(200)
R290
no.469

UNITED STATES
DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

OCCURRENCES OF ALUNITE, PYROPHYLLITE AND CLAYS IN THE CERRO LA TIZA AREA, PUERTO RICO

By

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U. S. Geological Survey
OPEN FILE REPORT
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59-54

Prepared by the U. S. Geological Survey in cooperation with the Puerto Rico Economic Development Administration

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Abstract

A deposit of hydrothermally altered rocks in the Cerro La Tiza area located between the towns of Comerío and Aguas Buenas, approximately 25 kilometers southwest of San Juan, Puerto Rico, was mapped and studied to determine the principal minerals, their extent, distribution and origin, and the possibility of their economic utilization, especially in Puerto Rico. The Cerro La Tiza area is about 7-1/2 kilometers long, has an average width of about 1-1/2 kilometers and embraces a total area of approximately 15 square kilometers. The principal mineralized zone, a dike-like mass of light-colored rocks surrounded by dark-colored volcanic country rocks, occupies the crest and upper slopes of east-trending Cerro La Tiza ridge and is believed to be of Late Cretaceous or Eocene age. This zone is approximately 5,200 meters long, 430 meters wide and has an area of approximately 225 hectares (556 acres). The rocks of the mineralized zone are of mixed character and consist mainly of massive quartzose rocks and banded quartz-alunite rocks closely associated with foliated pyrophyllitic, sericitic and clayey rocks. The principal minerals in probable order of abundance are quartz, alunite, pyrophyllite, kaolin group clays (kaolinite and halloysite) and sericite. Minerals of minor abundance are native sulfur, diaspore, svanbergite (?), zunyite (?), hematite, goethite, pyrite, rutile(?) ~~(?)~~ and very small quantities of unidentified minerals.

The mineralized zone has broken down to deposits of earth-rock debris of Quaternary age that cover much of the slopes and flanks of Cerro La Tiza. This debris consists generally of fragments and boulders with a very large size range embedded in a clayey matrix. The distribution of the earth-rock debris with respect to the present topography and drainage suggests that it may have undergone at least two cycles of erosion.

Underlying the earth-rock debris and completely enclosing the mineraliz zone are country rocks of probable Late Cretaceous age. These consist princ pally of low lava~~s,~~ flows and volcanic and flow breccias but contain thin interbed siltstones and sandstones. The lavas are generally predominant at the weste end of the area and the breccias at the eastern end.

The mineralized zone and the country rocks are sheared along two predominant directions that are approximately N. 70° E. and N. 70° W. The ridge of Cerro La Tiza appears to be a broad shear zone through which hydrothermal emanations gained access to the country rocks. The emanations are believed to have originated from intrusive rocks that probably underlie the area. The surrounding area contains both large and small exposed intrusive bodies. The largest one is the San Lorenzo batholith of Late Cretaceous or Eocene age whose exposed northwest edge is approximately 19 kilometers southeast of the eastern end of the Cerro La Tiza area.

Other zones of hydrothermally altered ~~minerals~~ rocks were discovered along a mineralized belt extending eastward from Cerro La Tiza through the Rio Gurabo Valley nearly to the Vieques Passage bordering the east coast of Puerto Rico. Other zones were discovered north and south of this belt and still others were found circumventing the San Lorenzo batholith.

The most abundant minerals of the mineralized zone can be exploited for economic utilization in Puerto Rico. Alunite can be utilized in the manufacture of aluminum sulfate for water purification. It can also be used in the manufacture of alumina refractory materials. Pyrophyllite can be used as a carrier for insecticides and fungicides. It can also be utili for the manufacture of ceramic products, as a filler in the soap industry and as a carrier for paint pigments. Kaolinite can be used in the ceramic industry and in the manufacture of glass as a substitute for feldspar. Halloysite might be utilized as a catalyst support in the cracking of petrol

Tonnages of reserve ore on Cerro La Tiza are calculated to be 1,590,000 inferred short tons (1,440,000,000 inferred metric tons) of mixed minerals. These tonnages are based on the assumption that the depth of the mineralized zone is one-half of the exposed width. The deposit is well situated for ope pit mining, but because of the existing cover of earth-rock debris, soil and foliage, exploration should preceed exploitation for better determination of the most promising areas containing the best concentrations of the minerals sought.

Introduction

Location

The Cerro La Tiza area lies between the towns of Comerío and Aguas Buenas about 25 kilometers southwest of San Juan, the capital city of Puerto Rico (pl. 1). The area lies partly in the Comerío quadrangle and

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Plate 1.—— Index map showing location of Cerro La Tiza area.

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partly in the Naranjito quadrangle and is transected by the boundary between Municipios de Comerío and Aguas Buenas.

Purpose and scope

Many occurrences of hydrothermally altered rocks occur throughout east-central Puerto Rico. This report is primarily limited to but one occurrence which is designated the Cerro La Tiza area. The study was undertaken to determine the character and extent of the deposit and the potential mineral reserves and their economic utilization especially in Puerto Rico. It was made under a joint program of the Puerto Rico Economic Development Administration and the U. S. Geological Survey to determine the mineral resources of Puerto Rico.

The investigation was directed toward a dike-like mineralized zone of hydrothermally altered rocks along the crest of a ridge known locally as Cerro La Tiza, but a brief examination of the country rocks_/ was made

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Country rock has a special connotation in this report because the mineralized zone is not in a strict sense a vein or dike. It is a zone of hydrothermally altered rocks surrounded by unaltered country rocks.

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for the bearing they have on the origin of the deposit. Surficial deposits of debris from the mineralized zone partially covering the country rocks were delimited primarily because of their possible economic utilization.

Other occurrences of hydrothermally altered rocks in east-central Puerto Rico were found by the authors (Smith and Hildebrand, 1953, p. 1476), while investigating other areas for their potential mineral resources during the early stages of the study. Other Survey geologists have found still other zones of hydrothermally altered rocks in southeastern Puerto Rico during the later stages of the investigation. A section briefly describing all these zones and their relationship to intrusive rocks outside of the Cerro La Tiza area accompanies this report. A more credible explanation for the origin of the Cerro La Tiza mineralized zone was arrived at by extending the study in this way.

History, field work and methods of investigation

Cerro La Tiza, meaning "mountain of chalk" was so named for the light-colored rocks occurring on its crest and slopes. These light colored rocks were first called to the attention of the U. S. Geological Survey in 1949 when Mr. R. Fernández García of the Puerto Rico Economic Development Administration suggested to C. A. Kaye of the U. S. Geological Survey, who was engaged in engineering geology investigations in Puerto Rico, that he examine light-colored rocks possibly of a bauxitic nature reported to occur near Comerío. Kaye collected a few light-colored rocks from this area and submitted one specimen to R. L. Smith of the U. S. Geological Survey who reported that it contained alunite. The Puerto Rico Economic Development Administration in 1950 acquired chemical analyses showing significant percentages of sulfate, potash, and alumina in similar rocks from the same area. Early in 1952, H. M. Bannerman of the U. S. Geological Survey, accompanied by the junior author briefly examined the Cerro La Tiza area and submitted a few more samples of light-colored rocks to the senior author for X-ray examination whereby alunite, quartz and kaolinite were found to be the principal constituents. Mapping and delimitation of the deposit was therefore justified on the basis of these mineral determinations, chemical analyses and the apparent broad extent of the mineralized area.

Mapping of the area was begun in April 1952 and carried on intermittently until July 1952. Approximately 120 samples were collected during this period. From August 1952 until May 1954, approximately 70 of these specimens were studied as time permitted in the laboratory, principally by X-ray and microscopic examination. In June 1956, the senior author spent approximately five days in the area reexamining the rocks with M. H. Pease, Jr. and R. P. Briggs of the U. S. Geological Survey, who were currently mapping the Comerio quadrangle. Their mapping from the Fall of 1955 to the Spring of 1957 includes the southern part of the Cerro La Tiza area and the area south of it. During Dec. 1957 and March and April, 1958, the senior author intermittently re-examined the area and revised the mappi

Mapping was done on U. S. Geological Survey topographic sheets at a scale of 1:10,000. Aerial photographs at a scale of approximately 1:15,000 were used occasionally for establishing locations.

Most of the mineral determinations were made by X-ray powder diffraction methods because of the fine-grained character of the minerals. Complet chemical analyses were made on five alunitic rocks that, according to X-ray studies, contain appreciable amounts of alunite and only small amounts of quartz. Thin-sections were used primarily to study the texture and crenulated nature of some of the finely-banded rocks. One sample of the most representative country rock was chemically analyzed.

Several test pits were dug with a hand shovel. Two hand auger holes were drilled around the edges of a small water-filled clay pit, to determin the nature and depth of the clay deposit. Samples from these holes were studied in the laboratory to determine their mineralogy.

Acknowledgements

The authors wish to gratefully acknowledge the cooperation of Mr. Rafael Fernández García former Director of the Department of Industrial Research of the Economic Development Administration, and his laboratory staff in providing space and offering encouragement for carrying on the investigation. Mr. Fernández García first recognized and pointed out to Survey geologists, the occurrence of rocks of possible economic importance in the Cerro La Tiza area. The authors are also grateful to Mr. Heliodoro Blanco, formerly of the Economic Development Administration, for introducing them to the area during the early part of the field work.

Mr. José Barreto assisted ably in the field work and Mr. Isabelino Ramos helped compile several of the illustrations.

Geography

Areal extent

The geographic limits of the Cerro La Tiza area were arbitrarily chosen and are indicated by the outer limits of the mapped area shown by plate 2. The Cerro La Tiza area is defined for the purpose of this report as that area lying between the base of the north and south flanks of the eastward elongated ridge named Cerro La Tiza and between the Rio de la Plata and the Rio de Bayamón that terminate the east and west ends of the ridge. The area investigated was extended slightly beyond these limits in places where it appeared that extensions or isolated occurrences of hydrothermally altered rocks might occur and also where deposits of earth-rock debris had been transported beyond the lowermost flanks of the ridge. The area so defined has an irregular shape with a maximum length of 7-1/2 kilometers, a maximum width of 3 kilometers near the western end, and an average width of about 1-1/2 kilometers toward the narrower eastern end. The total area investigated embraces about 15 square kilometers.

Physical features

The Cerro La Tiza area is nearly coincident with east-trending Cerro La Tiza ridge (Fig. 1). The highest point on the ridge, about 1/3 the

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Figure 1.— Profile view of Cerro La Tiza looking north from a point on the Cidra road on upland south of the saddle area. The arbitrarily chosen boundary limits of the western end, peak area, saddle area and eastern end along the crest are shown by the vertical lines. The outermost boundary limits at each end of the picture mark the east and west ends of the mineralized zone.

1 indicates the approximate position of the reference point.

2 indicates the central road at the point where it reaches the crest in the saddle area.

3 indicates the eastern road at the point where it crosses the crest.

4 indicates the road cut on the eastern road where the contact between the mineralized zone and the country rock is well exposed.

The Aguas Buenas-Comerio road lies in the east-trending valley in the centerground of the picture.

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distance from its western end, is designated by a triangulation point (VABM) at 659.8 meters elevation (Pl. 2, Pl. 3, Fig. 1). For convenience in this report, all locations unless otherwise specified will be referred to this centrally located 659.8 meter triangulation point which will be designated in the text as the reference point. The lowest point in the area is at the northwest edge in the valley of the Río de la Plata where the elevation is 175 meters.

Along its north and south flanks, Cerro La Tiza is bounded by small flowing or intermittent streams. Its average height above these streams is about 450 meters at its west end and 250 meters at its east end. The central part of Cerro La Tiza which is slightly lower and forms a saddle will be referred to as the saddle area.

