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THE UNDERGROUND GEOLOGY OF THE TONOPAH MINING DISTRICT, NEVADA

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By T. B. NOLAN

INTRODUCTION

One of the projects undertaken as a part of the cooperative work done by the Nevada State Bureau of Mines and the United States Geological Survey during the biennium 1929–30 was a geologic resurvey of the Tonopah district, in Nye and Esmeralda Counties. In the summer of 1929 the mine workings in the western part of the district were examined, and during the following winter a preliminary report based upon the work was prepared.[1] The remaining mine workings to the east were studied in 1930. It was originally planned that the results of this second season's work would be incorporated in the final report on the district to be published by the Geological Survey. Unforeseen delays in the preparation of that report, however, have made it desirable to prepare the present report in order that the information obtained may become available to those interested in the district. Photostatic copies of the assembled mine maps of the district upon which the geologic information is plotted have been placed on file in the Geological Survey offices at San Francisco and Salt Lake City and at the office of the Nevada State Bureau of Mines in Reno.

The preliminary report on the western part of the district is no longer available for distribution, the edition having become exhausted some time ago. A considerable part of the information in that report has therefore been embodied in this text. In addition certain general conclusions regarding the ore bodies of the district have been summarized here in advance of their presentation in the final report.

The writer desires again to express his appreciation of the many courtesies shown him by the mine operators of the district and his indebtedness to them for information regarding inaccessible workings. Ian Campbell continued as assistant in 1930 and freely made available the results of his microscopic study upon the rock specimens collected.[2] H. G. Ferguson and

[1] Nolan, T. B., The underground geology of the western part of the Tonopah mining district, Nevada: Univ. Nevada Bull., vol. 24, No. 4, 1930.

[2] Campbell, Ian, The petrography of Tonopah, Nev. (unpublished thesis for the degree of Ph.D., Harvard University).

G. F. Loughlin provided many helpful suggestions and criticisms during their visits to Tonopah.

PREVIOUS GEOLOGIC WORK

The first detailed report on the geology of the Tonopah district, based on field work in 1902–3 for the Geological Survey, was made by J. E. Spurr.[2a] He revisited the district several times between 1908 and 1915 and published two additional papers, in which some of his earlier conclusions were amplified or revised.[3] The following extract from the second of these papers summarizes his final conception of the geology:

> At Tonopah the oldest rock is a trachyte flow highly altered to quartz, sericite, and adularia. The lower part of this flow is a fine flow-banded glassy trachyte. The main body of the trachyte (Mizpah trachyte) contains the oldest and by far the most important group of mineral veins; the glassy trachyte appears practically barren.
>
> Stresses subsequent to the trachyte extrusion produced horizontal fissuring near the zone of transition between the main body of trachyte and its glassy lower portion; and along here an andesite (Sandgrass andesite) intrusion penetrated. After renewed fissuring along the same zone, a glassy trachy-alaskitic intrusion (Montana breccia), very full of inclusions, took place, usually following along immediately above the andesite. Subsequent movement reopened this line of weakness, and a second trachy-alaskitic intrusion came in—the West End rhyolite sheet—which penetrated along a fissure usually lying immediately above the Montana breccia. At a subsequent epoch came an eruption of andesite (Midway andesite) as a surface flow; at a still later epoch there was a series of rhyolitic and alaskitic surface flows and intrusions, of which the most important in the mine workings is a great intrusive mass called the "Tonopah rhyolite."
>
> The principal veins were formed after the trachyte eruption and before the Sandgrass andesite-Montana breccia-West End rhyolite intrusions. They are quartz veins carrying silver and gold. A second set of veins was formed after the West End rhyolite intrusion and before the Midway andesite eruption. This second set is divided into four successive groups—A, large typically barren quartz veins; B, tungsten-bearing veins; C, mixed quartz and adularia veins, typically barren; D, productive veins like those of the first set following the trachyte. A third set of veins was formed after the Tonopah rhyolite intrusion. They are quartz veins carrying occasional lead, zinc, and copper sulphides.
>
> All these veins formed at shallow depths, and the different types are held to represent various stages of temperature. The first-period veins represent the normal shallow-seated type and followed the trachyte eruption; the second-period B veins probably represent an abnormally intense shortly sustained temperature, following the trachy-alaskitic intrusion; the second-period D veins a subsequent briefly sustained stage of temperature more normal to shallow depths; the third-period a relatively high but briefly sustained temperature following the alaskitic (Tonopah rhyolite) intrusion. No vein formation followed the andesite eruption.
>
> The history of faulting is long and complex; important movements have taken place at every stage of the geologic history. These movements accompanied and were due to the volcanic disturbances.

[2a]Spurr, J. E., Geology of the Tonopah mining district, Nev.: U. S. Geol. Survey, Professional Paper 42, 1905.

[3]Spurr, J. E., Report on the geology of the property of the Montana-Tonopah Mining Co., Tonopah, Nev., published by the company, 1[illegible]9; Ore deposition at Tonopah, Nev.: Econ. Geology, vol. 10, pp. 713–769, 1915.

Somewhat earlier Burgess[4] reached a radically different conclusion from that formed by Spurr as to the nature of the several formations disclosed by the mining operations. He considered that the different formations originated as surface flows or accumulations of volcanic material, thus questioning Spurr's conclusion that many of these rock masses are intrusive. Burgess also noted that many of the productive veins continue downward from the Mizpah trachyte into the West End rhyolite, and he implied, although he did not so state, that the mineralization in the two formations is contemporaneous.

The district has also been briefly discussed by Locke,[5] who in general agreed with Burgess that the formations are present in their proper stratigraphic sequence. Locke also questioned the validity of Spurr's statement that the mineralization occurred in several epochs and noted that "There is no mineralogical distinction whatever to be made between many veins which, according to the hypothesis [Spurr's] should belong to different periods."[6]

The origin of the ore deposits was discussed in 1918 by Bastin and Laney.[7] These authors did not concern themselves with either the stratigraphic sequence or the geologic structure of the district. With regard to the ores, however, they noted that "Mineralogic differences between veins of supposed different ages are commonly no greater than may be observed in different parts of one continuous vein. * * * Upon the sole basis of the mineral composition and texture of the primary ore there would be little reason for the impartial geologic observer to regard the principal productive veins as of more than one age."[8]

The results of the geologic work prior to 1929 may perhaps be

[4]Burgess, J. A., The geology of the producing part of the Tonopah mining district: Econ. Geology, vol. 4, pp. 681–712, 1909.

[5]Locke, Augustus, The geology of the Tonopah mining district: Am. Inst. Min. Eng. Trans., vol. 43, pp. 157–166, 1912.

[6]Idem, p. 164.

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

[8]Idem, p. 9.

briefly summarized as follows: The district is underlain by a series of volcanic rocks, which are considered by Spurr to be in large part intrusive sills and by Burgess and Locke to be entirely of surficial accumulation. All these observers imply that these formations are relatively flat-lying and that differences in altitude of an individual bed are solely the result of faulting, the cause of which is attributed by Spurr to volcanic activity and by Burgess to irregularities in the original distribution of the formations. Spurr postulates several different periods of ore formation, a view which is directly challenged by Locke, indirectly questioned by Burgess, and not supported by the work of Bastin and Laney. Spurr, Burgess, and Locke all appear to agree that the "Midway andesite" is later than the period of ore formation and acts as a capping to the ore.

In the preliminary report published in 1930,[9] the writer, on the basis of the much more extensive exposures then available, presented several new interpretations of the geology. The sequence of rock formations was found to differ from that proposed by Spurr or by Burgess and Locke. The oldest formation was named the "Tonopah formation" and was interpreted as a series of interbedded rhyolitic flows, tuffs, breccias, and well-laminated silts. Dark lavas, identical with the rocks mapped by Spurr as the Sandgrass andesite, were found at two or more horizons interlayered with the Tonopah formation. The Mizpah trachyte was found to overlie the Tonopah formation, probably conformably, the contact between them in most places being occupied by an intrusive sill of West End rhyolite. An intrusive pluglike mass that was considered to be earlier than the West End rhyolite but younger than the other formations was mapped as the Extension breccia. Two post-ore divisions were also recognized—the Fraction breccia, or basal member of the Esmeralda formation, and rhyolite dikes similar to the Oddie rhyolite or Brougher dacite of Spurr. The post-ore "Midway andesite" of the older authors could not be distinguished in any of the accessible mine workings.

In place of the flat-lying series of formations of the earlier reports, it was found that the rock units had been considerably tilted to form a westward-dipping monocline. The dominant structural feature appeared to be a compound fault, which was named the "Tonopah fault" and whose appearance in cross section was described as that of a recumbent crescent, convex upward. A throw of about 1,500 feet was ascribed to the fault.

[9] Nolan, T. B., op. cit.

It was also found that almost all the known ore bodies of the district had been localized either in the compound fault itself or in branches from it, and that there was no evidence in favor of more than one epoch of silver mineralization. It was also suggested that both wall-rock alteration and the geothermal gradient may have influenced ore deposition.

Ian Campbell in 1931 prepared a doctoral thesis on the petrography of the rocks collected by the writer and himself during 1929 and 1930. This thesis has been used in the preparation of the present paper.

SUMMARY OF THE TERTIARY GEOLOGIC HISTORY OF THE TONOPAH DISTRICT

The examination of the mine workings in the eastern half of the district yielded information that gives a much more complete picture of the geologic history of the district, so far as it bears upon the formation and distribution of the ore bodies, than was possible in 1930, when the earlier report was prepared. As no pre-Tertiary rocks are exposed within the district, this account of the geologic history is confined to the Tertiary stage of geologic time.

The rock formations that enclose the ore bodies are all believed to have been derived from an igneous center west of the mining district, probably not more than a few miles away. The oldest of these formations, the Tonopah formation, is an interbedded series of rhyolitic flows, volcanic breccias and tuffs, and water-laid sediments made up of volcanic debris. In the eastern part of the district the very coarse volcanic breccias found to the west are lacking, indicating a greater distance from the center of volcanic activity. During the period in which this formation was accumulating, dark andesitic lavas were erupted on at least two occasions, and these flows constitute the Sandgrass andesite.

After the accumulation of the Tonopah formation, another series of andesitic flows, long known as the "Mizpah trachyte," was erupted. In several places underground the basal flows of the Mizpah trachyte interfinger with the uppermost beds of the Tonopah formation. There is also at least one bed of volcanic breccia within the Mizpah trachyte some distance above the base of the formation.

The eruption of the andesitic lavas was followed by an epoch of minor intrusive activity. The earlier of the two intrusives recognized, the Extension breccia, was found only in the western half of the district. It was intruded as a tabular mass along the contact of the Tonopah formation and the Mizpah trachyte and extended eastward only as far as the ground of the Tonopah Mining Co. The other intrusive mass, the West End rhyolite, also follows the contact between the Tonopah formation and the Mizpah trachyte, but is distinctly more sill-like than the Extension breccia. Like the breccia, it pinches out eastward and is absent in a number of places in the Belmont and Halifax mines.

The original nearly horizontal attitude of these formations has been greatly disturbed by widespread faulting. The earliest movement is thought to have occurred along a group of north-south faults of low easterly dip, which are found in the Halifax and Mizpah-Extension mines. This group has been named the "Halifax fault zone." Because of the rather steep westerly dips in the footwall of the fault zone, the rocks west of the zone are believed to have been uplifted during this period. The total amount of uplift is unknown but appears to have been several thousand feet.

Either contemporaneous with or slightly later than this early activity along the Halifax fault zone, the remarkable compound Tonopah fault and its subsidiary branches came into existence. The three major fractures composing the fault all have similar characteristics. Both in plan and in section they have curved traces, being convex eastward in plan and convex upward in section. The axes of curvature on all three fall along the same east-west line and plunge eastward at a low angle. The throw along each of the three branches appears to be between 500 and 1,500 feet, and the formations on the hanging wall have been relatively dropped. A natural assumption would be to regard the curvature along these fractures as the result of folding, but this is disproved by the absence of comparable deformation in the wall rocks. The fault is believed to have been formed as a result of forces similar to or perhaps even identical with those that caused the movement along the Halifax fault zone, but the uplifted footwall segment was of much less horizontal extent. A possible cause of the uplift along both faults lies in the intrusion of a large body of igneous rock, the introduction of the main mass of which would initiate movement along the Halifax zone, and the advance of a small protuberance or cupola from that mass would result in the uplift represented by the Tonopah fault. Many east-west faults of small throw extend from the crests of the three major branches of the Tonopah fault. Most of them dip to the north, but several dip to the south. These

small faults are thought to have formed at about the same time as the major fractures.

The uplift represented by the Halifax and Tonopah faults is believed to have been succeeded by a period of settling or collapse. This readjustment took place along at least three sets of faults. Two of these, one striking northwest and the other northeast, appear to have been essentially contemporaneous. The northwesterly faults, represented by the Mizpah, Monarch-Pittsburg, and other faults, commonly have the larger throws and are more persistent, but some of the northeasterly faults, such as the Belmont, Tesuro, and Silver Top faults, have been traced underground for considerable distances. In the Montana-Tonopah and North Star mines, there is a notable and rather complex association of faults belonging to these two groups which is believed to be the result of a progressively greater northward uplift along the Halifax fault zone. The third group of faults, which strike north and dip west, are largely restricted to the western half of the district.

