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EMPLACEMENT OF THE UNCLE SAM PORPHYRY, TOMBSTONE DISTRICT, ARIZONA.[1]

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ABSTRACT. The Uncle Sam porphyry is a quartz-poor latite porphyry whose exposed area is about 20 square miles. Its age is uncertain within wide limits, but is probably early Tertiary. It bears intrusive relations to rocks of the Pinal schist, Naco limestone, Bisbee formation, and Bronco volcanics (which rest unconformably upon the Bisbee formation), and may thus be either of Late Cretaceous or early Tertiary age. It is unconformably overlain by the Gila conglomerate of late Pliocene age. Contact exposures and mine workings indicate that the porphyry is floored near its northeastern border at a relatively shallow depth; its eastern contacts indicate only essentially vertical extension, but the relations are obscured by later faults and by dikes and sills of the porphyry. Most of the other original contacts are concealed, but at the west there are suggestions of a sill form. Observations of internal structures and contacts are consistent with the hypothesis that the intrusive is roughly laccolithic in form and has extended laterally along either a thrust or erosional surface. Petrographically, the rock is distinguished by an unusually fine-grained groundmass—almost vitrophyric over large areas—for so large an intrusive. It is also remarkable for the abundance and wide distribution of inclusions, which are estimated to constitute three to five per cent of the entire body. Local intrusive breccias—some of large volume—contain much higher proportions of inclusions. It is suggested that the fine-grain of the intrusive may be in part due to the chilling effect of these inclusions. Further, it is probable that these are neither stoped blocks nor products of channel abrasion, but are largely fragments of a tectonic breccia formed during the thrust faulting and already available to be picked up by the porphyry magma as it advanced along the surface of a thrust fault. The mildness of the contact effects of the intrusive is attributed to its poverty in volatiles.

INTRODUCTION.

THE Tombstone mining district is in central Cochise County, in the southeastern part of the State. Text Fig. 1. It has been studied by Church (1903), Ransome (1920), and Butler; Wilson, and Rasor (1938). My work, upon which this discussion is based, was done during the winter of 1936-1937

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and the spring of 1938. The assistance of Edgar Bowles and Ralph S. Cannon, Jr. is gratefully acknowledged, and the work was further facilitated by a copy of a detailed geologic map of part of the area prepared by F. L. Ransome. Inasmuch as the mines were being studied by Professor Butler and Doctor Wilson at the time of my field work, and it soon became evident upon field check that only very minor changes from Ransome's excellent map could be justified, most of the estimated two

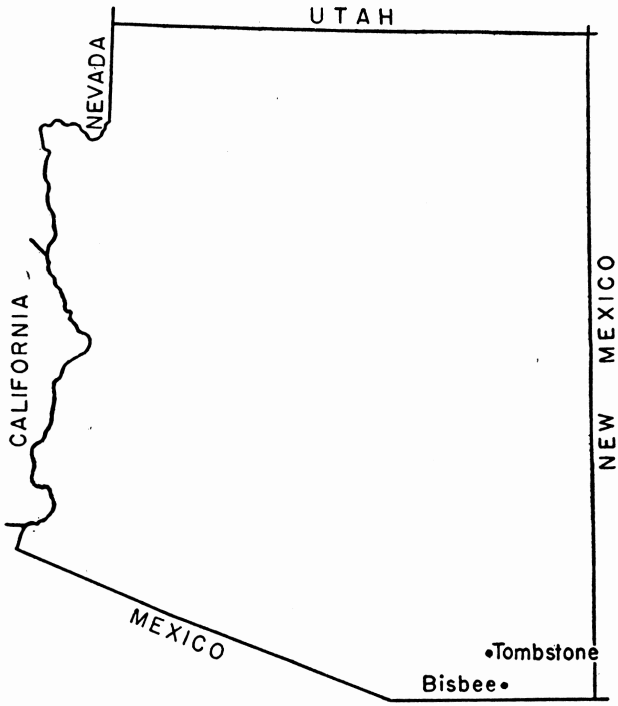

Fig. 1. Index map of Arizona, showing location of Tombstone mining district.

months' field work devoted to the present problem were spent in mapping areas to the south and west of that covered by Ransome, and to making supplementary structural observations within the area of his map. Of the accompanying map, Text Fig. 2, the part within T. 20 S., R. 22 E. is essentially Ransome's the remainder is a product of my own field work and that of my assistants.

GENERAL GEOLOGY.

The principal geological formations in the Tombstone district are the following:

FORMATIONS OF THE TOMBSTONE DISTRICT.

Age		Formation	Thickness, feet
Quaternary		Alluvium	nil to a few score
	unconformity		
Pliocene		Gila conglomerate	several hundred
	unconformity		
Probably early Tertiary		Schieffelin granodiorite Andesite porphyry dikes Uncle Sam porphyry	
	unconformity; possible overthrust faults		
Cretaceous or early Tertiary		Bronco volcanics[2]	5000-6000
	unconformity; possible thrust faults		
Lower Cretaceous		Bisbee formation	3000+
	unconformity		
Pennsylvanian		Naco limestone	4000
Mississippian		Escabrosa limestone	800
Devonian		Martin limestone	320
	unconformity		
Cambrian		Abrigo limestone Bolsa quartzite	800 400
	unconformity		
Pre-Cambrian		Pinal schist	very great

For the purpose of the present paper, the rocks older than the Bisbee formation are sufficiently described by their formal stratigraphic names. The Bisbee formation is represented in the Tombstone area by a series of gray, brown, and red-brown sandstones interfingering with shale and a minor amount of limestone. Locally there is a coarse conglomerate at the base, containing rounded cobbles and pebbles representative of all the Paleozoic rocks, together with schist and several varieties of granitic rock of unknown provenance. There is an important unconformity, both angular and erosional, beneath the Bisbee group in the Bisbee mining district (Ransome, 1904),

[2] The formation here called the Bronco volcanics has not hitherto been given a formal stratigraphic name. It is named from Bronco Hill, in whose neighborhood it is well exposed, and consists dominantly of andesite flow breccias and flows in the lower part and of quartz latite flows and tuffs in the upper. There is interfingering of the two varieties of rock; the andesitic rocks constitute about two-thirds of the formation. A more complete description is to appear in a Geological Survey paper in preparation.

about 20 miles to the southeast. Though the structural discordance between Lower Cretaceous and older rocks is not so dramatic at Tombstone as at Bisbee, there can be no doubt that a strong disturbance also occurred here within the same interval, and the conglomerate pebbles record it.

Studies of the country to the northeast, east, and southeast of Tombstone show that there are two systems of thrust faults of post-Bisbee age: one trending northwest, with overriding to the northeast (Ransome, 1904, 1913; Wilson, 1927; Gilluly, 1941), and the other trending east, with overriding to the south. There is some suggestion that the east-trending faults are older than the northwest-trending, but this is dubious and whether any important time interval separates the two groups is still questionable.

