PHASE EQUILIBRIA IN CALC-SILICATE HORNFE[LS] LEWIS AND CLARK COUNTY, MONTANA

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ABSTRACT

Siliceous dolomites are progressively metamorphosed through the "al[...] "hornblende" and "pyroxene granulite" facies around a granitic stock 12 [...] Lincoln, Lewis and Clark County, Montana. Contrasting initial composi[...] adjacent carbonate-rich beds gave rise to many irregularities in this prog[...] informative reaction relationships at bed interfaces.

These relationships and application of the phase rule, which is faciliatated [...] approximation of many of the beds to the CaO-MgO-SiO$_2$ system, indicate [...] equilibrium was attained within beds but that chemical potential gradients of [...] "inert" components existed across bed interfaces, (2) that low-variant a[...] common, but that assemblages with large variance predominate, and (3) th[...] volatile content determined in part the derived metamorphic assemblages.

Data on the composition and mineralogy of the Helena dolomite outside [...] allow inferences concerning the specific reactions by which the metamorphi[...] evolved. In addition, rough limits on the temperatures and total volatile pre[...] these reactions occurred can be estimated by a combination of field, petro[...] experimental data.

INTRODUCTION

Application of the Gibbs phase rule to problems in me[...] petrology has furnished much information concerning cond[...] metamorphism, particularly with regard to the behavior of [...] Such application, as recently reviewed by Zen (1963), is depe[...] proper identification of all minerals in a given assemblage, on th[...] relations between the minerals, and on the compositions of th[...] and whole rock. Such data were obtained through petrograp[...] diffraction and partial chemical analytical studies of a syst[...] collected suite of hornfels around an epizonal granitic stock in t[...] Mountains of west-central Montana.

Because of the small grain size of these hornfels and the sie[...] of many of the minerals, particularly of the diopside and [...] mineral separations are practically impossible. Thus, the stud[...] mainly on the absence or presence of minerals and on textu[...] rather than on the composition of co-existing minerals. H[...] compositional simplicity of many of the beds allows rela[...] inferences concerning the attainment and conditions of equil[...] particular, the carbonate beds closely approximate the C[...] system and the argillaceous beds may be interpreted in [...] CaO-MgO-SiO$_2$-KAlO$_2$ system.

The data bears particularly on the interpretation of CO [...]

[...] value" or "initial value" components (Zen, 1963) in an epi[...] [met]amorphic environment. The limitations of the phase [...] [ob]taining such information have been reviewed most recently by [...] and Fyfe (1964).

[Th]e Helena dolomite (Knopf, 1950), from which the hornfels were [...] consists largely of rhythmically interlayered argillaceous and [...] quartz beds on a hand specimen level. At some places these [...] be traced directly into the aureole. Such localities allow direct [...] of metamorphic assemblages in beds of contrasting composi[...] [whi]ch were subjected to the same temperatures and total volatile [...] Particularly interesting and informative in this regard are [...] effects at the boundaries of such beds and their indications of the [...] mobility of components under the influence of compositional [...]

[...] study of the hornfels from western Montana was suggested by [...] (1907) detailed study of contact metamorphism around the [...] [gr]anite stock, located a few miles southeast of the area described here.

GEOLOGIC SETTING

[...] Granite Peak stock is about 12 miles east of Lincoln, Lewis and [...] County, Montana, and is but one of many late Cretaceous or early [...] epizonal intrusions on the north side of the Boulder batholith [...] 1907; Pardee and Schrader, 1933; Knopf, 1913, 1950, 1957,

[...] stock, which was emplaced by magmatic stopping, is about $1\frac{1}{2}$ [...] a diameter and occurs in one limb of a broad fold involving the [...] [Cam]brian Belt series. The structure around the stock is thus rela[...] [si]mple as shown schematically by Fig. 1. Little or no doming [...] [accom]panied intrusion of the stock. Only the area from which most of the [...] samples were collected is shown in Fig. 1. The details concerning [...] [str]ucture of the area, and petrography and mode of emplacement of [...] [Gr]anite Peak and nearby stocks are discussed as part of the general [...] of the Lincoln area (Melson, 1966).

[...] where adjacent to the stocks, the Helena dolomite is essentially [...] [met]amorphosed. It is the only formation in exposed contact with the [...] Peak stock and is about 5,000 feet thick.

CONTACT AUREOLE

[Metamor]phic zones. On the south side of the aureole, where the Helena [...] may be traced into the contact aureole (Fig. 1), the first macro[...] [ch]ange on approach to the granite contact occurs abruptly over [...] feet and is marked by the occurrence of light-colored diopside

rocks. Tremolite rocks occur about 5 to 50 feet further from the granite contact than the diopside rocks but are commonly drab-colored and macroscopically indistinguishable from unmetamorphosed Helena dolomite.

Within about 300 feet of the granite contact the rocks are coarse grained, locally contain wollastonite and cordierite, and in places have
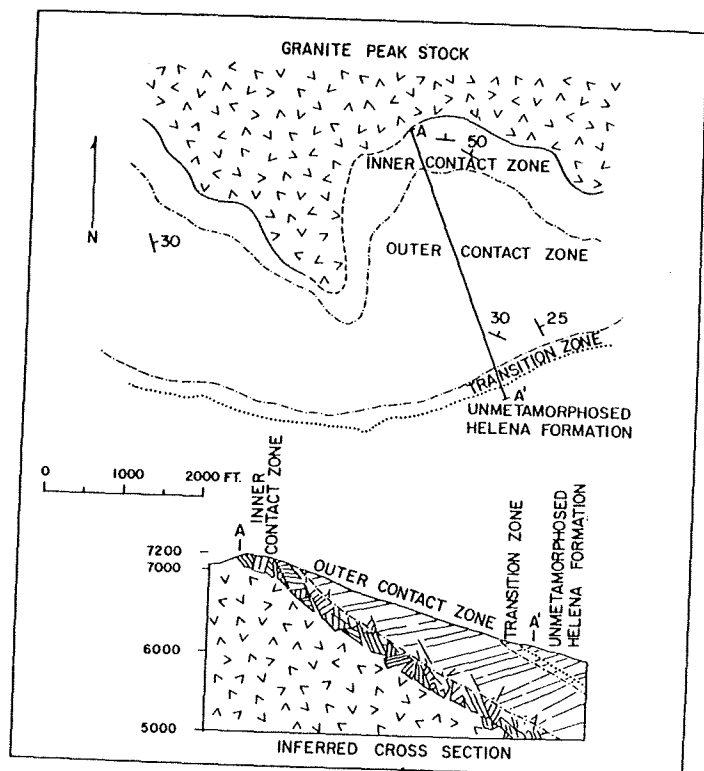

