7. CONTACT METAMORPHISM AT CRESTMORE, CALIFORNIA*

By C. Wayne Burnham †

Introduction. The Crestmore limestone mine and quarries of the Riverside Cement Company, located 3 miles north of Riverside, California, have received much attention during the past four decades from mineralogists and petrologists the world over, principally because of the occurrence there of a great variety of contact-metamorphic minerals. Most of the 20 or more published accounts dealing with the Crestmore deposits have been concerned primarily with description of the minerals and discussion of their paragenesis. The present paper is a preliminary and condensed version, mainly descriptive, of the results of a study aimed primarily at defining the occurrence and genesis of the minerals and rocks.

The contact zones lie between magnesian limestones and quartz diorite, and between the same limestones and a relatively small intrusive mass of quartz monzonite porphyry. The limestones occur as lenses of variable thickness and lateral extent within a thick section of predominantly siliceous metamorphic rocks, masses of which occur typically as roof pendants or screens in the intrusive rocks of the southern California batholith. The younger rocks of this composite batholith have been dated tentatively as Upper Cretaceous, and hence the engulfed metamorphic rocks, which in this area have yielded no fossils, are Mesozoic or older.

Pre-batholithic Metamorphic Rocks. The pre-batholithic rocks in the immediate vicinity of the Crestmore quarries consist mostly of coarsely crystalline magnesian limestones and subordinate feldspathic biotite-quartz gneisses, schists, and hornfelses. The limestones form two stratigraphic units, the lower of which is known as the Chino limestone and the upper as the Sky Blue limestone. The Chino limestone locally is as much as 400 feet thick, and recent diamond drilling east of the quarries indicates that the Sky Blue limestone may be 500 feet thick.

Separating these two limestones are gneissic hornfelses and schists that have been largely displaced and, to a small extent, replaced by a sill-like mass of quartz diorite. The noncalcareous metamorphic unit varies strikingly in thickness across the area, and ranges from 70 feet or less east of the Commercial quarry (see pl. 1) to more than 200 feet south of this quarry. These rapid changes do not appear to have resulted from deformation, and are therefore interpreted as the result of rapid facies changes between limestones and siliceous rocks. Additional tabular masses of gneissic hornfels and schist underlie and locally interfinger with the Chino limestone.

The trend of foliation in the metamorphic rocks is slightly west of north, and the dip ranges from 18° to 70° east. The steepest observed dips are in the vicinity of the Crestmore mine. This general attitude conforms to the regional homoclinal structure in the metamorphic rocks that are more extensively exposed south of Riverside, and to the flow structures in the igneous rocks of the batholith in the vicinity of Riverside. In many places, however, the attitude of the foliation varies considerably, owing to mild deformation accompanying intrusion of the quartz diorite. These deformational effects, as well as the general structural relations of all the rock units, are shown in plate 1.

The chemical and petrographic characteristics of both limestone units are similar in every respect. Both units are composed of alternating layers of predazzite and of light gray, coarsely crystalline limestone; this layering reflects original bedding prior to metamorphism. Except for the magnesium content, which, calculated as the carbonate, rarely exceeds 25 percent of the brucite-rich layers, the limestones are relatively pure. A weighted average of about 90 composite analyses of both limestone units, including a few thin chert-bearing zones, indicates over-all silica and alumina contents of 2.0 percent and 0.4 percent, respectively. The brucite grains in the predazzite range in diameter from half a mm. to 2 mm., and commonly have a crude octahedral form. Specimens of predazzite from the Jensen quarry, 3 miles west of Crestmore, contain octahedral crystals of periclase in all stages of alteration to brucite, and clearly indicate a secondary origin for the brucite.

Quartz Diorite. The country rock of the Crestmore region is principally a hornblende-biotite quartz diorite,‡ the Bonsall tonalite of Larsen (1948), and constitutes the northernmost known exposures of the intrusive rocks of the southern California batholith. It is generally a coarse-grained rock with hypautomorphic texture. The plagioclase is a calcic andesine that contains an average of 44 percent anorthite. The modal analysis in column 1 of table 1 is an average of three determinations on samples taken from three widely separated places in the area, and is thought to be representative of the bulk of the rock. Although this rock generally appears to be of uniform composition, some distinct local variations result in types that range from quartz monzonite to hornblende gabbro.

---

* Contribution No. 648, Division of the Geological Sciences, California Institute of Technology.

† Kennecott Research Fellow, California Institute of Technology.

‡ The igneous rock terms used herein are based on the classification by Johannsen, Albert, 1932, A descriptive petrography of the igneous rocks, vol. 1, pp. 141-161, Univ. of Chicago press, Chicago, Illinois.

Table 1. Mineral composition of intrusive rocks of the Crestmore area.

Mineral	1 Quartz diorite	2 Quartz monzonite prophyry
Plagioclase	56.7% (An44)	30.7% (An32)
Potash feldspar	0.3	34.5
Quartz	21.5	28.0
Pyroxene	1.4	5.2
Hornblende	9.1	0.6
Biotite	10.9	0.1
Accessories	0.1	0.7
Total	100.0%	99.8%

The structural elements of the quartz diorite consist of: (1) abundant ellipsoidal inclusions of gabbroid rock which show preferred orientation of their axial elements; (2) strong gneissic layering commonly developed near contacts with limestone; and (3) a planar structure that rarely is detected in hand specimen or thin section, but which clearly is a cause of a consistent westerly deflection of vertically directed diamond-drill holes. All of these elements strike approximately north and dip moderately eastward.

