shales of the Morrison give its distinctive and easily recognized lithology. The formation ranges in thickness from 210 feet at Lyons to approximately 320 feet near Eldorado, on Boulder Creek.

The Morrison formation is present nearly everywhere on the west slope of the Front Range, near the border of the pre-Cambrian area and in most places it rests directly upon pre-Cambrian rocks, although a short distance farther west it lies unconformably upon Mesozoic and Paleozoic formations. The Morrison formation is missing in the Georgia Pass area, however, and has apparently been overlapped by the Cretaceous Dakota quartzite a short distance to the west. In its normal development, the Morrison in the Breckenridge district[23] has a thickness of 240 feet. Fossils are relatively rare in the Morrison formation, although the beds are famous for the vertebrate fossils that have been found at the type locality [Morrison, Colo.] and in the region north of Canon City.

CRETACEOUS

UPPER CRETACEOUS

Dakota quartzite.—The persistent Dakota quartzite is present on both the east and west slopes of the Front Range and everywhere preserves a striking lithologic similarity. In most places, an upper and lower quartzite and an intermediate member comprising interbedded shale and quartzite or sandstone, are easily recognized. The basal member is a light-colored, well-washed quartz sandstone with a siliceous cement. It ranges from a siliceous sandstone to a true quartzite, and in most places has a conglomerate layer at the base. Few pebbles are found above the first 30 feet. The interbedded shale in the Dakota is gray to black and contains no clastic mica. Some of the light-gray shales make excellent fire clay and have been mined extensively in the region north and south of Golden. Each member shows a considerable range in thickness from place to place.. On the west slope the lower member is commonly the thickest of the three, but at most localities on the east slope it is the

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[23] Lovering, T. S., Geology and ore deposits of the Breckenridge mining district, Colo.: U. S. Geol. Survey Prof. Paper 176, pp. 6-7, 1934.

thinnest. On the east slope the lower quartzite is about 50 feet thick, the middle shaly sandstone is approximately 150 feet, and the upper quartzite is approximately 125 feet. On the west slope the thickness of the entire formation ranges from approximately 20 feet of conglomeratic quartzite at Georgia Pass to 240 feet of quartzite and interbedded shale in the valley of the Snake River a few miles east of Dillon. The pronounced hogback that marks the Dakota outcrop is caused by the resistance to erosion offered by the upper quartzite.

Benton shale.—Like the Dakota, the Benton shale is present on both the east and west slopes, and its composition in both areas is nearly the same. Near Boulder the Benton consists of approximately 500 feet of dark-colored clay shales containing a few fossiliferous concretions, and its top is marked by a bed of greenish sandstone 15 feet thick. On the west slope it is approximately 350 feet thick and contains a thin brownish bituminous limestone at its top.

East of Dillon in the Snake River Valley, the Benton shale lies disconformably on the Dakota quartzite, and the contact of the two formations is marked by a bed of conglomerate from 6 to 18 inches thick. The pebbles most abundant in the conglomerate are of Dakota quartzite, but some fragments of schist, granite, and limestone are present. In most localities, however, there is no evidence of a hiatus between deposition of the two formations.

Niobrara formation.—The Niobrara formation conformably overlies the Benton shale and comprises from 350 to 400 feet of limestone and limy shale. On the east slope the 15-foot bed of sandstone found at the top of the Benton is sharply set off from the basal limestone of the Niobrara, but on the west slope, where the uppermost member of the Benton is a limestone, the division between it and the overlying basal limestone of the Niobrara is less easily defined. This basal member, which is 15 to 20 feet thick in most places, commonly crops out in a low ridge that seems a subdued reflection of the great Dakota hogback a short distance away. Most of the formation is dark-brown to gray calcareous shale, which weathers white or grayish yellow.

Thin layers of limestone occur within the limy shales, and in some places persistent beds of *Ostrea*-bearing limestone about a foot thick are found in the upper part of the section. The transition from the black limy shales of the Niobrara to the black clay shales of the Pierre is inconspicuous, but the limy shales and thin-bedded limestones at the top of the Niobrara are generally characterized by the presence of numerous lenses and veinlets of secondary white calcite.

Pierre shale.—The Pierre shale conformably overlies the Niobrara formation, and attains a maximum thickness of about 10,000 feet south of Boulder. Its original thickness on the west slope is unknown but near Dillon it was in excess of 4,000 feet. The Pierre consists dominantly of sombre-colored shales which weather to a drab greenish-gray. A few beds of shaly limestone and calcareous sandstone are present in its lower half, but the great mass of the rock in the lower part of the section is clay shale. The shales of the upper half are more arenaceous than those below, and in the upper thousand feet, locally called the transition zone, yellowish limy and sandy shales are common. This portion was formally classed as a part of the Fox Hills formation, but that term is now restricted to the prominent sandstone overlying the shale at the top of the transition zone.

Above the Pierre shale are the Fox Hills and Laramie formations of Upper Cretaceous age and the Denver formation of Upper Cretaceous and possible Eocene age. These formations are extensively developed to the east of the Front Range and in places have been involved in Laramide folding, but do not appear in the mineral belt. Basalts interbedded with the Denver formation near Golden are thought to be closely related to some of the earliest intrusions in the mineral belt.

TERTIARY (?) AND QUATERNARY

With the exception of small areas of gravel south of Nederland and east of Idaho Springs which may be of Tertiary age, but are probably early Pleistocene till, no Tertiary sediments have been recognized in the mineral belt.

Early and late glacial sediments are widespread in the higher mountains but have not been distinguished on the geologic map, where bed rock has been shown, if known. In general, the glacial drift is found along the larger streams down to an altitude of approximately 9,000 feet on the west slope and approximately 8,000 feet on the east slope. Distribution of the early drift suggests ice-cap glaciation. The later drift (Wisconsin) is confined to steep-sided valleys. Three well-developed terraces, locally covered by terrace gravel to a depth of as much as 30 feet, are common in the major valleys below the limit of glaciation. The upper terrace is apparently contemporaneous with the early period of glaciation, and the lower terrace with an early stage of Wisconsin glaciation. It seems possible, therefore, that the intermediate terrace should be correlated with a glacial stage that is not marked by drift. Within the areas of pre-Cambrian rock the depth of the present gravel downstream from the terminal moraine is seldom more than 20 to 30 feet. In the valley of the Blue River, on the west slope, the gravel has an average depth of approximately 60 feet and is nearly as deep in the larger tributary stream valleys, such as the Snake River and the Swan River. The glacial moraines themselves show a great range in thickness and reach a maximum of about 150 feet near Breckenridge.