The slopes of Cerro La Tiza, particularly the south slope, have many transverse spurs or ridges seperated by ravines. These are for the most part continuous, down to the small streams or intermittent drainages ~~of~~ at the base. The deepest ravines are about 50 meters deeper than the crests of the adjacent spurs but most of the ravines are 10 to 20 meters or less in depth. The average angle of slope is about 15° to 20° at the eastern end, 20° to 25° at the western end and about 10° to 15° in the saddle area. In a few places, the slope exceeds 30° as for example below the pronounced spur on the northwest slope at 450 meters elevation, where the angle of slope is 33° and below a pronounced spur on the south slope about 400 meters south of the reference point, where the angle of slope is 37°. The west slope is notably steeper and broader than the east slope and the south slope is somewhat more precipitous than the north slope, particularly in the vicinity of the reference point. The northwest~~ern~~ slope is precipitous where it slopes down to the Río de la Plata.

Accessibility

Puerto Rico has a net work of good, all-weather roads. In the Cerro La Tiza area, the principal roads are paved but generally narrow. Access to the area is provided by a major highway, from Aguas Buenas to Comerío that passes along the south flank of Cerro La Tiza. This higway intersects another major highway, the Comerío-Bayamón road, near the southwest edge of the area. The Comerío-Bayamón road skirts the west end of the area along the west side of the Río de la Plata, has been widened and resurfaced recently, and is now the best access road to the area from San Juan. Cerro La Tiza is transected by three roads that originate from the Aguas Buenas-Comerío road. The easternmost road intersects the Aguas Buenas-Comerío road at a point approximately 1,970 meters east and 470 meters south of the reference point and passes northward over Cerro La Tiza. The pavement ends about 500 meters north of the ridge crest, but an unpaved road continues northwest from this point into the Naranjito quadrangle. This road will be referred to throughout this report as the eastern road. A centrally-located, unpaved road, intersecting the Aguas Buenas-Comerío road at a point approximately 820 meters east and 730 meters south of the reference point, passes northward over Cerro La Tiza in the saddle area where it branches into two roads that continue down the north slope into the Naranjito quadrangle. This road, where it occupies the south slope, will be referred to as the central road. The third road transecting Cerro La Tiza, intersects the Aguas Buenas-Comerío road at the east end of the Río de la Plata bridge approximately 130 meters south and 2410 meters west of the reference point, extends northeastward around the western end of Cerro La Tiza for a distance of approximately one kilometer and terminates near a small settlement (not shown on the topographic map) locally called La Prieta. This road will be referred to, throughout the report, as the western road. All the principal roads in the area are shown on plates 2 and 3. There are also many foot trails that provide ready access to all parts of the area. Most notable of these is a trail along the entire ridge-crest, but the trail has been abandoned in some places because of more extensive use of the eastern, central and western roads and newly made trails to intersect these roads at shorter vantage points.

Climate and vegetation

Puerto Rico, lying within the trade wind belt, has a tropical climate. The mean annual temperature in the Cerro La Tiza area is 76.5 degrees (44 year average) measured at the Comerío hydroelectric plant approximately one kilometer north of the northwest edge of the Cerro La Tiza area. The lowest temperature recorded at the Comerío hydroelectric plant is 43 degrees and the highest is 99 degrees. The average yearly rain fall, also measured at the Comerío hydroelectric plant is 72.5 inches (44 year average). Although the distribution of the monthly rainfall varies widely from year to year the driest months are generally January, February and March.

The vegetation of Puerto Rico is tropical. In the Cerro La Tiza area, the slopes of the ridges and valleys are wooded and covered with broad-leaved tropical plants except where areas have been cleared for cultivation in which places they are either bare or covered with grazing grass or crops. The maya, a barbed, pineapple-like plant is commonly used as a hedgerow along boundaries between farms. Ornamental trees, for example, the flamboyant and almendro are planted along the principal roads. Bamboo has been planted along some roads and it commonly grows in or near stream valleys, particularly along the Río de Bayamón. The planting of sugar cane, tobacco and fruit, the principal crops of the area, does not seriously hamper field work because these crops do not grow well and are not extensively planted in the mineralized zone.

General geology

No direct reference to the Cerro La Tiza area could be found in the literature. The area as defined in this report is but a small part of much larger areas described from broad view points by Semmes and Meyerhoff. Semmes (1919, geologic map) in his description of the San Juan district which includes this area, says that the rocks in the district consist of "varying ash and tuff with intrusives". Semmes (1919, p. 70) describes belts of conglomerates of volcanic origin that parallel a major tuff series "which apparently form the backbone of the island". Meyerhoff (1933, geologic map) classifies these rocks as "Upper Cretaceous pyroclastic rocks including massive andesitic tuffs and agglomerate and associated conglomerates

The principal rocks in the Cerro La Tiza area were found by this investigation to consist of a mineralized zone of hydrothermally altered rocks surrounded by volcanic ~~derived~~ rocks partially covered by surficial deposits of debris derived from this mineralized zone (Pl. 2). The volcanic ~~derived~~

Pl. 2.--- Geologic Map of the Cerro La Tiza area, Puerto Rico.

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rocks are the oldest rocks in the area. The hydrothermal metamorphism of these volcanic ~~derived~~ rocks along a line of weakness that coincides with the crest of Cerro La Tiza has produced the mineralized zone which has the shape of a vein or dike-like body. In a sense, the surrounding unaltered volcanic ~~derived~~ rocks can be likened to country rocks bordering a vein or dike. The term country rock in this report is used in this sense.

Several smaller zones of local mineralization in the area occur in the country rock outside of the principal mineralized zone. These zones do not appear to be offshoots from the principal zone but have simply developed in places where the hydrothermal solutions could gain access to the country rocks.

The youngest rocks in the area are surficial deposits of earth-rock debris that were produced as erosion processes carved out the valleys adjacent to Cerro La Tiza and left the ridge standing in relief. Subsequent weathering and erosion of the mineralized zone on the crest of Cerro La Tiza has produced the debris that now covers much of the country rock as well as the mineralized zone.

Country rocks

The country rocks consist predominantly of lava flows and volcanic and flow breccias. On the whole they are schistose and foliated and somewhat difficult to recognize in outcrops. The lavas contain thin interbedded siltstones, sandstones and breccias and conversely, the breccias contain interbedded ~~flow~~ lavas, siltstones and sandstones.

The lavas are generally amygdaloidal and vesicular and contain pillows. In some places the remnants of a dark red, fine-grained siliceous envelope around the pillows are the best criterion by which the lavas can be identified. The lavas are extensively exposed in the western part of the area. They are well exposed in outcrops of difficultly recognizable rocks throughout an interval of about 1,000 meters along the Comerío-Bayamón road from a point about 400 meters north of the Río de la Plata bridge, south along the road toward Comerío. In the northwestern part of the area, very good exposures of pillow lava occur in Quebrada Blanca from its mouth, where it empties into the Río de la Plata (2,060 meters west and 1,070 meters north of the reference point) northeastward for about 200 meters along the creek. The pillows here are well defined and some form zones of small pillows interbedded with zones of larger pillows. A sample of lava collected at a point approximately 70 meters south and 1,900 meters west of the reference point was chemically analyzed (table 1). Recomputation of this analysis omitting CO_2 and H_2O indicates that this rock is probably an altered basalt. The point at which the specimen was collected is along the axis of the mineralized zone about 200 to 300 meters west of the westernmost border of the mineralized zone.

Table 1. Analysis of Cerro La Tiza Lava

	# C-701	# C-701✓
SiO_2	41.99	46.24
Al_2O_3	11.96	13.18
Fe_2O_3	2.62	2.89
FeO	8.04	8.85
MgO	10.58	11.65
CaO	11.02	12.13
Na_2O	1.78	1.96
K_2O	1.32	1.45
H_2O^-	.36	——
H_2O^+	4.34	——
TiO_2	.71	.78
CO_2	4.47	——
P_2O_5	.39	.43
MnO	.18	.20
Total	99.76	99.76

✓ Recomputed, omitting CO_2, H_2O+ and H_2O^-.

Analyst, L. D. Trumbull.

The breccias are most prominent in the eastern part of the area. The size range of the fragments, and their roundness or angularity, shows that the breccias are both flow breccias and volcanic breccias. Interbedded lavas are more abundant than the siltstones and sandstones in this unit. The best exposures of the breccias occur in cuts along the Aguas Buenas-Comerío road from the central road junction eastward to the Río Bayamón.

Several small intrusive bodies were discovered within the mapped area of Cerro La Tiza. One of these is a dike-like body exposed along the Comerío-Bayamón road at a point approximately 120 meters south and 2,630 meters west of the reference point. It is also exposed nearby in another parallel road east of this location at a pointapproximately 120 meters south and 2,560 meters west of the reference point. Cursory examination of these dike rocks indicates that they are hornblende diorite. Another small intrusive body crops out in the bed of Quebrada Blanca at a sharp loop in the stream bed about 40 meters east and 850 meters north of the reference point. Cursory examination of this rock indicates that it is quartz diorite.

The country rocks are generally weathered to light tan, brown and brownish-red saprolitic clay that preserves the relict texture of the parent rock. The surfaces of some spurs that are not covered with surficial debris are composed of dark-greenish gray to black country rock that is relatively unweathered but crumbly and non-cohesive because of its sheared and close-foliated character. The sides of some spurs where cultivation exposes the rocks appear to be more weathered than the crests. The cohesiveness of the weathered rocks and their inability to absorb water from the abundant rainfall in the area is revealed by the large quantities of rain water that freely run off the surface slopes. It was observed that after heavy rains many small water falls and springs develop in the ravines of the country rock. In the more porous mineralized zone along the crest, the flat areas remain wet for many days, the water slowly seeping downward and outward to the ravines where it appears as springs that flow continuously during most or all of the dry interval between rains.

In this study, no attempts were made to identify the products of weathering of the country rocks.

The country rocks have undergone dynamic and mild regional metamorphism. Cerro La Tiza lies within and appears to occupy the major part of a broad east-trending zone of shearing as shown by the foliated and sheared nature of the country rocks. The principal zones of shearing and foliation shown on the geologic map (plate 2) have two principal directions that are approximately N. 70° E. and N. 70° W. The former predominate in the western half of the area and the latter in the eastern half. Brief petrographic examination of the country rocks shows that chlorite and epidote are of common secondary development, but the authors were unable to find sufficient evidence of albitization to establish whether or not these rocks fall in the classification of spilites of some geologists, the greenschist facies of others, or the keratophyres of still others.

Copper mineralization was observed in two places in the country rocks. At one locality near the northeast branch of Quebrada Naranja approximately 250 meters east and 930 meters south of the reference point native copper barely visible to the unaided eye is disseminated throughout float blocks of lava. The other location showing copper mineralization is on the central road approximately 680 meters east and 630 meters south of the reference point where a light-colored vein approximately 1.5 cm. wide, containing bright green and blue secondary copper minerals is exposed in the road bed. The wall rock here appears to be a greyish-black, coarsely-crystalline, somewhat trachytic lava.

Hydrothermally altered rocks

The mineralized zone occupying the crest of Cerro La Tiza has a maximum length of approximately 5,200 meters and an average width of about 430 meters. It pinches out at both ends and is completely surrounded by the country rocks. Its widest portions are toward the western end where it reaches a maximum width of about 700 meters. Toward the eastern end it is notably narrower and has an average width of about 200 meters. The contact of the mineralized zone with the adjoining country rocks is almost completely concealed by either a mantle of earth-rock debris or a cover of foliage and soil, but it is exposed in at least eight scattered places around the periphery of the zone. Although the contact was observed in only eight places, there are many other places where the concealed contact could be determined on the basis of rock types, within limits of a few meters, so it is believed that there is sufficient control for delimiting the deposit laterally.

