The Alaska Mineral Resource Assessment Program: Background Information to Accompany Folio of Geologic and Mineral Resource Maps of the Circle Quadrangle, Alaska

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CONTENTS

ILLUSTRATIONS

TABLES

The Alaska Mineral Resource Assessment Program: Background Information to Accompany Folio of Geologic and Mineral Resource Maps of the Circle Quadrangle, Alaska

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ABSTRACT

The geology, geochemistry, geophysics, and Landsat imagery of the Circle quadrangle were investigated by an interdisciplinary research team for the purpose of assessing the mineral potential of the area. The quadrangle covers approximately 15,765 km^2 in east-central Alaska; most of it is included in the mountainous Yukon-Tanana Upland physiographic division, but the northernmost part is in the low-lying Yukon Flats section. The Circle mining district, in the east-central part of the quadrangle, has been a major producing area of placer gold since its discovery in 1893.

For descriptive purposes, the Circle quadrangle is divided into three areas: the northwest Circle quadrangle, the area north of the Tintina fault zone, and the area south of the Tintina fault zone. The Tintina fault zone extends northwesterly through the northern part of the quadrangle. The northwest Circle quadrangle contains mostly folded and faulted, slightly metamorphosed sedimentary rocks that are intruded by Tertiary granitic plutons. In the northern part of the area north of the Tintina fault zone (Little Crazy Mountains and northern east Crazy Mountains), the rocks consist primarily of the gabbro and basalt of the Circle Volcanics and minor associated chert, graywacke, and limestone. Elsewhere in this area (south of the Circle Volcanics and in the western Crazy Mountains), the rocks are mostly slightly metamorphosed Paleozoic sedimentary rocks that have been folded and faulted. Rocks in the largest part of the quadrangle, the area south of the Tintina fault zone, consist largely of pelitic rocks that are regionally metamorphosed to greenschist and amphibolite facies. Felsic plutons, mostly Tertiary in age, occur throughout the area. The metamorphic rocks are separated from sedimentary rocks on the northwest by thrust faulting.

The aeromagnetic and gravity data show clear differences between the areas north and south of the Tintina fault zone. The metamorphic terrane to the south has low overall gravity and local gravity lows over exposed granitic plutons. It is hypothesized that magnetic chlorite schist infolded with nonmagnetic quartzite and schist account for east-northeast-trending magnetic highs that approximately parallel the regional strike of the most prominent foliation in the metamorphic rocks. North of the Tintina fault zone, the Circle Volcanics are characterized by high gravity and east-west-trending magnetic highs. The Tintina fault zone has an intense magnetic high near the western margin of the Circle quadrangle overlying the magnetic granodiorite of the Victoria Mountain pluton. A magnetic high near Circle Hot Springs is less intense, but broader, and could reflect a buried magnetic pluton similar to that of the Victoria Mountain pluton.

Computer-enhanced Landsat images of the Circle quadrangle show trends and patterns of concentrations of linear features. Features trending northeast-southwest predominate throughout the quadrangle; northwest-southeast-trending linear features are found mostly south of the Tintina fault zone. High concentrations of linear features were not found to correspond to areas of known mineralization in any consistent or significant way that could presently be used in locating areas of mineralization.

Geochemical and mineralogical studies of stream sediment and heavy-mineral concentrates from the Circle quadrangle identify areas of anomalous concentrations of metallic elements, including gold, silver, tin, tungsten, lead, antimony, zinc, thorium, uranium, and beryllium. The data delineate areas of known mineral occurrences and areas that may contain undiscovered mineral resources.

To date, placer gold has been the only significant metallic mineral resource from the Circle quadrangle, but the general geologic setting, especially the presence of post-orogenic plutons, is similar to that of regions that contain tin greisen deposits, tungsten skarn deposits, lode gold deposits in metasedimentary rocks, and uranium vein deposits. Six areas or tracts were identified in which such deposits might occur, and two more tracts were delineated as possible for the occurrence of shale-hosted lead-zinc deposits. The discovery of two diamonds in the gravels of Crooked Creek point to the slight possibility of finding placer or lode diamond deposits.

Although most of the past and present gold mining has taken place in four areas in the quadrangle, a sedimentary basin near the town of

Central was identified as possibly containing buried placer gold deposits or sedimentary uranium deposits.

INTRODUCTION

Purpose and Scope

This circular, together with a separately available folio of open-file maps of the Circle quadrangle, is one of a series of U.S. Geological Survey reports intended to provide information for formulating a sound long-range national mineral policy to aid in Federal, State, and local land-use planning; to provide significant data for mineral explorations; and to increase geologic understanding of the area. The work was carried out under the Alaska Mineral Resource Assessment Program (AMRAP), authorized by Congress to begin on July 1, 1974.

The Circle quadrangle mineral resource assessment consists of this circular, geologic, geophysical, and geochemical maps, interpretation of Landsat imagery, and an analysis of the mineral endowment (table 1). Most of the field and laboratory studies were carried on from 1978 through 1982 by an interdisciplinary team of scientists; some additional work and related projects have continued and are continuing through the time of this writing (1986).

Geography and Access

The Circle quadrangle covers approximately 15,765 km^2 in east-central Alaska (fig. 1) between lat 65° and 66° N. and long 144° and 147° W. Most of it is included in the mountainous physiographic division termed the Yukon-Tanana Upland (Wahrhaftig, 1965); the northernmost part is in a low-lying area known as the Yukon Flats section (fig. 2). The Yukon River flows along the northeastern edge of the quadrangle. Large streams that drain northward into the Yukon include Birch Creek and Preacher Creek. In the southern part of the quadrangle, the Chena and Chatanika Rivers drain southwestward, their waters reaching the Yukon via the Tanana River. The Salcha River heads in the southeastern part of the quadrangle and its water also reaches the Yukon River via the Tanana River.

The Yukon-Tanana Upland is a maturely dissected mountainous terrain, unglaciated except for a few of the highest areas, which supported small alpine glaciers during part of the Pleistocene. Altitudes range from around 500 m to a little more than 1,800 m, and relief of more than 300 m is common in many places. Much of the area is in alpine tundra; forest covers regions below 1,000 m in altitude, especially in most of the large river valleys and on lower slopes of valley walls.

The Yukon Flats section is underlain by thick

TABLE 1.--Component maps of the Circle mineral resource assessment

U.S. Geological Survey Open-File Report	Subject
83-170-A (Foster and others, 1983)	Preliminary geology
83-170-B (Menzie and others, 1983)	Mineral resources
83-170-C (Cady and Weber, 1983)	Aeromagnetic map and interpretation of aeromagnetic and gravity data.
83-170-D (Cady and Barnes, 1983)	Gravity map
83-170-E (Simpson, 1984)	Landsat imagery
83-170-F (Tripp and Crim, 1986)	Mineralogical maps showing distribution of selected minerals in the minus-30-mesh, nonmagnetic heavy-mineral fraction of stream sediment
83-170-G (Tripp, Hoffman, and Risoli, 1986)	Geochemical maps showing distribution of selected elements in the minus-30-mesh, nonmagnetic heavy-mineral fraction of stream sediment
83-170-H (Tripp, O'Leary, and Hoffman, 1986)	Geochemical maps showing distribution of selected minerals in minus-80-mesh stream sediment.

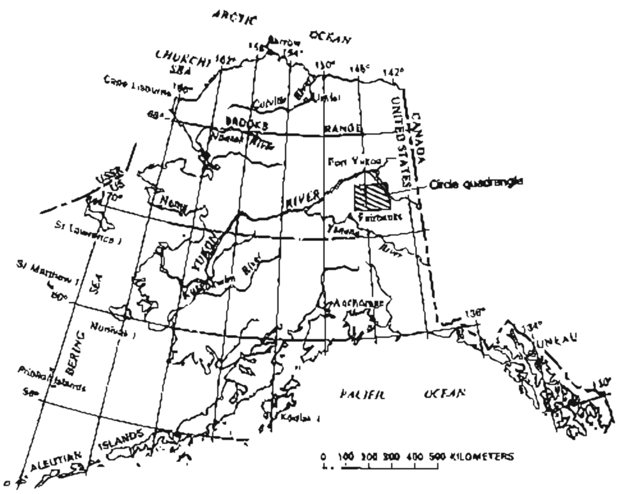

FIGURE 1.—Index map of Alaska showing location of Circle quadrangle (hachured area).

unconsolidated deposits, primarily alluvium of several ages and windblown deposits of loess and sand. Most of the Yukon Flats is heavily forested.

