CANADA

DEPARTMENT OF MINES AND TECHNICAL SURVEYS

GEOLOGICAL SURVEY OF CANADA

PAPER 55-30

GEOLOGY AND GEOCHEMISTRY OF SILVER-LEAD-ZINC DEPOSITS OF KENO HILL AND SOURDOUGH HILL, YUKON TERRITORY

(Preliminary Report, Map, and Eleven Figures)

By

R. W. Boyle

OTTAWA
1956

Price 50 cents

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The Geology and the Geochemistry of the Silver-Lead-Zinc Deposits of Keno Hill and Sourdough Hill, Yukon Territory

INTRODUCTION

This report summarizes the author's 1953 and 1954 field work on the lead-zinc-silver deposits of Keno and Sourdough Hills. The results of this field work show that the deposits on these two hills are located in brecciated fault zones cutting greenstone, quartzite, and phyllite beneath schist cappings and at fault junctions. A preliminary account of the mineralogy and a brief account of the geochemistry of the deposits are given. No attempt is made to discuss the genesis of the deposits because laboratory work on this problem has just commenced.

Lead-zinc-silver deposits were discovered in the Keno Hill area in 1919 and mining operations and exploration have continued since that year. The principal producing mines were the Ladue and Sadie-Friendship, Lucky Queen, Number 9 (Keno Hill Limited), Onek, and Shamrock. All of these mines had ceased operation by the end of 1932, and with the exception of recent exploration at the Onek and Shamrock no further work has been done on them.

During the years 1949 to 1953 mining exploration in the Keno Hill area was stimulated by the finding of large lead-zinc-silver orebodies at the Calumet-Hector mine on Galena Hill (See Figure 1) by United Keno Hill Mines Limited. Extensive exploration during this period on Keno Hill succeeded in finding some new veins, but of these none proved to be of economic value.

On Sourdough Hill exploration during the same period by Bellekeno Mines Limited succeeded in the development of two ore shoots. Production of lead-silver concentrates from these shoots commenced in late 1952 and ceased in August 1954.

During the summer of 1954 exploration on the two hills was limited. United Keno Hill Mines Limited investigated the downward extension of the ore shoots at the Shamrock mine, and exploration by Comstock-Keno Mines Limited on the northeast extension of the Porcupine vein fault on Keno Hill disclosed a promising ore shoot. Some ore was mined by lessees at the Mount Keno mine from the Runer vein fault.

ACKNOWLEDGMENTS

The author takes pleasure in extending his thanks for many favours and courtesies received from numerous individuals and companies during the two field seasons. Special thanks are due to the manager of United Keno Hill Mines Limited, Mr. C. White,

for providing accommodation for an office and field laboratory. Messrs. A. C. Carmichael and M. White, chief geologist and exploration manager, respectively, of United Keno Hill Mines Limited provided much valuable information and assisted in many ways. Mr. G. Campbell, manager of Bellekeno Mines Limited, provided maps and assay data for the Bellekeno system of vein faults. Mr. J. J. Hogan, manager, and Mr. J. D. Godfrey, geologist, of Mount Keno Mines Limited, supplied maps and diamond drill data for the Mount Keno vein faults. Mr. W. S. Ellis, in charge of exploration for Comstock Keno Mines Limited, provided maps of the Gambler and Nabob vein faults and assisted in many other ways. Mr. J. Walli provided maps and information on the Klondike-Keno workings and other properties. Many prospectors have contributed information on the present and past exploration carried out on the two hills; to them the writer is grateful.

The author had access to the lucid and informative annual reports written by the late Livingston Wernecke for the Treadwell Yukon Company Limited, and now in the geological files of United Keno Hill Mines Limited. These reports, containing numerous geological maps and sections, cover in great detail the former operations by the Treadwell Yukon Company, Limited in the Keno-Galena Hill area and have been an invaluable asset because many of the old workings have caved or are otherwise inaccessible.

The geological map of Keno Hill compiled by McTaggart (1950)[1] has been used as a guide throughout the investigation. This map has assisted and speeded the field work immeasurably.

Messrs. R. Hodder and P. Tarassoff assisted the author during the 1953 field season, and Messrs. C. T. Illsley, D. J. Mclean, and R. N. Green during the 1954 field season. These men showed a sustained interest in the progress of the work and carried out their duties in a painstaking manner.

Miss Ann Sabina, Radioactive Resources Division, Geological Survey of Canada, did the X-ray work and determined the complex minerals. The spectrographic analyses were done in the spectrographic laboratory, Geological Survey of Canada.

LOCATION

Keno and Sourdough Hills are located in central Yukon 35 miles northeast of Mayo and some 220 miles due north of Whitehorse. Mayo is served by an all-weather motor road from Whitehorse and by Canadian Pacific Airlines. Keno Hill can be reached by an all-weather motor road from Mayo.

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[1] Dates, etc., in parentheses refer to Bibliography at the end of the report.

TOPOGRAPHY, GLACIAL AND FROST ACTION, AND CLIMATE

The regional topography has been described by Bostock (1948). The Keno Hill area lies in the northeastern part of the Yukon Plateau. The topography is mountainous, with elevations from 6,750 feet (Mount Hinton) to 2,300 feet (Ladue-McQuesten River Valley).

Keno Hill and Sourdough Hill are adjacent hills separated by Lightning Creek. Keno Hill trends northeast and lies between the Ladue-McQuesten River Valley and Allen, Faith, Lightning, and Christal Creeks. The hill has gentle south and southeastern slopes and a precipitous northern slope, marked by two cirques, Faro Gulch and Silver Basin Gulch. The terrain above 4,500 feet is relatively flat and rolling with five prominent rocky knolls known as Keno, Minto, Monument (the highest point on Keno Hill, elevation 6,065 feet), Caribou, and Beauvette. On the north, northeastern, and southern slopes of the hill several streams follow steep gulches in the rock strata. The principal streams within these gulches are Gambler, Faro, McKay, and Silver Basin on the northern slope, Faith, Hope, and Charity on the northeastern and southern slopes, and Erickson on the eastern slope.

Sourdough Hill trends north between Thunder, Lightning, and Duncan Creeks. The part of the hill described in this report is on the north and northwestern slopes, which are gentle up to 4,200 feet and from there rise abruptly to a steep rocky hogsback that trends southeast for some 6,000 feet.

Below an elevation of 4,500 feet on the two hills rock outcrops are sparse, and the slopes are covered with till, soil, rock debris, muck, and muskeg in which conifers, birch, aspen, buckbrush, and other vegetation grow abundantly. Above 4,500 feet outcrops are numerous, soil and till are sparse, the ground is covered with local rock float, the terrain is treeless, and vegetation is limited to alpine varieties.

The lower slopes of both hills have been severely glaciated during Pleistocene time by an ice-sheet that spread over the general area from the east as an unbroken mass. Glacial till and gravel are widespread and are generally 5 to 20 feet thick, but in some areas, as on the southern slope of Keno Hill facing Lightning Creek and north of Christal Lake, the deposits are 30 to 50 feet thick. Some valleys exhibit U-shaped cross-sections and are floored with glacial sand, gravel, and till through which some streams have cut channels, bordered by a series of benches.

The two hills are in the region of permanently frozen ground. Wernecke (1932) has given an interesting account of the permafrost conditions in the area. The permafrost is patchy in its distribution depending upon the elevation, hillside exposure, depth of overburden, amount of vegetation, and presence of flowing underground and surface waters. The ground on the northern slopes of both hills is generally underlain by permafrost, whereas the lower southern slope of Keno Hill is relatively free of permafrost. Thus, on Keno Hill, the mine workings on the top of the hill and on the northern slope encountered permafrost and were coated with frost some 400 feet below the surface, and on Sourdough Hill frost and ice lenses were encountered in the Bellekeno mine workings 250 feet below the surface. On the lower southern slope of Keno Hill, however, the workings of the Mount Keno mine show no evidence of permafrost.

Frost action and solifluction have had a marked effect on the rocks on the top of Keno Hill and generally in all areas of permafrost. Rock float and in some places vein float are brought to the surface by frost heaving and solifluction, and stone rings, polygons, and stone rivers are widespread. On the steep slopes of both hills, especially in the gulches, land creep has moved the outcrops of some lodes 20 to 50 feet down the slope.

The climate of central Yukon is rigorous. The mean annual temperature at Mayo is 26°F., the average minimum temperature is + 14°F., and the average maximum + 37°F.[1]. Temperatures as low as - 80°F. and as high as + 90°F. have been recorded. The winters are long and cold with only a few hours of daylight each day, and the summers are short and warm with nearly continuous daylight.

The average annual precipitation at Mayo is 11.23 inches. The rainfall in the Keno Hill area during the spring and summer months is moderate with occasional torrential downpours. The snowfall is moderate and usually commences in mid-September or early October. Most of the snow has melted by the end of May, but local patches and small snowfields remain in sheltered places on northern slopes until late August.

GENERAL GEOLOGY

GENERAL STATEMENT

The general geology of the Mayo area was described first by Keele (1906) and later by Bostock (1947). The geology of Keno Hill was described by Cockfield (1920, 1923), and by McTaggart (1950). E. D. Kindle (1955) has restudied the geology of the area comprising Mayo Lake, Galena Hill, Keno Hill, and Sourdough Hill.

The consolidated rocks underlying Keno and Sourdough Hills and the immediate surrounding area belong to the Yukon group and may be Precambrian or Palaeozoic in age. They consist of

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[1] Data, courtesy Dominion Meteorological Service, Department of Transport, Ottawa, Canada.

sericitic, chloritic, and graphitic schists, phyllites, and thick- and thin-bedded quartzites. Three formations, a lower schist formation, a central quartzite formation, and an upper schist formation, represent the southern limb of a large anticline with its axis along Ladue-McQuesten River Valley (See Figure 1). Conformable lenses and sills of greenstone occur in the lower schist and central quartzite formations, and limestone lenses are a common feature in the upper schist formation. A few quartz-feldspar porphyry sills are exposed along the the northern slope of Keno Hill, and a granite mass outcrops 12 miles due east of Keno Hill townsite. Next to this granite the sedimentary rocks are altered to andalusite, garnet, and staurolite schists[1].

ROCK TYPES

The geological map accompanying this report shows the distribution of the rock types on the two hills. This report does not deal at length with the petrography and petrology of the rock types except in so far as these subjects affect the structural localization and geochemistry of the ore deposits. Only brief descriptions of the rocks and the author's interpretation of their structure will be given.

The geological map has been compiled during a detailed investigation of the deposits. On this map it has been difficult to portray all outcrop and float areas. The author has, therefore, grouped many small closely adjacent outcrops into one outcrop. In other cases he has also interpreted some areas covered with float as outcrop. Bulldozing and other surface work in recent years has shown that this can be done with some confidence on and near the tops of the two hills.

Keno Hill and that part of Sourdough Hill described in this report are underlain by the lower schist and central quartzite formations. The rocks of these two formations include schists, phyllites, quartzites, greenstones, and quartz-feldspar porphyries. Each of these is described briefly below.

The schists are sericitic, chloritic, and graphitic with layers of quartz-mica schist. In their outcrops, these rocks are highly foliated and locally exhibit many small drag-folds and innumerable crenulations. Such structurally disturbed zones and some layers showing bedding planes contain an abundance of stringers, masses, and bulbous lenses (boudins) of white quartz in many of which cubes and masses of pyrite are present. The mineral constituents of the schists vary in amount according to type, but quartz, sericite, plagioclase, and chlorite occur in all varieties and a fine carbon-like substance (probably graphite) is abundant in some producing the so-called graphitic schists. Carbonate minerals and pyrite occur in some schists.

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[1] Personal communication L. H. Green, Geological Survey of Canada.

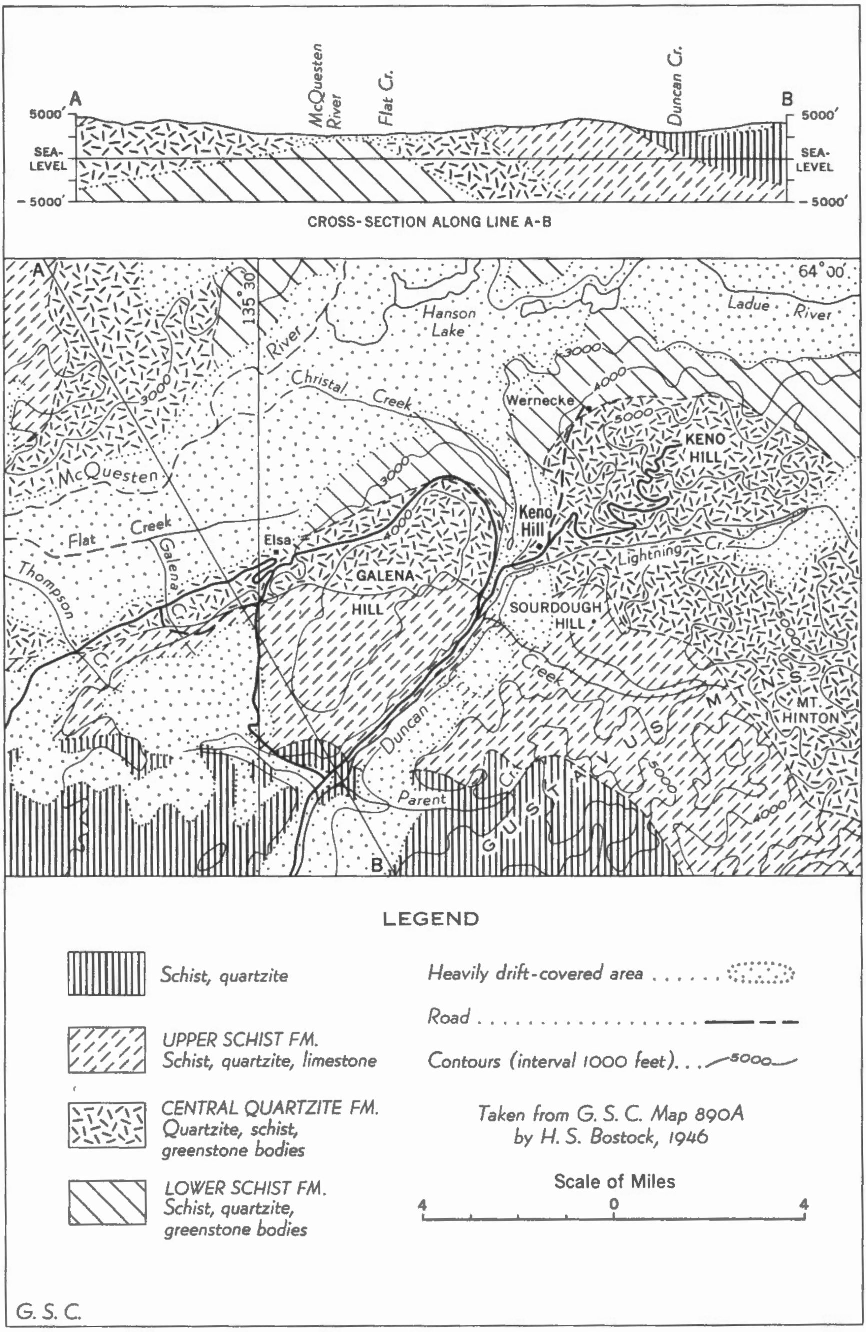


Figure 1. Geological map and cross-section of the Keno Hill-Galena Hill area, Yukon Territory

The phyllites are dark grey to black slaty rocks and occur in beds usually a few inches thick alternating with beds of graphitic schist or thin-bedded quartzite. Rock assemblages of this type occur in the various schist members and in the thick-bedded quartzites and may be several tens of feet wide. They exhibit abundant drag-folds and small crenulations and contain quartz boudins and stringers. In thin sections the phyllites contain quartz, sericite, plagioclase, carbonate, and graphite.

The quartzites are both thick and thin bedded. Bands of the thick-bedded quartzite include beds up to 10 feet thick with both thick and thin interbeds of the various types of phyllites and schists. The thin-bedded quartzites occur in beds up to a foot or so in width and are interbedded with schist beds about the same size. The thick-bedded quartzites are blocky, fairly homogeneous, grey to black, but locally some beds are light brownish and flinty in appearance. Ptygmatic-like stringers and small irregular veins and masses of quartz occur in some varieties and drag-folds up to 3 feet across have been observed in some beds. The thin-bedded quartzites are generally contorted and warped and some contain small drag-folds. Quartz veins and boudins are common in the interbedded schist and phyllite beds. The principal minerals in the quartzites are quartz, sericite, carbonate minerals, feldspar, and graphite, in that order of abundance. Accessory minerals are erratic in their occurrence and include zircon, tourmaline, apatite, pyrite, and epidote.

The greenstones are schistose, greyish green to dark green rocks that occur in conformable elongated masses and sills in the lower schist and central quartzite formations. Blackadar (1951) has described their nature and discussed their origin at some length. The greenstones weather differentially compared with the schists and quartzites and form prominent precipices and knobs. The rocks are jointed and present a slabby appearance. In thin sections the original minerals of the greenstone are highly altered to hornblende, actinolite, plagioclase, zoisite, chlorite, biotite, sericite, leucoxene, and carbonate minerals. Quartz, ilmenite, and apatite are common minor constituents.

The sedimentary rocks described above were originally sandstones and shales; the greenstones were probably sills of diorite or gabbro. All these rocks have undergone deformation and regional metamorphism with consequent rearrangement of the mineral constituents and the formation of stable low-grade metamorphic minerals. The mineral assemblage, sericite, chlorite, and carbonate in the schists and quartzites, and actinolite, biotite, chlorite, zoisite, and leucoxene in the greenstones, corresponds to the chlorite and biotite zones of Harker (1932) and the greenschist facies of Turner (1948).

The quartz-feldspar porphyries occur as sills exposed here and there on the north and northeastern slopes of Keno Hill. They are light-coloured rocks and weather buff to white. The phenocrysts of quartz and feldspar are set in a fine-grained groundmass of quartz, feldspar, muscovite, and chlorite. Locally, pyrite is abundant in the groundmass of the rock, and Cockfield (1923) and Visel state that galena, sphalerite, and tetrahedrite occur along some joint planes and slips as well as in the body of these rocks. This feature is now being investigated by the author.

STRATIGRAPHY

Throughout the area investigated the beds have an average dip of from 20 to 35 degrees to the south. Tops can rarely be determined, making it difficult to ascertain whether or not there has been local overturning. In the absence of this data the author has concluded that the stratigraphic sequence, notwithstanding the presence of faults and other complexities, is a simple homoclinal succession. As field work progresses it may be necessary to modify this viewpoint.

The stratigraphic sequence is disrupted by many low-angle faults, bedding faults, steep vein faults, and cross faults to be described later. It is the author's opinion, however, that certain members can be outlined with confidence because they appear to have a general continuity throughout the area. Some quartzite units appear to terminate abruptly, but this is thought to be due to changes in the sedimentary facies in some cases and faulting in others.

Each of the distinctive members in the lower schist and central quartzite formations is described below. Figure 2 is an idealized index map providing a key to the complexities of the stratigraphy and faulting. The purpose of outlining specific stratigraphic members is to emphasize those members and units that contain ore shoots and have, therefore, been structurally favourable to ore deposition. An analysis of the stratigraphic data and that obtained from studies of faults indicates that it is possible to suggest possible loci of ore shoots.

Lower Schist Formation. This formation outcrops along the north slope of Keno Hill. The principal members are:

(1) A lower graphitic schist and phyllite member containing numerous concordant lenses of greenstone and a few thin sills of quartz-feldspar porphyry. This member outcrops on the lower slopes of Keno Hill and on the whole of Beauvette Hill. To date no productive deposits have been found in this member, but it should be noted that many structurally favourable greenstone bodies occur along the whole length of the member.

(2) The Caribou Hill quartzite. This member consists of three quartzite units each interbedded with a sequence of sericite schist beds, and the member as a whole is overlain by a sequence of

graphitic schist beds. The three quartzite units outcrop on Caribou Hill and in the eastern wall of Silver Basin. From the latter point they outcrop at only a few points across Silver Basin to the western wall of the basin. Here the three units are still present, but the northern two are greatly reduced in thickness and appear to interfinger with thin-bedded quartzites, schists, and phyllites. The southern quartzite unit maintains its thickness to the eastern rim of Faro Gulch where the unit appears to terminate. West of Faro Gulch the rock types are different due either to a change in the sedimentation facies or to faulting. The rocks in this part of the member are phyllite, schist, thin-bedded quartzite, a few beds of thick-bedded quartzite, and many lenses of greenstone.

