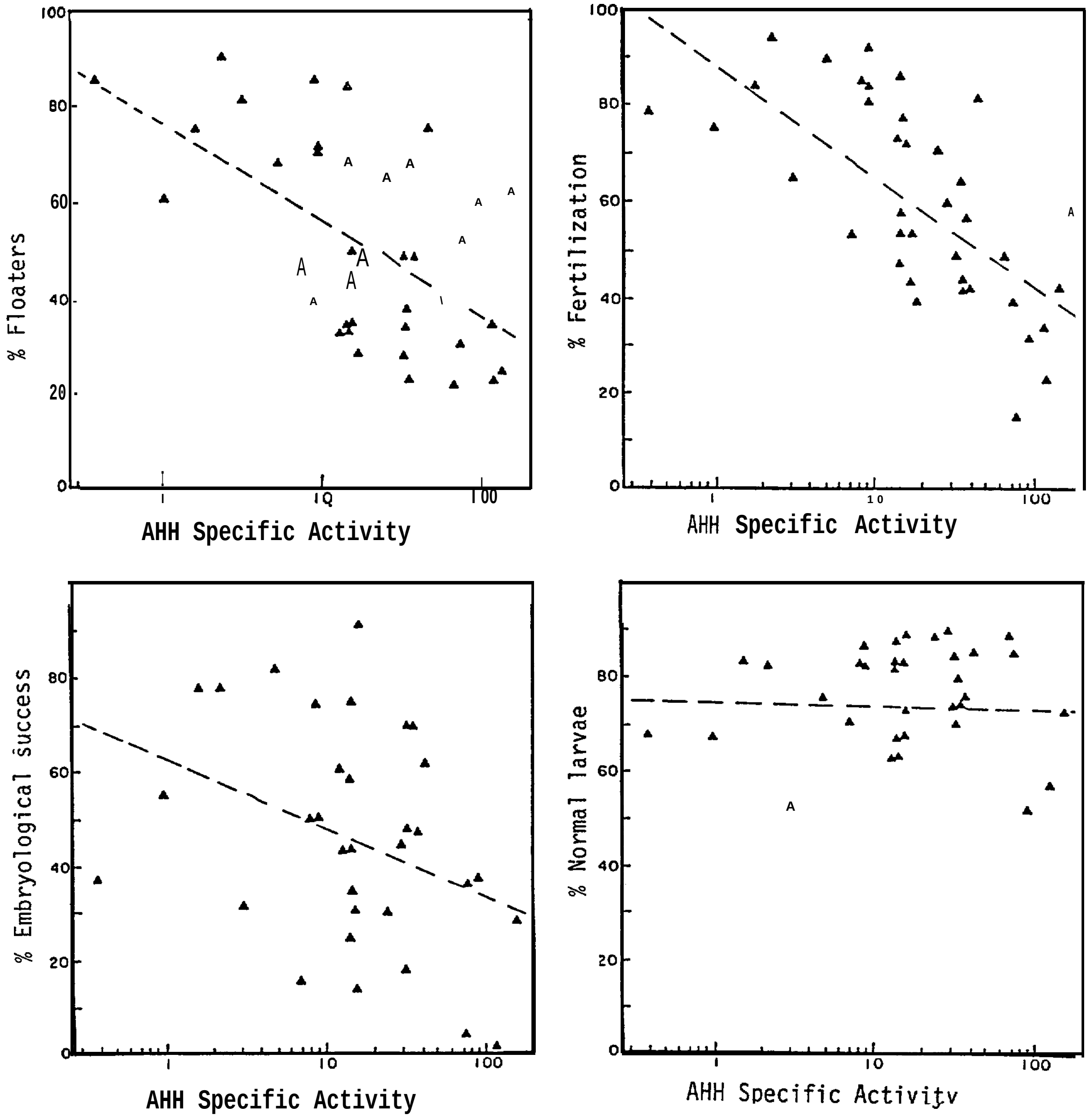

Figure 31. Relationship between hepatic Aryl hydrocarbon hydroxylase (AHH) activity and primary developmental success measures for starry flounder females collected in San Francisco Bay. (Spies et al., 1986)

levels of AHH activity in two species of sanddabs, Citharicthys sordidus and C. stigmaeus collected around the seeps in Santa Barbara Channel. Davies et al. (1984) measured increased enzyme activity in cod, whiting and haddock collected around offshore drilling platforms in the North Sea where oil-based drilling muds have been disposed. In neither case were the levels much above two-fold those of comparison fish. There were strong species-specific differences, however and in light of more recent work, e.g. Spies et al. 1986, separation of the fish by sex as well as species, might have resulted in clearer differences between fish collected in contaminated and non-contaminated areas.

