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U.S. GEOLOGICAL SURVEY CIRCULAR 1106

Mineral-Resource Assessments in Alaska—Background Information to Accompany Maps and Reports about the Geology and Undiscovered-Mineral-Resource Potential of the Mount Katmai Quadrangle and Adjacent Parts of the Naknek and Afognak Quadrangles, Alaska Peninsula

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By J.R. Riehle, S.E. Church, R.L. Detterman, and J.W. Miller

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Multiply	By	To obtain
	Length	
meter (m)	3.281	foot
kilometer (km)	0.621 4	mile
	Area	
square kilometer (km^2)	0.386 1	$mile^2$

GLOSSARY OF TERMS

For a complete glossary of geologic terms, see the Glossary of Geology (Bates and Jackson, 1980).

Airfall. Volcanic particles, typically sand-sized ash but including coarser and finer sizes, that are erupted into the air and fall therefrom; also the resulting deposit.

Andesite. A compositional term for a volcanic rock having a silica content (SiO_2) of between 56 percent and 63 percent by weight.

Ash-flow tuff. A volcanic rock that formed from a flowing mass of erupted gas and sand-sized particles of glass, rock fragments, and minerals.

Basalt. A compositional term for a volcanic rock having a silica content (SiO_2) of less than 53 percent by weight.

Batholith. A mass of intrusive igneous rock, underlying hundreds to thousands of square kilometers, typically intruded as a series of individual magma masses (plutons) that have a variety of compositions.

Conglomerate. A sedimentary rock formed of gravel, cobbles, and boulders.

Dacite. A compositional term for a volcanic rock having a silica content (SiO_2) of between 63 percent and 68 percent by weight.

Diabase. A dark-colored, intrusive igneous rock having a low silica content similar to that of basalt or andesite.

Dike. An intrusive igneous rock in which the form of the intruded magma is like a wall that cuts across layering in the wall rocks.

Dome. A volcanic rock consisting of lava that mounded above its vent because it was too viscous to flow.

Fault. A break in the Earth's crust across which the rocks have moved relative to one another.

Flow. The movement of erupted lava laterally on the ground surface; also refers to the resulting rock.

Fumarole. A vent for gases and vapors.

Gabbro. A dark-colored intrusive rock; the extrusive (volcanic) equivalent is basalt.

Gneiss. A metamorphic rock consisting of alternating bands of dark and light minerals.

Gossan. A mass of rock visually identifiable by a reddish color resulting from oxidation of iron; forms by weathering of rocks containing abundant pyrite, typically secondary.

Granite. An intrusive igneous rock consisting mainly of quartz and alkali feldspar.

Granodiorite. An intrusive igneous rock having as much quartz as does granite, and an alkali feldspar content between that of granite and tonalite.

Greenschist. A category of metamorphism that occurs at low to moderate temperatures (300–500 °C) and pressures (less than 20 km deep); metamorphic minerals characteristic of this category include several that are green.

Hydrothermal. An adjective referring to naturally occurring, heated water that contains dissolved solids and gases; heat sources are commonly either recently intruded magma or deep crustal rocks.

Indurated. Refers to a sediment hardened by pressure, heat, or cement into a rock.

Intrusion. The process in which magma moves chiefly vertically into a host rock where it solidifies by cooling; the resulting rock is an intrusive rock.

Limestone. A sedimentary rock that consists essentially of the mineral calcite, formed either of shell fragments or, less commonly, by chemical precipitation.

Metamorphic rock. A rock in which the original mineral grains have recrystallized to form new mineral grains, or new minerals, due to application of heat and (or) pressure.

Moraine. Any nonsorted glacial deposit, typically consisting of mixed silt, sand, and boulders; also refers to the landform resulting from the deposit.

Porphyritic. An adjective applied to volcanic or intrusive rocks having some mineral grains that are distinctly larger than others; the implication is that an early period of slow cooling (coarse grains) was followed by sudden rise of the magma to shallow crustal levels and chilling (fine grains).

Pumice. Volcanic glass that was highly inflated at the time of eruption by abundant gas pockets (bubbles).

Pyrite. Iron sulfide; not an ore-forming mineral but may be evidence of mineralizing fluids and so may be associated with ore minerals.

Quartz diorite. An intrusive igneous rock having little quartz or alkali feldspar, and a high content of plagioclase feldspar and dark accessory minerals.

Quartz monzodiorite. An intrusive igneous rock having contents of quartz and alkali feldspar that are between those of granite and quartz diorite.

Quartzite. A metamorphic rock consisting essentially of quartz grains; the original rock was typically a quartz sandstone.

Reverse fault. A steeply dipping fault along which the rocks above the fault have moved up relative to those below.

Rhyolite. A compositional term for a volcanic rock having a silica content (SiO_2) of between 68 percent and 77 percent by weight.

Silicification. The process of adding silica to a rock by chemical precipitation from fluids.

Sill. An intrusive igneous rock having a tabular form, of which the two long dimensions are parallel to bedding in the adjacent wall rocks.

Stratovolcano. A volcano, typically cone shaped and more than 300 m above its base, consisting of alternating layers (strata) of lava, cinders, and ash.

Subduction. A process of plate tectonics in which one crustal plate, commonly but not necessarily an oceanic plate, slides beneath another plate; the site of contact between the plates is usually a physiographic trench, and the region behind the trench is one of elevated seismicity and active volcanism caused by the downgoing plate.

Tonalite. An intrusive igneous rock having the same content of quartz as does granite, but less alkali feldspar than does granodiorite.

Vein. A fracture in a rock filled by secondary minerals, typically formed by chemical precipitation from hydrothermal fluids; such deposits commonly appear veinlike when viewed on rock faces.

Volcanic arc. A belt of aligned volcanoes that follows an arcuate trace in map view; volcanic arcs are typically formed above subducting plates.

Wall rock. Preexisting rock that hosts a younger rock such as a magmatic intrusion or a vein.

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ABSTRACT

Geologic and geochemical field studies were carried out from 1983 to 1987 in the Mount Katmai 1°×2° quadrangle and adjoining region, at the northeast end of the Alaska Peninsula. The region is nearly entirely within Katmai National Park and Preserve and has had almost no mineral production, so prior to this study there were few data by which to assess the mineral potential of the region. This report describes the folio of publications that have resulted from the study: geologic maps, geochemical results, fossil identifications, radiometric rock ages, and an assessment of the undiscovered-mineral-resource potential of the region.

The Katmai region is inferred to potentially have three types of undiscovered mineral deposits: porphyry copper (molybdenum), precious-metal vein, and hot-springs gold. These deposit types occur elsewhere on the Alaska Peninsula in similar geologic units. Evidence suggesting their occurrence in the Katmai region is the presence of trace amounts of metals typically associated with these kinds of deposits in bedrock of certain tracts and in sediments of streams draining those tracts. Magma to provide heat, fractures to provide pathways for mineralizing fluids, and altered rock are required by genetic models of these deposit types. Such features do occur in the Katmai tracts. Confirmation of any mineral deposit in the Katmai region requires detailed followup sampling and acquisition of subsurface information, which is beyond the scope of this study. However, producing porphyry deposits are unknown elsewhere on the Alaska Peninsula in similar rocks, so if any such deposits occur in the Katmai region, they are likely to be few in number. Conversely, vein deposits are typically small in size so there may be several of such deposits.