It seems clear that the Bronco volcanics are younger than the east-trending thrust faults. It is true that the volcanics are nowhere in contact with faults of this system, but in the area about two miles east of Bronco Hill they rest upon an erosion surface carved across strongly disturbed Bisbee beds. These beds immediately to the south are isoclinally folded along east-trending axes and therefore presumably record the compression elsewhere expressed by the thrust faults of this trend.

The relation of the Bronco volcanics to the northwest-trending thrust faults is not so clear. Only one thrust fault of this trend has been found in the Tombstone area. This fault is exposed for about 2000 feet along the northern spur of The Three Brothers Hill, west of Tombstone, trends about N. 45° W., and brings Naco limestone over strongly disturbed Bisbee beds. The fault dips southwestward at an angle of 20 to 30 degrees. It is cut off in both directions by the intrusive contact of the Uncle Sam porphyry, which is clearly younger than the fault, but there is no evidence as to the age of the fault with respect to the Bronco volcanics. This inconclusive evidence is disappointing as it leaves the question open as to the structural relations of the Bronco volcanics at the time of the intrusion of the Uncle Sam porphyry; i.e., it is unknown whether or not the Bronco volcanics are involved in the thrust faulting of the region. The absence of notable internal deformation of the Bronco cannot be given much weight as evidence of a post-thrust age, for study of other volcanic formations in the Dragoon thrust area shows little sign of deformation in them except immediately along the faults. Accordingly there are two possibilities as to the local structural conditions prevailing at the time of the intrusion of the Uncle Sam porphyry: if the Bronco is younger than all the thrusts, it rested as a structural unit on an erosion surface carved across the faulted older rocks and the considerable breccia bodies associated with that thrusting; if the Bronco is younger than the east-trending faults and involved in the northwest-trending, it is probable that breccias of at least the younger fault episode were present at the time of the emplacement of the Uncle Sam porphyry. It is clear that the Uncle Sam porphyry is younger than all the strong local deformation except the late normal faults.

UNCLE SAM PORPHYRY.

Name.—The Uncle Sam porphyry was named by Butler, Wilson, and Rasor (1938), from its outcrops on Uncle Sam Hill, about two and one-half miles southwest of Tombstone. They recognized the rock as a quartz latite porphyry and as intrusive. Ransome had called the rock "rhyolite porphyry" but also recognized it as intrusive (Jones and Ransome, 1920). Church referred to the rock as a rhyolite flow (Church, 1903). The rock is clearly intrusive at several contacts and has the composition of a quartz latite, so that the name and interpretation adopted by Butler, Wilson, and Rasor is here followed.

Distribution.—There are four main areas of exposure of the Uncle Sam porphyry. The largest, in the Tombstone Hills, is probably continuous, beneath the alluvium, with the area northwest of Charleston, and possibly both these areas represent portions of a single mass whose most westerly outcrops are those west of the San Pedro River, southwest of Fairbank. The fourth considerable body is that northeast of Bronco Hill; the limits of this mass are completely exposed and any connections it may have had with the larger body to the north must be at depth or have been eroded. Small dikes and sills of the porphyry are found east of the main mass in the Tombstone Hills and as inliers in the alluvium northwest and west of Fairbank. Some of these bodies near Fairbank are also definite sills and dikes.

Contact relations.—The Uncle Sam porphyry is intrusive into the Bronco volcanics, the Bisbee formation, and locally into the Naco limestone at the exposed surface. At Bronco Hill and a point about one and one-half miles to the southeast, it is cut by the Schieffelin granodiorite, but elsewhere its only contacts with younger rocks are with the valley fill of the San Pedro trough, which rests unconformably upon the eroded surface of the porphyry.

The contact relations of the porphyry are highly variable. At the north spur of The Three Brothers hill, west of Tombstone, the contact dips steeply to the southwest, under the

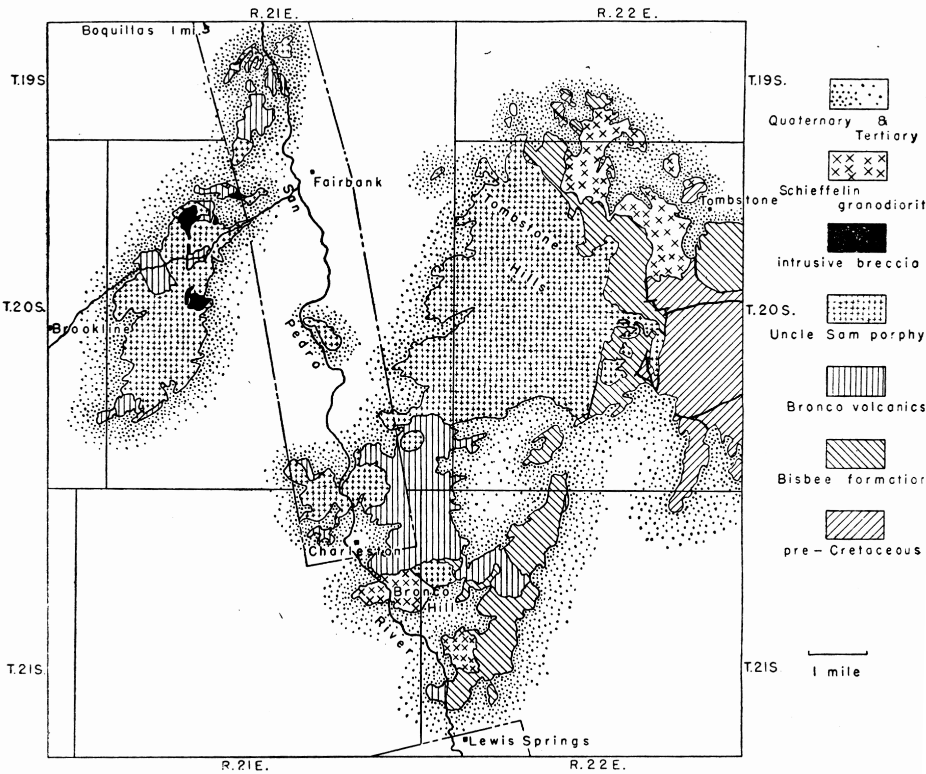

Fig. 2. Map showing distribution of the Uncle Sam porphyry and related rocks. Area near Tombstone largely after a manuscript map of F. L. Ransome. The scale of this map does not permit showing all the places mentioned in the text. They are, however, shown on the Benson Quadrangle of the U. S. Geological Survey's Topographic Atlas.

porphyry. Here the porphyry is in contact with the Naco limestone, which rests on a thrust fault that cuts the underlying Bisbee formation and dips southwestward, toward the porphyry, at angles between 20° and 30°. Just to the southeast the Bisbee formation of the footwall of the fault forms the country rock of the porphyry. From a point near the northwest corner of sec. 9, T. 20 S., R. 22 E., to the valley of the stream that passes just southeast of the center of the same section, the country rock of the intrusive is a breccia mass that consists of blocks of Naco limestone and conglomerate, sandstone, and mudstone of the Bisbee formation. None of these blocks of sedimentary rock can be followed along the strike for more than a few hundred feet; they are all thoroughly shattered and brecciated internally. Generally the Paleozoic fragments are more abundant near the porphyry contact and those of the Bisbee formation preponderate farther northeast. The breccia is generally sheared and many of the stronger shears dip westward at about 35°, roughly parallel to the contact with the porphyry which overlies it. The porphyry to the southwest shows no comparable brecciation. These relations strongly suggest that the porphyry occupies a thrust plane in this part of its outcrop, at least.

