QUARTZ XENOCRYSTS IN OLIVINE BASALT FROM THE SOUTHERN SIERRA NEVADA OF CALIFORNIA

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ABSTRACT

Isolated bodies of volcanic rocks heretofore but little known and found in the southern Sierra Nevada are described. Olivine basalts containing well defined quartz xenocrysts are common. The hypothesis is advanced that the quartz is derived from the alteration of numerous inclusions of grandiorite in the volcanic rocks. Radial cracks about some inclusions are described, and an hypothesis for their origin is discussed.

INTRODUCTION

Field work has been carried on by the writer in the southern Sierra Nevada for the past seven years; an areal map of the Kernville quadrangle has been prepared[1] and certain special problems have been investigated.[2] The purpose of this paper is to describe quartz xenocrysts in basalt, and associated volcanic rocks of the southern Sierra Nevada, principally south of lat. 36°N.

SKETCH OF THE REGIONAL GEOLOGY

The rocks of the region consist of a series of phyllites, quartzites, and marbles, to which the name Kernville series has been applied;[3] these have been invaded by (1) gabbro, locally varying to diorite and quartz diorite, which is closely associated with (2) quartz diorite, varying to granodiorite. These are intermediate in age between the Kernville series and (3) the Isabella[4] granodiorite which has quartz monzonite, granite, and quartz diorite facies, and is believed to belong to the major intrusive period of Sierran orogeny, the late Jurassic.[5] Basalts and quartz-bearing basalts, with other associated volcanic types rest on erosional surfaces beveling these rocks. A few lacustrine and fluviatile sediments comprise the youngest rocks.

[1] Miller, William J., and Webb, Robert W., Descriptive geology of the Kernville quadrangle, California: *Calif. Bur. Mines and Geol.*, in press.

[2] Webb, Robert W., Kern Canyon fault, Southern Sierra Nevada: *Jour. Geol.*, **44**, 631–638 (1936); Relations between wall rock and intrusives in the crystalline complex of the Southern Sierra Nevada of California: *Jour. Geol.*, **46**, 310–320 (1938).

[3] Miller, William J., Geologic sections across the southern Sierra Nevada of California: *Univ. Calif. Pub., Bull. Dept. Geol. Sci.*, **20**, 335 (1931).

[4] Miller, William J., *op. cit.*, 344.

[5] Hinds, N. E. A., The Jurassic age of the last granitoid intrusives in the Klamath Mountains and Sierra Nevada, California: *Am. Jour. Sci.*, **27**, 182–192 (1934).

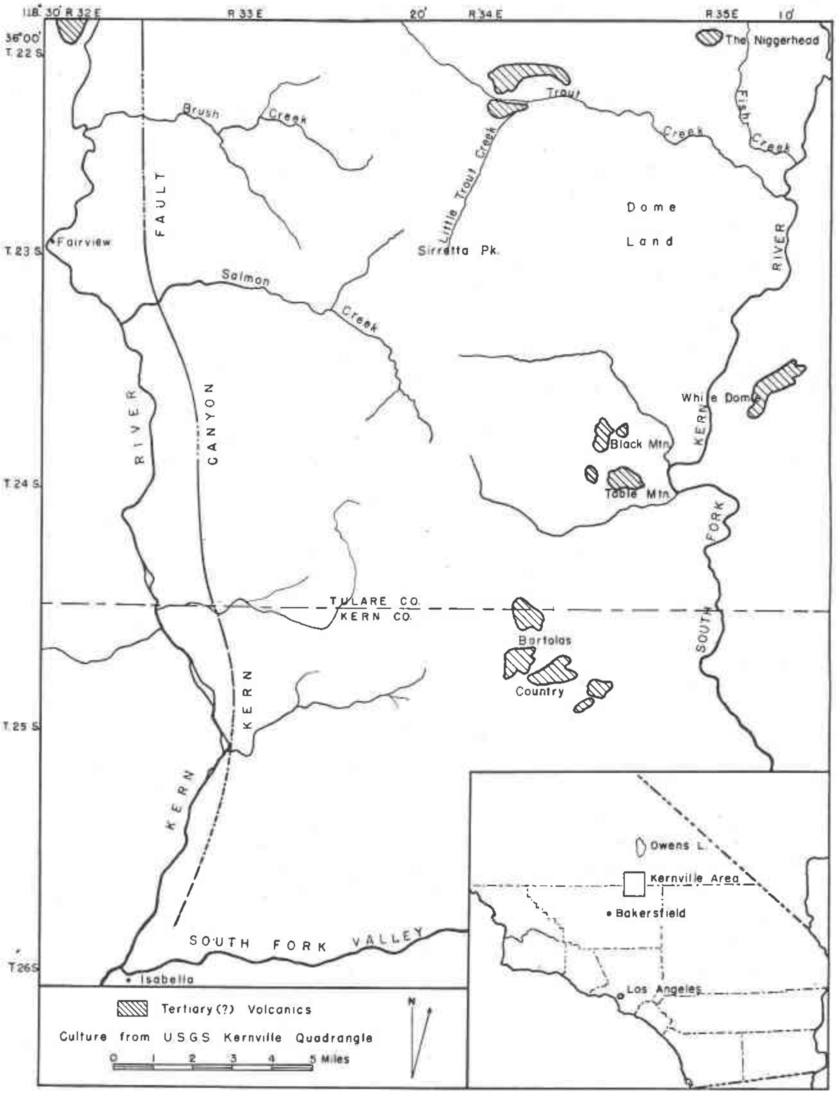

FIG. 1. Sketch map showing location of the Kernville area, and distribution of the volcanic sequences.

