THE RELATIONSHIP OF DOLOMITE AND ORE
WITH SPECIAL REFERENCE TO THE
JACKPOT PROPERTY, YMIH, B.C.

by

DUNCAN WALKER HEDDLE

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We accept this thesis as conforming to the
standard required from candidates for the
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Dr. H.C. Gunning,
Head, Department of Geology and Geography,
University of British Columbia,
Vancouver, B.C.

Dear Sir,

It gives me pleasure to submit the following thesis, "The Relationship of Dolomite and Ore with Special Reference to the Jackpot Property, Ymir, B.C.", in partial fulfillment of the requirements of the course leading to the degree of Master of Applied Science in Geology at the University of British Columbia.

Yours truly,

D.W. Heddle.
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The close association of lead-zinc deposits with dolomite and dolomitic limestone and the common occurrence of these deposits within dolomitic envelopes in limestone present an interesting and challenging problem to economic geologists.

A review has been made of the manners in which dolomite and lead-zinc ore are found to be associated. Possible reasons for the association of dolomite and ore and processes by which limestones in the vicinity of lead-zinc deposits may be altered to dolomite have been considered. Dolomites in general are believed to be very favorable host rocks for lead-zinc ore but whereas this favorability may facilitate the localization of ore in primary dolomites, it can hardly be regarded as the primary localizing factor in those deposits which occur within dolomitized zones in limestone.

The alteration of limestone in the vicinity of lead-zinc deposits may be best attributed to magnesium-rich hydrothermal solutions, the magnesium of which is not genetically related to the parent magma. The mechanism proposed by Faust, whereby magnesium-rich solutions are derived from dolomites which have been thermally dissociated in the vicinity of an intruding magma, adequately fulfills the requirements of a dolomitizing agent. If we can assume that ore-bearing solutions have arisen from the same magma that brought the dissociation of a pre-existing dolomite, then dolomite and ore may necessarily be closely associated by reason of dolomitizing
and ore-bearing solutions having been localized by the same structural controls.

A study of specimens from the Jackpot property, Ymir, B.C., a deposit occurring in dolomitized limestone, has revealed little information with respect to the process of dolomitization other than indicating that dolomitization preceded sulphide mineralization.

Most of the sulphide mineralization at the Jackpot property occurs within calcitic zones in dolomite. It is believed that dolomite has been replaced by the sulphide minerals and has been later partially replaced by calcite in the zones of sulphide mineralization.

If Faust's proposal that magnesium-rich solutions may be derived from a thermally dissociated dolomite in the vicinity of an intruding magma is valid, one may conclude that at a late stage in the hydrothermal activity, when magnesium has been largely removed from the thermally dissociated dolomite, the solutions may become relatively rich in the less soluble calcium carbonate. These later calcium carbonate-rich solutions may be responsible for the replacement of dolomite by calcite in the mineralized zones.
THE RELATIONSHIP OF DOLOMITE AND ORE
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Introduction

The problem of the origin of dolomites or dolomitic limestones is one which has engaged the interest of geologists for a great many years. The many theories proposed have resulted in much controversy. Some theories appear very convincing for certain occurrences but no one theory seems applicable to all occurrences. The broad problem of the origin of dolomites and dolomitic limestones of great areal extent, so often referred to as "primary" dolomites, however, will not be discussed in any detail by the writer.

The close association of lead-zinc deposits with dolomites and dolomitic limestones and the common occurrence of these deposits within dolomitic envelopes in limestones has been noted by geologists for a hundred years or more. This association has become of extreme interest to economic geologists within the present century. The great importance of lead and zinc in world economy during recent years has accentuated the study of dolomitization as a feature which may lead
to the discovery of new ore bodies.

The origin of the dolomitic envelopes so commonly developed around lead-zinc replacement deposits in limestone is believed to be a specialized case of dolomitization. While there may be a degree of parallelism in the origin of the dolomitic envelopes associated with lead-zinc deposits and some of the widespread "primary" dolomites and dolomitic limestones, the overall processes of their development are believed to be dissimilar.

Owing to the widespread occurrence of "primary" dolomites, some lead-zinc deposits might necessarily occur in these. The occurrence of lead-zinc deposits in dolomites or dolomitic limestones, however, seems too common to be fortuitous and suggests the possibility of them being exceptionally favorable host rocks. The common occurrence of dolomitic envelopes surrounding lead-zinc deposits in limestone suggests the possibility of there being some relationship between the processes of dolomitization and ore deposition. The writer has made a study of the possible relationships between these two processes.

The more general material for this thesis was obtained largely from a review of the literature. Studies were made of specimens from the Jackpot Property, Ymir, B.C. which is believed to be a fairly typical example of a lead-zinc deposit occurring in dolomitized limestone. The specimens examined are believed to be representative of the relationship between dolomitized limestone and ore.
The random manner in which the samples were taken and the inadequacy of the number of samples will probably allow no statistical conclusions to be arrived at from this study. It is hoped, however, that some of the relationships observed between the mineralization and the host rock will permit the formulation of conclusions of a general nature.

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Discussion and Definition of some Terms Involved

The term dolomite is commonly used by geologists as being equivalent to magnesian limestone. Properly the term should be restricted to the definite double carbonate (CaCO₃, MgCO₃) which occurs both as a well crystallized mineral and as a massive rock consisting of 54.35 percent CaCO₃ and 45.65 percent MgCO₃.

Most modern geologists differentiate between dolomites composed chiefly of the mineral dolomite and dolomitic limestone in which CaCO₃ is present in excess of MgCO₃. Limestones containing only small amounts of magnesium are commonly referred to as magnesian limestones. Pettijohn (1948, pp. 312-313) defines dolomites as follows: "Dolomites are those varieties of limestone containing more than fifty percent carbonate of which more than half is dolomitic". He goes further to break the rock types into three groups: dolomitic limestone, calcitic dolomite, and dolomite on the basis of the proportion of calcite to dolomite in the rock. Because of a loose usage by writers of the various terms involved, much of the value of the literature on the topic is lost.

The carbonates of calcium and magnesium do not form a complete isomorphous series. According to Steidtmann (1917, p. 433) the magnesia content of calcite rarely exceeds two percent. The CaO content of dolomite is nearly constant but MgO is commonly replaced by small amounts of FeO or of FeO and MnO. The maximum ferrous iron
content is probably about 10 percent.

Andrews (1950, p. 91) reports that MnCO$_3$ seems to form a complete series of solid solutions with calcite. He attributes this to the fact that the ionic diameter of manganese is nearer to that of calcium than magnesium or iron. Both the elements magnesium and iron form a double carbonate in which the ions of calcium on the one hand and magnesium or iron on the other occupy, in an ordered arrangement, the lattice sites which in calcite solid solutions would be occupied in a random manner. Andrews suggests that complete solid solutions are favored by ionic diameters which are not greatly different, whilst the dolomite type of compound is preferred if the difference becomes marked. Ford (1917, p. 211) has suggested that manganese carbonate would be expected to dissolve in calcium carbonate to the largest extent, iron carbonate next and magnesium carbonate the least, and that solid solutions would probably be restricted. No extensive solid solutions of FeCO$_3$ and MgCO$_3$ in calcite have been reported.

From a study of dolomitization, Bär (1924, p. 116)$^1$ found that calcite could exist next to dolomite in stable equilibrium but that the association of calcite with magnesite was unstable and would produce dolomite. Furthermore, magnesite and dolomite could exist

$^1$Cited from Faust and Callaghan (1948).
as an assemblage of minerals with stable relationships, whereas magnesite with a small amount of calcite would be unstable and dolomite would form as a reaction product.

In rare cases the magnesia content in dolomite exceeds the proportion required in normal dolomite and in these cases it must be assumed that this excess is due either to the existence of MgCO$_3$ in isomorphous mixture in the dolomite or to the presence of free crystals of magnesite. Ferruginous dolomite or ankerite is not rare. All the iron of the carbonate rock, however, is not necessarily a part of the carbonate. It may be present as hydroxide or in clay-like impurities, and these possibilities must be taken into account in any interpretation of the dolomites.

Dolomitization is defined by Rice (1948, p. 110) as a general term for the processes whereby dolomite takes the place of calcium carbonate in limestones, the latter thus becoming dolomitic limestones or dolomites. Dedolomitization is defined as a process whereby a dolomite, during metamorphism, loses its content of magnesium carbonate, the magnesium remaining as oxide or hydroxide or silicate. Rice does not believe it is desirable to extend the term to include the mechanical removal of dolomite.
A General Comparison of the Properties of Dolomite and Limestone

The colors, textures, and other physical properties generally ascribed to limestone also apply to dolomite. Dolomites have a tendency to weather to a buff or tan color, due in many cases to their iron content. Many dolomites are quite porous but this property is by no means universal. Dolomite is somewhat harder than limestone. It is also somewhat heavier than limestone, its specific gravity being 2.87 as compared to 2.71.

If a carbonate rock is pure dolomite, it effervescences in cold dilute hydrochloric acid either not at all or only feebly; but if it is finely pulverized, it effervescences vigorously even in cold acid. The use of stains (described in appendix) to distinguish between calcite nad dolomite is based on the difference in chemical properties between the two minerals.

The weathered surfaces of dolomitic limestones are often quite diagnostic. The dolomite grains are left standing in relief against the more rapidly weathering calcite.

The Origin of Dolomites in General

The origin of dolomites is a matter of much interest and controversy. Evidence points to the fact that dolomites have been formed in two general ways:
(1) as syngenetic dolomite which is a dolomite formed either by
direct precipitation from sea water or by the alteration of
limestone by sea water before the overlying stratum was laid
down.

(2) as secondary dolomite, by alteration of limestone to dolomite
long after the limestone was formed.

The most extensive dolomites are believed to have been pro-
duced by direct precipitation or a process of penecontemporaneous
dolomitization. Many geologists regard the common occurrence of in-
terbedded, sharply defined beds of dolomite and limestone as proof
of direct precipitation. There are a great many other points which
favor the formation of dolomite by direct precipitation but there are
also a great many points which show this view to be untenable. Dolom-
ite has been produced artificially as a direct precipitate, but ex-
periments have failed to indicate the conditions under which dolomite
can be precipitated directly at ordinary temperatures and pressures.
Most geologists favor a process of penecontemporaneous dolomitization
under shallow seas for the origin of extensive dolomite beds.

That dolomite or dolomitic limestone can be formed by the
alteration of limestone long after the formation of the limestone
there seems little doubt. These "secondary" dolomites or dolomitic
limestones generally occur in smaller masses than the "primary"
dolomites but in some districts thick uniform masses appear to have
been formed by the wholesale transformation of limestone. The
The Association of Dolomitized Limestone and Lead-Zinc Ore

Of all lead-zinc deposits, those occurring as replacements in limestone probably form the most important group. A great many of these deposits, indeed many of the more important ones, show the limestones in the vicinity of the orebodies to be dolomitized. It seems likely that many of the large deposits reported to occur in unaltered limestone do exhibit some degree of alteration but this alteration has been overlooked or considered to be of little significance by writers.

The lead-zinc deposits occurring in dolomitized limestone could be subdivided into many types. In general however, most of these deposits might be broadly subdivided on the basis of temperature of formation. The deposits form a gradational series from the well known low temperature telethermal or Mississippi type to the less common higher temperature contact metamorphic types.