Most of the material deposited by the early glaciers was removed by later erosion. Remnants of the early till and outwash gravel occur well above the level of the present valley bottom in many places. This early drift is commonly weathered more deeply than that of Wisconsin age. It is made up of unsorted boulders of pre-Cambrian rocks and Tertiary intrusives in a matrix of brownish-yellow sand and sandy clay. The early glacial deposits are not abundant, but nearly all the higher mountain valleys are occupied by thin discontinuous bodies of alluvium, late glacial till, and valley-train gravel. The poorly sorted material that makes up this late drift in most places is fresh and little weathered, but much-weathered boulders are not uncommon in it. Subangular boulders as much as 20 feet in diameter occur in the late glacial moraines, intermingled with small boulders, pebbles, and clay. Fluvioglacial deposits are conspicuous, both above and below the terminal moraines of the Wisconsin glaciers. They are made up chiefly of moderately well-rounded pebbles and sand, but small boulders are not uncommon.

LATE CRETACEOUS AND EARLY EOCENE IGNEOUS ROCKS

The igneous rocks of the Front Range that are later than pre-Cambrian range in age from late Cretaceous to Miocene, but within the area shown on the map of the mineral belt no igneous rocks later than lower Eocene are known. Both intrusive and extrusive activity accompanied the building of the Front Range during the Laramide revolution, but most of the extrusive rocks have since been eroded. Andesite flows are interbedded with tuff and volcanic breccia at the base of the late Cretaceous and Eocene (?) Middle Park formation between Granby and Hot Sulphur Springs. Tuff, breccia, porphyritic andesite, and rhyolite flows occur in the equivalent formation of South Park a few miles south of Georgia Pass, and interbedded basalt flows are conspicuous in the tuffaceous rocks of the Denver formation near Golden. Within the area shown on the map, however, no extrusive rocks of this age have been found. The topographic and structural relations of two small areas of basalt north of Ward suggest that they may be of extrusive origin, but if so their position on a relatively young erosion surface negates the possibility of an age earlier than middle Tertiary.

The late Cretaceous and early Eocene (Laramide) igneous rocks or "porphyries" of the mineral belt are readily distinguished from all but a very few of the pre-Cambrian rocks, and many different varieties are so distinctive in appearance as to justify correlation between districts separated by several miles. (See fig. 3.) These igneous rocks are commonly medium- to fine-grained and nearly all are porphyritic. Some of the early rocks of mafic or intermediate character are holocrystalline, and thin dikes of

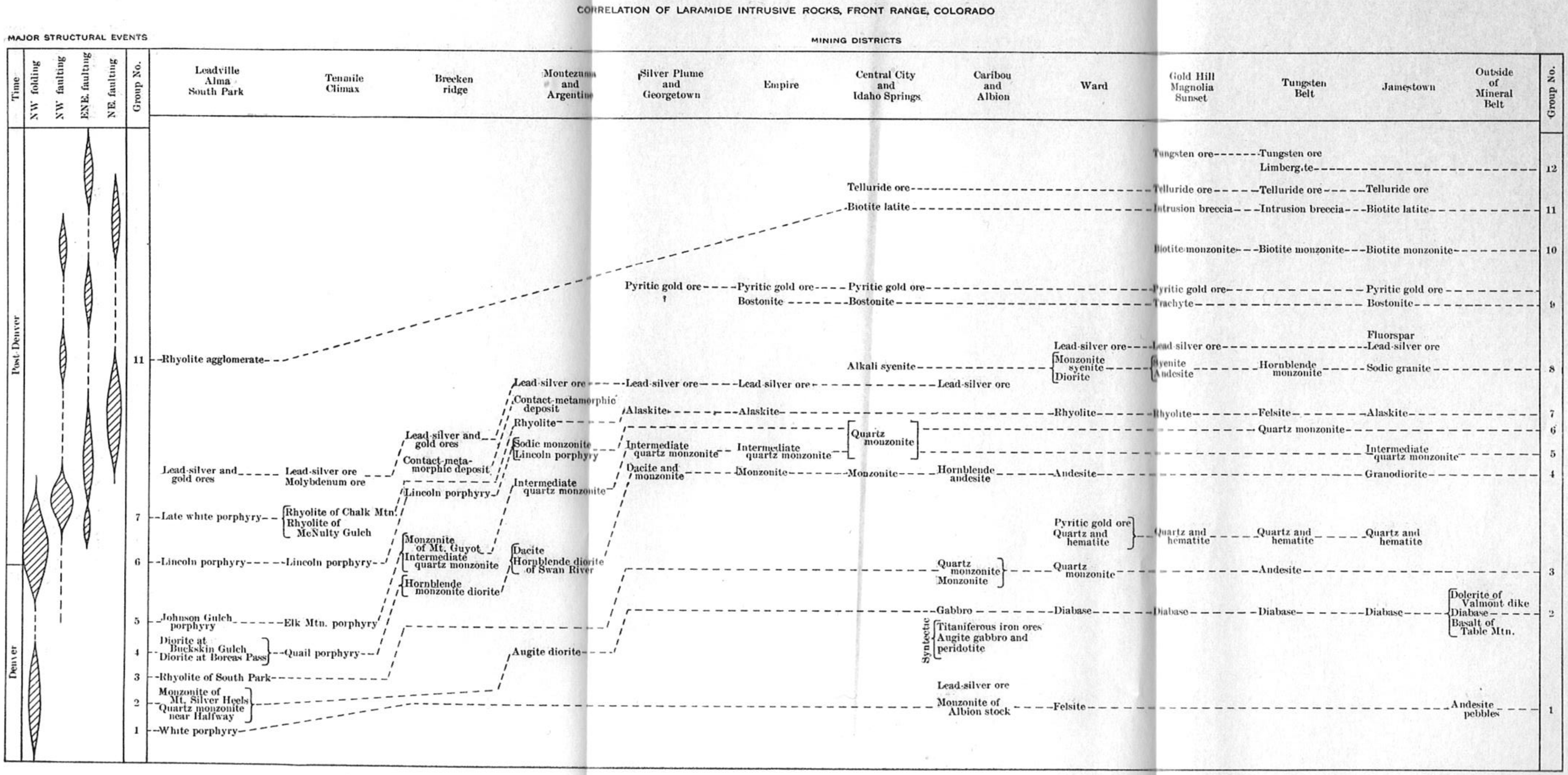

FIGURE 3.—CORRELATION OF THE LARAMIDE IGNEOUS ROCKS IN THE FRONT RANGE MINERAL BELT

Figure 3. Correlation of the Laramide igneous rocks in the Front Range mineral belt.

widely differing composition have felsitic to glassy textures. These intrusives show a wide range in chemical and mineralogic composition, and include dikes as mafic as limburgite, as silicic as alaskite, and as alkalic as aegirite syenite. Most of the intrusive rocks are intermediate or siliceous porphyries whose composition ranges from hornblende diorite to biotite-quartz monzonite. Petrographic descriptions of the different porphyries are given in the reports on the mining districts of the Front Range cited on the index map that accompanies the geologic map, and the reader is referred to them for detailed information. These descriptions have been used in preparing the tabular summary given in figure 4, which shows the general features of the rocks included in the different groups of Laramide igneous rocks recognized by the writers. The basis of the classification into separate groups is relative age, but in any one group most of the rocks are similar in composition, and in some groups the similarity extends to texture as well.

