U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

PAMPHLET TO ACCOMPANY MAP MF-2225-A

MAPS SHOWING AREAS OF POTENTIAL FOR MINERAL RESOURCES IN THE KILLIK RIVER 1° x 3° QUADRANGLE, ALASKA

By

Karen D. Kelley and Charles G. Mull

SUMMARY

Geological and geochemical data have been interpreted to identify areas of mineral resource potential in the Killik River quadrangle, north-central Alaska. The quadrangle consists mainly of clastic and carbonate sedimentary rocks, with minor extrusive and intrusive mafic igneous rocks. The types of mineral deposits expected to occur in the quadrangle are stratiform and (or) stratabound deposits. Therefore, geologic tracts favorable for hosting mineral deposits are defined by geochemical data within the boundaries of host rock lithologies.

A broad tract in the central part of the quadrangle is characterized by chert and shale of Mississippian to Jurassic age. Three small areas within this tract have a moderate potential for resources of lead, silver, and zinc (± barium) in sedimentary exhalative massive sulfide deposits in rocks of primarily Mississippian and Pennsylvanian age; the remaining area has a low potential. The southern third of the quadrangle is underlain by Upper Devonian and Lower Mississippian(?) clastic rocks of the Hunt Fork Shale, Noatak Sandstone, and Kanayut Conglomerate. Geochemical data indicate that approximately 40 percent of this area has a high potential for stratabound veins and vein-breccias containing resources for lead, silver, and zinc (± gold and copper). The remaining 60 percent of the area, which consists of clastic rocks, has a moderate potential for such deposits.

Chert, shale, and carbonate rocks permissive for hosting sedimentary barite, manganese, or phosphate deposits comprise much of the central and western parts of the quadrangle. Six small areas have moderate potential for barite resources, seven have moderate potential for manganese resources, and two areas have moderate potential for phosphate resources. Mafic pillow basalts and associated chert, exposed in two small areas (<10 km^2) in the central part of the quadrangle, are permissive for copper and zinc resources in Cyprus-type massive sulfide deposits. However, the relatively small volume of the mafic rocks and available geochemical data indicate that these areas have a low resource potential.

Nonmarine sedimentary rocks of the Cretaceous Nanushuk Group comprise the northern part of the quadrangle. Although these rocks are permissive host rocks for roll-front type uranium deposits (± copper and vanadium), placer deposits (chromium ± platinum group elements and gold), and coal, geochemical data suggest there is a low resource potential for all commodities.

Although the mountainous southern third of the quadrangle has no potential for petroleum resources, there is potential in the northern two-thirds. Potential source beds are present in black shale and limestone with high organic content, and the presence of hydrocarbon in porous dolomite suggests that generation and migration of hydrocarbons did occur. However, with the available data it is difficult to evaluate the relationship between the timing of hydrocarbon generation, migration, and trapping that must be considered to fully evaluate the level of potential. Therefore, the hydrocarbon potential is uncertain.

STUDIES RELATED TO AMRAP

The U.S. Geological Survey (USGS) is required by the Alaska National Interest Lands Conservation Act (ANILCA, Public Law 96-487, 1980) to survey Federal Lands to determine their mineral resources. Results from the Alaska Mineral Resource Assessment (AMRAP) must be made available to the public and be submitted to the President and Congress. This report presents geologic, geochemical, and mineralogical data that delineate areas in the Killik River quadrangle with potential for mineral resources.

INTRODUCTION

The Killik River quadrangle includes 14,125 km^2 (3,351,000 acres) in the northcentral Brooks Range of northern Alaska (fig. 1). The quadrangle is situated within a belt of Paleozoic and Mesozoic rocks that extends for nearly 800 km (500 mi) across the western and central Brooks Range. These rocks host several different types of mineral occurrences and deposits in quadrangles adjacent to and within the Killik River quadrangle.

Field and laboratory studies in the Killik River quadrangle were conducted by the USGS and the Alaska Division of Geological and Geophysical Surveys between 1981 and 1986 as part of the AMRAP program. The overall objective was to provide geologic, geochemical, and geophysical data for use in delineating areas favorable for hosting mineral deposits. The studies were also aimed at enhancing the geologic knowledge of a remote area that has received few recent earth-science investigations. The geologic and geochemical data were the primary sources of information that were used to assess the mineral resource potential of the Killik River quadrangle. These data were evaluated using mineral deposit models (Cox and Singer, 1986). Geophysical data from the quadrangle were of limited use, as only aeromagnetic data are available for the entire quadrangle. Furthermore, the flight lines were flown parallel to the range crest, making leveling from line to line (and thus evaluation of the aeromagnetic data) difficult (D.L. Campbell, oral communication, 1991).

LOCATION AND PHYSIOGRAPHY

The Killik River quadrangle is located in the central part of the Brooks Range and Arctic Foothills Provinces (Wahrhaftig, 1965) (fig. 1), along the northern flank and foothills of the Endicott Mountains (fig. 2). Approximately half of the quadrangle lies within the National Petroleum Reserve in Alaska (NPRA) or the Gates of the Arctic National Park (GANP). The quadrangle is also within the U.S. Bureau of Mines Colville Mining District (fig. 1).

Topography varies from moderately steep in the southern part of the quadrangle to nearly flat in the northern part of the quadrangle. The highest elevation is 2,236 m (7,335 ft) in the southern part of the quadrangle (fig. 2). Although the mountains were extensively glaciated during Tertiary and Quaternary time, glaciers are presently confined to a few north facing cirques at elevations above 1,500 m (5,000 ft) in the highest part of the mountains. Braided and meandering rivers drain northward through the quadrangle into the eastward-flowing Colville River, which eventually empties into the Arctic Ocean. The sparse vegetation includes willows, grasses, sedges, mosses, lichens, and flowering plants. Permafrost underlies the entire area.

There is no year-round human habitation in the Killik River quadrangle. The nearest supply centers are at Anaktuvuk Pass (50 km to the east), Barrow (250 km to the north), Kotzebue (400 km to the southwest), and Fairbanks (about 480 km to the south). Access is limited to aircraft, boat, snowmachine, or foot travel. All-weather gravel-surfaced airstrips are available at the abandoned Lisburne No. 1 test well site at the western end of the Ivotuk Hills, and at the abandoned Killik No. 1 test well site north of Kikiktat Mountain. In addition, an unimproved, marginally usable airstrip on a gravel bar is located at the confluence of the Etivluk and Colville Rivers in the extreme northwestern part of the quadrangle (fig. 2). Rivers that are navigable by raft or canoe include the Killik, Okpikruak, and Colville Rivers.

LAND STATUS

The Killik River quadrangle is mostly federally administered public land. The National Petroleum Reserve in Alaska (NPRA) is under the jurisdiction of the Bureau of Land Management, whereas the Noatak National Preserve and Gates of the Arctic National Park are administered by the National Park Service. Figure 2 shows the location of park and non-park federal lands, and State of Alaska and Native land selections within the quadrangle.

HISTORY OF LAND AND RESOURCE EXPLORATION

Mineral resource investigations in the Brooks Range began in the early 1900's, with several pioneer expeditions of geologists and geographers (Schrader, 1904; Brooks, 1909). Oil seeps and favorable geologic structures described in these reports and by early U.S. Navy expeditions led President Harding to establish the Naval Petroleum Reserve No. 4 (also called NPR-4) in 1923. From 1923 to 1926, the U.S. Navy commissioned the USGS to assess the potential for oil and other mineral resources in NPR-4 as well as in adjacent areas to the east, including the Killik River and Chandler River regions. The results of these investigations are summarized in Smith and Mertie (1930) and include the first topographic and geologic maps of the area.

Concern for long-term petroleum supplies during World War II prompted further petroleum investigations of NPR-4. As a result, a geologic and topographic mapping program was conducted from 1944 to 1953 in NPR-4 and adjacent areas. During these investigations, the only minerals noted were occurrences of sedimentary phosphate at widely scattered localities along the northern front of the Brooks Range and in the adjacent foothills. Detailed studies of selected phosphate occurrences were conducted by Patton and Matzko (1959). As part of these studies, selected rock samples were collected from the Killik River quadrangle and analyzed for phosphate and equivalent uranium.

In 1976, under the Naval Petroleum Reserves Production Act, Congress renamed NPR-4 the National Petroleum Reserve in Alaska and transferred administration of the reserve to the Department of the Interior. The USGS, as an agency in the Department of the Interior, was directed to continue exploration in the reserve to aid in assessing petroleum and other resources (Carter and others, 1977). Extensive geophysical surveys were conducted and a number of exploratory wells were drilled in the reserve under contract by Husky Oil, but there were no significant petroleum discoveries. One of these wells, Lisburne No. 1, was drilled in the Killik River quadrangle. Data obtained from this well and from the geophysical surveys are available from the National Geophysical Data Center (Ikelman, 1986). Interpretation of much of the seismic and borehole data and results of USGS mapping and field studies are summarized by Gryc (1988).

Three additional wells were drilled in the Killik River quadrangle outside NPRA (fig. 2). Two wells, West Kurupa No. 1 and East Kurupa No. 1, were drilled by Texaco, Inc. in 1976; Chevron USA, Inc. drilled Killik No. 1 in 1980. Drillhole data from the Kurupa wells are available from Petroleum Information, Inc. [(243 5th Ave., Anchorage, Alaska, 99501), unpub. data, 1992], but no data from the Killik No. 1 well have been released.

In recent years, numerous additional studies have focused on uranium and coal resources in the Arctic foothills (which includes parts of the central and northern Killik River quadrangle). Huffman (1985) evaluated the potential for uranium deposits in Cretaceous sandstone and conglomerate. Coal deposits are widespread in the Arctic Foothills and have been the subject of numerous reports (Barnes, 1967; Roehler, 1987; Affolter and Stricker, 1987; Sable and Stricker, 1987).

In 1978, much of the mountainous land in the Killik River quadrangle not already included in NPRA was designated by Presidential proclamation as Gates of the Arctic National Park. Consequently, since 1978, few mineral-exploration or geologic studies have been conducted in the southern Killik River quadrangle other than by governmental agencies such as the Alaska Division of Geological and Geophysical Surveys (DGGS) and the USGS.

During the late 1970's and 1980's, the U.S. Geological Survey conducted multidisciplinary mineral-resource assessments of several quadrangles adjacent to the Killik River quadrangle. Churkin and others (1978) conducted a mineral-resource assessment of the NPRA to the west of the Killik River quadrangle, which included parts of the Howard Pass and Misheguk Mountain quadrangles. Other completed studies included the Ambler River quadrangle on the southwest (Mayfield, Tailleur, Albert, and others, 1983), the Wiseman quadrangle on the southeast (Bliss and others, 1988), and the Chandler Lake quadrangle (Church and others, 1995) and Philip Smith Mountains quadrangle (Reiser and others, 1983; Menzie and others, 1985) on the east.

For the AMRAP investigations of the Killik River quadrangle, which began in 1981, geologic, geochemical, and geophysical field and laboratory studies were undertaken as part of a cooperative effort by the USGS and the DGGS. Detailed geologic mapping was conducted in specific areas and a geologic map of the Killik River quadrangle at a scale of 1:125,000 was prepared (Mull and others, 1994). This map was generalized and published at a scale of 1:250,000 as part of this report. A map of the Quaternary deposits was published by Hamilton (1980).

Geochemical data were collected from the Killik River quadrangle during two separate reconnaissance sampling programs. The USGS conducted reconnaissance and detailed geochemical studies from 1981 to 1986; these studies included collection of stream sediment, nonmagnetic heavy-mineral concentrate, and rock samples. Analytical results are contained in reports by Barton and others (1982), Sutley and others (1984), and Motooka and others (1989). The geochemical data were interpreted by Kelley and Kelley (1992) and Kelley and others (1995a; 1995b). During the course of the geochemical studies in the southern part of the Killik River quadrangle, four base-metal sulfide mineral occurrences were discovered. Descriptions of these occurrences and the geochemical exploration criteria used to delineate them are summarized in Duttweiler (1987), Kelley and Kelley (1992), and this report.