The Mississippi type of deposit is characterized by extremely simple mineralization. Galena and sphalerite are the most important ore minerals but some deposits contain silver and others chalcopyrite.
Characteristic gangue minerals are pyrite, marcasite, calcite, jasperoid and quartz. Barite and fluorite occur as gangue minerals in some deposits of this type. Visible intrusive rocks other than small post-ore intrusives are almost totally absent.

The contact metamorphic type of deposit is well exemplified by the lead-zinc deposits at Fahlun in central Sweden. Where the sulphides occur here in limestone, this rock is altered more or less completely to dolomite. The dolomite is more or less altered to ophicalcite and to skarn consisting of such minerals as tremolite, actinolite, diopside, anthophyllite, cummingtonite, humite minerals, forsterite, serpentine and talc. Usually sphalerite and galena appear in the skarn and dolomite.

From an economic point of view, the lower temperature type of deposit forms the more important group. Between the two extreme types mentioned there are types which show development of some silicate minerals which are predominantly magnesian. Higher temperature minerals such as pyrrhotite also become conspicuous. In these lead-zinc deposits from the one extreme to the other, it is interesting to note the prominence of minerals of high magnesium content. Dolomite is generally the only magnesium mineral present in the Mississippi type of deposit while magnesium silicates in addition to dolomite are commonly present in the contact metamorphic type. In either type of deposit, the dolomitization of limestone appears to be a significant type of alteration.
The form of the dolomitized zone associated with lead-zinc deposits varies a great deal. In some cases the deposits appear to be uniformly enveloped by the zone of alteration. In many of these cases the boundaries of the deposits coincide very well with the boundaries of the dolomitic aureoles. A good example of this phenomenon is shown at the Federal Gordon Mine, Picher Field in the Mississippi Valley (35, p. 57). In some deposits, however, large areas of dolomite occur without the presence of ore and ore sometimes lies against unaltered limestone. The width of the dolomitic zone about ore deposits is usually variable, varying from a very narrow zone to hundreds of feet. In most cases the dolomitic alteration has progressed both laterally and vertically throughout the limestone beds. The boundaries of dolomitized zones are in many cases poorly defined and in other cases may be very abrupt. Of the East Tennessee Field, Brokaw (35, p. 75) says:

The change from limestone to dolomite may be abrupt, particularly at a zone of fracturing, but just as commonly the change is gradational, from a completely dolomitized block to an adjacent block containing just a few dolomite scattered here and there in the limestone.

The dolomitization in many cases can be associated with fractures in the limestone. Of the Gold Hill Mining District, Utah, Nolan (1935, p. 94) says:

The marked distinction in color between the unaltered limestone and the dolomite makes it possible to prove dependence of the alteration upon lines of fracturing in the beds.

It seems probable that the dolomitization of limestone beds is related to zones of weakness in most cases but these zones have been obscured
by post dolomitization deformation or ore deposition.

In most instances the process of dolomitization is considered to have preceded ore deposition. In some cases the process is considered to have occurred during ore deposition. Of the Raibl Mine, Italy, Radcliffe (1936, p. 73) says:

The dolomite of the country rock was formed at the same time as the metallic sulphides, as is evidenced by the fact that the distance of outward dolomitization varies with the strength of the orebody.

The validity of such a deduction, however, seems very debatable.

Commonly several ages of dolomite are apparent, the later dolomite occurring in the form of a rather coarse grained pure gangue mineral. This gangue dolomite commonly fills fractures or breccia openings in the previously dolomitized limestone and is often associated with sulphide minerals. Some geologists believe this gangue dolomite results from the introduction of late magnesian solutions, others believe it results from the recrystallization of earlier dolomite along fractures and breccia openings.

In some instances sphalerite is more closely associated with dolomite than is galena. In the Picher Field, Mississippi Valley, galena tends to avoid the massive dolomite areas and to be associated characteristically with jasperoid and calcite gangue while the richest sphalerite deposits occur as a replacement of massive dolomite. Vertical and horizontal zoning are recognizable in the Tri-State District, U.S.A. Dolomite and silica increase with depth
while galena predominates at the higher horizons. The apparent association of sphalerite and dolomite here may be a function of temperature zoning rather than preferential replacement.

**General Theories on the Process of Dolomitization which may be applied to Lead-Zinc Deposits in Limestone**

Several theories have been proposed to account for the dolomitization of limestone in general, but a discussion will be made only of those which might have been effective in connection with the dolomitization associated with lead-zinc deposits in limestone. The two broad theories which might be applicable are:

1. The differential leaching theory
2. The alteration theory

**The Differential Leaching Theory**

When a dolomitic limestone is subjected to solvent action, calcite is taken into solution much more rapidly than dolomite, thus giving rise to concentration of the latter constituent. Many geologists have been of the opinion that by this process, a dolomite might in time result. The power of carbonated waters to remove calcite more rapidly than dolomite from dolomitic limestones under certain conditions, has been demonstrated. Van Tuyl (1916) has advanced the following points
in support of the differential leaching theory:

(1) The development of dolomite along lines of weakness such as fractures in limestone

(2) The apparent tendency of dolomite to be developed in limestone at those points where CO₂ and humus acids are abundant

(3) The porous character of some dolomites

(4) The existence of stalactitic and stalagmitic deposits of nearly pure CaCO₃ in caverns in dolomitic limestone

(5) The increase of magnesium content of weakly dolomitic limestone as an accompaniment of weathering

Some of these points however, support equally well the alteration theory.

Murray (1930, p. 462) in discussing dolomites as oil reservoirs, states that these rocks generally owe their porosities to differential leaching. He says:

Experiments on calcite and dolomite have shown that calcite is many times more soluble in weak acids than dolomite, and analyses of ground water and of streams which have their source in areas underlain by dolomitic limestone show that magnesium is being retained in the rocks whereas calcium is being removed. The residues of the rocks are therefore much higher in magnesium and lower in calcium than the original rocks and more porous, many having porosities greater than could possibly have been rendered by dolomitization. Since organic acids and carbonic acid operate most efficiently on the land surface where circulation has been established, it is concluded that the porosity of a dolomitic limestone is largely produced by leaching action while they are at or near the surface of the land mass.

While there appears to be much field evidence bearing on the fact that calcium carbonate is more soluble than dolomite under near surface conditions, evidence in the literature points
out that under certain conditions dolomitic limestones might provide magnesia-rich solutions. This somewhat controversial issue will be discussed further in a later section of this report.

The process of enrichment in dolomite by differential solution can be readily attacked on account of the very extensive solution and removal of CaCO$_3$ that is required before the percentage of MgCO$_3$ in the residual rock is appreciably raised. Van Tuyl (1916) points out that if only CaCO$_3$ is assumed to be removed, in an original limestone containing one percent MgCO$_3$, 93 percent of the original rock would have to be removed by solution before the MgCO$_3$ content in the remainder would reach 16 percent. Such an extensive removal of CaCO$_3$ would practically obliterate all primary rock structures. The dolomitized zones associated with lead-zinc deposits commonly show little or no obliteration of primary structure.

Sardeson (1940, p. 192) has suggested that the leaching of calcium carbonate in the Galena Limestone of the Upper Mississippi Valley may have been responsible for the concentrations of dolomite, galena and sphalerite. He of course takes the view, which is now considered rather radical, that galena and sphalerite were syngenetic constituents of a magnesian limestone. The solution of calcareous beds has been noted frequently in connection with lead-zinc deposits in limestone, but in no case (excepting the suggestion of Sardeson) has the writer found reference to
dolomitization being directly related to the leaching of calcium carbonate from beds in which dolomitization occurs.

The effect of solution action on calcareous beds has been noted particularly in the lead-zinc deposits of the Upper Mississippi Valley. The effect has been noted by Behre and Heyl (35, p. 65) at the Graham-Ginte Mine. They say:

A feature particularly well developed in this mine is the thinning by solution action of the calcareous beds, apparently during the period of ore deposition. This solution action resulted in partial or complete removal of the lime in the more calcareous layers, leaving only a shaly residue, in rare cases representing as little as a fourth of the original thickness of the bed. Such effects are concentrated in areas under the greatest tectonic pressure; thus, solution had the effect of accentuating the folding.

No mention, however, is made here of an enrichment in dolomite.

Although leaching may have been responsible in part for the dolomitization associated with lead-zinc deposits in limestone in isolated cases, there seems little evidence in favor of it being of general occurrence.

The Alteration Theory

With respect to the dolomite associated with lead-zinc deposits in limestone, the most generally accepted belief today is that it was formed by the alteration of limestone. The conversion of limestone to dolomite by alteration requires the addition of large quantities of magnesia and carbon-dioxide and the removal of large quantities of lime. This conversion in most
instances is apparently brought about by solutions carrying magnesium in some form which partially replaces the calcium in the limestone. If as is commonly conceded, one out of every two equivalents of CaCO$_3$ is replaced by MgCO$_3$, a loss in volume of 12.3 percent would result, providing all of the excess CaCO$_3$ is removed. Although dolomites are commonly more porous than limestones, porosities as high as 12.3 percent are rare. Many dolomites apparently formed by the alteration of limestones are indeed very dense.

Murray (1930) believes that dolomitization is not a molecular replacement but a volume replacement. He is of the opinion that if the replacement resulted in a loss of volume, fracturing and perhaps a decrease in thickness would be developed, but not porosity. He points out that igneous rocks, on loss of volume due to cooling, do not develop porosity but joints and cracks; the same is true of sediments on dehydration and of mud on drying. To Murray, the presence of large numbers of porous beds between dense beds of dolomite and dense mottlings of dolomite in limestones indicate that dolomitization is not a molecular replacement but usually a volume replacement. Cavities which cut across laminated dolomite without deformation show that the cavities were not produced by shrinkage. Lindgren (1933, p. 147) believes that contraction joints formed by shrinkage when limestone is changed to dolomite may provide channelways for mineral bearing solutions but makes no mention of an increase in porosity. Others, including Pettijohn (1948, p. 317) and Bateman (1946, p. 172), believe that the process involves a volume for volume
exchange so that no increase in porosity will result.

In connection with the alteration theory, the mediums by which the dolomitization was carried out must be considered. Two apparent alternatives are:

(1) Circulating groundwaters
(2) Solutions related to magmatic activity

The preceding two points will be considered separately.

(1) Circulating Groundwaters

While groundwaters may be capable of accomplishing local dolomitization by the alteration of limestone, there has been a tendency on the part of some writers to believe this method of alteration is of far reaching significance. Most writers who have supported this view have emphasized the importance of the \( \text{MgCO}_3 \) of groundwater as the dolomitizing agent. The local dolomitization effects in the Leadville Limestones of the Aspen district, Colorado, are attributed by Spurr (1898, p. 206) to the action of the magnesia of groundwater.

Analyses of groundwaters in both igneous and sedimentary rocks and analyses of waters from spring deposits show calcium to be most commonly present greatly in excess of magnesium. Analyses of surface waters given by Leroy and Crain (1949, pp. 188-210) likewise show an excess of magnesium over calcium to be very uncommon. An analysis given by Lindgren (1933, p. 43) of groundwaters in the Joplin district of Missouri where dolomitization is a common phenomenon, shows them to contain more than twice as much calcium as magnesium.
It is rather difficult to understand how such waters can dolomitize limestone when they already contain CaCO$_3$ greatly in excess of MgCO$_3$.

Although dolomites are more abundant in older rocks, pure limestones are quite common in the Grenville rocks. This fact suggests that groundwaters do not play an important role in dolomitization.

