Stratiform Zinc-Lead Deposits in the Drenchwater Creek Area, Howard Pass Quadrangle, Northwestern Brooks Range, Alaska

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By WARREN J. NOKLEBERG *and* GARY R. WINKLER

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Contemporaneous ocean-floor sedimentation, submarine volcanism, sulfide deposition, and hydrothermal alteration in Mississippian time

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STRATIFORM ZINC-LEAD DEPOSITS IN THE DRENCHWATER CREEK AREA, HOWARD PASS QUADRANGLE, NORTHWESTERN BROOKS RANGE, ALASKA

By WARREN J. NOKLEBERG and GARY R. WINKLER

ABSTRACT

Major zinc-lead deposits occur at Drenchwater Creek in the Howard Pass quadrangle in the National Petroleum Reserve in Alaska (NPRA). Detailed geologic mapping of a 31-km^2 area shows that sphalerite, galena, pyrite, marcasite, and sparse barite occur irregularly in a zone at least 1,830 m long and 6 to 45 m wide. The sulfide deposits are in deep-water marine rocks of Mississippian age that consists of dark-gray chert and shale, tuff, tuffaceous sandstone, and sparsely distributed keratophyre and andesite flows and sills. These Mississippian rocks constitute the oldest part of the Kagvik sequence, which includes rocks of late Paleozoic and Mesozoic age. The Kagvik sequence is in the lowermost structural plate of a terrane characterized by east-west-striking gently south dipping thrust faults. The bedrock of the Drenchwater Creek area is a tectonic breccia composed of a heterogeneous mixture of lenses of different rock types; these lenses are commonly several hundred meters long by a few tens of meters wide.

The sulfide minerals typically are present in hydrothermally altered chert and shale adjacent to volcanic and volcaniclastic rocks. Fragments of fine-grained feldspar, pumice lapilli, and mafic volcanic rocks in the chert and shale are commonly replaced by aggregates of kaolinite, montmorillonite, sericite, chlorite, actinolite, barite, calcite, quartz, fluorite, and prehnite. Locally the chert is altered to siliceous medium-grained metaquartzite. The sulfide minerals and barite form disseminated grains, massive sphalerite-rich layers, or, more rarely, quartz-sulfide veins that crosscut cleavage. Selected samples contain more than 1 weight percent Zn and 2 weight percent Pb, as much as 150 ppm Ag, greater than 500 ppm Cd, and as much as 500 ppm Sb and 1,500 ppm Ba. Electron microprobe analyses of sphalerite show the following atomic percentages: 44.3 to 47.5 Zn, 2.0 to 5.2 Fe, 0.3 to 0.4 Cd, and 0.1 to 0.2 Mn. Analyses of galena show the following atomic percentages: 47.8 to 49.9 Pb and 0.1 to 2.2 Sb. The pyrite and marcasite are nearly devoid of trace metals. Lead isotope analyses of galena show model lead ages of approximately 200 m.y. and indicate derivation of the lead from an average orogene, either an island-arc or Andean-type arc environment.

Field and laboratory data suggest that the stratiform deposits were formed from metal-laden hydrothermal fluids discharged onto a deep-ocean floor during submarine eruptions that yielded keratophyric to andesitic flows, tuff, and sills. Later intense deformation disrupted and partly remobilized the stratiform deposits.

The sulfide deposits in the Drenchwater Creek area represent a recent discovery in a region that has not been thoroughly explored. Zones of iron staining in the Kagvik sequence and zinc anomalies in stream sediments indicate favorable areas for exploration to the east and west of the Drenchwater Creek area.

INTRODUCTION

During the last few years, there has been great interest in stratiform zinc-lead-copper deposits. These deposits generally occur in carbonate rocks, in dark-gray shale and chert, or in mafic to siliceous submarine volcanic rocks (Gilmour, 1971; Hutchinson, 1973; Sillitoe, 1973; Lambert, 1976; Solomon, 1976; Urabe and Sato, 1978; Williams, 1978a, b). Deposits of this type are thought to originate from submarine volcanism through exhalation of sulfide-rich hydrothermal fluids (Sangster, 1972). This theory has led to the discovery of extensive stratiform sulfide deposits in the Yukon and Northwest Territories of Canada, including the extensive shale-hosted Howard's Pass deposit, which holds several hundred thousand tons of 10-weight-percent combined Zn-Pb values (Templeman-Kluit, 1978), and the shale-hosted Tom deposit, with published reserves of 7 million tons grading 8.4 weight percent Zn, 8.1 weight percent Pb, and 2.8 troy oz Ag per ton (Brock, 1976).

During fieldwork in 1950–53, 1976, and 1977, I. L. Tailleur (oral commun., 1977; Tailleur and others, 1977) observed iron staining from weathered pyrite, marcasite, sphalerite, galena, and minor barite in dark-gray chert and shale along Drenchwater Creek (fig. 1). During fieldwork in 1955 and 1968, Tailleur (1970) observed similar sulfide minerals in Mississippian rocks along Red Dog Creek in the De Long Mountains quadrangle, about 120 km west of Drenchwater Creek. Because of similarities between the two deposits, Tailleur (1970) suggested that other areas along the north front of the Brooks Range where prominent iron-stained dark-gray chert and shale of Mississippian age occur might be the sites of zinc, lead, and barium deposits of potential economic significance. The metallic-mineral resource potential of the area had previously been considered to be low.

Since 1970, the zinc-lead deposits at Red Dog Creek have been intensively explored (Plahuta, 1978; Plahuta and others, 1978; Nokleberg and others, 1979a, b). That area is now the site of extensive claim staking for stratiform zinc-lead-barium deposits; recent newspaper accounts estimate that two major companies have staked more than 5,000 mining claims. These discoveries have generated considerable interest in the stratiform sulfide deposits in the Brooks Range, and also in the geologic setting and genesis of these deposits in the northwestern Brooks Range. A large part of the National Petroleum Reserve in Alaska (NPRA) (fig. 1) between the Red Dog Creek and Drenchwater Creek areas contains rocks whose stratigraphy, structure, and age resemble those that host sulfide deposits in the Red Dog Creek area (Tailleur, 1977; Plahuta, 1978; Plahuta and others, 1978; Nokleberg and others, 1979a, b). In the same general area, Mayfield, Curtis, Ellersieck, and Tailleur (1979) also reported zinc-lead and barite deposits in the Ginny Creek and Nimiuktuk areas, in rocks similar to those hosting the deposits in the Drenchwater Creek and Red Dog Creek areas.

The Drenchwater Creek area contains the best exposed and most abundant zinc- and lead-sulfide deposits yet discovered in the NPRA (fig. 2). Consequently, we have studied the area in detail to acquire basic information on the genesis of the stratiform sulfide deposits for mineral-resource assessment and exploration within that region (Nokleberg and Winkler, 1978a, b, c). The results of our studies presented here include: (1) a detailed geologic map of about a 30-km^2 area at a scale of about 1:20,000; (2) petrologic analyses of host rocks and sulfide samples; (3) structural analysis of the tectonic breccia and melange that constitute most of the bedrock in the area; (4) semiquantitative analyses of whole-rock, soil, and stream-sediment samples; (5) electron microprobe analyses of silicate minerals from igneous flows and sills; (6) electron microprobe analyses of sphalerite, galena, pyrite, and marcasite from mineralized rocks; (7) lead isotopic analyses of sulfide minerals; and (8) discussion of the genesis of the deposits. The detailed geologic mapping and sampling was done during July 1977 with about 44 man-days of effort.

Drenchwater Creek flows northward from the crest of the Brooks Range, which is only a few kilometers south of the study area, into the Kiligwa River, a tributary of the Colville River. Relief in the area is moderate; low hills and ridges rise a few tens to a few hundreds of meters above the major drainages (fig. 2). To the south, the crest of the Brooks Range ranges in altitude from 1,500 to 2,000 m. Although vehicle movement is practicable in the winter, helicopters provide the only effective access to the area in the summer. The nearest communities are Kotzebue, Alaska, about 240 km to the southwest, and Umiat, Alaska, about 280 km to the northeast.

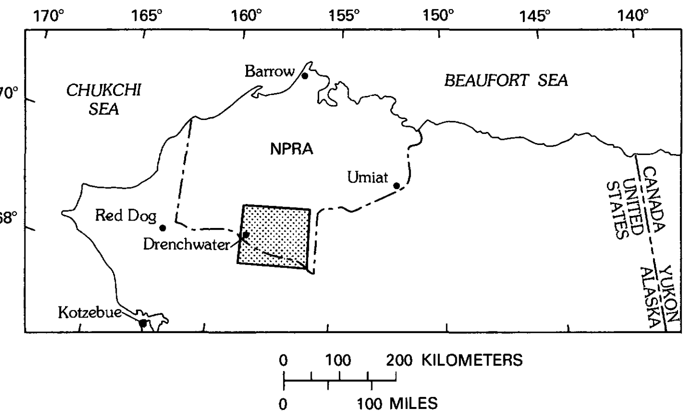


FIGURE 1.—Index map of northern Alaska, showing location of Drenchwater Creek area, Red Dog Creek area, Howard Pass quadrangle (shaded), and National Petroleum Reserve in Alaska (NPRA).

PREVIOUS WORK

This report is part of a mineral-resource assessment of the northern foothills of the Brooks Range within the NPRA and also part of the land-use study required by section 105(c) of the National Petroleum Reserves Act of 1976. Other reports include those by Churkin, Huie, Mayfield, and Nokleberg (1978a), Churkin and others (1978b), Mayfield, Tailleur, Mull, and Sable (1978), Theobald and others (1978), and Nokleberg, Plahuta, Lange, and Grybeck (1979a, b). Additional studies of soil geochemistry and of ground magnetic and ground mercury-vapor geophysics have been made by Metz, Robinson, and Lueck (1979) for the U.S. Bureau of Mines. The western part of the Howard Pass quadrangle was partly mapped by Tailleur, Kent, and Reiser (1966) at a scale of 1:63,360.

Acknowledgments.—We are indebted to the earlier mapping and studies of the region by I. L. Tailleur, C. F. Mayfield, and their associates, who gave freely of their time and expertise. Michael Churkin introduced us to the Drenchwater Creek area and provided excellent geologic guidance. The semiquantitative analyses were done mainly by P. K. Theobald and H. N. Barton. We appreciate the many discussions with D. K. Blasco, I. M. Lange, Uldis Jansons, Donald Grybeck, E. M. MacKevett, Jr., and J. T. Plahuta.

STRATIGRAPHY OF ZINC- AND LEAD-BEARING ROCKS

The bedrock of the Drenchwater Creek area comprises mainly the Kagvik structural sequence (Churkin and others, 1979), a structurally deformed mappable unit of rock that includes unnamed rocks of Mississippian age; the Siksikpuk Formation (Permian); the Shublik Formation (Triassic); and the Okpikruak Formation (Cretaceous). Other bedrock units are Mississippian carbonate rocks of the Lisburne Group and minor diabase dikes (Tailleur and others, 1966; Churkin and others, 1978, 1979). The Mississippian carbonate rocks of the Lisburne Group are in fault contact with the various units of the Kagvik sequence (pl. 1). The Mississippian through Triassic units of the Kagvik sequence, which have a total thickness of about 500 m, consist mainly of chert and shale deposited in a stable deep-water marine environment. The presence of volcanic and volcaniclastic rocks within only the Mississippian unit suggests some submarine volcanism during the Mississippian. The Kagvik sequence, which forms the lowest structural plate of the northwestern Brooks Range (Tailleur and others, 1966), is discontinuously exposed in erosional windows at least as far west as the Red Dog Creek area in the De Long Mountains quadrangle, across the Misheguk Mountain quadrangle, and in most of the Howard Pass quadrangle (fig. 3).

The four main sedimentary units in the Kagvik sequence are of Mississippian, Permian, Triassic, and Cretaceous age (fig. 4) The Mississippian unit consists mainly of dark-gray siliceous shale and radiolarian chert. Radiolarian chert from an area about 1.5 km east of the Drenchwater Creek area has yielded Mississippian radiolarians (B. K. Holdsworth and D. L. Jones, written commun., 1978). About 6.5 km southeast of the Drenchwater Creek area, an ammonite (*Ammonellipsites polaris*), found near the headwaters of Twisten Creek in dark shale of the Mississippian unit, indicates a Mississippian age (Gordon, 1957). In the Drenchwater Creek area the Mississippian unit contains keratophyre flows, pyroxene andesite sills, tuff, tuffaceous sandstone, and stratiform sulfide deposits. Biotite from the keratophyre cropping out about 1,600 m east of Drenchwater Creek (pl. 1) has been dated by potassium-argon methods at 319±17 m.y., also middle Mississippian. The minimum thickness of the Mississippian unit is approximately 150 to 200 m.

Conformably overlying the Mississippian unit is the Siksikpuk Formation, composed of 100- to 150-m-thick maroon and green argillite and olive-gray chert that contain radiolarians of Permian age (D. L. Jones, oral commun., 1978). The Siksikpuk Formation lithologically resembles the underlying Mississippian unit of the Kagvik sequence but differs in its lighter color, its greater degree of cleavage with a micaceous sheen, and the absence of obvious volcanic units.

The Shublik Formation conformably overlies the Siksikpuk Formation and consists of a 100- to 150-m-thick sequence of dark-gray paper-thin shale, medium-gray chert, and platy micritic limestone. The limestone is easily identified by ubiquitous coquina of the Triassic pelecypod *Monotis*.