In 1980, the Los Alamos National Laboratory conducted lake- and stream-sediment sampling in the northern part of the quadrangle as part of the National Uranium Resource Evaluation Program (Los Alamos National Laboratory, 1982). These data were evaluated and interpreted by Kelley and Mull (1995).

An aeromagnetic survey was flown across the Killik River quadrangle by the U.S. Geological Survey to provide regional data for the AMRAP study (U.S. Geological Survey, 1983). The aeromagnetic data are the only geophysical data available for the entire quadrangle; numerous gravity surveys were conducted during the NPRA studies, but only the extreme western part of the Killik River quadrangle was included.

REGIONAL GEOLOGIC SETTING

The Brooks Range is an east-west-trending fold and thrust belt that extends for nearly 800 km across northern Alaska and was formed during an orogenic event that began in Late Jurassic time and culminated during mid-Cretaceous time. The northern part of the Endicott Mountains, which constitute the central Brooks Range, consists primarily of Paleozoic sedimentary rocks in a series of thrust sheets that were stacked together during the Mesozoic orogenesis. The southern foothills, located north of the Endicott Mountains, consist of a zone of intensely deformed Paleozoic and Mesozoic sedimentary rocks that are parts of several major thrust sequences known as allochthons (Mayfield, Tailleur, and Ellersieck, 1983). These allochthons were thrust from the south during the formation of the Brooks Range. Farther north in the northern foothills, the Colville basin is a depositional foredeep that is filled with over 6,000 m of deltaic sedimentary deposits of Cretaceous age derived from the range.

GEOLOGY OF THE KILLIK RIVER QUADRANGLE

Map A shows the generalized geology of the Killik River quadrangle. The quadrangle consists mainly of Devonian to Cretaceous sedimentary rocks and minor intrusive and extrusive mafic igneous rocks. Rocks of the mountainous southern third of the quadrangle and the southern foothills are part of the Brooks Range thrust belt. The northernmost part of the quadrangle within the northern foothills is underlain by sedimentary strata deposited in the Colville basin north of the thrust belt. The rocks of the Brooks Range thrust belt have been divided into allochthons containing distinctive assemblages of rock units that have been telescoped northward by thrusting (Mayfield and others, 1987; Mull, 1982). At least five allochthons have been delineated in the quadrangle (Mull and others, 1987; Mull and others, 1994).

The southern third of the quadrangle consists of unmetamorphosed to weakly metamorphosed sedimentary rocks of the Endicott Mountains allochthon (structurally the lowest of the allochthons in the central Brooks Range) (Brosgé and others, 1979; Mull and others, 1994). In the Killik River quadrangle, this allochthon consists of sedimentary rocks ranging from Late Devonian to Early Cretaceous age. At the base of the allochthon is the Hunt Fork Shale of Late Devonian age, which consists of a dark-gray and olive shale member interbedded with brown-weathering calcareous siltstone and fine-grained sandstone, and an overlying gray-green wacke member consisting of gray-green wacke interbedded with shale, siltstone, and sandstone. Both members represent deposition in a marine environment (Brosgé and others, 1979).

Strata of the Hunt Fork Shale are overlain by the marine Upper Devonian Noatak Sandstone, which in the Killik River quadrangle consists of light-gray to brown, fine to coarse sandstone and quartzite interbedded with dark-gray to brown shale containing ironstone nodules (Nilsen and Moore, 1984). The Noatak Sandstone is volumetrically subordinate to the underlying Hunt Fork Shale and the overlying Kanayut Conglomerate. The Kanayut Conglomerate is a Late Devonian and Early Mississippian(?) nonmarine sequence (Nilsen and Moore, 1984). It is as much as 2,600 m thick and extends east to west for more than 800 km across the Brooks Range. Sedimentary features indicate that deposition of the Kanayut Conglomerate occurred in a deltaic environment with chert-rich source areas located to the north and northeast (Nilsen and others, 1981). In the type section east of the Killik River quadrangle, the Kanayut Conglomerate contains a coarse middle part consisting predominantly of interbedded conglomerate and sandstone, and upper and lower parts consisting predominantly of sandstone, siltstone and shale. However, the conglomerate beds become progressively thinner to the west and contain smaller clasts than those present in the type section, so that conglomerate is only a minor part of the formation in the western part of the quadrangle.

The sedimentary section of Hunt Fork Shale to Kanayut Conglomerate represents a southward- or southwestward-prograding deltaic complex; the fine-grained prodelta shale beds of the Hunt Fork Shale grade upward into the wacke member of the Hunt Fork Shale and into the marine sandstone of the Noatak Sandstone, and eventually into the coarse delta-plain deposits of the Kanayut Conglomerate (Nilsen and Moore, 1984). The Kanayut Conglomerate, therefore, forms the fluvial part of the delta that prograded to the southwest during the Late Devonian and retreated during the Late Devonian and Early Mississippian(?) (Nilsen and others, 1981).

Overlying the Kanayut Conglomerate are fossiliferous marine strata of the Lower Mississippian Kayak Shale that consist dominantly of shale, with lesser amounts of siltstone, and shaly sandstone near its base, and interbedded argillaceous and ferruginous limestone near its top (Brosgé and others, 1979). Platform carbonate rocks of the Mississippian and Pennsylvanian Lisburne Group (Patton and Tailleur, 1964; Mull and others, 1982) overlie the Kayak Shale and consist primarily of medium- to light-gray limestone and dolomite with an interval of sooty black phosphatic shale and limestone near the top. Along the mountain front in the eastern part of the quadrangle, carbonate rocks of the undivided Lisburne Group are more than 300 m thick, but the unit thins westward and apparently grades into about 50 m of black chert, sooty limestone, and shale of the Kuna Formation of the Lisburne Group in the western part of the quadrangle. The Kuna Formation formed in a euxinic basin in an epicontinental setting (Mull and others, 1982).

Disconformably overlying the Lisburne Group are rocks of the Etivluk Group, which consist of the Permian Siksikpuk Formation and the Triassic and Jurassic Otuk Formation (Mull and others, 1982). The Siksikpuk and Otuk Formations are combined as unit JPe on map A. The Siksikpuk Formation consists of about 100 m of pyritic siltstone, greenish-gray to maroon mottled mudstone and siltstone, greenish-gray silicified mudstone or chert, and an upper gray shale horizon. The greenish-gray to maroon siltstone and mudstone characteristically contain white barite lenses and nodules (Siok, 1985).

The overlying Otuk Formation is also about 100 m thick and consists of a basal interval of black shale that grades upward successively into black silicified limestone and then into thinly interbedded light-gray to black banded siliceous limestone and shale containing abundant pelecypod fossils (Mull and others, 1982). Locally, a thin (less than 3m) but distinctive marker interval of Early Cretaceous coquinoid limestone overlies the Otuk Formation and marks the stratigraphic top of the Endicott Mountains allochthon. This marker interval is too thin to be differentiated in the Killik River quadrangle.

North of the range front is a belt of complexly deformed rocks composed of at least four allochthons that structurally overlie the Endicott Mountains allochthon (Mull and others, 1987). The stratigraphy of this belt differs markedly from that of the Endicott Mountains allochthon to the south, although there are common characteristics that suggest that all of the allochthons represent parts of a formerly continuous sedimentary basin. These allochthons consist primarily of relatively thin Upper Mississippian and Lower Pennsylvanian black pyritic chert and limestone of the Akmalik Chert of the Lisburne Group, and overlying greenish-gray chert and green and maroon siliceous shale of the Pennsylvanian to Jurassic Imnaitchiak Chert (Mull and others, 1987; Mull and others, 1994). Locally, these siliceous rocks and limestone are underlain by a thin interval of the Mississippian Kayak Shale and Mississippian quartzose sandstone that was deposited as a turbidite. The Imnaitchiak Chert, Akmalik Chert, and local basal units are combined as unit JMc on map A. Rocks within this unit locally overlie the Upper Devonian Hunt Fork Shale. The allochthons in the deformed foothills belt also contain the Lower Cretaceous Okpikruak Formation. This formation consists dominantly of greenish-gray graywacke with interbedded mudstone and shale, but local massive boulder conglomerate and chaotic debris-flow deposits are also present. These Lower Cretaceous rocks represent the oldest detritus derived from uplift of the Brooks Range.

Mafic igneous rocks intrude some of the allochthonous siliceous rocks and limestone of the deformed belt in the Otuk and Iteriak Creek area in the western part of the quadrangle. In addition, pillow basalt and other extrusive igneous rocks are present in the Kikiktat Mountain and Itkilikruich Ridges area in the central part of the quadrangle and at one locality near the western edge of the quadrangle. The extrusive igneous rocks are part of probably one of the structurally highest allochthons in the Brooks Range and are an erosional remnant of oceanic crust transported from the south and emplaced during the formation of the range.

The complexly deformed rocks of the Endicott Mountains and overlying allochthons are regionally overlain by gently folded conglomerate and graywacke of the Lower Cretaceous Fortress Mountain Formation. These proximal coarse-grained beds were derived from the Brooks Range and interfinger laterally with more complexly folded gray to black shale of the Lower Cretaceous Torok Formation (Detterman and others, 1963).

The northernmost third of the quadrangle within the northern foothills is part of the Colville Basin and contains gently deformed clastic rocks of the Lower and Upper Cretaceous (Albian and Cenomanian) Nanushuk Group (Detterman and others, 1963; Huffman, 1989). The Nanushuk Group is a deltaic clastic wedge composed of interbedded conglomerate, sandstone, coal, and shale. It is composed of sediments derived primarily from pre-existing sedimentary rocks with a variable contribution from mafic and ultramafic rocks, as well as metamorphic rocks and volcanic detritus (Huffman, 1985). Transport directions determined from the nonmarine facies of the delta, as well as studies of sandstone percentage and modal grain-size distribution indicate that, in the Killik River quadrangle, the delta prograded generally northward from the Endicott Mountains (Huffman, 1989). This clastic wedge was folded into a series of long, linear, east-west-trending broad synclines and more tightly folded anticlines. Poorly exposed interbedded marine sandstone and shale of the Upper Cretaceous Colville Group (Detterman and others, 1963) overlie Nanushuk rocks in the northeast corner of the quadrangle, and Quaternary surficial deposits cover most of the central and northern parts of the quadrangle.

MINERAL DEPOSITS AND OCCURRENCES

DEPOSITS AND OCCURRENCES ADJACENT TO THE KILLIK RIVER QUADRANGLE

The Killik River quadrangle lies within an east-west-trending belt of clastic and carbonate sedimentary rocks with minor extrusive and intrusive mafic igneous rocks. The types of mineral deposits and occurrences that are present in this belt are stratiform and (or) stratabound types in sedimentary and mafic igneous rocks. There are no known skarns, porphyry deposits, or epithermal veins associated with igneous activity.

The known mineral occurrences in the Howard Pass and Misheguk Mountain quadrangles in the southern part of the NPRA and farther west in the De Long Mountains quadrangle are listed in table 1 and their locations are shown on figure 3. Most of these mineral occurrences have not had any production and only a few have been drilled or explored in any detail. Exceptions to this include the Su-Lik lead-zinc deposit and the giant Red Dog lead-zinc deposit, which is currently in production. Schmidt and others (1990, Planning document for mineral resource studies in the southern NPRA study area; unpublished USGS administrative report, 249 p.) categorized the occurrences and deposits in the western Brooks Range into the following deposit types: (1) sedimentary exhalative silver-lead-zinc massive sulfide deposits in Mississippian black shale and chert; (2) banded silver-lead-zinc veins and breccias in siltstone, sandstone, and conglomerate of latest Devonian and Early Mississippian age. This deposit type may also be characterized by disseminated sulfides in clastic rocks adjacent to veins. These were termed "western Brooks Range vein-breccias" by Schmidt and others (1990); (3) sulfide-bearing concretions in Mississippian sedimentary rocks, and lead- and zinc-bearing sulfides disseminated in siltstone or sandstone of Late Devonian and Early Mississippian age that do not have associated adjacent quartz veins; (4) massive barite lenses in chert, shale, and carbonate rocks of presumed Mississippian and

Pennsylvanian age; (5) diagenetic barite lenses, veins, and crystal aggregates in gray and green chert, shale, siltstone, and mudstone of the Etivluk Group; and (6) chromium with or without platinum group elements and (or) nickel in ultramafic rocks or surrounding placers.