Fig. 1. Geologic map of the Granite Peak aureole.

been compositionally modified by reactions with magmatic solutions. Such reactions, many of which involved considerable bedding-plane replacement, mainly produced andraditic garnet, vesuvianite, calcite, epidote and quartz-bearing tactites similar to those in the contact aureole of the Marysville stock (Knopf, 1950).

In the following discussion, the tremolite rocks define the "transition zone", the diopside rocks, the "outer contact zone", and the wollastonite-cordierite rocks, the "inner contact zone". The metasomatically altered rocks of the inner contact zone are the subject of a separate study. Much

TABLE 1. MINERALS IN VARIOUS LAYERS FROM SOME SPECIMENS FROM THE TRANSITION AND OUTER CONTACT ZONE. ORIGINAL COMPOSITION INFERRED FROM MINERALS PRESENT AND THEIR RELATIVE ABUNDANCE. LISTED IN APPROXIMATE ORDER OF DECREASING DISTANCE FROM THE GRANITE CONTACT. MINERALS PRESENT INDICATED BY (x). EACH COLUMN REPRESENTS A SINGLE LAYER

Minerals	Spec. no.[1]								
	1	2	3	4	5	6	7	8	9
tremolite	x	x	x	x	x x x	x x	x x	x x	x
phlogopite			x x		x	x x	x	x	
diopside		x	x x x	x x	x	x		x	x x x
calcite	x	x x		x	x	x x	x		
potassium feldspar	x	x	x	x	x		x	x x	x
plagioclase		? x	x x ?	x x	x	x x ?	x		x x
"clinozoisite"		? x	x x x	x x x	x x x	x x x	?	x	x
scapolite		x		x					
quartz	x		x	x x x	x x x	x x x	x x	x	x
sphene	x	x	x x x	x x x	x x x	x x x	x x	x x	
pyrite	x	x x x	x x x	x x x	x x x	x x x	x x	x x	
Initial comp.	1	2	3	4	5	6	7	8	9
carbonate-quartz beds		x		x	x	x	x		
argillaceous beds	x	x	x	x	x	x	x x	x x	
intermediate beds			x x	x	x				x

[1] Field number and approximate distance from mapped granite contact:

1. BH 1; 2000 (end of transition zone)
2. 44 m; 1500
3. 44 h; 1200
4. 44 i; 1200
5. 12a2; 1100
6. 12a1; 1000
7. 44 g; 1000
8. BH14; 900
9. 44 k; 800

of the following discussion is based on the transition and outer contact zones, representative assemblages of which are listed in Table 1. The minerals were identified petrographically and by whole-rock x-ray diffraction study. Clinozoisite as used in Table 1 refers to a clinozoisite-like epidote group mineral. The structural state of the feldspars was not determined.

TABLE 2. ESTIMATED RANGE IN COMPOSITION AND PRINCIPAL MINERALS IN WHICH CONSTITUENTS OCCUR IN THE UNMETAMORPHOSED HELENA DOLOMITE

Component	Estimated range (molar %)	Principal phases
SiO_2	25–60	detrital quartz
CaO	10–40	calcite and dolomite
MgO	10–30	dolomite, chlorite and perhaps magnesian illite
Al_2O_3	less than 6	illite, chlorite, other mica group minerals[1]
K_2O	less than 2	illite, detrital microcline
Na_2O	less than 2	detrital plagioclase and perhaps mica group minerals
FeO	less than 1	dolomite and pyrite
Fe_2O_3	less than 0.1	detrital mica group minerals?

[1] Kaolinite and montmorillonite were not noted in the Helena dolomite.

TABLE 3. MAGNESIUM AND CALCIUM CONTENT OF METAMORPHOSED AND UNMETAMORPHOSED HELENA ARGILLACEOUS BEDS

Specimen no.	Weight percent		Mg/Ca molar ratio
	MgO	CaO	
1	6.2	5.2	1.7
2	8.3	0.0	—
3	4.8	0.0	—
4	10.7	9.1	1.6
5	6.2	4.7	1.8
6	7.8	6.0	1.8
7	9.2	8.4	1.5

Analyst: W. G. Melson

1. Unmetamorphosed argillaceous bed. Diffractometer trace shows chlorite and illite with small amount of calcite. Quartz is principal constituent. (field no. 44e3)
2. Unmetamorphosed argillaceous bed. Insoluble residue (10% HCl solution). (field no. 1pc.)
3. Unmetamorphosed interbedded carbonate-quartz and argillaceous beds. Homogenized sample. HCl insoluble residue. (field no. 76d)
4. Tremolite-quartz-potassium feldspar-calcite hornfels. Beginning of outer contact zone. (field no. BH1)
5. Tremolite-quartz-plagioclase-phlogopite-calcite hornfels. Outer contact zone. (field no. 12a3)
6. Tremolite-phlogopite-quartz clinozoisite-plagioclase hornfels. Outer contact zone. (field no. BH14)
7. Tremolite-phlogopite-quartz-clinozoisite hornfels. Outer contact zone. (field no. 44i3)

The three zones correspond generally to the "albite-epidote hornfels," "hornblende hornfels", and "pyroxene granulite" facies of Turner and Verhoogen (1960).