The effects of low level chronic releases are not necessarily limited to the benthos. Concentrations of petroleum hydrocarbons as low as 10-90 ug/l under conditions of chronic exposure can affect the composition of planktonic communities (Lee & Takahashi, 1975; Elmgren & Frithsen, 1982). Observations of natural zooplankton after a major spill (Samain et al., 1981) or Arctic seeps (Gilfillan et al., 1986) indicate a reduction in feeding, and consequently reduced secondary productivity, resulting from exposure to low levels of petroleum hydrocarbons.

ARCTIC MARINE ECOSYSTEMS

Biological events in the Arctic are characterized by marked seasonality. Annual cycles in meteorological conditions, particularly temperature and day length, induce changes in physical factors, e.g. river flow and sea-ice conditions, and biological processes, e.g. primary production. As a result of these widely fluctuating environmental conditions, nearshore Arctic marine animals live in a very harsh environment compared to temperate species. They may experience unusually broad temperature fluctuations, salinity changes and photoperiod extremes. Daily salinity and temperature values change rapidly; changes up to 6°C and 15%. have been observed in Simpson Lagoon (Truett, 1978). Seasonal variations in the same lagoon have been reported by Craig and Haldorson (1979) as:

	spring	summer	fall	winter
temperature	O-5°C	7-10°C	O-6°C	-2-0°C
salinity	l-lo%	18-25%	18-25%	26-60%

Arctic marine food webs are generally short, involving at most four or five energy transfers through herbivorous and carnivorous zooplankton and fish to seabirds and marine mammals. Furthermore the diversity at each trophic level appears to be lower than that occurring in temperate waters.

Arctic marine zooplankton populations and communities share many basic attributes with their counterparts in more temperate waters. Copepods, particularly calanoid copepods, dominate arctic zooplankton in terms of number of species, abundance and biomass. They are common prey for many other species, including fish larvae and seabirds and have a pivotal role in marine food webs. Chaetognaths, pteropods, hyperiid amphipods and several other groups may also be locally abundant and account for a significant portion of the biomass. Zooplankton assemblages frequently include hydrozoans, ctenophores, polychaetes, isopods, ostracods, mysids, decapods and benthic invertebrate larvae. Zooplankton communities differ considerably in different areas and water masses. There is considerable variation in the abundance and species composition with season as a result of reproduction and development (Grainger, 1965) .

Arctic zooplankton generally have an extended life span; two years or more for species of Calanus and Pseudocalanus as, compared to four generations per year in temperate populations (Cairns, 1967). Many herbivorous zooplankton have developed reproductive cycles that coincide with the season of plant growth, whereas carnivorous species generally have a less well defined season of reproduction.

The porous crystalline matrix found on the underside of the characteristic Arctic ice cover is the substrate for a unique and very productive marine community. In the spring (April and May), a dense bloom of microalgae occurs on and in this matrix. It has been estimated that this bloom may account for as much as 25 to 30% of the total annual primary production in various Arctic areas (Homer, 1976, 1977). In addition, this bloom occurs before there is significant production by planktonic and benthic algae during the open water season; it is available to herbivores earlier in the season than is planktonic production (Dunbar, 1968) . The community consists of a trophic network of microalgae, herbivores and invertebrate and vertebrate carnivores. Both infauna and epifauna are present. Small organisms such as protozoa, nematodes, polychaetes, copepods and juvenile amphipods penetrate deep into the ice in brine channels. The epifauna, the largest and most conspicuous invertebrates associated with and utilizing this complex community of ice algae and meiofauna, are gammarid amphipods. Dominant species (On the order of 105 individuals/m^2) on the undersurface of the ice have included, at various places and times, Onisimus litoralis or O. glacialis, Gammarus setosus, Ischyrocerus anquipes and Apherusa glacialis (Cross, 1980, 1982) . The habitats of these species in the absence of landfast ice include the undersurface of pan ice, the water column and shallow sublittoral and intertidal areas. All are important food items for arctic cod (Craig et al., 1982), various marine birds (Bradstreet and Cross, 1982) and ringed seals (Finley, 1978) . These data indicate that the epontic community may be a critical element of arctic marine food webs.