The evidence for the relative age and correlation of the different intrusives and the stage of the Laramide revolution at which they were emplaced has been discussed elsewhere,[24] and only a summary of these relations will be given here. The writers' correlation of the porphyries in the mining districts of the mineral belt and the age groups to which they have been assigned are shown in figure 3. The group numbers correspond to those used in figure 4, where their composition and general character are given, and also correspond to the numbers used on the geologic map where their distribution and the form of the intrusive masses are shown.

The correlation of these porphyries is not final and may need to be revised as a result of future work. In many places in the field age relations are not clear, and many correlations have been based on lithologic character as observed by the writers or as described by others. Also, many rocks of the same composition and age differ widely in lithologic character from place to place, depending on the

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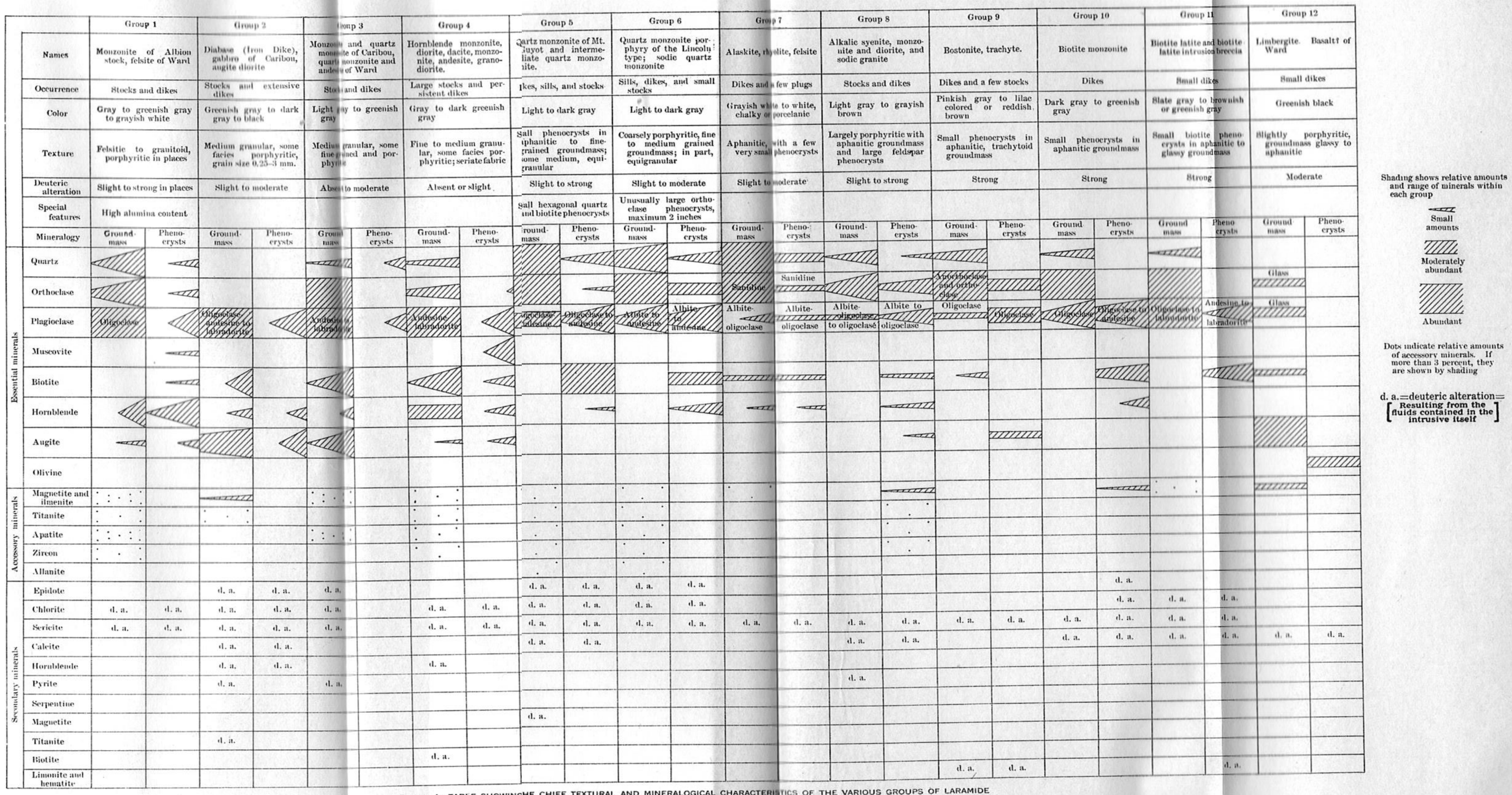
[24] Lovering, T. S., Geology and ore deposits of the Montezuma quadrangle, Colo.: U. S. Geol. Survey Prof. Paper 178, pp. 26-42, 1935. Lovering, T. S., and Goddard, E. N., Laramide igneous sequence and differentiation in the Front Range, Colo.: Geol. Soc. America Bull., vol. 49, pp. 35-68, 1938.



