RELATIONSHIPS AMONG THE GEOLOGY, ROCK TEMPERATURE AND ORE MINERALOGY AT THE MAGMA MINE, SUPERIOR, ARIZONA

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ABSTRACT

A study of the rock temperatures in the mine in relation to the vein and replacement ore bodies was made and is the basis of this paper. The work was mostly carried out within the replacement area due to the inaccessibility of the other parts of the mine and revealed a geothermal gradient of 2.0-2.5^{o}F per 100 feet of vertical distance, which, when extrapolated is reduced to 1.8-2.0^{o}F per 100 feet (see Figure 3). This gradient is not unusually high since it only slightly exceeds the 1.5^{o}F per 100 feet world average gradient.

The area studied is roughly 2000 feet by 2400 feet located north of No. 6 shaft where the Magma vein cuts and offsets the replaced horizon. On the surface, this area is capped by a 1200-foot thick welded dacitic ash-flow sheet of Miocene age which probably provided enough insulation to have elevated the temperature of the underlying rocks. Plate I shows relation of the underground replacement zone with respect to the dacite capping.

A similar study of rock temperatures by an unknown author in 1937 when the mine workings were still in the main Magma vein under sedimentary rocks west of the dacitic capping showed a geothermal gradient of only 1.5^{o}F per 100 feet.

No lateral temperature differences were found and if any relationships exist between the temperature, ore deposits and geology in the mine, they were not detected.

The ore deposit at the Magma mine in Superior, Arizona, has been compared by many writers to that of Butte, Montana, in mineralogy, paragenesis, zoning, and ore genesis. Magma, however, is a much smaller deposit, and the generalizations of mineral zoning and paragenesis at Butte as studied by Sales and Meyer,(1949), are not applicable in their entirety to the much more complex mineralogical problem at Magma.

The Magma mine has two distinct types of ore depoit: vein and limestone replacement. The geology of the area consists of Paleozoic and Tertiary rocks overlying Precambrian rocks, the whole cut by intrusive bodies of varying ages.

The results of a limited study regarding the mineralogy and paragenesis of the mineral assemblages served only to confirm the ideas of several previous workers. A rough mineral zoning found in the Magma vein has no definite correlation with the replacement bed. The replaced horizon, within itself shows no zoning anomaly whatsoever, neither vertically nor horizontally.

Examination of the ore minerals for possible polymorphs was made by x-ray analysis and some polished sections; the results were negative. The usual aggregate of sulfide minerals are however, easily identified, hence, the author is reasonably sure that no polymorphs, such as cubanite and wurtzite, exist among the ore minerals at the Magma mine.

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TABLE OF CONTENTS

TEXT

ILLUSTRATIONS

ILLUSTRATIONS

Figures

INTRODUCTION

The Magma mine is located just north of the town of Superior, in Pinal County, Arizona, about 65 miles east of Phoenix along U.S. Highway 60-70 (see index map). It is near the western edge of the Pinal Mountains which trend north by northwest and are comprised of tilted Paleozoic sedimentary rocks capped by a thick sequence of welded dacitic ash-flows of Tertiary age. The town of Superior is at an elevation of 2,800 feet and the steep dacite-capped escarpment immediately east of it rises abruptly to an elevation of 4,800 feet.

INDEX MAP

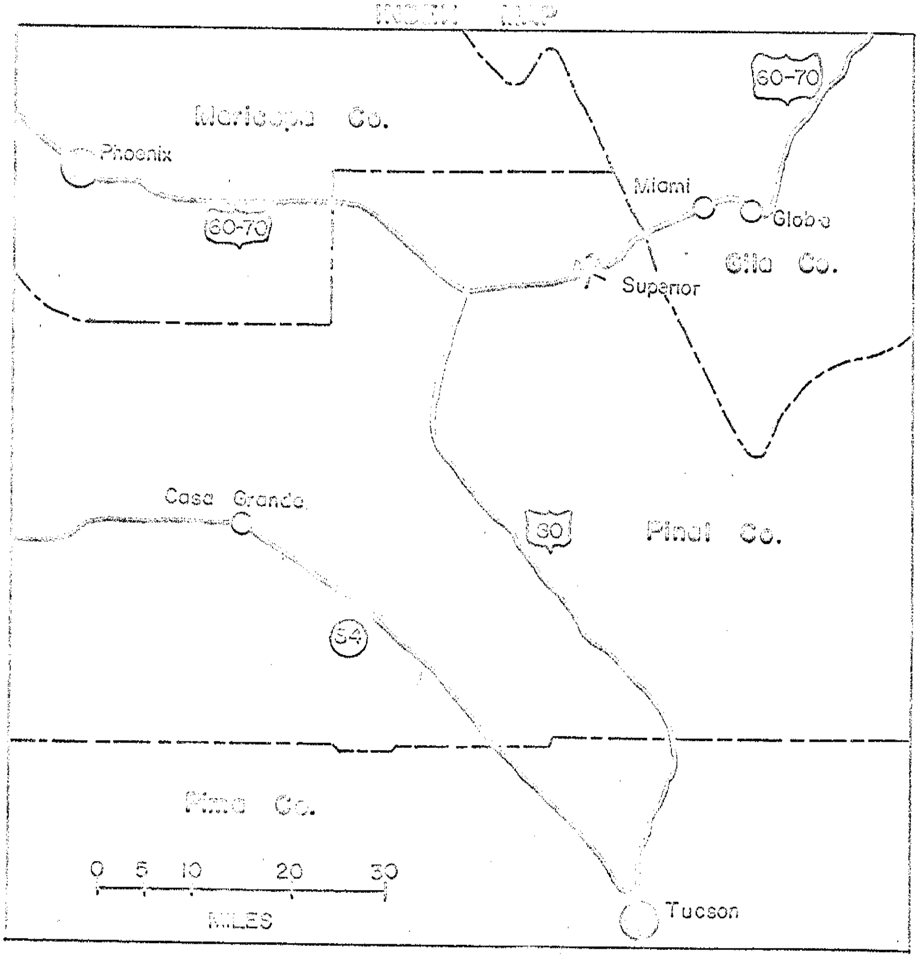


Figure 1 summarizes the geology of the area in an idealized general geologic column. All units have a uniform dip of 30-35 degrees to the east.

Of the several fault systems that cut the rock formations of the area, only the east-west system is mineralized. The Magma vein is an east-west trending mineralized fault zone that extends from the Precambrian in the west to the replaced horizon within the Devonian limestone in the easternmost part of the mine. The ore mineralogy of the vein and of the replaced bed does not differ to any great extent. Both deposits are probably products of the same ore solution. The apparent paragenesis and mineral zoning are also similar in both types of ore.

The Magma mine is the deepest mine in the state of Arizona and has enjoyed the dubious reputation of being a "hot" mine for many years. Many workers during the previous years have fairly thoroughly examined the geological and mineralogical aspects of Magma, but none dealt with the seemingly existing temperature anomaly. It is for this reason that this work was undertaken by the author.

The earth's thermal gradient varies from place to place around the world. There have been many theories proposed to explain these thermal anomalies(Van Orstrand,1939., Spicer, 1942., Birch,1954). In the case of the Magma mine, it is probably a combination of the presence of a magmatic body and low thermal conductivity of the dacite sheet.

The method of direct temperature measurement was used by the author. Two maximum-reading thermometers calibrated to the nearest degree and encased in metal holders provided the instruments desired. Each thermometer was clipped into a depression at one end of a 6-foot long, 1-inch diameter wooden pole. The other end of each pole was attached to a tapered wooden plug. So rigged, the pole was inserted into a diamond drill hole and plugging it for at least a day before a reading was made. In places where drill holes were absent, a thermometer was simply buried as deep as possible in a muckpile or in a crack in the wall rock.

Samples were taken at regular intervals in the vein and in the replaced bed for x-ray work in the identification of minerals.

Plates IV, V and VI show the locations of the temperature measurements and samples sites with local geology. Plate VII is a composite map of the area showing the relative position of the replacement horizon to the entire mine working area. The area north of No. 6 shaft where most of the work was done remained unexplored and unknown until a few years ago. This paper is the first to be written about that particular part of the mine.

Previous Work

The most recent paper published about the Magma mine mine was that of Hammer and Webster, (1962), which had only a brief description of the geology of the area. The paper by

Short, et al,(1943), is the most comprehensive of all the papers on the Magma mine. It includes reviews of the earlier works of Ransome,(1913), and Short and Ettlinger,(1926), and contains a good description of the regional setting and general mine geology of Magma. It has become a classic reference for geologists who work in the area. Other papers were published by Wilson,(1950), and Steele,(1952). Two recent papers, both unpublished works, describe in great detail the geology and mineralogy of the replacement ore body south of No. 6 shaft. These are by Sell,(1961), and by Gustafson,(1961). The author has relied almost entirely within the framework of accumulated knowledge contributed by the above mentioned men in the geology, paragenesis and mineral zoning aspects of this paper.

In the field of thermal gradient studies, a fairly new and largely unknown science, the author found no lack of papers published on the subject. Most notable among these are by Van Orstrand,(1939), Birch and Clark,(1940), Birch,(1954), and Spicer,(1942).