The total area of the mineralized zone, determined from the outer limits shown on the geologic map (pl. 2) is approximately 225 hectares (556 acres). There are no available data concerning its depth. The deepest exposure is in a road cut where the east road cuts across the crest of Cerro La Tiza and exposes at least six meters of mineralized zone.

The mineralized zone contains generally light-colored, reddish-brown to tannish-white rocks whose outcrops are almost entirely limited to the crest-line of Cerro La Tiza. Only a few outcrops can be traced with continuity for more than a few meters or tens of meters and in most places it is very difficult to determine whether or not large bouldery rocks and foliated rock masses are actually outcrops or large rock masses that have slumped off the ridge crest. The center of the mineralized zone along the crest of Cerro La Tiza consists principally of hard, banded, quartzose rock and intermixed smaller quantities of softer, clayey rocks. Generally the higher elevations along the ridge crest consist almost wholly of the hard, quartzose rock, whereas the lower elevations along the crest, for example, the saddle area, are more likely to contain a greater abundance of the softer, clayey rocks. In contrast to the generally hard rocks along the ridge crest, the outer margin of the zone, at all places where it was observed, consists of soft, clayey, foliated, but not commonly banded rocks. It could not be determined whether the soft, plastic, clayey character of the marginal rocks is due to its mineralogical composition or to weathering processes that soften the rocks because they are downslope and continually remain damp from drainage off the crest.

The mineralized zone contains no zoning of the principal hydrothermal minerals from the center-line of the ridge outward toward the margins, that is, there are not progressive zones of quartz alunite, pyrophyllite, sericite and kaolin group clays within the zone.

The mineralized zone, like the country rocks, has been dynamically metamorphosed and shows many strongly sheared or foliated zones that strike principally N. 70° E. and N. 70° W. A similar strike relationship is shown by the central axis of the mineralized zone which corresponds approximately to the ridge crest of Cerro La Tiza. This axis is shown on plate 3. From the saddle area westward the predominant direction of strike

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Plate 3.—— Sketch map of Cerro La Tiza area showing central axis of major mineralized zone, axis of smaller mineralized zone (northwest of major zone) bearing N. 75° - 80° W., principal drainages and access roads, outcrops of known pyrophyllitic rocks and locations of five, analyzed, alunitic rock samples.

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of the central axis is N. 65° E. to N. 80° E., whereas, east of the saddle area, the predominant strike direction is S. 75° E. to S.80° E. and due east. Thus, the alinement of the central axis of mineralization appears to correspond roughly to the principal directions of shearing in the country rocks and in the mineralized zone itself.

Several small, isolated, zones of hydrothermally altered rocks occur outside of the principal mineralized zone. The largest of these occurs as a linear zone of small stringer-like patches of hydrothermally altered rocks northwest of the principal zone, near the end of the western road. These are shown on plates 2 and 3. This long, narrow mineralized zone could not be traced east of the easternmost outcrop approximately 1,160 meters west and 460 meters north of the reference point and therefore is not a northwest-trending offshoot from the principal zone on the ridge crest. Another small, isolated zone of hydrothermally altered rocks is exposed on a spur of country rock approximately 1,800 meters west and 50 meters north of the reference point. The rock here has a thin-bedded, platy appearance and contains an abundance of greenish-white, subtranslucent sericite-/. Another small, isolated zone of alteration rock occurs north-

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-/ Determined by X-ray powder diffraction.

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east of the principal zone at a point 2,480 meters east and 900 meters north of the reference point. Its mineralogy has not been studied.

Surficial deposits of earth-rock debris

The mineralized zone and country rocks of Cerro La Tiza are partially covered with relatively thin, discontinuous, sheet-like deposits of earth-rock debris derived from the mineralized zone. The debris consists primarily of angular to subangular, reddish-brown to tannish-white fragments and boulders in a loosely compacted clayey matrix. The size of the fragments and boulders ranges from a fraction of one centimeter to as much as 10 meters. Most of the fragments and boulders consist of banded, quartz-alunite rock, a common rock type in the mineralized zone. Many of the larger boulders are poorly banded and appear to consist predominantly of quartz. The smaller boulders are more distinctly banded and appear to contain more alunite, although quartz is still their dominant constituent.

The partial cover of earth-rock debris over the mineralized zone is generally less than one to two meters thick, but over the country rocks down slope from the zone the debris is generally thicker. For example, in road cuts along the Aguas Buenas-Comerío road along the south flank of Cerro La Tiza, the debris is in some places five meters or more thick. Considering the area as a whole, the surficial deposits are thicker and more extensive over the country rocks at the western end where the mineralized zone is broader and hence the supply of debris to the slopes is greater. In areas of steep slopes the spurs of country rock and the adjacent ravines are generally devoid of debris, probably because of the cohesiveness and slippery nature of the country rock when it becomes wet and its consequent inability to retain the debris on its surfaces.

The broad apron-like distribution of the earth-rock debris down the slopes to the base of Cerro La Tiza (pl. 2) suggests that much of it moved downslope by slow creep. Landslide scars exposing the country rocks in areas that are otherwise debris covered, indicate that some of the debris moved downslope en masse. Some of the earth-rock debris particularly that which contains huge boulders on the lower slopes and around the base of Cerro La Tiza, has probably traveled rapidly downslope as landslide debris. The margin of the mineralized zone particularly where the slopes are steep is susceptable to slumping and landsliding. This condition was observed at several places around the margin and is especially well in evidence where the eastern road has slumped at the point where it crosses the contact of the mineralized zone and the country rocks approximately 2,580 meters east and 230 meters north of the reference point.

The distribution of the surficial deposits of earth-rock debris over most of the mineralized zone and the uppermost slopes of the country rock conforms to the present topography and drainage pattern. The debris is as a general rule well distributed over the present surface and some of it has moved downward for several tens of meters, tonguing into the heads of several large ravines. The distribution of the surficial deposits further downslope, however, does not conform to the present day topography and drainage pattern. The principal lines of evidence supporting this contention are (1) the debris on at least one spur of country rock is channel fill; (2) below the margin of the mineralized zone, present day ravines, transverse to the ridge are not as a general rule channeling debris and carrying it down slope; (3) earth-rock debris more commonly occurs only on one side of present day ravines; and (4) several patches of earth-rock debris at the base of Cerro La Tiza are isolated from the main deposits at a considerable distance from the source area. One of these patches approximately 2,340 meters west and 100 meters north of the reference point lies on volcanic rocks west of the Río de la Plata at least 35 meters above the present level of the river. The river must have incised itself at least 35 meters in order to isolate this patch of debris from the main mass on the east side of the river. These lines of evidence point to a long history of development of the surficial deposits and indicate that they may have developed through two or more cycles of erosion.

Age of rocks

The age of the country rocks comprising Cerro La Tiza is not known. Their relative age can, however, be established on the basis of analogous rocks in surrounding areas. Fossils collected in November, 1957, by N. F. Sohl of the Geological Survey from limestone units interbedded with rocks similar to those of Cerro La Tiza tentatively establish the age of these rocks as Late Cretaceous.

The small intrusive bodies in the Cerro La Tiza area are believed to be of the same age as the San Lorenzo batholith and the other large and small intrusive bodies in east-central Puerto Rico. Age determinations of zircon from two samples of granodiorite collected from the San Lorenzo batholith by James P. Owens were made by Howard W. Jaffe, both of the Geological Survey, in April, 1955. Jaffe found that the age of one sample is 51 million years and the age of the other, 56 million years which indicates that the rocks are of early Eocene age. He further stated that the limit of error in these age determinations might be as great as 20 percent because of the low lead content of the zircon. Allowing for this error, in each sample, the age range is 41 to 67 billion years, so that these rocks can at best be assumed to be of Late Cretaceous or Eocene age. The mineralized zone on the crest of Cerro La Tiza is believed to have formed contemporaneously with the emplacement of the San Lorenzo batholith and other intrusive rocks. Hence, it is also believed to be of Late Cretaceous or Eocene age.

There is no conclusive evidence by which the earth-rock debris can be dated. The distribution pattern of the surficial debris suggests that it is related partly to the present erosion cycle and partly to an older erosion cycle which may be of Pleistocene or older age. The debris is high up on the slopes just below the margin of the mineralized zone conforms more to the present erosion cycle than the debris on the lower slopes. Hence, the uppermost parts of the debris may be of Recent age and the lowermost parts may be of Pleistocene or older age.

Mineralized zone

Mineralogy and associated minerals

The principal minerals of the mineralized zone are quartz, alunite, pyrophyllite, kaolin group clays and sericite[1]. Minerals of minor abundance are sulfur, diaspore svanbergite, zunyite, hematite, goethite, pyrite, rutile and unidentified minerals, possibly phosphates or members of the plumbogummite group.

Seventy samples from the mineralized zone were studied to determine their mineral content and also to gain some concept of the overall distribution of the minerals. Of these 70 samples, 25 consist principally of alunite and quartz, and 7 of these 25 contain small to moderate amounts of diaspore. Also, of the 70 specimens studied, 15 contain pyrophyllite, 20 contain sericite, and 20 contain kaolinite. The latter three minerals, pyrophyllite, sericite and kaolinite, occur as major constituents. In a broad sense, alunite, quartz, diaspore, and sulfur compose one group of associated minerals; and pyrophyllite, sericite, and the kaolin group clays compose a second group, although intermixtures of minerals of the two groups are not uncommon.

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[1] Sericite, throughout this report refers to the mineral muscovite. The name sericite is retained to conform with general usage for rocks of a hydrothermal character.

Quartz and alunite.—Quartz appears to be the most abundant mineral in the mineralized zone. It was detected in nearly all of the samples studied and is a major constituent in many of them. It occurs not only as a fine-grained constituent in all rock types of the mineralized zone, but also as concentrations in veins and irregular-shaped, pod-like masses. The quartz concentrations appear to be more prevalent in the central part of the zone than in the more clayey rocks at the margin, but this relationship may be fortuitous because the best exposures of the mineralized zone are along its central axis and not at ~~the~~ its margins. In a few specimens, quartz occurs as small euhedral, terminated crystals, one to two millimters in length in vugs and fractures or as a coating of stubby prisms on a specimen surface.

Alunite is not found in isolated concentrations but is intimately associated with other minerals, particularly quartz. Its most common occurrence is in a banded rock that strikingly resembles flow-banded rhyolite. The banded rock in general consists wholly of alternating bands of quartz and alunite. Specimens showing the best banding were broken from well-weathered float blocks in which weathering has accentuated the banding. Some of these have a striking fluted appearance, the softer alunite-rich bands having weathered out leaving the quartz bands standing in relief. The banding is both coarse and fine, the width of the bands and their spacing, ranging in size from a fraction of one millimeter to about 0.5 centimeters. An example of a finely-banded phase of the rock is shown in figure 2. Somewhat more coarsely banded rock is shown in

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Figure 2.—— Photomicrograph of banded alunite-quartz rock ~~under crossed nicols (20X)~~. Alunite composes the bands whose coarser grains have a higher birefringence and show a tendency toward preferred orientation. crossed nicols (20X).

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figs. 3A and 3B. In some specimens, the quartz bands widen into large

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Figure 3A.—— Polished surface of highly crenulated and fractured alunite-quartz rock. The banding is continuous into the light colored zone in the lower portion of the photograph where the iron minerals have been bleached naturally.

Figure 3B.—— Polished surface of crenulated alunite-quartz rock showing only a slight degree of fracturing. The light colored bands are quartz and the darker gray ones are alunite.

