Studies of Mineralized Intrusive Complexes in North-Central Montana

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1301

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Mineralized Breccias in Intrusive Complexes of
Late Cretaceous and Paleocene age, North-Central Montana
By DAVID A. LINDSEY *and* FREDERICK S. FISHER

Relation Between Igneous Intrusion and Gold
Mineralization in the North Moccasin Mountains,
Fergus County, Montana
By DAVID A. LINDSEY *and* CHARLES W. NAESER

A Gold-Mineralized Breccia Zone at Kendall,
North Moccasin Mountains, Fergus County, Montana
By DAVID A. LINDSEY

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Geology, nature of hydrothermal alteration, and genesis of mineralized zones in and near intrusive igneous complexes of Late Cretaceous-Paleocene age in north-central Montana

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ABSTRACT

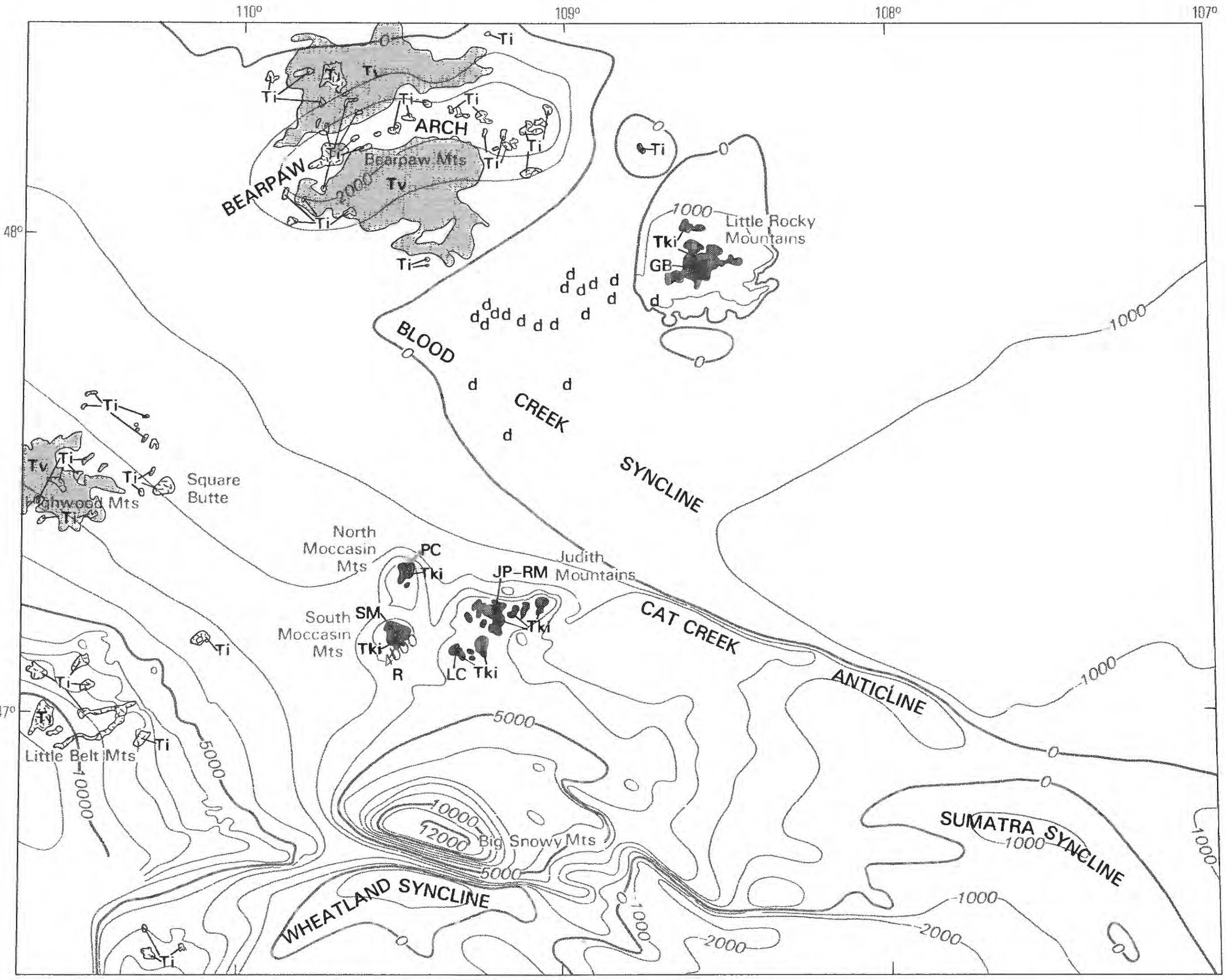
Mineralized breccias are found in most of the intrusive porphyry complexes of Late Cretaceous-Paleocene age in north-central Montana. Breccias have been mapped and studied in the central part of the South Moccasin Mountains and at the Republic claim south of the mountains, at the head of Plum Creek in the North Moccasin Mountains, at Limekiln Canyon and the Judith Peak-Red Mountain area in the Judith Mountains, and at Gold Bug Butte in the Little Rocky Mountains. Porphyry host rocks, which range mostly from syenite to quartz monzonite in composition, were emplaced as laccoliths, stocks, sills, dikes, plugs, and complex combinations of these forms at shallow depths (1,100–2,700 meters). The breccias probably were formed by hydraulic ramming of residual fluids and magma during cooling of the porphyry intrusions. Emplacement of magma continued after breccia formation in the Judith Peak-Red Mountain area. Mineralization preceded formation of breccias in the South Moccasin Mountains, but accompanied and followed formation of most of the other breccias.

The breccias intrude porphyry in all places studied except one; they generally form pipe-shaped bodies, although irregular masses and dikes are present also. Most breccias are composed of large to small fragments of syenite and related porphyry in a fine matrix of particles derived from the same rocks. Locally, Precambrian and Paleozoic rocks make up most of the fragments, and commonly are present in minor amounts where porphyry fragments predominate. Contacts between some of the breccias and the host porphyry generally are well defined within a few meters, but other contacts are gradational through fragment-rich breccia and crackle zones. Dikes of igneous rock cut intrusive breccia in the Judith Peak-Red Mountain area, and reaction rims surround breccia fragments at one locality in the Little Rocky Mountains; these features and evidence of mineralization indicate that the breccias were emplaced during the waning stages of intrusive activity.

Alteration and mineralization took place both before and after emplacement of the breccias, indicating a close tie between the two processes. Most of the breccias show evidence of incomplete hydrothermal alteration, ranging from minor kaolinite in breccias of the South Moccasin Mountains and at Limekiln Canyon in the Judith Mountains, to kaolinite and quartz-illite-sericite at Plum Creek in the North Moccasin Mountains, to quartz-sericite in the Gold Bug Butte area of the Little Rocky Mountains, and to quartz-potassium feldspar in the breccias of the Judith Peak-Red Mountain area in the Judith Mountains. Quartz-sericite and quartz-potassium feldspar altered breccias contain abundant limonite, jarosite, and, locally, pyrite. Spectrographic analyses of breccias from each area show no major chemical changes in the formation of kaolinitic breccias; analyses show that calcium, magnesium, sodium, and manganese have been leached and that iron and titanium have been redistributed during alteration to quartz-sericite and quartz-potassium feldspar breccias. Anomalous amounts of gold, silver, and vanadium are most widespread in quartz-sericite altered breccia and to a lesser extent in quartz-potassium feldspar breccia; anomalous amounts of copper, lead, and molybdenum are found in both.

INTRODUCTION

Intrusive breccias were emplaced during two periods of igneous activity in north-central Montana (fig. 1). The earliest period of igneous activity, during Late Cretaceous and Paleocene time, consisted of emplacement of intrusive porphyry complexes, including breccias, in the Moccasin, Judith, and Little Rocky Mountains about 69–60 m.y. (million years) ago (Marvin and others, 1980). The second period of igneous activity, during Eocene time, consisted of both volcanism and emplacement of plutons in the Bearpaw and Highwood Mountains 54–50 m.y. ago (Marvin and others, 1980) and emplacement of plutons 56–41 m.y. ago in the Little Belt Mountains (Marvin and others, 1973). Eocene igneous activity was accompanied by emplacement of breccias in the Little Belt Mountains, and also by eruption of the Missouri Breaks diatremes 52–47 m.y. ago (Hearn, 1979). In addition to differences in age and mode of emplacement, the Eocene igneous rocks of north-central Montana contain many examples of mafic alkalic and feldspathoidal rocks (Weed and Pirsson, 1896; Hurlbut and Griggs, 1939; Larsen, 1941; Witkind, 1973). In contrast, the intrusive complexes of Late Cretaceous and Paleocene age contain only minor volumes of mafic alkalic and feldspathoidal rocks—these are the tinguaite dikes of the Judith and Little Rocky Mountains (Weed and Pirsson, 1898; Brockunier, 1936; Wallace, 1953). The intrusive breccias associated with the Upper Cretaceous-Paleocene porphyry complexes are the subject of this report.



0 10 20 30 40 KILOMETERS

0 10 20 MILES

EXPLANATION

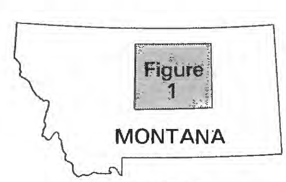
Ti — Intrusive rocks (Eocene)

Tv — Volcanic rocks (Eocene)
d, diatreme occurrence

Intrusive rocks (Paleocene and Upper Cretaceous)

x Locality of intrusive breccia
SM, South Moccasin Mountains;
R, Republic claim; PC, Plum Creek;
LC, Limekiln Canyon;
JP-RM, Judith Peak-Red Mountain;
GB, Gold Bug Butte

—4000— Structure contours in feet to base of Colorado Shale (restored); contour interval 1000 ft (from Dobbin and Erdmann, 1955)



Index map

FIGURE 1.—Map showing geologic setting of mineralized intrusive breccias in north-central Montana and principal geologic structures.

The large complexes of Upper Cretaceous-Paleocene intrusive porphyry (fig. 1) are mostly silica-saturated rocks of syenite, monzonite, and quartz monzonite composition and were emplaced at shallow depths (1,100–2,700 m). They take the form of laccoliths, stocks, sills, dikes, plugs, and complex combinations thereof (Weed and Pirsson, 1898, p. 572–587; Goddard, 1950; Knechtel, 1959; Miller, 1959; Lindsey, 1982). Some intrusive centers, notably that at Judith Peak in the Judith Mountains (Wallace, 1956), are composed of a varied assemblage of rocks, including syenite, quartz monzonite, alkali granite, and tinguaite, and probably resulted from multiple episodes of differentiation and emplacement. Intrusive activity was accompanied by formation of breccias and by mineralization of the porphyry complexes and their country rocks. Mineralizing fluids pervaded the intrusive breccias, circulated along fissures in porphyry (Weed and Pirsson, 1898, p. 592–593; Dyson, 1939), invaded country rocks along contacts with porphyry (Weed and Pirsson, 1898, p. 594; Forrest, 1971), and invaded fault breccias formed during intrusion of porphyry complexes (Lindsey, 1982). Mineralization of a fault breccia is discussed in chapter C of this paper.

Our study was made to provide a comprehensive description and comparison of the breccias and to interpret their origin and significance with respect to mineral resources. We have relied on the previously established geologic framework of north-central Montana, but have provided additional details on the geology of the breccias and new data on their petrographic and chemical composition. Published information on the breccias is scarce, although most of them have been prospected for gold and other metals. Those in the Moccasin Mountains were mapped and described recently (Lindsey, 1982); the intrusive breccias of the Judith Mountains had been mapped (Goddard and Wallace's map in Wallace, 1953) but not described; and those in the Little Rocky Mountains were recognized and described briefly by Weed and Pirsson (1896, p. 411–412), but have not been mentioned since that time. Geologic maps showing the breccias in the Moccasin Mountains were taken from the map of Lindsey (1982); a detailed map of Limekiln Canyon and vicinity in the Judith Mountains was compiled from the mapping of E. N. Goddard and S. R. Wallace; unpublished mapping of the Judith Peak-Red Mountain area of the Judith Mountains, by Goddard and Wallace, was adapted for the present report; and a map showing breccias in the Little Rocky Mountains was prepared by F. S. Fisher from his mapping and the geologic map of Knechtel (1959). All the breccias were sampled for petrographic study and chemical analyses. Thin-section and X-ray diffraction studies were conducted to characterize the degree and type of alteration of the breccias, and chemical analyses by spectrographic methods and gold analyses by fire assay and atomic absorption were made to identify anomalous concentrations of metals.

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C. A. Brannon, C. N. Culver, G. D. May, and M. R. Pawlowski assisted in fieldwork; Ezekiel Rivera prepared X-ray diffractograms; R. E. Phillips studied thin sections and made mineral identifications; and S. J. Ashe prepared photographs and compiled data; all are employees of the U.S. Geological Survey. Chemical analyses were done in laboratories of the U.S. Geological Survey in Denver, Colo.; six-step semiquantitative spectrographic analyses were done by L. A. Bradley, N. M. Conklin, and J. C. Hamilton; fire assay-atomic absorption analyses for gold were made by J. G. Crock, A. W. Haubert, and Joseph Haffty.

SOUTH MOCCASIN MOUNTAINS

Breccia pipes are found in syenite porphyry and quartz monzonite porphyry near triangulation station South in the central part of the Moccasin Mountains (fig. 2) (Lindsey, 1982). Both syenite porphyry and quartz monzonite porphyry of the South Moccasin Mountains have been dated radiometrically at 64–65 m.y. (Marvin and others, 1980). The breccias are poorly exposed in the center of the mountains except where cut by the access road leading to radio facilities at triangulation station South; where exposed, their contacts with syenite porphyry can be defined within 1–4 m (meters). Breccia in quartz monzonite porphyry is poorly exposed and little studied; in part, it appears to be "crackle" breccia, containing many fissures and unrotated fragments of the host rock. Additional occurrences of breccia may have gone undetected in poorly exposed areas of the South Moccasin Mountains. A bleached zone in syenite porphyry extends north from the breccias near triangulation station South.

A breccia pipe also occurs in the Lower Cretaceous Skull Creek Member of the Colorado Shale at the Republic claim south of the mountains (fig. 2). The Republic breccia crops out along a normal fault that probably formed during intrusion of syenite porphyry and accompanying uplift of the Hanover dome. Contacts of the breccia at the Republic claim can be located within a few meters; the host shale shows no obvious effects of alteration.

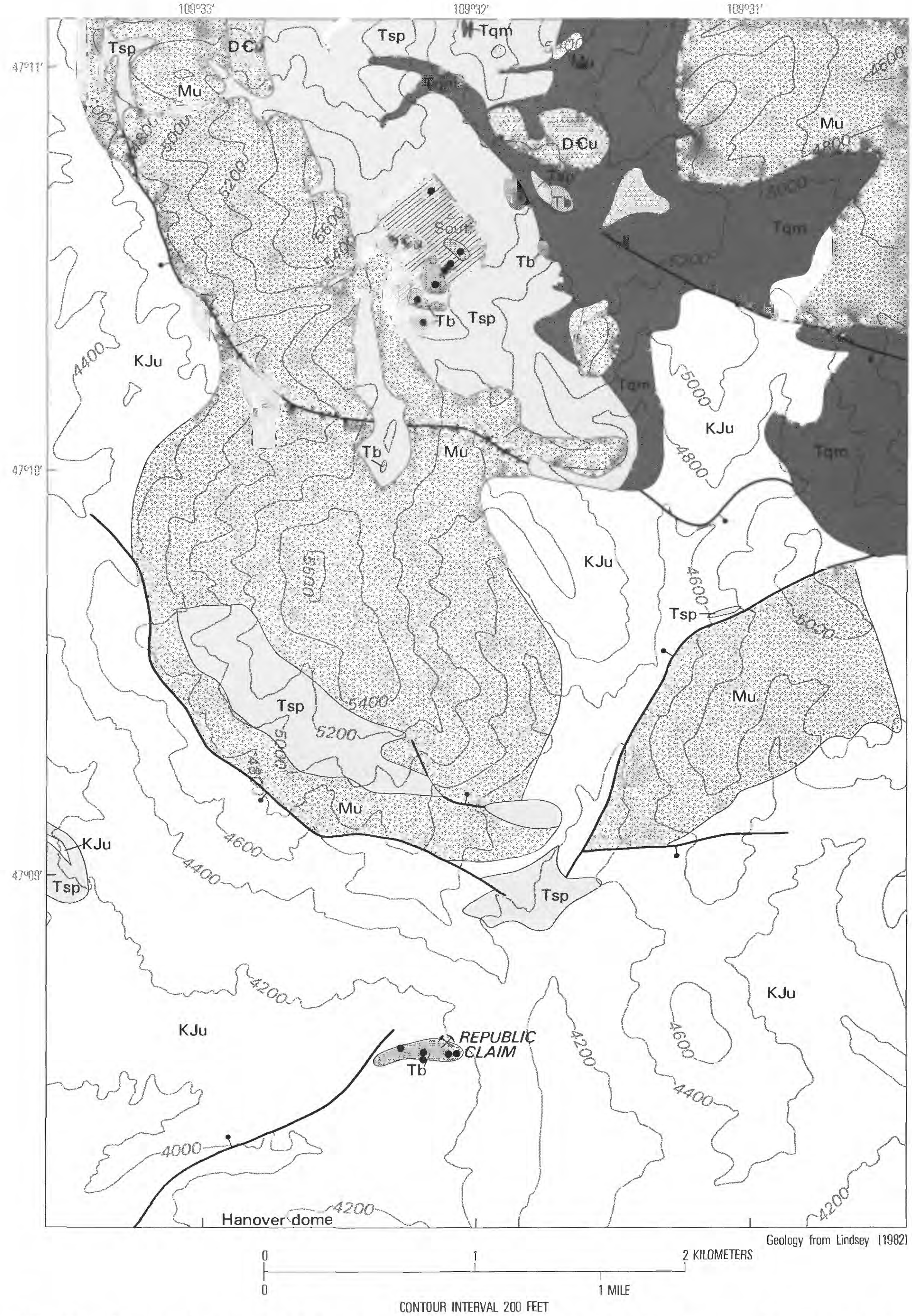


FIGURE 2 (above and facing page).—Geologic map showing intrusive breccias in the South Moccasin Mountains, Mont.

EXPLANATION

- Tb — Intrusive breccia (Paleocene?)
- Tqmp — Quartz monzonite porphyry (Paleocene)
- Tsp — Syenite porphyry (Paleocene)
- KJu — Undivided sedimentary rocks (Cretaceous and Jurassic)—Cretaceous Colorado Shale and Kootenai Formation, Jurassic Morrison Formation and Ellis Group
- Mu — Undivided sedimentary rocks (Mississippian) Mississippian Big Snowy and Madison Groups
- D€u — Undivided sedimentary rocks (Devonian and Cambrian)—Devonian Jefferson Formation and Cambrian Pilgrim Limestone
- Bleached area in syenite porphyry
- Contact
- Fault, ball and bar on downthrown side
- Sample locality
- Open pit

The breccias near triangulation station South are composed mainly of angular fragments and crystals derived from the host syenite porphyry and are set in a finely pulverized matrix shown by microscopic study to be composed of the same rock (fig. 3*A*). A few fragments of sandstone, quartzite, metamorphosed carbonate rock, and mineralized carbonate rock containing galena and pyrite, were found in some of the breccias. Minor amounts of kaolinite, identified in thin section and by X-ray diffraction, partly replace feldspar crystals and matrix in the breccias and in the adjacent zone of bleached syenite porphyry. Anomalous zinc ((500 ppm (parts per million)), probably from sphalerite in mineralized fragments, was detected in some of the breccias, but in general the breccias are not highly mineralized.

Breccia at the Republic claim contains a diverse suite of fragments (fig. 3*B*), including syenite porphyry, quartz, carbonate rocks, shale, sandstone, coal from the Lower Cretaceous Kootenai Formation, schist and gneiss of Precambrian age, and fragments containing galena, sphalerite, chalcopyrite, and pyrite that were mineralized before brecciation. Fragments are as much as 0.3 m across and are subround to round. The matrix of some of the breccia has a sandy appearance, but under the microscope is seen to be composed of small broken crystals and fragments derived from syenite porphyry. Elsewhere in the breccia mass, the matrix is composed of comminuted black shale of the host Skull Creek Member of the Colorado Shale. Little alteration of the breccia is visible, but small (0.02–0.1 mm (millimeters)) euhedral pyrite is abundant locally in the matrix. Highly anomalous quantities of copper, gold, lead, molybdenum, silver, and zinc were detected by chemical analysis, mainly in mineralized fragments in the breccia.

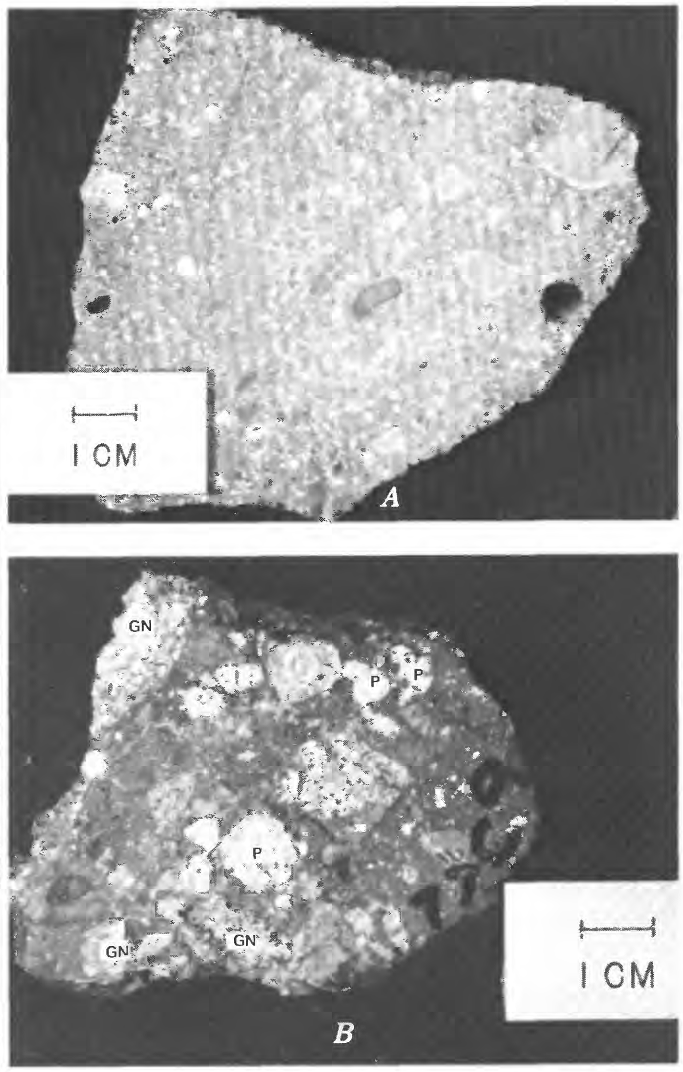


FIGURE 3.—Photographs of breccias of the South Moccasin Mountains, Mont. *A*, Breccia from south of triangulation station South, showing small fragments of mostly syenite porphyry in finely ground matrix of same material. Light rims around some syenite porphyry fragments are due to weak hydrothermal alteration or weathering. *B*, Breccia from the Republic claim, showing subround to round fragments of syenite porphyry (P) and Precambrian gneiss (GN) in matrix of shale and syenite fragments.

PLUM CREEK, NORTH MOCCASIN MOUNTAINS

The large (0.3 km^2 (square kilometers)) breccia pipe at the head of Plum Creek, in the North Moccasin Mountains, intrudes a laccolith of syenite porphyry dated radiometrically at 66 m.y. (fig. 4) (Lindsey, 1982; Marvin and others, 1980). Contacts between the breccia

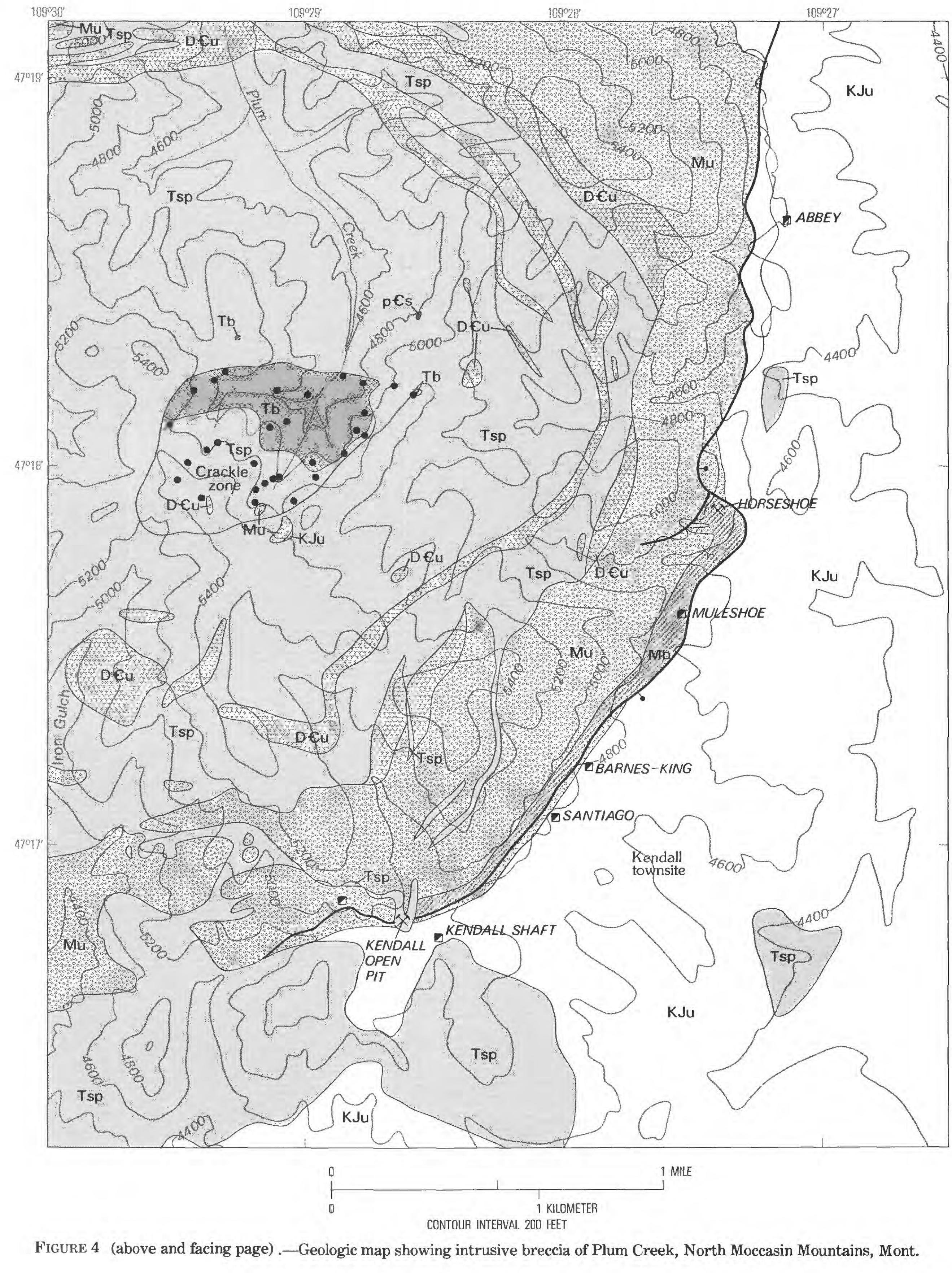


FIGURE 4 (above and facing page).—Geologic map showing intrusive breccia of Plum Creek, North Moccasin Mountains, Mont.

