American Mineralogist, Volume 60, pages 1105–1112, 1975

Feldspathic Geodes Near Black Mountain, Western San Luis Obispo County, California

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Abstract

Spherical geodes possessing a botryoidal outer surface, and ranging from a few centimeters to nearly a meter in diameter have developed in the Oligocene Cambria Felsite, a rhyolitic tuff and/or flow unit. The enclosing country rock has been altered locally to montmorillonite, clinoptilolite, and quartz adjacent to the sharp outer margin of the geodes. Peripheral portions of the geodes consist of an intimate, fibrous, subparallel to radiating intergrowth of potassium-rich feldspar ($Or_{42\pm02}$ to $Or_{63\pm03}$) of high structural state, sodic plagioclase and cryptocrystalline quartz. The geodes become more siliceous near their centers; they characteristically possess an internal cavity lined with chalcedony or rock crystal quartz. Sets of fractures, or microfaults, typically intersect at the central cavities.

Sill-like masses of Miocene diabase have invaded the Cambria Felsite extensively in the vicinity of the geode locality. Hydrothermal fluids charged with alkalis and silica are postulated to have been mobilized by this magmatic intrusion from pore solutions initially present in the country rock. The cavities, produced by the penecontemporaneous microfaulting, evidently acted both as nucleation centers and as sources of the metasomatizing fluids. In moving outward, the hot aqueous solutions promoted both the spherical growth of feldspathic + silicic material and the late, lower temperature, purely siliceous cavity linings. Judging from the lack of zeolites (except in the clayey country rock rims), the compositions and structural states of the coexisting feldspars and the estimated overburden of approximately 1000 m at the time of diabase intrusion, physical conditions for the early stage botryoidal growth of the geodes were: P_{total} = 100–300 bars; T = 600–650+ °C, assuming chemical equilibrium. Temperatures could have been substantially lower if the feldspars crystallized metastably.

Introduction

During the course of geologic mapping in the westernmost southern California Coast Ranges (Hall, 1973a, 1973b, 1974), a local development of abundant geodes was encountered approximately 13 km east of the town of Cambria, in San Luis Obispo County. These interesting spherical, nodular features occur within a newly recognized Oligocene silicic volcanic unit, the Cambria Felsite (Ernst and Hall, 1974). Because of the relocation of California State Highway 46 (formerly California State Highway 41) which passes through the area, fresh exposures have been provided, affording an excellent opportunity to study the origin of the geodes in terms of the geologic structures and petrology as well as the mineralogy.

General Geology

Areal geologic relationships and sample locations are shown in Figure 1. Sample numbers of geodes are located on the map; specimens are part of the Geology Museum collection, University of California, Los Angeles.

The region is characterized by a now folded series of Tertiary sedimentary and volcanogenic rocks (*e.g.*, see Jennings, 1959; Hall and Corbató, 1967; Hall, 1973a, 1973b, 1974), which have been sequentially deposited on a Mesozoic basement. This preexisting terrane consists of a severely deformed and pervasively but feebly metamorphosed Franciscan graywacke mélange plus a tectonically juxtaposed clastic sequence of well-ordered, less intensely folded and essentially unmetamorphosed Great Valley strata, the Toro Shale (Page, 1966, 1970a, 1970b).

The record of Tertiary deposition begins with rhyolitic erosional remnants of the Oligocene Cambria Felsite, chiefly a crystal-bearing, somewhat recrystallized pyroclastic unit which lies unconformably on the Franciscan-Great Valley basement. Amygdaloidal basalt is associated with the felsite and represents an integral part of the mapped unit at