The properties and thermal history of the sedimentary rocks that could serve as reservoirs for oil or gas are unfavorable in adjacent regions. Thus the potential of the Katmai region for producible quantities of fossil fuels is low. In theory the region has shallow concentrations of geothermal fluids, but specific evidence for their presence is obscured by heavy precipitation and cold young rocks or deposits. Small volumes of coal occur at tidewater sites on the Pacific coast.

INTRODUCTION

BACKGROUND

This report describes a set of maps and reports about the geology, geochemistry, and mineral resources of the Mount Katmai quadrangle and adjacent portions of the Naknek and Afognak quadrangles on the Alaska Peninsula. The reports, published under the auspices of the former Alaska Mineral Resources Assessment Program, provide information for decisions about landownership, for land-use planning, and for policymaking concerning the national mineral endowment. Such reports should be useful to State and Federal agencies, to private landowners, and to the mineral industry in Alaska.

The study area occupies 15,000 km^2 that extend east-west across the Alaska Peninsula at its northeast end (fig. 1). Most of the study area is within Katmai National Park and Preserve (fig. 2); a small area at the south margin is within Becharof National Wildlife Refuge. Mineral production in a national park, part of which is also wilderness, may be unlikely. Regardless, the study has three main benefits. First, geologic trends and rock units in adjacent areas were either traced through the study area or were

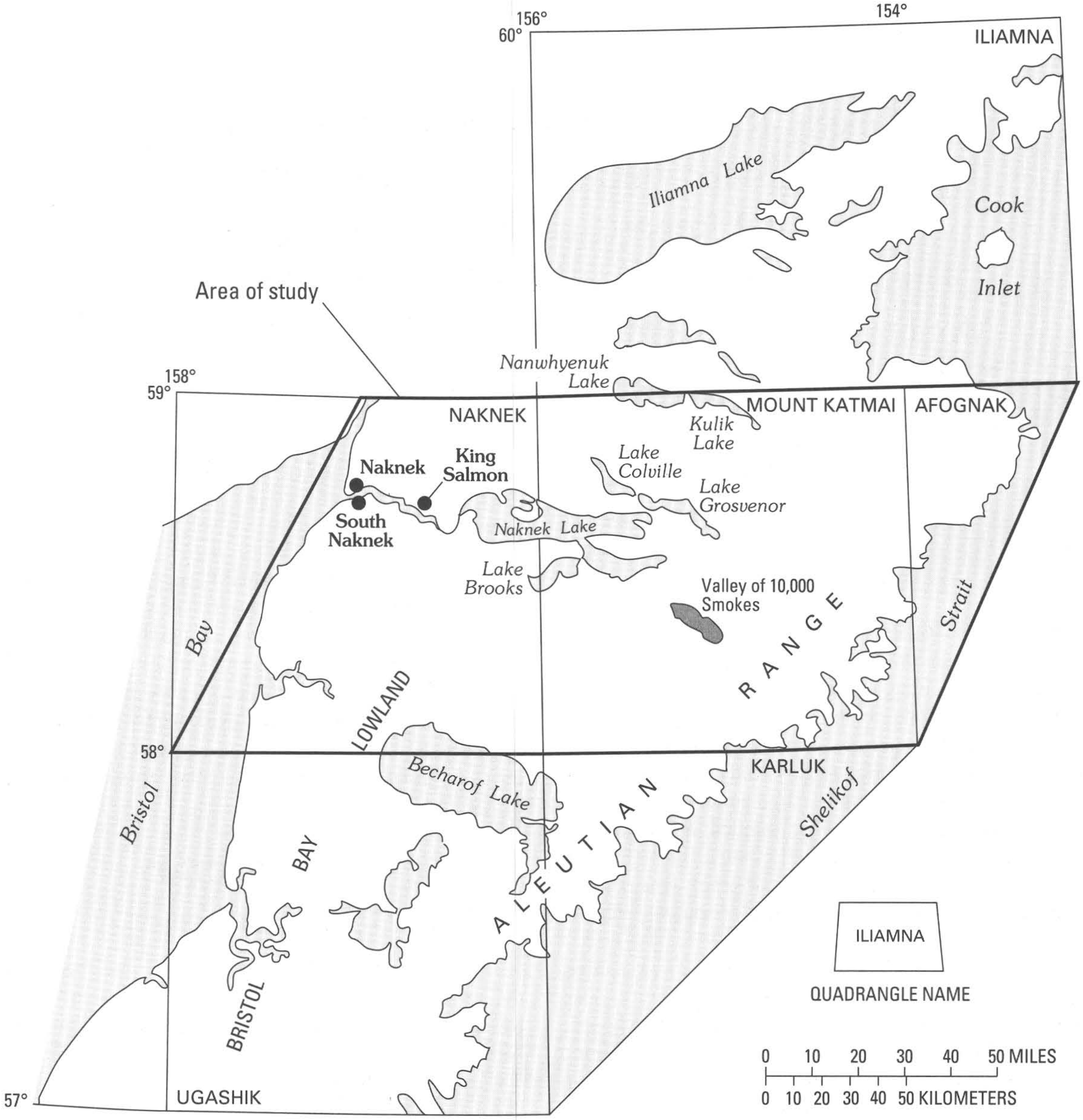

Figure 1. Location of Mount Katmai study area on the eastern Alaska Peninsula.

shown not to continue across the area. Such information aids in interpretation of the geologic history of the adjacent areas where mineral extraction is more feasible. Second, new insights into the geologic processes responsible for mineralization of similar rock units elsewhere on the Alaska Peninsula have been gained by their study in the Katmai area, regardless of whether any Katmai mineral deposits are ever exploited. And third, better understanding of the mineral resources of the Katmai area will permit more informed decisionmaking about the national mineral endowment.

Fieldwork was carried out from 1983 through 1987 by a team of earth scientists having a range of expertise. Individuals collaborated to produce specialized maps and topical reports. The maps (table 1) focus on bedrock geology, fossils, surficial geology, potassium-argon geochronology (rock ages), and the distribution of elements and minerals in stream-sediment and bedrock geochemical samples. The reports (table 1) focus on interpretation of the exploration geochemical data and its implications for the mineral potential of the study area.