North of Uncle Sam Hill there is a deep salient in which the Bisbee formation floors the valley in such a way as to suggest that it underlies the porphyry at a comparatively shallow depth, as, indeed, has been shown by the workings of the State of Maine Mine, which penetrate a considerable body of shale on the bottom (600 foot-) level of the workings (Butler, Wilson and Rasor), at an elevation of about 4300 feet. This section of the intrusive is therefore probably floored at a comparatively shallow depth, but farther southeast, near the Tombstone-Charleston road, the exposed contact becomes nearly vertical and transects the bedding of the country rock at a high angle. Part of this contact is a post-intrusive fault of high angle. Throughout the area between the Charleston road and the ridge that extends north from Ajax Hill, the porphyry forms highly irregular masses that cut the Bisbee formation without regard to its bedding. An interesting feature of this area is the mass of Uncle Sam porphyry that occupies the major fault which farther north separates the Bisbee formation on the west from the Bolsa quartzite on the east. This fault was undoubtedly formed at the time of the major deformation of the Tombstone district. It had a minimum displacement of 5000 feet and must extend to a very considerable depth. The porphyry that follows this fault is frozen to both walls and has remained entirely undeformed since its emplacement, showing that the intrusion occurred after the major orogeny.

In sec. 25, T. 20 S., R. 21 E., the contact of the main mass of porphyry and the quartz latite of the Bronco volcanics is steep and transects the volcanics at a high angle, but on the hill that reaches an altitude of 4540 feet in sec. 36, T. 20 S., R. 21 E., the Uncle Sam porphyry seems to have a laccolithic form and the andesitic member of the Bronco volcanics is upturned in a nearly complete ring around it. The same relations prevail in the mass just north of Charleston, though the andesite is not exposed at the surface. Here the quartz latite member of the Bronco volcanics dips away from the porphyry mass on all sides, again suggesting a laccolithic dome.

West of the San Pedro River few contacts of the porphyry, except those contacts with the late Tertiary and Quaternary sedimentary rocks of the valley-fill, are exposed. However, at the south end of the hills southeast of Brookline, the porphyry is in contact with the andesites of the Bronco volcanics. Here the andesite seems to form a conformable sheet between two masses of the Uncle Sam porphyry, or, stated in another way, the porphyry seems to form two sills separated by a thin septum of andesite. Both the bottom of the upper sill and the top of the lower appear to be conformable with the bedding of the andesite and the internal structures of the porphyry seem also to have the same attitude. (See section on inclusions.) The narrow band of Bronco volcanics along the east side of the porphyry mass in SE ¼, sec. 30, T. 20 S., R. 21 E., may represent the footwall of the lower sill, but the actual contact is concealed. The mass of andesite in the northwest ¼ sec. 20, T. 20 S., R. 21 E., appears to be an inclusion in the Uncle Sam porphyry, though it is possibly a part of the roof of the sill, if this form is maintained so far northward.

The Uncle Sam porphyry that abuts the andesite of the Bronco volcanics along the Babocomari River two miles northeast of Brookline seems to rest in general conformity upon the volcanic rock. However, it can hardly be interpreted as the base of a sill because the porphyry crosscuts the bedding of the andesite breccia along the south side of the andesite mass and furthermore the eastern contact dips eastward at about 35° (at a high angle to the bedding), with the porphyry overlying the andesite. This contact has been followed rather closely by a fault, but the fault displacement cannot have been great as there are many narrow dikes of porphyry in the andesite and many large boulders of andesite held as inclusions by the porphyry close to the contact. The small mass of andesite breccia

Fig. 1.
Outcrop of nodular-weathering porphyry, south of Brookline. The center of each nodule is formed by an inclusion. Knife approximately 4 inches long.

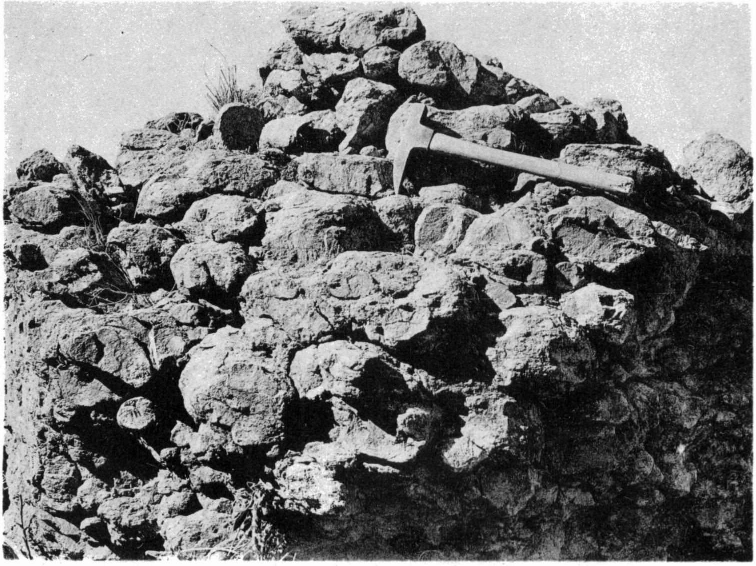

Fig. 2.
Another view of nodular-weathering zone south of Brookline. Hammer is 18 inches long.

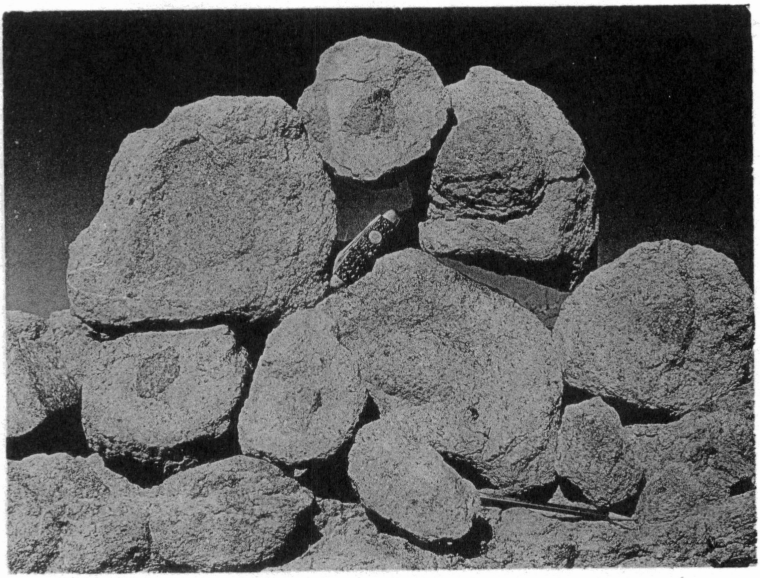

Fig. 1.
A collection of nodules weathered from the Uncle Sam porphyry south of Brookline.
An inclusion can be seen in each.