In the early 1900's, access to the region was by boat on the Yukon River to the town of Circle. Now, the all-weather Steese Highway connects Circle with Fairbanks and provides access to many short roads and trails leading into the principal placer gold mining areas. Some of these mining roads are maintained by the State of Alaska; however, neither they nor the Steese Highway are open during the winter months. Another highway extends from Fairbanks to Chena Hot Springs and is kept open all year. Good landing strips are maintained at Chena Hot Springs, Circle Hot Springs, Central, and Circle.

The only towns in the quadrangle are Circle, at the northern end of the Steese Highway, and Central, about 45 km to the southwest. There are two hot-spring resorts, Chena Hot Springs in the southern part of the quadrangle and Circle Hot Springs near Central.

Mineral Production and Exploration

Mineral production from the Circle quadrangle, excluding sand and gravel, is limited to gold and possibly a little silver and tin as byproducts from gold placer mining. Gold was discovered in the Circle quadrangle in 1893; placer mining began in the summer of 1894 and has continued to the present. No lodes have been mined. Bundtzen and others (1984) estimated that at least 850,000 oz of placer gold has been recovered from the quadrangle.

The major production of gold from the Circle quadrangle has been from the Circle mining district, an area of approximately 750 km^2 in the east-central part of the quadrangle; however, the amount of gold produced from the Circle mining district is unknown. Barker (1979) estimated that 277,650 oz of gold and 52,270 oz of byproduct silver had been recovered from the district through 1970, and a considerable amount of gold has been produced since that time. The district has been, and still is, one of Alaska's major gold-producing areas. Other gold-producing areas in the Circle quadrangle include Nome Creek, tributaries to the Chatanika River, and the Chena River and some of its tributaries, although the amount of production of these areas combined is much less than that of the Circle mining district. Most of the quadrangle has been intensively prospected for gold.

Cassiterite is abundant in the heavy concentrates of many placer mines, but no significant effort has been made to recover it. Scheelite also occurs in many concentrates, and considerable exploration for tungsten deposits, including drilling, has gone on recently in the southeastern part of the quadrangle. Prospecting for uranium has been carried on at various times: bedrock from road cuts and concentrates of stream gravels were checked in 1946 (Wedow, Killeen, and others, 1954); in 1949 and 1952, Geological Survey parties did brief reconnaissance investigations for radioactive deposits (Wedow, White, and others, 1954; Nelson and others, 1954); and in 1977, the U.S. Bureau of Mines carried out a limited sampling program (Barker and Clautice, 1977).

Although considerable exploration has taken place intermittently for many years in the Circle quadrangle, lode mineral deposits favorable for development under present economic conditions have not been found, but the potential for locating one or more economic deposits exists (Menzie and others, 1983). The University of Alaska and State and Federal agencies have made studies that included the geothermal potential of the Circle quadrangle and particularly of the Chena Hot Springs area (Miller and others, 1975; Turner and others, 1980; and Geophysical Institute, 1980). Commercial deposits of oil, gas, and coal are not known in the Circle quadrangle, and the geology is not favorable for locating significant deposits in the future.

Acknowledgments

Many scientists have participated in and contributed to geologic mapping in the Circle quadrangle and to Circle AMRAP. William E. Davies and Daniel B. Krinsley mapped large parts of the quadrangle in the summers of 1960-1963 under a U.S. Geological Survey military geology program. Much assistance was rendered by local Alaskans, particularly at Central, Circle, Circle Hot Springs, and Chena Hot Springs. Competent commercial helicopter crews were essential in carrying out the geologic mapping, geochemical sampling, and

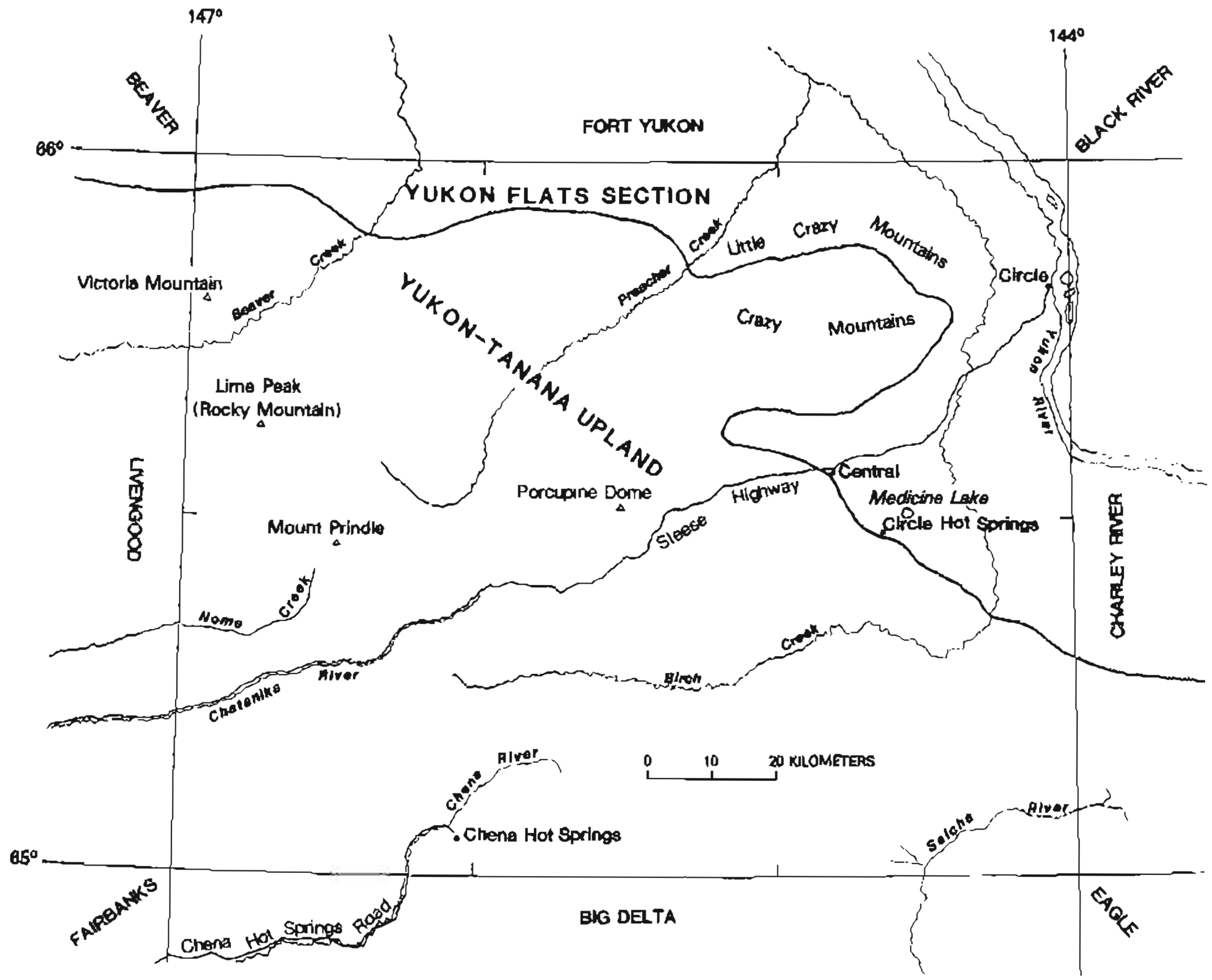

FIGURE 2.--Circle quadrangle showing adjacent quadrangles, physiographic divisions, and major streams and geographic features. Heavy line indicates approximate boundary between Yukon Flats section and Yukon-Tanana Upland.

geophysical observations. Able assistance in the field was given by Grant W. Cushing, Diana J. Nelson, Steven T. Luthy, Anna Burack Wilson, and others.

