# CAMPTONITE DIKES NEAR BOULDER DAM,[1] ARIZONA[2]

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ABSTRACT

Near Boulder Dam occur camptonite dikes of possible Quaternary age characterized by amphibole (kaersutite) phenocrysts of exceptional size and unusual distribution—a distribution which suggests that these phenocrysts have formed essentially in place. Rough calculations suggest that these crystals grew to four-inch size in less than 25 days. Serpentinization of olivine, formation and size of amygdules, and growth of amphibole phenocrysts are related to distribution of volatiles in the dike magma. Chemical analyses of the amphibole and of the chilled margin of a dike are presented and discussed.

## INTRODUCTION

Camptonite dikes occur within a limited area bordering U. S. Highway 93, approximately eight miles south of Boulder Dam, on the Arizona side. Several unusual features combine to make this occurrence unique:

1. Wall rocks: these are fan gravels, not greatly consolidated; not perceptibly metamorphosed.
2. Texture: the dikes exhibit a striking porphyritic texture, dominated by amphibole phenocrysts of exceptional size (up to four inches) and uncommon character.
3. Composition: the rock is a camptonite and the amphibole most nearly resembles kaersutite. Rocks with such alkaline affinities have been unknown in this region.
4. Age: the dikes are probably late Pleistocene or Sub-Recent.

The locality, lying as it does along a major highway, has been seen by many geologists and the exposures are sufficiently striking to attract the attention of even the casual tourist. Specimens have found their way into many collections, both public and private. Hence a report on field and laboratory studies, carried on at intervals over a period of several years, may be of interest.

The area (see Fig. 1), lies in the northwestern part of the old (1884) Camp Mojave (Arizona-California-Nevada) quadrangle of the U. S. Topographic Atlas. There is no published geological information giving

[1] In 1947 the name "Boulder Dam" was changed by act of the 80th Congress to "Hoover Dam." Inasmuch as our studies were initiated and our maps completed during the earlier regime, we have retained the name by which this structure was then known.

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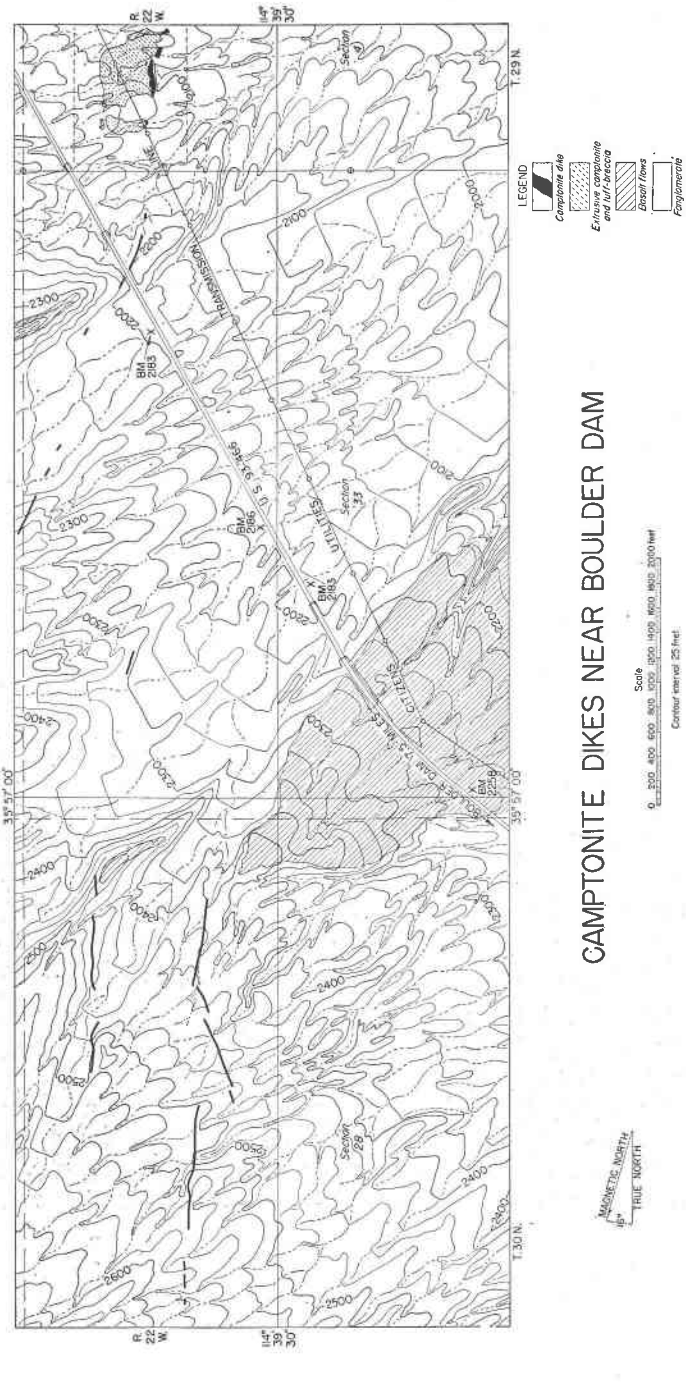

CAMPTONITE DIKES NEAR BOULDER DAM
LEGEND
Camptonite dike
Extrusive camptonite and tuff-breccia
Basalt flows
Fanglomerate
Scale
0 200 400 600 800 1000 1200 1400 1600 1800 2000 feet
Contour interval 25 feet
MAGNETIC NORTH
TRUE NORTH
15°
R. 22 W.
T. 29 N.
T. 30 N.
114° 39' 30"
35° 57' 00"
Section 33
Section 28
TRANSMISSION LINE
U. S. 93-466
CITIZENS UTILITIES
BOULDER DAM 7.5 MILES
BM 2183
BM 2186
BM 2258

Fig 1.

any detail on this region. Lee (1908), does not discuss the district, but does represent it on the map accompanying his report as an area of Tertiary basalt, flanking a preCambrian basement. Darton (1924) on the state map of Arizona shows the area as undifferentiated Tertiary (including possible Quaternary) and older volcanic rocks. Longwell (1936), in his excellent study of the geology of the floor of the Boulder reservoir, has summarized the literature dealing with the general region; but neither his report, nor that of Ransome (1923, 1931) extends far enough south to cover the tract under discussion.