Evidence of isochemical metamorphism. Table 2 summarizes the ranges in composition of the Helena dolomite near the Granite Peak stock based on (1) the amounts of insoluble residues and their mineralogy, (2) x-ray diffraction determinations of their dolomite-calcite ratios (Gulbrandsen, 1960), (3) calcium and magnesium contents (Table 3), and (4) an analysis given by Knopf (Table 4).

TABLE 4. CHEMICAL COMPOSITION OF A DOLOMITE SPECIMEN OF THE HELENA FORMATION (KNOPF, 1963)

	Weight %	Mole %
SiO_2	32.88	28.78
CaO	18.42	17.27
MgO	12.89	16.82
Al_2O_3	3.48	1.79
FeO	1.93	1.41
Fe_2O_3	0.16	0.06
Na_2O	0.73	0.62
K_2O	0.60	0.34
TiO_2	0.14	0.09
MnO	0.10	0.07
P_2O_5	0.05	0.02
CO_2	27.71	30.37
H_2O^+	0.72	2.10
H_2O^-	0.09	0.26
	99.90	

BaO, SrO, S, F not detected

Analyst: E. H. Oslund

These data and the mineralogy of the hornfels indicate that metamorphism proceeded isochemically in the transition, outer and most of the inner contact zone except with regard to CO_2 and H_2O. This necessitates large volume changes of the hornfels due to loss of CO_2 and H_2O perhaps on the order of those directly measured at Johnson Camp, Arizona (Cooper, 1957).

On the basis of the derived assemblages it is convenient to describe the composition of the Helena dolomite in terms of the system $MgO-CaO-KAlO_2-Al_2O_3$ with excess SiO_2. This system can be graphically portrayed in a tetrahedron (Fig. 2) on which the dolomitic carbonate-quartz beds will be represented by the single join $CaO-MgO$ with $CaO-1/MgO-1$, and

the argillaceous beds will plot on the magnesian side of the join and slightly within the tetrahedron because of the abundance of mica group minerals and small amounts of carbonate. As indicated by the derived metamorphic assemblages (Table 1), many beds are of intermediate compositions.

$CaO-MgO-SiO_2-H_2O-CO_2$ System

The carbonate-quartz beds principally contain assemblages of the following six minerals: quartz, dolomite, calcite, tremolite, diopside and wollastonite. These assemblages are easily interpreted in terms of the system $CaO-MgO-SiO_2-H_2O-CO_2$. Minerals characteristic of quartz-free
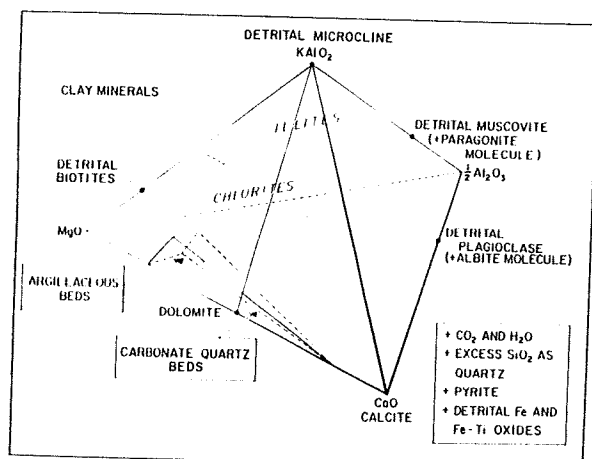
Fig. 2. Composition of Helena dolomite in terms of the system $CaO-MgO-KAlO_2-Al_2O_3$ with excess quartz

carbonate assemblages, such as spurrite and monticellite, are not abundant in the Granite Peak aureole because of the abundance of quartz in the carbonate-quartz and argillaceous beds.

According to the phase rule a maximum of three of these six minerals may co-exist at equilibrium in the $CaO-MgO-SiO_2-H_2O-CO_2$ system if temperature, total pressure, and chemical potentials of CO_2 and H_2O are externally controlled, that is, if there are four independent variables ($P = C + 2 - F = 3$, where $C = 5$, $F = 4$). These conditions are inherent assumptions in Goldschmidt's "mineralogical phase rule", and in Korzhinskii's classification of CO_2 and H_2O as "perfectly mobile" components. In general the mineralogy of the carbonate-quartz beds in Table 1 is consistent with the thesis that H_2O and CO_2 were perfectly mobile during metamorphism.

However, four mineral assemblages in the $CaO-MgO-SiO_2-H_2O-CO_2$ system occur in some hand specimens in two ways: (1) with three phases in individual layers, but with four in the specimen as a whole (e.g. No. 3 and No. 6, Table 1), and (2) as four phases in the same bed (e.g. No. 7, Table 1). The former case is characterized by reaction textures at layer interfaces (Figs. 3, 4).

Where four minerals co-exist in a five component system involving two volatile components, it is possible to write a devolatilization reaction between them (Korzhinskii, 1959). These reactions and their invariant point may be schematically portrayed as a function of two variables only by assuming all other variables constant. For two volatile systems, a plot of the reactions as a function of the composition of the co-existing volatile phase and temperature at fixed total volatile pressure is particularly useful in interpreting metamorphic assemblages. Figure 4 shows such a plot for the reactions which occurred in the carbonate-quartz beds. The excess of quartz allows plotting of the assemblages on the single join, $CaO-MgO$.