The nearshore benthic infauna and epifauna are extremely depauperate due to seasonal scour from bottom fast ice (Broad, 1979). Similar scouring resulting in depauperate benthic fauna may occur in the depth interval of 15 to 30 m due to ridge ice in the Stamukhi zone. These regions do contain small populations of annual species or juvenile immigrants from adjacent unscoured zones. Benthic faunal diversity increases with water depth seaward from the bottom fast ice zone, with the exception of the Stamukhi zone. Dominant taxa include polychaetes, gammarid amphipods, isopods and bivalve molluscs. The highly motile forms such as amphipods and isopods may invade the area in large numbers during the open-water season (Griffiths and Dillinger, 1981: Northern Technical Services, 1981) .

The Arctic Ocean is relatively impoverished of productive fish stocks. Marine mammals and sea birds are the principal top predators in Arctic marine food webs. Low primary and secondary productivity may be "inimical to the development of truly pelagic stocks of arctic marine fishes" (Johnson, 1983) . There are no endemic species of commercial importance. Stocks of Pacific herring in the Beaufort Sea and capelin, atlantic cod and Greenland halibut in the Eastern Arctic have some potential for local utilization. Most species that presently support local fisheries are anadromous; i.e. ciscoes, whitefishes and Arctic char. Although of no commercial importance, the arctic cod has been described as a “key species in the ecosystem of the Arctic Ocean” because of its abundance, widespread distribution and importance in the diets of marine mammals, birds and other fishes. Frost and Lowry (1984) calculate that Arctic cod are by far the most important consumer of secondary production in the Alaskan Beaufort Sea.

EFFECTS OF LOW LEVEL CHRONIC RELEASES OF PETROLEUM HYDROCARBONS ON ARCTIC MARINE ECOSYSTEMS

The impact of oil released into the environment, terrestrial or marine, is mediated by microorganisms, in particular the hydrocarbon utilizing bacteria, through the biodegradative removal of the oil. The "rate" of petroleum removal by biodegradation will reflect the simultaneous or sequential removal of various components of the release at various rates. These rates, in turn, are influenced by the abundance of hydrocarbon-degrading microorganisms, the composition of the oil, and environmental factors, such as temperature, dissolved oxygen levels and nutrient concentrations (see reviews by Bartha & Atlas, 1985; Atlas, 1985) . No crude oil, however, is completely biodegradable, even under the most favorable conditions.

Hydrocarbon-degrading microorganisms are ubiquitous. Studies in the Canadian and US Arctic substantiate the presence of hydrocarbon-degrading microorganisms in Arctic marine ecosystems and indicate that quantitative differences in the distribution of these microorganisms are relatively unimportant over large geographic distances (Bunch & Harland, 1976; Roubal & Atlas, 1978). Population levels of these microorganisms and their proportions within the microbial community seem to be more sensitive to previous exposure to hydrocarbons than to latitude. In fact, they appear to be extremely sensitive indices of environmental exposure to hydrocarbons as the introduction of hydrocarbons into the environment results in a significant increase in the numbers and proportions of hydrocarbon-degrading microorganisms. Atlas (1981) has reported that in unpolluted ecosystems, hydrocarbon degrading bacteria generally constitute less than 0.1% of the microbial community; in oil-polluted ecosystems, they can constitute up to 100% of the viable microorganisms. This increase in hydrocarbon-degrading microorganism serves both as an index of the extent of hydrocarbon impact and as a signal of the onset of hydrocarbon biodegradation, There is evidence that this increase in hydrocarbon-degrading microorganism is slower in Arctic than Subarctic marine ecosystems (Haines & Atlas, 1982; Eimjellen et al., 1982; Bunch et al., 1983a, 1983b).

The rates of hydrocarbon biodegradation in Arctic and subarctic Alaskan seas, however, seem to bear no significant correlation to the numbers of hydrocarbon utilizers but do correlate with latitude: they are lower in the Arctic Ocean than in more southerly Alaskan regions. <u>In situ</u> ^{14}C dodecane oxidation rates, based on $^{14}CO_2$ production, were measured by Arhelger et al. (1977) in Port Valdez (0.7 g/liter per day), Chukchi Sea (0.5 g/liter per day), and Arctic Ocean (0.001 g/liter per day). A second comparative study of biodegradation potentials in the sediments and water columns of these areas supported this conclusion and demonstrated large seasonal variations, probably due to seasonal depletion of available nutrients, in the Beaufort Sea (Roubal and Atlas, 1978) .