PREVIOUS REFERENCE TO VOLCANIC TYPES

In the Kernville region, Miller[6] reported the occurrence of a few small andesite dikes and waterworn pebbles of similar material in the valley of

[6] Miller, William J., *op. cit.*, 353.

the South Fork of the Kern River. Lawson[7] described basaltic cones and flows in the Olancha quadrangle to the north, with a brief petrographic description of the volcanic rocks. Later Knopf[8] described the volcanic cones of Templeton and Monachee Meadows in the Olancha quadrangle.

Description of the Volcanic Sequences

General Areal Relations

The volcanic rocks occur as flows in disconnected areas, all within the Kernville quadrangle and north of South Fork valley. They vary petrologically, in stratigraphic sequence, and structure. From south to north, the units may be designated as follows: (see Fig. 1)

(1) Bartolas. Volcanic rocks are exposed in five isolated areas. They rest on crystalline basement rocks which were previously reduced by erosion to the condition of an undulating oldland. The four southernmost of these probably were connected at one time, as indicated by their similar altitudes, compositions, thicknesses, structures, and areal patterns. They are uniform throughout, composed of platy, black basalt from 100–150 feet thick. The rocks in the fifth area, the northernmost of the Bartolas group, are black massive basalt, red banded basalt, and gray hornblende andesite, occurring in stratigraphic units in thicknesses of about 50 feet.

(2) Table Mountain. Two separated, but at one time continuous, flows, lie on an oldland surface north of the Bartolas country. These are composed of massive gray to black basalt, which is often agglomeratic at the base. Thicknesses are commonly 200 feet, but are thinner in the western of the two units.

(3) Black Mountain. Two areas, separated by erosion and closely adjacent to Table Mountain, are composed of scoriaceous red, and black massive basalt, occurring in several flows totaling 150–200 feet in thickness.

(4) White Dome. A single massive, black basalt flow represents the only volcanic rock in the region east of the South Fork of the Kern River. The rocks are similar to those of Table Mountain.

(5) Trout Creek. The gorge of Trout Creek, about 750 feet deep, separates into two areas what was formerly a continuous flow of gray to red, platy, banded basalt, with agglomerate at its base. These flows are the thickest in the region, about 300 feet.

[7] Lawson, Andrew C., The geomorphogeny of the upper Kern basin: *Univ. Calif. Pub., Bull. Dept. Geol.*, **3**, 300–301; 320–322; 374–376 (1904).

[8] Knopf, Adolph, A geologic reconnaissance of the Inyo range and the eastern slope of the Sierra Nevada, California: *U. S. Geol. Surv. Prof. Paper* **110**, 73 (1918).

(6) The Niggerhead. On the northern edge of the Kernville quadrangle, basalt caps 75–100 feet thick form a large monolith-like mass. The lava cap is astride a contact zone between the two major batholithic units (granodiorite and quartz diorite) of the Southern Sierra Nevada.

(7) Main Canyon of the Kern. It has long been known that there are large andesitic and basaltic flows along the valley of the Kern River.[9] These are the most extensive in the entire southern Sierra. They occur in isolated outcrops northward along the Kern River for twenty-five miles, from a point about twenty-five miles north of Kernville. They are thought to have been extruded during the same period as those described above. Since they extend far to the north, in the areas described by Lawson[10] and Knopf,[11] they will not be included in this discussion.

Basalts

All of the rocks of the volcanic areas have petrographic similarities. The dense, black, platy aphanites do not contain many minerals recognizable megascopically. Sporadic globular or lenticular xenocrysts of gray, glassy quartz, up to one-quarter of an inch in diameter, occasional grains of olivine, and xenolithic masses of granitic (and pegmatitic) country rock, up to three feet across, are all that can be seen in the average basalt.

Microscopically, subhedral to euhedral olivine microphenocrysts, often altered to iddingsite, labradorite laths, and magnetite occur in a holocrystalline pilotaxitic ground mass. Some facies carry prismatic subhedral crystals of augite, or pigeonite, also as microphenocrysts. Basaltic hornblende occurs in some andesitic facies. Occasionally the plagioclase is medium andesine instead of labradorite. In places these form abundant euhedrons, which show strong strain shadows and zoning. Iddingsite, pseudomorphous after olivine, is a wide-spread mineral, particularly abundant in the red flows. It occurs in large pseudomorphs, with cores consisting of unaltered olivine grains. The iddingsite is deep brown, slightly pleochroic with strong dispersion, and shows the characteristic concentration of limonite and hematite around each iddingsite individual. Accessory minerals are abundant coarse grained magnetite, some of it secondary, and apatite in coarse rods and hair-like needles. In places the groundmass is hypocrystalline; locally pitchstones are encountered although glassy facies are rare.