It is probable that the mineralization in the district was in a broad sense contemporaneous with the faulting. The earliest stage consisted in a wholesale albitization of the andesitic rocks particularly, and in most of the district this alteration was so intense that the andesites were originally believed to have been erupted as albitic rocks. Relatively unaltered blocks of the Mizpah trachyte, however, were found in the Halifax mine and show rather clearly that the albitization was a phase of the alteration. A second stage was less extensive and consisted in the introduction of a quartz-adularia-sericite mineral assemblage. In the ground of the Tonopah Mining Co. in the central part of the district, this stage reached a maximum and may well have been directly above the cupola that has been suggested as the cause of the local uplift along the Tonopah fault. Away from this central area, a chlorite-carbonate alteration is widespread, especially in the andesitic rocks.

All the faults, including the Tonopah and Halifax groups, are locally followed by quartz veins of considerable size but in many places of negligible silver or gold content. These quartz bodies have replaced the shattered walls of the faults. They are on the whole earlier than the introduction of the ore minerals. The ore shoots also follow the faults but are far less extensive in their distribution. Their limitation to faults or parts of faults with nearly east-west strike (the Tonopah fault and its branches and some of the northwest faults) suggests that these fractures were open to the passage of ore solutions as a result of tensional forces which acted concurrently with the settling that followed the uplift.

Several features of the ore deposits appear to fit in well with the conception that the local uplift along the Tonopah fault resulted from the intrusion of an immediately subjacent igneous cupola. The central location of the rocks affected by the quartz-adularia-sericite alteration has already been noted. A second feature is the apparent restriction of the ore shoots to a zone 600 to 1,000 feet in vertical thickness, which reaches its highest altitude in the vicinity of the zone of intense alteration and is at progressively lower altitudes away from it. This ore zone is believed to represent the temperature interval within which the silver minerals could be deposited in commercial concentration, and the symmetry of its upper and lower boundaries with the area of most intense alteration is considered significant. A further suggestion of a centrally underlying heat source is the regular decrease of the gold-silver ratio outward from the apical region of the productive zone.

Erosion must have attacked the elevated block that contains the ore deposits soon after the faulting was started, and rock fragments from the older formations composing the block are abundant in the Fraction breccia, which unconformably overlies the ore bodies and their enclosing rocks. The breccia is the basal member of the Esmeralda formation, of upper Miocene age, and is overlain by the upper member, composed of lake beds, in which volcanic material is dominant, and by later rhyolitic lavas and breccias. The veins on Mizpah Hill were probably exposed by erosion for a short time during the deposition of the lower part of the Esmeralda formation but were soon covered by the beds of the upper part. Then followed renewed faulting, along the Halifax fault zone, tilting the Esmeralda beds to the west, though at lower angles than the formations beneath. These beds were in turn beveled by erosion; and a group of rhyolite flows, known locally as the "Oddie rhyolite" and "Brougher dacite," covered them. Dikes of this rhyolite are found at several places underground, and one of the largest is within the Halifax fault zone. Recent erosion has cut through the rhyolite and the underlying Esmeralda beds to expose the silver-bearing veins a second time.

ROCK FORMATIONS

Of the seven formations recognized during the field work in 1929 and 1930, two are younger than the ore bodies; the remaining five form the wall rocks of the ore bodies. The following list, in which the youngest rocks are at the top, summarizes their relations:

Post-ore rhyolite: Dikes and lenticular masses intrusive into all the other formations.

Fraction breccia member of Esmeralda formation: A volcanic breccia that unconformably overlies the ore bodies and their wall rocks.

West End rhyolite: Sills, as much as 600 feet thick, intrusive into all the older formations.

Extension breccia: Tabular intrusive mass. Found only in the western half of the district.

Mizpah trachyte: A series of surface flows, with minor volcanic breccias, at least 2,000 feet thick originally, but much of this thickness removed by erosion locally.

Sandgrass andesite: Dark lavas, interlayered with the Tonopah formation.

Tonopah formation: Interbedded volcanic tuffs, breccias, and flows, which are conformably overlain by the Mizpah trachyte. More than 1,000 feet thick.

Tonopah formation — The name "Tonopah formation" was proposed[10] in the report on the western half of the district for the rocks originally described by Burgess[11] as the "Lower rhyolite." Spurr[12] considered the formation to be the intrusive equivalent of extrusive rocks now exposed on the surface and used the names "Tonopah rhyolite" and "Tonopah rhyolite-dacite." These surface rocks, however, appear to be much younger than the Tonopah formation and are believed to be, in part at least, contemporaneous with the Esmeralda formation. The Tonopah formation includes rocks that have been mapped previously as "Glassy trachyte" and "Montana breccia," but it does not include all the exposures that have been so assigned by Spurr, Burgess, and others.

The most significant and extensive exposures of the formation are found in the western half of the district, notably in the

[10] Nolan, T. B., op. cit., p. 10.

[11] Burgess, J. A., The geology of the producing part of the Tonopah mining district: Econ. Geology, vol. 4, p. 687, 1909.

[12] Spurr, J. E., Geology of the Tonopah mining district, Nevada: U. S. Geol. Survey Prof. Paper 42, p. 41, 1905; Ore deposition at Tonopah, Nev.: Econ. Geology, vol. 10, p. 745, 1915.

westerly workings on the 1,200-foot, 1,540-foot, and 1,880-foot levels of the Tonopah Extension mine. The rocks are also exposed, however, in the deeper workings of all the easterly mines, though in these extensive faulting and considerable alteration tend to mask the character and relations of the formation. The 1,000-foot and 1,100-foot levels from the Desert Queen shaft, the 700-foot level of the Silver Top, the 1,300-foot level of the Belmont, and the 1,155-foot intermediate of the Mizpah Extension mine all provide fairly good exposures of the beds.

The most striking feature of the formation is that it is composed of an interbedded sequence of volcanic breccias, massive tuffs of varying grain size, porphyritic flows, banded flows, and water-laid deposits of several kinds, including well-laminated silts that closely resemble beds in the Esmeralda formation.

The rocks described by Burgess[13] as bedded pyroclastic material belong in this formation, and the exposures in the Tonopah Extension workings add abundant proof of the nonintrusive character of the great bulk of these rocks. Bedding planes are apparent in many places, and numerous specimens show an obvious gradation from coarse-grained material at the bottom of a bed to fine-grained material at the top. On one bedding surface well-developed ripple marks were noted. In addition, the fact that these rocks are interbedded with amygdaloidal flows of Sandgrass andesite renders it certain that the great bulk of the formation is a surface accumulation.

Strongly flow-banded rhyolites interbedded with the other members of the formation are widespread. This rhyolite has been distinguished by some of the geologists who have visited the district as "Glassy trachyte." It was impossible, however, to map this rock separately because of its intimate interbedding in many places with tuff and breccia. Contortion of the flow banding is locally marked.

In the eastern mines the volcanic breccias contain much smaller fragments, and the rocks on the whole are much more uniform in texture and composition. This difference is believed to indicate an increased distance from the volcanic center from which the material was erupted.

Campbell has studied the rocks under the microscope and has described the microscopic features of the tuffs and breccias as follows:[14]

[13] Burgess, J. A., op. cit., pp. 687–689.
[14] Campbell, Ian, op. cit., pp. 34–35.

The tuffs consist typically of small angular fragments of quartz, orthoclase (both adularia and sanidine), albite, and, very rarely, microcline and microcline-microperthite, in a fine-grained groundmass. Quartz is much the most abundant of the larger fragments. Ferromagnesian minerals very likely were present, but the frequent occurrence of small flakes and shreds of chlorite is now the only indication of their former presence. Zircon and colorless apatite occur sparingly. A faint kaolinization is rather widespread, occurring over both the groundmass and the feldspars.

The groundmass is exceedingly fine grained, and although now much silicified and in part also sericitized and kaolinized, it still suggests its original ash structure. In many specimens the peculiar and distinctive cusplike and trilobate structures ("Bogenstructur") typical of rhyolitic tuffs can still be recognized in outline, although the originally glassy shards are now entirely devitrified or silicified. These are not usually apparent at first sight under the microscope, and often it is only with plane light and with the field slightly out of focus that the structures become recognizable. They stand out by virtue of the fact that in the general recrystallization coarser grains of quartz (or sericite, as the case may be) have replaced the shards, while the detrital paste which filled the interstices has produced a finer-grained secondary material. The contacts therefore show the outline of the former structures.

The breccias exhibit a more heterogeneous aggregation of material. In addition to the constituents found in the tuffs, a variety of rock fragments is found. These are generally rather severely altered (by kaolinization, sericitization, and chloritization), so that the original character is often in doubt. They seem to have been derived from rhyolitic and andesitic rocks, for the most part not definitely correlatable with any known in the district. In part, of course, the fragments are clearly from lower beds of the Tonopah formation itself.

Concerning the flow-banded rhyolites known locally as "Glassy trachyte," he writes:[15]

Fluidal texture is quite commonly seen. Phenocrysts are not common. Crystals of albite are found occasionally. They generally show a varying degree of sericitic and kaolinic alteration. More rarely chloritic pseudomorphs after biotite(?) are found. The matrix is always much altered. The glassy bands are formed of secondary quartz; while the white opaque material proves to be quartz with large amounts of kaolin and sericite. Pyrite is very commonly disseminated throughout the rock. In its distribution it seems to show little preference as regards the more or the less quartzose layers.

The bottom of the formation has not yet been exposed by the mining operations. In most places the upper limit of the formation is marked by the intrusive West End rhyolite, which separates it from the Mizpah trachyte. At a few localities in the southeastern part of the district, notably on the 1,100-foot level

[15] Idem, p. 44.

of the Rescue-Eula mine, the intrusive rock is absent and the normal contact between the Tonopah formation and the Mizpah trachyte is exposed. Here, as on the 1,330 - foot level of the Midway mine, the two formations appear to interfinger with each other, beds of tuff or breccia alternating with relatively thin layers of typical Mizpah trachyte. A lenticular mass of volcanic breccia resembling beds in the Tonopah formation is also found within the Mizpah trachyte several hundred feet above its base throughout the Belmont mine.

The total thickness of the formation exposed in the mine workings of the eastern half of the district is considerably less than the 1,000 feet found to the west.

In the previous report it was considered that the formation was of pre-Miocene but probably Tertiary age.[16] No additional direct evidence was obtained in the eastern half of the district. It seems probable, however, that the age difference between the Tonopah and Esmeralda formations may not be as great as the pronounced angular unconformity between them led the writer to suppose at first. The two formations are strikingly similar in many phases of their lithology, implying that their source and conditions of deposition may have been much the same. The discordance in dip between the beds appears to be due to movement along the Halifax fault zone, and such evidence as is available suggests that there was only a relatively short lapse of time between the faulting of the ore-bearing rocks and the deposition of the Esmeralda formation. Thus, the uplifted pre-Esmeralda beds must have been subject to erosion as soon as the faulting was completed, and as the basal Fraction breccia contains large boulders of these rocks, there is a strong probability that deposition of the Esmeralda formation started soon after the uplift. If this assumption is correct, the Tonopah formation may be of middle Miocene or early upper Miocene age.

Sandgrass andesite—The rocks belonging in the Sandgrass andesite were originally considered by Spurr to be an altered phase of the Mizpah trachyte and were known locally as the "calcitic phase of the earlier andesite." This correlation was soon abandoned and the name was locally shortened to "calcite andesite."[17] This abbreviated term was accepted by Spurr in 1910, although he considered that the rocks represented an intrusive phase of the "Midway andesite."[18] Finally, in 1915,

[16] Nolan, T. B., op. cit., p. 13.
[17] Burgess, J. A., op. cit., p. 691.
[18] Spurr, J. E., report to Montana-Tonopah Co., pp. 21–22, 1910.

Spurr proposed the name "Sandgrass andesite,"[19] at the same time recognizing the lack of relationship of these rocks with any of the other formations, and this name has persisted since that time.

The formation is found in many of the mines in the district, but the most extensive and least altered exposures are in the western mines. The 960-foot level of the West End, the 1,540-foot and 1,880-foot levels of the Tonopah Extension, and the 1,000-foot and 1,140-foot levels of the Sand Grass provide the best information as to its character and relations. In the eastern mines the 1,250 - foot level of the North Star and the 765 - foot level of the Montana provide minor exposures, and others may be present on the 1,400- and 1,500-foot levels of the Belmont, but neither of these was accessible in 1929 or 1930.

On the basis of the work done in the western mines[20] the writer considered that the Sandgrass formation represented a series of volcanic flows interbedded with the Tonopah formation. Two and possibly three separate bodies, having a total thickness of about 500 feet, separated from one another by tuff or breccia, were recognized in the Tonopah Extension mine. On the 960-foot level of the West End mine the formation contains flows of different composition and texture, including dense basalts, breccias, and strikingly amygdaloidal andesites. In the relatively few exposures that could be examined in the eastern mines the rocks are rather badly altered and have yielded essentially no additional information regarding the relations or character of the formation, although the North Star occurrences are best explained as being interbedded with the adjacent rocks of the Tonopah formation. The comparative scarcity of exposures, however, suggests that the andesite is thinner in this direction. No occurrences similar to those in the Sand Grass mine, where the uniformity of the formation prompted the suggestion[20a] that the rocks at that place might be intrusive, were found, and it seems probable that the uniformity there observed is due to the fact that the workings that cut the formation are nearly parallel to the general strike and thus expose only a single flow.

The boundaries of the formation in the Red Plume, Midway, Montana, and North Star mines are locally irregular, but in these localities crushing and rather intense alteration has tended to mask the true relations. It seems most probable that all these

[19] Spurr, J. E., Econ. Geology, vol. 10, p. 729, 1915.
[20] Nolan, T. B., op. cit., pp. 14–15.
[20a] Idem, p. 14.

occurrences are the result of minor warping or folding on interfingering contacts between the Sandgrass andesite and the Tonopah formation, with which it is interbedded.