Geologic information indicates the kinds of geologic processes that have occurred in the study area and which tracts could have certain kinds of mineral deposits. Geochemical studies provide specific evidence of mineralization. In order to assess the mineral potential, the available

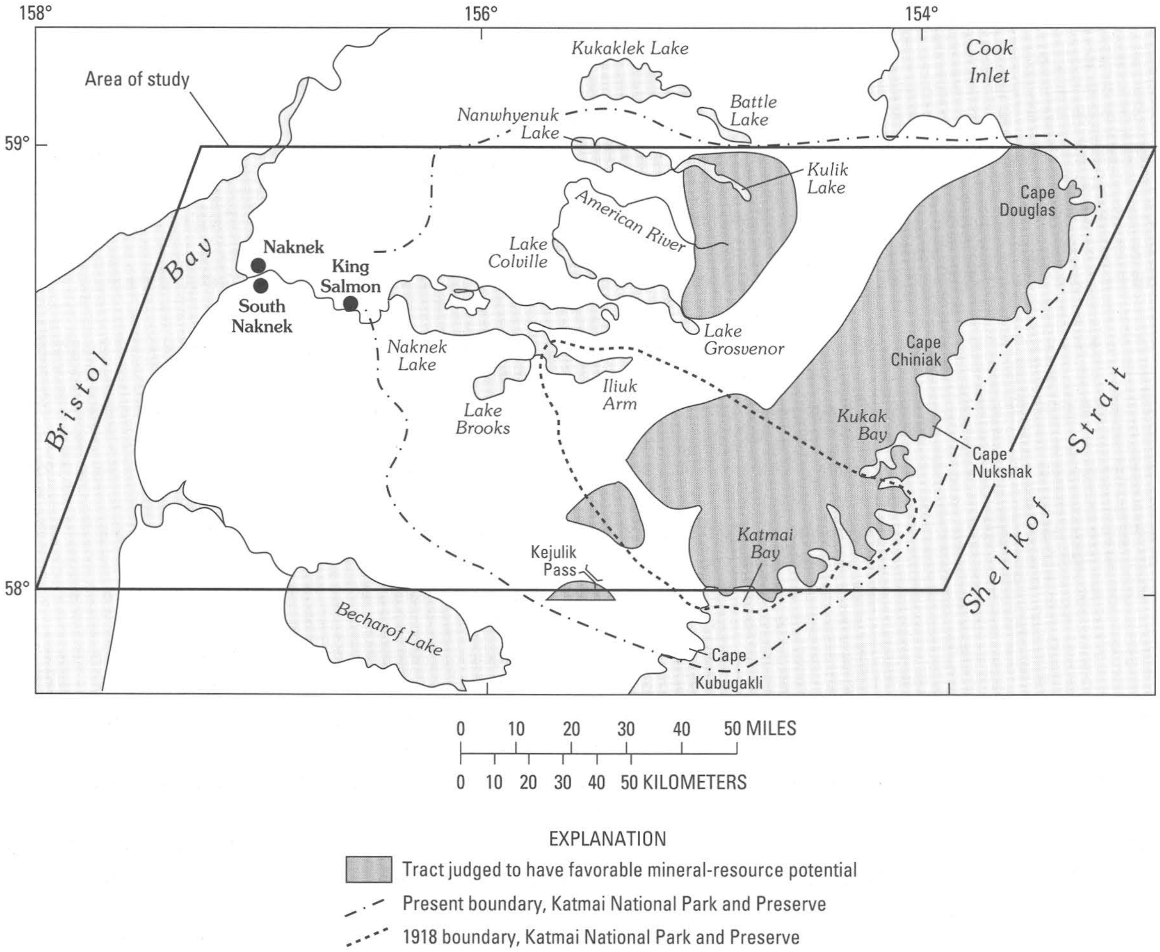

Figure 2. Physiographic features and tracts having favorable potential for mineral deposits, Mount Katmai study area.

geologic and geochemical data from the study area are combined with information from other, geologically similar areas that have been more thoroughly explored for minerals. The assessment is a professional judgment of the likelihood that undiscovered mineral deposits having potential economic value occur in the study area. To confirm the occurrence of mineral deposits requires subsurface information, typically acquired by drilling, which is beyond the scope of the present study and which has never been carried out in the region. Thus the assessment does not specify a precise number of undiscovered deposits, nor does it consider economic conditions of extraction and sale.

MINERAL-RESOURCE ASSESSMENTS

DEFINITIONS AND CONCEPTS

Basic terms and concepts of mineral-resource assessments are defined in this section. Other geologic terms used elsewhere in this report are defined in the glossary.

A **mineral resource** is a geologic deposit from which useful metallic, nonmetallic, or hydrocarbon material could potentially be extracted (Harris, 1984). A **deposit** is a volume of rock that formed during a limited interval of geologic time in response to a single set of geologic processes. A **mineral occurrence** is a concentration of a mineral that is of scientific or economic interest; a **mineral deposit** is an occurrence that could be economically produced under favorable circumstances (Cox and others, 1986). Mineral deposits can form at the same time as the rock in which they occur (**primary mineralization**) or they can form later (**secondary mineralization**).

Economic resources are those known to be economically extractable under specified market conditions (U.S. Bureau of Mines and U.S. Geological Survey, 1980). **Undiscovered resources** are the subject of this study and are hypothetical without intensive sampling, typically by drilling, to prove their vertical extent. An assessment of the undiscovered resources of the Katmai region is not, however, just speculation. Rather, it is a professional judgment

Table 1. Geologic, geochemical, and mineral-resource publications of the Mount Katmai study.

[Maps are 1:250,000 scale]

Map or report no.	Description	Author
Miscellaneous Investigation Map I–2032.	Geologic map of Quaternary rocks and deposits (in color)	Riehle and Detterman, 1993.
Miscellaneous Investigation Map I–2204.	Bedrock geologic map (in color)	Riehle and others, 1993.
Open-File Report 86–586	Analytical results and localities of stream-sediment samples and heavy-mineral concentrates.	Bailey and others, 1986.
Open-File Report 87–615	Mineralogy of nonmagnetic heavy-mineral concentrates from stream-sediment samples, and localities.	Bennett and Church, 1987.
Open-File Report 87–422	ICP analytical results for aqua-regia leachates of stream-sediment samples.	Ehrlich and others, 1988.
Open-File Report 89–570	Locality map, analytical results, and statistical summary of bed-rock samples.	Riehle and others, 1989.
Miscellaneous Field Studies Map MF–2021–A.	Map showing distribution of selected elements in stream-sediment samples.	Church and others, 1989a.
MF–2021–B	Maps showing distribution of selected leachable metals in stream-sediment samples.	Church and Motooka, 1989.
MF–2021–C	Map showing distribution of selected elements in nonmagnetic heavy-mineral concentrates from stream-sediment samples.	Church and Arbogast, 1989.
MF–2021–D	Map showing distribution of minerals in nonmagnetic heavy-mineral concentrates from stream-sediment samples.	Church and Bennett, 1989.
Bulletin 2020	Interpretation of bedrock and stream-sediment analytical data in terms of mineral-deposit types.	Church and others, in press.
MF–2021–E	Map showing potassium-argon ages of rocks	Shew and Lanphere, 1992.
MF–2021–F	Maps showing assessment of undiscovered mineral and energy resources.	Church and others, 1992.
MF–2021–G	Map of macrofossil localities and stratigraphic sections	Miller and others, in press.

based on mineral occurrences at the ground surface about the potential that mineral deposits occur at depth.

Three kinds of data were newly gathered for the Katmai assessment. (1) Geologic mapping permits identification of different geologic terranes and, by analogy with better studied areas elsewhere, suggests the types of deposits that are likely to occur in those terranes. (2) Stream sediments ideally provide a composite sampling of an entire drainage basin. (3) Samples of mineralized bedrock provide direct evidence for the occurrence, and something about the nature, of mineralization. Mineralized bedrock was specifically sought throughout the course of fieldwork. Based on these kinds of information, small tracts having both permissive and specific evidence of mineralization at the ground surface were identified.