History

Discovered in 1875, the Magma deposit was originally worked for silver. By the time of the formation of the Magma Copper Company in 1910, enough was known of the deposit to justify the sinking of a shaft. A total of 8 shafts have been sunk since then(Plate III), the last one in 1936. The mine produced copper ore until 1950 from the Magma vein, a steeply-dipping east-west fault zone, and from the much smaller Koerner vein, a subparallel fault about 1100 feet south of the Magma vein.

Exploration extended the life of the mine by the discovery of the east replacement ore body in 1950. At present, the bulk of the ore being mined comes from this replacement horizon. Only two stopes remain active in the Magma vein zone to the west at levels 4600 and 4800. Daily production is being maintained at 1100 tons of ore per day averaging 5% copper, 1.5 oz. silver and 0.03 oz. gold. The replacement area is not as rich in copper as the vein ore body, where in some stopes the extraction of almost pure bornite made Magma famous many years ago.

ROCK UNITS

The rock units found in the Superior area are summarized in a geologic column and time scale in Figure 1. Except for the Quaternary and Recent sediments, all metamorphic-sedimentary units have a general and uniform dip of 30-35 degrees to the east. The rocks exposed in the area consist of Precambrian Pinal schist unconformably overlain by the easterly dipping Apache group of younger Precambrian sediments, Cambrian quartzite and Paleozoic limestones. A thick Tertiary dacite ash-flow overlies all the others. The schist and pre-Devonian sediments are cut by diabase sill and the entire rock column has been intruded by quartz monzonite porphyry dikes with the exception of the dacite. The youngest igneous rocks are Quaternary basaltic dikes.

Stratigraphy

Pinal Schist (Early Precambrian)---The Pinal schist is a metamorphosed sedimentary and volcanic rock sequence. It is the oldest known formation in the area and has been penetrated by mine workings and exploration drill holes to a thickness of 1300 feet with no sign of underlying layers. Of early Precambrian age, it is light grey, fine-grained and sericitic with finely developed schistosity.

Apache Group (Late Precambrian)--- The Scanlan conglomerate is the basal member of the late Precambrian Apache group rocks. Exposures are poor in the area and the unit has not been recognized in the mine workings, but where it crops out it is about 15 feet thick.

The Pioneer shale overlies the Scanlan conglomerate and has a known maximum thickness of 230 feet in the mine workings. It consists of moderately hard, dark, purplish-brown arkosic shale which grades into hard arkosic quartzite in a few places.

Overlying the Pioneer shale is the Barnes conglomerate, which is about 15 feet thick and is composed principally of vitreous quartzite pebbles in a coarse, sandy arkosic matrix. This distinctive bed is a good horizon marker in the workings along the Magma vein.

A disconformity divides the Barnes conglomerate from the overlying Dripping Spring quartzite. The quartzite has a measured thickness of 820 feet. It is buff to yellowish-brown in color and is strongly banded. Towards the top, it changes into a series of shaly beds alternating with normal quartzite.

The uppermost member of the Apache group formation is the Mescal limestone. It is a thin-bedded buff to grey limestone with many chert bands parallelling the bedding and is about 350 feet thick.

Troy Quartzite (Late Precambrian)---Directly above the Apache group is the 730-foot thick Troy quartzite. Recent work by Shride,(1958), and Krieger,(1961), has demonstrated it to be of late Precambrian age, although it was formerly thought to be as young as Cambrian. It is composed of very characteristic cross-bedded quartzite.

An upper unit of quartzite in contact with the overlying Martin limestone is tentatively dated as Cambrian; it is separated from the late Precambrian Troy quartzite below by a thick intrusive mass of diabase and is the only rock unit in the mine that has an uncertain time relationship. Sell, (1961), and Steele,(1958), believe that it is Troy quartzite cut off from the lower members by the diabase intrusive. On the other hand, Hammer and Webster,(1962), regard it as an entirely different unit and assign it to the Cambrian, although their reasons are not very convincing. Both quartzite units are intruded by the diabase and could easily be of the same age.

Diabase (Late Precambrian)---Diabase sills have intruded the Pinal schist, Apache group and Troy quartzite with a recorded thickness of 3000 feet within the Magma vein workings. They are typically dark green to black in color, medium-grained and contain abundant magnetite. They do not intrude the overlying Devonian limestone and has been given a late Precambrian age.

Paleozoic Rocks---Immediately above the Troy quarzite (Figure 1), is the Martin limestone, 350-400 feet thick, of

Devonian age.

The lower part of the Martin contains the replacement ore body of the Magma mine. The replaced bed ranges from 6 to 30 feet in thickness and averages 15 feet. Where nonmineralized, it is light to medium grey with a fine crystalline structure and indistinct bedding which is usually marked by very thin layers of black shale.

The basal unit which makes up the footwall of the replaced horizon is 2 to 12 feet thick and is a very light grey dolomitic limestone or limestone containing small lenses and thin beds of sand and quartzite.

That part of the Martin overlying the replacement bed is known as the hanging wall beds. In normal mining operations, this unit is seldom exposed, but where observed, it is thicker bedded than the footwall limestone and has no sand grains or quartzite lenses.

The Escabrosa limestone overlies the Martin. It is of lower Mississippian age and averages about 500 feet in thickness. Immediately above the Escabrosa is the lower Pennsylvanian Naco limestone which is exposed on the surface to a thickness of 1400 feet. Both these limestone units do not affect mining and geological aspects at the Magma mine since they are not mineralized and are found far above the replacement ore body.

Tertiary Rocks---The 350-foot thick Whitetail conglomerate is the oldest Tertiary rock unit in the area. It consists of silt and coarse debris accumulated in mid-Tertiary time on the pre-dacitic erosion surface.

Numerous quartz monzonite dikes are located within the mine workings, the most prominent of which is in the replacement area (Plate IV), where a 30-foot thick porphyry dike cuts the replaced horizon in an east-west direction.

A porphyry unit of undetermined thickness is usually encountered above the replaced bed in diamond drilling operations (Plate V). It is a sill-like body consistently following the configuration of the beds and may or may not be related to the quartz monzonite dikes. It is of very light grey color and has abundant soft sericitized "phenocrysts." Identifiable quartz grains appear to be lacking in this unit. Intense alteration makes correlation impossible.

In an unpublished PhD dissertation, D.W. Peterson, (1960), has described the lithology and probable origin of the thick dacitic ash-flow sheet near the towns of Superior, Miami and Globe (see index map and Plate I). It is actually a quartz latite in composition, but to avoid confusion, all workers have stuck to the use of the original given name of dacite. Creasey and Kistler,(1962), has assigned it an age of 20 million years, or mid-Miocene, by the K-Ar ratio method. It is 1200 feet thick and could have been as much as 2000 feet thick before erosion. Peterson estimates that it could have covered originally an area of between 400 to 1500 square miles. The present erosional remnants are exposed over an area of only 100 square miles.

The dacite sheet is made up of at least 5 separate ash-flows; a single ash-flow resulting from the eruption of one nuée ardente (Smith, 1960). According to Smith, a nuée ardente has two parts: a basal avalanche that contains the bulk of the eruptive material, and an over-riding cloud of dust and expanding gas. The five stratigraphic zones have been recognized according to groundmass differences and all the zones are of the same normal quartz latitic composition, with predominant plagioclase feldspar phenocrysts and some visible quartz phenocrysts. It is partly welded and partly unwelded.

Lithologically, the flattening of the pumice fragments which shows an increase downwards, suggests that the dacite deposit formed as a single cooling unit. This suggestion is strengthened by the fact that the porosity increases upward but the specific gravity reaches a maximum in the upper vitrophyre zone and remains constant from that point to the top of the section, since, if any part of the sheet had cooled appreciably before a following eruption was deposited, its upper part would have shown a decline in specific gravity followed by an abrupt increase.

Since the dacite is mid-Miocene in age, topographic evidence of the source has been eroded. Peterson, (1960), has mapped a nearly circular fracture 3-3½ miles in diameter in the southwest corner of the Haunted Canyon quadrangle adjacent to and north of the Superior quadrangle (Plate I), and suggested that this may be the remnants of a collapse caldera that could represent the source of the extensive dacitic ash-flow sheet.

The youngest igneous rocks in the area occur as small basalt dikes that cut the dacite sheet and are assigned to the late Tertiary.

Tertiary-Quaternary Gila conglomerate and Recent alluvium blanket the area west of the steep dacite escarpment near Superior. The town stands on an unknown thickness of these sedimemtary units.

STRUCTURES

There are three major fault systems in the Magma mine area: the east-west, north-south and northwest-northeast conjugate system.

East-West System

An east-west set of steeply dipping faults is pre-ore with post-ore movement. The Magma vein fault is the largest and most important of these. It dips 70-80° north down to the 800 level (as measured from the No. 1 shaft collar). From the 800 level down it is vertical and below the 1200 level it dips south 70-75° and maintains this dip as deep as the lowest level of the mine (4900). The wall rocks have been displaced 300 feet downward and 375 feet westward on the south or hanging wall side of the fault. Movement occurred along a zone of closely spaced fractures. Vein mineralization was by replacement of the crushed zone between the walls. The vein is easily traceable and has definite walls in diabase but changes into an indeterminately wide shear zone in schist. It has also offset the replacement bed 300 feet down and 375 feet west on the south side (Plates II and VII).

The South Branch vein, which is a split of the Magma vein south of No. 6 shaft (Plate II), has a displacement of 30-40 feet with the south side downthrown. Displacement along the east-west strike is not known, although it is assumed to be in the same direction as the right-lateral Magma vein. Its dip is generally about 80° south.