The contact zone between quartz diorite and limestone is less than a foot thick in most places, and rarely is more than 2 feet thick. The minerals most characteristic of this zone are brownish grossularite garnet, grass-green diopside (diallage), and colorless wollastonite. Minor amounts of quartz, clinozoisite, and scattered grains of sulfides also are present. A nearly vertical pipe of highly siliceous rock that penetrated the Chino limestone in the Crestmore mine was fringed with masses, several feet thick, of pyrrhotite, sphalerite, and other sulfides. This pipe probably was derived from the quartz-diorite magma, as were similar axinite-bearing pipes discovered more recently in the Chino limestone.

Quartz Monzonite Porphyry. Exposed in both the southern and northern parts of the upper face of the Commercial quarry are blocky masses of very light gray quartz monzonite porphyry. The southern and structurally lower mass is the exposed part of an irregular pipe that was intruded upward from the east along the contact between Sky Blue limestone and the underlying quartz diorite (see pl. 1.). The northern and structurally higher mass also was intruded upward from the east as an irregular pipe-like mass, but it lies wholly within the Sky Blue limestone.

The texture of the porphyry is mainly xenomorphic porphyritic, but in detail it is highly variable, especially with respect to grain size and relative abundance of phenocrysts. The phenocrysts, which generally constitute about 10 percent and rarely exceed 25 percent by volume of the rock, are anhedral and range from 1 mm. to 7 mm. in diameter. They are andesine (An37), and are set in a microcrystalline groundmass of sodic andesine (An31), orthoclase, quartz, and variable minor amounts of green pyroxene, sphene, and apatite. Within a few feet of the contact with quartz diorite, the porphyry contains from 2 to 5 percent of dark minerals, mainly hornblende and biotite. Coincident with this change from pyroxene to hornblende and biotite, the sphene of the normal porphyry gives way to ilmenite or titaniferous magnetite with reaction rims of sphene. In column 2 of table 1 is presented an average of 11 modal analyses of quartz monzonite porphyry.

In the central parts of the larger masses, the porphyry is very leucocratic and contains 3 percent or less of dark minerals. Within a few feet or a few tens of feet of limestone-derived contact rock, the amount of diopsidic pyroxene increases to as much as 45 percent of the rock, strongly suggesting that the porphyry magma was contaminated by limestone. However, the anorthite content of the plagioclase in the groundmass evidently was little affected until the degree of contamination became very great. The contrast between the dark minerals of the porphyry near the quartz diorite, on one hand, and near limestone, on the other, emphasizes the effects of slight changes in composition on the stability relations among certain minerals.

The quartz monzonite porphyry is marked by joints, flow layering, and a weak lineation. Near station A (pl. 2 and fig. 2), in the southern part of the Commercial quarry, two sets of joints are conspicuous. One set, which parallels the plane of foliation and flow layering, strikes N 48° W and dips 28° NE near the footwall contact, but strikes N 30° W and dips 30° NE near the hanging wall. The other set strikes nearly east and dips 86° to 87° N. Near the footwall the line of intersection of these two sets of joints defines a lineation that nearly coincides with another lineation formed by the preferred orientation of mineral grains. Furthermore, this direction is roughly the same as the direction of flow of the magma, as determined by the shape and suspected source area of the porphyry intrusive.

Pegmatite dikes cut the contact rock, contaminated rock, and marginal parts of the porphyry. They clearly are related in origin to the porphyry, for all gradations between the two rock types have been found in a single dike or lens. Where they occur in the marginal parts of the porphyry, these dikes and lenses have two preferred attitudes, one parallel to the gently northeast-dipping joints mentioned above, and the other striking N 15° W and dipping 50°-80° E. This latter attitude is the more common, and is roughly parallel to that of another poorly developed set of joints. It is likely that both sets of joints exercised some control during emplacement of the pegmatite bodies.

Contaminated Rocks. The group of contaminated rocks is genetically related to the quartz monzonite porphyry, but these rocks differ from the porphyry because of assimilation of limestone. The group may be subdivided into two types that generally can be distinguished by differences in color, texture, composition, and occurrence, although nearly all transitions between the two have been observed. The less extensive type is very dark colored and porphyritic, and generally occurs as small, pipe-like masses or stringers. These stringers apparently represent the terminal parts of apophyses from the main mass of porphyry that penetrated contact rock and possibly limestone. Compositionally, this type ranges from a syenodiorite to a gabbro, the median probably lying in the diorite group. An extremely basic member is represented by the modal analysis in column 1 of table 2.

The more common type of contaminated rock generally is lighter in color, less porphyritic, and coarser grained. It occurs as relatively large masses that have engulfed large blocks of garnet-rich contact rock. These masses are marginal to the bodies of quartz monzonite porphyry and doubtless grade into them. In column 2 of table 2 is presented a modal analysis of an extremely potassic member of this type, which occurs as small stringers in contact rock near station J (pl. 2). Column 3 represents an average of 15 modal analyses of both types of contaminated rock. It is clear that the average contaminated rock, if such an average is significant, can be classified as a pyroxene monzonite.

Table 2. Mineral composition of contaminated rocks.