[9] Lawson, Andrew C., *op. cit.*, 300.
[10] Lawson, Andrew C., *op. cit.*, 320.
[11] Knopf, Adolph, *op. cit.*

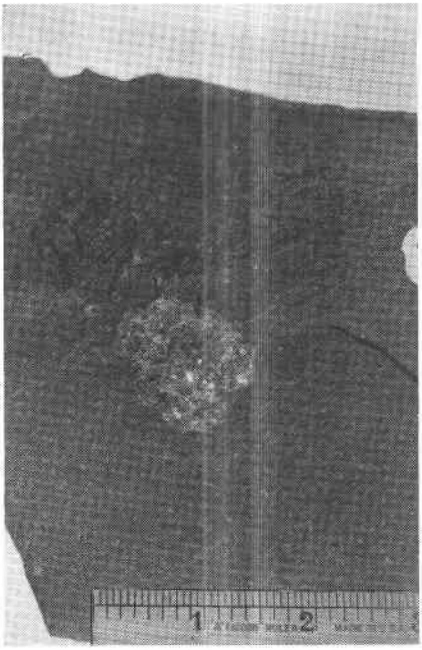

FIG. 2. Iron stained quartz-rich inclusion in basalt of the Bartolas group. Enclosure composed of a few grains of andesine with corroded margins, and many grains of strained quartz.

QUARTZ-BEARING BASALTS

Mode of Occurrence and Description of the Quartz

Quartz has been observed widely distributed in rocks of the Bartolas, Table Mountain, Black Mountain, Trout Creek, and Niggerhead areas. It occurs commonly as angular grains, and as angular and rounded granular aggregates. Usually it is much corroded at contacts with the basalt. Contacts of quartz grains with the basalt are always exceedingly sharp, although the quartz grains have been corroded and embayed. This seems anomalous in view of the reaction relations shown by some of the associated minerals[12] in the same environment; it has been suggested[13] that these sharp contacts are due to the fact that the quartz lacks a good cleavage. However, many of the contacts simulate the outlines of conchoidal to subconchoidal fracture, and it may be that the contacts repre-

[12] See below.

[13] Larsen, E. S., and Switzer, George, An obsidian-like rock formed from the melting of a granodiorite: *Am. Jour. Sci.*, **237**, 563 (1939).

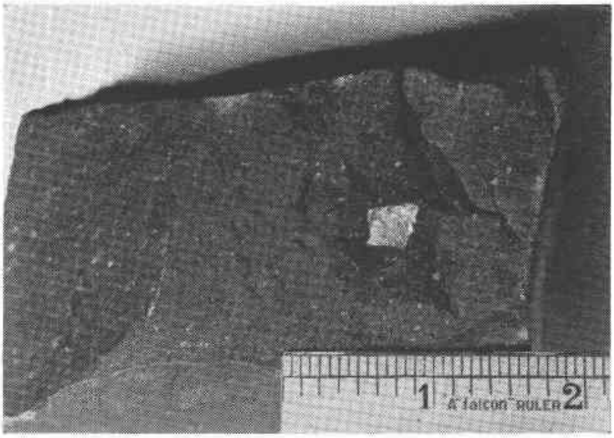

FIG. 3. Angular inclusion of quartz in olivine basalt of Big Table Mountain. Olivine grains are closely adjacent to this inclusion.

sent actual fracture surfaces, produced by temperature changes during the course of crystallization of the basalts. The crackling of quartz granules internally under similar conditions has been recognized.[14] In addition to the quartz granules, sporadic inclusions of pegmatite, composed of

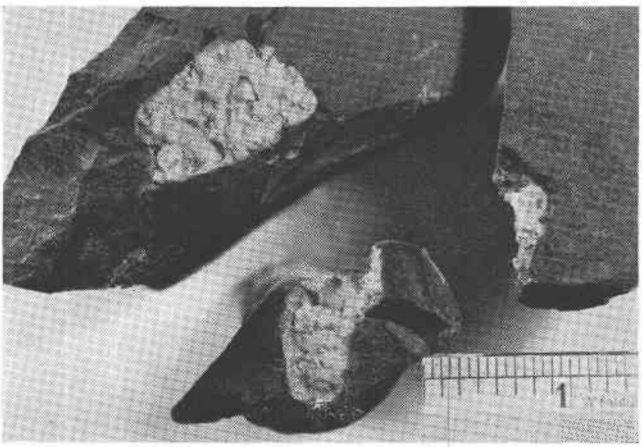

FIG. 4. Masses of quartz-rich pegmatite included in olivine basalt. Note the small percentage of feldspar. The fractured nature of the quartz may explain the source of many angular inclusions of pure quartz, since the original quartz might readily be broken up and mechanically incorporated as small angular grains similar to the one shown in Fig. 3.