The degradation of Prudhoe Bay crude oil in Arctic marine ice, water and sediment ecosystems has been examined by Atlas and co-workers (see Atlas 1985 for references). Degradation was slow. Loss of the light hydrocarbons was greatly restricted by ice cover and biodegradation of oil on the surface of, or under, sea ice was negligible. Hydrocarbon biodegradation potentials were lower in ice than in water or sediment. Biodegradation rates were slow and limited by temperature and concentration of available nitrogen and phosphorus. Optimal rates of hydrocarbon biodegradation typically occur at C:N and C:P ratios of 10:1 and 30:1 (Atlas and Bartha, 1972), which are several orders of magnitude higher than measured N and P concentrations in the experimental sediments. Oxygen availability also may have been a rate-limiting factor. O_2 and N are limiting factors in fine grained sediments (Gibbs & Davis, 1976) due to low rates of nutrient and oxygen exchange between the interstitial water of such sediment and the overlying water column. These exchange rates would be further decreased by the ice damping of wave action under winter conditions.

There is a large and growing data base on the effects of petroleum on arctic organisms and ecological processes (see review by Wells & Percy, 1985; Figure 32) . These data show effects and threshold concentrations, measured as 96 hour LC_{50}s, that are similar to those for organisms and processes in cold temperate waters and are the basis for the hypothesis that the sensitivities of species and life stages are similar in arctic, subarctic and temperate waters (Carls & Kern, 1985 ; Wells & Percy, 1985; Rice et al., 1984) . However, the sensitivity of an organism in a laboratory study is not the same as the vulnerability of an organism in its native habitat. Arctic organisms and habitats are more vulnerable to hydrocarbons than those of more temperate climates. As a result of the lower temperatures and slower rates of biodegradation, hydrocarbons are more persistent and stable than in warmer climates. Depending upon the vulnerability of the habitat being considered, this persistence provides the potential for long-term exposures and sub-lethal chronic effects, such as the reproductive effects discussed previously for benthic fish and reported for _Spio_ by Cross & Thomson (1987).

The pelagic environment is the first habitat to be impacted by an oil spill. In temperate waters, this habitat recovers quickly, depending on the time of year, zooplankton life cycle stages, and the amount of contact with the oil. Most zooplankton specialists consider that major pollution incidents will not have a lasting impact on zooplankton