Mineral	1	2	3
Plagioclase	50.1% (An70)	------	42.4% (An40)
Potash feldspar	------	83.4%	30.3
Quartz	------	------	0.4
Pyroxene	47.7	9.8	24.5
Sphene	2.2	0.3	1.8
Wollastonite	------	6.5	0.5
Total	100.0%	100.0%	99.9%

In addition to the minerals listed in table 2, minor amounts of biotite, hornblende, grossularite garnet, apatite, and rare scapolite and ilmenite or titaniferous magnetite are present in the contaminated rocks. Alteration products, which are not abundant, include calcite, zoisite, chlorite, and kaolinite.

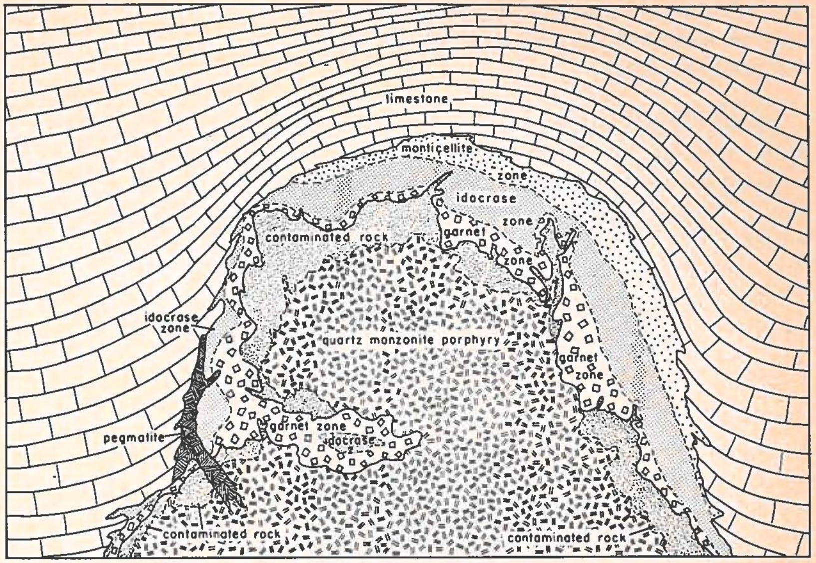


FIGURE 1. Idealized north-south cross section (not to scale) through the quartz monzonite prophyry intrusion at Crestmore.

Perhaps the most important mineralogical feature of the contaminated rocks is the occurrence, very near the contacts with garnet-rich contact rock, of two types of potash-bearing feldspar; these consist of an early, relatively coarse-grained feldspar with optical properties similar to those of anorthoclase, and a later, interstitial, fine-grained feldspar resembling common orthoclase. Much of the coarser-grained feldspar very near the contact is perthitic, a feature that is absent from the alkali feldspar of the quartz monzonite porphyry. Myrmekitic intergrowths of quartz and plagioclase have the same distribution as perthite, in that they are common in the contaminated rocks and nearly absent in the porphyry.

Many relatively small masses of dark, fine-grained, schistose rocks occur in the northern part of the Commercial quarry, especially in contaminated rock. Some of these masses are only partly schistose, the remainder appearing as massive porphyritic contaminated rock. Under the microscope, however, even the apparently massive part commonly is transected by numerous shear planes, along which there has been some displacement and granulation. In addition to these mechanical effects, some of the masses have been extensively recrystallized, with formation of biotite and hornblende as the principal dark minerals. These rocks apparently represent early stringers of porphyritic contaminated rock that were deformed by the subsequent intrusion of the main mass of porphyry. The space relations of the contaminated rocks to the quartz monzonite porphyry and to contact rock, as well as the relations of the various zones of contact rock to the parental limestones and intrusive rocks, are shown schematically in figure 1.

Quartz Monzonite Pegmatites. Pegmatites thought to be genetically related to the quartz monzonite porphyry are of common occurrence at Crestmore, although their total volume is relatively small. Near their source the dikes apparently differ very little in mineralogy from the porphyry, although the relative proportions of the constituent minerals might be different. The plagioclase is a calcic oligoclase or sodic andesine, and the potash feldspar is commonly perthitic. Microcline twinning is uncommon in those pegmatites that lie within or near the porphyry. On the other hand, the dikes in contact rock and near limestone show increasing amounts of twinned microcline, and locally contain abundant brown andradite garnet.

In the lower part of the Commercial quarry, along the face below station N, is a thin, discontinuous sheet or mesh of microcline crystals and, locally very near the limestone, wollastonite blades. This rock apparently represents the silicate end-product of crystallization of the pegmatite magma. The contact zone between the limestone and this wollastonite-microcline pegmatite generally is not more than half an inch thick, and locally the rocks are in knife-sharp contact. Where present, the transition zone ordinarily consists of wollastonite and minor amounts of diopsidic pyroxene.

Scattered patches and vein-like masses of epidote-microcline-calcite-quartz rock, somewhat pegmatitic in appearance, extend from station E, on the upper face of the Commercial quarry, downward along the face to the north. Near station E they consist principally of massive quartz, microcline, and epidote, but toward the north the ratio of calcite to quartz increases to such an extent that near station F they are mainly coarsely crystalline aggregates of greenish-gray calcite enclosing large, euhedral crystals of epidote. Aside from their coarse and variable grain size, these rocks bear little resemblance to the normal pegmatites, and they may well have been more hydrothermal in origin than the normal pegmatites.