Field examples which show that dolomitic limestones have resulted from the action of magnesium-bearing solutions on calcareous rocks seem to be related to pre-heated waters of some type or other. In the case of mineral springs it is conceivable that magnesia might be present in some cases in sufficient proportions to accomplish local dolomitization.

If the dolomitic alteration associated with mineral deposits were accomplished by groundwaters, fractures or other structural controls which localized the ore deposits must have existed long before the egress of the mineralizing solutions. The possibility that groundwaters have been responsible for the dolomitic alteration associated with ore deposits except in local instances seems to be questionable.

(2) Solutions Related to Magmatic Activity

The form of the dolomitic aureoles about many ore deposits suggests the possibility of there being some relationship between dolomitization and ore deposition. The fact that the distance of outward dolomitization from the orebody in some cases varies with the strength of the orebody is also suggestive of a relationship.
The common association of dolomite, galena and sphalerite may suggest a genetic relationship between these three minerals but such need not be the case. There are a number of possible explanations for the relationship between dolomitization and magmatic activity without proposing a genetic relationship.

Hayward and Triplett (1931) from a study of mineralized dolomite in northern Mexico, concluded that dolomitization was the result of regional metamorphism which preceded ore deposition. The ore bearing solutions added no magnesium but merely moved and concentrated it. These field observations agree closely with those of Vanderwilt (1935) in Colorado and Park (1938) in the Metaline district of Washington.

The emplacement of dolomite as a gangue mineral during periods of sulphide mineralization, as is evidenced in many of the deposits of the Mississippi Valley district, indicates that hydrothermal solutions can be called upon to transport magnesium. The close association of zones of dolomitic alteration with lead-zinc ores, both in space and in some cases time of formation, would favor hydrothermal solutions as the dolomitizing agent. Heated solutions, possibly containing permeating volatiles common to early hydrothermal solutions, might be best called upon to account for the broad zones of dolomitic alteration which envelope many lead-zinc deposits.

The form of the dolomitic envelopes surrounding many of the lead-zinc deposits almost requires that the dolomitizing and ore-bearing
solutions were localized by the same structural controls. If hydro-
thermal solutions can be called upon to account for the dolomitic alt-
eration, there need be no fortuity in the spacial association of zones
of dolomitic alteration and lead-zinc ore; the ore-bearing and dolo-
mitizing solutions were localized by the same structural controls.
The localizing structural controls may have been formed by deformation
accompanying the emplacement of the magma from which the dolomitizing
and ore-bearing solutions originated.

The following conclusions may be drawn with respect to the
process of dolomitization:
(1) An enormous transfer of material is required
(2) Dolomitization is probably an alteration process which
    proceeds on a volume for volume basis
(3) The process of dolomitization, as associated with ore de-
    posits, is probably in some way related to magmatic act-
    ivity.

Possible Reasons for the Association of Dolomite and Ore

Many reasons have been advanced to account for the associa-
tion of dolomite and ore; four points which will be considered are:
(1) The association of dolomite and ore might be entirely fort-
    uitous. Palaeozoic dolomites are widespread and hence
    necessarily frequently the host rock for ore occurring in
    Palaeozoic areas.
(2) The association of dolomite and ore might indicate that
dolomite is a preferred host rock for physical or chemical
reasons.

(3) The association of dolomite and ore is due to the fact
that the dolomitizing and ore-bearing solutions have an
identical source.

(4) The association of dolomite and ore might be due to the
fact that the dolomitizing and ore-bearing solutions have
been localized by the same structural controls but need
have no direct genetic relationships. In this case the
dolomitizing solutions may be circulating groundwaters or
hydrothermal solutions related to igneous activity.

The preceding four points will be considered separately.

(1) The Association of Dolomite and Ore is Entirely Fortuitous

A very large proportion of lead-zinc deposits occur in dol-
omites and dolomitic limestones of Palaeozoic age. These rocks are
much more common in Palaeozoic formations than in more recent form-
atations. Since Palaeozoic dolomites and dolomitic limestones are wide-
spread, they might necessarily frequently be the host rocks for lead-
zinc deposits occurring in Palaeozoic areas.

Behre (1940), from a great many observations, concludes that
in virtually all the lead-zinc mines in Europe, French North Africa
and the United States, wherever the stratigraphic sequence includes
both limestone and dolomite, the ore seeks out the dolomitic layers
preferentially or occurs in parts of the beds which have been dolomitized. Hayward and Triplett (1931) conclude that several mining districts in northern Mexico show the same feature. In the Goodsprings district of Nevada, Hewett (1928) found that of the ore bodies of seventy-five mines examined in the district, only two were found which were not enveloped in dolomite and these were on the outer edge of the district.

The widespread association of dolomite and lead-zinc ore seems too general to be entirely fortuitous. The lead-zinc deposits associated with dolomite and dolomitic limestone might be subdivided into two groups; those occurring in primary dolomites, and those occurring in dolomitized zones within limestone. While there may be a degree of fortuity in the association of ore and primary dolomites in formations where these rocks are prevalent, the occurrence of ore within dolomitized aureoles in limestones strongly suggests the possibility of there being some non-fortuitous relationship between the processes of dolomitization and ore deposition.

(2) **Dolomite is a Preferred Host Rock**

Dolomites or dolomitic limestones are believed by most economic geologists to be very favorable host rocks for ore. The chief characteristics of dolomites which have been considered to render them favorable to ore deposition are the following:

(a) The chemical nature of the rock
(b) The physical nature of the rock

(i) Porosity

(ii) Competency

These characteristics will be considered individually.

(a) The Chemical Nature of the Rock

Many geologists have attributed the favorability of dolomite as a host rock for ore to its chemical nature, but few if any modern geologists attempt to name definitely the chemical characteristics that make it more favorable to replacement than limestone. Behre (1940, p. 22) makes the following statement:

Some mines in the outlying parts of the Leadville district, Colorado, show mineralization in the higher parts only of the Leadville dolomitic limestone; analyses of carefully selected, representative samples extending from top to bottom of the formation show no chemical difference adequate to account for the localization of ore.

The chemical nature of dolomitic limestones, however, may indirectly facilitate the acquisition of favorable physical characteristics. The chemical nature of some dolomitic limestones may be such that favorable porosities are developed by differential leaching.

(b) The Physical Nature of the Rock

(i) Porosity

A great deal has been written with respect to the relative porosities of dolomite and limestone. Hewett (1928), from a study of dolomites and limestones from the Goodsprings area, Nevada, obtained the following results:

Range in porosity in 6 limestones...........0.36 to 1.49 %

Range in porosity in 6 dolomites...........1.69 to 3.20 %
He found that the dolomites contained drusy cavities filled with secondary calcite. Hewett felt that if this calcite were removed, the porosity would range from about 3 to 6 percent, probably an average for most secondary dolomites.

Of Mexico's lead-silver manto deposits, Fletcher (1929) stresses the importance of favorable beds. In the Mexican replacement deposits, a number of the best orebodies are found in dolomitic limestones, but it is Fletcher's belief that magnesian content is in no way an essential feature of a favorable horizon, and that the property of these beds that lent itself to magnesian replacement was the same one which later made them amenable to replacement by the mineralizer. It is the texture and not the magnesian element of their composition which was responsible for the mineralizers' invasion.

Bain (1936) made a quantitative evaluation of porosity with respect to replaceability in limestones. He concluded that crystalline limestones are replaced more often than very porous limestones and that cavities in cavernous beds and openings in breccias are usually filled, replacement being negligible. By experimental means, Bain found that rocks with openings $32 \times 10^{-7}$ cm. wide were most susceptible to metasomatic replacement. These rocks also had the greatest amount of linear contact between grains per square cm. and the greatest area of contact between grains per cubic cm.

Of the South-East Missouri District, U.S.A., Behre (35, p.59)
believes the coarser grained dolomite to be more favorable to replacement, but the finer grained types also contain disseminated ore and only the beds of dense dolomite are unfavorable.

(ii) Competency

From a review of the literature, the conclusion may be reached that the most important characteristic of dolomites or dolomitic limestones that makes them preferred host rocks is their manner of fracturing. The difference in competency between limestones and dolomites is such that limestone has the capacity to recrystallize or flow instead of fracturing under stress. Hewett reached this conclusion with respect to mineral deposits at Goodsprings, Nevada. Hayward and Triplett also reached this conclusion with respect to the deposits in northern Mexico. Behre (1940, p. 22) believes, however, that the favorability of dolomitic beds is modified by other factors such as the thickness of the beds. Behre concludes that within two chemically identical beds, the thicker is the more favorable because it tends to break in long continuous fractures rather than shattering in short irregular fractures.

The fracturing characteristics of dolomites alone, however, are inadequate to explain the widespread association of lead-zinc deposits and dolomites. The localization of ore in primary dolomites or in dolomitized limestones fractured subsequent to dolomitization may in many cases be attributed to fracturing characteristics. In such cases open space filling commonly occurs accompanied by some replacement. In the case of lead-zinc deposits occurring within
dolomitic aureoles in limestone, brecciation does not appear to be
the predominant localizing factor although breccia ores are quite com-
mon here also.

The relative favorabilities of the metamorphosed equiva-
lents of pure limestones as compared to dolomitic limestones might
also be discussed here since they appear to be largely dependent upon
physical characteristics. The original composition of these rocks
would seem to determine to a large extent their relative favorabil-
ities to the deposition of ore. Brown (1940) has formulated the
following rules with respect to the favorability as host rocks of
metamorphosed carbonate rocks:

(1) Bands or masses of pure limestone are very resistant to
replacement by ore solutions, and are likely either to
contain no ore or to resist replacement until near the
end of mineralization. The reason for this is apparently
physical, not chemical, since microscopic data indicate
that when ore is deposited by far the greater part of it
substitutes for carbonate. The chief factor is believed
to be lack of porosity in massive limestone that has under-
go ne flowage and recrystallization.

(2) Masses of intensely siliceous or silicated rock are like-
wise unfavorable ore receptacles. This seems to be account-
ed for by two factors; (a) chemical unsuitability or re-
sistance to replacement, and (b) physical resistance to
small-scale brecciation and opening of effective channel-
ways for solutions. Some low grade ore may occur, however,
and also sporadic fracture fillings.

(3) The optimum condition for ore reception appears to be
found in bands or masses containing carbonate and silici-
cates (or quartz) intimately mingled in something like
equal proportions. In this situation movement is likely
to result in mixed flowage and fracture, producing a fine-
textured porosity that admits solutions freely and pro-
vides access to an abundance of replaceable carbonate.
Cleavage cracks in some minerals such as diopside are
believed to facilitate the penetration of solutions.
(4) Certain minerals or assemblages are regarded as favorable impurities in a limestone and others as unfavorable. Original quartz and subsequently developed diopside, and perhaps garnet, are typical premineral gangue matter in general, rather equidimensional, brittle minerals. Tremolite, biotite, and probably wollastonite, are typical unfavorable premineral gangue—in general, highly elongated and somewhat flexible minerals likely to develop under strong shearing stresses.

(5) Tentative opinion is that the ratio of lime and magnesia in a limestone is of little or no importance.