GEOLOGIC INVESTIGATIONS

Previous Investigations

The earliest geologic notes on the Circle quadrangle were by R.G. McConnell, who in 1888 described the rocks along the Yukon River en route from Fort Yukon upriver into the Yukon Territory (McConnell, 1890). In 1889 I.C. Russell examined surficial features along the Yukon River (Russell, 1890). Spurr (1898), from his work in 1896, first introduced the term Birch Creek series for most of the metamorphic rocks of the area, and later Prindle (1913) and Mertie (1937) continued to use the name as Birch Creek Schist.

Collier (1903) gathered stratigraphic data along the Yukon River in 1902, but the first systematic geologic work was by Prindle, beginning in 1903 and continuing intermittently to 1911 (Mertie, 1937). In 1906, Brooks and Kindle studied the section along the Yukon River as far downstream as Circle (Brooks and Kindle, 1908). Mertie continued the work of Prindle and spent considerable time in the Circle quadrangle, particularly in the mining districts. Mertie's (1937) comprehensive report on the Yukon-Tanana region has formed a foundation for all future work in the Circle quadrangle and adjacent parts of the Yukon-Tanana region.

Numerous short special investigations, such as a reconnaissance for radioactive deposits in 1949 (Wedow, White, and others, 1954) and a reconnaissance for uranium and thorium in 1952 (Nelson and others, 1954), have involved the Circle quadrangle. Several theses have been done on small parts of the quadrangle by graduate students at the University of Alaska. The U.S. Bureau of Mines has carried on short investigations of selected commodities such as uranium and tin.

In 1960, Davies and Krinsley began geologic mapping in the eastern Circle quadrangle for the U.S. Geological Survey, but their work was not completed.

Prospecting and exploration by mining companies has continued intermittently throughout the Circle quadrangle from the 1890's to the present. Although gold has been the commodity of primary interest, other metals such as silver, tin, tungsten, antimony, and molybdenum are also sought. Uranium continues to be of interest, and the hot springs may get further consideration as geothermal areas.

Present Study

Reconnaissance geologic mapping under AMRAP began with a short field season in 1978 and continued in 1979, 1980, and 1981. Geochemical sampling was mostly done in 1979 and 1980, and most of the geophysical work in the field was in 1979 with a minor amount of work in 1981 and 1982. An area in the Crazy Mountains was geochemically resampled in 1983, and in 1984 additional geochemical samples were obtained in the Lime Peak area. A number of short reports were published in the U.S. Geological Survey Accomplishments Circulars from 1979 to 1984. Most samples for potassium-argon age determinations were collected in 1979, and a few other samples were collected throughout the course of the fieldwork. Several samples for uranium-lead dating were also collected and processed.

The aeromagnetic map of the Circle quadrangle used for aeromagnetic interpretation in this study was compiled from a survey flown in 1973 by Geometrics, Inc., and released by the U.S. Geological Survey in 1974.

Isotopic Age Data from the Circle Quadrangle

A total of 35 potassium-argon ages were determined on 15 igneous and 11 metamorphic rocks from the Circle and adjacent quadrangles as part of this AMRAP project. Analytical data for these ages have been reported in an open-file report (Dubois and others, 1986) and some of their significance discussed by Wilson and others (1984 and 1985).

Ages on biotite, muscovite, and hornblende from 13 granitic intrusions ranged from 77.6±2.0 Ma (million years) to 56.65±0.95 Ma. Most granitic rocks had ages ranging between 66 and 56 Ma; however, a very small body of tourmaline granite and two other granitic bodies had ages between 77.6 and 72 Ma. All three of the older intrusions are in the southeastern part of the Circle quadrangle and yield ages only slightly younger than the metamorphic rocks they intrude. Ages of these metamorphic rocks appear to be reset by Late Cretaceous through early Tertiary plutonism and thermal events associated with the youngest plutons.

Seventeen biotite, muscovite and amphibole ages from 11 metamorphic rocks ranged from 178.0 to 63.4 Ma; some are partially reset to different degrees by Late Cretaceous through early Tertiary plutonism and thermal events. Discordant ages ranging from 63.4±1.5 Ma to 78.1±3.0 Ma on biotite and 71.0±2.0 Ma to 92.0±5.0 Ma on muscovite from four augen gneiss samples from several localities in the southeastern part of the Circle quadrangle are considerably younger than ages on augen gneiss from the Big Delta quadrangle to the south (Wilson and others, 1985), where ages range from 113 to 106.5 Ma. Augen gneiss from the Circle quadrangle was apparently strongly affected by nearby Tertiary plutonic events, whereas Tertiary plutonism is not known in or near the augen gneiss of the Big Delta quadrangle. Metamorphic and possibly Cretaceous igneous rocks in the southeastern part of the Circle quadrangle show significant thermal resetting that can be related to proximity to large Late Cretaceous and early Tertiary granitic plutons.

Zircons from four samples collected in the Circle quadrangle were dated by the U-Pb method. The rocks from which the zircons were obtained include an augen gneiss, a quartzite, and two grits (table 2). The augen gneiss and quartzite are from the area south of the Tintina fault zone; one of the grits is from the northwest Circle quadrangle, and the other is from north of the Tintina fault zone in the east Crazy Mountains area (fig. 3). A concordia plot of the U-Pb data from zircons from the augen gneiss (sample 78AFr 150) forms a scatter pattern (fig. 4), which suggests that the zircons contain inheritance of radiogenic lead and may have also undergone at least one period of lead loss. A similar pattern occurs in data from augen gneisses in the adjacent Big Delta quadrangle (Aleinikoff and others, 1986). However, the augen gneiss from the Circle quadrangle has somewhat younger U-Pb ages (ranging from 254 to 301 Ma).

Because routine analyses of zircons did not yield an age for the protolith of the augen gneiss, an alternative method was attempted. Aleinikoff (1983) showed that the mineral in which zircons are included has an effect on its relative retentivity of Pb. In this case, zircons were separated from a mixture of quartz and potassium-feldspar and also from biotite. From these populations, the zircons were sized into different fractions and analyzed individually. The three fine-grained fractions

TABLE 2.--Uranium-lead isotopic data from zircons, Circle quadrangle, Alaska
[--, not determined]

Sample and fraction	Concentration (ppm)			Atomic percent				Ages (Ma)			
	U	Th	Pb	^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{232}Th$
78AFr 150 (augen gneiss)											
(+150)NM	1,759	113	78.5	0.068	85.84	5.680	8.415	277	290	395	901
(-325	2,099	111	90.6	.015	89.00	4.960	6.023	281	288	342	987
(+150)biot	1,975	289	86.1	.035	87.21	5.254	7.497	277	289	386	413
(-150+200)biot	1,929	167	87.8	.020	87.95	5.033	6.997	292	301	368	731
(-325)biot	2,160	138	88.0	.018	88.52	5.004	6.459	264	274	358	831
(+150)q-K	1,423	297	65.3	.137	82.08	6.492	11.29	268	283	404	303
(-150+200)q-K	1,618	226	70.2	.069	85.45	5.623	8.853	268	279	370	435
(-325)q-K	2,450	143	95.6	.023	88.82	5.058	6.097	254	263	343	793
80AFr 255 (quartzite)											
(+150)pink*	227	--	72.3	.042	74.53	10.19	15.23	1,558	1,797	2,086	--
80AFr 370 (grit from northwest Circle quadrangle)											
(+150)LT	159	--	38.2	.017	77.36	8.105	14.52	1,254	1,441	1,656	--
80AFr 253 (grit north of Tintina fault zone)											
(+150)red*	210	--	77.2	.054	72.64	10.71	16.59	1,723	1,949	2,198	--
(+150)gray*	1,501	--	131.	.233	70.94	11.33	17.49	437	748	1,888	--

*From Aleinikoff, Foster, and others (1984).

(minus 325 mesh) from biotite, quartz+potassium-feldspar, and the bulk group have the youngest $^{207}Pb/^{206}Pb$ ages of any of the analyzed fractions (table 2), suggesting that little or no inheritance occurred in the smallest zircons. A similar relationship was noted by Aleinikoff and Nokleberg (1985) in zircons from terranes north of the Denali fault in the Mount Hayes quadrangle.