The Katmai study lacks subsurface information and so does not rigorously assess the size or number of potential deposits. Geophysical data can help to constrain the size of favorable host rocks for certain deposit types. In the Katmai region, however, aeromagnetic data (Andreasen and others, 1963) are the only regionally extensive, geophysical data that are available, and these are available only for the Naknek quadrangle where bedrock is deeply buried beneath glacial drift. Moreover, the aeromagnetic data are too widely spaced to delineate any but the largest areas of magnetically anomalous rock.

RECENT MINERAL ASSESSMENTS IN ALASKA

By 1971, two National laws regarding landownership in Alaska had been enacted. The Alaska Statehood Act (1958) allowed the State to select about one-quarter of the landmass for State ownership. The Alaska Native Claims Settlement Act (ANCSA; 1971) allowed Alaskan Natives to select one-eighth of the State for private ownership and further authorized the Secretary of the Interior to withdraw another one-quarter for potential inclusion in parks or other preservation units. ANCSA required identification of the withdrawals by December 1978. Consequently, in 1974 Congress requested that the U.S. Geological Survey (USGS) provide information about the mineral potential of the probable withdrawals in time for Congress to use in the final decisions. Initially multidisciplinary teams undertook to produce folios of geologic, geophysical, and geochemical data for selected 1:250,000-scale quadrangles. Quadrangles were selected both for their mineral potential and for being likely candidates for withdrawal. In order to meet the 1978 deadline, however, the approach was modified to compilation of existing data, supplemented by limited fieldwork, at 1:1,000,000 scale (Singer and Ovenshine 1979). Results at this scale were completed early in 1978 (MacKevett and others, 1978).

The original concept of 1:250,000-scale assessments was given new impetus with passage of the Alaska National Interest Lands Conservation Act (ANILCA) in 1980. ANILCA requirements for more detailed information about mineral resources on Federal lands, together with continuing State and Native land selections from the territorial landpool, provided the basis for the Alaska Mineral Resources Assessment Program (AMRAP). The objective of AMRAP was to identify areas in Alaska having mineral-resource potential and to quantify that potential as far as possible (Grybeck and Berg, 1982). The AMRAP approach was to first compile available data, then in selected areas to carry out fieldwork by multidisciplinary teams for a period of 2 to 4 yr to acquire needed information. Such "Level III" studies of 1:250,000-scale quadrangles provide information that is used to periodically upgrade statewide or regional assessments (Levels I or II) as well as to focus on specific deposits for followup studies at larger scales (Level IV).

The Katmai study is such a Level III study. Since completion of the Katmai study, USGS assessments of mineral resources in Alaska have been carried out as part of a national assessment program.

GEOGRAPHIC AND PHYSIOGRAPHIC SETTING OF THE KATMAI STUDY AREA

The Katmai study area is sited on the Alaska Peninsula between 58° and 59° north latitude (figs. 1, 2); its northern boundary is at Cape Douglas, and the southern boundary transects Becharof Lake. The western and eastern boundaries are at the coasts of Bristol Bay and Shelikof Strait, respectively.

Two physiographic provinces compose the study area: the Bristol Bay Lowland province in the west and the Aleutian Range province in the east (Wahrhaftig, 1965). The Bristol Bay Lowland is characterized by broad coastal plains, low topographic relief, numerous bogs and small lakes, and low-gradient meandering streams. In contrast, the Aleutian Range is capped by active volcanoes. Elevations exceed 2,000 m at volcanoes such as Mount Katmai, Mount Mageik, Mount Griggs (Knife Peak), Snowy Mountain, Mount Denison, Fourpeaked Mountain, and Mount Douglas. Streams in the Aleutian Range have steep gradients and occupy youthful drainages. Glaciers are present on the large peaks; both Hallo Glacier and Fourpeaked Glacier extend nearly to sea level on Shelikof Strait. The Valley of Ten Thousand Smokes contains thick deposits of volcanic ash from the 1912 eruption of Novarupta.

There are three permanently inhabited communities in the study area: King Salmon, Naknek, and South Naknek. All three are sited within 30 km of one another, on the Naknek River at the west margin of the study area. The only other habitations are seasonally occupied lodges on Brooks, Kulik, Grosvenor, and Nanwhyenuk (Nonvianuk) Lakes. The lodge on Brooks Lake serves as a staging area for visitors to the interior of Katmai National Park and Preserve.

Katmai National Monument was created in 1918 as a consequence of the 1912 eruption of Novarupta dome (originally erroneously attributed to Mount Katmai). One of the purposes of the monument is to preserve the spectacular volcanic deposits of the eruption for scientific study and for public education about volcanic eruptions. The monument initially extended from the head of Kukak Bay southwest to Cape Kubugakli and northwest to encompass all of the Iliuk Arm of Naknek Lake (4,350 km^2; fig. 2) and was closed to mineral entry. There are no mining claims or prospects within this core area. Additions to the monument were made in 1931 (to 10,788 km^2), in 1942, and again in 1969, by which time all of Lake Brooks, Naknek Lake, Lake Grosvenor, and Lake Colville as well as offshore islands were included in the monument. Under the Alaska National Interest Lands Classification Act, the name was changed in 1980 to Katmai National Park and Preserve, and the total area was enlarged to 16,764 km^2. Most of this area is also designated as wilderness (Katmai National Park and Preserve, written commun., 1992).

GEOLOGIC INVESTIGATIONS IN THE KATMAI REGION

PREVIOUS STUDIES

Geologic fieldwork in the Katmai region prior to 1950 was infrequent and localized. Spurr and Post (1899) traversed the region from Bristol Bay to Katmai Bay in 1898, following an early trade route over Katmai Pass; they noted a lack of placer gold along their route and attributed it to "...the volcanic region being apparently without much mineralization...." Atwood (1911) reported no known mineral occurrences in the Katmai region as of 1908. The first lengthy, documented explorations followed the catastrophic eruption of Novarupta dome in 1912. Such explorations, summarized by Griggs (1922), focused on the deposits in and around the Valley of Ten Thousand Smokes.

The oldest claim in the Katmai area, filed in 1918, is a gold-placer claim on the American River south of Nanwhyenuk Lake (fig. 2). Martin (1920) reported secondhand on brief prospecting activity at Kukak Bay for copper and gold, and prospecting occurred sporadically after 1920 particularly in the area immediately south of Kulik Lake and along Shelikof Strait (see claims summary in Cobb, 1980). But owing to the remoteness, lack of producible surface mineralization, and withdrawal from mineral entry, the Katmai region missed intensive exploratory activity that was typical of mining districts elsewhere in Alaska.

The earliest systematic field studies in the region were carried out by industry while exploring for hydrocarbons. The publicly available data through 1975 were compiled by Magoon and others (1976) as a map, which includes that part of the study area north of Cape Chiniak and east of Kulik Lake (fig. 2). The first geologic map of the Mount Katmai quadrangle (Keller and Reiser, 1959) was based on mapping carried out from five fieldcamps occupied over the course of one summer, supplemented by air-photo interpretation. Use of helicopters in our study provided vastly better access, especially to the more remote parts of the study area.