The reaction of calcite and quartz to wollastonite is the only reaction noted in the aureole for which two-volatile experimental data are available at present (Greenwood, 1962). Although of particular interest in this and many other metamorphic terrains, experimental studies of the remaining reactions are lacking. These reactions are shown schematically in Fig. 3 on data from the Granite Peak aureole and on the basis of the CO_2 and H_2O evolved or added to the reactants (Greenwood, 1962).

Significance of initial water content. On the basis of field and petrographic features diopside was formed by two reactions at the beginning of the outer contact zone. Some dolomitic carbonate-quartz beds reacted directly to diopside (reaction 2, Fig. 5) although most reacted to diopside after the intermediate formation of tremolite (reaction 1, Fig. 6).

These two different paths are evidently related to the initial volatile content of the rocks. Where the H_2O content presumably was relatively low, dolomite and quartz reacted directly to diopside. For higher H_2O contents, tremolite formed. These two reaction paths may be related to volatile composition at constant total volatile pressure by Fig. 5. Alternatively, they may be shown in a more generalized manner on a CO_2-H_2O chemical potential plot at constant temperature and pressure (Fig. 6) as advocated by Korzhinskii (1959).

Talc is common in the low temperature portion of contact aureoles in impure carbonate rocks (Cooper, 1957; Tilley, 1948). Although searched for specifically, talc was not noted in the transition zone of the Granite Peak aureole. The absence of talc is perhaps also related to the initial
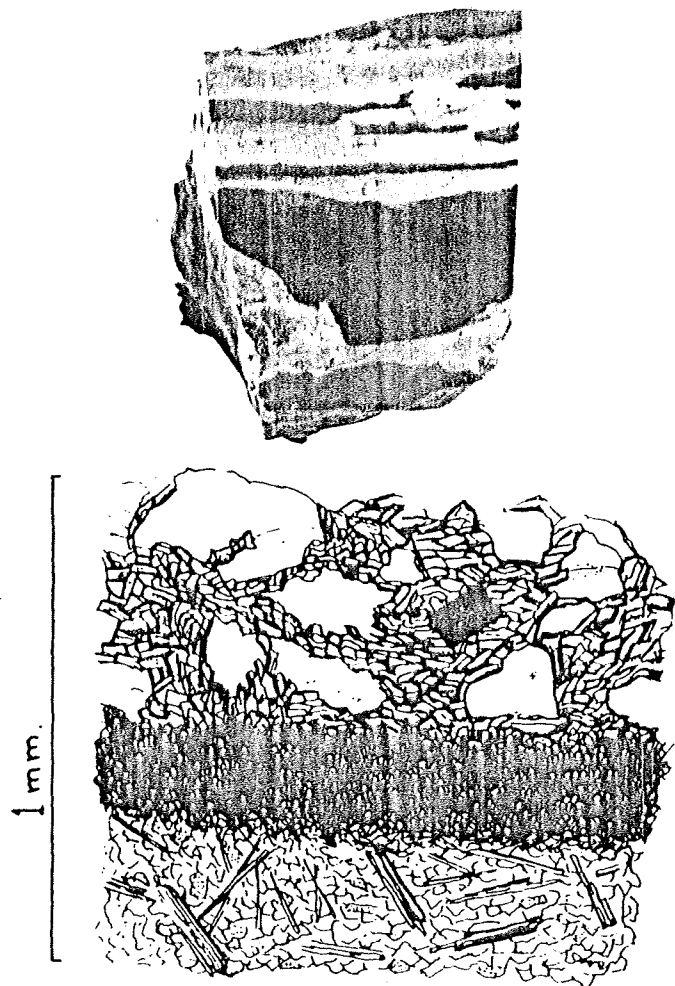
FIG. 3. Layered hornfels, outer contact zone. Dark layers are mainly quartz, tremolite, and phlogopitic biotite; light layers, diopside, quartz and calcite. Note expansion of diopside-rich reaction layer into quartz-tremolite-biotite layer on lower left hand side of specimen. Actual size. Southeast side of Granite Peak.

Sketch shows dense reaction zone of diopside between layers. Large embayed relict quartz grains in diopside-rich layer. Diopside shown by high relief; tremolite, elongate crystals; phlogopitic biotite, stippled; pyrite, opaque. Clinozoisite and plagioclase occur in both layers.

volatile content of the rocks. Intragranular fluids of the Helena dolomite were presumably low in H_2O, thus preventing the formation of talc.

The isothermal co-existence of the assemblages tremolite-calcite-quartz and dolomite-quartz requires volatile compositional gradients at their
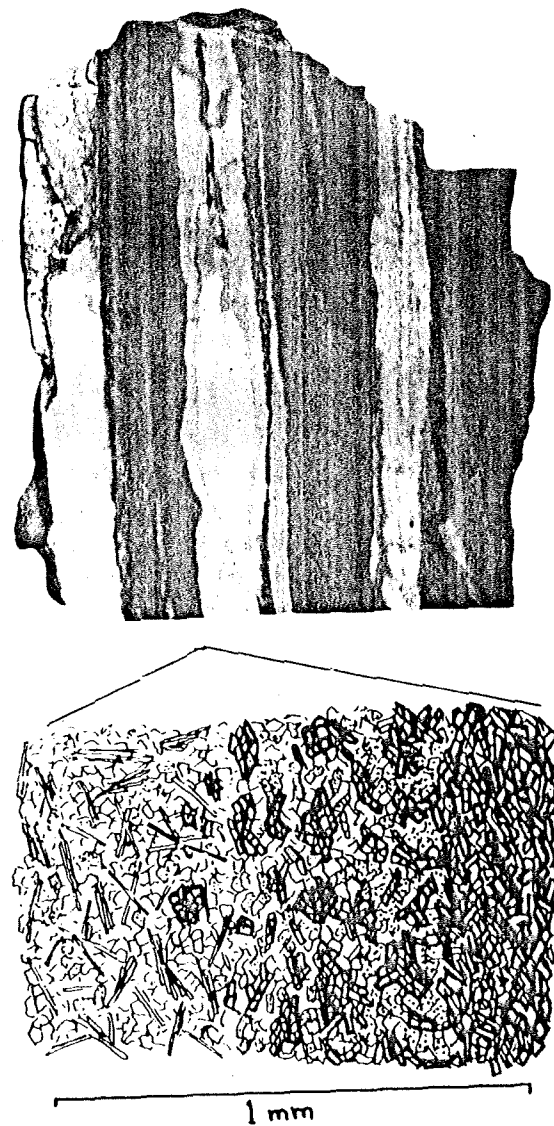