Contact Rocks. Surrounding the quartz monzonite porphyry and related contaminated rocks where they have invaded the Sky Blue limestone is an aureole of contact rock, the product of silica and alumina metasomatism. This aureole ranges in thickness from less than an inch to 50 feet. In addition, many remnants of limestone that were engulfed by the porphyry have been transformed into contact rock that consists of diopside, wollastonite, and grossularite garnet, with minor calcite and quartz. The quartz is present very near the intrusive contacts. Garnet is by far the dominant mineral in this type of contact rock, which is so abundant that garnet is therefore the dominant contact silicate mineral at Crestmore. Diopside and wollastonite generally are present in about equal proportions; locally, however, their relative proportions are highly variable, and apparently reflect the distribution of magnesium in the original limestones.

The diopside-wollastonite-garnet assemblage is also characteristic of the innermost zone of the contact aureole, and as such constitutes most of the dark outcrops near the summit of Sky Blue Hill, as well as the dark brown exposures above stations B and C on the upper face of the Commercial quarry (pls. 1, 2). Near the porphyry contact, in the vicinity of station B, this rock locally contains numerous calcite-filled veinlets, along the walls of which scapolite crystals commonly occur.

On the upper face of the Commercial quarry, above station C, are numerous small stringers of contaminated rock in diopside-wollastonite-garnet rock, and on the slope of Sky Blue Hill, above station D, a mixture of these two rocks in places resembles a ''puddingstone,'' with nodules of diopside-wollastonite-garnet rock in a matrix of dark contaminated rock. The nodules commonly are ellipsoids as much as 10 inches long, and are oriented with their longest axes plunging moderately eastward. In the vicinity of stations F and G, the diopside-wollastonite-garnet rock is noticeably brecciated, and the fragments are set in a matrix of light-colored contaminated rock or, locally, pegmatitic quartz monzonite.

The thickness of the part of the aureole that consists of diopside-wollastonite-garnet rock, and which henceforth will be termed the garnet zone, is highly variable, and ranges from only a few inches near station Q to 25 feet or more above station C. However, in the latter area the garnet zones of the two porphyry pipes overlap, producing an unusually thick mass of garnet rock.

The diopside-wollastonite-garnet assemblage also forms sheaths that surround the small stringers of contaminated rock that cut idocrase and monticellite-rich contact rocks between stations I and M. The sheaths range in thickness from 2 to 10 inches, and are very fine grained. The small blades of wollastonite appear to radiate outward from the stringers.

A zone characterized by the mineral idocrase lies beyond the garnet zone away from the porphyry, and occupies an intermediate position in the contact aureole. Associated with the idocrase is a great variety of minerals, but because of the intermediate position of this zone, the associated minerals in the inner part generally are different from those in the outer part. This variability in mineral assemblages is in contrast to the simple and monotonous garnet-zone assemblage. In the inner part of the zone, any one or all of the minerals of the garnet zone may be associated with idocrase, whereas monticellite is a common constituent in the outer part of the zone. However, the diopside of the garnet zone generally is darker green than that in the idocrase rock.

In addition to monticellite, several minerals make their first appearance in the idocrase zone. Two of these are wilkeite and its alteration product, crestmoreite, which are widespread minor constituents of both this zone and the monticellite zone. They also range somewhat beyond into the blue calcite of the Sky Blue limestone. Pink wilkeite occurs in the ridge between the Commercial and Wet Weather quarries, but has not been found recently *in situ* in the Commercial quarry. As far as can be determined, pink wilkeite was restricted to idocrase-zone rocks, whereas a yellow variety, which occurs as numerous wheat-shaped grains, is much more widespread.

Micaceous minerals are common in the outer part of the idocrase zone and in the inner part of the monticellite zone. Sheets of green phlogopite as much as 4 centimeters across occur in monticellite-idocrase rock above station K, and colorless xanthophyllite is abundant in the pale green idocrase rock near station C. The emerald green micaceous mineral that formerly was abundant in the diopside-bearing idocrase rock in the vicinity of station Q, although resembling xanthophyllite, yields an x-ray diffraction pattern that resembles neither phlogopite nor xanthophyllite. At the present time this mineral remains unidentified.

The monticellite zone lies beyond the idocrase zone and extends to the limits of silica and alumina metasomatism. Its contact with the idocrase zone generally is gradational, and is arbitrarily drawn where monticellite or its typically associated minerals constitute as much as 50 percent of the rock. In addition to monticellite, the minerals characteristic of this zone include gehlenite, spurrite, merwinite, tilleyite, forsterite, scawtite, spinel, and plazolite (?).