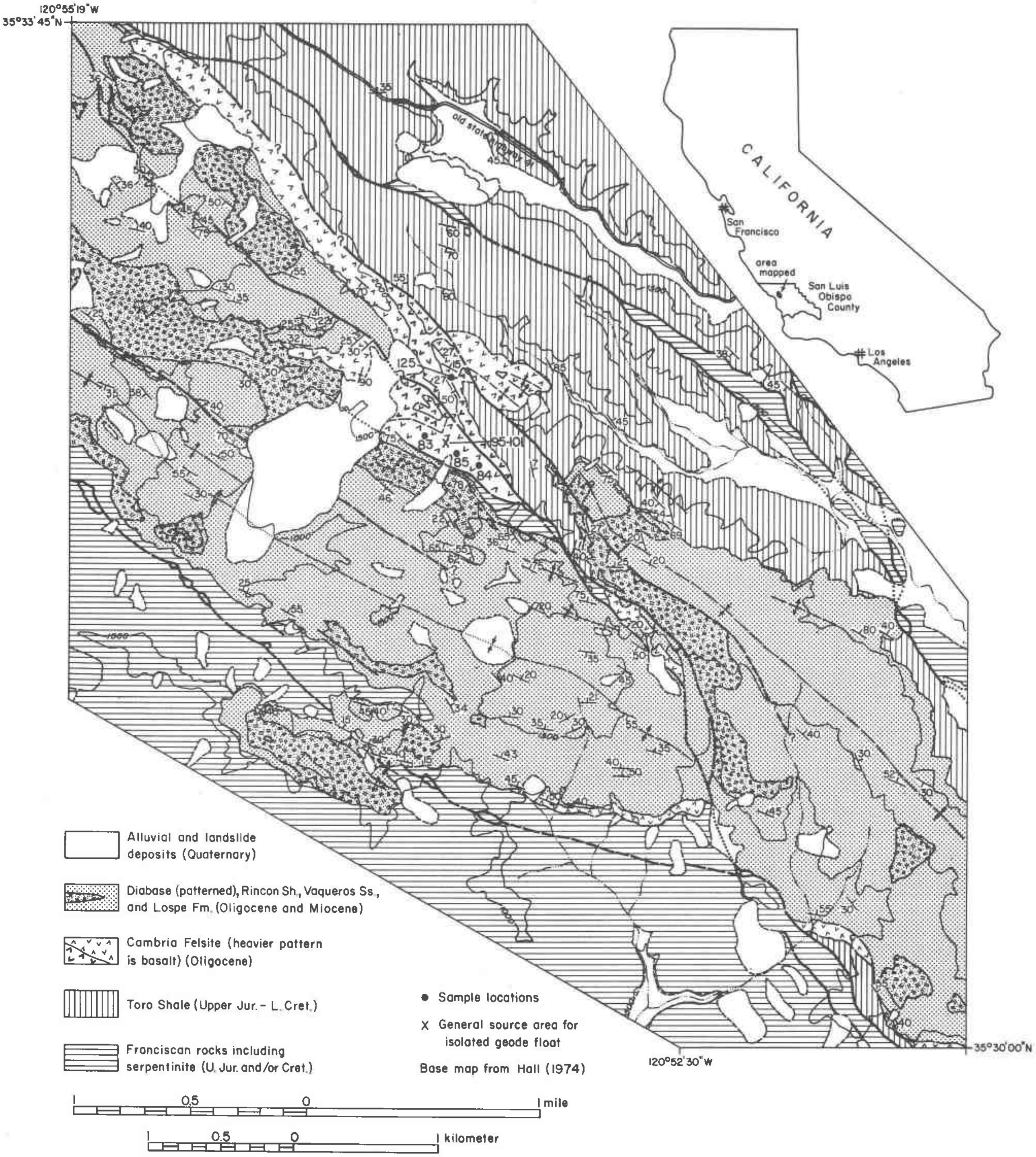

FIG. 1. General geology of the Black Mountain area, western San Luis Obispo County, California. SLO prefixes in specimen localities have been omitted for clarity.

Black Mountain; it appears to be hydrothermally altered and heavily oxidized. All of these units have provided detritus for the variegated continental conglomerates, sandstones, siltstones, and claystones of the upper Oligocene Lospe Formation. The Lospe interfingers with, but is chiefly overlain by, the Vaqueros Sandstone, a near-shore, fossiliferous, calcareous sandstone of late Oligocene age. Local unconformities separate the successively younger Miocene marine units in westernmost San Luis Obispo County: Rincon Shale and Obispo Formation (silicic, vitric tuff). The Rincon Shale is late Zemorrian to early Saucesian in age in the Black Mountain area (S. W. Prior, University of California, Los Angeles, personal communication, 1974). At the time of emplacement of the roughly tabular and concordant Miocene diabase bodies, the total thickness of the rock column above the Cambria Felsite probably was on the order of 1000 m (Ernst and Hall, 1974). Continental Quaternary gravels, landslide and alluvial deposits constitute the youngest portion of the geologic section.