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pod-like masses. Other specimens contain irregular-shaped, fragment-like pods of quartz around which the bands pass. In a few specimens, small white quartz veins of a second generation cut in irregular fashion across the banding. In some specimens, the banding is undistorted, and the rock breaks for the most part parallel to the banding giving it a blocky, platy appearance. In other specimens, the bands are crumpled or crenulated (fig. 4) and form miniature overturned folds (figs. 3A and 3B). The bands,

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Figure 4.—— Photomicrograph of crenulated, alunite-quartz rock. Alunite composes the randomly distributed light-colored grains with high relief. The crenulations are accentuated by the dark concentrations of hematite.

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for the most part, are continuous, but some are broken and brecciated and in effect are parts of small dragfolds through which it is difficult or impossible to trace the banding. The constituents within some bands show a tendency toward preferred orientation (fig. 2).

The authors suspect that the Juan Asencio chert beds of Semmes (1919, p. 65-66) are, in effect, the hydrothermal rocks of Cerro La Tiza. Semmes description of these "chert beds", particularly the lack of outcrops, bedding, and measurable attitudes fits the banded rocks of Cerro La Tiza very well. Even his photomicrograph (Semmes, 1919, p. 66, fig. 11) markedly resembles a comparable rock from Cerro La Tiza (fig. 4). However, Meyerhoff (1931, p. 236, p. 264, p. 288) states that R. J. Colony examined one specimen of Semmes' Juan Asencio Chert and found it to consist largely of laumontite. Laumontite has indices of refraction much lower than any of the minerals found in the hydrothermal assemblage of Cerro La Tiza, so it is still problematical as to where Semmes' specimen of the Juan Asencio Chart beds came from and what these beds represent. Semmes only describes these beds as occurring in the barrio of Juan Asencio, northwest of the limestones that he shows on his geologic map as a thin belt beginning about 3 kilometers south of Aguas Buenas and extending southwest to a point about one mile west of Cidra.

Mineralogical determinations of alunite were made from the banded specimens. Most of the alunite has a tannish, grayish or rarely a pinkish color, but some is clear and colorless or has a translucent appearance. Refractive indices determined from grains within the bands are $n\omega = 1.578$ and $n\epsilon = 1.601$. Five samples chosen on the basis of their higher alunite and lower quartz content and their position with respect to the mineralized zone were chemically analyzed. Samples numbered 409, 604, and 562 were collected from the crest of Cerro La Tiza, whereas samples 530 and 576A represent float blocks collected down slope from the crest, but within the boundaries of the mineralized zone. The localities from which these specimens were collected are shown on plate 3. The chemical analyses and their comparison with potassium and sodium alunites are shown in table 2. These data show that the alunite, of the analyzed samples from Cerro La Tiza, has a composition that can be expressed as approximately 1/3 sodium alunite and 2/3 potassium alunite. Mineralogically they can be called sodian alunite. In the powder patterns of these analyzed alunites as well as many others from the mineralized zone the diffraction lines for alunite all have identical interplanar spacings. Average unit cell dimensions determined from X-ray powder patterns of 10 alunite samples from Cerro La Tiza are as follows: $A_o = 7.01 \pm .05$ Å, $C_o = 17.12 \pm .05$ Å. These values correspond reasonably well with published unit cell data of synthetic and natural potassium and sodium alunites by Parker (1954). No alunites of a jarositic composition were found in the area.

Table 2.— Chemical analyses of [illegible] compared with theoretical sodium and potassium alunites.

Column	1	2	3	4	5	1a	2a	3a	4a	5a	6	7
Sample No.	576A	409	604	530	562	576A	409	604	530	562	—	—
SiO_2 a/	10.7	4.4	34.6	42.1	49.0	—	—	—	—	—	—	—
Al_2O_3	32.9	36.2	25.5	22.1	20.4	36.9	37.9	39.3	38.7	39.9	38.42	36.92
Fe_2O_3 b/	.07	n.d.	n.d.	n.d.	n.d.	.08	—	—	—	—	—	—
MgO	.00	n.d.	n.d.	n.d.	n.d.	.00	—	—	—	—	—	—
CaO	.22	n.d.	n.d.	n.d.	n.d.	.25	—	—	—	—	—	—
Na_2O	2.1	2.4	2.6	1.5	1.4	2.36	2.5	4.0	2.6	2.7	7.78	—
K_2O	6.4	6.4	2.8	3.7	3.4	7.19	6.7	4.3	6.5	6.7	—	11.37
TiO_2	.14	n.d.	n.d.	n.d.	n.d.	.16	—	—	—	—	—	—
P_2O_5	.67	n.d.	n.d.	n.d.	n.d.	.75	—	—	—	—	—	—
MnO	.00	n.d.	n.d.	n.d.	n.d.	.00	—	—	—	—	—	—
SO_3	33.3	36.0	24.3	21.2	19.2	37.3	37.7	37.5	37.2	37.6	40.22	38.66
H_2O	11.8	12.1	8.6	7.5	6.8	13.3	12.7	13.3	13.1	13.3	13.58	13.05
Totals	98.3	97.5	98.4	98.1	100.2	98.3	97.5	98.4	98.1	100.2	100.00	100.00

a/ Microscopic examination and X-ray powder diffraction patterns show that quartz is the only major impurity.

b/ Total Fe as Fe_2O_3.

Col. 1 — Harry F. Phillips and Elizabeth A. Nygaard, analysts.

Cols. 2 to 5 inclusive. — SO_3 determinations by Harry F. Phillips and Elizabeth A. Nygaard. All other determinations by Harry F. Phillips, Paul L. D. Elmore and Katrine E. White.

Cols. 1a to 5a inclusive. — Recomputed analyses of cols. 1 to 5 inclusive, omitting SiO_2.

Col. 6 — Theoretical sodium alunite calculated for $Na_2O.\ 3Al_2O_3.\ 4SO_3.\ 6H_2O$.

Col. 7 — Theoretical potassium alunite calculated for $K_2O.\ 3Al_2O_3.\ 4SO_3.\ 6H_2O$.

Pyrophyllite.—Pyrophyllite is distributed widely in the mineralized zone and appears to be associated more closely with the kaolin group clays and sericite than with the other minerals. It commonly occurs in foliated zones between banded quartz-alunite ~~type~~ rock. In some places seams of foliated pyrophyllite only a few centimeters wide were observed within the banded rock. The seams commonly pass around eye-like masses of the banded rock as though they had been squeezed around them. Pyrophyllite, because of its fine-grained character and its intimate association with the other minerals is difficult to recognize and distinguish, especially from sericite, in outcrops. In a few places where pyrophyllite is concentrated in foliated layers, it is tannish-white to greenish-gray, platy or micaceous and has a dull, somewhat glistening luster and a greasy, talcose feel. It does not occur as typical radiated, lamellar clusters. In its fine-grained form the optical properties of pyrophyllite are almost identical with those of sericite. It was not possible to distinguish pyrophyllite and sericite from each other by optical examination of the Cerro La Tiza rocks. However, they were readily distinguished and identified in X-ray powder diffraction patterns.

Clay minerals.—The clay minerals are distributed throughout the mineralized zone in close association with the other minerals. They are most abundant as veins and pockets at the margins of the mineralized zone, but they were also found in pocket-like concentrations in the banded quartz-alunite rock near the center of the zone. The clay minerals were studied and identified by X-ray powder diffraction methods supplemented by electron microscope examination and were found to consist either of kaolinite or halloysite. Samples of relatively pure clay are plastic and sticky when wet, but others that contain appreciable amounts of other minerals, particularly sericite and quartz are generally non-plastic. Some clayey-zones are locally stained with tan, brown or red iron oxides but none are heavily ferruginized.

Sericite.—Sericite is closely associated with the other minerals of the mineralized zone and seems to be most closely associated with pyrophyllite and the clay minerals. In each occurrence it is fine-grained and impossible to recognize and distinguish from pyrophyllite in hand specimens. Several fine-grained, gr~~e~~ayish-white specimens that were thought by megascopic examination to be clayey, alunitic rock or pyrophyllitic rock were found by X-ray examination to consist predominantly of sericite and quartz. Comparison of X-ray powder diffraction patterns of many sericite bearing rocks from Cerro La Tiza with patterns of analyzed muscovite specimens from several localities in other parts of the world shows that the sericite of Cerro La Tiza is muscovite of the common type. The micaceous mineral was carefully identified in order to establish that it is not hydrous mica because of the bearing that the type of mica has upon the origin of the mineralized zone.

Sulfur.—Native sulfur, although sparsely distributed, was observed in scattered localities throughout the mineralized zone. At all the places where it occurs the sulfur is intimately intergrown with quartz coloring it bright yellow. The bright yellow appearance gives the impression that the yellow substance is wholly native sulfur but the specimens are hard and actually are composed almost wholly of quartz. Attempts to detect the sulfur in X-ray patterns were unsuccessful because it is either in an amorphous state or is not sufficiently abundant to detect. However, heating the samples produced a sulfurous odor and the sulfur could be dissolved from the quartz using carbon disulfide as a solvent. It could not be determined why the samples repeatedly turned brown on heating and white again on cooling.

Sulfur also occurs widely distributed in many of the quartzose and alunite-quartz float blocks in the earth-rock debris on the slopes of Cerro La Tiza, indicating its wide distribution throughout the mineralized zone.

Diaspore.—Small quantities of diaspore were discovered by X-ray examination in several specimens from the mineralized zone. In each case it was found to be intimately associated with alunite and quartz. It could not be seen megascopically, nor detected in thin-sections of the alunite-quartz type rocks.

Svanbergite.—Svanbergite, a member of the beudantite group of phospha[te] minerals was tentatively identified in seven specimens. X-ray powder patte[rns] show that a beudantite group mineral is present in these specimens, but it is not sufficiently abundant to identify positively as svanbergite. Wet chemical tests also show that phosphate is present. In view of the occurren[ce] of significant quantities of barite in several places in the hydrothermal belt east of Cerro La Tiza, it seems likely that barium and also strontium might have been available from the hydrothermal emanations to aid in the formation of beudantite and plumbogummite group minerals.

Svanbergite appears to be most commonly associated with pyrophyllite and sericite. Svanbergite has been reported from several localities throughout the world in association with pyrophyllite (Dana, 1951, p. 1006). For example, at a French locality it is associated with pyrophyllite, kaolinite and diaspore.

Zunyite.—Zunyite was tentatively identified in three specimens in association with alunite and quartz. Zunyite contains fluorine and chlorine and is the only known mineral of the mineralized zone assemblage that contain[s] mineralizers or volatile constituents. Zunyite is known to occur in association with alunite and pyrophyllite at Quartzite, Arizona (W. T. Schaller, oral communication).

Hematite and goethite.—Hematite is not very abundant but occurs in urly all the rock types of the mineralized zone most commonly as thin ne-grained, reddish-brown, veins. In some rocks it occurs in bands that obviously Liesegang bands that cut across the primary banding and liation of the rocks. In the banded quartz-alunite rock, dark red and own hematite is concentrated in some of the alternate bands and serves accentuate the banding. Some of these banded rocks contain what appear to irregular-shaped bleached zones in which the iron-stained bands have been eached nearly white.

In a few specimens of banded quartz-alunite rock specular hematite concentrated in small thin veins, 1 millimeter or less in width. Some of ese cut across the banding. Specular hematite also lines the walls of me narrow open fractures. In some places, goethite is associated with matite and apparently has altered directly from it. Goethite is most mmon on weathered surfaces of the more hematite-rich rocks.

