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ASPEN-SNOWMASS MOUNTAIN AREA, COLO.

J.W.Vanderwilt,1937: Geology and mineral deposits of the Snowmass Mt. area, Gunnison Co.,Colo. USGS Bull.884.

Elk Mts.,west of Aspen.

Paleozoic seds. No deformation. Cretaceous,Upper Jurassic. Upper K Dakota ss.,Mancos shale. (Senomanian,Turonian,into Senonia).

81 Structural History: Earliest folding shown by angular unconformity ate base of Jurassic. Then K beds deposited. Eend of K,early Tertiary, displacements of more than 7000' along Elk Mt.fault zone,parallel to Castle Creek fault at Aspen,The 2 join to the NW and pass into Grand Higback fold.Regional SW dips W of Elk Mt.fault zone, NE dips E of it.

After faulting ceased,intrusion of GD in Elk Mts.,granite,Treasure Mt. Granite domed he beds,faults,fractures produced.Mineralized.

82 Unconformity at base of Ju now domed at Trasure Mt.Trend of bevelled edges of Paleozoics about N40 W,parallel to domiant trend of more recent Rocky Mts. Influence of earlier deformation on later.

83 Elk Mt.fault zone-zone of uplift,folding,faulting;three large intrusives along it. Grand Hogback fold contiinues to NW,then west along S side of Uinta Mts. to Wasatch Mts.

85 Three types of movement:(1)monoclinal fold,uplift on E.(2)reverse fa ulting,horizontal and vertical components equal;(3) thrusting,horizontal movement dominant. This changes to normal faulting to NW.Whole assemblage.

86-87 Grand Hogback Ranks White River Plateau.

89 Stages:(1) Monoclinal fold devel ped owing to uplift of area on E. (2) Horizontal component gecame relatively more importat;upper limb of monocline arched into an anticline.(3) Horizontal component dominant thrusting initiated alon a surface more or less parallel to bedding of upper block.

91-92 GD of Snowmass Mt.,granite of Treasure Mt.intruded along fault zone after faulting had ceased.

Dome elliptical,long axis NW parallel to Elk Mountain fault zone.

93-94 Faul s longitudinal,all but one on NE flank.Steep dip E. Mineralized.

95 Dome younger than fault zone becau se it is superimposed on regional SW dips W of fault zone.

96 Age of Grand Hogback fold s post-Bridger(middle Eocene). On this basis Treaure Mt,dome would be yunger;but there is evidence that movement Enlk Mts,was earlier than movement at Grand Hogback. So the dome and Hogback could be contemporaneous.

WISSER AND COX geologists - engineers

100 <u>Ore Deposits</u> 101. Veins, bedded replacements. Qtz main gangue in veins; fluorite. ZnS, ccpy, PbS. Silver not always commercial. Py. Mn-hedenbergite. Barite-, calcite -. Inramineral movements.

Bedded deposits similar but lack bulky qtz.

ASPEN, COLO.

E.W.analysis based on:

Spurr, J.E.,1898, Geology of the Aspen mining district,Colo. USGS Monograph 31. Spurr,1909,same title,Econ.Geol.vol.4,301-320.

Vanderwilt, J.W.,1935: Revision of structure and stratigraphy of the Aspen district,Colo.& its bearing on the ore deposits.Econ.Geol. v. 30,223-241.

R cks:Precambrian granie of Sawatch uplift on E. 6000' Paleo,4600' Jura-Trias. 4700' K. Only intrusion sills,K to Eocene.

After deposition of Laramie (uppermost Ku) folding in form of uplift along axis or present Sawatch Rge. Sediments dragged up to vertical along west flank. Castle Creek fault marginal "thrust." See Golden paper.

In opposing Spurr's theory of tangent al forces from intrusions on the W as causing Aspen deformation, Vandwerwile says (p.233): "Tangential have become the conventi nal explanation of mountain structure,but within the exposed vertical limi s of the regional structure described above there is little or no direct evidence f such forces;on the other hand,both the large vertical displacements"(Elk Mt,zone and Castle Creek fault zone)"as well as the zones of more highly disturbed formations,can be explained readily by vertical movements of the White River Plateau and the Sawa ch Range."

A sharp antic ine in the Paleozoics lies next the Castle Creek fault;sharp syncline on E .

Faults cutting anticline anf syncline:axial and cross faults,some of which cut the Castle Mt.fault,NE to E,crossing fold axes at 45-90.

Galena-blende ore low in silver;rich silver sulfantimnides and sulfarsenides;barite veins. Main ore bodies localized at intersection of faults and fissures at sedmen ary contacts. mai ly that between Leadville ls.and dolomite.

ORE DEPOSITION AT ASPEN, COLORADO.

J.E.Spurr: EG 4(1909) 301-320.

Abstract, with notes by E.W. Accompanying plan and sections from Spurr:Geology of the Aspen Mining District,Colorado.USGS Mon.31('98)

Column-				
	Cret.	Lower Laramie		
		Montana	4000'	
		Niobrara (Colorado)	450	4700' Cret.
		Benton		
		Dakota	250	
	Jura-Tr	Gunnison	3000	5600' Jura-Trias.
	Trias	Light red ss	2600	
	Upper Carb	Maroon	4000	Dark red sandy & limy seds.
		Weber	1000	Thin-bedded Carbonif ls & carb & calc sh.
1000' paleo	Lower "	Leadville		
		Limestone	125	
		Dolomite	200	
	Devonian	Parting qtzite	60	Shaly dolomite & qtzite
	Silurian	Yule	350	Dolomite
	Cambrian	Sawatch	300	Qtzite
	Pre-Cambrian granite.			

Intrusions: (1) Rhyolite porphyry,same as White porphyry of Leadville,which is across the Sawatch Range from (E of) Aspen. As a 250' sheet near base of Weber shales; steep feeder dikes below. Blocked by the soft shale, the rising rhyolite spread as a sheet.

(2)Diorite porphyry, green, fine-grained. As a single sheet nearly parallel to the beds. Pinches out going N at town of Aspen;it was followed 3.5 mi.S,where it is 150' thick. It gradually transgresses the beds,from the Devonian at S end of mapped area to the base of the Cambrian, where it dies out to the N. The diorite porphyry runs into the Castle Peak diorite mass, 10 mi.S of Aspen.

The age of these intrusions is Laramide: late Cret.to Eocene.

Structural History.- After deposition of the Laramie there was folding,partially contemporaneous with the above intrusions.

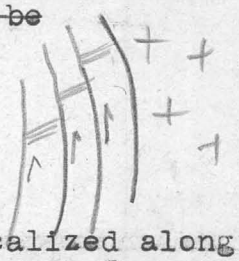
Dominant feature was uplift along the axis of the present Sawatch range,an uplift still going on. The sediments on the basal granite were upended and dragged up on the flanks of the growing granite range. (See sections).At about the same time there was thrusting from the west,probably connected with the great diorite intrusion along the axis of the present Elk Mts. This jammed the sediments against the Sawatch granite buttress producing a narrow belt of overturned, east-dipping folds (sections B,C,D & plan). The thrusting culminated in the great Castle Creek fault originating along the axis of the main overturned anticline.Maximum vertical element of dislocation as se en on a vert.section,9000'. The upthrown side is the Sawatch range.

Note by E.W. Compare sections mentioned with Plate IX, Behavior of Rocks under Deforming Stresses: Cloos experiment whereby a graben was fommed by a dropped center block. Here we deal with a pushed-up block, but as always, it makes no difference: differential vertical movements are the sole requirement. The Castle Creek fault is the synthetic shear plane along which the uplift was affected . Owing to the overturn shown on the sections, the beds tended to flow west (or bend) down the flank of the uplift, so the synthetic fault bent west ward likewise East of the fault, however, the beds on top of the granite, on the up-shoved block, were flattish , and the interbed antithetic slipping shown on Plate IX took place as described by Spurr below.

x x x x x x x x

The uplift of the Swatch Range and the up-dragging of the sediments along its base was accompanied by slipping of one bed upon another, those nearer the granite slipping upward past those farther away:

Compare with Plate IX: this is synthetic interbed slipping and corresponds to the strands of the synthetic fault of Plate IX; ~~it is not the antithetic interbed slipping to be described.~~



These slips were localized along the weaker beds and are often faults of great displa cement. The main such fault is the Silver, at the base of the Weber shale, in general, but it cuts slightly across the beds so that in the N part of the district it has eliminated whole formations (Section B, where the Silver fault has cut halfway up into the Weber). Movement along the Silver fault began early in the orogeny and still con tinue s. Other faults of this system lie along the contact of the limeste tone with the dolomite member of the Leadville formation; along the Weber-Marron contact, and along the Parting quartzite.

At the same time as the beginning of the Sawatch Range uplift (which produced these bed faults and the Castle Creek fault) and the intrusion of the Elk Mts. diorite (which produced the sharp folding and thrust stress) there began in the Aspen district local doming due to a vertical shove. The domed-up rocks include the pre-Cambrian granite just east of the Castle Creek fault, and the dome extends N & S for a limited ditance. This doming was accompanied and aided by faulting, and still continues. The Summit of the dome is broken by intersecting fractures bounding numerous fault blocks which moved one past the other as doming continued. Maximum uplift was 5000'. The doming was caused by an upward shove of igneous molten rock which never reached the surface.

Metallization occurred at the beginning of uplift, after considerable faulting & fracturing. Ore bodies along faults and fractures, either along steep faults or more commonly at intersections of steep faults with flatter faults. Epoch of mineralization short compared with that of the faulting.

The center of ore deposition corresponds to the center of domal uplift. The latter centers in Tourtelotte Park and Aspen Mt. Smuggler Mt. lies on the NE border of the uplift, and the deposits on the west of it include those along the Castle Creek fault in Queens Gulch and southward. The vertical range of mine workings is 3500' and exhibits no change in the nature of the ore deposits. There are notable deposits on the N slope of the dome, in Aspen a nd Smuggler Mts. Near the central and broader portion of the dome, the ore deposits, coincident with the faulted area, o ccupy a wide belt. Where the domal structure fades out to the north and is effaced by dominant powerful folding & faulting paralle l to the NE axis of the Sawatch Range, and caused by the uplift of that ra nge, the zone of faulting narrows in horizOntal section, and the coincident be lt of ore deposition becomes comfined to the areA OF ONE or two of the main bed faults (Silver, Clark faults; "Park Regent etc. mines).

Dips of the beds in the region, even where most steeply upturned are (except lo cally) away from the range. The ore solutions ascended so fa r as possible ve rtically, passing therefore first thru granite and then into successively higher formations. More or less ore is found along channels thru the whole sedimentary range and into the granite. But optimum deposition depended on favorable formations (precipitative reactions) and intersecting channe ls. Ore is neglible in granite and the Sawatch quartzite. Locally there are large OBs in the Yule dolomite, along faults. The Leadville dolomite and ls are highly productive. But the main ore horizon is at the base of the Weber shale, at the contact with the underlying ls. or dolomite. This contact is usually the Silver fault, which very nearly parallels the beds. There is very little ore in the Webe r shale. Along other faults, where Weber shale lies on one side there is abundant o re. Localization by damming by Weber shale or rhyolite porphyry sheet at its base. Three classes of mineralization: (1) galena-sphalerite, low in silver; rich silver sulphantimonite and sulpharsenite ores; barite veins.

<u>History, Smuggler Mine:</u> Faulting began with development of Silver faul t, striking NE, dipping 65° NW. (Section A'). Next, the Smuggler-Gibs n fault de veloped, striking NW, dipping 30 SW. This displaced the Silver fault and made a flat bench in the contact between the Weber shale above the Silver fault and the Leadville dolomite below it. Then came renewed movement along the Silver fault, with similar movement along the Parting quartzite (Clark fault). This movement, harmonizing with that on the Silv er and othe r bed faults (being the dragging up of the block on the SE side, neare r the Sawatch Range, past that on the SW side, farther away from the range, the whole recording the further growth of the range) separat ed the flat bench of the Smuggler-Gibson fault into two portions, an upper and a lower bench. The vertical (actually oblique movement) component of the Clark fault movement of this period was 300'. Next came ore deposition along all the faults, in three stages separated by faulting; finally, Clark post-mineral movement of 400' vert. component.

(1) Barre n barite veins in open fissure-filling veins following beds, along and near the bed faults; (2) with no sharp break, complex Ag-As-Sb, Cu mineraliz. Polybasite, argentite, tetrahedrite, tennantite. These minerals fill slight crevices in the barite veins. Main shoot of Smuggler-Molly Gibson bonanza. (3) Brecciation along Clark and Silver faults, deposition of galena low in silver and blende.

E.W. Note s from Pla n and Sections.- The Castle Creek, like most synthetic faults, was conditioned by the straight west side of the domed up granite, south of the town of Aspen, and as Spurr says, took its origin from the N-S anticline here. Since however the sharp folding was caused by thrist from the west against the Saw tch granite buttress, it is likely that the granite mass had a stright N-S side here. N of Aspen the fault w nders off into the sediments; its flat SE dip shows the great flow of the soft sediments down the flank of the major uplift. The Lenado fult is a second simi;ar synthetic fault conditioned by the NE side of the reentrant in the Sawatch mass. The Silver fault, hugging this flank in the reentrant, clearly has its origin as Spurr says. A s shown on Sections A''' to C''', the massive Sawatch qtzite, Yule dolomite and Leadville dolomite and ls. clung for the most part to the granite, but the soft Weber shale slipped at its base.

Development of the local dome on the west of the main uplift is well shown by Sections A' (north of dome, no dome); B', diapir uplift betwe en Mary B and Pride faults (N point of dome); C', same, betwe en Castle Creek and Pride faults.

The " set of sections cover the dome proper. The plan shows the Pride Sarah Jane and Schiller faults to be radiating fissures on the N end of the dome. E-W sections A" to F": A" shows little E-W arching, but such arching becomes marked in B" and more so in C", where (~~both~~ all sections) the Justice, Sarah Jane and Saddle Roc k faults are apparently antithetic faults toppling toward the west. E" and F" show essentially the same thing, and the dome runs south off the mapped area.

N-S sections G" to I": I" is too close to the west border of the dome to show much. H" and G" show the dome continuing to rise south, off the map. The plan shows numerous cross joints indicating that the uplift was accompanied by constriction normal to its major axis (Sawatch butt re ss on east, thrust stress on west. H" shows that these cross joints on the south part of the section acted as antithet c faults aiding the N-S elongation, and toppling to the N away from the highest or south part of the dome. Some of these cross joints are however synthetic faults aiding the uplift.

silver and the presence at one place of secondary calcite intergrown with the silver indicate that the silver-depositing waters were not acid.

10. Chemical data are cited to show that this interpretation of the quality of the enriching solutions is consistent with the observed solution of barite simultaneously with the deposition of native silver.

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Bulletin 750—C

OBSERVATIONS ON THE RICH SILVER ORES OF ASPEN, COLORADO

BY

EDSON S. BASTIN

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lets of later primary galena, sphalerite, bornite, chalcopyrite, pearceite, and calcite, as shown in Figures 13 and 14. Elsewhere a division into two groups can not be made, all the primary minerals having apparently been deposited essentially contemporaneously, as suggested by the relations shown at A, Figure 13. Texture characteristic of a common type among the rich silver ores is shown in Plate III. In one specimen tennantite, pearceite, and argentite occur intimately intergrown and all apparently primary. (See fig. 15.) No evidence was found of more than one general period of primary mineralization.

3. Downward enrichment in silver has been most effective in those ores in which primary silver minerals were abundant. The principal secondary silver mineral deposited by the waters working down through the ore bodies from the surface was native silver, but in some places secondary pearceite and argentite were also deposited, as shown in Figure 16.

4. Native silver plays out with depth and is clearly a product of downward enrichment. It was noted to vertical depths of around 1,200 feet.

5. Most of the native silver has been deposited through the replacement of older minerals. Silver compounds are commonly the first minerals to yield to such replacement, but the replacement eventually involves base-metal sulphides and finally barite. (See figs. 17 to 21.)

6. Some tapering and curling "teeth" and wires of native silver have grown outward from their point of attachment into the open spaces of vugs and fractures. Many of them are attached to a base of pearceite and have clearly formed at the expense of this silver compound. Some wires, teeth, and plates of silver in vugs and fractures are not now associated with any silver compounds, but it can not be demonstrated that such compounds were absent at the time the silver was deposited.

7. Notable oxidation was observed in or adjacent to the ore bodies to a depth of around 1,000 feet.

8. Mine waters were tested at several points. All were cool descending waters, neutral or very faintly alkaline in reaction. Two samples were analyzed, and their quality is shown diagrammatically in Figure 22. They are dominantly calcium and magnesium sulphate and bicarbonate solutions, though alkalies are also present.

9. It seems probable that the waters instrumental in the deposition of the native silver were similar in quality to those analyzed. It is known that silver can be effectively transported in solution in balance with either the sulphide or bicarbonate radicle. The abundance of limestone and dolomite in association with some of the native

It has been shown by Z. Karaglanow [10] that through the influence of various electrolytes the solubility of $BaSO_4$ in water may be increased or diminished. It is diminished if the electrolyte contains ions in common with $BaSO_4$; it is increased if the electrolyte possesses the property of removing barium or sulphate ions from the solution. He concludes that

> the solubility of $BaSO_4$ in different electrolytes is determined by two factors, the anion and the cation. The anion SO_4 diminishes the solubility, NO_3 increases it, and Cl is indifferent. Of the cations, Ba diminishes the solubility of $BaSO_4$, while Ca is indifferent, and K, Na, Sr, Pb, Fe, and H increase it.

The influence of the carbonate or bicarbonate radicle on the solubility was not studied by Karaglanow, but some observations by P. Carles [11] have a bearing on this point. In order to account for the simultaneous presence of barium and alkali sulphates in the mineral waters of Néris-les-Bains, France, the following experiment was made. A specimen of barytes from the district was boiled with twice its weight of sodium carbonate until partly converted into barium carbonate. The still alkaline paste was then supersaturated with carbon dioxide under pressure and filtered after 12 hours. The perfectly clear filtrate, which contained sodium sulphate, deposited barium carbonate when the excess of carbon dioxide was expelled by heating.

It is evident that alkali hydrogen carbonates in the presence of an excess of carbon dioxide are capable of holding barium hydrogen carbonate in solution in the presence of soluble sulphates.

From these experiments it would appear that the presence of alkali bicarbonates in a solution may appreciably facilitate the solution of barite. It is not unreasonable to suppose, therefore, that the waters that dissolved barite and deposited native silver at Aspen were of a quality similar to the present mine waters. It is well known that silver may be readily transported in mine waters in balance with either the sulphate or the bicarbonate radicle.

SUMMARY.

1. The lead ores of concentrating grade that constitute the present main economic resource of the Aspen district pass in places, apparently gradationally, into ores consisting dominantly of tennantite or of tennantite and barite but also rich in silver minerals. Some of these ores that carry silver only as primary pearceite and argentite are very rich.

2. In some places in the rich silver ores tennantite and barite are the oldest primary minerals and are traversed by replacement vein-

[10] Zeitschr. anal. Chemie, vol. 56, pp. 225–246, 1917.
[11] Chem. Soc. Jour. Abstracts, vol. 80, p. 506, 1901.

OBSERVATIONS ON THE RICH SILVER ORES OF ASPEN, COLORADO.

By Edson S. Bastin.

INTRODUCTION.

In September, 1913, the writer paid a brief visit to the famous old silver camp of Aspen, in Pitkin County, southwestern Colorado, to obtain samples of the rich silver ores for microscopic study. Systematic studies of the distribution of the rich silver ores in the mines and of many other factors that have a bearing on their origin were not practicable in the time available, but some incidental observations on the depth of oxidation and downward enrichment and on the quality of mine waters are here recorded. Two analyses of mine waters were made by Chase Palmer, then with the United States Geological Survey. For more detailed accounts of the general geologic features of the district the reader is referred to the well-known reports of J. E. Spurr.[1]

The writer's observations are offered as a brief contribution to the problem of the origin of the rich silver ores of Aspen, with full recognition of the desirability of amplifying them and of supporting them by other lines of field evidence. As the writer will be unable personally to undertake such studies the data are here placed at the disposal of other observers.

GENERAL GEOLOGIC FEATURES.

According to Spurr [2] sedimentary rocks exposed at Aspen include formations of Cambrian, Silurian [Ordovician], Devonian, Carboniferous, Triassic, Jurassic, and Cretaceous age, which rest upon pre-Cambrian granite. These rocks were intruded in late Cretaceous or early Tertiary time by rhyolite and diorite porphyries, of which the former are the more abundant.

The intrusions in the main assumed the form of sills or sheets forced in between the sedimentary beds and parallel to them. The largest is a sheet of rhyolite porphyry 250 to 450 feet thick intruded

[1] Spurr, J. E., Geology of the Aspen mining district, Colo.: U. S. Geol. Survey Mon. 31, 1898; Ore deposition at Aspen, Colo.: Econ. Geology, vol. 4, pp. 301–320, 1909.
[2] Spurr, J. E., op. cit. (1909).

at the base of the Weber (?) shale[3] (Carboniferous), which formed a yielding roof above the intrusion. Crosscutting dikes of rhyolite porphyry are probably offshoots from this sheet.

During the intrusion of the porphyries and subsequently the sedimentary rocks were folded and greatly faulted, and some of this deformation, according to Spurr, was a direct effect of the intrusion. Some of the faulting took place along bedding planes between formations; the fault of this type that is most significant in connection with ore deposition is the Silver fault, at the base of the Weber (?) shale.