In addition to these deposit types, there are unpublished reports of a few phosphate and fluorite occurrences associated with carbonate rocks in the Howard Pass quadrangle (Bureau of Mines, unpubl. data). Phosphate occurrences have also been reported in the Chandler Lake quadrangle east of the Killik River quadrangle (Patton and Matzko, 1959). Although there are no known metallic-mineral deposits in the Chandler Lake quadrangle, farther east in the Phillip Smith Mountains quadrangle there are several reported copper-lead-zinc quartz-vein occurrences hosted by Devonian clastic and carbonate rocks (Menzie and others, 1985).

MINERAL OCCURRENCES IN THE KILLIK RIVER QUADRANGLE

Except for coal and a few occurrences of phosphatic rock (table 2), no mineral occurrences were reported in the Killik River quadrangle prior to this study. During this study, four localities containing sulfide mineral occurrences were discovered in the western part of the quadrangle. These include the Kady, Vidlee, Otuk Creek, and Ivotuk Hills occurrences (table 2; map B). At the present time, none of these occurrences have commercial value, but they indicate that metal-rich fluids were present and may indicate the presence of associated undiscovered larger deposits and occurrences.

Vidlee

Mineralized rocks at the Vidlee occurrence (no. 1, table 2; map B) are primarily sulfide-bearing quartz veins and breccias hosted in shale and shaly siltstone of the Upper Devonian Hunt Fork(?) Shale (part of unit Dn, map A). The outcrop of mineralized rocks is exposed along a stream drainage over a distance of about 25 m. It cannot be traced from this single exposure due to tundra cover. Mineralized rocks are primarily quartz veins and breccias containing galena and sphalerite, although chalcopyrite and pyrite are also present. The breccias consist of clasts of shale and sandstone rimmed with quartz and containing sulfide minerals in the interstices. Mineralized rocks contain 150-300 ppm Ag, as much as 6,400 ppm As, 0.05-0.75 ppm Au, 0.015-1 percent Cu, 1.5-2 percent Pb, and 14-25 percent Zn (Duttweiler, 1987; Kelley and Kelley, 1992; Kelley and others, 1995a; 1995b).

Kady

The Kady mineral occurrence (no. 2, table 2; map B) is hosted by Upper Devonian sandstone and conglomerate of the Kanayut Conglomerate. Mineralized rocks display three distinctive textures: massive banded sulfides in quartz veins, sulfide-bearing breccias, and sulfide minerals disseminated in sandstone and conglomerate units adjacent to the veins. The most common sulfide minerals are sphalerite and pyrite, although minor galena and chalcopyrite are also present. The mineralized zone covers an area of at least 1.3 km^2. Although most of the area is covered by tundra, mineralized vein and breccia outcrops are visible at three separate localities. In addition, boulders and cobbles of massive and brecciated sulfides are found at the surface in frost boils and in colluvium. The veins, which strike north to northwest, range in width from 2-cm stockwork veinlets to massive veins about 0.6 m wide. The most highly mineralized rocks contain 12-21 percent Zn, 0.15-2 percent Cu, 150 ppm Ag, 500-700 ppm Pb, and 0.05-0.20 ppm Au (Duttweiler, 1987; Kelley and Kelley, 1992; Kelley and others, 1995a; 1995b). In addition to the Kady occurrence, numerous mineralized vein occurrences were found either as float or outcrop in tributaries of Outwash Creek to the northeast and southwest of the Kady occurrence (Meyer and Kurtak, 1992).

Otuk Creek

Iron-rich sulfide-bearing concretions are abundant in one outcrop of the Lower Mississippian Kayak Shale located in the upper tributaries of Otuk Creek (no. 3, table 2; map B). The concretions range in diameter from

7.6 cm to 20 cm, and probably formed during compaction and diagenesis of the shale. They contain abundant calcite, minor amounts of red-brown sphalerite and pyrite, and trace amounts of galena. In addition to anomalous concentrations of Fe (up to 20 percent), the concretions contain high concentrations of Ag (0.8-2.3 ppm), Ba (more than 5,000 ppm), Mn (3,000 ppm), and Zn (300-1,500 ppm). Although sulfide-bearing concretions such as these were not found in the Kayak Shale elsewhere in the quadrangle, they were found at one locality in the Howard Pass quadrangle to the west (K.D. Kelley, unpub. data, 1990) and in the Chandler Lake quadrangle to the east (J.M. Kurtak, oral commun., 1994). This indicates that they may be fairly common in the Kayak Shale.

Ivotuk Hills

Nodular pyrite occurs in float along Otuk Creek on the west side of the Ivotuk Hills (no. 4, table 2; map B). The coarse, massive-pyrite nodules are as large as 10 cm in diameter. One smaller pyritic nodule (5 cm diameter) was found that contains a core of sphalerite surrounded by pyrite. Geochemical analysis of one of the pyritic nodules without visible sphalerite yielded 200 ppm As, >20 percent Fe, and 500 ppm Zn. Although the source of the nodules is not known, they are probably derived from shale or chert of Permian to Jurassic age that is widespread south of the Ivotuk Hills.

CRITERIA FOR DETERMINING MINERAL RESOURCE POTENTIAL

The following discussion of mineral resource potential in the Killik River quadrangle is based on available geologic and geochemical data collected during the NURE and AMRAP studies. Geophysical data are of limited use, as only aeromagnetic data are available for the entire quadrangle (U.S. Geological Survey, 1983). Furthermore, the flight lines were flown parallel to the rangecrest, making leveling from line to line (and thus evaluation of the aeromagnetic data) difficult (D. L. Campbell, oral commun., 1991).

The primary emphasis of this report is on nonfuel metallic minerals and selected nonmetallic minerals (barite and phosphate). There have been numerous reports on coal, hydrocarbons, and uranium within the Arctic foothills of the Brooks Range as part of the NPRA studies, which included the Killik River quadrangle. This report only briefly summarizes the results of these studies.

The expected mineral deposits in the Killik River quadrangle are stratiform and (or) stratabound types hosted by sedimentary and mafic igneous rocks. No felsic plutonic rocks are present, and there are no aeromagnetic anomalies that would indicate the presence of buried intrusions (D. L. Campbell, oral commun., 1987); thus deposit types that cross-cut lithologic boundaries, such as skarns and porphyry deposits are not expected. Therefore, geologic tracts in the Killik River quadrangle that are favorable for hosting mineral deposits are defined by and confined to the boundaries of host rock lithology. The tracts are shown on maps B and C and the geologic and geochemical data used in determining them are summarized in table 3.

The criteria for determining resource potential and certainty of assessment are described in Goudarzi (1984) and are included on figure 4. Mineral resources include known deposits or occurrences that may not be economically or technologically recoverable at present, and unknown deposits that are inferred to exist. The degree of resource potential assigned to areas is based on geological and geochemical evidence, and does not take into account the extreme remoteness of the Killik River quadrangle or the availability of land for development of these resources.

MINERAL RESOURCE POTENTIAL

SEDIMENTARY EXHALATIVE MASSIVE SULFIDES (Ag, Pb, AND Zn WITH OR WITHOUT Ba)

Description of Deposit Type

Sedimentary exhalative massive sulfide deposits form during deposition of the enclosing strata in relatively deep marine basins under conditions of low oxygen concentration (Maynard, 1991a). Host rocks consist predominantly of black shale, argillite, chert, and siltstone. Turbidites and slump breccias may be present locally, and volcanic rocks of bimodal composition may be associated in time but not always in space. Stratiform layers of sulfide minerals are most common, although discordant veins and stockworks are common in vent or feeder zones underlying the stratiform bodies. These deposits are commonly referred to as Sullivan-type (Sawkins, 1990), sedimentary exhalative (Carne and Cathro, 1982), sediment-hosted submarine exhalative (Large, 1981), and shale-hosted lead-zinc deposits (Cox and Singer, 1986).

Although there are no known stratiform sedimentary exhalative massive sulfide occurrences and deposits in the Killik River quadrangle, they are present in the DeLong Mountains and Howard Pass quadrangles in the western Brooks Range (table 1; fig. 3), where they are hosted in black shale and chert of the Mississippian to Lower or Middle Pennsylvanian Kuna Formation of the Lisburne Group. The Red Dog mine in the western DeLong Mountains has announced reserves of 85 million tons of 17.1 percent Zn, 5.0 percent Pb, and 82 g/ton Ag (Moore and others, 1986; Koehler and Tikkanen, 1991), occurring as siliceous massive sulfides, making it one of the world's largest and richest Zn deposits. The Su-Lik deposit, also located in the western DeLong Mountains, contains reserves of at least 25 million tons of ore grading at 8.8 percent Zn, 3.0 percent Pb, and 34 g/ton Ag (Forrest, 1983). Other occurrences of this deposit type include the Competition Creek, Suds, Surprise, and Drenchwater Creek occurrences. The silver-lead-zinc (with or without barium) massive sulfide occurrences and deposits are delineated by anomalous concentrations of Ag, As, Ba, Cd, Sb, and Zn in stream-sediment samples (Theobald and others, 1978; Kelley and others, 1992).

Prospective Tracts in the Killik River Quadrangle

Black shale and chert of the Kuna Formation of the Lisburne Group, that host the known occurrences and deposits, crop out intermittently across the entire western and central Brooks Range, including within the Killik River quadrangle. In addition to the Kuna Formation, black shale or chert units that are permissive hosts for sulfide mineralization include the Akmalik Chert (included as part of unit JMc) and the Otuk Formation (included as part of unit JPe, map A). Although these units are not known to host massive sulfide deposits, they are considered permissive host rocks because they include black shale and chert units that represent basinal facies deposited under conditions of relatively low oxygen. The Upper Mississippian and Lower Pennsylvanian Akmalik Chert is considered to be a more favorable host rock than the Triassic and Jurassic Otuk Formation because the age of the Akmalik Chert is equivalent to the age of the Kuna Formation. The Lower Mississippian Kayak Shale also includes dark-gray and black shale, but it's depositional environment is uncertain. The presence of plant debris and phosphatic limestone beds near the top of the Kayak Shale are indicative of a near-shore shallow-water environment. Therefore, the Kayak Shale is not considered to be a permissive host rock for sedimentary exhalative deposits.

Tracts MS1 through MS4 are underlain by shale and chert that are permissive host rock types for massive sulfide occurrences and deposits (map B). Stream-sediment samples collected from tracts MS1 through MS3 contain anomalous concentrations of Ag (0.5-3 ppm), Cd (5-22 ppm), and Zn (250-524 ppm). Two black shale samples collected from tract MS1 contain anomalous concentrations of Ag (7-20 ppm), Cd (30 to more than 100 ppm), Cu (150-200 ppm), and Zn (1,000-2,000 ppm), values that are interpreted to indicate the presence of sulfide minerals (Kelley and others, 1995b; Kelley and Mull, 1995). Samples collected from tracts MS1 and MS3 also contain highly anomalous concentrations of barium, as well as abundant barite. Barite is commonly associated with sedimentary exhalative massive sulfide deposits. Although lead concentrations are relatively high (50-72 ppm) in stream-sediment samples collected from tracts MS1-MS3 compared to sediment samples collected outside these tracts, they are not considered anomalous. Nonmagnetic heavy-mineral concentrate samples collected from these tracts do not contain anomalous concentrations of any base metals (Kelley and others, 1995b). These geochemical data are consistent with the conclusions of Kelley and others (1992) that suggests that (a) stream-sediments are better sample media than nonmagnetic heavy-mineral concentrate samples in delineating shale-hosted sedimentary exhalative stratiform massive sulfide mineral occurrences and deposits in the arctic environment, and (b) silver and zinc (with or without arsenic, barium, cadmium, and antimony) are much better pathfinder elements than lead. This is probably due to the lower mobility of lead compared to that of silver or zinc, and therefore, it is not transported as readily during hydromorphic or chemical weathering

(Kelley and others, 1992). Based on the geological and geochemical data from tracts MS1-MS3, we consider them to have a moderate potential (certainty level C) for silver, lead, and zinc in sedimentary exhalative massive sulfide deposits.