The formation is dominantly gray-green to dark green. The bulk of the unaltered rock is porphyritic, the dull feldspar phenocrysts being three or four millimeters in maximum diameter. Much of this material in hand specimens resembles chloritized portions of the Mizpah trachyte. Breccia horizons in the formation are difficult to distinguish except by a study of thin sections, as the rock fragments are almost exclusively of the porphyritic type and the chloritized matrix is similar megascopically to the altered groundmass of the lavas. The amygdaloidal phases and the black, sparingly porphyritic basalts may both be readily recognized in the less altered exposures of the formation, such as those on the lower levels of the West End mine.

Campbell's notes upon the microscopic features of the formation follow:

In the amygdaloidal facies of the formation altered feldspars appear in a groundmass of chlorite. The feldspar phenocrysts are of small to medium size and, though mostly altered to calcite, appear to have been albite originally. Ferromagnesian phenocrysts were evidently rather rare. The amygdules show concentric filling by chlorite, calcite, and quartz. Pyrite is found as swarms of small cubes but is only rarely present in the amygdules.

The basaltic rock consists of about 30 percent of small tabular fresh crystals of calcic andesine in a typical basaltic texture. The groundmass material is made up of exceedingly small lathlike feldspars, the interstices between which are filled with a fine-grained aggregate of chlorite and calcite. Magnetite in small subhedral grains is abundant, but apatite is relatively rare. Pyrite and zircon are absent.

Specimens from the vicinity of the Sand Grass shaft show a seriate porphyritic texture of altered feldspar phenocrysts in a rather fine-grained, altered groundmass. The feldspars are almost completely altered to epidote, zoisite, sericite, chlorite, and calcite, but a few remnants indicate that their composition is that of albite. Other phenocrysts are also abundant, and their outlines suggest that they were originally hornblende and very probably biotite. These are now completely altered to elongate prismatic forms outlined with a heavy "fuzzy" border of black iron oxides, the inner portion of which consists of chlorite and quartz, with locally a little carbonate or sericite. The groundmass seems to have suffered less alteration than the phenocrysts. Outlines of small lathlike to tabular feldspars in subparallel arrangement can be distinguished. These seem to be albite chiefly, though there may be a little orthoclase and quartz. Among them can be found all the alteration products mentioned above, with chlorite and calcite the most abundant. Apatite is fairly common throughout

the rock, and all of it is the ordinary colorless variety. Zircon was not noted. Pyrite occurs sparingly in rather irregular aggregates.

As may be seen from these descriptions, most of the formation is albite-rich, and the term "keratophyre" might well be applied to these rocks, although the name "Sandgrass andesite" is retained here because of its long use in the district. In the earlier report the albite was considered to be an original constituent, but the field work in 1930 in the eastern part of the district indicated that the albite in the Mizpah trachyte, which is in many respects similar to the Sandgrass andesite, is rather certainly the result of alteration (page 21), and it seems probable that the same thing is true of the albite in this formation. Locally the Sandgrass andesite has also undergone a quartz-sericite-adularia alteration, like that observed much more widely in the Mizpah trachyte.

Mizpah trachyte—The rock of andesitic appearance first described by Spurr[21] under the name "earlier andesite," as originally defined included also the Sandgrass andesite, and therefore in 1915 he renamed the formation the "Mizpah trachyte."[22] This name is retained in the present report because of its long usage in the district, although the present survey has shown that the rock in almost all exposures is an albitized andesite or keratophyre, and not a trachyte. On the lower levels of the Tonopah Extension mine the local name "Victor andesite" has been used by some geologists for the formation.

In most of the mines in both the eastern and western parts of the district there are exposures of rocks that have been mapped by Spurr, Burgess, and others as "later andesite"[23] or "Midway andesite"[24] and described by them as lying unconformably above the Mizpah trachyte and forming a "cap rock" to the veins. In the report on the western part of the district[25] it was stated that the rocks in many places assigned to the "Midway andesite" cannot be separated from the Mizpah trachyte by reason of any original differences in composition or texture, nor was this rock anywhere seen to cap any of the veins. In many exposures of the supposed "Midway andesite" extensive chloritization had considerably changed their appearance, but within such altered masses less altered facies were

[21] Spurr, J. E., op. cit. (Prof. Paper 42), p. 31.
[22] Spurr, J. E., op. cit. (Econ. Geology, vol. 10), p. 720.
[23] Spurr, J. E., op. cit. (Prof. Paper 42), p. 33; Burgess, J. A., op. cit., p. 703.
[24] Spurr, J. E., op. cit. (Econ. Geology, vol. 10), p. 743.
[25] Nolan, T. B., op. cit., p. 16.

found to be of the same keratophyric nature as the unquestionable Mizpah trachyte. All the numerous exposures of supposed "Midway andesite" examined in the eastern mines in 1930 led to a similar conclusion.

Two places may be cited where veins were apparently considered to be terminated upward by the overlap of a younger andesite. These are the 270-foot level of the Tonopah Extension mine and the 800-foot level of the Belmont. At the former locality a stoped vein belonging to the Egyptian group of the Extension and West End mines may be followed up from the 320-foot intermediate level. The stope from below has broken through at two places on the 270-foot level. In both these places the hanging wall of the vein is seen to extend to the floor of the level, but above this point it steepens and frays out. In the more westerly of the two stopes a cave in the roof of the drift provides clear evidence of the upward dying out of the vein fracture. The wall rock on the level is considerably crushed and altered, but a thin section from a less altered phase, gradational into the altered material, is identical with the unquestioned Mizpah trachyte below. Similarly, on the 800-foot level of the Belmont, the upward extension of the Belmont vein clearly passes into a zone of branching veins, only portions of which are ore-bearing, though here the dip flattens rather than steepens. Although the rock on the walls of the nonproductive western extension of this branching zone is shown on the mine maps as "Midway andesite," no definite contact is marked between it and the Mizpah trachyte in the walls of the productive portions, and no change in lithology can be recognized on the level; indeed, subsequent to the mapping, a productive branch vein was found within the supposed barren "Midway andesite."

All the exposures of supposed "Midway andesite" that were accessible at the time of this survey have similarly yielded convincing evidence that the rock is identical with the Mizpah trachyte, either by their field relations to rocks that are admittedly Mizpah trachyte or by petrographic criteria, as noted below. Averill,[26] however, has recorded an occurrence of an andesitic rock overlying the Mizpah trachyte which he considers to represent the unconformable overlap of the "Midway andesite." This exposure was not seen by the writer, but it may well be that at shallow depths in certain parts of the district

[26]Averill, C. V., Tonopah geology: Eng. and Min. Jour., vol. 130, p. 532, 1930.

there is an overlying flow, related to the post-Esmeralda andesites or latites of the Divide district,[27] although it is most improbable that this rock is of any great extent or of any economic importance within the productive part of the Tonopah district.

The Mizpah trachyte is widely distributed throughout the district and makes up the bulk of the exposures in all the mines. Because of the supposed restriction of the ore-bearing veins to this formation, its limits have controlled exploration to a considerable extent, and much energy and ingenuity have been expended in the fruitless task of separating the formation from rocks believed to be younger.

The formation differs widely in appearance from place to place, but these variations are due in large part to alteration or deformation. By far the most common lithologic variety is a grayish-green porphyry. The phenocrysts of feldspar are almost invariably dulled by alteration, are somewhat variable in size and abundance, and are set in a dense matrix locally flecked with chlorite. Pyritization is common. Two other varieties of rock are found locally in the formation. One of these is a flow-banded rock, which is sparingly porphyritic; it is present to a minor extent in a number of the mines. The other is a fragmental rock, commonly a breccia but locally tuffaceous, which is generally well bedded. It too is found in many of the mines, and in the Belmont a bed of this material is sufficiently extensive to be separately mapped. Some of these clastic rocks are closely similar to beds in the Tonopah formation.

Each of these three varieties of rock has been subjected to at least three kinds of alteration. The most widespread has been an albitization of the feldspars, which has been so nearly complete throughout all but the extreme eastern end of the district that in the earlier report on the western half of Tonopah the albite was considered to be an original constituent of the rocks. This was the earliest alteration of the formation, as the albite has been replaced by minerals of the other types. The next most widespread alteration was chloritization, which has affected the formation to varying degrees everywhere except in the central area near the claims of the Tonopah Mining Co. It was most intense near faults, and the resulting dark green sheared rock shows almost no resemblance to the original porphyry. The

[27]Knopf, Adolph, The Divide silver district, Nev.: U. S. Geol. Survey Bull. 715, pp. 155–158, 1921.

chlorite is generally accompanied by carbonate minerals and pyrite. The third variety of alteration was best developed in the central area and consisted in the introduction of quartz, sericite, and adularia. Locally replacement of the older minerals by these three minerals has been essentially complete, and the resultant hard, bleached rock is in striking contrast to both the chloritized and the albitized phases of the formation.

Campbell's notes on the microscopic features of the formation follow. They apply to the albitized rock that has undergone relatively slight later alteration:

In thin section the Mizpah trachyte shows rather numerous and prominent albite phenocrysts, set in a fine-grained, somewhat orthophyric groundmass composed principally of albite and orthoclase. A little quartz in the groundmass may be primary, but it is difficult to distinguish from secondary quartz. In the interstices of the feldspars in the groundmass are scattered small shreds of chlorite and sericite. Ferromagnesian phenocrysts are very rare. Biotite may be inferred from its pseudomorphs, which are generally either sericite or chlorite. Apatite, much of which is pleochroic, is relatively abundant, and zircon rather scant. Magnetite or ilmenite may have been sparingly present, but if so, it is now entirely altered to rutile.

Albite, as noted above, is the chief feldspar. Its average composition is Ab[illegible]An[illegible]. The phenocrysts are tabular and usually show the typical polysynthetic twinning, except where this has been obscured by alteration. Neither pericline nor carlsbad twinning is particularly common. Zonal growths are almost unknown. All these phenocrysts are altered to a greater or lesser extent. Sericitization of the albite phenocrysts was the most widespread type of alteration. Locally, adularization occurred, and there has also been replacement by quartz, calcite, and chlorite. Any two or even three alteration products may be found on a single crystal. Alteration of the groundmass is more difficult to estimate with accuracy. It seems to have proceeded more rapidly than that of the phenocrysts, but along the same general lines except that much-altered specimens are found in which the phenocrysts have gone entirely to sericite, but the groundmass has become a mass of intergrown quartz and sericite, with quartz the more abundant. Even in specimens that appear to be but little altered it is common to find veinlets and nests of quartz or quartz and adularia.

Similar features have been found during the study of thin sections of specimens from rocks mapped previously as "Midway andesite." Albite phenocrysts are found in these rocks, as are also quartz-adularia veinlets; in addition pleochroic apatite crystals, identical with those in the unquestioned Mizpah trachyte, are present. Koschmann[28] has similarly found that no distinction can be made between the heavy mineral concentrates from the "Midway andesite" and Mizpah trachyte.

[28] Koschmann, A. H., unpublished thesis, University of Wisconsin, 1920.

A thickness of at least 2,000 feet of the Mizpah trachyte is indicated by the relatively unfaulted hanging-wall exposures in the Sand Grass and Tonopah Extension mines. The top of the formation is not known, except where it is unconformably overlain by the Fraction breccia. The Mizpah trachyte conformably overlies the Tonopah formation and must therefore be slightly younger.

Extension breccia—The name "Extension breccia" has been used locally for an intrusive mass of breccia which occurs only in the northwestern part of the district and whose relations are best exposed in the Tonopah Extension mine. It is probable that in some of the geologic mapping by mine geologists this formation has been included either with the Tonopah formation or with the "Montana breccia." No additional information regarding it was obtained in the eastern mines, and the following description is taken from the earlier report:[29]

On the lower levels of the Tonopah Extension mine the breccia is found in the footwall of the Murray and Merger veins. The exposure continues up to the 600-foot level, but the area of breccia present on each level steadily decreases upward, because of the fact that the dip of the breccia mass is somewhat steeper than that of the vein. The Extension breccia is also found on the hanging wall of the combined Murray and Merger veins in the lower levels of the Sand Grass and Merger mines but is by no means adequately outlined there because of the relative scarcity of mine workings.

The intrusive nature of the mass is clearly shown in only a few places, such as the 1,880-foot, 1,760-foot, 1,680-foot, and 950-foot levels of the Tonopah Extension and the 1,000-foot level of the Sand Grass, the relations in other localities being more or less masked by alteration near the veins. The intrusion appears to have been localized along an earlier fault, striking nearly east and dipping north, within the Tonopah formation. On the 1,140-foot level of the Sand Grass, for example, east of the main body of the intrusive, a narrow dike of the breccia is found in this fault zone, which here separates breccias and tuffs of the Tonopah formation from Sandgrass andesite. Still farther east on the 1,050-foot level from the Extension No. 1 shaft, however, the formation is absent from the fault zone. The actual contact of the intrusion is in many places difficult to locate exactly. Rock typical of the breccia passes gradually through a variety in which fragments of the invaded rock predominate, then to one in which they are exclusively present, and finally to shattered wall rock cemented by thin veinlets of the Extension breccia matrix.

The greater part of the intrusion is remarkably homogeneous in appearance, consisting of fragments of various rock types set in a characteristically reddish matrix containing rounded dark phenocrysts of quartz. The rock fragments included are largely of the Tonopah formation and less abundantly of the Sandgrass andesite and Mizpah

[29] Nolan, T. B., op. cit., pp. 17–19.

trachyte. Not uncommonly small fragments of black shale are also found. Locally it is difficult to distinguish the formation from the breccias of the Tonopah formation, for in the vicinity of veins alteration has masked its relations and obliterated its distinctive characters.