North-South System

A set of north-south faults cuts the ore bodies, both vein and replacement. Three are very prominent: the Main fault, the Concentrator fault, and the NS-5W fault. All three are right-lateral faults.

The Main fault has displaced the west end of the Magma vein 800 feet to the south and 600-700 feet downward as shown on Plate III. It dips about 57° west down to the 2000-foot level whereupon it flattens to an angle of 45°. It is of interest to note that (see Plate III) the stoped ore outline in the main ore body of the vein is roughly parallel to the westerly dipping Main fault along the fottwall, suggesting some kind of control of mineralization by the Main fault. Thus the Main fault may have had little pre-ore movement with its major displacement occurring after the ore deposition had ceased.

The Concentrator fault cutting the Magma vein is located about 1700 feet west of the Main fault (Plate III). The total amount of displacement along the Concentrator fault is not known, but it has brought the dacite into contact with the Pioneer shale, which is a vertical component of greater than 2000 feet with the west side downthrown. Nothing is known of any movement along the strike. The dip is a uniform 60°. The Magma vein cut off by the Concentrator fault has not been located on the downthrown or west side of the fault.

Plate I shows that that part of the Concentrator fault west of the mine area has a general strike of N30°W and that it converges with the Main fault at a point northeast of Superior. Beyond its junction with the Main fault, it continues south for miles on a fairly straight north-south line parallel to the dacite escarpment. Because of the indication that the Main fault had pre-ore origin, it is probably earlier than the Concentrator fault. Much of the movement in the Main fault probably occurred at the time the west side of the Concentrator fault was down-dropped.

The third major north-south trending fault is the NS-5W fault, so called because it strikes 5° west of the north-south direction. The fault is of great significance in the replacement area of the mine since it offsets the replaced horizon south of No. 6 shaft. It has 330 feet of horizontal offset and 90 feet of vertical separation. The left-lateral movement has moved the east side up and to the north relative to the western block. Its dip varies from 88° to vertical. The NS-5W fault is post-ore and offsets both the vein and the replacement ore bodies. It has been traced laterally in the mine workings for over 2000 feet. Within the diabase the fault tends to flatten, whereas in quartzite it steepens. In limestone, the fault surface is irregular.

The trace of the NS-5W fault on the surface of the dacite has not been found, which suggests that, unlike the Main and the Concentrator faults, the NS-5W fault was formed before the dacite deposition. However, the NS-5W fault has a small vertical separation when compared to the other north-south faults. It is possible that such a small movement would not be expressed by a surface trace. Thus, the NS-5W fault, as with the Main and Concentrator faults, all of which have the same left-lateral movement, possibly formed at the same time after the emplacement of the dacite sheet.

Northwest-Northeast Conjugate System

A conjugate system of transverse faults strikes N60°W and N45°E and dips steeply westward. The system is post-ore and is of no significance except to complicate and make mining dangerous due to broken ground.

SUMMARY OF MESOZOIC AND TERTIARY EVENTS

During Mesozoic or early Tertiary time, the Superior area was subjected to volcanism accompanied by the tilting eastward of the earlier sedimentary units. This tectonic action was probably contemporaneous with the economic mineralization of the area. The author believes the pre-ore Magma fault and its South Branch split acted as the channelways of the ore solutions that came up from some magmatic source. The replacement of the Martin limestone came first, was interrupted by movement along the Magma fault and followed by the formation of the vein deposit. After the cessation of mineralization and during mid-Miocene time, tremendous quantities of dacitic ash were erupted, covering hundreds of square miles of the surrounding region to depths of perhaps as much as 2000 feet. Following the deposition of the dacite, the north-south oriented faults were formed, offsetting both the Magma vein and the replacement deposits, and the crustal block west of the Concentrator fault subsided, forming the Superior basin. Subsequent erosion and deposition of sediments produced the present general topography of the region.

MINERAL DEPOSITS

Magma Vein

The Magma vein fault cuts all the pre-Tertiary rocks. It strikes a few degrees north of east and dips 70-80 degrees north from the collar of No. 1 shaft (zero level) downward for 800 feet where it becomes vertical. Below the 1200 level it dips south 70-75 degrees and maintains this attitude to the 4900 level. The south or hanging wall side of the Magma vein fault has moved about 300 feet downward and 375 feet westward, giving it a right-lateral movement. Plate III shows the geology of the north wall of the Magma vein and its relation to stoped ore. One only has to visualize another such section dropped 300 feet down and 375 feet to the west in order to show the relative down-dropped position of the south wall of the vein.

The fault zone occupied by the Magma vein ranges from 20 to 75 feet in width but the vein material averages only about 12 to 15 feet wide within the fault zone. Vein material throughout the mine has been emplaced almost entirely by replacement of the crushed zone between the wall rocks. Within the vein, ore grade mineralization may occur adjacent to any of the pre-Tertiary rocks that make up both walls of the fault. Structure, rather than chemical characteristics of the wall rocks appears to have been the effective ore control.

The vein had its highest grade of copper ore production from the stopes which, in gross outline, plunge westward and parallel to the west-dipping footwall of the Main fault(Plate III). Collectively, these high-grade stopes were known as the main ore body and has been followed to the 4900 level.

Mineralization persists, but prohibitive mining costs from so deep an ore body prevent the Company from continuing operations in the area. At the end of 1964, only two stopes were being worked and kept open in the entire vein deposit.

The so-called Koerner vein occupies a subparallel fault about 1100 feet south of the Magma vein and is similar in all respects but size to the Magma vein. The deposit has been exhausted many years ago and is now completely inaccessible.

Eastward from the main ore body, the structure of the Magma vein becomes more complex with numerous vein splits and discontinuous ore shoots. Economic vein mineralization dies out as the NS-5W fault is approached. This area of irregular stopes is called the central ore body and it is from here that the South Branch vein, which is of great importance in the replacement area, is thought to have split away from the Magma vein, although, because of the numerous splits and relatively low-grade mineralization, its exact junction cannot be determined.

Replacement Bed

Along a horizon near the base of the Devonian Martin limestone below the 2000-foot level and to the south of the Magma vein itself, lies the South Branch vein and the bulk of the replacement ore body (Plates II and VII).

The replacement horizon occurs in the Martin limestone in a zone 2 to 12 feet above the disconformity overlying the Troy quartzite. In thickness, the replaced bed varies from

6 to 30 feet but averages about 15 feet. It has been traced updip beyond the 2000 level where copper ore fingers and pinches out and has been explored down to the 3600 level with no sign of ending (Plate VII). The enclosing sedimentary beds dip 30-35 degrees east rather uniformly.

The replacement horizon could be divided into two general areas, although both are connected. The arbitrary dividing line is an east-west line through No. 6 shaft (Plate II) with the South Branch vein area to the south of the line and the Magma vein area to the north. Until Gustafson,(1961), the only replacement ore body known was that adjacent to the South Branch vein. Recent exploration has revealed that the replaced horizon does connect the South Branch vein to the Magma vein, although the area between the veins is somewhat erratic in mineralization (Plate VII).

In quartzite below the replacement bed, both the South Branch vein and the Magma vein are weakly mineralized and the veins disappear entirely a short distance above the ore horizon. The intersections of these faults with the replaced bed are the loci of irregular but massive tabular bodies of copper ore which finger out along the bedding. There are numerous barren embayments of unreplaced limestone within the mineralized horizon. The limits of the replacement body are generally sharp assay walls or faults.

Relation of Vein to Wall Rock

Short, et al,(1943), recognized "a definite relation between the diabase and the shape of the main ore shoot." As evidence, he stated that, "where both walls are diabase, there is a distinct increase in stope length and that the maximum increases are parallel to the diabase-sedimentary beds contacts."

Gustafson, (1961), disagreed, and stated that, "the specific chemistry of the wall rocks is not reflected in the ore pattern, with the exception of the limestone replacement." Indeed, Plate III tends to support Gustafson's statement. In the central area east of the main stopes where mineralization is extremely irregular, this conclusion is even more justified. The control by wall rocks on ore emplacement is insignificant, if any, and could have been indirectly asserted only due to the fracture pattern.

Relation of Veins to Beds

The Magma vein is easily traceable as it cuts through the replaced horizon by virtue of its steep dip transverse to the replaced bed. It is narrow (4-6 feet wide) and has a friable brecciated character due to numerous cross-cutting fractures. Mineralization is much weaker than the replaced bed and is composed mostly of hematite and pyrite with some sphalerite, chalcopyrite and bornite.

The South Branch vein is difficult to follow within the replaced bed. Only the presence of some quartz in the vein could help to identify it from the replaced horizon. The replacement zone that is associated with the South Branch vein has been more extensively mined and studied than the area north of No. 6 shaft. In diabase, the vein is a poorly mineralized fracture zone with hematite, sphalerite and very little copper. As quartzite is approached from below, the vein widens and the copper values become of commercial interest. The width and grade of the vein reaches a maximum in quartzite. In the downthrown or south side of the vein, the replaced bed has abundant quartz, pyrite, chalcopyrite and bornite. The vein is generally lost as the upthrown or north side of the replaced bed is encountered. Followed up into the hanging wall above the replaced horizon, only a fracture zone is found, with minor hematite and sphalerite.