Permissive host rocks are exposed in tract MS4, but the geochemical data revealed mostly back- ground concentrations of Ag, As, Cd, Sb, and Zn. There are anomalous concentrations of barium in some basins within tract MS4. Although this may indicate the possible existence of barite occurrences, the lack of anomalous concentrations of base metals suggests that there are no associated sulfide minerals. Therefore, we assign tract MS4 a low mineral resource potential at a certainty level of C.

WESTERN BROOKS RANGE-TYPE VEIN BRECCIAS (Ag, Pb, AND Zn WITH OR WITHOUT Cu AND Au)

Description of Deposit Type

Banded silver-lead-zinc quartz veins and breccias, described previously, occur at Kady and Vidlee in the Killik River quadrangle (map B). Several other similar occurrences are located in adjacent quadrangles (table 1; fig. 3). The vein occurrences do not belong to any well-established deposit model, and therefore, they were given the name "western Brooks Range vein breccias" by Schmidt and others (1990). The vein breccia occurrences are stratabound within Late Devonian and Early Mississippian(?) age sandstone, siltstone, or conglomerate of the Hunt Fork Shale, Noatak Sandstone, and Kanayut Conglomerate. The mineralized rocks consist of banded sulfides in veins, sulfide-bearing breccias, and disseminated sulfides in sandstone or conglomerate adjacent to quartz veins. The predominant sulfide minerals are chalcopyrite, galena, pyrite, and sphalerite.

It is probable that the vein breccias are genetically related to stratiform sedimentary exhalative massive-sulfide deposits; the vein breccia occurrences may represent the feeder systems of minimally developed, eroded, or structurally removed stratiform bodies. Lead-isotope analyses of sulfide samples collected from the Kady and Vidlee occurrences have Pb-isotope compositions that are very similar to those of sulfides from sedimentary exhalative sulfide deposits in the western Brooks Range (Gaccetta and Church, 1989).

All of the known sulfide-bearing vein occurrences were discovered by tracing regional geochemical anomalies of Ag, Pb, and Zn (with or without As, Au, Cd, Cu, or Sb) in stream-sediment or nonmagnetic heavy-mineral-concentrate samples. Typically, many samples surrounding an occurrence and downstream from an occurrence for distances up to 5 km contain anomalous concentrations of two or more of these elements (Theobald and others, 1978; Schmidt and others, 1990; Kelley and Kelley, 1992; Kelley and others, 1995a; 1995b). This geochemical association differs from the geochemical association related to shale- or chert-hosted massive-sulfide deposits by (1) the presence of anomalous concentrations of lead in stream-sediment and nonmagnetic heavy-mineral-concentrate samples, (2) the presence of anomalous concentrations of other base metals in nonmagnetic heavy-mineral-concentrate samples in addition to stream-sediment samples, and (3) the nearly complete lack of anomalous concentrations of barium or abundant barite in concentrate samples. In addition, two stream-sediment samples collected downstream from the Vidlee occurrence contain anomalous concentrations of Au (0.05 and 0.1 ppm) and mineralized rock samples collected from Kady and Vidlee contain 0.05 to 0.75 ppm Au and 0.015-2 percent Cu (Kelley and others, 1995a; 1995b). The gold and copper typically are not associated with shale-hosted stratiform massive sulfide deposits. Their presence in the sulfide-bearing vein breccias may represent geochemical zoning, with the feeder zones (i.e., the vein breccias) containing a different geochemical signature than overlying stratiform sulfides. This geochemical zonation has been postulated by several workers (Lydon and Sangster, 1984; Cox and Singer, 1986, p. 213) who have documented that feeder zones discordant with their associated stratiform bodies contain higher Pb/Zn, Cu/Zn, and Zn/Ba ratios than the stratiform sulfide bodies.

Prospective Tracts in the Killik River Quadrangle

The southern third of the Killik River quadrangle contains clastic rocks of the Hunt Fork Shale, Noatak Sandstone, and Kanayut Conglomerate. The presence of these rocks, the vein breccia occurrences within them, and (or) geochemical anomalies in stream drainages underlain by these rocks indicates that additional Ag, Pb, Zn (with or without Au or Cu) vein breccia deposits may exist. We have designated three different levels of resource potential and certainty of assessment: one area (tract W1) has high resource potential (certainty level D), two smaller areas (tracts W2-W3) have high resource potential (certainty level C), and one large area (tract W4) has moderate resource potential at a certainty level of B (map A). Tract W1, which contains clastic rocks, is characterized by a cluster of stream-sediment and nonmagnetic heavy-mineral-concentrate samples that contain highly anomalous concentrations of two or more elements, including Ag, As, Au, Cd, Cu, Pb, Sb, or Zn (Kelley and others, 1995a; 1995b). Many of these samples also contain visible sphalerite, galena, pyrite, and chalcopyrite. In addition, the Kady and Vidlee vein breccia occurrences are exposed at the surface. Therefore, tract W1 is considered to have a high resource potential (certainty level D) for silver, lead, and zinc (with or without gold and copper) contained in base metal-bearing vein breccias.

Tracts W2 and W3 are also assigned a high resource potential, but with a certainty level of C. Like tract W1, these areas contain favorable host rocks and are characterized by a cluster of nonmagnetic heavy-mineral-concentrate samples that contain highly anomalous concentrations of Ag, As, Cd, Cu, Pb, or Zn. These samples also contain visible sphalerite, galena, pyrite, and chalcopyrite (Kelley and others, 1995b). However, in contrast to tract W1, tracts W2 and W3 do not contain any known vein-breccia occurrences, and stream-sediment samples collected within them do not contain anomalous concentrations of these elements. Kelley and Kelley (1992) suggest that this may indicate that the volume of sulfides in the streams that drain these areas is not great enough to overcome dilution by quartz, feldspar, and other common rock-forming minerals that make up the bulk of the stream-sediment samples. Therefore, although base-metal sulfides are certainly present, they are not present in sufficient quantity to produce geochemical anomalies in the stream sediments.

Only small quartz-calcite veins in shale, siltstone, and sandstone units of the Hunt Fork Shale were found within tracts W2 and W3. These veins differ from the vein breccias described earlier in that they are thin (generally less than 0.7 cm wide) discontinuous veins containing calcite in addition to quartz; they probably formed as a result of dewatering and diagenesis. Although most are barren, some were found to contain isolated small grains of pyrite, galena, or sphalerite (Duttweiler, 1987). These quartz-calcite veins are widespread throughout the Killik River quadrangle, as well as in adjacent quadrangles (Duttweiler, 1986).

It is unlikely that these veins are the only source of the anomalous concentrations of base metals in the concentrate samples. Although massive sulfide-bearing vein breccias were not found in tracts W2 and W3, their presence cannot be ruled out. Mechanical dispersion would not yield significant geochemical anomalies in stream-sediment samples in instances where the aerial extent of mineralized rocks is small by comparison with the area sampled in the drainage basin. Many of the drainages in the central and eastern parts of the quadrangle have lower relief and typically larger, broader basins relative to those in the southwestern part of the quadrangle. Therefore, if vein and breccia mineral occurrences similar to those at Kady and Vidlee exist in tracts W2 and W3, the areal extent may still be too small relative to the size of the basin for mechanical dispersion to produce geochemical anomalies in the sediment samples.

Tract W4 contains favorable lithologies but stream-sediment and nonmagnetic heavy-mineral-concentrate samples do not contain anomalous concentrations of base metals. Instead, stream-sediment and (or) nonmagnetic heavy-mineral-concentrate samples contain mostly background (or slightly higher) concentrations of silver, copper, lead, or zinc and only a few visible grains of sulfide minerals (Kelley and others, 1995a; 1995b). Although follow-up studies were conducted in several of the drainages in this area, the source for the geochemical anomalies was not found. They may have originated from disseminated pyrite and other sulfide minerals that are common in the Noatak Sandstone and Kanayut Conglomerate, and that probably formed during dewatering and diagenesis of underlying shale units (Duttweiler, 1986). It is possible, however, that vein or vein-breccia occurrences may exist that are either (a) of small aerial extent or are more poorly exposed in comparison to known occurrences, and therefore, not delineated given the density of sample localities, or (b) of lower grade, resulting in only moderately high base-metal concentrations in sediment samples. Tract W4 is assigned a moderate potential (certainty level B) for silver, lead, and zinc resources in sulfide-bearing vein breccias.

SEDIMENTARY BARITE (Ba)

Description of Deposit Type

Stratiform massive bedded barite deposits commonly form in chert, shale, mudstone, and carbonate rocks in epicontinental marine sedimentary basins (Lydon and Dawson, 1984). Occasionally, they are spatially and genetically associated with sedimentary exhalative base-metal massive-sulfide deposits. The barite lenses may have formed from barite deposition near low temperature (<100° C) springs due to fixation of the barium content of springwater by seawater sulfate (Lydon and Dawson, 1984). Although none are known to exist in the Killik River quadrangle, massive barite lenses are associated with sulfide minerals at the Red Dog silver-lead-zinc deposit and at two other localities in adjacent quadrangles that do not have associated sulfides (fig. 3). All of these barite occurrences are hosted in Mississippian age black (and lighter colored) shale and chert (Mayfield and others, 1979; Barnes and others, 1982; J.S. Kelley and others, 1993).

In the Killik River quadrangle, thin veins and lenses, and crystal aggregates of barite are common in siltstone and mudstone of the Siksikpuk Formation of the Etivluk Group (Siok, 1985) (included as part of unit JPe, map A). Although most of the barite veins and lenses are small (less than 1 m long), at one locality on the Okokmilaga River in the eastern part of the quadrangle, a large lens (more than 5 m long) is present in the Siksikpuk Formation (C.G. Mull, oral commun., 1991). Smaller amounts of barite are also present in the Imnaitchiak Chert (included as part of unit JMc, map A). Barite in the Etivluk Group rocks and Imnaitchiak Chert most likely formed during diagenesis (Siok, 1985). Diagenetic barite is also found in rocks of the Siksikpuk Formation at several localities adjacent to the Killik River quadrangle (table 1; fig. 3). Although the grades of these occurrences may be high locally, their low tonnages preclude them from being rated as economic resources.

An additional barite occurrence is an unusual oncolitic conglomerate, present in the basal part of the Imnaitchiak Chert, in the Akmalik Creek area in the central part of the quadrangle. The dominant clast lithologies are shale, chert, limestone, and oncoids set in a glauconitic and phosphatic matrix (Siok and Mull, 1987). The barite, which preferentially replaces shale, limestone, and oncoid clasts, is probably of hydrothermal origin.