		Group 1		Group 2		Group 3		Group 4		Group 5		Group 6		Group 7		Group 8		Group 9		Group 10		Group 11		Group 12	
	Names	Monzonite of Albion stock, felsite of Ward		Diabase (Iron Dike), gabbro of Caribou, augite diorite		Monzonite and quartz monzonite of Caribou, quartz monzonite and andesite of Ward		Hornblende monzonite, diorite, dacite, monzonite, andesite, granodiorite.		Quartz monzonite of Mt. Guyot and intermediate quartz monzonite.		Quartz monzonite porphyry of the Lincoln type; sodic quartz monzonite		Alaskite, rhyolite, felsite		Alkalic syenite, monzonite and diorite, and sodic granite		Bostonite, trachyte.		Biotite monzonite		Biotite latite and biotite latite intrusion breccia		Limbergite. Basalt? of Ward	
	Occurrence	Stocks and dikes		Stocks and extensive dikes		Stocks and dikes		Large stocks and persistent dikes		Dikes, sills, and stocks		Sills, dikes, and small stocks		Dikes and a few plugs		Stocks and dikes		Dikes and a few stocks		Dikes		Small dikes		Small dikes	
	Color	Gray to greenish gray to grayish white		Greenish gray to dark gray to black		Light gray to greenish gray		Gray to dark greenish gray		Light to dark gray		Light to dark gray		Grayish white to white, chalky or porcelanic		Light gray to grayish brown		Pinkish gray to lilac colored or reddish brown		Dark gray to greenish gray		Slate gray to brownish or greenish gray		Greenish black	
	Texture	Felsitic to granitoid, porphyritic in places		Medium granular, some facies porphyritic, grain size 0.25–3 mm.		Medium granular, some fine grained and porphyritic		Fine to medium granular, some facies porphyritic; seriate fabric		Small phenocrysts in aphanitic to fine-grained groundmass; some medium, equigranular		Coarsely porphyritic, fine to medium grained groundmass; in part, equigranular		Aphanitic, with a few very small phenocrysts		Largely porphyritic with aphanitic groundmass and large feldspar phenocrysts		Small phenocrysts in aphanitic, trachytoid groundmass		Small phenocrysts in aphanitic groundmass		Small biotite phenocrysts in aphanitic to glassy groundmass		Slightly porphyritic, groundmass glassy to aphanitic	
	Deuteric alteration	Slight to strong in places		Slight to moderate		Absent to moderate		Absent or slight		Slight to strong		Slight to moderate		Slight to moderate		Slight to strong		Strong		Strong		Strong		Moderate	
	Special features	High alumina content								Small hexagonal quartz and biotite phenocrysts		Unusually large orthoclase phenocrysts, maximum 2 inches													
	Mineralogy	Ground-mass	Pheno-crysts	Ground-mass	Pheno-crysts	Ground-mass	Pheno-crysts	Ground-mass	Pheno-crysts	Ground-mass	Pheno-crysts	Ground-mass	Pheno-crysts	Ground-mass	Pheno-crysts	Ground-mass	Pheno-crysts	Ground-mass	Pheno-crysts	Ground-mass	Pheno-crysts	Ground-mass	Pheno-crysts	Ground-mass	Pheno-crysts
Essential minerals	Quartz	▨	▨			▨	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨	▨		▨		▨			
	Orthoclase	▨	▨			▨		▨	▨	▨	▨	▨	▨	Sanidine ▨	Sanidine ▨	▨	▨	Anorthoclase and orthoclase ▨	▨	▨		▨		Glass ▨	
	Plagioclase	Oligoclase ▨	▨	Oligoclase-andesine to labradorite ▨	▨	Andesine to labradorite ▨	▨	Andesine-labradorite ▨	▨	Oligoclase-andesine ▨	Oligoclase to andesine ▨	Albite to andesine ▨	Albite to andesine ▨	Albite-oligoclase ▨	Albite-oligoclase ▨	Albite-oligoclase to oligoclase ▨	Albite to oligoclase ▨	Oligoclase ▨	Oligoclase ▨	Oligoclase ▨	Oligoclase to andesine ▨	Oligoclase to labradorite ▨	Andesine to labradorite ▨	Glass ▨	
	Muscovite		▨						▨																
	Biotite		▨	▨		▨		▨	▨		▨		▨	▨	▨		▨	▨			▨		▨	▨	
	Hornblende	▨	▨	▨	▨	▨		▨	▨		▨		▨	▨	▨		▨				▨				
	Augite	▨	▨	▨	▨	▨		▨	▨								▨		▨					▨	
	Olivine																								▨
Accessory minerals	Magnetite and ilmenite	·		▨		·		·		·		·		·			▨				▨	·		▨	
	Titanite	·		·				·		·		·					·								
	Apatite	·				·		·		·		·					·								
	Zircon	·						·		·		·					·								
	Allanite									·		·													
Secondary minerals	Epidote			d. a.	d. a.	d. a.				d. a.	d. a.	d. a.	d. a.								d. a.				
	Chlorite	d. a.	d. a.	d. a.	d. a.	d. a.		d. a.	d. a.	d. a.	d. a.	d. a.	d. a.								d. a.	d. a.	d. a.		
	Sericite	d. a.	d. a.	d. a.	d. a.	d. a.		d. a.	d. a.	d. a.	d. a.	d. a.	d. a.	d. a.	d. a.	d. a.	d. a.	d. a.	d. a.	d. a.	d. a.	d. a.	d. a.		
	Calcite			d. a.	d. a.					d. a.	d. a.					d. a.	d. a.			d. a.	d. a.	d. a.	d. a.	d. a.	d. a.
	Hornblende			d. a.	d. a.			d. a.																	
	Pyrite			d. a.		d. a.										d. a.									
	Serpentine																								
	Magnetite									d. a.															
	Titanite			d. a.																					
	Biotite							d. a.																	
	Limonite and hematite																	d. a.	d. a.				d. a.		

Shading shows relative amounts and range of minerals within each group

▨ Small amounts

▨ Moderately abundant

▨ Abundant

Dots indicate relative amounts of accessory minerals. If more than 3 percent, they are shown by shading

d. a.=deuteric alteration=[Resulting from the fluids contained in the intrusive itself]

FIGURE 4.—TABLE SHOWING THE CHIEF TEXTURAL AND MINERALOGICAL CHARACTERISTICS OF THE VARIOUS GROUPS OF LARAMIDE INTRUSIVE ROCKS IN THE FRONT RANGE MINERAL BELT

Figure 4. Table showing the chief textural and mineralogic characteristics of the various groups of Laramide intrusive rocks in the Front Range mineral belt.

conditions of intrusion. Some of the stocks are compound and are made up of different porphyries, which are so mixed and merged that the relations can only be worked out by very detailed study. However, in spite of the fact that some of the details may be revised later, it is believed that the basis of correlation is sound and that the correlations themselves, which are essential to an adequate understanding of the geology of the Front Range and its ore deposits, are on the whole correct.

Nearly all the late Cretaceous and early Eocene intrusives of the Front Range are concentrated in a narrow diagonal belt that trends southwest across the range from Boulder to Breckenridge. Stocks are mostly confined to the northwest border of the porphyry belt, and most of them lie in a narrow, straight area only a few miles wide that extends from Tiger to Jamestown. In a northward-trending thumblike zone that branches from the main belt of stocks, porphyries of unusual character occur in stock-like bodies as far north as Mount Audubon. The character of the rocks and their structural relations indicate that this north-south zone is of earlier origin than the other stocks and is broadly contemporaneous with the tuffaceous rocks of the Denver formation. Dikes and irregular cross-breaking bodies too small to be classed as stocks are almost entirely confined to a strip 2 to 10 miles wide just southeast of the belt of stocks. The scarcity of dikes northwest of the stocks and their abundance to the southeast suggest the presence of subjacent magmatic bodies below the surface southeast of the stocks and a lack of them to the northwest. *It is in the area of porphyry dikes that most of the Eocene ore deposits of the Front Range occur.*

The presence of interbedded tuffs and lavas at the base of the Middle Park formation and the Denver formation in South Park and the absence of volcanic debris at the base of the Denver formation of the Denver Basin suggest either that sedimentation began earlier in the Denver Basin than on the west slope or that igneous activity occurred earlier on the west than on the east slope. Broad regional studies[25]

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[25] Lindgren, Waldemar, Ore deposits of the western United States, A.I.M.E. (Lindgren Volume), pp. 158-160, 1933; Burbank, W. S., idem., pp. 288-296.

support the conclusion that igneous activity began in the west and progressed slowly toward the east front of the Rocky Mountain system, and thus it is probable that the correlation of similar rocks in different parts of the Front Range is not a correlation of time equivalents but rather of equivalent facies. With this reservation in mind, the regional history of the porphyry belt is considered to be essentially as follows:

(1) Intrusion in early Denver time of sills and dikes of felsite and hornblende andesite in the southwestern part of the Front Range porphyry belt, while dikes and stocks of aluminous augite andesite were intruded in the central part of the rising Front Range arch near Mountain Albion, with attendant extrusive volcanic activity.

