GEOLOGICAL SURVEY OF CANADA

DEPARTMENT OF MINES AND TECHNICAL SURVEYS

BULLETIN 58

THE GEOLOGY OF KENO AND GALENA HILLS, YUKON TERRITORY

(105 M)

K. C. McTaggart

Price, 75 cents

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By

K. C. McTaggart

DEPARTMENT OF
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PREFACE

Keno and Galena Hills together are the site of the largest producing silver-lead-zinc deposits in Yukon Territory. The author spent three seasons studying the structure and stratigraphy of the area before leaving the Geological Survey of Canada to join the staff of the University of British Columbia, where this report was written. Information collected by the author on the individual mines is not included, as a report on the ore deposits based on a more recent investigation is being prepared by R. W. Boyle.

J. M. HARRISON,
Director, Geological Survey of Canada

OTTAWA, August 27, 1959

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Illustrations

THE GEOLOGY OF KENO AND GALENA HILLS, YUKON TERRITORY

Abstract

The rocks of Keno and Galena Hills are quartzites, phyllites and schists, with a wide range of composition, intruded by metamorphosed greenstone sills. All the metamorphic rocks have been intruded by rhyolite and lamprophyre sills.

Structures are highly complex. From a consideration of major and minor folds, 'gleitbrett' structures, lineations, foliation, joints and faults, it is concluded that the now metamorphic rocks were at an early stage overthrust in a northerly direction with a simultaneous development of tight, recumbent folds. At a later stage, this highly folded and overthrust terrane was further deformed by open folds that trend northwesterly. The faults that contain the rich silver-lead veins of the area were probably formed after this folding.

The area provides evidence of an early glaciation during which Galena Hill and most of Keno Hill were covered by ice and of a late glaciation when ice reached only low levels.

Résumé

Les roches des collines Keno et Galena sont formées de quartzites, de phyllites et de schistes, de composition très diverse, avec des intrusions de filon-couches de roches vertes métamorphisées. Toutes les roches métamorphiques renferment des intrusions de filon-couches de rhyolite et de lamprophyre.

Les structures sont très complexes. Après avoir étudié les plissements majeurs et mineurs, les structures «gleitbrett», les linéations, la foliation, les diaclases et failles, on en conclut que les roches métamorphiques actuelles ont à l'origine chevauché en direction nord pendant que se formaient des plis couchés et serrés. A un stade ultérieur, ce terrain fortement plissé et chevauchant a été déformé davantage par des plis ouverts orientés vers le nord-ouest. Les failles que contiennent les riches filons d'argent-plomb de cette région se sont probablement formées à la suite de la formation des plis ouverts.

La région fournit les preuves d'une ancienne glaciation, au cours de laquelle la colline Galena et la majeure partie de la colline Keno étaient recouvertes de glace, puis d'une glaciation plus récente, alors que la glace n'a atteint que des niveaux inférieurs.

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INTRODUCTION

Keno and Galena Hills, in north-central Yukon, contain the most important lode deposits so far developed in the Territory. The object of the present work was to map the rocks and structures in more detail than had been done before and thus to provide a geological framework for the detailed studies required in the exploration and development of the silver-lead-zinc deposits. The area mapped includes Keno and Galena Hills and a part of Sourdough Hill, a total area of about 60 square miles. The writer spent the field seasons of 1948, 1949 and 1950 in in the district.

The original settlement within the area is the village of Keno Hill which lies in a valley at the foot of Keno Hill. Its permanent population is small, however, compared with that of Elsa and Calumet mining camps on the northwest slope of Galena Hill. Mayo Landing, the nearest large centre, is some 40 miles to the south and may be reached by gravel roads from all settlements within the area. A gravel road from Whitehorse to Mayo was completed in 1949.

Nature of the Area

Keno and Galena Hills (*see* Fig. 1) are two mountains lying along a northeasterly trending arc on the northwest flank of the Gustavus Range, a subdivision

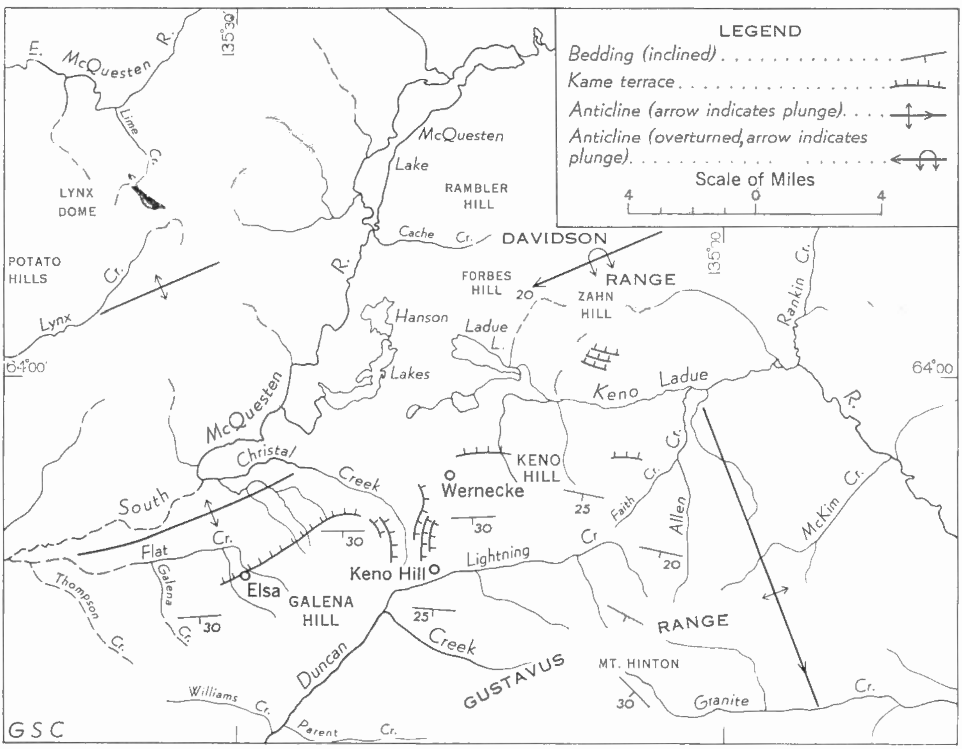

Figure 1. Index map showing Keno and Galena Hills, kame terraces, and regional structures.

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of the Yukon Plateau. They are separated from the other mountains on the Range and from each other by rather narrow valleys. To the northwest, the broad flat South McQuesten valley lies at an elevation of about 2,500 feet and, to the north, across Keno-Ladue valley, lie the Davidson Mountains.

Keno Hill, whose summit is at 6,065 feet, is deeply incised by cirque-like gulches on its north side (*see* Pl. I A). Large areas near summit elevation are almost flat and featureless (*see* Pl. I B) and merge gradually with the steep but fairly regular south and west slopes. Galena Hill, the summit of whose rounded ridge is at 4,740 feet, is characterized over much of its surface by regular monotonous slopes.

The upper parts of Keno and Galena Hills are above timber-line and covered by great areas of dwarf birch, growing knee-high to shoulder-high, or heath plants. Below timber-line, trees are small and scattered. In the early days, usable timber grew along the lower slopes of the hills, but almost all of this has been logged or burnt off, and it is now difficult to obtain light mine timbers locally. The lower parts of the north-facing slopes and valley floors are largely muskeg.

Outcrops are, in general, scarce. Extensive rock exposures are found only in the heads of gulches on the north side of Keno Hill; the upper slopes of Galena Hill and the southern and western sides of Keno Hill are almost devoid of outcrop. Areas of disintegrated outcrop in many places indicate the type of bedrock but give no structural data.

The summer weather is extremely variable. A week of hot weather may be followed by a week of cold, rainy, and in high elevations, foggy weather. The winters, according to Hicks (1952)[1],

> . . . are long, dark, and cold. The mines (most of which are on northwest slopes) are completely hidden from the sun for ten weeks each year, a fact which has a greater effect on morale than on any physical aspect of operation. Temperatures may be excessively low; a minimum of 81 degrees below zero was officially recorded in Mayo during the winter of 1947. As higher elevations are attained, the winter temperature tends to moderate. Precipitation is light, amounting to an average of 11 inches per annum, and the area is generally considered semi-arid.

Previous Geological Work

Keno Hill was mapped by Cockfield (1921) in 1920, shortly after the camp was first opened. This work was followed by the mapping of Galena Hill by Stockwell (1926) in 1925. The Mayo area which contains Keno and Galena Hills was mapped by Bostock and his map (1947) has provided information on the regional setting of the mining camp. Cockfield and Bostock have, periodically, published accounts of the mining industry of the Yukon, including that of Keno and Galena Hills.

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[1] Dates in parentheses are those of references cited at the end of this report.

Acknowledgments

The writer was ably assisted in the field in 1948 by H. Gabrielse, in 1949 by R. G. McCrossan, W. R. Wright, and J. A. Gibson, and in 1950 by R. G. Blackadar, W. R. Wright, and W. Montgomery.

He is indebted to the personnel of United Keno Hill Mines Ltd. for innumerable favours, and particularly to Mr. H. Brodie Hicks, Dr. W. V. Smitheringale, Messrs. Kenneth Wilson, Alex. Berry, William McBride, and Dr. B. Stewart-Murray. Mr. Barry O'Neil of Mayo Mines Ltd. was helpful on many occasions. The local prospectors were extremely cooperative, especially the late Bill Williamson, Messrs. Alex. Gordon, Charles Brefalt, and Alex Nicol. The writer is indebted to the American Smelting and Refining Company for making available to him certain private maps and reports dealing with certain properties in the area.

Glaciation

The glaciation of the Keno Hill area has been described by Wernecke (1932) and that of the Mayo area by Bostock (1947).

There is some evidence of two episodes of glaciation in the area, an early one in which Galena Hill and much of Keno Hill were covered, and a later one in which only the lower flanks of the hills were buried. Evidence of the earlier period is rather scanty. Erratic blocks of quartzite and boulders of gabbro and diorite are scattered across the top of Galena and Sourdough Hills and erratics are found almost to the top of Keno Hill. Glacial grooves and striations were not found and probably have been destroyed by intense frost action.

It might be considered that the younger glaciation is simply a continuation of the older. Topographic evidence of the earlier episode, however, is obscure, whereas below the level of the highest kame terrace (*see* Fig. 1) that marks the minimum upper limit of the later glaciation, rounded and scored outcrops, drumlins, kame terrace and outwash features are in many places perfectly preserved. This contrast suggests a long interval between the two glacial episodes during which the earlier glacial features were largely obliterated.

The most striking evidence of the more recent glaciation is a succession of kame terraces (lateral moraines of L. Wernecke) which are easily visible along Christal Creek valley between Keno and Galena Hills (*see* Pl. II A) and also on the northwest slope of Galena Hill. They are traceable also along various other parts of Keno Hill and on the flanks of the Davidson Mountains to the north. These terraces are deposits of sand and gravel laid down by rivers and streams held between the glacier margins and valley walls. The highest terrace observed is west of Wernecke at an elevation of nearly 4,000 feet. Along the valley of Christal Creek the terraces slope to the south at 200 to 300 feet per mile and on the northwest slope of Galena Hill they slope to the southwest at less than 100 feet per mile. These kame terraces thus partly delineate the margins of a large glacier that occupied the South McQuesten valley and outline also a lobe of this glacier that extended south up Christal Creek valley. As the glacier shrank, successively lower terraces were formed. Three such terrace levels are visible on the west slope of Keno Hill. In places, as for example, west of Wernecke, the stream flowing along the edge of the glacier cut into bedrock and, as the ice level dropped, was left temporarily trapped in its rocky channel. When the rock wall was breached, the higher channel was abandoned for a lower one at the ice-margin. Water flowing from the upper channel and from the slopes above cut abruptly downhill to the lowest channel, in many places scouring channels diagonally across the direction of the earlier ones, the two sets of channels producing diamond-shaped hillocks.

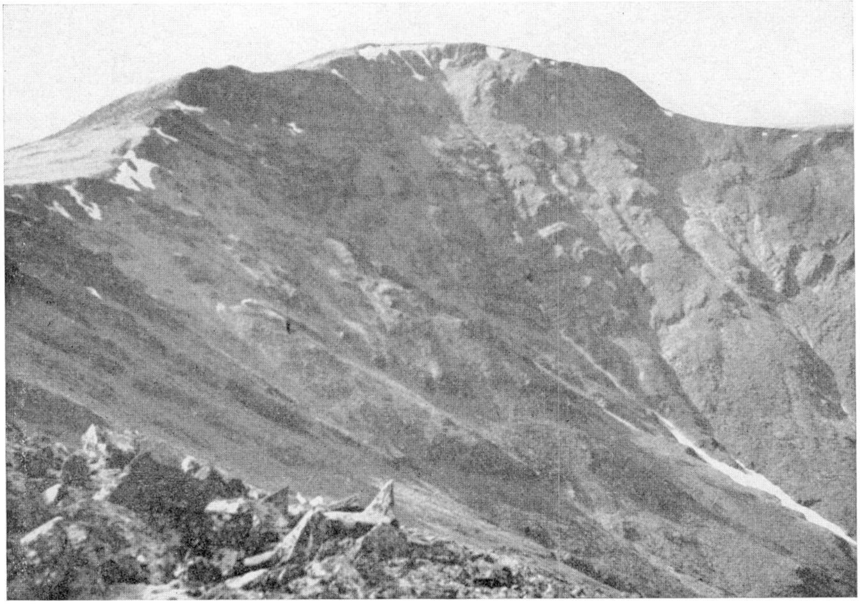
As the ice level dropped, the margins of the glacier contracted, and its snout, extending at first far down McQuesten Valley, retreated northeastward. The lobe that extended south up Christal Creek valley similarly thinned and retreated northward, and the glacial stream that flowed between its edge and Galena Hill and down Duncan Creek valley occupied successively lower and lower positions (marked by terraces) on the side-hill. At last, when an outlet to the northwest was opened around the base of Galena Hill, the upper part of this southward-flowing stream started to flow north to the McQuesten, capturing the temporary ice-margin stream on the north side of Christal Creek valley, and forming the present Christal Creek. Somewhat similarly, Flat Creek probably follows the final course of the ice-margin stream that deposited successively lower terraces along the northwest slope of Galena Hill as the level of the confining glacier fell.