In the replaced area around the Magma vein, stoping and development work have not been as extensive as that of the South Branch vein area, but all indications point to the same relationship between the vein and the bed as found in the South Branch vein area, although the Magma vein may be a stronger structure that facilitated weak mineralization farther above and below the replaced horizon.

Physico-Chemical Control of Mineralization

It has already been stated that the chief ore control in the Magma vein is the fault structure itself. Wall-rock chemistry had little or no influence on the emplacement of the vein ore minerals.

In the replacement horizon, it is evident that the chemical characteristics of a certain section of the Devonian

Martin limestone are the controlling factors on this type of mineralization. Samples from the unmineralized (barren embayments) parts of the replaced bed contain high amounts of calcium and very low magnesium or none at all (Sell, 1961). The same results were obtained from samples in the footwall of the replaced bed (Table I). From the results of sampling analysis, the replaced section of the Martin limestone was possibly dolomitic in composition, although there is no basis for comparison.

Sequence of Structural Events and Mineralization

In the replaced area, the ore horizon has been displaced by movement along the Magma fault and its South Branch split, indicating post-ore movement of the fault. The Magma fault was probably just an open fracture with little or no displacement in the beginning. Then mineralizing solutions came up some open channel in the fracture and found a haven for replacement of the Martin limestone. Because the Magma vein ore bodies to the west show very little evidence of post-ore movement, the principal displacement along the Magma fault must have occurred after the replacement action. Such movement might cut off the ore channelways leading to the replaced area and open up new ones leading to the western stopes of the main ore body in the Magma vein.

The postulate that the Magma fault had some pre-ore movement and that the solutions came up along it to selectively replace the upper and lower segments of the displaced

Martin limestone could hardly be possible due to the fact that the vein mineralization itself tends to die out above the replaced bed.

After the movement along the Magma fault occurred, the fault was offset by the north-south trending Main fault. Plate III shows a rough parallelism of the main ore body with the westerly dipping footwall of the Main fault, suggesting that the fault had some sort of controlling effect in the deposition of the main ore shoot. Although it is not very clear, the Main fault possibly acted as a sort of barrier against the mineralization of the Magma vein west of the Main fault. Some stoping was done west of the Main fault as shown on Plate III, indicating that the fault had allowed some of the mineralizing solutions to get through. It is possible, although difficult to prove, that some movement along the fault made it act as a barrier against mineralization west of it. Uneconomic mineralization extends from the stoped area to the Main fault.

Mineralization along the strike of the Magma fault was apparently not completed, leaving a deposit that dies out halfway between No. 1 and No. 6 shafts (Plate III). Considering the irregularity of the stopes, telescoping deposition of the ore shoots was the rule rather than the exception.

The direction of travel of the ore-bearing solutions can be deduced from the mineral zoning lines shown in Plate III. The hydrothermal fluids probably came up from somewhere to the west and below the main ore body, since the shape of the main ore shoot is oriented in that direction and the zoning lines are roughly perpendicular to it.

After the ore deposition had ceased, the western block of the newly deposited thick dacite capping subsided with displacement on the Concentrator fault. The fault possibly followed the line of weakness afforded by the earlier Main fault along much of its length south of Superior. Movement along the Concentrator fault could have given impetus to the final and principal movement along the Main fault.

The NS-5W fault could have formed and offset the vein and replaced bed contemporaneously with the Main fault, or it could have originated later and at the same time as the Concentrator fault, since it has no surface trace through the dacite, possibly due to its limited displacement as compared to that of the Concentrator fault.

Mineralogy

Most of the Magma ore minerals have been described by a few early workers, notably, Gustafson,(1961), and Sell, (1961). The author collected samples, mostly in the replaced area north of No. 6 shaft (Plates IV, V and VI) to see if other unreported minerals could be found. The results of x-ray analysis verified the thoroughness of the mineralogical work done previously and revealed no new minerals (Table I). The minerals reported from the Magma mine ore bodies are listed in Table II.

TABLE I

X-RAY ANALYSIS RESULTS OF ORE SAMPLES

Sample No.	Level	Ore Type	Minerals Identified	Remarks
1	3600	Replacement	Cp, Hm	
2a	3500	Replacement	Sp, Py, Cp	Outer zone
2b	3500	Replacement	Sp, Py, Cp, Cc, Hm	Inner zone
3a	3400	Replacement	Py, Cp	Inner zone, 2nd horizon
3b	3400	Replacement	Rh, Sp, Py, Cp, Bn	Inner zone, 2nd horizon
3c	3400	Replacement	Rh, Sp, Py, Cp	Outer zone, 2nd horizon
4	3400	Replacement	Cp, Hm	Inner zone, 1st horizon
5	3400	Vein	Sp, Py, Cp	
6	3400	Replacement	Sp, Py, Cp	In raise, south of vei
7	3200	Vein	Hm, Py, Cp, Tn(?)	
8	3200	Vein	Hm, Py, Cp	
9	3200	Vein	Hm, Py, Cp, Hm	
10a	3200	Replacement	Hm, Cp, Hm	Outer zone
10b	3200	Replacement	Py, Cp, Bn	Inner
10c	3200	Replacement	Py, Cp	Inner
11	3200	Limestone	Rh, Sp, Py	FW lms. with Mg trace
12a	3200	Replacement	Hm, Py, Cp	
12b	3200	Replacement	Hm, Py, Cp	
13	3100	Limestone	Rh, Sp, Py, Cp	FW lms. with Mg trace
14	3100	Replacement	Rh, Py, Cp	Qtzite in diabase brec
15a	3000	Vein	Rh, Hm, Sp, Py, Cp, Pb(?)	
15b	3000	Vein	Rh, Hm, Sp, Py, Cp	
16a	3000	Replacement	Py, Cp	Inner zone
16b	3000	Replacement	Py, Cp	Outer
16c	3000	Replacement	Hm, Py, Cp, Sp(?)	Outer
17a	3000	Replacement	Sp, Py, Tn, Cp	Inner
17b	3000	Replacement	Sp, Py, Cp	Outer

(continued)

Sample No.	Level	Ore Type	Minerals Identified	Remarks
18a	3100	Replacement	Py, Bn	In raise, outer zone
18b	3100	Replacement	Sp, Py, Cc, Bn	In raise, inner zone
19a	2800	Vein	Rh, Pb, Sp, Py, Cp	Inner
19b	2800	Vein	Pb, Sp, Hm, Cp	Inner
19c	2800	Vein	Rh, Sp, Py, Cp	Outer
20	2550	Vein	Sp, Py, Cp	
21	2550	Vein	Rh, Pb, Sp, Hm, Py, Cp	
22a	4600	Vein	Cp, Bn, En	Main ore body
22b	4600	Vein	Cp, Bn, En, Tn	Main ore body
23	3500	Limestone	Rh, Sp, Hm	Barren lms. in drill core ore zone, with Mg trace.
24	3600	Replacement	Hm, Py, Cp	
25	3500	Replacement	Hm, Py, Cp, Tn	
26a	3400	Replacement	Py, Cp	
26b	3400	Replacement	Hm, Py, Bn	
27	3300	Replacement	Rh, Sp, Py, Cp	South of No. 6 shaft
28a	3200	Replacement	Rh, Py, Cp	
28b	3200	Replacement	Sp, Py, Cp	
29	3100	Replacement	Hm, Py, Cp, Bn	
30a	3000	Replacement	Py, Cp	
30b	3000	Replacement	Hm, Py, Cp	

Explanation

Py — Pyrite
Cp — Chalcopyrite
Bn — Bornite
Cc — Chalcocite

Tn — Tennantite
En — Enargite
Di — Digenite
Hm — Hematite

Rh — Rhodochrosite
Sp — Sphalerite
Pb — Galena
Mg — Magnesium

TABLE II

LIST OF PRINCIPAL KNOWN MAGMA MINERALS

Copper Minerals (Sulfides)		Remarks
Chalcocite	Cu_2S	Secondary, primary
Covellite	CuS	Secondary(?), primary
Bornite	Cu_5FeS_4	
Chalcopyrite	$CuFeS_2$	Chief ore mineral
Tennantite	$(Cu,Fe)_{12}As_4S_{13}$	
Enargite	Cu_3AsS_4	In lower levels
Digenite	$Cu_{2-x}S$	
Copper Minerals (Oxides)		
Native Copper	Cu	Primary and secondary
Cuprite	Cu_2O	
Tenorite	CuO	All secondary minerals in oxide zone
Malachite	$CuCO_3 \cdot Cu(OH)_2$	
Azurite	$2CuCO_3 \cdot Cu(OH)_2$	
Chrysocolla	$CuSiO_3 \cdot 2H_2O$	
Iron Minerals		
Pyrite	FeS_2	Predominant gangue min.
Pyrrhotite	FeS	Minor
Hematite	Fe_2O_3	Abundant in repl. area
Magnetite	Fe_3O_4	Minor
Others		
Sphalerite	ZnS	In pockets
Galena	PbS	Minor
Rhodochrosite	$MnCO_3$	Minor
Stromeyerite	Ag_2SCu_2S	Rare

Gold and silver are always present in trace quantities. Other reported minerals are tetrahedrite, dioptase, chalcanthite and famatinite.