EXPLANATION

Tb	Intrusive breccia (Paleocene?)
Tsp	Syenite porphyry (Paleocene)
KJu	Undivided sedimentary rocks (Cretaceous and Jurassic)—Cretaceous Kootenai Formation, Jurassic Morrison Formation and Ellis Group
Mb	Brecciated and silicified limestone in Madison Group (Mississippian)
Mu	Undivided sedimentary rocks (Mississippian) Mississippian Kibbey Formation and Madison Group
D€u	Undivided sedimentary rocks (Devonian and Cambrian)—Devonian Jefferson Formation, Cambrian Pilgrim Limestone, Cambrian unassigned strata, and Cambrian Flathead Sandstone
p€s	Schist (Precambrian)

Contact

Fault, ball and bar on downthrown side

Sample locality

Shaft

Inclined shaft

Open pit

Adit

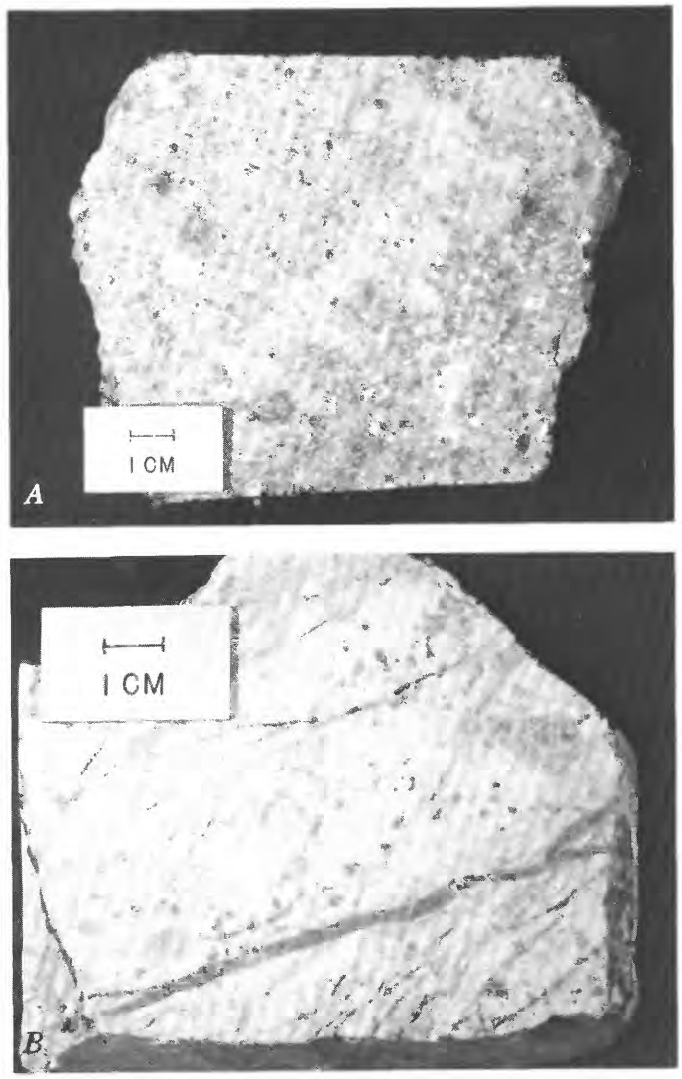


FIGURE 5.—Photographs of breccia of Plum Creek, North Moccasin Mountains, Mont.: *A*, Breccia composed mostly of small fragments of syenite porphyry in finely ground matrix of same material; *B*, crackle breccia in syenite porphyry south of breccia pipe, showing abundant quartz veinlets.

and host porphyry can be located within a few meters where exposures permit; along the southern contact, a large (0.3 km^2) zone of crackle breccia in syenite porphyry adjoins the pipe. Contacts between the crackle zone and host syenite porphyry are gradational over a few tens of meters. Two small ($\leq$20 m^2 (square meters)) breccia pipes were found north and northeast of the main pipe; other small breccia pipes may be present. Three large xenoliths of Paleozoic and Mesozoic rocks crop out within and near the southern boundary of the crackle zone.

The breccia is composed mainly of angular fragments of syenite, a few millimeters to centimeters across, a few fragments of Precambrian schist and Paleozoic sandstones, carbonate rocks and shale, and many broken crystals; all these are set in a fine-grained matrix of mostly altered particles derived from syenite porphyry (fig. 5*A*). Limonite, of probable supergene origin from oxidation of pyrite, and sericite or illite form reaction rims around many rock fragments and replace mafic minerals in rock fragments and in breccia matrix. Small amounts of kaolinite, illite, and sericite are widespread. (Sericite was distinguished from illite by its relatively sharp X-ray diffraction peak at 10Å (angstrom) and by its well-crystallized form in thin section.) Pyrite and limonite pseudomorphs after pyrite are disseminated in fragments and in the matrix of some of the breccia. Minerals that are the products of alteration appear to have formed both before and after transport of breccia fragments.

The crackle zone is composed of bleached, iron-stained syenite porphyry that is traversed by many closely spaced fractures as much as 0.5 cm (centimeters) wide (fig. 5*B*). Both open and quartz-filled fractures are common. Fresh specimens reveal sparse to abundant disseminated pyrite. Thin-section and X-ray diffraction studies reveal small amounts of kaolinite and locally abundant illite and sericite, mostly replacing ferromagnesian and feldspar phenocrysts. In contrast to the breccia and crackle zone, much of the nearby host porphyry shows only the effects of propylitic alteration.

Alteration and mineralization were more intense in part of the breccia pipe and adjoining crackle zone than in surrounding rocks, as shown by the distribution of sericite (fig. 6*A*) and anomalous copper ($\leq$150 ppm), gold ($\leq$4.11 ppm), lead ($\leq$1,000 ppm), molybdenum

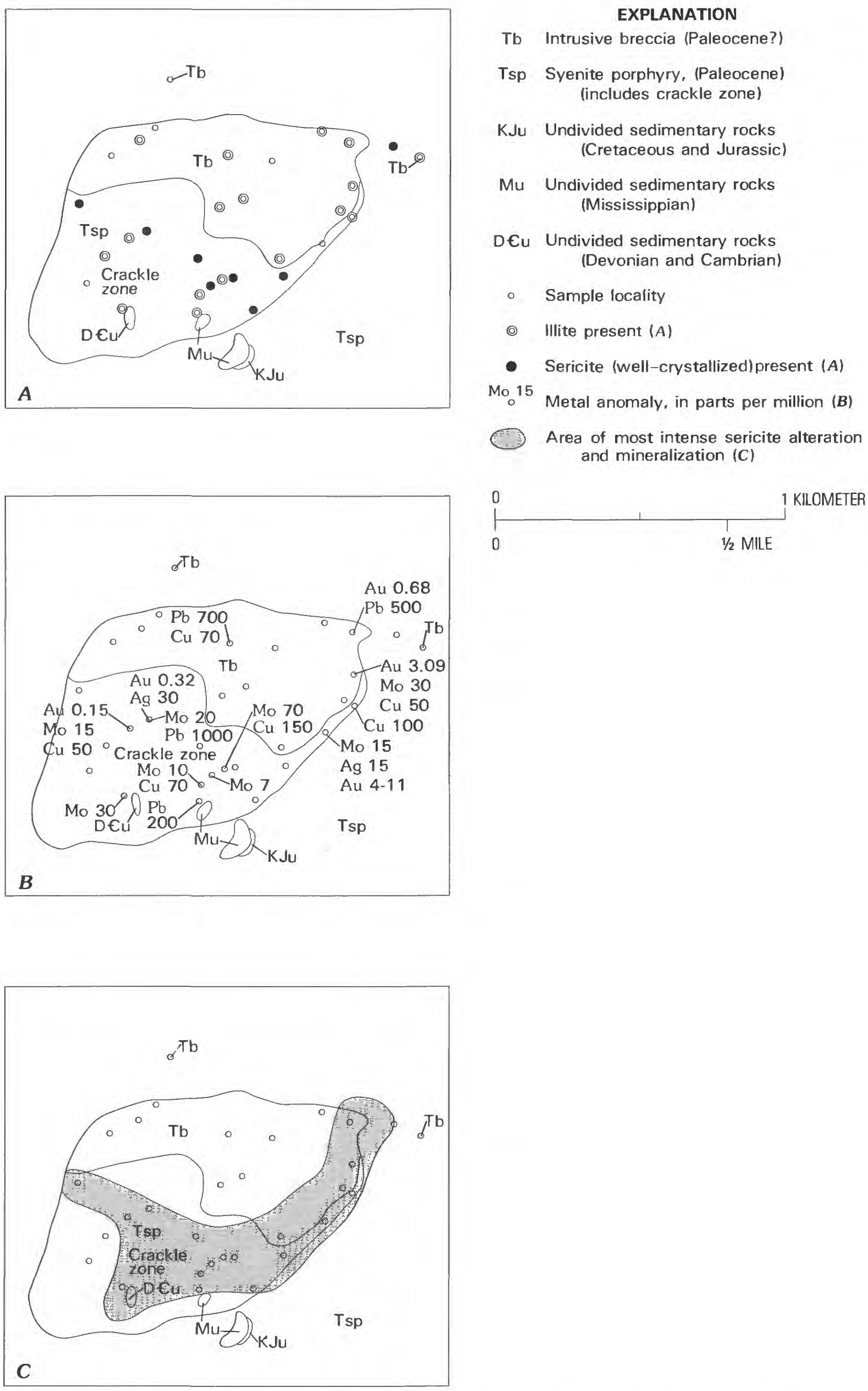


FIGURE 6.—Sketch maps showing alteration patterns and geochemical anomalies in the breccia of Plum Creek and adjacent syenite porphyry, North Moccasin Mountains, Mont.: *A*, Distribution of illite and sericite; *B*, metal anomalies; and *C*, area of most intense alteration and mineralization.

(≤70 ppm), and silver (≤30 ppm), (fig. 6*B*). The area of most intense alteration coincides approximately with that of anomalous metal values (fig. 6*C*). Most of the rock sampled has been oxidized, with pyrite visible in only a few samples, so that many of the metal values may have been reduced from their original concentrations. Downstream from the breccia, fine particles of gold were recovered by panning sediment in Plum Creek, and placer gold has been mined both from Plum Creek and from Iron Gulch, which also drains part of the crackle zone. A gold-mineralized zone in fault-brecciated limestone 2 km southeast of the mineralized breccia pipe is described in chapter C of this paper.

LIMEKILN CANYON, JUDITH MOUNTAINS

Breccia pipes occur in a laccolith of quartz monzonite porphyry of probable Late Cretaceous and Paleocene age in the upper part of Limekiln Canyon, located in the southwestern part of the Judith Mountains (fig. 7) (Goddard and Wallace in Wallace, 1953). Contacts with the host porphyry can be located within a few meters, but outcrops are poor. The breccia crops out mainly over one crescent-shaped area of 0.1 km^2; smaller pipes crop out a few hundred meters south, 1 km southwest, and 1 km east-southeast of the main pipe. No sizable zones of crackle breccia or altered rock more than a few meters beyond the margin of the pipes have been detected, but such zones may have escaped detection owing to generally poor exposures.

The breccia consists mostly of angular fragments of quartz monzonite porphyry as much as 0.5 m across in a matrix of broken crystals and fine particles of the host quartz monzonite porphyry; fragments of Precambrian schist and Paleozoic rocks are abundant locally. Thin-section and X-ray diffraction studies reveal that most of the breccia has been partly altered to kaolinite, minor illite, and around the northeastern side of the main pipe, to sericite (fig. 7). Much of the kaolinite appears to be restricted to the matrix, and probably postdates emplacement of the breccia. At a few places, illite and sericite replace fragments of porphyry, feldspar phenocrysts, and ferromagnesian phenocrysts as well as matrix. Secondary quartz was noted at only a few places. Limonite is common, but it appears to be derived from partial alteration of ferromagnesian minerals and magnetite instead of pyrite; iron-oxide pseudomorphs after pyrite were observed at one locality in the northeast part of the main pipe, and jarosite was noted at only one locality. In contrast to the kaolinitic alteration of the breccia, the host porphyry is propylitically altered; porphyry about 0.3 km east of the main pipe containsonly chlorite, calcite, and iron oxide replacing ferromagnesian minerals and matrix. Anomalous concentrations of metals were found in only one sample; no samples were taken from the two small pipes 1 km east-southeast of the main pipe.

JUDITH PEAK-RED MOUNTAIN AREA, JUDITH MOUNTAINS

The Judith Peak-Red Mountain area, mapped by E. N. Goddard and S. R. Wallace (Wallace, 1953), is a complex intrusive center (fig. 8) composed of quartz monzonite, syenite, and rhyolite porphyries, all of which are intruded by coarse-grained alkali granite on Judith Peak, by dikes of fine- and coarse-grained granite and granite porphyry, and by dikes of green and gray tinguaite (called trachyte by Hall, 1976) and tinguaite porphyry. Detailed descriptions of some of the intrusive rocks are given by Wallace (1956). The porphyry complex of Red Mountain and vicinity probably was emplaced about 65–67 m.y. ago, although many discordant radiometric dates make this estimate tentative (Marvin and others, 1980). The coarse-grained alkali granite of Judith Peak probably was emplaced about 62 m.y. ago (Marvin and others, 1980).

Breccia pipes intrude the complex of quartz monzonite, syenite, rhyolite, and related porphyries on Red Mountain, at the head of Lincoln Gulch, and in the upper part of Collar Gulch (fig. 8). Granite breccia, composed of fine- and coarse-grained alkali granite, intrudes two phases of alkali granite porphyry on Judith Peak; this breccia was not studied by us. The breccias of Red Mountain and nearby altered porphyries are intruded by dikes of alkali granite and tinguaite; the granite dikes probably emanated from the same magma as the alkali granite of Judith Peak. Inasmuch as the breccias contain fragments of granite as well as numerous intact dikes of this rock, it follows that formation of breccia was more or less contemporaneous with emplacement of the alkali granite of Judith Peak about 62 m.y. ago.

Contacts between the breccias and their host porphyries range from sharp to gradational. The crescent-shaped mass of breccia on the west flank of Red Mountain has generally well-defined contacts. At the north end of the breccia, a dike of granite porphyry crosses a sharp contact between breccia and porphyry (fig. 8); the dike contains pyrite but is not as highly altered as its wall rocks. The contacts of other breccias farther south are located with difficulty because of poor exposure and pervasive alteration of both breccia and host porphyry. Contacts of the breccia mass in Collar Gulch are generalized; unpublished mapping by E. N. Goddard and S. R. Wallace shows more than one interpretation of the outline of this breccia. The breccia at the

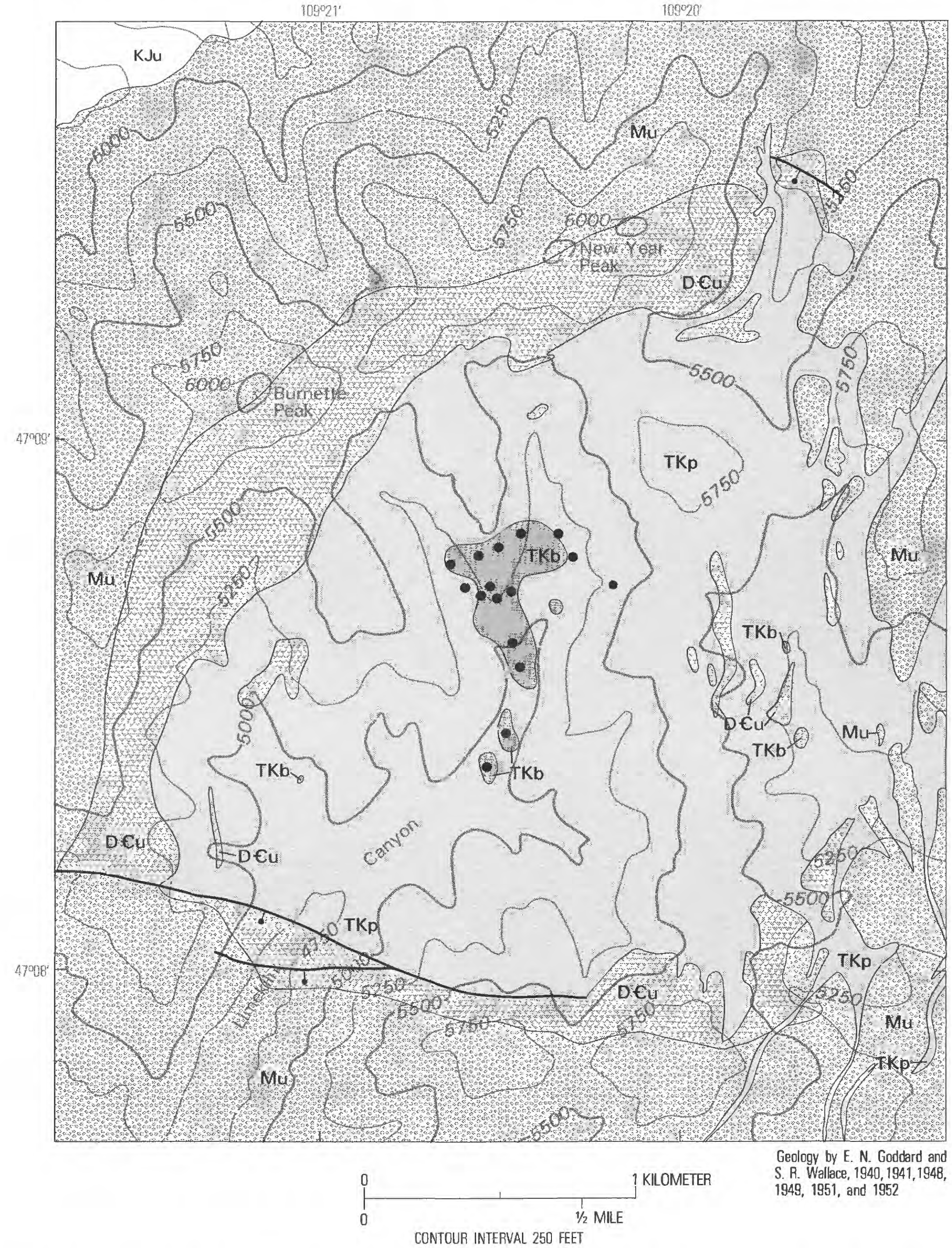


FIGURE 7 (above and facing page).—Geologic map showing intrusive breccia of Limekiln Canyon, Judith Mountains, Mont.

head of Lincoln Gulch is poorly exposed, and the relationship of the rhyolite porphyry there with other rocks is not understood.

The breccias that intrude the porphyry complex of the Judith Peak-Red Mountain area are composed mostly of angular fragments and broken crystals of the host porphyry; fragments range in size from a few centimeters to a few millimeters and are set in a finely comminuted, altered matrix of the same material. Large angular fragments of porphyry that do not appear to have been transported far are found in the breccia at Collar Gulch. More than one type of porphyry

EXPLANATION

- TKb — Intrusive breccia (Paleocene or Upper Cretaceous)
- TKp — Quartz monzonite porphyry (Paleocene or Upper Cretaceous)
- KJu — Undivided sedimentary rocks (Cretaceous and Jurassic)—Cretaceous Kootenai Formation, Jurassic Morrison Formation and Ellis group
- Mu — Undivided sedimentary rocks (Mississippian) Mississippian Big Snowy and Madison Groups
- DЄu — Undivided sedimentary rocks (Devonian and Cambrian)—Devonian Jefferson Formation, Cambrian Pilgrim Limestone, unassigned Cambrian strata, and Cambrian Flathead Sandstone
- Contact
- Fault, ball and bar on downthrown side
- Sample locality

is seen commonly in the breccia, and fragments of sandstone and other sedimentary rocks from country rocks adjacent to the porphyry complex are seen rarely. Fragments of granite porphyry and green and gray tinguaite porphyry were noted locally in the breccias of Red Mountain and Collar Gulch.

A large zone of post-breccia silicic and pyritic alteration, as mapped by E. N. Goddard and S. R. Wallace (fig. 8), pervades the porphyry complex and its associated breccias. Pyrite is present nearly everywhere where fresh rock can be found; well-crystallized jarosite and limonite of supergene origin both are widespread and attest to the former abundance of pyrite. Thin-section and X-ray diffraction studies of the altered rocks show that they contain abundant fine-grained potassium feldspar in the matrix, minor quartz in the matrix and as overgrowths on quartz crystals, and, locally, well-crystallized sericite in matrix and replacing breccia fragments. Calcite, quartz, fluorite, galena, and barite occur in sparse veins that cut altered rock (Hall, 1976). Chemical analyses show anomalous copper (≤700 ppm), gold (≤0.93 ppm), lead (≤3,000 ppm), and molybdenum (≤300 ppm). Chemical precipitates of limonitic iron are found along Collar Gulch and Armell Creek, both of which drain the Red Mountain area. An analysis of limonite precipitate from Collar Gulch revealed 1,500 ppm lead but no other anomalous concentrations of metals. Evidence of extensive late supergene alteration of the altered zone at Judith Peak-Red Mountain suggests that the metal values now found in rocks of the altered zone have been much reduced from their original amounts.

GOLD BUG BUTTE AND VICINITY, LITTLE ROCKY MOUNTAINS

In the Little Rocky Mountains, irregular stocks and laccoliths of syenite porphyry intruded Precambrian basement rocks and Paleozoic and Mesozoic strata during Paleocene time (67–60 m.y.), lifting them into a broad complex of domes about 15 km in diameter (fig. 1) (Brockunier, 1936; Knechtel, 1959; Marvin and others, 1980). Breccia pipes and breccia dikes are present in a few scattered localities in the Little Rocky Mountains and are especially well developed for about 1.5 km along the crest of Gold Bug Butte and the hill to the northeast (fig. 9). The breccia pipes have been emplaced mainly in altered syenite porphyry, but one pipe also cuts Precambrian schist and gneiss. In a few places the breccias form knobs a few meters high (fig. 10*A*) but there is little topographic difference between most breccias and their host rocks. Individual pipes generally crop out over small areas (≤1/16 km^2) and are poorly exposed.

Contacts between the breccia pipes and the country rocks are mostly gradational over a few tens of meters, but in a few places the contact zones are much narrower (less than 1 m). The outermost parts of the contact zones are characterized by slightly to moderately brecciated country rock (crackle breccias). In these outermost zones there has been no rotation of the fragments and there is little matrix. The amount of rotation of fragments and the amount of matrix increases toward the center of the pipes. Also, in most pipes the breccias are more heterolithologic towards the center.

The fragments in the pipes can be as large as 30 cm and are typically about 8 cm in diameter (fig. 10*B*). They are mainly subangular to angular and are composed of Precambrian schist and gneiss, Cambrian Flathead Sandstone (locally a quartzite), and several varieties of syenite porphyry. The relative abundance of rock types is highly variable and any of the just-listed rocks may comprise more than 95 percent of the fragments in an individual pipe. Usually one lithic type is predominant and makes up 75–90 percent of the breccia fragments. Matrix generally is sparse and is composed of fine-grained (<1 mm) particles of syenite and unidentified fragments.