Crescentic recessional moraines, concave to the north and pocked with kettles, lie south of Hanson Lakes and, as Wernecke pointed out, partly confine the lakes. Some of the Hanson Lakes, Ladue Lake and possibly McQuesten Lake, however, appear to mark the sites of ice remnants in the final stages of ablation, as shown by crevasse fillings that form projections into or islands in the lakes. Ladue Lake, when its drainage to the east was still restricted by the ice, drained westward to the South McQuesten valley along a wide channel that is now dry.

Drift over the South McQuesten flat has been partly dissected by rivers of meltwater that formed as the glacier retreated. Segments of their large meanders remain engraved in the morainal and pitted outwash deposits, their sweep dwarfing the meanders of the present day underfit South McQuesten River.

Alpine glaciers, fed by snowfields at high elevations, carved the U-shaped valleys of McMillan and McNeill gulches (*see* Pl. II B) which open towards Keno Hill from the south, and blocked Lightning Creek valley with their debris. They seem not to have interfered with or contributed to the late low-level glacier to the north and they may not have had contact with it.

Silver Basin (*see* Pl. I A) and Faro gulches may originally have been formed by ice action but the writer believes that their present form is, in part, due to mass wasting, the steep headwalls being maintained by the gently southerly dipping quartzites that form the rim-rock. Similar valleys with steep headwalls are known in unglaciated regions where gently dipping resistant beds 'hold up' the rim.



McT. 7.5.49

A. *View looking southwest into the head of Silver Basin. Greenstone, at the highest part of the rim, overlies quartzite and phyllite (Fig. 13).*

Plate I

B. *Easterly view showing gentle open slopes characteristic of much of the upper surface of Keno and Galena Hills. Buildings and dump of Shamrock property (38) in foreground. Main ridge in centre is the large greenstone band just southwest of No. 9 vein.*

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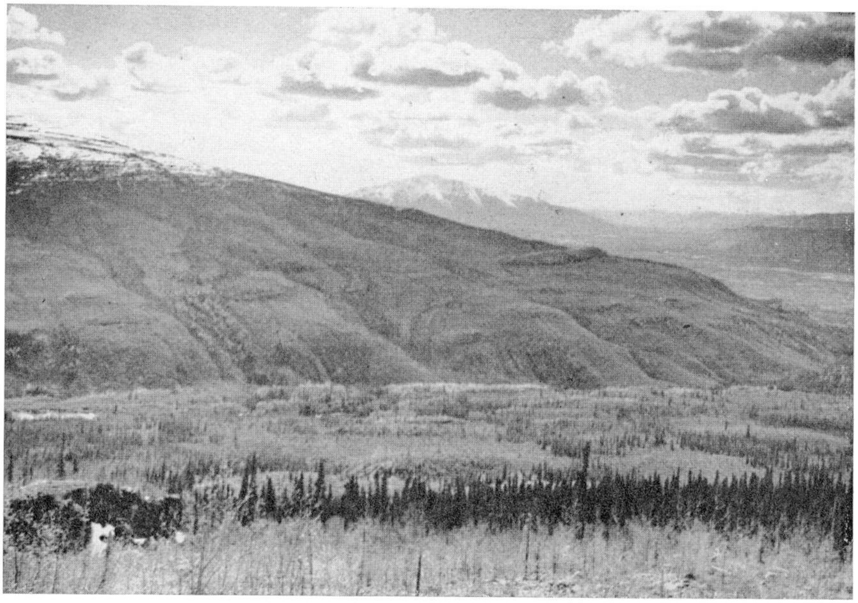

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A. View westerly from Keno Hill across Christal Creek showing southerly sloping kame terraces on east flank of Galena Hill. In foreground, dissected kame terrace and outwash deposits. Broad South McQuesten valley to extreme right, Mount Haldane in middle distance.

Plate II

B. View south from Keno Hill up McNeill Gulch, a glacial valley with terminal moraines in the middle distance. A greenstone body in the headwall of the gulch lenses out to the west. The prominent regular slope on the left is a dip slope in quartzite.

McT. 4.1.49

Permafrost is, in general, restricted to the northern slopes, but even there, if the subsurface flow is strong, such as at the Sadie mine (35, 36)[1] the ground may be thawed to the surface. Wernecke (1932) gives the following figures for the depth of frost encountered in some of the underground workings:

No. 9 vein (42)	400 feet, bottom of frost not reached. (The shaft is close to the headwall of Faro Gulch.)
Ladue vein (35, 36)	260 feet to unfrozen ground.
Lucky Queen mine (44)	360 feet, bottom of frost not reached.
Elsa mine (2)	300 feet to unfrozen ground.
Silver King mine (1)	200 feet to unfrozen ground.

Patterned ground, characterized by stone stripes and rock polygons, is widespread at higher elevations. The stone stripes are composed of coarse rubble up to 4 feet across of quartzite or greenstone and many are 200 feet or more wide. They may extend across contacts and obscure the underlying geology. Many of the tabular rock fragments that compose them stand with their large surfaces nearly vertical. Those on the southern slopes, where there is now little or no permafrost, seem to be stationary, for the assay office on the Porcupine Claim (41) on Keno Hill, which is built on one of them, seems undisturbed. The rock polygons, averaging perhaps 10 feet in diameter, are mostly on nearly flat ground and are composed of rather small fragments and flakes of phyllite and schist. They are nearly circular rather than clearly polygonal.

[1] Numbers in parentheses are those by which the property is marked on the geological map (Fig. 13).

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GENERAL GEOLOGY

Keno and Galena Hills are underlain by a series of metamorphosed and unfossiliferous sedimentary rocks, largely quartzite, phyllite, schist, and limestone, that are included by Bostock (1947) in the Yukon group of Precambrian and/or Palæozoic age. The sedimentary rocks were intruded first by basic igneous rocks, now metamorphosed to greenstones, and later by rhyolite and lamprophyre sills. Cockfield (1925) suggested that the greenstones may be of Palæozoic age, Devonian or younger. The writer found no evidence bearing on the absolute ages of the rocks in the area, and even the relative ages of the various sedimentary units are uncertain, for stratigraphic tops were rarely determined and beds may be overturned in many places.

Metamorphosed Sedimentary Rocks

Quartzite

Thick-bedded, grey to blue-grey quartzite underlies much of Keno and Galena Hills (Fig. 13). One prominent member some 3,500 feet thick extends east from the Silver King mine (1) on the west end of Galena Hill, across Galena Hill and west and south slopes of Keno Hill, to McNeill Gulch, south of Keno Hill. On Keno Hill other quartzite members, notably thinner, are exposed north of this one but apparently do not continue to the west. The quartzite beds increase in number and thickness to the southeast at the expense of members made up largely of phyllite and schist, so that a few miles south of Lightning Creek the rocks seem to be almost entirely quartzite.

Outcrops of quartzite are generally strongly jointed, displaced by frost action, and slumped, and the abundant partings and interbeds of black phyllite are inconspicuous. The quartzite is mostly pale grey, ranging through blue-grey and slate grey to dark grey. Pure white and buff varieties are found in a few places. The lustre of the quartzite is, in general, rather dull, but locally it is vitreous and glistening. Most of the joint blocks are angular. The few that break down into porous, brownish, somewhat rounded boulders were probably originally limy. The quartzite commonly shows a layering which, in most places, seems to be bedding. The layers, one-sixteenth to one-eighth inch thick, are indistinct and due to colour rather than to textural differences. Features such as variation in grain size, crossbedding, or ripple-mark were not found and stratigraphic tops were not determined. A crude foliation that in many places lies parallel with the layering shows oval ($\frac{1}{8} \times \frac{3}{16}$ inch) scales of wrinkled and somewhat rusty white mica.

The quartzites commonly contain stringers and irregular masses of white quartz. The stringers generally lie parallel with the bedding and are folded with it but in some places they are crosscutting. Some quartz veins are highly contorted and others show irregular and unpredictable ptygmatic folds (Godfrey, 1954). The stringers range from one-sixteenth inch to more than 2 feet in thickness, but most are near one-quarter to one-half inch. In some specimens the quartz stringers retain ghostly discontinuous remnants of carbonaceous partings that are common in certain of the quartzites. Irregular quartz masses are especially common in the axial parts of folds (*see* Fig. 3a) and are comparable to similar quartz bodies found in Idaho (Roberts, 1953). The quartz of the stringers and masses is believed to be not of hydrothermal origin but to be derived from the quartzites themselves during regional metamorphism, and localized along surfaces where composition, texture, and physical conditions were such that recrystallization and perhaps oxidation and removal of graphitic material were favoured. The quartz veinlets are thus believed to be of origin similar to that of the quartz-epidote-chlorite-calcite aggregates in the greenstones, described on page 14.

Thin sections of typical quartzite show it to be a fine-grained rock made up almost entirely of anhedral quartz grains averaging about 0.1 mm in diameter. In many specimens, where the grains are tabular or lenticular, the grains are about 0.07 mm thick and 0.1 to 0.2 mm in the other dimensions. Some specimens are made up of grains up to 0.5 mm across, set in a groundmass of smaller grains. Graphitic films with parallel platelets of white mica, probably marking the bedding, are commonly irregular, following the quartz grain boundaries, but in some specimens the black films are almost straight, separating regular lines of tabular quartz grains. In a few specimens, the vague outlines of original, relatively large clastic grains can be made out, but such grains have been reduced to aggregates of finer crystals. Many grains show strain shadows and boehm lamellae cutting directly or diagonally across elongate grains. Anhedral tourmaline, chlorite, and zircon are found in some specimens, and in others, carbonate makes up 5 per cent or so of the rock. The quartz grains of many of the quartzites show a preferred orientation that is considered in a later chapter dealing with structure.

Dark grey quartzite differs from the common grey quartzite by its higher proportion of black opaque films of graphitic matter and by the fairly common presence in these films of minute knots of radially arranged chloritoid.

In a few places the quartzite appears to have disintegrated into a sand. In the headwall of Faro Gulch a 3-foot section of incoherent grey sandy material with ¼-inch quartz stringers, parallel with the bedding, that stand out as resistant ribs, grades into normal quartzite a few feet along strike. Similar soft material, with the bedding and a thin layer of micaceous phyllite preserved within it, is visible in the Hector mine. The material, in part, crumbles between the fingers to a fine powder but is hard enough in places to spark when struck by a hammer. The soft material is seen under the microscope to consist of quartz grains a little smaller than those of the average quartzite. The grains are unstrained and show irregular sutured outlines. It seems possible that these soft rocks are the result of chemical action, the original quartzite being attacked by solutions circulating in vein openings and working along the intergranular surfaces thus destroying the coherence of the rock.

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Grey to black phyllite, alternating with quartzite within the quartzite members, is described on page 11. It is estimated that the quartzite members consist of about 80 per cent quartzite and 20 per cent black phyllite. Beds of pure quartzite range in thickness from an inch to more than 10 feet, most being about 2 feet. They are commonly separated by partings of phyllite. Individual beds of phyllite within the members range from mere partings to beds several feet thick.

Phyllite and Schist

Phyllite and schist underlie much of the area. Except on the northern slopes of Keno Hill, they are so poorly exposed that individual members cannot be traced and they can be mapped only in a general way. The closely spaced cleavage of most of these foliated rocks displays a high sheen but individual grains of mica or chlorite are not easily picked out, and the rocks are consequently referred to as phyllites. In a small proportion of the light coloured siliceous foliates, muscovite occurs on rather widely spaced cleavages as distinct scales and, in the absence of a more suitable name, the writer refers to them as schists. There are several easily distinguished types of foliates such as grey siliceous phyllite and schist, graphitic phyllite, chloritic phyllite, and chloritoid phyllite. Types intermediate to these are also present.