(2) Northwest folding and faulting, accompanied by the intrusion of dikes and small irregular stocks of augite diorite on the west slope and extensive northwestward-trending dikes of gabbro and diabase on the east slope near the close of Denver time.

(3) The intrusion of rhyolite and some quartz monzonite in South Park and the intrusion of hornblende quartz monzonite and andesite in the region bordering the northward-trending thumb of the belt of stocks. A feeble mineralization of pyritic gold and strong mineralization of quartz and hematite followed the intrusion of the quartz monzonite of epoch 3 in the northeastern part of the mineral belt.

(4) The culmination of the northwest faulting and overthrusting and the intrusion of stocks and thick sills of hornblende diorite and hornblende monzonite in the southwestern part of the mineral belt, and the intrusion of stocks and dikes of hornblende monzonite, hornblende diorite, and hornblende andesite in the northeastern half of the porphyry belt.

(5) The intrusion of hornblende and biotite-quartz monzonite porphyries as sills and dikes throughout the porphyry belt.

(6) The intrusion of the coarsely porphyritic biotite-quartz monzonite of the Lincoln porphyry type in the south-

western half of the mineral belt and the intrusion of biotite-quartz monzonite porphyry in the northeastern half of the belt. Most of the porphyries of the southwestern half of the mineral belt were intruded during epochs 4, 5, and 6.

(7) The intrusion of felsite and rhyolite porphyry in the southwestern part of the mineral belt and of alaskite, rhyolite, and felsite porphyries in the northeastern half, and the widespread formation of lead-silver ores in the region from Caribou to the southwest.

(8) The intrusion of alkali syenite, alkalic diorite, and sodic granite in the northeastern half of the mineral belt, followed by sparse lead-silver and lead-silver-fluorspar mineralization.

(9) The intrusion of bostonite and alkalic trachyte in the northeastern half of the mineral belt, followed shortly by an extensive pyritic gold mineralization.

(10) The intrusion of alkalic biotite monzonite porphyry in the northeasternmost portion of the mineral belt.

(11) The introduction of biotite latite dikes, rich in volatile material, and the formation of latitic intrusion breccias in dike and pluglike masses in the northeastern half of the mineral belt, closely followed by a gold-telluride mineralization.

(12) Intrusion of limburgite dikes in the tungsten belt, followed by the formation of the ferberite ore bodies.

The general relations of the different rocks to one another and to the epochs of folding and faulting are shown in figure 3. The chemical relations of the different rocks in the porphyry belt have been explained[26] as due to the gradual melting of a dioritic substratum in the western part of the mineral belt and of a gabbroic substratum in the eastern half and its subsequent slow consolidation and differentiation throughout a period of orogeny during which portions of it were withdrawn from time to time to shallower chambers where more rapid cooling resulted in changes of a different type. The diversity of rock types is caused by the presence of differentiates from both the deep and shallow hearths.

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[26] Lovering, T. S., and Goddard, E. N., op. cit.

In a broad way the porphyry belt may be divided into two petrographic provinces. The region southwest of Silver Plume is characterized by rocks that range in composition from rhyolite to diorite but mostly approximate an ordinary quartz monzonite. Northeast of Silver Plume rocks of much more alkalic character are present, and the quartz monzonites themselves are more sodic than those to the southwest. As recognized by Spurr[27] in 1903, the area in which the bostonite rocks are common corresponds to the region in which pyritic gold ores are found, and it now seems evident that the gold-telluride ores are confined to the rather small areas in this same general region where biotite latite and latitic intrusion breccias occur. The tungsten ores are confined to the zone in which rocks unusually rich in ferromagnesian minerals are found between Boulder and Caribou.

STRUCTURE

The structure of the Front Range mineral belt is complex and is closely related to the structure of the Front Range as a whole. Though the vein fissures and the porphyry stocks and dikes are confined to the mineral belt, many of the larger faults are traceable far beyond its limits. Nearly all the faults and fissures recognized in the mineral belt appear to have been formed during the Laramide revolution (late Cretaceous-early Eocene), but the strong influence exerted by the structure, character, and distribution of pre-Cambrian rocks on these later fractures is readily apparent.

PRE-CAMBRIAN STRUCTURE

The distribution of the pre-Cambrian rocks seems to have had a strong influence on the general trend and shape of the mineral belt, which is localized in the zone of relatively incompetent schist and gneiss in between and around the stocks of granite. The foliation of the schist and gneiss and the platy structure of the granite offered lines of weakness that were followed to a large extent by the Laramide fracturing.

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[27] Spurr, J. E., Garrey, G. H., and Ball, S. H., op. cit.

Schists and gneisses.—The foliation of the Idaho Springs formation, the Swandyke hornblende gneiss, and the quartz monzonite gneiss are shown on the map by a schistose pattern and by strike and dip symbols. In all three formations the structure is essentially conformable. As the structure was largely induced by the intrusion of pre-Cambrian granites, the schist and gneiss tend to wrap around the granite stocks and batholiths. The foliation has a general northerly trend in the southwestern part of the belt, swings to an easterly or southeasterly trend between Georgetown and Central City, then again shows a northerly trend that continues along the west side of the Boulder Creek granite to its northern end, around which it bends to assume a northeasterly trend in the northeastern part of the belt. The dip is generally steep and varies in direction because of the numerous anticlines and synclines. In many places where strike and dip seem uniform there is a close isoclinal folding that is difficult to recognize. The dip of the foliation is away from most of the large igneous bodies.

In general the schists yielded to the mountain-building forces by folding or by breaking along tight gougy fault fissures that are parallel to the foliation, poorly mineralized, and therefore difficult to trace. The gneisses were more rigid and brittle, and fault fissures in them tended to be more persistent, more open, and therefore more readily mineralized.[28]

Granites.—The platy and linear structure[29] in the granite masses has been recorded by the writers at many places and is shown on the map by strike and dip symbols or by arrows. In general the platy structure near the borders of igneous masses is roughly parallel to the contacts, but toward the center the trend is more irregular. In the unmetamorphosed igneous rocks the linear structure is interpreted as being parallel to the direction in which the

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[28] Lovering, T. S., Localization of ore in the schists and gneisses of the mineral belt of the Front Range: Colorado Sci. Soc. Proc., vol. 12, pp. 242-244, 1930.

[29] Balk, Robert, Primary structures in granite massives: Geol. Soc. America Bull., vol. 36, pp. 679-696, 1925. See also brief description by Grout, F. F., Petrography and petrology, McGraw-Hill Book Co., pp. 29, 30, 197, 1932.

magma was moving at the time of solidification. In several of the stocks the structure suggests funnel-shaped masses in which the magma moved up from eccentric sources. Such indication of the subsurface shape of igneous bodies may have an important bearing on prospecting for ore deposits at depth, for in many districts the more productive veins are close to the granite borders. The shape of the stocks had much local influence on the forces that produced the Laramide fissures and, therefore, on the positions and arrangement of the fissures themselves.