Ore deposition followed closely upon the intrusion of the porphyries and took place along steeply inclined faults and along bedding-plane faults near their contacts with steeper faults. Mineralization occurred in all the formations from the pre-Cambrian granite to the Tertiary (?) intrusive rocks. That in the pre-Cambrian is economically negligible. Some ore occurs in Ordovician dolomite, and much in lower Carboniferous (Mississippian) and Devonian (?) dolomite and limestone. The chief ore horizon is the Silver fault, at the base of the Weber (?) shale (Pennsylvanian).

According to Spurr primary ore deposition was limited to a single period, which was brief as contrasted with the duration of faulting. Within this period he recognized three stages characterized by dominance of different minerals but showing transitions.

The first stage recognized is the deposition of barite in regular veins, usually parallel to the stratification. Some of these veins barren of sulphides represent the beginnings of mineralization in the district.

The second stage involved the deposition of tetrahedrite, tennantite, polybasite (?) [probably mostly pearceite.—E. S. B.], and argentite. In places these minerals occur intercrystallized with barite and apparently about contemporaneous with it, but elsewhere they occupy fractures in barite and are therefore slightly though probably not greatly younger. The rich ore shoots that made the Smuggler Union and Mollie Gibson mines famous were mainly formed at this stage along the Silver fault, and many of the rich specimens that form the special subject of this report came from these ore shoots. These rich silver ores were largely worked out many years ago, and representative specimens could be obtained only from private collections and from jewelers at Aspen.

The third stage in the mineralization involved the deposition of finely crystalline galena and subordinate sphalerite, mainly by the replacement of dolomite and limestone and in some places after breccia-

[3] These rocks are not now regarded as equivalent to the Pennsylvanian Weber quartzite of Utah, the typical Weber formation. See Colorado Geol. Survey Bull. 10, pp. 64–67, 1916.

These waters resemble each other in their low content of alkalies and metals and their high content of earths. Both are low in chlorine. They contrast principally in the larger percentage of SO_4 radicle in the Durant tunnel sample. Both are dominantly calcium and magnesium bicarbonate and sulphate waters. Their composition is such as might be expected in waters of surface origin that have descended through a sedimentary series including limestone and dolomite. Their quality is neutral or slightly alkaline.

It is probable that the descending mine waters that deposited most of the native silver of the Aspen ores were similar in general composition to those analyzed.

As indicating that at least some of the native silver was deposited from calcium bicarbonate waters, the presence of calcite intergrown with native silver along fractures in dolomite at a depth of about 500 feet in the Aspen mine is noteworthy. The following statement by Spurr[9] is also of significance in this connection.

> In the concentrating works at Aspen, where ore is crushed and separated by means of ordinary cold water, certain iron parts of the apparatus become coated with native silver precipitated from the water that flows over them. This shows that ordinary surface waters have power to dissolve and carry away silver, which they deposit under favorable circumstances.

It is clear as a result of the microscopic studies that the waters which deposited native silver in many places simultaneously dissolved barite. In view of the extremely low solubility of barite under most natural conditions this observation warrants some discussion. The deposition of barite from natural waters, some of them of deep-seated and some of surface origin, has been repeatedly observed, but most of these waters are dominantly chloride solutions and so show no analogies to the Aspen mine waters.

Barium sulphate is soluble in pure water at 18° C. to the extent of about 24 milligrams per liter. The presence of free sulphuric acid in mine waters would not facilitate the solution of barite, for the solubility of barium sulphate in sulphuric acid solutions is actually diminished or even destroyed if the concentration of the acid is higher than 0.3 normal; with lower concentrations the solubility is almost the same as in pure water. The supposition that the enriching solutions carried free sulphuric acid does not, therefore, aid in explaining the unusual replacement of barite. Furthermore, the association of much of the silver with limestone and dolomite and the apparent deposition in one place of calcite with the silver are opposed to the conception that the enriching solutions were acid at the time that they deposited silver and dissolved barite.

[9] Spurr, J. E., Geology of the Aspen mining district, Colo.: U. S. Geol. Survey Mon. 31, p. 237, 1898.

vertically below the surface. The water was flowing in a voluminous stream from a watercourse in dolomite and was probably draining from ground between the fifteenth and thirteenth levels. It was clear and of ordinary temperature. Its analysis is given below, and its quality has been calculated in accordance with the Palmer method.[8]

Analyses of cool descending mine waters from Aspen, Colo.

Durant tunnel.

[Analyst, Chase Palmer, U. S. Geol. Survey.]

Radicle.	Parts per million.	Reacting value.			Adjusted reacting value (per cent).	
		By weight.	Per cent.			
Na	40.0	1.7400	6.2	8.4	8.4	50.0
K	24.0	.6144	2.2			
Ca	137.0	6.8363	24.4	41.7	41.4	
Mg	59.0	4.8498	17.3			
Mn	None.					
Fe[a]	1.4	.0501	.2		.2	
SO_4	481.0	10.0048	35.7	35.9	35.9	50.0
Cl	2.0	.0564	.2			
HCO_3	235.0	3.8540	13.8		14.1	
SiO_2	11.0					
	990.4	28.0058	100.0		100.0	

[a] Assumed as ferrous.

Alkalies balanced by strong acids	per cent	16.8
Earths balanced by strong acids	do	55.0
Earths balanced by weak acids	do	27.8
Metals balanced by weak acids	do	.4
		100.0

Fifteenth level, Smuggler Hill workings.

[Analyst, Chase Palmer, U. S. Geol. Survey.]

Radicle.	Parts per million.	Reacting value.			Adjusted reacting value. (per cent).	
		By weight.	Per cent.			
Na	12.4	0.5394	5.2	6.8	6.9	50.0
K	6.3	.1613	1.6			
Ca	43.0	2.1457	20.8	42.3	42.9	
Mg	27.0	2.2194	21.5			
Mn	None.					
Fe[a]	.6	.0215	.2		.2	
SO_4	49.0	1.0192	9.9	50.9	9.7	50.0
Cl	Trace.					
HCO_3	257.0	4.2148	40.8		40.3	
SiO_2	21.4					
	416.7	10.3213	100.0		100.0	

[a] Assumed as ferrous.

Alkalies balanced by strong acids	per cent	13.8
Earths balanced by strong acids	do	5.6
Earths balanced by weak acids	do	80.2
Metals balanced by weak acids	do	.4
		100.0

[8] Palmer, Chase, The geochemical interpretation of water analyses: U. S. Geol. Survey Bull. 479, 1911. Rogers, G. S., The interpretation of water analyses by the geologist: Econ. Geology, vol. 12, pp. 56–88, 1917.

tion of the rich silver ores. The mineralization of this stage was more extensive than the rich silver mineralization. It is the ore of this stage that constitutes the "milling ore" which is now the main industrial resource of the district.

Finally, the modifying action of descending waters of surface origin is recognized by Spurr as the agency that caused the deposition of native silver from very shallow depths down to vertical depths of about 1,000 feet. Some of this silver, he states, was clearly deposited hundreds of feet below the original ground-water level. No other secondary (supergene) silver minerals were recognized by Spurr, and he calls attention particularly to the absence of ruby silver (proustite). He appears to hold that primary mineralization rather than secondary deposition was the main cause of the rich bonanzas of the early days of mining.

MINERALOGY OF THE ORES.

The microscopic studies recorded in this paper were made mainly on specimens of very rich silver ores obtained from private collections in Aspen. Ores of comparable richness have not been mined in noteworthy amounts in recent years. Unfortunately the exact localities in the mines from which some of these specimens were taken many years ago could not be learned. Most of the ores studied came from the Mollie Gibson and Smuggler mines.

Ore minerals noted by the writer in the ores studied are as follows:

A. Early primary (hypogene): Barite, tennantite, pyrite (rare), quartz (rare).

B. Later primary (hypogene): Galena, sphalerite, chalcopyrite, bornite, pearceite, argentite.

Groups A and B are not separable in all the ores.

C. Secondary (supergene): A possible lead-silver sulphide, pearceite, native silver (abundant), argentite(?), chalcocite (rare), covellite (rare).

To these should be added, according to Spurr, tetrahedrite, polybasite, pyrargyrite, several carbonates, and numerous oxidation products.

The "brittle silver" of the Aspen miners is commonly an aggregate of pearceite with some tennantite, galena, sphalerite, and other minerals, but when pure it has the appearance and physical properties of polybasite and was so denominated by the earlier observers. In 1892, however, Penfield[4] analyzed specimens forwarded to him by Richard Pearce, of Denver, and found that the mineral was arsenical rather than antimonial, its composition corresponding closely to the formula $9Ag_2S.As_2S_3$. Subsequently, in 1896, Pen-

[4] Penfield, S. L., and Pearce, S. H., On polybasite and tennantite from the Mollie Gibson mine in Aspen, Colo.: Am. Jour. Sci., 3d ser., vol. 44, pp. 15–18, 1892.

field[5] assigned to this "arsenical polybasite" the name pearceite. Penfield appears also to have been the first to identify the "gray copper" of the Aspen ores as tennantite.

PRIMARY LEAD ORES.

Galena-rich ores of the type now being worked were studied at typical exposures in stopes following the so-called contact between the eleventh and thirteenth levels of the Smuggler Hill workings (blocks 30–33). This "contact" is the Silver fault, a zone of movement and intense brecciation between Leadville dolomite and the overlying Weber (?) shales. On passing from the footwall to the hanging wall of this bedding fault there are transitions from massive dark-gray dolomite into dolomite breccia with crushed dolomite matrix, thence into a breccia of dolomite fragments in a black shale matrix, and finally into black slickensided shale much resembling coal. Throughout thicknesses in places as great as 20 to 25 feet the breccia has been partly replaced by ore minerals, and small stringers of these minerals penetrate the shale of the roof. In one place (stope 33) there was noted a streak 3 to 6 inches wide of nearly pure galena traversing brecciated dolomite, and gradations could be traced from this into breccia in which replacement affected only the matrix, and finally into unmineralized breccia. Ores of this type, when examined under the microscope, are found to be mainly dolomite and galena with a few minute crystals of quartz and a very little sphalerite. The dolomite in places shows smooth, straight contacts next to galena that represent crystal or cleavage planes of the dolomite, but elsewhere the contacts are exceedingly ragged, clearly indicating replacement of the dolomite by galena.

PRIMARY SILVER ORES.

In some places in these stopes the galena ores described above give way, apparently by transition, to ores in which fine-grained tennantite is the dominant metallic mineral, and this change is usually accompanied by a notable increase in the silver content. One such ore body above the eleventh level (block 98, south of the Mollie Gibson shaft) carried very little visible galena but abundant tennantite. This ore averaged 20 ounces in silver to the ton, and single assays ran up to 125 ounces. A specimen of ore of this type from block 30, on the thirteenth level of the workings under Smuggler Hill, shows pink barite in aggregates of radiating blades inclosed by a fine-grained sulphide aggregate which is mainly tennantite, all replacing black shale of the Weber (?) formation. Some of the

[5] Penfield, S. L., On pearceite, a sulpharsenite of silver, and on the crystallization of polybasite: Am. Jour. Sci., 4th ser., vol. 2, pp. 17–29, 1896.

In the workings still farther southwest under Aspen Mountain the "contact" was well oxidized in places, even when first broken into near the level of the Durant tunnel, at a vertical depth below the surface of nearly 900 feet. Extensive oxidation was noted at other localities underground at lesser vertical depths, ranging from 600 to 900 feet.

As indicative of the spotty distribution of oxidation it may be noted that specimens of lead ore from a depth of only 30 feet in the Smuggler shaft were almost wholly unoxidized.

DESCENDING MINE WATERS.

Mine waters, all clear and cool and descending, were tested at several places in the workings, and two samples were analyzed. (See fig. 22.)

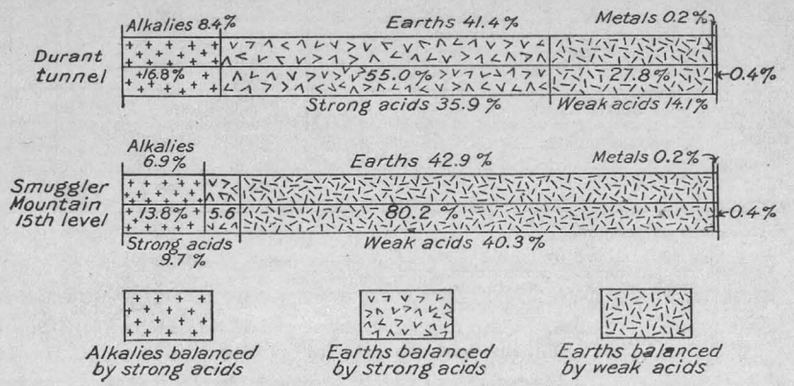


FIGURE 22.—Composition diagrams of cool descending mine waters of Aspen, Colo.

Cool, clear water dripping from the roof of stope No. 4 in the Durant tunnel workings under Aspen Mountain, at a vertical depth of about 900 feet, was not acid toward methyl orange but on the contrary gave a faint pink coloration with phenolphthalein, indicating faint alkalinity due to the presence of normal carbonates in solution. There were no stopes for considerable distances above this point. The analysis of this water is given on page 58. Water that was being pumped from the Smuggler mine gave similar reactions.

Water dripping through the "contact" on the first level of the Aspen mine, Aspen Mountain, at a depth of about 150 feet vertically below the surface, was neutral. There were no stopes above the point where this water was tested. Water dripping from the roof of the Hooper stope, on the third level of the Aspen mine, was also neutral.

A water sample for analysis was collected from the fifteenth level of the workings under Smuggler Hill in block 27, about 2,700 feet northeast of the Mollie Gibson shaft and about 1,000 feet

A specimen in the statehouse collection at Denver from the Millinee mine, in Aspen Mountain, shows native silver forming a veritable matrix between fragments of brecciated blue-gray dolomite.

To summarize the occurrence of native silver at Aspen, this mineral has been observed to vertical depths of around 1,200 feet. These depths are not greatly in excess of those to which local oxidation was observed. The microscope shows that some of the native silver was formed by a replacement of other minerals. Silver compounds such as argentite and pearceite seem to have been the first to yield to such replacement, and in general native silver appears to have been developed most abundantly in connection with ores rich in these silver compounds. Later the replacement by silver spread to base-metal sulphides, and finally even barite gangue was extensively replaced. The specimens of native silver in dolomite or black shale seen by the writer showed no evidence of the replacement of these rocks by silver, but it would be unsafe to conclude that such replacement nowhere occurred.

DEPTH OF OXIDATION.

No comprehensive study of ground-water conditions could be attempted in the brief time available, but enough was seen to make it clear that voluminous flows of ground water were present comparatively near the surface, far above the lower limits of oxidation. Most of these flows came from open watercourses. At the time of the writer's visit an open watercourse in Leadville dolomite below the "contact" had recently been tapped on the fifteenth level of the workings under Smuggler Mountain, in block 27, about 2,700 feet northeast of the Mollie Gibson shaft. This water was apparently draining from ground between the thirteenth and fifteenth levels. Similar heavy flows were obtained when the eleventh level was driven, from open watercourses that can still be seen but have long since dried up. Oxidation is pronounced on the fifteenth level below the "contact" or Silver fault, at slightly greater depths than the water flow above described. This was the deepest oxidation noted by the writer and was about 1,000 feet vertically below the surface. This oxidation is much too pronounced to have taken place since the mines were first opened.

More than half a mile farther southwest pronounced oxidation of Leadville dolomite below the "contact" or Silver fault was noted in block 98, to the south of the Mollie Gibson shaft, near the eleventh level. The material of the contact itself showed spotty oxidation at this locality. Small amounts of native silver were noted. This was at a vertical depth of around 1,000 feet.

barite may have been deposited before the sulphides, but some is intercrystallized irregularly with them and is clearly contemporaneous with them. The microscope shows in this ore a mineral composition and texture that is essentially identical with that noted in the specimen next to be described, which is shown in Figures 13 and 14.

FIGURE 13.—Tennantite traversed by veinlets of chalcopyrite, galena, bornite, sphalerite, and calcite. These are in part replacement veinlets. Their transition, as at *A*, into irregular intergrowths with tennantite suggests that the veinlets are not much younger than the tennantite. Pearceite is a component of many similar veinlets in this specimen. All probably belong to a single period of primary mineralization. Smuggler Hill workings, block 30, Aspen, Colo., thirteenth level. Camera lucida drawing from polished specimen.

A specimen of tennantite-rich ore said to run about 4,000 ounces to the ton in silver, from a stope just above the thirteenth level of the Smuggler Hill workings, block 30, was obtained through the courtesy of Mr. Charles E. Anderson. To the unaided eye it is a finely granular gray aggregate composed mainly of metallic minerals. This aggregate is bordered by and has apparently replaced black shale of the Weber (?) formation. Under the microscope

polished specimens of this ore presented the appearance shown in Figures 13 and 14. The microscope shows barite and tennantite intergrown apparently contemporaneously as in general the oldest of the ore minerals.

The tennantite is traversed in the fashion shown in Figures 13 and 14 by replacement veinlets of galena, sphalerite, bornite, chal-

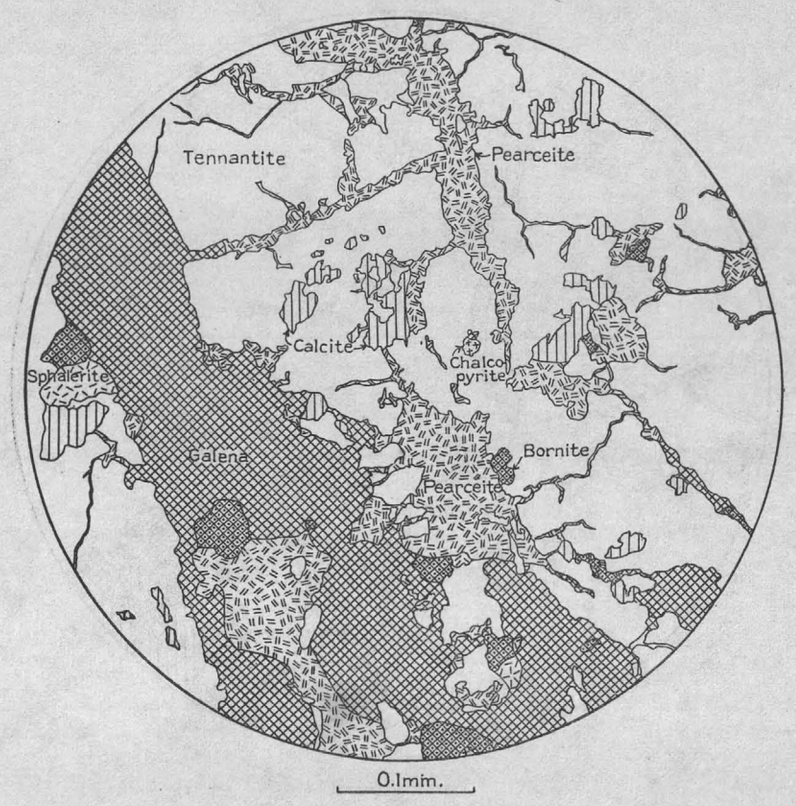


FIGURE 14.—Tennantite traversed by late primary replacement veinlets of pearceite, base-metal sulphides, and calcite. The textural relations suggest that some calcite and base-metal sulphides crystallized contemporaneously with the tennantite, but where they form veinlets they are clearly slightly younger. Smuggler Hill workings, block 30, Aspen, Colo., thirteenth level. Camera lucida drawing from polished specimen.

copyrite, pearceite, and calcite. In other parts of the specimen similar replacement veinlets follow the contacts of tennantite with bladelike crystals of barite. That this group of minerals is not greatly younger than the tennantite and barite is indicated by such relations as are shown at *A*, in Figure 13, where these minerals are irregularly intergrown with tennantite, and by such relations as are shown in Figure 15, where tennantite, argentite, and pearceite are in irregular contemporary intergrowth.

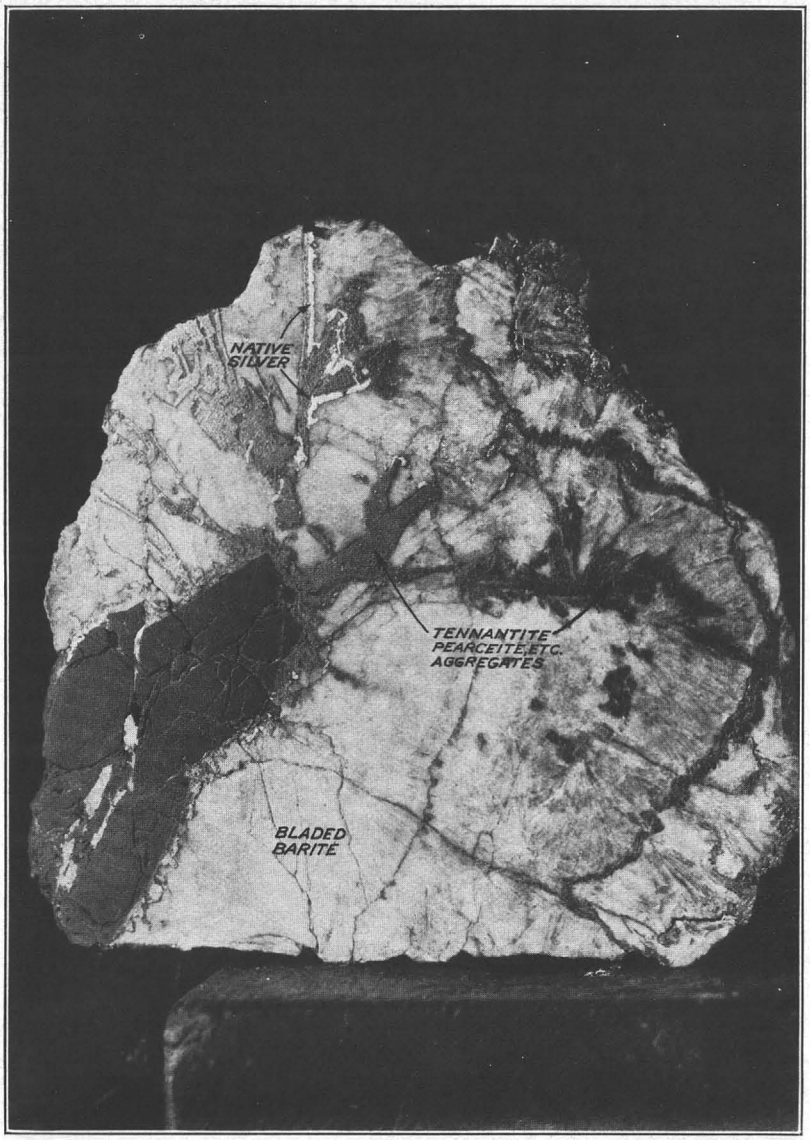
to that shown in Figure 21 or even directly replaced galena with contacts that under high power are found to be very irregular.