The most abundant type of phyllite and schist is a pale grey to buff, locally greenish rock with irregular cleavage along which the rock breaks into slabs up to about three quarters of an inch thick. The cleavage surfaces, which are covered by fine-grained mica, almost invariably show a minute corrugation or wrinkle lineation which is discussed in a later chapter on structure. In many places the cleavage is seen to intersect or cut off a banding that is commonly S-shaped, and almost certainly bedding, thus forming 'gleitbrett' structures (*see* Fig. 6). Surfaces other than along cleavages are commonly hard and siliceous, being made up largely of fine-grained quartz and feldspar. In some specimens relatively large (1 mm) equant quartz 'eyes' are scattered through the fine matrix. These may be colourless, bluish, or almost black and are probably original sand grains. Rusty pits or spots are probably from the oxidation of pyrite. Quartz lenses and stringers lying along the cleavages are commonly highly contorted and average perhaps one quarter of an inch in thickness. Knots of quartz up to 2 inches or so across occur in the axial parts of small recumbent folds. In many places, these quartz lenses, stringers, and knots make up 15 to 20 per cent of the total volume of the rock and probably formed in the same manner as the quartz veins in the quartzites mentioned previously. Although the cleavages are typically irregular and rather widely spaced, in places they are smooth, parallel with one another, and close together. With decreasing quartz, the rock grades into a buff, extremely fissile phyllite made up largely of fine-grained white mica.

Under the microscope the siliceous phyllites are seen to consist mainly of mosaics of quartz and less abundant albite (up to 20 per cent), the grains ranging in size from 0.05 to 0.15 mm. Chlorite and white mica lie along the cleavage or trace out elongate folds. The mica of several specimens shows an unusually small optic angle of about 10 degrees. Some specimens, in addition, contain small amounts of fine-grained stilpnomelane. Minute flakes of biotite (?) occur rarely and generally adjacent to grains of magnetite. Occasional grains of apatite, tourmaline, leucoxene, and rounded zircons are present. Carbonate, generally calcite but in some specimens euhedral dolomite, makes up to 10 per cent of some of the foliates. Thin sections of the 'gleitbrett' type (*see* Fig. 6) show the banding to consist of alternate layers of mosaic quartz and crumpled layers rich in white mica, chlorite, and graphitic matter.

Graphitic phyllites are abundant, both as interlayers a few inches thick in the quartzite members described above and as members scores of feet thick. The cleavage surfaces are grey to black, with a sheen due to a very fine-grained white mica and graphitic material, and invariably show fine corrugations. Surfaces not parallel with cleavages are generally light grey and look siliceous. The rock breaks down into folia about one eighth of an inch thick. Types intermediate between black phyllite and grey quartzite are also present. Thin sections of typical graphitic phyllite show it to be largely a mosaic of quartz grains averaging about 0.1 mm across. Certain layers consist of up to 30 per cent of black grains, some equidimensional but many flattened parallel with the foliation. This material is non-magnetic and presumably graphitic. The remainder of the material in the layers is quartz and minor white mica. Other layers are almost devoid of opaque material, and consist of quartz with fine-grained white mica lying along the cleavage.

Green schists containing abundant chlorite are not common and some are not easily distinguished from strongly sheared greenstones. The green schists, however, are commonly thinly banded and are more siliceous than the greenstones. Some contain porphyroblasts of albite and others of carbonate. A thin section of a chlorite schist shows banding, probably bedding, marked by crumpled layers of fine, mosaic quartz and bands of fine-grained magnetite. Scattered crystals of albite, about 1 mm in diameter, that enclose corrugated trains of magnetite and rutile make up some 20 per cent of the rock. The remainder is mainly chlorite and white mica, with minor chloritoid, leucoxene, and stilpnomelane which is associated with the magnetite.

Buff coloured chloritoid phyllite occurs very rarely. A specimen from near the head of McNeill Gulch shows abundant scales of chloritoid about 3 mm across in a fine-grained, weakly foliated rock. In thin sections it is seen to consist of about 60 per cent calcite, about 15 per cent quartz, 5 per cent muscovite, and 20 per cent chloritoid arranged in radiating aggregates that partly enclose contorted and S-shaped films of white opaque material resembling leucoxene.

The mineral assemblages of the phyllites and schists are characteristic of the greenschist metamorphic facies (chlorite-muscovite subfacies) as described by Turner (1948), indicating that metamorphism was of the lowest grade or intensity that is generally recognized. To the east, north of Mayo Lake, the grade of metamorphism is higher, and locally, garnet, staurolite, and sillimanite are developed in schists (L. Green, personal communication).

Limestone

Limestones occur fairly commonly in the southern part of the area and structurally above the main quartzite formation that crosses Galena Hill. They are well exposed along Flat Creek and on the top of Sourdough Hill. Limy bands occur sporadically in quartzites on both Keno and Galena Hills.

The limestones are grey, blue-grey, or buffish grey rocks, and finely crystalline. In several specimens the size of the grain is about 0.2 mm. In general the bedding is well marked by grey bands, probably graphitic, so that folds and other structures are clearly outlined. In some places, 'gleitbrett' structures (*see* Fig. 6) are developed, with bedding segments sharply truncated and standing out conspicuously on weathered surfaces.

Intrusive Rocks

Greenstone

Numerous bodies of dark green rock, referred to by Cockfield (1924) and Stockwell (1926) as greenstone, and by Bostock (1947) as diorite and gabbro, occur throughout the area. Because of its resistance to weathering and erosion, this rock forms most of the outcrops of the map-area.

Most of the greenstones are discontinuous sill-like bodies that occur commonly in the phyllites and schists and are especially abundant along the northern slopes of Keno and Galena Hills. There they tend to congregate along certain zones where they lie like linked sausages, *en échelon,* or one above the other, separated by narrow bands of phyllite. They occur also in the quartzite members, but not abundantly.

Hand specimens of greenstone show a considerable variety of textures, ranging from that of an ordinary gabbro or diorite to that of a foliated rock, the variation being due to the degree of shearing that the rock has undergone. The least sheared varieties, generally from rather thick bodies, show dark green crystals of amphibole up to 3 mm long, set in a greenish grey matrix of plagioclase so highly saussuritized that rarely can the cleavage of the feldspar be recognized. A small greenstone body in Hope Gulch appears to have amygdaloidal texture. A few bodies appear to be porphyritic with phenocrysts of feldspar. Less than 5 per cent of the greenstones are, in part, very dark green to brownish green and somewhat rusty. In such rocks, greenish brown stilpnomelane has developed in addition to the amphibole of the common types.

Most greenstones are sheared and show a strong tendency to split into rather coarse slabs. With increase in shearing, the individual minerals become less easily differentiated, and the rock is a greenish foliated mass in which green amphibole and purplish grey aggregates of zoisite are the only recognizable minerals.

Thin sections of the unsheared greenstone show more or less distinct lath-like or rectangular pseudomorphs of extremely fine-grained zoisite and albite after original plagioclase. These are as much as 2.5 mm in length but average close to 1 mm. The ratio of aggregates of zoisite to clear albite is about 2 to 1, but there is much variation. The arrangement of the pseudomorphs suggests the texture of a fine-grained gabbro. Crystals of hornblende of about the same order of size as the feldspar pseudomorphs are present in only some specimens, and there the characteristic pleochroism is preserved only in the middle parts of the crystals, the outer parts being colourless and having a slightly larger extinction angle ($Z_{\wedge}$ c=16 degrees compared to 14 degrees). These dirty- and corroded-looking crystals are partly replaced by fresh actinolitic amphibole. The replacement is not pseudomorphous, for needles, rods, and stout prisms, all with ragged terminations, seem to cut in all directions across the older hornblende and project irregularly into adjoining zoisite-feldspar masses. In some sections, aggregates of chlorite with only minor actinolite seem to have replaced earlier hornblende. Quartz, or graphic intergrowths of quartz and soda plagioclase form about 3 per cent of some specimens. In most, skeletal crystals of ilmenite (?) altered peripherally to nearly opaque masses of leucoxene make up 2 to 3 per cent of the rock. Prisms of apatite occur in accessory quantities. In several specimens it appears that the ratio of mafic minerals to plagioclase was originally about 3 to 2.

Needles and aggregates of stilpnomelane, identified by its high indices of refraction, peculiar colour, less-than-perfect basal cleavage, and cross cleavage, occur with chlorite, actinolite, zoisite, and albite. P. B. Read (1957) in an investigation of some of the greenstones of Keno Hill made a particular study of the mineral stilpnomelane. It ranges in composition between two end members, ferro-stilpnomelane (rich in Fe, Mg, MnO) and stilpnomelane (rich in $(Fe, Al)_2O_3$). In Read's table below of the optical properties of stilpnomelane from Keno Hill, the proportion of $(Fe, Al)_2O_3$ increases to the right.

Nz=nearly Ny	1.680@	1.685@	1.692#	1.725@	1.759#
Nx			1.599#		1.640#
Nz—Nx			.093		.110
2V	between 9½° and 15°				9° to 12°
Pleochroism					
z=y	Olive-brown to deep brown, dark brown, almost opaque				
x	Light brown to golden brown, golden to red-brown				

accurate to 0.002 @ approximate

With shearing, the mineral assemblages described above persist but the rocks take on a crude foliation. Actinolitic amphibole, aggregates of zoisite and albite, and leucoxene become elongate and finally form distinct lenses and bands. Some of the surviving older hornblende has been bent, twisted, and pulled out in the foliation and many of the newer actinolitic amphibole crystals lie with their long axes in the plane of the foliation. Some sheared varieties are speckled with small carbonate crystals.

The most common mineral assemblages are: zoisite-albite-actinolite-chlorite and zoisite-albite-actinolite-chlorite-stilpnomelane. These assemblages are commonly developed in basic rocks subjected to the lowest grade of regional metamorphism and fall into the muscovite-chlorite subfacies of the greenschist facies (Turner, 1948).

In some places the greenstones contain veinlets or pockets, generally only a few inches in longest dimension, composed of quartz and epidote, or quartz and chlorite. Calcite is commonly associated. The quartz may be in the form of crystals as much as an inch through, and the epidote occurs as aggregates of acicular crystals up to 2 inches long. Dark green chlorite is fine grained and unsheared, forming elongate, sinuous, accordion-like 'books'. These mineral aggregates have probably been formed by a process of metamorphic differentiation, the materials forming them having been extracted from the enclosing greenstones during regional metamorphism. They may thus be considered analogous to the much more abundant quartz veinlets of the quartzites and schists.

Internally, the greenstones show little structure. Thin greenstone bodies are generally more sheared than thick ones. The foliation of some of the bodies is folded but generally the folds are rather obscure and cannot be traced for any great distance. No sign of original layering was seen.

Some of the greenstones are sill-like, maintaining a nearly constant thickness for considerable distances. The greenstones of the upper part of Porcupine Creek on Galena Hill and those in McMillan Gulch, south of Keno Hill, are sills. In many places along the north slope of Keno Hill, the greenstones are seen to be lenticular or elliptical in surface exposure. In other places, the distribution of float indicates that the greenstones are markedly discontinuous and thus not sill-like, as for example just west of the summit of Keno Hill.

Some of the lenticular bodies have sharp ends (*see* Pl. II B) like the prows of ships, the phyllites and schists opening around them, but a few have blunt ends and the enclosing rocks are irregularly squeezed and folded. The contacts along the sides of the lenses, nearly everywhere conformable, are commonly shear zones. In a few places the contact is between little sheared greenstone and relatively unaltered argillite in which graded bedding can be observed.

The greenstone bodies range in dimensions from a lens 20 feet long by 3 feet thick to the lens (?) on Beauvette Hill at the eastern end of Keno Hill which is 4,000 feet long by 100 feet thick. On the north slope of Keno Hill many apparently lenticular bodies are nearly 1,000 feet long and 20 to 40 feet thick. There the ratio of length to thickness seems to range from about 40:1 to 5:1.