Numerous studies were carried out in the Valley of Ten Thousand Smokes after 1960, focusing on the volcanic deposits and history of the 1912 Novarupta eruption. These studies continue today (see Eichelberger and others, 1991); most have dealt with volcanic processes, although Hildreth (1983) mapped the boundary of the 1912 ash-flow deposit.

The Katmai region is part of the Peninsular terrane of Jones and Silberling (1979), which is adjacent to the Chugach terrane on the southeast. Wilson and others (1985) proposed renaming the Peninsular terrane the Alaska Peninsula terrane and subdividing it into the Chignik and Iliamna subterranes.

PRESENT STUDY

Fieldwork was carried out during the summers of 1983 through 1987. Due to the undeveloped nature and remoteness of the study area, self-supporting fieldcamps were needed throughout the period of fieldwork. The research vessel *Don J. Miller* served as both helicopter platform and living quarters on the Pacific coast (parts of two seasons). Fieldcamps were established at Becharof Lake (two seasons), Naknek Lake (one season), and Battle Lake (two seasons). Commercial facilities in King Salmon were also used briefly.

MAP I–2032: QUATERNARY GEOLOGIC MAP OF THE MOUNT KATMAI QUADRANGLE AND ADJACENT PARTS OF THE NAKNEK AND AFOGNAK QUADRANGLES, ALASKA

Quaternary deposits are those less than 1.65 million years old; that is, 1.65 Ma. Quaternary deposits in the Katmai study area are mainly either glacial deposits, or volcanic rocks and deposits of the active Aleutian volcanic arc. Although the entire Katmai area was glaciated several times, thick glacial deposits occur only west of the Aleutian Range in the Bristol Bay lowlands. The mountain lakes Naknek, Brooks, Grosvenor, Kulik, and Nanwhyenuk are dammed by moraines left at their west ends after the last major glaciation. The lake basins were ice free by at least 10,300 yr ago. The glaciers that scoured these basins originated in the adjacent Aleutian Range to the east. Prominent moraines between the west end of Becharof Lake and Bristol Bay were formed by glaciers that had moved south in Shelikof Strait and poured northwest through a low in the Aleutian Range.

Volcanic deposits of the Aleutian volcanic arc are found chiefly at or near the Aleutian Range crest, which in part consists of active stratovolcanoes. Rhyolitic or dacitic ash-flow tuffs occur at the south margin of the Katmai study area, in the Valley of Ten Thousand Smokes, and at Kaguyak Crater. Airfall deposits of the 1912 eruption are more than a meter thick in the area from the head of the Valley of Ten Thousand Smokes east to Shelikof Strait (Judy Fierstein, USGS, written commun., 1991). Several warm springs near the crest of the Aleutian Range are additional evidence of continuing volcanic activity.

MAP I–2204: GEOLOGIC MAP OF THE MOUNT KATMAI QUADRANGLE AND ADJACENT PARTS OF THE NAKNEK AND AFOGNAK QUADRANGLES, ALASKA

The Katmai study area is a continental margin that has been the site of several cycles of subduction-generated volcanism and associated intrusive activity. The oldest rocks in the study area of certain age are submarine basalt flows and diabase sills of the Cottonwood Bay Greenstone, now metamorphosed to greenschist facies. In the Katmai region, this unit occurs near the south margin of the study area as remnants of older rocks (roof pendants) that were intruded during Jurassic time (205–138 Ma). The basalt flows crop out near interbedded marine limestone and basalt flows; the limestone and flows are assigned to the Late Triassic (210–205 Ma) Kamishak Formation that overlies the Cottonwood Bay Greenstone in the Iliamna quadrangle north of the Katmai area (Detterman and Reed, 1980).

Some metamorphic rocks of Paleozoic(?) (570–240 Ma) or early Mesozoic (240–190 Ma) age are assigned to the Kakhonak Complex and may be older than the Cottonwood Bay Greenstone. The metamorphic rocks crop out in a northeast-southwest trending belt as roof pendants within Jurassic intrusive rocks. These rocks were probably metamorphosed by heat from the intrusions. Nonmetamorphosed parent rocks of the Kakhonak Complex in the Katmai area as well as in the Iliamna quadrangle include exposed, pre-Middle Jurassic rocks. However, quartzite and potassium-feldspar-bearing gneiss exposed on an island in

Naknek Lake have no obvious compositional equivalents among exposed nonmetamorphosed rocks, and their parent rocks may be otherwise unknown Paleozoic(?) rocks. The gneiss may have recrystallized under conditions of regional metamorphism prior to intrusion of the batholith.

The Late Triassic(?) and Early Jurassic Talkeetna Formation—volcanic rocks and interbedded marine sedimentary rocks—represents a volcanic arc (Reed and Lanphere, 1973) that crops out as far as 500 km to the north in the Talkeetna Mountains (Martin, 1926). The volcanic rocks are erupted equivalents of magmas that cooled underground to form the Alaska-Aleutian Ranges batholith. The intrusive rocks in the Katmai region are chiefly tonalite and granodiorite but include quartz diorite and granite. Potassium-argon (K-Ar) ages of 11 samples range from about 173 Ma to about 153 Ma (Reed and Lanphere, 1972; Shew and Lanphere, 1992); that is, from late Early to Late Jurassic time. Unlike areas to the north, no intrusive rocks of Cretaceous age (138–65 Ma) have yet been found in the Katmai region. One reason that some of the batholithic rocks have younger ages than the volcanic rocks is that K-Ar geochronology measures the time of cooling rather than intrusion, and subsurface intrusions cool more slowly than volcanic rocks erupted at the ground surface.

Two important results of the Katmai study are more detailed age determinations of the batholithic rocks and a better understanding of the distribution of prebatholith wall rocks.

The Naknek Formation, the most extensive rock unit of the Alaska Peninsula, was formed in Late Jurassic time (160–135 Ma). Subdivision of this widespread rock unit into five members (Detterman and others, in press) has been another important contribution of the Katmai study. The sequence of members indicates inundation of a continental margin by seas, ending with rapid uplift of the source area in the Alaska-Aleutian Range batholith to the northwest. The lowermost member is conglomerate and fluvial (river) sandstone; next is mixed marine and nonmarine sandstone and marine siltstone. The three youngest members are all marine rocks. The uppermost member occurs almost exclusively in the Katmai study area and consists of marine sandstone and conglomerate.

Cretaceous rocks in the Katmai region are, from oldest to youngest, the Staniukovich, Herendeen, Pedmar, and Kaguyak Formations. All are marine rocks, the Kaguyak Formation having structures indicative of deposition in a deep marine basin by submarine landslides (Keller and Reiser, 1959; Detterman and Miller, 1985). Some of these rocks in the northeast part of the study area were well known beforehand, but their distribution in the central and southern part of the study area was poorly known. In particular, the Pedmar Formation is one of only two local occurrences of rocks of Albian age (125–115 Ma) on the Alaska Peninsula (Detterman and others, in press); during the course of this study a third occurrence was discovered, and the unit was formally defined.