Some observations on the mode of occurrence of native silver made underground and on specimens in collections should also be recorded. Spurr states that native silver is found at depths of at least 900 to 1,000 feet below the surface. In the workings under Smuggler Mountain native silver was noted by the writer in the ore of the "contact" or Silver fault at vertical depths approaching 1,200 feet. Specimens said to have come from vertical depths of about 1,100 feet in the Durant tunnel workings under Aspen Mountain carried small plates of native silver along fractures. A short distance south of the Mollie Gibson shaft (block 98 south, near eleventh level) ore rich in tennantite carried scattered flakes and wires of native silver in vugs and fractures. This was about 1,000 feet vertically below the surface. In the workings under Aspen Mountain ore from the "contact" not far above the level of the Durant tunnel and about 900 feet vertically below the surface carried an abundance of native silver.

A specimen in the D. R. C. Brown collection at Aspen (exact locality uncertain) showed tapering and curling "teeth" of native silver implanted on "brittle silver" (probably pearceite) and clearly an alteration product thereof. Some of these teeth were half an inch in length. Another specimen in the same collection shows similar silver "teeth" implanted on a surface of black shale; these also may be alteration products of some silver compound, although no traces of such a compound remain.

A specimen in the Brown collection said to have come from a depth of about 700 feet in the Millinee mine, in Aspen Mountain, showed native silver in a slablike mass 5 by 6 inches across and half to three-quarters of an inch thick. This slab was not solid silver but was made up of a matt of silver wires, hairs, and teeth, in places loosely aggregated but elsewhere crowded closely together. This silver was deposited along a fracture in dark-gray shale, remnants of which are still attached to the silver. Isolated fragments of shale are inclosed by the silver. The silver-shale contacts are perfectly sharp, and it is clear that the silver (or some earlier mineral that it has replaced) has been deposited on the shale and not as a replacement of it. No silver compounds are associated with this native silver.

The Brown collection also contained a specimen of brecciated black dolomite from a depth of about 500 feet in the Aspen mine. Between the fragments of this breccia wires and plates of native silver have been deposited. It is noteworthy that some calcite is irregularly intergrown with the silver.



RICH BARITIC SILVER ORE FROM SMUGGLER MINE, ASPEN, COLO.

About 500 feet below surface. Typical of many of the richer ores. About seven-eighths natural size

The convex outlines of the silver against pearceite and similarly in a few places against argentite indicate a growth of the silver radially or concentrically from numerous centers. The pearceite may be interpreted either as a later filling between the masses of silver or as remnants of larger pearceite areas now mainly replaced by silver. The fact that the silver is in general restricted to the vicinity of the borders of the sulphide patches against barite favors the re-

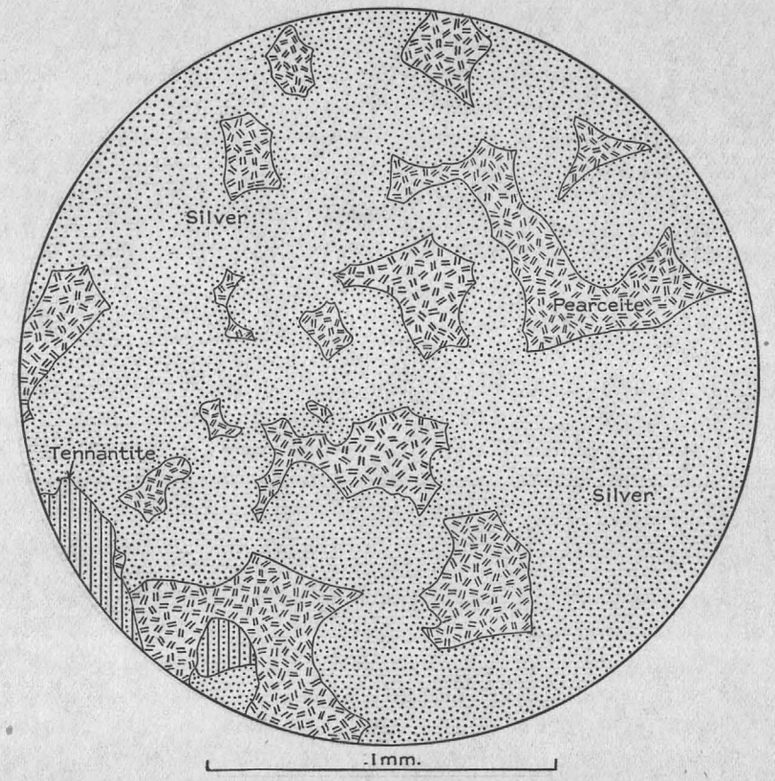


FIGURE 21.—Association of native silver and pearceite, Aspen, Colo. Note that the pearceite areas have curved outlines concave outward, suggesting that they are replacement remnants between areas of silver that have grown radially from numerous centers. Camera lucida drawing from polished specimen.

placement hypothesis. The silver is interpreted as a deposit from descending supergene solutions.

In the same specimen from which Figure 16 was sketched pearceite, argentite, and native silver have all been developed by replacement, presumably through the agency of descending solutions. A common replacement sequence is (1) lead-silver sulphide (?) after galena; (2) pearceite after lead-silver sulphide (?); (3) argentite after pearceite; and (4) native silver after argentite. In places, however, the silver directly replaced pearceite in a fashion similar

In the specimen from which Figures 13 and 14 were sketched the pearceite occurs in the replacement veinlets side by side with sphalerite, calcite, bornite, and galena; it does not follow contacts between these minerals and tennantite, nor does it follow galena cleavages or other planes of weakness. It is believed to have been deposited at the same time as galena, sphalerite, bornite, and calcite and like them to be late primary (hypogene). This forms an ex-

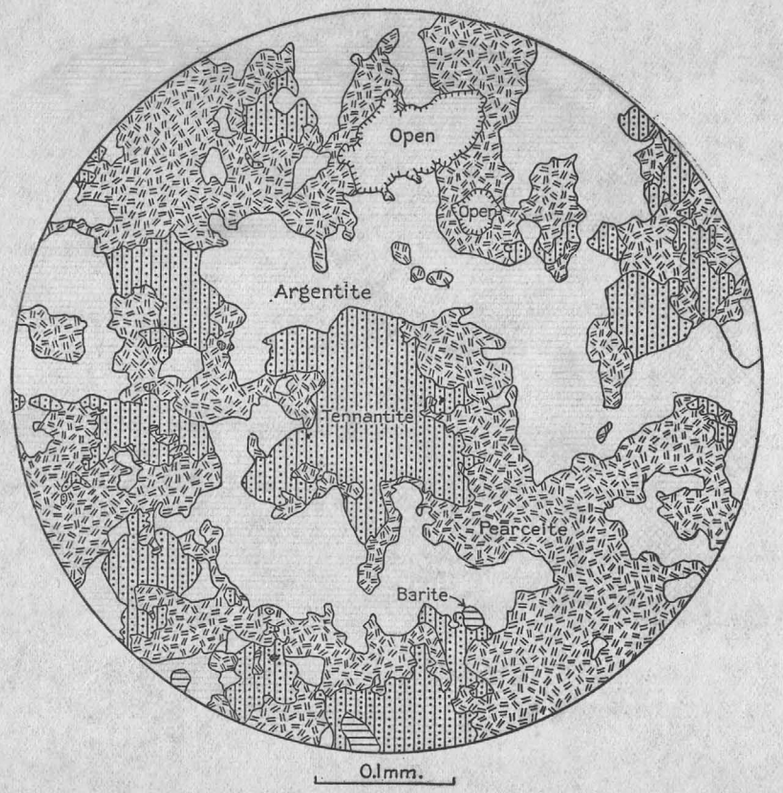


FIGURE 15.—Argentite, pearceite, and tennantite in irregular and apparently primary intergrowth. Aspen, Colo., precise location uncertain. Camera lucida drawing from polished specimen.

ample of the tendency emphasized by the writer in a previous paper [6] for the simultaneous replacement of ore mineral by a group of several minerals, common in hypogene replacement but rare in supergene replacement.

A specimen of rich baritic silver ore from Aspen, purchased from a jeweler, presents to the unaided eye a mottled appearance due to the scattering of dark aggregates of metallic minerals 1 to 5

[6] Bastin, E. S., Supergene processes at Neihart, Mont. (discussion): Econ. Geology, vol. 18, pp. 90–91, 1923.

millimeters across through a pinkish matrix of small bladed crystals of barite. Under the microscope the patches of metallic minerals are found to be mainly an aggregate of tennantite, pearceite, and argentite, the characteristic appearance of which is shown in Figure 15. The boundaries between these minerals are in general irregular, with a few suggestions of crystal boundaries. Contacts between tennantite and argentite are in some places smoothly curved and in others

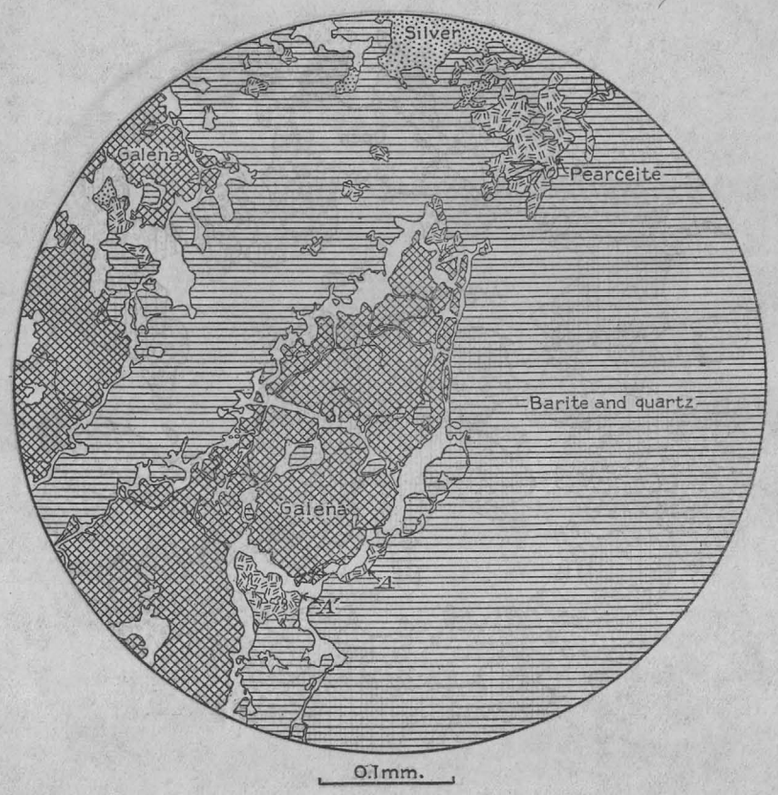


FIGURE 16.—Replacement of galena by a galena-like mineral, probably a lead-silver sulphide, followed by pearceite. The replacement follows the contacts between galena crystals or between galena and other minerals. Where replacement has proceeded further pearceite is developed, as at *A* and *A'*. Native silver occurs as a final replacement product in those parts of the specimen where pearceite is most abundant, as shown in the upper part of this figure. In parts of this specimen argentite is intimately associated with pearceite and seems to be of the same age. Mollie Gibson mine, Aspen, Colo. Camera lucida drawing from polished specimen.

straight or subangular. The subangular contacts suggest that tennantite slightly preceded argentite in crystallization. The tennantite in a few places exhibits its characteristic tetrahedral outlines against the pearceite, but most of the boundaries between these two minerals are irregular and tend to interlock. Argentite boundaries against pearceite are in general smooth but give no strong indication

tabular masses of metallic minerals occur between coarse crystals of barite. The metallic minerals include tennantite and some chalcopyrite. Partly replacing these is an aggregate of sphalerite, galena, bornite, and pearceite. Finally these primary minerals have been replaced by native silver, in the fashion shown in Figure 20. Small replacement remnants of tennantite, not shown in the figure, are scattered sparsely through some of the silver.

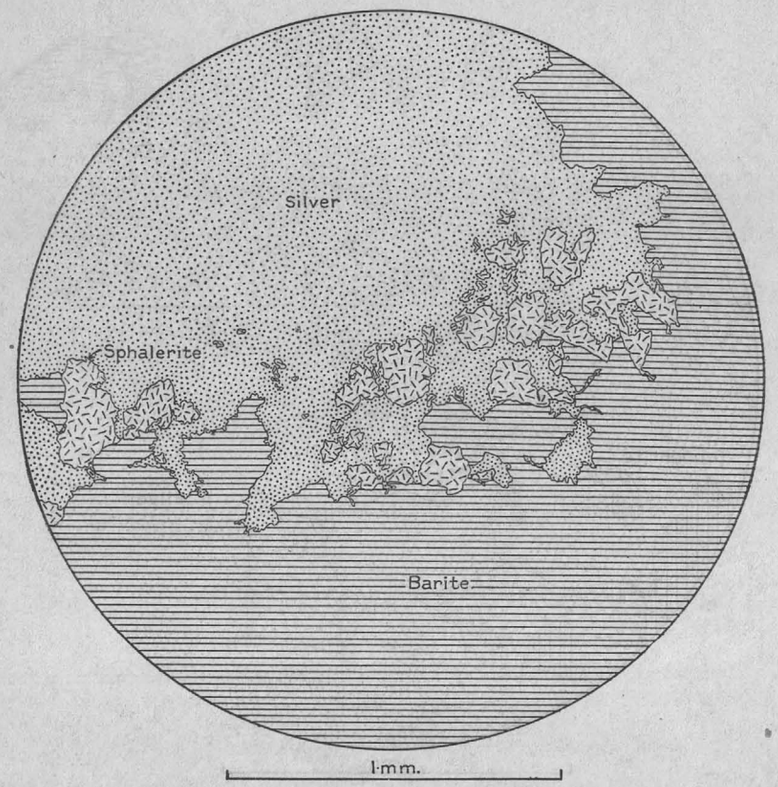


FIGURE 20.—Native silver replacing sphalerite and barite. Note exceedingly irregular silver boundaries and sphalerite replacement remnants within the silver. Small replacement remnants of tennantite (not shown) are scattered sparsely through the silver. Smuggler mine, Aspen, Colo., from depth of about 600 feet. Camera lucida drawing from polished specimen.

One specimen of very rich Aspen ore (exact locality uncertain) is of mottled appearance to the naked eye, black patches, as much as 5 millimeters across, of metallic minerals being scattered through a matrix of pink barite. The interiors of the patches of metallic minerals consist of tennantite, argentite, and pearceite in irregular primary intergrowth, as shown in Figure 15. About the peripheries of many of the patches of metallic minerals native silver is present. Its relations to pearceite are typically shown in Figure 21.

the same specimen. In the silver veinlet of this figure there are replacement remnants of both sphalerite and barite. The hand specimens of this ore show irregular patches of metallic minerals scattered through a matrix of bladed barite. The native silver was developed mainly near the peripheries of these areas of metallic minerals, the portions most accessible to the enriching solutions.

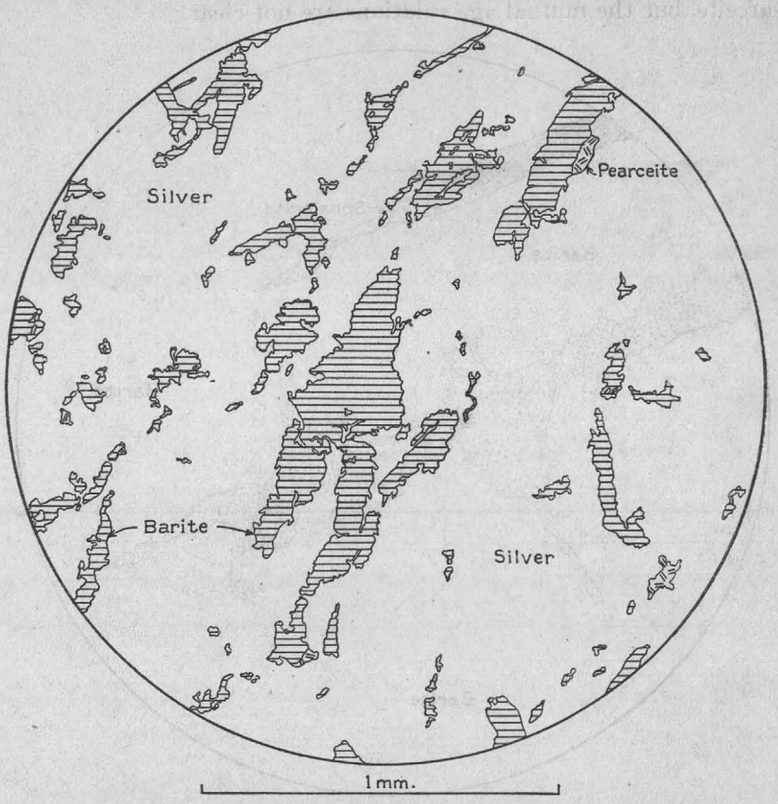


FIGURE 19.—Ragged replacement remnants of barite in native silver. Mollie Gibson mine, Aspen, Colo., from depth of about 500 feet. Camera lucida drawing from polished specimen.

Eventually, as is well shown by a specimen from the Mollie Gibson mine obtained from the D. R. C. Brown collections, the replacement of barite proceeded to a stage where only ragged remnants of barite remained in a matrix of silver, as is clearly shown in Figure 19. In the hand specimen this ore appears to be nearly pure silver. In parts of this specimen remnants of pearceite remain and are related to the silver in a fashion shown in Figure 21, sketched from ore from another locality.

In another specimen from the Smuggler mine (exact locality uncertain), obtained from the D. R. C. Brown collection, irregularly

of crystal faces. The cuspate boundaries and embayments in the upper right quarter of the figure suggest a tendency for argentite to replace pearceite; but there is no tendency for argentite to follow contacts between pearceite and tennantite, and it is regarded as chiefly or entirely a primary mineral. The argentite is distributed fairly evenly throughout the patches of metallic minerals; there is no tendency for it to develop most abundantly about the peripheries of these areas, such as was noted in the native silver and is described later. Therefore, although there is a little indication that tennantite slightly preceded and argentite slightly followed pearceite, the three minerals together with barite are interpreted as all primary (hypogene) and nearly contemporaneous.

Other specimens of the rich silver ores generally carried the same primary minerals that were noted in the tennantite-rich ores already described, although barite was in general more abundant and in larger crystals. A specimen from the Smuggler mine in the collections at the statehouse in Denver showed pearceite distinctly occupying cracks in pink barite, but this association grades into what appears to be a contemporaneous intergrowth of the two minerals in nearly equal amounts.

In some specimens of the very rich ores a division of the primary minerals into earlier and later groups is not feasible, all appearing to be intercrystallized essentially contemporaneously. Individual white, gray, or pink barite blades are not uncommonly a quarter to half an inch in length. The sulphides commonly form irregularly elongate patches between the blades of barite, as shown in Figure 17. A typical specimen of rich barite silver ore is shown in Plate III.

SECONDARY (SUPERGENE) ORE MINERALS.

Spurr has interpreted the native silver of the Aspen ores as a deposit from descending solutions—a product of downward enrichment. This interpretation is confirmed by the writer's studies, and several examples of silver developed by the replacement of primary minerals are described below.