Although it seems certain that many of the greenstone bodies are elliptical or lenticular in sections parallel with the strike, there is much less certainty about their nature downdip. Are they true lenses extending down the dip only a short distance, or do they extend more or less indefinitely down the dip as flattened pipes? Several facts favour the former hypothesis. The greenstones of the few downdip sections seen at Hope Creek for example, seem to be no more elongate than those of sections parallel with the strike. The greenstone at Minto Hill, near the summit of Keno Hill, if projected to the south with the average dip of this region should pass under the phyllites to the south. It apparently does not do so and thus appears to thin downdip. A greenstone body mapped in detail east of the Lucky Queen mine (*see* Fig. 2) seems not to extend downdip. The evidence

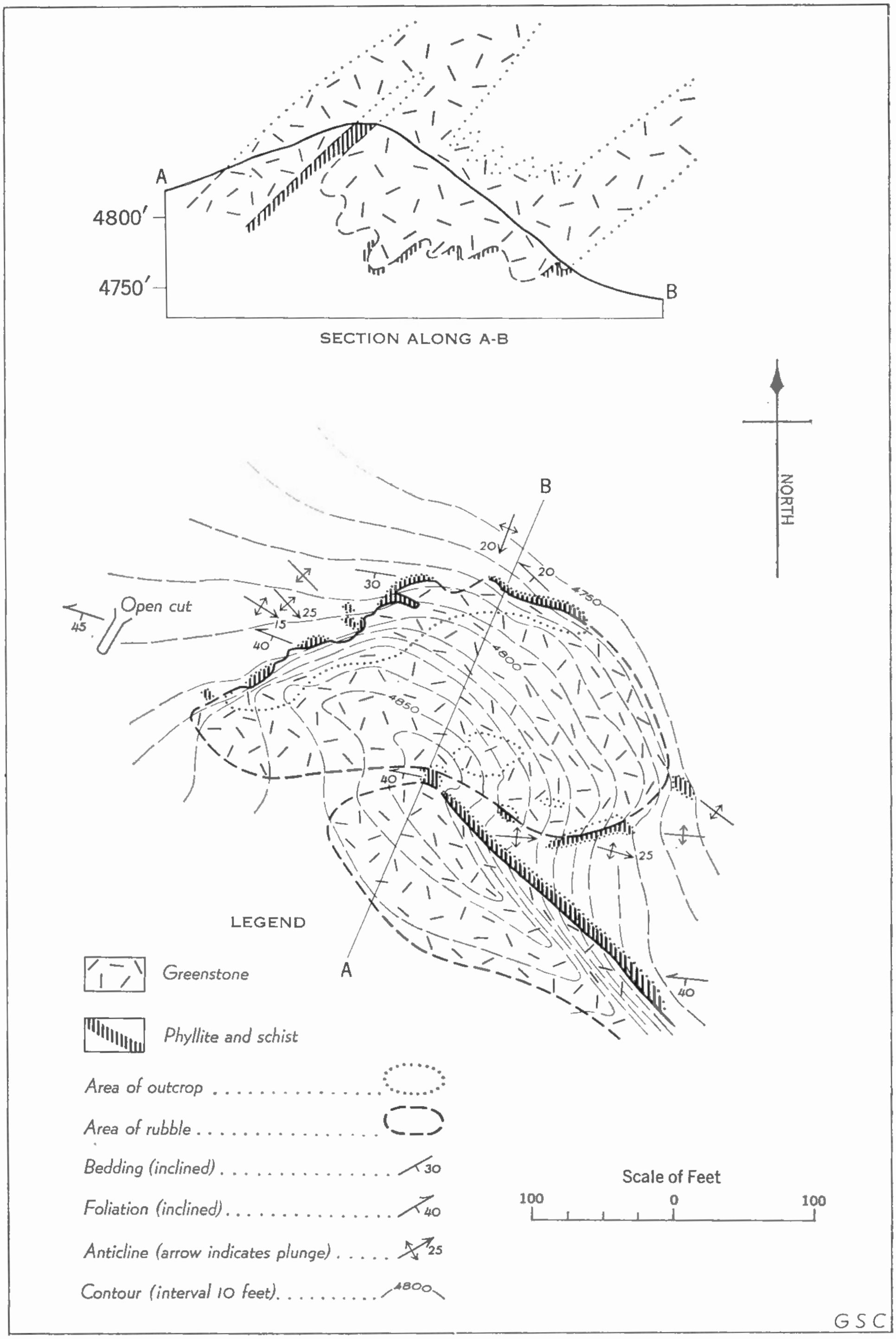

Figure 2. **Plan and projected section of a small greenstone body 4,000 feet east of the main Lucky Queen shaft. In plan the greenstone is nearly surrounded by phyllite and schist but the section suggests that it is the axial part of a syncline. In preparing the section, data were projected along lines plunging 10°SE.**

indicates that many of the greenstone bodies are lenticular in strike sections and that some at least, and perhaps many, are lenticular in all directions.

Cockfield (1924) regarded the greenstones as sills and laccoliths, Stockwell (1926) called them intrusive, and Bostock (1947) thought them to be flattened pipes. The relict igneous texture and the composition leave little doubt that they are igneous, and there is little evidence that they are lava flows. A doubtful occurrence of amygdaloidal texture and the possible pipe-like form of some of the bodies support the idea, but the dearth of fragmental or other volcanic textures, and the absence of recognizable volcanic debris in the overlying sedimentary rocks seem sufficient to condemn it.

Conceivably the discontinuous greenstone bodies are laccoliths, but although parts of the bases of a good many were seen, no feeders were found. Perhaps shearing has separated feeders from the main bodies. Intrusion in the form of phaccoliths or lenticular pipes is another possibility. Presumably such bodies would be emplaced along the bedding under special conditions of stress and load. It seems unlikely, however, that such special conditions could obtain through a thickness of some thousands of feet of strata.

Cockfield (1921) believed that certain of the greenstones at the summit of Keno Hill were cut off by transverse faults. R. W. Boyle (personal communication) has shown that certain discontinuous greenstones on Sourdough Hill are faulted segments of a single sill-like body whose thickness is markedly different in different places. Other greenstone bodies, such as those at the Stone showings, the Croesus No. 1 showings, and the Lucky Queen workings in Gambler Gulch, seem to terminate at faults. Faults of this type, however, would scarcely account for the prow-like or rounded terminations of most of the discontinuous bodies.

It is conceivable that the lenticular greenstone bodies are large boudins formed (Ramberg, 1955) by compression normal to a series of interbedded competent greenstone sills and incompetent phyllite beds. The resulting extension in the plane of the bedding might possibly disrupt the continuous greenstone layers into rectangular or polygonal, cake-like masses, some with tapering edges others ending abruptly. Boudins of this type have been produced in the laboratory by Ramberg using appropriate model materials and simple compression. This hypothesis will account for certain of the lenticular bodies but cannot alone account for tremendously thick and isolated greenstone bodies that occur throughout the area. Some of these are separated by thousands of feet along strike from the nearest possible mass from which they could have been detached.

The lenticular shape of several greenstone bodies is believed to be due to the partial preservation of the synclinal parts or to the partial exposure of the anticlinal parts of folded greenstone layers (*see* Fig. 2). This explanation could only apply in rare instances, however, for it requires a special combination of structural and topographic features.

Faults closely parallel with the bedding may slice a gently or highly folded bed or sill into lenticular segments. An example of one effect of this sort of mechanism, illustrated in Plate III, shows a gently folded quartzite bed that has

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Plate III. *Illustration of a thin band of quartzite that has been sliced into segments by an undulating fault. Some of the greenstone lenses may owe their forms to similar faults. (In this illustration, the lower contact of the quartzite lenses is a bedding plane and the upper is a fault.)*

been sliced across by an undulating fault that lies nearly parallel with the folded beds. Continued faulting of this type, involving both gently and complexly folded greenstone layers, might distribute segments of the same greenstone sill over a wide area.

The writer believes that several of the mechanisms outlined above worked in combination to produce the lenticular greenstone bodies. Intense folding and later preservation from erosion of the axial parts of the folds, locally strong compression and plastic flow with development of boudins, and slicing by thrust faults lying close to the axial planes of the earlier folds all contributed to their formation.

Lamprophyre

Lamprophyre sills as much as 5 feet thick are found in a few places, mainly on the north and east slopes of Galena Hill. Where unaltered they are brown, biotite-rich rocks with flakes of mica as much as 3 mm across set in a fine-grained groundmass. Like many other lamprophyres, they contain abundant inclusions which in these sills are rounded fragments of quartz up to an inch across. The rocks are mostly altered and grey to buff, the biotite being bleached so that it resembles muscovite and the rock impregnated with carbonate.

Thin sections of relatively unaltered specimens show them to be made up of euhedral biotite and augite set in a groundmass of quartz and orthoclase or quartz and microcline, commonly in micrographic or myrmekitic intergrowths. Colourless amphibole forms reaction rims around the augite crystals and radiating aggregates of it surround quartz xenoliths. Biotite is somewhat bleached. Irregular epidote aggregates may have been derived from plagioclase but the latter was not identified with certainty. Carbonate and pyrite replace the primary minerals.

Thin sections of highly altered specimens show the biotite to be altered to colourless mica and chlorite and the rest of the rock largely to be replaced by carbonate.

Rhyolite

Sills of rhyolite occur on both Keno and Galena Hills. The rock is grey to buff, rather fine grained, and locally contains phenocrysts of quartz, plagioclase, and rarely mica. In other places it is non-porphyritic.

Thin sections show the rock to be composed essentially of quartz and albite (An_4 or more sodic), the grains averaging about 0.2 mm in size. Phenocrysts of quartz as much as 2 mm across show rounded outlines, embayments, and inclusions of groundmass material. The plagioclase phenocrysts are unzoned. They are a little smaller than the quartz grains and tend to clump together in aggregates. What appear to be original biotite flakes are largely altered to chlorite. The groundmass is largely of albite and quartz, partly obscured by abundant secondary white mica, carbonate, and in some specimens, a little epidote. Potassium feldspar was not identified although small amounts may occur in the groundmass. The rock might be called a soda rhyolite or quartz keratophyre.

The rhyolite is unsheared but locally strongly and complexly jointed. Bodies of rhyolite are sill-like, ranging in thickness from about 5 feet to at least 60 feet. Several have been traced for more than 1,000 feet, and one may extend from a point near the Silver King mine to the ridge of Galena Hill, a distance of more than 5 miles.

The rhyolite bodies are conformable and sill-like where their contacts can be seen. Certain of them, however, appear to cut very gradually across the enclosing strata. In Silver Basin Gulch a rhyolite body lies at the contact between quartzite and overlying schist. Farther east it crosses the quartzite and, traced by float and outcrops to beyond Faith Creek, is finally exposed in the lower part of a schist member that underlies the quartzite. It is possible that the rhyolite steps down at intervals, that it lies along a low-angle fault, or that the boundaries between quartzite and schist themselves are low-angle faults.

The rhyolites are younger than the phyllites, quartzites, and greenstones and are possibly of about the same age as the lamprophyres. They are cut by veins and mineralized. Prospectors report that interesting gold assays have been obtained from ordinary looking rhyolite at several places.

STRUCTURAL GEOLOGY

The structural geology of the Keno Hill district appears, on first inspection, to be relatively simple, and was so regarded by the early workers. In recent years, however, as the extreme scarcity of outcrops was partly compensated for by prospect openings and mine workings and detailed maps were made, it became apparent that the structure was less simple than had been thought (*see*, for example, Smitheringale, 1950, p. 44). The various structural elements mapped in the area are described in the following sections.

Small Scale Folds

It is believed that the oldest structures are folds, most of which are overturned or recumbent. These are developed in all rocks of the area and are particularly conspicuous in the quartzites and limestones. Most of them are apparently small, a complete fold being shown in cross-section on an exposure of only 3 or 4 square feet. Some, however, are large, and isoclinal folds that can be traced for 30 feet or more from crest along the limbs are visible in a few places. Various types of folds are illustrated in Figure 3.

In many examples (*see* Fig. 3a), the synclinal parts of fold assemblages are missing, so that anticlines are stacked one on another with gently dipping faults between, and stratigraphic correlation is impossible from fold to fold.

The axial planes of the overturned folds are parallel, in general, with the prevailing southerly and southwesterly dipping beds and foliation, and the fold axes, of course, lie in these planes.

The orientations of the axes of overturned and recumbent folds are shown in Figures 4a and 5a. The axes of the 'chevron'-type folds (*see* Fig. 3d), which are believed to be younger than the overturned types, are not plotted on these diagrams. The axes show a fairly wide variation in attitude, but on Galena Hill (*see* Fig. 4a) they show a maximum at about due east which plunges about 5°E. On Keno Hill (*see* Fig. 5a) a clear maximum is shown at S60°W plunging at 20°SW. It is believed that there is a gradual swing rather than an abrupt change in the direction of the fold axes from the maximum on Galena Hill to the maximum on Keno Hill. The wide variation in the direction of individual axes is believed to be due to several episodes of movement in slightly different directions.

The geometric relations of most of the overturned folds indicate that the higher beds were moved northerly or northwesterly over the lower beds.

Because of the scarcity of outcrops and marker beds and because shearing accompanying or later than the folding has largely obscured the axial parts of folds, it is extremely difficult to trace out folds larger than single outcrops. The question of large overturned folds is considered in a later section.