Thick sequences of marine and continental rocks of Tertiary age (65–1.65 Ma) occur on the southern Alaska Peninsula (Detterman and others, in press) and in the subsurface of the Cook Inlet region (Calderwood and Fackler, 1972). Tertiary strata are thin, however, in the Katmai area where they are preserved mainly along Shelikof Strait. The lower Tertiary Copper Lake Formation occurs near Cape Douglas, and the upper Oligocene to lowermost Miocene (30–20 Ma) Hemlock Conglomerate is exposed near Cape Nukshak. The Copper Lake Formation consists of well-indurated conglomerate, fluvial sandstone, and siltstone. The younger Hemlock Conglomerate comprises poorly indurated conglomerate, fluvial sandstone including volcanic tuff beds, shale, and coal. Tertiary sedimentary rocks occur locally west of the Aleutian Range crest in the Katmai region; their localized development suggests deposition in small isolated basins.

Early to middle Tertiary lava flows, domes, and dikes crop out in the Bristol Bay lowlands in the western part of the Katmai area. The flows are mainly andesitic in composition, whereas crosscutting dikes and plugs are basaltic. These western volcanic rocks are little altered, which may reflect a shallow level of erosion and (or) absence of major centers of hydrothermal or magmatic activity. Five K-Ar ages of the western lava flows range from about 44 to 34 Ma, and a single dike is about 25 Ma (Shew and Lanphere, 1992).

Tertiary plutons northwest of the Bruin Bay fault, in the Alaska-Aleutian Ranges batholith, are chiefly granodiorite and quartz monzodiorite. K-Ar ages of nine samples range from about 38 to 26 Ma (Reed and Lanphere, 1972; Shew and Lanphere, 1992). Contact metamorphic effects (silicification and gossan development) are locally prominent where Tertiary plutons have intruded Mesozoic sedimentary rocks east of the Bruin Bay fault.

Sills, dikes, and plutons of tonalite or quartz diorite occur northwest of the Aleutian Range crest in the central part of the study area. These shallow intrusives are associated with gossans developed both in the intrusives and in their sedimentary wall rocks. Due to common alteration of the intrusive rocks, no radiometric ages are available. The rocks intrude sedimentary units as young as Cretaceous.

Late Tertiary lava flows, dikes, sills, and small plutons east of the Aleutian Range crest are a part of the Aleutian volcanic arc that was active during Miocene and Pliocene (24–1.65 Ma) time. Extrusive rocks are chiefly andesitic and dacitic lava flows that overlie and locally deform the sedimentary rocks of the Hemlock Conglomerate. Both sedimentary and volcanic rocks have been intruded by small plugs and plutons associated with extensive hydrothermal alteration, which is manifested primarily as gossans. Two lava flows of the eastern volcanic group are about 14 Ma, and several samples of the intrusive rocks range from about 10 to 2.5 Ma (Shew and Lanphere, 1992).

Another important result of the Katmai AMRAP study has been more detailed definition of the distribution, nature, and age of these Tertiary intrusive and volcanic rocks.

The major structural feature of the study area is the Bruin Bay fault, a high-angle reverse fault that extends from 400 km to the north in Cook Inlet (Detterman and others, 1976) to Becharof Lake at the south margin of the Katmai study area. Movement is clearly up on the west side of the fault in the Katmai study area. In the Iliamna quadrangle, as much as 3 km of vertical offset (stratigraphic throw) can be demonstrated, and there is evidence for as much as 65 km of right-lateral offset (Detterman and Reed, 1980; Detterman and Hartsock, 1966). Uplift began in Late Jurassic time, leading to deposition of the Naknek Formation to the southeast of the fault (Egbert and Magoon, 1981). The last movement occurred no later than middle Tertiary time, based on the ages of two plutons intruded along the fault near Kulik Lake.

Two main periods of folding have occurred in the Katmai region. Northwest of the Bruin Bay fault, rocks older than the Late Triassic(?) and Early Jurassic Talkeetna Formation are clearly folded, probably due to intrusion of adjacent plutons in Early to Middle Jurassic time. The Talkeetna Formation is tilted but is not folded. Southeast of the Bruin Bay fault, rocks as young as the Miocene volcanic rocks are regionally folded. In both areas fold axes trend generally northeast-southwest, parallel to the structural grain of the Alaska Peninsula elsewhere (Burk, 1965). Southeast of the Bruin Bay fault, sedimentary and volcanic rocks are commonly fractured or have minor faults, quartz veins, or dikes of average northwesterly trend.

OPEN-FILE REPORT 86–586: ANALYTICAL RESULTS AND SAMPLE LOCALITY MAP OF STREAM-SEDIMENT AND HEAVY-MINERAL-CONCENTRATE SAMPLES FROM THE MOUNT KATMAI QUADRANGLE, AND PORTIONS OF THE NAKNEK, AFOGNAK, AND ILIAMNA QUADRANGLES, ALASKA

Stream sediments are, ideally, an average sample of the bedrock underlying an entire drainage basin and can provide a rapid, cost-effective method for systematically sampling a large area. In glaciated regions, however, the results must be interpreted with caution because of the potential for contamination by glacial deposits. During this study, a sample of stream sediments was collected at nearly all junctions of two streams that had no more junctions upstream (about one sample every 5–10 km^2).

Results of analyses by semiquantitative emission spectrograph for 31 elements potentially indicative of mineralization are presented in this report for the bulk stream-sediment samples and for high-density concentrates. A map showing localities of 1,243 sampling sites is presented as well. The following elements are included: copper, silver, molybdenum, lead, zinc, boron, gold, nickel, cobalt, arsenic, antimony, and tungsten.

OPEN-FILE REPORT 87–615: MINERALOGY AND SAMPLE-LOCALITY MAP OF THE NONMAGNETIC HEAVY-MINERAL-CONCENTRATE SAMPLES FROM THE MOUNT KATMAI QUADRANGLE AND PORTIONS OF THE NAKNEK, AFOGNAK, AND ILIAMNA QUADRANGLES, ALASKA

Identifications of ore-forming minerals in the stream-sediment samples are tabulated. Samples are high-density, low-magnetic concentrates from bulk stream-sediment samples. Identifications are by visual examination aided by X-ray diffraction.

OPEN-FILE REPORT 88–422: ANALYTICAL DATA AND SAMPLE LOCALITY MAP FOR AQUA-REGIA LEACHATES OF STREAM SEDIMENTS ANALYZED BY ICP FROM THE MOUNT KATMAI QUADRANGLE, AND PORTIONS OF THE NAKNEK, AFOGNAK, AND ILIAMNA QUADRANGLES, ALASKA

Analytical results for 34 elements in aqua-regia leaches of the stream-sediment samples are presented. Leaching preferentially oxidizes sulfide minerals and minerals formed during rock alteration, as well as others, so the leaches ideally concentrate elements that reflect mineralization and alteration. Analytical results include copper, silver, lead, molybdenum, zinc, boron, gold, nickel, cobalt, arsenic, tin, antimony, tungsten, chromium, bismuth, cadmium, barium, and manganese.