Prospective Tracts in the Killik River Quadrangle

Chert and shale units of Mississippian to Jurassic age (units JMc and JPe, map A) are considered to be favorable host rocks for barite mineralization. These units are distributed primarily in the central part of the quadrangle. Tracts B1 through B7 contain favorable host rocks and, therefore, delineate areas having potential for barite resources (map B). Stream-sediment samples collected from tracts B1 through B5 contain anomalous concentrations of Ba (5,000 ppm) and nonmagnetic heavy-mineral-concentrate samples contain 50 percent barite. Several NURE sediment samples contain 1.0 to 6.4 percent Ba (Kelley and Mull, 1995). It is not possible to distinguish whether the barite was derived from massive lenses or widely scattered nodules and thin discontinuous veins, the former having a higher resource potential than the latter; both types would likely yield similar geochemical anomalies in stream-sediment and nonmagnetic heavy-mineral concentrate samples. Therefore, although the geologic and geochemical data indicate that the rocks of tracts B1 through B5 are highly favorable for barite occurrences, they are assigned a moderate potential for Ba resources (certainty level B). Area B6 is also assigned a moderate resource potential (certainty level B), although it is not delineated by anomalous concentrations of barium in stream-sediment samples; the density of stream-sediment samples in this area is not sufficient to target this small outcrop of the Siksikpuk Formation. However, barite was found in a lens more than 5 m long, which is significantly larger than most lenses or veins found in the Siksikpuk Formation. Tract B7 also contains permissive host rocks, but geochemical samples collected from the area do not contain anomalous barium and barite was not observed in the field; therefore, tract B7 is considered to have a low resource potential (certainty level C).

SEDIMENTARY MANGANESE (Mn)

Description of Deposit Type

Sedimentary manganese deposits form in shallow-marine environments on continental platforms, generally without synchronous volcanism (Force and Maynard, 1991). They form on the oxygenated margins of anoxic basins where a mixing zone exists between shallow oxygenated water and deep anoxic water. Very commonly they are hosted by carbonate rocks, clay, and glauconitic sand. Manganese is precipitated as an oxide or carbonate and may be associated locally with sedimentary phosphorite deposits. These deposits are also referred to as bathtub-ring manganese (Cannon and Force, 1986) or stratified-basin-margin manganese deposits (Force and Maynard, 1991). They may be very large tonnage, although usually low to moderate grade (Cannon and Force, 1986). Sedimentary exhalative silver-lead-zinc deposits that form in relatively deeper, more anoxic parts of the basin are often associated with sedimentary manganese deposits.

Although no sedimentary manganese deposits are known to be present in the Brooks Range, several occurrences of manganese-rich carbonate rocks, chert, and shale were found in the Misheguk Mountain and Howard Pass quadrangles (Jansons and Baggs, 1980; Jansons and Parke, 1981). Three shale samples collected from Sphinx Mountain in the western Misheguk Mountain quadrangle contain 10,000 ppm Mn, and stream-sediment samples collected from Sphinx Mountain and the Drenchwater Creek area in the Howard Pass quadrangle contain 29,000 ppm and 10,000 ppm Mn, respectively.

Prospective Tracts in the Killik River Quadrangle

In the Killik River quadrangle, platformal carbonate rocks of the Lisburne Group (PMl) and chert and shale of the Siksikpuk Formation of the Etivluk Group (included in JPe) are potential hosts for sedimentary manganese because they represent deposition in relatively oxygenated conditions on or near a continental margin. In addition, the Imnaitchiak Chert (included as part of unit JMc, map A), which represents the cherty equivalent of the Siksikpuk Formation (Mull and others, 1987), is a potential host for sedimentary manganese deposits. Locally, the Imnaitchiak Chert consists of a 1-m-thick basal unit of greenish-gray, glauconitic and phosphatic sandstone, which is overlain by green, maroon, and gray chert, siltstone, and shale (Siok and Mull, 1987). The Imnaitchiak Chert is distributed primarily in the west-central and central parts of the quadrangle.

The presence of all of these favorable host rocks with or without significant Mn anomalies in stream-sediment and rock samples suggests potential for sedimentary manganese deposits. Seven small tracts (M1 through M7, map C) contain permissive host rocks, and stream-sediment samples collected within them contain anomalous concentrations of manganese. Samples collected from these tracts during the AMRAP study contain greater than or equal to 5,000 ppm Mn, the upper determination limit for manganese with the emission spectrographic method. Sediment samples collected during the NURE survey contain from 0.48 to 1 percent Mn (Kelley and Mull, 1995). In addition, a few chert and shale samples collected from within these areas contain greater than or equal to 5,000 ppm Mn. Tracts M1 through M7 are assigned a moderate potential (certainty level C) for manganese resources in sedimentary rocks.

Tract M8 contains permissive host rocks, but stream-sediment and rock samples collected from this area contain less than 5,000 ppm Mn and are not considered anomalous concentrations (Kelley and Mull, 1995). A low potential (certainty level C) for manganese resources is therefore assigned to this area.

SEDIMENTARY PHOSPHATE (P WITH OR WITHOUT F AND U)

Description of Deposit Type

Sedimentary phosphate deposits form in shallow-marine environments, in areas of warm upwelling waters with a good connection to the open sea. These deposits are associated with clays, carbonate rocks, shale, and chert. Sedimentary phosphate deposits are commonly associated with sedimentary manganese deposits. Phosphatic pellets, oolites, and shell fragments are the most common textural components of mineralized rocks. Apatite, fluorapatite, iron oxides, pyrite, and the uranium-bearing mineral carnotite are the minerals most commonly associated with these deposits (Cox and Singer, 1986).

Phosphate-bearing zones are present in the upper part of the carbonate rocks of the Mississippian and Pennsylvanian Lisburne Group and the Triassic and Jurassic Otuk Formation of the Etivluk Group at a number of localities in the Killik River and adjacent quadrangles. Low-grade phosphate also may be present in the Mississippian to Lower or Middle Pennsylvanian Kuna Formation of the Lisburne Group.

A zone up to about 0.6 m thick of oolitic and pelletal phosphate, and phosphatic shale and limestone occurs near the top of the Lisburne Group at two localities in the western part of the Chandler Lake quadrangle, east of the Killik River quadrangle (Patton and Tailleur, 1964; Patton and Matzko, 1959). Thin intervals of phosphate rock within this zone were reported to contain up to 30 percent P_2O_5 (Chapman and others, 1964; Patton and Tailleur, 1964). This phosphate-bearing zone also crops out near the top of the Lisburne Group at the mountain front near Akmalik Creek in the central Killik River quadrangle (no. 6, table 2; map C); it is estimated to be about 0.5 m thick at this locality. It's lateral extent in the Killik River quadrangle is unknown, but it may be considerable, as it maintains about the same thickness and occurs at about the same stratigraphic level in the western Chandler Lake quadrangle. In addition to the Akmalik Creek occurrence, a poorly exposed unit (about 1 m thick) of pelletal and oolitic phosphate is present at the top of the Lisburne Group carbonate rocks on the western edge of the Ivotuk Hills in the west-central part of the Killik River quadrangle (no. 11, table 2, map C). Lisburne Group carbonate rocks pinch out farther south along the mountain front, but black shale and chert of the Kuna Formation of the Lisburne Group are present in this area. The Kuna Formation has a high organic content and possibly a low phosphate content, but no analytical data are available.

Locally in the quadrangle, the basal part (1 m thick) of the Imnaitchiak Chert consists of greenish-gray, glauconitic, and phosphatic sandstone (nos. 7 through 10, table 2; map C). In addition, in the Akmalik Creek area in the central part of the quadrangle, an unusual oncolitic conglomerate is present (Siok and Mull, 1987) that contains a glauconitic and phosphatic matrix (no. 5, table 2; map C).

Black shale units of the Otuk Formation in the Etivluk Group contain scattered phosphate pebbles and nodules at many localities throughout the Brooks Range; within the Killik River quadrangle, these pebbles are most abundant in the eastern part of the quadrangle. Although no analytical data are available concerning phosphates in the Otuk Formation, samples collected from the partially stratigraphically correlative Shublik Formation in the northeastern Brooks Range reportedly contain as much as 4 percent phosphorus (Tourtelot and Tailleur, 1971; Parrish, 1987).

Prospective Tracts in the Killik River Quadrangle

Tracts containing carbonate rocks of the Lisburne Group (ℙMl), black shale and chert of the Kuna Formation of the Lisburne Group (ℙMk), and chert and shale of the Etivluk Group (JPe) and the basal part of the Imnaitchiak Chert (JMc) are considered to be permissive host rocks for sedimentary phosphate. Tracts P1 and P2 contain permissive host rocks that were observed in the field to be phosphatic; these tracts are assigned a moderate resource potential, but because there are no available geochemical analyses for these rocks, they are assigned a certainty level of B. Other tracts (tracts P3-P4) are assigned a low resource potential because no phosphatic rocks have been reported in these areas. There are no available rock geochemical data from tract P4, and therefore, it is assigned a certainty level of B. However, there are geochemical data from tract P3 (Patton and Matzko, 1959), which indicate very low phosphate and uranium contents: three samples of Lisburne Group carbonate rocks collected from tract P3 contained less than 5 percent P_2O_5 (as low as 0.4 percent in one sample) and less than 0.004 percent uranium (Patton and Matzko (1959). This area has a low potential (certainty level C) for phosphate resources.

CYPRUS-TYPE MASSIVE SULFIDES (Cu, Zn)

Description of Deposit Type

Cyprus-type massive sulfide deposits are typically hosted in pillow basalts and associated chert or phyllite, and primarily consist of massive chalcopyrite, pyrite, pyrrhotite, and sphalerite with underlying sulfide stockwork or stringer zones (Cox and Singer, 1986). There are no known Cyprus-type massive sulfide occurrences or deposits in the Brooks Range; however, favorable host rocks are present at a number of localities in the western and central Brooks Range.

Prospective Tracts in the Killik River Quadrangle

In the Killik River quadrangle, pillow basalts with intercalated chert form Kikiktat Mountain, and fine- to coarse-grained basalt and volcanic breccias form the Itkilikruich Ridges to the north. The aerial extent of the basalts at Kikiktat Mountain is approximately 10 km^2. The extent of basalt and associated volcanic breccias of the Itkilikruich Ridges is approximately 7 km^2. There are additional, volumetrically smaller exposures of mafic igneous rocks scattered throughout the central part of the quadrangle. Many of these are diabase dikes or very thin slivers of pillow basalt.

Sediment samples collected from localities surrounding Kikiktat Mountain and the Itkilikruich Ridges contain 75-100 ppm Cu (Kelley and Mull, 1995). Samples of mafic igneous rocks collected from these localities, many of which contain disseminated pyrite, contain 0.5-0.7 ppm Ag, 100-300 ppm Cu, and Zn concentrations that are below the detection limit of 200 ppm. These values are generally close to the background levels for mafic igneous rocks (Levinson, 1974). Although minor chalcopyrite was found in one mafic igneous rock sample, most rock and nonmagnetic heavy-mineral-concentrate samples collected from drainages surrounding the mafic igneous rocks do not contain visible chalcopyrite or sphalerite (Kelley and others, 1995a; 1995b).

Given the relatively small volume of mafic extrusive rocks in the Killik River quadrangle, the general lack of anomalous copper or zinc in rock or stream-sediment samples, and the lack of visible copper- or zinc-sulfide minerals in most samples, the Kikiktat Mountain and the Itkilikruich Ridges areas (tracts CMS1 and CMS2) are assigned a low potential (certainty level C) for copper and zinc resources from Cyprus-type massive sulfide deposits.

PLACER CHROMITE (Cr WITH OR WITHOUT Au AND PGE)

Description of Deposit Type

Although chromite-bearing placer deposits are rare on a worldwide scale, they are present in beach sands along the southern coast of Oregon (Griggs, 1945), and some minor production of chromite has come from a few of the larger deposits. In addition to chromite, these deposits contain zircon, ilmenite, rutile, and magnetite. Gold and platinum group elements (PGE) are present in minor but significant concentrations. Much of the chromite is thought to have been derived directly by weathering of ultramafic and mafic igneous rocks in the area, but the largest deposits are thought to have formed by reworking of Tertiary sedimentary clastic rocks containing detrital chromite. The sorting and concentration of chromite during several cycles of erosion are key factors in accumulating the chromite in a deposit of sufficient size and grade to be economically mineable (Griggs, 1945).