The zircons from the fine (minus 325 mesh) bulk and fine quartz+potassium-feldspar fractions suggest an age of about 340 Ma for the intrusion of the protolith of the augen gneiss. The $^{207}Pb/^{206}Pb$ age of zircons from the fine biotite fraction is slightly older at 358 Ma. This may be related to the order of crystallization of the rock-forming minerals in the protolith. Earlier formed zircons (which probably would contain relatively more inheritance than later zircons) would be included within early crystallizing phases such as biotite. Later zircons, included within quartz and feldspar, would have less inheritance. Thus, the smallest, latest zircons should contain the least inheritance and possibly record the true age of intrusion of the protolith of the augen gneiss. The maximum age of the protolith of the gneiss, based on this date alone, appears to be about 340 Ma. This age is in excellent agreement with age determinations for augen gneisses in the Big Delta quadrangle, dated at 341±3 Ma (Aleinikoff and others, 1986).

Four fractions from three metasedimentary rocks were analyzed to provide the beginning of a data base to aid in determining the age of the provenance(s) for the sediments. As shown by Aleinikoff, Foster, and others (1984), detrital zircons from a quartzite in the area south of the Tintina fault zone (sample 80AFr 255) and a grit from north of the Tintina fault in the east Crazy Mountains (sample 80AFr 253) have Early Proterozoic $^{207}Pb/^{206}Pb$ ages and plot on a concordia diagram with other detrital zircons from the Mount Hayes quadrangle (fig. 5), indicating a provenance age of about 2.2 Ga (billion years). This age is also obtained by plotting similar data from the augen gneisses of the Big Delta quadrangle, which suggests that the Mississippian granitoid protoliths were derived from or included Early Proterozoic material. Thus, at least some of the sedimentary material of the area south of the Tintina fault zone appears to have been derived originally from Early Proterozoic sources.

A detrital zircon fraction from a grit in the northwest Circle quadrangle (sample 80AFr 370) has somewhat different U-Pb systematics. The gray, medium-grained grit contains abundant glassy quartz grains and brown-weathering specks that may have been feldspar, and is locally cut by carbonate veinlets. The $^{207}Pb/^{206}Pb$ age from the sample is 1.656 Ma; this data point does not plot on the previously established chord between about 2.2 Ga and 346 Ma. These 1.66-Ga zircons appear to have been derived from a different source than other detrital zircons analyzed from the Circle and Big Delta quadrangles. The provenance is also Early Proterozoic in age, but apparently somewhat younger than the provenance(s) of the other detrital zircons.

STATUS OF LAND IN THE CIRCLE QUADRANGLE

Most of the Circle quadrangle consists of Federal lands administered by several different agencies. A small amount of land, principally around the towns of Circle and Central and the resort areas of Chena Hot Springs and Circle Hot Springs, is patented land. Areas in the mining districts are held largely in claims by individuals and small companies. Some areas, mostly in the vicinity of Circle and some near Central, are Native lands. The State of Alaska and North Star Borough control some areas, particularly in the southern part of the quadrangle.

The largest areas of Federal lands are administered by the Bureau of Land Management, and others are under the National Park Service or Bureau of Fish and Wildlife Management. Regulations concerning mining and exploration are different in the various tracts. Very little land is open for new mining and exploration. Figure 6 shows the approximate distribution of major government-held tracts in the Circle quadrangle as of 1985.

DESCRIPTION OF COMPONENT MAPS AND RELATED REPORTS OF THE CIRCLE QUADRANGLE FOLIO

Geology (OFR-83-170-A)

The Circle quadrangle is located near the margin, possibly a fragmented margin, of the North

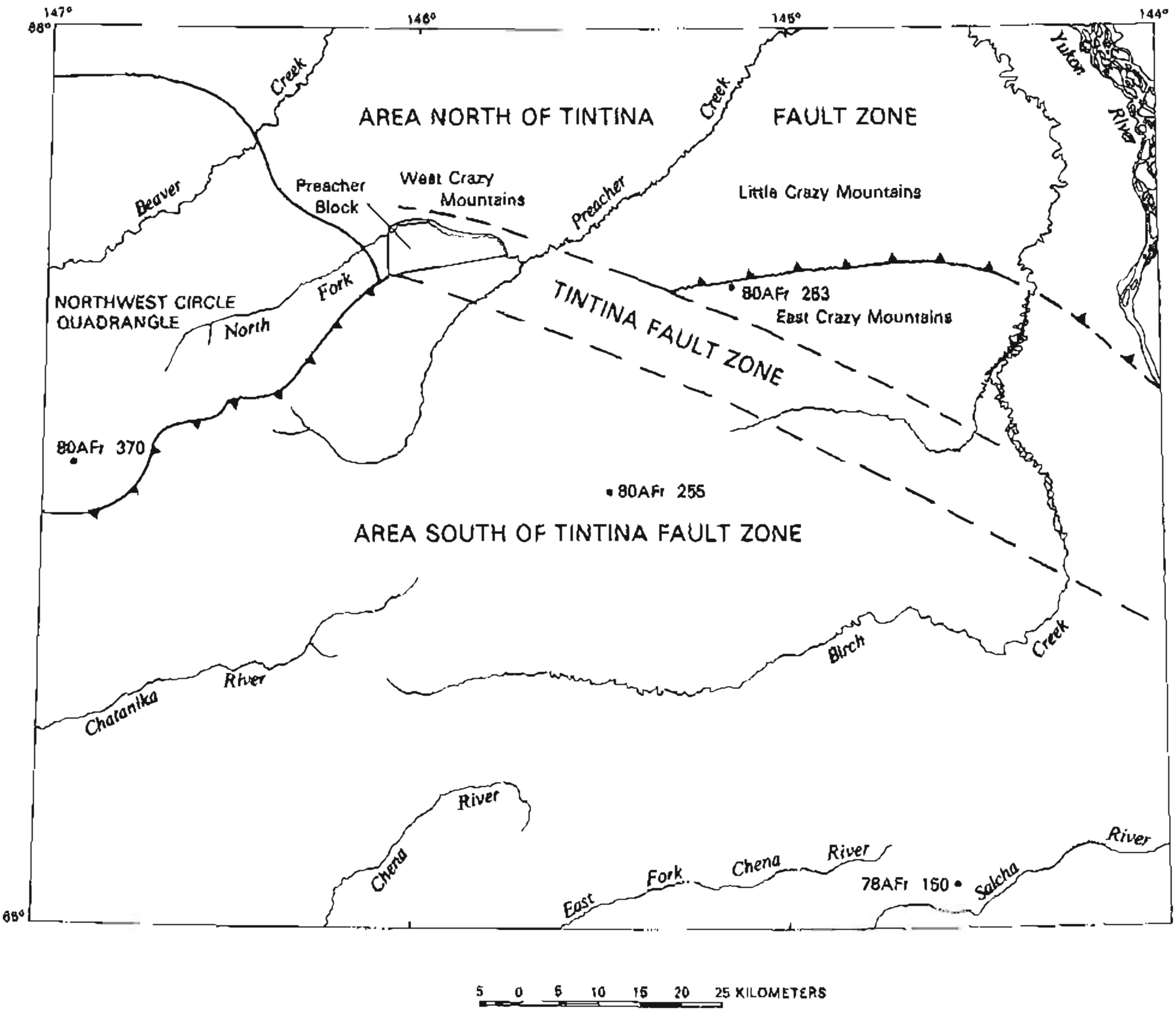

FIGURE 3.--Areas of the Circle quadrangle used in describing the geology, and sample locations (dots) used for uranium-lead age determinations (table 2). Faults are shown as heavy lines; sawteeth are on upper plate of thrust faults.

American craton and occupies a critical position for the interpretation of the geologic history of the Yukon-Tanana Upland. Because of large areas covered by vegetation and the lack of detailed geologic investigations, many of the complexities of this area remain to be worked out.

The Tintina fault zone trends northwesterly through the northeastern and central part of the quadrangle, and two boundary faults have been postulated, the Preacher fault on the north and the Hot Springs fault on the south. The zone is not clearly defined in either the northwestern or southeastern parts of the quadrangle. To the northwest, it may be buried; there is no clear field evidence for such a northwesterly trend, although gravity data suggest an ancient northwest-southeast-trending lineament (J.W. Cady, oral commun., 1984). The fault zone may bend southwestward, connecting with faults in the Livengood quadrangle, or it may lose its identity as a zone of strike-slip movement, the stresses instead resulting in faults with large thrust components.