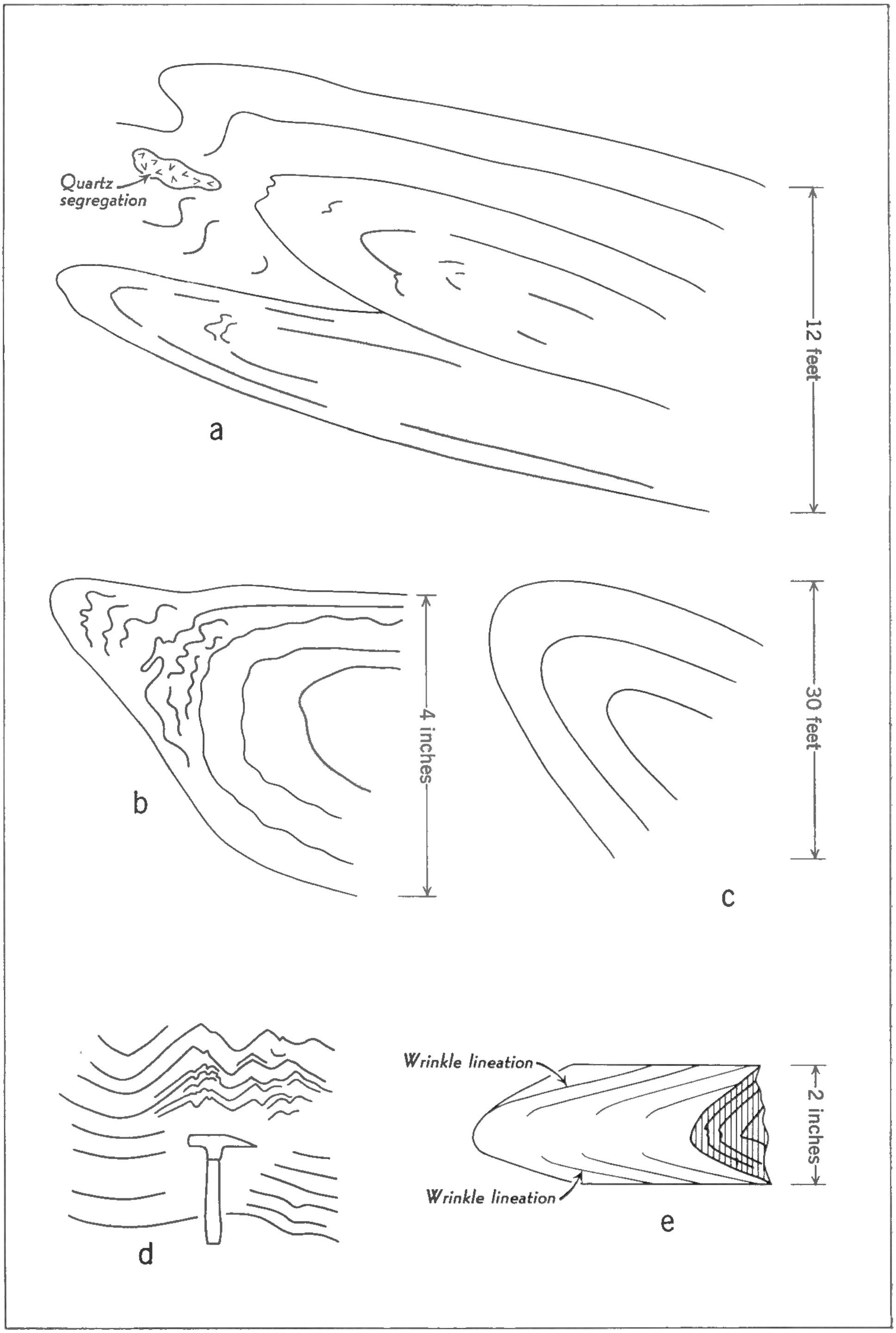

Figure 3. Small scale folds, Keno Hill and vicinity. a, nose between forks of Porcupine Creek, Galena Hill; b, north slope of Keno Hill; c, under road bridge, Silver King mine, Galena Hill; d, Sourdough Hill; e, Elsa mine.

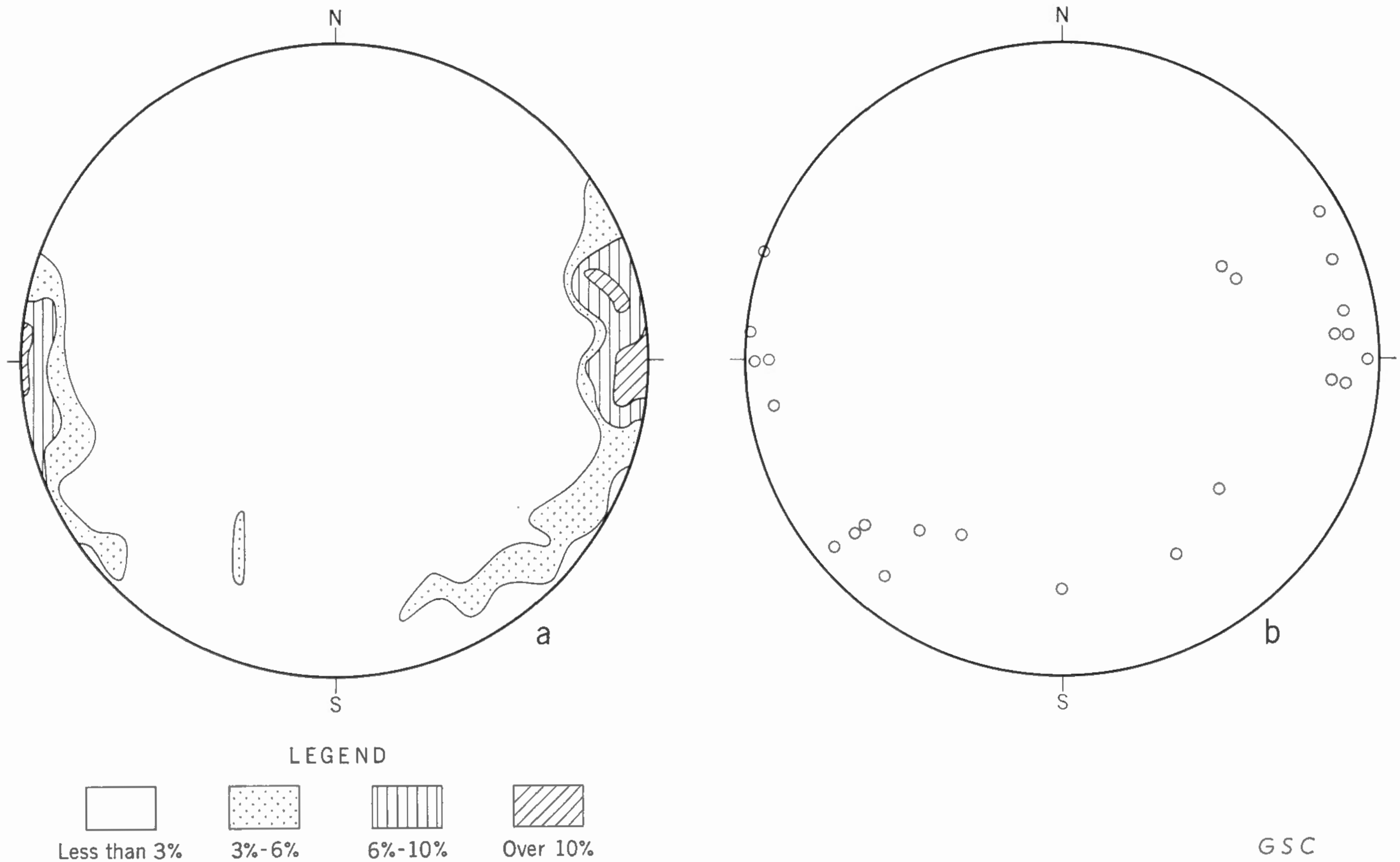

Figure 4. Galena Hill; a, 71 fold axes, plotted on a Schmidt net and contoured. Contours 10, 6, and 3% per 1% area. A concentration of axes strikes a little north of east and plunges about 5°E. b, 24 axes of intersection of bedding and cleavage in 'gleitbrett' structures plotted on a Schmidt net. The distribution of these few axes is similar to that of the fold axes in (a).

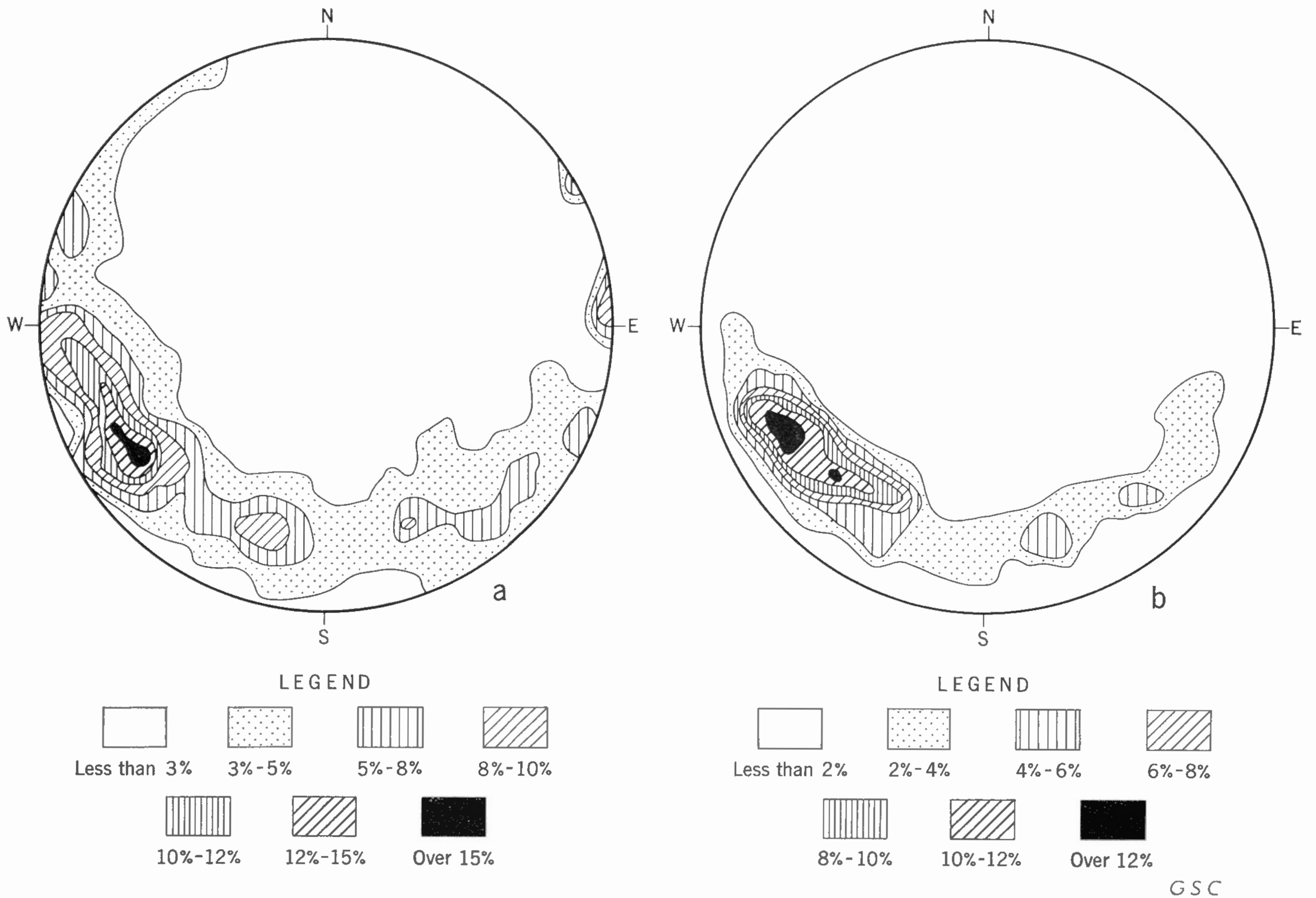

Figure 5. Keno Hill; a, 135 axes of overturned and recumbent folds plotted on a Schmidt net and contoured. Contours 15, 12, 10, 8, 5 and 3% per 1% area. A concentration of axes strikes about S60°W and plunges 20°SW. b, 150 axes of intersection of bedding and cleavage in 'gleitbrett' structures plotted on a Schmidt net and contoured. Contours 12, 10, 8, 6, 4, and 2% per 1% area. A maximum at S60°W, plunges at 20°SW. Compare with (a).

Foliation

All of the rocks except the late dykes and sills show a foliation or cleavage that strikes west or northwest and dips south or southwest. In the quartzite formations it is best developed in the graphitic phyllite interbeds but it is also seen in the quartzite itself as parting surfaces with scattered mica flakes. Most of the greenstones show some degree of foliation. In a few places the schists show two cleavages that almost coincide.

In the quartzite members the foliation appears in nearly all exposures to be parallel with the original bedding, the bedding being marked by the interlayering of quartzite and graphitic phyllite. At a few localities the foliation was seen to intersect the direction of bedding of the quartzite at high angles, and in most large exposures of phyllite and schist (e.g., the headwall of Silver Basin) this relation was seen to be the usual one. Structural relations observed in such places are illustrated in Figure 6c, d, and e and have been described elsewhere and referred to as 'gleitbrett' structures (Knopf and Ingerson, 1938, pp. 157-158) or 'totfalten' (Fairbairn, 1949). The first of these authors writes as follows:

> Schmidt has emphasized the importance of rock deformation of what he calls 'Gleitbrett', or sliding board folds. The principle of 'Gleitbrett' folding is that the displacement is distributed through certain layers in the moving mass that are particularly susceptible to differential displacement, in contrast to other layers that are relatively inert. The relatively inert 'boards' shown by the stippled sections in Figure 44 [here simplified as Figure 6a and b] move forward as a whole upon the sliding planes of the more mobile layers...... Schmidt found evidence for this mechanism in the long drawnout recumbent folds and extended transport of the East Alpine decken tectonics.

The 'gleitbrett' cleavage differs, apparently, from ordinary cleavage in its rather wide spacing and in the relatively great movement that takes place along it. Its relation to earlier-formed folds may be irregular or haphazard but where it corresponds to the axial planes of the folds, as it seems to do here, the axes formed by intersections of bedding and cleavage have their usual significance of being parallel with the fold axes. The directions of the axes of intersection of bedding and cleavage (Fig. 6c, 6d, lines X-Y) were measured and these are shown in Figures 4b and 5b. The positions of the maxima are closely similar to the maxima of fold axes in Figures 4a and 5a.