The uppermost unit of the Kagvik sequence is the

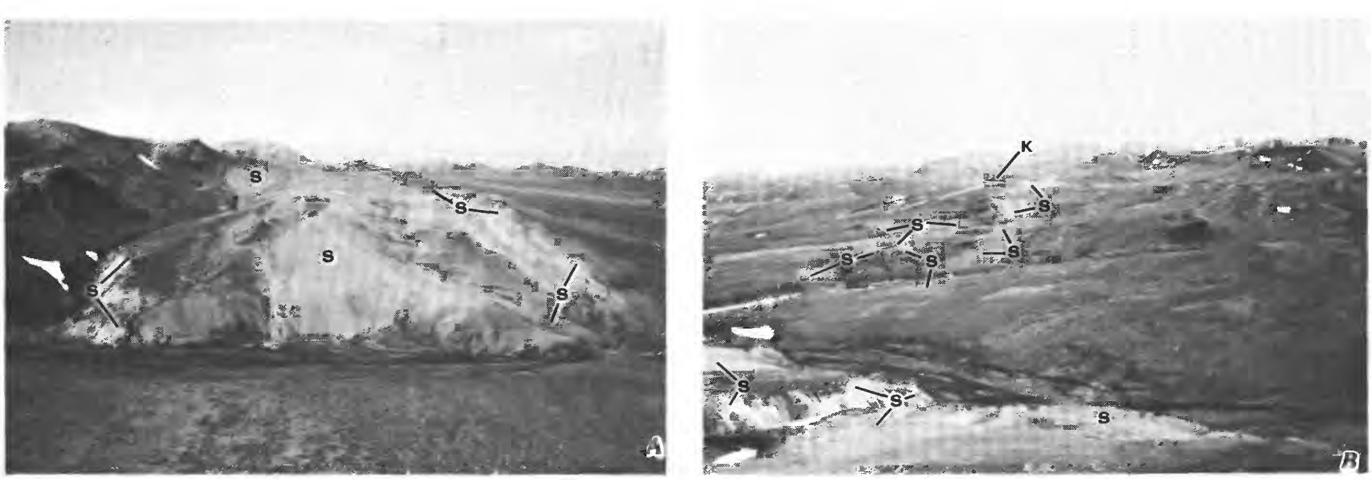


FIGURE 2.—Oblique aerial views of Drenchwater Creek area, showing prominent iron-stained zones (S) that are loci of zinc- and lead-sulfide deposits. *A*, View westward across Drenchwater Creek. Light areas of scree mark intense alteration from weathering of pyrite and marcasite in chert, shale, and tuff. Dark areas near left side are dark-gray shale and chert. Drenchwater Creek extends for about 1 km across lower half of photo. *B*, View northeastward across Drenchwater Creek toward Wager Creek. Light areas of scree mark intense iron staining. Hill (K) is underlain by keratophyre. Dark areas are outcrops of dark-gray shale, chert, tuff, and tuffaceous sandstone. Drenchwater Creek extends diagonally about 1 km across lower left of photo.

Cretaceous Okpikruak Formation, which consists of coarse-grained lithic graywacke, mudstone, and minor conglomerate, and contains prominent turbidite structures, plant fragments, and the Cretaceous pelecypod *Buchia*. The minimum thickness of the Okpikruak Formation is approximately 100 m.

The Mississippian through Triassic units of the Kagvik sequence probably consist of a deep-water marine assemblage (Churkin and others, 1979). The evidence for a deep-water marine origin includes abundant radiolarians, inferred slow sedimentation rates, little or no clastic component from a continental source, sparse siliceous sponge spicules, rare ichthyosaur bones, and burrows typical of bioturbated deep-water marine deposits.

Neither the Kagvik sequence nor any stratigraphic unit is fully exposed in the Drenchwater Creek area because of complex folding and faulting. The thick-

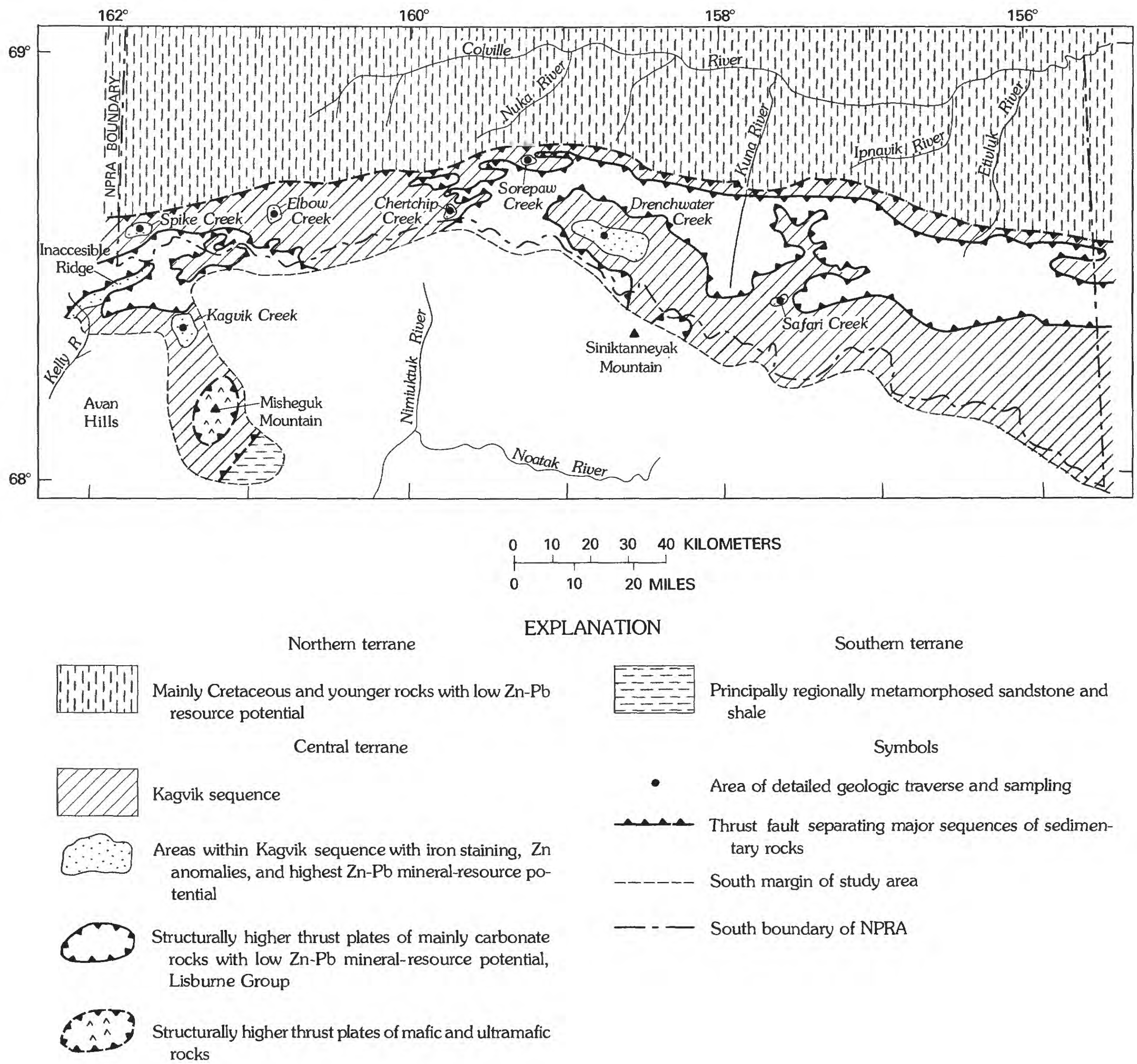


FIGURE 3.—Southern part of National Petroleum Reserve in Alaska, showing distribution of the Kagvik sequence and areas of high and low zinc-lead mineral-resource potential. Adapted from Churkin, Nokleberg, and Huie (1979, fig. 1).

ness and lateral extent of units in the Drenchwater Creek vary considerably, and many discontinuous tectonic lenses of different rock types occur. Graywacke, siltstone, and mudstone of the Cretaceous Okpikruak Formation are tectonically interleaved with all older units. In other parts of the western Brooks Range, the Okpikruak Formation unconformably overlies all older rocks and apparently indicates initial uplift of the ancestral Brooks Range during the Cretaceous (Tailleur, 1969, 1970; Churkin and others, 1979).

In the Drenchwater Creek area, sulfide deposits occur in tuff, tuffaceous sandstone, metaquartzite, and dark-gray chert and shale that make up part of the Mississippian rocks of the Kagvik sequence. The sulfide minerals consist of sphalerite, galena, pyrite, and marcasite; disseminated barite also occurs with the sulfide minerals. The sulfide minerals have been observed in several units of tuff, tuffaceous sandstone, metaquartzite, dark-gray chert, and dark-gray shale; however, intense folding and faulting, as well as poor exposures, preclude any precise determination of the number of mineralized horizons.

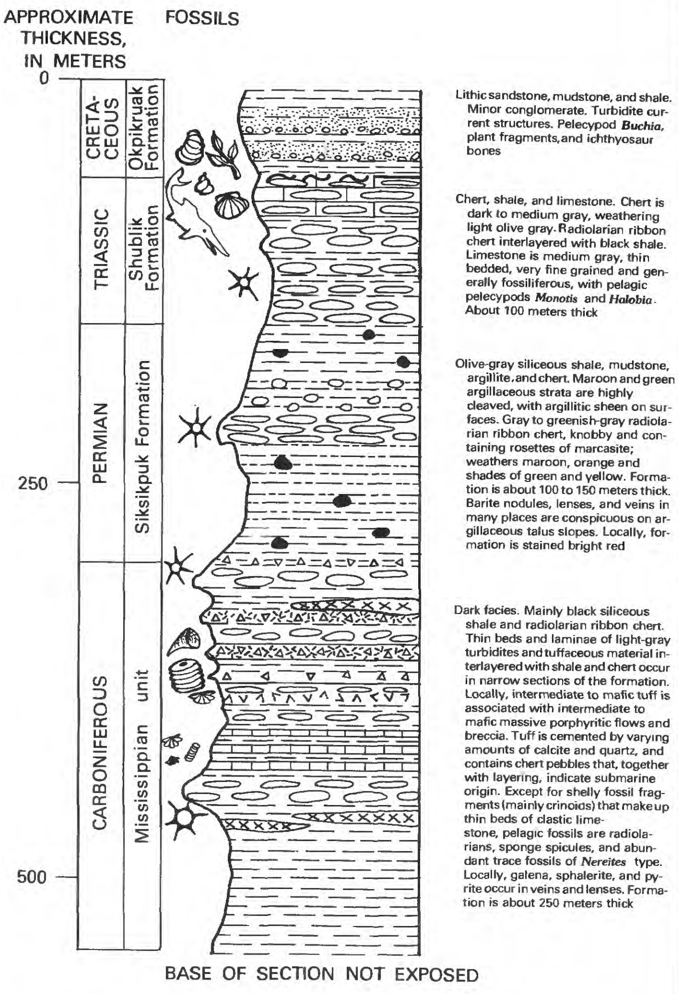


FIGURE 4.—Reconstructed stratigraphic succession, relative distribution of rock types and fossils, and approximate thicknesses of units in the Kagvik sequence. Vertical succession within units has been generalized. After Churkin and others (1978b, p. 23, fig. 4).

The Kagvik sequence structurally underlies nappes of carbonate rocks and calcareous sandstone of the Lisburne Group, here of Mississippian age (Churkin and others, 1979). In turn, these nappes or thrust slices of carbonate rocks are locally overthrust by apparently dismembered ophiolites, including ultramafic rocks, gabbro, and pillow basalt (fig. 3). These dismembered ophiolites, of late Paleozoic or early Mesozoic age, occur in the Avan Hills and in the Misheguk and Siniktanneyak Mountains (Patton and others, 1978; Roeder and Mull, 1978).

PETROLOGY—MISSISSIPPIAN ROCKS OF THE KAGVIK SEQUENCE

We have studied the petrology of the Mississippian rocks of the Kagvik sequence in detail because these rocks host the stratiform sulfide deposits not only in the Drenchwater Creek area but also in the Red Dog Creek area (fig. 3) (Plahuta, 1978; Plahuta and others, 1978). Typical petrologic characteristics of the Mississippian rocks of the Kagvik sequence (fig. 5) in the Drenchwater Creek area are listed in table 1, which summarizes the thin-section, chemical, and X-ray diffraction data.

Several important relations became apparent during petrologic studies subsequent to the fieldwork:

(1) Most of the fine-grained chert and shale contains low to high percentages of volcanic rock fragments, euhedral feldspar laths, and pumice. Many rocks labeled "chert" or "shale" on the geologic map (pl. 1) actually are tuffaceous sandstone that has been intensely hydrothermally altered and silicified; this alteration causes hand specimens to resemble dark-gray chert or shale. Table 1 lists both the petrologic name (underlined) and the field map (map unit) name and symbol on the geologic map (pl. 1). The field designations "chert" and "shale" are retained on the geologic map because hand specimens were used for rock identification during mapping.