[14] Knopf, Adolph, Partial fusion of granodiorite by intrusive basalt, Owens Valley, California: *Am. Jour. Sci.*, 5th Ser., **36,** 376 (1938).

milk-white quartz (80–90%) and microcline are found. These inclusions are as large as $1\frac{1}{2}$ inches in diameter, and are abundant locally.

Granodiorite Xenoliths

Inclusions of granodiorite, derived from the formation upon which most of the lavas were extruded, occur in many of the flows of the southern Sierra Nevada. The inclusions often are extremely abundant, and all stages of alteration and digestion have been recognized. In texture and mineral composition the inclusions are on the whole the same as the Isabella granodiorite, from which it is thought they were derived. Little alteration can be noted by megascopic examination, although microscopic studies show significant changes in some xenolithic margins.

Size and Shape of the Inclusions. Recognizable granitic inclusions vary in size from one inch to two or three feet in diameter. Only one inclusion has been observed in three dimensions; in this the average was two feet on a side; the smallest size given represents those that can be positively identified as granodiorite. Inclusions of much smaller size are commonly composed chiefly of quartz, with a few grains of altered feldspar. These are remnants of larger inclusions which have been almost completely digested or which have been torn from larger masses along the route of flow. Irregularly shaped masses are typical, although spheroid, ovoid, and elongate ones have been found.

Distribution of the Inclusions in the Flows. Inclusions have been observed in all flows in the Kernville area. They have random distribution in the flows, ranging throughout the thicknesses exposed, although local concentrations near and at the contact of the flows with the crystalline basement are encountered. In a one hundred foot vertical thickness in Table Mountain, one finds inclusions in all parts of the outcrop. The same is true of the Niggerhead, although the vertical face is higher. In the Niggerhead, inclusions are quite abundant near the base of the flow; in the Trout Creek group, they are more common at the top; in Table Mountain only very large inclusions are seen.

Alterations of the Xenoliths

Many of the xenoliths show evidences of alteration since their introduction into the basaltic magma. There are noted: (1) alteration rims about many inclusions varying from one to three centimeters in width, with gradations in grain size and texture from xenoliths to the basalt, (2) apparent leaching effects where feldspars have been largely removed, leaving granular and spongy-appearing quartz and residual feldspar, (3) visibly greater shattering of feldspars and fracturing of quartz in inclusions than in the normal granitic rock (this shattered condition has been noted by other workers in similar occurrences),[15] (4) almost complete removal of feldspar. Where this has occurred, quartz granules are considerably larger than the grains found in the normal granitic rock. Microscopic study shows different optical orientations in these grains, suggesting aggregations of smaller quartz units into quartz-rich areas, residual from altered xenoliths. Subhedral boundaries on quartz grains in pegmatitic inclusions, and their absence in these aggregations precludes their being pegmatitic xenoliths.

Microscopic examination of the transition zones between basalt and xenoliths show mineralogical and textural changes in the enclosed minerals. The alteration rims so prominent megascopically are seen microscopically to be composed of minerals which in part represent transitional products between basalt and granitic rocks, with intermediate recrystallization textures. Mineralogical relations within transition zones include (a) the inversion of orthoclase to sanidine, (b) the formation of clinopyroxene (probably diopside) in a zone transitional between olivine-rich basalt and granite but with no direct olivine-quartz contact, (c) etching and replacement of quartz by orthoclase, and (d) development of spinel.

A typical contact rim surrounding a xenolith is one to two centimeters in width. The rim is commonly in sharp contact with the enclosing rock and gradational with the granitic enclosure. This is interpreted as suggesting that the bulk of the material of the reaction rim is recrystallized xenolith and not material introduced by the magma. Resorption of the olivine and some iron ores contained in the basalt are the only apparent contributions of the basalt to the recrystallized zone. This interpretation is supported further by the absence of introduced glass in the reaction zone, glass being an important constituent of similar contact zones elsewhere.[16] The clinopyroxene, spinel, and iron ores of the contact zone occur in a groundmass of coarse grained potash feldspar, mostly sanidinized. The sanidine poikilitically includes all other minerals,[17] except quartz. Opening of the sanidine along its cleavage is prominent, although infiltration of other minerals has been slight. Some cleavage cracks have been filled with minute crystals of clinopyroxene and some iron ore.

Formation of clinopyroxene in a zone intermediate between olivine-rich and quartz-rich rocks has occurred in zones. The clinopyroxene oc-

[15] Lacroix, A., Etude sur Le Metamorphisme de Contact des Roches Volcaniques: *Memoires, L'Academie des Sciences de L'Institut de France*, **31,** 19 (1894); Knopf, Adolf, *op. cit.*, 74–75 (1918).

[16] Richarz, Stephen, Some inclusions in basalt: *Jour. Geol.*, **32,** 686 (1924). Knopf, Adolph, *op. cit.*, 374 (1938).

[17] Similar relations are described by Williams, Howel, Pliocene volcanoes of the Navajo-Hopi country: *Bull. Geol. Soc. Am.*, **47,** 151 (1936).