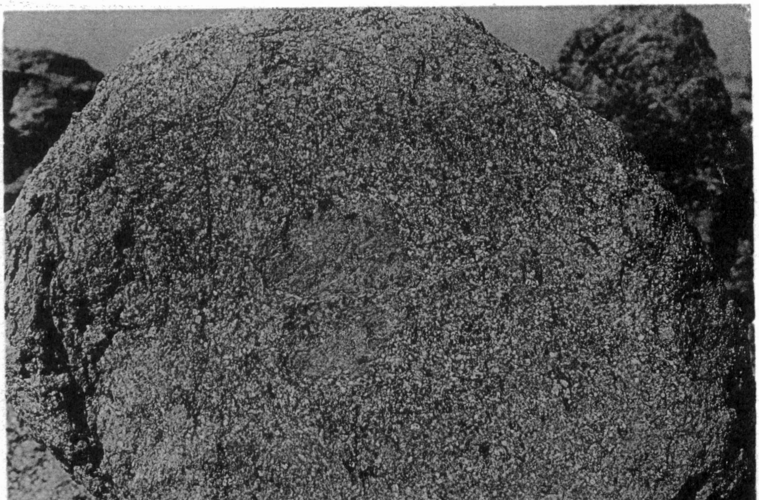

Fig. 2.
Andesite inclusions in Uncle Sam porphyry west of Fairbank.
The specimen is about 8 inches across.

of the Bronco that crops out half a mile farther east along the Babocomari is definitely an inclusion, for the contacts are all steep and irregular and the andesite is cut by many dikes of the porphyry.

The Uncle Sam porphyry that crops out west of the San Pedro River northwest of Fairbank apparently forms two intrusive sheets that conform only in the most general way with the structure of the associated Bronco volcanics. The relations are obscured here, but there are innumerable narrow sills of the porphyry along the bedding of the tuffs of the Bronco volcanics and considerable bodies of intrusive breccia, in which the fragments of tuff are strung out and bent by the viscous flow of the injected porphyry.

In the hills about two miles north of Boquillas, north of the area shown in Text Fig. 2, the Uncle Sam porphyry forms roughly sill-like masses that conform in general structure to the major folds of the associated Naco limestone, though they transect the second-order folds.

Intrusive breccia.—There are two areas of intrusive breccia associated with the Uncle Sam porphyry near the Babocomari River, one in sec. 8, T. 20 S., R. 21 E., and the other in sec. 17, a little more than a mile to the south. At the northern locality an intrusive breccia occupies about 100 acres, and is exposed in a topographic amphitheatre, drained by an east-flowing stream. The breccia is fairly well exposed in the stream bed and the walls above it. It consists of a jumble of rocks that range from more than 100 feet in diameter down to microscopic sizes. These rocks have the forms of blocks, boulders, and cobbles and are held in a matrix of Uncle Sam porphyry. Among the rocks included in the breccia can be recognized representatives of the andesite of the Bronco volcanics, both flows and breccias; of the sandstone, mudstone, and conglomerate of the Bisbee formation; and two members of the Naco limestone. These rocks are arranged in the most heterogeneous manner imaginable; limestone against andesite breccia, sandstone against conglomerate, dolomite against mudstone, in an apparently random accumulation. The blocks lie at random attitudes, the bedding in some is vertical, in others, that perhaps abut these, it is horizontal or at any angle between. They are separated from each other by dikes and sills of Uncle Sam porphyry that range in thickness from a fraction of an inch up to several feet. All these dikes and sills show very strong flow structures and are packed with even more inclusions than are normally contained in the porphyry. There seems to be a slight tendency for the more continuous sheets of the porphyry to lie at low angles and to dip away from the center of the mass in all directions. The normal porphyry overlying the breccia is almost surely domed over the breccia outcrop, as the rather definite boundary of the breccia dips away from the center of the exposure at angles of 10° to 20°. On this interpretation of the structure, a thickness of about 100 feet of the intrusive breccia is exposed here, with no bottom visible. A dike of andesite porphyry cuts across breccia and porphyry and is clearly much younger than both. It is probably not genetically related to these rocks.

Toward the east of this northern breccia mass is an unbroken block of andesite of the Bronco volcanics. It is likewise capped by a low dome (at least in north-south section) of Uncle Sam porphyry. At its eastern edge there is apparently a vertical mass of Uncle Sam porphyry about 100 feet wide that separates this unbroken body of andesite from a smaller mass of breccia like that to the west. The flow-banding in the porphyry overlying the andesite along the creek southeast of the breccia area dips about 50° S., but this steep dip is apparently local and may be due to faulting. Measured normal to these flow structures at least 300 feet of porphyry is exposed above the breccia.

The mass of intrusion breccia exposed to the south, in sec. 20, crops out in a subcircular area of about 70 acres. Here a breccia of sandstone, shale, and mudstone, probably derived from the Bisbee formation, is intimately cut by innumerable dikes and stringers of Uncle Sam porphyry that trend in all directions without apparent system. The porphyry stringers and dikes range from a few inches up to 50 feet in width. They show strong flow structures and are packed with inclusions of sandstone, shale, conglomerate, rhyolite, and a white granitoid rock of unknown age. Some of the inclusions are as much as four feet long but most of them measure only a fraction of an inch in length. Here, again, the overlying, less-contaminated porphyry appears to be domed over the breccia, though the exposures are not quite sufficient to make this certain.

Inclusions.—Some of the larger inclusions have been described in connection with the geological relations of the porphyry, as have the masses of intrusion breccia. However, inclusions are by no means confined either to these occurrences or to the border zones of the porphyry but are found in great profusion almost everywhere in the mass. They exhibit a great range in size. The largest noted outside of the breccias was 20 x 40 feet, many are as much as five feet across, but the great bulk of them are between a small fraction of an inch and an inch in diameter. They are so abundant in nearly all exposures that a normal hand specimen commonly shows at least one and may show half a dozen such inclusions on its surface. This is true not only near observed contacts where inclusions are commonly more abundant than elsewhere, but also far from any known contacts; for example, along the west slopes of the Tombstone Hills, and east of Brookline, half a mile or more from the nearest outcrops of country rock. In many places the inclusions are so numerous that the porphyry verges on a breccia.