## The Geologic Setting

### *Fanglomerate*

The oldest and most wide-spread formation in the area under consideration, is a deposit at least 100 feet thick of fanglomerate. This formation slopes southwesterly from the Black Mountains and extends some ten miles, practically to the Colorado River below Boulder Dam. The fanglomerate (see Fig. 2) at first sight gives the impression of having been formed relatively recently, but the deep insequent canyons incising the fan surface and the basalt-capped residuals suggest that the principal depo-

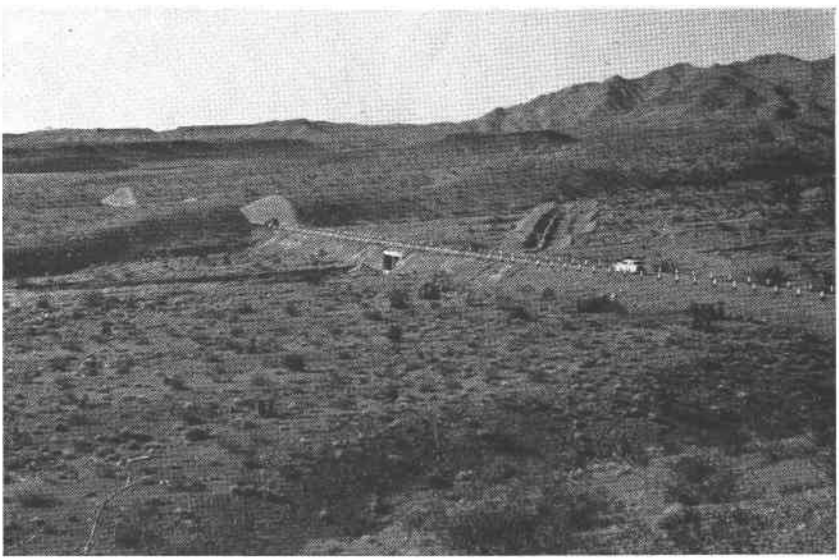


Fig. 2. Looking northeast across U. S. Highway 93 about eight miles south of Boulder Dam, Arizona. The Black Mountains are in right background; flows of olivine basalt form the dark cappings in left middle background and to right of center; fanglomerate sections are exposed by the highway excavations.

sition of the fanglomerate may belong to a somewhat earlier cycle than the present.

The bulk of the fanglomerate has been derived from "Basement Complex," and fragments of a wide variety of rock types are present. These include granite, gneiss, schist, amphibolite, pegmatite, and vein quartz. Locally there has been a slight amount of cementation by a calcareous "caliche," but in general the fanglomerate is very little indurated.

*Olivine Basalt*

Within the mapped area and also in the surrounding region, flows of olivine basalt are found intercalated with and overlying (see Fig. 2) the fanglomerate. These flows are not thick, the maximum noted being twenty feet. Specimens from different flows are lithologically almost identical. The rock is dark grey to black, very fine-grained, and dense for the most part, although small vesicles (filled and unfilled) occur, particularly near the top and bottom portions of flows. Thin-sections reveal that the rock is a typical basalt consisting of abundant narrow laths of median labradorite, averaging between 0.1 and 0.2 mm. in length and distributed in a microaphanitic groundmass. This groundmass contains numerous tiny euhedral grains of magnetite, less abundant pyroxene, occasional olivine, and attendant alteration products. Microphenocrysts of olivine, up to 2.0 mm. in diameter, occur sparsely in the rock, and millimeter-sized glomeroporphyritic aggregates of pigeonitic pyroxene are sometimes found. Labradorite is commonly quite fresh; the larger pyroxenes show a small amount of resorption rounding; olivine shows incipient to moderate serpentinization. Flow texture is frequently well exhibited by a subparallel arrangement of the feldspar laths.

*Camptonite*

The most interesting rock within the area and the one with which this paper is chiefly concerned is an intrusive camptonite found as dikes in the fanglomerate. By far the best exposure of this camptonite is in a road cut along Highway 93, 7.5 miles south of Boulder Dam. The vertical exposure here (see Fig. 3) is about twelve feet, and within this range the dike maintains a width of four feet between parallel, very straight, and nearly vertical walls. Southward from the cut the dike can be traced by small surface outcrops and residual talus for a distance of almost 2000 feet, and to the northeast for a slightly greater distance. Some three thousand feet north from the road cut, exposures occur of similar dikes, which may or may not represent bifurcations of the first. It may be significant, or it may be no more than a curious coincidence, that a float specimen, lithologically identical with these dikes, was found about thirteen miles distant near Callville Wash north of Lake Mead and in line with the general northerly trend of these dikes.

That the dikes intrude the fanglomerate seems clear; yet to some geologists the occurrence of well-defined dikes in fan gravels has seemed so astonishing that they have suggested that the camptonite was originally intruded into some older formation which has since been removed by differential erosion, and that the fanglomerate was subsequently laid down

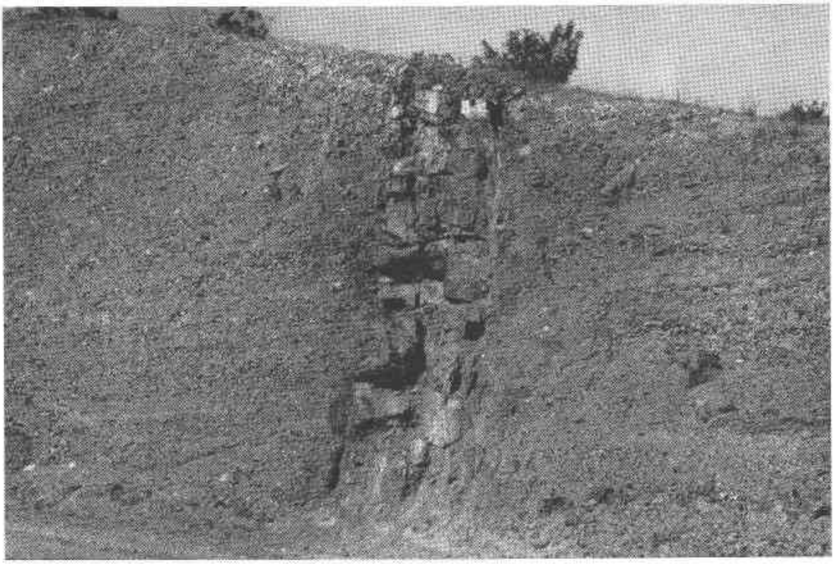


FIG. 3. Section of camptonite dike in fanglomerate, exposed in road cut on U. S. Highway 93, 7.5 miles south of Boulder Dam, Arizona.