It is believed that where the foliation cuts across the bedding as just described, the bedding before shearing was inclined to the shear direction, and that the effect of the shearing was simply to cut the bedding into segments and deform by drag the ends of the segments, rather than to rotate the bedding so as to produce the present attitudes. Thus, where these structures are developed, the attitude of the bedding in the rocks differed from that of the developing foliation and it is suggested that these structures are developed most strongly in the axial parts of folds, as illustrated diagrammatically in Figure 7. As the amount of deformation increases, zones of foliation may grade into the low-angle fault zones described on page 29.

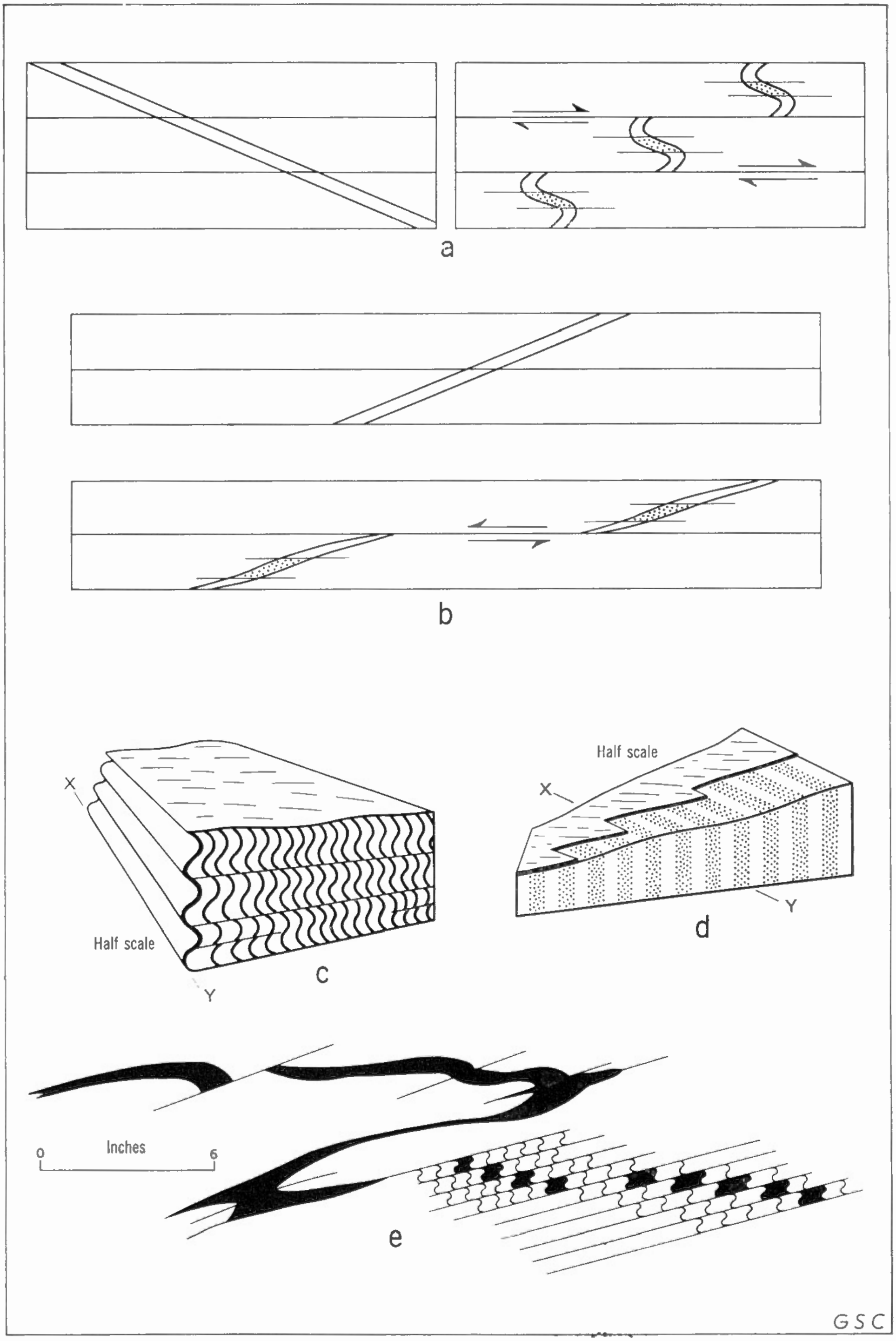

Figure 6. 'Gleitbrett' structures, a and b are hypothetical examples after Knopf and Ingerson (1938, p. 158) in each of which a single bed has been sliced into segments along closely spaced fractures. In each, the stippled part has moved forward as a whole without permanent deformation. c, d and e are examples of similar structures from Keno Hill. The bedding in c and e is shown by graphitic layers and in d by quartz-rich layers. c and d show wrinkle lineation on micaceous surfaces and the intersection of bedding and cleavage is shown by line X-Y.

Quartzite Fabrics

A crude lineation is developed on foliation and bedding planes of the quartzite. It consists of discontinuous troughs and ridges, 2 or 3 mm across, in the quartzite itself and little resembles the lineation in the phyllites described below. The direction of this quartzite lineation, not recorded as commonly as might be wished, is about west on Galena Hill and apparently a little north of west on Keno Hill.

During the intense deformation of quartzites, their fabrics are commonly altered radically, and the c-axes of quartz grains, originally oriented at random, assume a regular orientation that may show a definite relation to large structures such as folds, faults, and so on. With this in mind, the writer made several petrofabric analyses of the quartzites. The results show much variation. Some specimens from areas where deformation was believed to have been intense, show only random fabrics. Others, however, (Fig. 8a and b) show patterns more or less symmetrical around axes that lie in the foliation and such axes are generally thought to be normal to the direction of movement. Figure 8c shows the orientation of the axes of a number of these patterns. They strike, on the average, a little north of west. Plunges are to both east and west and it is thought that the degree

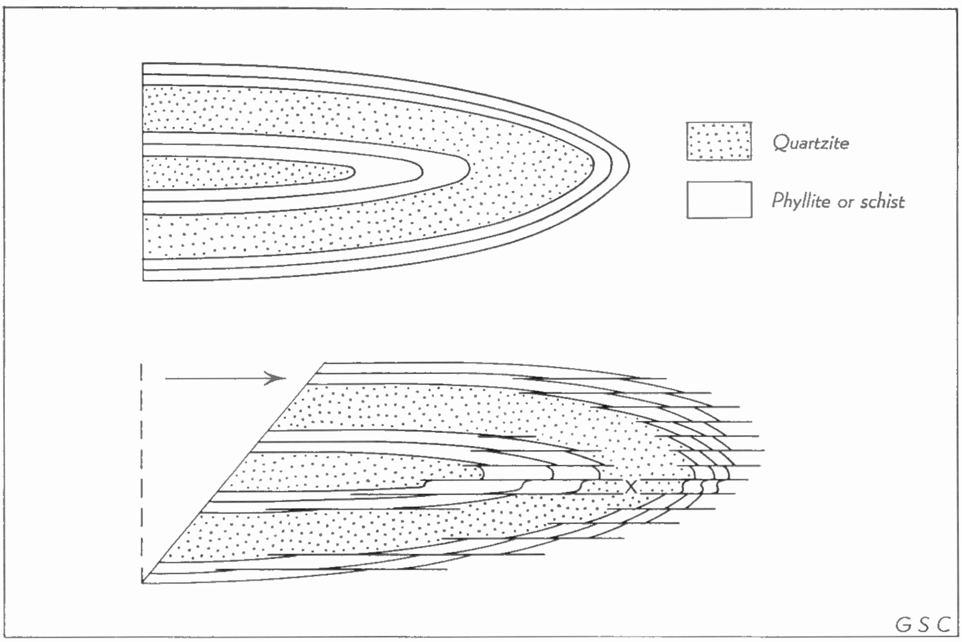

Figure 7. Diagram showing hypothetical development of 'gleitbrett' structure in the axial part of a fold. An isoclinal fold has been further deformed with the development of foliation parallel to the limbs of the fold. The foliation planes or shears are evenly spaced and each overlying layer has been advanced the same distance with respect to the layer beneath. 'Drag' at the sliding surfaces may produce S-shaped segments as in the layer marked X (cf. Figure 6).

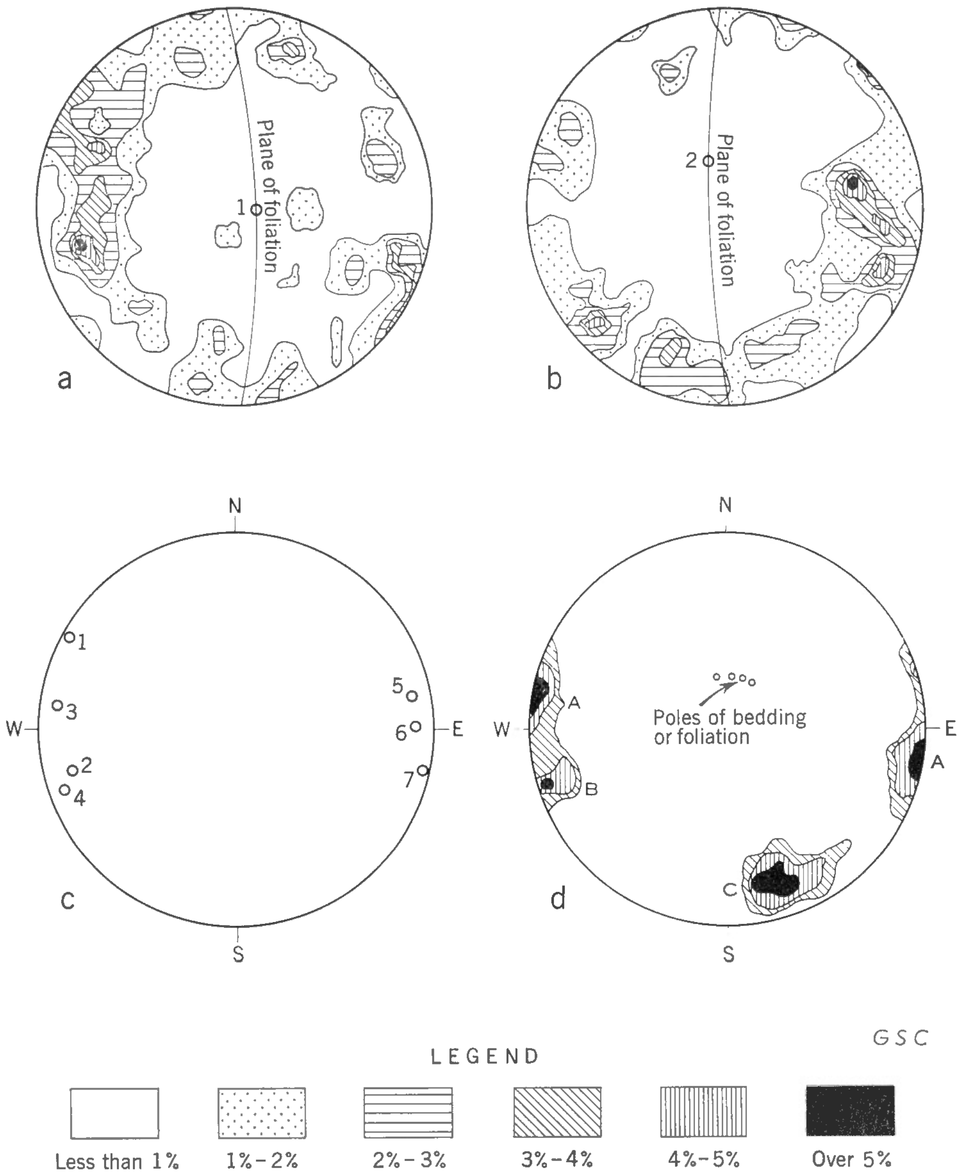

Figure 8. Petrofabric diagrams of quartzite and frequency diagram showing attitudes of joints. All data plotted on lower hemisphere.

a. Quartzite, head of Faro Gulch, Keno Hill. 200 grains. Contours 5, 4, 3, 2 and 1% per 1% area.

b. Quartzite, Elsa mine, Galena Hill. 200 grains. Contours as above.

c. Stereoplot of numbered axes in (a) and (b) and in five similar diagrams, showing their true orientations. Axis 3, Porcupine Creek, Galena Hill; axis 4, between Faro Gulch and Silver Basin, Keno Hill; axis 5, No Cash mine, Galena Hill; axis 6, Elsa mine, Galena Hill; axis 7, Duncan Creek, south of Galena Hill.

d. Poles of 414 joints in quartzite and greenstone, Keno and Galena Hills, contours 5, 4 and 3% per 1% area. Bedding joints not counted, but indicated near the middle of the diagram.

of plunge is not very significant and not very different from the error made in orienting the specimens. The axes seem to be about parallel with the lineations described in the previous paragraph.

Wrinkle Lineation

Almost every specimen of phyllite or schist shows a lineation consisting of minute wrinkles or corrugations on the foliation. They are found on successive layers and most commonly maintain parallelism from layer to layer, though in some specimens the direction ranges through wide angles. Some specimens show two or even three directions of lineation on the same surface. Most wrinkles have an amplitude of about 0.02 to 0.1 mm and a wave-length of 0.15 to 1.0 mm. Chevron-type folds (Fig. 3d) with amplitudes up to 6 inches are not common, but their axes seem invariably to lie parallel with the southeasterly wrinkle lineation and they are believed to be contemporary.