In the areas west of the San Pedro, most of the inclusions are andesite and quartz latite of the Bronco volcanics, though sandstone, shale, and mudstone derived from the Bisbee formation are also abundant and a few fragments of granitic rock occur. In the areas east of the river, the volcanics and Bisbee rocks are abundant, but quartzite, dolomite, and limestone of Paleozoic age and the pre-Cambrian Pinal schist can also be recognized, along with fragments of granitic rock of the same type as that found west of the river. The granitic inclusions seem more abundant east of the river than west of it. Near the contacts there is a definite tendency for the inclusions of the adjacent rock to preponderate, but even here there are many representatives of other formations.

Most of the inclusions are angular and show abrupt boundaries with the porphyry matrix, but a few are round and in hand specimen appear to blend with the porphyry. Most of the inclusions of shale or mudstone are more or less altered to hornfels but the alteration of other rocks is far less conspicuous. Microscopic study shows, however, that many of the andesite inclusions have undergone slight alteration and, especially, mechanical disruption.

As mentioned in an earlier paragraph, the inclusions are generally more abundant near the contacts than elsewhere, though this is not invariably true. Locally such aggregations of inclusions reach extreme proportions and preponderate greatly over the matrix, and form bands that are notably different from the main mass of the porphyry. At the south end of the hills southeast of Brookline such a layer of inclusion-rich porphyry is well developed at the base of the upper of the two sills there exposed. Here the upper part of the sill is eroded away and the topmost exposures are of normal Uncle Sam porphyry that contains many small inclusions. Toward the base the number and size of the inclusions increases and a layer about thirty feet thick consists of perhaps 10 per cent of inclusions. This layer weathers into peculiar nodular outcrops. The nodules range from a few inches to about 3 feet in diameter, and the center of each is an inclusion. Most of these inclusions are subrounded or subangular and consist of hornblende felsophyric andesite like that which underlies the sill. Around each of the inclusions, which range in size from an inch or so up to about a foot in diameter, the porphyry has a finer selvage and apparently has been quenched. The spheroidal weathering is in part a reflection of the smoothly-flowing curves of the flow-structure of the porphyry matrix, but this can hardly account for the closure of the spheroidal surfaces revealed by the nearly perfectly spheroidal form of the weathered boulders. The round forms emphasized by the weathering look like piles of cannonballs or coarse, rounded boulders and cobbles. See Plate 1, Figs. 1 and 2, Plate 2, Fig. 1. This layer grades downward rather abruptly into a layer that consists overwhelmingly of inclusions—seemingly as much as 60 per cent—and in which the strongly flow-streaked porphyry matrix hardly suffices to separate the inclusions but merely fills the interstices between them. The base of this zone is the base of the sill, and the contact with the underlying andesite breccia (Bronco) dips gently westward in approximate conformity with the bedding of the volcanic breccia.

Bands of similar "cannon-balls" occur at several other places in the hills southeast of Brookline. At one other locality such a band lies at the basal contact of a porphyry sill (in the north center of sec. 30, T. 20 S., R. 21 E.), but in several other localities in secs. 18 and 19 of the same township the nodular-weathering bands are definitely not at the base of the sill, though they may be near the top, which has been eroded away.

Petrography.—The Uncle Sam porphyry is gray to pinkish gray on fresh fractures but weathers to buff and rusty brown hues. The phenocrysts are inconspicuous on weathered surfaces, but crystals of plagioclase, biotite, and subordinate hornblende range from about 1 mm. to about 8 mm. in length. Quartz generally forms somewhat smaller and fewer phenocrysts. The groundmass is aphanitic and near the contacts is commonly glassy. Still more surprising, in view of the considerable bulk of the intrusive mass, is the occurrence of only partly devitrified facies hundreds of feet away from any exposed contacts. The inclusions, which are so abundant as almost to be characteristic of the mass, have been mentioned in the preceding section. They commonly have megascopically abrupt boundaries against the porphyry matrix, though there are some that appear to blend into the porphyry and in many places there are dark clots in the porphyry that suggest more completely digested inclusions. The microscope shows, however, that these apparently blending contacts are chiefly due to the mechanical strewing out of included material and not to reaction with the magma.

Under the microscope, the commonest facies of the porphyry is seen to contain phenocrysts of plagioclase, quartz, biotite, and hornblende, in a groundmass of quartz, orthoclase, plagioclase and biotite, or in a glassy base. A few specimens contain orthoclase phenocrysts also. These are cryptoperthitic or definitely perthitic. Commonly the plagioclase is zoned from about An_{43} to An_{30}, but there are exceptional phenocrysts whose cores are near An_{50}. Among the inclusion-rich rocks there are notable variations from these compositions, as is discussed in a subsequent paragraph. Quartz is generally embayed but some of it has modified rhombohedral forms. A few specimens of those studied contain no quartz phenocrysts. The biotite is of the normal brown variety, but much of it has been altered to chlorite. Hornblende is present in but few of the specimens examined though perhaps half of them contain chlorite that is pseudomorphous after it. In the fresh specimens the hornblende is of the common green variety, with extinction angles of 17-18 degrees. A notable feature of the porphyry is the fracture (and strewing out of the resulting fragments) of a large proportion of the phenocrysts.

The groundmass ranges from vitric to microcrystalline, with a maximum grain size of about .04 mm., though more usually the groundmass crystals do not exceed .01 mm. Some specimens collected at points hundreds of feet from exposed contacts are partly glassy, and contain microspherulites of orthoclase. Where determinable, the groundmass plagioclase is near to An_{30}

in composition and is contained, along with chlorite or biotite, in an intergrowth of orthoclase and quartz or glass.

Accessory minerals include magnetite, apatite, zircon, and sphene, but much of the sphene is an alteration product derived from biotite and presumable ilmenite. A few specimens contain rosettes of tourmaline, dichroic in greenish brown and brown. Many of the specimens are mildly altered, with sericite, epidote, and albite developed in the plagioclase crystals, and the mafic minerals altered to chlorite. Calcite is also present in some of the rocks.

The above descriptions apply to most of the Uncle Sam porphyry, which, as mentioned previously, generally contains abundant inclusions. In the small samples of the normal facies afforded by thin sections but few of these inclusions were seen. For this reason, several specimens from parts of the mass unusually rich in inclusions were selected for study. Several of these came from the Tombstone Hills but most were from the hills west of the San Pedro southeast of Brookline.

Most of the inclusions studied under the microscope show sharp boundaries against the porphyry and there is little or no sign of reaction between magma and inclusions. A cloudiness due to an indeterminable fine black dust in many of the feldspars is the only sign of alteration of the minerals of the inclusions. In view of the fact that most of the groundmass of the porphyry is either glassy or very finely crystalline, lack of strong reaction is not surprising. Nevertheless, there is evidence that the mechanical inclusion of the foreign rocks and the strewing out of fragments from them has resulted in a considerable local variation in the composition of the porphyry. The inclusions of andesitic material, probably chiefly derived from the adjacent Bronco volcanics, are especially noteworthy in this regard. In several rocks containing such inclusions small fragments apparently derived from larger ones can be seen arranged in flow patterns away from the larger ones and thus represent a stage in the scattering of xenocrysts through the porphyry. In order to investigate this aspect of the petrology and evaluate the extent of the contamination, the plagioclase of the porphyry was especially studied.