Pyrite.—No metallic pyrite was observed in the rocks of the minera-ized zone, but small amounts were identified with some uncertainty in ray powder patterns of two specimens. In several places along the margin the mineralized zone, where it is exposed to weathering, the clayey rocks locally colored bluish-gray, possibly from the decomposition of pyrite hydrous iron minerals.

Rutile.—Rutile was observed in small amounts in association with alunite and quartz in only one float-block specimen from the northwest slope of Cerro La Tiza. It is not known whether the rutile is of hydrothermal origin.

Unidentified minerals.—Small quantities of unidentified minerals were detected in X-ray powder diffraction patterns. Wet chemical tests for phosphate indicate that these unidentified constituents may be phosphate minerals. It is also possible that at least one of the unidentified minerals may be a member of the plumbogummite group whose strongest interplanar spacings unfortunately coincide with the strong lines of alunite that dominate the X-ray diffraction patterns.

Distribution of rocks and minerals by area

The mineralized zone, for convenience of description is arbitrarily divided into four areas, the western end, the peak area, the saddle area and the eastern end. These areas are indicated on plate 3 and figure 1.

Western end

Outcrops along the crest of Cerro La Tiza at the western end consist principally of quartzose rocks and banded, foliated, quartz-alunite rock. The spurs and knobs extending from the crest down the south and north slopes contain notable quantities of grayish-white fine-grained quartz closely resembling gray chert. The quartz on the south-trending spur approximately 840 meters west and 170 meters south of the reference point contains notable amounts of bright-yellow native sulfur. Where this spur joins the crest, the quartz-alunite rock is foliated and contains several slickensided surfaces which have an average east strike. A group of small exposures occurs on a trail down the northwest slope about two-thirds of the distance down from the crest to the margin of the zone. This area of exposures along the trail through a heavily wooded area is approximately 500 meters west and 150 meters north of the reference point. Pyrophyllitic rocks are exposed at several points in an interval of about 200 meters along the trail. Three samples collected here, consist predominantly of pyrophyllite with moderate amounts of kaolinite and quartz and smaller amounts of sericite and possibly a beudantite group mineral_/.

_/ Wet chemical tests show that a phosphate mineral is present.

The north slope at the western end is heavily wooded and covered by earth-rock debris that masks the contact of the mineralized zone with the country rocks. However, on a spur approximately 1,330 meters west and 210 meters north of the reference point, the contact is well exposed and the transition from the light-colored mineralized zone rocks to the dark-colored country rocks can be seen through an interval of about 3 meters. At the extreme west end of the mineralized zone, the hydrothermally altered rocks are exposed in a few places on the crests of spurs. These outcrops are close to the margin and consist for the most part of tan, foliated quartz-alunite rock. Some of these outcrops contain yellow sulfur-bearing zones. The margin of the mineralized zone on the south slope is concealed, but in many places the hydrothermally altered rocks are exposed in close proximity to the country rock as shown on the geologic map (Pl. 2). Most of these exposures are on steep slopes and the mineralized zone consists generally of clayey rocks that appear to be more pyrophyllitic than those at the extreme west end.

Peak area

In the vicinity of the reference point, concentrations of quartz as veins and pod-like masses occur in the banded quartz-alunite rock along the ridge crest. These hard rocks have resisted weathering and erosion and hence occupy the highest elevation on Cerro La Tiza. The north slope in this area is steep, well wooded and covered with earth-rock debris containing many large boulders derived from the high crest of the ridge. On the north slope there are no exposures of the mineralized zone nor its contact with the country rock. The south slope is also steep and well wooded, but near the margin of the zone, some areas have been cleared and the zone is exposed, particularly on some of the south-trending spurs. The best exposure of the contact is on the large spur about 250 meters due south of the reference point. The rocks of the mineralized zone on this spur are soft and clayey and the country rock is cut by many halloysite veins. The largest veins are about ~~1/2~~ half a meter in width, but there are many smaller ones 5 centimeters or less in width. The halloysite is soft, plastic and generally white in color but has a greenish-gr~~e~~ay hue and a translucent appearance. Halloysite was identified by X-ray powder diffraction methods and confirmed by electron microscope examination. Lesser amounts of sericite, quartz and alunite are associated with the halloysite.

An exposure of kaolinitic clay occurs at a small open pit within 200 meters of the peak of Cerro La Tiza (Pl. 4). This clay pit at the side of

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Plate 4.— Geologic sketch map of clay pit in peak area.

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the trail ~~which~~ that follows the ridge crest is approximately 150 meters east and 50 meters north of the reference point. The pit is filled with water but the clay is well exposed around the edges, particularly on the north and southwest sides. The clay is white and appears to be relatively pure. It is very sticky and plastic when wet, but is brittle and breaks with a crude conchoidal fracture when dry. X-ray examination of several samples from the southwest edge of the pit shows that the clay is not all kaolinite but contains moderate amounts of sericite, quartz and lesser amounts of pyrophyllite. Electron microscope examination shows that the kaolinite consists of moderately fine, hexagonal plates. At some places around the pit edge, the clay is stained red and brown and on the trail that passes along the north edge, the red and brown iron staining is more prominent. Hematite was identified in X-ray powder diffraction patterns. In some places, well defined ~~Z~~ Liesegang bands occur in the clay on the outcrop surface. Two hand augered holes near the edges of the clay pit (locations shown on plate 4) indicate that the iron-staining increases with depth. The data obtained from these auger holes are shown in table ~~as follows.~~ 3.

Table 3.—— Auger hole data from clay pit in peak area.

Hole	Depth	Nature of cuttings	Bottom sample
1	2.6 meters	Firm, white kaolinitic clay, iron-stained red and brown below half a ~~1/2~~ meter. Clay contains several hard, ferruginous layers.	Hard brown, gritty, ferruginous clay.
2	3.3 meters	Firm, white kaolinitic clay becoming iron-stained and gritty at 240 cm. Below 240 cm. contains alternating layers of hard, gritty and softer, non-gritty iron-stained kaolinitic clay.	Tannish-white gritty clay.

At the southwest edge of the clay pit, the pit wall projects about 2.5 meters above the water level in the pit. This outcrop shows that banded quartz-alunite rock and foliated pyrophyllitic rock are closely associated with the kaolinitic clay. The banded, quartz-alunite rock occurs in seams and eye-like lenses half a meter or less in width, separated by zones of foliated pyrophyllitic rock and kaolinitic clay. This small outcrop illustrates the abrupt changes in mineralogy and the close association of the minerals in the mineralized zone.

Saddle area

The mineralized zone in the saddle area pinches notably toward the east. Whereas it has an average width of 500 to 700 meters, west of the saddle area, it has pinched to a width of about 330 meters at a point about 900 meters east of the reference point. East of there the zone maintains an average width of approximately 350 meters nearly to its termination point.

The lower elevation of the ridge crest in the saddle area is indicative of the generally softer rocks that occupy this area. The central road and several trails that pass on or near the ridge crest provide more rock exposures than are generally available at other places along the ridge. These outcrops and their rock types are shown on plate 5. The

Plate 5.—— Geologic sketch map showing outcrops in saddle area.

outcrops consist mainly of mixed minerals but some are predominantly of pyrophyllitic rock or banded quartz-alunite rock. All the rock types are quartzose and the pyrophyllitic rocks are foliated. Samples from the larger zones of pyrophyllitic rock were examined by X-ray powder methods and were found to contain in addition to pyrophyllite, moderate amounts of sericite, quartz and kaolinite. Quartz occurs as veins and irregularly shaped masses around which the pyrophyllite folia pass as though the pyrophyllite had been squeezed into position around the quartz. On the whole quartz does not appear to be as abundant in the saddle area as in other places along the ridge crest.

The north slope of the saddle area is covered with earth-rock debris and well-weathered soil, but a few outcrops of the mineralized zone are exposed as shown on the geologic map (Pl. 2). The contact of the mineralized zone with the country rock is not exposed in this area.

The south slope below the saddle area is also covered with earth-rock debris, but several exposures of the mineralized zone occur on the central road between the south edge of the area shown by Plate 5 and the margin of the mineralized zone. One small outcrop about 550 meters east of the reference point was found to consist principally of pyrophyllite. X-ray examination shows that this sample also contains small amounts of sericite and kaolinite, and traces of quartz, alunite and possibly a beudantite group mineral. Still farther south, along the west side of the road, close to the margin of the zone, another outcrop of foliated pyrophyllite occurs. This pyrophyllitic rock contains quartzose zones and the pyrophyllitic rock between these zones is very strongly foliated and contains small dragfolds about 10 centimeters long. On the central road at the margin of the mineralized zone, white kaolinitic clays are exposed in a ditch about one meter deep on the west side of the road. The clay occurs in veins and pockets and one lenticular, vein-like mass exposed in the road ditch for at least 10 meters is about one meter wide and nearly pinches out at both ends of the exposure.

The contact of the mineralized zone with the country rock is well exposed in a deep ravine about 1,200 meters east and 170 meters north of the reference point. The contact here is very sharp and the light-colored rocks of the mineralized zone contrast strongly with the dark greenish-gray country rocks.

Eastern end

At the eastern end, exposures are nearly limited to the ridge crest. At the highest elevations along the crest, banded quartz-alunite rock and quartzose rocks are exposed. For a distance of about 200 meters west of the point where the eastern road crosses the ridge crest, the mineralized zone is concealed but the surface is strewn with many small float blocks of brown ferruginous, poorly-banded quartzose rock. The mineralized zone is exposed in road cuts on both sides of the eastern road, where it crosse the ridge crest. The rocks exposed here are strongly foliated and appear to be pyrophyllitic and in places ferruginous. The mineralized zone at its east end terminates under cover approximately 150 meters east of a large cluster of boulders of banded quartz-alunite rock that occur on a steep eastward slope approximately 3,110 meters east and 200 meters north of the reference point.

The north slope of the eastern end is covered by earth-rock debris, soil and vegetation. The contact of the mineralized zone with the country rock is not exposed, but on a spur 1,570 meters east and 680 meters north of the reference point, the two rock types can be seen within about 10 meters of each other.

The south slope is also well covered with earth-rock debris, vegetati and soil, but the mineralized zone is exposed along the eastern road and i the north edge of a landslide scar 1,770 meters east and 350 meters north of the reference point. The rocks exposed in this scar are tannish-white soft and clayey. Along the eastern road, outcrops of pyrophyllitic rock occur about one-third of the distance down slope from the crest to the mar of the zone. In one road cut on the eastern road approximately 2,650 mete east and 320 meters north of the reference point, foliated pyrophyllitic rocks are exposed along the north side of the road for several tens of met X-ray examination of several samples shows that the pyrophyllite is associated principally with sericite and quartz.

The eastern road crosses the contact of the mineralized zone and the country rock at a point about 2,420 meters east and 200 meters north of th reference point. At this place, the road crosses over the contact at a slight angle, but nearly parallels it and exposes the mineralized zone and country rocks in the cut banks for approximately 100 meters. The cut bank on the south side of the road contains brownish-black hydrothermally unalt country rocks, but the cut bank on the north side contains soft, clayey rocks of the mineralized zone. The clay is locally concentrated in a doze or so white pocket-like masses and veins of various sizes and shapes. The smallest one is nearly circular and is about two thirds of a meter in diameter; the largest is about 1-1/2 meters wide and 3 meters long. The clay mineral was found to be halloysite. Several specimens studied by X-ray powder diffraction methods were found to contain in addition to halloysite, appreciable amounts of sericite and quartz. An abundance of alumite was found in one specimen.