From Brown’s observations it might be said in general that the mineral assemblage produced by the metamorphism of a siliceous or silicated dolomite or dolomitic limestone would be more amenable to replacement than that of a siliceous or silicated limestone. Harker (1950, p. 84) states that in the thermal metamorphism of impure (siliceous) magnesian limestone, silica reacts with the magnesium in preference to the calcic carbonate. Unless disposable silica is present in an amount sufficient for complete decarbonation of the rock, one incident of the metamorphism is dedolomitization. The first mineral to form, and with a limited supply of silica, the only mineral, is the magnesian forsterite. If the rock contained more silica than would suffice to convert all the magnesia to forsterite, diopside makes its appearance accompanying or replacing forsterite. The mineral assemblage thus formed by the dedolomitization of a dolomitic limestone might be very amenable to replacement by ore-bearing solutions.
Dolomitizing and Ore-Bearing Solutions have an Identical Source

If dolomitizing and ore-bearing solutions have an identical source, dolomitization or some process involving the development of magnesian minerals might be expected to occur in all lead-zinc deposits regardless of the type of host rock. The host rock of the lead-zinc ores in the Coeur d'Alene district of Idaho are schists and slates rather than limestones and the veins are sideritic rather than dolomitic. The well known lead-zinc orebody of the Sullivan Mine at Kimberly, B.C. occurs in argillites and siltstones; magnesian minerals are not developed here in quantities that would suggest magnesia was introduced.

Hewett (1928) in reviewing the districts in which limestones have been dolomitized in the vicinity of metalliferous deposits, found the outcrops of pre-mineral intrusive rocks to be either sparse and small or totally absent. The rock types range from siliceous to basic, the average having a composition near that of quartz-monzonite. If magnesia is a constituent of hydrothermal solutions related to magmatic processes, it would be expected that genetically related, undifferentiated igneous rocks would be rather basic (magnesia-rich) in composition.

In conclusion, there is little or no evidence to suggest that dolomitizing and ore-bearing solutions are genetically related.
Dolomitizing and Ore-Bearing Solutions have been Localized by
the same Structural Controls but are not Genetically Related

The localized development of dolomite associated with ore
deposits cannot readily be attributed to primary deposition or alter­
ation by sea waters. If the dolomite or dolomitic limestone is assumed
to have been formed by the differential leaching of calcium carbonate
from syngenetic magnesian limestone, a consideration of the source of
magnesia is unnecessary. If the dolomitizing solutions cannot be
related genetically to hydrothermal solutions of magmatic origin, the
source of the magnesia must be considered; this of course does not
rule out the possibility that solutions related to magmatic activity
might be the agents of dolomitization.

Two remaining possible sources of magnesia are:
(a) Bodies of intrusive rock
(b) Sedimentary and metamorphic rocks

The merits of these possible sources of magnesia will now be con­
sidered.

(a) Bodies of Intrusive Rock

While igneous rocks are potential sources of appreciable
quantities of magnesium, some mechanism for its release is required.
Hewett (1928) noted that any intrusive rocks in areas where dolomitiz­
ation has taken place are generally sericitized, although in many cases
where dolomitization is apparent, the intrusive rocks are not sericit­
ized. The sericitization of mafic minerals is capable of releasing
both lime and magnesia. Comparative partial analyses of fresh and sericitized samples of two types of igneous rocks in which sericitization has been the predominant type of alteration are shown below.

<table>
<thead>
<tr>
<th></th>
<th>Qtz. Monzonite</th>
<th>Andesite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fresh</td>
<td>Sericitized</td>
</tr>
<tr>
<td>SiO₂</td>
<td>67.53%</td>
<td>69.61%</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>15.46%</td>
<td>15.12%</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.18</td>
<td>---</td>
</tr>
<tr>
<td>FeO</td>
<td>2.42</td>
<td>.37</td>
</tr>
<tr>
<td>MgO</td>
<td>.16</td>
<td>trace</td>
</tr>
<tr>
<td>CaO</td>
<td>3.24</td>
<td>.05</td>
</tr>
<tr>
<td>Na₂O</td>
<td>3.24</td>
<td>.42</td>
</tr>
<tr>
<td>K₂O</td>
<td>3.86</td>
<td>4.54</td>
</tr>
</tbody>
</table>

The above analyses show that both lime and magnesia can be released by the sericitization of these rock types.

Hewett considered that this process of sericitization would occur at considerable depths and the released magnesia might be transported by ascending groundwaters to fairly shallow depths where dolomitization would take place.

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1 Ransome, F.L. (1917): Geology and ore deposits of Breckenridge district, Colorado; U.S.Geo.Surv., Prof. Paper 75, pp. 95-101

Since the intrusive rocks most commonly found near dolomitized limestones are quite acid, enormous quantities of the rock must be sericitized to release an appreciable quantity of magnesia. While small amounts of magnesia may undoubtedly be supplied from this source, it can hardly be considered to be of general significance.

(b) Sedimentary and Metamorphic Rocks

Considerable quantities of magnesium are present in many sedimentary and metamorphic rocks but in those other than dolomites or dolomitic limestones, the magnesium is present largely in the silicate form. The problem of the release and transportation of magnesium seems to be one of great controversy. That groundwater is capable of transporting magnesium there is no doubt. Magnesium can be transported in large quantities in either the sulphate or chloride form.

Metamorphic rocks in general are probably not of great importance as potential sources of magnesium. While many metamorphic rocks such as chlorite schists and serpentines contain large amounts of magnesium, no mechanism for its release in large quantities is evident.

Sediments other than dolomites or dolomitic limestones may likewise be regarded as poor potential sources of magnesium. Sedimentary rocks such as graywackes can contain large amounts of magnesium, but again its release in large quantities would require a complex mechanism.
Dolomites and dolomitic limestones, both from the point of view of their magnesium content and their amenability to the release of magnesium, appear to provide an ideal source of magnesium. The widespread occurrence of these rocks also favor them as potential sources of magnesium for the process of dolomitization.

Laughlin and Behre (1934) have suggested that epigenetic dolomite in the Leadville district, Colorado, was derived from the country rock, especially as the lime-magnesia ratio of the country rock nearly coincides with that of the pure dolomite. Hayward and Triplett (1931) and Park and Cannon (1943), in speaking of the ore deposits of northern Mexico and the Metaline district of Washington respectively, believe that no magnesium was introduced during the mineralization of dolomites. These writers are of the opinion that magnesium derived from the country rock was partially redeposited during the replacement of the country rock. If however, the original immediate country rock contains no magnesium, one must assume it was introduced from a source some distance away. In such a case a mechanism for the release and transportation of magnesium must be considered. The two obvious mediums of transportation for the magnesium are groundwater and hydrothermal solutions.

The derivation of magnesium-rich solutions through the leaching of dolomite involves the relative solubilities of the carbonates of magnesium and calcium which make up the dolomite molecule.
Tyrrel's unmodified statement (1948, p. 228) that calcium carbonate is more soluble than magnesium carbonate is in direct contrast with Twenhofel's statement (1939, p. 334) that magnesium carbonate is more soluble than calcium carbonate. Lindgren (1933, p. 823) gives the solubility of magnesium carbonate in pure water at 18° Centigrade as 0.100 grams per hundred grams of water whereas the solubility of calcium carbonate is given as only 0.0013 grams per hundred grams of water. Twenhofel (1939, p. 353) summarizes much of the available data on the problem; in most instances magnesium carbonate is shown to be the more soluble of the two but the effect of the salinity of the medium is not fully known. Irving (1926, p. 1444) shows that an increase in alkalinity favors the precipitation of magnesium, especially after the pH rises above 10. The preceding observations, however, showing that magnesium carbonate is generally more soluble than calcium carbonate, may not be applicable to these components when they are incorporated in the mineral dolomite.

Balconi and Ferrario (1939, pp. 397-404) subjected dolomite to the action of water saturated at atmospheric pressure and room temperature with CO₂, under the following conditions:

1. keeping the dolomite with a definite unrenewed quantity of the liquid
2. treating it with flowing CO₂-saturated water

¹Cited in Chemical Abstracts, American Chemical Society, Vol. 34, 6899.
In the first case analysis of the liquid showed that the quantities of dissolved CaCO$_3$ and MgCO$_3$ were initially in the ratio of 1.4 : 1 and this ratio increased with time. In the second case the ratio of CaCO$_3$ to MgCO$_3$ dissolved remained at about 1.4 : 1. The results of this experiment suggest that under these conditions a magnesia-rich solution cannot be derived from dolomite rock.

A consideration of the derivation of magnesium-rich solutions through the leaching of dolomitic limestones, however, involves the relative solubility of calcite with respect to dolomite in addition to the relative solubilities of magnesium and calcium carbonates in the dolomite molecule. A considerable number of field examples indicate that, in the case of dolomitic limestones, calcite is more soluble than dolomite. Weathered surfaces of dolomitic limestones commonly show dolomite grains standing in relief against more readily soluble calcite. The occurrence of stalactites and stalagmites of pure calcite in caverns in dolomitic limestones would indicate that calcite is more soluble than dolomite. There is little evidence to indicate that the leaching of a dolomitic limestone, under near surface conditions at least, can provide a magnesium-rich solution.

While little evidence can be found in the literature and from field examples to indicate that a magnesium-rich solution can be derived by the leaching of dolomites and dolomitic limestones, the possibility cannot be overlooked. It seems quite probable that the relative solubilities of the two carbonates involved are dependent on the nature of the environment. Hence the effects of alkalinity,
salinity, pressure and temperature may be of considerable importance.

Faust (1949, p. 789) has found that if dolomite is partially dissociated to a mixture of CaCO$_3$ and MgO and this is reacted with a solution of water charged with carbon-dioxide, the MgO will be converted to MgCO$_3$ and remain in the solution, whereas the CaCO$_3$ is only slightly dissolved and a relatively small amount enters into the solution. The mechanism for the derivation of a magnesia-rich solution as outlined by Faust will be discussed in the next section.

The Derivation of a Magnesia-Rich Solution as Proposed by Faust

Faust suggests that within the aureole of metamorphism resulting from the intrusion of a magma into dolomitic rocks, dedolomitization takes place in those beds closest to the magma. The first stage in the dedolomitization of dolomitic beds is the thermal dissociation of the dolomite. The completeness of the decarbonatization is dependent on the temperature. If the temperature is sufficiently high, the reaction is as follows:

\[
\text{CaCO}_3 \cdot \text{MgCO}_3 + \Delta \rightarrow \text{CaCO}_3 + \frac{\text{MgO}}{\text{CaO}} + \frac{\text{CO}_2}{\text{CO}_2}
\]

At lower temperatures the dissociation is incomplete:

\[
\text{CaCO}_3 \cdot \text{MgCO}_3 + \Delta \rightarrow \frac{\text{CaCO}_3}{\text{CaCO}_3} + \frac{\text{MgO}}{\text{MgO}} + \frac{\text{CO}_2}{\text{CO}_2}
\]

Faust places the temperature for complete decarbonatization at 926°C and the incomplete decarbonatization at 792°C. The following factors
however, affect the dissociation temperature of dolomite: grain size, rate of heating, pressure, closure of the system and associated minerals.

If the system is closed so that CO₂ cannot escape, then the effects of thermal metamorphism will consist largely of recrystallization of the dolomite to dolomite marble. If the system is open, allowing CO₂ to escape, periclase can form. If the dissociation reaction goes to completion it is accompanied by a volume decrease of 38 percent. If the dissociation is only partially complete, that is, CaCO₃ does not dissociate, the reaction is accompanied by a volume decrease of 22 percent. As both of these reactions result in a diminution in volume, hydrostatic pressure will favor the thermal dissociation if CO₂ can escape. If the temperature is sufficiently high to dissociate dolomite completely, the resulting minerals would be lime (CaO) and periclase (MgO). No geologic occurrence of a completely dissociated dolomite which contains lime is known, whereas the partly calcined dolomites called predazzite and pencatite have been observed in many places.

