

Geochemistry of Mineralized Quartzite  
Beds in the Spokane Formation  
(Belt Supergroup), Rogers Pass Area,  
Lewis and Clark County, Montana

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By JON J. CONNOR and JAMES M. MCNEAL

DEPARTMENT OF THE INTERIOR  
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# Geochemistry of Mineralized Quartzite Beds in the Spokane Formation (Belt Supergroup), Rogers Pass Area, Lewis and Clark County, Montana

By Jon J. Connor and James M. McNeal

## Abstract

Scattered lenses of fine- to very fine grained, vitreous Cu-Ag-bearing quartzite (lithic arkose) in the Spokane Formation (Middle Proterozoic Belt Supergroup) crop out in the Rogers Pass area of western Montana. Individual beds are thin, lack obvious channeling, and are apparently elongated in a northerly direction. The lenses are composed largely of quartz, albite, and illitic mica, and they apparently represent the feather edge of a larger package of quartzite to the west.

These quartzite lenses throughout the Rogers Pass area contain low-grade, stratabound accumulations of Cu, Ag, Hg, and Ba. The Cu resides chiefly in malachite but also in chalcocite, bornite, and rarely covellite. The Ba is in barite. The form of the Ag and Hg is unknown, except at the Alice Creek Mine where both acanthite and native silver were observed. These low-grade accumulations are believed to have formed during the expulsion of diagenetic fluids.

Quartzite lenses close to outcrops of Tertiary intrusive rocks contain slightly more Hg than those distant from such outcrops. They also contain anomalous As, Ge, Sb, Pb, and Mo, and such beds are thought to have been weakly overprinted by a later (Tertiary) hydrothermal mineralizing event, presumably related to mineralization in the nearby Heddleston Mining District.

The Alice Creek Mine is an exceptionally rich pod of Ag (and Hg) in one of these low-grade mineralized beds. The origin of the Ag-rich pod is unknown, but its elevated Ag and Hg contents and the presence of acanthite suggest an origin distinct from the more typical (low-grade) stratabound Cu-Ag accumulations. The Ag-rich pod may have originated during the Tertiary hydrothermal event referred to above.

## INTRODUCTION AND ACKNOWLEDGMENTS

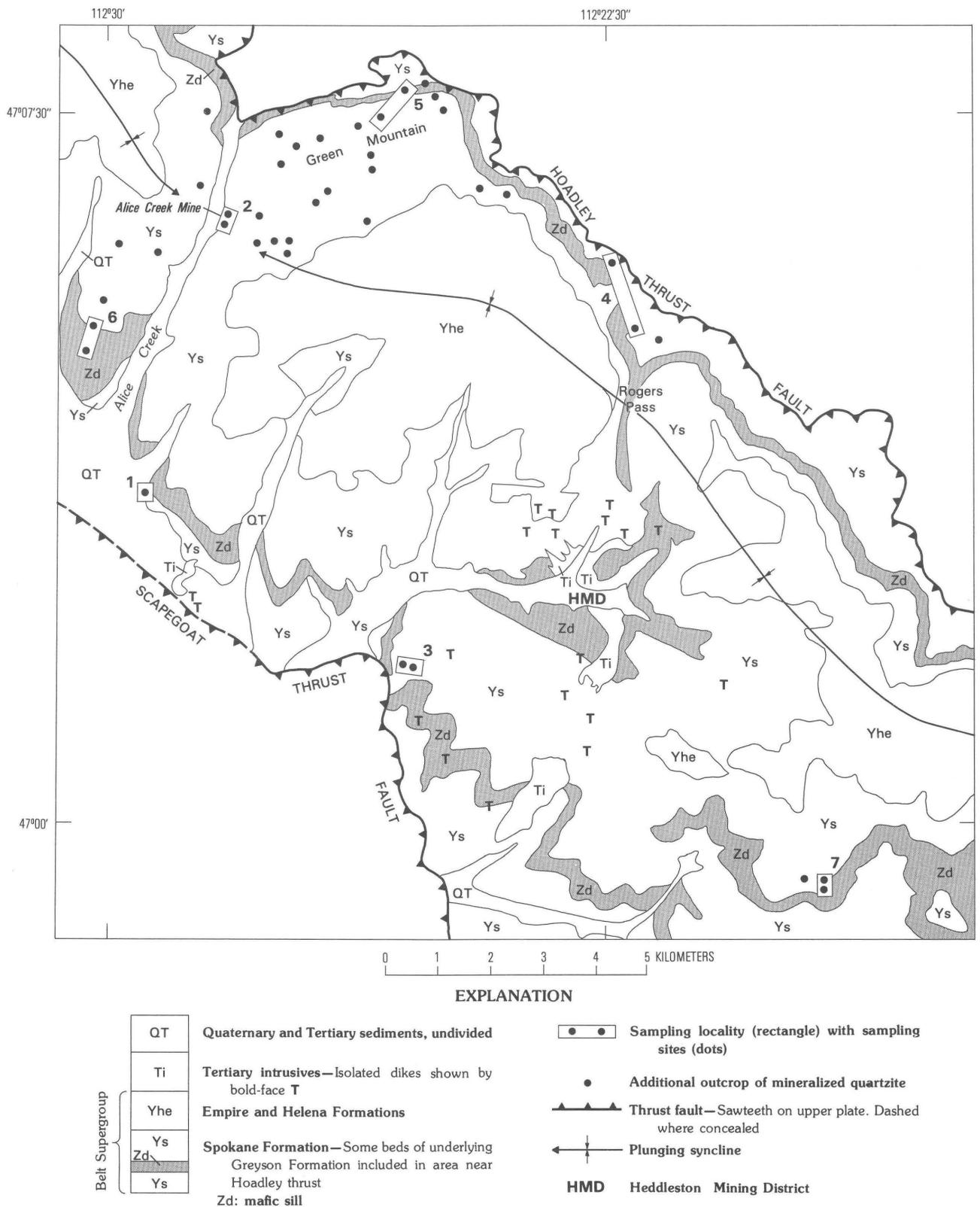
Stratabound accumulations of Cu- and Ag-bearing minerals occur in nearly all the formations of the Belt Supergroup of Middle Proterozoic age in western Montana. Harrison and Reynolds (1979, p. 2) classified these accumulations into two major kinds of occurrences: one whose host is quartzite or vitreous coarse-grained siltite

and one whose host is green laminated argillite enclosed by hematite-rich redbeds. Economic accumulations of Cu and Ag are known only from the quartzite type of occurrence and are typified by extensive resources in quartzites of the Revett Formation near Troy, Mont. None of the green-bed type of occurrences are known to be economic, although in the aggregate they probably exceed the quartzite type in total tonnage (Harrison and Reynolds, 1979, p. 3). Lange and Eby (1981, p. 934) discuss a third type of anomalous Cu-Ag accumulation, much rarer than the other two, in carbonate lenses of the Spokane and Helena Formations.