There may be potential for chromium resources in placers from valleys that drain chromite-bearing mafic and ultramafic igneous rocks in the western Brooks Range (Foley and others, 1986). These mafic and ultramafic rocks contain podiform chromite deposits (table 1; fig. 3) with estimated reserves of 0.6 to 1.4 million short tons of chromium oxide. Geochemical analyses indicate that only low concentrations of gold and palladium occur in a few chromite-rich rock samples (Foley and others, 1986).

Prospective Tracts in the Killik River Quadrangle

Mafic igneous intrusive and extrusive rocks are exposed in several areas in the Killik River quadrangle, such as at Kikiktat Mountain and the Itkilikruich Ridges, but there are no exposed ultramafic rocks within the quadrangle. Geochemical data do not indicate the presence of anomalous chromium or nickel associated with the mafic igneous bodies. However, many sediment samples that contain highly anomalous concentrations of Cr (1,400-2,340 ppm) and Ni (150-241 ppm) are spatially associated with exposures of the Lower and Upper Cretaceous Nanushuk Group (Kelley and Mull, 1995). The Nanushuk Group represents a deltaic complex that prograded northward from the Brooks Range. It is composed of sediments derived primarily from preexisting sedimentary rocks with a variable contribution from mafic and ultramafic rocks, as well as metamorphic rocks and volcanic detritus (Huffman, 1985). The source for the high concentrations of chromium and nickel in sediment samples is probably chromite that either resides as a detrital mineral in sandstone or conglomerate of the Nanushuk Group, or as a detrital mineral in Quaternary sand and gravel that was reworked from the Cretaceous sedimentary deposits (Kelley and Mull, 1995).

Similar anomalous concentrations of chromium and nickel in the adjacent Howard Pass quadrangle are contained in sediment samples collected in areas underlain by deltaic sedimentary deposits of Cretaceous age (Schmidt and others, 1990). Chromite was identified by X-ray diffraction studies to be the source mineral for the geochemical anomalies (K.D. Kelley, unpub. data, 1991). Analyses of platinum group elements and low-level gold of the most chromium-rich sediment samples (Jeff Foley, unpub. data, 1991) indicate that, in general, platinum group elements and gold concentrations are low in most samples (<30 ppb Pt, <10 ppb Pd, and <10 ppb Au). Although analytical data for platinum group elements and low-level gold are not available for sediment samples collected from the Killik River quadrangle, they probably contain similar low concentrations. In addition, nonmagnetic heavy-mineral-concentrate samples do not contain detectable gold (20 ppm lower detection limit), or visible gold.

Assuming that the source for the highly anomalous concentrations of chromium in sediment samples is chromite, the data indicate that chromite is widespread in areas that contain rocks of the Nanushuk Group (tract CR1, map C). Analytical data indicating the degree of concentration of the chromite or the concentrations of platinum group elements associated with it are not available, but gold was not detected or observed in either sediment or nonmagnetic heavy-mineral-concentrate samples. Tract CR1 is assigned a low resource potential (certainty level B) for chromium (with or without platinum group elements or gold) in placer deposits.

ROLL-FRONT SANDSTONE-HOSTED URANIUM (U WITH OR WITHOUT Cu AND V)

Description of Deposit Type

Roll-front uranium deposits are stratabound deposits that form epigenetically in the near-surface environment by reaction between oxidized, U-bearing water and a reductant in the host rock, which is commonly either pyrite or organic matter. In order to form a roll-front uranium deposit, the following criteria are required: (1) a source for uranium, such as felsic igneous rocks or volcanic ash, (2) oxidation and mobilization of the uranium, (3) sufficient permeability for transport of uranium-bearing fluids, and (4) a reducing host lithology. Most deposits of this type are Mesozoic in age (Maynard, 1991b).

Prospective Tracts in the Killik River Quadrangle

Although uranium has not been reported in northern Alaska, favorable environments for sandstone-type uranium deposits have been described by many investigators (Chapman and others, 1964; Detterman and others, 1963; Patton and Tailleur, 1964). The Lower and Upper Cretaceous Nanushuk Group, which is exposed in the northern part of the Killik River quadrangle, contains more than 1,500 m of nonmarine and fluvial sedimentary deposits derived primarily from preexisting sedimentary rocks with a variable contribution from mafic and ultramafic rocks, metamorphic rocks, and volcanic detritus (Huffman, 1985). Potential sources of uranium are bentonitic clays present in the uppermost part of the Nanushuk Group and the bentonitic and tuffaceous beds of the overlying Colville Group. There is also an abundance of carbonized plant debris distributed throughout the rocks of the Nanushuk Group that could act as a reductant for uranium-bearing solutions (Huffman, 1985).

The rocks of the Nanushuk Group were evaluated in detail by Huffman (1985) for their uranium resource potential by collecting rock samples from outcrops extending from the west coast of northern Alaska to the Sagavanirktok River east of the Killik River quadrangle. It was concluded that the generally low sand-shale ratio and the limited areal extent of sandstone bodies severely limit the overall uranium resource potential (Huffman, 1985). In addition, although there are bentonite-rich units that could serve as sources of uranium, they are typically associated with high mudstone contents in the upper part of the Nanushuk Group, so it is problematical whether any uranium released from these source beds could find its way to sandstone aquifers in sufficient quantity to form economic deposits.

Available geochemical data include the results of uranium analyses of rock samples of the Nanushuk Group throughout the Arctic Foothills belt (Huffman, 1985). All uranium concentrations of these samples are less than 4.2 ppm. In addition, NURE sediment data do not indicate the presence of uranium-mineral occurrences (Kelley and Mull, 1995). Although four sediment samples contain relatively high uranium concentrations (3.5 to 4.8 ppm), there are no associated vanadium or copper anomalies which are common pathfinder elements for roll-front type sandstone-hosted uranium deposits (Maynard, 1991b). Overall, the geologic and geochemical data indicate that the area containing rocks of the Nanushuk Group (tract U1, map C) has a low potential (certainty level C) for uranium (with or without copper and vanadium) resources.

COAL

Prospective Tracts in the Killik River Quadrangle

Although coal-bearing rocks are known or inferred to be present throughout most of northern Alaska from Cape Lisburne to the Itkillik River east of the Killik River quadrangle (Barnes, 1967), there has been no previous commercial production from these rocks, due partly to the remoteness of the area. In the Colville River basin area, which includes the northern part of the Killik River quadrangle, coal beds are most abundant and widespread in the Lower Cretaceous Killik Tongue of the Chandler Formation of the Nanushuk Group (Barnes, 1967).

Most of the coal is interbedded with shale, although locally it is associated with sandstone and siltstone. Bentonite and tuff are also commonly associated with the coal. Individual coal beds are generally less than 1 m thick and rarely more than 3 m thick (Barnes, 1967; Affolter and Stricker, 1987). Little is known about the lateral extent and variations in character of individual coal beds because most beds are known only from single outcrops (Barnes, 1967). However, at Killik Bend on the Colville River in the northern part of the quadrangle, an identical series of coal beds was noted at two localities 2.4 km apart (Chapman and others, 1964).

Results of chemical analyses of coal samples collected from the NPRA just west of the Killik River quadrangle indicate that the coal grade is high-volatile A bituminous. Compared to other western U.S. coal of Cretaceous age, this coal is significantly lower in ash, volatile matter, and trace elements such as As, Be, Hg, Mo, Sb, and Se (Affolter and Stricker, 1987).

The limited thickness of the individual coal beds and the probable limited lateral extent of most of the beds reduce their resource potential. Therefore, the area that contains rocks of the Nanushuk Group (tract C1, map C) is assigned a low potential (certainty level C) for coal resources.

HYDROCARBONS

Many of the conditions necessary for the generation, migration, and entrapment of hydrocarbons exist in rocks of the Killik River quadrangle. Although analytical data are limited, visual examination of outcrop samples indicates that hydrocarbon source rocks and reservoir beds are present. Geologic mapping and geophysical seismic-reflection studies indicate that structural traps may also be present in the quadrangle. Hydrocarbon exploration in the form of detailed geologic mapping, geophysical surveys, and drilling by petroleum companies and government agencies has been conducted along the entire length of the Arctic Foothills Province. North and east of the Killik River quadrangle, several wells have found subeconomic quantities of oil or gas. Four exploratory wells were drilled in the quadrangle; all were plugged and abandoned, but one tested subeconomic quantities of natural gas.

The mountainous southern third of the Killik River quadrangle is thought to have no hydrocarbon resource potential. The southern and northern foothills of the northern two-thirds of the quadrangle have some potential. However, the present data are not adequate to assign levels of resource potential for these areas. Therefore, this report will include only a discussion of the features present in the Killik River quadrangle that are indicative of petroleum resource potential. Additional discussion of details of the petroleum potential of some of the rocks in the Killik River quadrangle and adjacent areas is given by Chapman and others (1964) and Patton and Tailleur (1964).

Northern Foothills Subprovince

The Northern Foothills Subprovince, which underlies the northern third of the quadrangle (fig. 1), consists of the broad belt of gently folded rocks of the Lower and Upper Cretaceous Nanushuk Group (map A). The Nanushuk Group probably contains porous and permeable sandstones that have reservoir potential; the underlying shale beds of the Torok Formation are probable source beds. However, based on work done in the NPRA adjacent to the Killik River quadrangle, the best apparent reservoir beds on the anticlines in this belt appear to be breached to the surface, and there may be no large traps in the subsurface other than possible stratigraphic pinchouts at shallow depths in the Nanushuk Group. No oil seeps are known to be present in the area, but two possible gas seeps are present in the Colville River valley just to the north of the quadrangle (Chapman and others, 1964). Two exploratory wells, Texaco West Kurupa No. 1 (3,372 m; 11,060 ft) and East Kurupa No. 1 (3,870 m; 12,695 ft) were drilled within this belt in the northern part of the quadrangle (fig. 2). However, the East Kurupa No. 1 well indicated only subeconomic quantities of natural gas from several intervals of sandy siltstone of the Torok Formation.

Southern Foothills Subprovince

The Southern Foothills Subprovince, which trends east-west across the central third of the quadrangle (fig. 2), contains exploration plays in the carbonate rocks of the Lisburne Group in the Brooks Range thrust belt. At several localities along the mountain front and in the foothills, dolomite of the Lisburne Group contains well-developed vuggy porosity and contains solid black overmature hydrocarbon in some places. Potential hydrocarbon source beds include black shale and limestone with high organic content in the Triassic and Jurassic Otuk Formation and in the Lower Mississippian to Lower or Middle Pennsylvanian Kuna Formation. Bodnar (1984) reported that 48 samples of shale collected from the Otuk Formation in the Killik River quadrangle and adjacent Chandler Lake quadrangle yielded an average total organic content (TOC) value of 2.77 weight percent and thermal maturity analyses ranging from immature to overmature. These data indicate that the Otuk Formation, although relatively thin, is an excellent hydrocarbon source horizon. Solid black hydrocarbon is present in porous Lisburne dolomite units in a variety of structural orientations and in fractures in the Otuk Formation and Cretaceous rocks of the thrust belt, indicating that hydrocarbon generation and migration may have occurred before the rocks were involved in the development of the Brooks Range thrust belt. Previously formed hydrocarbon traps may have been destroyed during the formation of the thrust belt. However, the presence of submature source beds in the thrust belt indicates that there is potential for post-thrusting hydrocarbon generation and migration in the belt. However, the complex structures and intense faulting evident in the rocks of the thrust belt suggest that hydrocarbon traps in the subsurface may be small and structurally complicated.