Faust assumes that the heat necessary for the thermal metamorphism is supplied by a magma. The mobility of the emanations from a magma permits the gases and solutions to move out into the country rock, and accordingly is an important factor in the transfer of heat from the magma to the country rock. It is generally conceded that the principal constituents of emanations are H₂O and CO₂, the
former being more abundant. The thermal metamorphism of dolomite also releases additional CO₂ at high temperatures which contributes much heat to the system. In addition, small amounts of R, Cl, S etc. are present. As long as dolomite is being dissociated, there will be CO₂ gas available for the thermal metamorphic process. According to Faust, the three factors which make magmatic emanations important in contact metamorphism are; their mobility, which transports heat quickly to the country rock; their greater specific heat; their ability to enter into reaction with the country rock while at elevated temperatures.

From physico-chemical data concerning the system MgO-CaO-CO₂-H₂O, Faust has drawn the following conclusions:

1) calcite is much less soluble than magnesium carbonate in water containing carbon dioxide
2) MgO forms a highly soluble carbonate when it reacts with a solution rich in carbon-dioxide. As a result of these relationships, a dedolomitized dolomite, consisting of MgO (periclase) and CaCO₃ (calcite) will react with a solution of water rich in carbon-dioxide with the transfer of most of the magnesium but with only a minimum amount of calcium in the liquid phase.

If the hydrothermal solution migrating from the cooling magma is poor in carbon-dioxide, it will react with the earlier formed periclase to produce brucite. The hydrothermal solutions which form brucite do not contain much CO₂; brucite is unstable in contact with CO₂-rich solutions.
If the hydrothermal solution migrating from the cooling magma is rich in carbon-dioxide, the earlier formed periclase will be taken into solution. As this hydrothermal solution, rich in magnesium and carbon-dioxide migrates away from the zone of higher temperatures into the cooler country rock, some of the carbon-dioxide may be lost. Such a condition may bring about the precipitation of magnesite. If the hydrothermal solution rich in magnesium and carbon-dioxide migrates into limestone areas, dolomitization takes place. Channelways or fracture systems in limestone may be armoured by dolomite, and thus may yield channelways along which the hydrothermal solutions can migrate without further reaction with the limestone. Magnesite may be deposited in these armoured channelways.

Faust points out an interesting relationship which exists between the occurrence of the metamorphic rocks, predazzite and penticatite, and the type of intrusive rocks which are responsible for their metamorphism. These rocks are predominantly the silicious types such as granites and grandiorites. Their close association with the dedolomitized rocks suggests that the composition of the intrusive rock is a factor in determining the degree of metamorphism of the dolomite.

Possible Evidence Supporting Faust's Proposals

In most cases dolomitization is said to precede sulphide mineralization; the mechanism as proposed by Faust for the derivation of a magnesia-rich solution would fulfill this requirement.
Fluorine-bearing minerals are fairly common constituents of dolomites and dolomitic limestones. The occurrence of the mineral fluorite is common in many of the lead-zinc deposits in dolomitized limestone in the Mississippi Valley, U.S.A. and in the Pennine District of England. The fluorine-bearing minerals phlogopite and chondrodite commonly occur in metamorphosed dolomitic limestones. This association of fluorine-bearing minerals with dolomites and dolomitic limestones might suggest that the process of dolomitization is related to the introduction of early fluorine-bearing hydrothermal solutions. Griggs (1941, p. 527) has had moderate success in the artificial synthesis of dolomite from calcite. He believes that a promising mode of attack on the synthesis of dolomite is experimentation with the common permeating volatiles which leave their traces widespread in nature; namely, boron and fluorine.

Berg (1943)\(^1\) has found that the presence of chlorine lowers the dissociation temperature of dolomite. On heating some samples of dolomite, Berg found the first exothermal effect to appear at 730\(^\circ\) C. accompanied by superheating; in other samples dissociation began at a considerably lower temperature without any superheating. Those of the latter kind were found to contain chlorine, and when this was washed out, their behavior was normal. By the addition of small amounts of NaCl or other alkali salts the abnormal heating effect can be reproduced, the dissociation point falling to 490-520\(^\circ\) C. Since chlorine

\(^1\) Cited in Abstracts, Miner. Mag., 27(187), 1944.
also is generally considered to be a constituent of early hydrothermal solutions, its presence may well aid in the process of dedolomitization as proposed by Faust.

Faust's relationship between the occurrence of dedolomitized rocks and silicious types of intrusive rocks may be correlated with Hewett's observations of the relationship between the occurrence of dolomitized limestone and silicious types of intrusive rocks. Since dolomitized limestones and dedolomitized dolomites apparently occur under similar conditions, the conclusion might be drawn that a relationship exists between these two types of rocks.

The derivation of a magnesia-rich solution as proposed by Faust presupposes that dolomitic rocks must occur within the reaches of an intruding magma. In some formations, especially those of Palaeozoic age, in which limestones occur it seems almost inevitable that an intruding magma will contact dolomitic rocks at depth. The occurrence of lead-zinc deposits in unaltered limestones may suggest that the parent magma has not contacted dolomitic rocks.
The Jackpot Property

Introduction

The Jackpot property is in the Salmo district of British Columbia about 17 miles south of Nelson and 3 1/2 miles east of Ymir. The claims are situated on the crest and northern slope separating Porcupine and Hidden Creeks. New Jersey Explorations Limited hold an option on the property.

All work done on the property to date has been of an exploratory nature. Exploration by means of diamond drilling and open-cutting has been confined to several of the more favorable areas of the property.

General Geology

The rocks of the area consist of recrystallized and metamorphosed limestones and argillaceous to quartzitic sediments which have been complexly folded and faulted. These metamorphosed rocks are intruded by sill-like granitic and aplitic masses which are probably related to a granitic stock exposed a short distance to the south. The sediments are considered to be of Early Palaeozoic age.

1By personal communication with Dr. H.C. Gunning, Department of Geology and Geography, University of British Columbia and from British Columbia Dept. of Mines, Annual Report of the Minister of Mines; 1949, A169.
The northern part of the property is underlain by an assemblage of schist, phyllite and quartzite interbedded with impure limestone and injected and replaced by granite and aplite. This complex is considered to be the footwall of the ore-bearing ground. Overlying this complex is a bed of crystalline limestone having a maximum thickness of about 350 feet. This lower limestone member is succeeded upward by an assemblage of argillaceous and quartzitic sediments having a thickness of something less than 100 feet. The quartzite is in places injected and replaced by granitic rocks. The quartzitic and argillaceous members are overlain by a second limestone stratum which has a minimum thickness of about 350 feet.

The structural picture is very complex. In general the strata lie in broad flexures which dip at low angles southward. Locally the structure is complicated by close folds which plunge for the most part south-southwestward.

The known mineral deposits occur as disseminated sulphide replacements in dolomitized limestone. Both limestone members are extensively dolomitized, the dolomitic zones being generally parallel to the bedding. The dolomitic zones are characterized in surface exposures by granular dolomitic masses which stand out in relief against calcite. Serpentine and other silicate minerals are developed in parts of the dolomitic zone. The chief sulphide minerals are sphalerite and pyrite. Pyrrhotite is abundant locally and galena occurs erratically in the hangingwall or footwall of the
zinc bodies. The heaviest sulphide mineralization appears to be somewhat lenticular in form and is localized in calcareous zones within large dolomite envelopes. In general the areas in which serpentine and other silicate minerals are developed appear to be unfavorable to sulphide mineralization.

The Orebodies

The orebody known as the Main Showing occurs on the Jackpot mineral claim and lies near the base of the lower limestone. This ore zone has the form of a southerly plunging synclinal trough. The showing has been explored by means of numerous open cuts and some twenty diamond drill holes. Several lenticular bodies of disseminated sulphides occur within dolomitized limestone in this area.

The West Showing is on the Jamesonite mineral claim some 750 feet southwest of the Main Showing. This showing appears to be in the upper limestone member. Mineralization exposed by open cuts was of sufficient interest to justify diamond drilling. Substantial widths of rather low grade pyritic zinc mineralization were intersected by diamond drill holes.

The Lerwick Showing is on the Ink Spot mineral claim about 1400 feet southeast of the Main Showing. This showing probably occurs in the lower limestone member. Sparse mineralization with

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1 By personal communication with Dr. H.C. Gunning, Department of Geology and Geography, University of British Columbia and from British Columbia Dept. of Mines, Annual Report of the Minister of Mines; 1949, A169
much pyrrhotite has been found in two zones within dolomitized limestone.

The East Showing is situated some 2,400 feet northeast of the Lerwick Showing. The strata in this area dip fairly steeply eastward. Mineralization has been exposed in several open cuts which may represent one or more mineralized zones in the lower limestone member. This showing has been explored by several diamond drill holes, some of which have intersected encouraging mineralized zones. The mineralization here also appears to be confined to the more dolomitic zones. Zones of white marble do not contain significant amounts of sulphide mineralization. Some zones in which serpentine and other silicates are developed in small aggregates in the carbonate rock, however, do contain appreciable amounts of sulphide minerals.

Method of Study

Specimens selected from two general areas of the Jackpot property were studied in some detail. These two areas are the Main Showing and the East Showing. The specimens from the Main Showing were selected from drill hole J-15. The sections of core selected are believed to be fairly representative of the mineralized zones, the dolomite, the dolomitic limestone, and zones where serpentine and other silicates are developed. From a study of the drill hole log, an attempt was made to determine the relationship of the specimens to the drill hole section.
The specimens from the East Showing were selected from diamond drill holes J-33, J-34, and J-35. The diamond drill core from these three holes was examined roughly by the writer and some general relationships were determined. The specimens selected were believed to be representative of the various zones of the drill hole sections. One surface specimen of mineralized dolomitic limestone was examined.

In order to differentiate calcite from dolomite, the selected specimens of drill core were split by means of a diamond saw and polished and stained by the method described in the appendix. Thin sections were made of those parts of the core which showed interesting relationships on the stained polished surfaces. The specimens from diamond drill hole J-15 were studied in the greatest detail. Thirty power binoculars were used to study the stained polished surfaces.

Descriptions of Specimens Studied

Dolomite

Sections of diamond drill core which consist almost entirely of dolomite were studied in thin section. The rock is now recrystallized dolomite marble made up of anhedral grains varying in size from 0.5 to 1.5 mm. The grain boundaries are commonly very ragged and interlocking. Most of the dolomite grains are very heavily twinned. In addition to having the normal interlocking texture of
recrystallized carbonate rocks, some of the grains have what might be termed a "graphic" texture. Islands of dolomite which extinguish together and have parallel twinning are isolated within dolomite grains of different optical orientation (Plate I A). This "graphic" texture might suggest that the dolomitization of the original limestone took place in several stages. The dolomitization of a limestone is in most cases said to be accompanied by an increase in grain size. Interference during crystal growth gives rise to this interlocking texture. No dolomite crystals of rhombohedral outline were observed.

Some of the nearly pure dolomite rock contains small amounts of high magnesium olivine which will be referred to as forsterite. Forsterite occurs in small subhedral grains which are usually interstitial to dolomite grains but in some cases are completely within dolomite grains. A few laths of a micaceous mineral which is believed to be phlogopite occur in the dolomite sections.