As illustrated in Figure 1, the structure of the Tertiary rocks is relatively complex for this portion of the California Coast Ranges. Near Black Mountain it consists of a severely faulted syncline, complicated by angular unconformities (Hall, 1974). Portions of the section have been pervasively invaded by irregular bodies of diabase, correlated with the Obispo Formation as it is exposed in other parts of the County. At Black Mountain, the Cambria Felsite is extensively intruded by the diabase.

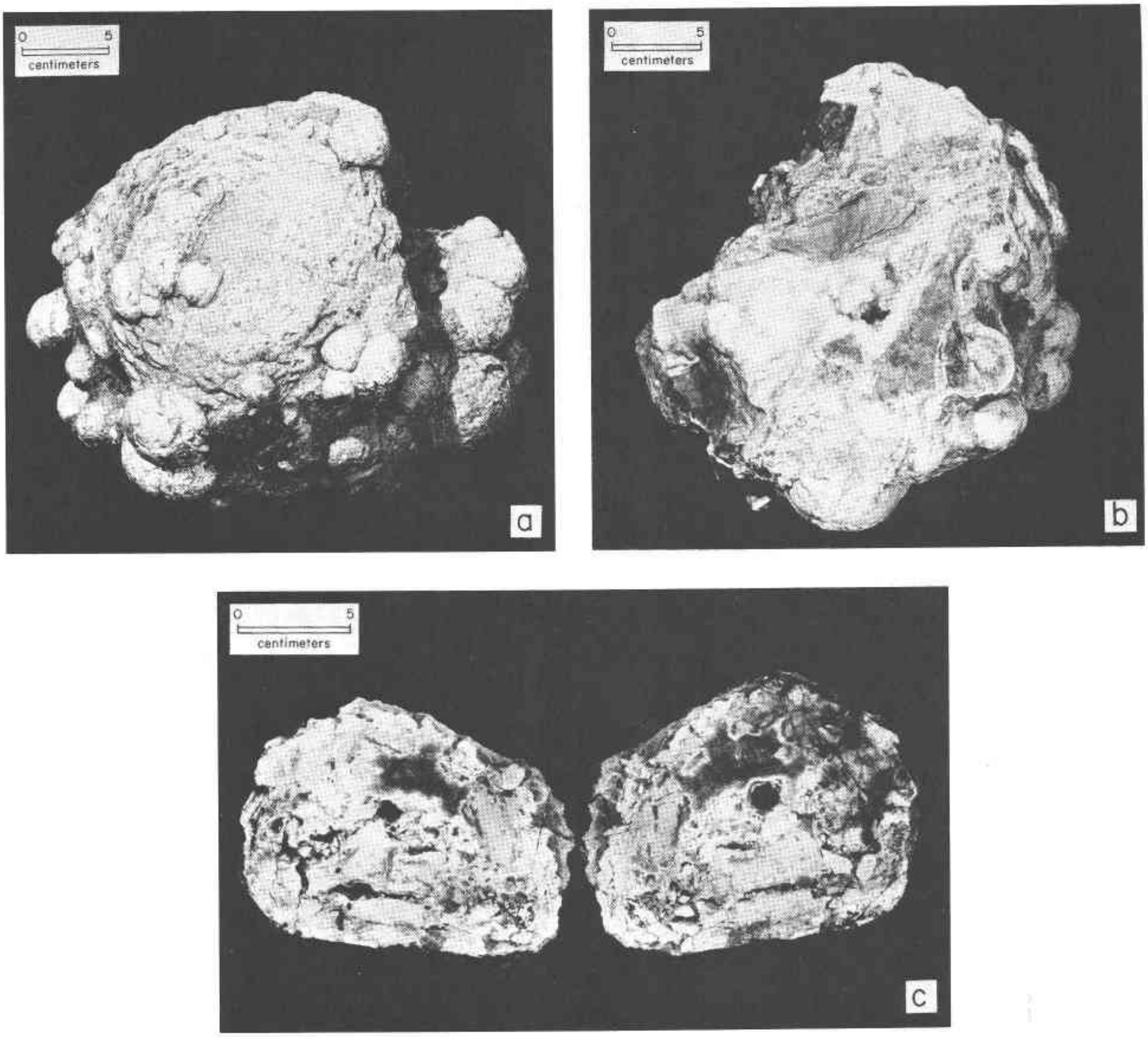

FIG. 2. Botryoidal, nodular outer surface, siliceous brecciated interiors of feldspathic geodes. (a) and (b) are photos of sample SLO-96; (c) is a picture of sample SLO-95. Note the core of rock crystal quartz and the external growth of nodules along offset fractures in SLO-96, and the brecciated, chalcedonic core of SLO-95.