Pre-Cambrian faults.—Faulting was probably widespread in pre-Cambrian time, but pre-Cambrian faults are very difficult to identify, except such minor ones as were occupied by granite and pegmatite dikes. It seems probable that many of the pre-Cambrian faults were obliterated or concealed by superposed Laramide structures.

The writers have identified an extensive pre-Cambrian fault in the eastern part of the mineral belt, and it is believed that others comparable in size will be found in the future. This fault extends in a direction N. 50° E. from the eastern edge of the Central City district to the mountain front at Coal Creek. The dip is apparently steep, but the direction of dip could not be determined. For the most part, this pre-Cambrian fault is marked by a wide zone of slight to moderate shearing a few hundred to 1,000 feet wide, and it is therefore shown on the map by closely-spaced discontinuous lines to indicate the shear. The syncline of quartzite on Coal Creek is limited on the southeast by this fault along which it has apparently dropped many hundreds of feet. The downfaulted area preserves what seems to be the only remnant of this quartzite in the Front Range. The fault zone was apparently reopened many times, for bodies of both Boulder Creek granite and granite gneiss have followed its trend, and discontinuous Laramide faults have broken along it. The folding of the quartzite and of the Idaho Springs formation and Swandyke hornblende gneiss farther to the southwest is thought to be contemporaneous with the formation of this fault and closely related to it. Some remarkable drag folds have been formed in the schist layers of the quartzite formation near the fault.

LARAMIDE STRUCTURE[30]

Two principal systems of faults were formed in Laramide time, both influential in the localization of ore deposits. The major system is made up of strong, persistent faults that are especially prominent on the flanks of the range, are traceable for distances of 10 to 25 miles, and are not confined to the mineral belt. Many of these faults, perhaps all of them, were formed before most of the porphyries were intruded. The second system is made up of smaller fault fissures, generally less than a mile long, which were opened during and after the intrusion of the porphyries. These fissures were sought out by magma and mineralizing solutions and became filled with dikes and veins of various types.

MAJOR FAULTS AND THEIR RELATIONS TO MINERAL DEPOSITS

The more extensive faults of the belt are of two groups —those of northwest trend, which are most abundant near the east border of the Front Range, and those of northeast trend, which are confined mostly to the western part of the range. These faults extend diagonally from the borders of the range toward the middle. Some of the northwest-trending faults assume a more and more westerly course as they approach the crest of the range, and it is possible that faults of both groups may swing around to join in a series of discontinuous east-west breaks. The faults of northwest trend are definitely dated as late Cretaceous in age, for they cut the late Cretaceous Pierre shale and Laramie formation and are cut by early Eocene intrusive rocks. It seems probable that the persistent faults of northeast trend along the west flank of the range are of the same age. A series of faults of east-west trend, essentially contemporaneous with those that trend northwest, is present in the northeastern part of the mineral belt.

Faults of northwest trend (breccia reefs).—The striking pattern of the extensive faults of northwest and west trend is exhibited over a large area in the northeast half

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[30] See note regarding use of term "Laramide" on page 9.

of the mineral belt. Because of the widespread silicification of these faults and their topographic prominence in many places they are known locally as "breccia dikes". As the term "dike" should be restricted to igneous rocks the writers suggest the term "breccia reefs" as more desirable. Some of these have been described in an earlier paper.[31] A few appear in other parts of the mineral belt, and it seems probable that the extensive Williams Range thrust fault,[32] on the west border of the Front Range, belongs to this group. The central part of the mineral belt was mapped before the existence of breccia reefs was generally known, and as they are less prominent in that part, they escaped observation. This region has not been restudied in detail, and few data are available on the extent of the faults in the districts mapped prior to 1927.

The breccia reef faults have a general north-northwest trend near the east edge of the Front Range but swing more toward the west near the crest of the range. Generally they dip steeply either to the northeast or southwest, but in the southeastern part most of them form steeply eastward-dipping thrust faults that pass into overturned folds in the sedimentary rocks.

If faults have a strong horizontal component of movement it is much more illuminating to consider the relative direction of movement of the walls than the actual compass direction—as all such fractures can be classified into two groups. If when standing on a fissure and looking along the strike it is found that the wall on the right has apparently moved forward, it will be observed that on turning about and facing the opposite direction the wall now on the right has also apparently moved forward. Thus it is possible to express the relative movement of the walls in the simple terms of the apparent forward movement of either the right-hand wall or the left-hand wall. It is of interest to note that, in pre-mineral faults having a strong horizontal component of movement, those in which the right-hand

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[31] Lovering, T. S., Preliminary map showing the relations of ore deposits to geologic structure in Boulder County, Colo.: Colorado Sci. Soc. Proc., vol. 13, pp. 78-88, 1932.

[32] Lovering, T. S., Geology and ore deposits of the Montezuma quadrangle, Colo.: U. S. Geol. Survey Prof. Paper 178, p. 47, 1935.

walls have moved ahead tend to become open and ore-bearing where their courses swing to the left. Conversely those in which the left-hand wall has moved ahead may be expected to contain ore where their courses swing to the right.

On most of the breccia reefs where the direction of movement could be determined the right-hand wall moved ahead; for example, the northeast wall moved northwest but either up or down. The total displacement is commonly several hundred feet. The fault zones range in width from a few feet to 200 feet. The shearing in the wider zones can be recognized with difficulty in granite or gneiss and is imperceptible in schist.

The faults of northwest trend are mineralized in many places, but the character of the mineralization differs greatly from place to place and seems to reflect their complex history, which included frequent local and regional reopening. The reopening continued through the period of vein formation, but only in a few places were the large faults filled with vein material of commercial grade. Quartz and hematite are the most characteristic minerals in these fault fissures. The hematite is very fine-grained and imparts a dark-red color to the fault zone, a characteristic most useful in the identification and tracing of these large breaks. The character of the quartz associated with the hematite varies. In some places the fissure is filled with a solid vein of coarse-grained white "bull" quartz 2 to 15 feet wide, such as the "Hoosier dike"; in such localities the breccia reef forms a high wall-like outcrop that has given rise to the local name " dike". In some places the fault zone is composed of strongly silicified, sheared granite or gneiss that forms a prominent rough knobby outcrop on a ridge or hilltop. In other places the silicification in a wide zone has been so slight that it is not easily recognized. Where not silicified the sheared wall rock and gouge of the fault zone weather down, forming soil-mantled topographic depressions that conceal the structure. Although such unsilicified faults are generally very difficult to trace, some parts show the hematite coloring that helps in tracing the breccia reef faults and in distinguishing them from more recent faults.

In places, the quartz and hematite contain from a trace to 0.03 ounce of gold to the ton. In general, the mineralization of the northwest-trending faults decreases from northeast to southwest in the porphyry belt.