**Dolomitic Limestone**

Two specimens which might be considered to be partially dolomitized limestone were studied in stained thin section. One specimen, J15-105, occurs in the drill hole section 100 feet or more from a mineralized zone of any significance. The other specimen was taken from a surface outcrop, the weathered surface of

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1. Determined as For.97 Fay.3 by Mr. G.A. Wilson by means of the Universal Stage Microscope.
which shows dolomite grains to be standing in relief against calcite. The dolomite grains form mosaic-like bands in the calcite which suggests an alignment with the original bedding of the rock. Some sulphides occur in the calcitic areas of the latter specimen (Plate III A).

The impression gained from the study of the stained thin sections of both these specimens is that they do not represent partially dolomitized limestone, but rather partially "calcified" dolomite. Veinlets of calcite penetrate dolomite grain boundaries and in some cases calcite cuts and embays portions of dolomite grains which have optical continuity (Plates I B, II A and III B).

Specimen J15-105 shows rounded forsterite grains to occur for the most part within the calcitic areas, although a few grains of this mineral were observed to be completely within dolomite grains. Some forsterite grains are partially altered to serpentine. Lath-like grains of phlogopite are fairly common in this rock and several small subhedral grains of apatite were observed. Pyrite occurs sparingly throughout the calcitic and dolomitic portions of the rock.

In several cases optically continuous islands of forsterite were observed to be completely embayed by calcite. If the forsterite were formed by the thermal metamorphism of a siliceous or silicated dolomite, the presence of some calcite in the vicinity
of forsterite would be expected. The amount of calcite present, however, appears to be in excess of that which would be expected by the reaction alone. Additional calcite was probably introduced after the thermal metamorphism of the dolomite. The introduced calcite has replaced dolomite, and to some extent forsterite, largely in the areas where calcite had been formed by the earlier metamorphic action.

Serpentine and Other Silicate Rock

Serpentine occurs typically in some of the more calcareous sections of the diamond drill core. Stained surfaces of serpentine rock, however, indicate that the carbonate is present largely as localized calcite halos which envelope and transect serpentine lenses.

The stained polished surface of specimen J15-327' (Plates VI A and B) clearly illustrates one relationship which exists between calcite and serpentine. The serpentine, varying in color from pale green to greenish-black, occurs in narrow irregular lenses which appear to be generally parallel to the original bedding of the rock. In thin section the serpentine lenses are seen to be transected by minute veinlets of cloudy calcite. The calcite envelopes are most commonly enclosed by dolomite but in several cases masses of fibrous diopside which are partially altered to serpentine occur adjacent to the outer calcite rim. Forsterite grains, some of which are partially altered to serpentine, occur in the dolomitic portions of the rock. While the thin sections reveal that the serpentine
occurs as an alteration product of both forsterite and diopside, there is little evidence in the larger serpentine lenses to indicate from which mineral they were formed. In some cases identically oriented diopside remnants appear to be replaced by calcite and no serpentine alteration is apparent. The serpentine bands contain a few scattered grains of pyrite. The greenish-black bands of serpentine owe their color to the presence of an opaque disseminated mineral which is probably graphite.

The most commonly observed silicate mineral to be developed, other than forsterite and its alteration product serpentine, is wollastonite. Some sections of core are composed almost entirely of this mineral. Specimen J15-431/2' shows an assemblage of wollastonite and diopside, wollastonite being present in the greater amount. The diopside occurs in lenses which have an alignment suggestive of original bedding. The larger wollastonite grains are rather ragged and appear in part to be replaced by diopside.

**Mineralized Sections - Main Showing**

The well mineralized sections, when stained, show in general that the sulphide mineralization is concentrated within well defined areas of calcite which are enveloped by almost pure dolomite (Plate V A). Some narrow bands and disseminated grains of sulphides, however, do occur in the dolomite, unaccompanied by calcite. Specimens from two mineralized zones of the Main Showing were studied, namely; J15-156' and J15-171'.
The sulphide minerals observed in the mineralized sections of drill hole J15 are pyrite, sphalerite and pyrrhotite. The sulphide grains appear to be completely anhedral with the exception of a few cubic crystals of pyrite which occur within blebs of pyrrhotite. The sulphide bands within any one mineralized section are essentially parallel and are probably in alignment with the bedding planes of the original carbonate rock. The contacts between bands of mineralized calcite and surrounding dolomite are abrupt, there being no apparent gradation of calcite into dolomite. In one case the boundary between calcite and dolomite is marked by a narrow somewhat intermittent veinlet of sulphide minerals.

Blebs and small irregular masses of dolomite occur within the areas of mineralized calcite. These irregular masses of dolomite are commonly closely associated with sulphide masses (Plate V B). In some cases blebs of dolomite are completely embayed by sulphide minerals, in other cases sulphide masses are partially rimmed by blebs of dolomite. Small masses of dolomite, however, occur unassociated with sulphide minerals within areas of calcite.

There is no apparent difference in grain size between the calcite and the dolomite, the average being about .7 mm. Calcite is definitely more cloudy in thin section than is dolomite. Most of the dolomite grains are broadly twinned while calcite grains show little twinning. The calcite grains, however, show much better cleavage than do the dolomite grains.
Thin section J15-171' reveals the fact that very few sulphide grains occur in calcite without the association of dolomite. Nearly all sulphide grains are at least partially rimmed by dolomite (Plate VII A). The sulphides are clearly younger than the dolomite as is evidenced by their cutting optically continuous grains of dolomite. In several cases veinlets of sulphide minerals were observed to finger out along dolomite grain boundaries from sulphide masses, possibly indicating the manner in which the replacement was initiated. Calcite also appears to be younger than dolomite since this mineral in some cases cuts optically continuous grains of dolomite. No reliable evidence was seen, however, to definitely determine the age relationship between the calcite and the sulphides. If the calcite was introduced prior to the sulphides, then the dolomite has definitely been replaced by the sulphides in preference to the calcite. The fact, however, that in one case calcite was observed filling a fracture in pyrite suggests that calcite is at least younger than this mineral. Since sphalerite fills fractures in pyrite and pyrrhotite, it is definitely younger than both these minerals. The occurrence of cubes of pyrite within masses of pyrrhotite suggests that the pyrrhotite is the younger mineral of the two. The paragenesis of the sulphide minerals from older to younger than is pyrite, pyrrhotite and sphalerite. In one instance both calcite and dolomite are cut by a narrow veinlet of dolomite (Plate IV). This may be taken to indicate that at least some of the dolomite was formed or emplaced at a late stage.
Mineralized Sections - East Showing

While the study of mineralized sections from the Main Showing indicates that zones in which silicate minerals have been developed are generally unfavorable to sulphide mineralization, this is not entirely true of the East Showing. An examination of mineralized sections from drill holes J33, J34 and J35 indicates also that sulphide mineralization is not necessarily accompanied by calcite, although this mineral is conspicuous in most mineralized sections. Thin sections of specimens J33-55U' and J35-12U' show sulphide mineralization to be closely associated with zones where silicate minerals have strongly but not massively developed in the carbonate rock.

The stained polished surface of specimen J33-55U' shows sulphide mineralization to occur in a calcitic zone. As in the specimens from the Main Showing, small particles of dolomite, which are probably unreplaced residuals, occur in the calcite, in some cases closely associated with sphalerite and pyrite. Since thin section J34-55U' was not stained, a precise distinction between calcite and dolomite could not be made. In the thin section, however, the sulphides are seen to be very closely associated with small aggregates of silicate minerals (Plate VII B). Serpentine, which appears to be an alteration product of forsterite, is the most abundant silicate mineral present. Irregular aggregates of sulphide minerals, most commonly sphalerite, embay or occur as isolated grains in serpentine masses. In some cases remnants of forsterite grains
occur as cores in the serpentine masses. A few unaltered grains of forsterite occur in portions of the section where sulphides are absent or weakly developed. This suggests that the serpentinization has been accomplished by the solutions which deposited the sulphides. Grains of a micaceous mineral which is believed to be phlogopite occur in all parts of the section but are most abundant adjacent to sulphide grains. In some cases laths of phlogopite occur within serpentine masses. The sulphides have shown a distinct preference for areas adjacent to silicate grains but there is little evidence to suggest that the silicates have been replaced in preference to the carbonate. In some cases islands of forsterite which have optical continuity are embayed by calcite. The abundance of calcite in the section, and the fact that it replaces forsterite suggests that this mineral has at least in part been introduced, probably at a late stage.

The thin section of specimen J35-12h' shows pyrrhotite and to a lesser extent pyrite to occur in a zone where silicate minerals have been developed. This thin section was not stained but the stained polished surface shows calcite to be present in abundance. Irregular masses and small blebs of dolomite occur within the calcite. Silicate minerals form approximately 25 percent of the section. The silicate minerals present are diopside, forsterite and phlogopite, diopside being the most abundant. While several large, almost complete, grains of diopside occur in the section, this mineral and forsterite occur for the most part as
clusters of small identically oriented grains which are replaced by carbonate (probably calcite). The sulphides appear to replace the carbonate-silicate mixture. Unreplaced grains and small masses of silicate minerals and carbonate are in some cases completely embayed by the larger sulphide masses. Veinlets of pyrrhotite finger out into the silicate-carbonate aggregate from these larger sulphide masses. A study of the stained polished specimen suggests that the carbonate replacing the silicates is calcite. It seems quite probable that the calcite has been introduced at a late stage, replacing the dolomite and to some extent the silicates formed by the thermal metamorphism of the dolomite. Serpentine has not been extensively developed in this section although a few grains of diopside have been partially altered to this mineral. Laths of phlogopite are scattered throughout the section.

**Discussion**

From the detailed study of a limited number of specimens, no real evidence has been found to indicate that the processes of dolomitization and mineralization are related. A study of diamond drill cross sections of the mineralized zones, however, does indicate that these mineralized zones are in general enveloped by dolomite or rock which is dolomitic. Calcareous dolomitic sections, which in field observation would probably be considered to be partially dolomitized limestone, when studied in stained thin section appear to be partially "calcified" dolomite. From the limited number of specimens studied, however, it cannot be said that all so-called
dolomitic limestones in the area are "calcified" dolomites. Evidence of "calcification" was observed in both mineralized zones within dolomite and unmineralized dolomites some distance from mineralized zones. Quite extensive thicknesses of pure limestone marble do occur in the drill hole cross sections. These limestone sections probably represent original limestone.

Most of the better sulphide mineralization occurs in calcitic zones within broad envelopes which are predominantly dolomitic. Some sulphides, usually disseminated, however, do occur in dolomite with no associated calcite. The paragenetic relationship of calcite and dolomite within the mineralized zones is not as clear as that in the unmineralized zones. The general impression gained by the writer is that dolomite has been replaced by the sulphides to be later partially replaced by calcite in the mineralized zones. Zones in which silicate minerals are strongly developed such as those consisting of massive wollastonite, diopside, forsterite and its alteration product serpentine, appear to be generally unfavorable to sulphide mineralization. Zones, however, in which small aggregates of forsterite and serpentine, and to a lesser extent diopside, occur in intimate mixture with dolomite (now largely replaced by calcite) appear to be quite favorable to sulphide mineralization.