Mineralogy of the Geodes

The geodes occur as spherical to botryoidal, fractured and slightly offset, generally hollow, mineralized portions of the crystal-bearing, devitrified rhyolite of the Cambria Felsite. Their outer surfaces are buff to dead white, whereas the interiors are commonly pale gray, tan, or nearly colorless. Variations in their general megascopic features are shown by the photographs of Figures 2 and 3 (see also Fig. 6). Individual samples range in diameter from 5–10 cm to nearly a meter. Most geodes are characterized by bulbous, nodular growths superimposed on the generally spherical surfaces of the geodes, thus imparting a somewhat botryoidal external appearance to them; such nodular growths are aligned along fractures and microfaults. These bulbous features, as well as the internal cavity lined with coarsely crystalline quartz, are shown by sample SLO-96 (Figs. 2a, 2b). A somewhat more irregular outer surface, internal brecciation, and a chalcedonic core characterize sample SLO-95 (Fig. 2c).

Ignoring the incrustation of crystalline silica, the central void generally is crudely angular in shape. This form results from the manner in which the open spaces apparently were produced: before and during growth of the geodes at the intersections of fractures, minor movements occurred (= microfaulting), thus providing the appropriate cavities and channelways which evidently acted as reservoirs for the hydrothermal solutions. The shape of the central void is well displayed by sample SLO-98 (Fig. 3). This photograph also suggests preservation of the original tuffaceous (?) lamination of the Cambria Felsite within the geode.