Mr. Campbell's observations on the thin sections of this formation are as follows:

"Under the microscope most of the inclusions are banded rocks, trachytic rocks, eutaxitic-textured rocks, and tuffaceous rocks and can be recognized as belonging to the Tonopah formation. The matrix is not usually easy to separate from the rest of the rock. It seems to consist almost entirely of fine-grained quartz, much of which is probably secondary. Large quartz grains are embedded in this matrix and are much corroded and resorbed. Throughout the matrix there is distributed a faint reddish-brown dust, undoubtedly an iron oxide, which must account for the red color observed in hand specimen.

"The Extension breccia shows the same kinds of alteration, with sericitization and silicification predominating, that the other formations have."

The maximum strike length of the Extension breccia mass was observed on the 1,5[illegible]0-foot level of the Tonopah Extension mine, where it amounted to nearly 1,500 feet. The maximum thickness (at right angles to the strike length) is not known because of the interruptions to the mass by faulting, but it is probably in the neighborhood of 1,000 feet.

The formation is later than the Mizpah trachyte, for it includes fragments of that rock, but it is older than the West End rhyolite, which intrudes it. It was probably formed in the same general period of volcanic activity as the Tonopah formation and its associated flows.

West End rhyolite—At the time of Spurr's earlier report the West End rhyolite had been exposed in only a few shafts and was considered to be a part of what is called in this report the "Tonopah formation." More extensive exposures, however, proved it to be a distinct rock, and it became known as the "Upper rhyolite," being described by Burgess[30] under that name, although he appears to have included with it rocks that are now assigned to the Tonopah formation. The formation was redefined in 1915 by Spurr[31] and named the West End rhyolite.

Burgess describes the mass as being a series of flows, in contrast to Spurr's contention that it is an intrusive sill-like body, but the newer mine workings have exposed abundant evidence showing that Spurr's view is correct. Burgess' interpretation seems to have been due to the fact that he included rocks now known to belong to the Tonopah formation.

The formation is best exposed in the western workings of the Tonopah Extension mine, where the main body occurs as a westward-dipping mass separating the Tonopah formation and the Mizpah trachyte. It thins notably to the northeast, east, and southeast, and at several places in these directions the mine workings show it to be absent—for example, on the 1,330-foot level of the Midway, the 1,300-foot level of the Belmont, the 1,200-foot level of the Halifax, the 1,100-foot level of the Buckeye, and the 500-foot level of the Gold Hill. There are in addition thinner and less continuous sills of the formation at other horizons. Many of these are within the Mizpah trachyte, as on the 800-foot level of the West End and on several of the Belmont levels; others are within the Tonopah formation, as in the deeper western workings of the Tonopah Extension.

[30] Burgess, J. A., op. cit., p. 692.

[31] Spurr, J. E., op. cit. (Econ. Geology, vol. 10), p. 737.

The intrusive nature of the formation is shown by several features. The most convincing is the fact that it cuts through the Extension breccia, which is itself intrusive. At several places there are small apophyses into the Mizpah trachyte, and in some localities inclusions of that rock are found in the main body of the rhyolite, which lies stratigraphically beneath the Mizpah trachyte. In addition, the rhyolite shows a narrow chilled upper border wherever later alteration has not been so intense as to conceal it.

Except where intensely altered, the formation is readily recognized by reason of the characteristic dense greenish matrix, in which are set abundant angular fragments of white chalky rock. The included fragments vary greatly in number and size. In the western part of the district they normally make up about a third of the rock and are commonly a quarter of an inch or more in diameter, some of them as much as an inch. Although the Tonopah formation, especially the tuffaceous members, has evidently supplied the bulk of the fragments, minor contributions have been made by all the older rocks, and those from the Extension breccia are the least abundant. To the east the fragments are generally much smaller, being commonly less than a quarter of an inch in diameter, and are, locally at least, less abundant. At the contacts of the formation, besides the chilled border, there are in some of the western mines coarse breccias with inclusions a foot or more in diameter. Similar coarse breccias were noted on the 400-foot level of the MacNamara mine as bands within the formation. Wherever these variations in the number and size of inclusions are found together, there is no sharp contact between the two phases, but rather a gradual blending over a distance of several feet. A faint flow banding was observed at several localities, both near the borders of the intrusion and within it.

Campbell gives the following notes on the microscopic features of the formation:

> In thin section the rock is seen to be a very fine-grained but generally holocrystalline rhyolite. Sparse phenocrysts of quartz, albite, and orthoclase are found in a matrix of feldspar (probably orthoclase) and quartz (much of which may be secondary).
>
> The white inclusions so prominent in hand specimens are distinguishable with difficulty under the microscope. The "Glassy trachyte" and associated rocks appear to have furnished the material for the inclusions, because textures seen in a few of the sections are [illegible] similar to those characteristic of parts of the Tonopah formation.
>
> The alteration of the rock was chiefly sericitization, with an indeter[illegible] amount of silicification. Pyrite is widespread and abundant [illegible] formation, and many of the pyrite cubes are bordered by [illegible] sericite. Quartz veinlets in the rock are of widespread [illegible], and in many of these adularia is a rather abundant acces[illegible]. Sericite occurs in such veinlets more rarely.

The maximum thickness of the formation is exposed in the West End Extension and Tonopah 76 workings, where the main intrusion is at least 600 feet thick. From this place eastward there is a rather regular decrease to zero. The West End rhyolite intrudes all the formations previously described but is, like them, unconformably overlain by the Fraction breccia.

Fraction breccia—This rock was first described by Spurr[32] as the "Fraction dacite breccia." It was renamed the "Fraction rhyolite breccia" by Knopf,[33] as a result of his work in the Divide district, south of Tonopah. The simplified name "Fraction breccia" was proposed in 1930,[34] because at Tonopah the basal portion of the member contains locally very large amounts of andesitic-appearing debris, with the result that there has at times been considerable confusion as to the proper correlation of the beds. They have, for example, been considered to represent the "Midway andesite"; indeed, all examples of "Midway andesite" cappings of veins that were seen by the writer proved to be this basal portion of the Fraction breccia.

No additional information about the breccia was obtained in the eastern mines and the following paragraphs are quoted from the earlier report:[35]

[32] Spurr, J. E., op. cit. (Prof. Paper 42), p. 39.
[33] Knopf, Adolph, op. cit., pp. 150-154.
[34] Nolan, T. B., op. cit., p. 21.
[35] Idem, pp. 21-22.

The formation is exposed in the workings of the Jim Butler, MacNamara, West End, West End Extension, Monarch-Pittsburg, and Tonopah 76 mines as a generally southward-dipping mass that unconformably overlies the older formations and the veins. In detail the lower contact of the beds is very irregular, showing that the surface upon which they were deposited had moderate relief. In many places the major faults that affect the veins appear to have exerted a control upon this old surface, for the breccia extends deeper where such faults formerly reached the surface. In addition, relatively slight renewed movement along many of the faults has resulted in shearing of the breccia.

The formation as exposed underground is almost everywhere a massive rock without any indication of bedding, although in a few places interlaminated fine-grained material may be observed. Near its contact with the older rocks it is generally sheared, presumably as a result of the later earth movements that imposed upon the formation its general southward dip. The basal beds are commonly made up almost exclusively of rock fragments that are andesitic in appearance, although most of them are undoubtedly keratophyres derived from the Mizpah trachyte. The proportion of matrix in this variety is in many places relatively small, and for the most part the matrix has the same dark color as the fragments. Higher up in the formation the rock is lighter colored and has a lower ratio of fragments to matrix. Of this portion Mr. Campbell writes:

"The matrix is light colored, exceedingly fine-grained, and under the microscope appears holocrystalline to hypocrystalline. Fluidal texture has been observed. The aggregate index is lower than canada balsam and higher than gamma of sanidine. Phenocrysts of quartz and sanidine are abundant, and there are a few of albite and biotite. The sanidine is generally much altered to calcite, the albite somewhat altered to sericite, the biotite also to sericite. There has been some silicification throughout the rock and heavy kaolinization locally. Pyrite, partly altered to limonite, occurs sparingly."

Only a small part of the formation is exposed in the underground workings so far examined, and the determination of the total thickness must wait until the surface exposures have been adequately studied.

The Fraction breccia is considered by Ferguson[36] to be the basal member of the Esmeralda ("Siebert") formation and is assigned to the upper Miocene.

Post-ore rhyolite—Dikelike masses of rhyolite are the youngest rocks found in the mine workings. They are exposed in several places, but only three of the bodies are large enough to warrant specific mention. One of these is a thin dike which occurs on the 1,680-foot, 1,760-foot, and 1,880-foot levels of the Tonopah Extension mine near the Cash Boy shaft. It definitely cuts across the veins in at least one place and is unaffected by the mineralization, being therefore post-ore. A much larger dike is exposed

[36] Ferguson, H. G., Geology and ore deposits of the Manhattan district, Nev.: U. S. Geol. Survey Bull. 723, pp. 42-43, 1924.

on the 800-foot level of the West End and West End Extension mines, where it cuts the Fraction breccia as well as the older rocks. It does not come into contact with any of the ore-bearing veins, so far as known.

The third and largest body is a bulbous dike that has been cut by the workings of the Belmont, Halifax, Mizpah Extension, and Rescue-Eula mines. This dike locally terminates the Belmont vein on the east and the Halifax vein on the west and is clearly later than the ore deposition. It has been intruded along the Halifax fault zone, and like that zone has a northerly trend and a low dip to the east. This dike appears to represent the feeding channel from which was erupted the rhyolite that forms the top of Mount Oddie.

In all these occurrences the rock is a light-colored, rather fine-grained rock with abundant quartz phenocrysts. On the 700-foot and 900-foot levels of the Belmont there are abundant inclusions of the older wall rocks, and in places the rock resembles the Fraction breccia, but thin sections of the matrix from these places, as well as the continuity in depth with the normal rock, show that this is a near-surface phase of the intrusion.

Campbell's notes on the thin sections are as follows:

In thin section the quartz phenocrysts stand out prominently. They are generally rounded but locally are embayed as a result of resorption, are slightly fractured, and are rather free from inclusions. Phenocrysts of sanidine are common, and in one specimen these show partial alteration to calcite. More rarely albite occurs. An occasional small flake of biotite, now altered to sericite, was noted. The groundmass has been much silicified, as is well shown in one specimen where the secondary silicification has produced "enlargements" of quartz phenocrysts, similar to the well-known quartz enlargements that occur typically in quartzites. If we discount this alteration it seems likely that this groundmass was holocrystalline and composed of quartz and orthoclase. There has been in places a slight sericitization, and locally small patches of calcite occur. Some pyrite was also noted.

In part, at least, these rhyolites are identical with the Oddie rhyolite as defined by Spurr,[37] but some of them may be similar to his Brougher dacite.[38] The surface rocks were not carefully studied, but there appears to be little difference between them.

FAULTING

The older reports on the Tonopah district have described the several formations as being essentially horizontal[39] and have

[37]Spurr, J. E., op. cit. (Prof. Paper 42), p. 49.
[38]Idem, p. 44.
[39]Burgess, J. A., op. cit., fig. 87, p. 705. Locke, Augustus, op. cit., pp. 157, 159. Spurr, J. E., op. cit. (Econ. Geology, vol. 10), p. 713.

implied that the bulk of the major faulting was later than the deposition of ore.[40] In the report on the western part of the district[41] evidence was presented to show that neither of these conclusions is valid, as the formations were found to be considerably tilted, and that their apparently horizontal attitude in the older central part of the district is the result of extensive premineral faulting.

The two block diagrams (plates 1 and 2, in pocket) show the principal structural features of the district and their relations to one another. Plate 1 was prepared for the earlier report and covers the western part of the district; plate 2, which is based on the exposures in the eastern mines, differs from plate 1 in that the region which it portrays has been split into three units, in order that more of the workings may be shown. In this plate the block is viewed from the northeast instead of from the northwest, as in plate 1.

The tilting of the rocks is shown chiefly by flow banding of the lavas and bedding planes of the sediments, and these correspond in attitude to unfaulted contacts projected from level to level in the mine workings. The dips are dominantly toward the west throughout the district, and in the extreme western part where there has been relatively little faulting, the westward dip is fairly uniform and averages about 45 . In the central and eastern parts, however, there is less uniformity, although the net result is a westward dip of approximately the same amount. In this more intensely faulted area individual dips either may be much steeper than 45°, as at many places in the Belmont mine, or much less than 45°, as in some workings from the Mizpah and Silver Top shaft. On the 700-foot and 800-foot levels of the Red Plume and the 700-foot level of the Mizpah there are low northerly and easterly dips. These caused the suggestion in the earlier report[42] that there might be an anticlinal fold in the rocks in this vicinity, but the additional work in the eastern mines showed that this conclusion was wrong, and the easterly dips observed at these places are now considered to be due to the proximity of several major faults.

The movement along the faults must have been largely accomplished before the deposition of the ore, for essentially unshattered quartz has been deposited in places along almost all of them. In some of these occurrences such quartz is continuous with the quartz of the ore-bearing veins, and in several

[40]Spurr, J. E., op. cit. (Econ. Geology, vol. 10), pp. 766-769. Burgess, J. A., op. cit., pp. 709-711.
[41]Nolan, T. B., op. cit., p. 23.
[42]Idem, pp. 23-24.

places ore has been stoped from shoots that follow the faults, as on the Merton fault or vein in the Tonopah Extension, West End Extension, and Tonopah 76 mines, the Rainbow fault in the MacNamara mine, the Mizpah fault in the Tonopah Mining and Belmont properties, and branches of the Halifax fault zone in the Halifax mine. There has been postmineral movement in several places, as shown both by the presence of quartz pebbles in fault gouge and by the faulting of younger formations, such as the Fraction breccia and post-ore rhyolites; but this movement appears to have been relatively slight.