(2) The entire suite of Mississippian rocks of the Kagvik sequence in the Drenchwater Creek area have been intensely hydrothermally altered. Almost all volcanic rock and pumice fragments are

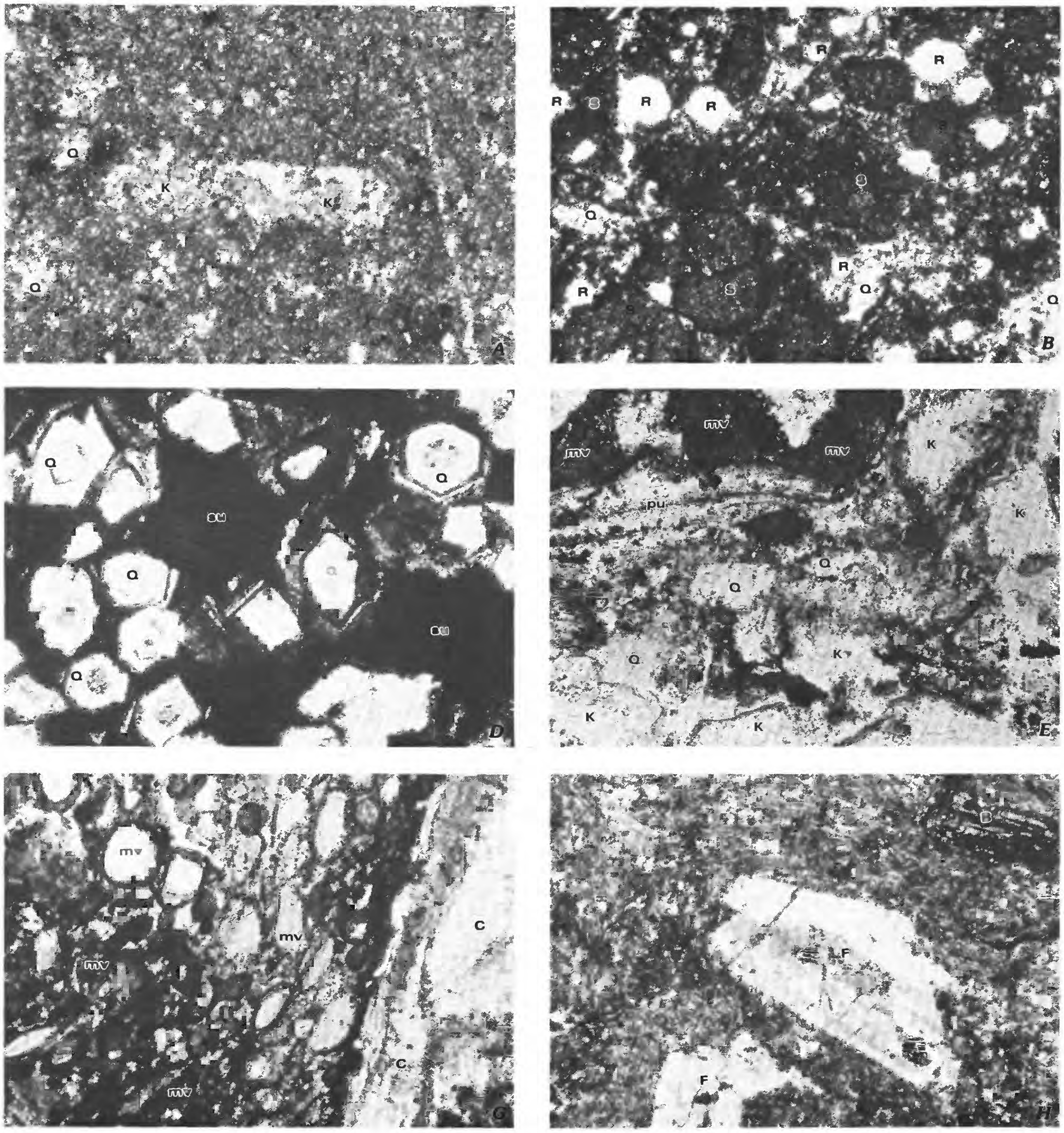
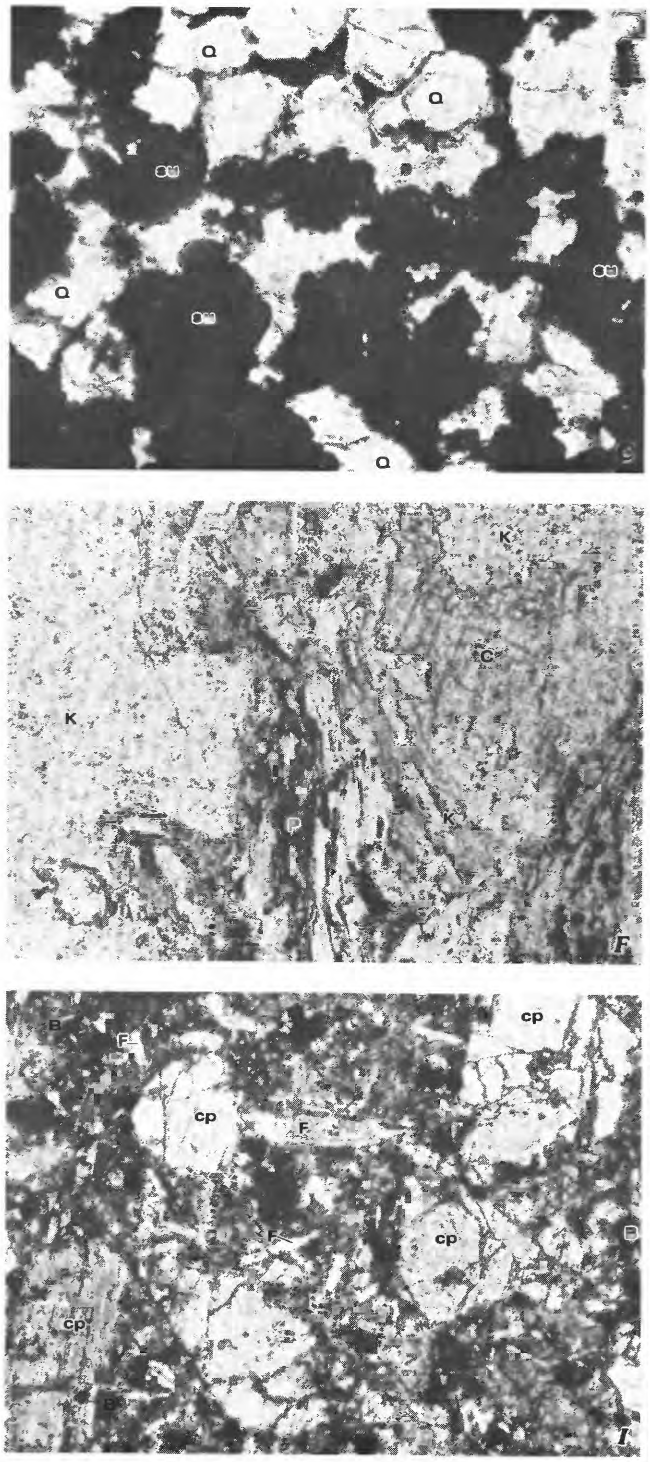


FIGURE 5.—Photomicrographs in transmitted light of thin sections of Mississippian rocks of the Kagvik sequence. S, sphalerite; G, galena; P, pyrite and marcasite; su, sulfide; Q, quartz; R, radiolarians; K, feldspar altered to kaolinite; pu, pumice lapilli; mv, mafic volcanic rock fragment; C, calcite; B, biotite; F, feldspar phenocryst; cp, clinopyroxene. *A*, Silicified mudstone. Crossed polarizers. Field of view is 1.0 mm long. *B*, Sulfide-bearing chert containing abundant sphalerite and recrystallized radiolarians. Plane-polarized light. Field of view is 2.3 mm long. *C*, Sulfide-bearing metaquartzite. Plane-polarized light. Field of view is 1.0 mm long. *D*, Quartz with hexagonal growth zones in sulfide-bearing metaquartzite. Plain-polarized light. Field of view is 1.0 mm long. *E*, Kaolinite tuffaceous sandstone. Plane-polarized light. Field of view is 2.3 mm long. *F*, Calcareous tuffaceous sandstone. Plane-polarized light. Field of view is 2.3 mm long. *G*, Mafic tuff. Plane-polarized light. Field of view is 1.0 mm long. *H*, Keratophyre. Crossed polarizers. Field of view is 2.3 mm long. *I*, Pyroxene andesite. Crossed polarizers. Field of view is 2.3 mm long.



altered to a low-temperature hydrothermal-mineral assemblage consisting of kaolinite, montmorillonite, sericite, quartz, chlorite, fluorite, actinolite, carbonate (mostly calcite and minor siderite), and prehnite (table 1). Feldspar is altered principally to kaolinite and lesser amounts of sericite and montmorillonite. The alteration is observed in rocks interpreted to be submarine volcanic flows and tuff, in tuffaceous sandstone, and in chert and shale derived from a volcaniclastic source. The hydrothermal alteration probably occurred during submarine volcanism and may relate directly to simultaneous stratiform sulfide mineralization.

(3) The occurrence of sulfide deposits in rocks petrographically identified as chert, tuff, tuffaceous sandstone, and tuffaceous siltstone strongly implies a direct link between submarine volcanism and stratiform sulfide mineralization. The Drenchwater Creek area is one of the few well-exposed places in North America where stratiform sulfide deposits can be directly related to a volcanic source.

Petrologic study of all samples from the Drenchwater Creek area involved microscopic examination of thin sections in transmitted light, microscopic examination of polished thin sections in reflected light, X-ray diffraction analyses of clay and related hydrothermal minerals, and electron microprobe analyses of silicate and sulfide minerals. All mineral chemical analyses were done by electron microprobe techniques, using an Applied Research Laboratory S.E.M. instrument and a theoretical corrections program developed by the U.S. National Bureau of Standards, as modified by M. H. Beeson and L. C. Calk. The general operating conditions were 15-kV acceleration potential, 0.02- to 0.03-μA sample current, fixed-beam current-integration times of about 10 s, subtraction of background counts, and use of natural or synthetic mineral standards similar in composition to the unknowns. For the sulfide analyses presented below, synthetic sulfide standards were provided by G. K. Czamanske. In the highly altered rocks, such as the keratophyre, great care was taken to analyze unaltered remnants of minerals and to avoid zones of alteration or recrystallization.

SILICIFIED MUDSTONE

The silicified mudstone contains relic feldspar microlites replaced by kaolinite in a very fine grained matrix of cryptocrystalline quartz and kaolinite (fig. 5*A*). The euhedral shape of the relic feldspar microlites indicates a nearby volcanic source. "Silicified mudstone" is the petrologic name for rocks designated "dark-gray chert and tuff" in the field.

SULFIDE-BEARING CHERT

The sulfide-bearing chert contains disseminated sphalerite, galena, pyrite, and marcasite in a matrix of recrystallized quartz and kaolinite (fig. 5*B*). Kaolinite has replaced euhedral feldspar phenocrysts, and

TABLE 1.—*Petrologic characteristics of the Mississippian rocks in the Kagvik sequence, Drenchwater Creek area, northwestern Brooks Range, Alaska*

[Original stratigraphic position unknown]