An attempt to determine the existence of ore mineral polymorphs by x-ray and polished section work proved to be negative, whereas the usual complement of sulfide minerals were readily identified. In the absence of other determinative work, the results indicated that no polymorphs, such as cubanite and wurtzite, exist in the Magma mine.

The oxidation line in Plate III does not follow the bedding attitude downdip, so that oxidation probably occurred after the beds were tilted. Movement along the Magma fault has separated the north side 300 feet higher than the south side of the fault. Laterally into the north side replaced horizon, oxidation has penetrated to a limited but unknown depth. Oxidation in the down-dropped south side is nonexistent, thus indicating oxidation before the Magma vein movement. Oxidation appears to extend deeper along the fault structure due to easier access. The supergene zone above the oxidation line exhibits the usual suite of secondary copper minerals, from chalcocite to chrysocolla. Having been mined out years ago, the area is now inaccessible.

Paragenesis

In any paragenetic study, it is customary to summarize the evidences of the apparent sequences of mineral formation in the form of a paragenetic diagram. Time is one axis of this diagram and the known minerals in their order, the other axis. The sequences thus obtained may represent a vein, an ore body or a mining district. Very rarely can one find the same mineral relationships in all the specimens studied, however. Thus, the great drawback in deriving mineral paragenesis from textural observation is that it is commonly somewhat ambiguous and influenced by the observer's bias(Gustafson,1961).

Mineral zoning and paragenesis at the Magma mine has been compared to that at Butte, Montana. It is true that both districts have certain similarities, but the generalized paragenesis at Butte cannot be fitted to the whole Magma deposit. The Magma mineralization is vastly more complicated than Butte, and the "telescoping" manner of deposition produced not one but several paragenetic sequences.

No single sequence fits the textural evidence in all types of ores found in the Magma deposits. The apparent paragenesis of various types of ores occupying similar positions in the zonal pattern are summarized in Table III. All sequences indicate that Magma is a mesothermal deposit. Gustafson, (1961), has an even more comprehensive description of the various sequences. Polished section work by the author agrees with Gustafson's conclusions, except for a few minor differences.

The sequences in Table III are discussed below in some detail for each ore type. Minerals separated by a comma are probably contemporaneous or deposited as a single solid-solution phase. Minerals in parentheses are rare or absent. The first named minerals is earlier than the one following it. The mineral symbols used are indicated in Table III.

TABLE III

PARAGENETIC SEQUENCES OF VARIOUS ORE TYPES AT MAGMA

(After Gustafson, 1961, revised)

Sequence: Early to Late	Area
(1) Py-Cp,(Bn)-Bn,Cc,Tn	Middle and upper main ore body.
(2) Py-En-Cp,(Bn)-Bn,Cc,Tn,Di	Lower main ore body.
(3) Hm-Py-Cp-Bn,(Tn)-Hm,(Sp)	Central ore body.
(4) Hm-(Rh,Sp)-Py-Cp-Bn,Cc,(Tn)	Replacement ore body.

Explanation

Py -- Pyrite

Cp -- Chalcopyrite

Bn -- Bornite

Cc -- Chalcocite

Tn -- Tennantite

En -- Enargite

Di -- Digenite

Hm -- Hematite

Rh -- Rhodochrosite

Sp -- Sphalerite

Minerals in parentheses are rare or absent.

Minerals separated by a comma may be contemporaneous or deposited as a single solid-solution phase.

Py - Cp,(Bn) - Bn, Cc, Tn (Sequence 1)

Sequence 1 refers to the rich copper ores from the middle and upper parts of the main ore body; the area that made the Magma mine famous for the pure massive bornite produced. These stopes are now completely exhausted. Bornite is predominant and exhibits beautiful patterns of exsolved chalcopyrite. Chalcopyrite and chalcocite are never found in contact. Tennantite is a common accessory mineral and could be a product of exsolution from bornite and chalcopyrite, but is probably of distinct hypogene deposition.

Py - En - Cp,(Bn) - Bn, Cc, Tn, Di (Sequence 2)

Sequence 2 belongs to the lower part of the main ore body where enargite is the predominant copper mineral. Tennantite replaces enargite selectively. Chalcocite and bornite are rare while digenite is a minor constituent.

Hm - Py - Cp - Bn,(Tn) - Hm(Sp) (Sequence 3)

Ore from the central area exhibits sequence 3. Hematite is abundant and spanned the entire length of time in deposition but was mostly replaced by pyrite. Bornite and tennantite are minor and sphalerite occurs in scattered patches associated with hematite.

Hm - (Rh, Sp) - Py - Cp - Bn, Cc,(Tn) (Sequence 4)

Sequence 4 belongs to the replacement horizon. Hematite and pyrite are predominant minerals. Hematite was formed mostly before the copper ore deposition but could have continued after it. Tennantite is minor and may be a product of exsolution from bornite. Sphalerite and rhodochrosite were both deposited prior to the copper minerals and may have been deposited together.

In all the sequences, gold and silver are present in small amounts. Silver sometimes occurs as rare stromeyerite.

Mineral Zoning

Plate III shows a general zoning of minerals in the Magma vein. No apparent zoning was found in the replacement bed, either vertically or laterally. Except for the irregular zinc line, all the zoning lines form a rough semi-circle, with the center somewhere below and to the west of the main ore body, indicating that region as the source of mineralization.

Copper Minerals---The top of the enargite zone is the line below which it becomes the predominant ore mineral. It corresponds remarkably with the top of the Pinal schist on the north side of the Magma vein fault (Plate III). This is probably just a coincidence, since it is the only one of the mineral zoning lines that have such a relation with lithologic boundaries. The line above which tennantite becomes more abundant than enargite is also shown. Enargite, however, is known to occur in scattered pockets above this line and in the tennantite zone as well. A third line which marks the upper limit of the occurrence of digenite is in between the two lines mentioned above.

Bornite (not shown in Plate III) is the predominant mineral in the main ore body above the 2550 level and is completely sheathed by chalcopyrite and pyrite. It has been noted in the course of mining that bornite is predominant where copper content is highest; in leaner areas, chalcopyrite and pyrite are predominant. This fact does not hold in the lower levels in schist where the massive ore, mostly enargite and bornite, occurs only as pods.

Sphalerite---The zinc line shown in Plate III is the lower limit at which the amount of zinc as sphalerite becomes less than the amount of copper. There is a sharp upward inflection of this zinc boundary as it approaches the main ore body westward. This difference in depth of the sphalerite zone is closely related to the apparent telescoping of mineral zones in the main ore shoot where the greatest flow of the ore solution probably occurred. The influx of the hot ore solution lifted the copper ore deposition higher and raised the critical isotherm at which sphalerite could be precipitated.

ROCK TEMPERATURE MEASUREMENTS

The method used by the author to determine rock temperatures in the underground workings of the Magma mine was by direct measurement. Two maximum reading thermometers were used. Both were of the type that registers the maximum temperature at any point and will not change in the interval between withdrawal and the actual reading of the instrument. Enclosed in metal sleeves to prevent accidental breakage, the sleeves were perforated to insure proper circulation of air or water while in place in a drill hole or muckpile.

There are numerous strategically located old diamond drill holes throughout the mine, especially near the ore bodies. These holes were ideal places in which to insert a thermometer and measure rock temperatures several feet within the rocks themselves. The thermometer was fastened into a hollow at one end of a 6-foot long wooden pole an inch in diameter. Where the hole was not caved, which fortunately was the case most of the time, the entire 6-foot pole was inserted. If the hole was shortened by caving, a shorter pole was used.

To prevent the relatively cold stope air from circulating in the hole and introducing an error, a tapered wooden plug was attached to the other end of the pole and used to plug the hole collar. In all cases, the instrument was left in the hole for at least a day before a reading was made. Whenever weekends intervened, the thermometer was left in the hole for at least 3 days.

Most of the holes flowed water in volumes ranging from a mere trickle to as much as 10 gallons per minute. The plug, in cases of wet holes, was so adjusted as to allow a small opening to release the water pressure and yet tight enough to prevent complete drainage during measurements, based on the assumption that the temperature of the water is in equilibrium with the surrounding rock.

Logging the core from the active diamond drilling exploration program going on underground north of No. 6 shaft provided the opportunity for the author to become acquainted with the behavior of holes during drilling. All the new holes were wet holes-----spurting hot water at rates up to 30 gallons per minute. The water being freshly released and in thermal equilibrium with the rocks, the thermometer was simply submerged in the water below the hole collar and a direct reading made.

In the areas where no holes were available, it was necessary to bury the thermometer deep enough to prevent the corculating stope air from reaching the instrument. This was accomplished by simply burying the thermometer in an undisturbed muckpile, usually a foot deep, or in a crack in the wall rock and covered with mud.

Plates IV, V and VI show the locations of the points where rock temperature measurements were made in the replacement area north of No. 6 shaft. Most of the work was done in this area where the author was assigned as a geologist during the time when data for this thesis was being gathered. It is a newly opened area with levels from 2550 to 3600 accessible and working. As a check, a few temperature measurements were made in the area south of No. 6 shaft. The results served only to support the data elsewhere.

Plate VII shows the relative positions of the areas north and south of No. 6 shaft with respect to each other.

Effects of Surface Atmospheric Conditions

The Magma engineering staff has been measuring air temperatures in the working stopes every two weeks for the last 30 years. Surface conditions are also recorded. Figure 2 is a compilation of surface conditions at Superior for the last 20 years. Underground temperatures have been found to fluctuate the same way as surface conditions, so that it was necessary to prevent circulation of stope air at the point of rock temprature measurements in order to minimize the possibility of errors.