The faults found underground may be divided into three general groups, based upon their strikes and dips. The faults in each of the three groups are believed to have a common origin and to represent phases of a single epoch of earth movement.

One group constitutes a fault zone of northerly strike and rather low east dip, which is restricted to the eastern part of the district. It has been called the "Halifax fault zone," from the Halifax mine, in which it is well exposed. A second group of faults, which is probably younger than the greater part of the movement along the Halifax zone, includes three major faults, known collectively as the "Tonopah fault," and subsidiary faults that branch from them and have an easterly strike and either northerly or southerly dip. The Tonopah fault is compound and is unique in the district in that its component faults have curved traces in both plan and section, being convex eastward in plan and convex upward in transverse section. All three of these component faults have axes of curvature that fall along the same east-west line and that plunge eastward at a low angle. Most of the ore bodies that have been mined in the district are localized along the Tonopah fault and its branches. The third group includes faults with northeast and northwest strikes and also some faults with north strike and west dip. The group as a whole is thought to be roughly contemporaneous and to be younger than the two other groups of faults.

Halifax fault zone—The Halifax fault zone is exposed in the Halifax, Mizpah Extension, Belmont, and Buckeye mines and consists of a linked group of slightly curving faults with a general northerly strike and an eastward dip that averages about 35° or 40°. Many of the workings in which the fault zone is exposed were not accessible in 1930; a considerable part of it, however, may be seen on the 1,100-foot level of the Halifax and the 1,155-foot level of the Mizpah Extension.

The fault zone has been of considerable economic interest, in that a member of it has terminated the Belmont vein eastward on the upper levels of the Belmont mine, and other members have cut the Halifax vein into several segments, only two of which are known to be ore-bearing. The difficulty of picking up the faulted vein segments is materially increased by the fact that post-ore rhyolite has been intruded along the fault zone, and some of the dikes are several hundred feet wide. In places there has been some mineralization along individual faults in the zone, and in a few of these places, such as the north end of the 1,100-foot level of the Halifax mine, small stopes have been opened. None of these workings appear to have been profitable.

The total amount of premineral movement along the Halifax fault zone is unknown but was probably more than 2,000 feet, to judge from the reported presence of Mizpah trachyte in the hanging wall of the most easterly branch on the 1,700-foot level of the Halifax mine. The throws of individual faults within the zone appear to vary greatly, but the accessible workings are too few to determine them accurately, especially in view of their branching habits. There has clearly also been some postmineral movement along the zone, as is shown by the tilting of the Fraction breccia and by the crushing of the rhyolite dikes. This movement is believed to have been somewhat less than 1,500 feet.

Tonopah fault and branches—The second group of faults includes a very large proportion of the fractures along which ore shoots have been found. The compound Tonopah fault is economically the most important one in the group, partly because of the ore bodies found along it but mainly because it has controlled the localization of the numerous ore-bearing minor fractures that branch from it.

The two lower segments of the Tonopah fault, each of which has the appearance in cross section of a recumbent crescent, convex upward, are exposed only in the western half of the district. Figure 1 shows the extent to which these branches have been exposed by the mine workings—for considerably more than 1,400 feet vertically on the north limb and for nearly 700 feet vertically on the south limb. Ore bodies along different parts of the fault have received different names, some of which are shown in the figure.

The northern junction of the lower branch with the upper branch is well exposed on the 500-foot level of the Tonopah Extension mine. This locality is not shown on plate 1, which

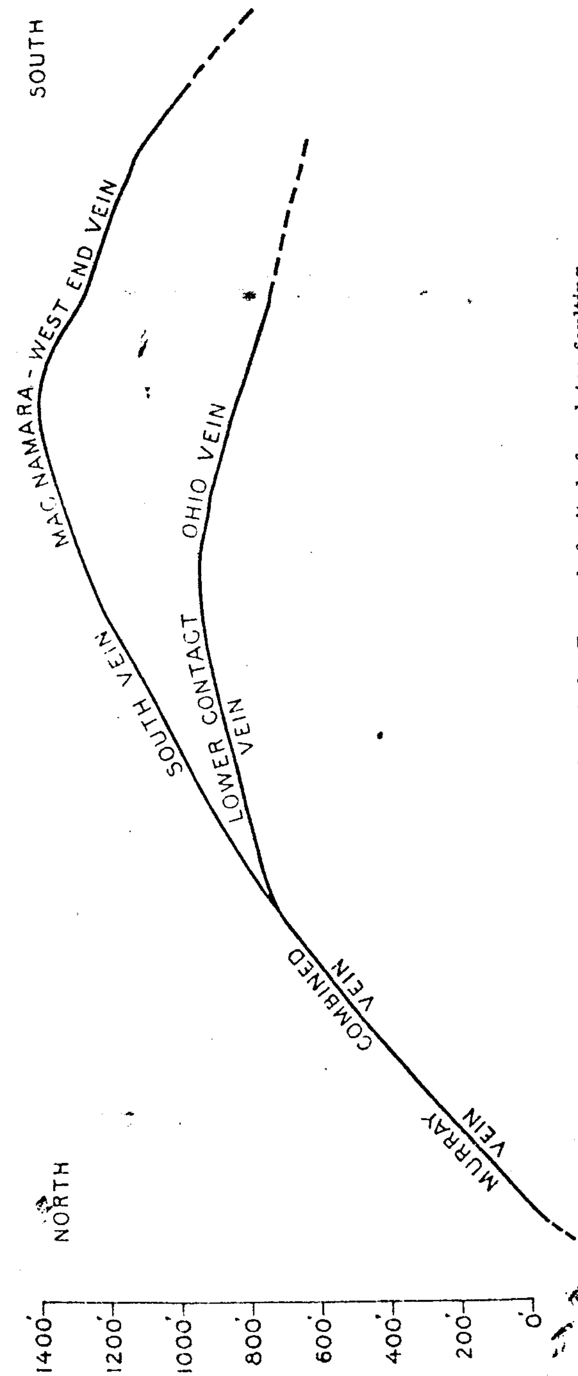


Figure 1—Generalized cross section of the Tonopah fault, before later faulting.

does, however, show the junction of the branches in cross section between the 600-foot and 660-foot levels of the Tonopah Extension, about 500 feet southwest of the Sand Grass shaft. The upper branch is apparently unmineralized at this point. The comparable junction to the south has not been found by mine workings, but the dips of the two branches indicates that it very probably exists. The crests of these two "anticlinal" branches both plunge to the east at low angles, ranging from 5° to 20°. The rather inadequate exposures of the crest of the lower branch suggests that it plunges at a lower angle than the upper.

The Stone Cabin fault, exposed in several workings in the vicinity of the Desert Queen shaft, is believed to be a third and higher branch of the Tonopah fault. It has a much greater radius of curvature in plan than the two lower faults and plunges more steeply to the east (about 30°); to the north it becomes nearly parallel with the branching Mizpah fault and cannot be confidently traced.

No ore shoots have been found along the Stone Cabin fault and consequently it has not been extensively explored. Its curvature, its alinement with the two lower branches, and the similarity of its relations have led to its assignment to this second group of faults, although the mine workings do not expose a junction with the other two branches.

The curved trace of the Tonopah fault suggests at once that it is simply a folded fault that originally had a uniform dip. This view is not tenable, however, because there is no similar folding in the formations adjacent to the fault—in fact, the strike of the wall rocks is rather uniformly at right angles to the axis of the crest of the fault.

The only mechanically probable direction of movement along the three branches of the fault appears to be a relative drop to the east, down the axis of the crest of the fault. As measured in this direction the contact of the Mizpah trachyte and the West End rhyolite has been shifted about 500 feet down the nose of the lower or Ohio vein branch, about 1,500 feet down the nose of the middle or MacNamara-West End vein branch, and about 1,000 feet down the nose of the upper or Stone Cabin branch—a total movement of about 3,000 feet. All these figures are approximate only, because of the numerous other faults that affect this contact in the region where the measurements must be made. On the lower levels of the Tonopah Extension mine, in the western part of the district, this same contact is shifted horizontally about 1,500 feet by the north limb of the fault and its splits (which here represent the union of the two lower branches of the fault), and this figure suggests that the movement was a few hundred feet less at this point.

The subsidiary related faults are most abundant in the central and eastern parts of the district at relatively shallow depths. The only large one found at depth occurs on the lower levels of the Tonopah Extension and Sand Grass mines. It is mineralized and is locally known as the "Merger vein." Its line of junction with the main fault plunges steeply to the east, and the two diverge from each other westward. West of the point of junction the displacement along the main fault decreases by about one-half, the remainder being along the branch. No comparable branch or split has yet been found on the south limb in the West End mine.

Most of the branch faults have a relatively small throw—a few hundred feet or less—and an east-west strike. They are found chiefly above the crests of the middle and upper branches of the Tonopah fault in the Tonopah Mining, Belmont, Jim Butler, Montana, and Midway mines. They differ from the Merger vein branch in that their lines of intersection with the main fault, where known, are nearly horizontal and their divergence is in a vertical rather than a lateral horizontal direction. In all these faults that have been adequately explored the amount of displacement decreases rapidly upward and, in some at least, westward as well. The upward dying out is commonly accompanied by the development of one or more branches and in many of the veins by a steepening in dip. The Belmont vein appears to be exceptional, as its dip decreases upward.

Two general types of these subsidiary faults may be distinguished. One steeply dipping set includes the Mizpah vein and its probable extension to the west as the Red Plume-Extension North vein; the Belmont, Lillie Belle, and other veins in the Belmont mine; the MacDonald and other veins in the Montana mine, all with steep northerly dips, together with the Fraction and some other veins in Jim Butler ground near the Desert Queen shaft, with steep southerly dips. The second set, with rather low (30° to 40°) north dips, is represented by the Valley View vein, and the Shaft and Favorite veins in the Belmont mine, and possibly by the Rescue vein in the Rescue-Eula mine. The Valley View and Favorite veins both appear to pass upward into steeply dipping veins like those of the first set. These small branch faults are much more numerous immediately north of

the crests of the Tonopah fault segments, and their close genetic relationship with that fault is therefore not beyond debate, especially as there is some evidence that at least part of the movement along them was later than that along the Tonopah fault. They are, however, cut and offset by all the members of the third group of faults, and it is believed that genetically they are best placed in this second set.

Other faults—Of the three varieties of faults in the third group, those with northwest strike and a northeast dip that is commonly about 40° have had the greatest effect upon subsequent mining operations in that they have offset the fractures that were later to become ore-bearing. Three of these faults have been developed for considerable distances underground. The most westerly one is exposed in the Tonopah Extension, West End Extension, and Tonopah 76 mines. It is locally mineralized, and the ore shoot in Extension ground has been called the "Merton vein." The horizontal shift of the contact between West End rhyolite and Mizpah trachyte along this fault amounts to about 1,000 feet, and as the contact in this region dips about 45°, the vertical movement along the fault was probably the same. On the Extension 1,540-foot level, southwest of the McKane shaft, the fault is made up of two major branches, which in places must be 200 feet apart. To the west, however, they appear to join. The workings on the 800-foot level of the West End Extension and Tonopah 76 do not show a similar branching, unless the two masses of quartz found in the workings south of the main crosscut represent the western junction of the branches.

The second fault has been named the "Monarch-Pittsburg fault,"[43] owing to its occurrence in the mine of that name, where it is apparently mineralized. It is also exposed on the 800-foot and 960-foot levels of the West End mine, where it cuts off the Ohio vein fissure, and on the lower levels of the Tonopah Extension, where it offsets the fissure followed by the Murray vein. The fault is essentially continuous between the exposures in the Extension and those in the Monarch-Pittsburg, but it is cut and displaced by two large faults in the region between the Monarch-Pittsburg and West End mines. The offset of the Murray vein in the Tonopah Extension mine indicates that the vertical movement along this fault must amount to about 1,000 feet. The Monarch-Pittsburg fault, like the parallel fault to the west, is compound—two major branches, which unite both

[43] Nolan, T. B., op. cit., p. 28.

to the southeast and to the northwest, being observed in the more westerly workings. In the Tonopah Extension mine this fault is known as the "Denver fault."

The Mizpah fault is the third and best known of the northwesterly faults. It has been explored at many places in the Midway, Montana, North Star, Tonopah Mining, Belmont, and Rescue-Eula mines, where it cuts off the main ore-bearing veins. Locally, eastward-striking portions of the fault contain ore shoots that have been stoped and are called parts of the Mizpah fault vein. The fault is actually a fault zone, as in most places there are two or more parallel fractures along which the fault movement has occurred. The number of branches appears to increase both to the northwest and to the southeast. It is difficult to determine with any accuracy the total throw along the Mizpah fault zone, partly because of its [illegible] habit but chiefly because of the numerous other [illegible] faults in its vicinity. In the North Star and Montana [illegible], for example, the northern extension of the Stone Cabin [illegible] joins with it; in the Belmont mine the northeasterly Bel[illegible] fault is a complicating factor; and in the Rescue-Eula its [illegible]terly extension is close to the equally branched Halifax [illegible] zone. From the position of the lower boundary of the Mizpah trachyte on each side of the zone, however, and with allowance for the effects of other faults, it appears that the total movement along the Mizpah fault must have been about 1,000 feet, or essentially the same as along the other two faults of this type.