Where the faults have been reopened, pyrite, fluorspar, or horn quartz are found either separately or together. In a few places within the mineral belt the breccia reefs are bordered by dikes or contain veins of lead-silver, pyritic gold, or gold-telluride ores, as, for example, respectively, the Yellow Pine vein in the Gold Hill district, the Livingston vein in the Sugarloaf district, and the Standard vein in the Jamestown district.

Several of the breccia reefs in Boulder County have been given names by the miners, and as the names are useful in discussion of the problems of ore localization, the writers have given to most of the other prominent reefs names based on those of nearby mining properties or topographic features. These reefs, or "dikes", are briefly described below in the order of the occurrence of the individual faults, from northeast to southwest.

The Standard "dike" is relatively short and marks the northeast limit of mineralization in the Jamestown district. In the vicinity of the Standard mine it is composed of dense red silicified breccia and crops out prominently, but in other places it is difficult to trace.

The Maxwell "dike", which bounds the Gold Hill district on the east, is the most extensive of the group and can be traced for more than 25 miles. It seems probable that it originally passed through the center of the Jamestown district, but has been cut off by a granodiorite stock. It is almost wholly within the granite terrane and is characterized by sheared and strongly silicified granite of red color. Its outcrops form prominent ridges in many places.

The Hoosier "dike" passes through the heart of the Gold Hill district and along the west edge of the Jamestown district. It has been traced for a distance of about 18 miles and in many places is a wide vein of white quartz that forms prominent wall-like outcrops.

The Livingston "dike" passes through the eastern part of the tungsten belt and of the Sugarloaf district and apparently marks the eastern limit of mineralization in the Ward district. It is traceable for about 18 miles and, like the Maxwell, is characterized by red sheared and silicified wall-rock and forms prominent ridges.

The Rogers "dike" passes through the central part of the tungsten belt and its southeastern part has many branches and irregularities. It also is characterized by silicified rock which is very prominent locally but not so persistent as in some of the other reefs. The relationship of the formations along the Rogers "dike" and the parallel fault east of it in the quartzite area near Coal Creek is noteworthy. The Rogers "dike" though well exposed to the northwest and southwest, is not traceable across the syncline of quartzite and schist in the Coal Creek area. The fault to the east is traceable throughout its course. The apparent large horizontal offsets of the northern part of the quartzite and the negligible offsets of the southern part along both faults are not reconcilable from an inspection of the map, but may be interpreted as follows: The pre-Cambrian granite was intruded at a low angle from the north against the down-faulted syncline of quartzite and developed a strong platy or gneissic structure of north-northwest trend. The aplite rose later from the southeast, breaking across the gneissic structure of the granite and in part across the bedding of the quartzite; its contacts that cross the strike of the quartzite are believed to represent intrusion faults obscured but not much dislocated by subsequent movements. Late Cretaceous faulting, which was controlled by preexisting planes of weakness at many places in the Front Range, took place locally along the gneissic structure of the granite and along the old intrusion faults between aplite and quartzite. Thus, although late Cretaceous movements and any later movements along the Rogers "dike" and the fault east of it were comparatively small, their effects cannot be distinguished on the map from those of the comparatively large pre-Cambrian intrusion faults.

The Hurricane Hill "dike" passes through the western part of the tungsten belt and appears to be nearly as extensive as the Maxwell. Like the Rogers, it has many branches. It is marked in places by a red strongly silicified zone, but for much of its course it is a gougy unmineralized shear zone and is difficult to trace.

The Junction Ranch "dike" passes just east of the Junction Ranch, on Guy Creek, and appears to terminate at Phoenix. It is apparently responsible for a sharp bend in Ralston Creek near Junction Ranch and is believed to be the controlling regional structure that localized the deposits of gold ore at Phoenix. In a few places the fault zone is strongly silicified, and near Phoenix it contains considerable white quartz, but elsewhere the silicification has been slight or is absent. In most places the hematite is so sparse that it merely imparts a faint pink color to the fault zone.

The Blackhawk fault passes just east of Blackhawk and forms a surprisingly sharp northeast boundary for the Central City district. The strong shear zone is silicified in only a few places and is not easily followed.

The strong shear zone of the Floyd Hill fault is exposed in road cuts on Floyd Hill and passes into the central part of the Central City district, where its position is indicated only by the northwest trend of several veins. It is silicified in only a few places.

Several westward-trending breccia reefs extend obliquely from one of the northwest faults to another. Of these, the "Blue vein", the Fortune "dike", and the Poorman "dike" extend from the Maxwell to the Hoosier in the Gold Hill district. Farther south the Copeland "dike" lies just north of South Boulder Creek and extends diagonally from the Livingston to the Rogers. These diagonal faults are more strongly silicified than adjacent parts of the reefs that trend north-northwest.

Faults of northeast trend.—The faults of northeast trend have a surprisingly regular strike of about N. 28° E. and seem to mark the northwestern limit of the mineral belt. Unfortunately, as most of them have not been mineralized they weather readily and occupy topographic depressions instead of ridges. As a result little has been learned about their dip, direction of movement, or age. They appear to be steep, and some certainly have displacements of several hundred feet. They are characterized by gougy shear zones 10 to 600 feet wide. The largest of the group is the Moffat Tunnel fault, which is intermittently exposed on the surface for a distance of more than 25 miles and forms a wide zone of "heavy ground" in the Moffat Tunnel,[33] 2,000 feet below the outcrop. It crops out in Berthoud Pass and in Loveland Pass and is apparently responsible for the position of the depressions that form these passes. In the Moffat Tunnel the fault comprises intensely fractured rock cut by a group of nearly vertical gouge seams that have an echelon arrangement in cross-section, forming a fault zone more than 1,000 feet wide with an average dip of about 50° W. The zone narrows both to the north and south; at Berthoud Pass it is little more than 200 feet wide and at Loveland Pass it is less than 50 feet wide. In both passes it is mostly concealed by debris. On a saddle of Wood Mountain, 5 miles northeast of Loveland Pass, the fault gouge contains a small amount of red hematite, which suggests that it may be related to the strong northwest-trending faults of the eastern part of the range.

The other faults of this group are much smaller. In some places they appear to be no more than wide fracture zones. In a few places they widen into lenticular fracture zones that contain disseminated pyrite. These zones are strikingly similar to those that surround the tops of some porphyry stocks in the main mineral belt, and it may be that the pyrite zones represent the roofs of porphyry bodies that rose along the faults.

Two of the most prominent of these fracture zones are 1 to 2 miles northeast of James Peak, and the one nearest the peak contains 0.01 ounce of gold to the ton. The pyritic zones are indicated at the surface by thin coatings of limonite in the fractured rock.

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[33] Lovering, T. S., Geology of the Moffat Tunnel, Colorado: A.I.M.E. Trans. vol. 76, pp. 337-46, 1928.

DIKE AND VEIN FISSURES

Nearly all the fissures occupied by porphyry dikes and veins were formed in the waning stages of Laramide orogeny and are later than the major strong faults. However, their formation extended over a considerable period of time and as a whole they are filled with several different kinds of porphyry and ore. The dike fissures and vein fissures are of essentially the same type, and the nature of the filling depended chiefly on the time at which they were opened. Some have been reopened several times and a few individual fissures contain one or more kinds of both porphyry and ore.