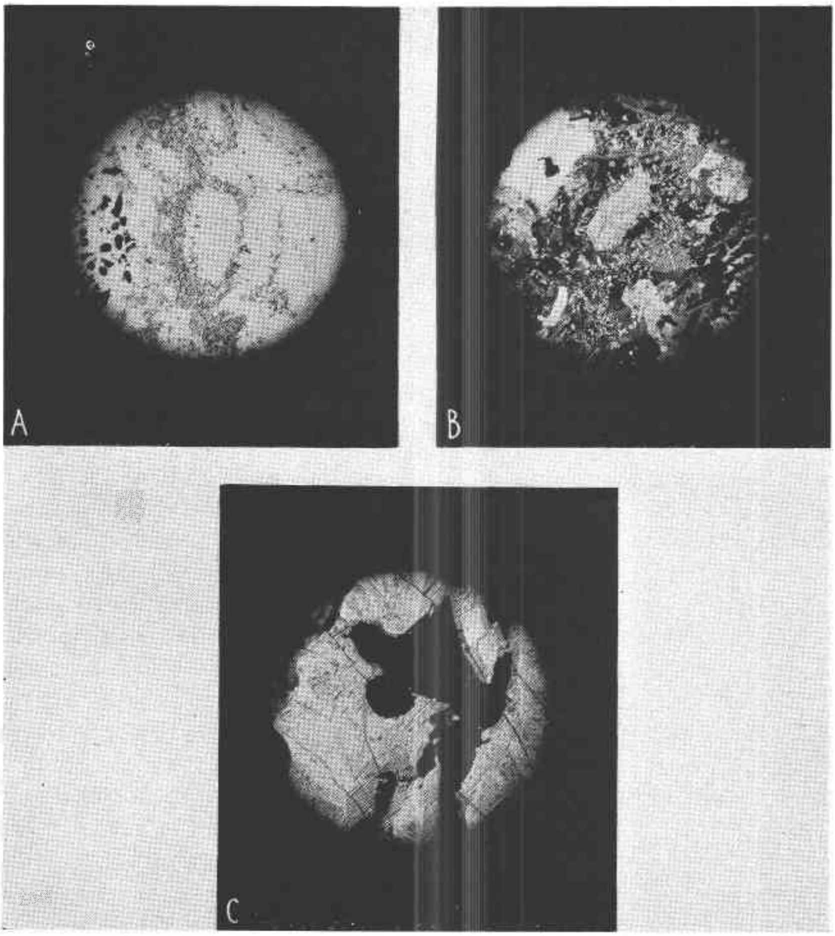

FIG. 5. Photomicrographs of three stages in alteration of a quartz monzonite inclusion in basalt.

A. Grain of quartz surrounded by clinopyroxene needles. Dark-colored grains are olivine stained with hematite in basalt. Note concentration of diopside grains toward basalt, and lesser concentration against quartz monzonite inclusion. ×16.5.

B. Quartz grain showing abundance of clinopyroxene in contact zone, and distribution of clinopyroxene throughout margin of inclusions; contrast between feldspar (lower right, showing Carlsbad twin) and quartz reaction well shown. × nicols. ×16.5.

C. Etched and corroded quartz grain which has reacted with adjacent perthitic orthoclase. Note the peculiar shape of the quartz anhedron. × nicols. ×16.5.

curs most prominently in halos about grains of quartz. Prisms commonly arrange themselves with their longest dimension normal to the contact surface of the surrounded mineral. The clinopyroxene in tinged greenish on its edges in certain grains, with some grains of a uniform green color over much of the surface of an individual. Always, however, the color grades off marginally into the normal colorless or nearly colorless clinopyroxene. In the contact zone where quartz grains of granitic inclusions lie at the adjacent contact or within the zone, the olivine has reacted directly to form clinopyroxene halos. Pyroxene grains are most abundant on the basalt side of the contact but they completely encircle the quartz. Where orthoclase lies in the contact zone, the clinopyroxene is less abundant. Where pyroxene is associated directly with orthoclase, textural relations suggest the source of silica to have been from the orthoclase. This may have been accomplished by (1) the extraction of the silica in a molecule of orthoclase and subsequent reunion of the alkalies and alumina with quartz to reform orthoclase, or (2) the loss of part of the silica in orthoclase, with a reaction stage in which leucite was present but in which concurrent reunion of leucite and quartz occurred to reform orthoclase.

The second hypothesis is extremely unlikely in view of the relations of the minerals actually present in the rock. The temperatures existent during the reaction period are suggested (1) by the presence of sanidine, (2) lack of intensive alteration of the xenoliths, and (3) the absence of tridymite inversion of quartz. Since sanidine has formed only in marginal rims, and not throughout the inclusions, a temperature not higher than 900° C.[18] is indicated, and the possibility is strong that the minimum temperature of 600° C. which must prevail if sanidine is to be stable was not much exceeded.[19] Some glass might be expected below 870°; at this temperature, also, quartz would invert to tridymite. Since neither of these changes are recorded, temperature relations are indicated which make it seem impossible for leucite to have formed even as a reaction stage during the development of the clinopyroxene from orthoclase.