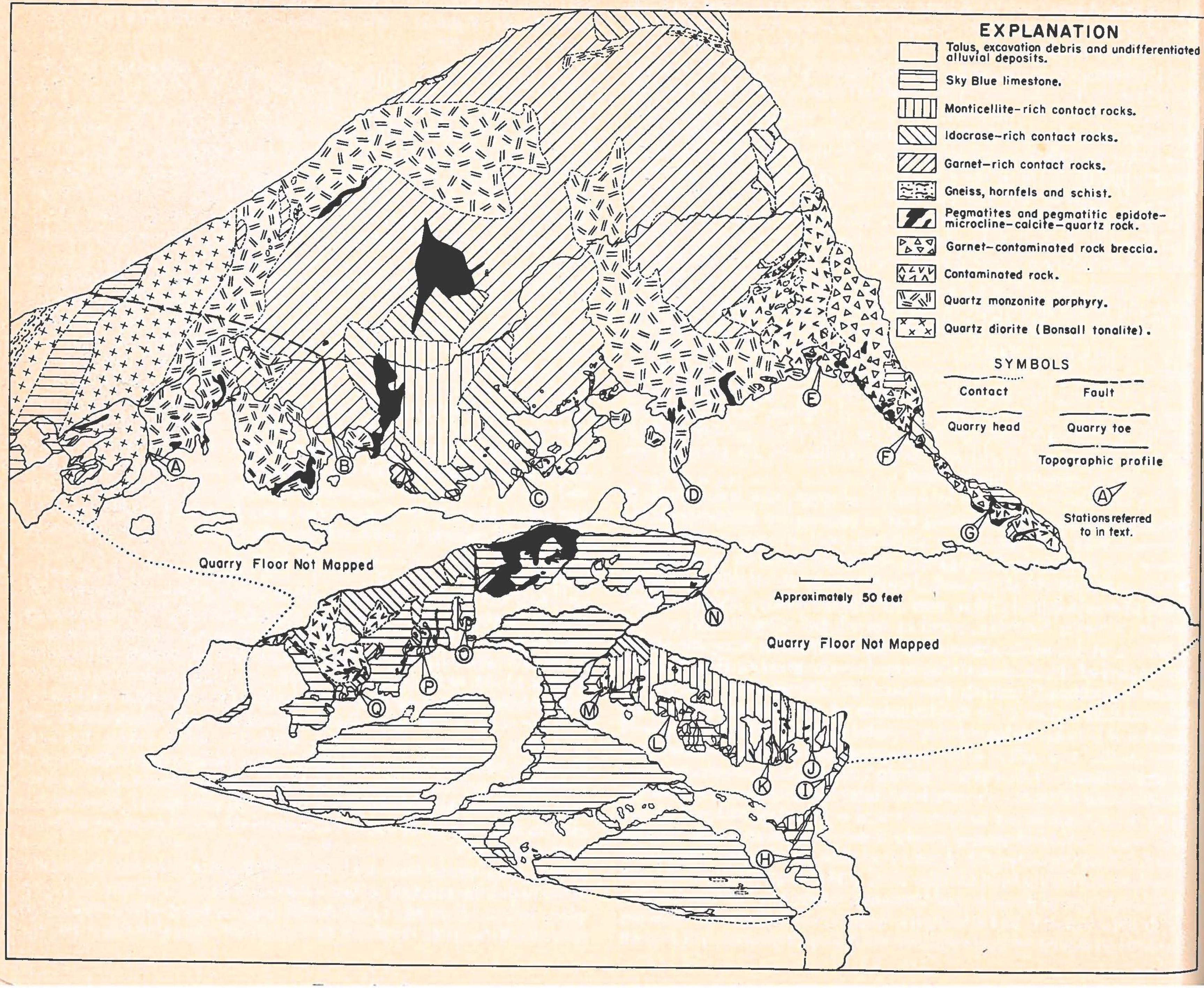
The most accessible exposures of the monticellite zone are in the lower part of the Commercial quarry, between stations H and M and between stations O and Q. Westward for several feet from station H, which is virtually on the boundary of the contact aureole, the rocks are largely carbonate, but contain abundant small crystals of monticellite and silky white pseudomorphs of crestmoreite after wilkeite. Small crystals of idocrase and spinel also are common minor constituents. Wilkeite, in relatively large lemon-yellow crystals, locally is common in the monticellite and monticellite-idocrase transition zones, where it occurs in and around residual masses of blue calcite. Dark green spinel, another common constituent, appears to be restricted to the monticellite zone. Above station I the massive gray rock generally contains sub-equal quantities of monticellite, gehlenite, spurrite, and merwinite, with minor amounts of idocrase, spinel, and calcite. A short distance northwest of here are a few small masses that resemble coarse-grained aggregates of quartz. Merwinite forms about 90 percent of these masses, the remainder being idocrase, spurrite, and calcite.

Some of the rock near station J contains abundant tilleyite; indeed, from this point southwestward for a distance of 25 or 30 feet, tilleyite, spurrite, and merwinite, together, appear to predominate over monticellite. Monticellite, however, is the most abundant constituent of this zone along the remainder of the face to station M, except above station L, where a relatively small mass of very light gray forsterite-rich rock, streaked with dark, fine-grained spinel, is present. This is the only known occurrence of forsterite at Crestmore; nearly 90 percent of the rock is forsterite at this one place.

Exposures of monticellite-zone rocks along the face between stations O and Q in the lower part of the Commercial quarry are smaller and fewer in number than along the face just described, mainly because the over-all thickness of the metamorphic aureole is not as great. The consequent telescoping of the zones caused a considerable overlap of mineral assemblages. Above station P, for example, wollastonite and idocrase form vermicular growths in host crystals of monticellite in calcite. A mineral that has been tentatively identified as scawtite occurs sparingly about 15 feet south of station P, where it is associated with spurrite, merwinite, gehlenite, idocrase, and calcite. The mass of monticellite-zone rock near station C, in the upper face of the Commercial quarry, consists mainly of merwinite and gehlenite, with subordinate monticellite, spurrite, and plazolite (?).