From Figure 2, the mean annual air temperature at Superior is found to be 68.5°F. The mean annual soil temperature was arrived at by burying a thermometer about a foot deep in the ground. This continued from July to February, from summer to winter, encompassing the periods of temperature extremes at Superior. The soil temperatures recorded were always 4-5°F higher than the air temperatures and a figure of 73°F, which is several degrees higher than the 68.5°F mean annual air temperature, is taken as the mean annual soil temperature.

Geothermal Gradient

Within the replaced horizon, the estimated thermal gradient as derived from the rock temperature measurements is 2.0-2.5°F per 100 feet (dotted line, Figure 3). This dotted line as extended to the 73°F surface soil temperature, suggests an increasing gradient at greater depths. It is possible that

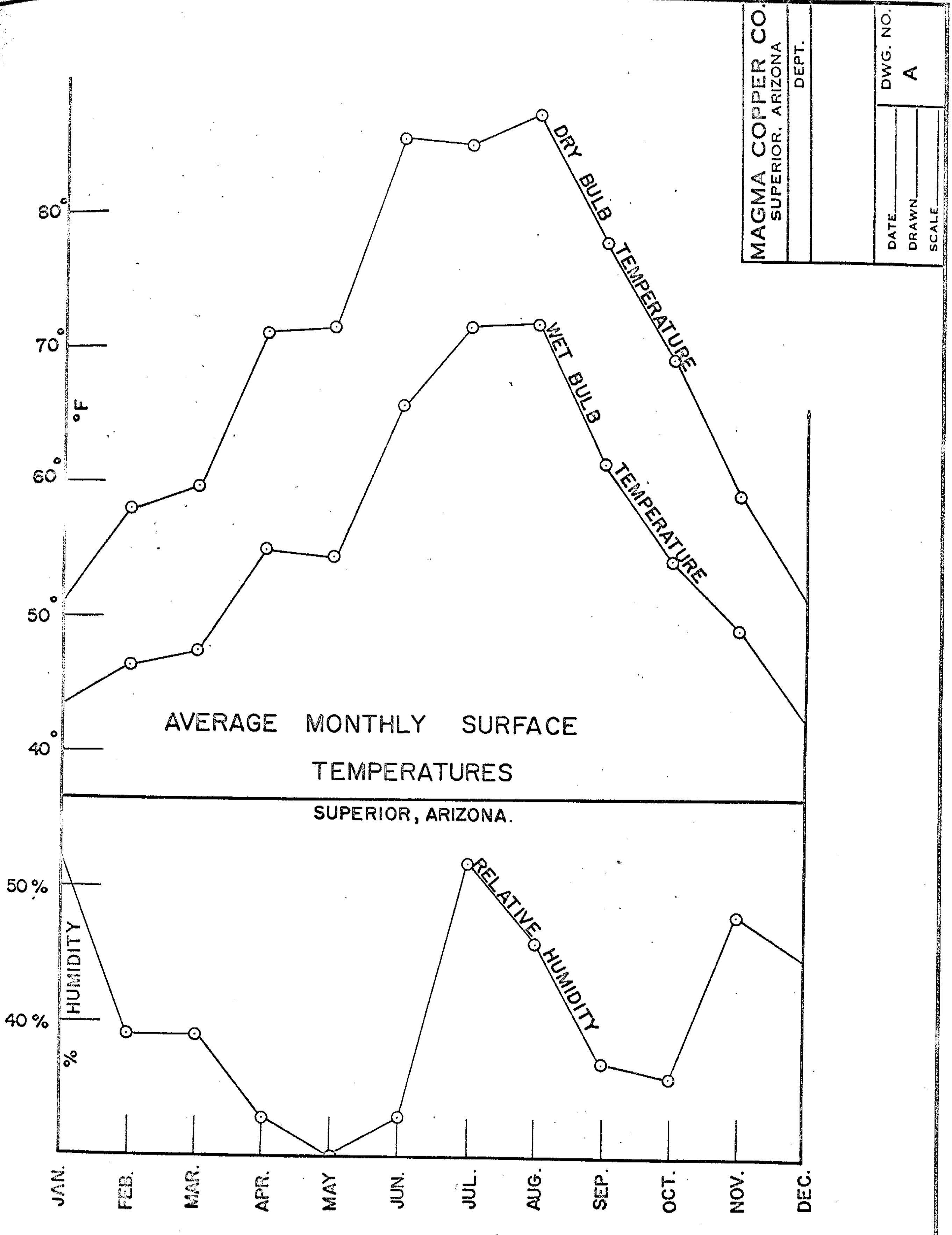

MAGMA COPPER CO.
SUPERIOR, ARIZONA
DEPT.
DWG. NO.
A
DATE
DRAWN
SCALE
80°
70°
60°
50°
40°
°F
DRY BULB TEMPERATURE
WET BULB TEMPERATURE
AVERAGE MONTHLY SURFACE TEMPERATURES
SUPERIOR, ARIZONA.
50 %
40 %
% HUMIDITY
RELATIVE HUMIDITY
JAN.
FEB.
MAR.
APR.
MAY
JUN.
JUL.
AUG.
SEP.
OCT.
NOV.
DEC.

FIGURE 2

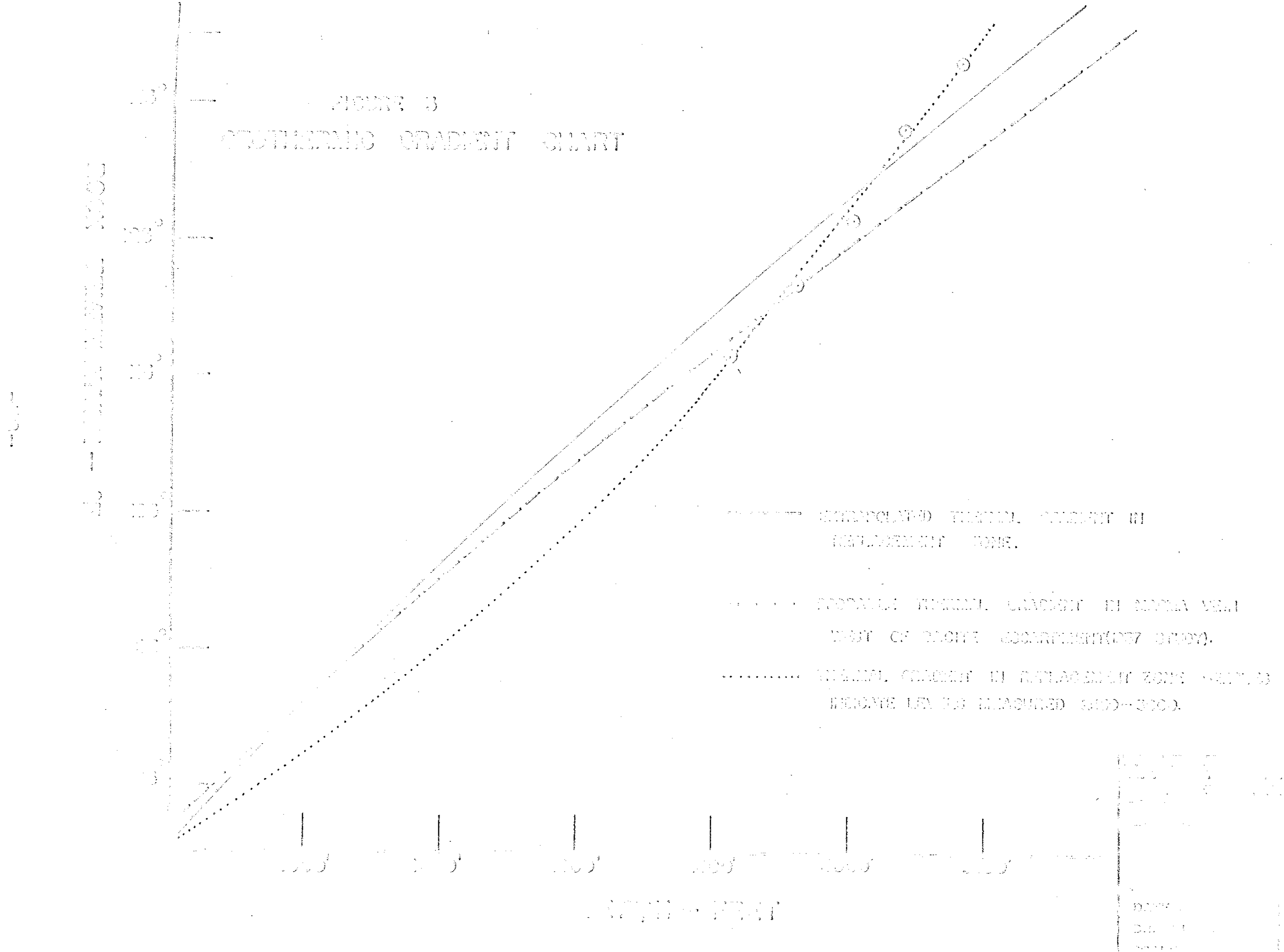


FIGURE 3
GEOTHERMAL GRADIENT CHART

this gradient (dotted line) is just a local variation and that it will flatten or decrease at depth. Geothermal studies around the world (Birch, 1954, 1955) show local gradient variations within the first measurable 10,000 feet depth from the surface. To correct for this variation, a solid line has been extrapolated from the results, which gives a gradient of only 1.8-2.0°F per 100 feet. The average for most of the observed thermal gradients around the world is 1.5°F per 100 feet, hence, the results at Magma are comparable and are only slightly higher. The temperature measurements done were confined to the levels between 2550 and 3600 in only one area of the Magma mine, since all levels above 2550 were inaccessible.