The other hypothesis that silica was subtracted from orthoclase, and the residual alkalies driven toward the central portions of the granitic inclusions, receives support from peculiar textures developed inside of the sanidine rim and marginal to the less altered inclusion. In and adjacent to the marginal zone an anastomosing myrmekite-like texture is produced in the quartz anhedrons. Each irregular quartz grain extinguishes uni-

[18] Merwin, Herbert E., The temperature stability ranges, density, chemical composition and optical and crystallographic properties of the alkali feldspars: *Jour. Wash. Acad. Sci.*, **1,** 59–60 (1911).

[19] Winchell, A. N., Elements of Optical Mineralogy, Part II, Description of Minerals. Wiley and Sons, *New York*, 362 (**1933**).

formly and is physically and optically continuous. Small embayed quartz grains often extinguish with other quartz grains nearby, even when completely surrounded with perthitic orthoclase which has not been altered to sanidine. Inside the margins of xenoliths, there are normal contact relations between the quartz and orthoclase. This is cited as evidence that after reaction of orthoclase in the margin with olivine to form clinopyroxene, the residual alkalies migrated inward and combined with quartz to reform orthoclase. That this pseudo-myrmekitic texture was not produced by late-stage alkalies, introduced after the magmatic stage, is suggested by the absence of biotite in the suite, since the clinopyroxene of the reaction zone would normally be expected to proceed toward biotite and chlorite, if a late stage post-pyroxene alkali episode occurred. Occasionally small remnants of quartz lie irregularly along orthoclase cleavages, or astride them always with embayed margins. Although this textural relation has often been cited to show that quartz has replaced orthoclase[20] it has recently been suggested that too close adherence to this interpretation may lead to error.[21]

A few grains of a deep green euhedral isotropic mineral are identified as spinel. They are rare, and when found, occur in mats of clinopyroxene crystals.

Sources of Xenoliths

The presence of granodioritic xenoliths in various stages of alteration suggests that the granodiorite basement contributed siliceous material to the subsiliceous magma late in its magmatic history. It is believed that many of the inclusions were torn off fissure walls while the magma was rising through conduits in the granodioritic rocks. Fragments were detached and included in the magma, and were carried out with the extrusion. Concentrations near the base of some flows indicate that other xenoliths were picked up from exposed surfaces or that some settled out during cooling. Where basal concentrations of xenolithic material occur, it is common to find (1) radial tension cracks around inclusions, (2) no appreciable alteration of the xenoliths, and (3) rounded xenoliths, more deeply weathered than many of the abundant angular inclusions higher in the flows. The basal concentrations are therefore probably due chiefly to inclusions picked up from the weathered surface upon which the basalt was extruded.

It seems that xenoliths derived at depth would be more completely altered texturally and mineralogically than those derived from exposed

[20] Schaller, Waldemar T., Mineral replacements in pegmatites: *Am. Mineral.*, **12,** 61 (1927); Bastin, E. S., and others, Criteria of age relations of minerals, etc., *Econ. Geol.*, **26,** 605 (1931).

[21] Wahlstrom, Ernest E., Graphic granite: *Am. Mineral.*, **24,** 698 (1939).

surfaces at a time when congealment of the magma was imminent. The association of olivine and quartz in the same rock, often nearly side by side, and the general relations shown by the xenoliths to the enclosing rock establishes the fact that some silicic material was introduced in a late magmatic stage.

Radial Tension Cracks

Surrounding some of the inclusions, radiating outward from them, tension cracks often appear, generally in 5 or 6 directions. The larger cracks often extend distances as great as six feet into the basalt, radiating from

Fig. 6. Inclusions of granitic material in olivine basalt. Note tensional joint cracks radiating from inclusions. Small joints are developed subradial with the larger ones around the inclusions. Inclusion two inches on longest side. From the Niggerhead.

inclusions as small as two inches on a side. Between the master radii lie shorter cracks, often less than an inch in length. These seem to be the result of tensional forces applied in the magma, just prior to consolidation and continued during cooling to atmospheric conditions. The mechanism of their development is less obvious, however, particularly since the size of the master cracks are quantitatively disproportional to the size of the foreign inclusions about which they form; yet it is obvious that the tensional forces producing the cracks must have been set up following the introduction of the xenolith.

Of the many inclusions examined, tension cracks were found only about those xenoliths which showed little or no alteration of the included material. This immediately suggested later introduction of those xenoliths about which cracks developed, at a time when crystallization was nearly complete.