Two exploratory wells were drilled in the thrust belt in the Southern Foothills Subprovince. The USGS-Husky Lisburne No. 1 well (5,184 m; 17,005 ft), drilled near the eastern boundary of the NPRA (fig. 2), penetrated five repeated sections of Lisburne Group carbonate rocks, and demonstrated that these rocks are also present in the subsurface north of the outcrop belt of Lisburne Group rocks. Drilling indicated no significant hydrocarbon shows, but organic geochemical data indicate that hydrocarbon source beds are present at relatively shallow depths. The Chevron Killik No. 1 well, drilled just north of the mountain front in the central part of the quadrangle, was plugged and abandoned as a dry hole, but no information is available concerning this well.

REFERENCES

Affolter, R.H., and Stricker, G.D., 1987, Geochemistry of coal from the Cretaceous Corwin and Chandler Formations, National Petroleum Reserve in Alaska (NPRA), in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope Geology: Society of Economic Paleontologists and Mineralogists Book 50, p. 217-224.

Barnes, F.F., 1967, Coal resources of the Cape Lisburne-Colville River region, Alaska: U.S. Geological Survey Bulletin 1242-E, 37 p.

Barnes, D.F., Mayfield, C.F., Morin, R.L., and Brynn, Sean, 1982, Gravity measurements useful in the preliminary evaluation of the Nimiuktuk barite deposit, Alaska: Economic Geology, v. 77, p. 185-198.

Barton, H.N., Odland, S.K., O'Leary, R.M., and Day, G.W., 1982, Geochemical data for the Killik River and Chandler Lake quadrangles, Alaska: U.S. Geological Survey Open-File Report 82-1026, 53 p.

Bliss, J.D., Brosgè, W.P., Dillon, J.T., Dutro, J.T., Jr., Cathrall, J.B., and Cady, J.W., 1988, Mineral Resource Assessment of the Wiseman 1° x 3° quadrangle: U.S. Geological Survey Open-File Report 88-533, 84 p., 3 plates, 1:250,000.

Bodnar, D.A., 1984, Stratigraphy, age, depositional environments, and hydrocarbon source rock evaluation of the Otuk Formation, north-central Brooks Range: Fairbanks, University of Alaska, M.S. thesis, 232 p.

Brooks, A.H., 1909, Petroleum in the mining industry in 1908: U.S. Geological Survey Bulletin 379-A, p. 21-62.

Brosgé, W.P., Reiser, H.N., Dutro, J.T., Jr., and Nilsen, T.H., 1979, Geologic map of Devonian rocks in parts of the Chandler Lake and Killik River quadrangles, Alaska: U.S. Geological Survey Open-File Report 79-1224, scale 1:200,000.

Cannon, W.F., and Force, E.R., 1986, Descriptive model of sedimentary Mn, in Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 231.

Carne, R.C., and Cathro, R.J., 1982, Sedimentary exhalative (sedex) zinc-lead-silver deposits, northern Canadian Cordillera: CIM (Canadian Institute of Mining and Metallurgy) Bulletin, v. 75, no. 840, p. 66-78.

Carter, R.D., Mull, C.G., Bird, K.J., and Powers, R.B., 1977, The petroleum geology and hydrocarbon potential of Naval Petroleum Reserve No. 4, North Slope, Alaska: U.S. Geological Survey Open-File Report OF-77-475, 61 p.

Chapman, R.M., Detterman, R.L., and Mangus, M.D., 1964, Geology of the Killik-Etivluk Rivers region, Alaska: U. S. Geological Survey Professional Paper 303-F, p. 325-407.

Church, S.E., Kelley, J.S., and Bohn, D., 1995, Mineral resources of the Chandler Lake quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-2144-E, in press.

Churkin, Michael, Jr., Mayfield, C.F., Theobald, P.K., Barton, H.N., Nokelberg, W.J., Winkler, G.R., and Huie, Carl, 1978, Geological and geochemical appraisal of metallic mineral resources, southern National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 78-70A, 82 p.

Cox, D.P., and Singer, D.A. (eds), 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.

Detterman, R.L., Bickel, R.S., and Gryc, G., 1963, Geology of the Chandler River region, Alaska--Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, Northern Alaska, 1944-53, Part 3, Areal geology: U.S. Geological Survey Alaska--Accomplishments during 1985: U.S. Geological Survey Professional Paper 303-E, p. 233-324.

Duttweiler, K.A., 1986, Sulfide occurrences in the Itkillik River region, southeast Chandler Lake quadrangle, Brooks Range, Alaska: U.S. Geological Survey Circular 978, p. 10-13.

Duttweiler, K.A., 1987, Use of factor analysis in locating base metal mineralization in the Killik River quadrangle, Alaska, in Hamilton, T.D., and Galloway, J.P., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1986: U.S. Geological Survey Circular 998, p. 27-30.

Ellersieck, Inyo, Jansons, Uldis, Mayfield, C.F., and Tailleur, I.L., 1982, The Story Creek and Whoopee Creek lead-zinc-silver occurrences, western Brooks Range, Alaska, in Coonrad, W.L., ed., U.S. Geological Survey in Alaska--Accomplishments during 1980: U.S. Geological Survey Circular 844, p. 35-38.

Everhart, D.L., 1983, Uranium in phosphate, in Shanks, W.C., III, ed., Cameron volume on unconventional mineral deposits: New York, American Institute of Mining, Metallurgical, and Petroleum Engineers, p. 61-69.

Foley, J.Y., Barker, J.C., and Brown, L.L., 1986, Chromite resources in Alaska, in Daellenbach, C.C., ed , Chromium-chromite: Proceedings of USBM briefing--U.S. Bureau of Mines Information Circular 9087, p. 23-29.

Force, E.R., and Maynard, J.B., 1991, Manganese--Syngenetic deposits on the margins of anoxic basins, in Force, E.R., Eidel, J.J., and Maynard, J.B., eds., Sedimentary and diagenetic mineral deposits--A basin analysis approach to exploration: Reviews in Economic Geology, v. 5, p. 147-157.

Forrest, Kimball, 1983, Geologic and isotopic studies of the Lik deposit and the surrounding mineral district, DeLong Mountains, western Brooks Range, Alaska: University of Minnesota, Ph.D dissertation, 161 p.

Forrest, Kimball, Rye, R.O., and Sawkins, F.J., 1984a, Sulfur and oxygen isotope systematics of sedimentary exhalative Zn-Pb-Ag deposition in a fault-bounded basin, Lik deposit, western Brooks Range, Alaska [abs.]: Geological Association of Canada, Program with Abstracts, v. 8, p. A23.

Forrest, Kimball, Sawkins, F.J., and Rye, R.O., 1984b, The Lik Deposit, western Brooks Range Alaska: sedex mineralization along axial vent sites in a structural basin [abs.]: Geological Society of America, Abstracts with Programs, v. 16, no. 6, p. 511.

Forrest, Kimball, and Sawkins, F.J., 1987, Geologic setting and mineralization of the Lik deposit: implications for the tectonic history of the western Brooks Range, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Society of Economic Paleontologists and Mineralogists Field Trip Guidebook 50, p. 295-305.

Gaccetta, J.D., and Church, S.E., 1989, Lead isotope data base for sulfide occurrences from Alaska, December, 1989: U.S. Geological Survey Open-File Report 89-688, 60 p.

Goudarzi, G.H., 1984, Guide to preparation of mineral survey reports on public lands: U.S. Geological Survey Open-File Report 84-787, 51 p.

Griggs, A.B., 1945, Chromite-bearing sands of the northern part of the coast of Oregon: U.S. Geological Survey Bulletin 945-E, 150 p.

Gryc, George, 1988, Geology and exploration of the National Petroleum Reserve in Alaska, 1974-1982: U.S. Geological Survey Professional Paper 1399, 940 p.

Hamilton, T.D., 1980, Surficial geologic map of the Killik River quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1234, scale 1:250,000.

Huffman, A.C., Jr., 1985, Introduction, in Huffman, A.C., Jr., ed., Geology of the Nanushuk Group related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 1-6.

Huffman, A.C., Jr., 1989, The Nanushuk Group, in Mull, C.G., and Adams, K.E., eds., Dalton Highway, Yukon River to Prudhoe Bay, Alaska; Bedrock geology of the eastern Koyukuk basin, central Brooks Range and east central Arctic Slope, Guidebook: Alaska Division of Geological and Geophysical Surveys Report no. 7, v.2, p 303-309.

Ikelman, J.A., 1986, Catalog of Geological and Geophysical Data for the National Petroleoum Reserve in Alaska: National Geophysical Data Center, 325 Broadway, Boulder, Colorado, 80303.

Jansons, Uldis, 1982, Zinc-lead occurrences in and near the National Petroleum Reserve in Alaska: U.S. Bureau of Mines Mineral Lands Assessment Report MLA 121-82, 55 p.

Jansons, Uldis, and Baggs, D.W., 1980, Mineral investigations of the Misheguk Mountain and Howard Pass quadrangles, Alaska: U.S. Bureau of Mines Open-File Report 38-80, 76 p.

Jansons, Uldis, and Parke, M.A., 1981, 1978 Mineral investigations in the Misheguk Mountian and Howard Pass quadrangles, Alaska: U.S. Bureau of Mines Open-File Report 26-81, 195 p.

Kelley, J.S., Tailleur, I.L., Morin, R.L., Reed, K.M., Harris, A.G., Schmidt, J.M., and Brown, F.M., 1993, Barite deposits in the Howard Pass quadrangle and possible relations to barite elsewhere in the northwestern Brooks Range, Alaska: U.S. Geological Survey Open-File Report 93-215, 13 p.

Kelley, K.D., Borden, J.C., Bailey, E.A., Fey, D.L., Motooka, J.M., and Roushey, B., 1992, Geochemically anomalous areas in the west-central part of the Howard Pass Quadrangle, National Petroleum Reserve, Brooks Range, Alaska, in Evans, D.C. and Dusel-Bacon, Cynthia, eds., Geologic studies in Alaska by the U.S. Geological Survey during 1991: U.S. Geological Survey Bulletin 2041, p. 60-69.

Kelley, K.D., and Kelley, D.L., 1992, Reconnaissance exploration geochemistry in the central Brooks Range,northern Alaska: Implications for exploration of sediment-hosted zinc-lead-silver deposits: Journal of Geochemical Exploration, v. 42, p. 273-300.

Kelley, K.D., and Mull, C.G., 1995, Maps showing the distribution of selected elements in minus-100-mesh and minus-80-mesh sediment samples from the Killik River quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies MF-2225-B, scale 1:250,000.

Kelley, K.D., Mull, C. G., and Barton, H. N., 1995a, Maps showing the distribution of selected elements in minus 30-mesh stream-sediment samples from the southern part of the Killik River quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-2225-C, scale 1:250,000.

Kelley, K.D., Mull, C. G., and Barton, H. N., 1995b, Maps showing the distribution of selected elements and mineralogy of nonmagnetic heavy-mineral-concentrate samples from the southern part of the Killik River quadrangle: U. S. Geological Survey Miscellaneous Field Studies MF-2225-D, scale 1:250,000.

Koehler, G.F., and Tikkanen, G.D., 1991, Red Dog, Alaska: Discovery and definition of a major zinc-lead-silver deposit, in Hutchinson, R.W., and Grauch, R.I., eds., Historical Perspectives of genetic concepts and case histories of famous discoveries: Economic Geology Monograph 8, p. 268-274.

Lange, I.M., Nokleberg, W.J., Plahuta, J.T., Krouse, H.R., and Doe, B.R., 1981, Geochemistry of volcanogenic Zn-Pb-Ba deposits, NW Brooks Range, Alaska: U.S. Geological Survey Open-File Report 81-355, 16 p.

Lange, I.M., Nokleberg, W.J., Plahuta, J.T., Krouse, H.R., and Doe, B.R., 1985, Geologic setting, petrology, and geochemistry of stratiform sphalerite-galena-barite deposits, Red Dog Creek and Drenchwater Creek areas, northwestern Brooks Range, Alaska: Economic Geology, v. 80, no. 7, p. 1896-1926.