Origin

Source of hydrothermal emanations

The deposits of alunite, pyrophyllite and clays on Cerro La Tiza are believed to be of hydrothermal origin, that is, they were deposited from emanations derived from a magmatic source. The largest exposed intrusive body in Puerto Rico is the San Lorenzo batholith about 20 kilometers southeast of Cerro La Tiza. Another large intrusive body occurs in the vicinity of Utuado and Jayuya about 40 kilometers west of Cerro La Tiza. Between these two large exposures, Meyerhoff (1933, geologic map) shows many smaller scattered bodies of intrusive rocks that lie along two crude belts, one that passes about 10 kilometers north and the other 10 kilometers south of the Cerro La Tiza area. Systematic geologic mapping started in 1954 by U. S. Geological Survey geologists has confirmed some of these smaller intrusive bodies and has revealed other heretofore undiscovered ones. Thus, in a broad sense, Cerro La Tiza is surrounded by large and small exposed bodies of intrusive rocks, whose distribution strongly suggests that much of central and eastern Puerto Rico is underlain by plutonic rocks. These plutonic rocks are believed to be genetically responsible for the hydrothermal alteration of the volcanic rocks of Cerro La Tiza as well as the other mineralized zones in east-central and southeastern Puerto Rico shown on plate 6. The occurrences of the larger bodies of hydrothermally altered

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Plate 6.— Distribution of hydrothermally altered rocks in east-central Puerto Rico.

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rocks, that is, the Cerro La Tiza, Lago de Cidra and Monte El Gato zones at considerable distances northwest and west of the exposed portion of the San Lorenzo pluton would suggest that it extends west-northwest possibly at shallow depth under the volcanic rocks.

Mode and conditions of hydrothermal alteration

The magmatic emanations that produced the major mineralized zone of the Cerro La Tiza area presumably rose along the central axial line of Cerro La Tiza, gaining access to the volcanic rocks through a broad east trending shear zone that passes through and occupies most of the central part of the area. Within the mineralized zone, so produced, all textura features of the parent volcanic rock have been destroyed. The hydrother emanations caused profound mineralogical and compositional changes in th volcanic rocks, producing a mineral assemblage totally unlike that of th parent volcanic rocks. The principal minerals of the country rocks are those of borderline basalt-andesite. The principal minerals of the mineralized zone are quartz, alunite, pyrophyllite, kaolin group clays and sericite. No distinct paragenetic relationships were discernible.

The following chemical and mineralogical observations indicate that much of the iron, calcium, and magnesium content was removed from the parent rocks and the silica, sulfur, and probably the potassium content of the altered rocks was increased by the hydrothermal activity.

1) The country rocks are generally dark colored because of their content of iron-bearing minerals (ferromagnesium minerals, chlorite, epidote, and other mine ~~etc.~~), whereas the mineralized zone rocks are generally light colored because of their lack of iron-bearing minerals.

2) Petrographic examinations, and chemical and x-ray analyses indicate that calcium, magnesium, and iron content of the country rocks is appreciably greater than that of the mineralized zone rocks and that potassium content of the mineralized zone rocks is greater than that of the country rocks.

3) Quartz is probably the most abundant mineral of the mineralized zone where it occurs in finely disseminated form as well as in pod-shaped concentrations and veins. Quartz veins are rare and of small size in the country rock.

4) Small quantities of native sulfur intimately associated with quartz are distributed throughout the mineralized zone.

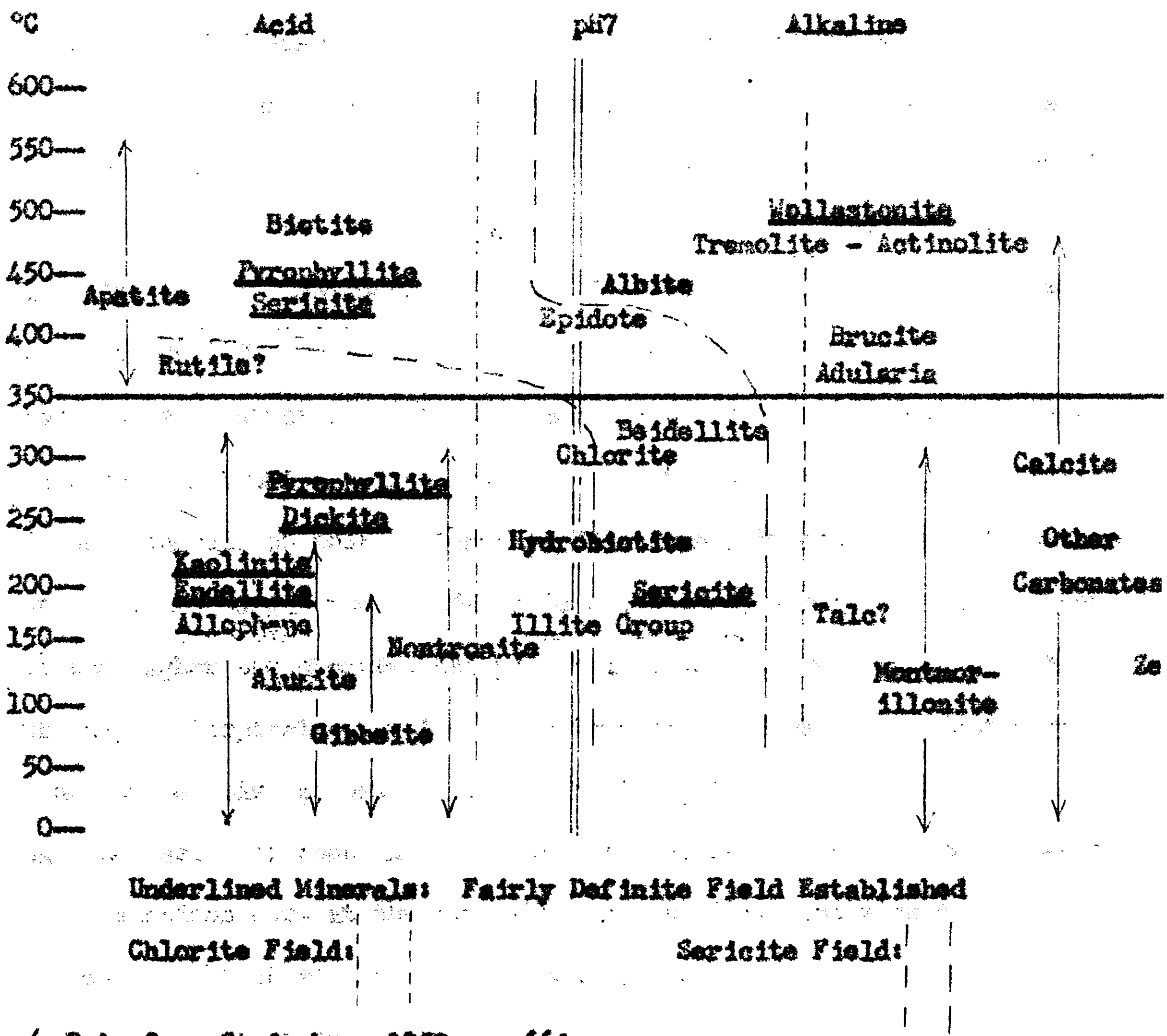
Changes in the aluminum and sodium content of the country rock during the hydrothermal alteration processes could not be determined from the evidence at hand.

The mineral assemblage of the mineralized zone of Cerro La Tiza is indicative of the nature of the hydrothermal emanations that altered the parent volcanic rocks. The abundance of quartz, aluminum silicates and sulfate bearing alunite, are evidence that the emanations were acid, sulfate bearing, and silica rich. The scarcity of quartz veins and quartz concentrations in general in the country rocks, but their obvious abundance in the mineralized zone leaves little doubt that considerable quantities of silica were introduced into the mineralized zone. The occurrence of native sulfur_/, although minor, indicates that the emanations were probably in part, at least, gaseous and possibly solfataric in nature.

_/ According to Rankama and Sahama (1950, p. 754-755), native sulfur is of either volcanic or sedimentary origin. Volcanic sulfur is produced in the reaction between hydrogen sulfide and sulfur dioxide in the volcanic gases according to the equation $2\ H_2S + SO_2 \longrightarrow 2\ H_2O + 3S$.

A diagram summarizing data on fields of formation of some common hydrothermal minerals has been prepared by Stringham (1952, p. 662) and is useful here to show some of the conditions by which the hydrothermal emanations altered the volcanic rocks. Stringham's diagram, (table 4), shows that all of the principal hydrothermal minerals with the exception of sericite, that is, alunite, pyrophyllite and the kaolin group clays form in the field of acidic conditions. The diagram further shows that this mineral assemblage forms at temperatures of about 250°C or lower with the exception of sericite which forms at a temperature of about 400° - 450°C. Sericite can form at lower temperatures in an alkaline environment as shown in the diagram, but in view of the complete lack of evidence in the Cerro La Tiza mineralized zone of hydrothermal minerals shown on the alkaline side of the diagram, it seems unlikely that sericite could have formed at these lower temperatures, under alkaline conditions. It is concluded, therefore, that sericite probably formed under acid conditions at the higher temperature designated. From this study it is also concluded that all the minerals thus far discovered in the mineral assemblage formed under acidic conditions.

Table 4.--- Fields of formation of some common hydrothermal minerals a/



a/ Data from Stringham, 1952, p. 663.

Pyrophyllite is generally believed to form in silica-rich systems at temperatures upward from 400°C (Turner & Verhoogen, 1951, p. 493); but Gruner (1944 , p. 578-589) has shown by laboratory experiments on the alteration of feldspars in acid solutions that pyrophyllite can also form in the lower temperature range (250°C to 300°C) shown in table 4. According to gruner, pyrophyllite forms in this lower temperature range instead of kaolinite if the active solutions are low in Al^{3+} ion concentration and high in Si^{4+} ion concentration. He further states that at the higher temperature (400° - 450°C) sericite instead of pyrophyllite forms when both the concentration of the K^+ ions and the ratio Al^{3+} ions/Si^{4+} ions is high. In brief summary, assuming that the sericite and pyrophyllite in the mineralized zone of Cerro La Tiza formed by alteration of the feldspars of the parent rocks under acid conditions, sericite must have formed at the higher temperature, but pyrophyllite might have formed at either the higher temperature or the lower temperature depending principally upon the relative concentrations of the Al^{3+}, Si^{4+} and K^+ ions. The authors have no basis for speculation on what the concentration of these ions in the emanations were at the time the Cerro La Tiza mineralized zone was formed and therefore make no statement as to whether pyrophyllite was likely to have formed at the higher or the lower temperature.

The association of pyrophyllite and alunite together has not heretofore been reported in the literature, but the senior author has had the opportunity to examine a suite of alunitic and pyrophyllitic rocks from Quartzite, Arizona, in the possession of and brought to his attention by W. T. Schaller of the Geological Survey. These rocks, consisting of a few small hand specimens, contain in addition to alunite and pyrophyllite the minerals zunyite, kaolinite, muscovite and quartz. It is possible that the sodian alunite (natroalunite) from Sugarloaf Butte near Quartzite, Arizona, referred to in Palache and others ~~Dana~~ (1944, p. 559) is from the same area as Schaller's samples, thus making the suite of minerals from Arizona even more strikingly similar to those of Cerro La Tiza.

Possibly in other areas of hydrothermally altered rocks described in the literature, fine-grained pyrophyllite has been mistaken for sericite, which has nearly identical optical properties, and has been overlooked.