Specimens of the porphyry that contain relatively few inclusions (none seen in the particular thin sections studied) show rather remarkably constant compositions of the plagioclase. As mentioned above, few crystals have cores more anorthitic than An_{45}, and An_{50} was the extreme noted. In eleven of these rocks the range was only from An_{35} to An_{30}. These determinations were made by immersion methods and examination of thin sections by ordinary methods. For study of the apparently contaminated rocks it seemed desirable to resort to a method by which the composition of an individual crystal could be determined and several such specimens were examined by universal-stage methods. The zonal method of Rittmann, as presented by Chudoba (1932), was used in most of the determinations, but resort was had to the more precise though laborious methods of Nikitin (1936), for grains not favorably oriented for the more rapid determination. The results of this work on individual plagioclase crystals are summarized in the following table.

Anorthite content of individual feldspar grains of the Uncle Sam Porphyry.

Specimen No.	125	255	256	260	261A	261D	283	286	287
	32 h	35 h	50 i	30 i	50 g	32 g	39 g	36 g	33 g
	32 h	37 h	50 i	31 i	52 g	32?g	40 i	38 g	35 g
	32 h	37 h	52 i	30−22zi	52 g	36 g	40 g	38 g	35 g
	32 h	37 h	52 i	37− 8zi	54−42zg	38 g	40 g	38 g	36 g
	33 h	37 h	54 i	25± 4 i	55 g	38 g	40± 5 i	39 g	37 g
	36 h	38 h	55 i	37−20zi	58 g	45 i	40± 5 i	40 g	38 g
	37 h	38 h	55 i	47− 8zi	58 g	55 i	41 i	40 g	39 g
		38 h	55-45zi	36 g	60 g	55 i	41 g	40 g	
		38½h		36 g	65−56zg	55 i	43 g	50 g	
		39 h		38 g	67 g	56 i		50 g	
		43 h		38 g	70−60zg	58 i			
Mean (incl.)	−	−	52	27	−	56	40	−	−
Mean (por.)	32	38		37	57	35	40	41	36

z, zoned crystal; i, crystal definitely part of an inclusion; g, crystal in glassy base; h, crystal in holocrystalline groundmass.

Of the above specimens, Nos. 125 and 255 contain no identifiable inclusions; No. 256 is an andesite inclusion in the rock of No. 255; No. 260 is porphyry with a glassy groundmass that contains an inclusion of granitoid rock, the feldspars of which have the compositions indicated; 261A is largely devitrified andesite in fragments separated by stringers of highly fluidal glass, containing feldspars essentially identical with those of the andesite, and interpreted as xenocrysts freed from the inclusion; 261D, which is part of the same intrusion breccia as 261A, consists of andesite inclusions in more abundant glassy porphyry; No. 283 is glassy porphyry containing inclusions of quartz latite (Bronco?); Nos. 286 and 287 contain inclusions chiefly of shale, and no feldspars are identifiable in the inclusions. It is somewhat surprising to find that the feldspars in the glassy matrix of No. 261A are wholly those of the andesite inclusion, for, aside from this specimen, the plagioclase of the porphyry, even in glassy facies, is more albitic. Accordingly, one would expect some of the indigenous feldspar of a composition near An_{40-30} to be intermingled with the xenocrysts derived from the andesite, especially as such feldspars are found in the neighboring specimen, No. 261D. Possibly the absence of these primary feldspars from the narrow glassy seams that separate the fragments of andesite in this specimen is due to the constricted passages between the fragments, which perhaps strained out the larger feldspars in the porphyry magma. This explanation seems a bit far-fetched, but no other occurs to me.

It is perhaps significant that all the specimens listed in the table are glassy except for Nos. 125 and 255. The constancy of the composition of the feldspars of these glassy rocks—ranging between An_{43} and An_{30}—is such as to make it seem likely that the two crystals in No. 286 with anorthite content of 50 per cent are xenocrysts from inclusions of andesite, some of which were seen in the neighboring rock. If so, the few crystals seen in the porphyry elsewhere, which have cores as calcic as An_{50}, are probably to be similarly interpreted. In these other rocks in which the groundmass is more largely crystalline, there should have been better opportunity for reaction between xenocrysts and magma than in the glassy facies, with correspondingly more chance for zoning around the nuclei of any xenocrysts that might be present. This, of course, is not a necessary interpretation of these more calcic cores, for the natural evolution of the magma would lead from more anorthitic to more albitic feldspars, and these cores may record an earlier intratelluric stage in the history of the magma. The uniformity of the feldspars in so many specimens, however, suggests that the porphyry magma was rather uniform as emplaced and hence that these more calcic cores may not represent intratelluric feldspars but xenocrysts, a suggestion that is fortified by their sporadic distribution.

Chemical composition.—The following chemical analyses of the Uncle Sam porphyry have been made:

Chemical analyses and norms of the Uncle Sam Porphyry.

Anal	1	2	3	4
SiO_2	66.59	68.16	68.04	67.60
Al_2O_3	16.77	16.07	15.82	16.22
Fe_2O_3	1.94	1.75	2.34	2.01
FeO	1.26	1.15	.84	1.08
MgO	1.04	.90	.80	.91
CaO	2.86	2.61	3.26	2.91
Na_2O	3.66	3.79	3.93	3.79
K_2O	3.77	3.64	3.32	3.58
H_2O+	.98	1.01	.77	.92
H_2O-	.21	.25	.37	.28
TiO_2	.38	.43	.42	.41
P_2O_5	.26	.16	.15	.19
MnO	.11	.11	.07	.10
ZrO_2	n.d.	n.d.	none	....
CO_2	n.d.	n.d.	.14	....
S	n.d.	n.d.	tr	....
NiO	n.d.	n.d.	none	....
BaO	n.d.	n.d.	.06	....
SrO	n.d.	n.d.	.01	....
Li_2O	n.d.	n.d.	tr	....
Cu	n.d.	n.d.	tr	....
Zn	n.d.	n.d.	none	....
	99.83	100.03	100.24	100.00

Norm	1	2	3	4
Q	23.88	25.98	24.60	24.72
or	22.24	21.13	19.46	21.13
ab	30.92	31.96	33.54	31.96
an	12.51	11.95	15.29	13.62
C	2.14	1.63	.10	1.12
hy en	2.60	2.20	2.00	2.30
hy fs	.26	.13	....	....
mag	2.78	2.55	1.86	2.55
il	.76	.76	.76	.76
hem	....	....	.96	.32
ap	.67	.34	.34	.34

Symbol:
I″, 4, 2, 3(4) I, 4, 2(3), (3)4
I, 4, 2, 3(4) I″, 4, 2″, 3(4)

1. (Lee C. Peck, analyst) Porphyry from a point about 1500 feet NE of Bronco Hill, in sec. 7, T. 21 S., R. 22 E.
2. (Lee C. Peck, analyst) Porphyry from southernmost exposure on west side of San Pedro River, in sec. 25, T. 20 S., R. 20 E.
3. (R. C. Wells, analyst) Porphyry from a point 2½ miles west of Tombstone and ½ mile east of The Dome (Butler, Wilson and Rasor).
4. Mean of analyses 1, 2 and 3.