The broken line in Figure 3 was taken from a paper on the ventilation study at Magma by an unknown author in 1937 as found in the Company files. It is presumably based on rock temperature measurements, but the method was not indicated; possibly also using a few diamond drill holes. This gradient is 1.5°F per 100 feet or the same as the world's average. Considering the time of this study, this result, if taken at face value, is the thermal gradient of the main ore body in the Magma vein far to the west of the replaced are. This 1937 study is included here only as a basis for comparison with the present study, since there has been no other temperature study done at the Magma mine until now.

No lateral variation in temperature was noted along any level from both sides of the vein or the replacement ore body. Figures 4 and 5 summarize the results that lead to this conclusion.

Below is a tabulation of the rock temperature averages in each of the level studied:

2550 -- 116°F
2800 -- 123°F
3000 -- 128°F
3100 -- 130°F
3200 -- 133°F
3400 -- 138°F
3600 -- 143°F

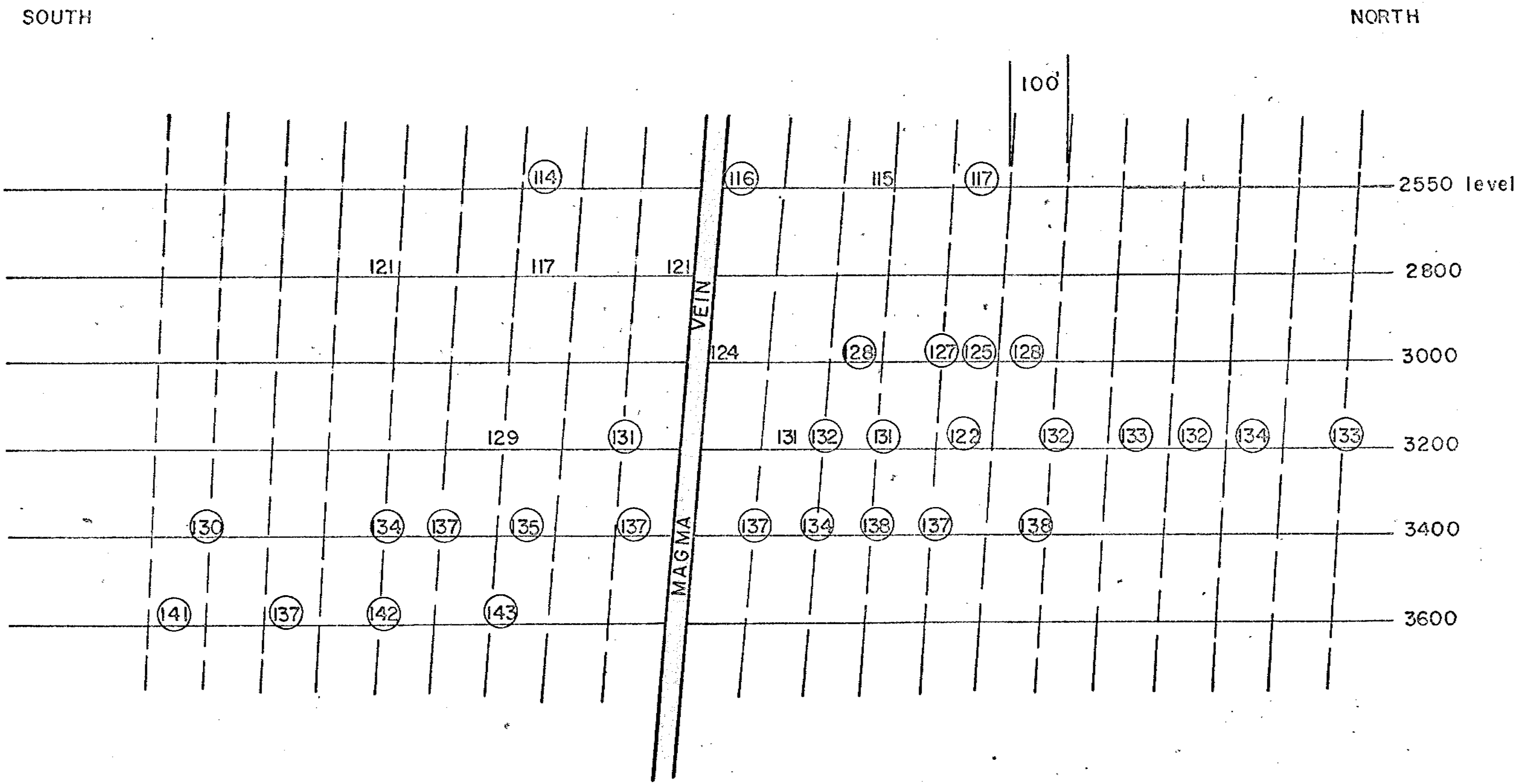
Comparison of Thermal Gradient with Other Areas

The observed 2.5°F per 100 feet (45.5°C per kilometer) thermal gradient at the Magma mine compares favorably with most of the recorded readings around the country. A few areas, notably in California, show much higher gradients than the Magma deposit. The temperatures are measured in oil wells, steam wells and metal mines (Spicer, 1942., Van Orstrand, 1951 and McNitt, 1963). Below are listed 4 of the areas with abnormally high thermal gradients:

Pine Island, Louisiana ---- 51.86°C/Km.
Virginia City, Nevada ---- 61.90°C/Km.
Seal Beach, California ---- 53.75°C/Km.
Salton Sea, California ---238 + °C/Km.

Relation of Temperature to Rock Units and Ore Bodies

Plates IV, V and VI showing the locations of temperature measurements indicate no variation of temperature among the different rock units. There is no lateral change in tempera-



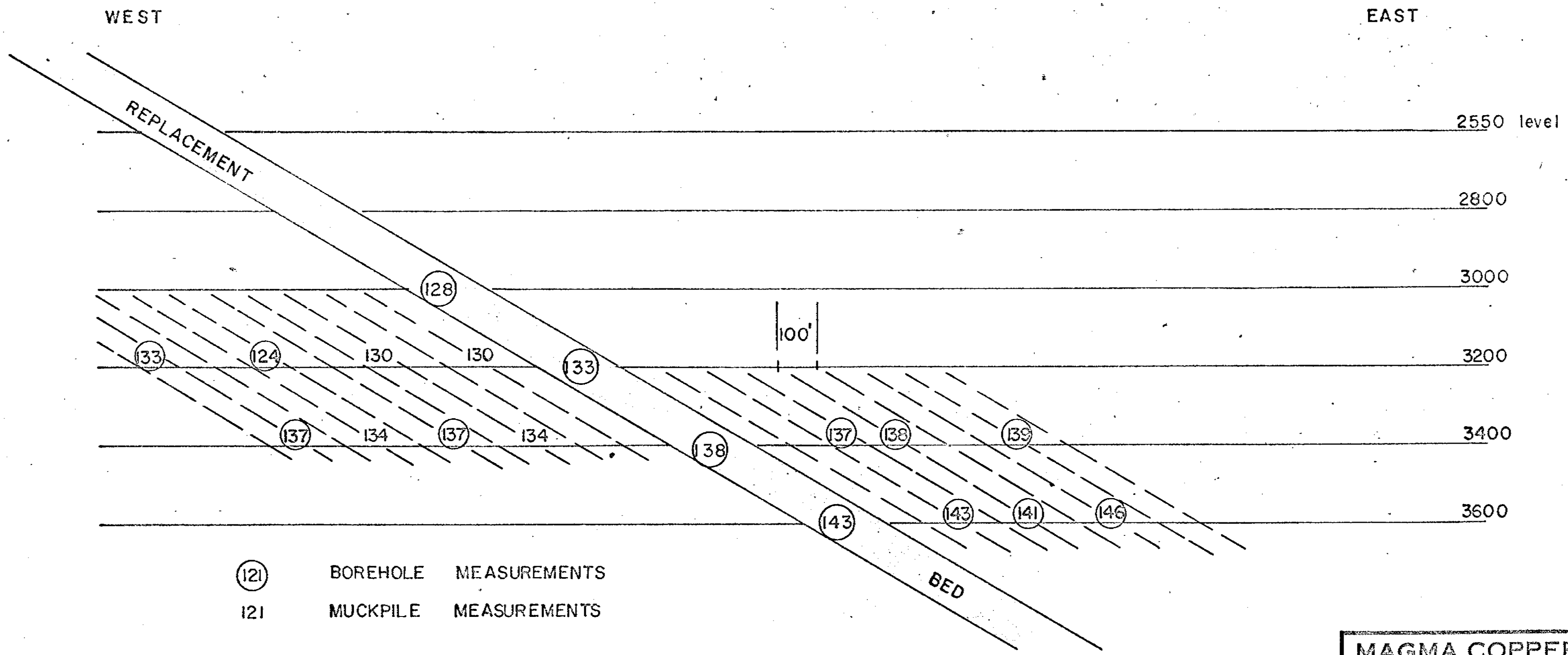
(121) BOREHOLE MEASUREMENTS

121 MUCKPILE MEASUREMENTS

DISTANCES FROM MAGMA VEIN TO SCALE
(one interval = 100')

FIGURE 4

MAGMA COPPER C
SUPERIOR, ARIZONA
DEPT.
TEMPERATURE READINGS IN
RELATION TO THE
MAGMA VEIN
DATE 6/29/65
DRAWN dcu
SCALE
DWG. N



DISTANCES FROM REPLACEMENT BED TO SCALE
(one interval = 100')

FIGURE 5

MAGMA COPPER CO
SUPERIOR, ARIZONA
DEPT.
TEMPERATURE READINGS
IN RELATION TO THE
REPLACEMENT BED
DATE 6/29/65
DRAWN dcu
SCALE
DWG. N

ture from one rock unit to another at the same elevation.