Petrologic name (italic), map unit, map symbol	Percentage of major and minor minerals	Textures and structures	Alterations, replacements or recrystallization
Silicified mudstone Black chert, Mc Fine-grained tuff, Mft	Cryptocrystalline quartz .... 60–100 Detrital quartz .... 0–10 Kaolinite .... 0–16 Opaque minerals .... 0–10 Chlorite, sericite .... <1–4	Very fine grained. Detrital biotite and quartz in slightly recrystallized matrix of cryptocrystalline quartz and kaolinite. Relic plagioclase microlites.	Matrix locally recrystallized to polycrystalline quartz. One sample completely recrystallized to metaquartzite. Sparse new growth of chlorite and sericite. Thin quartz veins.
Sulfide-bearing chert Black chert, Mc Black shale, Ms	Quartz .... 40–45 Sphalerite .... 25–45 Galena .... 10–25 Kaolinite .... 0–10 Sericite .... 0–<1	Very fine grained. Angular quartz, mostly recrystallized. Disseminated sulfide grains. Radiolarians replaced by quartz. Sparse tiny fluid inclusions.	Sparse thin quartz veins contain sulfides.
Sulfide-bearing metaquartzite Black chert, Mc	Quartz .... 50–90 Sphalerite .... 5–35 Galena 5–15	Medium-grained mosaic of hexagonal quartz containing interstitial sulfides. Sparse inclusions of sulfides. Galena inclusions outline growth stages of hexagonal quartz. Abundant fluid inclusions. Wavy beds or bands of sulfides.	Sparse thin quartz veins contain sulfides.
Silicified kaolinite tuffaceous sandstone, locally sulfide bearing Black chert, Mc Black shale, Ms Medium-grained tuff, Mmt	Kaolinite .... 50–55 Quartz .... 5–40 Volcanic fragments .... 0–10 Galena and sphalerite .... 0–30 Ankerite? .... 0–10 Chlorite, sericite, montmorillonite .... <1	Medium-grained fragments. Very fine grained replacements. Relic volcaniclastic texture, pumice lapilli, and vesicles.	Many medium-grained angular fragments of quartz, vesicles, and feldspar, replaced by very fine grained quartz and kaolinite. Sparse new growth of sericite and chlorite. Thin quartz veins contain sulfides. Strong schistosity and preferred orientation of minerals.
Calcareous tuffaceous sandstone-sandy tuff Medium-grained tuff, Mmt Coarse-grained tuff, Mct Keratophyre, Mke	Calcite, siderite .... 20–50 Quartz .... 15–20 Kaolinite .... 34–50 Opaque minerals .... <1–1 Sericite, montmorillonite 0–<1 Fluorite .... <1	Medium grained. Relic volcanic lapilli and detrital carbonate grains. Relic radiolarians. Relic plagioclase laths. Relic mafic minerals.	Plagioclase laths replaced by kaolinite, montmorillonite, or carbonate. Radiolarians replaced by quartz. Volcanic lapilli replaced by kaolinite and quartz. Mafic minerals replaced by clay, opaque minerals, and kaolinite. New growth of sericite.
Kaolinite lapilli tuff or *tuffaceous siltstone, locally sulfide bearing* Fine-grained tuff, Mft Medium-grained tuff, Mmt	Kaolinite .... 40–75 Quartz .... 15–40 Opaque minerals .... 0–10 Montmorillonite, actinolite, sericite .... <1–10 Fluorite, barite .... <1–3 Galena 0–10	Very fine to fine grained. Relic volcanic lapilli replaced by kaolinite. Locally highly schistose. Strong preferred orientation of crystals. Sparse tiny fluid inclusions. Relic mafic volcanic lapilli. Sparse relic shards.	Plagioclase laths replaced by kaolinite. Mafic volcanic lapilli replaced by montmorillonite, sericite, kaolinite, and actinolite. New growth of sericite.
Calcareous lapilli tuff Fine-grained tuff, Mft Medium-grained tuff, Mmt	Carbonate .... 30–55 Quartz .... 10–15 Kaolinite .... 10–50 Opaque minerals .... 4–20 Montmorillonite, sericite .... <1 Sphalerite .... 0–1 Chlorite .... 0–5 Fluorite, barite(?) .... <1	Medium grained. Relic vesicular volcanic lapilli, replaced by kaolinite and quartz, in a carbonate matrix. Sparse fragments of angular detrital quartz.	Volcanic lapilli and feldspar replaced by kaolinite and quartz. Some lapilli and feldspar replaced by carbonate. New growth of mica.
Vitric crystalline mafic tuff Mafic tuff, Mma	Carbonate .... 50 Kaolinite, sericite, montmorillonite .... 35 Chlorite .... 10 Quartz .... 5 Sericite, prehnite .... <1	Medium grained. Relic vesicular mafic lapilli. Relic feldspar clots.	Mafic lapilli replaced by chlorite, carbonate, montmorillonite. Feldspar replaced by kaolinite and quartz, and vesicles mostly by chlorite, some by quartz and carbonate. New growth of mica.
Limestone Crinoidal limestone, Mls	Carbonate .... 95 Quartz .... 3 Kaolinite 2	Fine to medium grained. Interlocking mosaic of calcite containing sparse interstitial kaolinite and sparse angular detrital quartz.	

TABLE 1.—*Petrologic characteristics of the Mississippian rocks in the Kagvik sequence, Drenchwater Creek area, northwestern Brooks Range, Alaska*—Continued

Petrologic name (italic), map unit, map symbol	Percentage of major and minor minerals	Textures and structures	Alterations, replacements or recrystallization
Keratophyre Keratophyre, Mke Fine-grained tuff, Mft	Albite, anorthoclase .... 50–65 Sanidine .... 20–25 Hornblende .... 5 Sericite, montmorillonite, kaolinite, carbonate, chlorite .... 5–10 Opaque minerals .... <1–10 Biotite .... <1–5	Medium to coarse grained. Porphyritic feldspar and hornblende. Pilotaxitic plagioclase groundmass.	Feldspar phenocrysts replaced by kaolinite, sericite, and montmorillonite. Mafic phenocrysts replaced by opaque minerals and chlorite. New growth of sericite and chlorite.
Pyroxene andesite Andesite and andesite tuff, Mat	Augite .... 60–65 Labradorite-bytownite .... 26–28 Opaque minerals .... 5 Biotite .... 2–10 Carbonate 2	Medium grained. Ophitic to porphyritic. Large zoned augite enclosed in mosaic of plagioclase. Interstitial biotite.	Replacement of groundmass plagioclase by carbonate.

round polycrystalline quartz aggregates represent recrystallized radiolarians. "Sulfide-bearing chert" is the petrologic name for rocks designated "dark-gray shale" in the field.

SULFIDE-BEARING METAQUARTZITE

The sulfide-bearing metaquartzite contains mainly disseminated sphalerite and includes sparse galena, pyrite, and marcasite in a matrix of angular to hexagonal quartz (fig. 5*C*). The sulfide minerals also occur in rare 2- to 10-mm-thick quartz-sulfide veins. The hexagonal quartz contains concentric zones rich in galena (opaque minerals, fig. 5*D*) and sparse fluid inclusions as large as 15 μm in diameter. The abundant liquid and very small vapor bubbles in the fluid inclusions indicate a deposition temperature of about 100°C (T. G. Theodore, oral commun., 1978). The metaquartzite is interpreted as representing chert recrystallized to a medium-grained metamorphic rock that contains mostly hexagonal quartz and sulfide minerals. The inclusions of galena in growth zones in the quartz indicate that sulfide deposition occurred simultaneously with recrystallization of the chert. Chert recrystallization to metaquartzite was probably contemporaneous with submarine volcanism because the metaquartzite is stratigraphically parallel and adjacent to the volcanic and volcaniclastic rocks. The recrystallization of quartz during sulfide deposition is an important link between sulfide deposition and hydrothermal replacement.

TUFFACEOUS SANDSTONE, TUFFACEOUS SILTSTONE, AND TUFF

The tuffaceous sandstone, tuffaceous siltstone, and tuff contain abundant clasts of volcanic rocks, feldspar replaced by kaolinite and quartz, pumice lapilli replaced by kaolinite, sericite, montmorillonite, and clasts of quartz and carbonate. Rocks containing abundant subrounded clasts of quartz, calcite, or feldspar replaced by kaolinite are here designated "sandstone" or "siltstone," depending on grain size, whereas rocks containing abundant angular to subangular clasts of volcanic rock, pumice lapilli, or feldspar replaced by kaolinite are here designated "tuff." The modifying terms "kaolinite," "calcareous," "vitric," and "crystal" are used to describe the more common clasts in each rock. The tuffaceous sandstone, tuffaceous siltstone, and lapilli tuff are closely associated with the keratophyre (pl. 1), which appears to grade laterally into tuff and tuffaceous sandstone. This lateral gradation appears to represent sea-floor extrusion during which volcaniclastic debris was spalled from the sides of flows and mixed with volcaniclastic debris emanating from the vent. The close association of mafic tuff with pyroxene andesite is considered to reflect a period of shallow intrusion and submarine volcanism of slightly different chemical composition from that of the tuffaceous sandstone and tuff associated with keratophyre flows.

The kaolinite tuffaceous sandstone contains: euhedral feldspar crystals and fragments replaced by kaolinite and quartz; pumice fragments, also replaced by kaolinite, quartz, sericite, and montmorillonite; mafic volcanic rock fragments; and clasts of quartz and minor carbonate (fig. 5*E*). Sphalerite and galena occur as disseminated grains. Through crossed polarizers, medium-grained kaolinite is visible as the chief replacement of feldspar (fig. 5*E*). "Kaolinite tuffaceous sandstone" is the petrologic name for rocks named "dark-gray chert" or "dark-gray shale" in the field. The calcareous tuffaceous sandstone contains calcite fragments, replaced pumice lapilli, mafic volcanic rock fragments, feldspar altered to kaolinite, and minor hydrothermal fluorite (fig. 5*F*). Round aggregates of quartz represent recrystallized radiolarians.

The clastic and volcaniclastic rocks in the Drenchwater Creek area fall into three main fields: mudstone consisting principally of quartz and minor kaolinite; kaolinite tuffaceous sandstone, siltstone, and lapilli tuff; and calcareous tuffaceous sandstone and lapilli tuff (fig. 6). The mafic tuff contains principally vesicular basalt fragments, calcite fragments, and sparse quartz clasts (fig. 5*G*); vesicles in the basalt fragments are commonly filled by chlorite and sparse prehnite. "Mafic tuff" is the petrologic name for rocks designated "volcanic agglomerate" in the field. The mafic tuff contains numerous hydrothermal-replacement minerals, including kaolinite, sericite, montmorillonite, chlorite, carbonate (mostly calcite and minor siderite), and prehnite.

KERATOPHYRE FLOWS

The keratophyre contains large phenocrysts of alkali feldspar (albite, anorthoclase, and sanidine) in a very fine grained matrix of alkali feldspar microlites (figs. 5*H*, 7); sparse hornblende and biotite with chlorite cores also form medium-grained phenocrysts. The feldspar phenocrysts and microlites are mostly replaced by kaolinite, sericite, and montmorillonite, and the mafic phenocrysts by opaque minerals and chlorite. "Keratophyre" is the petrologic name for rocks designated "dacite" in the field. The minimum thickness of the keratophyre is 150 m.

Most of the feldspar phenocrysts are alkali feldspar. However, three analyzed phenocrysts had either plagioclase cores or rims of composition between about An_{22} and An_{52}, and two plagioclase phenocrysts had rims that were more calcic than the cores. The rims of sanidine phenocrysts were either more potassium rich or more sodium rich relative to the core. The microlites range in composition from almost pure albite to almost pure orthoclase. The wide variations in both feldspar phenocryst and microlite composition indicate disequilibrium crystallization and probably reflect rapid quenching of the magma during sea-floor eruption.

The keratophyre contains an unusual occurrence of medium-grained biotite phenocrysts with chlorite cores. Biotite is not replaced by chlorite along cleavage planes; instead, biotite uniformly rims chlorite. This relation indicates that chlorite was the first layered silicate to crystallize, probably during initial eruption and rapid quenching of the magma during submarine volcanism. The later, peripheral biotite probably crystallized at higher temperatures after more magma was extruded and hotter conditions prevailed. This interpretation would explain the unusual occurrence of magmatic chlorite in the keratophyre.

PYROXENE ANDESITE SILL

The pyroxene andesite contains mostly medium-grained augite and fine-grained plagioclase and biotite (fig. 5*I*). Plagioclase is extensively altered to calcite. The pyroxene andesite, which generally contains medium-grained augite and biotite in a groundmass of very fine grained plagioclase, consequently is interpreted as a shallow-intrusive rock. However, the presence locally of adjacent mafic tuff (pl. 1) indicates that some of the mafic magma forming the pyroxene andesite also vented onto the sea floor.

All the feldspar in the pyroxene andesite is unzoned plagioclase ranging in composition from about albite to andesine; two analyzed crystals consisted of labradorite (fig. 8*A*). Augite in the pyroxene andesite is diopside rich (fig. 8*B*). Cores and rims are of nearly the same composition; the rims, however, are slightly richer in ferrous iron than the cores. Electron micro-

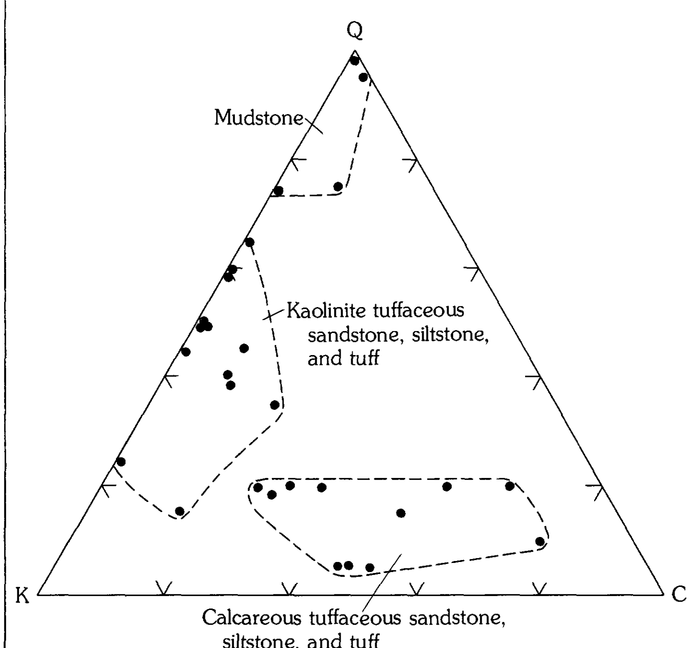


FIGURE 6.—Modes of Mississippian clastic and volcaniclastic rocks of the Kagvik sequence. Q, quartz lithic grains; K, feldspar altered to kaolinite; C, calcite and mafic volcanic rock fragments. These three components make up 90 percent or more of each sample.