This member is ore bearing. In the eastern part, principally in the headwall of Silver Basin and on Caribou Hill and between Faith and Hope Gulches, several prospects have been opened up, and small ore shoots investigated. These shoots tend to occur in quartzites below sericite schist or graphite schist beds. Two prospects occur in sericite schists. In the western part small ore shoots occurred in or near greenstones west of Faro Gulch, and the orebodies of the Ladue-Sadie-Friendship occurred in phyllite, quartzite, and greenstone.

Central Quartzite Formation. The principal members in this formation are:

(1) The number 9 quartzite. This member, composed of quartzite units and interbedded thin schist beds, outcrops on Monument Hill, in the headwall of Faro Gulch, and can be traced westward to the area south of Wernecke. Here the member is severely disrupted by vein faults and cross faults and appears to interfinger with interbedded schists, quartzites, and phyllites. The orebodies of the Number 9 system, Shamrock, and Lucky Queen mines occurred in this member.

(2) The Keno Hill schist and greenstone. This member is composed of a lower unit of sericite schist, a central complex of phyllites and greenstone lenses overlain by graphitic schist, and an upper unit of sericite schist. Beds of the member can be traced from the area east of Hope Gulch westward across the top of Keno Hill, thence along Erickson Gulch to the area west of Wernecke road. Orebodies occur in this member principally in greenstone lenses below graphitic schist.

(3) The principal quartzite. This member is composed of units of thick- and thin-bedded quartzites with interbedded schists and phyllites and a few greenstone sills and lenses. It outcrops over the southern slope of Keno Hill and the northern slope of Sourdough Hill. The ore shoots of the Onek and Bellekeno mines occurred in this member, and numerous other prospects have been found.

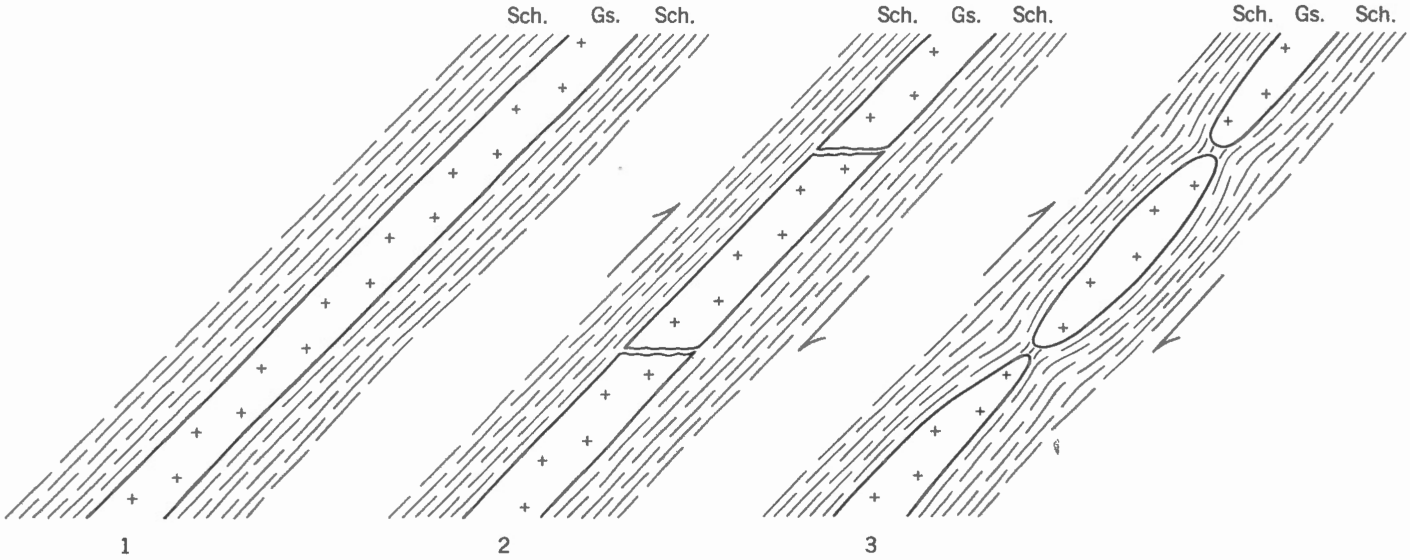
(4) Sourdough schist, phyllite, and thin-bedded quartzite. This member overlies the principal quartzite member, outcrops on the northern slope of Sourdough Hill, and can be traced westward over Galena Hill. No orebodies are known to occur in this member.

STRUCTURAL FORM OF THE GREENSTONES

In the following sections evidence is presented that ore shoots are localized in some vein faults where greenstone forms one or both walls and terminate when the vein faults pass into schist. It is on this account imperative to obtain an idea of the geometry of the greenstone bodies in attempting to assess the extent and continuity of ore shoots in these rocks.

Blackadar (1951) has described the form of the greenstone bodies and discussed their origin at some length. He suggests two origins -- the greenstone lenses are remnants of a highly faulted series of pipe-like intrusives or the greenstone lenses are due to shearing with consequent formation of boudins; he favours the first hypothesis.

Field and underground investigations by the author show that the greatest number of greenstone bodies occur in the lower schist formation and in the schist members of the central quartzite formation. In the schist members the bodies are lens-like and discontinuous both along the strike and down the dip but appear to follow certain definite zones. Where greenstone occurs in quartzite as on the northern slope of Sourdough Hill the bodies are fairly continuous and appear to be sills. In both schist and quartzite the greenstone lenses and sills are cut by numerous shear zones and are highly sheared at their contacts with both quartzite and schist. This evidence suggests that the discontinuous lens-like bodies of greenstone along specific zones were once continuous sills that were fractured parallel with and perpendicular to the strike and then sheared into sausage-like bodies (boudins). The details of the process of forming boudins have been outlined by Cloos (1946), who also gives several references. Figure 3 illustrates the formation of simple boudins. These have been further cut and displaced by an extensive series of bedding plane faults, low-angle thrust faults, shear zones, vein faults, and cross faults. The fact that most of the greenstone bodies (competent rocks) occurring in the schists (incompetent rocks) show well-developed boudinage strongly supports the boudinage hypothesis. In the quartzites where the competency of the two rocks (greenstone and quartzite) is nearly the same the results of the surface and the underground mapping suggest that the greenstone bodies are faulted sills.



1. *Greenstone sill is intruded into schist*
2. *Tension fractures form across greenstone sill due to shearing action*
3. *Shearing of greenstone rounds off edges and schist flows into spaces between lenses*

Incompetent schist . . . . . Sch. *Competent greenstone* . . . . Gs.

G. S. C.

Figure 3. Sketches illustrating the formation of greenstone boudins

THE VEIN FAULT AND FAULT SYSTEMS

GENERAL STATEMENT

Two types of faults occur in the area; those that contain veins and lodes of economic minerals are designated by the term vein fault in this report, and those that contain only small amounts of economic minerals generally of a supergene origin are called cross faults, bedding faults, etc. The surface traces of both types of faults are shown on the enclosed map.

Field studies indicate that there are three main ages of faults. These are, the oldest first:

(1) Bedding faults and low angle faults.

(2) Vein faults. These may show evidence of two or more periods of movement and mineralization.

(3) Cross faults, low-angle faults, and bedding faults that cut and offset 1 and 2 above.

Fracture and joint planes are widespread and occur in nearly all types of rocks, but particularly in thick-bedded quartzites and massive greenstones. Several ages are present; some are offset by the vein faults and others cross both vein faults and late faults. Most joint and fracture planes contain quartz and carbonate minerals.

INTERNAL NATURE AND STRUCTURE OF FAULTS

Vein Faults

The vein faults occur in all types of rocks but differ in their internal nature when cutting through greenstones, quartzites, and schists respectively. In most greenstones and all thick-bedded quartzites the vein faults are breccia zones or sheeted zones or transitions between these two types; in some greenstones the vein faults are shear zones and some chlorite schist is developed along them. In the schists, phyllites, and thin-bedded quartzites the vein faults are represented by narrow fractures, slips, crenulated zones, or narrow breccia zones.

The breccia and sheeted zones constituting the vein faults in the greenstones and thick-bedded quartzites vary from 5 to 50 feet in width and can be traced with ease along their strike and dip. The breccia zones are composed of rock fragments that are generally angular, but some are rounded indicating considerable attrition during fault movements.

In some faults the fragments have been ground into a clay or sandy gouge. The breccia type vein fault is widespread; those at the Bellekeno, Ladue, Sadie-Friendship, Onek, and Comstock-Keno mines are of this type. The sheeted zone type consists of rectilinear slabs of quartzite or greenstone separated in most occurrences by small breccia- or gouge-filled fractures a fraction of an inch to a few inches in width. Faults of this nature are not abundant, but good examples occur in the surface pits on the Black Cap property of Brewis Red Lake Mines Limited and in the Lucky Queen mine.

Below the oxidation zone the breccia fragments and rectilinear slabs in the vein fault zones are cemented in places by siderite and some quartz, and in addition in the mineralized parts and orebodies by sphalerite and galena. Barren parts show little cementation with the exception of some carbonate minerals. In the oxidized zone the fragments and slabs are cemented by limonite, manganese oxides, galena, carbonates, and sulphates in mineralized parts and orebodies. Barren sections contain only breccia, gouge, and limonite.

In the schists, phyllites, and thin-bedded quartzites individual vein faults are narrow, seldom exceed a foot in width, and contain some gouge and breccia. In many places the vein fault is difficult to trace because it is a simple fracture or slip an inch or so in width along which the walls of schist or phyllite have been dragged, contorted, and mashed. Such vein faults contain limited amounts of ore and gangue minerals, similar to those listed above for the oxidized and unoxidized zones of the breccia vein faults.

The structural details of the vein faults are complex in all occurrences. In no place are the fault planes simple, but rather a number of parallel to sub-parallel gouge- or breccia-filled surfaces along which recurrent movement has taken place. Slips and fractures abound throughout a single fault zone. Some parallel the zone and cut through the breccia, gouge, and mineralized sections. Others branch from and join the main vein fault, or branch into schists in the foot- and hanging-walls and die out. Slickensides on wall-rock, siderite, and sphalerite along fault and slip surfaces are common in many fault zones, and in some mineralized sections near late slips the galena exhibits a fine-grained or schistose appearance (steel galena).

The habit of the vein faults when they pass from one rock type to another is important in mining and in understanding the structural control of some ore shoots. Figure 4 is an idealized sketch of the habit of a vein fault in the various types of rocks. Vein faults that pass from greenstone into thick-bedded quartzite show little change in character or strike and dip in most places; in both rocks they tend to be breccia or sheeted zones that are favourable sites for orebodies. The passage of a vein fault into an area where schists, phyllites, and thin-bedded quartzites form both walls is marked by a

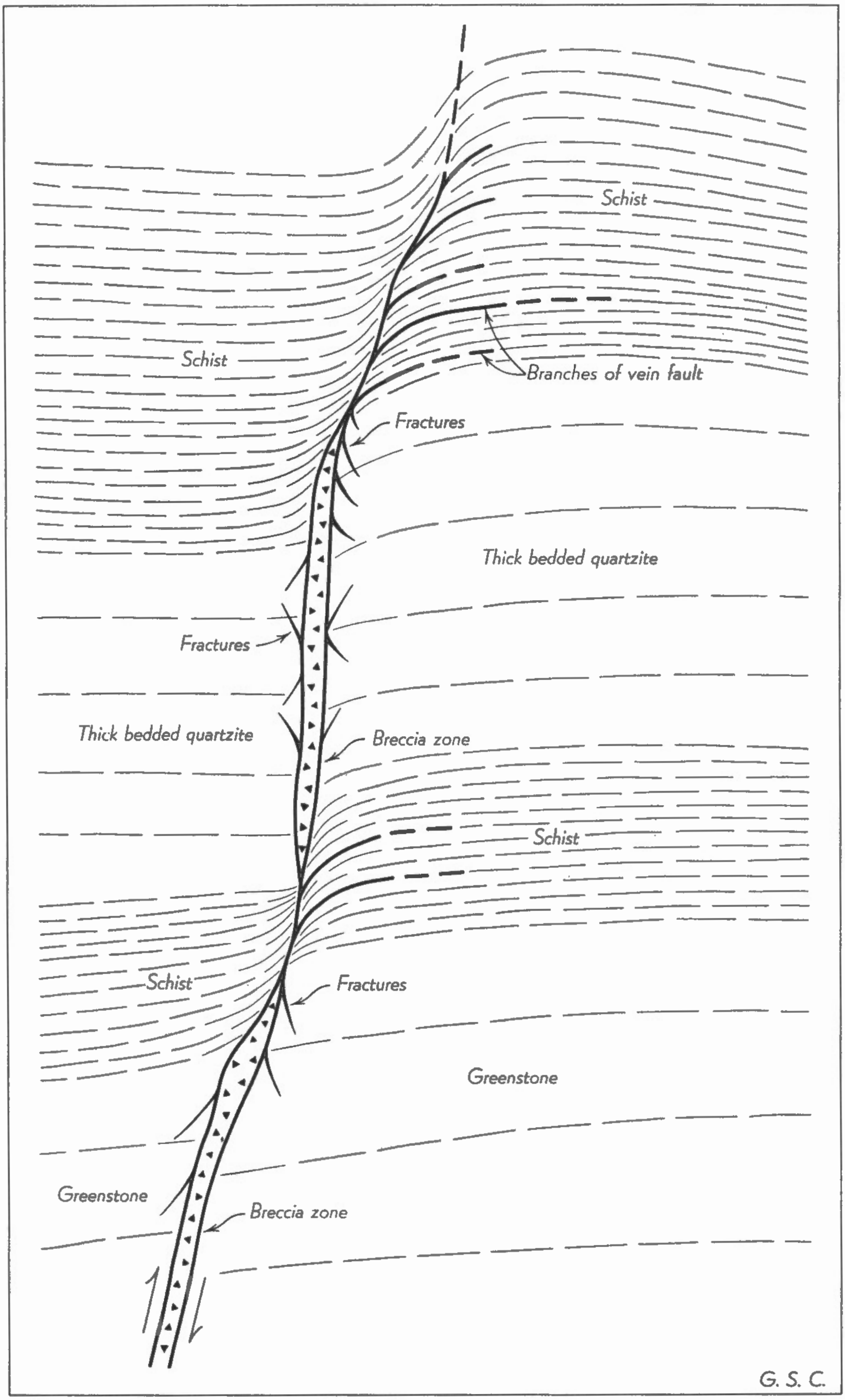


Figure 4. Sketch illustrating the nature of a vein fault in various types of rocks

sharp reduction in the width of the fault zone and a gradual or total disappearance of breccia. Strikes and dips of individual fault and slip planes constituting the vein fault zone become erratic with a general tendency for these structures to branch and follow bedding planes and finally die out in a drag-folded or crenulated part of a bed. The schists or phyllites adjacent to individual slips are contorted and mashed, and the fault zone as a whole is hard to follow during mining operations.

Field studies indicate that the degree of competency of the rock types and the tendency to form breccia or sheeted zones favourable to mineralization varies in the following descending order -- thick- bedded quartzites, greenstones, thin-bedded quartzites, phyllites, and schists. This does not mean that members composed of thin-bedded quartzites, phyllites, and schists should be neglected during exploration. On the contrary, if these members contain greenstone lenses or a few thick beds of quartzite, conditions may be favourable for ore shoots; as an example it should be noted that the orebodies of the Ladue-Sadie-Friendship mine occurred in a complex of this type.

From the foregoing description of the nature of the vein faults in the various types of rocks the question of the continuity of the vein systems arises. In all areas it is difficult to trace extensions of vein systems along their strike on account of the heavy drift deposits but also owing to the narrow and unpretentious nature of the vein faults in schist areas. Underground work and extensive bulldozing at the surface on the projected extensions of vein systems, however, show beyond a doubt that the vein faults carry through the schist as tight fractures and contorted zones, and barring the presence of offsets on cross faults the vein faults may appear along strike again as wide breccia zones in quartzites and greenstones. The No. 6 system affords an example of this feature of the vein faults.

Cross Faults, Low-angle Faults, and Bedding Faults

These faults are not unlike vein faults, and in some places it is difficult to distinguish members of this group from vein faults unless cutting relationships are found.

The bedding faults are represented by slippage zones along and between beds and by mashed and contorted schist beds between more competent quartzites and greenstones. The low-angle faults are somewhat similar structures that may follow bedding planes or schist beds for some distance and then cut across competent beds of quartzites where they are marked by a large-scale brecciation or comminution of the rock. Faults of this type have a strike close to that of the beds of the sedimentary rocks from 100 to 110 degrees, a steeper dip than the beds, and may be 20 to 50 feet in width.

Several of these faults were encountered in the workings of the Mount Keno mine, and one is known to cut off the Onek vein fault just north of the two shafts on this property.

Cross faults occur throughout the area. Most of these are recognized by offsets on vein faults or contacts. These faults are generally a complex of slips and fractures ramifying through a crushed and brecciated zone.

DESCRIPTION OF VEIN FAULT SYSTEMS

General Statement

Vein faults in this area are grouped within two principal directions. These are:

(a) North to north 45 degrees east (transverse vein faults)

(b) North 50 to 70 degrees east (longitudinal vein faults)

Both (a) and (b) types appear to be normal faults with dips varying from 60 to 80 degrees southeast.

No precise data on the age relationships of the two types have been obtained. The (b) type vein faults are mineralized by a suite of minerals that have been fractured and cemented by a suite of minerals predominating in (a) type vein faults. This suggests that the (b) vein faults are older than the (a) vein faults if one assumes successive stages of faulting and mineralization.

On the other hand, the (b) vein faults appear to truncate the (a) vein faults as shown on the enclosed map, and the angles of intersection of the two types are generally greater than 45 degrees. These relationships suggest that the (a) type vein faults may be subsidiary to the (b) type vein faults, but until some intersections are investigated thoroughly this assumption will remain in doubt.

Vein Faults that Strike North to North 45 degrees East

(Transverse Vein Faults)

General Statement

Eight well-defined systems in this group have been extensively explored, and their nature and mineralization are well known. Of these, the Ladue-Sadie-Friendship, Lucky Queen, Number 9, Bellekeno, and Onek systems were responsible for the production of lead-zinc-silver concentrates in past years. The Shamrock, and Runer vein faults of the Mount Keno system contained small, though rich, ore shoots, and the Moth contains an orebody high in zinc but low in silver, which makes it uneconomical at the present time.

The internal nature and the mineralization of these vein faults are similar in nearly all occurrences. In quartzites and greenstones the vein faults are breccia or sheeted zones and can easily be traced; in schists they are narrow fractures, slips, and crenulated zones that are difficult to follow during surface and underground exploration.

The mineralization in most vein faults is complex and is described in detail in the section on mineralogy. Siderite, galena, sphalerite, freibergite, quartz, and pyrite are the principal hypogene minerals, and limonite, manganese oxides, anglesite, calcite, dolomite, and copper carbonates are the main supergene minerals in the oxidized zones.

Ladue-Sadie-Friendship System

This system (33 and 34)[1] consists of at least two parallel vein faults striking from north 30 to 40 degrees east and dipping southeast. Other parallel vein faults occur between this and the Lucky Queen system and will be described separately below. The system is poorly exposed in surface pits and caved stopes of the Ladue and Sadie-Friendship mines. However, the annual reports of Livingston Wernecke, former manager of the two mines, provide an accurate description of the principal vein fault of the system, and much of the data given below was obtained from a study of these reports and their accompanying maps and sections.

The principal vein fault of the system has been followed in the underground workings of the Ladue and Sadie-Friendship mines to a depth of 500 feet down dip and along the strike from the northern contact of the large greenstone body at Wernecke southwesterly for 2,500 feet to the intersection of the vein fault with a thick graphitic schist and phyllite bed. At this point the main vein fault narrows in width and splits into several branches that contain small siderite lenses with a little galena. The southern extension beyond this point is not known with certainty, but diamond drill-holes by Klondyke Keno Mines, Limited, intersected narrow fractures containing some siderite and galena, and this suggests that the main vein fault may extend at least 1,500 feet to the south. The main vein fault is offset by a number of northwest striking faults giving a general westerly offset as it is followed south.

The vein fault explored at the Klondyke Keno mine (32) strikes north, dips east, and may represent the southern extension of a vein fault parallel with the main Ladue-Sadie-Friendship vein. The northern extension of this vein fault has, however, not been found. In the Klondyke Keno mine the vein fault is the breccia type, from 2 to 5 feet wide, and has interbedded greenstone lenses and phyllites for hanging-wall and foot-wall along its northern extension. Traced south the vein fault passes into graphitic schist and there narrows down to a

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[1] These numbers refer to property locations shown on the geological map.

few inches in width and probably follows several branching fractures. Deep bulldozer cuts in the graphitic schist on the assumed southern extension failed to locate its occurrence. Orebodies were not encountered during the exploration of this vein fault.