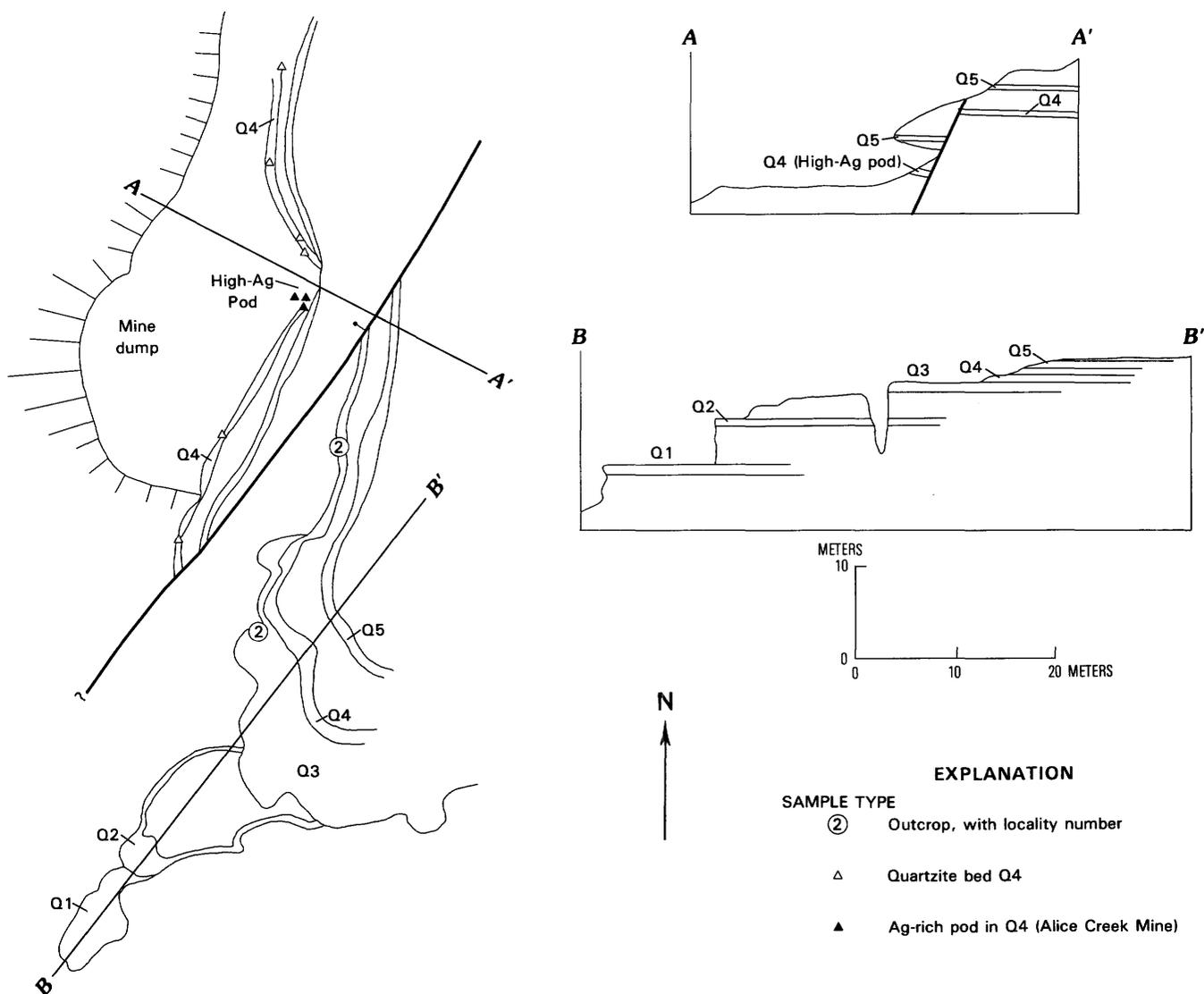
The Spokane Formation in the Rogers Pass area of western Montana contains an abundance of small, quartzite-type accumulations (fig. 1), one of which at the Alice Creek Mine constituted a small Ag-rich pod containing up to 280 oz/t Ag (fig. 2). The accumulations occur in small, individual quartzite beds scattered through the formation. These beds crop out most abundantly on Green Mountain, about 6 km north of Rogers Pass, and were collectively and informally called the Green Mountain quartzite by Trammell (1975, p. 3). The Spokane in this area also contains an abundance of small Cu-Ag deposits of the green-bed type, particularly near the contact with the overlying Empire Formation, but the focus of this report is on the mineralized quartzite in the area.

The field work on which this study was based was undertaken in the summers of 1977 and 1978. The study itself was suggested by R. L. Earhart and J. W. Whipple as part of an evaluation of the mineral-resource endowment of the Rogers Pass area. We thank J. W. Whipple in particular for his invaluable assistance in locating outcrops of Cu-Ag-bearing quartzite, and we thank G. Desborough and R. Christian for assistance in polished-section identification and microprobe analysis, respectively. Special thanks are due Mr. Leonard Orr of Lincoln, Mont., for permission to map and sample the Alice Creek Mine.

The analytical work for this study was performed in the Denver laboratories of the U.S. Geological Survey



**Figure 1.** Index map showing sampling localities and distribution of mineralized quartzite beds in the Spokane Formation in the Rogers Pass Area, Montana.



**Figure 2.** Sketch map of the Alice Creek Mine and vicinity, Rogers Pass area. Quartzite beds labeled from Q1 through Q5.

by J. W. Baker, A. Bartel, C. Bliss, P. Briggs, G. Burrow, M. F. Coughlin, J. G. Crock, C. M. Ellis, K. E. Horan, J. McDade, C. McFee, V. Merritt, H. T. Millard, Jr., F. Perez, S. Prelipp, G. Riddle, V. Shaw, M. W. Solt, J. A. Thomas, M. L. Tuttle, R. B. Vaughn, J. S. Wahlberg, and B. Walz. A complete listing of the analytical data appears in Connor, McNeal, and Crock (1979).

## METHODS OF STUDY

Mineralized quartzite beds in the Spokane Formation of the Rogers Pass area were sampled according to a hierarchical, four-level analysis of variance design. The primary purpose of such a design is to test for the possible presence of regional variation in the geochemistry of

the mineralized lenses. Concurrently, the magnitude of smaller scaled (nonregional) variation may also be examined, as well as the importance of variation across bedding within lenses and the importance of laboratory error. Miesch (1976) describes the uses of such designs in detail.

The first, or top, level of the analysis of variance design consisted of seven sampling localities (fig. 1) spread over the area of Spokane outcrop. A sampling locality was defined as an outcrop area approximately 1 km or less in its largest dimension that contained an exposure or exposures of mineralized quartzite. The second level of the design consisted of two sampling sites within each sampling locality, except for locality 1 which because of its very small size contained only one site. A sampling site was defined as a vertical section of exposed mineralized quartzite in the locality. The two sites were selected

randomly from all possible vertical sections in the locality. If multiple mineralized lenses were exposed in a section, all were included in the sampling site. The third level of the design consisted of two samples within each sampling site (the vertical section). The two samples were located randomly in the vertical section, and each sample consisted of chips taken from approximately 15 cm of section. The fourth, and lowest, level of the design consisted of replicated chemical analyses. Twenty-six samples were collected from the seven localities; nine were split into two parts, giving a total of 35 rock analyses for the analysis of variance.

An exceptionally Ag-rich pod in a quartzite bed in sampling locality 2 (Alice Creek Mine) was being mined for its Ag at the time of sample collection. Because of the atypically high Ag content of this pod, it and the adjacent parts of the lens were not included as part of the formal sample design described above. However, a small set of samples was collected from the mine workings as part of a separate study. Three samples were collected from the working face and six others from the same quartzite bed (Q4) but outside the Ag-rich pod. Locations of these samples are shown on figure 2 by triangles.

All samples were analyzed for a variety of chemical constituents. SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO, total Fe (as Fe<sub>2</sub>O<sub>3</sub>), P<sub>2</sub>O<sub>5</sub>, K<sub>2</sub>O, total S, and TiO<sub>2</sub>O were determined using X-ray fluorescence (Wahlberg, 1975); total C was done by a Leco gasometric device (Huffman and Dinnen, 1976); total Cu was done by atomic absorption; and soluble Cu was done following an acid extraction (Connor and others, 1979). Ag, B, Ba, Be, Ce, Cd, Co, Cr, Dy, Er, Eu, Ga, Gd, La, Li, Mg, Mo, Mn, Nb, Nd, Ni, Pb, Pr, Sc, Sm, Sr, Tm, V, Y, Yb, Zn, and Zr were determined by an automated spectrographic plate-reading device (Sutton, 1976). Ag in samples from the Alice Creek Mine was analyzed by conventional fire assay. U and Th were determined by neutron activation (Millard, 1975), and Hg was analyzed by flameless atomic absorption. Sb, As, Ge, Se, and Sn were analyzed by X-ray fluorescence following a sulfide extraction (Wahlberg, 1975).

Semiquantitative estimates of quartz, feldspar, and mica were obtained from thin-section, X-ray diffraction, and normative analyses. Fifty points were counted in each thin section. The thin sections also provided information on textures and mineral varieties. A few polished sections of sulfide-bearing samples were examined. In the normative analysis, illite was assumed to contain 7 percent K<sub>2</sub>O and 26 percent Al<sub>2</sub>O<sub>3</sub>.

A persistent problem in geochemical data is the presence of left-censored data; that is, data in which some samples contain element concentrations below the limits of the analytical method. In the analysis of variance and the factor analysis used in this report, the following convention was used to circumvent the effects of the missing element concentrations. Where less than a third of the

values were censored, a concentration equal to 0.7 of the limit of determination was substituted. If censoring was greater than one-third, the variable was not analyzed. Except for SiO<sub>2</sub>, typical element concentrations were estimated with the geometric mean. Censored distributions were adjusted for the censoring by a procedure of Cohen (1959) prior to computation of the geometric mean.