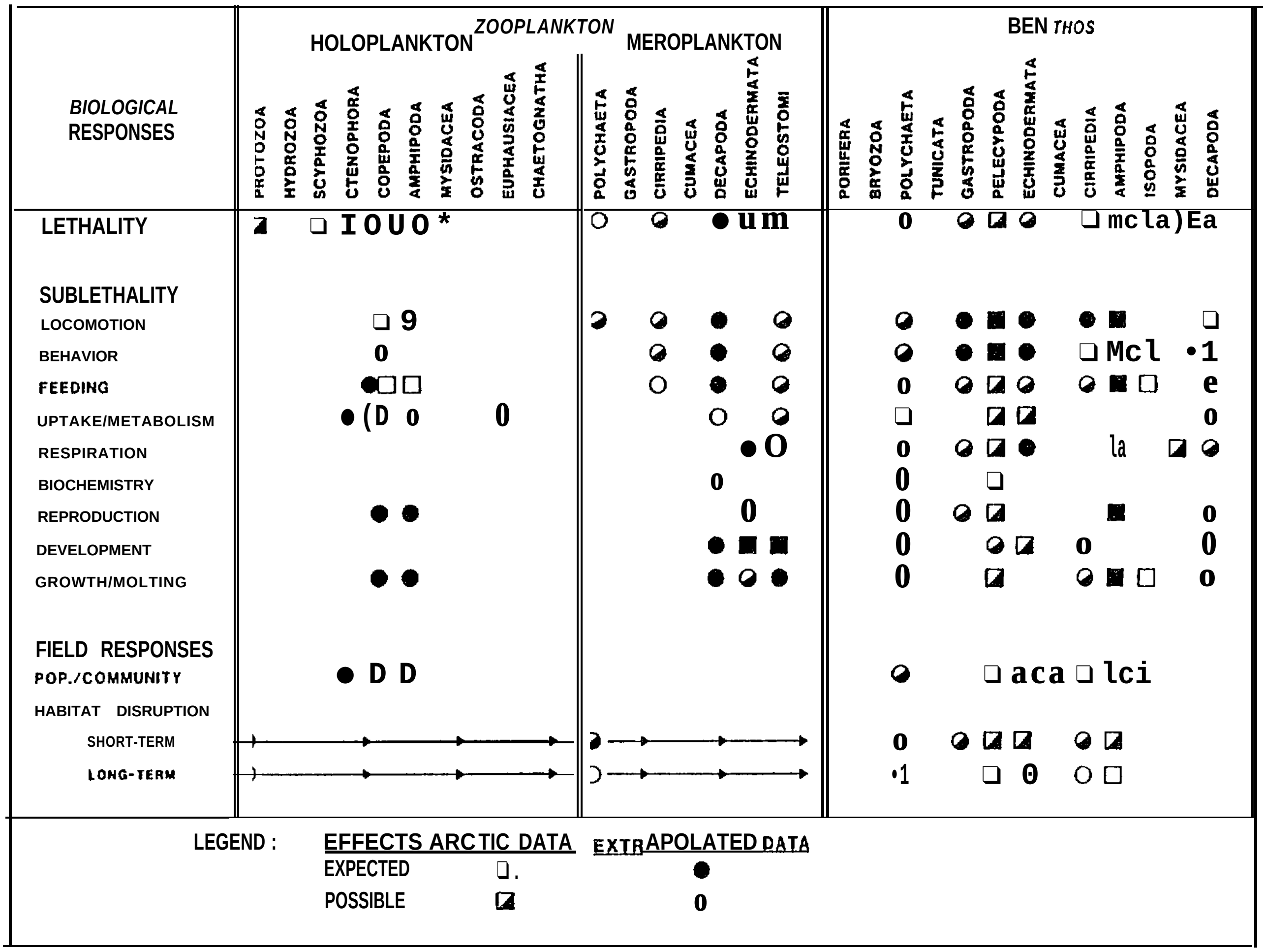

Figure 32. **Anticipated Effects of Spilled Oils** on **Arctic Marine Invertebrates. Figure** based on **information** available **to** Wells and Percy (1985) through **April** 1984.

communities, due to the transient nature of their populations and their wide distribution, and would result in little if any significant effect (Conover, 1979; Homer, 1981) . Although Arctic communities are more vulnerable than those in lower latitudes due to the persistence of the oil at lower temperatures, the longer exposure times and the longer generation times of many Arctic species, this conclusion is most probably valid for Arctic as well as temperate communities.

The epontic communities are very vulnerable to oil contamination. The potential exists for quantities of oil to accumulate under the ice cover and interact with the components of this community for relatively long periods of time. It has been speculated that the impact on this community could be severe (Milne & Smiley, 1976; 1978) although there is little direct evidence, and data from more temperate latitudes, concerning the effects of oil on components of this community, are conflicting and confusing.

The intertidal and shallow subtidal environments are also vulnerable to oil contamination. The intertidal habitat will be rapidly, severely and visibly affected by the stranding of floating oil. However, because of the impoverishment of the biological communities in this habitat the impact will be negligible. The beached oil may serve as a reservoir for the chronic input of hydrocarbons into the subtidal sediments, where they could have a biological impact (Owens et al., 1987; Cross & Thomson, 1987; Cross et al., 1987; Humphrey et al., 1987).

Low concentrations of oil in the subtidal sediments, whether the result of anthropogenic activities or not, will exert effects on the benthic communities. These effects may be most noticeably expressed as changes in populations or communities and may be the result of altered reproductive potentials or avoidance. The effects of oil on reproductive processes can be detected at the site of disturbance only for species lacking planktonic larvae. In the Arctic many benthic species develop directly, allowing this sort of determination. The objectives of the microbiological component of the Baffin Island Oil Spill (BIOS) Experiment, which was conducted at Cape Hatt in the Canadian Arctic were to assess the effects of oil and dispersed oil on the macrophytic algae, the relatively immobile benthic infauna (e.g. bivalves, polychaetes) and motile epibenthos (e.g., amphipods, urchins) in shallow arctic waters. The study design resulted in the incorporation of low levels (<10 ppm) of oil in the subtidal sediments of the two experimental bays. The subsequent long-term monitoring of biota of these bays revealed only minor effects in analyses of density, biomass or size data for 28 individual infauna and 13 epibenthic taxa. The longterm effects were in two categories, reproductive and behavior.