around the dikes. In other words, this hypothesis would have the present contact of fanglomerate and dikes a depositional one rather than intrusive. Certainly no one would question the intrusive character of the dikes themselves: their pattern on the map; their vertical walls; their chilled margins—all point to typical intrusive structures. The problem is therefore whether or not the present fanglomerate was the country rock at the time of intrusion. If the dikes had been intruded into an earlier formation, then it would seem reasonable that some small residual of this should have been discovered; but in our examination of the several thousand feet of exposures of these dikes nothing like this has come to light, nor is any such hypothetical formation known from the section, although our knowledge of this is admittedly scant. If the dikes had been left standing as buttresses to be filled around by the fanglomerate, some depositional "lee and stoss" features should be apparent in the sediments. Yet in the excellent cross section provided by the highway cut, the same sedimentation units are present in the fanglomerate on both sides of the dike. These points are, in a sense, negative evidence; unfortunately there is little positive evidence of intrusion of the dikes into the present fanglomerate. The dikes commonly show sharp and surprisingly smooth contacts against the fanglomerate. Although no distinct apophyses were discovered, in a few instances minor protrusions

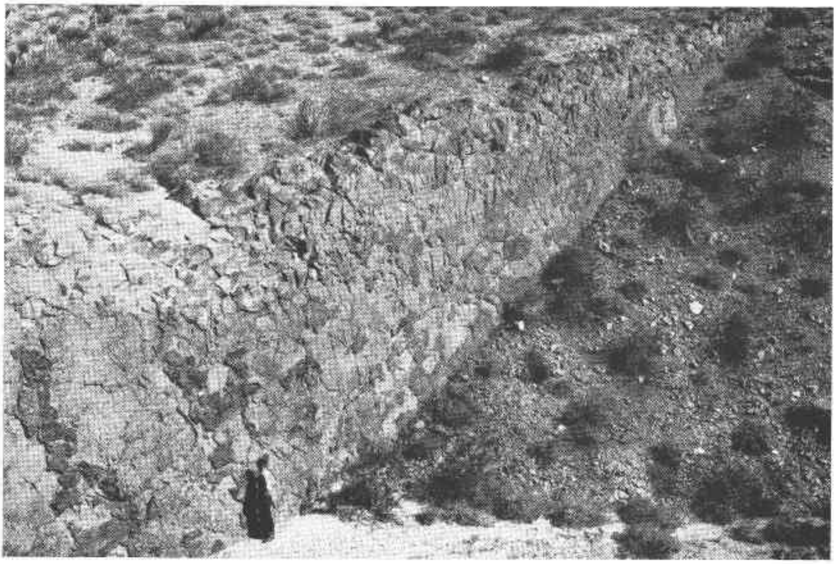


FIG. 4. Downstream face of "dam" formed where camptonite dike crosses a dry wash in fanglomerate, in northern part of map area, along central segment of the three northwesterly striking camptonite outcrops shown in Fig. 1.

from walls of the dikes have bulged around cobbles in the fanglomerate in a manner highly unlikely to result from depositional contact of gravel against a residual dike. In certain favorable lights a faint zone of reddening is apparent at the highway cut extending for a distance of eight to ten feet into the fanglomerate equally on either side of the dike, and clearly related to the intrusion. Our conclusion is that the dikes are intrusive into and younger than the fanglomerate.

The age relations between the camptonite dikes and the basalt flows are obscure. Nowhere have the two formations been discovered in actual contact. Meager evidence, in the form of basalt fragments included in a camptonite breccia (discussed beyond) suggests that the camptonite is younger than at least some of the basalt.

Throughout most of the exposures of these dikes, the same general features and relationships persist. Widths vary from two to six feet, but average close to four for most of the dikes; dips vary from 65° E to 75° W, but average close to vertical; strikes vary from N 20° W to N 25° E, but average nearly north. Commonly the dikes are somewhat more resistant than the fanglomerate and therefore appear as ridges. In a few places, where a dike crosses a wash, a notable "dam" has developed (see Fig. 4). It is possible that the offsets appearing at several points along the course of the dikes (Fig. 1) are due to faulting, but in the absence of marker beds in the fanglomerate, this cannot be demonstrated. The offsets might equally well represent sharp inflections in strike of a dike, coupled with a pinching in the conduit; that is to say, these "segments" may be connected and continuous in depth.

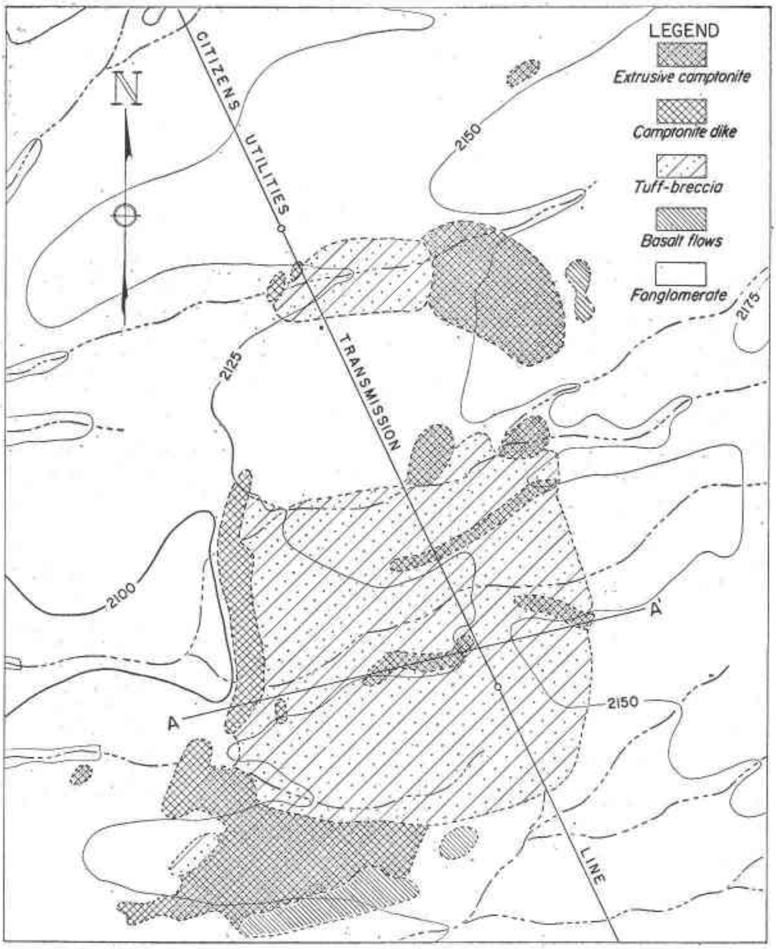
In the southern part of the map area, where outcrops of the camptonite terminate, complex relations exist which cannot be entirely resolved from the limited exposures. Because of the presence here of pyroclastic facies, not elsewhere recognized, and of sill-like structures of the camptonite, the suggestion is strong that at this point there may have been a focus of the volcanic activity associated with the intrusion of the dikes. From detailed mapping of the limited exposures (see Fig. 5), the most probable chronology of events appears to be:

First: deposition of the fanglomerate.

Second: flow of basaltic lava, source unknown.

Third: development of a small vent (position is indicated on section $A-A'$, Fig. 5). Largely filling the vent is a pyroclastic formation, mapped as "tuff-breccia," which varies from a brown tuffaceous rock carrying small crystals of amphibole identical in its optical properties with phenocrysts of the dikes to a coarse breccia containing larger amphibole crystals, "bread-crust bombs" (one to two feet in diameter) of camptonite, and abundant material of accidental origin, such as pebbles from the fanglomerate, and some large (two foot) fragments of basalt. The texture of this formation coarsens rapidly from east to west, suggesting that the source lay to the west in the direction of the assumed vent. Since the base of this formation is not exposed, the thickness is unknown, but presumably not more than a few tens of feet are involved.

Fourth: intrusion of camptonite magma along the western margin of the supposed vent, where, having pushed through to the surface, it appears also as an extrusive facies overlying the tuff-breccia. This extrusive facies is characterized by abundant amygdules with horizontal or gently dipping elongation. The possibility has been recognized that the "extrusive camptonite" might actually be a sill with the roof now completely stripped. However, since it overlies sub-aerial pyroclastics and elsewhere also overlies fanglomerate, the possibility of its being a sill seems remote.

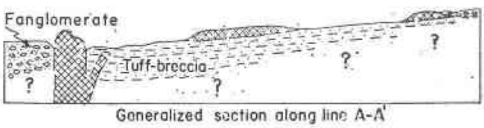



MAP OF

THE AREA* AT THE SOUTHERN END OF THE CAMPTONITE DIKES

Scale

0 100 200 300 400 500 600 feet




Generalized section along line A-A'

*Outlined by dashed-line rectangle within figure 1.

FIG. 5.

## Petrology of the Camptonite Dikes

The only well-exposed cross section of a camptonite dike is in the highway cut (Fig. 3) described above. The following discussion therefore pertains principally to this exposure. Texture is the most striking feature of this dike. Distributed through a grey, aphanitic groundmass are abundant, large, glisteningly fresh, black crystals of amphibole some of

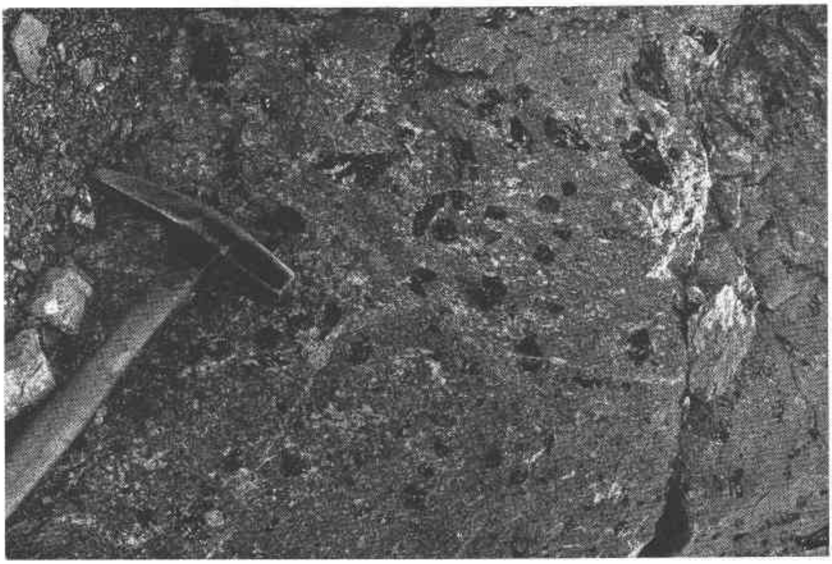


Fig. 6. Large black phenocrysts of amphibole in displaced block of camptonite. Note increase in size of phenocrysts from bottom margin of photograph toward the top. Bottom of photograph represents portion of block nearest to wall of dike. Small white areas are calcite and calcite-analcime amygdules and veinlets.

which measure as much as four inches in greatest diameter. At first sight most laymen and some geologists have identified these amphibole phenocrysts as obsidian fragments (see Fig. 6). The resemblance is indeed close, for the amphibole cleavage is not often apparent, and resorption rounding on some crystal surfaces has simulated the conchoidal fracture of obsidian. In addition to the amphibole phenocrysts, rust-colored pseudomorphs of olivine one-half inch or less in diameter occur occasionally. Amygdules are common, the smaller ones completely and the larger ones partly, filled with calcite. Inclusions are absent, except for a few small aggregates of quartz which appear to be of accidental origin.