At one locality on Gold Bug Butte and at the Hawkeye Mine (fig. 9), discontinuous breccia dikes about 2 m wide cut the syenite porphyry. The relationship between the breccia pipes and breccia dikes is uncertain; the dikes may be either offshoots or feeders for the pipes, but there is no field evidence to establish these relationships. Fragments make up about 20–30 percent

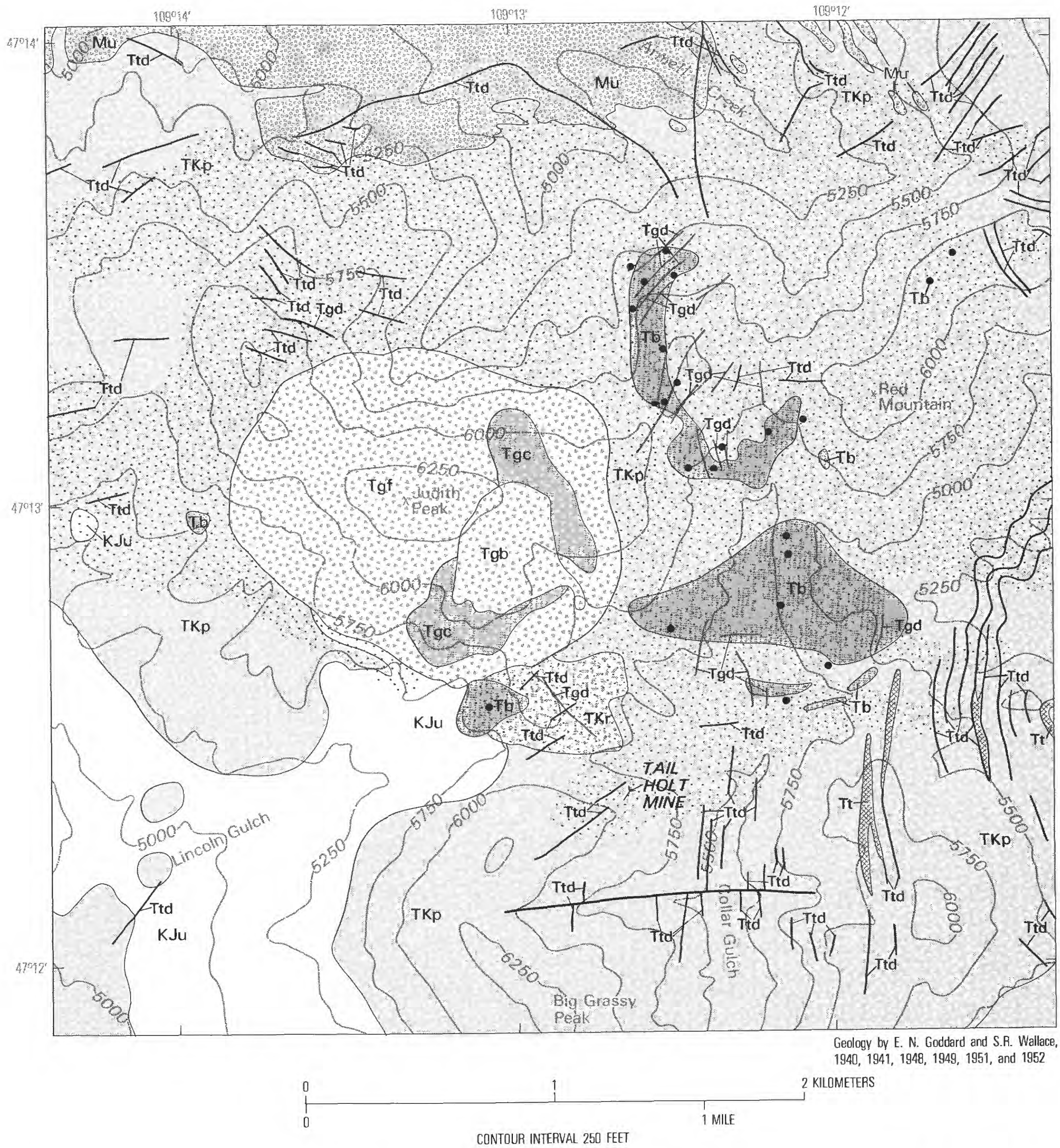


FIGURE 8 (above and facing page).—Geologic map showing intrusive breccia of Judith Peak-Red Mountain area, Judith Mountains, Mont.

of the breccia dikes and are composed mainly of porphyritic syenite and sparse to rare Precambrian schist and gneiss. Most of the fragments are about 5 cm in diameter but may be as large as 40 cm, are subrounded to angular, and in the breccia dike at Gold Bug Butte, have well-developed reaction rims (fig. 10*C*). The matrix of the breccia dikes is composed mostly of fine (<1 mm) fragmental grains of quartz and potassium feldspar from the wall rock as well as small amounts of sericite, limonite, magnetite, and pyrite. Some of the pyrite also occurs as larger (1–2 mm) euhedral grains. Rock fragments 1–2 mm in size are also a common constituent in the matrix. Secondary quartz and limonite are the major cements.

EXPLANATION

Tgb — Intrusive granite breccia (Paleocene)

Tgc — Alkali granite porphyry (Paleocene) Coarse-grained phase; Tgd, dikes

Tgf — Alkali granite porphyry (Paleocene) Fine-grained phase, brecciated and silicified; Tgd, dikes

Tt — Tinguaite and tinguaite porphyry (Paleocene?) Ttd, dikes

Tb — Intrusive breccia (Paleocene?)

TKr — Intrusive rhyolite (Paleocene or Upper Cretaceous)

TKp — Porphyry (Paleocene and Upper Cretaceous)—Quartz monzonite; monzonite, quartz diorite, diorite and syenite porphyry

KJu — Undivided sedimentary rocks (Cretaceous and Jurassic)—Cretaceous Colorado Shale and Kootenai Formation Jurassic Morrison Formation and Ellis Group

Mu — Undivided sedimentary rocks (Mississippian) Mississippian Big Snowy and Madison Groups

Altered rocks—Contain disseminated pyrite and iron oxide

Contact

Fault

Sample locality

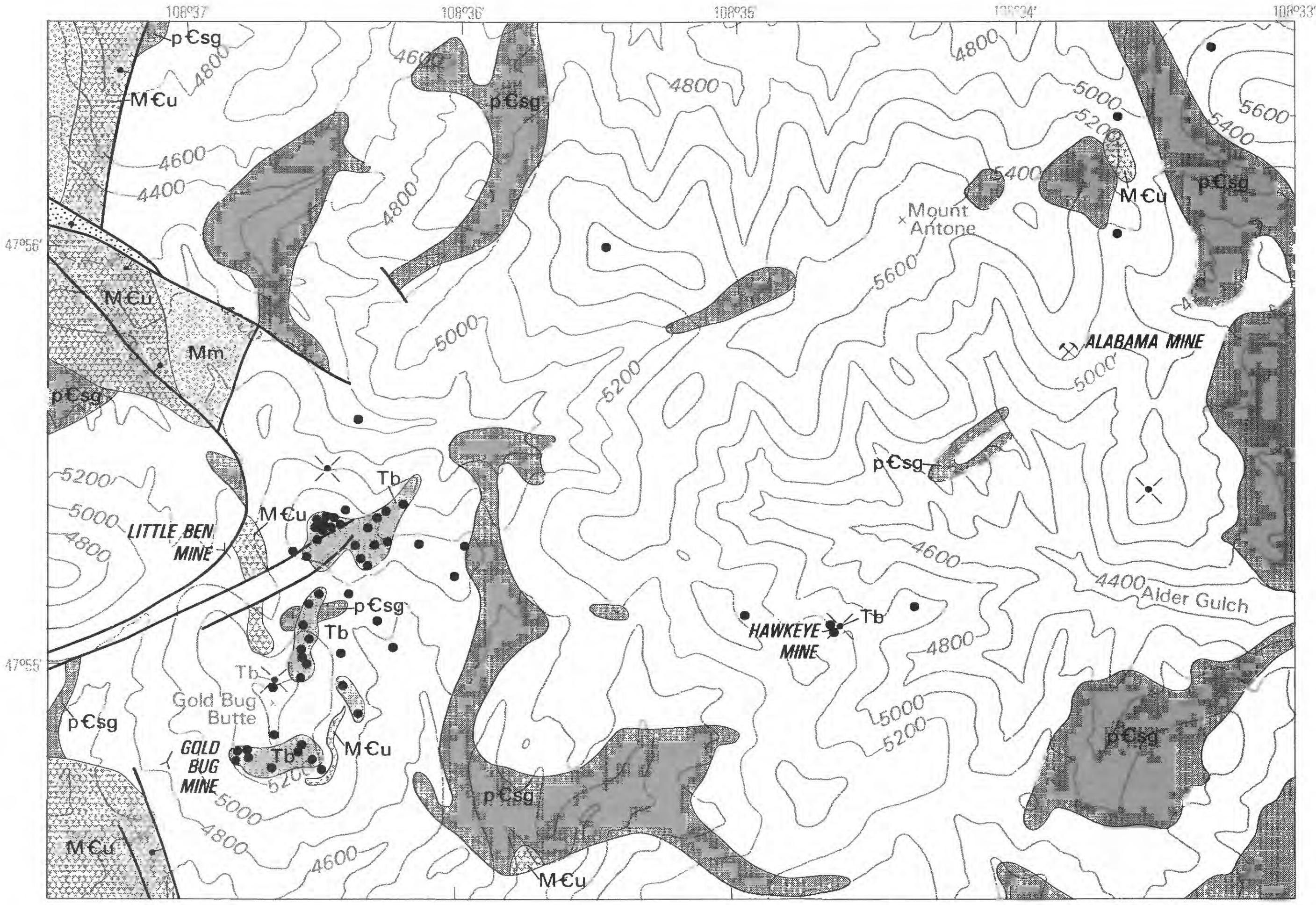
Adit

Breccia fragments and adjacent wall rocks (especially the syenite porphyry) on Gold Bug Butte have been altered to varying degrees and contain abundant well-crystallized sericite, quartz, pyrite of hypogene origin, and jarosite and limonite of probable supergene origin. These minerals replace feldspar and ferromagnesian minerals, fill small cracks, and are disseminated in the groundmass of syenite porphyry fragments and in wall rock. Secondary quartz is abundant locally and occurs as fracture fillings and cavity fillings. Secondary potassium feldspar was observed in a few samples. Kaolinite is present locally in moderate amounts, but is confined mainly to breccia fragments of feldspathic schist and gneiss. Irregular patches of limonite (in places as pseudomorphs after pyrite) and jarosite are more abundant than pyrite; pyrite occurs as euhedral grains and as interstitial fillings. The matrix of the breccias contains small fragments of wall rock, shredded masses of sericite, and rounded limonite grains (after pyrite?) that probably predate transport of fragments to their present position. The matrix is traversed by fissures filled with limonite, jarosite, quartz, and rarely pyrite, that are clearly post-breccia. All the breccias have been mineralized and contain anomalous amounts of copper (≤700 ppm), gold (≤5 ppm), molybdenum (≤700 ppm), lead (≤3,000 ppm), and silver (≤300 ppm). However, in hand specimens pyrite is the only sulfide mineral observed.

COMPARISON OF ALTERATION AND GEOCHEMICAL FEATURES

The type and degree of alteration of the breccias can be related to a single sequence (table 1), although whether this sequence represents the effects of duration or intensity of alteration, thermal gradients, or variation of the concentrations of chemical species in the altering fluids is unclear. In general, the alteration sequence in breccias and their adjoining host rocks begins with fresh or propylitized rocks and proceeds through the sequence kaolinite, quartz-illite or quartz-sericite, and quartz-potassium feldspar. Generally, only two members of this sequence can be observed in any one breccia pipe or cluster of pipes. Thus, kaolinite and quartz-illite-sericite assemblages were observed at Plum Creek and Limekiln Canyon, and quartz-sericite and quartz-potassium feldspar were observed at Gold Bug Butte and the Judith Peak-Red Mountain area. Most of the alteration appears to have been incomplete; although ferromagnesian minerals were altered completely in most breccias, potassium feldspar that formed during crystallization of the host porphyries was altered only partly in most rocks studied. Pyrite, commonly indicated only by its oxidation products limonite and jarosite, probably was introduced during quartz-sericite alteration. The alteration sequence kaolinite, quartz-sericite, and quartz-potassium feldspar differs from that of illite (sericite?), kaolinite, and quartz observed in breccia pipes of the San Juan Mountains of Colorado; the latter sequence has been interpreted as the product of hydrogen ion metasomatism (Fisher and Leedy, 1973). The quartz-sericite alteration assemblage observed in the breccias of Gold Bug Butte also is found along gold telluride-bearing fissure fillings in porphyry of the Little Rocky Mountains (Bailey, 1974), where it is reminiscent of sericite alteration found in wall rocks of the gold telluride-bearing veins of Boulder County, Colo. (Kelly and Goddard, 1969, p. 25).

Alteration of the breccias began during formation of crackle zones, as seen by intense alteration of these breccias and of fragments but not matrix in some breccias with rotated and transported clasts; alteration continued after emplacement of breccias, but varied greatly in intensity. Alteration during the crackle stage of brecciation clearly is evident at Gold Bug Butte; minor



Geology modified from Knechtel (1959)

0 1 2 KILOMETERS

0 1 MILE

CONTOUR INTERVAL 200 FEET

EXPLANATION

Tb	Intrusive breccia (Paleocene?)
Tsp	Syenite porphyry (Paleocene) Includes syenite porphyry of Antone, alaskite porphyry of Silvertip mine and quartz syenite porphyry of Old Scraggy (Brockunier, 1936) and several types of syenite porphyry with trachytic texture that occur as dikes and small plugs (Brockunier, 1936)
Kk	Kootenai Formation (Lower Cretaceous)
Mm	Madison Group (Mississippian)
M€u	Undivided sedimentary rocks (Mississippian, Devonian, Ordovician, and Cambrian)—Mississippian and Devonian Three Forks Formation, Devonian Jefferson and Maywood Formations, Ordovician Bighorn Dolomite, Ordovician and Cambrian Emerson Formation, and Cambrian Flathead Sandstone
p€sg	Schist and gneiss (Precambrian)
	Dike of intrusive breccia
	Contact
	Fault, ball and bar on downthrown side
	Sample locality
	Adit

FIGURE 9.—Geologic map showing intrusive breccias of the Little Rocky Mountains, Mont.

FIGURE 10.—Photographs of breccias at Gold Bug Butte, Little Rocky Mountains, Mont. *A*, West end of southernmost breccia pipe, cutting syenite porphyry on Gold Bug Butte. This is one of the few places in the Little Rocky Mountains where the breccia pipes have significant topographic expression. *B*, Detail of breccia showing abundant fragments of syenite porphyries. *C*, Detail of breccia dike showing reaction rims around fragments.

alteration, including filling of fissures with quartz, limonite, and jarosite, followed emplacement of these breccias. Alteration and mineralization of fragments in the South Moccasin and Republic breccias took place almost entirely before emplacement. Major alteration at Plum Creek began before emplacement of breccia with abundant matrix and continued after emplacement. At the Judith Peak-Red Mountain area, post-breccia alteration was intense, depositing quartz, potassium feldspar, and pyrite in the breccia matrix. Such post-breccia alteration may have accompanied intrusion of alkali granite on Judith Peak.

Geochemical anomalies in the breccias are closely related to the type and degree of alteration (table 1); these anomalies were interpreted from study of histograms for each element analyzed (fig. 11, at end of this chapter). Breccias with weak kaolinitic alteration, as in the South Moccasin Mountains and at Limekiln Canyon in the Judith Mountains, do not have significant geochemical anomalies. Breccias characterized by quartz-sericite and quartz-potassium feldspar alteration, seen at Plum Creek in the North Moccasin Mountains, Judith Peak-Red Mountain in the Judith Mountains, and at Gold Bug Butte in the Little Rocky Mountains, show significant depletion of readily leached alkalis and alkaline earth elements except potassium, and they show significant enrichment of potassium and of base and precious metals.

Although the chemical composition of the host rock may vary among areas somewhat, such differences may be largely ignored in comparing the effects of alteration and mineralization because these processes have brought major changes in the chemical composition of the altered rocks. Using the relatively weakly altered, unmineralized breccias at Limekiln Canyon as a basis for comparison, the parallel effects of alteration and mineralization can be described. The average content of iron and titanium does not appear to have changed much with weak kaolinitic alteration, but the two metals have been redistributed extensively in more highly altered quartz-potassium feldspar and quartz-sericite breccias, as indicated by the wide variation in iron and titanium content at Judith Peak-Red Mountain and Gold Bug Butte as compared with Limekiln Canyon. Manganese has been depleted in highly altered breccias and also, to a lesser extent, in the quartz-sericite altered zone at Plum Creek. Calcium, magnesium, and sodium are most depleted in the highly altered breccias of Judith Peak-Red Mountain and depleted to a lesser extent in breccias of the Little Rocky Mountains. Potassium is enriched at Judith Peak-Red Mountain and at Gold Bug Butte. Barium is enriched at Judith Peak-Red Mountain but nowhere else; it may be present as barite reported in calcite-fluorite-quartz veins by Hall (1976).

TABLE 1.—*Summary of alteration and geochemical features of breccias in north-central Montana*
[Leaders (---) indicate no change in chemical composition; dominant alteration assemblage is underlined]

Locality of mineralized breccia	South Moccasin Mountains	Limekiln Canyon	Plum Creek	Gold Bug Butte	Judith Peak-Red Mountain
Alteration assemblage	Kaolinite	Kaolinite, quartz-sericite, and illite	Kaolinite, quartz-sericite and illite	Quartz-sericite, quartz-potassium feldspar	Quartz-sericite, quartz-potassium feldspar
Degree of alteration	Least altered <---> Most altered.				
Fe, Ti	---	---	---	Redistributed	Redistributed.
Mn	---	---	Slightly depleted	Depleted	Depleted.
Ba	---	---	---	---	Enriched.
K	---	---	---	Enriched	Do.
Au, Ag, V	---	---	Slightly enriched	Strongly enriched	Do.
Cu, Mo, Pb	---	---	Enriched	Enriched	Do.
Co, Cr, Ni	---	---	---	---do	---

Gold, silver, and vanadium were enriched moderately at Plum Creek and Judith Peak-Red Mountain, but strongly enriched in breccias at Gold Bug Butte; copper, molybdenum, and lead appear to have been enriched about equally at these three localities. Anomalous concentrations of beryllium, cobalt, chromium, and nickel are found only in the Little Rocky Mountains; some of these anomalies may represent differences in mineralization or merely the presence of abundant fragments of Precambrian schist and gneiss of mafic ancestry in some of the breccias there. The concentration of most other elements does not vary appreciably among breccias having differing degrees of alteration (fig. 11).

Some elements, notably iron, magnesium, calcium, sodium, and manganese, have distinct bimodal or polymodal frequency distributions that probably represent sampling of both slightly altered and highly altered breccia; for example, the most altered rock of the Judith Peak-Red Mountain breccia pipes contains 0.5–0.7 percent sodium, but some less-altered parts of the breccia complex still retain as much as 3 percent sodium. The frequency distributions of some metals, such as chromium in the breccias of Gold Bug Butte, show many modes distributed in every other class of abundance; this may represent an analytical problem. Other polymodal distributions, such as those of silver and gold, may represent multiple pulses of mineralizing fluids or other complexities in the process of mineralization.

DISCUSSION AND CONCLUSIONS

The breccia pipes of north-central Montana evidently were formed by the activity of residual vapor and partially solidified magma that collected in the upper regions of cooling intrusive bodies. Breccias in the North and South Moccasin Mountains, and at Limekiln Canyon in the Judith Mountains, are centrally located within host porphyries, and thus are below the projected apex of the porphyries; those of the Judith Peak-Red Mountain area and at Gold Bug Butte and vicinity in the Little Rocky Mountains are located in large intrusive complexes where the apex of intrusion is not evident. At Judith Peak-Red Mountain, breccias were formed before intrusion of late granitic magmas into the porphyry complex, but the source of the breccias has not been determined. All the breccias of north-central Montana contain abundant fragments of the host syenite, quartz monzonite, and related porphyries, and contain lesser quantities of sedimentary rocks of Paleozoic and Mesozoic age and of Precambrian schist and gneiss. The host porphyries were evidently the principal site of breccia formation. No fragments of alkalic ultramafic rocks, or peridotites from the upper mantle, such as those found in the Eocene diatremes of north-central Montana (Hearn, 1968, 1979), were found in the breccias associated with Upper Cretaceous-Paleocene porphyry intrusions.

The depth of breccia formation, and emplacement of the host porphyry, can be estimated directly from the thicknesses of horizontal sedimentary strata (assuming no thinning above the intrusions) that overlay each intrusive complex during early Paleocene time; this method is simple and yields independent estimates in good agreement with each other. Estimates of depth are as follows: North and South Moccasin Mountains, 1,700–2,300 m; Limekiln Canyon, Judith Mountains, 1,600–2,700 m; Judith Peak-Red Mountain, Judith Mountains, 1,100–1,900 m (see also Wallace, 1956, p. 370); and Gold Bug Butte, Little Rocky Mountains, 1,400–2,300 m. The ranges in depth represent the lowest and highest stratigraphic levels of emplacement of each main mass of porphyry. Intrusive rocks in each complex contain sanidine phenocrysts and an aphanitic groundmass, and country rocks show little evidence of contact metamorphism; all these features imply a shallow depth of emplacement and rapid cooling, and are thus in general agreement with the estimates of depth of porphyry emplacement and brecciation.

Most of the breccias of north-central Montana have characteristics attributed by Kents (1961, 1964) to be the result of hydraulic ramming by hydrothermal and magmatic fluids. After emplacement and partial cooling of the main mass of magma, residual fluids that collected in the apical parts of the intrusion were subjected to hydraulic pressure from surges of magma below. Under pressure, the residual fluids shattered the overlying cap of chilled intrusive porphyry and country rocks over areas of several hundred to a thousand meters, forming rupture breccias (also known as crackle breccias) marked by a myriad of fissures and unrotated angular fragments. Part of the breccia at Plum Creek and the margins of breccias at Gold Bug Butte are crackle breccias. The fragments were altered and mineralized by hydrothermal fluids, and the fissures commonly were filled with quartz. Withdrawal of magma from below may have caused collapse of the crackle zone, forming a breccia of rotated angular fragments derived from overlying rocks and containing abundant open spaces; but this seems not to have occurred to a noticeable extent in the Montana breccias. Continued or repeated surges of magma from below also could have caused the crackle breccia to disintegrate into a breccia of rotated and transported fragments surrounded by a matrix of fine-grained fragments. Eventually, these processes led to formation of well-defined pipes of intrusive breccia dominated by matrix and breccia containing well-rounded fragments (kneaded and milled breccias of Kents, 1964). Breccias composed of small fragments and dominated by matrix are well developed in the South Moccasin Mountains, at Plum Creek, Limekiln Canyon, and at Judith Peak. The Republic breccia contains rounded clasts and clearly extends above its source; it must have been forced up through the host shale formation. In a few places the breccia columns were then intruded by igneous dikes (Judith Peak-Red Mountain area) and by breccia dikes (Gold Bug Butte area).

Considering stratigraphic evidence for shallow emplacement of the breccias, some of the breccias may have broken through the surface. Possible detritus from such an eruption in the Little Rocky Mountains has been found in the lower part of the Fort Union Formation (Marvin and others, 1980, p. 21–22). Evacuation of the pipe and concomitant release of pressure might have been followed by withdrawal of breccia material into the resulting partial vacuum; such up and down movement would further aid production of breccia and matrix and would account for the occurrence together of fragments from stratigraphically higher and lower levels.

Other mechanisms for breccia emplacement were considered but some, such as postmagmatic hydrothermal solution and collapse (Sillitoe and Sawkins, 1971), and collapse by the exsolved magma vapor mechanism (Norton and Cathles, 1973), seem to apply best where there is evidence for substantial downward movement of breccia fragments, and where the breccias lack a fine matrix. The widespread presence of fragments of Precambrian schist and gneiss, which must have been derived from below the porphyry intrusions, is strong evidence that the breccias of north-central Montana were not formed entirely by collapse. Most of the Montana breccias have abundant fine matrix and little open space between fragments. The possibility that the breccias were emplaced into voids formed by faulting (Mitcham, 1974) was dismissed also, because most of the breccias are not near faults.

Hydrothermal fluids permeated the breccias during and after their formation, altering and mineralizing them to varying degrees. In general, alteration was incomplete and followed the sequence kaolinite, quartz-illite and quartz-sericite, and quartz-potassium feldspar. Kaolinitic alteration was extremely weak. During alteration, iron and titanium were redistributed; calcium, magnesium, sodium, and manganese were leached; and potassium and base and precious metals were concentrated. The highest concentrations of gold and silver were deposited in areas of most intense quartz-sericite alteration. Feldspathic alteration does not seem to have been accompanied by continued deposition of gold and silver, but quartz-sericite alteration and gold-silver deposition may have occurred on the fringes of feldspathic alteration. Using the model of alteration and mineralization developed here, the breccias most favorable for gold and silver, in decreasing order of favorableness, are (1) Gold Bug Butte and vicinity, Little

Rocky Mountains, (2) Plum Creek, North Moccasin Mountains, and (3) the fringes of the Judith Peak-Red Mountain altered area, Judith Mountains.

We believe that alteration and gold-silver mineralization accompanied closely the formation of breccia pipes during final stages of cooling of intrusive porphyry. This was true undoubtedly at Judith Peak-Red Mountain, where less-altered dikes cut altered breccia. If alteration and igneous activity were contemporaneous or nearly so, then alteration and mineralization must have taken place at depths comparable to the 1,100–2,700 m depth range estimated for the cooling porphyry.

The occurrence of mineralized (copper, lead, and zinc) fragments in breccias that otherwise show only weak effects of alteration and mineralization, as in the South Moccasin Mountains and at the Republic claim nearby, indicate that base-metal mineralization took place prior to formation of some of the breccias. Mineralized (chalcopyrite-pyrite) inclusions have been found in quartz monzonite porphyry in the South Moccasin Mountains (Lindsey, 1982) and in unmineralized porphyry south of Judith Peak in the Judith Mountains (Marvin and others, 1980). These inclusions were derived from deposits of metal sulfides that formed prior to or during emplacement of the porphyry complexes. The significance of these mineralized inclusions, in both breccia and porphyry, is that base-metal sulfide mineralization began early during Late Cretaceous-Paleocene intrusive activity and continued after the formation of breccias, as indicated by widespread anomalies of copper, lead, and molybdenum in the breccias and altered wall rocks. Gold and silver mineralization, and accompanying quartz-sericite alteration of intrusive breccia, appears to have been confined more closely to the time of breccia formation.