There is no evidence to indicate that all the calcite observed in the mineralized zones and "calcified" dolomite zones
has been formed by dedolomitization. One incident in the metamorphic process, however, has been dedolomitization. The presence of calcite envelopes surrounding masses of forsterite (now largely serpentine) suggests that a form of dedolomitization has occurred.

The thermal metamorphism of a siliceous or silicated dolomite will produce forsterite and calcite according to the following reaction:

\[ 2\text{CaMg}(\text{CO}_3)_2 + \text{SiO}_2 \rightarrow 2\text{MgO}\cdot\text{SiO}_2 + 2\text{CaCO}_3 + 2\text{CO}_2 \]

Since no free quartz was observed in any of the thin sections, it is believed that the silica necessary for this reaction was introduced, although it is quite possible that this mineral may have been a primary constituent localized in some horizons of the original limestone. It is generally believed that the fundamental cause of dedolomitization is found in the fact that magnesium carbonate has a much lower dissociation temperature than calcium carbonate. It is for this reason that magnesia takes precedence over lime in the reactions which accompany the thermal metamorphism of a dolomite. According to Harker (1950, p. 84) the first mineral to form, and with a limited supply of silica, the only mineral, is forsterite. If the reaction which produced forsterite proceeded on a molecular basis, the reaction would be accompanied by a volume decrease of about 22 percent. The volume of calcite formed with respect to forsterite would have a ratio of almost 2 : 1. The proportion of calcite to forsterite observed in some of the calcite-forsterite associations appears to be approximately this ratio, but
in most cases the ratio of calcite to forsterite is much greater. This excess of calcite and the fact that calcite appears to replace forsterite strongly suggests that some calcite at least was introduced.

The product of the thermal metamorphism of limestone in the presence of sufficient silica is a wollastonite rock. The presence of a little magnesia will bring about the formation of some diopside. If silica is present in a dolomitic rock or is introduced in greater quantities than would suffice to convert all the magnesia to forsterite, diopside will be formed. Harker (1950, p. 85) states that the formation of diopside does not in itself import dedolomitization but, if the mineral is subsequently converted to serpentine and calcite, the same result is reached indirectly. It is quite possible that the serpentine and calcite in some of the specimens examined was formed by the alteration of diopside.

The diopside, forsterite and calcite assemblage, according to Bowen (1940), is one formed under conditions of medium temperature metamorphism. Turner (1948, p. 73) notes that the derivatives of dolomitic limestones with silica as the sole impurity fall within the left hand half of Fig. 1.
In order of decreasing silica, and increasing magnesia content, the silica-deficient assemblages are: calcite-wollastonite-diopside, calcite-diopside-forsterite and calcite-forsterite-periclase. Since no periclase (or brucite) was found in any of the sections examined, it might be concluded that silica was present or was introduced in sufficient amounts to form the silicates, or that the metamorphism took place under conditions of high pressure which are said to be unfavorable to the formation of periclase.

The formation of calcite by the type of dedolomitization just described cannot be called upon in most cases to explain the close association of calcite and sulphide mineralization. The close association of sulphide minerals with small masses of forsterite (now largely altered to serpentine) as observed in specimens from the East Showing may, however, indicate that calcite formed by the thermal metamorphism of a siliceous or silicated dolomite is amenable to
sulphide replacement. The greater part of the sulphide mineralization, however, occurs in zones in which magnesian silicates have not been extensively developed. Several tentative possible explanations for the association of calcite and sulphide minerals within dolomitized zones in which silicate minerals have not been extensively developed follow:

(1) The calcitic zones represent portions of the original limestone which have been incompletely dolomitized. The islands of dolomite occurring in the calcite, in many cases rimming sulphide minerals, may represent metasomes of replacing dolomite. The fact that the calcite in the mineralized zones has a very low degree of transparency might be taken as an indication that it is primary. If such is the case, zones of undolomitized or partially dolomitized limestone were more amenable to sulphide replacement than the enclosing dolomite.

(2) Perhaps the process of dolomitization was followed by one of partial dedolomitization in zones where sulphide minerals were deposited. The magnesia formed by the partial thermal dissociation of the dolomite was removed by solutions rich in CO$_2$, leaving calcite. The process of dedolomitization as outlined by Faust might be progressive, that is, dolomitization accomplished by the early emplacement of a magma is followed by dedolomitization at a later stage in the hydrothermal activity.
This process of later dedolomitization might be more localized than the preceding process of dolomitization, following chiefly the channelways and zones of weakness where sulphides were deposited. If such is the case, the islands of dolomite within the calcitic zones are residuals which have not been dedolomitized.

While no concrete evidence was observed in a study of specimens to support this explanation, some suggestive evidence was observed. The calcite in some of the sulphide zones is rather vuggy—a loss of volume may have been brought about by dedolomitization. Pyrrhotite appears to be more common in the mineralized zones of the Main Showing than in those of the East Showing. Similarly calcite appears to be more abundant in the mineralized zones of the Main Showing than in those of the East Showing. If pyrrhotite can be considered a high temperature mineral, one might conclude from these observations that higher temperatures prevailed where calcite is more abundant. Since the process of dedolomitization as proposed by Faust requires fairly high temperatures, the calcite may have been formed as a result of this process.

(3) The calcite associated with the sulphide mineralization may have been transported by hydrothermal solutions at a late stage in the hydrothermal process. The calcite has partially replaced the dolomite in the zones where sulphides were deposited. Residual masses of dolomite have
been left within the calcite and as partial rims around sulphide masses. The calcite has been localized by the same structural controls as the mineralizing solutions. The paragenesis of the dolomite, sulphides and calcite, if it can be relied upon, would indicate that calcite is the later mineral.

According to Faust, the MgO derived from the incomplete thermal dissociation of a dolomite is more soluble than CaCO$_3$ in waters rich in CO$_2$. At a late stage in the hydrothermal activity, it seems quite conceivable that the hydrothermal solutions will become poor in magnesia due to the fact that this material has been largely removed from the zone of thermal dissociation. The hydrothermal solutions will then become relatively rich in lime. These later solutions, rich in lime as compared to magnesia, may account for the replacement of dolomite by calcite in zones where sulphide minerals have been deposited. The magnesia taken into solution by the replacement of dolomite in the mineralized zones will be transported elsewhere. These solutions, enriched in magnesia at a late stage in the hydrothermal activity may be called upon to account for the dolomite which commonly fills post-ore fractures.

Of the three explanations proposed for the association of calcite and sulphide minerals within dolomitized zones, the writer
is of the opinion that the latter is the most applicable to the phenomenon as observed in specimens from the Jackpot property.

Conclusions

While dolomite appears to be very favorable host rock for lead-zinc ore, this favorability is probably not entirely responsible for the localization of the ore within dolomitized envelopes in limestones. The fact that the dolomitic alteration generally precedes ore deposition and is favorable to ore deposition may be merely a very providential circumstance. Evidence suggests that the occurrence of dolomitic aureoles enveloping lead-zinc deposits in limestone is an inherent characteristic in a great many deposits of this type. The zones of dolomitic alteration are undoubtedly localized by structural controls. Lead-zinc ores are probably to a large extent localized by the same general structural controls and may therefore occur for the most part within dolomitized zones. The general structural localization of ore within dolomitized zones is probably further modified by the favorable characteristics which are attributed to dolomite as a host rock.

From both the point of view of their magnesium content and their amenability to the release of magnesium, dolomites or dolomitic limestones provide a most adequate source of magnesium for the dolomitization of limestone. The mechanism proposed by Faust for the release of magnesium from dolomites and its transportation to outlying areas where the dolomitization of limestone
is accomplished fulfils the requirement that dolomitization precedes sulphide mineralization and dolomitizing solutions are directly but not genetically related to magmatic solutions.

Field evidence indicates that the mineralized zones of the Jackpot property occur within broad dolomitic envelopes in limestone. The writer's study of specimens from this property indicates that dolomitization preceded the deposition of sulphide minerals. No evidence was found to indicate the manner in which dolomitization was accomplished. Practically all significant sulphide mineralization is associated with calcite either within pure dolomite or within dolomite in which silicate minerals have been strongly, although not massively, developed. In either case the calcite is a late mineral being for the most part at least, post-sulphide in age. The dedolomitization accompanying the thermal metamorphism of the dolomite is undoubtedly responsible for the presence of some calcite in the silicate zones but it is believed that additional calcite has been subsequently introduced.

Sections of carbonate rock, which from a field study might be considered dolomitic limestone, when studied in thin section appear to be partially "calcified" dolomite rather than partially dolomitized limestone. The areas surrounding mineralized zones probably were originally completely dolomitized but have been subsequently partially replaced by calcite.
A dedolomitized dolomite in the vicinity of the parent magma of the ore-bearing solutions might be called upon as a source for the later calcite in both the mineralized and unmineralized zones within the dolomite. At a late stage in the hydrothermal activity, when the magnesia has been largely removed from the thermally dissociated dolomite, the hydrothermal solutions might have become relatively rich in the less soluble calcium carbonate. The calcium carbonate carried by these solutions may have replaced dolomite in structurally favorable zones of the previously dolomitized limestone, mineralized zones being especially favorable.
Suggestions for Future Study

From a review of the literature pertaining to dolomitization and the relationship of dolomite to lead-zinc deposits, and also from a study of specimens from a lead-zinc deposit occurring in dolomitized limestone, the writer concludes that the problem of the association of dolomite and ore warrants much further investigation. Some suggestions will be made with regard to the phases of the problem which most require study and several possible means of acquiring a more complete knowledge of the problem will be proposed.

One basic requirement is a knowledge of the process or processes by which limestone is altered to dolomite. Laboratory experiments have been only moderately successful in duplicating the apparently simple reaction by which calcium in limestone is partially replaced by magnesium to form dolomite. Additional experimentation in this phase of the problem is essential. Controlled laboratory experiments on the synthesis of dolomite under conditions which might be applicable to its formation in nature could be best accomplished by the cooperative efforts of chemists and geologists.

The field relationships of dolomite and ore must be studied in greater detail. Staining methods are applicable, to some extent, to field use. General relationships between calcite, dolomite and ore in diamond drill core and in reasonably smooth-surfaced
rock specimens can be determined in the field by the copper nitrate staining method.

The determination of general field relationships will facilitate the selection of specimens from representative zones which require detailed study. Many detailed relationships can be determined from a binocular microscope study of stained polished surfaces. A more detailed study may be accomplished by a petrographic examination of stained thin sections. Staining is essential if the overall picture of the association of calcite and dolomite in a thin section is to be gained from a petrographic study.

A careful study should be made of the relationship of dolomitized zones to possible structural controls. For optimum conditions of study, deposits should be selected in which the structural picture is simple and which exhibit a minimum amount of contact metamorphic effects. If the structural picture is complex or if the dolomitized zones have been thermally metamorphosed, the relationship of the dolomitized zones to possible structural controls may be obscured.
Appendix

Staining Technique

Principles Underlying Staining Methods which Distinguish Calcite from Dolomite

The success of stains in distinguishing calcite from dolomite is dependent on the following two facts:

(1) Calcite has different chemical properties than dolomite. A reagent must be selected which reacts with one mineral only, or reacts with the two minerals at different rates.

(2) No complete mineralogical gradation exists between calcite and dolomite. If the two minerals formed a complete isomorphous series, staining methods would probably not provide a sharp index of composition.

Staining methods in general employ the salt of a strong acid and a weak base, the solution of which acts like a weak acid. The salt chosen is such that upon attacking the calcite, it leaves a coating of a compound that is colored or that can be made to acquire a color.