Compounds of silver of supergene origin were not noted by Spurr and certainly are not conspicuous, native silver being the principal supergene mineral. In one specimen, however, such compounds were noted in abundance. This specimen came from the collection of Mr. Charles E. Anderson at Aspen and was taken from the Mollie Gibson mine, though the exact locality is now uncertain. The dominant mineral of this ore is pink barite, but with it are irregularly intergrown as primary and apparently contemporary minerals abundant galena and small amounts of quartz. By replacement of the galena and subordinately of the barite, silver minerals have been

developed in this ore in such abundance as to convert it into a rich silver ore, in the fashion shown in Figure 16. Galena has first been replaced along its contacts with barite and along contacts between different galena crystals by a galena-like mineral, probably the same that was previously noted by the writer in the ores of Tonopah, Nev.,[7] distinguishable from the galena under the microscope only when the galena is tarnished with hydrogen peroxide. The galena-

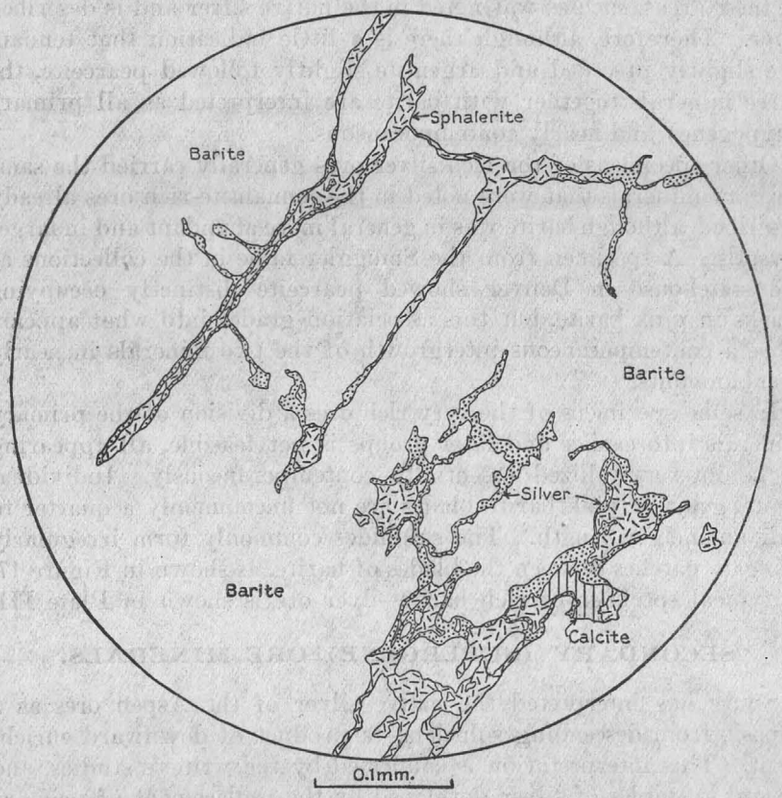


FIGURE 17.—Replacement of sphalerite stringers in barite by native silver. Smuggler mine, Aspen, Colo., from depth of 140 feet in shaft. Camera lucida drawing from polished specimen.

like replacing mineral is probably a lead-silver sulphide, but it is present in too small amounts to be isolated for testing. As replacement proceeded the galena-like mineral was replaced by pearceite, as at *A* and *A′* in Figure 16. Finally, as at the top of Figure 16, native silver was formed, usually as a replacement of pearceite. These replacements are interpreted as the result of downward enrichment. In contrast to the ore shown in Figures 13 and 14 a primary mineral

[7] Bastin, E. S., and Laney, F. B., The genesis of the ores at Tonopah, Nev.: U. S. Geol. Survey Prof. Paper 104, p. 21, 1918.

has been replaced by three minerals, not simultaneously but in definite succession. This succession involves progressive enrichment in silver, because pearceite, which contains about 57 per cent of silver, is probably more argentiferous than the galena-like mineral and is itself later replaced by native silver. In parts of this specimen some argentite, which contains 87 per cent of silver, is associated with the pearceite, but the mutual age relations are not clear.

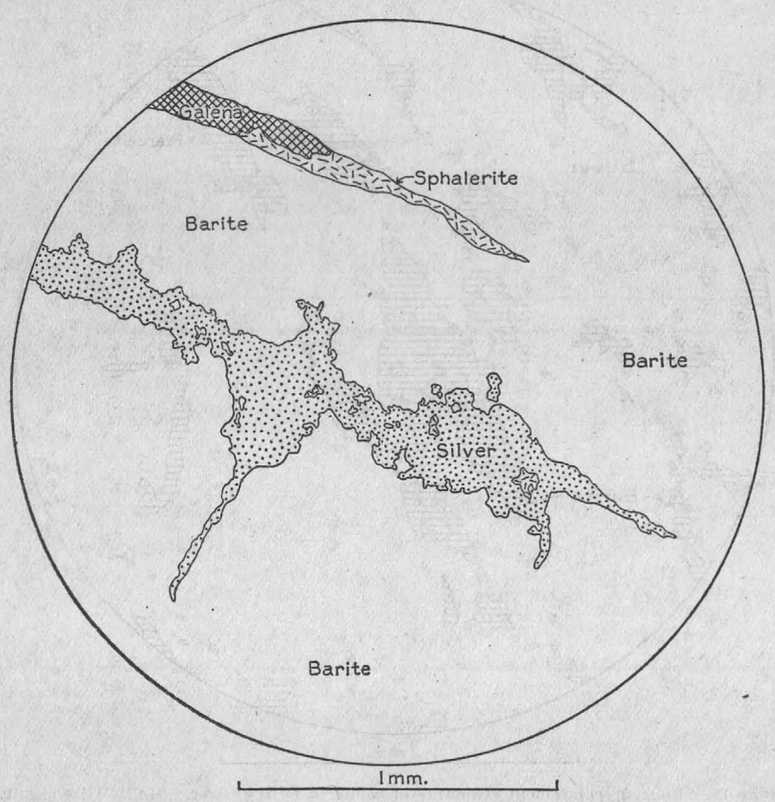


FIGURE 18.—Replacement of barite by native silver. Smuggler mine, Aspen, Colo., from depth of 140 feet in shaft. Process began with replacement of narrow areas of sphalerite between bladelike crystals of sphalerite and spread to the bordering barite. Camera lucida drawing from polished specimen.

A specimen from the second level of the Smuggler mine at the shaft and about 140 feet vertically below the surface showed the relations sketched in Figures 17 and 18. Late primary replacement veinlets of sphalerite, galena, bornite, and calcite, traversing barite, exhibit peripheral replacement of the sphalerite by native silver, as clearly indicated in Figure 17. Although the replacement began with sphalerite, as the more susceptible mineral, it later extended to the barite, as shown in Figure 18, drawn on a larger scale from

Wissel

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U. S. GEOLOGICAL SURVEY
George Otis Smith, Director

Bulletin 785—A

RECENT DEVELOPMENTS IN THE ASPEN DISTRICT, COLORADO

BY

ADOLPH KNOPF

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Work in the tunnel had been suspended at the time of visit, and on account of its length and crookedness its continuance would be unprofitable. Operations were concentrated on the 300-foot level at the Midnight shaft, ingress to the workings being had by permission of the Hope Mining, Milling & Leasing Co. through a branch from the Little Annie tunnel, whose portal is at an altitude of 10,250 feet.

The ore occurs in the northern extension of the ore zone of the Little Annie mine. It consists of a breccia of black chert and jasperoid fragments which are cemented by galena, sphalerite, quartz, and barite. In places the cement is insufficient in quantity to fill the interspaces between the angular fragments of chert and jasperoid, and the resultant ore is markedly vuggy. The ore is reported to carry 2 ounces of silver per ton to each per cent of lead.

O

CONTRIBUTIONS TO ECONOMIC GEOLOGY, 1926

PART I. METALS AND NONMETALS EXCEPT FUELS

RECENT DEVELOPMENTS IN THE ASPEN DISTRICT, COLORADO

By ADOLPH KNOPF

INTRODUCTION

The Aspen district of Colorado was mapped and studied with great detail and thoroughness in 1895 by J. E. Spurr, who made it the subject of a well-known monograph.[1]

With the lapse of 30 years mining in the area surveyed by Spurr has come to a standstill. During the last decade, however, much exploratory work has been done in the vicinity of Richmond Hill, a little farther south, and public demand has consequently arisen for a southward extension of the early survey. In response to this demand the writer was instructed by the United States Geological Survey to visit the district, and he did so in July, 1923. The only topographic base map available was on a scale of 1:62,500 (about 1 mile to the inch), a scale too small for representing the geology in as much detail as on Spurr's main map (scale 1:9,600, or 800 feet to the inch), or his maps of the more productive areas (scale 1:3,600, or 300 feet to the inch). The complicated geology shown on Spurr's maps continues southward and has been mapped by the writer in the vicinity of the Little Annie mine, or Richmond Hill. Plate 1 is a composite geologic map in which Spurr's work is supplemented by that of the writer.

The principal contributions in this brief report are descriptions of the recent mining developments in the southern part of the district, the correlation of the occurrence of ore in the Richmond Hill area with geologic structure, the account of the relation of oxidation

[1] Spurr, J. E., Geology of the Aspen mining district, Colo.: U. S. Geol. Survey Mon. 31, 1898.

of the ores to glacial history, and a more detailed discussion of the igneous geology, which is considerably more complex than has hitherto been thought.

THE ASPEN MONOGRAPH

The public demand for a resurvey of the Aspen district was in essence a strong tribute to the great practical usefulness of the Aspen monograph, by J. E. Spurr. In no other district in the writer's acquaintance has the local geology become so thoroughly part and parcel of the working knowledge of the mining population as at Aspen. "Cambrian quartzite," "Silurian dolomite," "Weber shale" are everyday terms among these men, and the stratigraphic and lithologic significance of the terms are fully understood. The accuracy and the detail of the geologic maps accompanying the monograph have made them often do service in determining the exact location of the portals of mining tunnels that were to be driven. Some of these tunnels have been driven along the cross sections shown in the Aspen monograph and have verified the geologic conditions depicted in the cross sections. Occasionally long tunnels have been run to intersect ore at depth, as at the Newman tunnel, in defiance of the geologic conditions shown in the cross sections, and the result has been that much money was unnecessarily expended.

One element in the long-continued usefulness of the Aspen monograph has been the complete representation of the complex faulting that has affected the rocks of the district. Because the deposition of the ore bodies was controlled in a remarkable way by the faults, the geologic maps showing these faults have proved to be particularly useful in the search for undiscovered ore.

On the other hand, the theoretical conclusions as to the origin of the ore-depositing solutions, a problem that looms so large in current discussions of ore genesis, have had little practical bearing. At the time of writing the Aspen monograph Spurr sought to show that the ores were deposited from hot-spring waters—meteoric waters that had sunk from the earth's surface and become heated by coming into contact with a body of hot igneous rock—and the hot-spring waters of Glenwood Springs, 40 miles away, were cited in analogy. His views on this problem have changed or been modified several times since, but their practical importance as an aid in finding ore remains far behind that of the objective presentation of the areal and structural geology given in the Aspen monograph and its atlas.

It is somewhat surprising, after scanning the geologic maps of the Aspen district, to find in the field that much of the district is

Annie sill of alaskite porphyry was cut. (See fig. 6.) The contact is a normal igneous contact, dipping 55° W., like the bedding of the Weber(?) shale above it. To the operators it was somewhat of a surprise that no ore, or even signs of ore, were found on this contact, for it was thought that the conditions were the same as those in which ore occurs at the surface. The fact is, however, that the ore at the surface (at the Little Annie and Midnight shafts) occurred along a fault—the Annie fault—and that this fault, which was the controlling factor in determining the deposition of the ore, passes at depth through the alaskite porphyry sill. Farther in the porphyry was again cut, but here its contact with the Weber(?) formation is a vertical fault along which the rocks have been greatly shattered. This contact also is unmineralized. On account of the highly faulted condition of the rocks near the face of the tunnel heavy ground was encountered, which greatly impeded progress. The Annie fault is east of the tunnel; it is nearest to the tunnel at survey mark 130, where it is about 300 feet east. It does not appear to be worth prospecting here, except as a long chance.

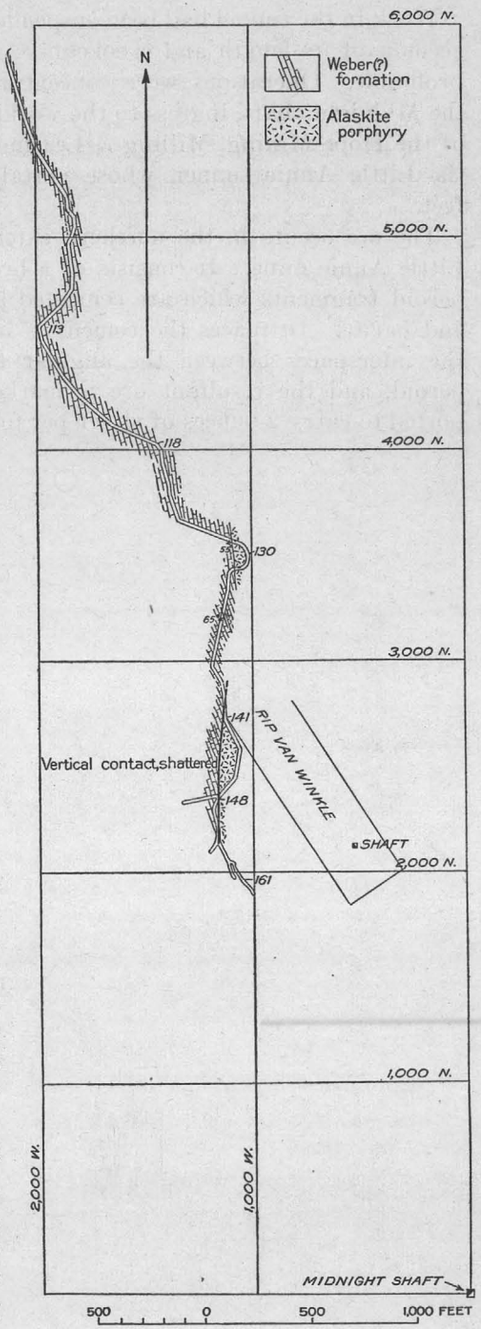

FIGURE 6.—Geologic sketch map of the Midnight tunnel, Aspen district, Colo.

The Second East crosscut, extending east from station 732, shows that the alaskite porphyry sill is here not split in two by aplite but is solid and 360 feet wide. Both contacts are normal undisturbed, unshattered igneous contacts and dip 70° W. The geologic features of part of the inner workings of the Hope tunnel are shown in Figure 5, which is drawn through the line *A A′* on Figure 2.

This cross section shows the geologic relations in the fault block that lies south of the Hope fault. The position of the Annie fault in this block is unknown. It will be seen that the hanging-wall contact of the Little Annie sill of alaskite porphyry, which is excellently exposed in both the Jewell and the Hope workings, is a normal igneous contact and that consequently no ore occurs along it.

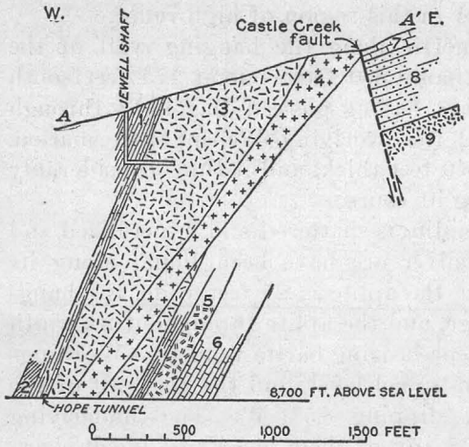

FIGURE 5.—Section through the Jewell shaft and Hope tunnel, Aspen district, Colo. 1 Weber(?) formation; 2, gypsum in Weber(?) formation; 3, alaskite porphyry; 4, aplite; 5, diorite porphyry; 6, Leadville limestone; 7, Yule dolomite; 8, Sawatch quartzite; 9, pre-Cambrian granite

MIDNIGHT MINING CO.

The Midnight shaft is 400 feet north of the Little Annie shaft. Originally it was sunk to a vertical depth of 500 feet, but the present workings are connected with the Little Annie tunnel, a branch from which intersects the shaft at a depth of 300 feet. At the time of visit it was planned to unwater the shaft. The main operations were on the Little Annie tunnel level and on a sublevel 50 feet below.

The largest piece of development work undertaken by the company is the Midnight tunnel, begun in 1914. The portal of this tunnel is in Queens Gulch, at an altitude of 9,700 feet. The tunnel is now more than 5,000 feet long, although in a straight line toward its objective, the Midnight shaft, it has progressed but 4,200 feet, and there still remains 2,200 feet to be driven; the vertical depth that will be attained when the shaft is reached is reported to be 878 feet. The tunnel traverses the country shown in the detailed geologic cross sections of the Aspen monograph (sections E–E and F–F of sheet XIV) and reveals the fact that the structural conditions are even more complicated than shown in those sections. The Weber(?) formation, which is shown in the sections as undisturbed, is in reality broken by numerous faults. At 2,800 feet from the portal the Little

deeply covered with glacial drift and that consequently much of the bedrock is completely concealed. Smuggler Mountain is a striking example of this state of affairs. From the highly detailed geologic maps it would not be suspected that there are but one or two outcrops of bedrock on the mountain. The bedrock geology of Smuggler Mountain as shown on the maps was extrapolated to the surface from exposures in prospect pits, shafts, and mine workings, and this same procedure was followed throughout the district. None of these openings are now accessible, and geologic maps showing detail equal to that of the maps in the Aspen monograph could not be made from the data available in the field. The policy of ignoring the covering of glacial drift was of the highest practical utility, in that it plainly indicated the places at the surface favorable for exploratory work.

OUTPUT

The total value of the output of the Aspen district from 1880 to 1922, inclusive, as estimated by C. W. Henderson, of the United States Geological Survey, is nearly $100,000,000, almost wholly in silver and lead.

The detailed figures of the output of metals in Pitkin County, from 1880 to 1922, inclusive, as assembled by Mr. Henderson after an exhaustive inquiry, are $577,930 in gold; 97,641 ounces of silver, valued at $72,988,357; 1,128,463 pounds of copper, valued at $197,443; 562,582,702 pounds of lead, valued at $25,573,729; and 16,377,002 pounds of zinc, valued at $1,028,289; total value, $100,365,748. The gold can not be credited to Aspen, but the remainder of the output of the county has come almost entirely from Aspen.

The production attained its maximum in 1892, when the value of the output reached nearly $8,000,000. The next year, however, it fell to $4,500,000, and by 1908 the value of the yearly output had fallen below the million-dollar mark. It fluctuated around that figure, with some increase during the war years, until 1921. In that year a further severe decline occurred, which has been greatly accentuated by the practical cessation of mining in 1923.

GENERAL GEOLOGY

PRE-CAMBRIAN GRANITE AND THE OVERLYING PALEOZOIC SEDIMENTARY ROCKS

The basement rock of the district is a massive granite of pre-Cambrian age. It is a fairly coarse light-pink variety containing both muscovite and biotite; the white mica is the more abundant. This muscovite appears as detrital flakes in a number of the overlying formations and thus indicates that the granite was exposed to erosion in adjacent regions at different times.

On the granite rests a conformable series of sedimentary beds, the descriptive details of which may be found in the Aspen monograph. The formations extending up to and including the Maroon formation, which are those of main interest because they underlie the productive part of the district, aggregate 6,200 feet in thickness. Their sequence and general features are shown in Figure 1. The identification of the sedimentary formations at Aspen and the establishment of their sequence are the results of the work of Lakes, S. F. Emmons, Brunton, Henrich, Newberry, and Spurr, as shown by Girty.[2]

The Sawatch quartzite, or Cambrian quartzite, as it is invariably called in the district, overlies the granite. It is a hard vitreous white rock. The basal beds are obscurely cross-bedded and locally are current rippled; and as the top beds also are cross-bedded it is evident that the whole Cambrian section was laid down in a shallow sea. The Cambrian is succeeded by thin-bedded dolomite, designated "Lower Silurian" in the Aspen monograph but now referred to the Ordovician—a mere change in terminology, however, Ordovician being the name adopted to replace "Lower Silurian" of early usage. Locally this formation is always called the "Silurian dolomite." In the Aspen monograph it was designated the Yule formation, but it represents only the lower part of the typical Yule limestone. Above this dolomite is the "Parting" quartzite, which was thought by Spurr to be Devonian but is believed by Girty,[3] on cogent evidence, to be Ordovician, and which is now treated as a member of the Yule limestone. The Leadville limestone lies above the "Parting" quartzite and is divided into a lower dolomite member and an upper pure limestone member. The upper member is the blue limestone, which, as is well known, has been preeminently the ore-producing rock at Aspen, as well as in other districts in Colorado. The Leadville limestone is overlain by the black shales and thin-bedded limestones designated Weber formation in the Aspen monograph and Weber (?) formation in this report, because they are now generally regarded as probably not equivalent to any part of the typical Weber quartzite of Weber Canyon, Utah. The name Weber is, however, here retained, with a question mark, for the convenience of the mining public, which has long known these rocks under that name. The Weber (?) formation as here mapped corresponds to only the lower part of the rocks to which the name Weber has been applied in the Leadville and other districts of central Colorado—that is, to the rocks designated in earlier reports "Weber shales," the equivalent of the overlying "Weber grits" of

[2] Girty, G. H., The Carboniferous formations and faunas of Colorado: U. S. Geol. Survey Prof. Paper 16, pp. 15–17, 52–53, 1903.
[3] Idem, p. 161.

Weber (?) limestone being unshattered and there being no mineralization along the contact. In these respects conditions are entirely different from those at the Little Annie shaft, where the ore is in the shattered rocks that overlie the alaskite porphyry sill. The First East crosscut discloses the interesting fact that the alaskite porphyry is here split in two by an aplite dike 172 feet wide, with the result that 215 feet of porphyry lies west of the aplite and 65 feet of porphyry lies east of the aplite. The portion of the crosscut beyond the footwall of the alaskite porphyry was inaccessible at the time of visit but is said to extend back nearly to the pre-Cambrian granite. Great volumes of water under heavy pressure issue roaring from channel ways in the limestone and testify impressively to the active downward circulation of water in this region of high relief.

The main tunnel follows north along the hanging wall of the alaskite porphyry for more than 1,500 feet; but at 175 feet south of station 732 the aplite appears, having pierced diagonally through the porphyry and penetrated the overlying Weber (?) formation. The aplite is here only about 40 feet thick, and it thins considerably more in the next 300 feet along its course.