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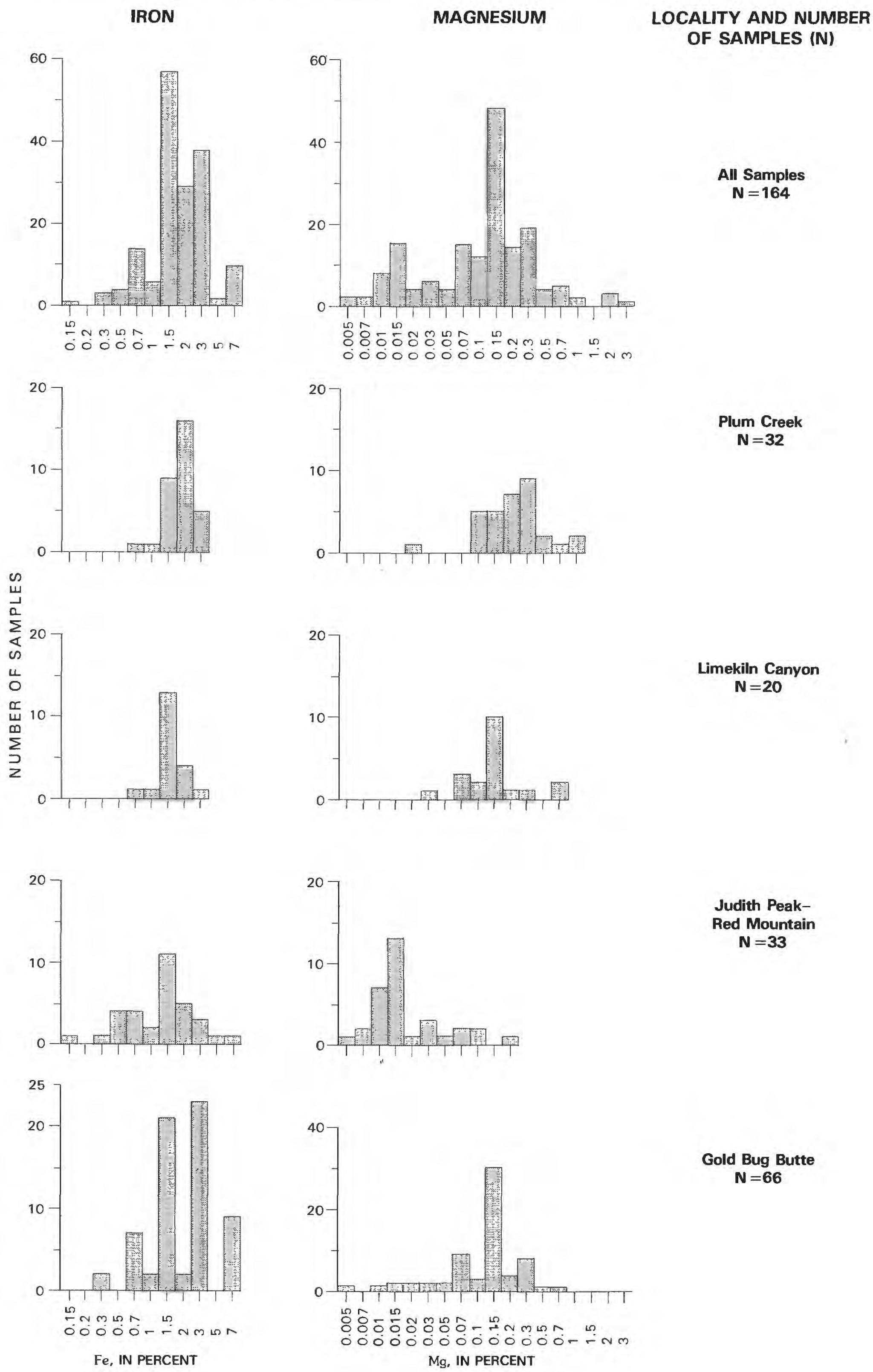
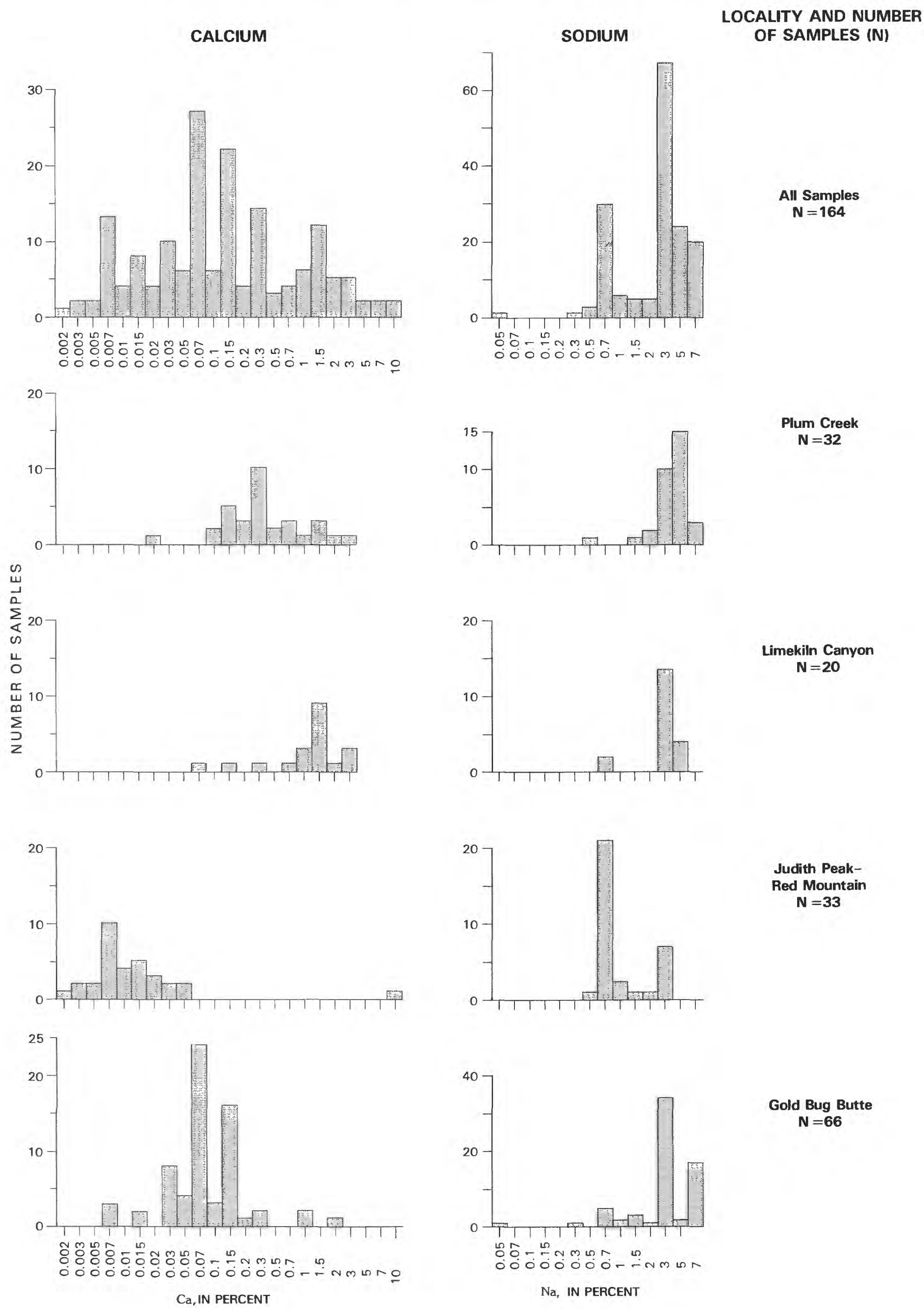
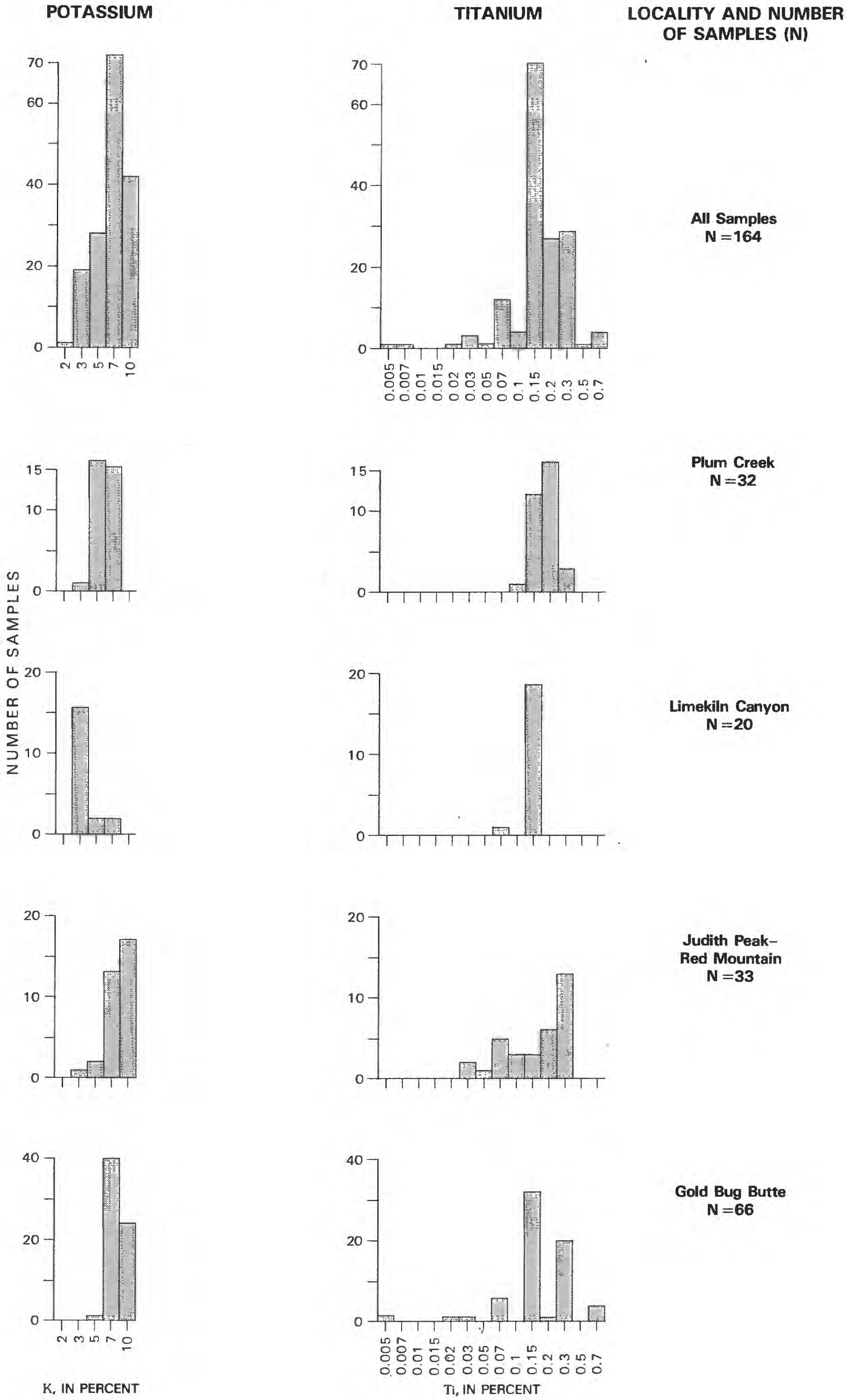
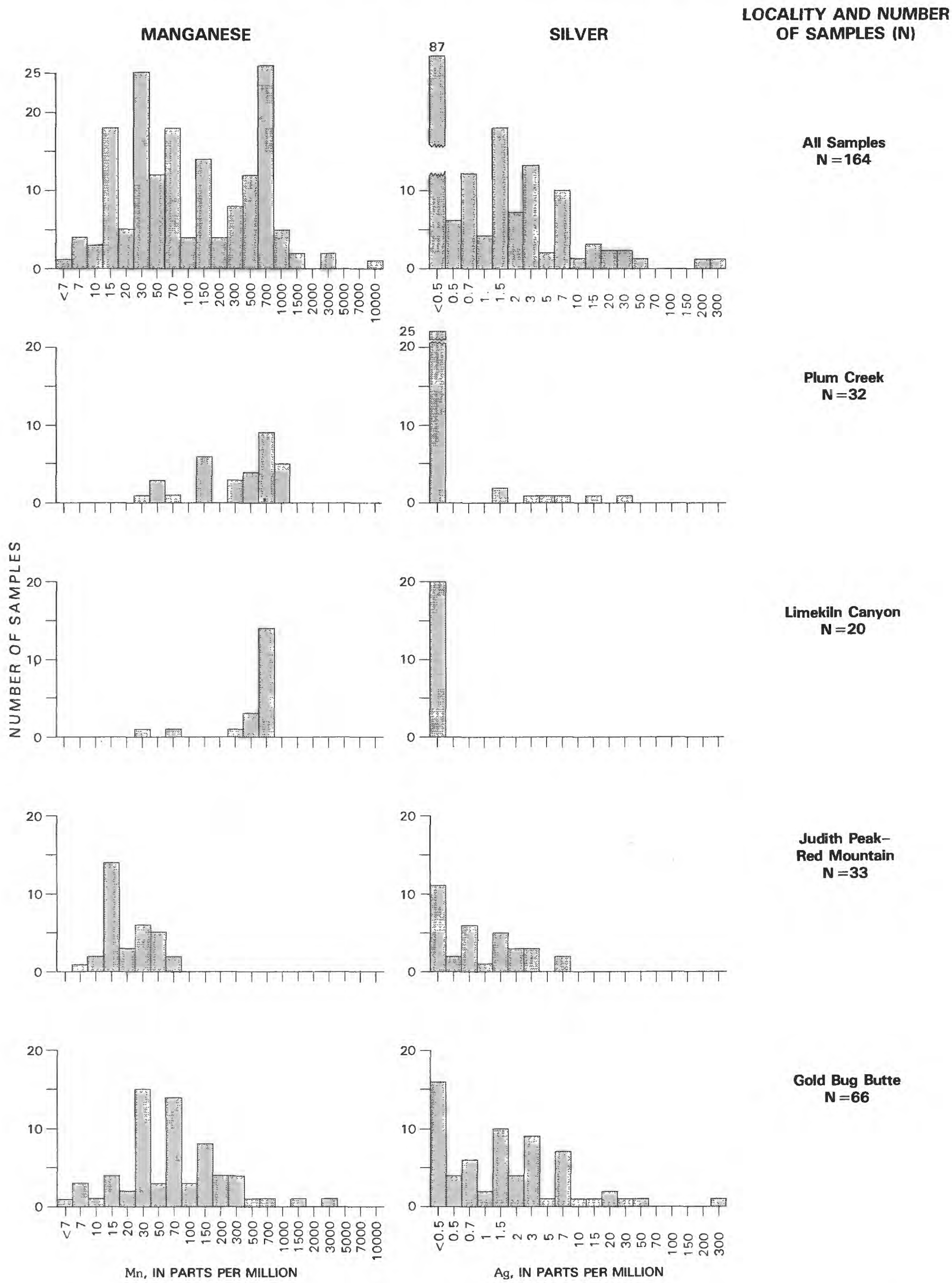
FIGURE 11.—Histograms showing the frequency distributions of elements in 164 samples of breccias and wall rocks in Upper Cretaceous and Paleocene intrusive porphyry complexes of north-central Montana. Separate histograms are shown for breccias at Plum Creek in the North Moccasin Mountains, Limekiln Canyon in the Judith Mountains, the Judith Peak-Red Mountain area in the Judith Mountains, and Gold Bug Butte and vicinity in the Little Rocky Mountains. Gold analyzed by fire assay-atomic absorption spectrometry; all other elements analyzed by six-step semiquantitative spectrographic method. N, not found.


IRON
MAGNESIUM
LOCALITY AND NUMBER OF SAMPLES (N)
All Samples
N = 164
Plum Creek
N = 32
Limekiln Canyon
N = 20
Judith Peak–Red Mountain
N = 33
Gold Bug Butte
N = 66
NUMBER OF SAMPLES
0.15 0.2 0.3 0.5 0.7 1 1.5 2 3 5 7
0.005 0.007 0.01 0.015 0.02 0.03 0.05 0.07 0.1 0.15 0.2 0.3 0.5 0.7 1 1.5 2 3
Fe, IN PERCENT
Mg, IN PERCENT


CALCIUM
SODIUM
LOCALITY AND NUMBER OF SAMPLES (N)
NUMBER OF SAMPLES
All Samples N=164
Plum Creek N=32
Limekiln Canyon N=20
Judith Peak-Red Mountain N=33
Gold Bug Butte N=66
0.002 0.003 0.005 0.007 0.01 0.015 0.02 0.03 0.05 0.07 0.1 0.15 0.2 0.3 0.5 0.7 1 1.5 2 3 5 7 10
0.05 0.07 0.1 0.15 0.2 0.3 0.5 0.7 1 1.5 2 3 5 7
Ca, IN PERCENT
Na, IN PERCENT


POTASSIUM
TITANIUM
LOCALITY AND NUMBER OF SAMPLES (N)
All Samples N =164
Plum Creek N =32
Limekiln Canyon N =20
Judith Peak– Red Mountain N =33
Gold Bug Butte N =66
NUMBER OF SAMPLES
2 3 5 7 10
0.005 0.007 0.01 0.015 0.02 0.03 0.05 0.07 0.1 0.15 0.2 0.3 0.5 0.7
K, IN PERCENT
Ti, IN PERCENT


MANGANESE
SILVER
LOCALITY AND NUMBER OF SAMPLES (N)
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All Samples
N = 164
Plum Creek
N = 32
Limekiln Canyon
N = 20
Judith Peak–
Red Mountain
N = 33
Gold Bug Butte
N = 66
NUMBER OF SAMPLES
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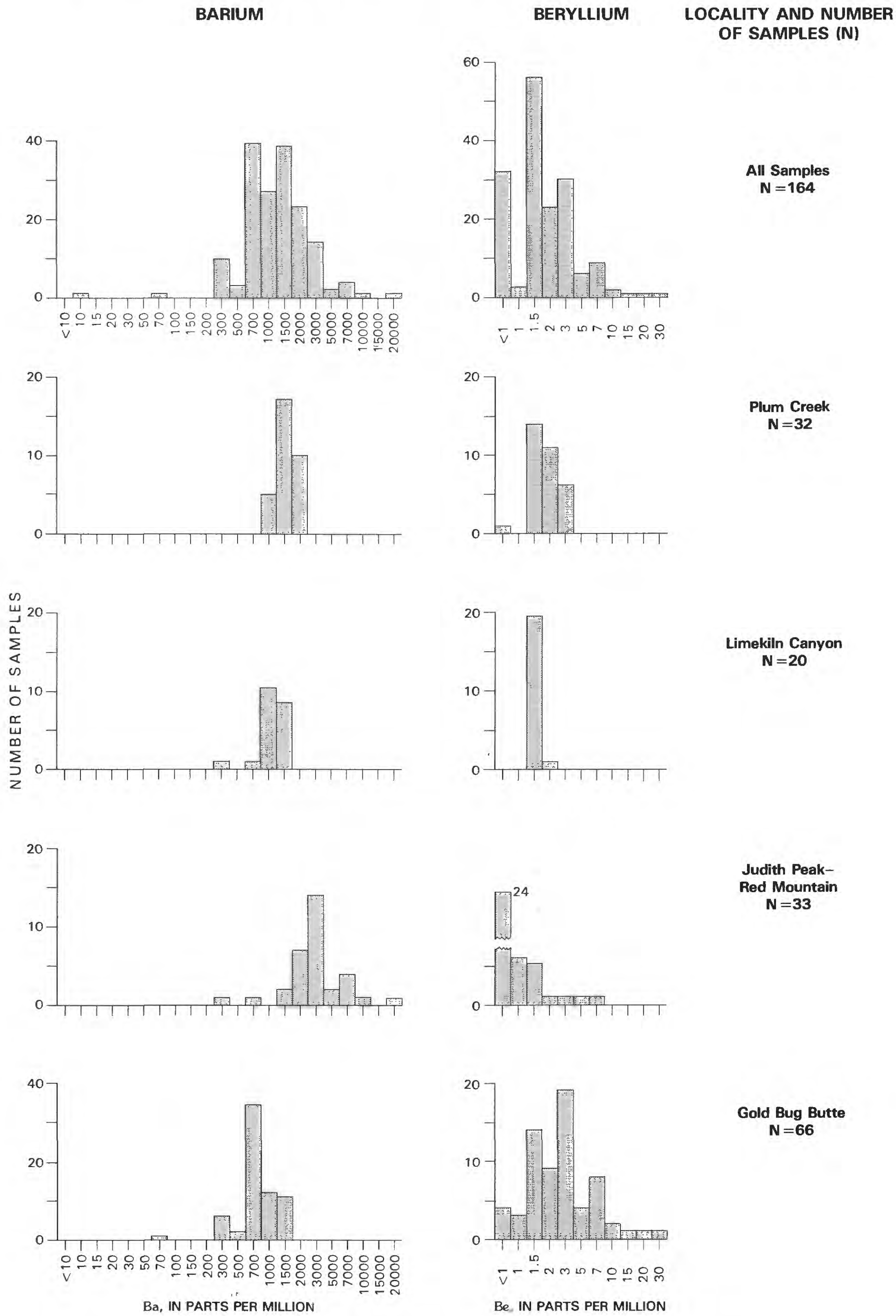
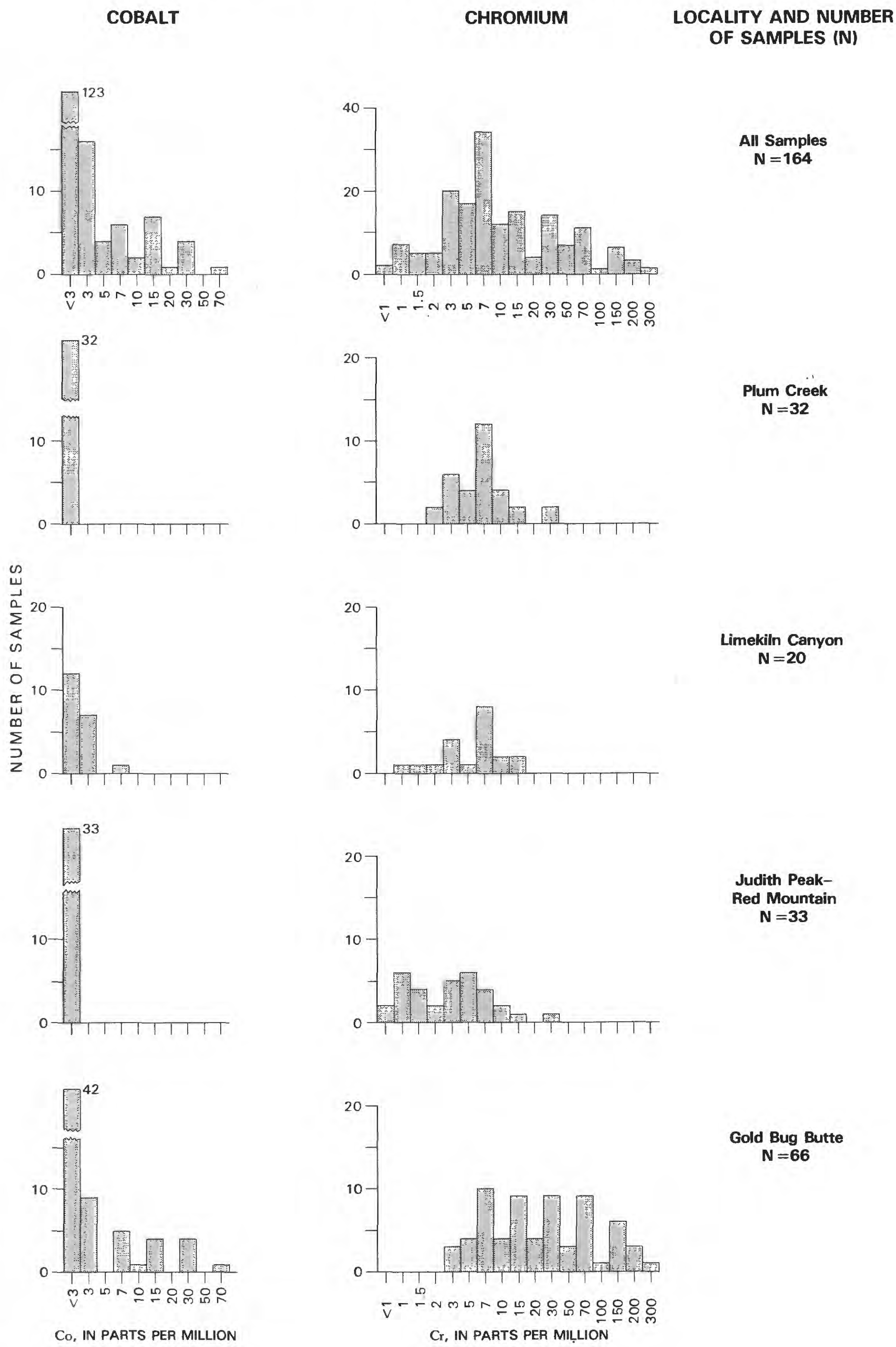
<0.5 0.5 0.7 1 1.5 2 3 5 7 10 15 20 30 50 70 100 150 200 300
Mn, IN PARTS PER MILLION
Ag, IN PARTS PER MILLION