The distribution of phenocrysts and of amygdules within the dike is at once interesting and significant. A chilled selvage of aphanitic rock, in which amygdules and amphibole phenocrysts are practically absent, makes up the outer four to six inch margin along both walls of the dike. Inside of this selvage, amphibole phenocrysts and amygdules appear, increasing progressively both in size and in number toward the central portion of the dike. This change is distinctly gradational and rather symmetrical with respect to both walls of the dike. As a check on what would otherwise be only a strong visual impression, an attempt was made to get a quantitive evaluation of this textural change with respect to the amphibole phenocrysts. If a large plane-surfaced cross section had been available, a megascopic Rosiwal analysis might have been possible; but lacking this, the most practical method and one sufficiently rigid to exclude personal bias seemed to be to mark off convenient vertical zones in the dike and measure the maximum diameter of each hornblende phenocryst within an arbitrarily drawn cross section. Between 25 and 50 crystals were measured in each of seven zones, numbered in sequence from the selvage on the east or west wall of the dike, toward the center. Thus Zone $I_e$ (see Table 1) is the first zone beyond the chilled border adjoining the east wall of the dike; Zone $I_w$ is the corresponding zone adjoining the western chilled margin. The figures immediately below the zone number give the distance in inches from the wall of the dike. Measurements were made only to the nearest tenth of an inch, consequently the second decimal given in the figures for average diameter is perhaps more of arithmetical interest than of statistical significance. Krumbein (1935) has shown and Chayes (1950) has recently confirmed the fact

TABLE 1

| *Zone:* | Chilled border | $I_w$ | $II_w$ | $III_w$ | $IV_{ew}$ | $III_e$ | $II_e$ | $I_e$ | Chilled border |
|---|---|---|---|---|---|---|---|---|---|
| Distance from wall of dike (inches): | 0–6 | 6–10 | 10–14 | 14–20 | 20–26 | 20–14 | 14–10 | 10–6 | 6–0 |
| Average maximum diameter of amphibole phenocrysts (inches): | absent | 0.27 | 0.46 | 0.54 | 1.38 | 0.61 | 0.53 | 0.31 | absent |
| Range in diameter: | — | 0.1–0.5 | 0.2–1.0 | 0.3–1.1 | 0.5–2.5 | 0.2–2.1 | 0.2–1.7 | 0.2–1.6 | — |

Average maximum diameter for entire section: 0.59 inches.

that "the trace of any grain dimension along a section of the grain will usually be shorter than the true dimension." This is recognized in the presentation above, but relative dimensions are here of more significance and these are probably of the right order of magnitude. At the same time, the absolute size of the amphibole phenocrysts deserves mention. They range up to four inches in maximum diameter, an astonishing figure for this mineral in this kind of rock. Palache (1932) lists the largest known hornblende as 15×15×46 cm. This was a hastingsite from a pegmatite, a very different type of occurrence from what we are here considering. Feniak (1944) in his study of grain dimensions in igneous rocks gives the average cross-sectional area for hornblende as only 0.42 sq. mm., with the average long dimension as 0.8 mm. Although no exhaustive search of the literature has been made, it seems likely that these 4-inch crystals are among the largest amphibole phenocrysts known from camptonite and related igneous types.

The amygdules show the same general pattern of size distribution as do the amphibole phenocrysts. They show also a moderate degree of alignment with the longer axes paralleling the walls of the dike. No such flowage texture is exhibited in the case of the amphibole phenocrysts which show on the whole a nearly random orientation. Unlike amphiboles and amygdules, the rusty subhedrons of altered olivine are distributed evenly although sparsely throughout the dike, *including the chilled margins.*

A series of six thin-sections cut at intervals from a two foot wide specimen of the dike afforded detailed comparisons across a section from chilled margin to center. The microscopic data presented is based upon these together with various random sections cut from this and other dikes in the area.

The groundmass is in considerable part microaphanitic and shows little change from wall to center of dike. Microlites of calcic andesine, usually less than 0.1 mm. in length, are abundant, as are tiny euhedrons of magnetite and somewhat larger subhedrons of olivine largely altered to serpentine and "limonite." Apatite is a rare accessory. Distributed rather abundantly, even in the groundmass of the dike margins, are small vesicles completely filled with calcite, or less commonly with calcite and analcime, and still more rarely with analcime alone. Where these two minerals occur together, analcime appears to have been the earlier. Analcime is also somewhat more common in the larger amygdules. The vesicles are usually ovoids, ranging in size from 0.25 mm. to several centimeters in the case of the larger amygdules near the center of the dike. A few vesicles are highly irregular in shape and some pass into calcite or calcite-analcime veinlets. The elongation, like that of the feldspar microlites, parallels the walls of the dikes.

In addition to the large crystals of amphibole a number of other minerals are present as phenocrysts and microphenocrysts: olivine, diopside, labradorite, sanidine, and quartz. With the exception of olivine these are all rare; seldom are more than one or two grains present in a single thin-section. All except olivine are fresh. All, again excepting olivine, show considerable resorption rounding, but only quartz shows any reaction border, and this is of indeterminate character. Quartz in some instances consists of composite grains, and it is not improbable that these are xenocrysts rather than crystallizations from the dike magma.

In thin-section, just as in hand specimen and in the field occurrence, the amphibole phenocrysts are the most striking constituent. Under the microscope these crystals appear exceptionally fresh. Occasionally they may be veined by calcite especially along opened cleavages, but this is in the nature of an open-space filling rather than an alteration. Indeed, in the larger crystals it is often possible to split a layer of calcite from a cleavage plate of the amphibole leaving it entirely free of the carbonate. Indices of the amphibole are: $\alpha=1.670$; $\beta=1.692$; $\gamma=1.701$. Extinction angle ($c\wedge Z$) is 8° to 10°; $2V$ (−) is 81°. Crystals are strongly pleochroic with $X$ = light yellow brown, $Y$ = reddish brown, $Z$ = dark reddish brown, and $X<Y<Z$. Measurement of alpha and gamma indices and of extinction angles* on a series of amphibole phenocrysts spaced at intervals across the width of the dike show no differences beyond such as fall within errors of measurement in this group (Turner, 1942). Phenocrysts in thin section show uniform and sharp extinction throughout, save for a very few in which an outer rim (less than 0.1 mm.) has an extinction angle greater by 2° to 3° than that of the main body of the crystal. Therefore, it is concluded that no significant compositional changes are involved, either within individual phenocrysts or with respect to phenocrysts in different zones within the dike.