Analogous development of radial cracks seems to be found in certain reactions of glasses in the laboratory. When mounting metal tubes or rods in glass under atmospheric conditions, it is common knowledge[22] that glass, containing a platinum mount, even when prepared with extreme care, invariably upon cooling shows tension cracks in the glass radiating outward from the platinum. The size of these cracks is proportional to the coefficient of expansion of the glass, diameter of the metal rod, rate and uniformity of heating and of cooling, and other factors. The cracks develop in response to tensional forces set up in the glass tangential to the rod at all points. Only when the enclosure is coated with a cushion of liquid,[23] or some substance which can react with the glass, is the tensional force equalized (or minimized by the composition gradient) in all tangential directions. If the rod is dry, the forces are unequal tangentially, and cracks develop. Furthermore, if a square cross section of metal is introduced the forces are greatest at the corners, longer cracks develop radiating from the sharpest angles, and smaller cracks develop elsewhere, normal to the metal surface, and with random distribution. By analogy, then, xenolithic material, included in a basaltic magma, which crystallizes partially as glass, or of uniform fine grain, might be expected to act similarly. Since, in the case in question, the coarse grains of the inclusions would provide many irregularities for a maximum concentration of tangential force, and since little or no coating of low-viscosity would be expected on an inclusion that was introduced at a late stage, a maximum development of cracks might be expected, with some cracks more prom-

[22] Houskeeper, William G., The art of sealing base metals through glass: *Jour. Am. Inst. Elect. Eng.*, **42,** 954 (1923).

[23] A French patent by G. Berlemont describes a method of sealing platinum wire, containing iridium, into quartz tubes by heating the quartz in the oxyhydrogen flame with one end of the tube in platinic chloride ($PtCl_4$) with a suction pump drawing the solution up the tube and around the wire between wire and glass during heating, to insure a tight seal around the joints. *Chemical Abstracts*, **8,** 411 (1918); and Houskeeper, William G., *op. cit.*, 957, for a similar process with base metals.

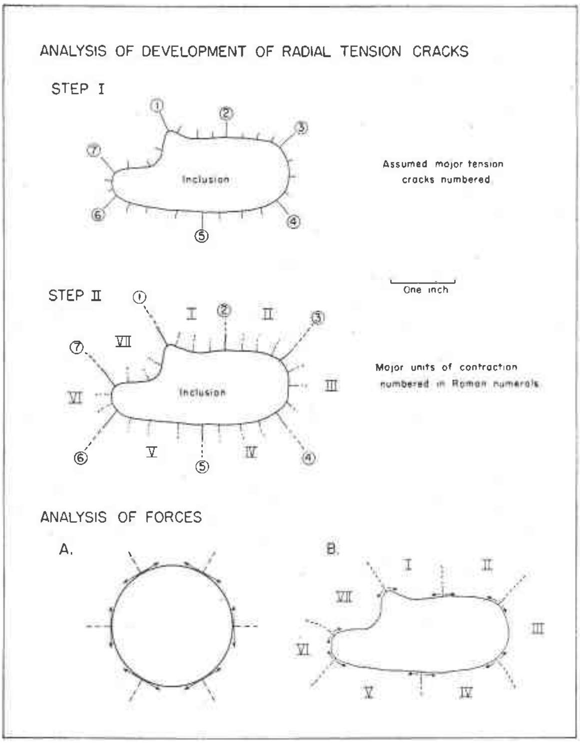

FIG. 7. Assuming a cushion of liquid of low viscosity about a sphere of composition such that it would react with the liquid, tangential forces under the composition gradient produced would be insufficiently strong to develop tensional cracks in the cooling matrix. If cushion of liquid is absent, or the liquid is super cooled, *regularly spaced* and *equal length* cracks would be expected in the same time period. An inclusion of irregular shape would act similarly to the sphere, given a cushion of liquid; however, without the liquid cushion, cracks would develop whose length and spacing were determined by the irregularity of the inclusion, the longest cracks to be expected where the sharpest angles were found on the inclusion. Such major cracks, radial to the inclusion, would define major contraction units.

inent than others, but none quantitatively disproportionate to the other. Since complete congealment of a basalt might reasonably be expected at a minimum temperature of 500° C.,[24] considerable contraction of the basaltic rock is to be expected as atmospheric conditions are approached.[25]

[24] Day and Shepherd reported surface temperatures at the top of the lava column of Kilauea of 1070° and 1185° C., respectively. [Water and volcanic activity: *Bull. Geol. Soc. Am.*, **24,** 601 (1913)]. Grout, [Petrology and Petrography, McGraw-Hill, 145 (**1932**)] states that lava at Kilauea flows slowly at 600° C.

[25] "Diabase contracts between 3.5–4% on solidification," Barus, Carl, High temperature work on igneous fusion and ebullition: *U. S. Geol. Surv., Bull.* **103,** 25 (1893).

Since cracks of maximum size develop about those xenoliths with maximum marginal irregularities it would be expected that during cooling toward air temperature, the lines of maximum cracking would continue to enlarge outward as on the spokes of a wheel with 5–6 directional radii most common. This might be likened to the extension of a crack in a plate or other glass as time elapses after a small crack forms. This is in essence considering a mass of infinite size, contracting about a nucleus of foreign material considered as a point.

By the development of the maximum tensional cracks, units of volume are defined which are bounded by these master radii, which continue in their development outward, and encompass larger and larger units of volume. Figure 7 expresses diagrammatically these relations.