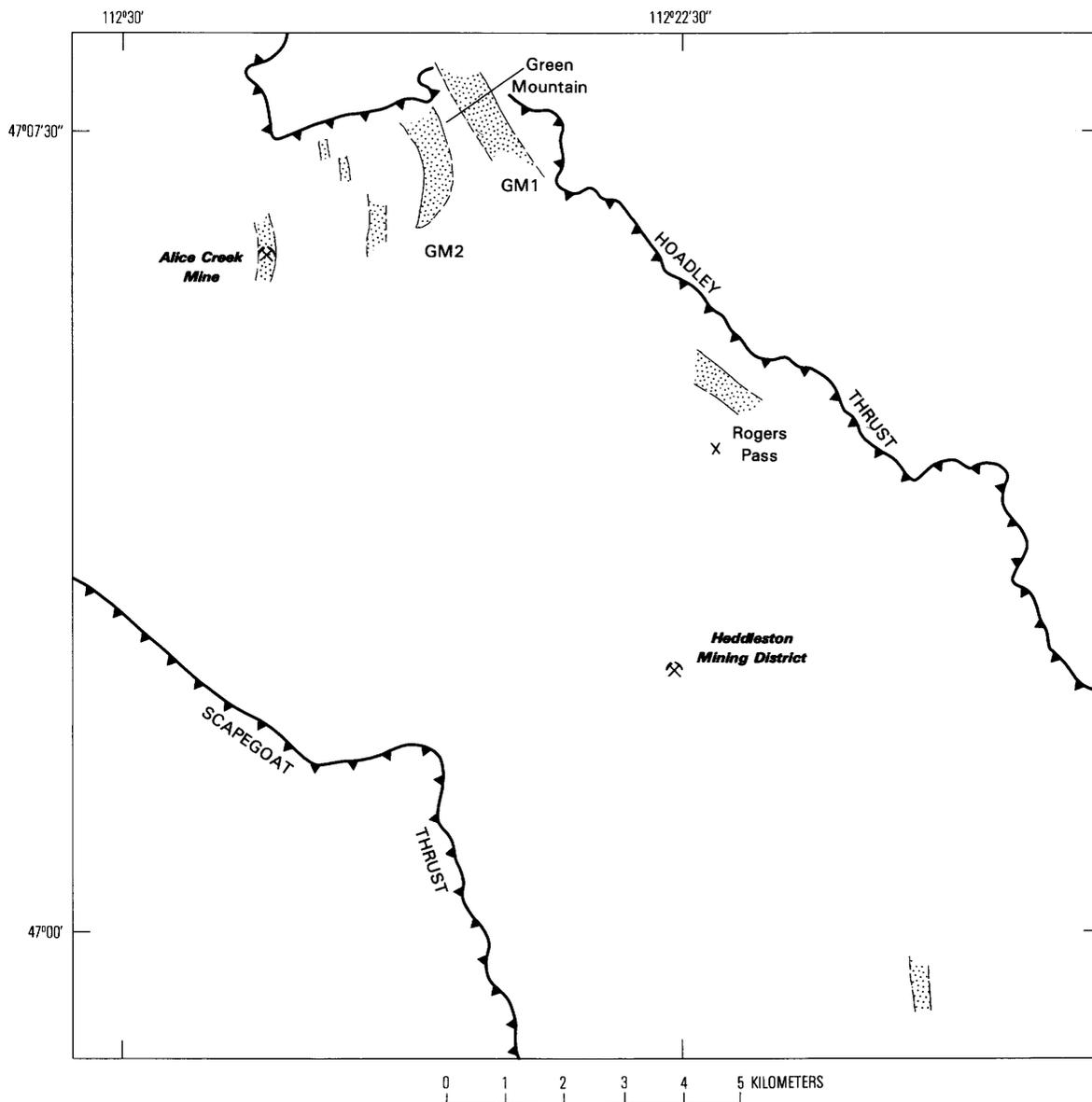
## GEOLOGIC SETTING

The Spokane Formation was named by Walcott (1899, p. 207) for exposures of "siliceous and arenaceous shales of a deep red color" in the Spokane Hills of the Helena Embayment some 75 km southeast of the Rogers Pass area. In the area of the Embayment, the Spokane has been subdivided into five informal units, partly on the basis of color (Connor, 1982). All five units are dominated by argillite, silty argillite, and siltite. Quartzite is rare and occurs mostly in the lower two units as laterally discontinuous beds of coarse, calcareous quartzite. The formation is about 1500 m thick where not reduced by pre-Flathead erosion.

The Spokane Formation in the Rogers Pass area is anomalously thin—about 500 m—perhaps because of structural truncation. The study area lies in an allochthonous thrust block between the Hoadley thrust below and the Scapegoat thrust above (fig. 1) near the western edge of the Montana Disturbed Belt. The formation here, as in the Helena Embayment, is dominated by red argillites and siltites, but representatives of only the upper two informal units of Connor's divisions (1982) were recognized in this thrust plate.

The mineralized quartzite lenses in the Rogers Pass area constitute a minor part of the Spokane section, but they contrast strongly in composition with the calcareous quartzite beds observed in the lower part of the formation in the Embayment. The lenses in the Rogers Pass area are very fine grained, noncalcareous, vitreous, lithic arkoses. About 25 km to the west (above the Scapegoat thrust), the Spokane Formation contains appreciably more of this kind of quartzite, and the lenses in the Rogers Pass area probably represent an eastern feather edge of a regionally extensive package of quartzite-rich beds in the Spokane. These quartzite beds are petrographically and texturally similar to much of the quartzite in the Revett and adjacent formations of the Ravalli Group approximately 150 km to the west.

The quartzite lenses in the Rogers Pass area are small, rarely exceeding 1000 m in outcrop length (average 30 m) or 1 m in thickness (average <0.5 m), and are everywhere enclosed, apparently conformably, by red argillite or siltite. They tend to be thick-bedded, locally ripple-marked and crossbedded, and in places intercalated with green argillite or siltite. Their bases appear to lack



**Figure 3.** Geometry of some of the mineralized quartzite beds (stippling) in the Rogers Pass area.

channeling and, where the lenses are sufficiently exposed to be mapped, they are elongated in a northerly direction subparallel to each other (fig. 3). Some outcrops exhibit multiple lenses, stacked upon each other, as at the Alice Creek Mine (fig. 2). The origin of the lenses is obscure, but the subparallel arrangement, the stacking, and the lack of basal scouring are consistent with deposition on or near a strand line.

In the Rogers Pass area, the Spokane is intruded by a thick diorite sill of Late Proterozoic age. Whipple and Bregman (1981) noted a maximum thickness of 185 m for this sill in the Hoadley thrust plate. Locally, mineralized quartzite lenses of the Spokane are caught up in this sill, but most lenses, including the one at the Alice Creek Mine, are not. This intrusion is not likely

to bear any genetic relation to the events that mineralized the bulk of the quartzite beds. The primary effect of this intrusion on the Spokane Formation was to produce a thick zone of dark hornfels on either side of the sill.

The most intensely mineralized locale in the Rogers Pass area is the Heddleston Mining District (fig. 1), an intrusive complex of Eocene age and a host to Cu-Mo porphyry-type mineralization (Miller and others, 1973). The stocks and dikes of the district apparently are just the upper part of a large system of unexposed porphyritic intrusions extending to the northwest. This buried zone passes to the south of Green Mountain (Earhart and others, 1981). In the Heddleston District, where the porphyries intrude the Spokane Formation, they have

produced a characteristic and pervasive yellow-brown alteration halo in the Spokane red beds. As no such alteration was observed adjacent to any of the mineralized quartzites in the area, it is unlikely that the quartzites were affected by the Heddeleston mineralizing episode in any substantial way, with the single (and important) possible exception of the Ag-rich pod at the Alice Creek Mine, described below.

## MINERALIZED QUARTZITE

### Mineralogy and Petrography

The quartzite lenses in the Spokane of the Rogers Pass area are composed principally of quartz, plagioclase, and illitic mica (fig. 4, table 1). Detrital quartz is generally clear; some of it is polycrystalline, and rare grains are stretched metaquartzite. Quartz is the common cement; carbonate is rare but occurs as calcite in patches or veins in localities 4, 6, and 7, where it is associated with minor epidote and presumably reflects the metamorphic effects of the nearby Late Proterozoic sill. Albite (<7 percent An) is an important constituent and ranges up to 38 percent in both the norm and the X-ray diffraction analysis. Rock fragments are also important and include abundant illitic pellets.

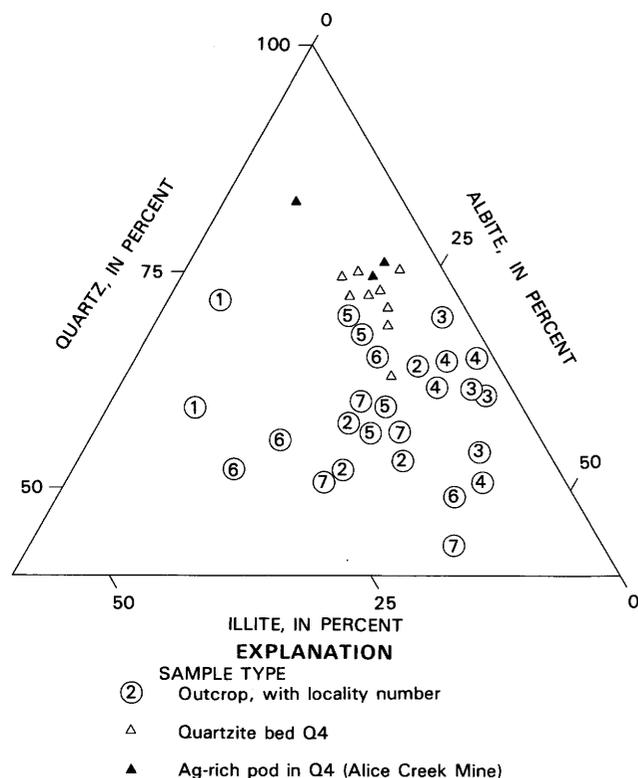


Figure 4. Normative mineralogy of mineralized quartzite beds in the Spokane Formation of the Rogers Pass area, Montana.