Limestones and Predazzites. Many small masses of sky-blue calcite are scattered throughout the contact aureole. Most of them appear to be remnants of Sky Blue limestone that persisted unchanged, except for partial recrystallization and blue coloration, during formation of the enclosing silicate rocks. A similar coarsely crystalline blue calcite forms a sort of halo, ranging from less than an inch up to a few tens of feet thick, that surrounds the contact aureole in the Sky Blue limestone. In addition, distinctly bluish calcite has been found as haloes a few inches thick surrounding recrystallized chert nodules in the Chino limestone. These nodules, which occur nearly 100 feet from the quartz-diorite contact, are separated from the enclosing blue calcite by an inch or more of white, sugary to fibrous wollastonite.

The cause of the blue color in this calcite is unknown. Its spatial distribution in relation to the structural features of the area suggests that it is not due to deformationally induced strain. Similarly, it is doubtful that it is due to contained organic matter. On the


EXPLANATION
Talus, excavation debris and undifferentiated alluvial deposits.
Sky Blue limestone.
Monticellite-rich contact rocks.
Idocrase-rich contact rocks.
Garnet-rich contact rocks.
Gneiss, hornfels and schist.
Pegmatites and pegmatitic epidote-microcline-calcite-quartz rock.
Garnet-contaminated rock breccia.
Contaminated rock.
Quartz monzonite porphyry.
Quartz diorite (Bonsall tonalite).
SYMBOLS
Contact
Fault
Quarry head
Quarry toe
Topographic profile
A
Stations referred to in text.
Approximately 50 feet
Quarry Floor Not Mapped
Quarry Floor Not Mapped
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q

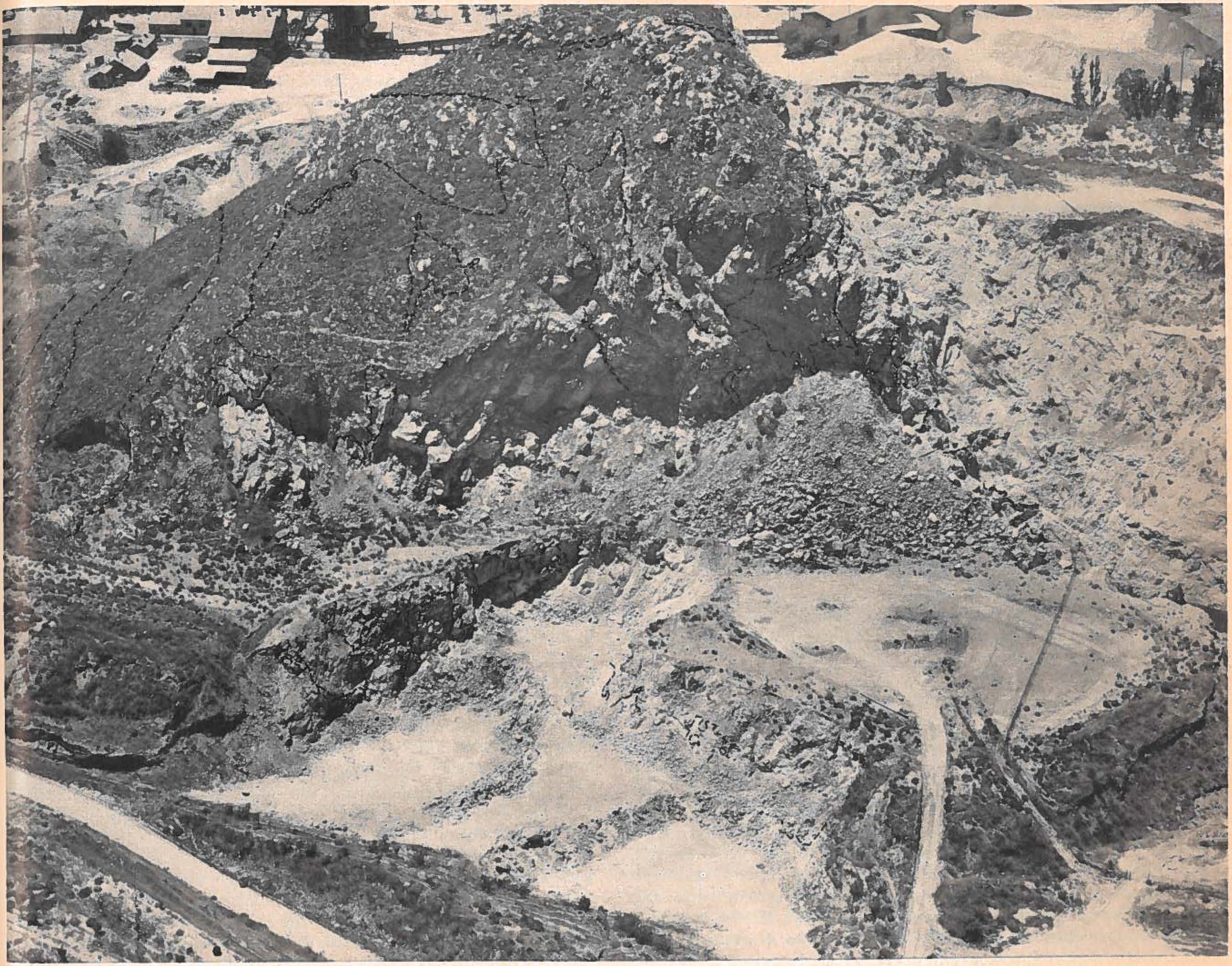


FIGURE 3. Oblique aerial view of the Commercial quarry, Crestmore. *R. C. Frampton photo.*

other hand, its distribution in the calcite does suggest that it might be related to lattice defects or to the introduction of minor or trace impurities during metamorphism. Although the most intense blue color is associated with brucite-free calcite, bluish predazzite also has been found.