The Circle quadrangle comprises several different geologic components. Therefore, for description the geologic map is divided into three major areas: the northwest Circle quadrangle, the area north of the Tintina fault zone, and the area south of the Tintina fault zone (fig. 3).

The northwest Circle quadrangle consists mostly of slightly metamorphosed, folded, and faulted sedimentary rocks that include chert, slate, argillite, sandstone, grit, graywacke, conglomerate, limestone, dolomite, and tuff of dominantly

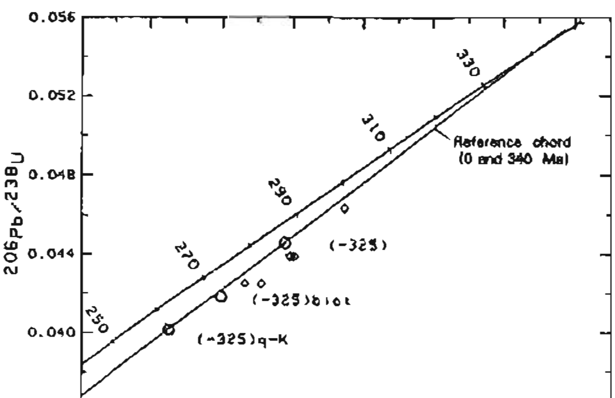

FIGURE 4.—Concordia plot of U-Pb data from zircons from augen gneiss (sample 78AFr 150, table 2), Circle quadrangle. Circles represent three fine-grained fractions (minus 325 mesh) of zircons included in quartz-potassium feldspar (q-K), biotite (biot) and the bulk group (not labeled) of the augen gneiss. Diamonds represent all of the larger fractions of zircons analyzed from the augen gneiss. Note that the reference chord goes through two fine fractions and slightly above a third fine fraction.

Paleozoic age, but some rocks are Mesozoic in age. Lime Peak (Rocky Mountain) and Victoria Mountain are Tertiary granitic intrusions. Mafic rocks occur as dikes, sills, and small intrusions. Small ultramafic and greenstone bodies are believed to have fault contacts. The area includes the Beaver, White Mountains, Kandik River, and Livengood terranes of Churkin and others (1982) (the Wickersham, White Mountains, and Livengood terranes, and deformed upper Mesozoic flysch of Jones and others, 1981). Lithologic units and major faults mapped in the Livengood quadrangle to the west (Chapman and others, 1971) have been extended into the Circle quadrangle, but locally there are problems in identifying contacts due to poor exposure and lack of detailed mapping in both quadrangles.

The area north of the Tintina fault zone is composed of two very different groups of rocks. On the north, including the Little Crazy Mountains and probably extending beneath the Yukon Flats, are gabbros and basalts with some chert, graywacke, and limestone, which are mostly included in the Circle Volcanics and compose the Circle terrane of Churkin and others (1982) (the Innoko terrane of Jones and others, 1981). These rocks have an age range from Mississippian to Triassic based on radiolarians (Foster and others, 1983). Most of the rocks in the Crazy Mountains and the Preacher block, which compose the Crazy Mountains terrane of Churkin and others (1982) (Wickersham terrane of Jones and others, 1981) are slightly metamorphosed sandstone, grit, argillite, conglomerate, chert, and limestone. Locally they include or are cut by sills, dikes, and small mafic intrusive masses. The rocks are folded and faulted. In general, rocks in the Crazy Mountains area are considered to be mostly of Paleozoic age and include Devonian limestones. The trace fossil Oldhamia, which indicates rocks of

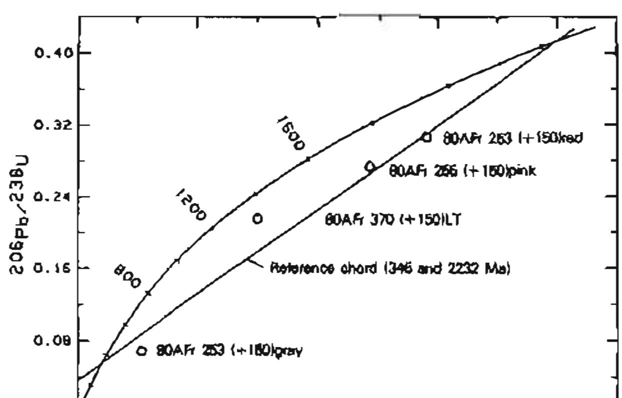

FIGURE 5.—Concordia plot of U-Pb data of detrital zircons identified by sample number (table 2) from the Circle quadrangle with previously established reference chord (Aleinikoff, Foster, and others, 1984).

probable Cambrian or possibly Late Proterozoic age, is a rarely found fossil. In the Tintina fault zone, Tertiary(?) conglomerate and sandstone crop out locally and are commonly overlain by Quaternary loess and alluvial deposits.

The largest part of the quadrangle, the area south of the Tintina fault zone, contains regionally metamorphosed pelitic rocks intruded by Late Cretaceous and early Tertiary granitic plutons. Some orthogneisses, including augen gneiss, also occur. This is the Yukon crystalline terrane of Churkin and others (1982) (the Yukon-Tanana terrane of Jones and others, 1981). Rocks range from very slightly to highly metamorphosed (mid to upper amphibolite facies). Contact metamorphism, locally superimposed on regional metamorphism, has resulted in some hornfelsing and local seritization and chloritization. Contacts between rocks of different metamorphic grade are both sharp, indicating faults, and gradational, indicating gradual change in metamorphic conditions. Some faulting occurred before metamorphism, complicating the interpretation of many contacts. A thrust fault separates this metamorphic terrane from the slightly metamorphosed rocks to the northwest. Several very small exposures of eclogite are present in the southwestern part of the quadrangle; the eclogite is similar to that found in the Livengood quadrangle east of Fairbanks.

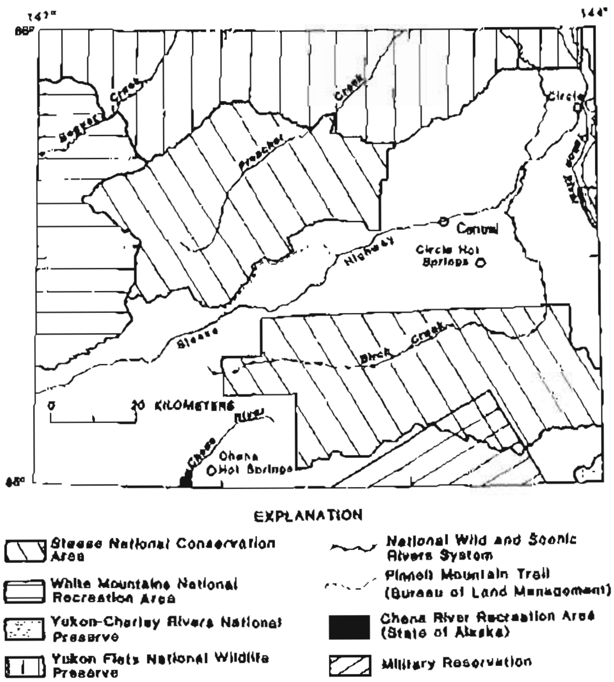

FIGURE 6.--Distribution of major government-held tracts in the Circle quadrangle (from U.S. Department of Interior Planning Group, 1980, and Bureau of Land Management, 1978).

The age of the protoliths is uncertain, as no fossils have been found. On the basis of very scarce fossils elsewhere in the Yukon-Tanana region and possible stratigraphic relations, they are believed to be at least partly Paleozoic but may also include Precambrian protoliths. Information from the study of zircons indicates that at least some of the sediment in many protoliths contains some zircon derived from Proterozoic rocks. The time of regional metamorphism is also unknown. Data from adjacent quadrangles suggest that it was probably during the Mesozoic, but Paleozoic metamorphism may have affected at least part of the quadrangle. No clear petrographic evidence for more than one regional metamorphism has been found in most of the rocks, but the area of eclogitic rocks may have a more complex metamorphic history. A few small serpentinized ultramafic masses are scattered throughout the metamorphic terrane; all are believed to have fault contacts.