BARIUM
BERYLLIUM
LOCALITY AND NUMBER OF SAMPLES (N)
All Samples N =164
Plum Creek N =32
Limekiln Canyon N =20
Judith Peak–Red Mountain N =33
Gold Bug Butte N =66
NUMBER OF SAMPLES
24
<10 10 15 20 30 50 70 100 150 200 300 500 700 1000 1500 2000 3000 5000 7000 10000 15000 20000
<1 1 1.5 2 3 5 7 10 15 20 30
Ba, IN PARTS PER MILLION
Be, IN PARTS PER MILLION


COBALT
CHROMIUM
LOCALITY AND NUMBER OF SAMPLES (N)
All Samples N = 164
Plum Creek N = 32
Limekiln Canyon N = 20
Judith Peak–Red Mountain N = 33
Gold Bug Butte N = 66
NUMBER OF SAMPLES
123
32
33
42
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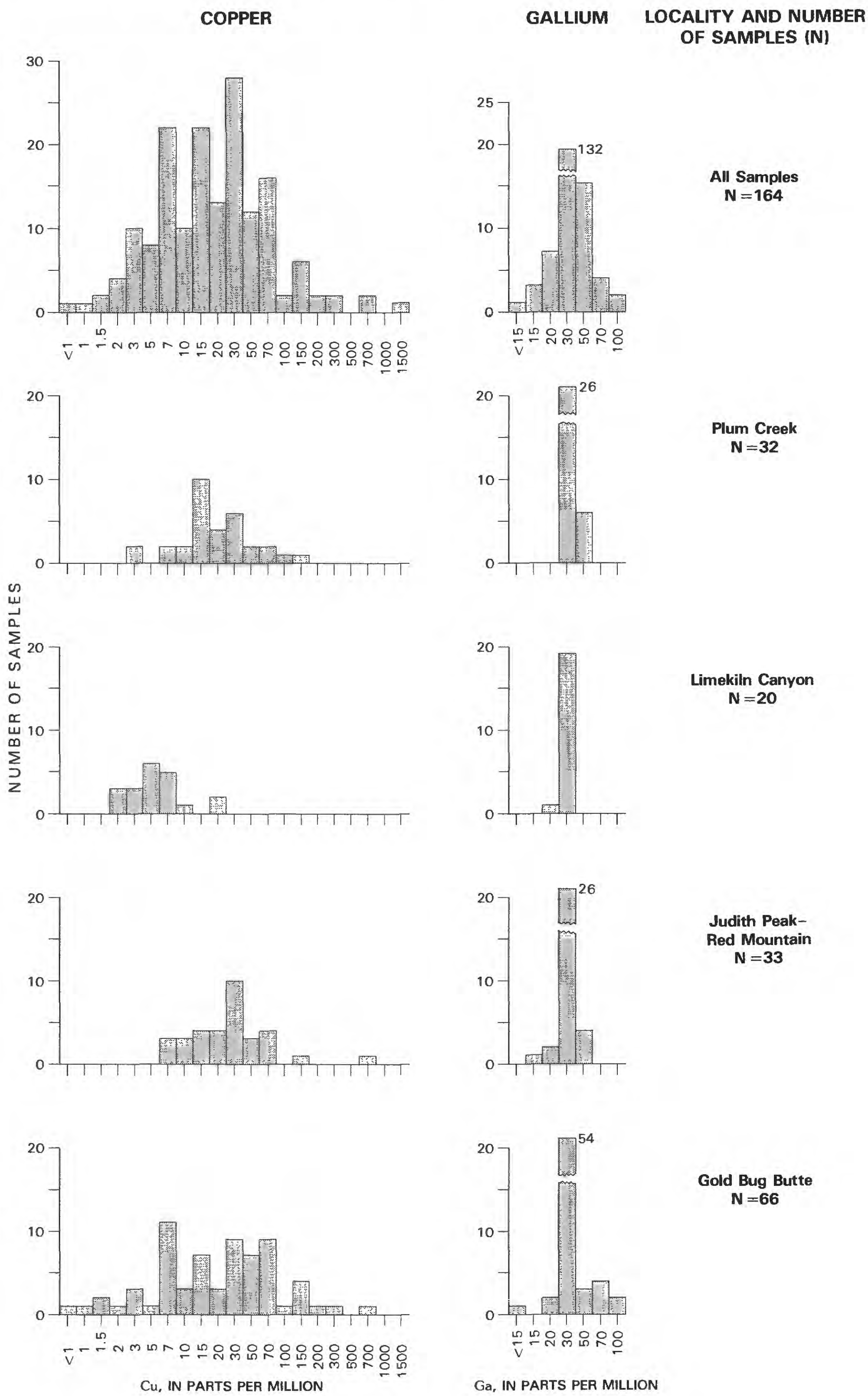
<1 1 1.5 2 3 5 7 10 15 20 30 50 70 100 150 200 300
Co, IN PARTS PER MILLION
Cr, IN PARTS PER MILLION


COPPER
GALLIUM
LOCALITY AND NUMBER OF SAMPLES (N)
All Samples N = 164
132
Plum Creek N = 32
26
Limekiln Canyon N = 20
Judith Peak–Red Mountain N = 33
26
Gold Bug Butte N = 66
54
NUMBER OF SAMPLES
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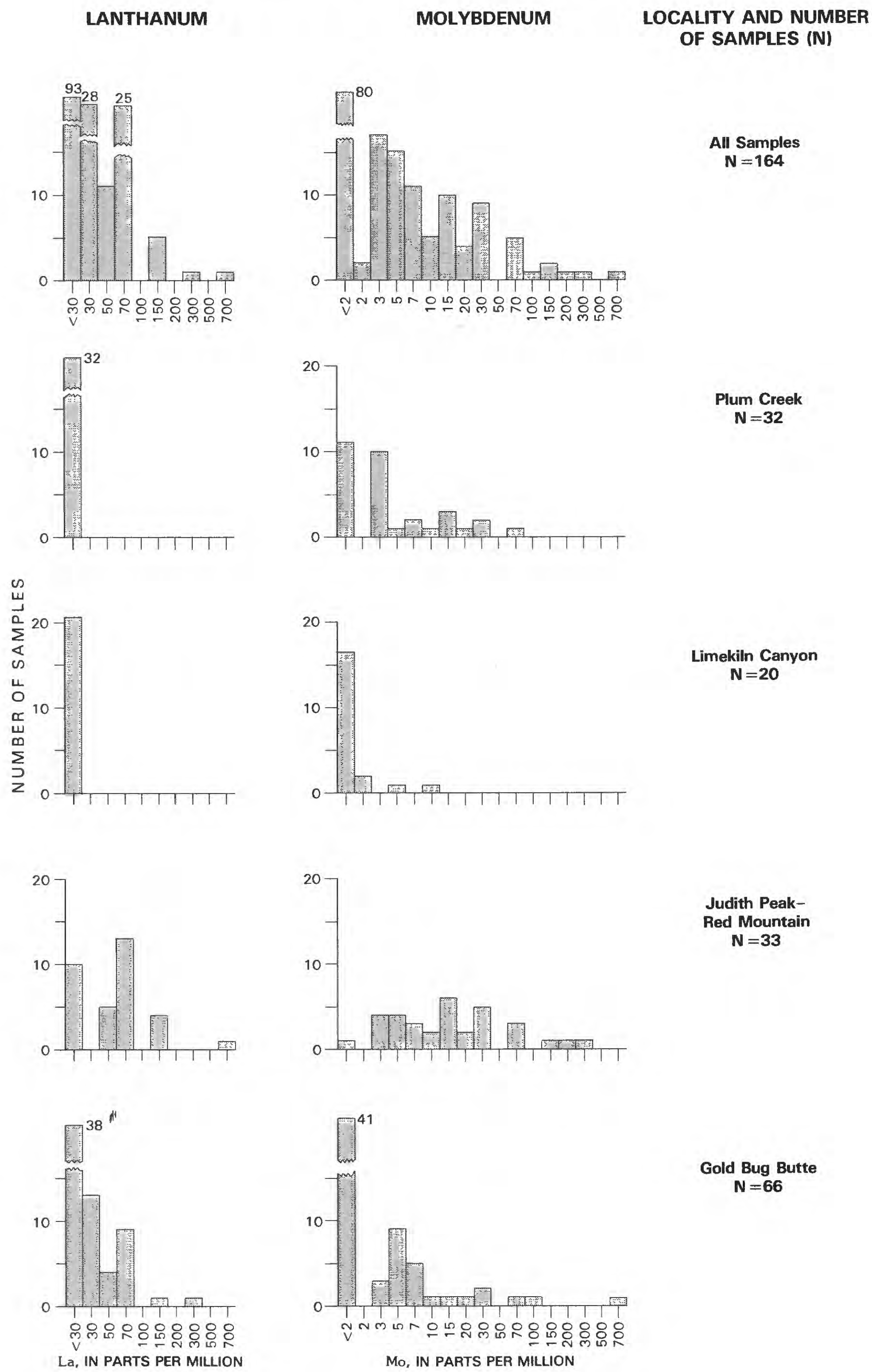
<15 15 20 30 50 70 100
Cu, IN PARTS PER MILLION
Ga, IN PARTS PER MILLION


LANTHANUM
MOLYBDENUM
LOCALITY AND NUMBER OF SAMPLES (N)
All Samples N=164
Plum Creek N=32
Limekiln Canyon N=20
Judith Peak–Red Mountain N=33
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NUMBER OF SAMPLES
La, IN PARTS PER MILLION
Mo, IN PARTS PER MILLION
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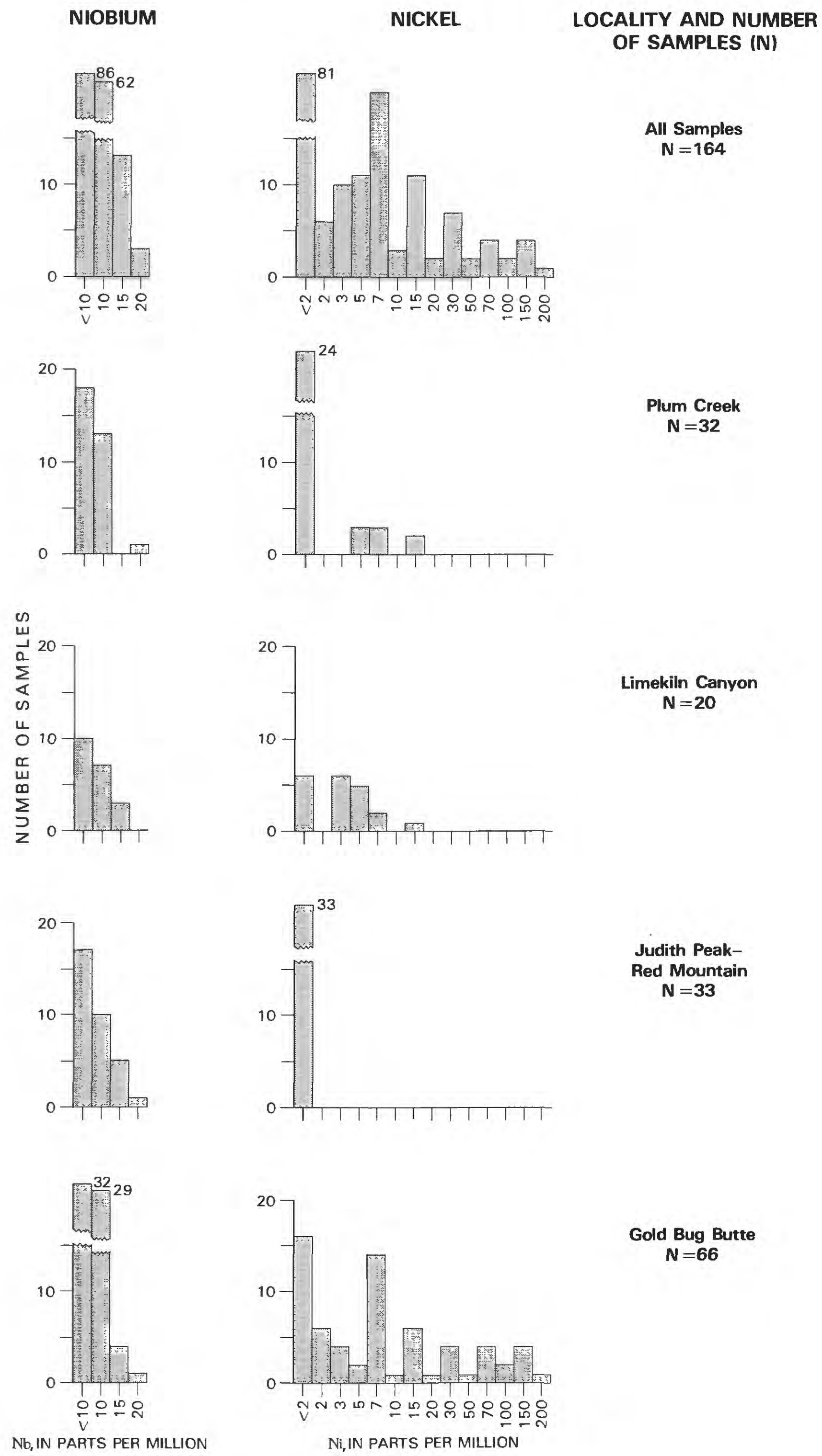
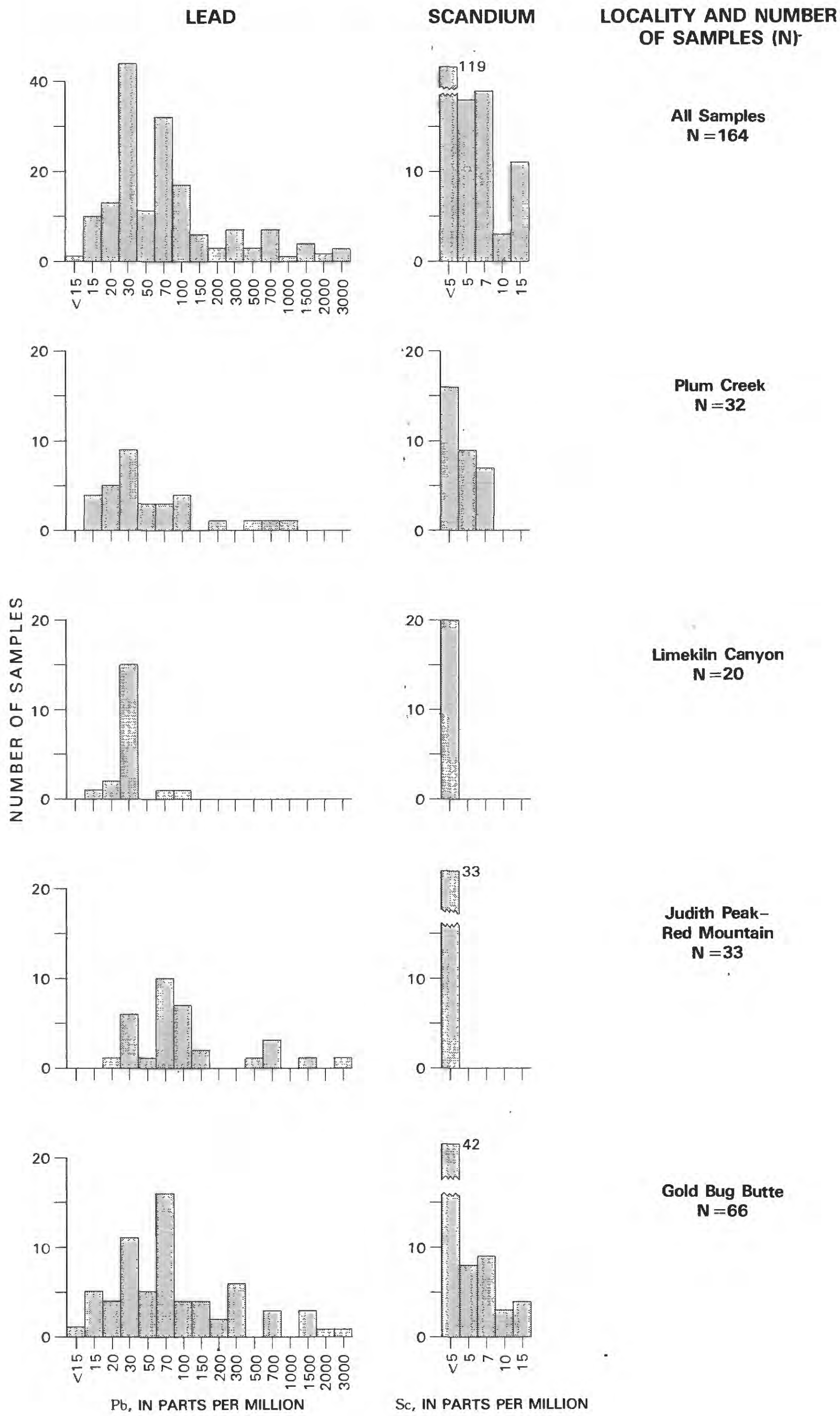
25
80
32
38
41


NIOBIUM
NICKEL
LOCALITY AND NUMBER OF SAMPLES (N)
All Samples N =164
Plum Creek N =32
Limekiln Canyon N =20
Judith Peak–Red Mountain N =33
Gold Bug Butte N =66
NUMBER OF SAMPLES
Nb, IN PARTS PER MILLION
Ni, IN PARTS PER MILLION


LEAD
SCANDIUM
LOCALITY AND NUMBER OF SAMPLES (N)
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Limekiln Canyon N =20
Judith Peak– Red Mountain N =33
Gold Bug Butte N =66
119
33
42
NUMBER OF SAMPLES
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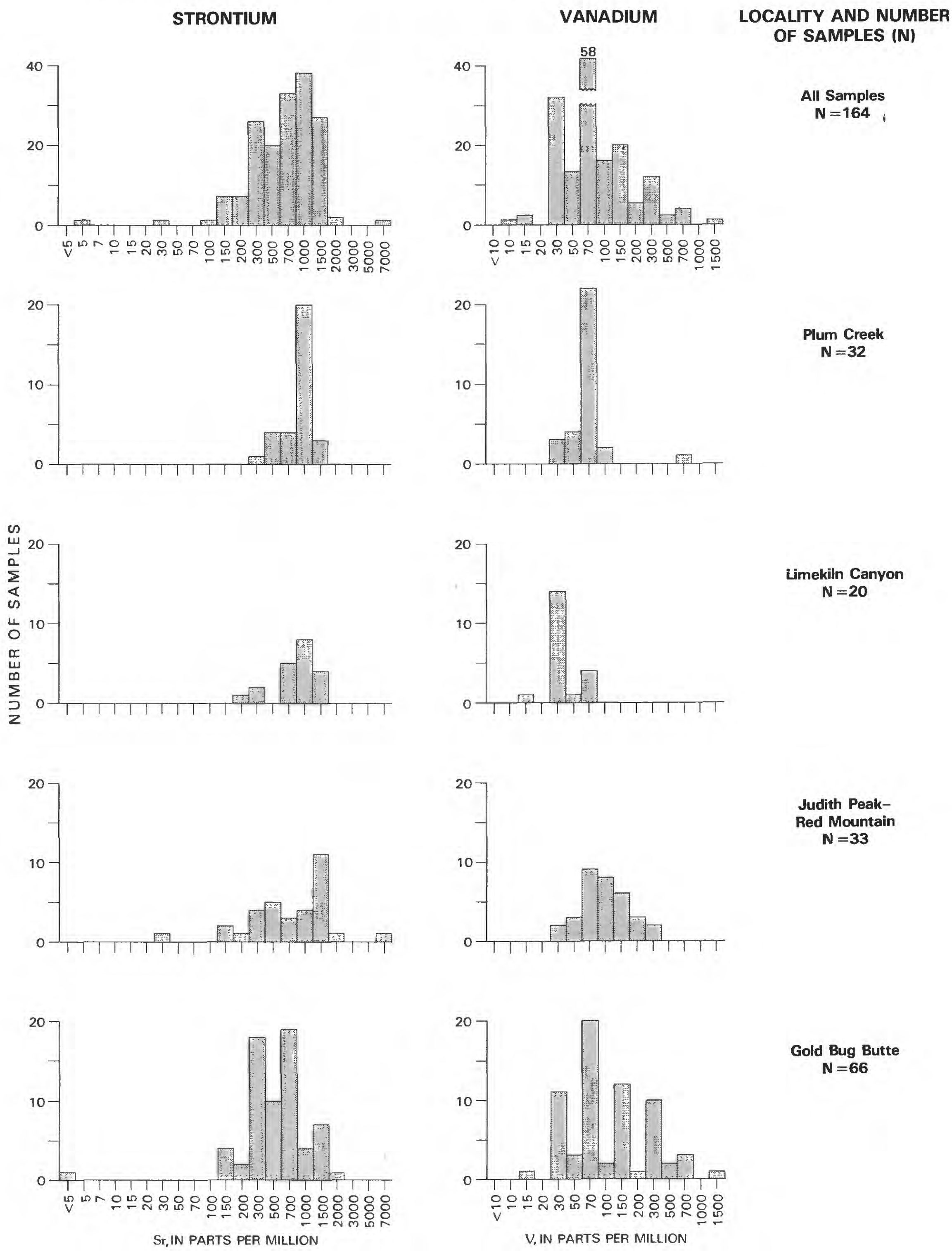
<5 5 7 10 15
Pb, IN PARTS PER MILLION
Sc, IN PARTS PER MILLION