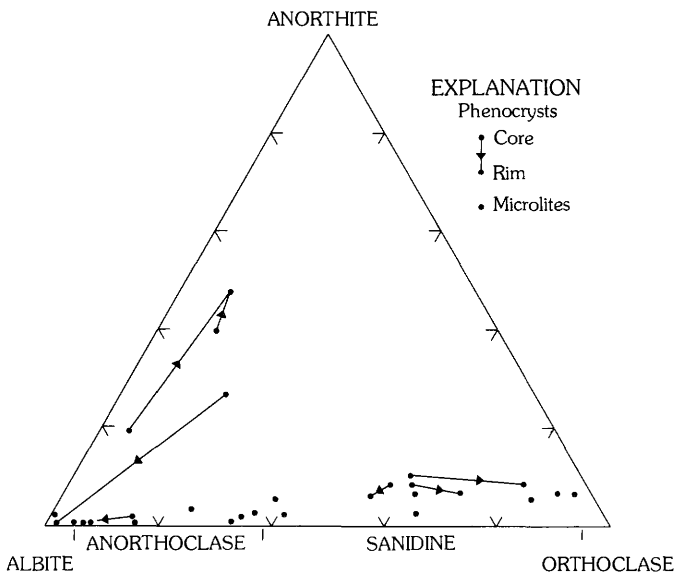


FIGURE 7.—Feldspar compositions of keratophyre in terms of anorthite, albite, and orthoclase end members, based on electron microprobe chemical analyses by W. J. Nokleberg. Lines with triangles show compositional changes from core to rim of zoned phenocrysts.

probe examination of the pyroxene andesite revealed no olivine in the rock.

STRUCTURE

MAJOR STRUCTURES

The bedrock of the Drenchwater Creek area is a tectonic breccia marked by interleaved fault-bounded lenses of different rock types that pinch out within a few hundred meters. The area is intensely faulted and folded at all scales. On the structure map (fig. 9) and the geologic map (pl. 1), major faults are indicated only in areas of extensive shearing or in areas of stratigraphic discontinuity; the many shear zones are not shown for simplicity. The heterogeneous mixture of lenses of different rock types is evident in most areas of the geologic map (pl. 1), particularly in the center and to the south. Locally the bedrock is a melange defined by large to small blocks of chert in a pervasively sheared matrix of chert and shale (fig. 10) In the Drenchwater Creek area, most of the contacts are faults; however, faults are designated on the geologic map and cross sections (pl. 1) only where extensive stratigraphic disruption exists. In the eastern part of the area the units are somewhat more continuous.

Despite intense deformation, discrete thrust plates can be recognized in the Drenchwater Creek area, each defined by the proportions of different rock

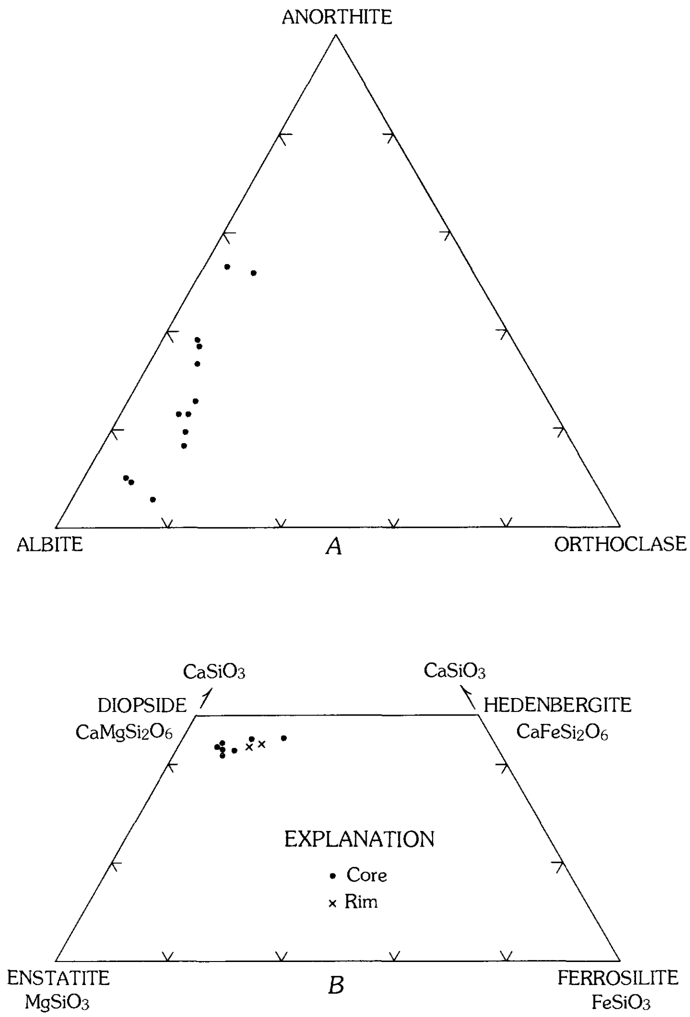


FIGURE 8.—Compositions of feldspar and clinopyroxene in pyroxene andesite, based on electron microprobe chemical analyses by W. J. Nokleberg. *A*, Feldspar analyses in terms of anorthite, albite, and orthoclase molecular end members. *B*, Clinopyroxene analyses in terms of diopside, enstatite, hedenbergite, and ferrosilite molecular end members.

types and by distinct structural domains. From north to south, we define the following thrust plates (pl. 1): (1) the Mother Bear—a series of overturned south-dipping east-plunging asymmetric folds, mainly in the Lisburne Group and the Siksikpuk Formation; (2) the Two Cubs—the only occurrence of carbonate rocks of the Lisburne Group; (3) the Drenchwater—marked by sphalerite- and galena-bearing tuff, tuffaceous sandstone, and keratophyre flows forming part of the Kagvik sequence; (4) the Spike Camp—a series of interleaved lenses consisting mainly of the Siksikpuk and Shublik Formations and lesser amounts of the Okpikruak Formation; and (5) the Gas Drum—chert and shale of the

Mississippian and Permian units of the Kagvik sequence. The thrust plates, in turn, may be tectonic slivers in an even coarser tectonic breccia.

The tectonic breccia exposed in the Drenchwater Creek area appears to extend at least several tens of kilometers to the west and perhaps many tens of kilometers to the east along the north front of the Brooks Range. We observed interleaved lenses or blocks of Paleozoic and Mesozoic formations westward into the central part of the Misheguk Mountain quadrangle as far as the Nuka River and Chertchip Creek, and eastward into the Howard Pass quadrangle as far as Story Creek. The term "tectonic breccia" represents a reinterpretation of the disturbed belt of I. L. Tailleur (oral commun., 1977). In the Drenchwater Creek area, sparse evidence exists that the units are generally upright and dip south. In parts of the Shublik Formation where the pelecypod *Monotis* is abundant, the generally convex upward orientation and southward dip of the valves indicates

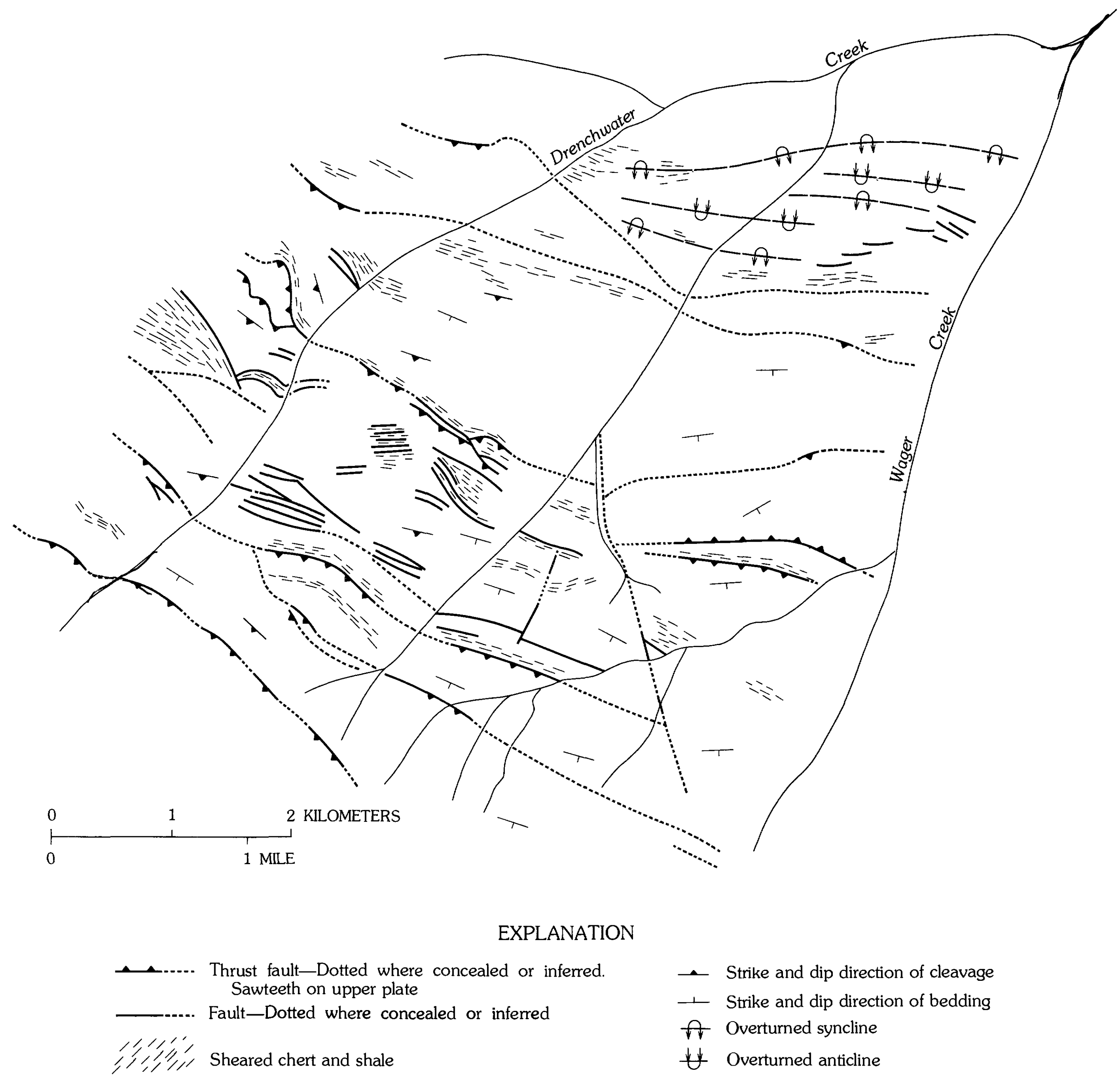


FIGURE 9.—Simplified structure map of Drenchwater Creek area, showing highly deformed terrane constituting the Kagvik sequence.

tops to the south. In seemingly coherent thrust plates, younger rocks are generally exposed in the more southerly outcrops.

MINOR STRUCTURES

Complex deformation in the Drenchwater Creek area is also indicated by minor structures consisting of cleavage, minor folds, and mineral streak lineations parallel to the fold axes. Bedding is best preserved in massive chert and limestone of the Shublik Formation (pl. 1). In chert and shale of the Lisburne Group and the Siksikpuk Formation, the common planar surface is cleavage, consisting of subparallel planes that generally crosscut bedding at small to large angles, and marked by incipient recrystallization of kaolinite, sericite, montmorillonite, and calcite. Cleavage generally parallels the axial planes of minor folds. Minor folds are generally isoclinal and in places rotated around fold axes that coincide with the original fold axes in any given fold.

We analyzed the minor structures by determining the number and order of periods of deformation. Each generation of structures consists of folds, faults, cleavage, schistosity, and lineation, formed in response to a common stress field. Minor structures are plotted on equal-area lower-hemisphere sterograms (fig. 11). The stereogram of poles to bedding (fig. 11*A*) shows that the bedding is partially rotated around two great-circle girdles. The corresponding β-axes or major-fold axes plunge 18° toward azimuth 110° and 30° toward azimuth 292°; the average bedding strikes N. 84° W. and dips 45° S. The stereogram of poles to cleavage (fig. 11*B*) shows that the cleavage is rotated around a great-circle girdle and that the corresponding β-axis plunges 28° toward azimuth 295°; the average cleavage strikes N. 75° W. and dips 48° S. The stereogram of poles to axial planes (fig. 11*C*) shows that the axial planes are rotated around a great-circle girdle and that the corresponding β-axis plunges 28° toward azimuth 295°; the average axial plane strikes N. 45° W. and dips 25° S. Fold axes and lineations plunge at varying angles close to the average attitudes of bedding, cleavage, and axial planes (fig. 11*D*). The β-axes or major-fold axes also plot near the average attitude of planar structures (fig. 11*D*). The stereograms show a remarkably similar geometry for bedding, cleavage, and axial planes: all planar structures have roughly parallel average strikes of about N. 45°-84° W. and dips of 25°-48° S. The planar structures are rotated around nearly parallel β-axes or major-fold axes plunging 28°-30° toward azimuths 292°-295°. These β-axes or

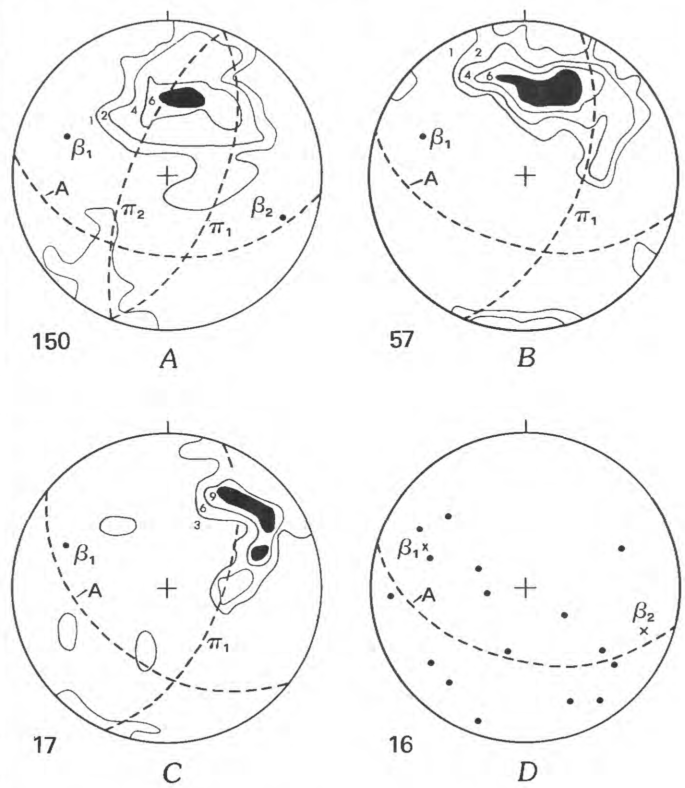


FIGURE 11.—Lower-hemisphere stereograms of structures measured in Drenchwater Creek area. *A*, Poles to bedding. *B*, Poles to cleavage. *C*, Poles to axial planes of minor folds. *D*, Minor-fold axes and lineations. Densities of data points are contoured as percentage of points per 1 percent of area of stereogram. Dashed great-circles labeled "A" are average attitudes of planar structures. Dashed great circles labeled "$\pi_{1,\,2}$" are great circles of rotated poles to planar structures. Points labeled "$\beta_{1,\,2}$" are major-fold axes that are poles to great circles of rotation. Numeral at lower left edge of stereogram denotes number of samples.