The thin wedge end of the aplite is shattered and mineralized and some pockets of high-grade silver ore have been found along its footwall. At the Turley raise the aplite is 25 feet wide, the hanging wall is a heavy black gouge, and the aplite throughout its width is sparsely interlaced with galena-bearing barite veinlets. Workings extend 80 feet above the main-tunnel level, and the footwall of the aplite is excellently shown, dipping 65° W. The underlying Weber (?) beds are thin, and many of them consist of black chert. The ore found along the footwall of the aplite consisted chiefly of galena in barite, with some calcite and polybasite and a very little chalcopyrite. Wire silver was common in some of the ore. The depth of this occurrence is 1,500 feet vertically below the surface; it is, however, above the level of Castle Creek. The silver appears to have been derived from the polybasite on which it occurs, and not to have been deposited as an enrichment product by water that descended from the surface.

In 1920 several carloads of ore high in silver were shipped.[25] The finding of this high-grade ore aroused strong hopes, but its spottiness has proved disappointing. Moreover, it led at first to the belief that the downward extension of the Little Annie ore body had been cut. This ore, however, is in a totally different geologic environment. The Hope tunnel has not yet been driven far enough north to cut through the Hope fault and into the fault block that contains the ore at the surface.

[25] U. S. Geol. Survey Mineral Resources, 1921, pt. 1, p. 502, 1923.

MINES

HOPE MINING, MILLING & LEASING CO.

Since 1911 the Hope Mining, Milling & Leasing Co. has been driving a tunnel to cut the Little Annie ore body at a depth of 1,800 feet. The portal of this tunnel, the Hope tunnel, is on Castle Creek 6 miles south of Aspen, at an altitude of approximately 8,700 feet. The ore body is on the west flank of Richmond Hill, at an altitude of 10,540 feet.[24] The distance from the portal to a point vertically below the Annie shaft is 6,600 feet as measured in a straight line; yet although more than 11,000 feet of work has been done, the face of the tunnel is still far from the ore body. Three men were employed at the time of visit.

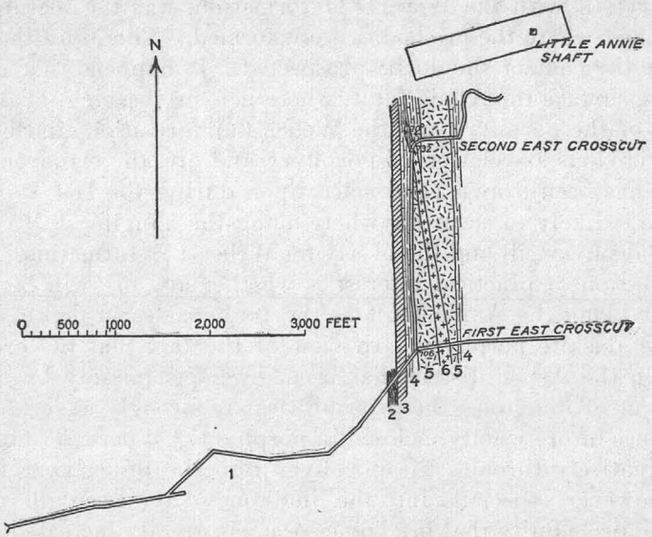

FIGURE 4.—Geologic map of the Hope tunnel, Aspen district, Colo. 1, Maroon formation; 2, black gouge; 3, gypsum; 4, black shales and limestones of Weber(?) formation; 5, alaskite porphyry; 6, aplite

The Hope tunnel traverses the sandstone of the Maroon formation for several thousand feet, then cuts through nearly 100 feet of black gouge containing angular fragments of gypsum and slabs of laminated sandstone, 165 feet of gypsum (true thickness, 100 feet), and 170 feet of the black limestones of the Weber(?) formation (fig. 4). At this point (station 706) the alaskite porphyry of the Little Annie sill was intersected and the First East crosscut was driven. The alaskite porphyry sill, as the term sill implies, has been injected parallel to the bedding and dips 80° W. here; its hanging-wall contact is a normal igneous contact, both the porphyry and the overlying

[24] Spurr, J. E., op. cit. (Mon. 31), pl. 43, *D*.

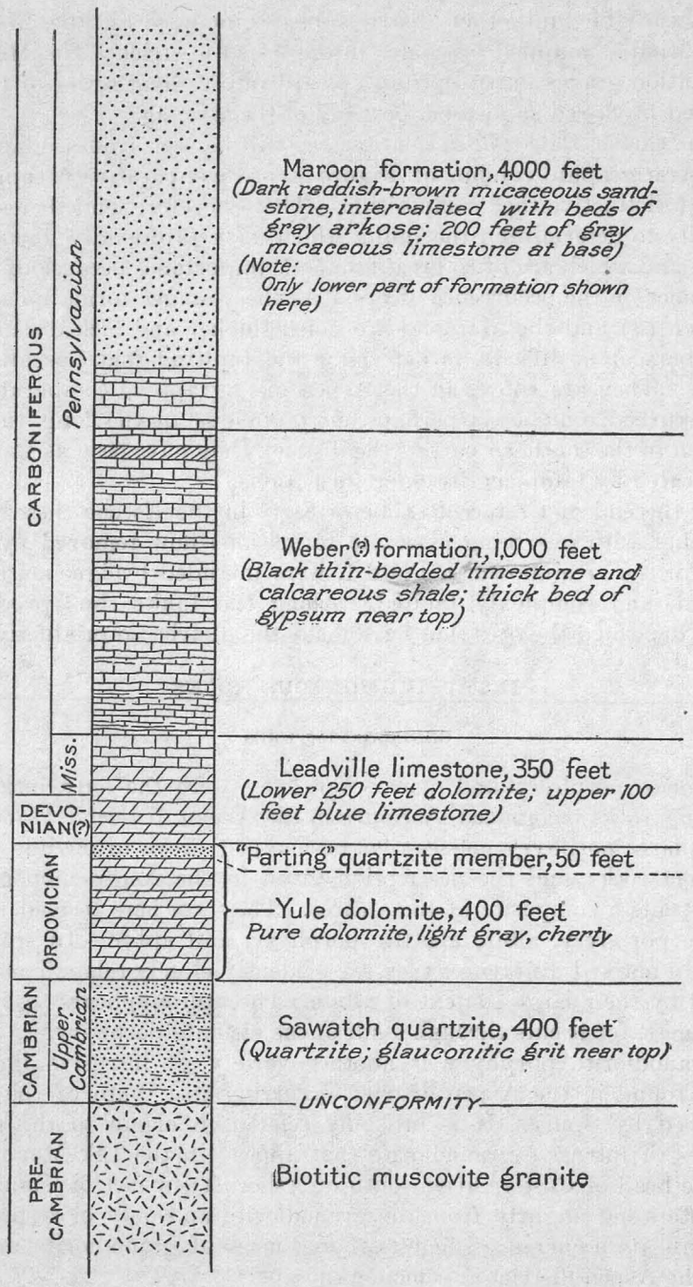

FIGURE 1.—Generalized columnar section of Carboniferous and older rocks in the Aspen district, Colo. Stratigraphic units as defined in Aspen monograph; names and lithologic designations modified to conform with present usage.

the Leadville and other districts being included in the Maroon formation as mapped by Spurr in the Aspen district. The Maroon formation grades imperceptibly upward into a great series of thick-bedded brick-red sandstone, possibly of Triassic age.

The earlier Paleozoic formations, as will be seen from a glance at the stratigraphic column of Figure 1, are comparatively thin and are of distinctive rock composition. They therefore lend themselves readily to determining the faults which have profoundly dislocated them and which are of so great economic importance because of their influence on the occurrence of ore. As the younger formations—the Weber (?) and the Maroon—are much thicker and lack distinctive members, it is difficult to determine the faulting that has affected them. They are shown in the Aspen monograph as comparatively undisturbed, but, as is perhaps most obvious in the long tunnels driven in the southern part of the district, they have been as severely dislocated by faults as the older formations.

At the end of Cretaceous time or early in the Eocene these rocks together with overlying Mesozoic formations now removed by erosion in the area shown in Plate 1, were intruded by igneous rocks, folded, and complexly faulted. Along the faults thus produced were deposited the ores that have made the district so productive.

INTRUSIVE IGNEOUS ROCKS

GENERAL FEATURES

Diorite porphyry and quartz porphyry were the only intrusive igneous rocks recognized by Spurr in the Aspen district. However, the quartz porphyry masses that he mapped prove to include three distinct rocks, and the description given in the Aspen monograph represents a composite of these three. They are here termed albite aplite porphyry, albite alaskite porphyry, and aplite. In spite of certain marked differences they are evidently closely related, as indicated by their large content of albite. The aplite appears to be the youngest, for it cuts through a sill of the alaskite porphyry.

Granodiorite porphyry is another variety of intrusive igneous rock found in the Aspen district, occurring just south of the area mapped by Spurr. It is probably related in origin to the great bodies of intrusive granodiorite that appear in the Elk Mountains at the head of Castle Creek, south of Ashcroft; in fact, inasmuch as it differs but slightly from the granodiorite and only in respect to texture, its occurrence suggests that a mass of granodiorite underlies the Aspen district at some depth.

Because of the importance attached to igneous rocks in current theories of the origin of ore deposits, the intrusive igneous rocks are here described in some petrographic detail, though briefly.

sulphides, sulphantimonides, and sulpharsenides of silver or silver and copper; (3) deposition of galena poor in silver and sphalerite.[22] Bastin's careful study of the microstructure of the ores can not be said to confirm this interpretation, but it indicates that the barite and other minerals were deposited essentially contemporaneously.[23] The evidence from the southern part of the district, which affords the new item that the ore-forming solutions were hot enough to develop tourmaline, favors the interpretation that the several minerals of the ore bodies were deposited during one stage.

PRACTICAL CONCLUSIONS

The Annie fault, not the hanging-wall contact of the alaskite porphyry sill with the Weber (?) formation, was the feature that determined where the ore bodies were formed. Therefore the fault and not the contact should be prospected. It happens that at and near the surface the Annie fault, where it is ore bearing, is also the contact of the porphyry and the Weber (?) formation, and because of this obvious association of porphyry and ore, the erroneous conclusion has been drawn (and acted upon during the last 15 years) that ore is likely to occur anywhere along the hanging-wall contact of the porphyry sill and the overlying Weber (?) formation.

A question of practical interest is whether any ore will be found to occur along the Annie fault as the fault passes in depth wholly into the alaskite porphyry. In view of the fact that the ore elsewhere in the Aspen district has been developed mainly by the replacement of limestone, the probabilities are strongly adverse to the occurrence of ore wholly inclosed in porphyry. Where the fault has passed entirely through the porphyry into the underlying formations, however, especially into the limestone of the Leadville formation, the probability that ore bodies occur is greatly increased.

The only valuable ore body so far known is that of the Little Annie mine, and it occurs in the fault block bounded on the north by the Winnie fault and on the south by the Hope fault. It can not be too strongly emphasized that the deep-level exploratory work so far done has not yet entered this fault block. Therefore, future work should be so prosecuted as to enter this known ore-bearing block as soon as possible. The intersections of the cross faults—the Hope and Winnie faults—with the Annie fault are possibly the most favorable places to search for ore in the unprospected portions of the fault block.

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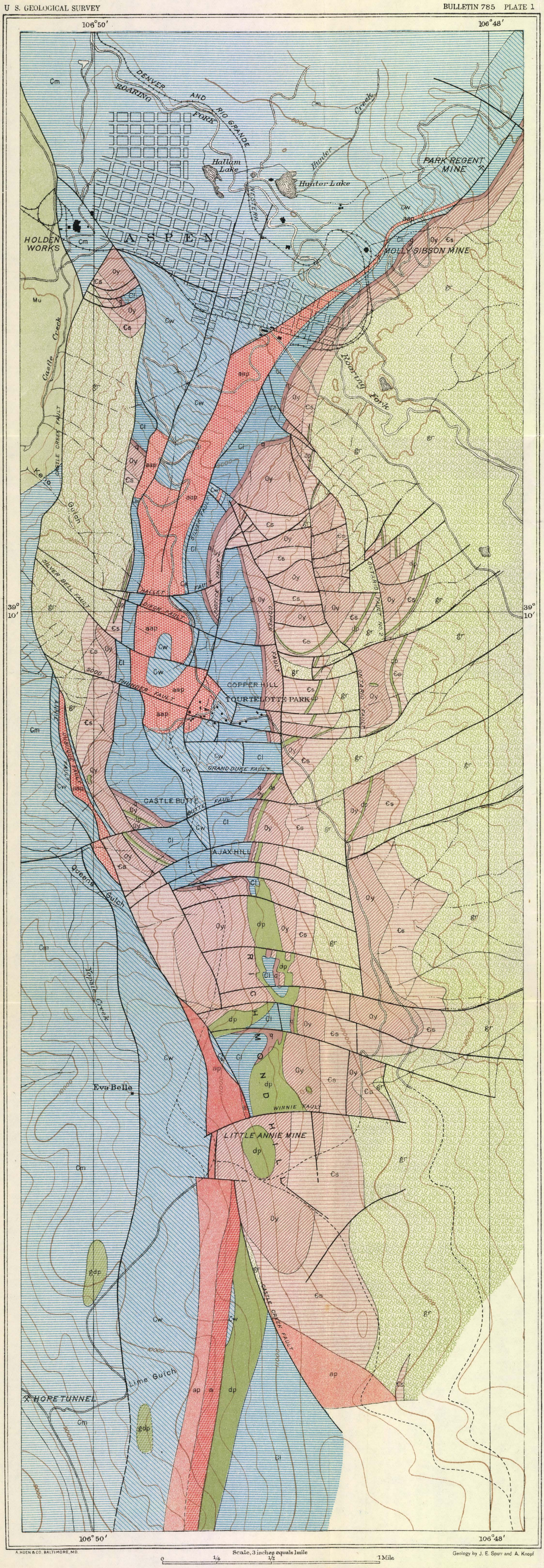
[22] Spurr, J. E., Econ. Geology, vol. 4, pp. 313–314, 1909.

[23] Bastin, E. S., Observations on the rich silver ores of Aspen, Colo.: U. S. Geol. Survey Bull. 750, p. 49, 1924.



EXPLANATION

SEDIMENTARY ROCKS

Mu — Undifferentiated Mesozoic rocks

Cm — Maroon formation (*Dark reddish-brown micaceous sandstone, intercalated with beds of gray arkose (grit); at base 200 feet of gray micaceous limestone. As here mapped includes the equivalent of the "Weber grits," which in the Leadville district are included in the Weber (?) formation*) — *Pennsylvanian*, CARBONIFEROUS

Cw — Weber (?) formation (*Black shale and thin-bedded limestone Thick gypsum bed near top*) — *Pennsylvanian*, CARBONIFEROUS

Cl — Leadville limestone (*Upper 100 feet blue limestone; lower 250 feet dolomite. Lower part may be of Devonian? age*) — *Mississippian*, CARBONIFEROUS

Oy — Yule dolomite (*Pure dolomite, thin bedded, light gray, and cherty, with "Parting" quartzite member, q, at top*) — ORDOVICIAN

Ꞓs — Sawatch quartzite (*Chiefly quartzite; glauconitic grit near top. Unconformable on pre-Cambrian granite*) — *Upper Cambrian*, CAMBRIAN

IGNEOUS ROCKS

gdp — Granodiorite porphyry — *Late Cretaceous or early Eocene*, CRETACEOUS OR TERTIARY

a — Aplite — CRETACEOUS OR TERTIARY

aap — Albite aplite porphyry — CRETACEOUS OR TERTIARY

ap — Albite alaskite porphyry — CRETACEOUS OR TERTIARY

dp — Diorite porphyry — CRETACEOUS OR TERTIARY

gr — Biotitic muscovite granite — PRE-CAMBRIAN

Fault

GEOLOGIC MAP OF THE ASPEN DISTRICT, PITKIN COUNTY, COLORADO

Some of the ore from the Midnight shaft is notable mineralogically, in that it contains galena graphically intergrown with a resinous sphalerite, the scale of intergrowth being sufficiently coarse to be easily apparent to the unaided eye. The galena, which predominates in the intergrowths, forms rather narrow individuals as much as 0.7 inch long.

NATURE OF THE ORE-DEPOSITING SOLUTIONS

Microscopic examination of the ore from the Midnight mine throws some unexpected light on the nature of the ore-forming solutions of this part of the Aspen district. Along with the minerals recognizable in the ore by the unaided eye—galena, sphalerite, pyrite (extremely rare), quartz, barite, and calcite—there occur minute prisms of tourmaline and a little sericite. The prisms of tourmaline are nearly colorless where embedded in quartz, but where they project from the quartz into the fragments of country rock inclosed in the ore they show the distinctive deep-brown pleochroism of tourmaline.

The aplite inclosing the baritic galena-polybasite veinlets recently found in the Hope tunnel (see p. 25) has obviously been profoundly altered by the ore-forming solutions. Under the microscope it is seen to have been largely replaced by coarse sericite, barite, quartz, and dolomite, all these minerals being essentially of contemporaneous origin.

From this association of minerals—sericite, barite, and dolomite with tourmaline—it follows that the ore-depositing solutions were at a fairly high temperature, between "high" temperature and "moderate." The ore deposits are accordingly in the transition range between hypothermal and mesothermal deposits, to use the terms recently proposed by Lindgren.[21]

The ore-forming solutions are probably related genetically to the granodiorite porphyry. The evidence for this conclusion is as follows: The granodiorite, as has been shown, appears to have been intruded after the epoch of folding and faulting and is consequently the youngest igneous rock in the district. The ore deposits also were formed after the epoch of folding and faulting, and as the ore-forming solutions had a fairly high temperature it is reasonable to link them in origin with the granodiorite porphyry. More definite or conclusive evidence as to the nature of this relation has not yet been obtained at Aspen.

Spurr interpreted the mineralization at Aspen as having occurred in three stages—(1) deposition of barite veins; (2) deposition of

[21] Lindgren, Waldemar, A suggestion for the terminology of certain mineral deposits: Econ. Geology, vol. 17, pp. 292–294, 1922.

The igneous rocks, with the probable exception of the granodiorite porphyry, were all injected before the powerful folding and faulting that dislocated the rocks of the Aspen district and before the ores were deposited. They were doubtless intruded during the Laramide revolution, in late Cretaceous or early Eocene time. The diorite porphyry, being the most basic rock in the district, was probably the earliest, in conformity with the general rule that the more basic rocks are injected before the more siliceous varieties. It was followed by albite alaskite porphyry, which is peculiarly distinguished by its sporadic stout prisms of muscovite, and this in turn was followed by albite aplite porphyry, which is especially conspicuous as forming the great sill in Tourtelotte Park, and by almost felsitic aplite, which is without doubt the nonporphyritic finer-grained equivalent of the aplite porphyry. These three last-named rocks represent injected masses of highly differentiated magma, which were doubtless squeezed out from a deep-seated source at slightly different stages during the course of differentiation.

The granodiorite porphyry, which was not known to Spurr, was probably intruded after the epoch of folding and faulting and is therefore the youngest igneous rock in the district.

DIORITE PORPHYRY

Diorite porphyry occurs as a sill in the Paleozoic rocks; near Aspen it is in contact with the basement granite, but toward the south it rises gradually, cutting at a narrow angle across the beds, until at Richmond Hill and Lime Gulch it lies above the Leadville limestone and is overlain by Weber (?) shale. As it rises southward it increases in thickness from 15 feet to more than 300 feet on the ridge on the south side of Lime Gulch. It is particularly abundant on the west slope of Richmond Hill and at the head of Lime Gulch, where its extensive exposure is in part due to repetition by faulting.

The diorite porphyry is a dark fine-grained rock, and as it is not obviously porphyritic, it resembles a finely granular diorite. Its most distinctive feature is that it is spotted black by sporadic phenocrysts of hornblende or its alteration products. It is a rock of marked individuality and is easily distinguishable from any of the other intrusive rocks of the district. On Richmond Hill it is liberally spotted with small areas of yellowish-green epidote, as well as by the dark spots of altered hornblende.

Under the microscope the diorite porphyry from Richmond Hill is seen to consist of feldspar phenocrysts, now completely altered to epidote except where rarely the peripheral zone of albite has re-

mained intact, and ferromagnesian phenocrysts, largely chloritized, embedded in a microgranular groundmass of quartz and albite. The feldspar of the groundmass is fresh and clear, thus contrasting notably with that of the phenocrysts; it has evidently escaped alteration to epidote, like the peripheral zones of some of the plagioclase phenocrysts, because of its albitic, noncalcic composition. From the abundance of chlorite in the rock, the diorite porphyry was evidently a fairly basic variety, much more basic than any of the other igneous rocks in the district.

ALBITE ALASKITE PORPHYRY

The albite alaskite porphyry is a striking rock, of much local interest in the southern part of the Aspen district because the ore body of the Little Annie mine occurred in the Weber (?) formation just above the upper contact of a steeply inclined sill of this porphyry. The porphyry is a white microgranular rock carrying sporadic hexagonal prisms of muscovite, abundant prominent phenocrysts of quartz, and numerous inconspicuous phenocrysts of feldspar. The muscovite prisms, which are blackish because of their length and therefore resemble biotite, are a particularly distinctive feature of the alaskite porphyry and are uniformly distributed throughout the rock, occurring in full size even up to the very edges of the chilled contacts of the porphyry against the inclosing Weber (?) shale. The muscovite prisms are evidently early (intratelluric ?) separations from the magma.