Reproductive effects were inferred for an infaunal polychaete, _Spio_ _sp_., and the amphipod _Pontoporeia femorata_ (Figure 33). Comparisons of the population densities in the experimental and control bays indicated that a natural population increase of _Spio_ did not occur in the experimental bays. Assuming direct development, Cross & Thomson (1987) suggest 1) that breeding of mature adults or development of their offspring in the oiled bays was affected in the year following the spill, or 2) that juveniles released on oiled sediments the second spring or summer were unable to survive. Length-frequency data for _P_. _femorata_ indicated recruitment of the second year class following the spill was reduced in one experimental bay. Again, Cross et al. (1987) suggest that oil incorporated into the sediments of this bay disrupted some aspect of reproduction. Previous studies, reported in the literature for both groups of organisms, support the hypothesis of an effect on reproduction. Rossi and Anderson (1976, 1978) reported that for the polychaete _Neanthes arenaceodentata_, fecundity was suppressed and hatching success was reduced upon exposure of the adults to fuel oil. Carr and Reish (1977) reported similar results in polychaetes exposed to the seawater-soluble fractions of crude oil. Elmgren et al. (1983) reported a greater frequency of abnormal eggs in _P_. _affinis_ following the Tsesis spill and Gundlach et al., (1983) reported a lower frequency of egg-carrying lobsters in commercial catches after the Amoco Cadiz spill. The mechanism being developed and verified in benthic flatfish for the disruption of reproduction through induction of the P-450 system by xenobiotics, including components of petroleum, may very well be applicable to invertebrates as well as vertebrates. In any case, reduced fecundity will probably result in population decreases and must be considered an effect of serious ecological consequence. This is particularly true for benthic organisms without pelagic larvae, such as those in the Arctic, because recolonization of large disturbed areas would be slow (Chia, 1970) .

The length-frequency data for the amphipod, _Anonyx_ is difficult to interpret; two years after the releases, _Anonyx_ juveniles emigrated to shallow water earlier in experimental bay which had the highest sediment oil concentrations than anywhere else. The suggestion that this was avoidance is based on prior data (e.g., Percy, 1976, 1977) for similar species. Changes in the densities of the urchin, _Strongylocentrotus droebachiensis_ appeared to be the result of avoidance behavior. The urchins apparently moved rapidly away from high concentrations of dispersed oil and returned shortly thereafter, when oil concentrations in the water were much reduced. This had no obvious negative