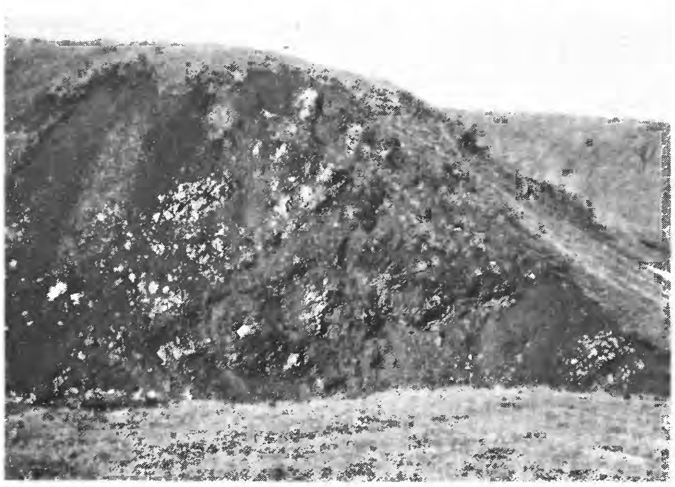


FIGURE 10.—Highly deformed dark-gray chert and shale in Mississippian rocks of the Kagvik sequence in southwestern part of Drenchwater Creek area. Light-gray blocks and lenses of chert are set in an intensely sheared and cleaved matrix of dark-gray shale. Maximum height of outcrop is about 12 m.

major-fold axes are also distributed along the average planar structure with the fold axes and lineations.

Several important deductions can be made from the stereograms. The parallelism of bedding, cleavage, and axial planes indicates that folding was isoclinal. The rotation of poles to bedding, cleavage, and axial planes along coinciding great-circle girdles indicates refolding of folds and axial-plane cleavages around the same fold axes that characterize the initial folds. The distribution of minor-fold axes and lineations, and of major-fold axes, along the average bedding and axial plane indicates that folding was partly by slip mechanisms (Weiss, 1959). Deformation was so intense that earlier formed structures were refolded or rolled. The refolding was the last phase of a single complex deformation, characteristic of such shallow-dipping thrust belts as the Roberts Mountain thrust studied by Evans and Theodore (1978).

ORIGIN OF STRUCTURES

The minor planar structures also parallel the fault-bounded major lenses of different rock types, the major thrust faults, and the axial planes of major isoclinal overturned asymmetric folds (compare attitudes in fig. 11 with those of major structures in pl. 1). This parallelism of major and minor structures indicates that both formed during the same period of deformation.

The simplest explanation for the formation of these structures and the tendency for tops to dip south is a single period of deformation involving both thrusting and asymmetric folding, in which blocks from the north were relatively thrust and folded under blocks from the south. Continued deformation resulted in shearing or faulting along the axial planes of asymmetric folds and left stacks of disrupted limbs of the isoclinal folds. Continued intense deformation refolded or rolled fold axes and axial planes around the original fold axes. The deformation occurred during or after Late Cretaceous time because all the Mississippian to Cretaceous formations were equally deformed.

SULFIDE DEPOSITS

OCCURRENCE AND LIMITS

The sulfide deposits occur along a relatively narrow 6- to 45-m-wide zone that extends eastward along strike from Drenchwater Creek for about 1,830 m; the deposits appear to be restricted to the Drenchwater thrust plate. The sulfide minerals consist of sphalerite, galena, pyrite, and marcasite, which, along with disseminated barite, occur principally in dark-gray chert, dark-gray shale, metaquartzite, tuffaceous sandstone, and tuff. On the geologic map (pl. 1), sphalerite and galena localities are marked "Zn" and "Pb," respectively.

The sulfide deposits are strongly iron stained (fig. 2) owing to weathering of pyrite and marcasite, which are sparsely disseminated in the tuff. Stream sediments are also iron stained downstream from the tuff. In the Mississippian rocks of the Kagvik sequence, barite occurs mainly as isolated disseminated grains in metaquartzite and chert and as microscopic inclusions in galena. Barite also forms small lenses or nodules in undifferentiated yellow-green chert of the Shublik or Siksikpuk Formations in the southeastern part of the study area. Barite localities are marked "Ba" on the geologic map (pl. 1).

The Siksikpuk Formation commonly exhibits intense iron staining as a weathering product of disseminated pyrite and marcasite. Iron staining should not, however, be used as a definitive guide to sulfide deposits in this region because many areas of iron-stained bedrock contain no visible sphalerite or galena, and no significant amounts of zinc or lead were found by semiquantitative analyses. Also, sphalerite- and galena-bearing rocks in the absence of pyrite or marcasite weather to shades of dark gray to black.

The east and west limits of the zone of sulfide deposits in the Drenchwater Creek area are probably defined by the extent of the Drenchwater thrust plate. To the east, the Drenchwater thrust plate thins and is absent east of Wager Creek (pl. 1). To the west, the thrust plate also thins and is absent in the area of Rolling Pin Creek, about 2 km west of Drenchwater Creek. Minor sulfide deposits may occur farther south, in the central part of the Gas Drum thrust plate (pl. 1). In that area, a thin layer of iron-stained tuff, and boxwork aggregates of weathered sulfide minerals, are present locally, but no sphalerite or galena has been observed.

The occurrence of sulfide minerals as disseminated grains in the sedimentary and volcaniclastic rocks (fig. 5*C*; table 1) strongly suggests that sulfide crystallization occurred coincidentally with or just after sedimentation. Less commonly, the sulfide minerals occur in 1- to 2-cm-thick quartz-sulfide veins crosscutting brecciated chert and shale (fig. 5*D*). Local crosscutting of cleavage by the veins suggests a period of mobilization and redeposition of sulfide minerals after deformation. The sparse occurrence of sphalerite and galena in the sulfide deposits possibly reflects an intense weathering of sulfide minerals that may be more prevalent at depth. In a few thin sections, sphalerite ranges from 5 to 35 volume percent, and galena from 5 to 25 volume percent. The average grain size of the sulfide minerals ranges from 0.5 to 2 mm in diameter. Galena is the only sulfide mineral observed toward the east end of the sulfide deposits, an intensely weathered area of low relief and thick soil, where it occurs as sparse relic grains in a chert boxwork.

PETROLOGY

DISSEMINATED SPHALERITE

The most common occurrence of sulfide minerals is sphalerite in chert, principally as disseminated single grains or disseminated composite grains. The composite grains have triple-point boundaries that reflect simultaneous crystallization around closely spaced nuclei or remobilization associated with metamorphism (fig. 12*A*). The matrix of the chert is mainly cryptocrystalline quartz and kaolinite. Clear zones of fine-grained recrystallized quartz rimming the sphalerite reflect dissolution of sphalerite rims and crystallization of quartz from solution, or recrystallization of quartz from the matrix. The dissolution of sphalerite rims probably coincided with the formation of massive sulfide and quartz-sulfide veins.

DISSEMINATED SPHALERITE, GALENA, PYRITE, AND MARCASITE

Other common occurrences of sulfide minerals are sphalerite, galena, pyrite, and marcasite as single disseminated grains or, less commonly, as composite grains (fig. 12*B*). Galena, pyrite, and marcasite form rare inclusions in sphalerite. The pyrite and marcasite commonly have a colloform habit that also is common in Kuroko-type volcanogenic sulfide deposits (Hayakawa and others, 1974; Sato and others, 1974). The concentric zonation in pyrite and marcasite

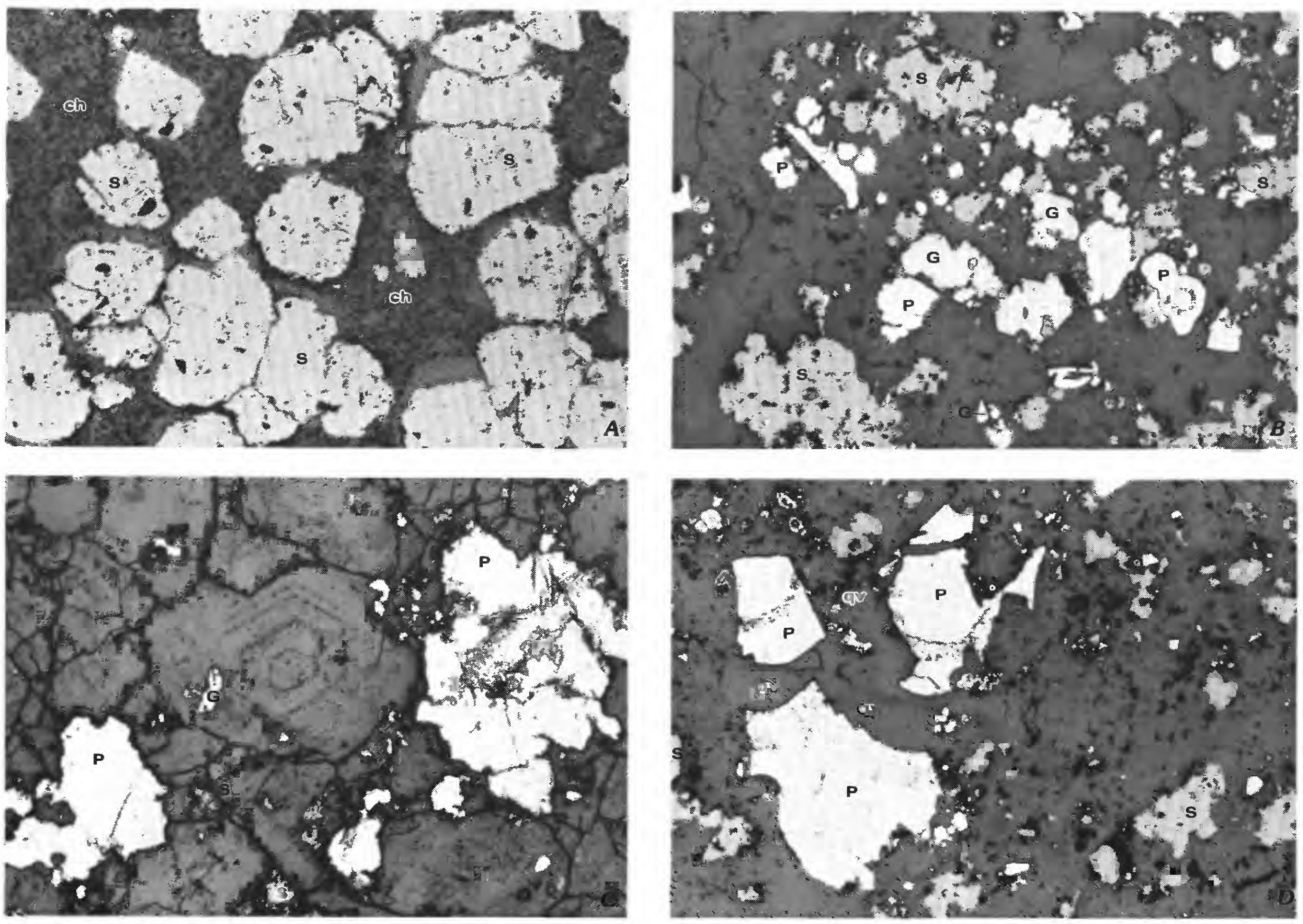


FIGURE 12.—Polished thin sections of sulfide minerals in Mississippian chert and metaquartzite of the Kagvik sequence in Drenchwater Creek area; numerous dark inclusions in sphalerite are polishing imperfections. Reflected plane-polarized light. S, sphalerite; G, galena; P, pyrite and marcasite; qv, quartz vein; ch, chert. *A*, Disseminated sphalerite in chert. Field of view is 1.8 mm long. *B*, Disseminated sphalerite, galena, pyrite, and marcasite in metaquartzite. Field of view is 0.9 mm long. *C*, Metaquartzite containing inclusions of sulfide minerals and hexagonal growth zones. Field of view is 1.8 mm long. *D*, Metaquartzite containing quartz vein and fractured pyrite and marcasite; quartz vein is between large pyrite and marcasite fragments. Field of view is 0.9 mm long.

consists of rings of pyrite and marcasite grains with different crystal habits. Sphalerite, galena, pyrite, and marcasite all form inclusions in quartz (fig. 12*C*). The interlocking boundaries between quartz and sulfide minerals reflect simultaneous crystallization or crystallization of sulfides in voids between quartz grains. Quartz forms rare inclusions in pyrite and marcasite and is almost absent as inclusions in sphalerite and galena. Sphalerite and galena commonly form tiny inclusions outlining hexagonal growth zones in quartz (figs. 5*C*, 12*C*). The occurrence of disseminated sulfide minerals and the presence of sulfide minerals as inclusions in quartz indicate sulfide crystallization during crystallization of the quartz rather than later replacement of the quartz by sulfide minerals. The presence of barite as rare inclusions in galena indicates simultaneous crystallization of the sulfide minerals and barite.