North of the Ladue mine, the principal vein fault of the system weakens as it passes into graphitic schists and a few hundred feet to the northeast no trace of the vein fault is discernible on the surface. Deep bulldozer cuts in the graphitic schist on the assumed northern extension expose only narrow unmineralized fractures. Some vein float was found along the assumed extension, but the schists are structurally unfavourable and it is doubtful if a strong vein fault exists in these rocks.

On the Lake property (35) immediately west of Gambler Gulch two parallel vein faults containing a little siderite and galena have been explored by cuts and an adit. These vein faults have a northeast strike and a southeast dip and may represent the northern extension of the system. East of Gambler Gulch no vein faults are known to occur on the strike of the system.

The productive part of the main vein fault occurred where it transected phyllites, quartzites, greenstones, and interbedded schists of the Caribou Hill quartzite member. The vein fault in this part dips south 70 degrees east and consists of a breccia and mashed zone 5 to 30 feet in width with several subsidiary faults that branch from and join the plane of the main fault. Slips and faults cross this complex producing offsets and longitudinal slicing of the ore shoots. In addition, numerous northwesterly striking faults and slips producing the general westerly offset mentioned above were encountered, and these conditions made mining and exploration difficult.

According to Wernecke the ore shoots, consisting of irregular bodies of siderite, galena, sphalerite, and tetrahedrite, tended to occur where the vein fault transected quartzites or where greenstone formed one wall. This latter relationship is well shown on the surface at the Sadie-Friendship mine where greenstone forms the foot-wall and graphitic schist the hanging-wall of a large ore shoot. Another favourable site for pods of ore was at the intersection of the main vein fault and south-striking fractures that branched from the main fault into the foot-wall or hanging-wall.

Two orebodies (See Figure 5) occurred in the Ladue part of the vein fault. The Number 1 orebody near the No. 1 shaft had an average length of 120 feet and an average width of 5 feet. Its northeastern part was tabular in shape; its southwestern part split into two branches; one of these followed the main vein fault and the other a southwestern striking fracture in the foot-wall. The orebody as a whole raked north at approximately 40 degrees for some 450 feet down the dip before it tapered down and ended. Both hanging- and foot-wall rocks are phyllites. The foot-wall was rough and irregular with numerous branch faults and slips, the hanging-wall was smooth and marked by a post-ore fault. The vein filling was principally galena, sphalerite, and freibergite. The Number 2 orebody occurred north and south of No. 2 shaft and had a length of 550 feet on the 200-foot level. The average width was 7 feet. The shape was roughly saddle-like with the eastern limb following the main vein fault and the western one a north-striking fracture in the foot-wall. The rake of this saddle-like body was steeply north; the rake length approximated 400 feet. The wall-rocks were highly shattered greenstones (chlorite schists) and phyllites, and the orebody consisted of a stock-work of reticulating veinlets containing principally siderite, galena, sphalerite, freibergite, and quartz.

Three orebodies were found in the Sadie-Friendship part of the main vein fault. Two of these occurred north of a prominent northwest cross fault and the other south of this fault. The most northerly shoot was 60 feet in length on the second level and had a width of 2 to 3 feet. The wall-rocks were schists and phyllites. The shoot just north of the northwest cross fault was 100 feet in length and 3 to 4 feet in width. The foot-wall was greenstone and schist, and the hanging-wall was schist. The southern shoot occurred 170 feet south of the cross fault and appears to have consisted of a stock-work several feet in width of siderite, galena, and sphalerite veins in crushed and fractured greenstone and schist. The foot-wall was greenstone and the hanging-wall graphitic schist. The rake of the three shoots was slightly north to vertical. No ore was found below the 400-foot level.

Between the Sadie-Friendship workings and the Lucky Queen system two prominent lineaments represented by quartzite bluffs occur on the ground and are clearly shown on vertical aerial photographs. Another series of lineaments occur in the greenstones east of the Ladue workings, and a narrow vein fault is exposed in greenstone midway between the Ladue and Lucky Queen workings. Fractures in the quartzite along the western lineament contain siderite and some galena, and the vein fault in the greenstone contains a little siderite. Geochemical work (Boyle, 1955) carried out on water from springs situated below the western quartzite bluff indicates that a metal source lies nearby. The existence of lineaments and known mineralized fractures and the presence of a geochemical anomaly warrant some prospecting in this area.

The Lucky Queen System

This system (36) occurs some 5,000 feet east of the Ladue-Sadie-Friendship system and consists of at least four sub-parallel breccia vein faults and sheeted zones, two of which intersect in the area southwest of the main Lucky Queen shaft. The strikes of the vein faults vary from north 20 to north 45 degrees east and the dips are steeply southeast. Only one of the vein faults, the main Lucky

Queen break, contained sizable orebodies. This break is strong and can be traced with some continuity.

The main Lucky Queen break is exposed in caved stopes and pits for a distance of 1,200 feet southwest from the main shaft. In these localities a breccia fault and sheet zone from 5 to 40 feet wide is present and this along the strike is cut into several segments by a series of parallel northwest striking cross faults. These faults cause a general westward offset of the breccia fault and sheeted zone as it is followed south.

Southwest of the southern shaft on the Lucky Queen property the vein fault does not outcrop, but a strong lineament to the west of the projected strike of the structure suggests that the main vein fault is slightly offset to the west, and its trace is probably marked by the lineament shown on the geological map. Geochemical work (Boyle, 1955) carried out along this lineament indicated an anomalous zinc content in water from springs and this evidence further supports the presence of a vein fault.

The lineament when traced southwest from the south shaft on the Lucky Queen property passes into the Black Cap property (28). Here, several pits, a shaft, and a tunnel expose the vein fault. The pits expose two sheeted zones 50 feet apart. These dip 75 degrees southeast, are from 2 to 10 feet wide, and contain some siderite, galena, and freibergite. Southwest of the pits an adit has been driven, and a drift follows a sheeted zone and breccia zone for about 200 feet. Along the drift the vein fault is a foot or so in width and difficult to trace because it has been offset by both bedding plane faults and northwest striking cross faults. The northern part of the vein fault is in quartzite; traced south it passes into sericite schist where it forms horsetails and dies out in a series of slips and crenulations in the schist. In the quartzite the vein fault contains limonite, siderite, quartz, and a little freibergite in galena. No orebodies were found during exploration.

South of the Brewis Red Lake adit the terrain along the projected strike of the vein fault is underlain by sericitic and graphitic schists, and the system is not well developed. Two shafts sunk many years ago in the schist appear to have followed a fracture or narrow vein fault carrying a little siderite. Bulldozer cuts across the southern extension of the main vein fault, however, failed to locate it.

On the Croesus property (29) a series of bulldozer cuts, pits, shafts, and two caved adits investigated a south-striking vein fault with greenstone on the east wall and sericite schist on the west wall. Coarsely crystalline siderite filled part of the vein fault, and a little galena and freibergite are reported to have occurred in the siderite.

Across Erickson Gulch the fault system is not exposed in workings along the projected strike of the structure. Fractures on the Dorothy property may indicate the presence of a vein fault, for some of these fractures contain coarsely crystalline siderite similar to that on the Croesus dumps.

In the Lucky Queen area the Lucky Queen system consists of two intersecting vein faults. One of these strikes north 20 degrees east, the other north 45 degrees east. North of the main Lucky Queen shaft the north 20 degrees east vein fault passes first into schist and then into an area of interlayered schist and greenstone. Where greenstone formed the foot-wall of this vein fault a small ore shoot containing quartz and freibergite occurred; other parts of the vein fault were barren. The north 45 degrees east striking main vein fault enters a zone of schist north of the main Lucky Queen shaft, where outcrops are so scattered that the structure cannot be traced. It is probable that northward along the strike a series of northwest trending faults offset the main vein fault back and forth. In one exposure on the Highlander claim (37) a series of open-cuts have been excavated and a shaft sunk. These workings are now inaccessible, and little data could be obtained. Cockfield (1923) in his description of the vein fault says that some ore was mined from these workings. The orebody apparently occurred in quartzite and contained siderite, pyrite, galena, freibergite, and sphalerite.

Northeast of the pits on the Highlander claim the system is not exposed for 1,500 feet. On the Stone claim (38) a vein fault striking north 50 degrees east and dipping to the southeast may be the northeastern extension of the Lucky Queen system. This vein fault has been investigated by pits, open-cuts, and adits, all of which are caved or ice-filled. According to Mr. Matt Butyer, owner of the claim, exploration work disclosed a vein fault with a greenstone and schist hanging-wall and schist foot-wall. A small amount of ore was removed from the vein fault. The minerals in the ore shoot were siderite, quartz, galena, freibergite, sphalerite, and chalcopyrite. The mineralized part of the vein fault was apparently in greenstone below a schist capping. Many post-mineral faults were encountered during mining. In 1952 Jersey Yukon Mines Limited investigated the vein fault by driving an adit in a southern direction between the two adits driven during early exploration. The adit was started in graphitic schist and the material on the dump suggests graphitic schist throughout. From reports it would appear that the tunnel passed through the vein without its being recognized, and if so, this illustrates the difficulty in recognizing vein faults in schists.

Northeast of Faro Gulch the system has not been exposed in any workings. In this area it passes into the unfavourable lower graphitic schist and phyllite member of the Lower Schist formation.

Two parallel vein faults occur on the Cub and Bunny claims 1,000 and 1,500 feet southeast respectively of the Highlander open-cuts. The western vein fault occurs in greenstone and contains siderite, galena, freibergite, and sphalerite. A little ore was probably removed from this vein fault. The eastern vein fault occurs in sericitic and graphitic schists and is not clearly defined in the large number of bulldozer cuts and pits dug to explore it. No ore is known to have been taken from this vein fault.

The vein fault that contained the orebodies at the Lucky Queen mine was explored on three levels. Two ore shoots (See Figure 6) were mined to a depth of 300 feet. Below this depth the vein fault was barren. The vein fault was severely disrupted by northwest striking faults, and the ore shoots were cut by parallel and longitudinal slips. The wall-rocks of the vein fault were principally quartzites, but a greenstone lens was intersected at the northeastern end of the drift on the 300-foot level. Surface investigations and a study of the maps and plans of the Lucky Queen mine indicate that the two ore shoots are localized in the main north 45 degrees east vein fault near its intersection with the north 20 degrees east vein fault.

The ore shoots consisted of veins, stringers, and masses of ore and gangue minerals. Siderite, galena, sphalerite, and freibergite were the principal hypogene minerals. Ruby silver and native silver were common below the 100-foot level, and limonite, manganese oxides, siderite, galena, and freibergite were the principal minerals from the surface to the 100-foot level.

The No. 9 System

This system (20) consists of several parallel to subparallel vein faults that outcrop in the headwall of Faro Gulch and on the greenstone knob known as Keno Summit. These vein faults strike from north 30 to north 40 degrees east, dip steeply southeast, and appear to be small displacement cross-over faults between the two longitudinal faults known as the Main fault and No. 6 system. Field mapping of the vein faults of the system indicate that they occur only between these two longitudinal faults.

The vein faults are the breccia type in quartzite and greenstone, and in the schist they narrow down in width to fractures and crenulated zones that cannot be followed with any continuity. The numeration and location of the vein faults and the location of ore shoots in the principal vein faults are shown on Figure 7.

The No. 9 vein fault was the most productive one within the No. 9 system and was investigated to a depth of 300 feet by shafts and adits and below 300 feet by an internal inclined shaft. This vein fault dips 70 degrees southeast, varies from 2 to 5 feet in width, and is a strong breccia fault in the quartzites; in the schists it is a series of closely spaced fractures that cannot be traced with confidence. The ore shoots in the vein fault contained siderite, galena, sphalerite, freibergite, and quartz, and were localized below the point where the vein fault entered schist on both walls (See Figure 7 (b)). These ore shoots were irregular in outline with an apparent flat southeast rake and had a quartzite foot-wall and schist hanging-wall or quartzite on both walls.

The No. 3 vein fault was investigated by an adit and a shaft to a depth of 140 feet. Five small ore shoots were found in this vein fault, which dips 80 degrees southeast, varies from 2 to 5 feet in width, and shows a strong development of breccia in the quartzites. A study of the longitudinal section of this vein fault indicates that the ore shoots were localized where one or both of the walls were quartzite. Where the vein fault passed into an area with schist on both walls it narrowed down in width and no ore shoots were found. The mineralization of the No. 3 was similar to that of No. 9. The ore shoots were irregular in outline and they raked flatly southeast following the contact of the schist capping.

According to Visel, No. 12 vein fault yielded only a very small shoot of ore near the portal of an adit driven along the vein fault for some 350 feet to the schist-quartzite contact. A winze was driven on the shoot and encountered some milling-grade ore.

No. 2 vein fault is probably the continuation of No. 9. It occurs in greenstone, dips 75 degrees southeast, is 2 to 5 feet in width, and is mineralized locally with siderite, some galena, and freibergite, but ore shoots are not known to occur. No. 5 vein fault contained a small ore shoot in greenstone. Nos. 4 and 6 vein faults also occurred in greenstone and contained ore shoots comparable in size to those of No. 5.

The No. 9 system as a whole contained only small ore shoots. Records show that about 9,000 tons averaging 200 ounces silver a ton and 60 per cent of lead were taken from the No.9 vein, and Visel estimates that 10,000 to 12,000 tons averaging 60 ounces silver a ton (disseminated ore) remain in the mine. The other veins produced small ore shoots of which only a few contained more than a few hundred tons.

The ore shoots in all vein faults were localized just below the contact where the vein faults passed into schist on both walls, and no ore shoots were found at a greater perpendicular distance than 200 feet from this contact. In the greenstones, siderite was an important gangue mineral, whereas in the quartzites it was not abundant, the ore was relatively free of other gangue, and could be sacked and shipped without concentration.

The Shamrock System

This system (27) outcrops at the head of Erickson Gulch and consists of a main vein fault and at least two subsidiary vein faults that branch from the main vein fault into the foot-wall as shown on the geological map. The strike of the main vein is north 40 degrees east and the dip is 60 degrees southeast.

The main vein fault is the breccia type, 4 to 6 feet in width, and is severely disrupted by cross fractures and longitudinal slips. The vein fault has quartzite walls and has been traced by adits, shafts, and cuts from the flat area at the head of Erickson Gulch to the eastern branch of Christal Pup Creek. The underground workings consist of an inclined shaft and two adits, all now inaccessible. In the summer of 1954 United Keno Hill Mines Limited explored the downward extension of the main vein fault by an adit driven below the old workings.

According to Cockfield (1929) the main vein fault was thought to be an extension of the Gambler vein fault, but the author disagrees with this hypothesis because the strikes of the two are markedly different. In the author's opinion the main vein fault of the Shamrock system should intersect the Gambler vein fault.

The ore shoots in the main vein fault of the Shamrock system were sporadic and small, with widths seldom exceeding 4 feet. The minerals in the ore shoots were galena, cerussite, and iron and manganese oxides. The ore shoots in the main vein fault probably were localized beneath the sericite schist, overlying the No. 9 quartzite, but now removed by erosion. In this respect the structural control is similar to that which localized orebodies in the No. 9 system. In the area south of the adits on the main vein fault one small shoot occurred at or near the junction of the main vein fault and a branch fault in the foot-wall.

The Mount Keno System

This system consists of two principal parallel vein faults 2,000 feet apart and striking north 40 degrees east. Other small vein faults and fractures occur in the vicinity of these main faults as shown on the map.

The eastern vein fault or Hogan vein fault (4) was investigated by an adit, crosscuts, and drifts at an elevation of 3,300 feet by Mount Keno Mines Limited, and by an adit, crosscut, and drifts at an elevation of 3,800 feet by Ankeno Mines Limited. Cuts and pits expose the vein at several places along its strike.

The Hogan vein fault as exposed in the Mount Keno and Ankeno workings is a strong break dipping 60 to 80 degrees southeast and 5 to 10 feet in width. The vein fault consists of highly brecciated and comminuted quartzite and some greenstone, and the western wall of the break has moved southwest about 100 feet relative to the east wall. Along its exposed length, the vein fault is cut by longitudinal and cross slips and by one assumed and two known northwest striking faults that dip southwest at about 45 degrees. Movement along these faults is usually a few hundred feet horizontally.

The Hogan vein fault contains massive siderite now partly oxidized to limonite and manganese oxides, massive pyrite lenses, and a little sphalerite and galena. No orebodies were located during the exploration work.

The eastern vein fault or Runer vein fault (6) has been investigated by Mount Keno Mines Limited by means of two adits and drifts, one at an elevation of 3,700 feet, the other at the 3,850-foot elevation. Several pits, cuts, and shafts expose the vein fault along its strike.

The Runer vein fault is a breccia zone varying in width from 1 foot to 5 feet in the quartzite and a sheeted zone about the same width in the greenstone rocks. The vein fault is irregular in dip, varying from 45 to 70 degrees west. Many branches and rolls are present both along the strike and on the dip. Many longitudinal and cross slips occur, and cross faults offset the vein fault in two places as shown on the enclosed map.

The minerals in the Runer vein fault are oxidized siderite, limonite, galena, sphalerite, freibergite, and pyrite. Two small ore shoots were located during exploration. One of these, on the 3,800 level occurred in thick-bedded quartzite below a series of graphitic schist and phyllite beds.

The northern extension of the Runer vein fault is not exposed, but the location and similarities in strike and dip of the Vanguard vein fault (7) suggest that it may be the northern extension. This vein fault has a steep western dip and locally contains siderite, limonite, and a little galena and freibergite. The Vanguard vein is probably cut off by a fault on both its southern and northern extensions but the offset parts have not been located.

The Bellekeno System

The Bellekeno system (1) occurs on the northern slope of Sourdough Hill and consists of two main parallel vein faults and several other small parallel and intersecting vein faults (See Figure 8). These vein faults have been investigated by numerous shafts, adits, and cuts.

Bellekeno Mines Limited investigated and developed two ore shoots on the strongest vein fault (48 vein) and explored a parallel vein fault (50 vein) on the first level. Figure 9 shows the disposition

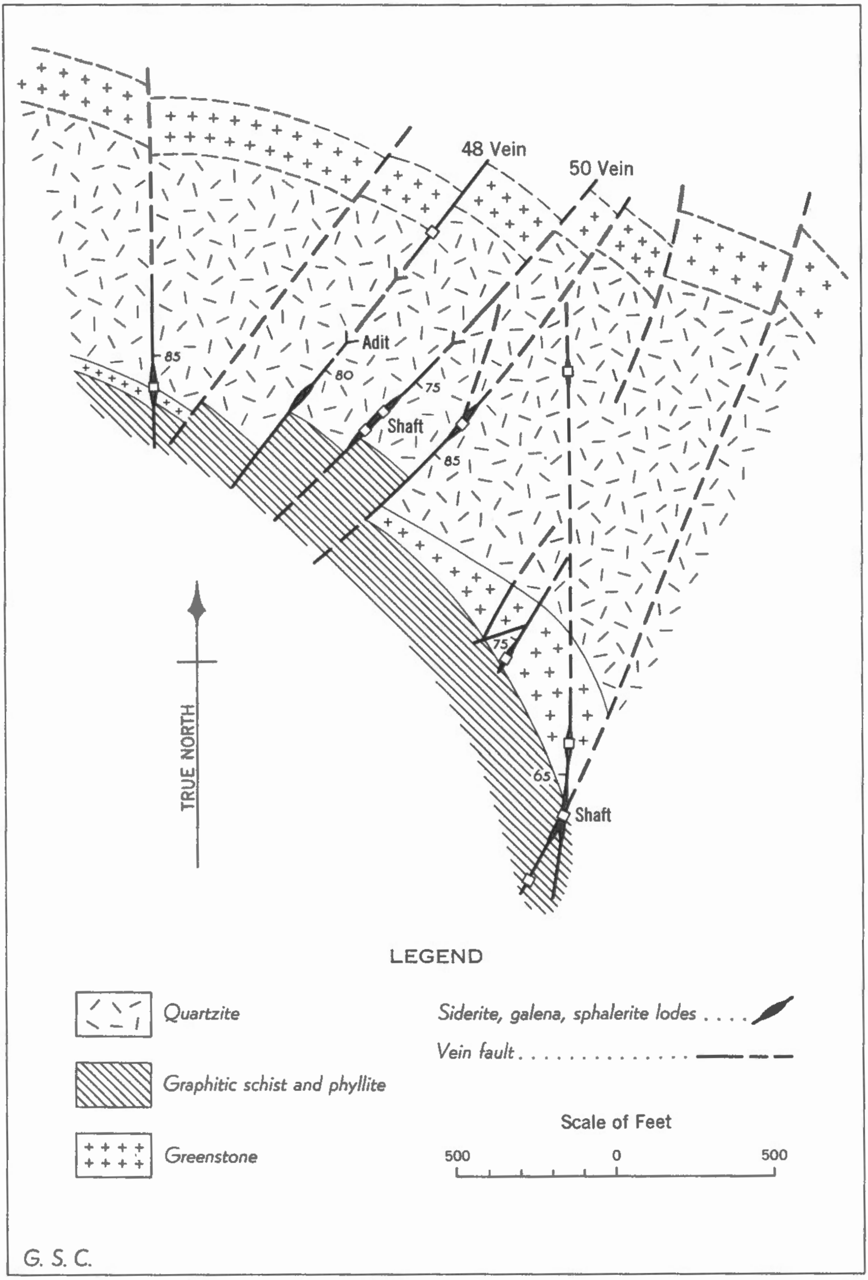


Figure 8. Plan showing location of ore shoots and mineralized zones, Bellekeno System, Sourdough Hill, Yukon Territory

of the ore shoots and other geologic features of 48 and 50 veins. All the vein faults in this system are similar in structure but differ in width and continuity. A description of the 48 vein will suffice as an example for the system.