OPEN-FILE REPORT 89–570: SAMPLE LOCALITY MAPS, ANALYTICAL DATA, AND STATISTICAL SUMMARY OF ANALYSES OF ROCK SAMPLES FROM THE MOUNT KATMAI QUADRANGLE AND ADJACENT PORTIONS OF THE NAKNEK AND AFOGNAK QUADRANGLES, ALASKA

Results are presented on 1,205 bedrock samples analyzed by semiquantitative emission spectrograph for 31 elements potentially indicative of mineralization. Results are also included for analyses of selected samples by methods more sensitive for elements of particular interest such as gold and mercury. Results are grouped according to geologic unit and are statistically analyzed to determine the concentration of each element that is considered unusually high (anomalous) for each rock type in the study area. A map showing the localities of sample sites is included. Of the ore-related elements, anomalous concentrations were noted in copper, molybdenum, lead, and zinc, less commonly in silver, and uncommonly in gold. The geologic setting of each of the 197 anomalous samples is discussed in Bulletin 2020.

MF–2021–A: GEOCHEMICAL MAP SHOWING THE DISTRIBUTION OF SELECTED ELEMENTS DETERMINED IN STREAM SEDIMENTS FROM THE MOUNT KATMAI AND PORTIONS OF THE AFOGNAK AND NAKNEK QUADRANGLES, ALASKA

Maps MF–2021–A through 2021–D show the spatial distribution of anomalies identified by the different analytical techniques reported in Open-File Reports 86–586, 87–615, and 88–422 for the set of stream-sediment samples. The analytical results of all techniques are interpreted together in Bulletin 2020.

Results are statistically analyzed to determine the concentration of each element that is unusually high (anomalous) in stream sediments according to the dominant type of bedrock that underlies the drainage basin of the sample. Spatial clustering of samples having anomalous concentrations and the occurrence of multiple elements in anomalous concentrations in those samples indicate likely sulfide (iron, copper, lead, zinc, or arsenic) and (or) precious-metal (gold, silver) mineralization in tracts near Cape Douglas and Kulik Lake and in the central part of the study area (fig. 2).

MF–2021–B: GEOCHEMICAL MAPS SHOWING THE DISTRIBUTION OF SELECTED LEACHABLE METALS DETERMINED BY ICP IN STREAM SEDIMENTS FROM THE MOUNT KATMAI AND PORTIONS OF THE AFOGNAK AND NAKNEK QUADRANGLES, ALASKA

Results confirm most of the three tracts outlined in MF–2021–A. A fourth tract defined exclusively by leachates is the area underlain by Tertiary volcanic rocks north of Naknek Lake. Such an alteration signature may reflect widespread, low-grade cooling alteration of the lava flows; it may also reflect older deposits of glacial till, or buried altered rocks.

MF–2021–C: GEOCHEMICAL MAP SHOWING THE DISTRIBUTION OF SELECTED ELEMENTS DETERMINED IN NONMAGNETIC HEAVY-MINERAL CONCENTRATES FROM THE MOUNT KATMAI AND PORTIONS OF THE AFOGNAK AND NAKNEK QUADRANGLES, ALASKA

The high-density concentrates should contain most ore-forming minerals. Samples anomalous in copper, lead, gold, or silver occur near Cape Douglas; anomalous concentrations of copper, lead, zinc, molybdenum, and boron occur from Kukak Bay southwest to Katmai Bay, near Kejulik Pass at the south margin of the study area, and in the central part of the study area. Anomalous concentrations of copper, molybdenum, lead, and zinc occur immediately south of Kulik Lake. A few samples having anomalous concentrations of gold, molybdenum, and silver occur in the northwest part of the map area, in the tract underlain by Tertiary volcanic rocks.

MF–2021–D: MINERALOGIC MAP SHOWING THE DISTRIBUTION OF SELECTED MINERALS IDENTIFIED IN NONMAGNETIC HEAVY-MINERAL CONCENTRATES FROM THE MOUNT KATMAI AND PORTIONS OF THE AFOGNAK AND NAKNEK QUADRANGLES, ALASKA

Pyrite-, copper-, lead-, and zinc-sulfide minerals, and uncommon gold occur in samples from southwest of Cape Douglas. A few samples from a tract underlain by altered volcanic rocks at the south margin of the study area have copper- and zinc-sulfide minerals. A few samples from the center of the study area and from a tract south of Kulik Lake have copper-, lead-, or zinc-sulfide minerals and a tungsten mineral. The tract north of Naknek Lake, underlain by Tertiary volcanic rocks, yielded a few samples having tungsten, tin, or zinc minerals.

BULLETIN 2020: INTERPRETATION OF EXPLORATION GEOCHEMICAL DATA FROM THE MOUNT KATMAI QUADRANGLE AND ADJOINING PARTS OF THE AFOGNAK AND NAKNEK QUADRANGLES, ALASKA

Interpretation of analytical results for the bedrock and stream-sediment samples is aided by comparison with results from mineralized tracts in adjacent areas. In the Chignik-Sutwik Island quadrangles south of the Katmai area, porphyry mineralization occurs near Tertiary or Quaternary intrusions in marine and nonmarine sedimentary rocks (Wilson and Cox, 1983). The metals of interest in a porphyry mineral deposit are chiefly copper and molybdenum but may include gold, silver, or zinc. The ore minerals occur in thin veins at the margins of plutons or in adjacent wall rocks. Areas of possible porphyry mineralization occur in the Ugashik and Karluk quadrangles as well, immediately south of the Katmai area (Church and others, 1989b). In these areas, stream sediments have anomalous concentrations of copper, molybdenum, and one or more of lead, zinc, arsenic, silver, and gold; rock samples have anomalous concentrations of these elements and tin or tungsten.

Precious-metal veins occur at the Apollo mine on Unga Island 470 km southwest of Katmai. The Apollo produced $3 million worth of gold and silver between 1893 and 1908. The occurrence is as near-vertical quartz veins in Tertiary lava flows and domes (Wilson and others, 1988). The Apollo and other prospects on Unga Island are sited on faults that have localized quartz veins, silicification, and alteration (White and Queen, 1989). Stream sediments in the area of the Apollo mine have anomalous concentrations of silver, copper, lead, molybdenum, and zinc; bedrock samples have anomalous concentrations of these elements as well as gold (J. Frisken, written commun., 1988).

Numerous prospects and mineral claims for gold, silver, copper, and iron have been filed in the Iliamna quadrangle north of the Katmai region. These occurrences are either replacement deposits (skarns) formed in limestone or volcanic rocks of the Talkeetna Formation at the contact with intrusive rocks or are magnetite in gabbro of the Jurassic batholith (Detterman and Reed, 1980). Gabbro and limestone are uncommon in the Katmai study area, and there are few appropriate geochemical anomalies. Thus, there is little evidence for similar deposits in the Katmai region. A gold-, silver-, and copper-bearing quartz vein occurs 13 km north of Kulik Lake in slightly altered, Tertiary volcanic rocks; the vein probably formed above a buried pluton.

Bedrock and stream-sediment samples from the Katmai area that have anomalous concentrations of ore-related elements were examined for spatial clustering. Some anomalous samples occur isolated from others and (or) have concentrations that only marginally meet the definition of anomalous. These samples probably represent weakly developed mineralization. Other anomalous stream-sediment samples occur in tracts having few anomalous bedrock samples and no other geologic evidence for mineralization. These results are provisionally interpreted to be due to contamination of stream sediments by glacial deposits. Tracts having (1) clusters of both bedrock and stream sediment samples that are (2) anomalous in several elements, and (3) evidence for geologic processes favorable for mineralization, are discussed in detail.