The northeasterly faults of the group are somewhat more abundant but appear to have smaller throws than the northwesterly faults. Some of them show notable curvature along the strike, the northeasterly trend swinging into a north-south trend. The dip is to the southeast or east at about 60°. Individual faults of this strike show different relations to both the northwesterly faults and the northerly faults with west dip, leading to the conclusion that all three types are roughly contemporaneous.

The Sand Grass fault is the farthest northwest of the larger faults of this kind and is well exposed only on the 600-foot level of the Sand Grass mine, where it cuts the shaft, and on the 660-foot level of the Extension mine. Other exposures of faults that are believed to be extensions of the Sand Grass fault are reported on the 770-foot and 1,050-foot levels from the Extension No. 1 shaft, the 1,000-foot level of the Ohio, the 600-foot level of the

Monarch-Pittsburg, and the 800-foot level of the West End Extension-Tonopah 76. To the east the Tonopah fault is dropped more than 150 feet vertically by the Sand Grass fault, but on the 660-foot level of the Extension this displacement is distributed along several branches.

The Rainbow fault, named in the Extension mine, is best exposed about midway between the Extension No. 1 and Sand Grass shafts on the 600-foot levels. In most of these exposures the strike is nearly north, but southward toward the 600-foot level of the MacNamara mine the fault splits and the main branch assumes a northeasterly strike. The workings in the Ohio vein, particularly on the 555-foot level, show that this southeasterly branch is cut and offset by the Extension fault of the third group. The vertical movement along the fault is about 150 feet on the lower levels of the mines. On the upper levels the throw decreases and is divided between several branches; the movement along the main southwesterly branch was about 50 feet.

The MacNamara fault is found throughout the mine of that name, where it displaces the upper branch of the Tonopah fault, and is probably continuous westward with a similar fault that cuts the lower branch on the 800-foot level of the West End. Eastward it is found in the 500-foot and 600-foot levels of the Red Plume but appears to die out in the Midway and Montana mines. The vertical displacement along the fault is more than 200 feet in the western part of the Ohio 800-foot level, but is less than 50 feet on the 500-foot level of the Red Plume. To the west the MacNamara fault cuts and offsets the Rainbow, Monarch-Pittsburg, and Extension faults.

The Edwards fault was named and is best exposed in the West End mine, where its several branches are roughly parallel to the southern limb of the portion of the Tonopah fault known as the "West End vein." It is similar in many respects to the MacNamara fault, which it parallels. Along the plunging crest of the Tonopah fault on the 600-foot level of the Red Plume and Mizpah mines the dip of the Edwards fault flattens notably, being about 10°.

The two faults of this type in the Belmont mine both show a change in strike from northeast to north-south. The more westerly is the Favorite fault. The strike of this fault appears to curve from nearly north-south to northeast-southwest when traced to the south, but its extent and exact relations are somewhat obscure because it is near the Mizpah and Stone

Cabin faults. Both of these faults are dropped as much as 100 feet in some places by the Favorite fault, but in others it cannot be recognized as distinct, and it is believed to follow the Stone Cabin fault, at least locally.

The Belmont fault may be recognized in many places in the Belmont and Rescue-Eula mines. To the south its strike is nearly due north, but northward this curves to about N. 40° E., and the most northeasterly exposures, where the fault branches, show strikes of N. 60° E. The movement along the fault was about 600 feet, and there is some evidence from the correlation of thicknesses of the West End rhyolite on both sides that horizontal movement to the east has been about equal to the vertical movement. Mine workings on several levels of the Belmont near the west end of the Belmont vein show that the Belmont and Mizpah faults intersect each other with little or no offset, although the movement along both of them has been considerable. This relation implies that the two faults were essentially contemporaneous.

Among the minor faults of northeasterly strike the Silver Top fault in the Tonopah Mining Co. ground and the Tesuro fault in the Belmont have been most extensively developed. The movement along both of them has been 50 feet or less, but both have been traced laterally for more than 1,000 feet.

Northeasterly and northwesterly striking faults of small throw are unusually common in parts of the Montana and North Star mines. The relations of the faults of one type to those of the other are complex and here also seem to be best explained by the contemporaneity of the two kinds of faults.

Faults with north-south strike and west dip are also included in the third group of faults. They are found chiefly in the western mines, but a few with only minor displacement along them are exposed to the east. The most thoroughly explored fault of this type is the Extension fault, which has been exposed throughout the vertical range of the Tonopah Extension workings and is also found in parts of the MacNamara and West End mines. On the lower levels of the Extension mine the vertical movement along the fault amounted to about 125 feet, but on the upper levels it appears to have been somewhat less, in part at least because of the development upward of several branches.

The most westerly of these faults is the 76 fault, exposed both in the Extension and in the West End Extension and Tonopah 76 mines, where it offsets the Merton vein. The vertical throw

is somewhat less than 100 feet. Another, which may be called the "McKane fault," is found near the McKane shaft, where it offsets the Monarch-Pittsburg fault. The vertical movement along it is about 150 feet just above the 1,540-foot level but appears to decrease rapidly upward, amounting to about 50 feet in the Monarch-Pittsburg workings. These levels were not accessible, and it is not clear whether this decrease in throw is the result of branching upward, as in the Extension fault.

The fault to the east behaves somewhat differently. This fault, which is unnamed, is about halfway between the McKane and Extension faults and is exposed in the workings from the Extension No. 2 shaft and the Extension incline. The maximum displacement along the fault in this vicinity appears to have been close to the 1,260-foot level, where the Murray vein has been dropped on the hanging-wall side about 100 feet vertically. Below this level the fault passes into a flexure, as is shown by the curving hanging wall of the Murray vein on the 1,540-foot level. Above the 1,260-foot level the throw decreases, and on the 850-foot level it is comparatively insignificant. This fault appears to be represented to the south by a fault of similar strike and dip that is exposed in two places on the 800-foot level from the Ohio shaft. Here, however, the throw is considerably greater, as the offsetting of the Monarch-Pittsburg fault by it indicates a vertical drop of at least 200 feet.

The Buried fault, exposed in the western workings from the Mizpah and Silver Top shafts, is the most easterly of the larger faults of this type. It cuts the nose of the middle branch of the Tonopah fault and drops it to the west slightly more than 100 feet. The workings from the Wandering Boy shaft indicate that it frays out southward and upward, and, as it could not be recognized in the Midway mine, it must also die out northward.

The faults of this strike and dip are both offset by and themselves offset the northeasterly and northwesterly faults. Faults of all three groups are locally mineralized and are therefore earlier than the ore deposition.

Origin of the faulting — The observed characteristics and relations of the three groups of faults have led to the following theory concerning their origin:

After the accumulation of the volcanic flows, sills and pyroclastic rocks that constitute the pre-Esmeralda formations, the present site of Tonopah was uplifted. The cause of the uplift is not definitely known, but several features suggest that it may have been due to the introduction of a body of igneous rock. The earliest uplift took place along the Halifax fault zone, the rocks in the footwall of the zone being pushed upward, and tilted to their present westward dip. Certain details of the trend of the upper boundary of the Tonopah formation suggest that this early uplift was progressively greater to the north.

A less extensive uplift was accomplished by the development of the compound Tonopah fault, during which the rocks in the footwalls of the three major branches were forced upward relative to those in the hanging walls. The localized uplift thus effected may have been due to a small protuberance or cupola from the hypothetical igneous mass mentioned above. Concomitant with the formation of the major fractures, several minor fractures developed above the crests of the curved Tonopah fault segments, possibly as a result of stretching in the hanging-wall blocks due to the increase in the volume of rock in the uplifted footwall block.

The period of uplift, represented by the Halifax and Tonopah fault groups, was succeeded by one of settling or collapse. The faults of the third group were formed at this time, and the movements along them reflect the readjustments attendant upon the settling. Their relations to one another suggest that the three types of faults in the group were essentially contemporaneous, and their distribution conforms to what might be expected from a progressively greater settling to the east and northeast. It is also probable, from the relations of some of these faults to certain of the minor fractures related to the Tonopah fault, that the readjustment may also have utilized these older fractures as well.

ORE BODIES

The mineralogy of the Tonopah ores has been studied by Eakle,[44] Burgess,[45] and Bastin and Laney,[46] and the textures and character of the silver-rich ore bodies have been described by Spurr[47] and by Bastin and Laney.[48]

[44] Eakle, A. S., The minerals of Tonopah, Nev.: California Univ., Dept. Geology Bull., vol. 7, pp. 1-20, 1912.

[45] Burgess, J. A., The halogen salts of silver and associated minerals at Tonopah, Nev.: Econ. Geology, vol. 6, pp. 13-21, 1911.

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

[47] Spurr, J. E., op. cit. (Prof. Paper 42), pp. 83-96, 115-207.

[48] Bastin, E. S., and Laney, F. B., op. cit.

The ore bodies are replacement veins that follow faults or minor fractures and commonly are without well-defined walls. According to Bastin and Laney,[49] "ore-cemented breccias, true crustification, comb structure, and other features characteristic of the filling of open spaces are rare or developed only on a small scale. Banding somewhat resembling true crustification, which is locally conspicuous, is possibly to be explained by diffusion during replacement."

The size of the ore shoots and the grade of the ore mined have both varied within rather wide limits. As most of the veins have only assay walls, the price of silver and the methods and cost of mining and milling at the time of extraction have been determining factors as to what could be profitably mined. The Mizpah vein has been stoped for 1,500 feet along its strike on some levels, and stope widths of 40 feet were reached on several veins. On the other hand, trial stopes on some of the outlying veins are very small. The average grade of ore mined has on the whole decreased as the district has grown older. Up to 1904 the average value per ton was more than $100, but it dropped to $20 by 1911 and ranged around $15 for many years thereafter. A further drop to $10 occurred in 1930. In some mines considerable quantities of $6 or $7 ore has been mined. The total production, from 1901 through 1934, has been slightly less than $150,000,000.

Electrum (probably selenium-bearing), argentite, polybasite, arsenical pyrargyrite, and other silver and base-metal sulphides are found in the hypogene ore, with quartz, a fine-grained pinkish carbonate, and barite, together with altered wall rock, as the gangue. The greater part of the quartz appears to have been introduced earlier than the silver minerals; the carbonate, however, is believed to be essentially contemporaneous with them.

Cerargyrite, iodyrite, and embolite are reported by Burgess to have been abundant in the veins of the Tonopah Mining Co., and Bastin and Laney[50] report some local supergene sulphide enrichment, which, however, they consider "to have been quantitatively much less important than the hypogene mineralization."

The discussion on the following pages has been directed to the factors that are believed to have controlled the localization of the ore bodies, as the search for new ore bodies is the most

[49] Idem, pp. 9-10.

[50] Bastin, E. S., and Laney, F. B., op. cit., p. 10.

pressing problem now confronting the district. In the earlier report[51] it was suggested that the ore bodies were restricted to those portions of the Tonopah fault and its branches and to faults of east-west strike that were open at the time the silver-rich solutions were circulating and had wall rocks that would facilitate precipitation and accumulation of the silver minerals. It was also suggested that depth might have some bearing on the localization of the ore bodies, but this factor was not considered adequately proved.

The additional field work in the eastern part of the district has required some revision of these conclusions. The Tonopah fault and its branches are still regarded as having controlled the location of individual ore shoots and in most places as having provided the channels along which the mineralizing solutions traveled, but it is now believed that locally at least other major faults, specifically the Belmont, Mizpah, Monarch-Pittsburg, and Merton faults, also were effective in determining the course of the ore-bearing solutions. The requirement that the fractures be open at the time of mineralization is still considered to have been necessary for ore deposition. The influence of the wall rock on the localization of ore shoots is also believed to have been significant, but its relative importance was probably somewhat exaggerated in the report of 1930. The principal change in the conclusions bearing upon the distribution of ore is the increased importance attributed to the depth factor, because the known ore bodies at Tonopah now appear to have been limited to a relatively thin zone or shell, which reaches its highest altitude in the central part of the district. The upper and lower boundaries of this shell, although locally irregular, transgress both faults and formation boundaries. Because of their symmetrical relations to a zone of intense alteration that coincides with the high point of the shell, it is thought that the boundaries may represent isotherms, or lines of equal temperature, which existed at the time of mineralization, and that the shell represents the temperature interval within which ore deposition could take place.

The extent of this shell or productive zone is shown in plate 3, which has been prepared from maps of the individual mines in the district. The upper and lower boundaries of the zone are indicated by contour lines, which are probably only approximately accurate but nevertheless show clearly the elongated

[51] Nolan, T. B., op. cit., pp. 32-34.

dome-shaped productive zone. The block of ground thus enclosed has yielded all of the ore mined in the district except very minor quantities from such mines as the California-Tonopah and Buckeye.

The east-west elongation of the zone and the coincidence of its median line with the crests of the three major branches of the Tonopah fault suggest strongly that this fault played a very important part in localizing the ore. Individual ore shoots in the western half of the district are largely restricted to portions of the two lower branches of the fault, and in the eastern half of the district to the subsidiary east-west fractures that are considered to be genetically related to it. There is, of course, no direct connection in time between the ore and the Tonopah fault, because there are many younger faults that are also mineralized. It would seem rather that when the silver mineralization occurred, the compressive forces resulting from the settling that produced the third group of faults (page 40) were still in existence, and that the east-west Tonopah fault and its subsidiary fractures were parallel to the direction of these forces and were therefore capable of being open to the passage of mineralizing solutions. Younger faults with a parallel strike might also receive ore solutions, but those whose strike was more nearly normal to the direction of the compressive forces would remain closed.