The metamorphic rocks are intruded by Cretaceous and Tertiary granitic plutons that range in age from 77.6±2 Ma to 56.65±0.95 Ma. Small shallow felsic intrusions also occur in the central part of the quadrangle. Most mineral occurrences are largely associated directly or indirectly with the felsic intrusions. The metamorphic rocks are structurally complex, and much more detailed work is required to understand the structural relations within the quadrangle and within the Yukon crystalline terrane. At least three sets of folds can be recognized, two with axes trending northeast-southwest and one with a northwest-southeast-trending axis. One or more of these folding events is probably related to thrusting, which occurred at least two different times in the metamorphic terrane south of the Tintina fault zone. A complex, but different history of folding and thrusting typifies the area north of the Tintina fault zone. High-angle northeast-southwest-trending faults postdate metamorphism, plutonism, folding, and thrusting.

Mineral Resources (OFR-83-170-B)

The mineral resources report, which consists of a map, explanatory text, and appendices, assesses the metalliferous mineral resources of the Circle quadrangle and discusses selected nonmetallic resources. The assessment is based upon the general methodology of Singer (1975). Tracts (areas) that are geologically permissive for the occurrence of various types of mineral deposits were delineated, descriptive and grade/tonnage models of the deposit types were constructed from data in the literature, and numbers of deposits that may occur within delineated tracts were estimated. Types of resources that did not lend themselves to representation by deposit models or to delineation of tracts are discussed separately in the text.

The Circle quadrangle has been an area of gold placer mining since the 1890's; the amount of placer mining increased significantly from 1977 to 1982, the period of fieldwork for the report. The general geologic setting of the Circle quadrangle, especially the presence of post-orogenic plutons intruded into regionally metamorphosed rocks, is similar to regions that contain tin-bearing greisen deposits, tungsten-bearing skarn deposits, lode deposits of gold in metasedimentary rocks, and vein deposits of uranium associated with peraluminous granites, though no such deposits are known to exist in the quadrangle. This report identified six tracts that may contain deposits of these types: four tracts, considered permissive for tin-bearing greisen deposits, were estimated to contain at least one deposit at a 50 percent probability level and at least three deposits at a 10 percent probability level, and two tracts considered permissive for tungsten skarn deposits were estimated to contain at least one deposit at a 50 percent probability level and at least two deposits at a 10 percent probability level. Two other tracts, which contain rocks with anomalous amounts of lead and zinc, were delineated as permissive for shale-hosted lead-zinc deposits. The rocks in these tracts are similar to Paleozoic sedimentary rocks in Canada that host such deposits; however, the anomalous values may merely represent elevated background values, as is common in these kinds of rocks.

Most of the past and present gold placer mining in the quadrangle has taken place in four areas (Menzie and others, 1983). A fifth area, the sedimentary basin near the town of Central, was identified that may contain buried placer deposits and possibly sedimentary uranium deposits. Lastly, the quadrangle contains sources of crushed stone and sand and gravel for local use.

Studies and events since publication of the mineral resource assessment in 1983 permit several additions and modifications to that report. First, two diamonds, 0.3 carat and 1.4 carat, were discovered in gravels of Crooked Creek in the Circle mining district. Although no source for the diamonds has been identified (Forbes, 1985), the possibility exists that the quadrangle could contain placer or lode diamond deposits. Second, new grade/tonnage models are available for tin deposits (Menzie and others, 1985), and the model that is most appropriate for the delineated tracts in the Circle quadrangle is the tin greisen model (figs. 7 and 8). This model should supersede the vein/greisen grade/tonnage model in Open-File Report 83-170-B. Third, subsequent sampling confirmed the presence of rare-earth minerals, stibnite, scheelite, and cassiterite in stream concentrates in the eastern part of the Crazy Mountains (R.B. Tripp, oral commun., 1984). Additional field studies recognized small granitic dikes that cut the mafic igneous rocks on the west side of the sampled area (T.E.C. Keith, oral commun., 1984). Therefore an additional area (the eastern Crazy Mountains) is recognized as being permissive for the occurrence of tin deposits, tungsten skarns, and lode gold deposits. Finally, studies in 1983-1984 by the U.S. Bureau of Mines (Burton and others, 1984) and the U.S. Geological Survey in the Lime Peak area (tract I) confirm and further document the geologic characteristics of this area, as reported in Open-File Report 83-170-B, but do not change the resource estimates.

Aeromagnetic and Gravity Maps and Their Interpretation (OFR-83-170-C and 83-170-D)

Aeromagnetic and gravity data and their interpretation are contained in two separate open-file reports of the Circle AMRAP folio. The aeromagnetic survey of the Circle quadrangle was flown and the map compiled in 1973 by Geometrics, Inc. and released by the U.S. Geological Survey in 1974. With the aeromagnetic map in the report (OFR-83-270-C) is an aeromagnetic interpretation map with a geologic base and a smaller reproduction of a spectrally colored aeromagnetic map overlaid with the complete Bouguer gravity anomaly contours. Some of the data upon which the complete Bouguer gravity map (OFR-83-170-D) was compiled were collected prior to the Circle AMRAP project by several different workers, and the remainder were obtained during the AMRAP fieldwork.

The aeromagnetic map of the Circle quadrangle reflects the distribution of magnetic minerals in the upper few kilometers of the crust.

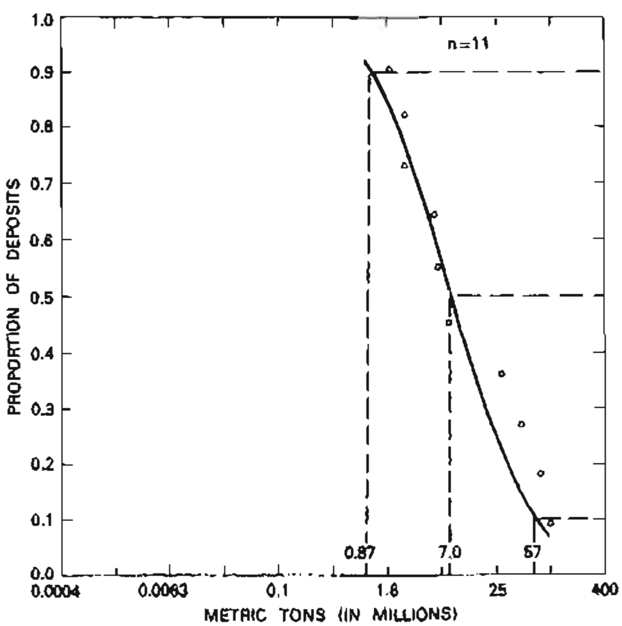

FIGURE 7.--Distribution of tonnage of greisen tin deposits. n, number of data points.

Major discontinuities in the pattern of magnetic anomalies commonly coincide with boundaries between major tectonostratigraphic terranes.

At the local scale, elongate magnetic anomalies indicate that lithologic units have greater continuity along strike than can readily be observed by the geologist in the field. Aeromagnetic interpretations were used to make hypotheses and to plan geologic traverses. Magnetic marker units, traced from aeromagnetic maps and checked in the field, are a useful geologic mapping tool.

The quadrangle can be subdivided into three geophysical terranes on the basis of aeromagnetic and gravity data. The metamorphic terrane south of the Tintina fault zone has low overall gravity and local gravity lows over exposed and inferred granite plutons. These unmetamorphosed, nonmagnetic granites, which commonly occur in the cores of anticlines and are elongate parallel to the strike of foliation, are expressed as magnetic lows. They belong to the ilmenite series of Ishihara (1981) and are probably S-type granite according to the classification of Chappell and White (1974). Magnetic chloritic schist and minor serpentinite, infolded with nonmagnetic quartzite and schist, is associated with east-northeast-trending magnetic highs that approximately parallel the regional strike of the most prominent foliation (foliation D_1, Cushing and Foster, 1982). Too few magnetic rocks of this type were found in outcrop to easily explain the observed magnetic anomalies, therefore, it was hypothesized in the report that the magnetic chloritic schist is an easily eroded unit commonly hidden by a resistent carapace of quartzite.