In thin sections cut perpendicular to the wrinkles they are seen to be restricted largely to micaceous or graphitic layers lying between quartzose layers. Although most wrinkles, or micro-folds, are seen in thin section to be symmetrical, some are overturned, resembling drag-folds. In the few oriented sections studied, a consistent direction of drag could not be established. The directions of lineations are shown in Figure 9. Maxima are obvious at S33°E (plunge about 20°SE) for Galena Hill and S46°E (plunge about 22°SE) for Keno Hill.

Some specimens show two lineations and in several it was possible to establish fairly conclusively that a lineation at about N75°E is later than and superimposed on the lineation trending southeast.

Even allowing for the fact that azimuths of fold axes and lineations are measured rather rapidly and in a horizontal plane (i.e., projection of plunge), it is clear that their maxima are not at right-angles and this is believed to be significant. This relation is especially clear for data from Galena Hill (Figs. 4a and 9a), where the true angle between them is about 60 degrees. However, it is noted that weak or secondary fold maxima trending northwest are close to the wrinkle lineation maxima.

The main wrinkle lineation seems to have been produced after the movements that resulted in the development of the overturned folds. In a few places parallel lineations have been found on both limbs of isoclinal folds. This lineation is at about 60 degrees to the fold axis (Fig. 3e), which shows that the lineation has not been folded. The lineation seems to be contemporaneous with or later than the development of the 'gleitbrett' structure (*see* Fig. 6c and d). The lineation is earlier than the principal movement on the vein faults for the vein breccias contain abundant fragments of lineated phyllite.

Broad Open Folds

Keno and Galena Hills (*see* Fig. 1) lie along the irregular western flank of a great southeasterly plunging anticline, the Mayo Lake anticline, mapped by Bostock (1947) and Green (1957). The axis of the fold trends southeast and

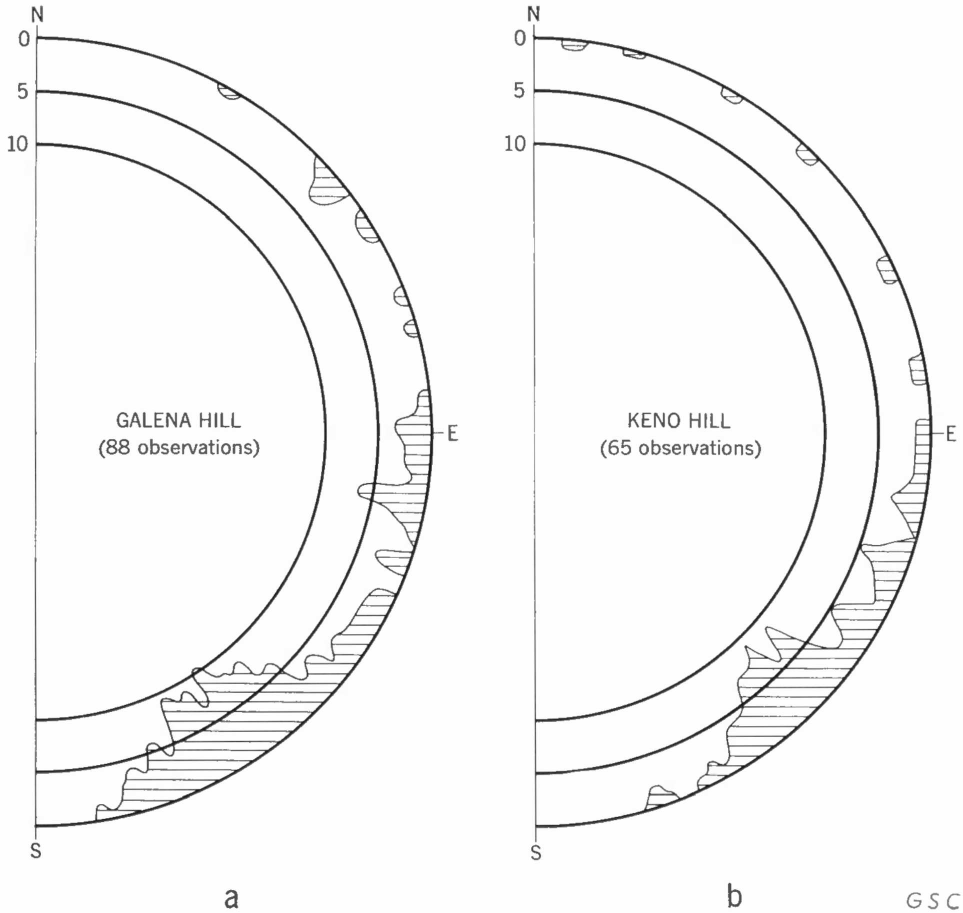

Figure 9. Frequency diagrams of the directions of wrinkle lineations, Galena and Keno Hills. The graduations 0, 5, and 10 refer to the number of observations within a four-degree sector.

apparently two subsidiary anticlines, the McQuesten and Lynx Creek anticlines, extend westward from the main fold. Keno and Galena Hills are on the south limb of the McQuesten anticline.

Attitudes on either side of Christal Creek suggest a weak cross flexure at Christal Creek, but attitudes west of the creek, on Galena Hill, are neither reliable, because of slumping, nor numerous.

Faults

There are at least three groups of faults: faults lying close to or along the bedding (i.e., low-angle faults, dipping, generally less than 45 degrees); vein-faults (steeply dipping, mostly trending north, northeast, or east); and northwest-trending, apparently steeply dipping, faults. In addition to these clearly defined groups, there are many faults that cannot be easily included in any of these. Most exposures of faults of the second and third groups are visible only in mine openings.

Most low-angle faults strike easterly and dip at low angles to the south. In the quartzite formations, most faults of this class lie along beds of phyllite and it is rare to find a bed of phyllite more than a few inches thick along which there is no sign of movement. Drag-folds are commonly associated with the faults and these suggest that the higher beds moved, in general, to the north over the lower beds. In thick layers of phyllite in the quartzites the low-angle fault zones are complex, generally including disconnected and twisted fragments of quartzite, incomplete folds and subsidiary shears, and related joints running in all directions. In formations of phyllite and schist low-angle faults are especially common. The combined effects of shearing, faulting, and folding is to destroy the stratigraphic continuity of beds, and though large areas of such rocks were mapped in detail in the headwall of Silver Basin Gulch, it was generally found impossible to trace distinctive but thin units for any distance. As has been suggested above, certain greenstone sills may have been sliced into lenticular segments during low-angle faulting of this type.

It is probable that many of the main contacts are low-angle faults rather than stratigraphic contacts. For example, if the lower contact of the main quartzite that cuts across the south part of Keno Hill is projected east from a point near the road at Erickson Gulch (Christal Pup), using the attitudes available in the vicinity, its theoretical course lies a considerable distance north of the actual course eastward on the flank of Keno Hill. Certain units that immediately underlie this quartzite seem to vary in thickness or to disappear at different points along the contact. These features may be more apparent than real, for outcrops are scarce at critical points but because of the prevalence of low-angle movement in the area, the writer feels that there has probably been considerable movement along this and other contacts where competent quartzites overlie yielding phyllites and schists.

The strikes of the main vein faults are shown in Figure 10. Almost all strike between north and east, and show a fairly symmetrical distribution around N45°E. Cockfield (1921 and 1924) suggested, largely on the basis of what he had seen at the original claims at the top of Keno Hill, that the veins could be classified according to attitude, and that there were two sets of veins, one striking a little east of north ('transverse veins') and the other a little north of east ('longitudinal veins'). Although this distinction may be made in a few places, generally it seems not to be applicable.

Most of the vein faults dip southeast at 45 to 85 degrees but a few, such as some of the shorter vein segments in the Elsa mine, dip northwest.

Movement on many of the simple northeasterly striking vein faults has been such that the southeast wall, or hanging-wall, shows an apparent offset to the northeast (for example, the veins of the U. N. claim, Keno group, Lucky Queen mine, and Gold Hill claims). Of eleven sets of slickensides measured on the walls of what appear to be uncomplicated vein faults, eight of them pitch between 30°

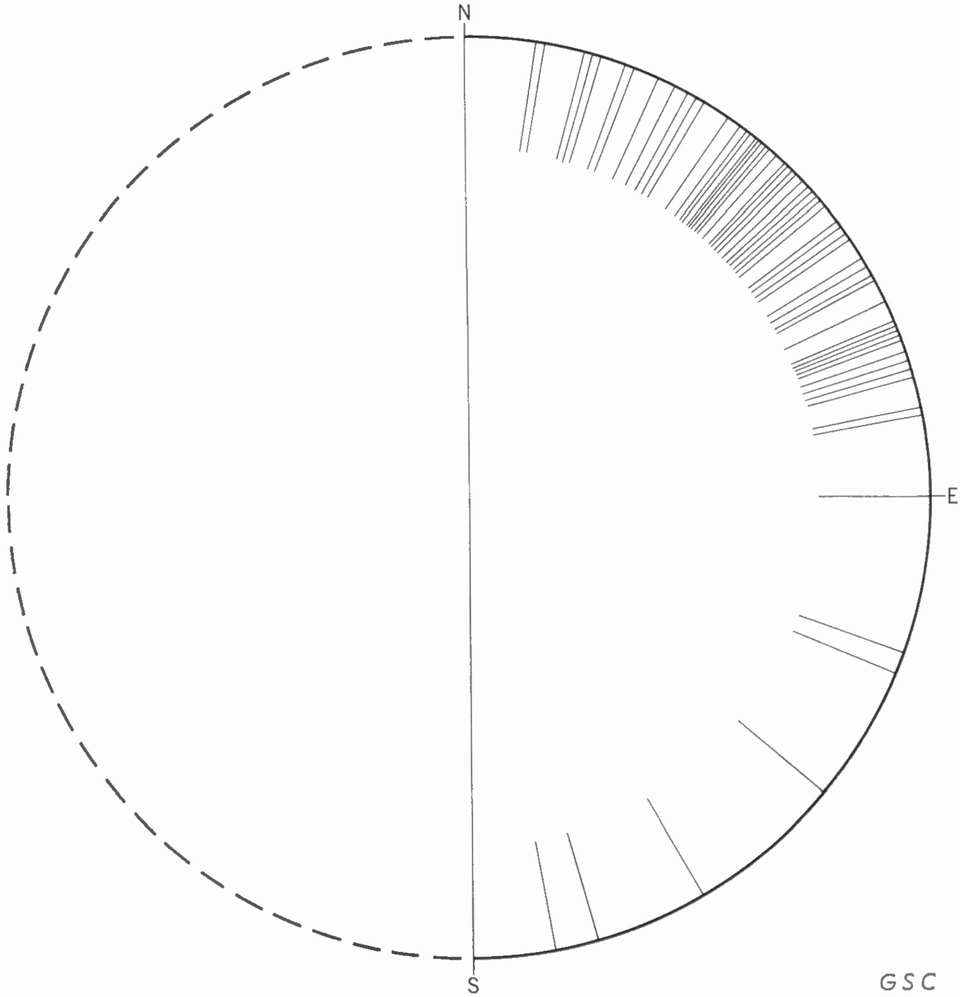

Figure 10. Diagram showing the strikes of fifty-nine veins, Keno and Galena Hills. Elsa and Hector mines veins omitted. There is some generalization in the northeast quadrant to avoid duplication of lines.

and 70°NE, suggesting that movement of the hanging-wall was, in general, relatively downwards towards the northeast. In the more complex vein systems as at the Elsa mine, such generalizations probably break down although it may be possible to regard the vein patterns as composed of one or more principal faults with related subsidiary fractures.

Movement has been relatively small on many of the vein faults, probably not exceeding a few hundred feet, and on some, only a few feet or tens of feet. Some of the veins, however, do not cross recognizable contacts, so the apparent horizontal offset is unknown. Apparent displacement on the Lucky Queen vein may exceed 2,000 feet.

Post-mineralization faulting along the veins is extremely common and to the mine operator is a troublesome feature. The effect has been to brecciate and mechanically weaken the vein material making extraction difficult, and to offset and hide slices of the vein filling.

Because of deep overburden and because exploration has stopped near or at the ends of ore shoots at many of the properties, it is difficult to be certain whether one vein is the continuation of another or is entirely separate. Those on which displacement has been some hundreds or even thousands of feet must, it would seem, persist for several times those distances, provided they continue on the same strike. In some places (Fox fraction, Ladue fraction, Elsa mine) vein faults of appreciable offset stop at contacts, possibly changing attitude and joining bedding faults. Alternatively, late adjustment on bedding faults may have offset the vein faults.

Northwest-striking faults of moderate to steep dip commonly offset the vein faults. They are common in mine workings and two such faults have been mapped on the surface. Relative movement along these faults is such that the southwest side is moved northwest. A fault of this type, lying west of the Elsa mine, crosses Brefalt Creek and shows an apparent offset on the surface of some 3,000 feet. Another was observed east of Mount Hinton, south of Keno Hill, but there the bedding is nearly parallel with the fault, and the displacement could not be estimated.