The introduction of cold rock into a viscous mass near the temperature of congealment would also aid in the development of the radial cracks because of a slight chilling effect, setting up stresses similar to those formed during development of columnar joints, where the effective control is cooling from a plane or nearly plane surface downward.[26] If, however, a cooling surface is irregular, such as it would tend to be where xenoliths were adjacent, such stresses would be more irregular than in columnar jointing, accentuating further the development of tensional cracks, particularly at sharp and reentrant angles on the cooling (xenolithic) surface. The small size of the xenoliths, however, compared to the bulk of matrix would suggest that this was only a slight contributing factor.

Another contributing, though lesser factor, is the difference in coefficients of thermal expansion (and contraction) of the minerals of the xenoliths and the xenolith itself compared to the coefficient of the matrix.

It has been pointed out that such radial cracks have been observed around only a few zenoliths—those without reaction rims. About other xenoliths of granite, but of larger size, where cracks are absent, are found reaction rims forming a transition zone between matrix and enclosure. Referring again to laboratory techniques in glasswork, if some more chemically active metals are mounted in glass, such as copper or tungsten tubes or rods, it is possible to produce a mount without cracks around the rod when an intermediate mixture of glass and oxide of metal can be formed. Thus in tungsten rods, if they are thoroughly cleaned, then oxidized, and inserted in molten glass, the tungsten oxide diffuses through the glass marginal to the metal rod and forms a reaction rim or "corona" between the glass and tungsten equalizing thermal coefficients in metal and glass and preventing radial tension cracks.[27] Thus, Dr. J. B. Ramsey,

[26] Iddings, J. P., igneous Rocks. Vol. **1** (Wiley), 320 (1920).

[27] Houskeeper, William G., *op. cit.*, 957 (copper). McCullough, James D., Department of Chemistry, University of California, Los Angeles, personal communication.

of the Department of Chemistry, University of California, Los Angeles, having the above field facts described to him, predicted on the basis of the analogy with rod mounts in glass, that those inclusions without surrounding cracks would show reaction rims, and those with cracks little or no "corona." It seems, therefore, that those inclusions which show radial fractures must have entered the basalt late in its consolidation history, at a time when the magma was near enough to its consolidation temperature to preclude alteration.

Origin of the Quartz

Hypotheses for the origin of quartz in basalts have been discussed in many papers. The present status of these hypotheses has been summarized by Finch and Anderson,[28] and by Daly.[29] Theories of direct crystallization from a primary magma,[30] differentiates of normal basalts,[31] deuteric alteration,[32] hybridism,[33] and contamination of basaltic magma,[34] have been advanced at various times to account for occurrences of quartz-bearing basalt. Study of the quartz grains found in the basalts of the southern Sierra Nevada suggests that mechanical contamination of a basaltic magma by granodiorite and granite xenoliths, with but limited reaction developing new minerals, produced the quartz xenocrysts.

In summation, evidence has been presented to show that, (1) various stages of alteration of granodiorite xenoliths are represented in the basic flow rocks, (2) small inclusions are now composed mainly of quartz, with few feldspar remnants, but with all gradations from pure quartz to pure granodiorite, and (3) olivine and quartz, closely adjacent, have not completely reacted. Since there is abundant proof of an originally uniform subsilicic composition of all the flow rocks, the conclusion seems inescapable that the free quartz described was derived from granodiorite and associated rocks in two ways: (1) as residues after alteration of very small granodiorite xenoliths, introduced late in the magmatic history, or from

[28] Finch, R. H. and Anderson, C. A., The quartz-basalt eruption of Cinder Cone, Lassen Volcanic National Park, California: *Univ. Calif. Pub., Bull. Dept. Geol. Sci.*, **19**, 259–260 (1930).

[29] Daly, R. A., Igneous Rocks and the Depths of the Earth. McGraw-Hill, New York, 404–407 (1933).

[30] Diller, J. S., The latest volcanic eruption in northern California and its peculiar lava: *Am. Jour. Sci.*, 3rd Ser., **33**, 45–50 (1887). A late volcanic eruption in northern California and its peculiar lava: *U. S. Geol. Surv., Bull.* **79**, 21–33 (1891).

[31] Bowen, N. L., The evolution of the igneous rocks, Princeton University Press, 83–85 (1928).

[32] Fenner, C. N., The Katmai magmatic province: *Jour. Geol.*, **34**, 753 (1926).

[33] Harker, A., The Natural History of Igneous Rocks, Methuen & Co., 356 (1909).

[34] Daly, R. A., *op. cit.*, 407.

larger xenoliths introduced at an earlier stage, (2) as products of mechanical fragmentation of larger quartz-rich or pure quartz masses. The shattering of giant-textured quartz-feldspar aggregates during extrusion is suggested by the peculiar angularity of residual quartz grains, and also by the presence of broken, but unseparated, xenolithic masses of nearly pure milk-white quartz, often an inch or more in diameter.

The angularity of the quartz grains, without crystal boundaries, together with the fact that granular masses are composed of many grains of different optical orientation, seems to the writer to warrant the conclusion that no process calling for direct or indirect crystallization from a magmatic body could account for the quartz.

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