Table 1. Average mode of mineralized quartzite in the Spokane Formation of the Rogers Pass area [Data are in percent and are based on counts of 50 points in each of 24 thin sections. Locality 1 was excluded because it is anomalous in texture and mineralogy]

Quartz	
Monocrystalline	30
Polycrystalline	7
Stretched metaquartzite	1
Authigenic	9
Vein	2
Feldspar <sup>1</sup>	19
Mica <sup>2</sup>	
Muscovite	3
Chlorite	1
Matrix	12
Rock fragments	11
Other	4

<sup>1</sup>X-ray diffraction showed 25 percent plagioclase (<7 percent An); the norm contains 27 percent albite. The underestimate of feldspar in the mode probably reflects misassignment of rock fragments.

<sup>2</sup>The norm contains 12 percent illite.

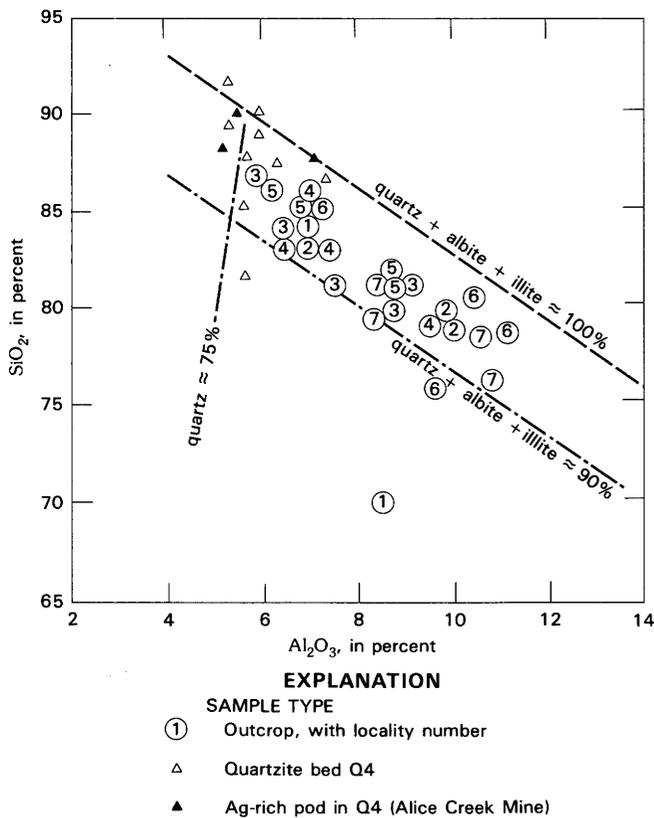
Few samples contain more than 75 percent quartz (fig. 5), and those that do are from bed Q4 in the Alice Creek Mine. SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> are readily accounted for in normative quartz, albite, and illite with albite generally greater than illite (fig. 6). Thus, the mineralized lenses in the Spokane are in fact lithic arkoses. The term "quartzite," however, has been conventionally applied because the lenses are so vitreous, and that term is retained here.

Accessory minerals include chlorite, microcline, blue-green hornblende, epidote, calcite (as noted above), and zircon. Epigenetic mineralization was apparently restricted largely to chalcocite and bornite, now mostly oxidized to malachite. The pervasive development of fine-grained illite and chlorite, the extensive albitization of the feldspar, and the local ragged overgrowths on the hornblende indicate that these rocks are in the greenschist facies of metamorphism.

Grain size in the mineralized quartzite beds ranges from about 0.01 to 0.1 mm, and most samples are mixed coarse silt and fine sand. Authigenic quartz, where distinguishable from the detrital core grains, composes up to 20 percent of the rock, suggesting that, at least locally, original porosity was fair to good. In general, these lenses appear to be texturally submature and mineralogically immature.

### Regional Geochemical Variability

The analysis of variance (table 2) demonstrates that strong geochemical differences exist among the seven sampled localities, and even stronger differences exist in



**Figure 5.** Variation in  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  in mineralized quartzite beds of the Spokane Formation of the Rogers Pass area. Composition based on normative minerals.

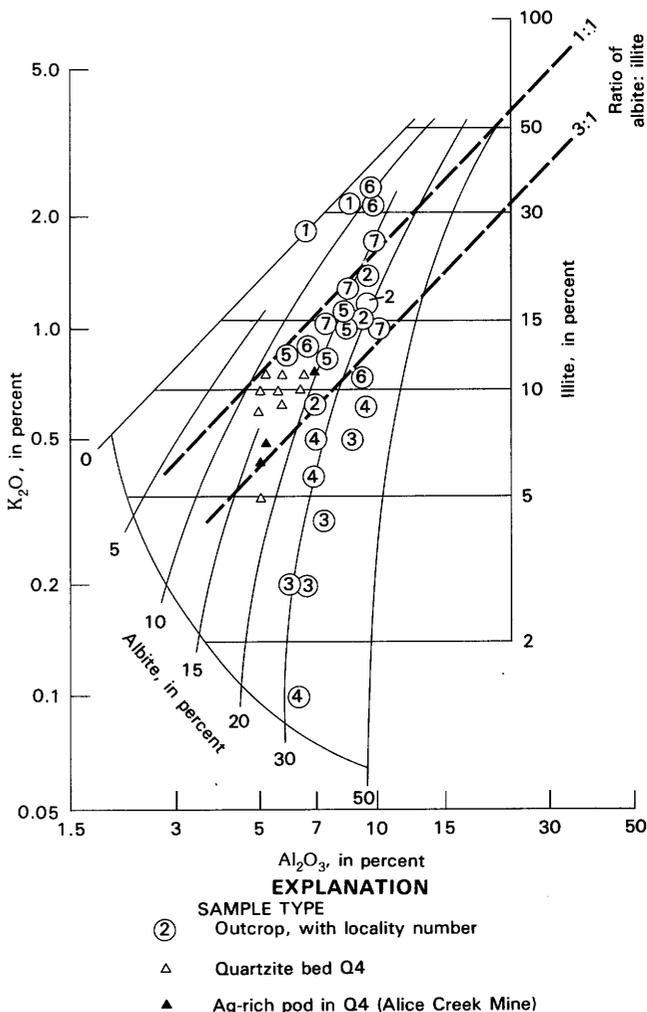
plagioclase and illite (table 3). These differences are quantified in table 4. Clearly, locality 1 is the most unusual of the seven; it is distinctly high in  $\text{K}_2\text{O}$  (and illite), As, Ge, Hg, and V and distinctly low in plagioclase. Locality 1 is also unique in that regional differences for As and Ge become nonsignificant if locality 1 is excluded from the test. The two samples from locality 1 are strongly sheared and sericitically altered, and the high content of the volatile elements As, Ge, and Hg suggest that the locality may have been altered hydrothermally. This suggestion is examined in more detail below.

Of the remaining elements showing regional differences, 11 are highest in localities 6 and 7:  $\text{Al}_2\text{O}_3$ , Co, total Fe as  $\text{Fe}_2\text{O}_3$ , Gd, La, Mg, Mn, Nb, Ni, Sc, and  $\text{TiO}_2$ . All of these are mica-related elements in sedimentary rocks, and the suggestion here is that these two localities are richer in argillaceous rock fragments than the other localities. Ba and S are highest in locality 3, in part because of elevated barite (about 0.5 percent normative barite), and Sc is highest in locality 6. In turn, localities 4 and 5 are the lowest in many of these constituents. These differences suggest, but only weakly, that quartzite lenses to the west or south tend to be richer in transition elements (more lithic) than those to the east or north. Expected element concentrations (estimated as

the geometric mean) based on all seven localities of mineralized quartzite are listed in table 5.

Geochemical and mineralogical differences between sites (tables 2 and 3) are nonsignificant except for Eu. This finding indicates that the mineralized quartzite lenses, although differing strongly among themselves, are each rather compositionally homogeneous. The reason for anomalous behavior in Eu is unknown, but the large imprecision in the analysis (between-replicates component, table 2, is 51 percent of the total variance) makes reliable interpretation of this element difficult. Compositional variation among samples within sections is significant for most constituents, which is not unexpected inasmuch as the samples are largely mixtures of quartz and illitic micas (in either matrix or rock fragments).