In color, in high refringence and birefringence and in strong pleochroism this amphibole resembles basaltic hornblende or lamprobolite (Rogers, 1940). Winchell (1945) in codifying the properties of the oxyhornblendes (another name for this type of amphibole), pointed out that the size of the extinction angle is a guide to the amount of oxidation (the smaller the angle, the greater the oxidation). Hence it would seem that this amphibole is one in which relatively little oxidation has taken place as compared to the majority of this group for which extinction angles are commonly less than 5°.

Indeed despite much excellent work on the subject, the nomenclature of amphiboles is still unsatisfactory. As pointed out by Larsen and Berman (1934, p. 220) nomenclature has depended more on optical peculiarities than on the more fundamental feature of chemical composition. An analysis of this amphibole is given in Table 3, column $C$. This corresponds approximately to a formula of $Ca_4(Na,K)_2(Mg,Mn,Fe^{++})_7$

* To facilitate obtaining favorable orientations, use was made of "grain thin sections" (Von Huene, 1949) prepared from fragments chipped from phenocrysts in the dike.

$(Al,Fe^{+++})_6TiSi_{12}O_{46}(OH,F)_2$. The relatively high content of titanium is a significant feature, and because of this, coupled with its other characters, Berman (1940) suggested *kaersutite* as the best available designation for this amphibole. In terms of compositional relationships, it is of interest to point out that the analysis of this amphibole places it just on the border (toward CaO and adjoining the pyroxene field) of the amphibole field in Kennedy's (1935, Fig. 2) diagram. Hallimond (1943) has developed a graphical presentation of significant atomic ratios in amphiboles and has delimited thereon the fields of amphiboles from various rock types. Data for this amphibole, when plotted on Hallimond's chart, place it in a vacant triangle (close however to Hallimond's analysis No. 143) which lies in a zone where the fields of basalt, diorite, and nepheline syenite approach or overlap. This is consistent with other evidence, which has indicated the basaltic and alkaline characteristics of the camptonite in which this amphibole occurs.

## Classification

It is impractical to obtain a volumetric mode for this rock because of the very fine grain and indeterminate character of part of the groundmass and because of the extreme variation of grain size and variable distribution of some constituents. A summary of the mineral components, listed in approximate order of decreasing abundance, is given in Table 2.

Table 2. Mineral Composition of Boulder Dam Camptonites

| |
|---|
| Plagioclase (calcic andesine): microlites in groundmass. |
| Olivine (largely altered to serpentine and "limonite"): phenocrysts and groundmass. |
| Amphibole: (kaersutite) phenocrysts. |
| Calcite: confined to amygdules and veinlets. |
| Magnetite: groundmass. |
| Diopside: phenocrysts. |
| Labradorite: phenocrysts. |
| Quartz: xenocrysts (?). |
| Analcime: confined to amygdules and veinlets. |
| Sanidine: phenocrysts. |
| Apatite. |
| Zeolites (small amounts of an as yet unidentified zeolite may be present along with analcime in some of the amygdules). |

This assemblage clearly places the rock in Johannsen's (1937) family No. 3216H (Camptonite) and in practically all respects the rock corresponds to the usual definitions of camptonite.

A chemical analysis of this rock is given in Table 3 column *A*, and in column *B*, for comparison, is Daly's (1933) average of 15 camptonites.

The analysis was made upon material taken from chilled margins of the dike, since this, as will be shown presently, is believed most nearly to represent the original composition of the dike magma.

TABLE 3

| | *A* | *B* | *C* |
|---|---|---|---|
| $SiO_2$ | 42.26 | 40.70 | 41.46 |
| $TiO_2$ | 3.18 | 3.86 | 5.70 |
| $Al_2O_3$ | 14.61 | 16.02 | 14.24 |
| $Fe_2O_3$ | 5.38 | 5.43 | 3.32 |
| FeO | 4.56 | 7.84 | 5.70 |
| MnO | .05 | .16 | .08 |
| MgO | 6.12 | 5.43 | 13.68 |
| CaO | 9.40 | 9.36 | 11.62 |
| $Na_2O$ | 2.64 | 3.23 | 2.29 |
| $K_2O$ | 1.48 | 1.76 | 1.72 |
| $H_2O^-$ | 2.72 | 2.62 | — |
| $H_2O^+$ | 3.93 | | .12 |
| $CO_2$ | 2.99 | 2.97 | — |
| $P_2O_5$ | .62 | .62 | — |
| S | .09 | nd | nd |
| BaO | .16 | nd | nd |
| F | nd | nd | .42 |
| | 100.19 | | 100.35 |
| | | Less O=F | .18 |
| | | | 100.17 |
| | | (Sp. Gravity=3.215) | |

Norm (from Column *A*):

| | |
|---|---|
| orthoclase | 8.90 |
| albite | 22.01 |
| anorthite | 23.35 |
| nephelite | 0.28 |
| diopside | 15.55 |
| olivine | 5.74 |
| magnetite | 5.34 |
| ilmenite | 6.08 |
| hematite | 1.76 |
| apatite | 1.34 |

C.I.P.W. classification: Camptonose, (II)III.5.3″.4.

A—Camptonite dike from eight miles south of Boulder Dam, F. A. Gonyer, *analyst.*
*B*—Daly's (1933) average for 15 camptonites.
*C*—Amiphibole phenocryst from Boulder Dam camptonite, F. A. Gonyer, *analyst.*

Calculation of the norm of this rock presents some difficulties with respect to the $CaCO_3$ content. Washington (1917, p. 1167) states (rule 3*h*) that "if the modal calcite is primary, this normative molecule is to be regarded as femic; if the modal calcite is secondary or due to the assimilation of limestone, the calculated calcite molecule is to be disregarded as not forming part of the norm." In short, one is faced with the necessity of deciding whether the calcite is primary or secondary. Primary calcite is viewed with deep suspicion by some petrographers: Johannsen (1931, p. 150); others appear to accept it without question: Poitevin and Cooke (1946). In this occurrence it does not appear to be an alteration product, nor do we have any real evidence that it has formed as the result of assimilation of limestone. It is perhaps worth noting Pirrson and Washington's (1906, p. 499) remarks on a camptonite from the Belknap Mountains, New Hampshire, in which calcite is present in much the same relationships as in the present rock. They say "calcite . . . does not appear as an ordinary alteration product . . . but rather as infiltrated material, if it is not indeed an original component." In obtaining the norm for this rock these authors (*idem*, p. 501) compromise by calculating in CaO and disregarding $CO_2$, a practice rather generally followed (Washington, 1917). The present calculation has followed this procedure with the results as given in Table 2. If calcite had been calculated as femic, nephelite and olivine would disappear from the norm, being replaced by quartz (1.51%) and hypersthene (14.90%). This however does not change the classification of the rock as Camptonose.