Joints

Quartzite and greenstone are well jointed, so well that some of the rubble areas near the top of Galena Hill consist largely of diamond-shaped slabs of quartzite. The attitudes of joints were recorded in many places and the results are plotted in Figure 8d.

One prominent set (marked A in Fig. 8d) strikes a little east of north and dips vertically. Joints (marked B in Fig. 8d) striking somewhat west of north should perhaps be included in this set. A second well-defined set (point C in Fig. 8d) strikes N72°E, and dips 70°N.

Structural History

The earliest formed structures are believed to be the overturned and recumbent folds produced during intense overthrusting towards the north and northwest normal to the fold axis maxima (*see* Figs. 4a and 5a). The rocks were probably metamorphosed to their present low rank at this time. During this folding they behaved plastically and possibly greenstone boudins were developed. It is probable that large-scale overturned folds were formed during this episode and the evidence for these is considered on page 33.

Subsequent shearing and thrusting directed towards the north followed with the development of the foliation and of the present quartzite fabrics. The direction of shearing may have differed from that of the folding, for the fold axes suggest northerly and northwesterly movement whereas the quartzite fabrics suggest northerly movement. During this later shearing, the early folds were sheared out, producing the 'gleitbrett' structures, and new drag-folds were produced, somewhat obscuring the earlier trends. During the shearing, folded greenstone layers were possibly sliced into lenticular bodies and these displaced. The low-angle bedding plane faults probably date from this time.

The next recognized deformation is the folding of the already complexly folded and faulted region along a southeast-plunging axis to form the Mayo Lake anticline. The development of the southeast-trending wrinkle lineation is probably related to this folding, the arching of the great thickness of sediments causing bedding-plane slippage that was concentrated in the phyllitic beds. Perhaps late in this folding the subsidiary Lynx Creek and McQuesten River anticlines were formed, and these are possibly contemporaneous with the second and younger wrinkle lineation (*see* p. 27).

If the sequence of events outlined above is correct, the vein faults, or at least the main movement on them, post-dates the Mayo Lake anticline and contemporaneous lineation, for lineated fragments of phyllite are common in vein breccias. The forces that produced the vein faults may be related to those that formed the anticlines on the flank of the Mayo Lake anticline. Later stresses produced the northwest faults.

Owing to the several more or less distinct periods of deformation, it is difficult to decide when the various joint sets were formed. It may be suggested, however, that the northerly striking joints correspond to 'a-c' joints and are due to south-to-north stresses developed during the first or first and second episodes of folding and shearing. The rather broad scatter of joints in this set may be due to changes in the shearing direction. The group trending N72°E is possibly related to the last cross-folding and arching, with the formation of the McQuesten anticline. The latter set shows less scatter than the earlier 'a-c' set, possibly because of uniform stresses during their formation.

The question arises as to whether the various structures were produced during a single, long drawn out orogeny or whether there were appreciable intervals of crustal stability between the early recumbent folding and the later low-angle shearing, and between the low-angle shearing and the open folding. The writer believes it possible that a considerable time elapsed between the early folding and the shearing during which most of the low-angle faults and 'gleitbrett' structures were developed. In the first episode, for example, limestones and other rocks deformed plastically, forming, at least on a small scale, alpine-type folds, but later, even limestones were sliced by shears to form 'gleitbrett' structures. These different behaviours suggest greatly different environments: in the first, possibly at moderate depth, under high confining pressure, rocks deformed plastically; in the second, near the surface under low confining pressure, rocks failed by shearing.

Of the interval between the northerly directed shearing and thrusting movements and the development of the open folds, it may be suggested that quite different types of crustal stresses would be involved to produce the two, and that at least a short interval elapsed between their applications.

Disappearance of Quartzites on Keno Hill

Thick quartzite members disappear westward on Keno Hill (*see* Fig. 13). The disappearance may be explained by hypotheses involving either major thrusting and recumbent folding or sedimentary facies change.

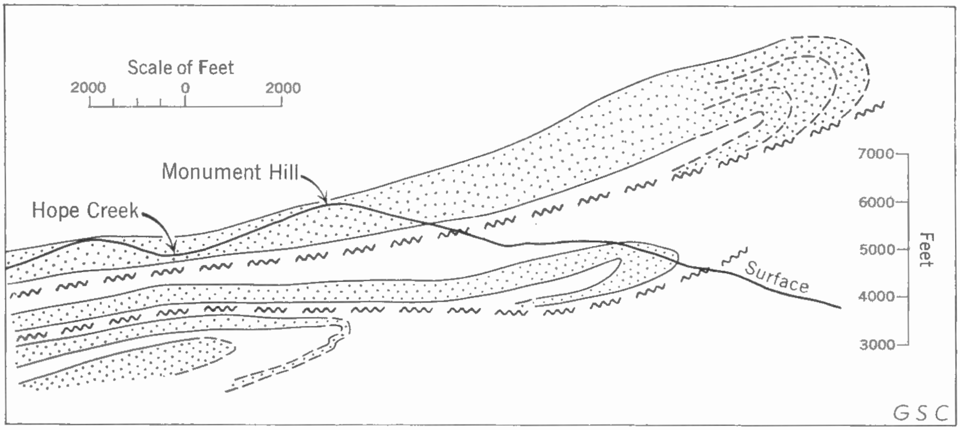

Figure 11. Projected section illustrating one hypothesis to account for the disappearance of quartzite members (stippled) on Keno Hill. The member that is continuous across Galena and Keno Hills lies above those shown in this projection. The section plane is vertical, strikes N30°W, and passes through the summit of Monument Hill. The data were projected along lines plunging 20° in a direction S60°W. The dashed contacts are inferred. Greenstone bodies are not shown, nor is the effect of the Lucky Queen vein fault.

The first hypothesis is that some of the quartzite members of Keno Hill terminate in large-scale, highly compressed and sheared recumbent folds with axial planes about parallel with the bedding. The fold axes would plunge southwest and the folds would be separated by surfaces or zones of thrusting (*see* Fig. 11). There is incontrovertible evidence, mainly in the presence of attenuated drag-folds, of strong movement parallel with the bedding in a northerly and northwesterly direction, much greater than the movement that would be produced by bedding plane slippage during the formation of a simple arch such as the McQuesten anticline. The shape of the termination at the nose between Faro Gulch and Silver Basin suggests such a fold. The common presence of 'gleitbrett' structures along the north slope of Keno Hill, interpreted here as the sheared out axial parts of folds, fits the hypothesis. The plunge of the axes of small folds and of the intersections of bedding and cleavage in gleitbrett structures suggest a southwesterly plunge for larger structures. An example from Silver Basin (*see* Fig. 12) where outcrops are plentiful shows the relation between bedding, foliation, fold-axes, and intersections of bedding and cleavage in gleitbrett structures par-

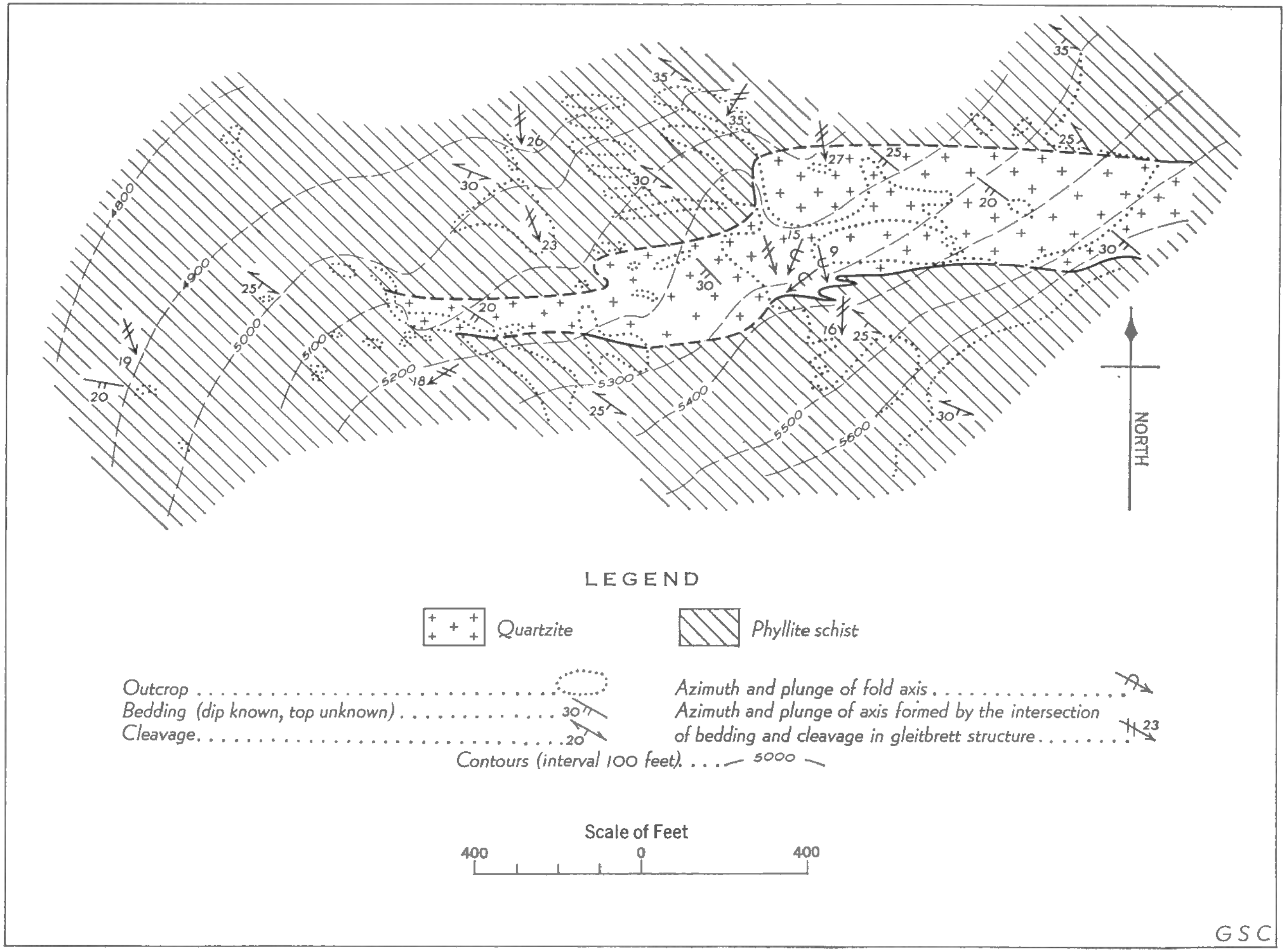

Figure 12. **Outcrop map of an area north of Caribou Hill, Keno Hill, illustrating the relation between fold axes, 'gleitbrett' structures, and the general attitude of foliation and bedding. These observations suggest that folds plunge mostly southerly in this particular area, across the trend of the general northwesterly strike of bedding and cleavage.**

ticularly clearly. The fold and gleitbrett axes plunge southerly in the bedding and foliation planes and abruptly cross the strike of the bedding and cleavage. Evidence for the existence of large overturned folds was obtained during a brief visit to the Davidson Mountains (*see* Fig. 1) where the rocks are somewhat less intensely deformed than immediately to the south at Keno Hill. The main structural feature appears, on brief inspection, to be an over-turned anticline, plunging to the west. [Subsequent mapping by L. Green (personal communication) has shown the presence of an overturned anticline and syncline, amplitude more than 2 miles, with axes plunging 20°SW and axial planes dipping about 15°S.]

The main quartzite member that crosses the south slope of Keno Hill and the summit of Galena Hill does not terminate within the area mapped, and, on the principal of the hypothesis outlined above, is probably a thrust sheet separated from the underlying units by zone of movement nearly parallel with the bedding. The nature of the underlying quartzite, the upper one in Figure 11, is uncertain. There is so little outcrop in the vicinity of its termination (*see* Pl. I A) that its nature can only be guessed. It may be the upper limb of a fold disconnected from the lower by shearing as suggested in Figure 11, an attenuated fold, or possibly a thrust sheet terminated by a steepening thrust.

That the westward disappearance of the quartzite beds is due to a sedimentary facies change is suggested by the gradual increase in the ratio of phyllite and siliceous schist from southeast to northwest and west. A few miles south of Lightning Creek little except quartzite is found, but to the northwest phyllite and impure quartzite increase and on Keno Hill several thick quartzite members disappear. On Galena Hill, only the main member persists. Rather slight differences in composition of the sediments would be heightened by metamorphism, pure quartz sandstones changing only to quartzite, the slightly impure sandstones altering to siliceous schists. The fact that the rocks along strike to the west of the thick quartzite member just south of Wernecke are largely quartz-rich foliates, not greatly different in composition from the quartzites, lends support to the idea. Scattered outcrops of quartzite and graphitic quartzite west of Faro Gulch suggest that the quartzite member that appears to terminate there may continue as a succession of schist and minor quartzite.

The thickening of the main quartzite member just before it disappears (*see* Fig. 11) does not, however, suggest a sedimentary facies change, and the writer favours the hypothesis involving thrusting and recumbent folding as an explanation for the disappearance of quartzites.

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