The alaskite porphyry mass of main economic interest is the sill at the Little Annie mine and the faulted extensions of the sill both north and south of the mine. (See pl. 1.) It varies greatly in width from place to place, being as much as 1,000 feet wide on the north side of Winnie Gulch and narrowing to a point a thousand yards farther north, owing to the convergence of the faults that bound it; and, in general, the notable variations in width appear to be similarly due in the main to the effects of faults. The sill is well shown in the workings of the Hope tunnel, where it is 340 feet thick, in the Midnight tunnel, in the Jewell prospect, and in Lime Gulch. Wherever seen it appears to have been injected parallel to the strike and dip of the inclosing Weber (?) formation. At one point in the Midnight tunnel it is accompanied by a parallel subsidiary sill, 2 feet thick, which lies 50 feet above it. Another sill or dike of the porphyry occurs near the Eva Bell shaft; it is in the Weber (?) formation, 300 feet below the overlying Maroon formation. Other masses are common west of the Jewell shaft, but they are not well exposed.

The segment of the Little Annie sill south of the Hope fault dips 70° W.; the dip of the segment at the Little Annie mine is not accurately known but is probably 70° W.; and the segment north of the Winnie fault dips 55° W., as determined in the Midnight tunnel. Now, because the Annie fault, which at the surface forms the west boundary of the sill, dips westward more steeply than the sill, the fault must, north of the Hope fault, in depth pass through and under the sill, and the upper contact of the sill must become a normal igneous contact. This behavior of the Annie fault in depth has been shown on cross sections B–B to F–F on Plate 14 of the Aspen monograph; but the section F–F is of particular interest now, because the graphic prediction as to the downward extension of the Annie fault made in that section has been verified at a depth of 1,000 feet in the Midnight tunnel, driven 20 years after the publication of the monograph. As will be shown, the deposition of the ore was determined by the Annie fault, which evidently afforded a passageway for ascending ore-forming solutions, and not by the contact of alaskite porphyry against the Weber (?) formation. The failure to grasp this significant distinction has caused much perplexity to some of the operators. The objective of all prospecting, as already mentioned, has been the contact of the alaskite porphyry sill with the Weber(?) formation instead of the Annie fault.

The ore occurs as irregular shoots or pods without definite walls in a wide zone of disturbed Weber(?) formation 400 feet long, extending from the Little Annie shaft to the Midnight shaft. The normal strike of the Weber(?) beds is north and the dip 70° W., but the beds resting on the alaskite porphyry sill are shattered and broken through a thickness of 200 feet, with resulting wide variations in strike and dip, locally even striking east. The Weber(?) formation consists here of black thin-bedded limestone, cherty dolomite, and shale. The shattering and disturbance of these beds in contact with the Little Annie sill is evidently due to movement on the Annie fault. Where the Annie fault is not present the Weber(?) beds are undisturbed, the contact of the sill against them is a normal igneous junction, and no ore occurs. The ore consists of a breccia in which the angular fragments of the Weber(?) beds are cemented by galena, sphalerite, quartz, barite, and calcite. Generally an insufficient amount of the sulphides and gangue minerals has been deposited to fill completely the interspaces between the angular fragments of country rock, so that the ore has characteristically a porous, drusy, or vuggy appearance. To a minor extent the fragments of country rock in the breccia have been replaced by galena, sphalerite, quartz, and barite.

position of the ore bodies, the sill has been the incentive of much exploratory work.

The sill trends north and dips steeply west; 1,000 feet north of the Little Annie shaft it is displaced along Winnie Gulch by a transverse fault, which is locally known as the Winnie fault, and 500 feet south of the shaft it is cut by another transverse fault, which may be called the Hope fault. This segment of the Little Annie sill lying between the Winnie fault on the north and the Hope fault is thus roughly 1,500 feet long. (See fig. 2.) In this all-important segment the sill is poorly exposed, but it does not exceed 100 feet in thickness. This narrow width is due to the fact that the sill here lies between two strike faults that diverge in depth. (See fig. 3.) The west boundary of the sill is the fault termed by Spurr the Annie fault. The east boundary is in the main the Castle Creek fault, although east of the Little Annie shaft there is some sericitized aplite, which is the rock encountered in the so-called Porphyry shaft.[20]

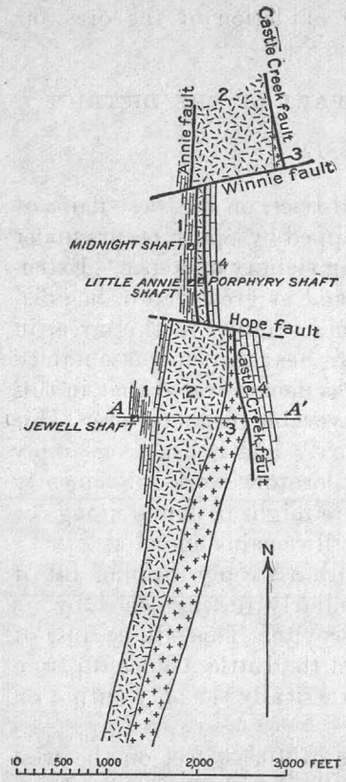


FIGURE 2.—Geologic map of area surrounding Little Annie mine, south of Aspen, Colo. 1, Weber (?) formation; 2, alaskite porphyry (Little Annie sill); 3, aplite; 4, Yule dolomite. *A–A'*, Line of section in Figure 5

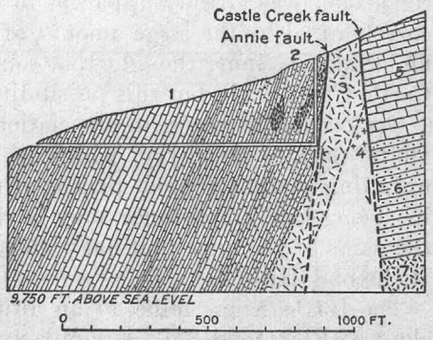


FIGURE 3.—Diagrammatic section through the Little Annie shaft, south of Aspen, Colo. 1, Weber (?) formation; 2, ore zone; 3, alaskite porphyry; 4, aplite; 5, Yule dolomite; 6, Sawatch quartzite; 7, pre-Cambrian granite

[20] The cross section through the Little Annie mine given on Plate 43 of the Aspen monograph is erroneous to the extent that it does not distinguish the highly porphyritic alaskite porphyry from the nonporphyritic aplite.

The largest mass of the alaskite porphyry is near the south end of Richmond Hill, where it extends from the head of Lime Gulch eastward across the divide. It forms a roughly elliptical stock which breaks through the pre-Cambrian granite and the overlying Paleozoic strata as high as the blue limestone of the Leadville formation.

Under the microscope the feldspar phenocrysts of the alaskite porphyry are found to be fairly abundant, much more so than the quartz crystals that are so conspicuous to the unaided eye. They prove to be a nearly pure albite. As they are referred to in the Aspen monograph as orthoclase, it is perhaps necessary to give the diagnostic properties determined concerning this feldspar: Multiple twinning with maximum symmetrical extinction of 20°, optically positive, birefringence 0.010, refractive indices less than 1.54. The euhedral hexagonal phenocrysts of mica, generally 0.1 inch in thickness, are found to be muscovite, as proved by their colorlessness and wide axial angle. The occurrence of muscovite phenocrysts in porphyry is highly unusual, and its presence in alaskite porphyry in other Colorado districts has been pointed out by Spurr, Garrey, and Ball.[4] It was first established by Cross to occur in Colorado in the "White" porphyry at Leadville.

The phenocrysts of albite, quartz, and muscovite are set in a coarsely microgranitic groundmass of quartz, the more abundant constituent, and lamellated albite. Secondary constituents, muscovite and carbonate, either calcite or dolomite, are abundant and have developed at the expense of both the albite of the phenocrysts and that in the groundmass.

This porphyry was called quartz porphyry by Spurr; it is the only one at Aspen to which that name is at all applicable, but the term is now obsolescent. In 1908 he referred to it as an alaskite porphyry,[4] but in 1909 he termed it a rhyolite porphyry,[5] without, however, realizing that he was including three distinct intrusive rocks under that designation. As this porphyry gives no evidence of having been related to the extrusion of any surface volcanic rock and as in its textural development and content of muscovite phenocrysts it shows clearly that it is a closely allied differentiate of a deep-seated intrusive rock, the name alaskite porphyry will be retained, and to signalize that its feldspar content is wholly albite instead of the more usual orthoclase it will be called an albite alaskite porphyry.

[4] Spurr, J. E., Garrey, G. H., and Ball, S. H., Economic geology of the Georgetown quadrangle, Colo.: U. S. Geol. Survey Prof. Paper 63, pp. 132–133, 1908.

[5] Spurr, J. E., Ore deposition at Aspen, Colo.: Econ. Geology, vol. 4, pp. 305–306, 1909.

ALBITE APLITE PORPHYRY

The albite aplite porphyry is most prominently represented by the great homogeneous sill in Aspen Mountain, which extends southward into Tourtelotte Park. This sill is about 300 feet thick and has been intruded near the base of the shale of the Weber (?) formation, thus lying above the horizon at which the diorite porphyry sheet occurs. As the two rocks are nowhere in contact, their relative ages are undetermined.

This rock is a gray porphyry, pure white where unweathered, carrying somewhat inconspicuous phenocrysts of striated feldspar, 0.1 to 0.2 inch in diameter, which are embedded in a nearly phanerocrystalline groundmass. It was mapped as quartz porphyry by Spurr, but it does not show the quartz phenocrysts which according to that designation might be expected to occur.

Specimens obtained near the portal of the Veteran tunnel, at Aspen, and near the Best Friend shaft, in Tourtelotte Park, are essentially alike in their general features. The phenocrysts are found to be polysynthetically twinned albite ($Ab_{96}An_4$), although specifically referred to by Spurr[7] as orthoclase. The groundmass is made up of polysynthetically twinned albite and quartz, the fabric ranging from microgranitic to panidiomorphic. In the specimen from Tourtelotte Park much of the quartz of the groundmass is remarkably idiomorphic. No satisfactory name is available to apply to this rock, so in order to signalize its more important features it will be termed an albite aplite porphyry. It differs markedly from the alaskite porphyry in not containing phenocrysts of muscovite and quartz.

The porphyry has been much altered by ore-forming solutions, as shown by the abundant sericite, pyrite, and ferriferous dolomite that have been developed in it. The oxidation of the secondary iron minerals has given much of the rock a speckled appearance.

APLITE

Aplite occurs as a thick dike in the southern part of the district. So far as known to the writer, it extends only a short distance into the area mapped by Spurr, who did not distinguish it from the quartz porphyry with which it is there associated. It is well shown in the workings of the Hope tunnel, where it cuts through the alaskite porphyry dike. The same aplite dike is well shown on the north side of Lime Gulch, where it is 300 feet thick and lies just under the alaskite porphyry sill, which dips 70° W. and is separated from it by only 3 feet of metamorphosed black shale.

[7] Op. cit. (Mon. 31), p. 50.

below an older surface of erosion, is the enormous amount of degradation that has been effected in geologically recent time. Nevertheless, the rate of oxidation of the ores has more than kept pace with the rapid rate of degradation. Possibly the reason is, as already hinted, that the great relief produced by the profound canyon cutting has so strongly stimulated the downward movement of oxygen-charged waters as to accelerate oxidation of the ores far beyond the rate of areal denudation.

ORE DEPOSITS IN THE SOUTHERN PART OF THE DISTRICT

MODE OF OCCURRENCE

The ore in the southern part of the district, on the west flank of Richmond Hill, just south of the area mapped by Spurr, occurs under different conditions from those in the near vicinity of Aspen. Extensive prospecting, both near the surface and at great depth, has disclosed no ore along the Silver and Contact faults in this area, in spite of the fact that the bulk of the ore near Aspen was obtained along these faults. It must be accepted as demonstrated that in this part of the district these faults are not favorable places for ore. This conclusion was already apparent to Spurr,[19] and it has been amply corroborated by the large amount of exploratory work subsequently undertaken. Spurr thought that some ore might be found along the Castle Creek fault, but this possibility still remains unrealized.

Ore occurs, however, in association with a steeply dipping sill of albite alaskite porphyry, which is peculiarly distinguished by its unfailing content of stout prisms of muscovite. This sill, because of its strong local importance, may be called the Little Annie sill, from the name of the mine that has yielded practically the only output on Richmond Hill.

The Little Annie mine, at an altitude of 10,540 feet on the west slope of Richmond Hill, is popularly credited with having produced $1,000,000 from silver-lead ore. To cut at considerable depth the ore body from which this ore was taken is the goal set for two long adits that are now being driven—the Hope tunnel and the Midnight tunnel, described on pages 24–28. The southward extension of this sill is being prospected at the Jewell shaft, at the Orinogo tunnel, in Lime Gulch, and at the tunnels of the Hurricane Mining & Milling Co., south of Lime Gulch.

The ore at the Little Annie mine occurs in a zone of shattered Weber (?) formation forming the hanging wall of the Little Annie sill of alaskite porphyry. As it has been assumed by the operators that the porphyry contact was the main factor in determining the

[19] Op. cit. (Mon. 31), p. 168.

the hanging valley of Hunter Creek, was probably done during the earlier glaciation.

Notwithstanding the great stream and glacial erosion so plainly indicated in the Aspen district, oxidized ores are common, and the effects of descending waters of surface origin are perceptible at considerable depths. Bastin has recently discussed the depth of oxidation at Aspen, and has shown that notable oxidation occurs in or adjacent to the ore bodies to a depth of 1,000 feet, though in distribution this oxidation is markedly spotty.[17] Analysis of the data presented by Bastin shows that all the deep oxidation he observed was above the level of Roaring Fork, the master stream of the district. Similarly, the wire silver seen by the writer at a vertical depth of 1,500 feet in the Hope tunnel is above the level of Castle Creek. According to Spurr, wire silver is abundant to considerable depths below water level, occurring at least as deep as 900 to 1,000 feet below the surface, even in places where the water level originally stood only a few hundred feet down.[18] But whether any notable quantity of oxidized ore or wire silver occurs below the level of the master streams of the district is not recorded.

The Aspen district is an area of abrupt, high relief, underlain by carbonate formations, and consequently it has a vigorous circulation of underground waters, especially along solution channels. Doubtless this combination of great relief and active movement of surface waters charged with oxygen along solution channels has produced the great depth of oxidation recorded by Bastin.

In the highest mines in the district, in Tourtelotte Park, all the ore is oxidized, as was noted by Spurr. For example, the ore bodies recently cut by the Park tunnel 600 feet below the outcrop are completely oxidized to porous, highly limonitic material, although in places they are 40 feet thick. This extensive oxidation is not wholly of postglacial origin but dates back at least to interglacial time. Tourtelotte Park lies above the upper limit of the last main glaciation, so the outcrops were not planed off by the ice erosion of that epoch. As Tourtelotte Park is the floor of a wide, shallow cirque high above Roaring Fork, it was not deeply eroded during the earlier, more mighty glaciation, as its shallowness proves. Therefore the oxidized ores of the park may date back to preglacial time.

The amount of glacial erosion in the Aspen district and the depth to which oxidized ores extend form but one side of a larger problem. That problem is the rate of oxidation as contrasted with the rate of erosion. One of the dominant impressions that the Aspen district makes, with its great canyons 3,000 and 4,000 feet deep intrenched

[17] Bastin, E. S., Observations on the rich silver ores of Aspen, Colo.: U. S. Geol. Survey Bull. 750, pp. 56–57, 1924.

[18] Spurr, J. E., Ore deposition at Aspen, Colo.: Econ. Geology, vol. 4, p. 315, 1909.

The aplite is a white or cream-colored rock without porphyritic crystals, fine grained, almost verging on the felsitic in appearance. At contacts it has in fact been chilled to a felsite with almost imperceptibly faint flow structure.

Under the microscope a few "microphenocrysts" of albite become apparent, set in a panidiomorphic groundmass of albite and quartz. The quartz is abundant, and much of it occurs as sharp dihexahedrons. The texture is typical of aplite, and as the rock contains no orthoclase it is here termed an albitic aplite. Sericite is generally abundant as a secondary product.

GRANODIORITE PORPHYRY

The two stocks of granodiorite were found during the present work to be intrusive into the Maroon formation southwest of the Little Annie mine. The larger and more conspicuous mass is well exposed in prominent cliffs along the canyon of Little Annie Creek; the other mass is half a mile to the south. The porphyry in appearance practically resembles a medium-grained quartz diorite, although much of the quartz, unlike that of a normal quartz diorite, occurs as distinct porphyritic crystals.

Andesine ($Ab_{55}An_{45}$), quartz, and biotite are the phenocrysts; they are closely set in a groundmass that is a remarkably well-developed micrographic intergrowth of orthoclase and quartz in the porphyry of Little Annie Creek and is a hypidiomorphic granular aggregate of plagioclase, orthoclase, and quartz in the other porphyry mass. On the basis of their phenocrysts these rocks would be named quartz diorite porphyry, but on the basis of bulk composition, which is obviously like that of the granodiorite at the head of Castle Creek, in the Elk Mountains, south of Aspen, they would be termed granodiorite porphyry, and this name is adopted in order to emphasize their probable genetic relation to the granodiorite in the Elk Mountains.

GRANODIORITE

The mass of intrusive plutonic rock nearest to the Aspen district occurs in the Elk Mountains, on the headquarters of Castle Creek, 12 miles south of Aspen, near the old mining camp of Ashcroft. This mass is the northward extension of the great body mapped by Cross as making up the Sawtooth Range of the Elk Mountains, in the Anthracite and Crested Butte quadrangles; it was termed by him diorite. From his description of the rock it is apparent that it would now be termed a granodiorite. Where seen by the writer, on the road to the Montezuma mine, it conforms closely to the description given by Cross. It is a homogeneous body of clear-

gray fresh-looking fine-grained granodiorite, of light color, because it carries only sparse biotite.

Microscopically, the granodiorite is found to consist dominantly of andesine ($Ab_{54}An_{46}$), together with quartz, orthoclase, and biotite, named in the order of decreasing abundance. The rock is of normal granitic texture and is therefore a biotite granodiorite.

The granodiorite has exerted a powerful, widespread metamorphic effect on the rocks of the Maroon formation, which it has invaded—the cement in the arkose has been altered to epidote, the argillaceous beds have been converted into biotite hornfels, and the calcareous beds into calc hornfels, such as the epidote-scapolite-titanite hornfels in the vicinity of the mill of the Montezuma mine, near the head of Castle Creek. This marked metamorphism indicates, as Cross long ago pointed out, that the granodiorite magma contained such mineralizing agents as fluorine and chlorine at the time of its intrusion.[8] Contact-metamorphic magnetite deposits are associated with the granodiorite at Taylor Peak, 15 miles south of Aspen, and have been described by Harder.[9] At Snowmass Peak, 15 miles west of Aspen, and at Mount Sopris, 20 miles northwest of Aspen, similar granodiorite evidently occurs, as reported by S. F. Emmons.[10]

The granodiorite, according to Cross,[11] is of Eocene or later age. It was intruded after the folding of the Cretaceous rocks, as shown by structure section B–B on the Crested Butte geologic map.

IGNEOUS ROCKS OF PORPHYRY MOUNTAIN

At Porphyry Mountain, 14 miles north of Aspen, on the northward extension of the Aspen mineral belt, is a large intrusive mass of porphyritic aplite. It is an irregularly crosscutting body about 1,000 feet wide, but its major dimension is in the direction of the bedding of the steeply tilted sedimentary rocks that inclose it. Along its periphery, in the inclosing Leadville limestone, occur a few small contact-metamorphic deposits composed of garnet and magnetite.

It is a white rock of sugary texture and is inconspicuously and sparsely porphyritic through the presence of scattered phenocrysts of feldspar and flakes of biotite. Under the microscope the phenocrysts are seen to comprise albite and orthoclase and to be embedded in a panidiomorphic matrix of albite, orthoclase, and quartz; much

[8] Cross, Whitman, The laccolitic mountain groups of Colorado, Utah, and Arizona: U. S. Geol. Survey Fourteenth Ann. Rept., pt. 2, pp. 180, 230, 1894.

[9] Harder, E. C., The Taylor Peak and White Pine iron-ore deposits, Colo.: U. S. Geol. Survey Bull. 380, pp. 188–194, 1909.

[10] U. S. Geol. Survey Geol. Atlas, Anthracite-Crested Butte folio (No. 9), p. 2, 1894.

[11] Idem, p. 5, and legend of geologic map of Crested Butte quadrangle.

large pit formed by the caving of the Boulder shaft, on Smuggler Mountain. The granite boulders are oxidized and stained by limonite through and through, and in the sides of the pit the boulders do not project in relief, as they do in cuts in the younger moraines. As the sides of the pit slumped the crumbly granite boulders broke as readily as the finer material in which they are embedded.

In contrast to this thoroughly weathered condition the granite boulders of the younger glaciation, consisting of the granite of the same kind as that in the older moraines, are firm, coherent, and brilliantly fresh. Manifestly, a long time separated the two epochs of ice action. Other evidence of a considerable interglacial interval is afforded by the gullies that are deeply cut in bedrock above the younger lateral moraines on the northwest extension of Red Mountain but hardly notch these moraines where they cross them. This anomalous condition that the headward portions of the gullies are cut deeper in bedrock than the lower portions are cut in loose morainal material indicates that the headward portions were eroded during interglacial time. Presumably they could not have been formed before the earlier glaciation, because the ice of that epoch extended far above their upper limits, and therefore glacial erosion would undoubtedly have obliterated them. The lower stretches of these bedrock gullies were buried by the morainal detritus of the subsequent glaciation. Postglacial erosion has been too feeble to exhume the buried portions and has succeeded only in faintly notching the top of the lateral moraine. On the basis of the comparative amounts of erosion done, the interglacial interval must have been many times as long as the time that has elapsed since the retreat of the last glacier.