Analytical reproducibility (between-replicates component, table 2) is reasonably good for many elements. Error variances for Cr, Eu, Si, and Yb exceed 50 percent,



**Figure 6.** Variation in  $\text{Al}_2\text{O}_3$  and  $\text{K}_2\text{O}$  in mineralized quartzite of the Spokane Formation in the Rogers Pass area, Montana. Composition based on normative minerals.

**Table 2.** Components of geochemical variance in mineralized quartzite in the Spokane Formation of the Rogers Pass area [Components given as percentages of total logarithmic variance (Total  $\text{Log}_{10}S^2$ ); Tot, total element concentration; Sol, acid-soluble fraction; \*, component significantly different from zero at the 0.05 probability level]

Constituents	Total $\text{Log}_{10}S^2$	Between localities <sup>1</sup>	Between sites	Between samples	Between replicates
Ag	0.3901	<1%	22%	35%	43%
Al	.0085	30*	<1	66*	4
As	.2489	44*	10	<1	45
Ba	.2196	48*	11	36*	6
C-Tot	.1336	11	<1	44	46
Co	.1477	32*	5	58*	4
Cr	.0332	<1	<1	44	56
Cu-Tot <sup>2</sup>	.5905	2	<1	95*	2
Cu-Sol <sup>2</sup>	.5221	<1	<1	97*	2
Eu	.0549	<1	49*	<1	51
Fe-Tot	.1171	40*	<1	56*	4
Gd	.1410	36*	<1	19	45
Ge	.0614	42*	19	<1	39
Hg	.3848	66*	<1	19	15
K	.1458	64*	<1	34*	2
La	.0645	55*	<1	27	18
Mg	.1556	36*	<1	59*	4
Mn	.1333	52*	11	29*	8
Nb	.0319	45*	<1	34	21
Ni	.1283	30*	<1	61*	9
Pb	.1363	14	<1	83*	3
S	.1115	76*	<1	<1	23
Sc	.0708	57	<1	37*	6
Si <sup>3</sup>	11.05	13	<1	26	60
Sr	.0532	10	<1	64*	26
Th	.0173	7	<1	82*	11
Ti	.0146	34*	<1	65*	2
U	.0388	17	<1	80*	3
V	.0615	42*	<1	52*	6
Y	.0249	16	10	42*	31
Yb	.0130	<1	20	21	58
Zn	.1248	22	<1	73*	5
Zr	.0253	10	18	47*	24

<sup>1</sup>Locality 1 (fig. 1) is fractured and probably affected by hydrothermal activity; exclusion of this locality from the analysis of variance results in a nonsignificant component for As and Ge at the between-localities level of the design.

<sup>2</sup>Sample JC7Q411 from locality 4 contained only background amounts of Cu (<20 ppm); however, no change in the significance tests were noted upon deletion of this sample from the computation.

<sup>3</sup>Computed on untransformed data.

**Table 3.** Components of mineralogical variance in mineralized quartzite in the Spokane Formation of the Rogers Pass area

[Components given as percentages of total logarithmic variance (Total  $\text{Log}_{10}S^2$ ); M, determined in the mode; N, determined in the norm; X, determined by X-ray diffraction; \*, component significantly different from zero at the 0.05 probability level]

Constituents	Total $\text{Log}_{10}S^2$	Between <sup>1</sup> localities	Between sites	Between samples
Quartz, M				
Monocrystalline	0.0347	18	<1	82
Polycrystalline	.1669	42	<1	58
Authigenic	.2083	23	<1	77
Matrix, M	.1534	38	<1	62
Plagioclase, X	.1456	93*	<1	7
Albite, N	.0973	81*	7	12
Illite, N	.1587	61*	<1	39

<sup>1</sup>Between-localities variance for quartz, matrix, and grain size is based on only 6 localities; Locality 1 (fig. 1) was too severely fractured to permit distinction of these properties.

**Table 4.** Locality medians (averages) of minerals, elements, and oxides in mineralized quartzite in the Spokane Formation of the Rogers Pass area

[Data are given in parts per million except where noted as percent; GD, geometric deviation; X, determined by X-ray diffraction; N, determined in the norm. Localities are arranged in decreasing order of normative illite. See figure 1 for locations]

	GD	Locality No.						
		1	2	7	6	5	4	3
<b>Minerals:</b>								
Illite, %, N	1.77	29	15	15	14	11	6.3	3.4
Plagioclase, %, X	1.26	1.0	32	30	29	27	20	21
Albite, %, N	1.28	5.9	26	30	21	30	23	24
<b>Elements and Oxides:</b>								
Al <sub>2</sub> O <sub>3</sub> , %	1.19	8.5	9.4	10	9.6	6.9	7.1	6.5
As	2.36	13	.9	1.1	.8	.9	.4	2.2
Ba	2.18	160	770	390	1300	300	200	3100
Co	2.07	4.2	3.0	6.7	4.7	2.2	1.3	1.5
FeTO <sub>3</sub> , % <sup>1</sup>	1.84	1.7	.95	2.5	1.3	.50	.40	.51
Gd	2.00	10	4.6	10	11	<2.2	<2.2	4.4
Ge	1.54	4.0	.9	1.5	1.1	1.1	.95	.9
Hg	2.30	2.6	.16	.04	.02	.16	.06	.41
K <sub>2</sub> O, %	1.69	2.1	1.1	1.1	.98	.80	.45	.25
La	1.48	19	22	29	35	6.9	22	12
Mg, %	2.07	.33	.29	.63	.54	.10	.14	.19
Mn	1.79	97	75	310	140	57	66	52
Nb	1.36	13	12	17	14	7.1	10	7.1
Ni	1.99	7.1	5.3	15	8.0	3.0	3.4	3.7
S, %	1.46	.1	.15	<.1	<.1	.1	.15	.3
Sc	1.49	3.4	3.1	5.7	8.7	1.8	2.1	2.5
TiO <sub>2</sub> , %	1.25	.3	.3	.42	.32	.23	.3	.4
V	1.54	37	19	20	20	11	8.2	11
Y	1.40	22	31	21	17	17	23	24

<sup>1</sup>Total Fe measured as Fe<sub>2</sub>O<sub>3</sub>.

**Table 5.** Summary geochemistry of mineralized quartzite in the Spokane Formation of the Rogers Pass area  
 [Data are in parts per million except where noted as percent (%); GM, geometric mean; GD, geometric deviation; GE geometric error; dashes (—), no data; Ratio, number of analyses in which constituent was determined to total number of analyses; X, determined by X-ray diffraction; N, determined in the norm]

	GM	GD	GE	Ratio		GM	GD	GE	Ratio
Ag	6.2	3.65	2.57	34:35	Mo <sup>1</sup>	<1.0	—	—	7:33
Al <sub>2</sub> O <sub>3</sub> , %	8.1	1.20	1.04	35:35	Mn	88	2.25	1.27	35:35
As	1.1	2.63	2.16	34:35	Nb	11	1.49	1.21	35:35
B	8.5	2.37	1.51	20:35	Nd	40	1.50	1.26	11:35
Ba	510	2.83	1.30	35:35	Ni	5.1	2.13	1.28	35:35
Be	1.1	1.40	1.28	20:35	P <sub>2</sub> O <sub>5</sub> , %	.059	2.92	2.16	11:35
C-Tot, %	.039	2.28	1.77	35:35	Pb <sup>1</sup>	6.2	1.74	1.16	33:33
CaO, %	<.10	—	—	16:35	Pr	<60	—	—	1:35
Ce	38	1.91	1.47	11:35	S-Tot, %	.11	1.78	1.45	21:35
Cd	<10	—	—	0:35	Sb <sup>1</sup>	<.20	—	—	9:33
Co	2.7	2.37	1.19	34:35	Sc	3.3	1.72	1.16	35:35
Cr	17	1.49	1.37	35:35	Se	<.20	—	—	3:35
Cu-Sol, %	.10	4.10	1.27	34:35	SiO <sub>2</sub> , % <sup>2</sup>	81	3.2	2.6	35:35
Cu-Tot, %	.12	4.21	1.28	35:35	Sm	<46	—	—	1:35
Dy	<10	—	—	5:35	Sn	.58	3.01	3.23	30:35
Er	5.0	1.24	1.29	21:35	Sr	120	1.54	1.31	35:35
Eu	1.6	1.63	1.65	26:35	Tb	<22	—	—	3:35
FeTO <sub>3</sub> , % <sup>3</sup>	.88	1.95	1.17	35:35	Th	7.7	1.30	1.11	34:35
Ga	1.4	2.13	—	8:35	TiO <sub>2</sub> , %	.31	1.27	1.04	35:35
Ge	1.1	1.69	1.43	35:35	Tm	<2.2	—	—	5:35
Gd	4.7	2.67	2.21	25:35	U	2.1	1.53	1.08	35:35
Hg	.13	3.85	1.74	34:35	V	15	1.67	1.15	35:35
K <sub>2</sub> O, %	.74	2.27	1.13	35:35	Y	23	1.43	1.22	35:35
La	18	1.75	1.28	34:35	Yb	1.5	1.30	1.22	35:35
Li	<100	—	—	1:35	Zn	27	2.20	1.20	35:35
Mg, %	.27	2.38	1.20	35:35	Zr	250	1.43	1.20	35:35

<sup>1</sup>Sample JC7Q121 in locality 1 contained anomalously high Pb (25 ppm) and Sb (26 ppm). Sample JC7Q322 in locality 3 contained anomalously high Mo (9 ppm) and Pb (85 ppm).