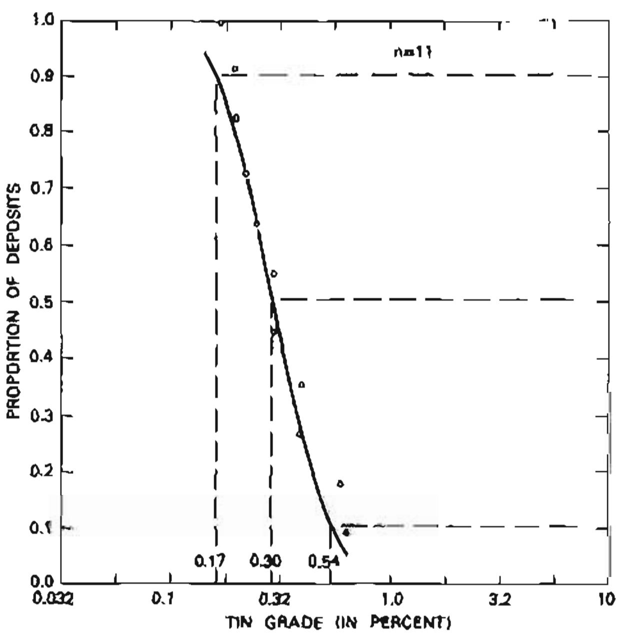

FIGURE 8.—Distribution of tin grade of greisen deposits. n, number of data points.

Furthermore, magnetite may have been destroyed by oxidation due to weathering near the surface.

North of the Tintina fault zone is an oceanic terrane characterized by high gravity. Elongate east-west-trending magnetic highs are postulated to be caused by allochthons of gabbro and peridotite, probably thrust south from the Yukon Flats. Good exposures of these oceanic rocks are found in the Crazy Mountains and along the Yukon River south of Six Mile Bluff near the town of Circle. Layered gabbro and peridotite occur in laccolith-like plutons that exhibit chilled contacts with quartz- and carbonate-rich marine sedimentary rocks and chert. Further north, in the Little Crazy Mountains and Yukon Flats, ovoid and irregular magnetic highs are interpreted to indicate buried volcanic centers. A broad, 30-mgal gravity high centered over the Little Crazy Mountains has no associated broad magnetic high, thus buried, nonmagnetic dunite or gabbro are possible explanations for the gravity anomaly.

The Tintina fault zone is 10 to 13 km wide and marked by several magnetic highs. An intense magnetic high in the fault zone near the western boundary of the Circle quadrangle overlies magnetic granodiorite of the Victoria Mountain pluton. The Victoria Mountain pluton is a magnetic series granitoid according to the classification of Ishihara (1981) and probably is an I-type granitoid according to the classification of Chappell and White (1974). A pronounced contact-metamorphic aureole suggests that it was intruded hot into comparatively cool rocks in the upper crust. A magnetic high near Circle Hot Springs is less intense, but much broader than the Victoria Mountain magnetic high. Magnetic modeling showed that the high could reflect a source with the same magnetic susceptibility as the Victoria Mountain pluton, but buried at least 4 km deeper. The absence of a gravity high indicates that the pluton must be a low density rock such as a granodiorite, not a gabbro or peridotite. A narrow gravity low indicates that the inferred pluton is overlain by a narrow sedimentary basin coincident with Medicine Lake. In the report it was speculated that the pluton has stoped country rock and caused the local subsidence that has diverted many drainages into Medicine Lake.

Several magnetic anomalies have possible implications for mineral exploration. The magnetic map suggests the presence of zonation within or contact aureoles around parts of the Lime Peak pluton. Some geochemical anomalies may be correlated with details of the magnetic anomaly. For example, one magnetic high appears to be correlated with an area of anomalous fluorine, another with one of anomalous lanthanum. A detailed aeromagnetic map might help to delineate mineral zonation within the pluton and surrounding rocks. Broad magnetic lows indicate that felsic hypabyssal rocks northeast of Mount Prindle are underlain by a large, nonmagnetic granitic pluton. Arcuate patterns of subdued magnetic highs and lows near the center of the Circle quadrangle, correlated with zonation in stream-sediment mineral concentrate data, indicate a buried pluton with possible economic importance. The continuity of magnetic lows over known and inferred plutons between the headwaters of the streams of the Circle placer gold mining district and Mount Prindle to the west suggests a common type of origin for gold placers in the western and central parts of the Circle quadrangle. A curious ring-shaped magnetic high in the western part of the Tintina fault zone surrounds a body of felsic tuff associated with a magnetic low. Barite, zinc, and nickel anomalies may be associated with a mineralized caldera, metamorphic aureole, or ring dike--all manifestations of a shallow pluton. Stream sediments anomalous in antimony, zinc, and thorium occur in the oceanic terrane in the northeastern part of the quadrangle. There is no magnetic evidence for a local felsic pluton, the expected source of the anomalies, although hydrothermally altered felsic dikes have been found cutting mafic volcanic rocks of the oceanic terrane.

Interpretation of Landsat Imagery (OFR-83-170-E)

In 1981, Le Compte presented two preliminary maps of numerous lineaments and circular and arcuate features observed on Landsat imagery of the Circle quadrangle. The lineament map was prepared following a method employed by Raines (1978). Later, a remote sensing study (OFR-83-170-E), using computer-enhanced Landsat images (fig. 9) of the Circle quadrangle, was undertaken to identify geomorphic characteristics of the region as well as to determine trends and patterns of concentrations of linear features (Simpson, 1984). The multispectral scanner (MSS) data for Landsat scene 2944-20083 (August 23, 1977) was processed by REMAPP remote sensing array processing procedures (Townsend and Sawatzky, 1976) to prepare enhanced images with optimal contrast for image interpretation. Bands 4, 5, and 7 were processed for black-and-white positive film transparencies and edge-enhanced images (Knepper, 1982), and for a color-infrared composite of blue, green, and red, respectively, at a scale of 1:800,000. All these images were used for geomorphic interpretation and for mapping linear features.

From Landsat imagery, the Circle quadrangle south of the Tintina fault zone can be divided into two geomorphic domains on the basis of differences in surface characteristics. Domain A is a roughly rectangular, northeast-southwest-trending area of relatively low relief and simple, widely spaced drainages, except where igneous rocks are exposed. Domain B, which bounds two sides of domain A, is more intricately dissected and shows abrupt changes in slope and relatively high relief. The northwestern part of geomorphic domain A includes the Beaver terrane, a tectonostratigraphic terrane mapped by Churkin and others (1982). The southeastern boundary of domain A lies entirely within the adjoining Yukon crystalline terrane. Analysis suggests that the southeastern part of domain A may be a subdivision of the Yukon crystalline terrane.

Domain B appears to be divisible into several areas with somewhat different geomorphic characteristics by east-northeast-trending curved lines apparent on Landsat images. The curved lines possibly separate different geomorphic regions along segments of boundaries of subterranes mapped by Churkin and others (1982). On Landsat images, prominent north-south-trending lineaments together with the curved lines form a large-scale regional pattern that is transected by mapped north-northeast-trending high-angle faults (Foster and others, 1983). The lineaments indicate possible lithologic variations or structural boundaries. As used in this report, the term lineament, adapted from O'Leary and others (1976), describes a linear alignment of geomorphic features that forms a regional break in the terrain and is transverse to the structural grain of the region.

A map of linear features was made in order to study trends and patterns of concentrations of linear features, using standard photogeologic methods on a transparent overlay that was transferred from image to image. Linear features were drawn on straight-appearing topographic features, such as stream valleys, slope breaks, and cliffs; for consistency a straight valley was mapped rather than the adjacent parallel straight ridge. Short aligned features were not connected by long interpretative lines.

The final digitized map was analyzed by a statistical strike-frequency procedure to determine important azimuthal trends in the linear features data (Sawatzky and Raines, 1981). The number, or frequency, of linear features trending in each of 180 1-degree classes was determined, and the frequencies were compared to the mean frequency of the 180 classes. The farther the frequency deviates from the mean, the higher its significance value. The strike-frequency histogram was examined for azimuthal intervals with frequencies above the 90 percent significance value. Generally, northeast-southwest-trending features predominate in the Circle quadrangle, although north-south, east-west, and two northwest-southeast intervals also have frequencies well above the mean.