FIG. 4. Layered hornfels. Dark layers principally tremolite, quartz, calcite, and phlogopitic biotite; light layers are diopside, quartz and calcite. Note concentration of phlogopitic biotite in some areas at contact of layers. Outer contact zone, southeast side of Granite Peak. Actual size.

Sketch shows details at a layer contact. Diopside, high relief; tremolite, elongate crystals; phlogopitic biotite, stippled. Matrix mainly quartz.

contacts. Figure 5 clearly shows this. If CO_2 and H_2O were homogenized between such layers, only one of these assemblages would be stable unless · volatile composition coincided with the reaction curve (1, Fig. 5). It is thus likely that on an outcrop and even hand specimen scale original
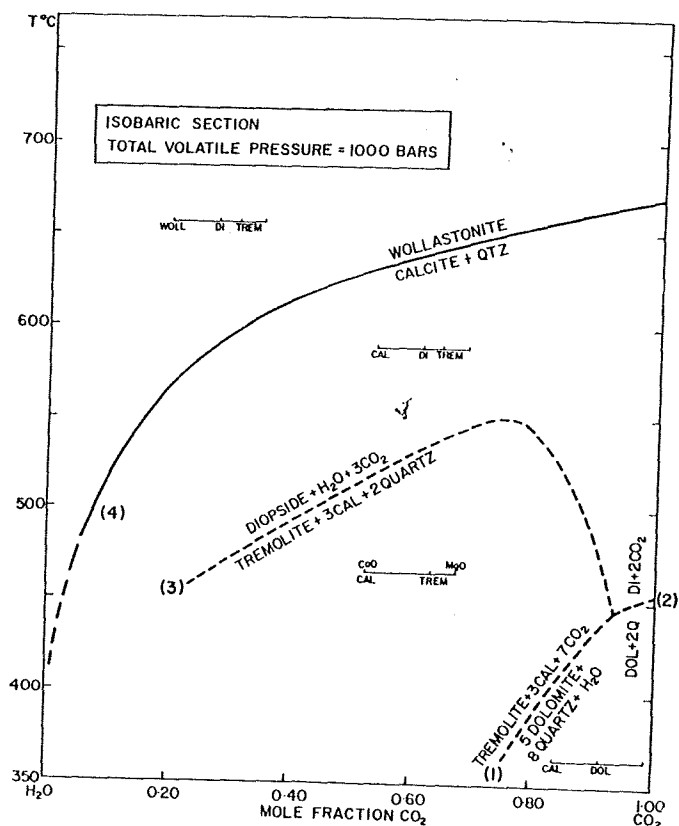

FIG. 5. Volatile composition-temperature diagram for reactions in the carbonate-quartz beds.

differences in volatile contents created compositional gradients in the lower metamorphic grades.

The contact between such assemblages may be regarded as an isograd produced by pore fluid compositions rather than temperature. The existence of such isothermal isograds was predicted by Greenwood (1962) on theoretical grounds. In this regard, it is interesting that such features occur only in the transition and beginning of the outer contact zone, that is, in the low temperature portion of the aureole.

In the terms proposed by Zen (1963), CO_2 and H_2O, although "boundary value" components on an individual bed scale, behaved as "initial value" components on a hand specimen or outcrop scale in the low temperature portion of the aureole. The "perfect mobility" of CO_2 and H_2O
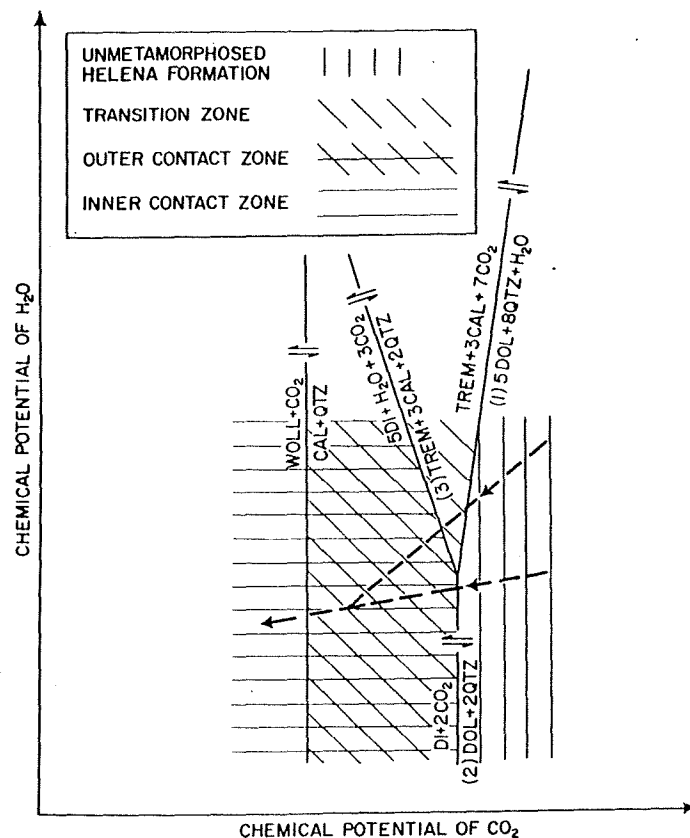

FIG. 6. CO_2-H_2O chemical potential diagram for reactions in the carbonate-quartz beds.

at higher temperatures in the aureole is schematically shown by the convergence of the two paths of metamorphism shown in Figure 6.