STRONTIUM
VANADIUM
LOCALITY AND NUMBER OF SAMPLES (N)
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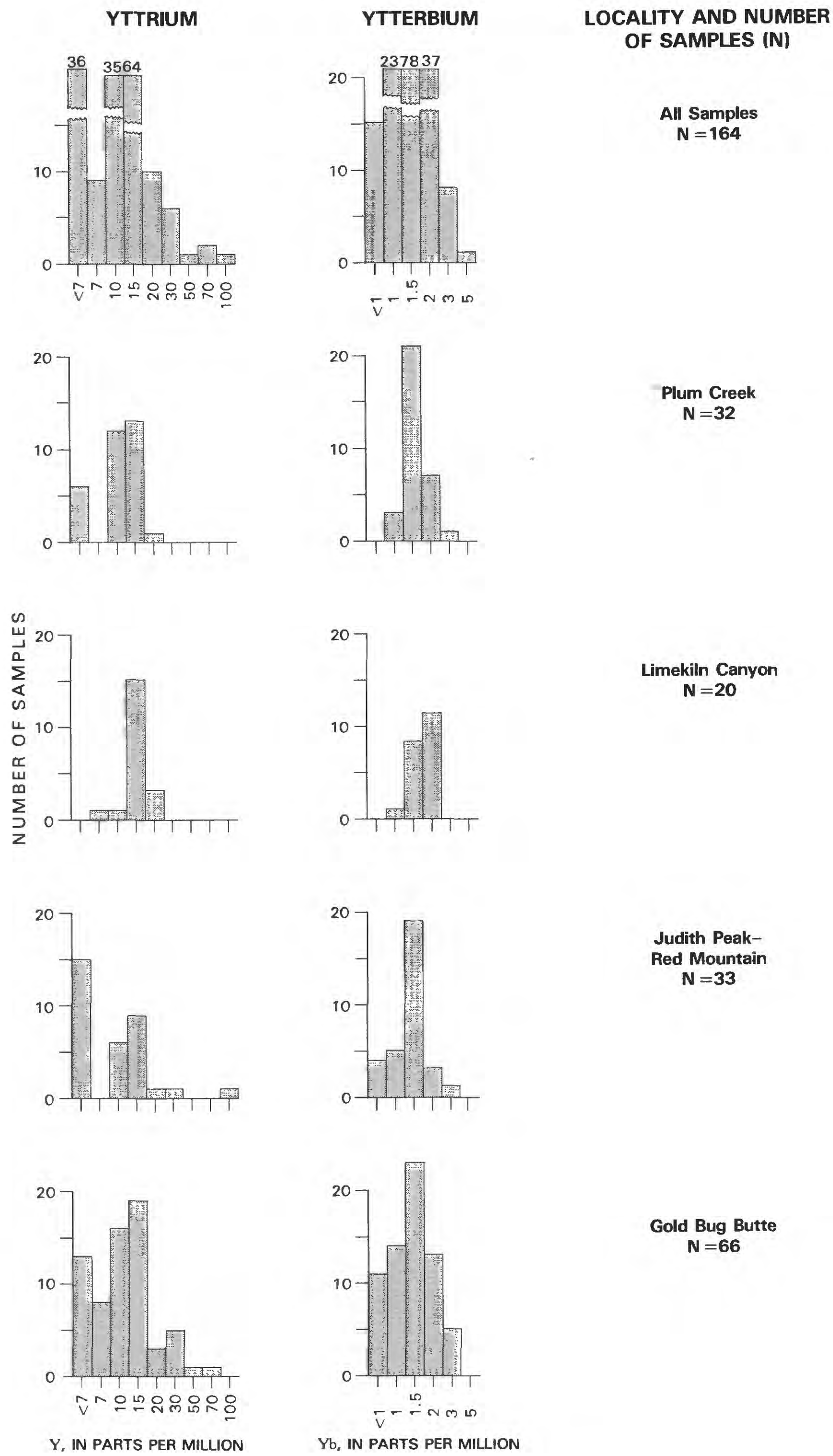
All Samples
N =164
Plum Creek
N =32
Limekiln Canyon
N =20
Judith Peak–
Red Mountain
N =33
Gold Bug Butte
N =66
NUMBER OF SAMPLES
<5 5 7 10 15 20 30 50 70 100 150 200 300 500 700 1000 1500 2000 3000 5000 7000
<10 10 15 20 30 50 70 100 150 200 300 500 700 1000 1500
Sr, IN PARTS PER MILLION
V, IN PARTS PER MILLION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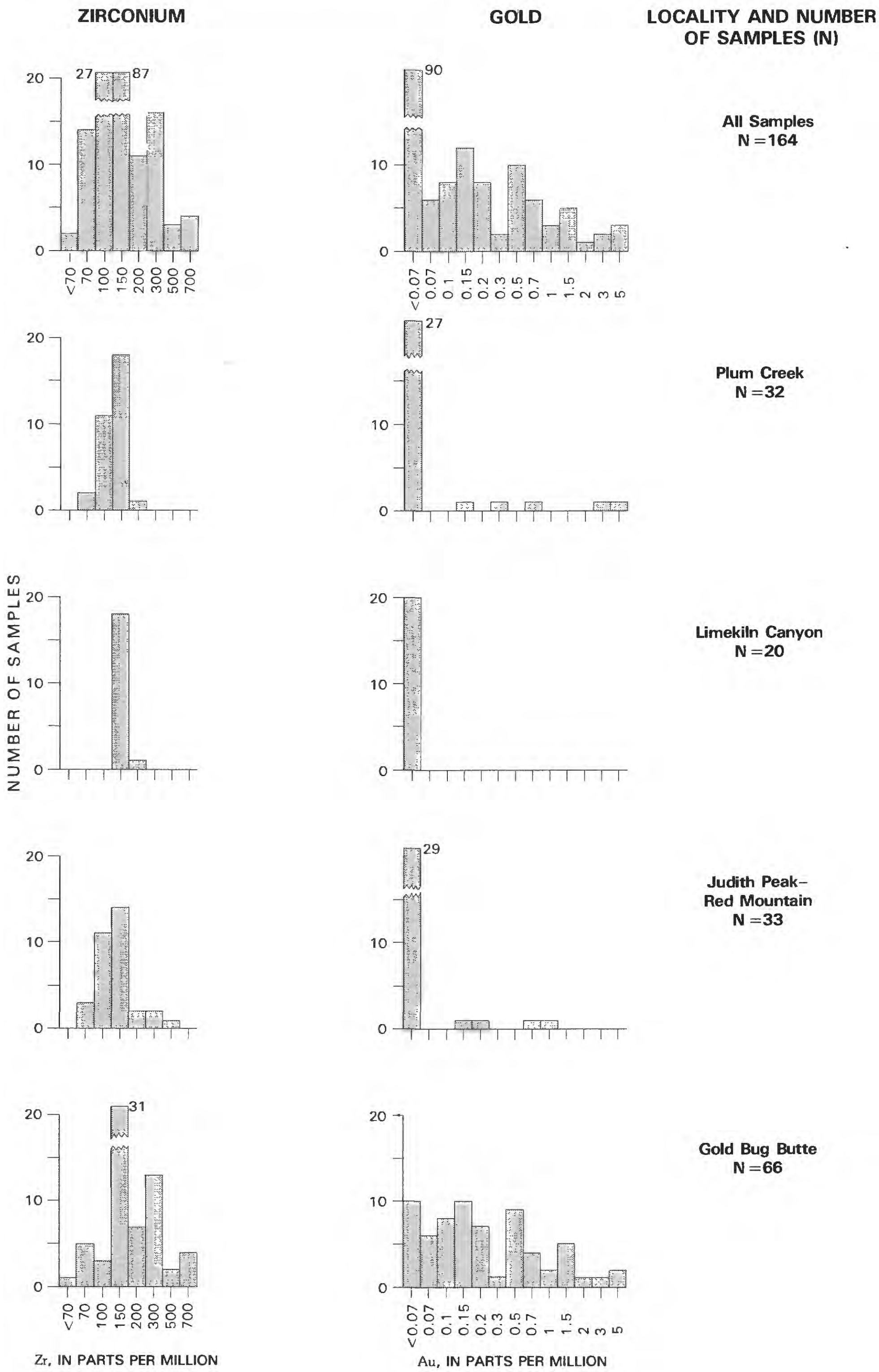
YTTERBIUM
LOCALITY AND NUMBER OF SAMPLES (N)
36
3564
237837
All Samples
N =164
Plum Creek
N =32
Limekiln Canyon
N =20
Judith Peak–
Red Mountain
N =33
Gold Bug Butte
N =66
NUMBER OF SAMPLES
0
10
20
<7 7 10 15 20 30 50 70 100
<1 1 1.5 2 3 5
Y, IN PARTS PER MILLION
Yb, IN PARTS PER MILLION


ZIRCONIUM
GOLD
LOCALITY AND NUMBER OF SAMPLES (N)
All Samples
N = 164
Plum Creek
N = 32
Limekiln Canyon
N = 20
Judith Peak–Red Mountain
N = 33
Gold Bug Butte
N = 66
NUMBER OF SAMPLES
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20
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87
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27
29
31
<70
70
100
150
200
300
500
700
<0.07
0.07
0.1
0.15
0.2
0.3
0.5
0.7
1
1.5
2
3
5
Zr, IN PARTS PER MILLION
Au, IN PARTS PER MILLION

Relation Between Igneous Intrusion and Gold Mineralization in the North Moccasin Mountains, Fergus County, Montana

By DAVID A. LINDSEY *and* CHARLES W. NAESER

STUDIES OF MINERALIZED INTRUSIVE COMPLEXES IN NORTH-CENTRAL MONTANA

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1301-B

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RELATION BETWEEN IGNEOUS INTRUSION AND GOLD MINERALIZATION IN THE NORTH MOCCASIN MOUNTAINS, FERGUS COUNTY, MONTANA

By DAVID A. LINDSEY and CHARLES W. NAESER

ABSTRACT

Gold mineralization in the North Moccasin Mountains probably closely followed emplacement of syenite porphyry. Radial and concentric faults were formed during intrusion of a central laccolith, and these faults became pathways for intrusion of small apophyses of syenite porphyry and for hydrothermal fluids that altered and mineralized the apophyses and fault breccias. The age of emplacement of the main laccolith of syenite porphyry is 66 million years as estimated from seven concordant radiometric dates; this age is only slightly older than the average zircon age of 59 million years for three small apophyses of altered, mineralized porphyry. The zircon age of altered porphyry indicates either (1) the age of intrusion and cooling of apophyses from the main laccolith, or (2) the age of alteration and mineralization by hydrothermal fluids. Either interpretation is consistent with field evidence for control of mineralization by faults formed during intrusion of the main laccolith and hydrothermal alteration and mineralization soon after intrusion. Alteration and mineralization probably did not occur during a thermal event much later than intrusion of the main laccolith.

INTRODUCTION AND ACKNOWLEDGMENTS

The North Moccasin Mountains contain one of three centers of gold mineralization associated with Late Cretaceous-Paleocene intrusive activity in central Montana; the other centers of intrusion and mineralization are the Little Rocky Mountains and the Judith Mountains (Corry, 1933; Marvin and others, 1980; chapter A, this paper). Gold deposits in each area occur as disseminations in intrusive breccia, as fissure fillings in porphyry, in contact zones around porphyry, and in brecciated carbonate rocks. In this report, the results of radiometric dating, mostly by the fission-track method, are discussed in relation to the temporal and spatial relationship between intrusion and mineralization in the North Moccasin Mountains. We acknowledge the help of Ezekiel Rivera, who prepared mineral separates, and Patty Billings, who processed them for fission-track dating; both are employees of the U.S. Geological Survey.

GEOLOGY

The core of the North Moccasin Mountains is a laccolithic dome of syenite porphyry intruded into carbonate rocks below the Mississippian Madison Group (Blixt, 1933; Lindsey, 1982) (fig. 1). Above the Madison Group, a major sill and many small dikes and sills of syenite porphyry intruded strata of Jurassic and Cretaceous age. Small intrusions of syenite porphyry cut the Mississippian Madison Group and connect the main laccolith with the upper zone of intrusions, but the massive limestone of the Madison Group acted in part as a barrier to intrusion. Intrusion of syenite porphyry was accomplished by doming and development of concentric and radial normal faults in the overlying sedimentary rocks. Breccia zones in faults that formed during intrusion served as pathways for intrusion of small sills and dikes of syenite porphyry and for ascent of hydrothermal fluids that altered country rocks and deposited gold. The most extensive alteration and mineralization occurred along a zone of fault breccia and small apophyses of syenite porphyry near the townsite of Kendall. That gold mineralization is described in detail in chapter C.

METHODS OF RADIOMETRIC DATING

The ages of intrusion and gold mineralization were estimated by comparing dates of hydrothermally altered (kaolinized) and mineralized syenite porphyry with those of fresh syenite porphyry (reported by Marvin and others, 1980). Dates of sanidine in fresh rocks were determined by the potassium-argon method and dates of accessory apatite, sphene, and zircon were determined by the fission-track method (Naeser, 1976). Details of dates of fresh syenite porphyry and of one date of altered syenite porphyry have been reported by Marvin and others (1980). New dates of zircon from three samples of altered and mineralized syenite porphyry, and of apatite from two samples of fresh syenite porphyry, are reported here (table 1).

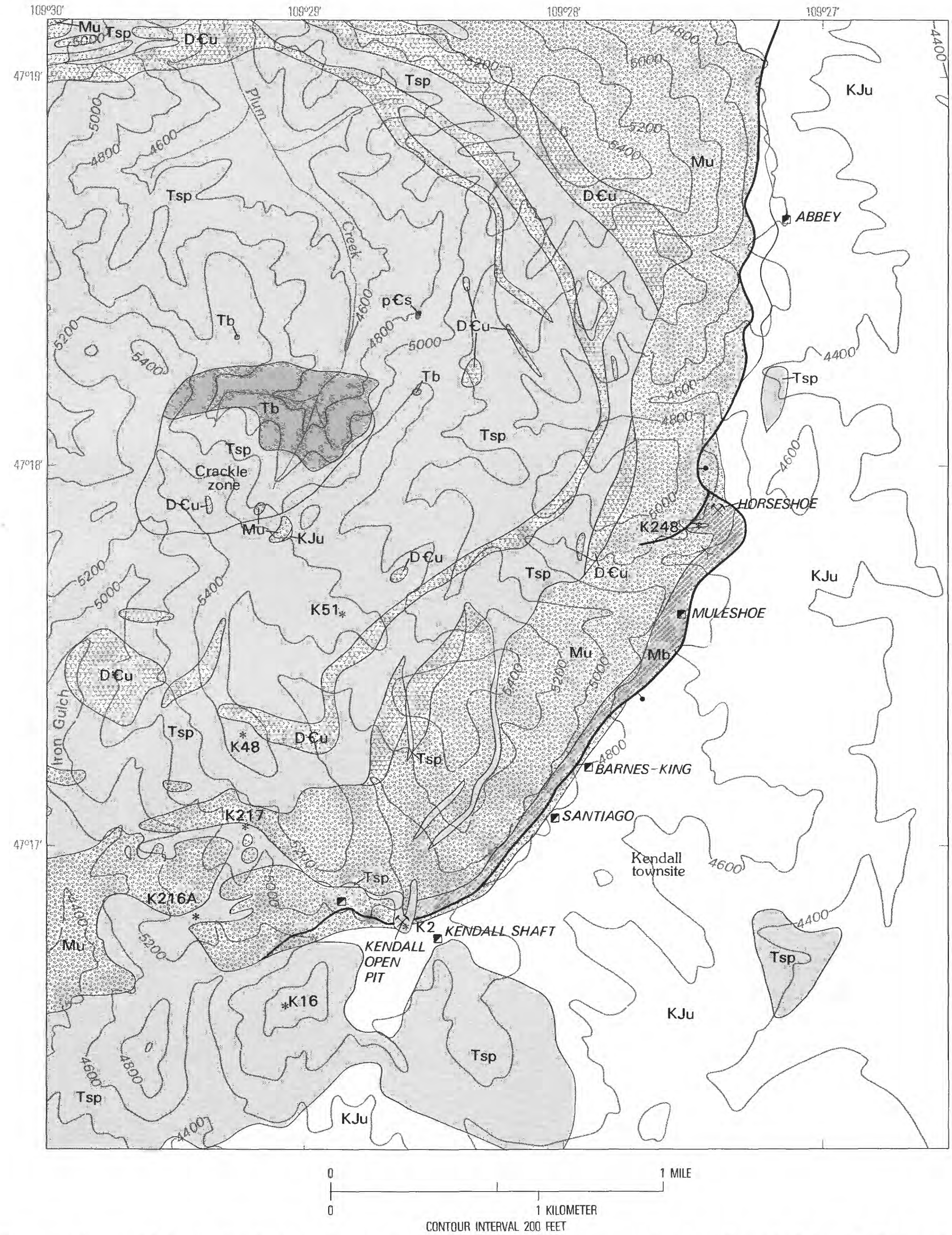

FIGURE 1 (above and facing page).—Geologic setting and localities from which samples were taken for radiometric dating, North Moccasin Mountains, Fergus County, Mont.

EXPLANATION

- Tb — Intrusive breccia (Paleocene?)
- Tsp — Syenite porphyry (Paleocene)
- KJu — Undivided sedimentary rocks (Cretaceous and Jurassic)—Cretaceous Kootenai Formation, Jurassic Morrison Formation and Ellis Group
- Mb — Brecciated and silicified limestone in Madison Group (Mississippian)
- Mu — Undivided sedimentary rocks (Mississippian) Mississippian Kibbey Formation and Madison Group
- D€u — Undivided sedimentary rocks (Devonian and Cambrian)—Devonian Jefferson Formation, Cambrian Pilgrim Limestone, Cambrian unassigned strata, and Cambrian Flathead Sandstone
- p€s — Schist (Precambrian)

- Contact
- Fault, ball and bar on downthrown side
- * Sample locality for radiometric date
- Shaft
- Inclined shaft
- Open pit
- Adit

RESULTS AND DISCUSSION

The age of emplacement of the central laccolith of syenite porphyry in the North Moccasin Mountains is estimated at 66 m.y. (million years), based on two previously published potassium-argon dates of 64.1±1.5 m.y. and 65.8±1.6 m.y. on sanidine, and five previously published fission-track dates ranging from 62.1±3.9 m.y. to 70.9±6.5 m.y. (Marvin and others, 1980) (fig. 2). All the dates are concordant within the ranges of overlap that may be attributed to analytical uncertainty, and the age of emplacement is well established.

An eighth radiometric date, of 39±11 m.y., determined by the fission-track method on apatite from fresh syenite porphyry, is strongly discordant with dates of the other three minerals dated from the same fresh syenite porphyry sample (K48, fig. 2). The date evidently reflects a local, post-emplacement thermal event. South of the mountains, there is evidence for post-emplacement thermal activity that may have reset ages; warm water flows from springs south of The Park and large travertine deposits of Pleistocene age (Lindsey, 1982) crop out in The Park.

Three small plutons of altered and mineralized syenite porphyry, which are probably apophyses of the main laccolith, yield zircon dates that are slightly younger than the estimated age of emplacement. The age of zircon from mineralized porphyry of the small plutons is estimated at about 59 m.y. by averaging concordant fission-track dates of 57.6±3.2, 59.4±3.6, and 59.8±3.1 m.y. A somewhat younger date of 53.5±3.7 m.y. on zircon was reported for one of the plutons (Marvin and others, 1980), but a second determination on the same sample yielded a date of 59.8±3.1 m.y., which is consistent with the other zircon dates of altered porphyry (fig. 2). The 59-m.y. zircon age of altered syenite porphyry is slightly less than, but close to the average of 63 m.y. for zircon from fresh porphyry, based on three dates of 60.5+3.1 m.y. on the south sill, and 62.1±3.9 and 65.5±3.4 m.y. on the main laccolith (fig. 2).

The results permit two interpretations.

1. The zircon dates of altered porphyry in the satellite plutons are primary and therefore represent the age of emplacement of apophyses from the main laccolith. This interpretation is compatible with the close agreement between the age of altered porphyry and the youngest zircon date (60.5±3.1 m.y.) from fresh porphyry, which is from the large sill in the southern part of the mountains. If the dates are primary, thermal effects of post-emplacement hydrothermal fluids were insufficient to reset zircon fission-track dates, and little can be concluded about the age of hydrothermal alteration and gold mineralization in the North Moccasin Mountains except that it followed emplacement of syenite porphyry apophyses about 59 m.y. ago.
2. Alternatively, the zircon dates are secondary, reset by the thermal effects of hydrothermal fluids that deposited gold in the North Moccasin Mountains. If the dates are secondary, they suggest that hydrothermal alteration and mineralization closely followed emplacement about 66 m.y. ago of the main laccolith of syenite porphyry and its apophyses. In order to evaluate this alternative, independent estimates of alteration temperatures are required; such estimates are unavailable. Search of thin sections for fluid inclusions that might be studied to estimate temperatures yielded none suitable for study.

Both interpretations are consistent with field evidence which suggests that alteration and mineralization were structurally controlled by emplacement of syenite porphyry. Faults that formed during intrusion of the main laccolith provided pathways for intrusion of small plutons and for movement of hydrothermal fluids that altered and mineralized both syenite porphyry and adjacent sedimentary rocks. Hydrothermal alteration and gold mineralization probably closely followed intrusion of syenite porphyry. This conclusion is consistent with the sequence of events suggested by radiometric dating of intrusive rocks and gold deposits in the Judith Mountains: the age of most intrusive activity in the Judith Mountains is estimated at about 69–60 m.y., and the age of gold mineralization at the Spotted Horse Mine in the Judith Mountains is estimated at about 59 m.y.

TABLE 1.—*Analytical data for new fission-track dates of syenite porphyry in the North Moccasin Mountains, Fergus County, Mont.*
[Zircon dates by external detector method; apatite age by population method. Neutron dose determined by C. W. Naeser. cm^2, square centimeters; m.y., million years]

Sample No.	Rock description	Sample locality (see also fig. 1)	Mineral dated	Number of grains	Fossil tracks: Number counted	Fossil tracks: Density (tracks/cm^2)	Induced tracks in detector: Number counted	Induced tracks in detector: Density (tracks/cm^2)	Neutron dose (neutrons/cm^2)	Age[1] ±2 (m.y.)
[2]K2	Kaolinized syenite porphyry.	SW1/4NE1/4 sec. 31, T. 18 N., R. 18 E., Kendall open pit.	Zircon---	6	795	$1.38x10^7$	408	$7.08x10^6$	$1.03x10^{15}$	59.8±3.1
[3]K48	Fresh syenite porphyry.	SW1/4SW1/4 sec. 30, T. 18 N., R. 18 E.	Apatite--	100	641	$2.97x10^5$	917	$4.25x10^5$	$9.36x10^{15}$	39±11
K216A	Kaolinized syenite porphyry.	SE1/4NE1/4 sec. 36, T. 18 N., R. 17 E., prospect.	Zircon---	7	965	$1.49x10^7$	514	$7.93x10^6$	$1.03x10^{15}$	57.6±3.2
K217	Fresh syenite porphyry.	NW1/4NW1/4 sec. 31, T. 18 N., R. 18 E.	Apatite--	50	235	$2.18x10^{15}$	218	$2.02x10^5$	$1.03x10^{15}$	66±15
K248	Kaolinized syenite porphyry.	SE1/4NW1/4 sec. 29, T. 18 N., R. 18 E., prospect west of Horseshoe mine.	Zircon---	7	856	$1.37x10^7$	442	$7.08x10^6$	$1.03x10^{15}$	59.4±3.6

[1]Computed using $_D$=1.551x10^{-10}/yr and $_F$=7.03x10^{-17}/yr. $_D$, Total decay constant for ^{238}U; $_F$, decay constant for spontaneous fission of ^{238}U.

[2]Zircon (fission-track) date from same sample, different split, reported as 53.5±3.7 m.y. (Marvin and others, 1980).

[3]Discordant age; other dates on same sample are 64.1±1.5 m.y. (potassium-argon method on sanidine), 62.1±3.9 m.y. (fission-track method on zircon), and 67.4±4.2 m.y. (fission-track method on sphene) (Marvin and others, 1980).

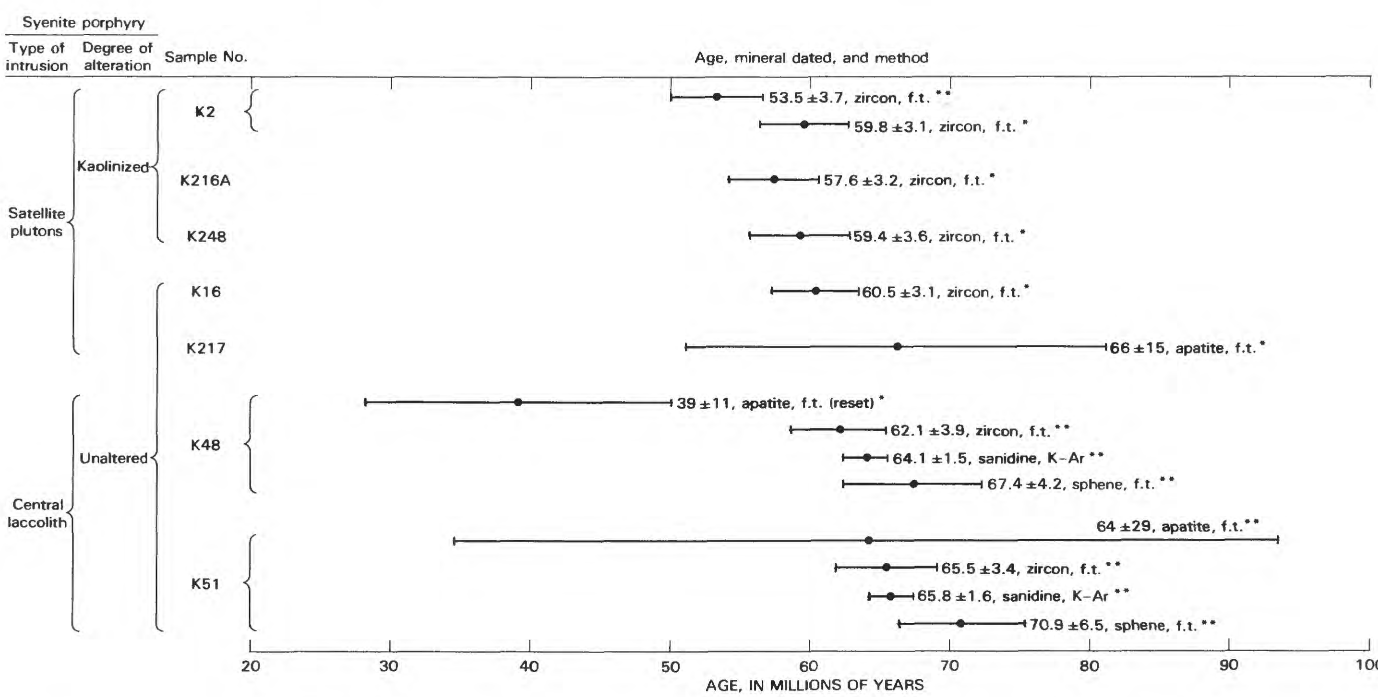

FIGURE 2.—Graph comparing radiometric dates of fresh and hydrothermally altered syenite porphyry, North Moccasin Mountains, Fergus County, Mont. ±2σ values of dates reported by Marvin and others (1980) have been recalculated according to newer statistical methods. f.t, dated by fission-track method; K-Ar, dated by potassium-argon method; *, date reported in this paper; **, date reported by Marvin and others (1980).

(Marvin and others, 1980). Late hydrothermal events, such as those that deposited travertine south of the mountains, cannot be excluded as causes of mineralization at Kendall, but there is no evidence connecting such events with mineralization.

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A Gold-Mineralized Breccia Zone at Kendall, North Moccasin Mountains, Fergus County, Montana

By DAVID A. LINDSEY

STUDIES OF MINERALIZED INTRUSIVE COMPLEXES IN
NORTH-CENTRAL MONTANA

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1301-C

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A GOLD-MINERALIZED BRECCIA ZONE AT KENDALL, NORTH MOCCASIN MOUNTAINS, FERGUS COUNTY, MONTANA

By DAVID A. LINDSEY

ABSTRACT

Kendall is one of three gold-mineralized areas associated with laccolithic porphyry complexes in north-central Montana. Most gold production (about 450,000 ounces) at Kendall was from limestone fault breccia at the top of the Mississippian Madison Group. This breccia was formed by doming and faulting of sedimentary rocks during emplacement of a syenite porphyry laccolith about 66 million years ago. Syenite porphyry magma and hydrothermal fluids from the laccolith invaded the fault zone; hydrothermal fluids leached syenite porphyry, formed silicified limestone fault breccia, and deposited disseminated gold and metal sulfides in both. Low gold contents are widespread in the breccia zone.

The gold-mineralized breccia zone at Kendall contains anomalous arsenic, mercury, and antimony, a geochemical association present in the disseminated gold deposits of northern Nevada. Statistical analysis of geochemical data on oxidized mineralized limestone breccia indicates that mineralizing fluids introduced three separate suites of elements: (1) gold, mercury, vanadium, and antimony; (2) arsenic, iron, zinc, and antimony, probably as sulfides and accompanied by SiO_2; and (3) copper and silver in trace amounts. Gold occurs separately from sulfides and silica, so that the latter two, although conspicuous in outcrop, are not specific indicators of gold ore. Gold mineralization, sulfidization, and silicification by hydrothermal fluids were followed by oxidation of sulfides and concentration of trace lead and manganese, probably during weathering of the mineralized breccia.