<sup>2</sup>Computed on untransformed data.

<sup>3</sup>Total Fe measured as Fe<sub>2</sub>O<sub>3</sub>.

**Table 6.** Eigenvalues and cumulative variance associated with the first 10 principal components of the geochemistry of mineralized quartzite

Principal component	Eigenvalue	Cumulative variance (percent)
1	12.8	36.6
2	3.9	47.6
3	3.3	56.9
4	2.4	63.7
5	2.2	70.1
6	2.0	75.8
7	1.4	79.7
8	1.2	83.1
9	1.1	86.2
10	1.0	89.1

and these four elements were dropped from further evaluation (except for listing in table 5, the error variance contributes to GE rather than to GM, the expected concentration). It is important to remember that each error variance is given as a percentage of the total observed variation for that constituent and that a large percentage error may indicate a small total variance rather than an imprecise analysis.

The analysis of variance tests have, thus, demonstrated that locality 1 is compositionally unique and that the lenses may be slightly more argillaceous to the west or south. These differences, however, are not paralleled by any observable differences in the primary mineralizing elements, Cu and Ag (if the Ag-rich pod at the Alice Creek Mine in locality 2 is excluded). Variation in Cu and Ag resides chiefly at the between-sample level. The uniform distribution seen in these two elements at the highest level of the design reflects either a uniformity in

the intensity of the original mineralizing processes or of the weathering processes. Without an examination of unweathered samples, no real basis exists for choosing between these two alternatives, although if the weathering effects are of equal intensity over the area of study (as well they might be), then the regionally uniform distribution of Cu and Ag reflects original distribution.

## Geochemical Factor Analysis

Element associations were investigated by factor analysis (see Davis, 1973, p. 478) of the logarithmic linear correlation coefficients among the measured constituents. For this examination, the two samples from locality 1 were excluded because the locality is geochemically

unique. Also excluded were variables with more than 33 percent censored values (see ratio, table 5) and variables showing more than 50 percent error variance (see between-replicates component, table 2). Two mineralogical variables (modal quartz and normative albite) were added to the list of chemical elements. Thus, the factor analysis was based on 24 samples and 31 variables. Eigenvalues of the correlation matrix for this data set are listed in table 6. A six-factor solution accounted for a respectable 76 percent of the total variability in the system which, considering the average percentage error in table 2, seems reasonable. The rotated and ranked factor loadings for these six geochemical factors are listed in table 7. This particular rotation is an arbitrary (orthogonal) rotation and was chosen because the resulting table of loadings is more easily interpreted geologically than other examined rotations.

**Table 7.** Rotated and ranked factor loadings of geochemical and mineralogical properties of mineralized quartzite in the Spokane Formation of the Rogers Pass area  
[Tot, total; Sol, soluble. The error variance is the between-replicates component of table 2]

Logarithmic property	Factors						Variance (percent)	
	1	2	3	4	5	6	6-factor model	Error
Al	0.91	0.00	0.00	0.00	0.00	0.00	83	4
Fe-Tot	.90	-.15	-.11	.06	.25	.02	91	4
Sc	.89	-.11	-.21	.10	.09	.24	92	6
V	.88	-.03	-.08	-.14	.35	.04	93	6
Co	.85	-.16	-.18	.24	.28	.15	94	4
Mg	.84	-.19	-.07	.27	.28	.19	93	4
Ni	.84	-.26	-.07	.24	.20	.13	89	9
Zn	.75	-.20	.12	.14	.41	.19	84	5
Mn	.73	-.20	-.18	.30	.18	.39	88	8
K	.72	-.20	-.16	-.50	.07	.01	84	2
La	.69	.19	-.01	.33	-.02	.38	77	18
Nb	.68	.15	-.08	-.15	-.08	.44	71	21
Ti	.61	.16	.43	-.14	.43	.09	80	2
Gd	.58	-.35	.16	-.11	.06	.25	56	45
Th	.50	.40	.02	.10	-.31	-.37	65	11
Quartz <sup>1</sup>	-.84	-.14	-.02	-.32	-.22	.00	88	-
Zr	.00	.85	.00	.00	.00	.00	72	24
Y	.04	.85	.29	-.14	-.13	.10	85	31
Cu-Tot	.06	-.21	.87	.00	.00	.00	80	2
Cu-Sol	.07	-.19	.89	.01	.00	-.01	83	2
Ge	.42	.13	-.59	-.05	.23	.21	64	39
Ag	.14	-.09	.56	-.42	.00	.46	73	43
S	-.52	.45	.54	-.05	.19	-.20	84	23
Ba	-.27	.03	.48	-.17	.40	.38	64	6
Albite	-.05	.35	.36	.65	.00	.00	68	-
Sr	-.23	.15	-.09	.48	.37	.28	53	26
Hg	-.37	.04	.29	-.44	.21	-.36	59	15
Pb	-.04	-.02	-.04	.17	.80	.13	69	3
As	.08	.10	-.12	-.22	.75	.23	69	45
U	.31	.20	-.17	-.23	-.09	.77	82	3
C-Tot	-.02	-.25	-.41	.32	-.29	.46	63	46

<sup>1</sup>Computed on untransformed data.

Geometrically, the six factors may be viewed as orthogonal axes in six-dimensional space, and the geochemical constituents may be viewed as a cluster of vectors in that space. The rotation mentioned above was performed (conceptually) in the following manner. The vector for Log Al was positioned coincident with factor 1 while holding the angular relations between it and all the other vectors constant. Then, the vector for Log Zr was positioned as close to factor 2 as possible, consistent with its angular relations to the remaining vectors. In this particular case, Log Zr just happened to become coincident with factor 2. Then, the vector for Log total Cu was positioned as close as possible to factor 3, consistent with its angular relations to the remaining vectors. And similarly, the vectors of Log albite and quartz were positioned as close as possible to factors 4 and 5, respectively. Following rotation, the constituents were ranked within groups in descending order of the strongest loadings.

The loadings in table 7 are the correlations between the geochemical vectors and the new factors, and geologic interpretations of each factor are based on that particular group of constituents which is most strongly associated with the factor. Quartz and a host of illite-related elements load strongly on factor 1, the quartz-mica factor. As noted above, the quartzite beds are to a large extent simple mixtures of quartz and mica, and factor 1 reflects that property. The negative relation of quartz to mica in this factor reflects the mathematical property of closure (Chayes, 1960); that is, as the percentage of mica increases, the percentage of quartz must decrease.

Factor 2 is defined largely by the association of Log Zr with Log Y. The independence of these from factor-1 constituents indicates that they are not being held to any great extent by the illitic component; rather, they are in their own phase, presumably a heavy-mineral component which must include zircon.

Factor 3 is defined by high positive loadings for the Logs of Cu, Ag, S, and Ba and a high negative loading for Log Ge. Clearly, factor 3 represents to a large extent the mineralizing event which produced the anomalous low-grade Cu-Ag stratabound accumulations in the quartzite lenses. Element loadings in this factor except for Log Cu are somewhat diffuse, perhaps as a result of later hydrothermal activity or redistribution during weathering. The high negative loading of Log Ge on this factor is intriguing, but further work is necessary to determine if this relation actually represents some kind of element depletion during the mineralizing event.

Factor 4 is also rather poorly defined, and the element association is not a particularly enlightening one. The importance of albite indicates that variation in this major rock-forming mineral bears little relation to variation in the other two important constituents (quartz,

mica). The positive association of Log Sr and Log Hg with this factor, and the negative association with Log K, is enigmatic. The Log correlations of albite with both Sr and Hg are quite low (0.18 and -0.01, respectively). The distribution of Hg, as suggested below, has likely been affected by later hydrothermal activity.

Factor 5 is defined in terms of a pair of common ore-forming elements, Pb and As. Pb is anomalous in locality 3 (up to 85 parts per million (ppm)), and As is anomalous in general in the study area but not in samples from the localities used in the factor analysis. Factor 5 apparently reflects another mineralizing event, separate from that of the stratabound one (factor 3), and one probably related to the same, later hydrothermal activity mentioned for factors 3 and 4.