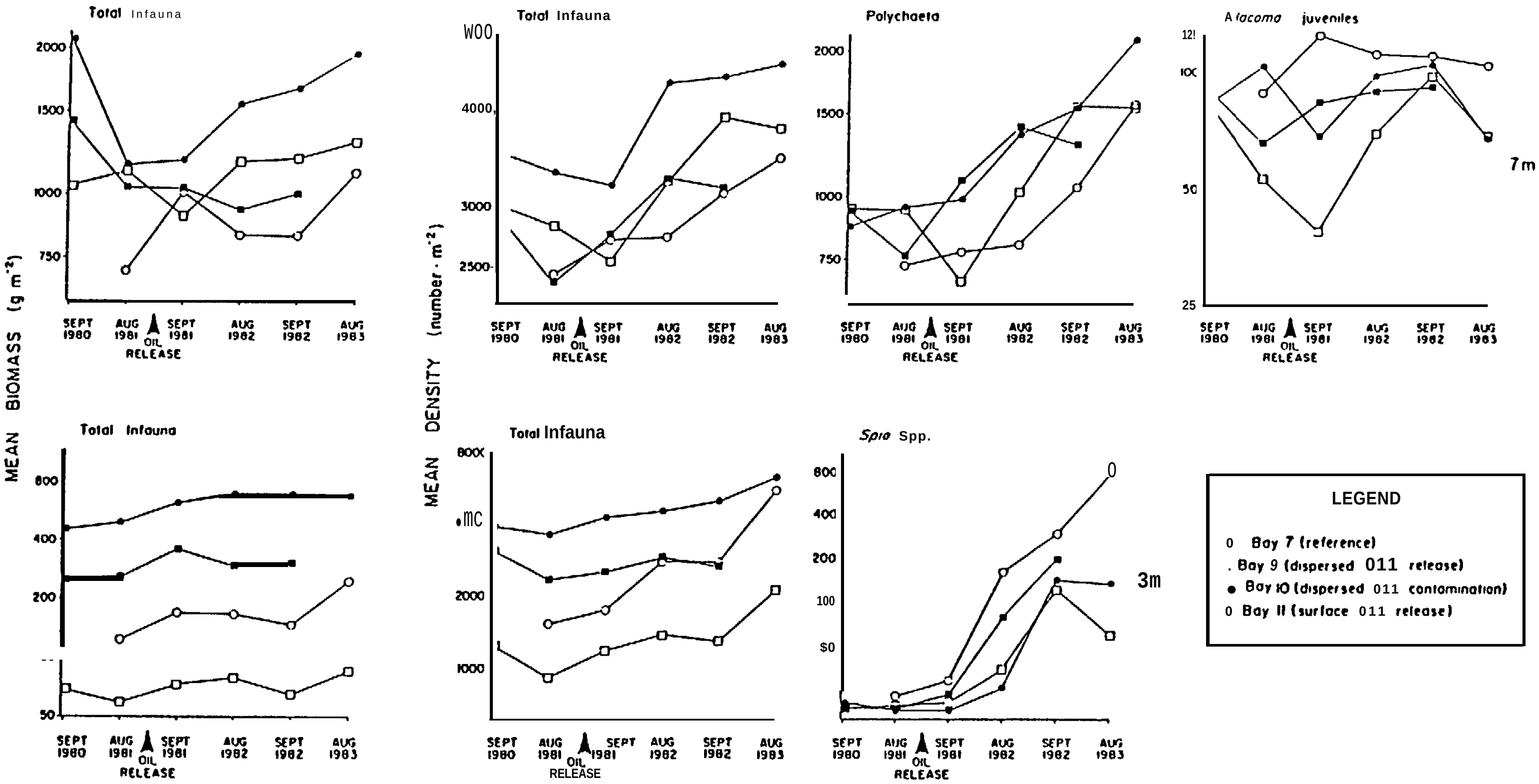

Figure 33. Mean biomass and density of total infauna and mean density of each taxon where analysis indicated possible oil effects, in four bays at Cape Hatt, northern Baffin Island, during pre- and post-spill sampling periods, September 1980-August 1983. Each symbol represents the back-transformed mean of log-transformed data from 24 replicate 0.0625 m2 airlift samples for each depth, bay and period. (from Cross & Thomson, 1987)

consequences and may in fact have prevented adverse effects. Long term avoidance of oil was indicated by decreases in urchin densities between 1982 and 1983, together with concurrent increases in oil concentrations in sediments and in the urchins themselves (Boehm et al. 1985) . In contrast to the short-term avoidance of dispersed oil, long-term avoidance of oiled sediments may have had significant ecological consequences later in the summer of 1983 or in subsequent years. Elsewhere, changes in urchin densities not related to oil have caused major changes in abundance and structure of macroalgal communities (e.g., Paine and Vadas, 1969; Himmelman et al., 1983). Massive algal blooms have been attributed to oil-related depletion of other herbivores (e.g. North et al., 1965). The significance of urchin depletion in the arctic is uncertain, however, because urchin diets and feeding rates are poorly known and because urchins are much less abundant than in boreal or temperate waters.

CONCLUSIONS

1. Twenty-nine oil seepage areas have been reported to occur along the Alaskan coast; 14 of these areas have been confirmed as containing actual oil seeps while 15 are unconfirmed reports. None of the confirmed seeps are subtidal but range in distribution from just above the low tide datum on a beach face (Skull Cliff, Chukchi Sea) to inland sites that could influence the marine environment through input via freshwater streams (Yakataga, Gulf of Alaska).

2. The coastal seepage areas having the greatest amount of background data and information are the Arctic sites Of: Angun Point, Manning point, Cape Simpson, and Skull Cliff; and the Gulf of Alaska sites of Puale Bay, Iniskin Peninsula, Katalla, and Yakataga.

3. The coastal seepage potential classification proposed by Wilson et al. (1973, 1974) works fairly well when applied to the Alaskan coastline. The high potential of the central Gulf of Alaska is well reflected in the large areas of seepage that have been identified in the Yakataga and Katalla areas.

4. The evidence for submarine oil seepage in Alaska is rather limited. Shallow gas deposits are quite common in the Beaufort Sea and seem to commonly occur adjacent to high-angle faults that may act as conduits for gas migration. If petroleum seepage occurs here, such faults might also act as conduits for petroleum seepage. However, the authors of this report could locate no information confirming the presence of submarine oil seeps in the Alaskan Beaufort and Chukchi seas.