INTRODUCTION

About 450,000 oz of gold was produced near Kendall in the North Moccasin Mountains between 1900 and 1923 (Blixt, 1933; Robertson, 1950). Kendall was one of three gold-producing areas associated with laccolithic igneous complexes in north-central Montana; other areas were in the Judith and Little Rocky Mountains (Corry, 1933). The gold-mineralized area at Kendall was studied in detail, with the ultimate goal of developing a model for use in mineral exploration and assessment in north-central Montana. Details of the geologic setting of the Kendall area have been set forth in a map and report (Lindsey, 1982) and the relationship between igneous activity and gold mineralization has been discussed in chapter B of this paper. This last chapter (C) presents a statistical analysis of the geochemistry of the mineralized zone at Kendall, and integrates these data with information on the geologic setting and associated igneous rocks to provide a model of gold mineralization in country rocks of the laccolithic intrusive complexes of north-central Montana.

ACKNOWLEDGMENTS

C. N. Culver assisted with field mapping of the North Moccasin Mountains in 1977; Ezekiel Rivera prepared X-ray diffractograms and mineral separates; R. A. Schaefer assisted in statistical analysis; B. F. Leonard provided advice and help in identifying minerals in polished sections; and R. P. Christian provided electron microprobe analyses. Other members of the U.S. Geological Survey performed chemical anaylyses; they are acknowledged in table 1. James Webb and A. W. Tipton of GeoSurveys Inc. provided information about the Kendall area and samples from the Abbey mine.

GEOLOGIC SETTING

The gold-mineralized zone at Kendall was formed by the intrusive-hydrothermal event that uplifted the North Moccasin Mountains. Uplift began with emplacement of a laccolith of syenite porphyry about 66 m.y. ago (Lindsey, 1982; Marvin and others, 1980). Intrusion of the laccolith was accompanied by emplacement of intrusive breccias, by formation of concentric and radial normal faults in overlying sedimentary rocks, and by intrusion of small plutons along some of these faults. Intrusive breccias in the central part of the laccolith were mineralized by gold-bearing hydrothermal fluids as discussed in chapter A. The mineralized zone at Kendall townsite formed by faulting and intrusion of small dikes and sills along the east side of the range in response to intrusion of the central laccolith. The fault breccias at Kendall were mineralized by gold-bearing hydrothermal fluids, probably soon after intrusion of the central laccolith, as discussed in chapter B.

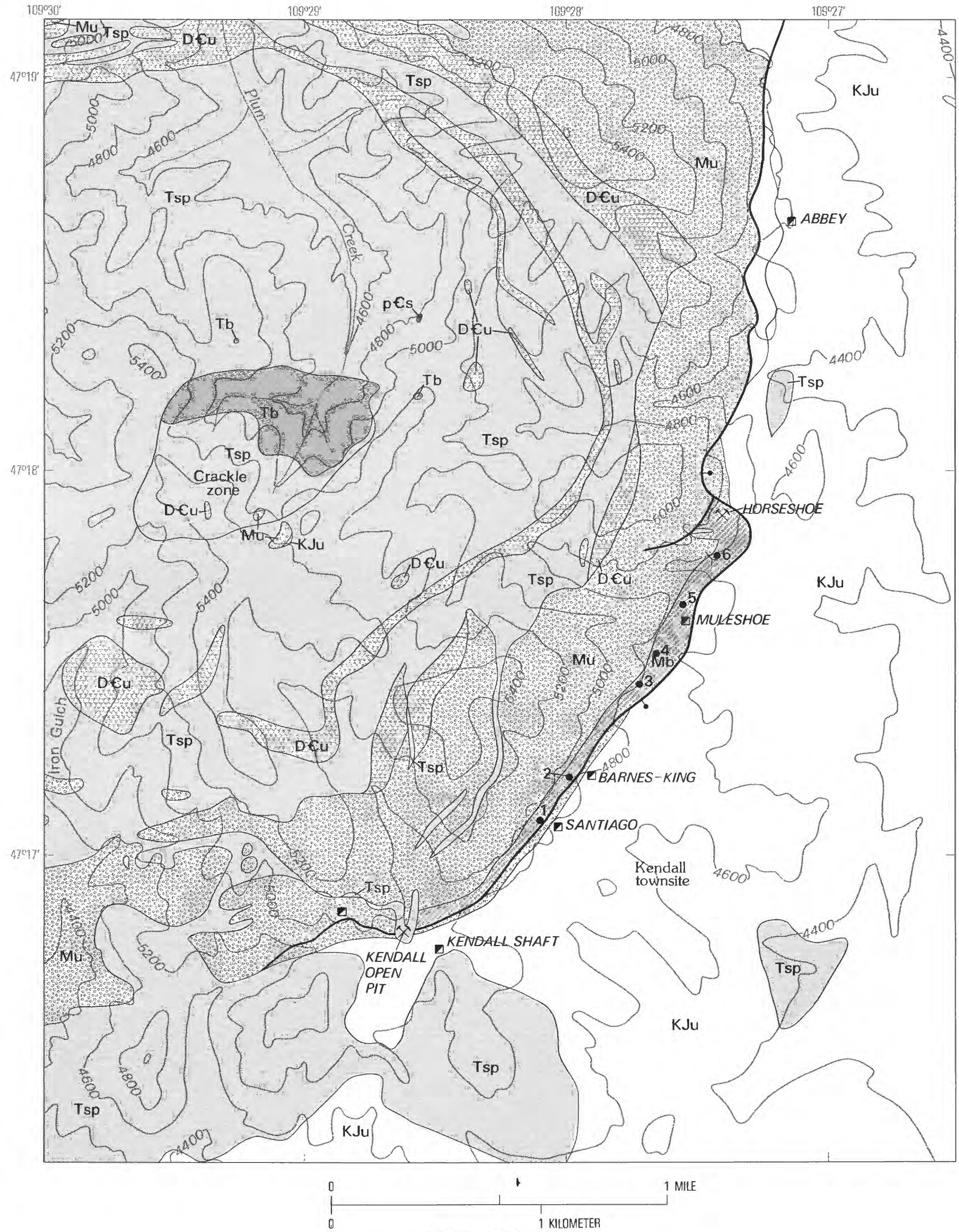

FIGURE 1.—Map showing geologic setting of the Kendall area, North Moccasin Mountains, Fergus County, Mont., and location of open pits sampled for this study.

EXPLANATION

- Tb — Intrusive breccia (Paleocene?)
- Tsp — Syenite porphyry (Paleocene)
- KJu — Undivided sedimentary rocks (Cretaceous and Jurassic)—Cretaceous Kootenai Formation, Jurassic Morrison Formation and Ellis Group
- Mb — Brecciated and silicified limestone in Madison Group (Mississippian)
- Mu — Undivided sedimentary rocks (Mississippian) Mississippian Kibbey Formation and Madison Group
- D€u — Undivided sedimentary rocks (Devonian and Cambrian)—Devonian Jefferson Formation, Cambrian Pilgrim Limestone, Cambrian unassigned strata, and Cambrian Flathead Sandstone
- Schist (Precambrian)
- Contact
- Fault, ball and bar on downthrown side
- Shaft
- Inclined shaft
- Open pit
- Adit

The mineralized zone at Kendall extends as much as 3.5 km along a normal fault that is concentric to the syenite porphyry laccolith and mostly parallel to bedding in adjacent sedimentary rocks (fig. 1) (Lindsey, 1982). Surface exposures of the mineralized zone are oxidized and consist mainly of silicified, rusty-weathering limestone breccia in the uppermost part of the Madison Group and of minor rusty-weathering kaolinized porphyry. Black, unoxidized limestone ore is reported at depth (Blixt, 1933, p. 21). Blixt (1933) believed that the mineralized zone was controlled by bedding-plane faults and by favorable beds in the uppermost part of the Madison Group; new mapping (Lindsey, 1982) showed that the zone is fault-controlled at the surface, although the dip of the fault and its relation to underground workings are unknown. Underground workings at Kendall are reported to follow argillaceous and carbonaceous limestone in the uppermost Madison Group (Blixt, 1933); however, such beds crop out at the surface only in the lower part of the Jurassic Piper Formation, and these are mineralized in the Abbey mine. The structure and stratigraphy of the subsurface need to be re-examined before these inconsistencies can be resolved, but a reasonable supposition is that the mineralized zone follows fault breccia and extends into adjacent favorable strata such as carbonaceous limestone in the lower part of the Piper Formation.

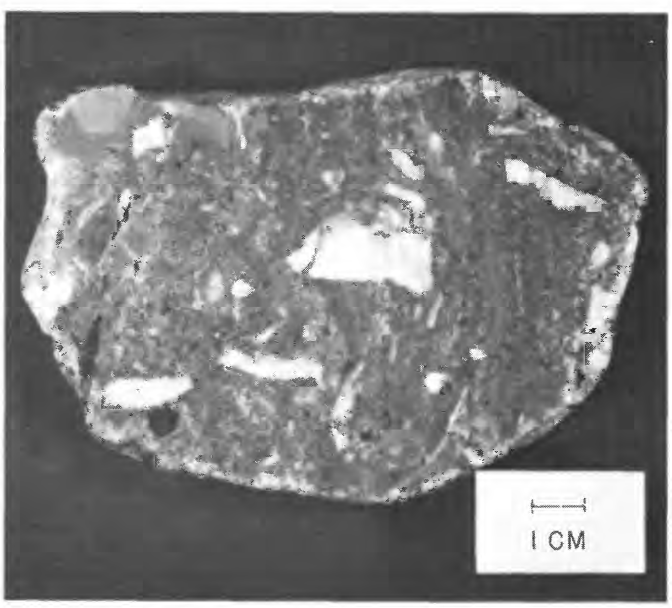

FIGURE 2.—Photograph of oxidized, mineralized limestone breccia, showing fragments of silicified limestone and coarsely crystalline calcite in a matrix of calcite and quartz.

DESCRIPTION OF MINERALIZED ROCKS

OXIDIZED LIMESTONE BRECCIA

Silicified rusty limestone breccia is the most abundant rock in the mineralized zone (fig. 2). It consists mostly of angular fragments of limestone from the Madison Group, fragments of coarsely crystalline calcite derived from fracture fillings, and, locally, fragments of sandstone from the Mississippian Kibbey Formation—all are set in a cement of mostly calcite and quartz. Limestone fragments in the breccia are variably silicified and some contain limonite, magnetite, and traces of pyrite. The breccia cement varies from clear, coarsely crystalline calcite to a mixture of calcite and quartz (both microcrystalline and chalcedonic forms) and generally contains traces of dolomite, fluorite, barite, and clay, as shown by X-ray diffraction and thin-section study. Some quartz cement is quite late in the paragenetic sequence because it fills cavities and appears to replace calcite; other quartz is confined only to silicified limestone fragments and appears to have been deposited prior to brecciation. Likewise, coarsely crystalline calcite appears as both cement and fragments, indicating that calcite cement was deposited in open spaces both before and after brecciation. Limonite, a few partially oxidized remnants of pyrite, traces of goethite after pyrite, and traces of sphalerite—all identified in polished sections—are found mainly in fractures, interstices of the cement, and along the margins of clasts; no gold was observed in polished sections. Qualitative electron microprobe analyses showed the pyrite to be nearly pure, and the sphalerite to contain abundant iron and arsenic. Accessory heavy minerals, concentrated from breccia containing about 10–11 ppm gold, proved to be mainly limonite, fluorite, and barite; gold was not visible in the mineral concentrates, but gold was detected in a fluorite-rich concentrate by energy dispersive X-ray spectrometry.

UNOXIDIZED LIMESTONE

Unoxidized rock from the lower part of the breccia zone was not available for study, but unoxidized gold-bearing limestone from the Abbey mine, located north of the mineralized zone, was examined as a possible analog to the unoxidized part of the breccia zone. Unoxidized gold-bearing rock from the Abbey consists of thin-bedded black, microcrystalline limestone from the lower part of the Piper Formation; three samples contained 0.32–1.43 ppm gold and almost no other ore metals (Lindsey, 1982, table 3). Study of polished thin sections revealed finely crystalline calcite, scattered quartz silt, minor dispersed fluorite, and fine-grained (less than 10 microns across) interstitial pyrite having both euhedral and ragged forms; in one specimen, very fine grained pyrite crystals less than 1 micron across and organic carbon outline oval, calcite-filled voids and form flattened, discontinuous laminae; these features may be relict shell fragments. No gold was seen. Microprobe analysis of interstitial pyrite shows most to be nearly pure; as much as 4 percent arsenic was detected in a few grains. No metals except iron were detected by microprobe analysis of very fine pyrite in cavities.

ALTERED SYENITE PORPHYRY

Hydrothermally altered syenite porphyry occurs as small irregular sills and dikes in and near the fault zone of limestone breccia at Kendall; these are believed to be apophyses of the main laccolith. Some of the syenite porphyry is brecciated near its contact with limestone breccia. Altered porphyry is tan to white and is composed mainly of kaolinite (identified by X-ray diffraction), partly altered feldspar phenocrysts, and rusty specks of iron oxides after pyrite. Porphyritic texture is evident; feldspar phenocrysts are partly altered to kaolinite and ferromagnesian phenocrysts are completely altered to sericite and iron oxides. Altered porphyry has low gold values (Lindsey, 1982; chapter A, this report). Chemical analyses of altered and fresh syenite porphyry (samples K–2 and K–51, Lindsey, 1982, table 1) show that altered porphyry has lost most of its former content of iron, alkalis, and alkaline earth metals, leaving a residue of mainly quartz and kaolinite.

GEOCHEMISTRY OF OXIDIZED LIMESTONE BRECCIA

SAMPLING METHODS

The fault zone of mineralized limestone breccia at Kendall was sampled to determine the nature of alteration and geochemical anomalies in the district. Six open pits (fig. 1) in mineralized breccia were sampled by random methods according to a barbell design (fig. 3). In

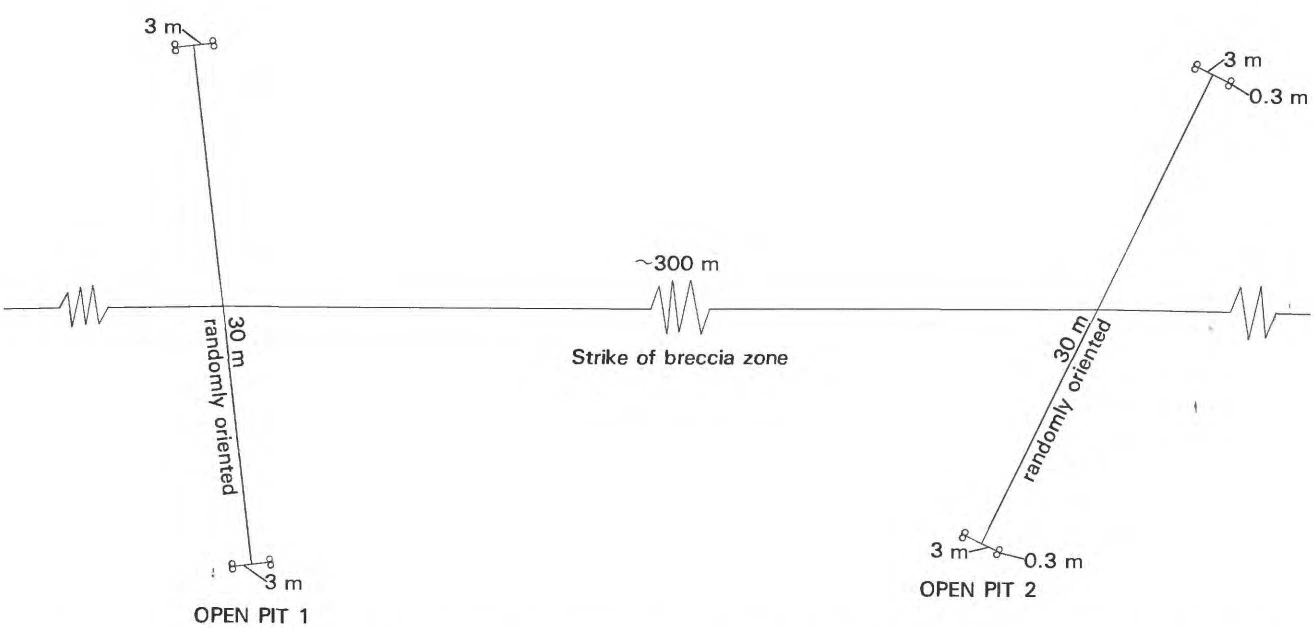

FIGURE 3.—Sampling plan for open pits in mineralized breccia zone at Kendall, Mont. Six open pits were sampled. Sites at which two samples were collected 0.3 m apart are designated by "8."

all, 48 samples of limestone breccia were collected; each sample consisted of about 0.5 kg (kilogram) of rock chips taken from an area of about 0.1 m^2. Twenty-four of the samples were selected at random and split. These splits, together with the other 24 samples (76 samples total), were placed in random order prior to chemical analysis.

Sampling of the freshest mineralized rock available from surface exposures may provide reliable information about the entire mineralized zone at Kendall, but sampling of the subsurface parts of the zone will ultimately be needed to test the data and conclusions presented here. With respect to estimating the gold content of the Kendall deposits, the sampling is biased in that (1) sampling was restricted to open pits where mineralized rock could be obtained, (2) early mining probably removed the best ore, and (3) only oxidized rock was available for sampling. Most of the rock sampled proved not to be of ore grade, but to be altered rock with low gold contents.

CHEMICAL COMPOSITION AND VARIATION

The overall chemical composition of the mineralized limestone breccia varies widely from nearly pure calcite (as much as 58.5 percent CaO) to about half calcite (24.3 percent CaO) and half quartz (as much as 52.9 percent SiO_2) (table 1). Other major rock-forming elements generally make up less than 1–2 percent of the breccia. Total iron as Fe_2O_3, representing mostly the presence of pyrite and its oxidation products, and MgO, present in calcite, are the most abundant minor constituents. The quantity of SiO_2 and iron in breccia is a function of the degree of alteration of originally nearly pure limestone.

Much of the mineralized breccia contains small amounts of gold; of 48 samples, 34 contained gold in quantities at or above the limit of analytical detection (0.05 ppm) (table 2). Typical gold values are extremely low (geometric mean of 0.12 ppm) as is the average grade (arithmetic mean of 0.7 ppm), but variation of gold content in the mineralized breccia is large, with a measured maximum concentration of 11.7 ppm; in comparison, the ores mined previously contained about 4–10 ppm (Blixt, 1933, p. 20).

The breccia contains a number of trace metals and elements that might be expected to be associated with gold and sulfide ores; compared with unmineralized limestone, arsenic, mercury, antimony, zinc, silver, vanadium, lead, thallium, and possibly barium are present in anomalous but trace quantities (table 1). The presence of anomalous concentrations of arsenic, mercury, antimony, and thallium is noteworthy; this geochemical association is characteristic of disseminated gold deposits in northern Nevada (Erickson and others, 1966; Wells and others, 1969; Radtke and others, 1972; Radtke and Dickson, 1974).

TABLE 1.—*Summary statistics for chemical composition of 48 samples of mineralized limestone breccia, Kendall area, Northern Moccasin Mountains, Mont.*

[SiO_2, Al_2O_3, total Fe as Fe_{O3}, CaO, TiO_2, MnO, P_2O_5, Cl and total S by X-ray fluorescence by J. S. Wahlberg; MgO, Na_2O, and K_2O by atomic absorption by V. M. Merritt; As by graphite furnace-atomic absorption method by J. G. Crock; Au by fire assay-atomic absorption method by A. W. Haubert, L. M. Lee, and Claude Huffman, Jr.; Hg by wet oxidation-atomic absorption method by J. A. Thomas and G. O. Riddle; Sb by Rhodamine-B method by G. T. Burrow; Zn by atomic absorption by J. G. Crock; all other elements by six-step semiquantitative spectrographic method by H. G. Neiman; elements looked for but not found, with lower limits of detection are: P_2O_5 (0.10 pct), Cl (0.010 pct), total S (0.04 pct), Bi (10 ppm), Cd (20 ppm), Ce (200 ppm), Eu (100 ppm), Ga (5 ppm), Ge (10 ppm), Hf (100 ppm), In (10 ppm), La (30 ppm), Nb (10 ppm), Pd (1 ppm),Pt (30 ppm), Re (100 ppm), Sn (10 ppm), Ta (200 ppm), Te (2000 ppm), Th (200 ppm), U (1000 ppm), and W (100 ppm); leaders (---) indicate not calculated because of insufficient values above limit of detection]

Oxide or element	Number of samples below limit of detection	Lower limit of detection	Geometric mean[1]	Geometric deviation	Range
Chemical composition, in weight percent					
SiO_2	0	0.2	8.4	2.23	2.1-52.9
Al_2O_3	9	0.2	0.5	2.51	<0.2-3.4
Total Fe as Fe_2O_3	0	0.02	0.28	2.32	0.04-1.55
MgO	0	0.01	0.31	1.53	0.10-1.09
CaO	0	0.1	48.9	1.21	24.3-58.5
Na_2O	0	0.01	0.03	1.30	0.02-0.05
K_2O	0	0.01	0.15	1.96	0.04-0.77
TiO_2	23	0.02	0.02	2.04	<0.02-0.12
MnO	3	0.02	0.10	1.96	<0.02-0.22
Chemical composition, in parts per million					
As	0	0.1	63	2.93	2.7-480
Au	14	0.05	0.12	5.76	<0.05-11.7
Hg	0	0.01	0.10	2.35	0.01-1.25
Sb	[2]4	0.1	5	2.26	0.4->15
Zn	0	5	112	2.00	27-425
Ag	15	0.5	1	3.68	<0.5-20
B	47	10	---	---	<10-10
Ba	0	1.5	64	4.39	3-5,000
Be	47	1	---	---	<1-1
Co	45	3	---	---	<3-3
Cr	0	1	9	1.87	2-30
Cu	6	1	2	2.41	<1-20
Li	47	50	---	---	<50-70
Mo	41	3	---	---	<3-5
Ni	20	5	3	2.41	<5-15
Pb	1	10	47	1.99	<10-200
Sc	36	3	---	---	<3-7
Sr	0	5	184	1.75	30-500
Tl	37	50	---	---	<50-300
V	0	7	28	1.82	10-200
Y	40	10	---	---	<10-10
Yb	45	1	---	---	<1-1
Zr	19	10	10	1.95	<10-150

[1]Geometric mean for censored distributions computed by method of A. C. Cohen (Miesch, 1967).

[2]Four samples above limit of detection of 15 ppm.

The spatial variation in chemical composition of the breccia, particularly of the content of gold and other metals, is of interest in exploring and evaluating the gold-mineralized zone at Kendall and similar occurrences elsewhere. Variation in the composition of the breccia is defined by a five-level nested analysis-of-variance design (Krumbein and Graybill, 1965, p. 205–218)

TABLE 2.—*Gold content in mineralized limestone breccia at Kendall, Mont.*

[Analyses by fire assay-atomic absorption method by A. W. Haubert, L. M. Lee, and Claude Huffman, Jr. Sample numbers ending in "B" are splits of those ending in "A". Open-pit localities are shown on figure 1. ppm, parts per million]

	Sample No.	Au (in ppm)		Sample No.	Au (in ppm)		Sample No.	Au (in ppm)
Open pit 1:	3111A	0.87	Open pit 3:	5111A	0.05	Open pit 5:	7111A	1.50
	3112A	0.23		5111B	<0.05		7112A	0.30
	3112B	0.24		5112A	<0.05		7112B	0.30
	3121A	0.37		5121A	<0.05		7121A	1.20
	3121B	0.33		5121B	<0.05		7122A	0.90
	3122A	0.10		5122A	<0.05		7122B	0.87
	3211A	0.30		5122B	<0.05		7211A	0.14
	3212A	0.30		5211A	<0.05		7211B	0.13
	3221A	<0.05		5212A	0.07		7212A	0.18
	3222A	0.15		5221A	<0.05		7212B	0.15
				5222A	0.15		7221A	0.21
Open pit 2:	4111A	11.70		5222B	0.13		7222A	0.22
	4112A	10.90					7222B	0.21
	4112B	11.00	Open pit 4:	6111A	0.10			
	4121A	0.25		6112A	0.06	Open pit 6:	8111A	<0.05
	4121B	0.22		6121A	0.08		8112A	<0.05
	4122A	0.50		6121B	0.08		8112B	<0.05
	4211A	0.17		6122A	<0.05		8121A	<0.05
	4211B	0.17		6122B	<0.05		8122A	0.05
	4212A	0.25		6211A	0.35		8211A	<0.05
	4221A	0.17		6211B	0.30		8211B	<0.05
	4221B	0.23		6212A	0.29		8212A	<0.05
	4222A	0.60		6212B	0.31		8212B	<0.05
				6221A	0.07		8221A	<0.05
				6222A	0.41		8221B	<0.05
							8222A	<0.05
							8222B	<0.05

that follows the sampling plan of figure 2. The model for variation in the mineralized zone is:

$$x_{ijkmn}=\mu+\alpha_i+\beta_{ij}+\gamma_{ijk}+\delta_{ijkm}+\epsilon_{ijkmn}$$

where x_{ijkmn} is the nth value on the mth sample taken of a pair 0.3 m apart, in the kth sampling site of a pair 3 m apart, in the jth sampling area of a pair 30 m apart, and in the ith open pit in the mineralized zone. Each value (x_{ijkmn}) is equal to the sum of the grand mean (μ) of all values modified by deviations representing compositional variation among open pits about 300 m apart (α_i), between sampling areas 30 m apart (β_{ij}), between sampling sites 3 m apart (γ_{ijk}), between samples 0.3 m apart (δ_{ijkm}), and between splits (ϵ_{ijkmn}); where i is as high as 6 and j, k, m, and n are as high as 2.