Finally, factor 6 is associated with U and total C. This relation is more apparent than real, however, as the logarithmic correlation of U and total C is low, 0.24 (only 6 percent common variance). The relation is dominated by a single sample from locality 7 which contained both high U (14.9 ppm) and high calcite (1.7 percent in the norm). Expected concentrations (table 5) are 2.1 ppm for U and <0.2 percent for normative calcite (based on <0.1 percent CaO). If that sample is discarded, the log correlation between U and C becomes -0.10. The variation in total C is largely controlled by the distribution of calcite which, as noted above, has probably been localized by the Late Proterozoic diorite sill.

U shows a moderate loading on factor 1, and its highest log correlation is with Nb ( $r=0.56$ ; 31 percent common variance). Some part of the variation in U can, thus, be attributed to variation in factor 1 (probably in the mica distribution), but the larger part of its variability appears to be essentially independent of all other elements in the factor analysis. Possibly, this variation reflects a postdepositional rearrangement of U, but, as no anomalous U concentrations are known in the Rogers Pass area, it is unlikely that this represents a mineralizing event. The moderate positive loadings of Log Nb and Log Ag on this factor suggest that this rearrangement of U may have been accompanied by minor rearrangement of Nb and Ag, also.

In summary, the factor analysis has identified the Cu-Ag mineralization as an event independent of host-rock composition, clearly indicated the existence of a second mineralizing event (Pb-As), and suggested that the U distribution in these rocks results largely from some kind of postdepositional process(es) separate from the two episodes of mineralization.

## Mineralization

The typical quartzite lens in the Spokane Formation of the Rogers Pass area is enriched in Cu, Ag, Hg,

and Ba, when compared to levels in nonmineralized sandstone:

	Mineralized quartzite (table 5)	Nonmineralized sandstone (Rossler & Lange, 1972)
Cu, ppm	1200	10-40
Ag, ppm	6.2	0.X
Hg, ppm	.13	.03
Ba, ppm	510	X0

Cu, Ag, and Ba are enriched as much as 100 times background, and Hg is enriched four times over background.

Stratabound Cu-Ag mineralization in the typical Spokane quartzite in the Rogers Pass area is spotty and low-grade and exhibits a simple mineralogy. The main sulfide mineral is chalcocite; bornite is rare and always occurs as relict cores in chalcocite. The bornite is, therefore, prechalcocite but may nevertheless be part of the same mineralizing event. Trammell (1975, p. 27) noted digenite and native silver in these rocks as well. Locally, covellite occurs as needles in or coatings on chalcocite. The covellite is postchalcocite and is likely the product of weathering.

The most prominent weathering product is malachite. In general, more than 70 percent of the Cu in these

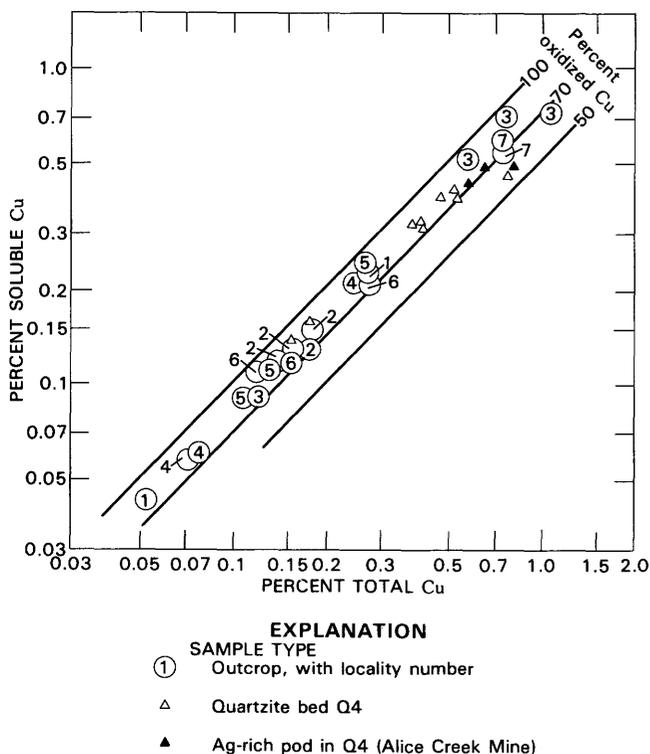
lenses has been oxidized to malachite (fig. 7). Even in the relatively fresh working face of the Alice Creek Mine, over 50 percent of the Cu is in malachite. The malachite occurs as disseminated specks or splotches or in veins and cracks and may or may not be associated with relict sulfide.

Most of the Ba in these rocks is in barite, which has three modes of occurrence. The most common form is anhedral blebs. In samples from locality 3, however, the barite occurred as euhedral crystals in large (1-mm diameter) clots of intermixed malachite, relict sulfide, and low-refracting clay of unknown composition. Locally, euhedral crystals of barite were observed in veins. Each of these three occurrences might represent a different mineralizing episode, although the barite associated with the oxidizing sulfide and the dispersed anhedral blebs were both likely part of the stratabound Cu-Ag event. Hayes (1984b) suggested that barite forms an integral part of mineralization in occurrences in the Revett Formation.

The mineral form of the Ag and the Hg in the typical mineralized bed is largely unknown, although Trammell (1975, p. 27) noted some disseminated native Ag. Logarithmic correlations of Ag and Hg with other elements are given in table 8. The correlations are based on the same 24 samples used in the factor analysis. The highest correlation for Ag is with Cu at  $r=0.44$  (19 percent common variance); the highest correlation for Hg is with S at  $r=0.64$  (41 percent common variance). This suggests that at least some of the Ag probably resides in the copper minerals and at least some of the Hg may be in cinnabar. These low correlations may reflect the effects of dispersion upon weathering or the presence of other, unknown phases, or both.

The timing of the stratabound Cu-Ag mineralization in quartzite beds of the Spokane Formation in the Rogers Pass area is unknown. In general, such mineralization in Belt rocks is believed to be diagenetic (Hayes, 1984a) or at least prelithification (Harrison and Reynolds, 1979). Trammell (1975) conjectured that at least some occurrences were formed by expulsion of connate fluids.

The Rogers Pass area displays abundant evidence of Tertiary hydrothermal activity, centered on the Heddleston Mining District (fig. 1). As noted previously, Earhart and others (1981) suggested that a large area of buried porphyritic plutons extends to the northwest from the Heddleston District. Part of the evidence for this buried system is a regional Hg anomaly above it (Earhart and others, 1981). And Hg in the Spokane lenses shows a strong regional effect (table 2), at least part of which appears to be related to nearness of known Tertiary intrusives (fig. 8). Samples collected 3900 m or more from known intrusive outcrops average about 0.2 ppm Hg, whereas samples from localities 1 and 3, collected within 1500 m of known intrusive outcrops, average twice that amount and range up to 3 ppm Hg. Samples from



**Figure 7.** Oxidized Cu (malachite) in mineralized quartzite beds of the Spokane Formation in the Rogers Pass area, Montana. One sample each from localities 4, 5, and 6, and two from locality 7 contained less than 0.03 percent total Cu.

**Table 8.** Logarithmic correlation coefficients of Ag and Hg with other elements in mineralized quartzite in the Spokane Formation of the Rogers Pass area

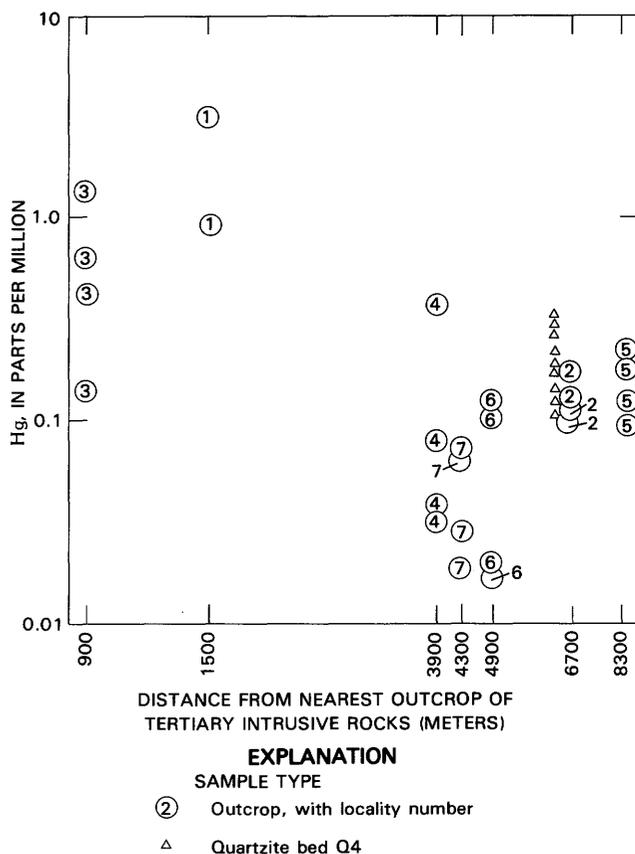
Log	Log Ag	Log Hg
Al	-0.12	-0.43
As	.13	.15
Ba	.34	.29
C	-.13	-.32
Ca	.12	-.50
Co	-.06	-.59
Cr	.02	-.26
Cu	.44	.22
Eu	.30	-.04
Fe	-.01	-.43
Gd	.38	.00
Ge	-.14	-.25
Hg	.26	--
K	.04	-.27
La	-.03	-.52
Mg	.01	-.50
Mn	.08	-.61
Na	-.03	-.53
Nb	.06	-.26
Ni	.03	-.47
Pb	-.05	-.19
S	.29	.64
Sc	-.04	-.59
Sn	-.10	-.19
Sr	-.20	-.27
Th	-.21	-.28
Ti	.21	.03
U	.30	-.44
V	.06	-.30
Y	.22	-.02
Yb	.03	-.33
Zn	.21	-.31
Zr	-.06	.04

localities 1 and 3, however, are not appreciably higher in Cu or Ag than samples from other localities (table 2).