In view of the fact that each of the two specimens (1 and 2) collected for the present study contains abundant inclusions of shale and granite, respectively, the differences in chemical composition are surprisingly trivial. Evaluation of the quantitative contamination of the quartz-latite magma would be merely guess-work because of the small silica variation shown, and it has not been attempted. The determinable rocks in the inclusions are of such diverse composition—ranging from quartzite to limy shale and from granite to andesite—that it would be practically impossible to obtain a quantitative determination of the extent of contamination in any event. It is perhaps noteworthy that in the area southeast of Brookline, where the exposed wall rocks are andesite, there are abundant inclusions of both granite and quartz latite (resembling the quartz latite of the Bronco volcanics which elsewhere overlies the bulk of the andesite of that formation).

Internal structural features of the porphyry.—Despite the abundance of inclusions and the prominence of biotite in the Uncle Sam porphyry, flow structures are only locally conspicuous and in many places are impossible to discover despite careful examination. The orientations of such structures as were observed are shown on Text Fig. 3; more careful and systematic

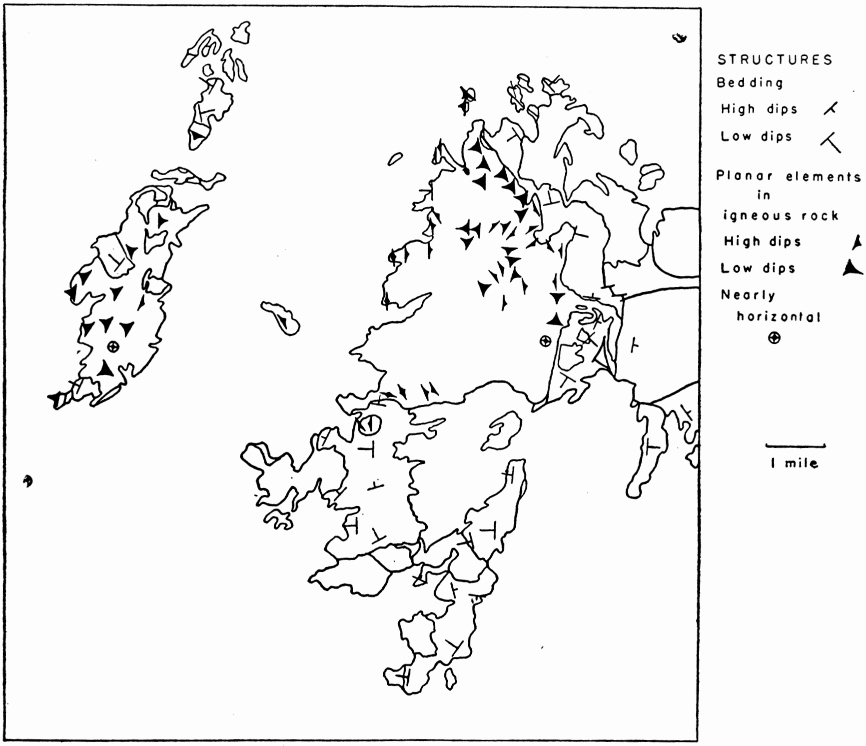

Fig. 3. Structural features of the Uncle Sam porphyry.

examination than was possible during this study might give considerable additional data, but it seems clear from the widely variant attitudes shown that the structural trends recorded by the foliation and by the alignment of inclusions do not correspond very closely to the contacts of the mass. This conclusion was reached also by Ingerson (1939), after a more intensive study of the northeastern part of the mass in the Tombstone Hills. He stated that, "A glance at the projection shows that there is no significant preferred orientation of the platy inclusions. Even near the contacts there is slight tendency for inclusions to lie parallel to the contact surfaces, there being only 5 out of 21 inclusions measured near contacts that are within 20° of parallel to the contact surfaces. Two of the inclusions stand almost normal to the contacts and two others make angles of over 60°, the average being 40°." He also pointed out that the joints measured in the same part of the intrusive are more or less randomly oriented as to azimuth but that a majority dip at steep angles. Whether the scarcity of low-dipping joints is real or due to difficulties of measurement on gentle slopes is difficult to decide, but as Ingerson correctly points out, the available information on the joints does not indicate any relation to a shallow floor. It might be added that the area studied by Ingerson includes that near the State of Maine mine, in which both surface exposures and mine workings strongly suggest that the floor lies at a rather shallow depth. From this it may be concluded that such features as joints and inclusions are not, in this area, reliable clues to either the proximity or attitude of the contacts.

In the hills southeast of Brookline the zones of inclusion-rich porphyry are rather closely parallel to the exposed contacts and this also is the impression given in the area of the intrusive breccias north of the Babocomari River. In this portion of the intrusive, accordingly, a sill-like form is suggested both by internal structures and contacts.

Emplacement of the Uncle Sam porphyry.—The wide area of younger rocks that separates the main exposures of the porphyry on the two sides of the San Pedro River prevents any decision as to whether these exposures form parts of a single large body or of separate masses. Even if the exposures west of the river belong to a separate intrusive, however, the problem of the emplacement of the porphyry is only slightly less puzzling: the emplacement under cover—even a shallow cover—of a body of igneous rock several hundred and perhaps more than a thousand feet thick and at least three miles in diameter does not normally yield a microcrystalline to vitrophyric rock. How so large a mass could be so quickly quenched is difficult to understand.