The ice streams obviously accomplished a large amount of erosion at Aspen. This is indicated by the great breadth and depth of the U-shaped troughs of Roaring Fork and its tributaries. A minimum measure of the amount of the deepening of the Roaring Fork Valley by ice action appears to be afforded by the hanging condition of the Hunter Creek valley, just northeast of the town of Aspen. This fine glacial trough stands 500 feet above the floor of Roaring Fork. Accordingly at least 500 feet of glacial downcutting was accomplished at the site of Aspen.

When was this work done? The glacier of the last epoch was not over 1,000 feet thick at Aspen and probably terminated a short distance below the site of the town, as shown by the large moraine partly spanning the valley just below the confluence of Maroon Creek. Near their ends glaciers as a rule have weak erosive power. The earlier glacier was nearly three times as thick at Aspen as the later one. Consequently most of the downcutting, as measured by

3 ounces of silver to the ton; it contained but little zinc, which did not increase in amount in depth.

The deepest workings in the Aspen district—those in the Molly Gibson mine—reached a vertical depth of 1,450 feet below the collar of the Molly Gibson shaft, or 2,880 feet below the outcrop. The Molly Gibson mine is regarded as exhausted, and it was closed down in July, 1923.

An enterprise of comparatively recent date is that of the Park Mining & Milling Co., which in 1921 completed a tunnel 3,165 feet long driven from the head of Keno Gulch to tap the large bodies of oxidized ore under Tourtelotte Park. Extensive bodies of highly limonitic ore were found, but previous operators had already removed through numerous devious workings the more valuable portions. On account of the low prices of silver and lead it did not pay the company to extract the remaining low-grade material, and in 1923 operations were at a standstill.

The Cowenhoven tunnel, which penetrates Smuggler Mountain somewhat north of the Molly Gibson mine for a distance of 2¾ miles, was being reopened by the Silver Mines Co. of America in 1923. It had been made accessible to a distance of 5,000 feet from the portal, and some prospecting was undertaken to find bodies of ore in or adjacent to the old workings. It was reported that the main purpose, however, was to explore some unprospected ground at 10,000 feet from the portal.

OXIDATION OF THE ORES AS RELATED TO THE GLACIAL HISTORY

There were plainly two epochs of alpine glaciation at Aspen. The earlier of these gave rise to ice streams that were by far the larger. An immense amount of erosion was done by the ice streams in drastically remodeling a region already deeply trenched by stream canyons, yet, remarkably enough, oxidized ores are common in the district, and the effects of oxidizing solutions have extended to great depths. It is purposed to discuss briefly the problem that is thus presented.

The moraines of the earlier epoch appear at altitudes above 9,000 feet, for below this they are covered by the younger moraines, and they extend up as high as 10,800 feet. The long summit of Richmond Hill is free from any evidence of glaciation, negativing Spurr's idea that a continuous ice sheet once covered the whole region. The older moraines consist of granite and quartzite boulders, but the granite boulders have crumbled to a coarse sand, so that only quartzite débris appears at the surface over large areas, and the normal forms of the moraines have been considerably subdued. The weathered state of the older moraines is excellently shown in the

of the quartz is sharply euhedral. Porphyritic aplite seems the most appropriate designation for this rock. It evidently has close affinities with the albite aplite porphyry at Aspen. It is far better preserved, having been much less altered by the action of mineralizing solutions.

In addition to the porphyritic aplite, there occurs at Porphyry Mountain a sill of granite porphyry, the lower contact of which is being prospected by the Aspen Silver Lead Mines Co. This porphyry is crowded with phenocrysts of quartz, feldspar (mainly orthoclase), and biotite, which are inclosed in an aphanitic groundmass. It does not resemble any porphyry that occurs elsewhere in the Aspen district.

CORRELATION OF THE IGNEOUS ROCKS

The igneous rocks in the region east of Aspen, which were intruded at the end of the Cretaceous or beginning of the Tertiary period, have recently been described by Crawford.[12] The sequence of events deduced by him is as follows: (1) Intrusion of porphyries from great depth; (2) large-scale folding and faulting; (3) intrusion of quartz diorite in small bodies throughout a wide region; (4) invasion by granodiorite or quartz monzonite batholiths; (5) minor faulting; (6) deposition of minerals that emanated from the quartz monzonite magma; (7) a second intrusion of porphyries; (8) more faulting.

This sequence is a generalized statement that applies to the region as a whole, and it is improbable that the full succession of events has occurred in every district or even that the events have occurred everywhere in the same order. The logically most secure procedure demands that the sequence of events be determined locally for each district as well as may be, because the supplementing of an incomplete local history by evidence obtained from distant areas is inherently more or less hypothetical.

The established sequence at Aspen is as follows: (1) Intrusion of diorite porphyry, alaskite porphyry, aplite porphyry, and aplite, the order of arrival being unknown from field evidence except that the aplite cuts the alaskite porphyry and is therefore the younger of the two; (2) folding and faulting; (3) deposition of ore; (4) more faulting. The time of intrusion of the granodiorite porphyry is not fully known from the local evidence; but if the granodiorite porphyry is the more rapidly cooled equivalent of the granodiorite in the Sawtooth Range of the Elk Mountains, as appears highly probable from their identity of composition, then it was intruded after

[12] Crawford, R. D., Contribution to the igneous geology of central Colorado: Am. Jour. Sci., 5th ser., vol. 7, pp. 365–388, 1924.

the folding and is accordingly the youngest igneous rock in the Aspen district. The sequence of events at Aspen is accordingly in the main like that in the districts east of Aspen as given by Crawford. Spurr, on the other hand, correlated the diorite porphyry of Aspen with the granodiorite ("diorite") of the Elk Mountains,[13] but this correlation appears to be erroneous, because the rocks are unlike in composition and because the diorite porphyry was intruded before the epoch of powerful folding and faulting and the granodiorite was intruded after the epoch of folding.

Spurr believes that the marked doming up of the rocks at Aspen, amounting to 5,000 feet at the center of greatest uplift, was the result of a "very local uplift, such as would arise from a vertically exerted force."[14] To account for this remarkable feature of the district "it was reasoned out that this domal uplift was due to the upward propulsion of a column or pipe of molten igneous rock, which never reached the surface." Possibly the stocks of granodiorite porphyry in the southern part of the district are the tops of cupolas on an underlying body of granodiorite, whose emplacement domed up the rocks in the productive part of the Aspen district in the way described by Spurr.

THE ORE BODIES

GENERAL FEATURES

The ore bodies of the Aspen district are silver-bearing lead deposits that have been formed mainly through the replacement of limestone. Most of the ore bodies were situated along one or the other of two faults, both of which are essentially parallel to bedding planes—the Silver fault, between the Leadville limestone and the overlying Weber (?) formation and the Contact fault, which separates the dolomite member of the Leadville formation from the overlying blue limestone. Particularly large ore bodies occurred where the Silver or Contact faults were cut by cross faults. So well is this mode of occurrence of the ore understood and so much more readily are faults found at the surface than outcrops of ore bodies, that the usual method of exploring for new ore bodies is to drive tunnels for such intersections, regardless of whether ore is known to occur at the surface or not.

The remarkable control that the structure has exerted in determining where the ore bodies were deposited is the outstanding feature of the geology of Aspen. Although most of the ore bodies along the two main productive faults have been found and exhausted, it is nevertheless probable that the future output will be

[13] Spurr, J. E., Econ. Geology, vol. 4, p. 305, 1909.
[14] Idem, p. 308.

derived chiefly from the Silver and Contact faults and from the minor parallel or "sympathetic" bedding faults in the zones adjoining those faults.

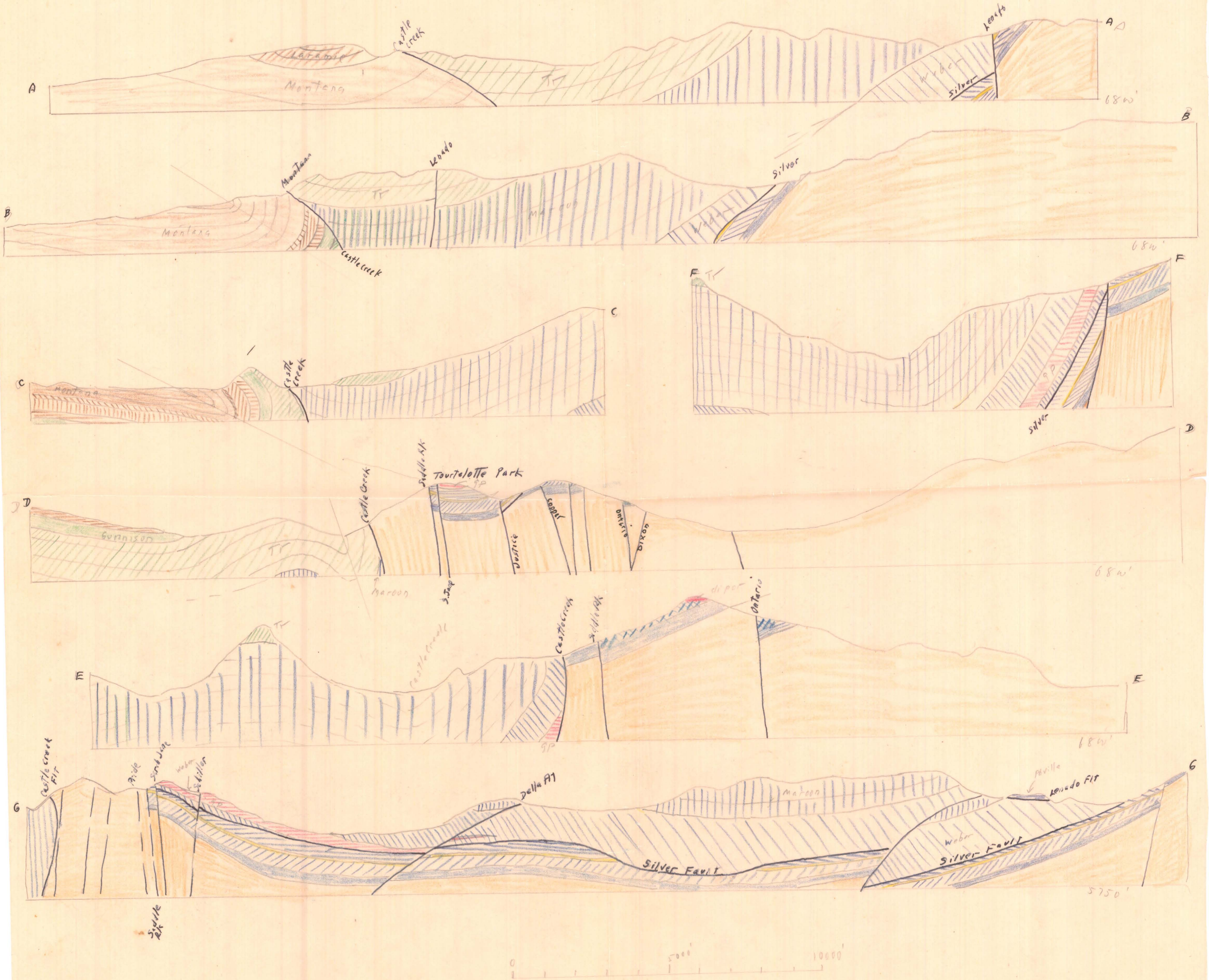
The ore worked in early days was rich in silver, owing to its content of native silver, pearceite ("arsenical polybasite"), argentiferous tennantite, and argentite. Barite is a characteristic associate of such ore. Bastin,[15] who visited the district in 1913, when some ore of this kind was still to be seen in place, concludes from his detailed study of the microstructure of the high-grade silver ore that the rich silver-bearing minerals are essentially of primary (hypogene) origin; that supergene enrichment has been most marked in those ores in which primary silver minerals were abundant; that the chief silver mineral of supergene origin was native silver, but in some places supergene pearceite and argentite were also deposited; and that the native silver disappears at depth and has clearly been deposited from descending water of surface origin. Spurr,[16] on the other hand, believes that the native silver has grown in place as the result of the oxidation of rich silver compounds and that there has been little downward migration and enrichment of silver. The fact, noted by both Spurr and Bastin, that the native silver is mainly associated with the rich primary silver-bearing minerals appears to favor Spurr's interpretation; but quantitative proof of either proposition is not at hand.

Native silver was found by Bastin to occur to a vertical depth of 1,200 feet. In the southern part of the district it persists to an even greater depth—1,500 feet; it is in tight ground in which the ore shows no other sign of alteration. Small bodies of such ore were found in the Hope tunnel, consisting chiefly of galena in barite with polybasite and a little chalcopyrite; the native silver is in prongs and wires, which are striated and grooved and thus appear as if they had been extruded from the polybasite upon which they are implanted.

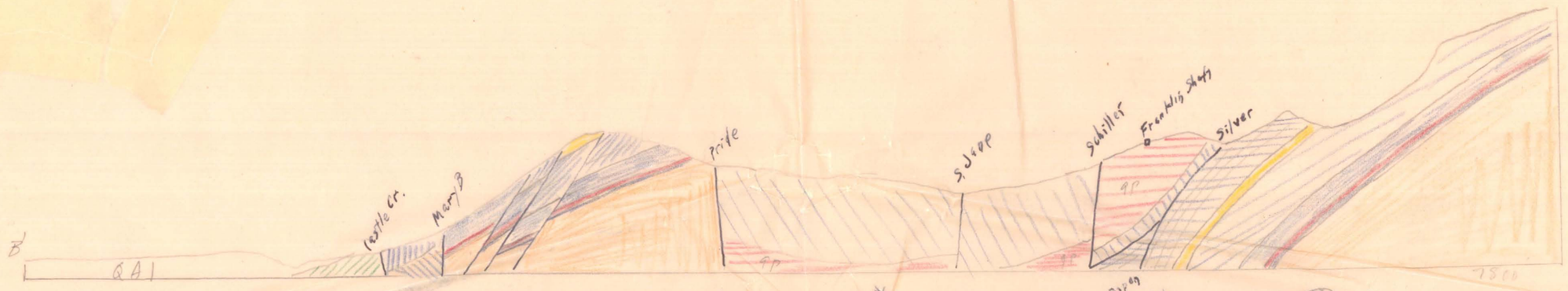
Ore, to pay for shipment and smelter charges, must carry from 15 to 20 "points" (ounces of silver per ton plus units of lead), or, roughly, $15 to $20 a ton in silver and lead. Most of the ore mined in the last decade, however, has not been shipping ore but has been milling ore that carried a moderate percentage of lead in the form of galena and a few ounces of silver to the ton.

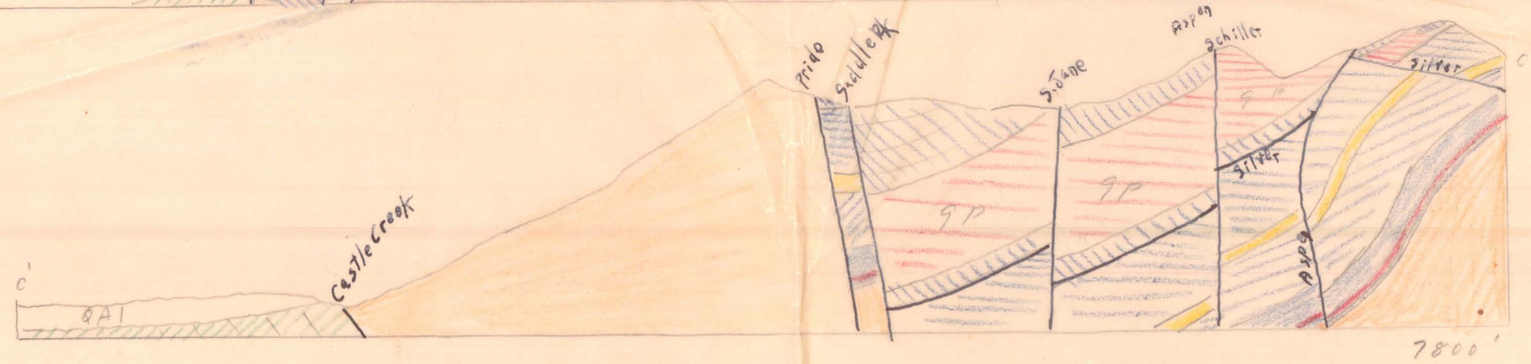
The chief producer has been the Molly Gibson mine. The ore from the deeper levels of this mine, according to Mr. Charles E. Anderson, manager, averaged from 2 to 3 per cent of lead and

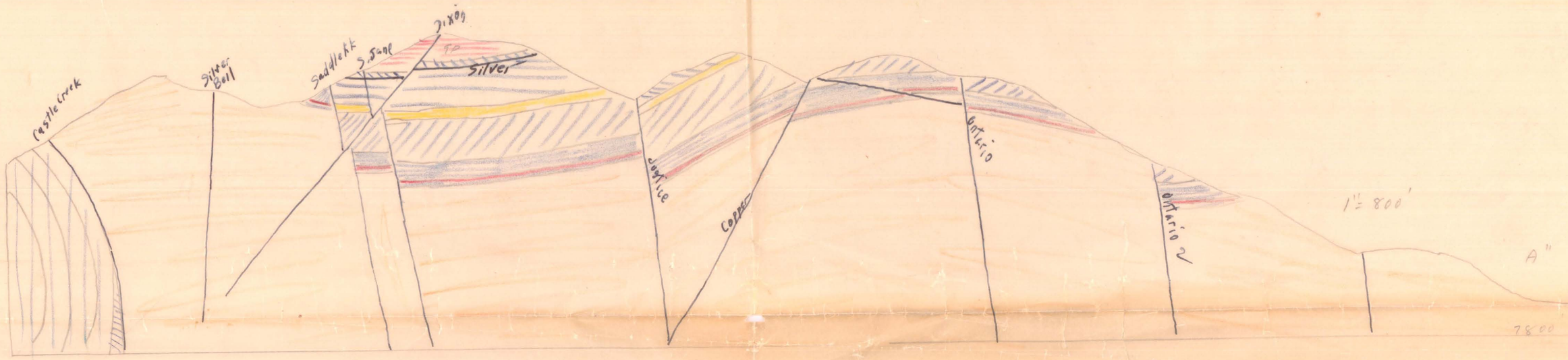
[15] Bastin, E. S., Observations on the rich silver ores of Aspen, Colo.: U. S. Geol. Survey Bull. 750, pp. 41–62, 1924.
[16] Spurr, J. E., Econ. Geology, vol. 4, p. 316, 1909.