Another common occurrence of sulfide minerals is in sparse discordant quartz veins that crosscut the sulfide deposits and locally crosscut and fragment various sulfide minerals (fig. 12*D*). Pyrite, marcasite, and other sulfide minerals are commonly fractured or partly replaced by the solutions from which formed the quartz veins (figs. 12*A*, 12*D*). Sphalerite and galena were concentrated in quartz-sulfide veins in two rock samples from along Drenchwater Creek; in both samples the quartz-sulfide veins crosscut disseminated sulfide minerals that appear to be the source for the sulfide minerals in the veins.

GEOCHEMISTRY

ROCK, SOIL, AND STREAM-SEDIMENT SAMPLES

A suite of 62 rock, soil, and stream-sediment samples from the Drenchwater Creek area were analyzed by semiquantitative methods for 30 elements; the data and sample locations were reported previously by Churkin and others (1978b). The geochemical distribution of zinc, lead, barium, and silver—the chief elements of interest—are mapped separately for the rock, soil and stream-sediment samples (pl. 2).

The rock samples contain: less than 200 ppm (the lower detection limit) to more than 10,000 ppm Zn, 15 to more than 15,000 ppm Pb, 150 to more than 5,000 ppm Ba, and less than 0.05 ppm (the lower detection limit) to more than 150 ppm Ag. The highest values for zinc, lead, and silver were in the sulfide deposits within the Drenchwater thrust plate, between Drenchwater Creek and the unnamed creek between Drenchwater and Wager Creek.

The soil samples contain: less than 200 ppm (the lower detection limit) to 300 ppm Zn, 10 to 500 ppm Pb, 500 to more than 5,000 ppm Ba, and less than 0.5 ppm (the lower detection limit) to 7 ppm Ag. The highest values for zinc, lead, and silver also were mainly in the sulfide deposits within the Drenchwater thrust plate.

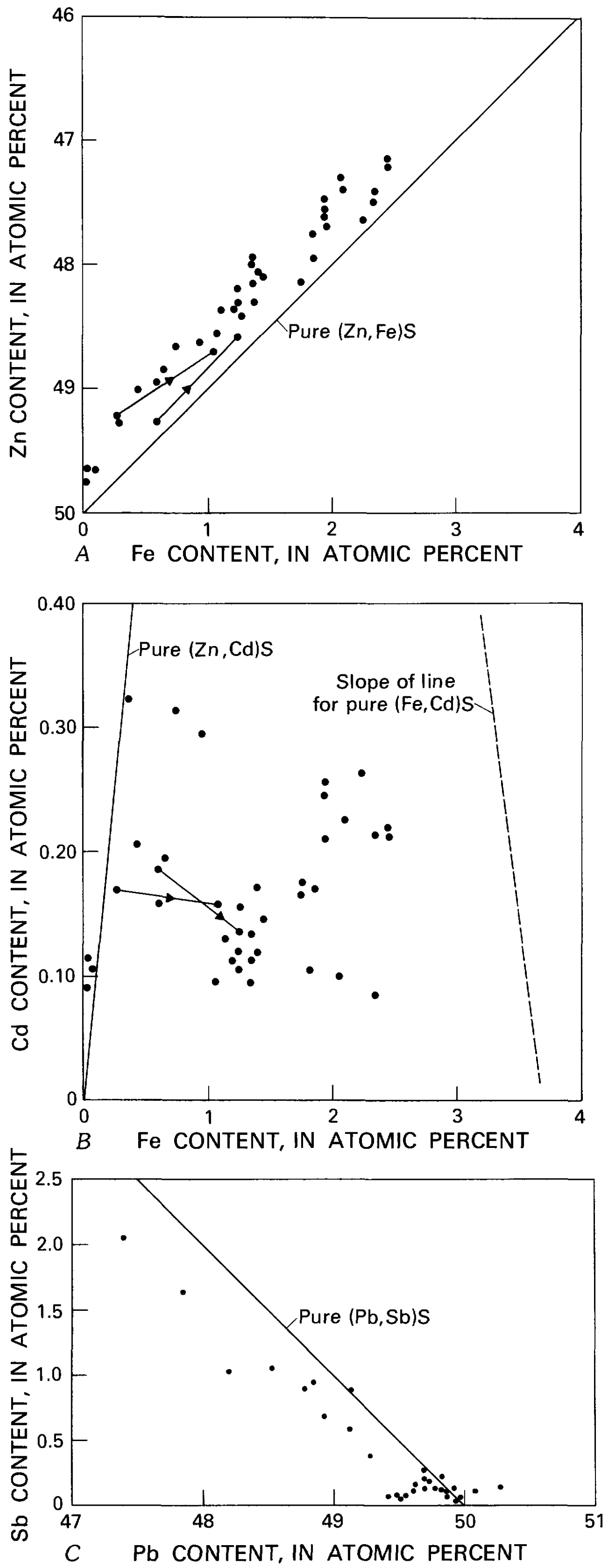
The stream-sediment samples contain: less than 200 ppm (the lower detection limit) to 1,500 ppm Zn, 20 to 300 ppm Pb, 2,000 to greater than 5,000 ppm Ba, and less than 0.5 ppm (the lower detection limit) to 7 ppm Ag. The highest values for zinc, lead, and silver were mainly downstream from the sulfide deposits within the Drenchwater thrust plate. However, relatively high values for these elements were also measured in samples from an unnamed tributary flowing eastward into Drenchwater Creek near the north boundary of the area, and from an unnamed north-flowing tributary in the east-central part of the area. These values may indicate potential sulfide deposits now obscured by thick soil and tundra. Churkin and others (1978b), Theobald and Barton (1978), and Theobald and others (1978) found a substantial zinc anomaly in stream sediments from an area about 22 km long in an east-west direction by about 7 km wide in a north-south direction, centered on the Drenchwater Creek area. Their data and the data in this report indicate a possibility for undiscovered sulfide deposits in and around the Drenchwater Creek area.

The analyses of rock, soil, and stream-sediment samples show relatively high values for barium. Barium content ranges from 150 to more than 5,000 ppm in rock samples, from 500 to more than 5,000

TABLE 2.—*Anomalous abundances of metallic elements in selected rock samples from the Drenchwater Creek area, northwestern Brooks Range, Alaska*

[Analyses in parts per million; n.d., not detected]

Sample	77ANK4D	77ANK116B	77AMD116	77AMK13D	77ANK13G	77ANK13K	77ANK14B
Ag	10	15	100	30	150	20	0.5
As	n.d.	n.d.	300	n.d.	n.d.	n.d.	n.d.
Ba	300	200	700	500	1,500	700	300
Cd	n.d.	>500	>500	200	150	150	n.d.
Cu	20	1,000	500	50	200	200	30
Pb	15,000	700	>20,000	15,000	>20,000	1,000	70
Sb	n.d.	n.d.	500	100	300	100	n.d.
Zn	n.d.	>10,000	>10,000	1,500	>10,000	>10,000	1,000



ppm in soil samples, and from 2,000 to more than 5,000 ppm in stream-sediment samples (pl. 2). The high values in rock and soil samples can be related to (1) nodules of barite sparsely distributed in the Siksikpuk or Shublik Formation, or (2) disseminated barite in the Mississippian rocks of the Kagvik sequence. The high values in stream-sediment samples represent placer concentrations of barite weathering from these sources.

The highest values for barium, zinc, lead, silver, arsenic, cadmium, copper, and antimony are in just seven of the rock samples from the Drenchwater Creek area (table 2), and the highest values for all these elements but barium and zinc are in just two of the samples (77AMD116 and 77ANK013G), which contained abundant sphalerite and galena. Electron microprobe analyses (table 3) show that the sphalerite contains abundant zinc and iron and minor amounts of cadmium and manganese. The galena contains abundant lead and minor amounts of silver, arsenic, and antimony (table 4). Neither sphalerite nor galena contains any detectable copper, and no copper-bearing sulfide has yet been identified in the study area. Local malachite staining in areas of sphalerite and galena deposits may represent either weathering of very sparse copper sulfide or, less likely, primary copper carbonate minerals deposited during hydrothermal alteration.

SULFIDE MINERALS

The compositional variations in the major-element contents of sphalerite and galena are plotted in figure 13. In sphalerite, the antipathetic variation of zinc with iron content indicates the well-known substitution of zinc for iron. Sphalerite composition ranges from essentially pure ZnS to about 2.5 atomic percent Fe and about 47.5 atomic percent Zn. Sphalerite analyses plot at small distances from the line for pure (Zn,Fe)S (fig. 13*A*); the distance between any given data point and the line for pure (Zn,Fe)S represents either minor-element content (principally Cd) or error in the analysis. A few large crystals show zoning, from relatively zinc rich and iron poor cores to rims richer in iron and poorer in zinc.

Cadmium content varies somewhat antipathetically with iron content (fig. 13*B*), but the variation is not systematic. Systematic substitution of cadmium for zinc or iron would produce compositional trends parallel to the lines for (Zn,Cd)S or (Fe,Cd)S. A

FIGURE 13.—Sphalerite and galena compositions based on electron microprobe analyses by W. J. Nokleberg. Lines with triangles show compositional changes from core to rim of large zoned crystals. *A*, Variation of Zn content with Fe content in sphalerite. *B*, Variation of Cd content with Fe content in sphalerite. *C*, Variation of Sb content with Pb content in galena. Sphalerite analyses from table 3, galena analyses from table 4.

limited trend is evident in a few analyses, parallel to the line for (Zn,Cd)S; most analyses, however, fall randomly in the field of the diagram.

In galena, antimony varies antipathetically with lead content (fig. 13*C*). Most analyses cluster in the area near 50 atomic percent Pb and 0 atomic percent Sb, although a few analyses trend parallel to the line for (Pb,Sb)S. The maximum antimony content is just more than 2.0 atomic percent. The distance between any particular data point and the line for (Pb,Sb)S (fig. 13*C*) most likely represents experimental error in determining small amounts of antimony in galena. Besides the minor amounts of antimony in galena, trace amounts of arsenic and silver were also found, in a range of a few tens of parts per million for each element. X-ray compositional scans on the electron microprobe show microscopic inclusions, as large as a few tens of micrometers in diameter, of an unidentified sulfosalt containing abundant antimony and lesser arsenic and silver. Electron microprobe analyses of pyrite and marcasite show only iron and sulfur with no major impurities.

LEAD ISOTOPE ANALYSES OF GALENA

Lead isotope analyses of galena (table 5) indicate model lead ages of approximately 200 m.y., according to the model of Stacey and Kramers (1975). The analyses also indicate that the lead was derived from a large volume of average-orogene material which may have included a considerable component of continental material (B. R. Doe, written commun., 1979). Derivation of the lead from an average orogene indicates either an island-arc or an Andean-type arc environment, rather than a sea-floor-rifting environment, for the formation of the stratiform zinc-lead deposits in the Drenchwater Creek area.

ORIGIN AND MODIFICATION

SUBMARINE VOLCANOGENIC HYDROTHERMAL ORIGIN

Several lines of field and petrologic evidence indicate a submarine volcanic origin for the volcanic and volcaniclastic rocks, for a significant part of the dark-gray chert and shale, and for the stratiform zinc-lead deposits in the Mississippian rocks of the Kagvik sequence in the Drenchwater Creek area:

(1) The keratophyre flows grade laterally into bedded tuff, tuffaceous sandstone, and tuffaceous siltstone that are interbedded with dark-gray chert and shale containing some volcaniclastic debris as well as radiolarians.