Anomalous concentrations in both bedrock and stream-sediment samples of copper, molybdenum, lead, zinc, silver, arsenic, tin, and tungsten are suggestive of undiscovered porphyry copper or molybdenum deposits. Such anomalies occur in tracts at the center of the study area, at Cape Douglas in the northeast, and immediately south of Kulik Lake at the north margin of the study area. Less intensely developed patterns of anomalies occur as well at the south margin of the study area near Kejulik Pass and in the northwest. In all of these tracts there are porphyritic intrusive rocks or there is permissive evidence for the occurrence of such rocks at shallow depth.

Anomalous concentrations of copper, molybdenum, lead, zinc, silver, and arsenic may indicate the presence of polymetallic veins. Where gold, silver, mercury, or arsenic occur in anomalous concentrations, potential gold-silver (precious metal) veins are suggested. Samples having anomalous concentrations of such elements occur in the same tracts as those outlined for porphyry deposits: in the center of the study area, near Kulik Lake, and at Cape Douglas. Another tract having a large number of samples anomalous in the vein suite is the area from Cape Douglas south to Katmai Bay. This tract is underlain by altered Tertiary and Quaternary volcanic rocks that have abundant quartz veins, fractures, and dikes and other small intrusive masses that may have been sources of mineralizing fluids.

The occurrence of active fumaroles or warm springs near some of the Quaternary volcanoes is permissive of undiscovered hot-springs gold deposits. Some stream-sediment samples collected in basins draining the flanks of active volcanoes have anomalous concentrations of elements characteristic of hot-springs deposits (such as mercury, lead, arsenic, and silver). However, specific sites having well-developed geochemical anomalies were not identified.

MF–2021–E: MAP AND TABLE SHOWING K-AR AGES FROM THE MOUNT KATMAI AND ADJACENT PARTS OF THE NAKNEK AND AFOGNAK QUADRANGLES, ALASKA

Analytical data are presented for 46 new potassium-argon ages determined on samples of intrusive and volcanic rocks collected during the course of this study. Data are included for 18 additional ages that were previously determined but some not previously published. Sample localities are plotted on a base geologic map. The ages define two main clusters: an early to middle Jurassic intrusive event (the Alaska-Aleutian Ranges batholith) and a middle Tertiary to Quaternary, intrusive and volcanic event that includes the modern Aleutian volcanic arc. The new sample ages have important implications for the mineral-resource assessment: for example, mineralization in areas underlain by batholithic rocks is preferentially concentrated near plutons of Tertiary age.

MF–2021–F: MINERAL AND ENERGY RESOURCE ASSESSMENT MAPS OF THE MOUNT KATMAI, NAKNEK, AND WESTERN AFOGNAK QUADRANGLES, ALASKA

These maps summarize the evidence and interpretations in the other publications, and outline tracts having evidence permissive or suggestive of undiscovered mineral deposits. A major contribution of the Katmai study is the first systematic resource assessment of the region.

In the north-central part of the study area, near Kulik Lake, evidence is favorable for the occurrence of an undiscovered porphyry-copper deposit and (or) for polymetallic vein deposits. There is also potential for placer gold deposits in this tract. Bedrock in this tract includes Tertiary plutons that have intruded Jurassic plutons and their older wall rocks, similar to the types of bedrock that occur around claims and mineral occurrences in the Iliamna quadrangle. Specific evidence for mineralization includes quartz veins, disseminated pyrite, rock alteration, and anomalous concentrations of metals including copper, gold, and silver in both rock samples and stream sediments. Some claims and prospect pits occur in the area.

No direct evidence for replacement (skarn) deposits at the margins of Jurassic or Tertiary plutons was found in the Katmai region during the course of this study.

There is potential for a porphyry copper (molybdenum) deposit and (or) for polymetallic vein deposits in the central part of the study area. The geologic setting is Tertiary plutons that have intruded fractured and locally altered, Mesozoic sedimentary rocks. Anomalous quantities of copper, lead, zinc, silver, and gold occur in both bedrock and stream-sediment samples. Alteration and quartz veins are present in the plutonic rocks. A similar geochemical signature occurs in a tract of altered volcanic rocks near Kejulik Pass, at the south margin of the study area. There are, however, no exposed intrusive rocks at Kejulik Pass except for small sills and dikes, and the geochemical signature is less intensely developed than in the central tract.

The entire Aleutian Range, from Cape Douglas south to Katmai Bay, is judged to have potential for undiscovered deposits of porphyry copper, hot-springs gold, and (or) polymetallic veins. The underlying bedrock is late Tertiary and Quaternary volcanic rocks and small intrusive masses, and older Mesozoic and Tertiary sedimentary wall rocks. All rock types are altered or fractured, providing pathways for mineralizing fluids, and have quartz veins that are parallel to the prevalent northwest-trending fractures. Some geochemical anomalies are associated with areas of particularly intense alteration and veining. Anomalous concentrations of zinc, silver, copper, molybdenum, and gold are identified in both stream-sediment and bedrock samples.

The number and size of undiscovered mineral deposits that may occur in the Katmai region are unknown. No producing porphyry deposits occur in similar rocks elsewhere on the Alaska Peninsula, thus it is unlikely that many such undiscovered deposits would occur in the study area. On the other hand, vein deposits may extend for only tens to hundreds of meters along a narrow zone, so there could be numerous undiscovered vein deposits within the study area.

The only known mineral production from the study area has been from a gold-placer claim on the American River south of Nanwhyenuk Lake. A few tidewater claims for pumice (lightweight aggregate) are still valid on the Shelikof Strait; there has been no known production from these claims. Sand and gravel for construction are abundant in the inhabited western portion of the study area. The few known warm springs are too low in temperature for direct uses. Hydrocarbon potential within the study area is low, due to unfavorable rock characteristics and geologic history. Minor coal seams in Tertiary rocks along Shelikof Strait could constitute a small, locally marketable resource under favorable conditions of economics and land classification.

MF–2021–G: MACROFOSSIL LOCALITY MAP, CHECKLISTS, AND PRE-QUATERNARY STRATIGRAPHIC SECTIONS OF THE MOUNT KATMAI QUADRANGLE AND ADJACENT PARTS OF THE NAKNEK AND AFOGNAK QUADRANGLES, ALASKA

A total of 338 collections of macrofossils were made during the course of the study, many from measured stratigraphic sections. The report presents fossil identities, localities, ages, and measured sections. The combination of fossil and stratigraphic data is useful not only for determining the exact ages of the rocks but for describing precisely the sequence of environmental changes during deposition of the rock layers.

Most collections are from the Naknek Formation, the main rock unit of the Alaska Peninsula. Marine deposits of the upper part of the Naknek Formation are richly fossiliferous, the clamlike genus *Buchia* predominating. Different species of *Buchia* indicate different marine environments.

Ammonites—marine invertebrates related to modern squids—and the clam *Inoceramus* are important fossils in the Cretaceous rocks of the area. Ages of nonmarine Tertiary rocks are determined from plant fossils.

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