In addition to a possible Hg effect, anomalous concentrations of As, Ge, Sb, Pb, and Mo were also found in localities 1 and 3. Locality 1 contained 13 ppm As and 4.0 ppm Ge on average (table 4) compared to expected levels in these rocks of 1.1 ppm for both elements (table 5). Also, samples from locality 1 contained up to 26 ppm Sb (table 5, footnote 1) compared to an expected level of <0.2 ppm (table 5). One sample from locality 3 contained 85 ppm Pb and 9 ppm Mo (table 5, footnote 1) compared to expected levels of 6.2 and <1.0, respectively (table 5). The factor analysis suggested a mineralizing event separate from the Cu-Ag stratabound event based on concentrations of Pb and As. These two trace metals, along with the Ge, Sb, Mo, and the Hg, appear to constitute a hydrothermally related overprint on the Cu-Ag-bearing lenses in localities 1 and 3. Both localities lie near the trace of the Scapegoat thrust (locality 1 is intensely fractured) whose sole conceivably could have acted as a conduit for hydrothermal fluids.

## Alice Creek Mine

The Alice Creek Mine consists of a small, high-grade pod of Ag in quartzite bed Q4 of locality 2 (fig. 2). Inside this pod, samples ranged up to 280 oz/t Ag (8400 ppm; see Connor and others, 1979). Outside the pod but still in Q4, samples ranged from 0.5 oz/t to 4 oz/t Ag (18-130 ppm). Cu concentrations inside the pod are no higher than in the richest samples taken from other lenses, but the exceptionally high Ag may indicate a source of Ag different from that which produced the typical stratabound accumulations. Silver minerals in the high-Ag pod include acanthite and native silver, but these were not unobserved outside the pod. Samples from the high-Ag pod are extraordinarily high in Hg also, up to 427 ppm (Connor and others, 1979). They are also anomalously high in Pb (table 9), and one sample from the pod contained 55 ppm Ge (table 9, footnote 2). The form of the Hg, Ge, and Pb is unknown, but if the anomalously high Hg, Ge, and Pb content here represents Tertiary hydrothermal activity (as it appears to do in localities 1 and 3), then most likely so does the anomalously high Ag.



**Figure 8.** Hg in mineralized quartzite beds of the Spokane Formation in the Rogers Pass area, Montana. (Samples from high-Ag pod not shown.)

**Table 9.** Geochemical comparison of the Alice Creek Mine to typical mineralized quartzite in the Spokane Formation of the Rogers Pass area

[Data are in parts per million, except where noted as percent (%); GM, Geometric mean; M, Median; Tot, Total; Sol, Soluble; dashes (--), no data; number in parentheses is number of analyses on which estimate is based]

Constituents	Alice Creek Mine (bed Q4)		Typical quartzite (from table 5)
	High-Ag pod M (4)	Outside pod GM (13)	
Ag	7300.0	53.0	6.2
Al <sub>2</sub> O <sub>3</sub> , %	5.4	5.9	8.1
As	<.2	1.2	1.1
B	<5	<5	8.5
Ba	3400	1700	510
C-Tot, %	.035	.025	.039
CaO, %	<.1	<.1	<.1
Ce	84	68	38
Co	1.6	.97	2.7
Cr	8.3	7.5	17
Cu-Sol, %	.46	.29	.10
Cu-Tot, %	.61	.36	.12
Er	<4.6	<4.6	5
Eu	<2.5	1.9	1.6
FeO, %	.15	.15	--
FeTO <sub>3</sub> , % <sup>1</sup>	.12	.24	.88
Ga	<2.2	<2.2	1.4
Gd	<2.2	5.8	4.7
Ge	23.1	.68	1.1
Hg	280	.2	.13
K <sub>2</sub> O, %	.48	.64	.74
La	20	20	18
Mg, %	.15	.17	.27
Mn	110	100	88
Nb	10	9.2	11
Nd	<46	<46	40
Ni	2.2	2.6	5.1
P <sub>2</sub> O <sub>5</sub> , %	<.1	<.1	.059
Pb	65	8.4	6.2
S-Tot, %	<.1	<.1	.11
Sc	2.8	2.7	3.3
SiO <sub>2</sub> , % <sup>3</sup>	90	88	81
Sn	<.6	.39	.58
Sr	160	160	120
Th	4.8	6.5	7.7
TiO <sub>2</sub> , %	.16	.22	.31
Tm	3.3	2.8	<2.2
U	2.2	2.2	2.1
V	7	6.6	15
Y	14	17	23
Yb	1.1	1.3	1.5
Zn	16	17	27
Zr	140	190	250

<sup>1</sup>Total Fe measured as Fe<sub>2</sub>O<sub>3</sub>.

<sup>2</sup>Sample JM8BC5 contained 55 ppm Ge.

<sup>3</sup>Computed on untransformed data.

The origin of the elevated Ag and Hg in the Alice Creek Mine remains obscure. The mine is adjacent to a fault, but the fault is small (about 6 m of throw) and unmineralized and appears to be a slip face on a slump block rather than a fault of regional extent. The linearity of nearby Alice Creek suggests that the creek was developed along a fault trace, but no other evidence exists for faulting there. The Alice Creek mine does not seem to be fault controlled.

Many of the mineralized lenses on Green Mountain are cut by a series of thin, roughly east-west trending, nearly vertical quartz veins. These veins are perpendicular to the probable direction of least stress and may have formed during the time of regional thrusting in the area. In the Alice Creek mine, these veins contain some chalcocite and secondary oxidation products but no acanthite or native Ag, and because of the general lack of ore mineralization in these veins elsewhere, the origin of the high-Ag pod is not likely related to either the vein formation or to the thrusting. The Alice Creek Mine sits in the axial plane of a gentle syncline of regional extent (fig. 1), which also probably formed during thrusting, and which may have localized or helped to localize the hydrothermal ore-forming fluids postulated as the source of the high-Ag pod at the mine.

## SILVER RESOURCE OF GREEN MOUNTAIN

No other Ag-rich pods have been found in quartzite beds of the Spokane Formation in the Rogers Pass area, but a large number of typically low-grade mineralized lenses crop out on Green Mountain (fig. 1). These lenses collectively constitute a moderately large tonnage of mineralized rock.

Almost all of this tonnage lies in two bodies near the crest of Green Mountain, labeled GM1 and GM2 on figure 3. GM1 (Green Mountain lens 1) is the larger of the two and was judged as having a minimum length of 1200 m, a minimum width of 600 m, and an average thickness of 1.5 m. This estimate gives a volume of approximately 1,000,000 cubic meters or about 2.7 million metric tons. GM2 (Green Mountain lens 2) was estimated to have a minimum length of 1500 m, a minimum width of 500 m, and an average thickness of 0.5 m. This estimate gives a volume of approximately 375,000 cubic meters or a little more than 1.0 million metric tons.

Of about 20 smaller lenses seen at the surface in the area, none exceeded an outcrop length of about 100 m (a bit larger than some of the lenses in locality 2, fig. 2), and most were much less than half a meter in thickness. Based on an estimated average length of 30 m, an average width of 15 m, and an average thickness of 0.5 m, the collective tonnage of 20 bodies is approximately 4500 cubic meters, or at most 12,000 metric tons. The

median Ag content of all lenses is estimated at 6.1 ppm (table 5) or 0.2 oz/t.

The 3.7+ million metric tons estimated in outcrops on Green Mountain thus could contain over 700,000 oz Ag. To the extent that the Green Mountain area contains additional Ag-rich pods of the Alice Creek type, this estimate would rise by about 10,000 oz for each occurrence. However, as the 700,000-oz estimate is based solely on outcrop sampling, it must be viewed very cautiously.

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