The 48 vein is a breccia type vein fault that strikes north 35 degrees east and dips 80 degrees southeast. It consists of 5 to 10 feet of brecciated quartzite in the thick-bedded quartzite and narrows down to a series of fractures and slips containing gouge and comminuted schist in the graphitic schist overlying the quartzite. Numerous longitudinal slips occur throughout the vein fault, cutting both the barren parts and ore shoots. Cross slips with small displacements offset the vein fault in many places along its exposed length. The vein fault branches and joins along its length and small horses occur in the vein fault zone. At the graphitic schist contact the vein fault tends to fray out into branches and slips and is difficult to follow.

As shown by Figure 9, two main ore shoots and other mineralized zones are present in the vein fault. The ore shoots contain limonite and manganese oxides, galena, sphalerite, freibergite, siderite, calcite, anglesite, smithsonite, and quartz. Mineralized zones contain limonite and other oxides, siderite, and small amounts of galena and sphalerite.

The principal ore shoots of the Bellekeno mine are localized directly beneath the Sourdough schist member. Thick-bedded quartzites generally form the walls of the ore shoots, but the upper part of the largest ore shoot in the Bellekeno mine occurred where the foot-wall and hanging-wall were quartzite and graphitic schist respectively. No ore shoots occur in the schist member. The mineralized zones and ore shoots rake 45 degrees northeast.

The Bellekeno system affords an excellent example of the localization of ore shoots and mineralized zones at quartzite-schist or greenstone-schist contacts. This relationship is shown clearly by Figure 8. Similar relationships also exist at the Moth property and some properties on adjacent Galena Hill. During exploration it is, therefore, important to examine all places where vein faults pass from thick-bedded quartzite and greenstone into overlying schists.

The Moth System

The Moth system occurs west of Keno Hill in the low-lying area between the townsite and Christal Lake. It consists of one principal vein fault with other narrow vein faults and fractures that cannot be traced far owing to heavy overburden.

The principal vein fault strikes north 30 degrees east, dips 75 degrees southeast, and has been traced from Lightning Creek in a northeast direction for 2,500 feet. The vein fault is a breccia and sheeted zone varying from 5 to 15 feet in width in the quartzites and a shattered breccia zone of the same width in the greenstone. Longitudinal faults, cross faults, and slips interrupt the continuity of the vein fault along its length.

The mineral content, which is somewhat different from that of other transverse veins, consists of quartz, pyrite, arsenopyrite, dark sphalerite, a little galena, and some siderite.

Two mineralized zones in the main vein fault are known. The one on the Moth property (2) was investigated by an inclined shaft, crosscuts, and a drift at a depth of 90 feet and an ore shoot was located. This ore shoot is high in zinc and low in lead and silver, making it uneconomic at the present time. On the 90-foot level the explored part of the shoot has an average width of 10 feet; its horizontal and vertical extent are unknown. The shoot occurs in a highly brecciated section of the vein fault where greenstone and quartzite form the foot-wall and quartzite the hanging-wall. Several cross and longitudinal slips cut the shoot into several parts.

The other mineralized zone in the main vein fault occurs 800 feet northeast of the Moth shaft. This mineralized zone is small, contains mainly pyrite and a little arsenopyrite, and has greenstone on the hanging-wall and quartzite on part of the foot-wall.

Other fractures and vein faults occur in the system, but these are poorly exposed and little is known about them. One, however, is the sheeted zone that occurs some 750 feet southeast of the principal vein. Along almost all its length this zone is marked by lineaments of which perhaps the most striking is the straight part of Lightning Creek between the two sharp bends in the stream. No mineralized parts of this sheeted zone have been found. Another vein fault, with small mineralized zones containing siderite, outcrops a few hundred feet southeast of the Mackeno mill. This vein fault can be traced only a few feet on the rock outcrop, and both extensions are hidden beneath heavy overburden.

The ore shoot at the Moth property is localized at the contact of the principal quartzite member and the Sourdough schist member. This contact is influential in localizing ore shoots as has been shown above by the occurrence of ore shoots in the Bellekeno system at this same contact.

The Onek System

The Onek system (3) consists of a principal vein fault with subsidiary intersecting and subparallel vein faults and fractures. The system outcrops northeast of Keno Hill townsite, strikes north 45 degrees east, and can be traced from a point a few hundred feet northeast of Keno Hill townsite northeast for 3,000 feet. Both extensions on the surface are covered with drift.

The principal vein fault (See Figure 10) has been investigated by a shaft (Lone Star shaft) and drifts, and an adit driven from a point north of Keno Hill townsite. This adit connects with a drift that explored the vein fault along its strike for 1,300 feet. Raises driven at intervals along the drift connect with other drifts that investigated the upward extension of the vein fault. The northern intersecting vein fault has been investigated by a shaft (Fisher shaft) and drifts. Some ore has been shipped from both the main vein fault and northern intersecting vein fault.

The vein fault pattern of the system is not entirely clear due to heavy overburden on the surface and the presence of many cross faults and slips. Surface mapping by the author indicates that the main vein fault branches along its southern extension and is joined or cut by two north 25 degrees east striking vein faults along its northern extension. The existence of the assumed vein faults shown on the map is borne out by apparent offsets along greenstone bodies and by underground mapping on the 400-foot level. Cross faults, however, may complicate this simple pattern, and other interpretations may be possible.

On the 400-foot level the main vein fault is a breccia zone 10 to 20 feet in width dipping 70 degrees southeast. Numerous longitudinal slips and cross faults occur along the vein fault separating it into a number of segments. Two hundred and seventy-five feet northeast of the intersection of the crosscut and drift on the 400-foot level the main vein fault is joined by a series of vein faults and fractures striking south 40 degrees west into the hanging-wall. Eight hundred feet northeast of the same drift and crosscut intersection the main vein fault is again joined or cut by a prominent vein fault with a steep eastern dip and striking south 40 degrees west into the hanging-wall. At each of these junctions and for some distance along the vein faults from the junctions mineralized zones and ore shoots occur, as shown in Figure 10.

The northern extension of the Onek system terminates against a fault zone some 20 or more feet in width. The data from an examination of the drag effects in this fault zone on the 400-foot level suggest that the main vein fault is offset an unknown distance to the east. It is possible that the fault offsetting the Onek system is the same as that offsetting the Hogan vein fault of the Mount Keno system. However, so many of these faults are present in the Onek-Mount Keno area that it is difficult to make correlations.

The strike and location of the Onek system suggest that it may be the southern extension of the Comstock-Porcupine system. Evidence of some mineralization in isolated cuts on the northern extension of the Onek system suggests that a continuous vein may exist, but the common occurrence of northwest trending cross faults and the general heavy drift make it impossible to trace the Onek system beyond its extent as shown on the map.

Vein Faults Striking from North 50 to North 70 Degrees East

(Longitudinal Vein Faults)

General Statement

Three well-defined vein fault systems in this group have been explored and their nature and mineralization are fairly well known. These are called for purposes of identification in this report -- the Nabob-Main Fault system, the Number 6 system, and the Comstock-Porcupine system. The vein faults of these three systems are essentially parallel both in strike and dip. Many other vein faults with parallel and sub-parallel strikes to the foregoing three systems occur on Keno Hill. The most important are the No. 1 vein fault, Gambler vein fault, Klondyke-Keno east-west vein fault, Helen Fraction vein fault, and the Faith system of vein faults.

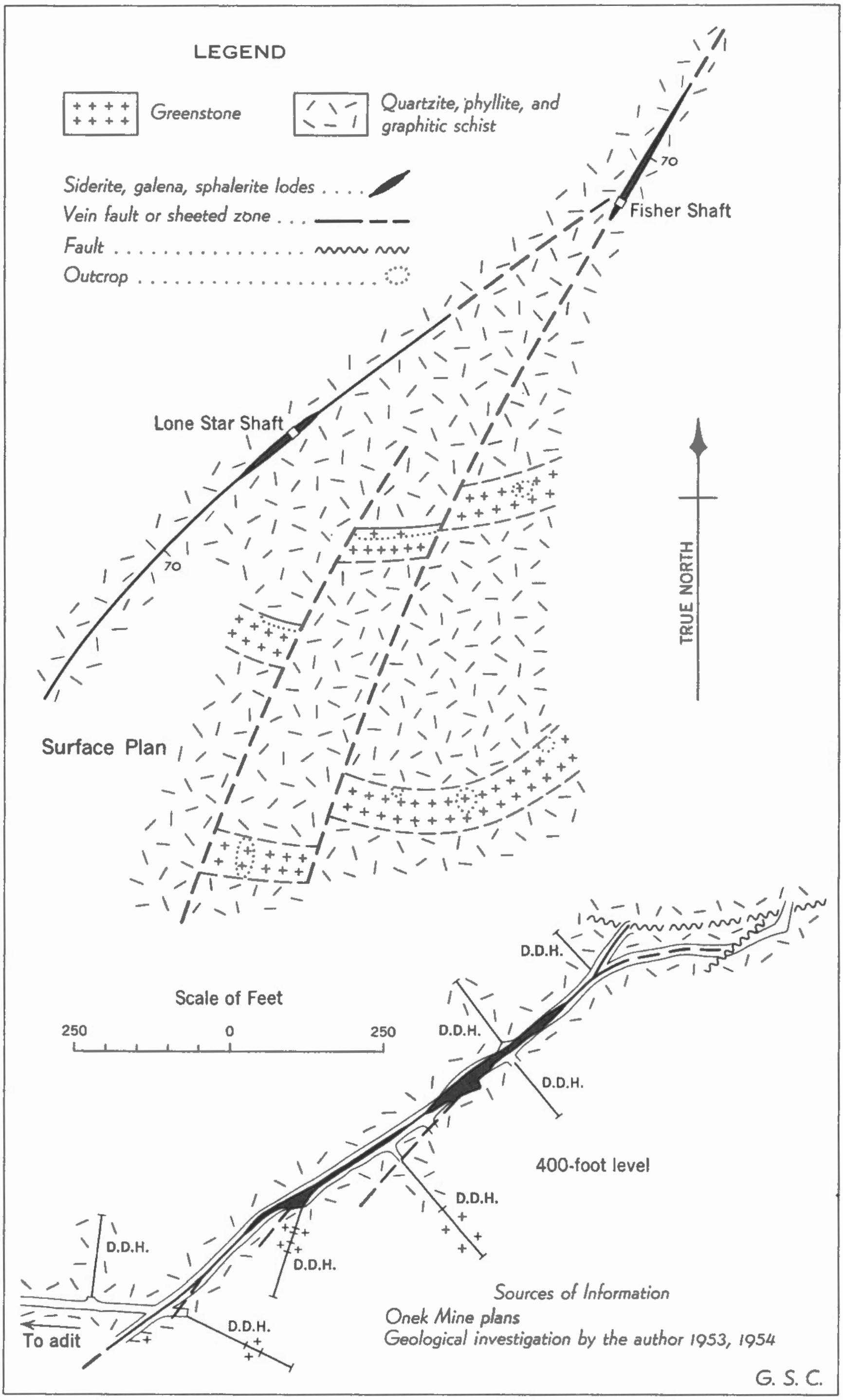
In nearly all cases the internal nature and the characteristics of these vein faults are similar to those described for the transverse vein faults, and the details are not repeated. In quartzite and greenstone they are breccia zones or sheeted zones that can be traced with some ease; in schists they are narrow fractures, slips, and crenulated zones difficult to trace.

The veins were mineralized during two main stages to be described in detail below. During the first stage quartz, arsenopyrite, and pyrite were deposited; this stage was followed by fracturing and deposition of siderite, galena, sphalerite, and freibergite.

The Nabob-Main Vein Fault System

This system (19) outcrops in the headwall of Faro Gulch and can be traced northeast to Silver Basin as shown on the map. The system strikes north 75 degrees east and dips from 65 to 70 degrees southeast, and the main vein fault varies from 5 to 10 feet in width.

The only workings of any consequence in this system are those of Comstock-Keno Mines Limited on the Nabob claim where pits, an adit, crosscut, and drift investigated the vein fault. Underground the vein fault was a breccia and sheeted zone and contained



Sources of Information
Onek Mine plans
Geological investigation by the author 1953, 1954

Figure 10. Plans of surface and 400-foot level, Onek Mine, Keno Hill, Yukon Territory

some oxidized siderite, limonite, and a little galena. No orebodies were located.

The southwestern extension of the Main vein fault has not been located mainly because no work has been done on it. From the map and Figure 7 it will be noted that it passes from the No. 9 quartzite into a thick bed of overlying schist, a favourable structural location for ore shoots. It would seem that early work carried out on the surface in the schists failed to find anything, thus discouraging further work. Underground work or diamond drilling might be more rewarding.

The No. 6 System

The main vein fault of this system is exposed intermittently from the Dorothy property (30) to a point some 2,000 feet northeast of the No. 6 shaft (24). The northeast extension beyond this point is not known with certainty, but float indicates that the main vein fault of the system may continue, as shown on the geological map. The southwest extension of the main vein fault does not outcrop, but a pronounced lineament suggests that it may continue for at least 3,000 feet southwest of the Dorothy shaft.

The main vein fault strikes north 65 degrees east, dips 75 degrees southeast, and varies from a width of a foot or so, in the schists to 15 feet or more in the greenstones. It is significantly mineralized with the minerals peculiar to this type of vein fault in three known localities - in the vicinity of the No. 6 shaft, 1,500 feet southwest of this shaft, and in the vicinity of the Dorothy shaft. No orebodies are known to occur at these points. It is interesting to note, however, that only significant amounts of the ore minerals are present where the wall-rocks are quartzites or where greenstones form one or both walls and are capped by schist. The favourable condition of quartzite capped by schist is met at the probable northeastern extension of the main vein fault of the No. 6 system. This area merits some investigation.

The Comstock-Porcupine System

This system is exposed in the workings of the Porcupine (23) and Comstock Keno mines (22). From the latter exposure the principal vein fault can be traced northeast through the Gold Hill No. 2 (21) property to the Silver Basin area. The southwest extension passes through the Apex property where it is faulted as shown on the map. The faulted extension has not been located with certainty, but certain factors such as location, strike, and dip suggest that the Onek system described above may be the southern extension of the Comstock-Porcupine system.

The main vein fault as exposed in the Comstock-Keno drift dips 70 to 85 degrees southeast and is a breccia zone 8 to 10 feet wide that contains pods of galena in places a foot or more in width. These pods together with disseminated sphalerite, quartz, arsenopyrite, and oxidation products of siderite, pyrite, etc., form an ore shoot the dimensions of which have not been fully investigated. It is noteworthy that this shoot is restricted to parts of the vein fault where greenstone forms one or both walls. The same conditions are present in the Porcupine part of the system where a small ore shoot occurs.

Small mineralized zones occur in the principal vein fault on the Apex property (8) and at the Gold Hill No. 2 shaft. No ore shoots have been found in these areas, but it should be noted in the latter area that a favourable site for ore shoots exists in the No. 9 quartzite below the sericite schist cap. This favourable locus rakes into the Comstock-Keno and Porcupine properties and merits some investigation.

The No. 1 Vein Fault

This vein fault (25) outcrops in the headwall of Faro Gulch 500 feet north of the Main fault, dips 65 degrees southeast, is 5 to 10 feet in width, and has been investigated by three adits, now caved. According to Cockfield (1923), a small ore shoot was encountered in the vein fault on the upper levels. This ore shoot was 60 feet long, 14 inches thick, and pinched out on the lower levels.

The northeastern extension is covered by extensive amounts of scree and has not been located. The southwestern extension is also obscured by rock float and drift. Geochemical work done in an attempt to trace the vein fault suggests that it may extend as shown on the map.

The Gambler Vein Fault

This vein fault (26) outcrops on the steep western slope of Faro Gulch and had been prospected by two adits prior to 1950. More recently Comstock-Keno Mines Limited investigated the vein fault by extending the workings from the lower adit.

The vein fault dips 70 degrees south and varies in width from 5 to 15 feet. Locally small pods of galena with sphalerite, pyrite, and arsenopyrite are present along the vein fault. A few tons of shipping ore have been removed from the mineralized parts of this vein fault.

Some hold the opinion that the Gambler vein fault and Shamrock vein fault are the same. The strike, however, is markedly different for the two, and the mineral content is somewhat different. The author interprets the Shamrock vein fault as a transverse vein fault that probably intersects the Gambler vein fault.

Other Vein Faults

Numerous other vein faults that have strikes paralleling those described above occur on Keno Hill. In most cases these vein faults have short strike lengths and cannot be traced far owing to heavy overburden or a poor development in the schists.

The east-west vein fault at the Klondyke-Keno property (32) where it cuts greenstone contains arsenopyrite, pyrite, and galena. No ore shoots are present, however. The vein fault on the Helen fraction (10) is narrow and sparsely mineralized with galena This vein fault may extend eastward on the lower slope of Monument Hill. Two sub-parallel vein faults (12) outcrop in sericite schist on the flat area between Hope and Faith Creeks. These contain some arsenopyrite, galena, and siderite. Owing to heavy overburden they cannot be traced beyond the limits shown on the map.

Structural Control of Ore Shoots and Mineralized Zones

The details of the influence of the vein fault junctions and schist cappings in localizing ore shoots and mineralized zones have been described in the previous sections for each of the systems Table I (in pocket) summarizes these details and facilitates an analysis of the influence of certain features of the vein faults and wall-rock types in the localization of the ore shoots.

Thirty-eight deposits were examined in detail. Of these the structural elements localizing mineralized zones are unknown in eleven cases. In most of these eleven cases poor exposures or inaccessibility of workings are the main reason for the poor analysis of the structural factors. In twenty-three cases ore shoots or mineralized zones are located below actual schist cappings or were located below these cappings before erosion removed the schist. In eight cases vein fault junctions are favourable sites. Four properties have both features present.

Quartzites are the most favourable types of rocks forming the wall-rocks of the ore shoots in twenty-four cases. Greenstones and differing wall-rocks are next with twelve cases, and phyllites and schists are last with six cases.

The ore shoots of the most productive mines - Bellekeno, No. 9, Shamrock, Sadie-Friendship, and Ladue No. 2 orebody, occurred in quartzite or greenstone below schist cappings, and the Lucky Queen, Onek, and Ladue No. 1 orebody occurred in quartzites or phyllites at vein fault junctions. In certain cases, as in the No. 9

and Ladue, both schist cappings and vein fault junctions were present making the conditions especially favourable.

The structural reasons for localization of the ore shoots below schist cappings and at junctions can be logically explained by recourse to the dynamics of faulting. Considering the first, the influence of schist cappings, a detailed study carried out at the Bellekeno mine shows that as the fault enters the schists and phyllites it is deflected in strike slightly to the right. The dip likewise shows a deflexion, but this is not uniform. The movement on the fault is left hand, and the foot-wall part of the fault immediately below the point where the fault enters the all schist area is highly brecciated and fractured. The extent of the brecciation and fracturing diminishes markedly in a perpendicular direction from the all schist contact, and along a line paralleling and some 350 feet below this contact the fault is relatively tight. It will be noted (See Figure 9) that the ore shoots are restricted to this favourable zone of brecciation and fracturing. A study of the longitudinal section of the No. 9 vein (See Figure 7) indicates nearly identical phenomena to that found in the Bellekeno mine.