These fissures have a general northeast strike and steep southeast dip, although some groups trend west or northwest. Most of them range in width from a few inches to 5 feet and in length from a few hundred feet to 1 mile. A few are as much as 10 to 15 feet wide in places. Displacements along these fissures are small, commonly between 2 and 30 feet. On most of those of northeast trend where the direction of movement has been determined, the left-hand wall moved ahead (page 38) and commonly the southeast wall has dropped while moving southwest. Similarly the left-hand wall moved ahead on many of those of west or northwest trend but in these fissure systems the downthrow is not consistently on one side.

Fault fissures of this group are largely confined to a zone on the southeast side of the belt of porphyry stocks, and they tend to follow the zones of weakness in the schists and gneisses bordering the more competent granite bodies. In many places, owing to irregularities of contact, the vein fissures cut through alternating bodies of schist, gneiss, and granite, and such areas seem to be the most favorable for ore deposition, as the heterogeneity of the rock renders it especially subject to fracturing; but in such places the most open and therefore most mineralized parts of the fissures are in granite. In most of the districts the coming together of two different veins or of branches of the same vein appears to have been a very important factor in the formation of openings and in the localization of ore, but in a few places the junction resulted in the formation of strong gouge zones which were too tight for the deposition of ore. The irregularities in the fissures and the direction and amount of movement were also very strong factors in the formation of openings. The influence of openings on the localization of ore in the pre-ore fissure cannot be too strongly emphasized, for the bulk of the ore-forming solutions followed courses through the most permeable portions of the fissure fillings available and deposition took place in the more open places along those passageways.

The alternating sequence of porphyry intrusions and ores as tentatively worked out by the writers is shown on the correlation chart in figure 3. On the basis of distribution and age it appears that certain ores are related to certain porphyries. The earliest well-developed veins appear to be the strong pyritic gold veins of the Ward district, which the writers believe to be contemporaneous with the extensive northwest-trending faults, or breccia reefs, and to be related to an early quartz monzonsite porphyry. These veins were evidently somewhat enriched at a later period, but the degree of enrichment is uncertain. After the formation of the strong faults valuable lead-silver ores related to a diorite-quartz monzonite-alaskite series of porphyries were deposited in the Breckenridge, Montezuma, Silver Plume-Georgetown, Central City-Idaho Springs, and Caribou districts. Slightly later lead-silver deposits of minor value are found in the Ward, Gold Hill-Sunset, and Jamestown districts, and their age and areal distribution suggest that they are genetically related to an alkalic diorite-syenite-granite group of porphyries. Related to this series also are the fluorspar veins of Jamestown, formed in fissures that seem to be a result of local stresses produced by the intrusion of a porphyry stock.[34] Pyritic gold ores were extensively deposited in the Empire, Central City-Idaho Springs, Gold Hill-Sunset, and Jamestown districts and seem to be related to the alkalic syenite-bostonite series. The age and distribution of the telluride ores of Gold Hill, Magnolia, and James-

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[34] Goddard, E. N., Influence of Tertiary intrusive structural features on the mineral deposits of the Jamestown district, Colo.: Econ. Geology, vol. 30, pp. 370-386, June, 1935.

town and the few telluride veins found in the Central City district and in the tungsten belt indicate a close genetic relation to a biotite-monzonite-latite series, the late members of which occur in places as the matrix of explosion breccia. The tungsten ores of the Nederland district are later than the telluride ores[35] and are believed to be the latest of the ore deposits in the mineral belt.

STRUCTURAL RELATION OF THE MAJOR FAULTS AND VEINS

Strong lateral compression in an east or east-northeast direction seems to have been largely responsible for the formation of both the major faults and the vein fissures. The major faults were apparently formed at the height of Laramide orogeny, when most of the movement was taken up by folds and thrusts in the sedimentary formations and by the formation in the more rigid pre-Cambrien rocks of steep-angle diagonal faults along which there was a strong horizontal component of movement. The vein fissures seem to have formed in the waning stages of Laramide compression and to have followed a zone of weakness nearly at right angles to the trend of the major faults. Although the pattern of the veins shows them to be the result of regional forces it seems probable that local factors, such as the minor movement along the major faults or the intrusion of porphyry bodies, were locally important in setting up stresses that were relieved by the vein fissures. In a very late stage of Laramide movement lateral compression caused a slight westward movement of a wedge of granite in Boulder County, which opened the east-west fissures of the tungsten belt and some of the northeast fissures of the Gold Hill and Jamestown telluride veins.

In addition to any structural influence that the major faults may have had in the formation of vein fissures, they had an important influence on the distribution of the ores in these fissures. As shown on the map, the veins in many districts are confined generally to one or more blocks bounded on the northeast and in places on the southwest

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[35] George, R. D., The main tungsten area of Boulder County, Colo.: Colorado Geol. Surv., 1st Rept., 1908.

by the northwest-trending faults of the breccia reef group. The Central City veins end abruptly against the Blackhawk fault, the Hoosier "dike" marks the eastern limit of the veins of the tungsten belt, the Gold Hill veins all lie within 2,000 feet of the Hoosier "dike", the veins of the Sunshine district all lie west of the Maxwell "dike", and those of the Jamestown district end against the Standard "dike". These breccia reef faults were tight for the most part, and they may have served as dams or baffles to ore-forming solutions that moved up from the southwest. However, in many places they were apparently more open at greater depth than were the less persistent transverse fissures of the vein series and were able to serve as deep channels for the movement of ore fluids; solutions damned off at one place moved up and along the breccia reefs until they reached the surface or found more permeable cross fractures. Thus it is possible that in fault blocks where no ore deposits appear at the present surface, in some places ore may have formed at higher levels and have been eroded; at other places ore may be present at depth near some of the breccia reefs.

In a few places ore-forming solutions apparently traveled along the breccia reefs to the fringes of the mineral belt and deposited ore in isolated districts, such as the Phoenix, the Perigo, and the Eldora districts, which are scattered along the major northwest-trending faults in the areas where they die out. In the Gold Hill and Jamestown districts and the Nederland tungsten belt, many of the most productive veins are situated close to strong breccia reefs. The evidence suggests that throughout the mineral belt vein fissures adjacent to the strong northwest-trending faults were the most favorable sites for the formation of ore deposits, provided they were open during the period of deposition.

CONCLUSION

In this brief text, the writers have endeavored to bring out the strong influence of rock type and structure on the distribution of ore deposits. The distribution of the pre-

Cambrian rocks and their structure had a marked influence on the major Laramide structural features, and these in turn had a determining influence on the distribution of ore deposits. Many of the earlier geologists working in the Front Range emphasized petrography rather than structure, and as some of the major faults are so thoroughly concealed that they can be identified and traced only by detailed work, it is readily apparent that further geologic study is needed, not only in the mineral belt but throughout the Front Range.