## Petrogenesis

The source of this camptonite magma is unknown. Its field association with olivine basalt suggests that it might be a differentiate from such magma. However, considerations as to the origin of the magma can be nothing more than speculative with so little known of the general geological history of this region. Since the occurrence lies in a block probably down-faulted against the Black Mountains, it is not unlikely that Upper Paleozoic limestones are present in the section at depth, and assimilation of such rock may be in part responsible for the development of the camptonite magma. To those who may regard camptonites as belonging to a diaschistic series, as first suggested by Brögger (1894), there will be little comfort in knowing that no complementary leucophyres have been discovered in the region.

Of more immediate interest than the origin of the magma is the problem of the amphibole phenocrysts. The typical amphibole of camptonites (Holmes, 1928) ordinarily is barkevikite, which differs from the amphibole of these dikes chiefly in its much higher ratio of magnesia to ferrous iron and in its lower titania and somewhat higher silica content. It is the distribution of the amphibole phenocrysts, however, rather than their composition, that presents the major problem. No one viewing the road-cut exposure can avoid the impression that these phenocrysts must have formed very nearly in place, and consequently under no more than a few hundred feet of cover. If the amphibole phenocrysts were of intratelluric origin, a more or less even distribution throughout the dike would be expected. But as shown previously, these phenocrysts are practically absent from the selvages of this dike and show considerable diversity in development within the main body of the dike. An hypothesis of multiple intrusion might explain this textural diversity. Haff (1939) in his study of the Cape Neddick dikes has illustrated the very great complexity that may develop in such types of intrusion. But none of the criteria of multiple intrusion is recognizable at this exposure, although in certain of the more northerly dikes there are faint suggestions of internal chilled contacts. Multiple intrusion, though it might account for diversity of texture, fails to explain the symmetrical size distribution (see Table 1), unless one makes the unlikely assumption of a series of closely spaced intrusions carrying phenocrysts of progressively larger dimension and each intrusion perfectly bisecting the preceding intrusion! Composite intrusion is likewise an unlikely hypothesis in view of the uniform character of the groundmass throughout the dike.

Before attempting an explanation of the distribution of the amphibole phenocrysts in the rock, certain significant features should be recalled. (1) The olivine phenocrysts, presumably one of the earliest ferromagnesian minerals to form, are found evenly distributed throughout the dike in selvages and central portions alike. (2) All of the olivine has undergone a considerable degree of serpentinization; but the olivine in the chilled margins shows less alteration than that in the central portions of the dike. (3) The amygdules show the same size distribution as do the amphibole phenocrysts, that is, they are larger and more abundant toward the central portions of the dike. Unlike the amphibole phenocrysts they are not absent from the selvages, but occur therein as microscopic vesicles.

Without wanting to put precise limits on the definition of the term "deuteric" (Shand, 1944) is it not significant that both the serpentinization of olivine (Hess, 1935) and the formation of some amygdaloidal minerals (Moehlman, 1936) have been regarded as falling within the category of this process; furthermore, the presence of volatiles is one of the generally recognized conditions for the formation of amphibole (Kennedy, 1935). In the present occurrence, each of these features is clearly related to position within the dike. It seems not unreasonable to suppose, therefore, that the initial intrusion consisted of camptonite magma in which only olivine and magnetite had already crystallized. Volatiles in the magma would find easy escape through the permeable fanglomerate, so easy indeed that no trace remains of their passage. Magma in immediate contact with fanglomerate walls and thus depleted of its volatiles would chill rapidly, thereby providing a fine-grained, dense seal which prevented loss of volatiles to the walls from the remainder of the intrusion. The slowest cooling, more fluid central portions subsequently may have been enriched by access of volatiles from depth. It was the volatiles thus concentrated in the central portion, which were chiefly responsible for formation of the amygdules, which by lowering viscosity permitted growth of exceptionally large amphibole crystals, and which caused serpentinization of olivine. But these volatiles, largely excluded or escaped from the chilled margins, formed practically no amphibole, developed only microscopic vesicles, and produced a lesser degree of serpentinization of olivine in the selvage of the dike. Within intermediate portions of the dike these processes operated to intermediate degrees.

A process, analogous to this in some respects, has been described by Fuller (1938) in which deuteric alteration of columnar lavas has occurred principally in central portions of columns and flows, whereas unaltered rock occurs at the surface of flows and adjoining the vertical fissures on edges of columns. In brief, where volatiles have opportunity to escape, deuteric effects are at a minimum; where gases have been sealed into the rock, such effects have tended to a maximum.

The calcite- and analcime-filled amygdules need little additional comment. Presence of amygdules in intrusive bodies is uncommon, but by no means unknown: Morris (1930); Moehlman (1936). Morris has noted that in most such occurrences gases responsible for formation of vesicles in intrusives have been derived from external sources, such as coal beds and other rocks rich in volatiles. In the present instance, two such possibilities may be suggested: (1) water in the porous fanglomerate—but this is unlikely on the presumption that the fanglomerate is little more than a veneer, and the dike magma had therefore relatively little contact with it; (2) carbon dioxide from assimilation of limestones deeper in the section—but this is no more than speculation. It seems best therefore, to consider, as Moehlman did, that the volatiles were probably of magmatic origin.

To what extent these observations and deductions apply to the other camptonite dikes in the area is not known, for in no other dikes are comparable cross sections exposed. Occasionally in the more northerly dikes small amphibole phenocrysts are found in the chilled margins. In a majority of these dikes the size range shown by the amphibole phenocrysts is not as great nor are the crystals of as large size, although the distribution is of the same type (larger sizes toward the center). These differences may be explained by the difference in level of the exposures: the northern exposures being 300 to 400 feet above the section exposed in the road-cut. Wentworth and Jones (1940, Fig. 8) have shown graphically how rapidly textural characters of dikes may vary at upper levels. This is especially true if, as appears here to be the case, these levels were near enough to the top of the section so that volatiles could escape to the surface through the dike magma, thereby conditioning the development of only smaller phenocrysts and amygdules.