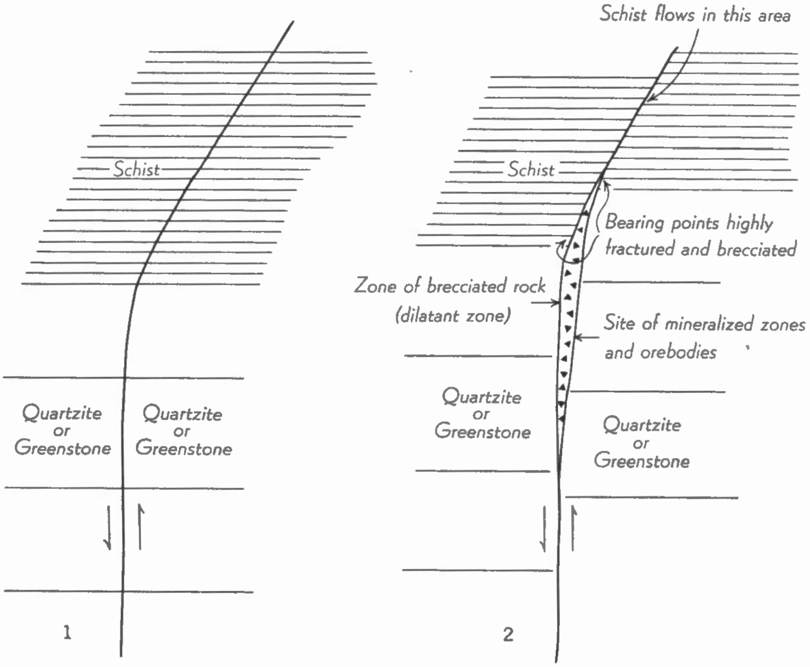
Figure 11 illustrates in a diagrammatic manner how extreme brecciation occurs below schist cappings. The main point from a physico-chemical viewpoint is that the area below the schist capping is a dilatant zone where a marked increase in volume has taken place. This dilatant zone would be an area of low pressure toward which migrating solutions would move and deposit their mineral content. The junctions of the vein faults also are dilatant zones and low pressure areas due to brecciation and fracturing (a volume increase) caused by movements along the various fault planes.

From a practical viewpoint the formation of the favourable dilatant zones does not appear to be restricted to any particular vein fault system. The so-called longitudinal vein faults appear to be as favourable to mineralization as the transverse type. The main and important fact seems to be the correct structural conditions, viz., a change in the rock type producing brecciated zones beneath schist cappings or vein fault junctions. Some of the favourable places have been pointed out in the description of the vein fault systems; others will suggest themselves to the interested investigator.

DESCRIPTION OF THE FAULT SYSTEMS

This section gives a brief description of the bedding faults, low-angle faults, and cross faults that occur in the area. Some of these faults are exposed; others are hidden by drift and are inferred by offsets on contacts and vein faults.

Early bedding faults and low-angle faults occur throughout the area. These faults occur at contacts of beds, at greenstone



1. *Initial break occurs due to couple. Break is deflected as it enters schist*

2. *Subsequent movement forms wedge-shaped dilatant zone in quartzites. Effect of deflection in break lessens with distance and a few hundred feet from schist contact break is tight and unmineralized*

G. S. C.

Figure 11. **Sketches illustrating formation of dilatant zone below schist cappings**

contacts, and within schist beds between competent quartzites or greenstones. These faults strike with the beds and generally have a similar dip, but locally they may cut across one bed or a series of beds at a low angle and continue in lower or higher beds. They appear to be thrust faults, but the amount of movement along the faults can rarely be determined. Locally some of these faults may contain a little quartz, siderite, and the ore minerals. In general, however, they are tight structures and not amenable to mineralization. They are earlier than most of the vein faults, but some faults of this type may cut and offset the vein faults a few feet.

The most characteristic faults are the northwest striking cross faults that have been recognized in nearly all the underground workings on Keno Hill and on the surface by offsets on vein faults and contacts. Many lineaments on the ground and on aeroplane photographs probably mark the traces of many of these faults, and the straight parts of the streams in the gulches on the northern slope of Keno Hill may be controlled by them. The enclosed map shows a few of these northwest cross faults, but it is probable that a great many more occur throughout the area obscured by drift and rock float.

In surface and underground exposures the cross faults consist of a zone 5 to 20 feet in width of highly comminuted and brecciated rock. The local strikes are generally irregular and many branches and slips are always present. The dips of the overall zones range from 45 to 70 degrees. Drag features in some faults suggest that they are thrust faults. The horizontal displacement of the earlier vein faults and ore shoots along the cross faults varies from a few feet to 500 feet and greater displacements may occur. The amount of vertical displacement can seldom be determined.

The northwest striking faults rarely contain the hypogene gangue or ore minerals found in the earlier vein faults, but hypogene drag ore derived from adjacent veins may occur in places. Most of the faults are the courses for underground waters carrying various elements found in the vein faults. In the oxidized zone the faults may contain pockets and seams of supergene minerals.

Late slips and fractures are ubiquitous, but show a marked concentration in vein fault and cross fault zones. Many ages are present; some are associated with the early vein faulting, others with cross faulting, and still later ones cut through the mineralized zones and ore shoots and offset the northwest cross faults a few feet. Some late slips are watercourses, and nearly all contain supergene minerals.

THE MINERALIZATION OF THE AREA

AGE RELATIONSHIPS

The mineralization of the faults and fractures in the Keno Hill-Sourdough Hill area has been a long and complex one consisting of both hypogene and supergene processes. The tentative structural history and mineralization stages are enumerated below, the oldest first.

1. Quartz stringers and boudins formed along bedding planes, fractures, shear zones, drag-folds, and contorted areas in sedimentary rocks and greenstones. These are cut by all structures listed below.

2. Faults formed in a north 50 to 70 degrees east direction (longitudinal vein faults). Some transverse vein faults may have formed at this time. This was followed by deposition of quartz, arsenopyrite, pyrite, and small amounts of galena and sphalerite in the longitudinal vein faults and in some transverse vein faults.

3. Faults formed in a north to south 45 degrees east direction (transverse vein faults). The age relationships of the faults formed during this stage with respect to those of stage 2 are unknown. It is probable, however, that at the time of formation of stage 3 faults the stage 2 faults and their quartz lenses were fractured. Following both the formation of the north to north 45 degrees east faults and fracturing of the lodes in the longitudinal faults, siderite, galena, sphalerite, pyrite, and freibergite were deposited in both stages 2 and 3 faults.

4. Brecciation of the lodes in the stage 2 and 3 faults took place and was followed by deposition of dolomite, barite, grey quartz, quartz crystals, and some sphalerite and galena. Some or all of these minerals may be supergene in origin.

5. Faults formed mainly in a northwest direction. The faults formed during this stage cut those faults of all previous stages.

6. Fractures formed in country rocks and vein faults. Fractures and slips of this age cut across and slice through vein faults and lodes. Some fractures that slice through the vein faults offset faults of stage 5.

7. Supergene oxidation processes (both before and after formation of present permafrost).

    (a) Oxidation of pyrite, sphalerite, siderite, galena, and freibergite produced limonite, manganese oxides, copper carbonates, gypsum, anglesite, smithsonite, cerussite, and arsenic and antimony oxides in oxidized zones. At the same time soluble sulphates were formed that migrated downward with underground waters. The oxidation processes are going on at the present time in faults not sealed by permafrost.

(b) Deposition of supergene calcite, pyrite, sphalerite, hawleyite (cadmium sulphide), native silver, and ruby silver took place in the zone of reduction, in brecciated lodes, faults, and fractures. These minerals are forming at the present time in faults not sealed by permafrost.

(c) Formation of ice lenses took place in some vein faults, faults, and fractures during Pleistocene time.

MINERALOGY

General Statement

The following description of the minerals include the most important ones found in the deposits. As the research proceeds it is possible that other minerals will be added to the list. The common minerals were determined in thin and polished sections and by visual examination. The complex minerals were determined by X-ray and spectrographic methods.

Hypogene Minerals

Quartz ($Si0_2$)

Quartz is a ubiquitous mineral in all sedimentary rocks, quartz porphyries, and some greenstones. In the sediments it occurs in discrete grains between other minerals in the rock and in small segregations, seams, and veinlets. The grains are of detrital origin, and the segregations, seams, and veinlets probably resulted by local solution, transport, and deposition of silica. In the quartz porphyry the quartz occurs in phenocrysts and in the groundmass and is primary in origin. In the greenstones it appears as small segregations and is probably the result of alteration.

Quartz makes its first appearance in the mineralization sequence in the quartz stringers and boudins in schists, phyllites, and quartzites. Almost all these bodies are less than a foot or so long, and a few inches wide. They have sharp contacts with the wallrocks and have no discernible feeder channels.

The quartz is white in colour, massive, and may contain diffuse ribbons of sericite and other minerals. Small vugs lined with delicate quartz-crystal prisms may occur in the bodies, and a few scattered pyrite crystals are present in places.

In the greenstones lenses of quartz, commonly less than 20 feet in length and 2 feet in width, occur in discontinuous shear zones and fractures. This quartz is massive, white in colour, and may contain irregular masses of calcite in some places and epidote in others. No ore minerals were observed in these lenses.

Quartz younger than that of the lenses and stringers described above occurs in lenses in the longitudinal veins, and this quartz is generally intimately mixed with arsenopyrite and pyrite. The quartz of this age is massive and milky and contains many vugs lined with crystal prisms and in addition galena and sphalerite. The lenses vary from a foot up to several tens of feet in length and seldom exceed 3 feet in width. Their contacts with the wall-rocks in most places are irregular showing replacement features, in others the quartz exhibits sharp frozen contacts.

Following the formation of the transverse vein faults and brecciation of quartz lodes in the longitudinal vein faults small amounts of quartz were deposited in both transverse and longitudinal veins. In most occurrences this quartz is an early mineral occurring as white anhedral to euhedral grains and crystals lining fractures and surrounding fragments in the sheeted zones and breccia zones. This age of quartz is followed by deposition of siderite, galena, and sphalerite. In some lodes a crude rhythmical deposition of siderite and quartz may occur.

After the brecciation of the lodes several ages and types of quartz have been deposited. In some lodes, especially in the Bellekeno system, one age of quartz occurs as clear euhedral prisms encrusting the brecciated oxidized fragments of ore. This quartz probably owes its origin to supergene processes. In other lodes, as in the Ladue-Sadie-Friendship system, a grey massive quartz fills the fractures and spaces between hypogene ore and gangue fragments. The origin of this grey quartz is uncertain, but some facts suggest that it had a secondary hypogene origin.

Carbonates

Siderite $Fe(Mg,Mn,Ca)CO_3$, dolomite $Ca(Mg,Fe,Mn)(CO_3)_2$, calcite $CaCO_3$, and cerussite $PbCO_3$ occur in the lodes. Of these carbonates, siderite and some dolomite and calcite are hypogene. Most of the calcite and dolomite and all of the cerussite are supergene in origin and are described in the next section.

The hypogene calcite occurs in the stage 1 quartz lenses and stringers, and fills fractures in greenstones. It is white in colour and occurs as coarsely crystalline masses intergrown with quartz and epidote or chlorite. The age of this calcite is uncertain because cutting relationships are uncommon. It appears to be the earliest age of carbonate and was probably deposited contemporaneously with the first age of quartz.

Siderite is the principal gangue mineral in the lodes in the transverse vein faults and in the refractured parts of the longitudinal vein faults. In these occurrences it is intimately associated with galena, sphalerite, and freibergite and was probably deposited contemporaneously with these minerals.

Below the oxidized zone the siderite is cream to light brown, and in the oxidized zone it is brown to black due to oxidation of the contained manganese and iron. The siderite forms coarse to fine crystalline masses surrounding breccia fragments and occurs in veins and stringers throughout the lodes. Vugs and cavities lined with many fine rhombohedral crystals showing curved and composite faces are abundant.

The siderite is manganiferous and contains a high content of magnesium, as shown by the two analyses in Table II.

Table II

Analyses[1] of Siderite, Keno Hill Area

Constituent	Sample A	Sample B
	Per cent	Per cent
FeO	39.60	40.90
Total Fe	31.20	32.90
MnO	14.42	16.84
MgO	11.40	7.90
CaO	00.30	00.53

Sample A - light brownish white crystalline masses of siderite from the Ladue mine.

Sample B - light brown coarsely crystalline masses of siderite from the Bellekeno system.

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[1] Analyses by P. Tarassoff, McGill University.

Table III

Spectrographic Analyses of Siderite from Keno Hill Area

Locality and Description	100% to 10%	10% to 1%	1% to 0.1%	0.1% to 0.01%	0.01% to 0.001%	Not found
Onek mine, unoxidized	Fe	Mn Mg		Al, Pb Ca, Zn	Ni, Si, Ba, Ag Cu	
Sadie-Friendship mine, unoxidized	Fe	Mn Mg		Si, Al Zn	Cu, Ca Pb	Sb, As Co, Ni
Bellekeno system, slightly oxidized	Fe	Mn Mg		Si, Al	Cu, Ca	Zn, Pb Sb, As Co, Ni

Barite ($BaSO_4$)

Barite occurs in a few lodes in the Bellekeno system on Sourdough Hill, and in small amounts in other lodes on Keno Hill. Barite is not an important gangue mineral in any of the lodes and that present forms crystal aggregates or individual crystals on brecciated nodules of galena and siderite and in the vuggy parts of the lodes. In these occurrences it is usually associated with calcite.

The age relationships of barite are not clear. In some places it was probably deposited after the brecciation of the lodes and is in part hypogene. In other places it appears to be supergene in origin.

A spectrographic analysis of barite is given in Table IV. This analysis indicates that the barite contains a relatively high content of strontium. This is not unusual because Sr^{2+} may substitute for Ba^{2+} in the barite structure and a complete series probably extends to celestite ($SrSO_4$).

Table IV

Spectrographic Analysis of Barite, Keno Hill Area

Description	100% to 10%	10% to 1%	1% to 0.1%	0.1% to 0.01%	0.01% to 0.001%
Barite crystals Bellekeno system	Ba	Sr		Fe, Si Al	Mn, Cr Cu, Pb Ca, Mg

Galena (PbS)

Galena is one of the principal ore minerals. In most of its occurrences it is a hypogene mineral, but in a few lodes it may have a supergene origin. Galena is an abundant and characteristic mineral in the lodes in the transverse vein faults and in fractured quartz lodes of the longitudinal vein faults. In a few localities, as at the Klondyke Keno mine, galena occurs in vugs in quartz lenses in the longitudinal vein faults and may belong to the early stage of mineralization of these vein faults.

The hypogene galena occurs in crystalline masses, veins, and stringers in the lodes where it is associated with freibergite, sphalerite, siderite, and quartz. In most occurrences galena, freibergite, and sphalerite are intimately intergrown and are probably contemporaneous in deposition. Galena generally encrusts siderite and quartz surrounding fragments of wall-rock and fills vugs and spaces between quartz combs and crystalline siderite bands lining fractures. In these occurrences it follows siderite and quartz in the depositional sequence. In other places, however, galena is interbanded with siderite and quartz, and several stages of deposition of galena and gangue minerals are apparent.

In lodes that have not been severely disrupted by brecciation slips, or faults, the galena occurs in coarsely crystalline masses forming irregular and tabular bodies. Crystal groups, individual cubo-octahedral crystals, and twins are widespread in the vuggy parts of many veins. Where brecciation has occurred and where slips and faults slice through the lodes the galena is plumrose in some places and fine grained with a schistose appearance (steel galena) in others.

Spectrographic analyses of the galena are given in Table V. The persistence of silver, tin, and antimony in the galena from all occurrences is notable.

Table V

Spectrographic Analyses of Galena, Keno Hill Area

Description	100% to 10%	10% to 1%	1% to 0.1%	0.1% to 0.01%	0.01% to 0.001%	Not found
Galena crystal, Bellekeno system	Pb		Ag	Sb, Sn Si, Al	Cu, Cr Mn, Ca Ba, Sr Bi, Cd Fe, Mg	Zn, As Te
Massive galena Bellekeno system	Pb		Ag	Sn, Sb Al	Cd, Si Fe, Mn Cr, Cu Mg, Ni Ca	
Massive galena Sadie-Friendship mine	Pb		Ag	Sb, Sn Al	Cd, Si Ca, Mn Fe, Cu Cr, Mg Ni, Bi	
Schistose galena Bellekeno system	Pb	Ag	Sb	Sn	Mg, Mn Fe, Si Al, Ca Cu	
Massive galena No. 6 system	Pb		Ag Sb	Fe, Si	Cd, Mg Sn, Al Cu	
Schistose galena No. 6 system	Pb	Fe	Ag Cu Sb, Bi	Mg, Mn Zn, Sn Ca	Cd, Si Al	

Sphalerite (Zn, Fe, Cd)S

Sphalerite occurs in varying amounts in all the vein faults of the area and constitutes one of the ore minerals in the orebodies. It is abundant in the lodes in the transverse vein faults and in the fractured quartz lodes of the longitudinal vein faults. It does not figure in the early stage of mineralization in the longitudinal vein faults except in one or two places where it accompanies galena. In the zone of reduction in many vein faults a secondary age of sphalerite occurs in slips and fractures and is described below.

The hypogene sphalerite is dark brown to black and occurs in crystalline masses associated with galena and siderite in the lodes. Crystal groups and individual irregular crystals occur in the vuggy parts of lodes.

In the deposition sequence sphalerite is associated with galena, and the two minerals appear to be contemporaneous in most occurrences. It follows quartz and siderite in its depositional history in some lodes, but in others it is interbanded with these gangue minerals.

In nearly all lodes sphalerite varies in abundance with depth. In the oxidized parts of the lodes it is present in small amounts as highly altered crystalline masses in a limonitic boxwork. Deeper down, as the oxidation effects lessen, more sphalerite is present, and in the hypogene zones it is a ubiquitous mineral in the lodes. The details of the oxidation of sphalerite will be described in the section on geochemistry.

Table VI

Spectrographic Analyses of Sphalerite, Keno Hill Area

Description	100% to 10%	10% to 1%	1% to 0.1%	0.1% to 0.01%	0.01% to 0.001%
Massive sphalerite Sadie-Friendship mine	Fe, Zn		Cd, Cu Ag	Sb, Mn	Si, Pb Co
Massive sphalerite Bellekeno system	Zn	Fe	Pb, Ag Cd	Sb, Cu	Mg, Mn Ca, Al
Sphalerite No. 6 vein	Zn	Fe	Cd	Si, Ag Cu	Mg, Mn Pb, Sn Al, Zr, Ca

Freibergite (Grey Copper) $(Cu, Fe, Zn, Ag)_{12} (Sb, As)_4 S_{13}$

Freibergite is a hypogene mineral in all occurrences observed by the author. In most lodes it is usually intimately intergrown with galena. In some lodes, however, it occurs disseminated in siderite (Sadie-Friendship) or with quartz (Lucky Queen system).

Freibergite is responsible for almost all the silver in the ore, and the quantity of silver in the unoxidized ore usually varies directly with the content of this mineral. The freibergite is iron-black to metallic grey in colour and occurs in the galena as irregular intergrowths and in the siderite and quartz as small masses, irregular crystals, and crystal groups.

In the deposition sequence freibergite is intimately associated with galena, and the two minerals appear to have been deposited together. Where it occurs in siderite and quartz freibergite was probably deposited with these two minerals.

Table VII

Spectrographic Analyses of Freibergite, Keno Hill Area

Description	100% to 10%	10% to 1%	1% to 0.1%	0.1% to 0.01%	0.01% to 0.001%
Massive freibergite Sadie-Friendship mine	Fe	Ag	Cu, Sb Mn	As, Zn	Cd, Si, Pb Mg, Ca
Freibergite Bellekeno system	Ag	Fe, Cu Zn	Sb, As Pb, Cd	Si	Mg, Mn, Ca Al, Ba

Pyrite (FeS_2)

Pyrite is present in all stages of hypogene mineralization and occurs in small amounts as a supergene mineral in the zone of reduction. It occurs in schists, quartzites, and porphyries, and in small amounts in the greenstones. In these occurrences it is apparently original with the rock, but it may have been redistributed during metamorphism of the sediments and greenstones.

Crystals of pyrite are present in the quartz stringers and boudins in the sedimentary rocks and greenstones. In these occurrences the pyrite was probably deposited simultaneously with the quartz and calcite with which it is associated. Pyrite also is abundant in the quartz lodes of the longitudinal vein faults. In these it occurs as masses and crystal groups in quartz and in the wall-rock alteration zones enclosing the quartz lodes and is nearly always associated with arsenopyrite. Its intimate intergrowth and relationship with quartz and arsenopyrite suggest that the three minerals were deposited at the same time.