The close association of all the minerals of the mineralized zone suggests contemporaneity of their development, but does not preclude the possibility that pyrophyllite and sericite could have developed by post-ydrothermal dynamic metamorphism. Pyrophyllite in particular might have eveloped from kaolinite in this manner. This possibility is suggested y the sheared, foliated character of incompetent seams of pyrophyllitic nd clayey rocks between more competent zones of quartzose rocks and quartz-lunite rocks. Ross and Hendricks (1945, p. 71) state that pyrophyllite s commonly associated with sericite and that it probably forms at mode-ately high temperatures by either hydrothermal processes or dynamic meta-orphism or both. In the Cerro La Tiza mineralized zone, the quartz-lunite rocks show but little brecciation and the pyrophyllitic and seri-itic rocks may have absorbed most of the stress and acquired their foliation ecause of their soft, micaceous character.

The supposition that sericite and pyrophyllite may have formed by post-ineralization, dynamic metamorphism obviates the necessity of explaining y sericite and possibly pyrophyllite are the only two minerals of the drothermal mineral assemblage that form at higher temperatures.

Origin of banded quartz-alunite rock

In addition to the chemical and mineralogical observations cited above, the foliation of the country rocks and the band~~ed~~ing of the quartz-alunite rock of the mineralized zone have a bearing on the origin of the hydrothermally altered rocks of the mineralized zone.

1) The country rocks bordering the mineralized zone are on the whole closely foliated, in fact, so much so that their rock types are generally unrecognizable.
2) The country rocks are strongly foliated in some places but not in others. Likewise, the mineralized zone rocks are banded in some places, but not in others.
3) The folia of the country rocks show only a little waviness and are generally straight. Although the banding in the quartz-alunite rock of the mineralized zone is generally straight, it is crumpled and crenulated in some places. (Figs. 3A, 3B and 4).
4) The width of the bands in the quartz-alunite rock of the mineralized zone is of the same approximate order of magnitude as the folia of the country rocks.
5) The country rocks contain no flow-banded rocks such as banded rhyolite. Only insignificant quantities of finely-banded siltstones and sandstones, generally in small isolated patches, were seen in the country rocks.

From these observations the authors postulate that the banding of the quartz-alunite rock was inherited from foliation rather than banding in the parent volcanic rock. The abundance of banded quartz-alunite rock in the mineralized zone and the lack of similarily banded rocks in the country rocks of the area precludes the possibility that the banding is inherited from a similarily banded rock such as a banded rhyolite. Furthermore, it is difficult to understand how the banding could have developed by difusion processes alone, particularily in view of the close association of all the minerals in the mixed mineral assemblage and the lack of any type of zoning throughout the deposit. The authors therefore believe that the banded rock has developed as a consequence of the injection of the hydrothermal emanations into the inherent folia of the parent rock. In a sense, the injection process can be likened to the well known "lit par lit" injection of schists by granitic magma. The crenulated, contorted banding is interpreted as evidence that the rocks were under some stress and in a soft or plastic condition during the period of hydrothermal injection into the foliated parent volcanic rocks.

Mineralized zones of similar origin in western United States

Hydrothermally altered volcanic rocks with mineral assemblages similar to those at Cerro La Tiza have been described from localities in western United States. Loughlin (1916, p. 250-264) has described from Sheeprock, near Beaver, Utah, a banded and contorted quartz-alunite rock that bears a striking mineralogical and structural resemblance to the alteration rock of Cerro La Tiza. He implies that the banding was developed by a diffusion of colloidal silica while the mass was still soft and that the contorted banding, followed by some brecciation, developed before the mass became rigid. Loughlin further states that the relations of the deposit to the andesitic country rock are very obscure and that in view of a deficiency of critical evidence, any statement concerning the origin of this quartz-alunite deposit must be regarded merely as a working hypothesis.

Day and Allen (1925, p. 140-144) cite the chemical decomposition of lavas by sulphuric acid formed by the volcanic activity at Lassen Peak, with the contemporaneous formation of free silica, "sulfates of the metals of the silicates", "kaolin" and alunite. They describe alteration of banded lava by bleaching and disintegration but with preservation of the banded structure.

Burbank (1932, p. 71-80) has described hydrothermal alteration, chiefly of andesitic rocks, by widespread silicification in the Bonanza district of Colorado. He says that the alteration is characterized by the substitution of silica for most of the original mineral constituents of the volcanic rocks and that the silica was acquired from the solutions causing the decomposition. He cites hydrothermally altered rocks containing quartz, "kaolin" minerals, diaspore, alunite zunyite, sericite, iron oxides, rutile and pyrite. Burbank also says that large amounts of "alumina," "alkalies" and "alkaline earths" were removed from the original rocks and the principal additions were silica and minor amounts of sulfur.

Ransom (1901, p. 128-131) has described various hydrothermally altered rocks in the Silverton quadrangle, Colorado. He cites a greenish-gray monzonite porphyry altered to a light-gray rock in which the feldspar phenocrysts are altered to "kaolin", diaspore, and quartz and the ground-mass altered to fine-grained quartz, "kaolin," sericite, and pyrite. He says that silica, water and sulfur have been introduced and iron, magnesium, calcium, alkalies, and carbon dioxide have been removed by acid solutions. Ransome also described one andesitic rock that has been altered to a fine aggregate of quartz and barite and small amounts of sericite and pyrite, another andesite or latite altered to quartz, sericite, "kaolin," barite, and a small amount of epidote, and still a third andesite altered to quartz and sericite in which the primary structure has been completely destroyed. He also describes a rhyolite altered to quartz and alunite and small amounts of "kaolin" and rutile with complete destruction of the original texture.

Economic geology

Exploration and exploitation

The position of the mineralized zone on the ridge-crest of Cerro La Tiza is advantageous with regard to exploratory work as well as exploitation. Exploration by trenching, diamond drill boring or stripping should precede exploitation because of lack of exposures showing rock types and their distribution. The overburden is generally thin and of a loose, clayey character so that these methods of exploration could be employed at a minimum cost. Careful and detailed sampling, both surface and sub-surface is neccessary for full evaluation of the deposit because of the intimate mineral mixture and range of overall composition through short distances.

The deposit is well situated for open-pit mining. Exploitation should probably start with the removal of the light cover of overburden to expose the mineralized zone and determine the nature of the mixed mineral assemblage. The direction of mining operations would have to be determined as the strip mining progressed, avoiding the quartzose zones as much as possible. Crushing and sizing equipment could probably be used advantageously to remove some of the hard quartzose material.

The saddle area (fig. 5) appears to offer the best prospects for the

gure 5.— View of saddle area (middle ground) along crest-line of Cerro La Tiza looking west from point above house shown on trail on east side of plate 5. Outcrops occur along central road which can be seen in middle ground of picture. Grass, vegetation and earth-rock debris (boulders on slope in left foreground) cover most of the mineralized zone.

art of mining operations, especially from the standpoint of quality of e and accessibility. This area is easily accessible by the central road d its generally lower elevations suggest that it contains softer and ssibly less quartzose rocks than would be encountered at other accessible aces in the mineralized zone. The ridge crest throughout the saddle area traversable by truck as far west as the clay pit in the peak area. cess to the mineralized zone west of the clay pit would require the con- ruction of a road.

The eastern end of the mineralized zone is accessible by the eastern ad, but the ridge crest is not traversable by truck in either direction om the point where the eastern road passes over the crest. The area along e eastern road on the south slope of Cerro La Tiza from the crest to the rgin of the mineralized zone is also a potential area for exploitation, pecially for the clay minerals and pyrophyllitic zones exposed along the road. is area also would require exploration similar to that for the saddle ea prior to mining.

RESERVES

Calculated tonnages of reserve ore on Cerro La Tiza are necessarily ıferred values, because the depth of mineralization must be assumed. The ?ea of the mineralized zone as shown on the geologic map (plate 2) is ?25 hectares. The 225 hectare area contains 6,746,000 inferred short tons ?,120,000 metric tons) for each meter of depth. Arbitrarily assuming that ?e depth of mineralization is only one-half the width of the zone, there ?e 1,590,000,000 inferred short tons (1,440,000,000 inferred metric tons) ? mixed minerals.

Assuming, on the basis of the field and laboratory investigations, ?at the mixed mineral assemblage of the mineralized zone contains 35% quartz, ?0% alunite, 15% pyrophyllite, 15% clay minerals (kaolinite and halloysite) ?nd 15% sericite, iron oxides and other minerals of minor abundance, the ?lculated inferred tonnages are shown in table 5.

There is also a large reserve of hydrothermal minerals, particularly ?lunite, in the earth-rock debris on the slopes and around the base of ?erro La Tiza, but because of the indeterminate and variable thickness of ?he debris, no attempt is made to evaluate its potential economic reserve.

Table 5.—— Tonnages (inferred) of minerals on Cerro La Tiza

Minerals	Short Tons (inferred)	Metric Tons (inferred)
Quartz	557,000,000	504,000,000
Alunite	319,000,000	288,000,000
Pyrophyllite	238,000,000	216,000,000
Clays (principally kaolinite and halloysite)	238,000,000	216,000,000
Sericite, and other minerals	238,000,000	216,000,000
Totals	1,590,000,000	1,440,000,000

Utilization of hydrothermal minerals

Alunite, pyrophyllite, and the kaolin-group clays are sufficiently abundant at Cerro La Tiza to warrant exploitation, and they can be utilized from an economic standpoint in Puerto Rico. Quartz and sericite, although abundant do not appear to occur in sufficiently pure concentrations to warrant their use. Likewise, the occurrences of diaspore, sulfur and the other minerals of minor abundance do not appear to be economically useful at this time.

Alunite

One of the principal uses of alunite is in the manufacture of potassium sulfate and aluminum sulfate. From aluminum sulfate, the crystal alums, for example, ammonium, potassium, sodium and chrome alum can be made (Faith, Keyes and Clark, 1950, p. 59-62). Potassium alum can be made directly by leaching alunite. The plant requirements are simple and can be of almost any size. In the manufacture of alum, the presence of silica is said to be non-detrimental.

Alunite has been used in the manufacture of high-grade alumina refractory materials (Knizek and Fetter, 1950, p. 202-249) and the possibility of using it as a source for metallic aluminum is being investigated, although production on a commercial scale has not yet been achieved (Knickerbocker and Koster, 1936, pp. 47-49).

Alunite is also used in the manufacture of fertilizers, paper, fire-fighting compounds, mordants, baking powders (soda-alum), statuettes, cast stone and stucco products. It has some medicinal uses and is also used for water purification, treating furs, tanning leather, tawing skins for white leather and for decolorizing and deodorizing mineral oils (Johnstone, 1954; Mudd, 1949).

A useful publication prepared by Thoenen (1941) shows reserves, grade requirements (percent alunite vs. utilization of the rock) and patents regarding the processing and utilization of alunitic rocks.

The alunitic rock of Cerro La Tiza contains appreciable amounts of quartz so that its use should be restricted to processes by which the quartz could easily be removed or to fields of application in which high ilica is not detrimental. Puerto Rico imports considerable quantities f aluminum sulfate [$Al_2(SO_4)_3$] for use as a coagulant in water purifi-ation processes. The alunitic rocks of Cerro La Tiza could be calcined nd leached, whereby a mixture of potassium alum [$Al_2(SO_4) \cdot K_2SO_4 \cdot 24H_2O$] nd sodium alum [$Al_2(SO_4)_3 \cdot Na_2SO_4 \cdot 24H_2O$] would be produced and could be sed as a substitute for the imported aluminum sulfate. Another promising ossibility for the utilization of the alunitic rocks in Puerto Rico is in he manufacture of high-grade alumina refractory materials. The sodium ontent of the Cerro La Tiza alunite restricts its use for the production f fertilizer, inasmuch as high potash alunite is more desirable. The high ilica content of the alunite obviates its use for the production of metallic luminum.