Outside the contract aureole and beyond the halo of blue calcite, the magnesian limestones that were transformed into coarsely crystalline gray limestones and predazzites, either prior to or at the time of intrusion of the quartz diorite, were little affected by the quartz monzonite prophyry except in a few places near the contact, where scattered crystals of yellow chondrodite are present. This extremely abrupt change from rocks of very high metamorphic rank to unaffected limestones evidently is due to high thermal stability of the brucite-calcite assemblage and, perhaps more important, to the extreme instability of this same assemblage in the presence of very hot silica-bearing solutions.

Origin and Emplacement of the Quartz Monzonite Porphyry. Present evidence indicates that the quartz monzonite prophyry was intruded as a pipe-like body, 200 to 300 feet in diameter, upward and northward from points beneath the southeast corner of the area (see pl. 1). The wall rocks of the pipe in this part of the area were quartz diorite and a small remnant of the Chino limestone. At the point where the pipe intersected a large fragment of metamorphic rocks that directly underlie and interfinger with the lower members of the Sky Blue limestone, it split into two smaller pipes, one of which extended westward along the contact between quartz diorite and the metamorphic rocks.

The remainder of the porphyry magma continued on its northerly course, passing through the remnant of metamorphic rocks and through additional quartz diorite to the quartz diorite-Sky Blue limestone contact. Within the Sky Blue limestone, the porphyry formed a complex network of anastomosing pipes and stringers, the main mass of which was directed either westward along and near the footwall contact, or steeply upward into the limestone. As far as can be determined, the porphyry does not extend for more than a short distance north of the present south wall of the Wet Weather quarry.

The mechanical effects of the emplacement of the porphyry were highly variable. The quartz diorite apparently was little affected, but the Sky Blue limestone was arched up sharply into an eastward-plunging anticline. The distribution of CaO in contaminated and uncontaminated porphyry indicates that less than 15 percent of the space now occupied by the intrusive rock can be accounted for by the assimilation of limestone; hence, it might be assumed that the porphyry made room for itself largely by doming the limestone roof rocks.

The differences in the metasomatic effects associated with the quartz monzonite porphyry, as compared with those of the quartz diorite, must be related in some way to differences in physicochemical conditions at the time of emplacement, for the same limestones were the host rocks in both cases. Although absolute values for the variables of temperature, pressure, and composition would be difficult to establish, comparative values can be deduced with a certain degree of probability on the basis of composition and internal fabric of the crystallized products.

The quartz diorite exhibits features of texture and internal structure that are compatible with a magma of high viscosity and incompatible with one of low viscosity, and hence it is inferred that the magma contained a relatively high proportion of crystallized material at the time of its emplacement. This in turn implies that: (1) temperatures in the magma were in the lower part of the range of crystallization, and (2) the amount of water and other volatile constituents in the magma was relatively small.

The implication that the magma was deficient in water at the time of its emplacement follows from a consideration of the role played by this compound. Presumably it tends to reduce the viscosity of a magma by preventing the formation of large polymers of silica, and conversely, a deficiency in water and certain other volatiles permits the formation of these large polymers of silica, with attendant increases in viscosity of the liquid phase. Therefore, it is inferred that at the time of its emplacement, the viscous quartz diorite magma probably was deficient in water. Furthermore, because of the lack of the abundant water and uncombined silica that are necessary for large-scale silica metasomatism, the quartz diorite magma produced only a foot or two of silicate contact rock where it encountered limestone. The water-deficient condition that is here postulated to account for the thin contact zone between quartz diorite and limestone might have resulted from early crystallization of the hydrous minerals hornblende and biotite, which make up about 20 percent of the quartz diorite.

In contrast, textural evidence indicates that the quartz monzonite porphyry was not much more than 10 or 15 percent crystalline at the time of initial intrusion, and that therefore its temperatures probably were in the higher part of the crystallization range. Furthermore, because the porphyry magma apparently was originally very poor in iron and magnesium, necessary components of hornblende and biotite, none of the original water of the magma was fixed in early solid phases. Thus with high temperatures and with the existence of abundant water and uncombined silica and alumina, some of the most important conditions for large-scale metasomatism were satisfied. However, unless conditions in the system had been favorable for the separation of these potential metasomatizing solutions, the surrounding limestones obviously would have been little affected.

The derivation of the metasomatizing solutions from the residuum of crystallization is precluded, for there is strong evidence that extensive metasomatism actually preceded final emplacement and crystallization of the porphyry. Therefore, it is suggesed that the sudden relief of confining pressure on the highly fluid porphyry magma upon its entry into the easily deformable limestones, coupled with a copious evolution of CO_2 by reaction beween magma and limestone, caused the separation of large quantities of CO_2-rich aqueous solutions that served as transporting media for heat, silica, and alumina.

Origin of the Contact Rocks and Metamorphic Zones. An adequate theory for the origin of the contact rocks at Crestmore must explain the following features: (1) the occurrence of relatively rare, presumably high-temperature contact minerals such as merwinite and spurrite; (2) the very sharp contact between unaffected limestones and rocks composed of these minerals; and (3) the general zonal distribution of mineral assemblages with the monticellite-zone assemblage, containing many of the critical minerals of the sanidinite facies, adjacent to the unaffected limestones; with the garnet-zone assemblage, the characteristic minerals of which are critical for the pyroxene hornfels facies, lying next to the intrusive; and with idocrase in between.