(2) The tuff, tuffaceous sandstone and siltstone,

TABLE 3.—*Electron microprobe analyses and structural formulas of sphalerite from the Drenchwater Creek area, northwestern Brooks Range, Alaska*

[Analyst: Warren J. Nokleberg]

Sample	11bA						13E				
Grain No.	1-Core	1-Rim	2-Core	2-Rim	3	4	1a	1b	2	3a	3b
Major elements (weight percent)											
S	32.934	33.039	33.055	32.971	33.098	33.157	32.893	32.907	32.731	33.067	33.179
Mn	.026	.043	.045	.026	.033	.032	.225	.217	.217	.101	.228
Fe	.679	1.439	.329	1.232	1.609	.865	2.238	2.262	2.543	2.702	2.256
Zn	66.156	65.494	65.491	65.504	65.039	65.528	63.914	64.140	64.022	64.070	64.043
Cd	.433	.316	.392	.367	.276	.724	.552	.783	.611	.200	.487
Total	100.227	100.332	99.762	100.099	100.054	100.305	99.823	100.309	100.124	100.139	100.193
Structural formulas											
S	49.970	49.983	50.295	50.014	50.136	50.226	49.980	49.850	49.675	49.983	50.153
Mn	.023	.038	.040	.023	.029	.028	.199	.192	.193	.089	.201
Fe	.591	1.250	.287	1.073	1.399	.752	1.952	1.967	2.215	2.344	1.957
Zn	49.229	48.593	49.208	48.732	48.317	48.681	47.629	47.653	47.653	47.497	47.478
Cd	.187	.137	.170	.159	.119	.313	.239	.338	.264	.086	.210

Sample	13F					13HB					13HC	
Grain No.	1A	1B	2	3	4	2a	2b	3	5	6	1	2
Major elements (weight percent)												
S	32.908	33.022	33.050	32.991	33.119	32.998	32.980	33.028	33.075	33.020	33.191	33.028
Mn	.055	.032	.061	.039	.046	.052	.045	.029	.038	.035	.228	.238
Fe	1.559	1.474	.000	1.376	1.185	.074	.108	2.091	1.607	1.638	2.417	2.219
Zn	64.210	64.945	66.941	64.676	65.186	66.676	66.653	63.957	64.400	64.363	64.071	63.932
Cd	.314	.238	.219	.267	.226	.258	.252	.232	.391	.332	.525	.585
Total	99.047	99.711	100.271	99.348	99.763	100.058	100.038	99.337	99.511	99.388	100.431	100.002
Structural formulas												
S	50.306	50.181	50.093	50.291	50.286	50.114	50.099	50.288	50.330	50.303	50.074	50.071
Mn	.049	.029	.054	.035	.041	.046	.040	.026	.034	.031	.200	.211
Fe	1.368	1.286	.000	1.204	1.033	.064	.094	1.828	1.404	1.433	2.093	1.932
Zn	48.140	48.402	49.759	48.354	48.542	49.663	49.657	47.758	48.062	48.089	47.406	47.534
Cd	.137	.103	.095	.116	.098	.112	.109	.101	.170	.144	.226	.253

TABLE 4.—*Electron microprobe analyses and structural formulas of galena from the Drenchwater Creek area, northwestern Brooks Range, Alaska*
[Analyst: Warren J. Nokleberg]

Sample	13E			13F				13HA				13HB			13HC	
Grain No.	1a	1b	2	2	3	5	6	1	2	4	5	1	3	4	1	3
Major elements (weight percent)																
S	13.428	13.538	13.272	13.409	13.319	13.398	13.318	13.579	13.543	13.657	13.603	13.415	13.414	13.418	13.308	13.372
Ag	.022	.044	.005	.108	.127	.099	.132	.066	.093	.044	.050	.069	.061	.071	.106	.000
Sb	.175	.969	.111	.348	.106	.215	.104	.072	.696	.924	1.086	.812	.190	.082	.261	.211
Pb	86.869	85.241	86.276	86.479	86.038	86.130	86.248	86.241	85.181	85.649	84.842	85.178	86.051	86.549	85.855	85.973
Bi	.000	.000	.000	.080	.163	.000	.130	.050	.037	.000	.113	.037	.000	.000	.067	.112
Total	100.493	99.791	99.663	100.425	99.752	99.842	99.933	100.008	99.550	100.273	99.695	99.510	99.716	100.119	99.597	99.668
Structural formulas																
S	49.879	50.148	49.798	49.800	49.842	49.971	49.788	50.350	50.272	50.273	50.291	49.991	50.059	49.969	49.839	49.995
Ag	.024	.048	.005	.119	.141	.110	.147	.072	.102	.048	.055	.076	.067	.078	.118	.000
Sb	.171	.945	.109	.341	.104	.211	.103	.071	.680	.895	1.057	.796	.187	.081	.257	.208
Pb	49.926	48.859	50.088	49.695	49.820	49.708	49.888	49.478	48.925	48.784	48.533	49.116	49.687	49.872	49.748	49.733
Bi	.000	.000	.000	.045	.093	.000	.074	.028	.021	.000	.064	.021	.000	.000	.038	.064

dark-gray chert, and dark-gray shale are pervasively hydrothermally altered in areas adjacent to keratophyre flows, andesite sills, and mafic tuff.

(3) Sphalerite, galena, pyrite, and marcasite are disseminated in chert that contains euhedral feldspar replaced by kaolinite. Textural relations indicate that this replacement was penecontemporaneous with deposition.

(4) In the metaquartzite, tiny inclusions of galena outline growth zones in hexagonal quartz that recrystallized from chert during hydrothermal alteration.

(5) The sulfide minerals, volcanic rocks, tuff, tuffaceous sandstone and siltstone, and hydrothermal-alteration minerals are intimately associated along a relatively narrow stratigraphic horizon in the Drenchwater thrust plate (pl. 1).

(6) Fluid-inclusion data indicate that the mineralizing fluids were around 100°C, that is, near boiling—a temperature compatible with submarine volcanism and mineralization.

(7) Sphalerite, galena, pyrite, and marcasite occur only in tuff, tuffaceous sandstone, metaquartzite, or dark-gray chert and shale adjacent to tuff or tuffaceous sandstone.

GEOLOGIC CONTROLS

Several major geologic controls on sulfide mineralization exist in the Drenchwater Creek area. First, sulfide deposition was stratiform and volcanogenic; that is, deposits were formed simultaneously with or just after sedimentation and volcanism. Second, volcanic exhalations (including magma) and hydrothermal fluids mixing with and heating seawater were the source of the mineralizing fluids. Third, hydrothermal fluids altered the volcanic rocks, volcaniclastic rocks, and dark-gray chert and shale in the Mississippian rocks of the Kagvik sequence to such hydrothermal minerals as kaolinite, montmorillonite, sericite, chlorite, actinolite, calcite, siderite, fluorite, barite, prehnite, and quartz. And fourth, intense deformation, including isoclinal folding, faulting, and dismembering of formations, has severely disrupted the former stratiform deposits. The Drenchwater Creek sulfide deposits were prob-

TABLE 5.—*Lead isotope ratios for galena from the Drenchwater Creek area, northwestern Brooks Range, Alaska*
[Analysts: Bruce R. Doe and Maryse Delevaus]

Sample	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
77ANK-13H Drenchwater (lat 68°34.3′ N., long 185°41.3′ W.)	18.428	15.609	38.351

ably much more extensive before that period of intense deformation. Similar tectonic lenses of sulfide deposits may be present in the subsurface along strike to the east and west of the Drenchwater Creek area.

MODEL

The submarine volcanic origin of the stratiform sulfide deposits is illustrated in a cartoon model (fig. 14*A*) that depicts penecontemporaneous sea-floor volcanism, hydrothermal activity, and sulfide deposition.

Gilmour (1971), Hutchinson (1973), Sillitoe (1973a), and Solomon (1976) demonstrated that copper-zinc volcanogenic deposits are generally associated with ophiolite complexes and newly formed oceanic crust in rifting environments. On the other hand, zinc-lead (and minor copper) volcanogenic deposits commonly occur in or are associated with more felsic calc-alkaline submarine deposits in island-arc or Andean-type arc environments; the Kuroko deposits in northeastern Japan are one prominent example (Hayakawa and others, 1974; Sato, 1974; Sato and others, 1974). Because the igneous rocks of the Drenchwater Creek area are keratophyre and pyroxene andesite, the source of the magma in that area was most likely incipient submarine Andean-type arc volcanism or, less likely, incipient island-arc volcanism rather than sea-floor rifting, which would yield basalt and possibly form ophiolite complexes.

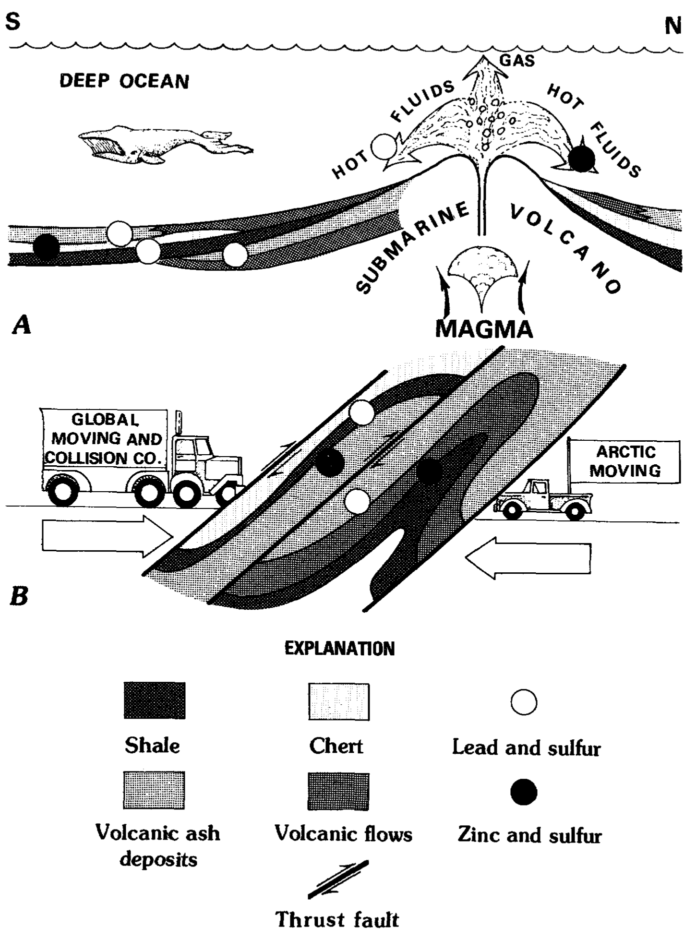


FIGURE 14.—Model for origin and deformation of stratiform sulfide deposits in Drenchwater Creek area. *A*, Formation of stratiform zinc-lead deposits in association with island-arc or Andean-type arc volcanism. *B*, Intense thrust faulting, folding, and formation of tectonic breccia and melange in rocks hosting sulfide deposits.

During the period of Cretaceous deformation, the Kagvik sequence, including the stratiform sulfide deposits and associated rocks in the Drenchwater Creek area, was intensely deformed by thrusting, isoclinal folding, and small-scale shearing. This deformation extensively dismembered the stratiform sulfide deposits, as illustrated in figure 14*B*; the two moving trucks represent the convergent forces that caused the deformation. Churkin, Nokleberg, and Huie (1979) related the intense deformation of the Kagvik sequence during the Late Cretaceous to telescoping of a Mississippian continental margin, caused in part by rifting and opening of the Canada basin and in part by accretion of the schist belt in the southern Brooks Range to the Kagvik sequence.

REGIONAL MINERAL POTENTIAL AND EXPLORATION GUIDELINES

Significant potential for stratiform zinc-lead deposits exists in the northwestern Brooks Range. Recent studies by Plahuta (1978), Plahuta, Lange, and Jansons (1978), and Nokleberg, Plahuta, Lange, and Grybeck (1979a, b) of the Red Dog Creek area, about 120 km west of the Drenchwater Creek area, showed that stratiform zinc-lead deposits similar to those in the Drenchwater Creek area also occur in the Mississippian rocks of the Kagvik sequence. In addition, Churkin and others (1978b) showed that (1) the Kagvik sequence can be traced along a continuous east-west-trending belt in the northern Brooks Range, and (2) the Mississippian rocks of the Kagvik sequence are quite favorable for zinc-lead deposits. These relations are evident on the map of the southern part of the NPRA (fig. 3), which shows: (1) the extent of the Kagvik sequence, (2) the areas of prominent iron staining in the Kagvik sequence, and (3) the areas of significant zinc geochemical anomalies in stream sediments. Coinciding areas of iron staining and zinc geochemical anomalies in the Kagvik sequence were considered by Churkin and others (1978b) as having the greatest potential for stratiform zinc-lead deposits; these areas include Spike, Kagvik, Elbow, Chertchip, Sorepaw, Drenchwater, and Safari Creeks.

In addition, we propose several guidelines to further exploration for stratiform zinc-lead deposits in the northwestern Brooks Range. First, because of the stratiform nature of deposition at Red Dog Creek, Tailleur (1970) suggested that all areas of iron staining along the north front of the Brooks Range should be examined for potential economic value. We further suggest that areas underlain by the assemblage of dark-gray chert, dark-gray shale, and tuff in the Mississippian unit of the Kagvik sequence should be examined in detail, particularly in the areas of significant zinc geochemical anomalies in stream sediments. Second, the dark-gray chert and dark-gray shale should be petrographically examined to determine areas that have been substantially hydrothermally altered and that contain abundant, though perhaps highly altered, volcanic fragments; such areas should have a greater potential for sulfide deposits formed in conjunction with hydrothermal exhalations and submarine volcanism. Third, iron staining should not be used as the sole prospecting guide because sphalerite and galena, without accessory pyrite and marcasite, weather to shades of dark gray to black; consequently, every dark-gray chert and dark-gray shale should be examined directly, or indirectly by means of geochemical analyses. And fourth, because of the intensity of deformation in the Drenchwater Creek area, future exploration should concentrate on detailed geologic mapping and geophysical or geochemical methods for locating lenses of the original deposits.

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