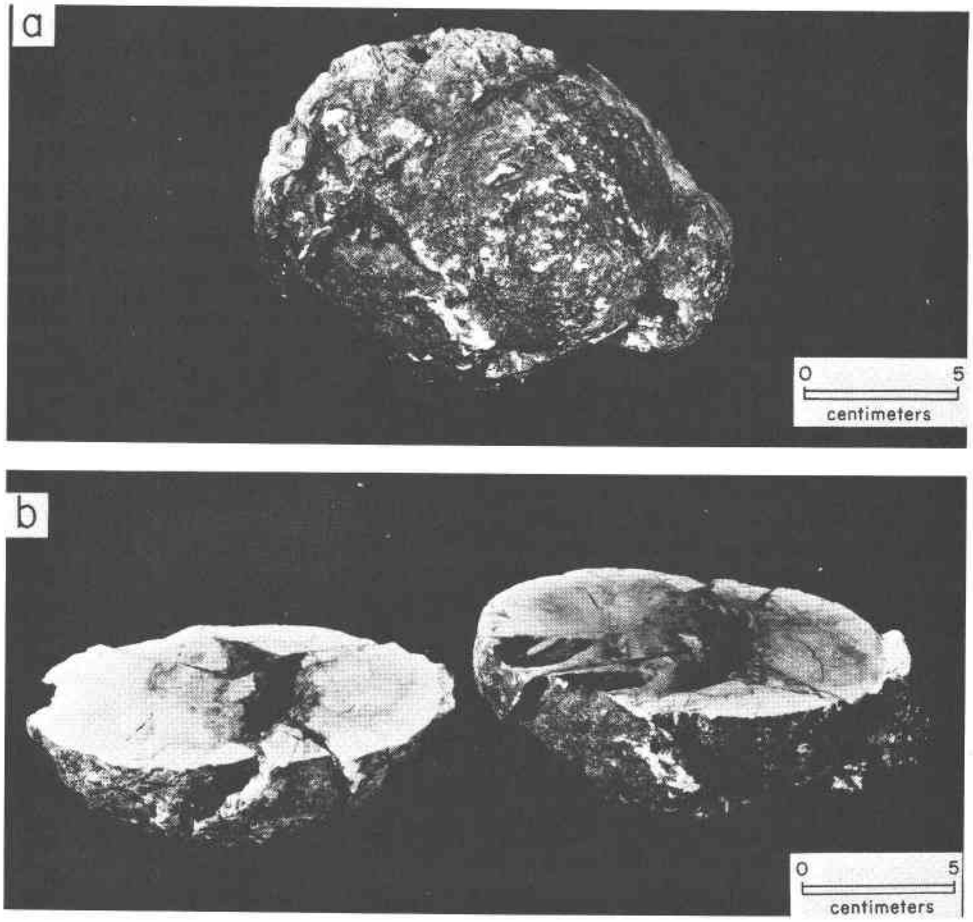

FIG. 3. Intersecting microfaults in geode sample SLO-98. The interesting fractures, well displayed externally in (a), seem to have produced the angular central cavity observed in (b). Clearly, movement on the microfractures occurred during geode growth, for the outer surfaces of the geodes are offset. Also evident in (b) is the original lamination of the felsite, with banding striking directly toward the viewer.

Some geodes possess a yellowish or greenish clayey rind at their contact with more or less altered tuff. X-ray diffraction study demonstrates that this argillaceous envelope, which grades outward diffusely into less altered country rock, is principally montmorillonite, clinoptilolite, and minor quartz; minor amounts of tridymite (?) could be present, but were not positively identified. A sharp contact separates this clay from the geode itself. The outer portion of a typical geode consists of a very fine-grained to cryptocrystalline intergrowth (*i.e.*, 5 × 100 microns) of parallel, subradiating, fibrous sodic plagioclase plus potassic feldspar; the more central part contains coarser, sieved porphyroblastic aggregates (~ 100 microns in diameter) of the same phases, and of chalcedonic quartz, respectively. X-ray diffraction peaks attributable to cristobalite or tridymite could not be found in the geodes. The intimate nature of the exceedingly fine-grained intergrowths of feldspars + quartz and the irregular sieved porphyroblasts preclude mineral separation and analysis of the phases by electron microprobe.

Judging from the observed phase proportions as determined by both petrographic and X-ray diffraction techniques, as well as bulk rock X-ray fluorescence analyses of Cambria Felsite in the Black Mountain area, the potassic feldspar of the geodes must be an intermediate $KAlSi_3O_8$–$NaAlSi_3O_8$ solid solution (see: Ernst and Hall, 1974; and this paper, Tables 1 and 2). The data of Table 1 show that where K-rich feldspar is sufficiently abundant in the geodes to obtain reliable X-ray diffraction data, it appears to be a relatively disordered form. The alkali feldspar approaches sanidine in structural state, as demonstrated employing the *060* vs *$\bar{2}04$* method of Wright (1968). The X-ray data are presented graphically in Figure 4. The compositional range of the potassium feldspar, determined using Wright's plot of $2\theta_{201}$ after Orville (1967), is from $Or_{42\pm02}$ to $Or_{63\pm03}$ on a weight percent basis, definitely in the hypersolvus region (Orville, 1963; Luth and Tuttle, 1966). Inasmuch as potassium-feldspar compositions were determined on fine-grained, multiphase aggregates, it is possible that the K-rich feldspars are actually cryptoperthites. Accordingly, homogenization experiments were performed on five specimens (for a rate study, see Ernst, 1960). Annealing was carried out at 1050 ± 20C° and atmospheric pressure for 60 minutes. X-ray data and apparent compositions are presented in Table 2. All K-rich feldspar-bearing samples became more albitic, presumably partly as a

TABLE 1. X-Ray Diffraction Data and Inferred Compositions of Potassium-Feldspar from Geodes, Black Mountain, California

Sample Number	$2\theta_{060}$	$2\theta_{\bar{2}04}$	Composition* (weight percent)
SLO-83	41.756	50.894	$Or_{42\pm02}$
SLO-84	41.710	50.945	$Or_{44\pm02}$
SLO-85	41.700	50.916	$Or_{47\pm02}$
SLO-96	41.643	50.884	$Or_{61\pm03}$
SLO-98	41.673	50.910	$Or_{44\pm02}$
SLO-101	41.716	50.925	$Or_{45\pm02}$
SLO-125C	41.650	50.849	$Or_{63\pm03}$
SLO-125C"	41.726	50.950	$Or_{43\pm02}$

*from $2\theta_{\bar{2}01}$ measurements (Orville, 1967; Wright, 1968).