In the transverse vein faults and fractured parts of the quartz lodes in the longitudinal vein faults the pyrite occurs as crystals and masses associated with sphalerite and galena and appears to have been deposited simultaneously with these minerals. In the Hogan vein of the Mount Keno system massive pyrite occurs in lenses and is associated with some siderite.

Pyrite, like sphalerite, varies in amount in the lodes with depth. The reasons for this variation are secondary being related to the oxidation processes, which will be discussed in the section on geochemistry.

Table VIII

Spectrographic Analyses of Pyrite, Keno Hill Area

Description	100% to 10%	10% to 1%	1% to 0.1%	0.1% to 0.01%	0.01% to 0.001%
Pyrite Bellekeno system	Fe			As	Ag, Mg, Mn Pb, Ni, Cu Ca, Al
Pyrite Sadie Friendship mine	Fe		Al, Si Mn	As, Mg Ca	
Pyrite No. 6 vein	Fe, Si		As	Pb	Sb, Mg, Al Cu, Ag, Zn

Arsenopyrite (FeAsS)

Arsenopyrite is concentrated in quartz lodes in the longitudinal vein faults but may occur in some quartz lenses in the transverse vein faults. In the siderite lodes and fractures and faults cutting these lodes it is notably absent.

In the quartz-pyrite lodes the arsenopyrite occurs as masses, intergrown crystal groups, and individual prismatic crystals in the quartz and in the wall-rock alteration zones of the lodes. The arsenopyrite quartz, and pyrite occur together and probably were deposited simultaneously.

Table IX

Spectrographic Analysis of Arsenopyrite, Keno Hill

Description	100% to 10%	10% to 1%	1% to 0.1%	0.1% to 0.01%	0.01% to 0.001%
Arsenopyrite No. 6 vein	Fe, As			Sb, Bi	Si, Pb, Cu Ag, Ca

Gold (Au)

Free gold has not been observed in the deposits, but assays of samples indicate that it occurs principally in the quartz-pyrite-arsenopyrite lodes in the longitudinal vein faults. In these lodes the gold is associated with the pyrite and arsenopyrite, but the nature of its occurrence in these minerals had not been fully investigated at the time of writing. Assays of samples from the siderite-galena-sphalerite lodes indicate a low content of gold.

Gold has been won from placers in Thunder Creek, Duncan Creek, and Lightning Creek in the past. The origin of this gold is beyond the scope of this report and will not be considered further

Other Minerals

Chalcopyrite ($CuFeS_2$) occurs in small amounts in most lodes. In all of its occurrences the chalcopyrite is associated with galena and sphalerite.

Argentite (Ag_2S) is uncommon and has not been observed by the author. Cockfield (1923) notes that it occurs as small microscopic crystals in galena.

Covellite (CuS) is also recorded by Cockfield as occurring in small particles in ore from the No. 9 system.

Supergene Minerals

Limonite ($HFeO_2$) and Other Iron Oxides

Limonite is the most abundant of the oxides in the oxidized parts of the vein faults and is widespread throughout the rocks, fault zones, and fractures near the surface. X-rays indicate that much of the so-called limonite is goethite, but the term 'limonite' as used in this report includes all the supergene iron oxides.

The limonite is derived from siderite, sphalerite, and pyrite. It is brown to orange-yellow in colour depending upon its derivation; the brown material derives from siderite and pyrite and the orange-yellow variety from sphalerite.

The limonite occurs in many forms, ranging from ochreous and earthy material coating ore and gangue minerals and breccia to botryoidal forms and hard compact masses cementing breccia and nodules of ore minerals. It is generally, though not always, associated with the black hydrous manganese oxides described below.

The amount of limonite in the vein faults does not seem to depend entirely upon the presence of nearby mineralized zones. The oxidized lodes are high in limonite, but other sections of the vein faults likewise contain considerable amounts of limonite, suggesting that the surface waters have coursed the vein faults thoroughly, depositing limonite in all open or porous parts.

The oxidized ore shoots, in most places, contain a deep brown iron oxide that results from the oxidation of the freibergite and galena. This brown iron oxide is generally high in silver and is looked upon favourably as indicative of ore.

Hydrous Manganese Oxides

Next to limonite the hydrous manganese oxides are the most abundant supergene minerals in the vein faults and in fractures and faults in the rocks near the surface. X-ray determinations indicate that psilomelane is present, but most of the manganese oxides are so intimately intergrown that they cannot be separated and determined. The term 'wad' best describes these mixtures and will be used in this report. All of the manganese oxides are undoubtedly derived by oxidation processes from the manganiferous siderite.

Wad is especially characteristic of the surface outcroppings of the lode deposits and manganese stain on float is indicative of a vein fault not far distant. Geochemical testing of soils for anomalies in the manganese content in the vicinity of vein faults has yielded positive results in some areas and suggests that some vein faults can be traced by this method.

Wad occurs in a variety of forms. In the oxidized zones incipient oxidation of siderite develops thin films and specks of black manganese oxides along cleavages and throughout the mineral. This imparts a black colour to the siderite. In several oxidized parts of the lodes the siderite is obliterated leaving only irregular earthy and compact masses of wad and limonite. In parts of some lodes botryoidal forms and banded aggregates of psilomelane and wad rim and cement breccia and nodules of ore minerals and gangue thoughout the oxidized zones. Slips, fractures, and breccia are generally coated with a thin layer of the black oxides.

Quartz (SiO_2)

Supergene quartz is widespread in nearly all oxidized parts of the vein faults. Some of this quartz occurs as small clear prisms arranged in aggregates in the earthy oxidized material of the vein faults or as small prisms lining druses and cavities. In these occurrences the quartz is intimately associated with limonite and wad and often forms on crusts and nodules of these minerals.

In some vein faults, especially those in the Bellekeno system, quartz is commonly associated with the hypogene minerals, anglesite, gypsum, smithsonite, and calcite. In such occurrences the quartz forms aggregates of short milky to clear prisms to give cockade structures about nodules of oxidized siderite, galena, and sphalerite.

It is probable that most of the prismatic quartz in the zones of oxidation and reduction is supergene because definite supergene minerals are present with it. Furthermore, meteoric waters presently migrating downward in the veins contain silica in solution, and probably quartz is being deposited from these waters in favourable sites in the veins.

Calcite ($CaCO_3$)

Supergene calcite is present in nearly all oxidized parts of the vein faults and in the zone of reduction. This calcite occurs as earthy masses and coarse-grained crystal aggregates surrounding breccia fragments and lining fractures and vugs in the vein faults. The largest ore shoot in the No. 48 vein of the Bellekeno system contained coarse calcite filling the spaces between quartz encrusted fragments of oxidized ore minerals and gangue. In this shoot the calcite was white to nearly colourless. Locally a grey to black variety containing carbon was present. Associated minerals were smithsonite, gypsum, and quartz.

Cerussite ($PbCO_3$)

Cerussite is uncommon in the oxidized parts of the veins. In the near-surface ore shoots of the main Shamrock vein it occurred with galena as white earthy masses, but has not been observed in other veins in any quantity.

Malachite ($Cu_2(OH)_2(CO_3)$) and Azurite ($Cu_3(OH)_2(CO_3)_2$)

These two hydrous carbonates of copper occur in small amounts principally in the surface outcrops of lodes. In a few places in the Bellekeno No. 48 vein malachite was observed in oxidized ore some 400 feet below the surface. Both minerals are derived by alteration of freibergite or chalcopyrite during the oxidation processes.

Smithsonite ($ZnCO_3$)

Smithsonite occurs in the No. 48 vein of the Bellekeno mine with gypsum, calcite, anglesite, and supergene quartz. In many places the smithsonite is interbanded with fine-grained crystals of gypsum. The smithsonite is obviously of supergene origin and was probably derived from the oxidation of sphalerite and carbonates. The mineral does not occur in economic quantities.

Anglesite ($PbSO_4$)

Anglesite is the most abundant of the secondary lead minerals and has a general widespread occurrence in the oxidized parts of the lodes. So far as is known it does not occur in the unoxidized parts of lodes.

The anglesite is grey in colour and occurs as concentric cryptocrystalline bands about nodules of galena in most occurrences. In a few lodes, as in the Bellekeno No. 48 vein, it occurs as banded layers lining fracture walls and cavities and is usually overgrown by supergene quartz and calcite. A spectrographic analysis of anglesite is given in Table X.

Table X

Spectrographic Analysis of Anglesite, Keno Hill

Description	100% to 10%	10% to 1%	1% to 0.1%	0.1% to 0.01%	0.01% to 0.001%
Anglesite	Pb		Fe, Ag Si	Al, Sb Ca, Sn	Mg, Cu, Sr Ba, Cd

Gypsum ($CaSO_4 . 2H_2O$)

Gypsum is a common secondary mineral in some vein faults, particularly in the No. 48 vein of the Bellekeno system where it occurs as intergrown crystals arranged in concentric bands with smithsonite, limonite, and supergene quartz. Selenite crystals and crystal aggregates are also present in vugs and as overgrowths on calcite. These crystals are transparent, long prismatic in habit, often bent or twisted, and may be up to 3 inches long.

Native Silver (Ag)

Native silver occurs both in the oxidized zone and in the zone of reduction as thin films on galena and as arborescent and wiry forms in vugs and small openings in the vein faults. In a few places it has been observed in ice lenses.

Many highly oxidized parts of lodes in vein faults are enriched in silver. The nature of this silver, however, has not as yet been definitely established, but there are indications that some of the silver may occur as the native metal in a finely divided state.

In most occurrences the native silver is associated with white calcite and other secondary minerals such as ice, limonite, and gypsum. In the Lucky Queen mine much native silver was associated with pyrargyrite. This association and its occurrence in vuggy parts of the vein faults suggest that the native silver is supergene and was probably derived from freibergite.

Pyrargyrite (Ruby Silver) (Ag_3SbS_3)

Pyrargyrite is restricted in its occurrence and has been observed only in specimens from the Lucky Queen and Sadie-Friendship mines. According to Wernecke and Cockfield the mineral was abundant on and below the 200-foot level of the Lucky Queen mine where it was associated with native silver.

The occurrences of pyrargyrite could not be examined because the workings of the two mines where it occurred in quantity are inaccessible. The specimens in the writer's possession, however, show that the pyrargyrite usually occurs in small fractures cutting across hypogene minerals and is generally associated with a second age of quartz cementing siderite. Other associated minerals are supergene sphalerite and calcite. In a specimen from the Sadie-Friendship mine the ruby silver occurs in late fractures and vuggy areas and is associated with freibergite and galena in siderite.

Wernecke considered that the pyrargyrite was supergene in origin. An investigation of the occurrence and derivation of the pyrargyrite has not been completed, but the facts available, such as its association with native silver in the zone of reduction just below the oxidized zone in the Lucky Queen mine, suggest that the mineral is supergene in origin.

Galena (PbS) and Sphalerite (ZnS)

Supergene galena and sphalerite have been observed in both the zones of oxidation and reduction in most vein faults. The difficulty of determining supergene from hypogene galena and sphalerite makes it impossible to estimate the amount of the two supergene minerals present. Only the galena and sphalerite definitely associated with supergene minerals such as anglesite and quartz crystals are considered by the author to be supergene in origin. Using this criterion, the amount of these two minerals in both the oxidized zone and zone of reduction is not great.

Supergene galena occurs in a microcrystalline state associated with anglesite and smithsonite in the No. 48 vein of the Bellekeno mine and in the Nabob vein fault. In other veins on Keno Hill supergene galena has been observed in late fractures and slips and in vuggy parts of the lodes generally in the zone of reduction but also in the oxidized zone. This galena is usually well crystallized in small cubo-octahedrons that grow on supergene calcite or crusts of quartz. In some places small amounts of supergene pyrite or chalcopyrite may accompany the supergene galena.

Supergene sphalerite has a more widespread occurrence than supergene galena. The sphalerite generally occurs in the zone of reduction, but small amounts have been observed in the oxidized zone of vein faults. The sphalerite occurs in cavities and along late fractures as small amber or ruby coloured crystals. Associated minerals include calcite, supergene quartz, and dolomite.

Hawleyite (Beta CdS)

Hawleyite is a new mineral and crystallizes in the isometric system. Chemically it is identical with greenockite. It is bright yellow in colour and forms earthy coatings on sphalerite and siderite in the vugs and late fractures of some vein faults.

Ice

Ice occurs in a massive form in veins, stringers, and small irregular pods in the vein faults, faults, and fractures and as delicate skeletal and stellate forms as hoar frost on the walls of the mine openings in the permafrost zone. The best exposures of the ice veins and stringers occur in the vuggy parts of the vein faults where they are seldom over 6 inches in width, and usually short in length. Wernecke (1932) has described some of these ice veins in the Ladue and Lucky Queen mines and states that they may be up to 150 feet in length along pronounced faults but shorter, 25 to 30 feet, along irregular cracks. Some ice veins form a stock-work cementing slabs of rock in sheeted zones.

In some ice veins the ice is crystal clear to white and opaque and contains numerous rod-shaped and round bubbles probably filled with oxygen and/or carbon dioxide. In other ice veins the ice presents the same phenomena as above, but also contains up to 50 per cent pulverulent limonite and manganese oxides, earthy calcite, and yellow ochres of arsenic and antimony oxides. In a few places wires and thin foils of native silver occur in the ice in or adjacent to high-grade silver ore shoots.

The origin of the water from which these ice veins and pods crystallized may seem at first sight an easy problem, but in some cases it is by no means simple. Wernecke (1932) suggests that the water probably came from below because at the time of formation of the ice veins during the glacial period the surface would be frozen, thus sealing the veins and preventing the downward movement of water. He suggests that the water was meteoric water migrating along fault or fracture zones or vein systems that rose into the permafrost zone where it congealed into ice. The presence of bubbles probably containing oxygen and carbon dioxide certainly suggests a meteoric origin. However, the water could not have travelled far without losing its free oxygen during the oxidation processes that have taken place throughout the vein faults. This latter consideration suggests that at least some of the water responsible for the ice came from the surface immediately above the ice veins and pods.

Other Minerals

Small amounts of plumbojarosite ($PbFe_6(SO_4)_4(OH)_{12}$) have been identified by X-ray in several vein faults. The mineral is yellowish brown in colour and occurs as an alteration product of galena containing freibergite in the oxidized part of the lodes.

Scorodite ($(Fe,Al)(AsO_4) \cdot 2H_2O$) has been identified from several vein faults. It occurs as greyish green earthy coatings, cellular masses, and crusts in the oxidized parts of the vein faults. It has probably developed from arsenopyrite or freibergite during the oxidation processes.

Sulphur (S) has been determined in several vein faults. The mineral occurs as thin crusts on sphalerite and other sulphides and in seams or coatings on gangue minerals. The sulphur is apparently restricted to the oxidized zones and has not been observed in the hypogene parts of the lodes.

THE NATURE OF THE MINERALIZATION

Hypogene Mineralization

Vein Textures

In the longitudinal vein faults the unbrecciated lenses of the oldest quartz containing pyrite and arsenopyrite show a coarsely crystalline massive texture in which the pyrite and arsenopyrite are intimately intergrown with the quartz. In most places the contacts of the quartz lenses and wall-rock are sharp; in a few places the lenses grade through a silicified zone containing pyrite into the wall-rock. Fragments of wall-rock caught in the quartz lenses are highly altered, and some quartz veins show a crude ribbon structure. In some longitudinal vein faults, as at the Klondyke-Keno mine, comb quartz is present and vugs lined with galena and sphalerite are common. The parts of the quartz lodes in longitudinal vein faults that have been fractured and cemented by the second stage of minerals exhibit features that are identical with those described below for the lodes in the transverse vein faults.

The hypogene lodes in the transverse vein faults and fractured parts of the longitudinal vein faults present differing characteristics depending upon the amount of brecciation they have undergone. In the relatively unbrecciated lodes the most striking feature is the crustified and drusy character and the excellent crystal development of both gangue and ore minerals. Quartz, siderite, galena, pyrite, and barite have a strong tendency to crystal development in the lodes, whereas sphalerite, freibergite, and chalcopyrite are much less commonly found well crystallized.

The relatively unbrecciated lodes have the features of a stock-work in some places and consist of a multitude of stringers and veinlets of siderite containing galena and freibergite. These stringers and veinlets ramify through the vein fault zone and may extend out into the walls for 20 feet or more. In other places the lodes consist of tabular bodies of ore minerals, siderite, and quartz all of which cement and encrust breccia fragments. Alternate banding of gangue and ore minerals may be present, and cavities containing crystals of gangue and sulphides are usually abundant. In most lodes the siderite-galena-sphalerite veins and stringers have knife-sharp contacts with the wall-rock, and the hypogene minerals break cleanly from the fracture walls.

In the brecciated lodes it is difficult to determine whether or not the minerals deposited after brecciation are hypogene or supergene. In a few lodes, as at the Sadie-Friendship mine, some of the minerals deposited after brecciation appear to be derived by secondary hypogene processes and their textures are as follows. Brecciation of the lodes, has reduced the hypogene gangue and ore minerals to a rubble of variously sized fragments both irregular and rounded in shape. Consequent mineralization by grey quartz and dolomite has cemented this rubble into a compact mass in parts of the Sadie-Friendship and Ladue mines. Banded structure, vugs, and euhedral crystals are widespread in these secondary mineralized zones.

The nature of the hypogene mineralization, especially the extensive development of vugs and open spaces containing crystals of all the characteristic minerals, suggests that the lodes were formed in the parts of the vein faults that were under tension conditions. The quartz lodes in the longitudinal vein faults contain an assemblage of minerals indicating higher formation temperatures than those in the lodes of the transverse vein faults. Work is proceeding on the geothermometry of both types of lodes, but at the time of writing the data are not extensive enough to warrant conclusions.

Wall-rock Alteration

The wall-rock alteration effects induced by the hypogene mineralization are slight in all sediments, but marked where the lodes occur in greenstones. The effects are nearly the same in both longitudinal and transverse vein faults and the description to follow covers the main features of both types.

The lodes in the sediments are characterized in most cases by innumerable stringers and veinlets extending out as far as 25 feet into the wall-rocks. These stringers contain siderite and quartz and small amounts of the ore minerals, and show sharp contacts with the wall-rock. Alteration of sedimentary wall-rock in the vicinity of lodes or individual stringers is indistinguishable to the eye in most places. Under the microscope the only change visible is an impregnation by small amounts of carbonate.

Lodes in the greenstones are marked by distinctive alteration zones extending out varying distances into the greenstone wall-rock. As in the sediments, the greenstone walls of the veins carry stringers and veinlets of quartz, siderite, and the ore minerals at distances up to 25 feet from the lodes.

The greenstone rocks were originally diorites or gabbros containing hornblende, plagioclase, magnetite, ilmenite, and sphene. In the alteration zones enveloping the lodes these minerals are completely destroyed and replaced by a soft confused schistose mass of carbonate, sericite, leucoxene, and quartz. In a few places pyrite occurs in the alteration zones generally adjacent to early quartz-arsenopyrite-pyrite lenses. The contacts of the siderite, galena, and sphalerite veins with the greenstone wall-rocks are generally sharp, and the ore minerals are rare in the matrix of the alteration zones.

Supergene Mineralization

Vein Textures

All vein faults and their contained lodes have been oxidized from a few tens of feet in depth to a maximum of 500 feet. Supergene minerals occur both in the zone of oxidation and in the vein faults below the oxidized part (the zone of reduction). The textures and features developed in these two zones are different.

In the zone of oxidation the most important feature is the breakdown of the hypogene minerals such as siderite, sphalerite, and freibergite and the formation of oxides and carbonates, among which are limonite, various manganese oxides, azurite, malachite, and arsenic and antimony oxides. The general breakdown of the hypogene minerals renders the vein faults porous, and irregular open spaces, some large enough for a man to crawl into, have developed where the vein faults were highly mineralized. These open spaces are the result of extensive solution and removal of lode material, principally siderite, pyrite, and sphalerite. The open spaces as well as the other parts of the vein fault are marked by an abundance of pulverulent limonite and wad, and the presence of coatings or crusts of antimony and arsenic oxides, calcite, azurite, and malachite. Nodules and tabular masses of galena are rimmed locally by banded anglesite, and crusts of small quartz crystals on fragments of ore and gangue minerals are common. Boxworks resulting from the solution of pyrite, sphalerite, and siderite are widespread in all parts of the oxidized zone. Ice veins, with features already described, occupy solution cavities and other open spaces in the permafrost zone.