Maps of spatial concentrations of linear features show that northeast-southwest-trending linear features predominate throughout the quadrangle, and that most northwest-southeast-trending linear features are found south of the Tintina fault zone. A major trend interval of N. 64°-72° E. corresponds to the average strike of foliations in metamorphic rocks (measured on the geologic map; Foster and others, 1983) and to the average strike of magnetic anomalies (measured on

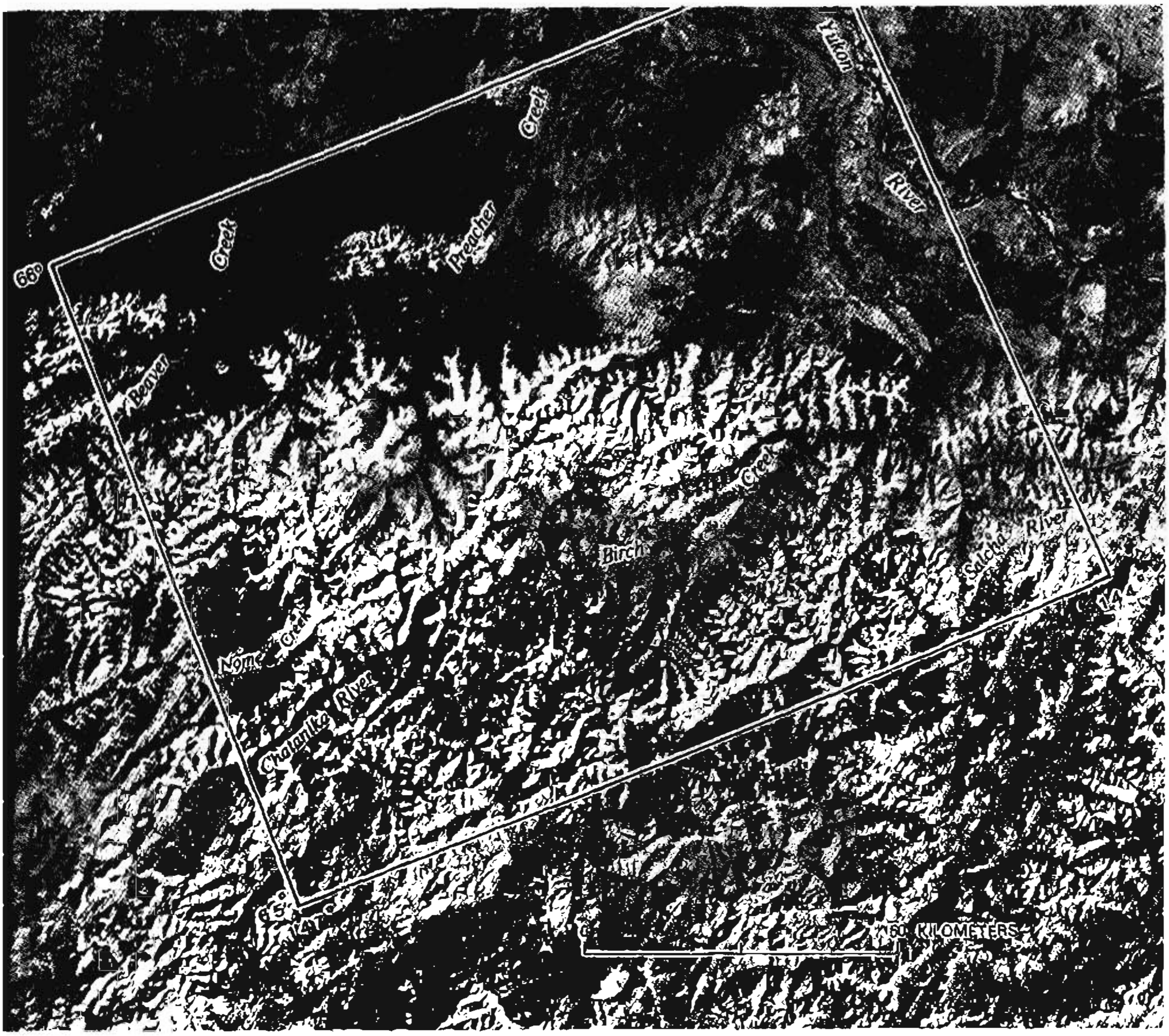

FIGURE 9.--Computer-enhanced Landsat image of band 7 for scene 2944-20083 showing Circle quadrangle and names of some streams. Processed in the Geophysics Image Processing Laboratory, U.S. Geological Survey, Denver, Colorado.

the aeromagnetic map; Cady and Weber, 1983) reflecting compositional variations; this correspondence suggests that most linear features in the southern part of the quadrangle probably are related to lithologic variations brought about by folding and foliation of metamorphic rocks. A second important trend interval, N. 14°-35° E., may be related to thrusting south of the Tintina fault zone, as high concentrations of linear features within this interval are found in areas of mapped thrust faults. Linear features trending N. 14°-35° E. also occur in moderate to high concentrations near the plutons of Victoria Mountain, Lime Peak (Rocky Mountain), Circle Hot Springs, and the pluton between Lime Peak and Mount Prindle. The contour map of all linear features shows low concentrations in most areas of igneous intrusions. High concentrations of linear features do not correspond to areas of known mineralization in any consistent or significant way that would allow concentration patterns to be easily used as an aid in locating areas of mineralization.

The conclusions of this remote sensing study are based on interpretation of Landsat images and information from published reports and have not been field checked; however, they are consistent with complementary studies of the Circle AMRAP project. The results of this study indicate that there are several possibly important areas where further detailed studies are warranted to check the relationship between geology, mineral occurrences, and interpretation of Landsat images.

Geochemistry and Selected Mineralogy (OFR-83-170-F, G, H)

Geochemical and mineralogical studies of stream sediment and heavy-mineral concentrates were made in the Circle quadrangle to identify areas of anomalous concentrations of metallic elements. The data delineate areas of known mineral occurrences and other areas that may contain undiscovered mineral resources.

During the summers of 1979 and 1980, sediment samples were collected at 874 sites in streams whose drainage areas range from approximately 4 to 13 km^2. The minus-80-mesh fraction of these samples was analyzed for 31 elements by a semiquantitative emission spectrographic method (Grimes and Marranzino, 1968), for gold by atomic absorption (Ward and others, 1969), and for uranium by a fluorometric method (Centanni and others, 1956). Heavy-mineral concentrates of stream sediment were taken from 860 of the stream sites. The nonmagnetic fraction of these samples was also analyzed for 31 elements by the spectrographic method and scanned under the binocular microscope to identify ore-related minerals. The spectrographic and geochemical results are available in an open-file report (O'Leary and others, 1986).

In the Circle quadrangle, heavy-mineral concentrates have proved to be an excellent reconnaissance tool. Some areas of known mineral occurrences are well defined by the distribution of anomalous amounts of metals in the heavy-mineral concentrates of stream sediment. Gold, arsenic, antimony, lead, tin, and tungsten anomalies were found in nonmagnetic heavy-mineral concentrates collected from streams that drain Cretaceous or Tertiary granite and the Precambrian or Paleozoic quartzitic schist sequence in the Circle mining district. Spectrographic analysis of the heavy-mineral fraction of bulk samples from zones of mineralized quartzite and schist indicates anomalous amounts of gold, copper, antimony, lead, tungsten, bismuth, and zinc. Galena from pods and stringers in the mineralized zone contains anomalous amounts of tin, bismuth, antimony, silver, cadmium, and copper (Tripp and others, 1982). At least some of the anomalous tin found in heavy-mineral concentrates is derived from small altered zones within the Circle Hot Springs pluton and from altered felsic dikes that cut both the granite and country rock.

Anomalous values of tin, tungsten, thorium, uranium, lanthanum, and beryllium form clusters around granite plutons near Lime Peak, Mount Prindle, between Lime Peak and Mount Prindle, and 25 km east of Mount Prindle. In the Lime Peak area, sources of the anomalous tin are areas of altered sheared granite.

Anomalous amounts of barium, silver, and zinc are found in stream sediment and in heavy-mineral concentrates from the south-central part of the Circle quadrangle. The metals are apparently derived from highly carbonaceous Paleozoic quartzite, meta-argillite, phyllite, calcareous phyllite, and marble that could contain shale-hosted lead-zinc deposits. Several gold and silver anomalies are also found within this area.

The distribution of specific elements and minerals observed in the heavy-mineral concentrates and in stream sediment indicates potential for lode occurrences of the noble and base metals as well as tin, tungsten, beryllium, uranium, and thorium.

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