Lange, I.M., and Nokleberg, W.J., 1987, Geologic setting, petrology, and geochemistry of stratiform sphalerite-galena-barite deposits, Red Dog Creek and Drenchwater Creek areas, northwestern Brooks Range, Alaska--A reply to discussion by Young, L.E., and Moore, D.W., 1987, in Economic Geology, v. 82, no. 4, p. 1077-1079.

Large, D.E., 1981, Sediment-hosted submarine exhalative lead-zinc deposits--A review of their geological characteristics and genesis, in Wolf, K.H., ed., Handbook of Strata-bound and stratiform ore deposits, Amsterdam, p. 469-507.

Levinson, A.A., 1974, Introduction to exploration geochemistry: Calgary, Alberta, Applied Publications Ltd., 612 p.

Los Alamos National Laboratory, 1982, Uranium hydrogeochemical and stream-sediment reconnaissance of the Killik River quadrangle, Alaska: U.S. Department of Energy Report GJBX 37(82), 80 p.

Lueck, Larry, 1980, Lead isotope ratios from the Red Dog and Drenchwater Creek lead-zinc deposits, DeLong Mountains, Brooks Range, Alaska, in Short notes on Alaskan geology, 1979-1980: Alaska Division of Geological and Geophysical Surveys Geologic Report 63, p. 1-5.

Lydon, J.W., and Dawson, K.R., 1984, Sediment-hosted barite, in Eckstrand, O.R., ed., Canadian mineral deposit types--A geological synopsis: Geological Survey of Canada Economic Geology Report 36, p. 36.

Lydon, J.W., and Sangster, D.F., 1984, Sediment-hosted sulfides, in Eckstrand, O.R., ed., Canadian mineral deposit types--A geological synopsis: Geological Survey of Canada Economic Geology Report 36, p. 35.

Mayfield, C.F., Curtis, S.M., Ellersieck, Inyo, and Tailleur, I.L., 1979, Reconnaissance geology of the Ginny Creek zinc-lead-silver and Nimiuktuk barite deposits, northwestern Brooks Range, Alaska: U.S. Geological Survey Open-File Report 79-1092, scale 1:63,360, 20 p.

Mayfield, C.F., Ellersieck, Inyo, and Tailleur, I.L., 1987, Reconnaissance geologic map of the Noatak C5, D5, D6, and D7 quadrangles, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1814, scale 1:63,360.

Mayfield, C.F., Tailleur, I.L., Albert, N.R.D., Ellersieck, Inyo, Grybeck, Donald, and Hackett, S.W., 1983, The Alaska Mineral Resource Assessment Program--Background information to accompany folio of geologic and mineral resource maps of the Ambler River quadrangle, Alaska: U.S. Geological Survey 793, 31 p.

Mayfield, C.F., Tailleur, I.L., and Ellersieck, Inyo, 1983, Stratigraphy, structure, and palinspastic synthesis of the western Brooks Range, northwestern Alaska: U.S. Geological Survey Open-File Report 83-779, 58 p., scale 1:1,000,000.

Maynard, J.B., 1991a, Shale-hosted deposits of Pb, Zn, and Ba--Syngenetic deposition from exhaled brines in deep marine basins, in Force, E.R., Eidel, J.J., and Maynard, J.B., eds., Sedimentary and diagenetic mineral deposits--A basin analysis approach to exploration: Reviews in Economic Geology, v. 5., p. 177-183.

Maynard, J.B., 1991b, Uranium--Syngenetic to diagenetic deposits in foreland basins, in Force, E.R., Eidel, J.J., and Maynard, J.B., eds., Sedimentary and diagenetic mineral deposits--A basin analysis approach to exploration: Reviews in Economic Geology, v. 5, p. 187-197.

Menzie, W.D., Reiser, H.N., Brosgé, W.P., and Detterman, R.L., 1985, Map showing distribution of mineral resources (excepting oil and gas) in the Phillip Smith Mountains quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-879-C, scale 1:250,000.

Meyer, M.P., and Kurtak, J.M., 1992, Results of the 1991 U.S. Bureau of Mines Colville Mining District study: U.S. Bureau of Mines Open-File Report 75-92, 101 p.

Meyer, M.P., Kurtak, J.M., and Hicks, R.W., 1993, Results of the 1992 U.S. Bureau of Mines Colville Mining District study: U.S. Bureau of Mines Open-File Report 12-93, 35 p.

Moore, D.W., Young, L.E., Modene, J.S., and Plahuta, J.T., 1986, Geologic setting and genesis of the Red Dog zinc-lead-silver deposit, western Brooks Range, Alaska: Economic Geology, v. 81, no. 7, p. 1696-1727.

Motooka, J.M., Adrian, B.M., Church, S.E., McDougal, C.M., and Fife, J.B., 1989, Analytical data and sample locality map for aqua-regia leachates of stream sediments analyzed by ICP, and emission spectrographic and ICP results for many NURE stream sediments from the Killik River quadrangle, Alaska: U.S. Geological Survey Open-File Report 89-12, 77 p., 2 sheets, scale 1:250,000.

Mull, C.G., 1982, The tectonic evolution and structural style of the Brooks Range, Alaska--An illustrated summary, in Powers, R.B., ed., Geological studies of the Cordilleran thrust belt: Denver, Colorado, Rocky Mountain Association of Geologists, v. 1, p. 1-45.

Mull, C.G., Crowder, R.K., Adams, K.E., Siok, J.P., Bodnar, D.A., Harris, E.E., Alexander, R.A., and Solie, D.N., 1987, Stratigraphy of the Picnic Creek allochthon, Killik River quadrangle, central Brooks Range, Alaska, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Society of Economic Paleontologists and Mineralogists Field Trip Guidebook 50, p. 650-662.

Mull, C.G., Moore, T.E., Harris, E.E., and Tailleur, I.L, 1994, Preliminary geologic map of the Killik River quadrangle, central Brooks Range, Alaska: U. S. Geological Survey Open-File Report 94-679, scale 1:125,000.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., Ellersieck, Inyo, and Curtis, S., 1982, New Upper Paleozoic and lower Mesozoic stratigraphic units, central and western Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, no. 3, p. 348-362.

Nilsen, T.H., Brosgé, W.P., Dutro, J.T., Jr., and Moore, T.E., 1981, Depositional model for the fluvial Upper Devonian Kanayut Conglomerate, Brooks Range, Alaska, in Albert, R.D., and Hudson, Travis, eds., The United States Geological Survey in Alaska--Accomplishments during 1979: U.S. Geological Survey Circular 823-B, p. B20-21.

Nilsen, T.H., and Moore, T.E., 1984, Stratigraphic nomenclature for the Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate, Brooks Range, Alaska: U.S. Geological Survey Bulletin 1529-A, 64 p.

Nokleberg, W.J., and Winkler, G.R., 1982, Stratiform zinc-lead deposits in the Drenchwater Creek area, Howard Pass quadrangle, northwestern Brooks Range, Alaska: U.S. Geological Survey Professional Paper 1209, 22p.

Parrish, J.A., 1987, Lithology, geochemistry, and depositional environment of the Triassic Shublik Formation, northern Alaska, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Society of Economic Paleontologists and Mineralogists Field Trip Guidebook 50, p. 391-396.

Patton, W.W., Jr., and Matzko, J.J., 1959, Phosphate deposits in northern Alaska: U.S. Geological Survey Professional Paper 302-A, p. 1-17.

Patton, W.W., Jr., and Tailleur, I.L., 1964, Geology of the upper Killik-Itkillik region, Alaska: U.S. Geological Survey Professional Paper 303-G, p. 409-499.

Reiser, H.N., Brosgè, W.P., Hamilton, T.D., Singer, D.A., Menzie, W.D., Bird, K.J., Cady, J.W., LeCompte, J.R., and Cathrall, J.B., 1983, The Alaska Mineral Resource Assessment Program--Guide to information contained in folio of geologic and mineral resource maps of the Philip Smith Mountains quadrangle, Alaska: U.S. Geological Survey Circular 759, 22 p.

Roehler, H.W., 1987, Depositional environments of coal-bearing and associated formations of Cretaceous age in the National Petroleum Reserve in Alaska: U.S. Geological Survey Bulletin 1575, 16 p.

Sable, E.G., and Stricker, G.D., 1987, Coal in the National Petroleum Reserve in Alaska, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Society of Economic Paleontologists and Mineralogists Field Trip Guidebook 50, p. 195-215.

Sawkins, F.J., 1990, Metal deposits in relation to plate tectonics, New York, Springer-Verlag, 461 p.

Schindler, J.F., 1988, History of exploration in the National Petroleum Reserve in Alaska, with emphasis on the period from 1975 to 1982, in Gryc, George, ed., Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 13-76.

Schmidt, J.M., Bohn, D., Kelley, K.D., Dumoulin, J.A., Morin, R.L., Krohn, M.D., Bradley, D.C., Karl, S.M., Kelley, J.S., and Pohn, H.A., 1990, Compilation of geologic, geochemical, and geophysical data for Misheguk Mountain, Howard Pass, and western Killik River quadrangles, Alaska with special emphasis on the southern National Petroleum Reserve in Alaska (NPRA): U.S. Geological Survey Administrative Report, 249 p.

Schrader, F.C., 1904, A reconnaissance in northern Alaska across the Rocky Mountains, along Koyukuk, John, Anaktuvuk, and Colville Rivers and the Arctic coast to Cape Lisburne, in 1901, with notes by W.J. Peters: U.S. Geolgical Survey Professional Paper 20, 139 p.

Siok, J.P., 1985, Geologic history of the Siksikpuk Formation on the Endicott Mountains and Picnic Creek allochthons, north central Brooks Range, Alaska: Fairbanks, University of Alaska, M.S. thesis, 253 p.

Siok, J.P., and Mull, C.G., 1987, Glauconitic phosphatic sandstone and oncolite deposition at the base of the Etivluk Group (Carboniferous), Picnic Creek allochthon, north-central Brooks Range, Alaska, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Society of Economic Paleontologists and Mineralogists Field Trip Guidebook 50, p. 367-370.

Smith, P.S., and Mertie, J.B., 1930, Geology and mineral resources of northwestern Alaska: U.S. Geological Survey Bulletin 815, 351 p.

Sutley, S. J., Duttweiler, K. A., and Hopkins, R. T., 1984, Analytical results and sample locality map of stream-sediment and panned-concentrate samples from the Killik River 1°x3° quadrangle, Alaska: U.S. Geological Survey Open-File Report 84-406, 18 p.

Theobald, P.K., Barton, H.N., Billings, T.M., Frisken, J.G., Turner, R.L., and Van Trump, G., Jr., 1978, Geochemical distribution of elements in stream sediment and heavy-mineral concentrate samples in the southern half of the National Petroleum Reserve, Alaska: U.S. Geological Survey Open-File Report 78-517, scale 1:500,000.

Tourtelot, H.A., and Tailleur, I.L., 1971, The Shublik Formation and adjacent strata in northeastern Alaska--description, minor elements, depositional environments, and diagenesis: U.S. Geological Survey Open-File Report 71-462.

U.S. Geological Survey, 1983, Aeomagnetic map of the Killik River and Chandler Lake 1°x3° quadrangles, Alaska: U.S. Geological Survey Open-File Report 83-607, scale 1:250,000.

Wahrhaftig, Clyde, 1965, Physiographic divisions of Alaska: U.S. Geological Survey Professional Paper 482, 52 p.

Young, L.E., and Moore, D.W., 1987, A discussion of "Geologic setting, petrology, and geochemistry of stratiform sphalerite-galena-barite deposits, Red Dog Creek and Drenchwater Creek areas, northwestern Brooks Range, Alaska": Economic Geology, v. 82, no. 4, p. 1077-1079.