Although the younger faults are only locally ore-bearing, some of the larger ones also appear in several places to have played an important part in guiding the passage of the ore solutions. Thus the Merton fault, in addition to itself being ore-bearing, seems probably to have been the source of the ore in the Bermuda and parallel veins of the Tonopah Extension mine. The intersections of the Monarch-Pittsburg fault with the Tonopah fault coincide with large ore bodies, such as the Denver and Murray ore shoots in the Tonopah Extension mine and the large ore body on the Ohio vein in the West End mine. The hanging-wall regions of the Mizpah fault and the Belmont fault are both marked by an unusual concentration of ore shoots, which decrease in value and become unworkable away from the faults. The influence of these faults in localizing ore shoots is believed to have consisted in part in furnishing a channel for the ore solutions to follow, eventually depositing their contained silver, as with the Merton fault and portions of the Mizpah fault; and in part in deflecting or intercepting the solutions from the main channelways and guiding them into new channels without, however, being themselves mineralized. The Belmont, Monarch-Pittsburg, and portions of the Mizpah fault appear to be examples of the latter class. The Halifax fault zone also appears to have been especially effective as a barrier in preventing the passage of ore solutions eastward, to judge from the relative scarcity of known ore bodies in its hanging wall.

The Tonopah fault and its branches and the younger faults, however, are ore-bearing only in relatively small parts of their known extent. The productive portions of these faults and fractures are included within the zone whose boundaries are indicated by the contours shown in plate 3. The block of ground thus outlined is a relatively symmetrical domed shell, whose surfaces cut across the mineralized faults and the contacts between the several formations.

Deviations from the regular trends of the contours occur in several places. The most striking of these is the pronounced terrace extending westward from the West End mine to the West End Extension at an altitude of about 5,200 feet, causing a notable thinning of the productive zone. This feature appears to be due wholly to post-ore erosion, as the younger Fraction breccia is found at this altitude throughout much of this region. A different type of deviation from the smooth curves results from the intersection of the productive zone with the large faults of the third group. Thus the northeasterly bulge in the contours on the top of the zone in the Belmont mine coincides with the presence of the Belmont fault, and the northwesterly trend of the contours near the boundary between the Belmont and the Tonopah Mining Co.'s ground reflects the presence of the Mizpah fault. The westward-dipping Buried fault west of the Mizpah and Silver Top shafts apparently caused the terrace in this region; and it is possible that the Monarch-Pittsburg fault has caused the crowding of the contours observed in the vicinity of the Cash Boy shaft in the Tonopah Extension mine.

The lack of relationship between the surfaces of the productive zone and either the known extent of the major fractures or the formation contacts seems to show that some factor other than these two features must have played an important part in the localization of the ore shoots. As suggested above, this factor, which has controlled the depth of ore deposition, may

have been the temperature limits within which the silver minerals were deposited in commercial quantities, and the upper and lower surfaces of the productive zone are thought to represent roughly the isothermal lines for the two limiting temperatures.

Two features of the geology appear to offer support to this belief. One of these is the spatial distribution of the quartz-sericite-adularia and chlorite-carbonate types of alteration, and the other is the variation in the silver-gold ratio from place to place.

The quartz-sericite-adularia alteration was most intense in a relatively small area in the ground of the Tonopah Mining Co., coinciding almost exactly with the highest contours on the upper surface of the productive zone. Beyond this central area, the chlorite-carbonate alteration was the dominant type.

Similarly the ratio of silver to gold varies with respect to this central zone. Plate 3 shows this ratio for all the mines that have produced more than 100,000 ounces of silver. These show a range from about 85 parts of silver by weight to 1 part gold in the central area to more than 100 parts both to the east and the west, reaching a maximum of 111.5 parts in the ore from the Esmeralda County portion of the Tonopah Extension mine. The correspondence between the ratios and the contours would be even closer if corrections were applied to two of the ratios shown in plate 3. That for the Tonopah Mining Co. (90.1) is unquestionably too high to represent the hypogene ore, for it includes the oxidized ore mined at the surface. This ore has been relatively enriched in silver, as is shown by the ratio of 151.2 obtained from lessees' ore, containing over 2,000,000 ounces of silver, mined in the early days. The ratio of 78.1 for the North Star mine, on the other hand, appears to be considerably too low. Lessees have mined nearly half of the ore produced by this mine and apparently have selectively extracted ore rich in gold; for the two years 1913–14, during which more than half of the total silver output was mined through operations on a moderately large scale, the ore had a silver-gold ratio of 93.3, which fits very nicely between the Montana ratio of 92.5 and the Belmont ratio of 95.3.

In addition to the influence of the Tonopah fault and other east-west branches and of the temperature factor in localizing the ore bodies, it would appear that local conditions were also effective. The most important of these is believed to have been the necessity of the fractures being open to the passage of ore solutions. There seems to be fair evidence that the silver mineralization was in large part independent of and later than the introduction of the bulk of the quartz in the veins, and that the quartz mineralization in places effectively sealed the fractures against the passage of the silver-rich solutions. Thus, parts of the Tonopah fault within the productive zone contain large masses of quartz whose silver content is too low to be minable, and in other places, particularly in the hanging-wall branches of the Tonopah fault, there are veins containing ore of rather high grade in which quartz is relatively scarce. Renewed movement along the fractures following an earlier quartz mineralization is thought to have been essential for the formation of an ore body.

In the earlier report [52] the character of the wall rock was emphasized as an important factor in localizing the ore, the more brittle rocks being considered especially favorable for ore deposition. It was recognized, however, that an individual formation, such as the Mizpah trachyte, might be either favorable or unfavorable, depending upon the type of alteration it had undergone. This feature is thus in part a reflection of the temperature factor, as there is a rough correspondence between the distribution of types of alteration and the outlines of the productive zone. It would appear, however, from the work in the eastern half of the district that the type of alteration, and consequently the physical character of the rock, has had less influence in determining the location of ore shoots than the factors that have already been discussed.

The formation of the ore bodies may be briefly summarized as follows: After the uplift and settling that resulted in the several groups of faults described on pages 28–40, hot mineralizing solutions that had their source beneath the central part of the district, presumably coming from a body of cooling igneous rock, caused the widespread albitization observed throughout the district and, in so doing, established a thermal gradient in which the isotherms were convex upward, reaching their highest points in the same central area. At a later stage other types of alteration occurred, characterized by quartz, adularia, and sericite especially in the central area, and by chlorite and carbonate in the outer regions, and these were possibly accompanied by a widespread introduction of quartz. Quartz deposition, however, was largely confined to faults and fractures, especially those with an east-west trend. The silver-rich mineralization followed and appears to have been still more limited, some of the fractures that had earlier been filled with quartz apparently having been sealed to the later ore solutions. The silver mineralization, even more than the quartz introduction, appears to have been controlled by the major fractures, utilizing those with east-west trend as channels of entry and being dammed or deflected by those with a north-south strike. Furthermore, deposition of the silver was limited to a relatively narrow zone that is thought to correspond with isothermal surfaces affected by an igneous mass below. Only the veins in the highest central part of this zone were exposed to erosion, and these appear to have been relatively enriched in silver.

[52] Nolan, T. B., op. cit., pp. 33-34.

SUGGESTIONS FOR PROSPECTING

The recent increase in the price of silver has considerably revived mining activity in the Tonopah district, which has been expressed so far in an increase in the number of lessees working in several of the mines. A prolonged maintenance of the existing price, if mining costs do not show a parallel rise, or further increases in the price, may be expected to result in renewed prospecting operations by the mining companies themselves. It is hoped that the following notes may be useful both for the lessee type of operation, in which dead work must be kept at a minimum, and for the more elaborate prospecting campaigns that require company operations.

It is probably true that past exploration through both mine workings and drill holes has been sufficiently extensive over much of the district, especially the central part, to indicate that no large new veins will be found. Possibly, however, segments of known veins will be found to contain profitable ore shoots. Several such segments appear to have been unexplored and might be prospected at relatively small expense. One such segment is believed to occur on the 600-foot level from the Extension No. 1 shaft, where the Red Plume or Extension North vein has been unexplored on the hanging-wall or east side of the Rainbow fault, the drift having been driven on a hanging-wall branch of the vein. Similarly on the 400-foot level from the Mizpah shaft there appears to be a lack of correspondence between branches of the Mizpah vein on the two sides of an eastward-dipping fault 200 feet east of the shaft, suggesting that there may be unexplored segments of veins in this region. It is thought that close study of the mine maps will bring out similar possibilities. It is, of course, possible that such segments of veins, if found, may be barren, but the relatively low cost of exploration of this type would seem to make it a worthwhile gamble for lessees. Such exploration naturally should be confined to the productive zone and might well be limited to the vicinity of the major fractures that have obviously guided the ore solutions.

The success of the Tonopah Mining Co. in economically extracting the silver and gold from the low-grade material that was drawn from the caved area along the Mizpah vein above the 200-foot level would seem to justify a thorough sampling of the walls of other parts of this vein, in order to determine if a large body of low-grade ore could be developed that would be amenable to cheap large-scale mining and local milling. Although other veins in the mines of the West End, Belmont, and Tonopah Mining Co. properties have wall rocks that contain numerous small silver-bearing veinlets, the region adjacent to the Mizpah vein appears to offer the best chances of success in the mining and milling of very low grade ore.

Prospecting designed to discover hitherto unknown veins or ore shoots will probably require considerably greater expenditures of time and money. The writer believes that such ore bodies can be found only in those parts of the productive zone that have been either unexplored or but little explored. For all practical purposes this means working at greater depths in the eastern or western parts of the district, with consequent high costs due to the necessity of pumping quantities of hot water. Such prospecting also faces the probability that mineralization was less intense in these outlying regions—in other words, that less silver was deposited per unit volume of ground than in the central region. Exploration within the zone north or south of the developed area appears to be much less likely to be successful, because there appear to be relatively few favorable fractures in these regions in which ore might have been deposited.

The eastern extension of the productive zone is probably less favorable for prospecting than the western, because the Halifax fault zone dips at a steeper angle than the productive zone, and the work in the Halifax and other eastern mines leads to the conclusion that it was only locally possible for the ore solutions to penetrate this zone. The western extension of the productive zone offers more favorable possibilities. Thus the south limb of the Tonopah fault in the footwall of the Monarch-Pittsburg fault has never been found, owing to the presence of the post-ore Fraction breccia in this region. The north limb of the fault carries the major ore bodies in the western workings of the Tonopah Extension mine, and the region in which this fault falls within the extension of the productive zone would seem worthy of careful prospecting, should the price of silver be maintained at a figure that would warrant the probably high costs of exploration and mining. The country immediately in the hanging wall of the Merton and similar large northwesterly faults within the productive zone would also warrant exploration under these circumstances, as veins similar to the Bermuda vein might be expected to occur there. In connection with exploration in the western part of the district, it is possible that the unsatisfactory results on the 1,880-foot level of the Tonopah Extension mine were due to the fact that the Denver and Merton veins, where they were cut, are probably very close to the lower limit of the productive zone; the trend of the contours on plate 3 suggests that at this altitude ore shoots might be found farther west along the two veins.

A much more speculative possibility is the exploration of the region for a few miles north of Tonopah. The origin of the faults and the ore bodies as outlined in the preceding pages is thought to be connected with a localized uplift in the footwall of the Halifax fault zone. It seems logical to assume that in other places along the Halifax zone there may have been similar local uplifts, which may also have been mineralized. Unfortunately the region to the north, which for several reasons is believed to be the more favorable, is largely covered by younger rocks, so that direct surface examination for signs of local uplift or mineralization is not possible, and the large area involved would make the cost of adequate subsurface exploration, either by drilling or by shaft sinking, much too great. It is possible that detailed instrumental mapping of the few scattered outcrops of the pre-Esmeralda formations might give some suggestions as to favorable regions, which in turn could be explored by drilling.