Other puzzling features of the dikes deserve mention. (1) Plagioclase microlites show a high degree of parallelism (flowage texture), amygdules show moderate stretching, but the amphibole phenocrysts show very little dimensional orientation. Why should there be this contrast within the same body? It is believed that the difference in grain size may afford an explanation: the small plagioclase microlites could have been aligned by movements of magma insufficient to orient the very much larger amphibole phenocrysts. The amygdules, of intermediate size, would exhibit intermediate response. (2) Why do the amphibole phenocrysts show a notable size distribution with respect to dike walls, while other minerals do not? Winkler (1949) points out, in his study of the influence of cooling rates on crystal dimensions, that hardly any change in crystal size is to be expected in thin dikes (that is, those with a width of six feet or less). These camptonite dikes, with widths averaging only four feet, should show no change in grain size—which is indeed the case for most of their minerals. It is the amphibole phenocrysts that are aberrant, and to explain them one must assume that extremely favorable conditions of composition (Kennedy, 1935) and of ionic mobility of the requisite components persisted for a sufficient length of time in the central portions of the dikes, with a gradual reduction in these factors toward the margins. Slight difference in concentration of volatiles might produce considerable difference in crystal size, for as Buerger (1948) has recently shown, even small amounts of (OH) and F are structurally very significant in reducing viscosity of magma and in speeding crystal growth. (3) How long did it take the largest amphibole phenocrysts to grow? There is no direct answer to this, but rough computations, following Lovering's (1935) discussion of cooling in a dike, can be made that will indicate how long favorable temperatures may have obtained in the central portion of the dike. For this certain assumptions are necessary. The temperature at which the amphibole began to crystallize was probably not over 800° C., for above this point the mineral might be expected to show the very low extinction angles characteristic of the more highly heated oxyhornblendes (Barnes, 1930). A lower temperature limit of 200° C., based on the analcime filling, is suggested by the formation of amygdules which require a relatively high viscosity in the magma—a viscosity which would probably preclude further growth of the amphibole. 800° C. to 200° C. is presumably an extreme temperature range; in all probability it was far less than this, as suggested by the lack of zoning in the amphibole phenocrysts. No diffusivity constant for camptonite is available, so the value ($h^2 = .0083$) given for basalt by Birch (1942, p. 253) was employed in the calculation. Using these data, a period of about 25 days is obtained for the fall of temperature at the center of the dike from 800° C. to 200° C.

This of course assumes that all heat loss was by conduction through the walls. Actually there may have been loss of heat by gas transport, and—remembering that these are shallow structures—by escape of heat to the surface. Both of these factors would further reduce the 25-day figure. Opposed to this is the strong possibility of transfer of heat by volatiles from below, which might partly balance or even exceed conduction and other losses. At any rate, it remains an interesting speculation that these exceptionally large amphiboles may have grown in a relatively short time. Some have suggested that, considering the anomalies in this occurrence, the amphiboles may best be explained as porphyroblasts rather than phenocrysts, and Smith (1946) in a general discussion of the lamprophyre problem has emphasized that not all the crystallizations therein should be regarded as orthomagmatic. Nevertheless we regard this hypothesis as untenable for these amphiboles. That the metasomatism required to produce crystals of this composition and of this size could operate at the low temperatures and pressures that the general geologic setting requires—much less, that it would leave no mark on the country rock—is unthinkable. The amphibole is igneous.

## Mechanics of Intrusion

Wherever well-exposed relatively recent dikes are found, there springs the hope of discovering new data on the mechanics of dike intrusion. In this instance, the rudely defined or almost absent stratification in the fanglomerate country rock precludes any possibility of making accurate measurements of any displacement of walls of dikes, direction of movement, etc. The absence of even local crumpling or contortion in strata adjoining the dikes, as well as absence of any sizable protrusions of the magma into the relatively permeable fanglomerate, suggests that the magma came in under no great pressure. On the other hand, it seems unlikely that an open fissure in fanglomerate could have existed into which magma up-welled. The most plausible assumption is that the dikes formed in fractures, actual or potential, which were widened in part by tensional forces, as magma pushed in. No physiographic or stratigraphic evidence has been observed that would indicate control of the dike loci by faults; but it is significant that the trend of the dikes parallels the "grain" of the area and of the general northerly trend of the major faults of the region (Longwell, 1936).

## Age and Correlation

Except for these camptonites, rocks of alkaline affinities have hitherto been unknown in Western Arizona. Indeed, the nearest alkaline rocks are the small bodies of nepheline-syenite described by McAllister (1940) from the Death Valley region, California, over 150 miles distant. The closest approaches to lithologic similarity are the occurrences of camptonite dikes and sills in the Northern Argus Range and the Darwin District, California, reported by Hopper (1947) which he correlates with lamprophyres of the Searles Lake (California) quadrangle described by Hulin (1934) and shown by Hulin to be pre-Middle Miocene and probably early Eocene in age.

Since no fossils have been found in the fanglomerate country rock of these Arizona dikes, the age of the formation is unknown. About a mile south of the mapped area, the fanglomerate lies with angular unconformity upon beds of the Muddy Creek formation (Longwell, 1936) of Lower Pliocene (?) age. This establishes the dikes as post-Lower Pliocene (?). The upper age limit could be approximated only by detailed physiographic studies which are impractical until accurate topographic maps or airphotos of the general area become available. Sklar (1938) has suggested that lavas, with which the flows of the map-area may be correlated, are Pleistocene and possibly Recent. The best conclusion for the time being seems to be that the fanglomerate may be Pleistocene and the Camptonite intrusions late Pleistocene or Sub-Recent.

## Summary

This occurrence of camptonite dikes near Boulder Dam is of interest because it provides a convincing demonstration of the control by volatiles of certain crystallization processes; because of the development of a somewhat unusual type of amphibole; because it is the only known occurrence of rocks of this character in Western Arizona; and finally, perhaps, because of the striking exposures and excellent specimens provided on a route frequently travelled by geologists.

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do we assign any responsibility for the conclusions reached or the hypotheses presented.

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