All the features of the oxidized zones indicate extensive solution and removal of material from the zones. Siderite, pyrite, and sphalerite are the minerals most affected and galena the least. The silver content of the oxidized parts is enriched in some vein faults. The reason for this enrichment is discussed in the section on geochemistry.

In some vein faults the deep parts of the oxidized zones exhibit interesting textures and structures. In the No. 48 vein fault of the Bellekeno mine one of the ore shoots presented a remarkable development of cockade structures and banding. This ore shoot was severely brecciated after the deposition of siderite, galena, pyrite, and sphalerite. This resulted in rounded aggregates of both gangue and ore minerals. Subsequent deep oxidation produced limonite and wad and darkening of the siderite. The sphalerite and pyrite were highly oxidized in some places leaving boxworks, and anglesite developed in concentric bands around cores of galena. This brecciated mass has been cemented by quartz, calcite, gypsum, smithsonite, and anglesite. The quartz occurs as short prismatic crystals encrusting the ore and gangue fragments and is overgrown by calcite, which fills the spaces between the quartz-encrusted fragments. In other parts of the ore shoot alternating bands of gypsum, smithsonite, and limonite occur about fragments of ore and gangue, and seams of anglesite overgrown by quartz are present. These textures and the presence of sulphates and oxides suggest deposition from downward percolating waters that have derived their mineral load from the upper oxidized parts of the ore shoot. The fact that this particular vein fault is now sealed by permafrost and that circulating waters are not leaching the ore shoot at the present time suggests that the oxidation and cementation took place prior to the formation of the present permafrost.

In the zone immediately below the oxidized parts of the vein faults (zone of reduction) supergene quartz, calcite, and dolomite cement the fragments of ore and gangue minerals in some lodes into compact masses. These minerals may also occur in cavities and along late fractures. In most vein faults supergene sphalerite, pyrite, and galena occur as crystals in late fractures in the lodes and wall-rocks, and in a few veins, as at the Lucky Queen and Sadie-Friendship, pyrargyrite and native silver were abundant in late fractures and cavities.

The zone of reduction, if well developed, is a zone of cementation. In the Keno Hill area, however, it usually retains much of the original vuggy nature arising from hypogene mineralization and brecciation of the lodes. The crystals and aggregates of quartz and carbonate in the zone of reduction result from precipitation of dissolved material derived from the oxidation zones. The chemical factors bearing on this problem are discussed in the section on geochemistry.

Wall-rock Alteration

In nearly all vein faults meteoric waters migrating downward alter some of the wall-rock minerals and leach soluble compounds leaving the rocks soft and porous. In the sediments where a hypogene alteration zone is absent, supergene effects are not marked. For a few inches outward from the lodes the few hypogene carbonates in the wall-rocks are attacked and oxidized to limonite and hydrous manganese oxides. In some quartzite wall-rocks the carbonate cement is leached, and in schists silica and alumina may be removed leaving the rock porous or the remaining grains incoherent, resulting in the breakdown of the rock to a sand or mud. This effect is usually localized and seldom exceeds a foot in width outward from the veins.

The hypogene alteration zones in the greenstones are the most severely affected. These alteration zones are highly oxidized and softened owing to the breakdown of the hypogene carbonates and pyrite to limonite, wad, and soluble salts.

The fractures in and about all hypogene lodes in both sediments and greenstones are stained with limonite or manganese oxides as a result of the migration of meteoric solutions into them and consequent precipitation of the oxides along them. This staining may extend out from the lodes for distances of 50 feet or more, and it is often possible to locate mineralized parts of vein faults by tracing this supergene dispersion halo.

THE GEOCHEMISTRY OF THE DEPOSITS

General

The detailed geochemistry of the hypogene processes of mineralization and the origin of the deposits have not yet been fully worked out. The outline of the geochemistry of the supergene processes has been investigated and will be described briefly. Laboratory work is continuing on samples from the deposits, and some of the statements and conclusions given below are tentative.

Hypogene Processes

The geochemical setting of the deposits is of first importance in a discussion of their origin. The rocks in which the deposits occur are quartzites, sericitic, chloritic, and graphitic schists, graphitic phyllites, and greenstones. Although chemical analyses are not yet available for these rocks thin section and field studies suggest that the main feature of the sediments is their high silica, alumina, and carbon (graphite ?) content. The schists and phyllites also contain significant amounts of pyrite and carbonate minerals, and it is probable that these rocks owe their relatively high content of sulphur and carbon dioxide to original sedimentary processes. The greenstones are highly altered rocks that were originally diorites or gabbros. The quartz-feldspar porphyries are not numerous and are the only evidence of granitic intrusions in the immediate vicinity of the deposits. The sedimentary rocks and greenstones have both been highly altered during regional metamorphism and fall into the chlorite-sericite zone or greenschist facies.

The vein faults cut and offset all ages of rocks on the two hills and the greenstones and quartz-feldspar porphyries have been altered by the mineralizing solutions. It seems improbable that any of the near surface intrusive rocks, namely diorite or gabbro (greenstone) and quartz-feldspar porphyry, are responsible for the mineralization. It is difficult to see how these rocks could give rise to magmatic metal bearing solutions that found their way into the vein faults because the greenstones and porphyries were fully consolidated before faulting took place. An alternative source for the mineralizing solutions and metals exists in the sediments and consolidated igneous rocks, but the amount of metals present in these rocks and the processes leading to their concentration in the lodes must await further geochemical work now being pursued.

The sequence of hypogene mineralization has been outlined in the sections above. The earliest stage of mineralization was the formation of quartz stringers and lenses in both sediments and greenstones and carbonate-epidote stringers and lenses in greenstones. Both types of lenses and stringers are small and are localized in contorted parts of schist beds or in fractures in the quartzites and greenstones. They are disconnected in the rocks, not related to any fault or fracture system, and contain minerals the components of which are abundant in the rocks in which they occur. These facts suggest that this type of stringer and lens derived its mineral content locally, and it seems probable that the quartz and carbonate represent a concentration of SiO_2, CO_2, Ca, and other elements mobilized during an early period of metamorphism. These compounds and elements have evidently migrated into low pressure dilatant zones (fractures and contorted schist areas) where they have been precipitated.

The early quartz lenses and stringers are cut by vein faults containing quartz-pyrite-arsenopyrite lodes with a significant gold content and a low silver content. Some of these early vein faults have suffered a second stage of movement with consequent fracturing of the quartz lodes. Other early vein faults appear to be associated with a series of transverse vein faults that may be subsidiaries. Both the fractured quartz lodes and other parts of the early vein faults and the transverse vein faults have been mineralized with siderite, quartz, galena, sphalerite, pyrite, freibergite, chalcopyrite, and barite. The silver content of these mineralized zones is high and the gold content is low.

If we assume a closed system for the chemical processes that produced the deposits we may speculate on the nature of the solutions and their changes during the hypogene mineralization of the lodes.

A study of the mineralogy supported by spectrographic analyses and assays of the quartz-arsenopyrite-pyrite lodes indicates that silica was the principal component of the mineralizing solutions. The silica was accompanied by significant amounts of sulphur and arsenic, and some carbon dioxide may also have been present. Iron was abundant and was accompanied by small amounts of antimony, bismuth, silver, lead, zinc, gold, and copper. The iron has been bound by sulphur into pyrite and by sulphur and arsenic into arsenopyrite. Spectrographic analyses of these minerals indicate the general presence of antimony, bismuth, silver, lead, zinc and copper all of which may substitute in small amounts for one or other of the major elements in the minerals. Gold occurs in the pyrite and arsenopyrite where it may substitute for iron in the semi-metallic structures of pyrite or arsenopyrite. All the components of the minerals in the early quartz lodes probably migrated in solution together because all minerals are intimately intergrown, and there are no apparent cutting or other relationships indicating different ages for the minerals.

The mineralizing solutions from which the siderite-galena-sphalerite lodes were derived apparently differed in composition from their earlier counterparts. Carbon dioxide, sulphur, and silica were the principal components in that order of abundance. Arsenic and antimony were relatively abundant. The principal metals accompanying the above components were Fe, Mn, Mg, Ca, Pb, Zn, Cd, Cu, Bi, and Sn. Small amounts of Ba, Sr, Al, and Na were also present.

The partition of these elements into the various mineral phases is shown clearly by mineralogical studies and spectrographic analyses.

Carbon dioxide has bound some of the iron and nearly all of the manganese, magnesium, and calcium into siderite. Traces of strontium and barium occur in some siderite, but where these elements reached a high concentration barite has formed incorporating both these elements.

Sulphur has bound much of the iron into pyrite. This mineral also contains some arsenic, but the concentration of arsenic was apparently too low in the solutions for a separate phase, arsenopyrite, to form. The arsenic not bound by pyrite occurs in the freibergite. Pyrite contains traces of silver and other metals probably substituting for iron or in interstitial sites. Gold is generally associated with pyrite, but it has also been determined spectrographically in the galena from some lodes.

Lead has been bound by sulphur into galena. This mineral also contains considerable amounts of silver. The presence of silver in galena is universal and much has been written about the phenomena, but space does not permit a discussion here. In the deposits under discussion some of the silver may occur in small specks of freibergite or some other silver sulphide in the galena. On the other hand, single nearly perfect crystals of galena from the deposits contain a high content of silver, and it would seem that the silver partakes of the structure of galena by substitution for lead or by interstitial solid solution. Similar phenomena probably explain the presence of gold, bismuth, tin, antimony, and other elements in the galena.

The greater part of the zinc and the cadmium has been bound by sulphur into sphalerite, and only small amounts of these two elements occur in other mineral phases. Iron is abundant in most hypogene sphalerite, and traces of silver, copper, lead, and antimony are present. These latter elements may be in a substitutional form in the sphalerite, but in some specimens they are probably due to admixed specks of galena and other minerals.

Much of the silver and nearly all of the copper, antimony, and arsenic in the mineralizing solutions have been bound by sulphur into freibergite. Some iron and zinc are also present as essential constituents of this mineral and traces of lead and cadmium are common. In some lodes some copper and iron are bound by sulphur into chalcopyrite. This mineral is not abundant, however, and most of the copper occurs in freibergite as stated above.

Regardless of the fact that some veins show alternate banding of siderite and ore minerals there is little evidence to suggest that the elements and compounds were precipitated except locally from successive solutions rich in one or the other components. In all lodes the gangue and ore minerals are so intergrown and intimately intermixed that the conclusion seems inescapable that they were precipitated from solutions that fluctuated only slightly in composition.

The siderite lodes in some vein faults have been brecciated and cemented by grey quartz and a little dolomite, both of which may have been precipitated from hypogene solutions. On the other hand, this second stage of quartz and dolomite are generally restricted to the lodes and these minerals are not found in any abundance in brecciated parts of the vein faults outside the siderite lodes. In some vein faults this space relationship in conjunction with the ready availability of SiO_2, Fe, Mg, and CO_3 in the pre-existing hypogene vein minerals suggests local solution of these compounds and elements, transport, and precipitation in dilatant zones resulting from brecciation. In other vein faults it is probable that some of the minerals have been precipitated from downward migrating meteoric waters. Occurrences of this kind are discussed below.

If the assumption is again made that the hypogene mineralization took place in a closed system during a period of falling temperature with other factors such as the availability of water being constant, it is evident that the mobility of the various compounds and elements have varied during the mineralization processes. Thus, silica had a high mobility during the three stages of mineralization, being highest during the formation of the early quartz lenses and stringers and quartz-pyrite-arsenopyrite lodes and lower during the formation of the siderite lodes. Arsenic had a high mobility during the formation of the quartz-arsenopyrite lodes and a lower mobility during the formation of the siderite lodes. Sulphur maintained a relatively high mobility during the formation of the quartz-pyrite-arsenopyrite lodes and reached a maximum during the formation of the siderite lodes. Carbon-dioxide apparently had a low mobility during the early mineralization stages because the amount of carbonate minerals present in early quartz stringers and carbonate lenses and in the quartz lodes is low. The second period of mineralization is primarily a carbonate one attesting to the high mobility of CO_2 during the formation of the siderite lodes.

Iron appears to have maintained a high mobility during all stages of mineralization because iron minerals are relatively abundant in all deposits. Manganese, magnesium, and calcium were highly mobile during the formation of the siderite lodes, but few minerals containing these elements are present in earlier periods of mineralization. Pb, Zn, Cd, Ag, Sb, and Sn are concentrated in the siderite-galena-sphalerite lodes and reached their highest mobility during their formation.

During all periods of hypogene mineralization the elements and compounds, whatever their source and mode of transport, have been precipitated in low pressure dilatant zones beneath schist cappings, at vein fault junctions, in fractures in quartzites, or in severely contorted areas in schists.

Supergene Processes

General Statement

The supergene processes in the vein faults are primarily due to the action of meteoric waters containing dissolved oxygen and carbon dioxide of atmospheric origin. During these processes the mobility of the various elements in the deposits is a function of the solubility of their salts, generally sulphates or carbonates, the pH of the migrating solutions, and the presence of free oxygen.

The supergene waters near the surface have effected a widespread oxidation of pre-existing lode minerals and have removed various soluble components. As the waters passed downward from oxidizing to reducing conditions some of the dissolved components have been precipitated as new minerals that cement brecciated parts of the lodes and occur along late fractures and in vugs and cavities.

The oxidation of the upper parts of the veins is not uniform throughout the area, due mainly to the presence of permafrost. In some veins the greater part of the oxidation must have taken place prior to the formation of the present permafrost, which in places may seal the veins to depths of 200 feet or more. In other veins the depth to which frost penetrates is relatively shallow, and this disappears in the summer entirely, and in these deposits oxidiation is proceeding at the present time.

Analyses of the meteoric waters (Table XI) show them to contain most of the elements present in the lodes. Fe, Mn, Mg, Ca, Al, Si, Na, and K are abundant, and Zn and Cu are readily detected. The principal anion is SO_4 and the pH of the waters varies from 4 to 6.

Table XI

Partial Analysis[1] of Water from Spring on Keno Hill

	ppm.
SO_4	258
Cl	None detected
CO_3	Strong trace
NO_3	None detected
Fe	4
Mn	0.92
Zn	2.00
Cu	0.06
pH (at source)	5
Temperature at source	3°C

Spectrographic analyses of the residue from the above sample after evaporation yielded the results given in Table XII.

Table XII

Spectrographic Analysis of Residue from Sample of Water from Spring, Keno Hill

100% to 10%	10% to 1%	1% to 0.1%	0.1% to 0.01%	0.01% to 0.001%	Not found
Mg Ca	Al Si	Fe, Mn Ni, Na	B. Zn K. Li	Co, Cu Ba, Sr Cs	Rb, Ag Pb, Cd Sb, As

The meteoric solutions passing downward in the vein faults are multicomponent systems, and the phase relationships are complex and undergo constant change due to reaction with gangue or ore minerals. In view of these complexities it seems best to discuss

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[1] Analysis by R. W. Boyle.

the fate of the various minerals and their constituent components individually and attempt an integration of the chemical factors from the final chemical results as observed in the field.

The minerals that show the highest degree of oxidation in the lodes are siderite, pyrite, sphalerite, and freibergite. These minerals yield hydrous iron oxides (limonite), psilomelane, and other hydrous manganese oxides, anglesite, scorodite, azurite, and malachite in all oxidized zones. In some parts of the oxidized zones the foregoing minerals are present in addition to calcite, quartz, smithsonite, gypsum, native silver, and plumbojarosite. In the zone of reduction, below the lower part of the oxidized zone, supergene sphalerite and galena, pyrargyrite and native silver, calcite, quartz, and dolomite cement hypogene minerals in the brecciated lodes and line fractures and vugs in some vein faults. This zone in turn grades imperceptibly into the hypogene zone.

The above outline is an attempt to synthesize the downward zoning in the lodes, but it must be understood that all lodes do not show this zoning arrangement. Some exhibit only a poor development of secondary minerals in the zone of reduction, others grade imperceptibly from the oxidized to hypogene zone without a marked formation of new minerals. Each lode must be considered separately when considering the possibility of enrichment by pyrargyrite, silver, and supergene sphalerite and galena.

Oxidation Processes

Siderite influences many reactions in the oxidizing and reducing zones. The analyses of siderite (Table II) indicate a high content of Fe and Mn and lower contents of Mg and Ca. Meteoric water containing atmospheric oxygen and carbon dioxide attack the siderite in the zone of oxidation forming insoluble hydroxides (limonite, wad, and psilomelane, etc.) and soluble hydrogen carbonates.

In the complex reactions it is probable that the soluble hydrogen carbonates of the principal elements Fe, Mn, Mg, and Ca in the siderite are formed first. Thereafter, the presence of free oxygen modifies the course of the chemical reactions and results in a differential separation of the above elements. Thus most of the iron and manganese are fixed as insoluble hydroxides, and the calcium and the magnesium migrate downward with the solutions. The reactions while complex may be discussed simply as follows.

Siderite attacked by water containing CO_2 yields soluble hydrogen carbonates thus -

$\underline{FeCO_3}$ (iron component) + $H_2O + CO_2 = Fe(HCO_3)_2$
$\underline{MnCO_3}$ (manganese component) + $H_2O + CO_2 = Mn(HCO_3)_2$
$\underline{MgCO_3}$ (magnesium component) + $H_2O + CO_2 = Mg(HCO_3)_2$
$\underline{CaCO_3}$ (calcium component) + $H_2O + CO_2 = Ca(HCO_3)_2$

Near the surface, the acidity of the water would be high owing to the presence of H_2SO_4 from the oxidation of pyrite, and the oxidation potential for the couples[1] ($Fe^{2+} = Fe^{3+} + e$, and $Mn^{2+} = Mn^{3+} + e$) would likewise be high. However, after moving downward a few feet the waters by reaction with carbonates and silicates would decrease in acidity due mainly to removal of CO_2 and any H_2SO_4 present. This would result in a decrease of the oxidation potential thus facilitating the formation of insoluble ferric and manganese hydroxides.

The reactions leading to the precipitation of insoluble hydroxides of iron may be represented as follows. The reactions for manganese would be similar but more complex.

$$4\ Fe(HCO_3)_2 + O_2 + 2H_2O = 4\ Fe(OH)_3 + 8CO_2$$

$$\downarrow \text{dehydration}$$

$$\underset{\text{Limonite}}{\underline{4\ FeHO_2}} + 4H_2O$$

The presence of pyrite in the deposits may modify the reactions with siderite. Oxidation of pyrite yields H_2SO_4, which will react with siderite producing soluble ferrous sulphate, manganous sulphate, and calcium and magnesium sulphates. The reaction for the iron component of the siderite may be written as follows:

$$FeCO_3 + H_2SO_4 = FeSO_4 + H_2CO_3$$

The reactions leading to the formation of limonite from $FeSO_4$ are discussed below under the oxidation of pyrite. The other sulphates

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[1] The oxidation-reduction potential is that energy required to remove or add electrons. It is a relative figure expressed in volts referred to the standard couple $H_2 = 2H^+ + 2e$. For unit activity of the reactants the oxidation potential is fixed as 0.00 volt and the scale of oxidation potentials may have either a positive or negative value. The oxidation potential varies with varying concentration of the reactants, and with the H+ concentration, i.e., the pH, of a solution. For reactions with which we are concerned in this report the oxidation potential decreases with increase in pH. A detailed account of the theory of oxidation potentials is given by Latimer, W. M.: The Oxidation States of the Elements and their Potentials in Aqueous Solutions; Prentice-Hall, New York, 1952.

are relatively unaffected by the presence of free oxygen and migrate downward with the meteoric solutions.

In the oxidized zones a separation of manganese and iron may take place. This is manifested in some vein faults by the presence of limonite derived from manganiferous siderite and the virtual absence of wad. In other vein faults parts of the oxidized zones at depth contain an abundance of wad, suggesting an enrichment in manganese. This evident separation of manganese from iron may be explained by a difference in oxidation potentials. Thus, the oxidation potential for ($Fe^{2+} = Fe^{3+} + e$) is much less than for the reaction ($Mn^{2+} + 2H_2O = MnO_2 + 4H^+ + 2e$). This means that at the same pH and in the presence of abundant oxygen iron is readily precipitated and fixed as limonite whereas manganese remains in solution longer and migrates into lower parts of the oxidized zone where some may be precipitated as wad.

The presence of free oxygen has little or no effect on the soluble calcium and magnesium components of the siderite because these elements exist in only one oxidation state in nature (oxidation state 2). Their mobility is essentially dependent on the pH of the solutions, the concentration of CO_2 in solution, or the concentration of SO_4^{2-}. If favourable conditions are met, as they seem to have been in most vein faults, the calcium and magnesium readily migrate downward where they may be precipitated by changing conditions as outlined below.