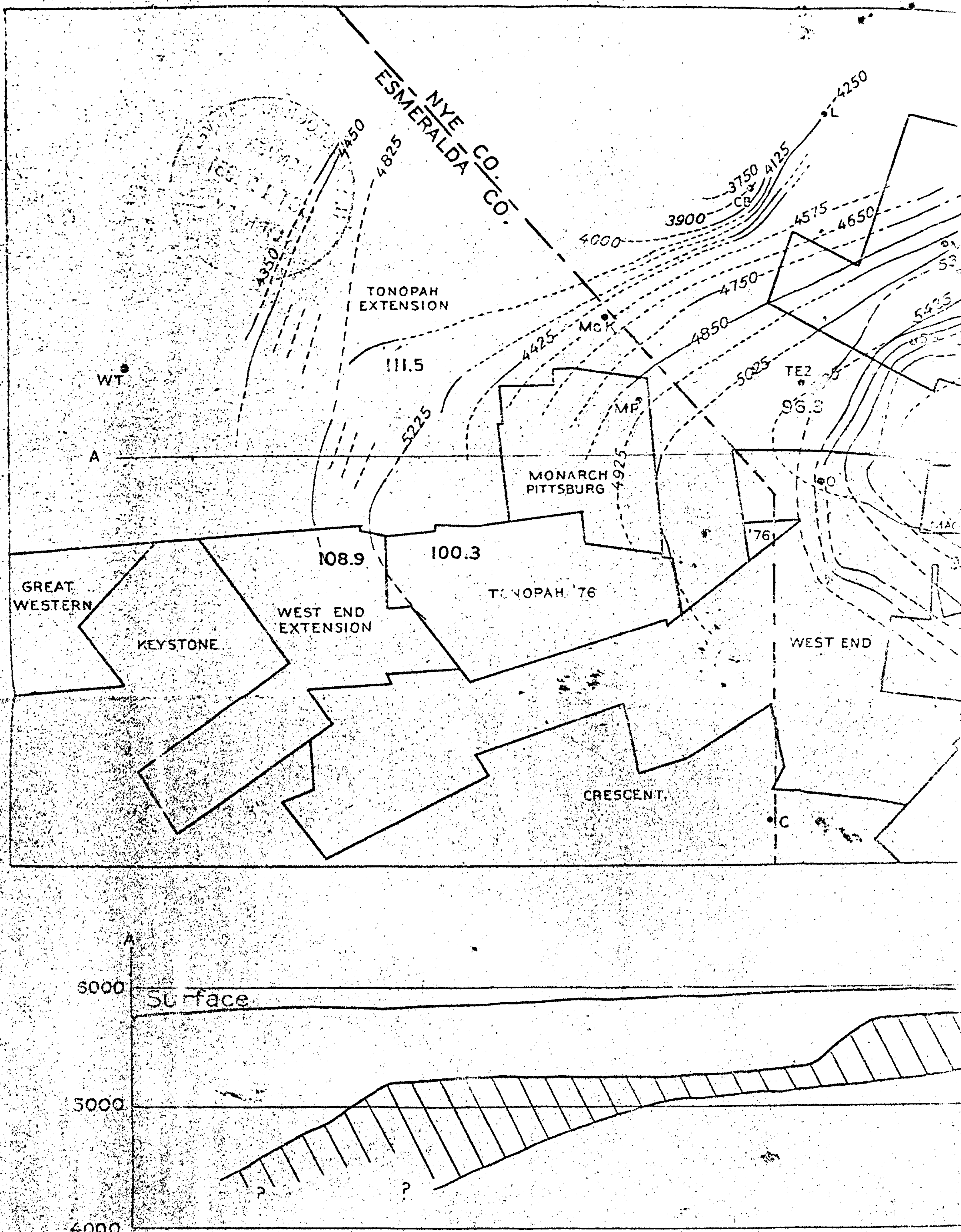
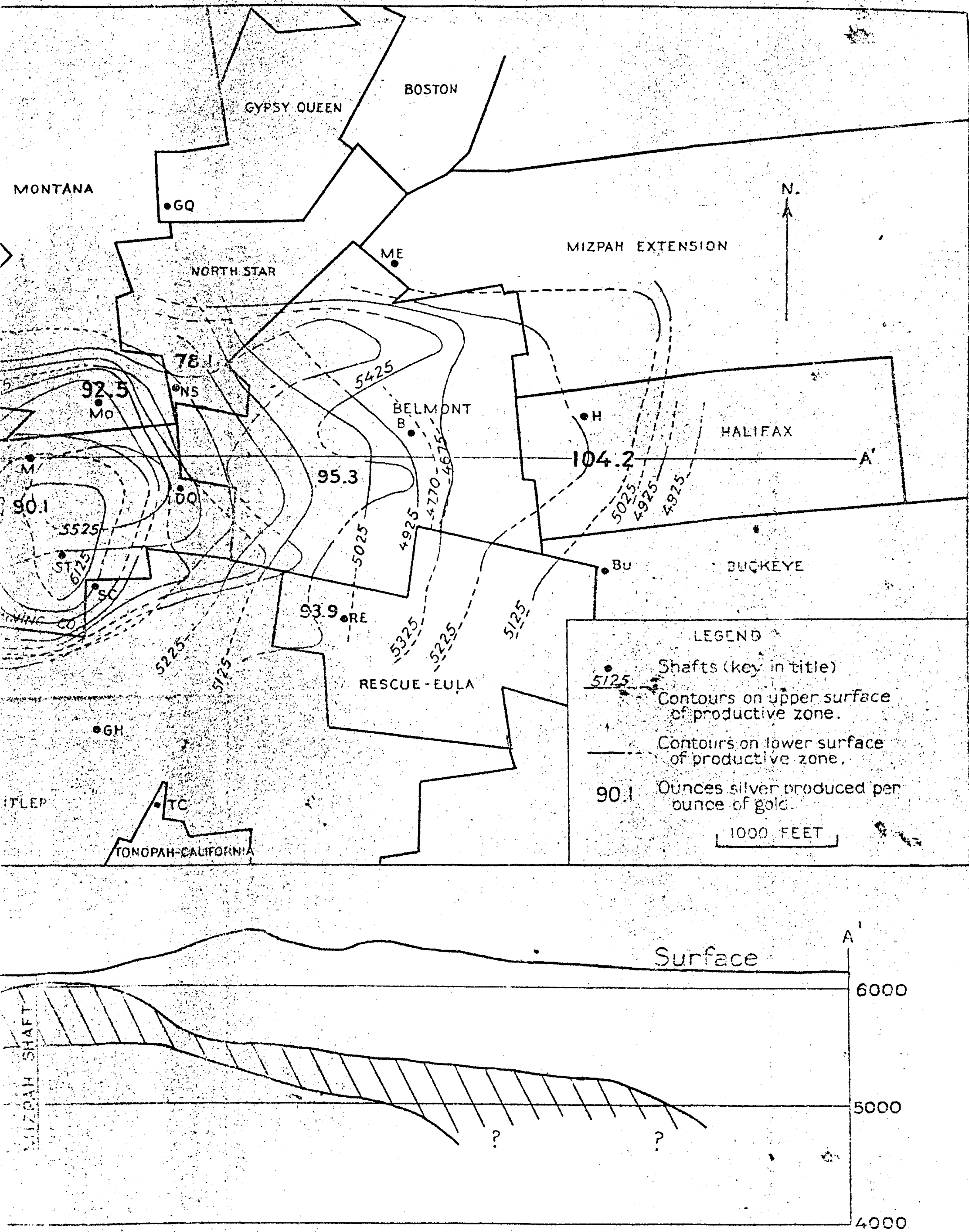
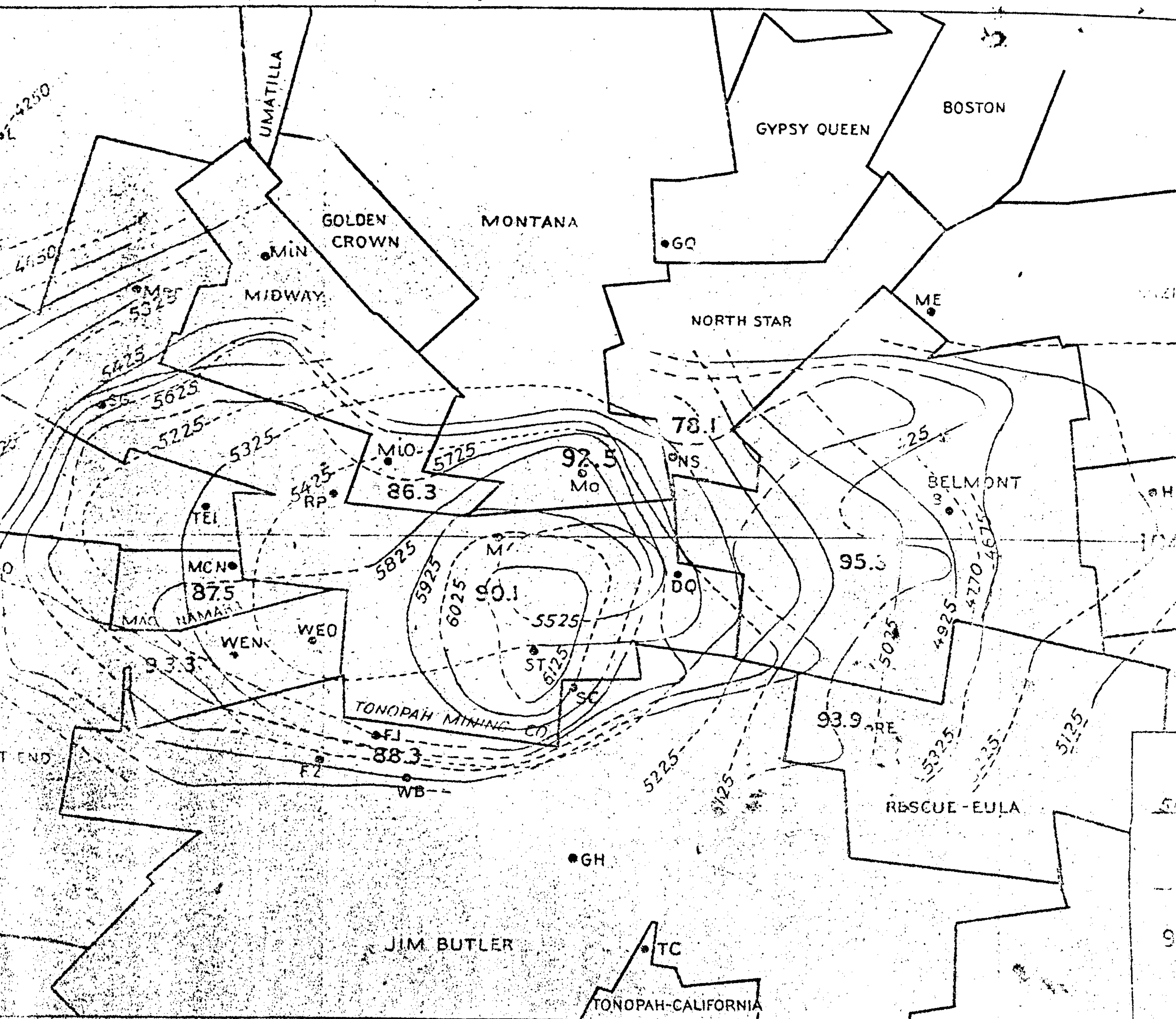


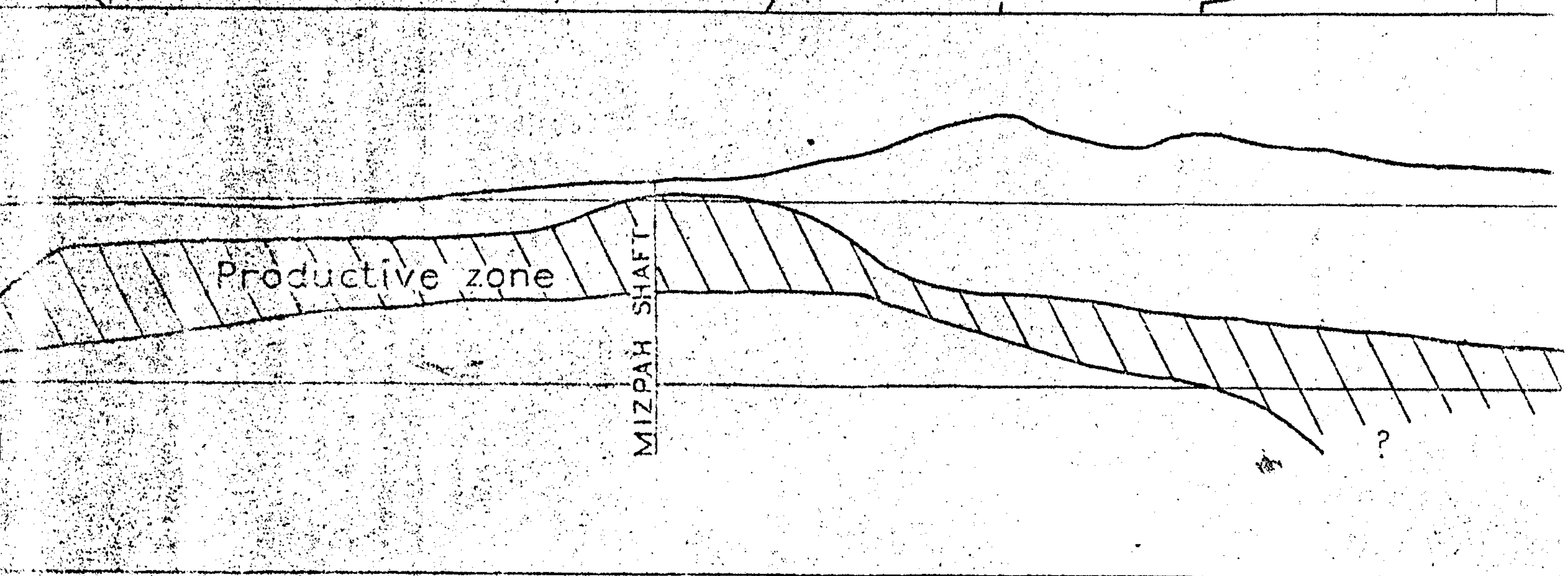
PLATE 3. SKETCH CONTOUR MAP AND SECTION OF PRODUCTIVE ZONE AT TONOPAH. Key to shafts: B, Bel...; McK, ...; McN, MacNamara; ME, Mizpah Extension; Mer, Merger; MIN, New Midway; MIO, Old Midway; ... TE1, Tonopah Extension No. 1; TE2, Tonopah Extension No. 2; L, Victor; WB, Wandering Boy; WEN, New West End; ...



A - A'

Key: DQ, Desert Queen; F1, Fraction No. 1; F2, Fraction No. 2; GH, Gold Hill; GQ, Gypsy Queen; H, Hal[illegible]; M, Mizpah; [illegible]orth Star; O, Ohio; RE, Rescue-Eula; RP, Red Plume; SC, Stone Cabin; SG, Sand Grass; ST, Silver Top; TC, Tonopah-California;





Section along A-A'

... Buckeye; C, Crescent; CB, Cash Boy; DQ, Desert Queen; F1, Fraction No. 1: F2. Fraction No. 2; GH, Gold Hill; GQ, ... North Star; O, Ohio; RE, Rescue-Eula; RP, Red Plume; SC, Stone Cabin; SG, Sand Grass; ... WT, West Tonopah.