Figures 4 and 5 are idealized vertical sections across the vein and the replacement ore bodies showing the temperature measured along different levels going away from each side of both ore bodies. They also show no anomalous relationship between the ore deposits and the recorded temperatures.

Probable Errors

In temperature measurements as crude as these, there are bound to be errors introduced. Some are known errors that can be corrected. Others are indeterminate errors whose correction is left to the judgment of the observer.

The temperatures taken in muckpiles showed a tendency to be lower than those in nearby boreholes. This was expected, since muckpiles are not in place and are more permeable to air circulation than solid rock. Most of the muckpile temperatures were utilized only in the study of lateral changes, since any error would have to be fairly constant for all of them at any one level and any existing temperature variation would still be detectable.

In a few instances where a borehole happened to be located at a junction of two drifts, the notably low temperature reading was due to the fact that two sides of the enclosing rocks are exposed to the air in the drifts, giving the rock more surface area in which to disperse heat. No applicable equation has been formulated to calculate this heat loss and its affected depth, hence, these holes were not used in the calculations.

According to the ordinary pressure-temperature equation at constant volume, water under pressure will increase in temperature when the pressure is released. This temperature increase is probably effective here, as there were some down holes that welled out water, apparently under pressure. If effective however, the error probably would be constant downward and would not alter the thermal gradient at all.

Throughout this study, water has been assumed to be in thermal equilibrium with the rocks. Any heat transfer from rock to water would also be constant downward.

During the time used for temperature measurements, two drifts were being actively driven in advance of the diamond drilling operation. These drifts are shown in Plate IV as the easternmost headings, one each in the 3400 and the 3600 levels. The temperatures recorded in the boreholes in these drifts, since they were taken in newly broken ground, were considered to be very close to the true rock temperatures and were used as standards of comparison for the other measurements.

CONCLUSIONS DERIVED FROM THE TEMPERATURE STUDY

The geothermal gradient of the replacement area below the dacite capping is 2.0-2.5°F per 100 vertical feet, as shown by the dotted line in Figure 3. This gradient, even when extrapolated to 1.8-2.0°F per 100 feet is slightly higher than the 1.5°F per 100 feet for the world's average.

Of the several hypotheses put forward to explain the anomalies of the earth's internal heat distribution, only two are considered relevant in the explanation of the Magma mine's slightly higher than normal thermal gradient. These are:

1. heat insulating effect of the dacite
2. recent volcanism and presence of a nearby magma body.

Plate I shows that the replacement area is under the thick dacite capping, while most of the Magma vein is located west of the dacite escarpment (Plate III). Assuming that the results of this study are valid, then the replaced area has a higher thermal gradient than the Magma vein workings. It therefore follows that the thick dacite capping the replaced zone may be in some way related to this phenomenon. The dacite probably elevated the temperature of the underlynig rocks to a certain degree. It is assumed that the dacite having been deposited 20 million years ago, the heat flow from the underlying rocks through the dacite and into the atmosphere must have reached equilibrium and could be considered to be in steady-state conditions. Another point is the fact that the collar of No. 1 shaft from which all underground level elevations are based is about 1000 feet lower than the top of the dacite escarpment. Hence, at any one level, the vein area has a rock cover 1000 feet thinner than the rocks overlying the replacement area. This could elevate the temperature in the replaced area since isotherms of heat flow are taken to be parallel to the configuration of the land surface.

The difference in gradients between the replaced area at 2.0-2.5°F per 100 feet and the Magma vein at 1.5°F per 100 feet is slight and the possibility of errors is not discounted. The replacement area and the main ore body are about 4000 feet apart on an east-west line; whether this distance is sufficient to make a difference of half a degree to one degree in the geothermal gradient is not known.

Economic mineralization is presumed to have occurred in Mesozoic or early Tertiary time. An event that began and ended about 70-100 million years ago can hardly be called recent. Any magma chamber that acted as the source of hydrothermal fluids that deposited the ores has had enough geological time to cool off. Still, a nearby cooling magma body could not be entirely discounted as an explanation to the thermal gradient at the Magma mine.

RECOMMENDATIONS FOR FUTURE WORK

To verify the conclusions of this paper, a laboratory study of the thermal conductivities of the rocks exposed in the area should be carried out that would include not only the dacite but also the other rock units underlying it.

If it is possible to do so, a drill hole collared on top of the dacite escarpment that could penetrate the entire dacite thickness is invaluable for measuring temperatures.

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This thesis is accepted on behalf of the faculty of the Institute by the following committee:

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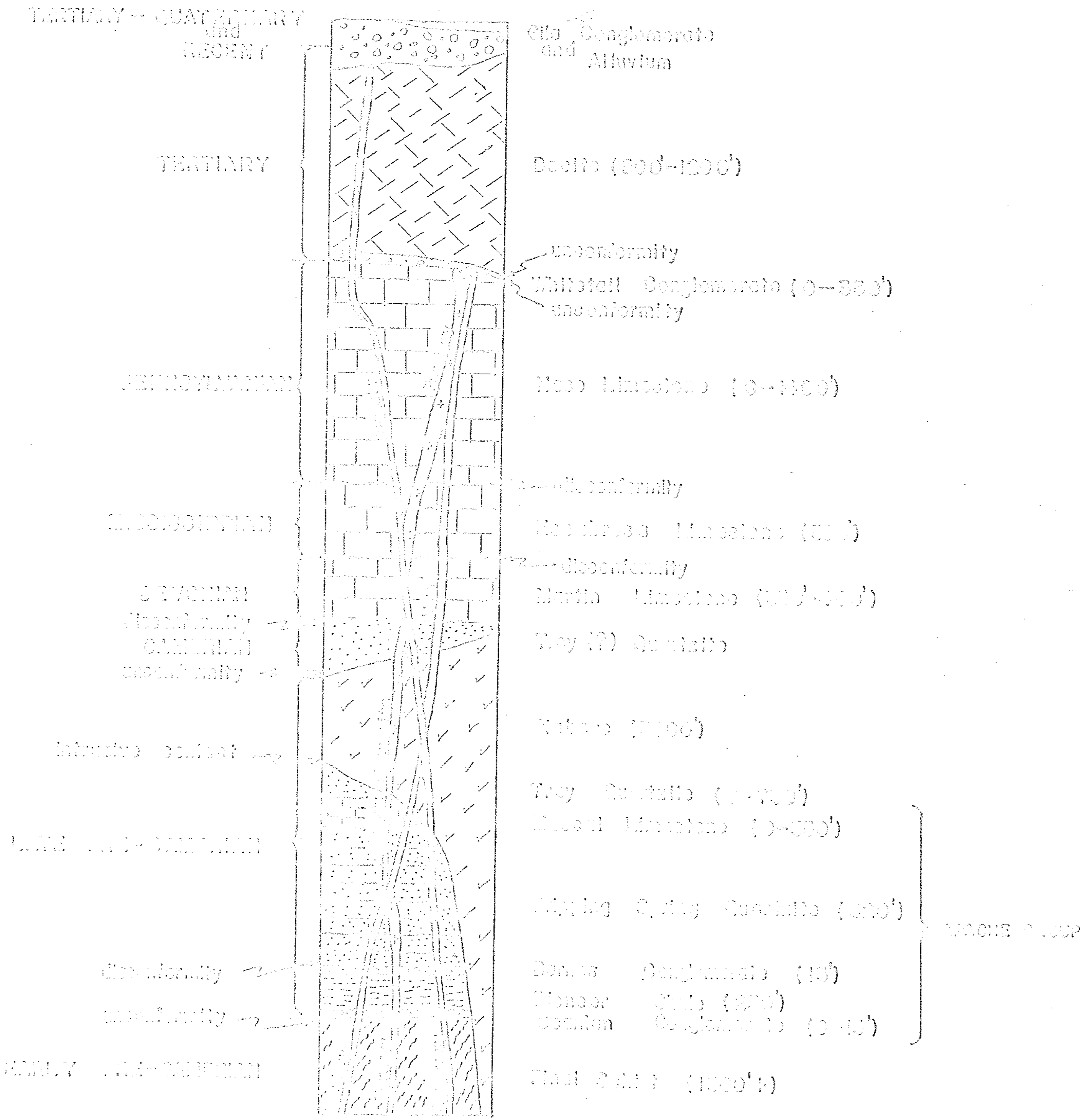

FIGURE 1

(After [illegible])

[illegible]