That the magma was within its crystallization range when it was emplaced is clear from the similarity in both size and composition of the phenocrysts in the glassy facies with those in the more largely crystalline phases. The considerable fracturing of both inclusions and phenocrysts also suggests a high viscosity of the magma. How so highly viscous a magma could incorporate so large a proportion of inclusions and distribute them more or less uniformly through its mass is also difficult to comprehend, as the possibility of turbulent flow seems remote. These anomalous features of the Uncle Sam porphyry are probably connected with its mode of emplacement. It may be recalled that the northeast contact of the main mass in the Tombstone Hills is locally formed by a wide zone of overturned and brecciated beds belonging to the Bisbee formation and the Naco limestone, in which the Naco rests in part upon overturned beds of the Bisbee. The Naco is thrust over the Bisbee on a clean-cut fault at the north end of the Tombstone Hills north of The Three Brothers. The contact along this side of the porphyry dips southwestward beneath the intrusive and Bisbee beds are penetrated beneath it in the State of Maine mine. These relations suggest that the porphyry here occupies a thrust plane; unfortunately not enough of the other contacts are to be seen to establish whether or not this is a general relation. It is clear that the intrusion of the porphyry did not itself cause the overturning of these beds because the intrusive is not itself deformed nor does it have systematic flow structures related to the contacts. This is also the conclusion of Ingerson. Additional evidence that the intrusive is younger than the major deformation of the region is furnished by the dike of Uncle Sam porphyry that occupies, with frozen contacts, one of the major normal faults of the Tombstone district just west of Ajax Hill. This fault is younger than most, if not all, of the folding in this area. Accordingly, it seems reasonable to attribute the relations just discussed to the occupation of a low-angle, west-dipping thrust fault by the porphyry.

If this is true, it seems that the innumerable fragments incorporated in the porphyry need not be attributed to stoping—which would be decidedly unlikely for a magma so near consolidation temperature at the time of emplacement—nor to abrasion of the walls of the conduit. The fragments may reasonably be regarded as breccia along the thrust fault, already comminuted and ready for engulfment when the magma occupied the fault space.

It is by no means intended to imply that the porphyry is limited to a thrust surface. At many places between the

Tombstone-Charleston road and Ajax Hill the porphyry forms irregular dikes and sills and consequently cannot have been governed in detail by a pre-existing fault pattern. Similarly, near Bronco Hill and north of Lewis Springs the assumption of fault control would be gratuitous. However, in neither of these localities are the inclusions so abundant as they are in the main mass, and at least in the southern localities the groundmass of the porphyry is more coarsely crystalline than in the average of the main mass. Unfortunately, the possible significance of this feature was not realized at the time of the field work and collections were not sufficiently extensive to warrant any statement as to details of crystallinity of the minor masses west of Ajax Hill.

The abundance of inclusions of andesite of the Bronco volcanics suggests that the fault breccias postulated as the source of the other inclusions were younger than the Bronco. This is not certain, though, for flow and tuff breccias make up much of the Bronco volcanics. The diversity of the inclusions may perhaps equally well result from incorporation of pre-Bronco thrust breccias and of pyroclastic andesite (Bronco) deposited on them. Thus, even if the suggestion here offered is correct, i.e., that many of the inclusions represent thrust breccia fragments—it does not prove that the thrusts are younger than the Bronco volcanics. It would be reasoning in a circle to cite the abundant andesite fragments as evidence of a post-Bronco thrust, however consonant with such an interpretation they may be.

In the hills west of the San Pedro, contacts with pre-porphyry rocks are even fewer than in the Tombstone Hills. That the intrusive is more or less sheet-like seems indicated by the local relations at the most southerly outcrops, but farther north no contacts with older rocks are found except northwest of Fairbank where the exposures are poor, and far to the northwest, near Boquillas. Near Boquillas the porphyry is generally sill-like, though it sends out a dike for several hundred feet into the upper member of the Naco limestone, which is here the country rock. There is no suggestion of fault control of the intrusive in this northernmost exposure; although the intrusive breccias east of Brookline do not necessarily imply that the porphyry has here incorporated a thrust breccia, they are certainly compatible with such an interpretation. The strong suggestion of a sheet-like form of the breccia and the apparent conformity of the structure of the porphyry above the largest of these masses, together with the intimate jumbling of blocks of very diverse stratigraphic position, all fit very well with the view that the porphyry here, also, occupies a thrust plane. That such an assumption is compatible with the geologic history of the region is pointed out in the paragraphs dealing with the structure of the area, though there is no direct evidence, owing to the overlap of younger formations, that the thrust faults occur west of the San Pedro River.

A sheet-like form for the larger bodies of Uncle Sam porphyry seems an almost necessary corollary of its fine grain and even vitrophyric texture. If this sheet-like form is conditioned by a pre-existing fault surface or by several of them, a reasonable explanation is afforded for the high content of inclusions of diverse origins. The possibility immediately arises that the inclusions may have contributed to the quick chilling of the intrusion. Although this would almost surely have been their qualitative effect, the quantity of incorporated material hardly seems adequate to accomplish very drastic chilling. Their quantitative effect is discussed in the following paragraphs.

In order to evaluate the temperature effect of the inclusions on the magma, certain assumptions are necessary. These include estimates of the proportions of the inclusions, of the specific heat of inclusions and magma, and of the original temperatures of inclusions and magma at the time of the incorporation. In view of all the uncertainties involved, only estimates can be made for any of these factors. It is here assumed that the specific heat of both magma and inclusions is the same (Daly, 1933).[3] The temperature of the inclusions at the time of their incorporation in the magma can only be guessed at, but if they were picked up near the final resting place of the magma, they were probably not at great depth—perhaps 3000 feet—and with a normal thermal gradient of 1° C. per 100 feet, would have had a temperature not far from 50° C. The temperature of the magma may be assumed as 700°, within the crystallization range of quartz latite magma as estimated by Larsen (1929). These assumptions thus postulate a temperature difference between magma and inclusions at the time of their immersion, of 650°. Inasmuch as the specific heats of

[3] Daly's figures differ slightly for vitreous and solid phases and the specific heats of both are functions of temperature, but as a rough approximation, identical specific heats may be assumed without serious error.

the two can be regarded as the same, the final temperature of the mixture would be related to their initial temperatures inversely as the masses of the material involved.

Let x be the temperature increment of the inclusions, y the temperature decrement of the magma. Then, if the inclusions amount to 3 per cent of the final mixture,

$$3x = 97y$$
$$x + y = 650$$

The solution of these equations gives $y = 19.5°$ as the temperature drop in the magma as a result of the chilling effect of the inclusions. If the inclusions are assumed to amount to 5 per cent of the final rock—an improbably high figure for the mass as a whole—the magma would be cooled 32.5° by their incorporation.

Although these calculations are very rough, and based upon assumptions that may be considerably in error, it seems unlikely that the chilling effect of any reasonable amount of inclusions could have exceeded 50° C. and probably was not more than half that. Little is known of the rates of crystallization of the rock-forming minerals and their variation with temperature, and it may be that a rapid chilling of this seemingly moderate amount might suffice to preserve the glassy or extremely fine-grained groundmass that characterizes the porphyry. However, it seems that this would only be true if the magma as intruded were also unusual in some other respect. The unusual character most likely to have contributed in this way is poverty in fluxes, a poverty that is consistent with the insignificant chemical reaction of the inclusions with the magma and with the slight contact alteration of the country rocks. Accordingly, it is concluded that the unusually fine grain of the groundmass of the Uncle Sam porphyry may be in part a result of the incorporation of the unusual amount of inclusions but that this was probably combined with poverty in volatiles also.

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