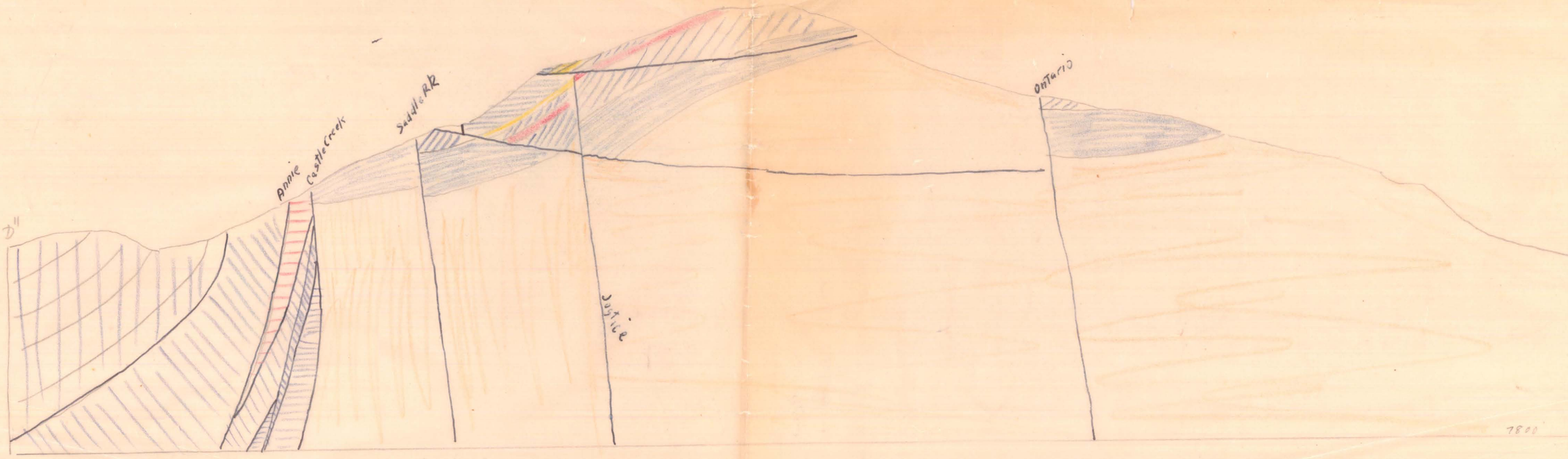

A
Laramie
Castle Creek
Montana
Tr
Weber
Leadville
Silver
A
6800'
B
Montana
Leadville
Tr
Maroon
Weber
Silver
Castle Creek
B
6800'
C
Montana
Castle Creek
C
F
Tr
Silver
F
D
Gunnison
Tr
Castle Creek
Saddle Rock
Tourtelotte Park
Maroon
Justice
Copper
Ontario
Dixon
D
6800'
E
Tr
Castle Creek
Saddle Rock
Ontario
E
6800'
G
Castle Creek Flt
Ride
Sub Junc
Weber
Schiller
Della Flt
Maroon
Leadville Flt
Weber
Silver Fault
Silver Fault
G
5750'
Saddle Rock
0
5000'
10000'

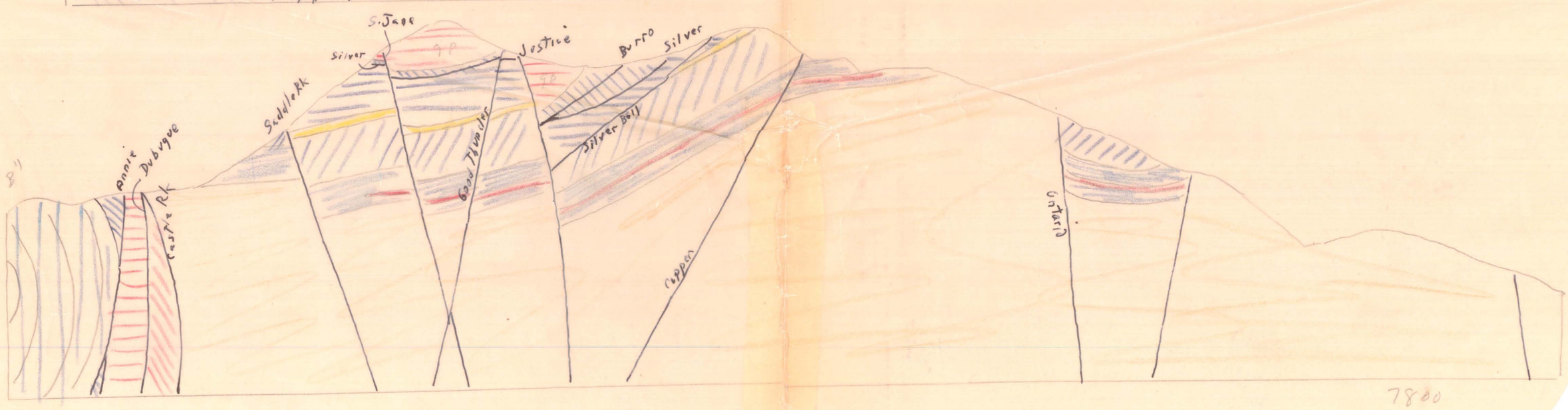
1" = 800'
A'
A
qp
Silver Clark
Della
7800'

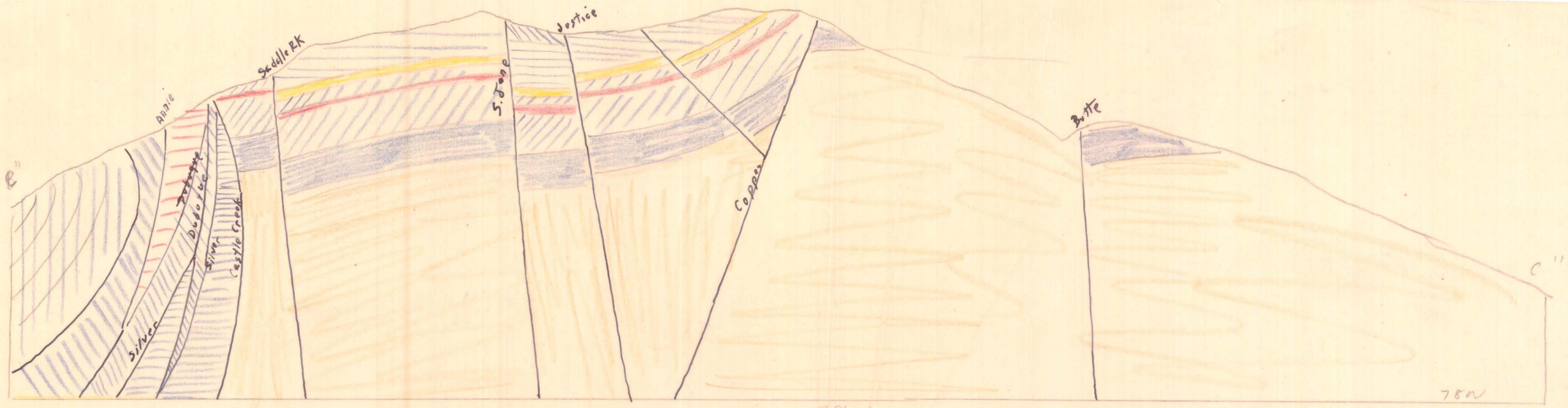

B'
B
QAl
Castle Cr.
Mary B
Pride
S. Jane
Schiller
Franklin Shaft
Silver
qp
7800

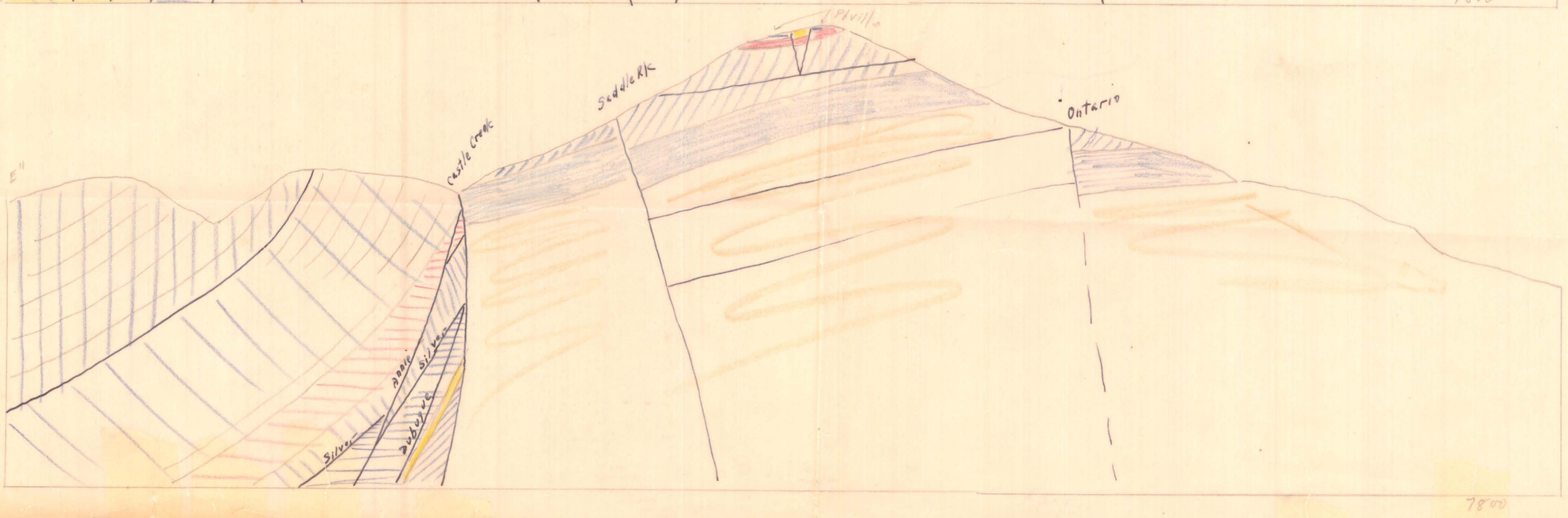

C'
C
QAl
Castle Creek
Pride
Saddle Rk
S. Jane
Aspen
Schiller
Silver
qp
7800'

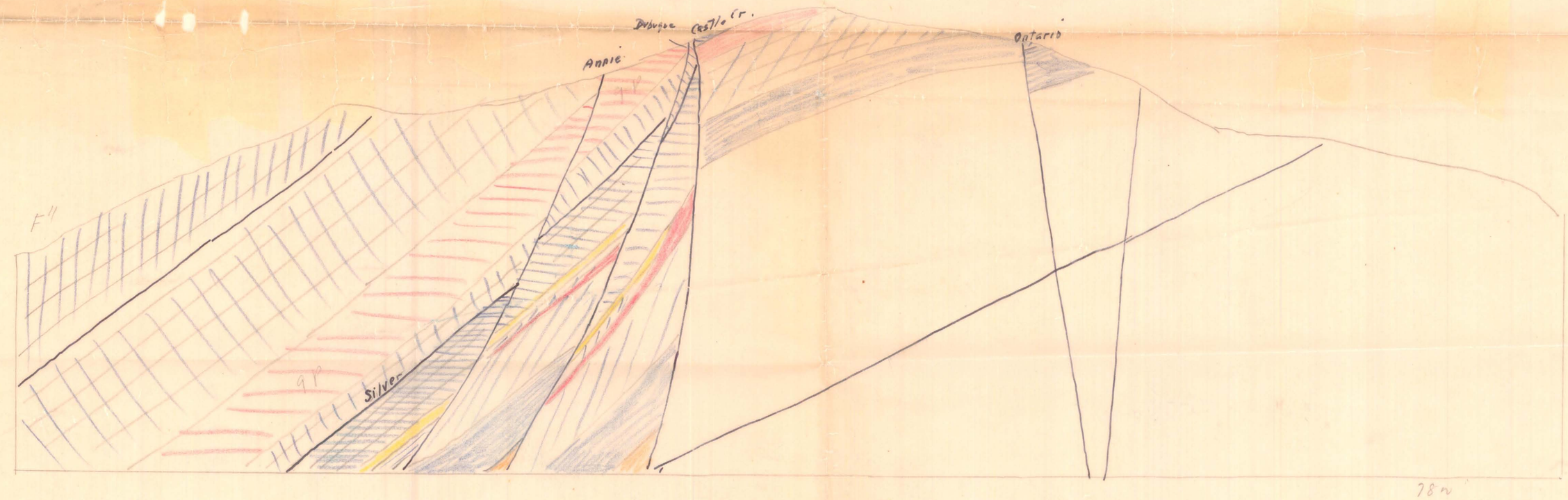

A"
Castle Creek
Silver Bell
Saddle Rk
S. Jane
Dixon
Silver
qp
Justice
Copper
Ontario
Ontario 2
1" = 800'
7800

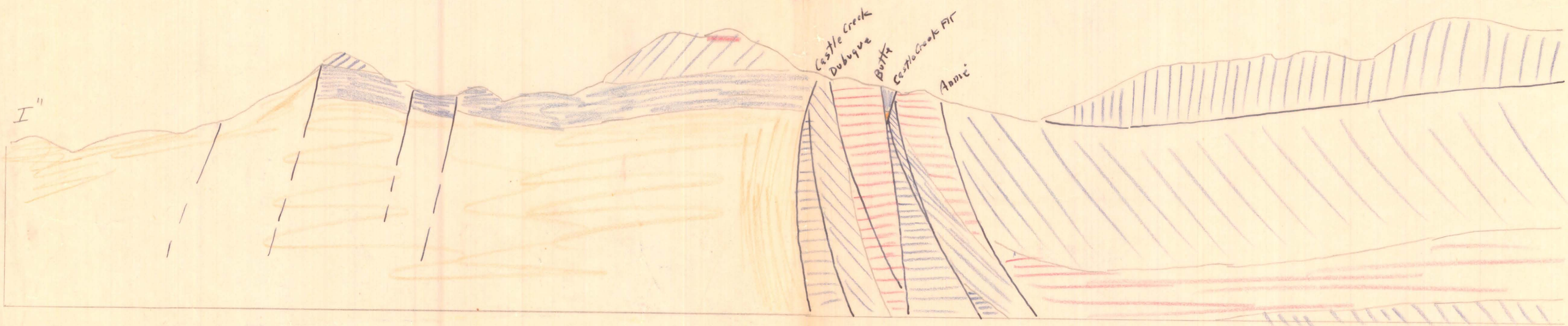

D"
Annie
Castle Creek
Saddle Rk
Justice
Ontario
7800

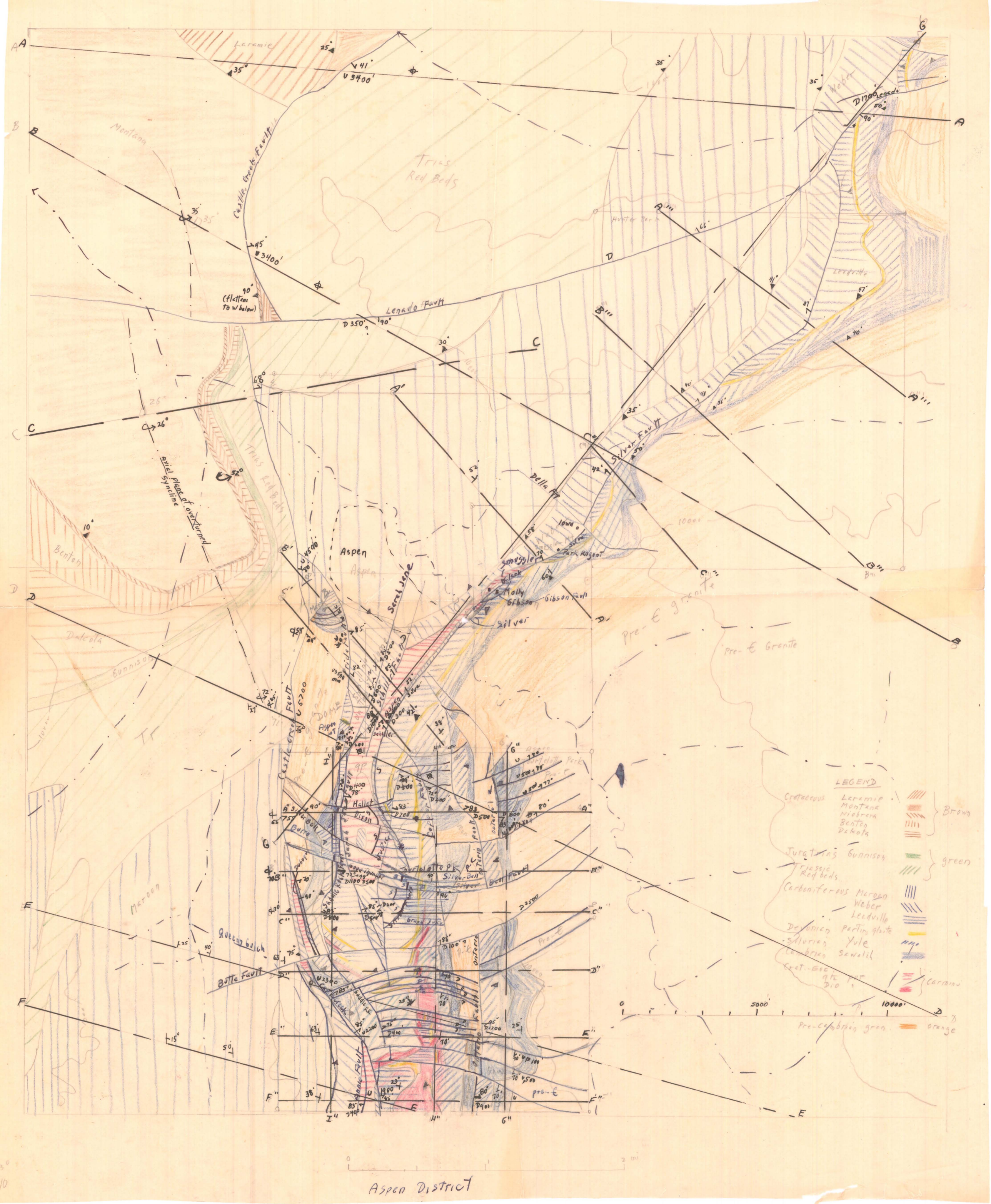

B"
Annie
Dubuque
Castle Rk
Saddle Rk
S. Jane
Silver
qp
Justice
Good Thunder
Burro
Silver
Silver Bell
Copper
Ontario
7800


E''
Annie
Dubuque
Silver
Castle Creek
Saddle Rk
S. Jane
Justice
Copper
Butte
C''
78 N

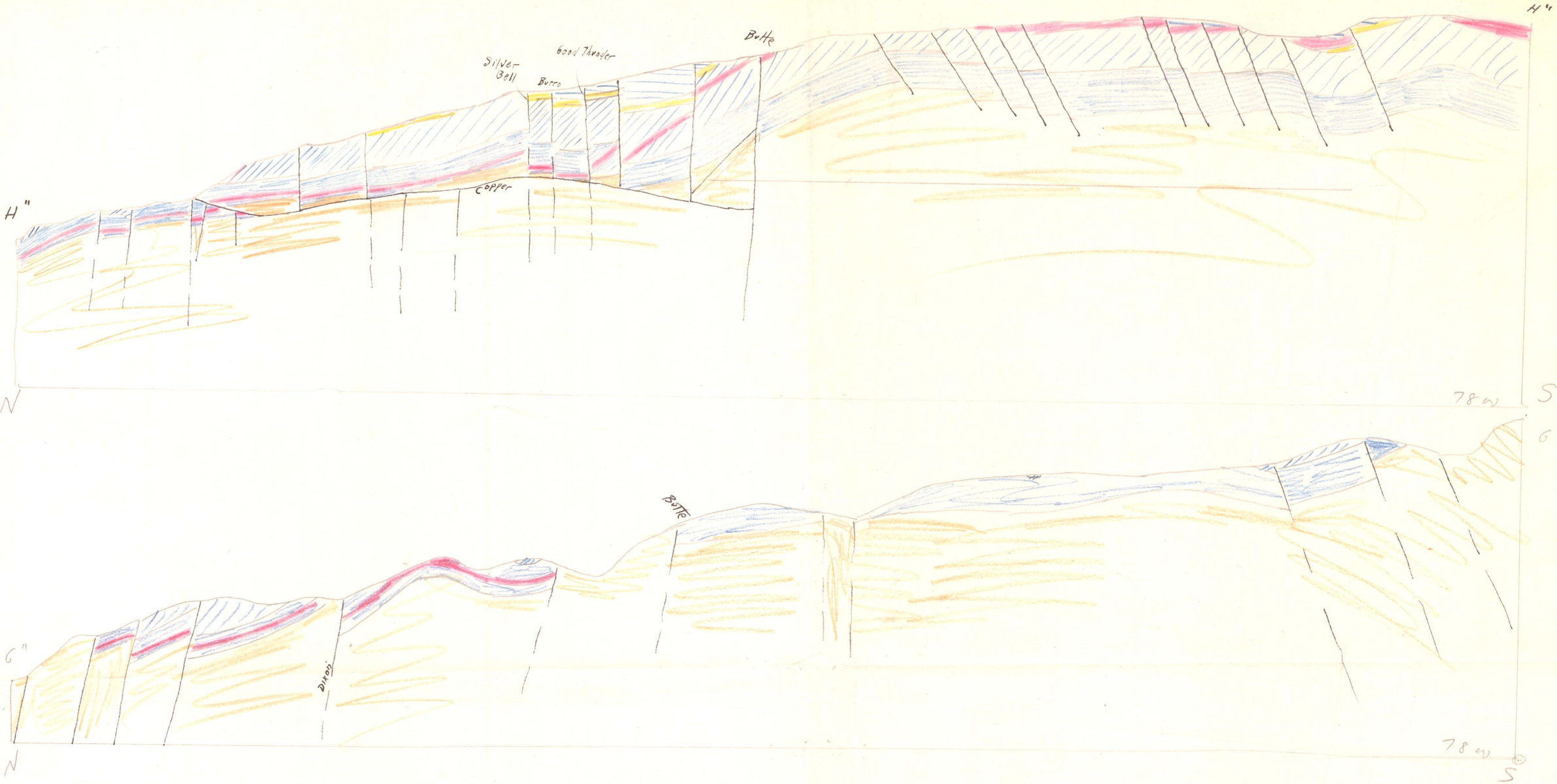

Pavilion
Saddle Rk
Ontario
Castle Creek
E''
Annie
Silver
Dubuque
Silver
E''
78 N


Dubuque
Castle Cr.
Ontario
Annie
F''
Silver
F''
78 N


Castle Creek
Dubuque
Butte
Castle Creek Fit
Annie
I''
1" = 80'

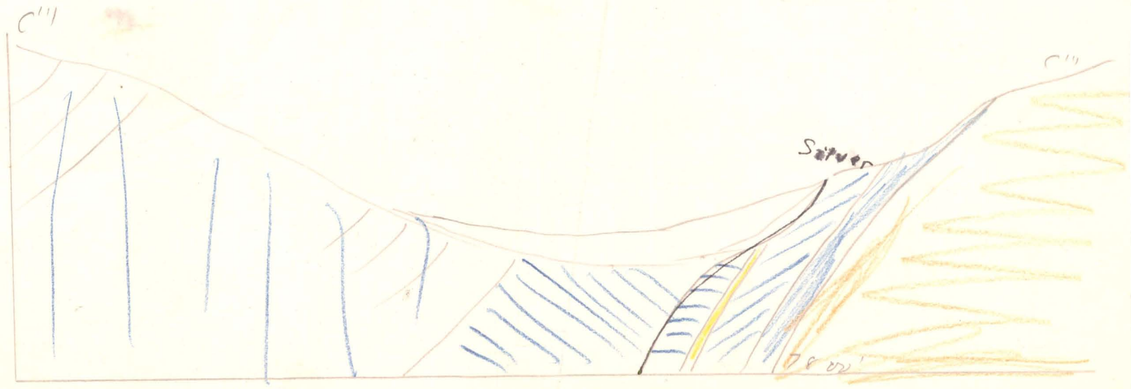


Aspen District


H"
H"
Silver Bell
Good Thunder
Butte
Copper
N
S
7800
G"
G"
Butte
N
S
7800

Lenado
Silver
A'''
A'''
7800'

B'''
Silver
B'''
7800'


C'''
C'''
Silver
7800'