TABLE 2. X-Ray Diffraction Data and Inferred Compositions of Heat-Treated Potassium-Feldspar from Geodes, Black Mountain, California

Sample Number	$2\theta_{060}$	$2\theta_{\bar{2}04}$	Composition* (weight percent)
SLO-83	41.781	50.953	$Or_{36\pm03}$
SLO-85	41.86	51.02	$Or_{27\pm05}$
SLO-96	41.777	50.987	$Or_{36\pm03}$
SLO-101	41.814	51.115	$Or_{28\pm03}$
SLO-125C	41.783	50.955	$Or_{35\pm03}$

*from $2\theta_{\bar{2}01}$ measurements (Orville, 1967; Wright, 1968).

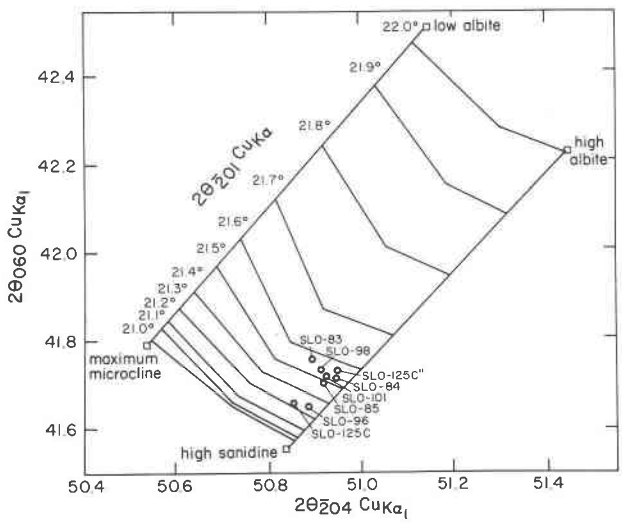

FIG. 4. X-ray diffraction data of Table 1 displayed on a $2\theta_{\bar{2}04}$ vs $2\theta_{060}$ Cu$K\alpha_1$ plot along with high and low alkali feldspar end members, after Wright (1968, Fig. 3). Corresponding 2θ values for the *$\bar{2}01$* reflection are also shown; compositions have been obtained employing the *$\bar{2}01$* determinative curve of Wright (1968, Fig. 4, after Orville, 1967, Fig. 8). See also heat treated samples listed in Table 2.

result of the homogenization of cryptoperthitic lamellae, and partly due to reactions between the potassium-feldspar and the separate, intergrown plagioclase crystals. The relative magnitude of the two effects was not evaluated, but it is clear that the potassium-feldspars from the geodes possess hypersolvus compositions (Orville, 1963, and Luth and Tuttle, 1966, place the crest of the solvus at about Or_{30-40} on a wt percent basis).

Because of interference by quartz and potassium-feldspar X-ray peaks and differences in the proportions of the phases, the degree of ordering and the precise composition of the plagioclase feldspars could not be ascertained in these samples (*e.g.*, see Orville, 1963, 1967; Borg and Smith, 1969). Employing the $\Delta 2\theta_{131-1\bar{3}1}$ technique of Smith and Yoder (1956), whole rock X-ray diffraction studies of the Cambria Felsite by Ernst and Hall (1974) demonstrated that the composition of the plagioclase of the parent rock could range from oligoclase of low structural state to albite of intermediate order. Utilizing the same method, plagioclases of geode samples SLO-96, −98, −101, −125C, and −125C″ appear to possess maximum An contents on a mole percent basis of $An_{17\pm05}$ to $An_{31\pm05}$ (see Table 3, Fig. 5) if they are of low structural state, or are more albitic if only intermediate ordering has occurred. Evidently no change of $\Delta 2\theta_{131-1\bar{3}1}$ attended the recrystallization of plagioclase during botryoidal growth.

The central cavities of the geodes characteristically are lined with chalcedonic or coarsely crystalline quartz; the latter also constitutes abundant fracture fillings as veins and irregular patches in the geodes.