Four phases in the CaO-MgO-SiO_2-H_2O-CO_2 system in a single bed, all in mutual contact, such as in specimen No. 7, Table 1, requires internally buffered CO_2 and H_2O fugacities, or disequilibrium if CO_2 and H_2O are assumed to have been "perfectly mobile." The latter is unlikely in view of the evidence just presented and in the textural equilibrium of the minerals.
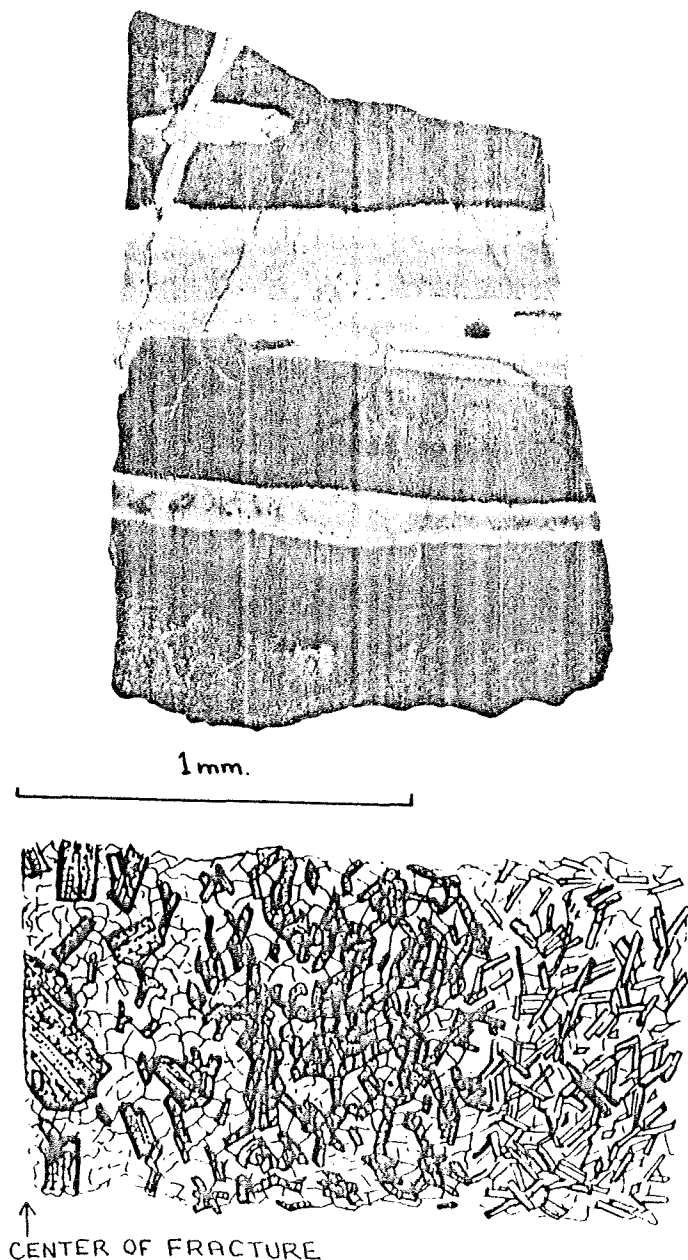
1 mm.

↑
CENTER OF FRACTURE

FIG. 7. Hornfels, outer contact zone. White layers mainly diopside, quartz, and calcite. Gray layers mainly tremolite and quartz. Tremolite, calcite, and quartz have reacted to form diopside along fracture. Actual size. Southeast side of Granite Peak.

Sketch shows detail along fracture. Diopside indicated by high relief; tremolite in elongate crystals. Quartz and calcite in matrix.

Significance of initial CaO-MgO ratio. As shown by Table 3, argillaceous beds may contain CaO-MgO ratios of less than one. Such beds, after metamorphism, may contain tremolite without calcite. Where such beds are in contact with carbonate-quartz beds (diopside-calcite beds) in the inner part of the outer contact zone, reaction 3 (Fig. 6) occurs (Figs. 3, 4, 7). However, because of the low diffusion rates of "inert" components, this incompatibility is commonly preserved. Diffusion was, however, sufficiently rapid along fractures (Fig. 7) to allow rapid equilibration of the assemblages.

Where reaction (3) occurred at layer interfaces, the composition of the pore fluids may have been maintained in the entire specimen at a molar ratio of $CO_2/H_2O = 3/1$. This is the ratio at which reaction (3) proceeds at a maximum temperature for a given total pressure of volatiles (Fig. 5; also Greenwood, 1962). Such buffering may continue until either calcite or tremolite is completely eliminated. This last process will be strongly controlled by the diffusion rate of CaO (Fig. 7).

$CaO-MgO-KAlO_2-Al_2O_3-SiO_2-CO_2-H_2O$ SYSTEM

The application of the phase rule to the argillaceous beds is complicated by the larger number of constituents involved and resulting uncertainties in assessing the behavior of components. Some simplifications nonetheless allow graphical portrayal of most of the assemblages by a tetrahedron.

Components which may be neglected occur in a single phase and are not involved in "discontinuous" reactions, that is, reactions which produce new phases at the expense of others on approach to the granite contact. TiO_2(sphene), FeS_2 (pyrite) and Na_2O (plagioclase, or rarely scapolite) are three such components.