According to Rodgers (1940, p. 788), all rhombohedral carbonates except calcite react to weak acid in the same way as dolomite, and the orthorhombic carbonates (except cerussite) react in the same way as calcite. Separation can therefore be effected between these two groups. In the calcite-rhodochrosite isomorphous series, distinction can be made between pure calcite and material high in manganese.
The Staining Methods

Several staining methods have been devised for distinguishing calcite from dolomite. Some of these stains are more exacting than others. Leroy (1949, p. 162) lists the following five staining methods in the order of his preference:

1. Fairbank's Method
2. Copper Nitrate Method
3. Silver Nitrate Method
4. Lemberg Method
5. Potassium Ferricyanide Method

Most writers who have used staining methods to distinguish calcite from dolomite prefer the Fairbank's method, although it is said to have some disadvantages. The color contrast provided by this method is not particularly good in dark calcareous rocks, especially for photographic purposes. The film of stain is said to check and peel in some cases.

Leroy's second choice, the Copper Nitrate method, as described by him, does not make use of the most recent modifications made in the procedure. The writer found the modified Copper Nitrate method to give excellent staining results. While no other method was used by the writer, some staining results of other methods used by Jory (1950) were observed and considered inferior to those obtained from the modified Copper Nitrate method.
History of the Copper Nitrate Staining Method

Staining by copper nitrate solution appears to have been introduced into the English literature by Holmes (1921, p. 267). He, however, found it necessary to powder the mineral to be tested and boil the powdered mineral for a few minutes in a concentrated copper nitrate solution. By this method, the calcite particles acquired a strong green coloration while the dolomite remained unaffected. No reagent was used to fix the stain.

Ross (1935, p. 8) appears to have been the first to make extensive studies of polished surfaces stained by immersion for several hours in a cold dilute solution of copper nitrate. After several hours of immersion in the solution, the more readily attacked calcite acquires a faint blue-green stain of copper carbonate. The faint blue-green stain of copper carbonate so obtained is in no way fixed to the calcite but rubs off readily. The blue-green stain acquired in the nitrate solution is washed in ammonium hyd­roxide, which produces a deep blue stain of $\text{Cu(NH}_3\text{)}_4\text{(OH)}_2$ on the calcite. Ross found the stain to be coherent and firm. The blue stain provided a distinctive contrast with other minerals and photographed extremely well. The method provided, in Ross' case, a means of distinguishing pure calcite from siderite, ankerite, rhodochrosite, and manganiferous calcite, all of which are unaffected by copper nitrate.

Rodgers (1940, p. 788), using the same general procedure
as Ross, refined the staining method and made an effort to further increase the color contrast between calcite (stained blue) and dolomite (white). By a series of laboratory tests on calcite-dolomite specimens, conducted under variable concentrations of nitrate solution and variable immersion times, Rodgers arrived at what he believed to be the optimum conditions for staining according to the requirements of the study.

Keith (1946, p. 971), used the copper nitrate staining method as described by Rodgers to distinguish between calcite and dolomite. He concluded that this method produced less uniform staining results than the Lemberg method.

Staining Procedure as Outlined by Rodgers

Rodgers concluded that a molar solution of copper nitrate produced the most satisfactory results. A molar solution of copper nitrate is prepared by adding the given amounts of either of the following compounds to 1000 gm of water:

188 gm Cu(NO₃)₂
255 gm Cu(NO₃)₂·3H₂O
332 gm Cu(NO₃)₂·6H₂O

The specimen to be stained must have a fairly well polished surface. The polished surface is immersed in the nitrate solution in such a way that it is elevated from the floor of the containing vessel. The polished surface must be free from contamination which might prevent the surface from wetting. It is advisable to wet the polished surface prior to immersion so air bubbles do not
adhere to it.

Rodgers recommends immersion for a period of five to six hours at room temperature unless there is an excess of calcite. For specimens high in calcite, two and one-half to four hours is sufficient, depending on the purpose of the study. On removal from the nitrate solution, the polished surface is immersed, without washing and before drying, in ammonium hydroxide. A few seconds of immersion in the ammonium hydroxide is sufficient to fix the stain, a longer immersion has no apparent undesirable effects. After the stain is fixed, the specimen is washed and may be slightly buffed to remove any excess precipitate. After the ammonia treatment the stain is permanent and will stand up to considerable buffing.

Dolomite, especially after long immersions in the nitrate solution, may develop a faint green haze. For optimum conditions of distinction between calcite and dolomite, the calcite stain should be deep and uniform while the dolomite has not begun to stain on the borders to blur the contacts. Some lack of uniformity in the coating on the calcite may be preferable to the lack of distinctive contacts. In specimens consisting largely of calcite, long immersions in the nitrate solution results in a heavy stain and structural details may be obscured. Structural details are best observed with thin but uniform stains.

This staining method can not be relied upon for calcite-dolomite distinctions in rocks having porous or weathered surfaces.
These surfaces soak up the solution and react with the ammonium hydroxide regardless of the mineralogical composition of the rock. On reasonably well polished surfaces of compact rocks the stain is reliable. The stain appears to be very selective even in rocks containing very fine aggregates of calcite.

The copper nitrate solution is very stable and is not affected by standing unused. The solution can be used to stain a great many specimens before becoming exhausted, but should be filtered occasionally. The ammonia solution quickly turns a deep blue color but this does not cause anomalous staining. The ammonia solution can be used as long as it smells strongly of ammonia.

Observations and Modifications of the Writer

The surface of diamond drill core of compact rocks is sufficiently smooth to provide diagnostic distinctions between calcite and dolomite, although smoother surfaces are desirable for detailed study. Very good staining results were obtained on surface ground with #240 Carborundum and #95 Aloxite on a cast iron lap. Specimens ground successively with the two aforementioned abrasives and then highly polished on a felt lap did not appear to stain as well as those ground with the abrasives. With equal immersion times in the nitrate solution, the stain acquired by the more highly polished surfaces was thinner and paler in color than those acquired by the less highly polished surfaces. The more highly polished surfaces probably resist the wetting action of the nitrate solution to a greater extent than do the rougher surfaces, thus the
chemical reaction is retarded.

With respect to the strength of the ammonium hydroxide solution that is used to fix the stain, Rodgers merely states that a strong solution should be used. The writer found that very strong solutions tend to dissolve the stain rather than fix it. A rather dilute solution of ammonium hydroxide in which the odor of ammonia can be distinctly detected was found to be of sufficient strength to fix the stain. A 2N. solution of NH$_4$OH produced very satisfactory results.

Even greater calcite-dolomite contrast can be attained by etching the polished surfaces in dilute hydrochloric acid prior to staining. Polished surfaces thus treated were immersed for about one minute in five percent hydrochloric acid and then stained in the usual manner. The dolomite, unetched by the acid, stands out distinctly against the blue stained calcite of lower relief. Most sulphide and silicate minerals are likewise unaffected by the dilute hydrochloric acid and stand out from the calcite after etching. The etching process facilitates the observation of a partial three dimensional picture of the mineral associations. The distinction between calcite and unetched minerals can be very effectively shown in photographs of the etched stained surfaces taken under oblique lighting. The shadows cast by the unetched minerals effectively accentuate the relief (Plate V B).
The Preparation of Stained Thin Sections

The copper nitrate staining method provides an equally diagnostic means of distinguishing calcite from dolomite in thin section (Plate II B). The technique used in preparing stained thin sections will be described here.

One side of the rock slice from which the thin section is to be made is ground and polished. The polished surface of the rock slice is stained and mounted with Canada balsam on a glass slide with the stained surface facing the glass. The mounted rock slice is then ground to the desired thickness from the unstained side and sealed with a cover glass.

If the thin section is stained on the side adjacent to the cover glass after the section has been mounted and ground to the desired thickness, some anomalous staining will probably result. Porous areas of the slide or areas from which mineral grains have been plucked will trap the nitrate solution and stain, regardless of the mineral composition. Also, the immersion in the nitrate solution of the mounted slide may disintegrate the Canada balsam.

The stained calcite has a bluish green color when viewed in thin section. Presumably the yellow tint of Canada balsam superimposed on the blue stain produces this greenish color. The textural relations of calcite aggregations are largely obscured by the almost opaque stain (Plate II B).
Merits of the Copper Nitrate Staining Method

(1) It appears to be as delicate as other methods
(2) The stain does not shrink or crack
(3) The stain is usually very uniform
(4) The stain does not rub off easily
(5) The staining can be accomplished at room temperatures
(6) The solutions are easily prepared and are stable
(7) The stain shows up equally well on light or dark-colored specimens
(8) The stain contrasts well with other minerals in photographs
(9) The stain is applicable to both polished rock surfaces and thin sections

The one obvious disadvantage of this staining method with respect to some of the other methods is the time required for staining. Staining by some of the other methods requires only a few minutes.
A. Specimen J15-71'-thin section. Dolomite showing "graphic" and interlocking grain texture.

B. Jackpot surface specimen-stained thin section. Calcite(blue) cuts and replaces an optically continuous dolomite grain(white).
A. Specimen J15-105'-stained thin section. Calcite (blue) cuts and replaces an optically continuous dolomite grain (white). Pyrite (yellow) is closely associated with a grain of dolomite.

B. Specimen J15-105'-stained thin section. Photograph shows the association of calcite (black) and dolomite (white) in "calcified" dolomite.
A. Jackpot surface specimen—stained polished surface. Residual bands of dolomite (white) in calcite (dark grey). Sphalerite (black) is confined to the calcite areas. A vein of late dolomite (upper right) cuts older dolomite, calcite and sphalerite.

B. Jackpot surface specimen—stained polished surface. An enlarged section of the dolomitic portion of the specimen shown in Plate III A. Calcite (black) is believed to replace dolomite (grey). Fingers of calcite penetrate dolomite grain boundaries.
Jackpot surface specimen - etched and stained surface. Enlarged section of upper right hand portion of specimen shown in Plate III A. A vein of dolomite (white) cuts earlier dolomite (light grey), calcite (dark grey) and sphalerite (black).
A. Specimen J15-156'-stained polished surface. Mineralized bands of calcite (dense lighter grey) occur within dolomite (mottled darker grey). The sulphides are shown to occur almost exclusively within the calcite bands.

B. Specimen J15-156'-etched and stained surface. Enlarged portion of mineralized band shown in Plate V A. The sulphides sphalerite (black) and pyrrhotite (grey shagreen surface) occur in most cases closely associated with blebs of dolomite (grey smooth surface) in a groundmass of calcite (white). Blebs of dolomite and sulphide minerals are less commonly individually embayed by calcite.
A. Specimen J15-327'-stained polished surface. Serpentine lenses (black) are shown to be enveloped by halos of calcite (white) within dolomite (grey).

B. Specimen J15-327'-stained polished surface. An enlarged section of the lower right hand portion of the specimen shown in Plate VI A. Calcite veinlets are seen to transect the serpentine lenses.
A. Specimen J15-171'-stained thin section. The sulphides sphalerite(brown) and pyrite(yellow) are shown in most cases to be partially rimmed by dolomite(white) within calcite(blue). A mass of pyrite(right center) is seen to replace optically continuous islands of dolomite.

B. Specimen J33-554'-unstained thin section. Sphalerite(brown) is shown to be closely associated with a mass of serpentine(grey) which contains residual cores of forsterite. The greater part of the carbonate(white) is believed to be calcite.
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