The preceding analysis-of-variance design was used to partition the variance into four distance-related components. The analysis assumes that x_i, x_{ij}, x_{ijk}, x_{ijkm}, and x_{ijkmn} are random variables with means of zero and variances of s_α^2, s_β^2, s_γ^2, s_δ^2, and s_ϵ^2, that are additive: $s_T^2=s_\alpha^2+s_\beta^2+s_\gamma^2+s_\delta^2+s_\epsilon^2$ where s_T^2 is the total variance; s_α^2 is the variance among open pits 300 m apart; s_β^2, s_γ^2, and s_δ^2 are the variances that represent sampling 30 m, 3 m, and 0.3 m apart, respectively; and s_ϵ^2 is the variance due to laboratory procedures such as splitting, grinding, and analysis. The variance components s_α^2, s_β^2, s_γ^2, and s_δ^2 provide insight to the scale of variation in the mineralized zone.

Estimates of the variance in chemical composition of the mineralized zone show that most constituents vary a great deal at distances of about 30 m or less, but that four elements— manganese (as MnO), gold, mercury, and chromium—have relatively large variance components among the open pits, which average about 300 m apart (table 3). This conclusion is somewhat tentative, however, because the variance components estimated for these elements are not quite significant at the 0.05 level. For gold, 44 percent of the variance reflects differences among open pits; most of the remaining variance (41 percent) is distributed among sites 30 m apart and 3 m apart. The analysis shows that gold is the most likely of all elements studied to be concentrated in blocks of ground greater than 30 m across; such blocks might have a reasonable chance of being detected by a sampling density that takes such large-scale variation into account. The large-scale component of variance is readily apparent from a scan of the gold content (table 2); localities 1, 2, 4, and 5 (fig. 1) account

TABLE 3.—*Estimates of total variance and components of variance for major oxides and trace elements in mineralized limestone breccia at Kendall, Mont.*

[Analysis of variance performed after transformation of all data to logarithms; five-level analysis of variance design. Asterisk (*), variance of MnO among open pits is significant at the 0.13 level; of Au, at the 0.07 level; of Hg, at the 0.23 level; and of Cr, at the 0.22 level. pct, percent; ppm, parts per million; T-Fe_2O_3, total Fe as Fe_2O_3]

Oxide or trace element	Total variance	Components of variance as percent of total variance				
		Among open pits (300 m apart)	Among areas (30 m apart)	Among sites (3 m apart)	Among samples (0.3 m apart)	Among sample splits
	as $(\log pct)^2$					
SiO_2	0.117	0	24	6	69*	1
Al_2O_3	0.146	0	27	1	30*	42
T-Fe_2O_3	0.169	0	65*	0	34*	<1
MgO	0.038	0	61*	7	32*	<1
CaO	0.007	1	0	13	85*	1
Na_2O	0.014	0	25	30*	14	31
K_2O	0.098	0	54*	0	45*	1
TiO_2	0.063	0	49*	0	47*	4
MnO	0.113	39	42*	2	17*	<1
	as $(\log ppm)^2$					
As	0.305	0	64*	4	26*	6
Au	0.441	44	19	22*	14*	<1
Hg	0.142	21	32	21*	21*	5
Sb	0.160	0	63*	12	20*	5
Zn	0.140	0	69*	0	31*	<1
Ag	0.296	0	70*	3	21*	6
Ba	0.447	0	36*	7	55*	2
Cr	0.068	16	24*	0	48*	12
Cu	0.189	0	63*	2	31*	4
Ni	0.037	0	14	0	70*	16
Pb	0.137	0	59*	0	34*	7
Sr	0.069	9	2	18	0	71
V	0.083	1	48*	14	21*	16
Zr	0.081	0	61*	3	27*	9

for most of the high values. The variation in readily observable features such as degree of silicification (SiO_2) is only local (69 percent at a scale of 0.3 m), so that the proportion of quartz (SiO_2) in the breccia appears to be a poor guide to ore. Variance of trace elements that might serve as pathfinders for gold is also mainly local, with the possible exception of manganese and mercury, which have large-scale variance components of 39 and 21 percent, respectively.

The variance due to analytical uncertainty is of importance in evaluating covariation among elements, a topic to be examined next. Variance among splits is large only for Al_2O_3, strontium, and perhaps, Na_2O; correlations among these elements must be interpreted with caution because of the high component of error variance.

FACTOR ANALYSIS OF GEOCHEMICAL DATA

The chemical composition of the mineralized breccia zone, and the variation within that zone, is the result of several geochemical processes. A complete list of these processes and the effects that they have had on the composition of the rock would serve as a geochemical model of the breccia, and would serve to identify the effects of hydrothermal mineralization on chemical composition. Such processes may be thought of as factors, and a general model for the effect of the factors on the concentration of an element measured in the breccia zone is:

$$x_{ji}=\alpha_{j1}F_{1i}+\alpha_{j2}F_{2i}+\cdots+\alpha_{jp}F_{p1}+\alpha_{j}U_{ji}$$

where x_{ji} is the chemical concentration of the ith sample for the *j*th element, and is assumed to be a linear function of *p* common factors (*F*) operating with intensities ofα_{j1} through α_{jp}. U_{ji} is a unique factor introduced to account for the variation unexplained by the model (Cooley and Lohnes, 1962, p. 160). To illustrate, x_{ji} may represent the observed amount of gold in a sample *i*; the amount of gold in the sample is assumed to be a function of various factors (F's) operating at various intensities (α 's). In this study, the parameters (α' s, F's) in the model are estimated by *R*-mode factor analysis.

The method of *R*-mode factor analysis (Harman, 1960; Cooley and Lohnes, 1962, p. 151–172; Miesch and others, 1966) involves four steps; (1) an $m \times m$ correlation matrix (*R*-matrix) is computed, where *m* is the number of measured variables—in this case oxides and elements; (2) the *R*-matrix is solved for *m* roots (eigenvalues) and a number of roots (*p*) is selected as the minimum number needed to account for a reasonable percent of the total variance; (3) an initial matrix of factor loadings defines the principal (uncorrelated) components of the system; and (4) a final matrix of factor loadings is derived from the initial matrix by the Varimax criterion. These loadings are then taken as the intensities (α's) of the equation for the model.

Principal-components analysis (step 3) may be visualized in terms of *m*-dimensional space, where *m* is the number of original variables. Each variable defines an axis in the *m*-space and the position of each of *N* samples can be plotted in terms of the *m*-axes. Commonly, the *N* samples will tend to cluster as an elongate swarm of points in the *m*-space. The object of the principal-components analysis is to define new, uncorrelated variables (axes). The first principal component is positioned along the major axis of the sample cluster so that the sample projections onto it are minimized. This axis defines a new variable that describes the largest proportion of the variance in the data. A second axis is located at right angles to the first but in a direction such that the next largest proportion of variance is explained, and so on. Although as many as *m* axes are possible, some number $p<m$ generally will account for most of the variance. The variances of the new variables, the principal components, are their eigenvalues. The relationship between the principal components and the original variables is defined by a matrix of factor loadings (α's).

Commonly, the principal-components axes in *p*–space are rotated in order to interpret the new variables (step 4). The method of rotation used here is the Varimax criterion (Harman, 1960, p. 301), which requires that the variance of the squared factor loadings be maximized. Rotation simplifies interpretation of the factors because it tends to yield large positive or negative loadings for only a few variables on each Varimax axis; the rest of the variables tend to have extremely small loadings. The resulting Varimax factor loadings specify the relationship of the original variables to the *p* Varimax axes, which are then interpreted as factors. Because only $p<m$ axes are retained in the Varimax solution, less than 100 percent of the total variance for each variable is accounted for; the percentage accounted for is called the communality (h^2) and is a measure of how well the solution explains the original data. The remaining, unexplained variance ($1-h^2$) is the unique component (U_{ji}); it consists of variance caused by unrecognized factors and by error.

A correlation matrix was computed for those 23 oxides and elements for which the majority of samples were above the limit of analytical detection (table 4). The 23×23 *R*-matrix (table 4), with unities in the diagonal, was used for the factor analysis. Three criteria were used to select the number of principal components for rotation and interpretation. (1) The eigenvalues for the first 10 principal components were compared to determine which components were relatively large; the first five eigenvalues appear to be markedly larger than the others and the first five principal components account for 77 percent of the cumulative variance (fig. 4). As a first approximation, a solution containing five principal components was considered for rotation. (2) The sum of the non-error variances (table 3) was compared with the communalities of various solutions; a five-factor model (table 5*A*) has high communalities that explain most of the non-error variance of the system. The communalities of most variables, except Al_2O_3 and strontium, do not exceed the non-error variance. (3) Finally, the five-factor solution appears amenable to geochemical interpretation.

A five-factor model accounts for a reasonably high proportion of the variance of all chemical oxides and elements except nickel and barium (table 5*A*). The model is interpreted in genetic terms (table 5*B*) and contains the following factors or processes.

Factor 1 (Gold, mercury, vanadium and antimony).—Concentration of these elements probably occurred during hydrothermal alteration and mineralization of the limestone breccia. Arsenic, which occurs in anomalous quantities, is not strongly correlated with gold (r=0.27) and hence does not appear in factor 1. The strong association of vanadium with gold at Kendall may be due to its presence in roscoelite, a vanadium mica that occurs also in gold-bearing fluorite veins at the Spotted Horse and other mines in the Judith Mountains (Corry, 1933).

Factor 2 (K_2O, TiO_2, zirconium, chromium, Al_2O_3, nickel, and Na_2O).—These elements are among the main constituents of clastic minerals such as feldspar, clay, mica, iron-titanium oxides, and zircon; chromium

TABLE 4.—*Correlation coefficients between major oxides and trace elements in mineralized limestone breccia, Kendall, Mont.*

[Linear correlation coefficients were computed from logarithms of original data; T-Fe_2O_3, total Fe as Fe_2O_3]

	SiO_2	Al_2O_3	T-Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	As	Au	Hg	Sb	Zn	Ag	Ba	Cr	Cu	Ni	Pb	Sr	V	Zr
SiO_2	1.00	0.57	0.66	-0.60	-0.84	0.39	0.52	0.43	0.02	0.61	0.37	0.56	0.55	0.58	0.43	0.11	0.47	0.61	0.46	0.21	-0.17	0.57	0.44
Al_2O_3	---	1.00	0.43	-0.10	-0.51	0.56	0.82	0.73	0.12	0.29	0.36	0.43	0.30	0.41	0.47	0.31	0.60	0.49	0.49	0.26	0.14	0.49	0.59
T-Fe_2O_3	---	---	1.00	-0.36	-0.53	0.21	0.48	0.44	0.30	0.89	0.31	0.48	0.72	0.81	0.32	0.01	0.33	0.55	0.59	0.43	-0.17	0.56	0.41
MgO	---	---	---	1.00	0.46	-0.11	0.04	0.20	0.09	-0.45	-0.13	-0.33	-0.33	-0.27	-0.28	0.35	-0.07	-0.41	-0.08	-0.05	0.47	-0.27	0.07
CaO	---	---	---	---	1.00	-0.52	-0.38	-0.42	0.18	-0.49	-0.44	-0.54	-0.44	-0.47	-0.35	0.11	-0.34	-0.49	-0.45	-0.18	0.19	-0.44	-0.32
Na_2O	---	---	---	---	---	1.00	0.53	0.44	-0.45	0.15	0.28	0.22	0.00	0.04	0.14	0.08	0.56	0.25	0.30	-0.28	0.19	0.30	0.33
K_2O	---	---	---	---	---	---	1.00	0.80	0.16	0.29	0.39	0.40	0.24	0.42	0.46	0.13	0.80	0.54	0.58	0.22	0.30	0.59	0.70
TiO_2	---	---	---	---	---	---	---	1.00	0.16	0.33	0.37	0.37	0.31	0.43	0.29	0.03	0.60	0.37	0.47	0.24	0.28	0.56	0.80
MnO	---	---	---	---	---	---	---	---	1.00	0.25	0.30	0.26	0.48	0.27	0.20	0.20	-0.10	0.15	0.05	0.51	-0.07	0.26	0.08
As	---	---	---	---	---	---	---	---	---	1.00	0.27	0.49	0.72	0.77	0.31	0.00	0.26	0.52	0.49	0.41	-0.29	0.55	0.31
Au	---	---	---	---	---	---	---	---	---	---	1.00	0.83	0.60	0.29	0.30	0.02	0.25	0.30	0.34	0.28	0.09	0.67	0.10
Hg	---	---	---	---	---	---	---	---	---	---	---	1.00	0.72	0.51	0.40	0.04	0.24	0.49	0.48	0.37	-0.02	0.65	0.16
Sb	---	---	---	---	---	---	---	---	---	---	---	---	1.00	0.70	0.38	0.06	0.09	0.49	0.48	0.53	-0.05	0.58	0.17
Zn	---	---	---	---	---	---	---	---	---	---	---	---	---	1.00	0.45	0.21	0.39	0.60	0.57	0.67	-0.05	0.53	0.36
Ag	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.00	0.21	0.47	0.79	0.31	0.59	-0.07	0.46	0.22
Ba	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.00	0.19	0.17	0.15	0.21	-0.03	0.09	-0.04
Cr	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.00	0.50	0.53	0.17	0.28	0.58	0.52
Cu	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.00	0.54	0.52	-0.01	0.55	0.29
Ni	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.00	0.33	0.39	0.48	0.38
Pb	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.00	-0.02	0.29	0.02
Sr	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.00	0.11	0.27
V	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.00	0.42
Zr	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.00

and nickel would be expected to be present in iron-titanium oxides. Concentration of these minerals probably occurred by accumulation of terrigenous detritus in lime mud of the Mississippian Madison sea; if so, then elements having high loadings on factor 2 have little relationship to mineralization.

Factor 3 (MgO, CaO, and strontium versus arsenic, total iron as Fe_2O_3, SiO_2, zinc, and antimony).—MgO, CaO, and strontium are components of the carbonate breccia which, when mineralized, was depleted in these elements and enriched in silica and sulfides containing iron (as pyrite), arsenic, zinc (as sphalerite), and antimony. Copper also was concentrated somewhat by factor 3. Subsequent oxidation of mineralized breccia produced the rusty-brown silicified breccia of the mineralized zone. High positive and negative loadings of major rock-forming components on factor 3 suggest that this factor largely represents closure (Chayes, 1960) in the data, a situation that exists when an inverse relationship is produced by two or more components that tend to sum to 100 percent. Nevertheless, the association of total iron, SiO_2, zinc, and antimony represents the process of silicification and sulfidization during hydrothermal alteration of the limestone breccia.

Factor 4 (copper, silver, and barium).—Traces of these three metals evidently were concentrated during hydrothermal mineralization; lead also was concentrated to some degree by factor 4. These elements evidently were concentrated by chemical processes somewhat different but unknown from those that deposited gold and associated metals of factor 1 and the sulfides of factor 3. Barium, present as barite at Kendall, evidently tends to occur separately from other effects of mineralization, as shown by its low communality and by low correlation coefficients with all other elements analyzed. Its appearance in factor 4 is regarded as spurious.

Factor 5 (Na_2O versus lead and MnO).—This factor evidently represents the effect of weathering on the mineralized breccia. Weathering could be expected to leach Na_2O and to concentrate manganese as oxides, and manganese is well known for its ability to scavenge lead and other heavy metals (perhaps zinc and antimony, which are weakly associated with factor 5). Presumably, factor 5 was responsible for oxidation, but not for appreciable concentration or depletion, of iron.

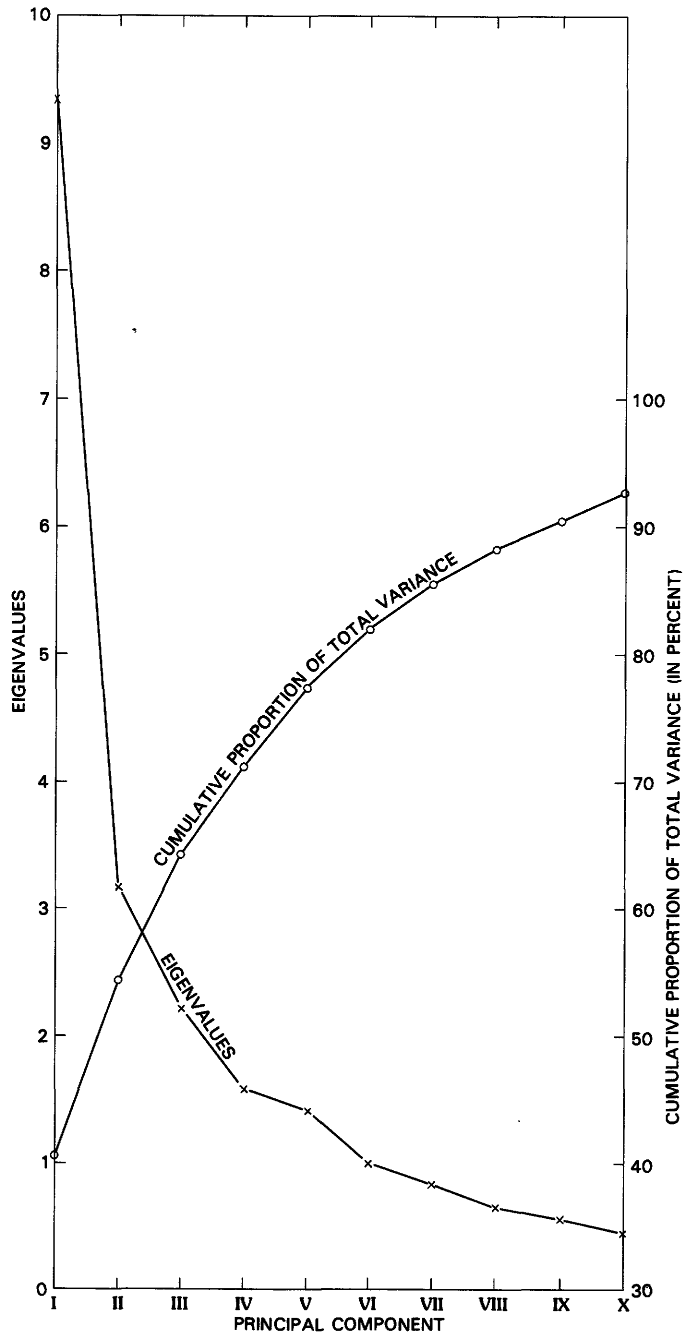

FIGURE 4.—Eigenvalues and cumulative proportion of total variance explained by the first 10 principal components.

A MODEL FOR GOLD MINERALIZATION

Studies of field and geochemical relationships at Kendall indicate that gold was deposited in limestone fault breccia by hydrothermal fluids that emanated from or circulated near cooling syenite magma. The host breccia occurs along a concentric fault that formed in response to doming of sedimentary rocks during emplacement of a syenite porphyry laccolith about 66 m.y. ago (Lindsey, 1982). Emplacement of the main laccolith and attendant faulting probably was followed closely by emplacement of small dikes and sills of syenite porphyry along the fault zone and by hydrothermal alteration of these small plutons and of the fault breccia (chapter B).

TABLE 5.—*A five-factor geochemical model for mineralized limestone breccia, Kendall, Mont.: A, Varimax factor loadings, and B, interpretation of model*

[Loadings greater than 0.50 shown in boldface type]

A	Factor					
	1	2	3	4	5	Communality (h^2)
Au	**0.94**	-0.17	-0.05	-0.03	-0.09	0.93
Hg	**0.84**	-0.18	-0.32	-0.11	-0.15	0.88
V	**0.59**	-0.48	-0.29	-0.14	-0.15	0.70
Sb	**0.57**	-0.13	**-0.54**	0.04	-0.48	0.87
Ni	0.27	**-0.60**	-0.24	-0.16	-0.16	0.54
Al_2O_3	0.24	**-0.74**	-0.16	-0.30	0.05	0.72
Cr	0.10	**-0.77**	-0.07	-0.35	0.12	0.75
Zr	-0.08	**-0.84**	-0.18	0.15	-0.02	0.77
TiO_2	0.19	**-0.88**	-0.09	0.09	-0.10	0.83
K_2O	0.22	**-0.89**	-0.06	-0.19	-0.03	0.88
MgO	-0.17	-0.25	**0.70**	0.41	-0.23	0.80
CaO	-0.40	0.32	**0.63**	0.16	-0.30	0.77
Sr	0.11	-0.48	**0.58**	0.06	-0.04	0.58
Zn	0.14	-0.39	**-0.60**	-0.23	-0.48	0.81
SiO_2	0.32	-0.40	**-0.72**	-0.19	0.14	0.83
T-Fe_2O_3	0.17	-0.41	**-0.76**	0.03	-0.32	0.89
As	0.17	-0.25	**-0.83**	0.02	-0.30	0.87
Cu	0.24	-0.39	-0.41	**-0.55**	-0.23	0.73
Ag	0.23	-0.29	-0.19	**-0.67**	-0.28	0.71
Ba	-0.07	-0.14	-0.02	**-0.75**	0.12	0.58
Na_2O	0.25	**-0.55**	-0.12	-0.07	**0.64**	0.79
Pb	0.17	-0.12	-0.17	-0.44	**-0.75**	0.84
MnO	0.23	-0.02	-0.02	0.14	**-0.80**	0.71

B Factor 1 (Au, Hg, V and Sb)—Hydrothermal gold mineralization.

Factor 2 (K_2O, TiO_2, Zr, Cr, Al_2O_3, Ni and Na_2O)—Concentration of clastic minerals (feldspar, clay, mica, iron-titanium oxide minerals and zircon) in limestone.

Factor 3 (MgO, CaO and Sr versus As, Total Fe as Fe_2O_3, SiO_2, Zn and Sb)—Hydrothermal sulfide (pyrite and sphalerite) mineralization and silicification. Inverse relation between major constituents CaO and SiO_2 reflects closure in data (Chayes, 1960).

Factor 4 (Cu, Ag, Ba)—Trace mineralization.

Factor 5 (Na_2O versus Pb and MnO)—Alteration by weathering, characterized by concentration of Pb in manganese oxides.

Hydrothermal fluids leached iron, alkali metals, and alkaline earth metals and deposited finely disseminated gold and pyrite in syenite porphyry plutons along the fault; the fluids deposited abundant silica (as quartz), finely disseminated pyrite, and gold in the limestone fault breccia. Three distinct suites of elements were deposited by hydrothermal fluids: (1) gold, mercury, vanadium, and antimony; (2) arsenic, iron, zinc, and antimony, probably in sulfides and with SiO_2; and (3) copper and silver in trace amounts. The three suites tend to occur separately in the mineralized breccia, but in close proximity to one another; their depositional sequence is unknown. A fourth suite of lead and MnO probably was concentrated by weathering. Weathering oxidized the sulfides deposited by hydrothermal fluids, but evidently did not redistribute them far from their original site of deposition.

The occurrence of gold and iron oxides after pyrite in fine-grained, disseminated form in silicified calcareous rocks as well as in intrusive igneous rocks and the nearby breccia pipe in Plum Creek (chapter A), and the general association of gold with geochemical anomalies of arsenic, mercury, antimony, and thallium suggests that the gold deposits at Kendall belong to the same class as the disseminated gold deposits (for example, Carlin) of northern Nevada, which share these features. Perhaps the geologically similar deposits of the Giltedge mine in the Judith Mountains (Forrest, 1971, p. 140–148) are also of the Carlin type. Surface exposures of Nevada gold deposits are oxidized, silicified limestone containing free gold and iron oxides replacing pyrite (Hardie, 1966; Erickson and others, 1966; Wells and others, 1969); beneath the oxidized zone, gold occurs in disseminated pyrite in some of the Nevada deposits (Wells and Mullens 1973; Radtke and others, 1980). A noteworthy feature of both the Kendall deposit and the Nevada deposits is the occurrence of arsenic, mercury, antimony, tungsten (not analyzed at Kendall), and thallium with gold (Erickson and others, 1966; Wells and others, 1969; Radtke and Dickson, 1974). The strong statistical correlation between gold and mercury, noted at Kendall, is present at Carlin, also (Harris and Radtke, 1976). Evidence for a gold suite (concentration of gold, mercury, vanadium, and antimony by factor 1) and a separate base-metal suite (concentration of sulfides by factor 3) at Kendall is analogous though not identical to that reported for some Nevada deposits (Wrucke and Armbrustmacher, 1975; Harris and Radtke, 1976).

The Kendall deposit differs from those in northern Nevada in containing disseminated fluorite and anomalous amounts of vanadium that probably are derived from roscoelite. Although no roscoelite was observed at Kendall, the mineral occurs with fluorite and the gold-silver telluride mineral sylvanite in mines of the Judith Mountains (Corry, 1933; Forrest, 1971, p. 87–93) and free gold occurs with fluorite and sylvanite in the Little Rocky Mountains (Corry, 1933; Dyson, 1939); all these might be found below the oxidized zone at Kendall or in nearby mineralized zones in syenite porphyry. The gold-tellurium-vanadium-fluorine association is best developed in fissure-filling veins and replacement deposits adjacent to or within intrusive igneous rocks in the Judith and Little Rocky Mountains, thus indicating that this association is more characteristic of the intrusive environment. The Kendall deposits, and perhaps gold deposits of the Giltedge Mine in the Judith Mountains (Forrest, 1971), evidently represent the effects of mineralizing fluids more distant from the intrusive porphyry.

Differences between the gold deposits of north-central Montana and those of northern Nevada may represent differences in the depth of mineralization, source of hydrothermal fluids, and composition of source rocks. The Kendall gold deposits probably formed at a depth of about 1,700–2,300 m (chapter A). In contrast, Nevada gold deposits such as Carlin are believed to have formed in a shallow hydrothermal environment (Radtke and others, 1980). The source of metals in the Kendall gold deposits is not known but may have been the associated intrusive rocks; the source of metals in the Nevada gold deposits is thought to have been the host sedimentary rocks (Dickson and others, 1979). Studies of fluid inclusions and stable isotope composition of some of the Montana gold ores should be undertaken to answer these questions.

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