In addition to the peripheral nodules and the microfaults which commonly intersect at the centers of the geodes, concentric hemispherical stromatolite-like structures (Fig. 6) are present in many geodes from Black Mountain. They consist of sprays of intergrown feldspars and chalcedony, and exhibit a successive development towards the margin of the geode, with more internal portions of a particular hemisphere terminated by the yet more centrally located—and previously formed—concentric structure. This relationship demonstrates that these geodes in large part must have grown outwards

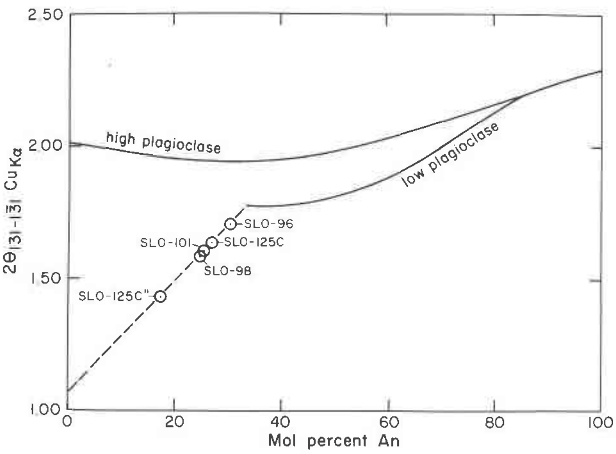

FIG. 5. X-ray diffraction data of Table 3 displayed on a $\Delta 2\theta_{131-1\bar{3}1}$ CuKα plot, along with high and low plagioclase solid solutions, after Smith and Yoder (1956, Fig. 3). Assuming an ordered structural state, the $\Delta 2\theta_{131-1\bar{3}1}$ measurement provides maximum An contents for the investigated $CaAl_2Si_2O_8$–$NaAlSi_3O_8$ solid solutions; to the extent that the plagioclases are actually somewhat disordered, compositions would shift towards pure Ab.

TABLE 3. X-Ray Diffraction Data and Inferred Maximum An Contents of Plagioclase from Geodes, Black Mountain, California

Sample Number	$\Delta 2\theta_{131-1\bar{3}1}$	Maximum An Content* (mol percent)
SLO-96	1.71	$An_{31\pm05}$
SLO-98	1.58	$An_{25\pm05}$
SLO-101	1.59	$An_{26\pm05}$
SLO-125C	1.629	$An_{27\pm02}$
SLO-125C"	1.43	$An_{17\pm05}$

Assuming ordered structural state, and employing $\Delta 2\theta_{131-1\bar{3}1}$ measurements (Smith and Yoder, 1956).

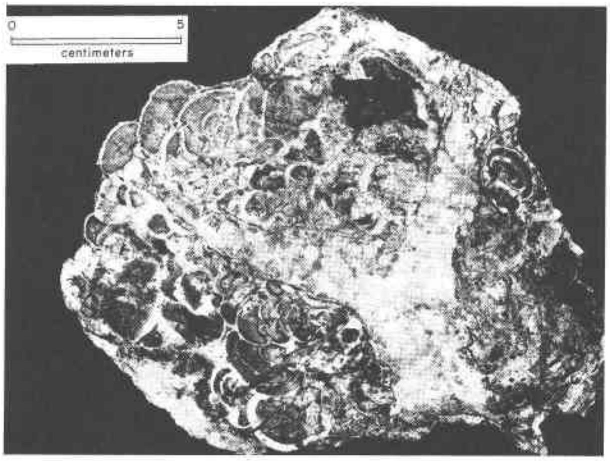

FIG. 6. Geode sample SLO-101, which exhibits well-developed stromatolite-like structure. Note the bifurcating cavity filled with coarsely crystalline quartz.

(radially) rather than chiefly inwards; in contrast, inward growth is evident for geodes from most other localities (*e.g.*, see Sinotte, 1969; Rennix, 1969). Growth of the hemispherical structures took place principally in the solid state, and the original euhedral phenocrysts of quartz and plagioclase in the felsite have been preserved.

Origin of the Geodes

The Cambria Felsite contains these unusual geodes only where it has been pervasively invaded by Miocene diabase. The amygdaloidal basalt is also confined to the portion of Cambria Felsite in which the rhyolitic unit has developed geodes (see Fig. 1), and it might be argued that the extrusion of the basalt in some way was linked to production of the geodes. However, the amygdaloidal basalt is a small unit, is fine grained (hence cooled quickly), and appears to be older than the geode-bearing rhyolitic unit as seen by examination of the map; furthermore, like the more siliceous unit, the amygdaloidal basalt is hydrothermally altered in the vicinity of the large Miocene diabase intrusions.