Components which are present in such small amounts that they apparently do not give additional phases but rather substitute isomorphously for major components may also be neglected in qualitative interpretations. For example, FeO and MnO, which are present in small amounts (Table 2), probably substitute for MgO. Similarly, any small amount of Fe_2O_3 present initially substitutes mainly for Al_2O_3 in the epidote minerals or in cordierite.

In view of this simplification, reactions in the argillaceous beds may be reduced to the $CaO-MgO-KAlO_2-Al_2O_3-SiO_2-CO_2-H_2O$ system. The component $KAlO_2$ is preferred rather than K_2O because reactions involving phlogopitic biotite and potassium feldspar involve transfer of K_2O and Al_2O_3 as the single component $KAlO_2$.

It is now possible to portray the assemblages of the argillaceous beds, and aureole as a whole, in terms of a tetrahedron. SiO_2 need not be plotted as a separate component because of its presence in excess.

Similarly, CO_2 and H_2O, where they are "perfectly mobile", do not give rise to additional phases. Thus, the assemblages may be expressed in terms of the $CaO-MgO-KAlO_2-Al_2O_3$ system with excess quartz.

On this tetrahedron (Fig. 2), the assemblages derived from the carbonate-quartz beds reduce to the single join $CaO-MgO$. The treatment of the non-volatile components as a whole is given in Table 5 in terms defined by Korzhinskii (1959).

Figure 8 summarizes the development of the aureole in terms of this tetrahedron and the reactions relating one tetrahedron to another. These reactions are based mainly on petrographic data. In the transition zone, the reactions in argillaceous beds are particularly difficult to infer because various original mica group minerals were involved. "Illite" as used in Fig. 8 applies to a hypothetical mean composition of the mica group

TABLE 5. TREATMENT OF COMPONENTS. DESIGNATION OF COMPONENTS FOLLOWS TERMS DEFINED BY KORZHINSKII (1959)

Determining "inert" components	CaO, MgO, K_2O, Al_2O_3
Excess component	SiO_2
Accessory (indifferent) components	TiO_2, Na_2O, S_2
Isomorphous components	FeO, Fe_2O_3, MnO

minerals in a given bed. Thus, reactions 5 and 6 are particularly schematic.

Assemblages in the transition and outer contact zones were determined evidently by composition and pressures of pore fluids as well as temperature and thus alternative assemblages are shown in Fig. 8.

The five phase assemblage potassium feldspar, quartz, diopside, tremolite, and phlogopite occurs in some assemblages in the outer contact zone (Table 1, nos. 3, 8). This assemblage suggests disequilibrium if the above treatment of components is correct, that is, if there was not an additional determining "inert" component to the four listed in Table 5. However, this assemblage does not indicate that the beds were partially closed to volatiles because potassium feldspar, quartz, diopside, tremolite and phlogopite include both the reactants and products of a solid-solid reaction (no. 7, Fig. 8). The problem as to whether this assemblage reflects disequilibrium or the effect of an additional component may be resolved in part by determinations of the mineral compositions. This is presently being attempted by means of electron microprobe analyses as part of a general study of component partitioning in the contact aureole.

The validity of Fig. 8 in portraying the actual evolution of metamorphic assemblages in the Granite Peak aureole is subject to two important

limitations. First, a total of but 40 specimens were examined in detail. Even a single new assemblage may modify joins shown in a single $CaO-MgO-KAlO_2-Al_2O_3$ tetrahedron. This is particularly true for assemblages in the inner contact zone. As shown by the reorientation of most planes
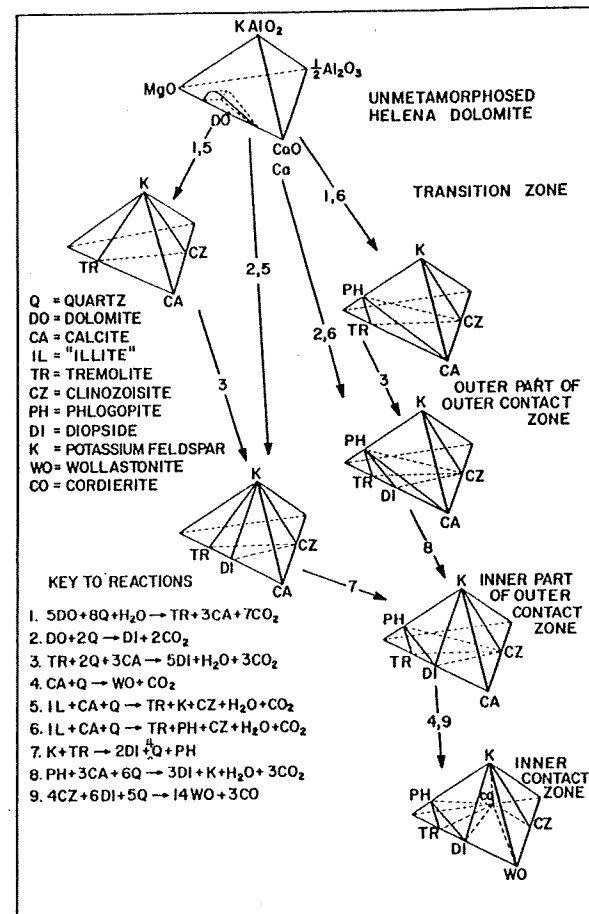

FIG. 8. Summary of development of assemblages in terms of the $CaO-MgO-KAlO_2-Al_2O_3-CO_2-H_2O$ system with excess quartz.

within the tetrahedron on passage from the outer to inner contact zone, many other reactions in addition to 9 were involved. In the specimens at hand there is little direct textural evidence for these reactions.

The second limitation to Fig. 8 is in the restricted compositional range of the Helena dolomite. Only stability relations in volumes of the tetrahedron which are near the $CaO-MgO$ join may be inferred from the horn-

fels. For example, little information was obtained from the hornfels for the behavior in the ternary $KAlO_2$-Al_2O_3-MgO with excess silica.