Pyrite varies in abundance with depth in the lodes. In the oxidized zones it occurs as highly oxidized nodules in small amounts whereas in the hypogene zones it is an abundant mineral intergrown with sphalerite and galena. Near the surface the pyrite is attacked by oxygen bearing waters yielding a soluble sulphate and H_2SO_4 according to the following equation:

$$2FeS_2 + 7O_2 + 2H_2O = 2FeSO_4 + 2H_2SO_4$$

In the presence of abundant free oxygen such as would prevail in near surface parts of the lodes the ferrous sulphate would be oxidized to ferric sulphate and insoluble ferric hydroxide as follows:

$$12FeSO_4 + 3O_2 + 6H_2O = 4Fe_2(SO_4)_3 + 4Fe(OH)_3$$

Hydrolysis of the ferric sulphate may take place with the formation first of basic salts and finally the insoluble ferric hydroxide and H_2SO_4 thus

$$Fe_2(SO_4)_3 + 6H_2O = 2Fe(OH)_3 + 3H_2SO_4$$

Dehydration of the ferric hydroxide yields limonite as follows:

$$Fe(OH)_3 = \underbrace{FeHO_2}_{\text{Limonite}} + H_2O$$

The final products in the oxidation of pyrite near the surface where abundant oxygen is present are limonite and free H_2SO_4. With depth the concentration of oxygen is reduced, and ferrous sulphate is stable in solution and migrates with the meteoric waters.

The alteration of arsenopyrite in the quartz-pyrite-arsenopyrite lodes generally yields scorodite $(Fe,Al)(AsO_4).2H_2O$ and limonite. Soluble arsenates may result from attack by the meteoric waters. These would migrate downward into the lower parts of the vein faults.

Sphalerite, like pyrite, shows a marked variation in abundance in the various zones. Analyses of bulk samples from the oxidized parts of lodes (Table XIII) show an average of 2 per cent zinc whereas the hypogene zones may contain up to 6 per cent zinc.

Table XIII

Analyses[1] of Ores showing Variation in Zinc Content

Mine	Zn	Nature of ore
	Per cent	
Bellekeno	1.51	Highly oxidized
Lucky Queen 200 level	3.7	Unoxidized
Moth 100 level	5.9	Unoxidized

Cadmium appears to vary in a manner similar to that of zinc but sufficient analyses are not yet available to draw positive conclusions. The geochemistry of cadmium is markedly similar to that of zinc and except for minor details the statements made about zinc are applicable to cadmium.

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[1] Analyses are average values of zinc content taken from development and production records.

During the attack by oxygenated meteoric waters sphalerite yields limonite and soluble zinc and cadmium salts. The reactions involving the iron component are similar to those discussed above for pyrite, where it is shown that this element is generally fixed as limonite. The zinc and cadmium, however, form soluble sulphates that migrate downward with the meteoric solutions. The equations for the oxidation of sphalerite may be represented as follows:

$$\text{ZnS (zinc component)} + 2O_2 = ZnSO_4$$
$$\text{CdS (cadmium component)} + 2O_2 = CdSO_4$$

Wang (1915) has shown experimentally that ferric sulphate in aqueous solution attacks sphalerite forming ferrous sulphate, zinc sulphate, and sulphur. He gives the following equation for the reaction:

$$ZnS + Fe_2(SO_4)_3 = 2FeSO_4 + ZnSO_4 + S$$

The presence of crusts of sulphur on sphalerite in some places may be due to this reaction. Some sulphur may also be derived by oxidation of H_2S as discussed below.

The oxidation of galena and the tetrahedrite with which it is generally intimately associated has an economic significance in the deposits, and it is desirable to know to what extent lead and silver are removed from or concentrated in the oxidized zones and zones of reduction. The oxidation of galena will be considered first.

In the oxidized parts of some veins galena occurs as masses and nodules surrounded by concentric bands of anglesite. In others the study of the boxworks indicates that nearly all the galena has been removed. The oxidation of galena proceeds according to the reaction

$$PbS + 2O_2 = \underset{\text{anglesite}}{\underline{PbSO_4}}$$

Galena is also attacked by solutions of ferric sulphate producing anglesite.

Because $PbSO_4$ has a low solubility in water (0.0425 gms. per litre at 25°C.) and the solubility is reduced by the presence of H_2SO_4, which hinders the hydrolysis of the salt, it is to be expected that relatively little migration of $PbSO_4$ would take place. In most lodes this seems to be the case. In others, however, there is ample evidence from boxworks, solution cavities, and the presence of up to 0.05 ppm lead in the waters leaching the lodes that lead has a considerable mobility and that given sufficient time a large amount of lead can be removed from the oxidized parts of the lodes. Furthermore, veinlets and seams of anglesite have been observed in the Bellekeno mine, suggesting some transport of $PbSO_4$.

Cerussite ($PbCO_3$) is found in the oxidized parts of some veins. This mineral has probably been derived directly from galena in some places and from anglesite in others by the action of carbonated meteoric water. The reactions may be represented as follows:

$$PbS + H_2O + CO_2 = PbCO_3 + H_2S$$
$$PbSO_4 + H_2O + CO_2 = PbCO_3 + H_2SO_4$$

Cerussite is slightly soluble in water containing CO_2 (10.9 milligrams dissolves in 1 litre water containing 43.5 milligrams of CO_2 at 18°C.) and part of the lead may migrate as the soluble lead hydrogen carbonate.

Garrels (1954) has examined the stability fields of PbS and $PbSO_4$ as functions of pH and oxidation-reduction potentials and concludes that the transport of lead may involve unusual complexing agents such as organic compounds. It is known from other work by the author (Boyle, Illsley, and Green, 1955) that organic compounds are present in many spring and stream waters in the area, and it is possible that these compounds may also occur in the meteoric waters leaching the lodes and contribute to the transport of lead.

The reactions involving the silver in the galena will be considered in the discussion of the oxidation of freibergite.

To summarize, it is evident that there has been little migration of lead in some lodes where a crust of anglesite usually surrounds the galena, inhibiting its complete oxidation. In other lodes, however, the galena and anglesite appear to have been removed from the oxidized zones. The quantity of meteoric water that has coursed the deposits has undoubtedly determined the extent of removal of lead because, as shown above, both $PbSO_4$ and $PbCO_3$ have an appreciable solubility and are ultimately removed from the oxidized zone.

The oxidation of freibergite is not uniform in the oxidized zones due principally to the fact that in many places the tetrahedrite is intimately associated with galena and, as noted above, may be isolated from oxidizing waters by the crust of anglesite surrounding galena nodules. With increasing oxidation of galena, however, the freibergite is finally broken down, yielding soluble salts and coatings of antimony or arsenic oxides, azurite, or malachite.

Freibergite has the complex formula $(Cu,Fe,Zn,Ag)_{12}(Sb,As)_4S_{13}$. Considering the copper and antimony components of this mineral and assuming complete oxidation the equation may be written as follows:

$$2Cu_{12}Sb_4S_{13} + 57O_2 + 2H_2O = 24CuSO_4 + 4Sb_2O_3 + 2H_2SO_4$$

The copper sulphate formed during the reaction is soluble and may migrate downward in the solutions. The iron, zinc, arsenic, and antimony components of the freibergite may yield soluble sulphates in the case of the first two and an arsenate and antimonate in the case of the last two. Part of the iron may be precipitated as limonite by oxidation of the $FeSO_4$ and other reactions as discussed under the oxidation of siderite.

Malachite may form from the copper sulphate by reaction with carbon dioxide, siderite, or other carbonate. The reaction for siderite is given by Mellor (vol. III, p. 271) as follows:

$$2CuSO_4 + 2FeCO_3 + H_2O = \underset{\text{malachite}}{\underline{Cu_2(OH)_2CO_3}} + 2FeSO_4 + CO_2$$

The malachite loses water and takes up carbon dioxide as follows to form azurite:

$$3Cu_2(OH)_2CO_3 + CO_2 = \underset{\text{azurite}}{\underline{2Cu_3(OH)_2(CO_3)_2}} + H_2O$$

Arsenates and antimonates are not as abundant in the oxidized zone as would be expected from the amount of freibergite that has undergone oxidation. This may indicate that the greater part of the arsenic and antimony has migrated downward in the form of soluble arsenates or antimonates.

Silver is contained in the galena probably as a solid solution and in the freibergite substituting for copper. As both of these minerals are oxidized their silver content is liberated and may migrate with the meteoric waters or be precipitated within the oxidized zone according to circumstances.

Assays of samples from some highly oxidized parts of lodes show them to contain several hundred ounces of silver a ton. These results are much higher than those from the hypogene zones, which average 20 to 60 ounces a ton. In general the lead content of these highly oxidized parts is low, and the silver is contained in a fine, chocolate-coloured, powdery limonite. A part of the enrichment of silver in the oxidized zones is undoubtedly due to the removal of gangue such as siderite and pyrite. Some enrichment, however, may be chemical and the possibilities are discussed below.

The exact nature of the silver in the highly oxidized vein material at the time of writing has not been determined by laboratory investigation, but there are indications that the silver occurs both in unoxidized sulphide particles and as the native metal or sulphide in a very finely divided state. In a few vein faults wires of native silver have been observed. Spectrographic analyses of anglesite show that some silver occurs in this compound, but the nature of this silver is difficult to determine. Some of the silver may substitute for Pb^{2+} in the anglesite structure, and some may be present as silver sulphate. There is also the possibility that some may be present in microscopic nodules of unoxidized galena that cannot be separated from the anglesite.

Ravicz (1915) and other writers have investigated the factors leading to enrichment of silver ores. Silver forms a soluble sulphate Ag_2SO_4 and a slightly soluble carbonate Ag_2CO_3. In the presence of solutions saturated with CO_2 the carbonate is soluble to the extent of 0.846 grams per litre at 15 degrees C.

Ferrous sulphate in solution readily precipitates metallic silver from solutions of Ag_2SO_4 and Ag_2CO_3, but due to the formation of ferric sulphate during the reactions the precipitation is not complete. The reactions are as follows:

$$Ag_2SO_4 + 2FeSO_4 = 2Ag + Fe_2(SO_4)_3$$
$$Ag_2CO_3 + 3FeSO_4 = 2Ag + FeCO_3 + Fe_2(SO_4)_3$$

The presence of freibergite, chalcopyrite, and arsenopyrite causes nearly complete precipitation of either metallic silver or argentite. Pyrite has little effect.

Mellor (vol. XIV, page 366) states that siderite reduces a solution of silver sulphate to form silver. Ravicz, however, argues that neither siderite nor rhodochrosite alone is effective in precipitating silver and states that sulphides such as freibergite, chalcopyrite, etc., must be present for precipitation.

In the Keno Hill deposits oxidation of the galena and freibergite yields silver to the oxidizing solutions probably as the soluble sulphate and carbonate. During the early stages of oxidation of the veins abundant siderite and pyrite would be present and yield $FeSO_4$, which would tend to precipitate the silver as the native metal or sulphide before it had migrated far. However, with increasing oxidation and removal of siderite and pyrite near the surface and consequent removal of high concentrations of $FeSO_4$ and sulphides the silver would be more mobile and would perhaps migrate downward into the lower parts of the oxidized zones. Here, it would again encounter a high $FeSO_4$ concentration and be precipitated. With time this downward stepwise migration would lead to enrichment of silver in the lower parts of the oxidized zones. This seems to explain the fact that some oxidized parts of the lodes are relatively enriched in silver compared with the hypogene zones.

In some vein faults, as at the Lucky Queen and Sadie-Friendship, it is evident that silver has migrated downward into the zone of reduction immediately below the oxidized zone. Here native silver and pyrargyrite occur in cracks, seams, and vuggy parts of the lodes. These minerals usually occur in siderite or associated with tetrahedrite and are probably due to reduction of silver sulphate and carbonate by siderite or by reaction of silver and antimony bearing solutions with tetrahedrite.

Analyses of the oxidizing waters after passing through vein material show that they contain the alkalis, alumina, and silica. These elements and compounds are readily available in the silicates in the wall-rocks and breccia of the deposits and are probably rendered mobile by the attack of H_2SO_4. The alumina liberated from the silicates probably migrates as the sulphate and the silica and alkalis as soluble alkali silicates. Some silica may migrate in an ionic form as $SiO_3{}^{2-}$.

The action of sulphuric acid on the sulphides, especially sphalerite, will yield some hydrogen sulphide according to the reaction for sphalerite:

$$ZnS + H_2SO_4 = ZnSO_4 + H_2S$$

In the presence of free oxygen H_2S is slowly oxidized to sulphur, and this may account in part for the presence of sulphur encrusting sphalerite and occurring with other partly oxidized sulphides. H_2S is appreciably soluble in cold water (2.6 litres of gas dissolving in 1 litre of water at 20°C.). This gas would, therefore, migrate downward in the meteoric solutions into the lower parts of the veins.

In some vein faults, principally in the Bellekeno system, the brecciated ore shoots contain abundant secondary calcite, selenite, some crustified quartz, and alternating bands of microcrystalline gypsum, anglesite, smithsonite, and limonite. These minerals cement oxidized siderite and sphalerite and nodules of galena encrusted with anglesite. The alternating bands of gypsum, smithsonite, and limonite and the occurrence of a few crystals of selenite 2 inches or more in length suggest deposition in highly brecciated and open parts of the veins. The details of the precipitation of the minerals in this type of occurrence have not yet been fully investigated, but the occurrences suggest a marked change in conditions permitting precipitation of the various minerals.

The calcite may owe its precipitation to a loss of CO_2 by the solutions during reactions with the highly brecciated vein material. The intimate distribution of calcite, smithsonite, and gypsum together in the deposits strongly suggests a reaction between dissolved zinc sulphate and calcite as follows:

$$ZnSO_4 + CaCO_3 + 2H_2O = ZnCO_3 \text{ smithsonite} + CaSO_4.2H_2O \text{ gypsum}$$

Calcium sulphate is rather soluble, however (2.09 gms. dissolve in 1 litre of water at 30°C.), and some of the gypsum may owe its origin to migration of this compound downward in the vein faults with consequent precipitation in open spaces.

Reduction Processes

Mineralogical observations and analyses indicate that the meteoric solutions passing downward would contain principally Fe, Mn, Mg, Ca, Al, Si, Na, K, B, Zn, Cd, Cu, Ni, Pb, As, Sb, and Ag. The Fe, Mn, Mg, Ca, Al, K, Na, Zn, Cd, Cu, Ni, Pb, and Ag probably migrate as sulphates, but some Fe, Mn, Mg, Ca, K, Na, Pb, and Ag may migrate as soluble hydrogen carbonates or carbonates. Silica probably migrates as soluble alkali silicate or in a complex ionic form involving SiO_3^{2-}. Boron forms soluble borates and probably migrates in this manner. The arsenic and antimony probably migrate as soluble arsenates and antimonates or as complex ions. Hydrogen sulphide and carbon dioxide migrate downward as dissolved gases.

At first, in the upper parts of the oxidized zones, the amount of oxygen and carbon dioxide would be high, and the solutions would be acid, oxidizing, and leaching. As they pass downward, however, the oxygen and carbon dioxide are rapidly spent by reaction, and the acidity is neutralized by siderite and other minerals. The conditions then become reducing, thus promoting the precipitation of several components.

Hydrogen sulphide migrating downward in the solutions is probably responsible for the reduction of $ZnSO_4$, $PbSO_4$, and $CdSO_4$. This leads to the precipitation of supergene sphalerite, galena, and cadmium sulphide in fractures and vuggy parts of the brecciated hypogene lodes below the zone of oxidation. The reduction is simply illustrated by the following three equations:

$$ZnSO_4 + H_2S = ZnS \text{ (sphalerite)} + H_2SO_4$$
$$PbSO_4 + H_2S = PbS \text{ (galena)} + H_2SO_4$$
$$CdSO_4 + H_2S = CdS \text{ (hawleyite)} + H_2SO_4$$

The formation of hawleyite (Beta CdS), which is a new mineral, has been discussed by Traill and Boyle (1955).

Reduction of silver solutions, particularly Ag_2SO_4, by siderite in the presence of sulphides yields native silver. Reaction of this silver with the soluble antimonates may give pyrargyrite. In a similar manner reactions of silver and antimony bearing solutions with tetrahedrite may also produce pyrargyrite.

Supergene quartz, dolomite, and calcite are widespread in the zone of reduction and have been precipitated from the meteoric solutions due to changing conditions such as reduction in acidity and removal of CO_2 by reaction. The details of these reactions have not yet been investigated.

The formation of supergene ore minerals in the zone of reduction is determined by many special structural and chemical conditions. Brecciated hypogene lodes and abundant fractures and open spaces are a necessary structural feature. Porous near surface parts of the veins promote the rapid oxidation of sulphides. During the oxidation of the sulphides H_2SO_4 is formed, which may react with sphalerite and other sulphides to form H_2S. Escape of H_2S in the solutions to the lower parts of veins must be fairly rapid to prevent its oxidation and thus make it available for the reduction processes. Silver must be stabilized in the solutions in some manner to prevent its precipitation in the oxidizing zone, thus allowing migration to the zone of reduction. Finally, the elements Zn, Pb, Cd, and Ag must be available in sufficient quantity in the zones of oxidation.

These conditions have been met in some cases for silver, as at the Lucky Queen mine where abundant ruby silver and native silver formed rich ore shoots. Ore shoots containing strictly supergene galena and sphalerite are unknown in any of the veins, but nearly all lodes contain small amounts of these supergene minerals. It is doubtful if any of the ore shoots in the zone of reduction on Keno and Sourdough Hills have been sufficiently enriched by supergene galena and sphalerite to have made much difference in the over-all grade and tonnage. Geochemical work carried out by the author (op. cit.) on stream and spring waters indicates that much of the zinc taken into solution during the oxidation processes escapes completely from the deposits. This may also be true for lead, cadmium, and copper in some places.

SUMMARY

The rocks underlying Keno and Sourdough Hills include chloritic, sericitic, and graphitic schists, quartzites, and lenses and sills of greenstones. These rocks belong to the green schist facies. A few quartz porphyry sills occur in sediments and are the only local evidence of granitic intrusives.

Two formations are recognized and these are subdivided into six members for discussion in this report. Some of these members are ore bearing, others are barren. Ore shoots occur principally in those members containing thick-bedded quartzites or greenstones. Schist, phyllites, and thin-bedded quartzites alone are structurally unfavourable to the occurrence of ore shoots.

The ore-bearing vein faults cut all the rocks of the area. These vein faults are brecciated zones and sheeted zones in quartzites and narrow fractures in the various schists. Late faults and fractures offset the vein faults and cut through ore shoots throughout the area.

The sequence of mineralization is complex, entailing both hypogene and supergene processes. The hypogene mineralization consists of three distinct types, representing three periods. The earliest of these is marked by the formation of small quartz lenses and stringers in quartzites and schists and carbonate-epidote lenses and stringers in greenstones. These bodies probably formed as a result of a local secretion process. These quartz and carbonate bodies are cut by the vein faults, which contain two types of lodes. The earliest of these types contains quartz, pyrite, arsenopyrite, and some gold. The other type, which occurs alone in some vein faults and in brecciated parts of the vein faults containing the quartz lodes of the earliest type, consists mainly of siderite, galena, sphalerite, and tetrahedrite. These latter lodes are high in silver and contain only small amounts of gold. The siderite lodes are mainly responsible for the production of lead-silver-zinc concentrates.

The ore shoots in the vein faults are localized in two structurally favourable sites: (1) in thick-bedded quartzites or greenstones beneath schist cappings, and (2) at junctions of vein faults. The latter sites appear to be more favourable for the formation of large and continuous orebodies than are the former.

The siderite lodes are highly oxidized near the surface and down to 400 feet or more in some vein faults. The chemistry and certain features of the oxidation processes have been discussed. In most vein faults oxidation of the lodes has resulted in the general removal of zinc and to a less degree lead. In addition, the oxidation processes have produced an enrichment silver in the oxidized parts of some lodes both by removal of siderite and other gangue and by chemical solution and precipitation of silver.

The chemistry and some of the features in the zone of reduction have been outlined. In this zone supergene sphalerite and galena have been formed in nearly all lodes, but it is doubtful if these supergene minerals have produced any marked enrichment of lead and zinc in the deeper parts of the lodes. At one mine secondary enrichment of silver has occurred in the zone of reduction, producing ore shoots rich in pyrargyrite and native silver.

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