Evidently prior to, but at least in part contemporaneous with, this diabase intrusive episode, fracturing and minor differential movement of the rhyolitic host provided suitable channelways for the associated hydrothermal fluids. Where two or more microfaults intersected, cavities were produced—the sites of future geodes. Such intersections would allow for maximum circulation of hydrothermal fluids highly charged with alkalis and silica, and consequently for the observed very local metasomatic recrystallization of the country rock. As temperatures declined, the solutions apparently became depleted in the components required to produce alkali feldspars, and the residual, late stage precipitation was exclusively crystalline SiO_2 which lined cavity walls. This paragenesis is reminiscent of that observed for pegmatites and appears to be a function of the more rapid impoverishment of the Or and Ab components in the aqueous solution relative to the solubility of silica with falling temperatures (*e.g.*, see Burnham, 1967; Jahns and Burnham, 1969).

It is possible that these solutions were released during crystallization of an aqueous mafic magma. However, although the plagioclase is saussuritized extensively and the titanaugite is somewhat uralitized, there does not appear to have been any primary magmatic amphibole (or any other hydrous mineral) in the diabase. We believe it more likely that interstitial fluids already present in the tuffaceous rocks of the Oligocene Cambria Felsite became enriched in K_2O, Na_2O, and SiO_2 during heating accompanying intrusion by the Miocene diabase.

Whether these solutions were migrating chiefly out into the felsite from the cavities or were diffusing towards these voids from the country rock is not known; in either case, circulation is implied. It is clear from the hemispherical accretionary pattern of the botryoidal feldspar intergrowths (Figs. 2, 6) and from the siliceous geode linings, that crystallization utilized these cavities as nucleation surfaces, and that at least a substantial portion of the metasomatism-induced growth was outward.

Elsewhere in western San Luis Obispo County, the Obispo tuffs locally carry mordenite, clinoptilolite, phillipsite, analcime, and montmorillonite (Surdam, Turner, and Hall, 1970). The apparent absence of zeolites from the Cambria Felsite in the vicinity of Black Mountain, except as late (?) rinds of clinoptilolite + montmorillonite + minor quartz in the altered tuff enclosing the geodes, may be ascribed to the somewhat higher temperatures inferred to have accompanied the formation of these bodies. Presuming the presence of an H_2O-rich fluid at pressures approximating hydrostatic to lithostatic values (1000 m overburden $\approx$ 100–300 bars), and a moderately close approach to chemical equilibrium during growth of the geodes, the occurrence of Ca-bearing sodic plagioclase plus quartz—instead of analcime, wairakite, and zeolites such as laumontite and heulandite—indicates temperatures of recrystallization probably exceeding 300°C, judging from experimental work on these phases by Coombs *et al* (1959), Nitsch (1968), Liou (1970, 1971a, 1971b), and Thompson (1970, 1971). The intermediate, hypersolvus composition of the coexisting potassic feldspar suggests that temperatures most likely exceeded roughly 600–650°C if chemical equilibrium was attained (Orville, 1963; Luth and Tuttle, 1966), or that the K-rich feldspar solid solutions crystallized metastably. In this latter connection, it should be noted that the growth of authigenic sanidine (nearly stoichiometric $KAlSi_3O_8$) has been reported by Sheppard and Gude (1965) from the Barstow Formation—hence the high structural state of the potassic feldspars does not necessarily preclude a low temperature of formation for the Black Mountain geodes.

Acknowledgments

We thank Mr. and Mrs. Abbott Fitzhugh of Cambria, California, for introducing us to the mineralogic problem posed by the occurrence of geodes at Black Mountain, for access to their ranch, and for initial help in collecting specimens. The University of California, Los Angeles, supported this research. The manuscript benefited from critical reviews by W. A. Dollase, University of California, Los Angeles; R. C. Surdam, University of Wyoming; and T. L. Wright, U. S. Geological Survey, Reston, Virginia.

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Manuscript received, April 21, 1975; accepted for publication, June 27, 1975.