EXTERNALLY CONTROLLED VARIABLES

Lithostatic pressure. The amount of lithostatic pressure at the time of intrusion of the Granite Peak stock is uncertain but limits may be established. The principal source of uncertainty is in the estimate of the amount of erosion which occurred between the end of Mesozoic deposition and the time of intrusion of the Granite Peak stock (Melson, 1966).

About 20,000 to 30,000 feet of sedimentary rocks were above the Helena formation at the end of Mesozoic deposition and about at the time of late Cretaceous folding and faulting, or "Laramide orogeny." The Granite Peak stock was emplaced after folding and evidently at about the same time as the Boulder batholith. It is difficult to place a lower limit on the amount of cover at the time of intrusion although a maximum limit is about 2.5 kilobars assuming a mean rock density of 2.7 gms/cc. Inasmuch as considerable erosion occurred between folding and intrusion, and on the basis of considerations presented by Barrell (1907) for the Marysville stock, a value of about 1 kilobar was probably attained at the present level of exposure.

Volatile pressure. During metamorphism large quantities of CO_2-rich volatiles were evolved producing volume changes between 20 to 30 per cent in the initially dolomitic carbonate-quartz beds. Fluid inclusions in quartz veinlets and diopside crystals require the presence of a fluid phase during their formation and suggest that volatile pressure equalled total pressure for at least part of the time.

If, in response to rapid increase in temperature, volatiles were evolved rapidly, volatile pressure may have exceeded the value of initial load pressure for a short time, particularly in rocks of low permeability. Irregular breccia bodies and dikes composed of hornfels occur in places and perhaps formed when volatile pressure exceeded the strength of the rocks.

Fractures which show evidence that volatiles moved along them are locally abundant. In areas where such fractures gave access to the surface, the volatile pressure may have been slightly less than load pressure.

The aureole thus contains features which suggest that total volatile pressure varied from equal to initial load pressure plus the strength of the rocks, to perhaps less than load pressure.

Temperature distribution. The temperature at the granite contact may be inferred from experimental work on the granite solidus (Tuttle and Bowen, 1958). The composition of much of the stock, as indicated by

modal analyses, falls near the granite minimum at water pressures on the order of one to a few kilobars and is similar to that of the Quincy and Westerly granites which have experimentally determined melting temperatures as a function of water pressure. These curves suggest that minimum temperatures at the granite contact were around 700° C. for water pressures of about 1 kilobar. Higher water pressures than the inferred 1,000 bars will not greatly lower this minimum temperature because the solidus is not greatly lowered by pressure increases above 1 kilobar. This contact temperature is in accord with the occurrence of wollastonite in the inner contact zone if CO_2 pressures were about 1 kilobar (Harker and Tuttle, 1956).

Most of the reactions which occurred in the aureole evolved a CO_2-rich fluid. On the other hand, the abundant biotite and hornblende of the granite, and local abundance of chlorites in the hornfels at the granite

TABLE 6. APPROXIMATE TEMPERATURES AT WHICH REACTIONS IN THE CaO-MgO-SiO_2-CO_2-H_2O SYSTEM OCCURRED IN THE GRANITE PEAK AUREOLE

Reaction Number (Fig. 4)	Approximate temperature (C)	Facies and temperature range (Turner and Verhoogen, 1960)
1	350–400	albite-epidote hornfels 430
2	400	hornblende hornfels 500–665
3	400–500	hornblende hornfels 500–665
4	650–700	pyroxene granulite 700

contact suggest H_2O was an abundant constituent in the granite. It is thus likely that gradients in pore fluid composition occurred across the inner contact zone even though total volatile pressure may have been maintained at around 1 kilobar.

The lack of chilled contacts and the abundant evidence of emplacement of the stock by magmatic stoping (Melson, 1966) indicate that the stock was active over a considerable period of time. Aided by increased rock conductivity as a result of the movement of volatiles from the aureole, the aureole thus may have approached a steady state temperature gradient.

On the basis of stability relations calculated by Weeks (1956) for the reaction of dolomite and quartz to diopside, a temperature of 400° C. for a CO_2 pressure of 1 kilobar existed at a minimum of 700 feet from the granite contact where this reaction evidently occurred. Thus, if the temperature at the contact was about 700° C., the temperature gradient was on the order of 0.5° C. per foot.

Table 6 gives the approximate temperatures at which some of the reac-

tions occurred based on distances from the granite contact and the above assumptions of the temperature gradient. These temperatures correspond approximately to estimates for the albite-epidote hornfels, hornblende hornfels and pyroxene granulite facies of Turner and Verhoogen (1960).

Because some reactions evidently occurred at different distances from the Granite contact, particularly in the transition and outer contact zones, they probably proceeded or began over a temperature interval. Based on the evidence of the previous sections, this interval and the reaction which occurred were related to the initial volatile content of the beds and interactions between layers of contrasting compositions.

CONCLUSIONS

Mineral assemblages in the Granite Peak aureole were determined primarily by temperature, externally controlled volatile pressures, and the initial content of non-volatile constituents in the Helena dolomite. However, in the lower temperature portion of the aureole, the reaction which occurred at a given temperature was evidently also related to the initial volatile content, particularly of H_2O. Thus, contrasting assemblages, some of which are thought to represent different facies and temperatures in present classifications, co-exist in the same hand specimen or outcrop.

The textures and co-existence of such assemblages suggest that CO_2 and H_2O may not be regarded a priori as "perfectly mobile" or "boundary value" components during metamorphism, particularly in the lower metamorphic grades. Disequilibrium in response, for example, to slow reaction rates is an alternative explanation of the isothermal co-existence of such assemblages. However, textural features and application of the phase rule to individual beds suggest that this co-existence is not a result of disequilibrium.

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