The occurrence of minerals that presumably require higher temperatures for their formation than ordinarily are attributed to even the hottest granitic magmas is most easily explained as the result of development under non-equilibrium conditions. The large number of mineral phases that can be observed in a single thin section, some of them in reaction relationship, and the consistent decrease in silica content of the contact rocks outward from the intrusive masses, strongly suggest that equilibrium was not generally attained and that the system was essentially open. Under these conditions, the CO_2 evolved during formation of the silicate minerals would have escaped and thereby allowed the reactions to proceed at much lower temperatures than would have been possible in a closed system.

A possible cause of the sharp contact between the monticellite zone and the unaffected limestones may be deduced from the conditions imposed by the nature and position of the zones themselves. Specifically, the temperature of metamorphism was sufficient, even in the outermost part of the contact aureole, for the formation of the monticellite-zone assemblage, and, in order to account for the absence of a so-called lower-grade zone (characterized by such minerals as tremolite) beyond the monticellite zone, these temperatures must have been reached prior to, or at the time of, introduction of the silica and alumina. The high thermal conditions thus imposed upon the calcite-brucite assemblage rendered it highly reactive to the silica- and alumina-bearing solutions, and therefore capable of rapidly and almost quantitatively removing these constituents from the solutions.

Inasmuch as the relative positions of the contact zones are just the reverse of what would be expected on the basis of thermal zoning, it is concluded that, during metamorphism, either the temperature gradient was very small from the intrusive outward to the boundary of the aureole, or metasomatic effects completely overshadowed the thermal effects. If metasomatic processes actually were responsible for the zoning, the mineral assemblages of each zone should exhibit some consistent compositional difference with respect to the assemblages of an adjacent zone. That this is the case can be shown by computing the atomic ratios of calcium plus magnesium to silicon for the various minerals of the contact aureole. It is found that the minerals characteristic of the inner or garnet zone have ratios of about 1:1, those characteristic of the outer or monticellite zone, 2:1, and idocrase of the intermediate zone, 1.5:1.

Conclusion. This summary of contact metamorphism at Crestmore would not be complete without at least a brief discussion of the concept advanced by Bowen (1940), wherein it is postulated that various contact minerals are formed in a stepwise sequence by progressive decarbonation of a siliceous limestone or dolomite, as a consequence of rising temperature. The only evidence found at Crestmore to date that supports such a scheme comes from textural studies of the monticellite-zone rocks, which indicate that monticellite, gehlenite, spurrite, and merwinite formed in that order, coincident with Bowen's "index minerals" 6 to 9, inclusive. From the same studies, however, it is evident that the reactions by which these minerals were formed were not, in general, those suggested by Bowen. The principal cause of failure in the attempted application of this scheme appears to stem from the lack of silica in the limestone. The effect of this deficiency of the system was to make the various minerals dependent for their formation on the silica introduced during metasomatism. It is concluded, therefore, that the contact metamorphism at Crestmore should be viewed as progressive decarbonation, at elevated temperatures, attendant upon increasing concentrations of metasomatic constituents, rather than as progressive decarbonation attendant simply upon rising temperatures.

Acknowledgments. The writer is grateful for the wholehearted cooperation of the officials of the Riverside Cement Company, and particularly for their generosity in allowing him complete access to diamond-drill records and cores. Dr. A. O. Woodford and Dr. R. H. Jahns offered many valuable suggestions and criticisms during the course of the work and in the preparation of the manuscript. The Claremont Graduate School supplied funds for the aerial photograph shown in figure 3.

REFERENCES

Bowen, N. L., 1940, Progressive metamorphism of siliceous limestone and dolomite: Jour. Geology, vol. 38, pp. 225-274.

Larsen, E. S., Jr., 1948, Batholith and associated rocks of Corona, Elsinore, and San Luis Rey quadrangles, southern California: Geol. Soc. America Mem. 29, 182 pp.

For a fairly complete list of papers pertaining to the geology and mineralogy of the Crestmore region prior to 1943, the reader is referred to Woodford, A. O., 1943, Crestmore minerals: California Jour. Mines and Geology, vol. 39, pp. 333-365.

Since 1943, the following papers have appeared:

Forman, S. A., 1951, Xanthophyllite: Am. Mineralogist, vol. 36, pp. 450-457.

Mackevett, E. M., 1951, Geology of the Jurupa Mountains, San Bernardino and Riverside Counties, California: California Div. Mines Special Rept. 5, 14 pp.

Murdoch, Joseph, 1951, Perovskite: Am. Mineralogist, vol. 36, pp. 573-580.

Murdoch, Joseph, 1952, Nasonite from Crestmore, California (abstract): Geol. Soc. America Bull., vol. 63, p. 1341.

Rosenholtz, J. L., and Smith, D. T., 1950, Crestmore Sky Blue marble, its thermal expansion and color: Am. Mineralogist, vol. 35, pp. 1049-1054.

Taylor, H. F. W., 1953, Riversideite and crestmoreite: mineralogical and chemical composition (abstract): Mineralog. Abstracts, vol. 12, no. 1, p. 59.