5. The existing data base on the hydrocarbon constituents of the sediments in the Beaufort Sea could not be used to located areas of probable seepage. The data base was very limited in areal coverage and the elevated fossil-derived hydrocarbons measured in some areas could be attributed to many possible sources: known coastal terrestrial seeps, unidentified submarine seeps, and freshwater stream input from oil seeps, coal deposits, oil shale deposits, and peat in the drainage basins.

6. There is some sediment geochemical evidence suggesting that an area of submarine oil seepage might occur in the southeastern Bering Sea, between the Aleutian Islands and Pribilofs. The suspected area occurs at the 200-m depth contour, in the Outer Shelf Domain at about the Shelfbreak Front. Bottom environmental

conditions are thought to be relatively constant here as compared to more shallow areas of the Bering Sea. The productivity and standing biomass of bottom communities are probably much lower than more shallow areas, which might provide an opportunity to investigate the phenomenon of "organic enrichment" if oil seepages are actually found to occur here.

7. It is difficult to estimate the volume of oil that might be entering the Alaskan marine waters via natural oil seepage. Volumes of oil that might issue from the Arctic coastal seeps have not been estimated; however, past estimates by McGee (1972) suggest that the amount of oil entering the Gulf of Alaska from known coastal seepages is rather small when compared to known seepage rates on the coast of California.

8. Any future efforts to estimate the amount of hydrocarbons entering Alaskan marine waters, from human induced and natural sources will have to consider a wide variety of natural sources, seepages being only one. Erosional sources might be significant in the Beaufort Sea. Erosional input includes: coastal erosion (peat and coastal seeps) as well as drainage basin erosion of coal and oil shale deposits, terrestrial oil seeps and peat.

9. Oil released in the Arctic would impact the pelagic, intertidal, benthic and under-ice habitats. The rates of chemical weathering and biological degradation in this environment are slow, compared to more temperate climates, and allow for the persistence of the oil in all of these habitats.

10. The under-ice habitat is the most acutely vulnerable. The potential exists for oil to interact with the components of this community for a length of time sufficient to lose that portion of the total annual productivity contributed by this community. This is offset by the probable spatial limitation of this interaction.

11. The pelagic environment is the least vulnerable. The increased persistence of the oil and the long generation times of many species of Arctic zooplankton will contribute to an increased impact, as compared to more temperate waters, but the similarities in the distributions of temperate and Arctic species indicate that the impact would not be significant.

12. The impoverishment of high latitude intertidal zones would alleviate the impact of oil on these areas.

13. The benthic habitat exhibits the potential for chronic, sublethal effects. These effects would be expressed as alterations in populations or communities as the result of organic enrichment, reduced fecundity or altered behaviour. Organic enrichment of the benthic community by seeping oil has been demonstrated in the Isla Vista seep off the coast of California. While a similar enrichment is possible for benthic communities associated with seeps in the Arctic, the slower rates of oil degradation by the Arctic hydrocarbon utilizing microorganisms and the "pauses" induced in microbial activity by environmental fluctuations such as ice cover, would indicate an effect of a much lower magnitude. Effects on reproduction, mediated by the induction of the P-450 system by petroleum hydrocarbons, has been demonstrated for benthic flatfish. This mechanism may be involved in the observed effects of oil exposure on the reproduction of marine invertebrates. For benthic organisms without pelagic larvae, e.g., many Arctic species, and the consequent potential for rapid recolonization and restoration of a disturbed area, a reduction in fecundity may be a long-term effect of major ecological consequences. The avoidance of oiled sediments has been demonstrated in echinoderms and amphipods. The significance, if any, of the avoidance of oiled sediments by these species in the Arctic is unclear.

14. Within any given environment, factors such as the structure of the hydrocarbons and the feeding strategy of the organisms and their capacity to metabolize hydrocarbons will significantly influence the uptake, accumulation and total exposure of the organisms to oil and be reflected in the sensitivity of the organisms.

15. The data do not support the hypothesis that Arctic marine organisms are more sensitive to petroleum and its components than organisms from warmer waters. The vulnerability of Arctic marine organisms, because of their long generation times and the increased persistence of oil in this environment, is greater than that of organisms from more temperate climates.

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