Pyrophyllite

Pyrophyllite, because of its softness, non-alkaline property and its
)eous character is used as a dust diluent for insecticides and fungicides
as D. D. T., rotenone, pyrethrum, chlordane, and other chlorinated
)carbons. D. D. T., for example, cannot be ground to a powder and dis-
)d in water because it is waxy and tends to stick together and form
)s. However, when ground in certain proportions with pyrophyllite,
lsperses readily, the pyrophyllite acting as a carrier or distributing
; for the insecticide which then flows easily and adheres well when
led in the dispersed state (Brown, 1951, p. 51).

Pyrophyllite is also used in the manufacture of high grade ceramic products, especially refractories. It acts like talc for this purpose but does not flux when fired. For ceramic uses, it is important when quarrying to reject as much quartz and sericite as possible. The sericite content of the quarried rock should not exceed about 4 percent because the sericite acts as a flux. Quartz may be present to the extent of 10 to 30 percent. Low-grade pyrophyllite, containing as much as 15 percent ~~of~~ sericite can be substituted for all the flint and some of the feldspar in the production of porcelain, sanitaryware, artware, vitreous floor tiles and hotel chinaware. Its use in electrical insulators compares with that of porcelain. In semi-vitreous dinnerware, pyrophyllite contributes to high strength and reduces delayed crazing. Substituted for feldspar in wall tiles, it lessens crazing due to thermal shock, fire cracking, shrinkage and warpage and it increases the maturing of firing range. It also serves as a source for aluminum in glass manufacture and is used as a loading material for good quality paper, a filler in hard and soft rubber and a filler or an extender of expensive pigments in paint. Pyrophyllite is used for mine dusting, polishing rice, welding-rod coatings and in the manufacture of soaps, roofing felts, wallboard and plasters, cotton cordage, bleaching powder, textiles, sagger bodies, stove linings, baby powder, lubricants, foundry facings, porcelain enamel and in cosmetics where it competes with talc (Johnstone, 1954; Mudd, 1949).

Small quantities of pyrophyllite from Cerro La Tiza have been successfully used as a filler in the soap industry. It might also be useful in the paint industry as a non-porous, low-particle-size carrier for pigments for which purpose it is coequal with kaolinite, talc, iron oxide, chromia and carbon black. (Emmett, 1954). The pyrophyllite in Puerto Rico might also be used in the ceramic tile and the insecticide and fungicide industries.

Kaolin group clays

The principal uses of kaolinite are in the ceramics industry where it is used for china, porcelain, white-ware, red-earthenware, pottery, terracotta, fire-clay brick, building and paving brick, drain tiles and sewer pipes. Kaolinite is also used in the manufacture of paper, cement, inorganic and organic chemicals (~~e.g.~~ for example aluminum sulfate, alum and ultramarine), medicines, polishing powders and cosmetics. It is used in the clarification of food products and as a covering powder for finishing textiles. It is also used as a dust diluent or carrier for insecticides and fungicides, an extender in zinc and lead white pigments, a pigment in oil paints and a filler or stiffener in fabrics, lineoleum, oil cloth, papier mache, rubber and imitation leathers (Johnstone, 1954; Mudd, 1949).

In 1945 the Puerto Rico Industrial Development Company removed approxi-
ely 500 tons of kaolinitic clay from the clay pit on Cerro La Tiza to
as a substitute for imported feldspar in the manufacture of glass at
Cataño, Puerto Rico, glass plant. It was found that the clay, caused
ding (clumping into pellets) in the melt supposedly because of its fine-
s of grain, and its use was abandoned. Samples of clay from the clay
were also found to be useful as a ceramic glaze by an industrial concern.

Halloysite and kaolinite have the same composition and have many of
same economic applications. However, they are structurally different/

Halloysite has a higher surface area than kaolinite and serves as an effective catalyst support probably because it has a tubular morphology (Bates, and others, 1950, p. 463-484). Its higher surface area can probably be attributed to inner and outer tube surfaces and its inability to pack like kaolinite. Kaolinite occurs most commonly as thin hexagonal plates that acquire a preferred orientation with their sheet-like surfaces adjoining each other.

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d therefore have some different physical properties that place them in
fferent categories with regard to economic applicability. Halloysite,
r example, is used as a porous catalyst support of high surface area in
e cracking of petroleum (Emmett, 1954, p. 261).

Other occurrences of hydrothermally altered rocks in

eastern Puerto Rico

During the first month of field investigations of the rocks in the ro La Tiza area, nearly identical rocks were discovered in two small lls near the small settlement of Pueblito del Río approximately 34 kilo- ers east of the Cerro La Tiza reference point (plate 6). Further explo- ion throughout the Río Gurabo valley revealed other outcrops of light- lored hydrothermally altered rocks that stand in relief because of their dness and resistance to erosion. Throughout this valley the occurrence l distribution of mineralized rocks indicates that much of the flat low- d covered by grass and sugar ~~ca~~ne crops may be underlain by hydrother- lly altered rocks. A few scattered occurrences were also discovered be- en the Cerro La Tiza area and the western end of the Río Gurabo valley. s, it was evident that a belt of hydrothermally altered rocks of consider- le length extends eastward from Cerro La Tiza. The somewhat later disco- y of light-colored mineralized rocks at Colonia Junio, a small settlement proximately 4.3 kilometers east and 1 kilometer north of the Humacao plaza, J. P. Owens and R. B. Guillou of the Geological Survey (written communi- tion) extended the belt still farther east to the alluvium covered coastal ain within 3 kilometers of the Vieques Passage. This belt of hydrother- lly altered rocks has been designated the Cerro La Tiza-Río Gurabo Valley lt.

Occurrences of hydrothermally altered rocks were also found outside of the Cerro La Tiza-Río Gurabo Valley belt. During the early stages of the investigation the junior author found hydrothermally altered rocks on Cerro Marquesa approximately 2.7 kilometers north northwest of the Aguas Buenas plaza. The junior author also investigated a large light-colored mineralized zone in the vicinity of Lago de Cidra northeast of Cidra. Still later, hydrothermally altered rocks were found by other Survey geologists at several localities south of the Cerro La Tiza mineralized belt where they appear to be distributed peripheral to the San Lorenzo batholith. All the localities where rocks of hydrothermal origin are known to occur east and south of Cerro La Tiza are shown on plate 6.

Cerro La Tiza - Río Gurabo Valley belt

The rocks along the Cerro La Tiza-Río Gurabo Valley belt were identi-
ied in the field, on the basis of their similarity to the studied rocks of
rro La Tiza. On the whole they are light colored, fine grained, hard,
d siliceous and range in color from white through shades of gray and tan
shades of brown and red depending upon their iron content and the degree
d state of iron oxidation. Diagnostic features by which they can be
cognized in outcrops are: (1) pocket-like patches or stringers of white
olinitic clay or waxy, sub-translucent, halloysitic clay; (2) light colored
nes in which the iron minerals have been bleached, leaving irregular-shaped
ite or mottled, red and gray patches; (3) hard, nodular, ferruginous zones;
) micaceous zones, some coarsely crystalline and highly foliated; (5) sheared
foliated pyrophyllitic zones; (6) white to greenish-gray partially sili-
fied volcanic rocks; (7) banded rock (fine to coarse banding) with alter-
ting bands of quartz and alunite; (8) quartzose zones consisting of either
ite vein quartz, massive gray chert-like nodules or fine grained white or
ght gray aggregates of quartz, and sericite; and (9) fist-size or smaller,
dules of barite. The foliated, micaceous zones are especially noteworthy
two knolls on each side of the Río Grande de Loiza in the extreme southeast
rner of the Aguas Bueneas quadrangle. It is not known whether these mica-
ous zones are related to shearing along the mineralized belt or to meta-
rphism at the border of the San Lorenzo pluton. Nevertheless this foliated
caceous rock indicates that there may be a major shear zone through this
ea.

Pueblito del Río locality

Hydrothermally altered rocks occur in two knolls northwest of Pueblito Río (1 and 2 on plate 6) which is approximately 6.6 kilometers due east the Juncos plaza. One of these knolls is 0.8 kilometers northwest and other 0.4 kilometers north of Pueblito del Río. The hydrothermally ered rocks in these two knolls have the same general megascopic appear-e as the Cerro La Tiza rocks. Laboratory studies were made on samples m this area because of their striking resemblance to the banded quartz-nite rocks of Cerro La Tiza. Thirty samples were collected and in eight these, the predominant minerals are quartz, alunite, and pyrophyllite; or constituents are diaspore, hematite, barite and zunyite (?). Identi-ations were made by X-ray examination. Unit cell dimensions of alunite e determined on five samples and were found to be identical with those the Cerro La Tiza alunite indicating that the Pueblito del Río alunite probably sodian alunite of the same composition. Fist-size nodules of ite were found on the floor of a small quarry at the south base the ternmost knoll. No sericite was found, but this may be because only the ded, quartz-alunite rock was sampled.

Cantagallo locality

At the Cantagallo locality (3 on plate 6) a prominent ridge approximately 2.7 kilometers northwest of the Juncos plaza, nine samples were collected along the ridge from the base at its western end along the crest to the base at its eastern end. These samples were examined megascopically but mineral determinations were not made in the laboratory. Most of the rocks are tan to grayish-white, foliated, and pyrophyllitic.(?). In places the rocks are stained or mottled reddish-brown and contain specular hematite in thin veins and lining the walls of small open fractures. Other zones consist of dull, gray, translucent pyrophyllite (?) with a soapy feel and still others contain small glistening micaceous plates of tannish-white muscovite (?).

Most of the ridge appears to consist of foliated pyrophyllitic rocks particularly at the western end where there are more exposures. The small detached knoll east of the main ridge (3 on plate 6) contains similar rocks but some of these are harder and may contain alunite. Just below the crest of this knoll on its northwest slope two small prospect pits and dumps contain both aluntic (?) and pyrophyllitic (?) rocks.

Colonia Junio locality

At the small settlement of Colonia Junio (4 on plate 6) foliated pyrophyllitic (?) rocks in contact with highly-sheared, greenish-gray volcanic rocks are exposed in a quarry on the west slope of the hill that bounds the settlement on its northeast side. Ferruginous quartzose float blocks also occur on this west slope. At the time this area was investigated, the other slopes of the hill were inaccessible, but banded light-colored rocks reportedly occur at the east end of this hill.

Minor occurrences

The localities (5 on plate 6) of hydrothermally altered rocks shown in the intervals between Pueblito del Río and Colonia Junio were discovered by J. P. Owens and R. B. Guillou of the Geological Survey (written communication). These localities were not visited by the authors but the senior author has had the opportunity to examine the specimens collected from them. They are light-colored fine-grained siliceous and ferruginous rocks that appear to be of hydrothermal origin. Their mineralogical character could not be determined by megascopic examination.

At the locality shown at Las Piñas (6 on plate 6), reddish-gray quartz rocks and tannish-white and reddish-white alunitic (?), pyrophyllitic (?), or sericitic (?) rocks crop out in road cuts. Small pockets of white crystalline barite occur in these rocks and small loose nodules of barite were found at the base of a cut on the east side of the road to Las Piñas.

Other zones of hydrothermally altered rocks

Cerro Marquesa

At Cerro Marquesa (7 on plate 6), light-colored rocks of hydrothermal origin occupy the crest and have been well exposed by a new access road to two television towers. Although the rocks at the highest elevation near the northwestern tower are ferruginous, good exposures of light-colored hydrothermally altered rocks were seen in road cuts near the base of the southeastern tower. Pyrophyllite occurs here in greenish-white, foliated, radiating, fibrous clusters, and diaspore occurs in large, tannish-white, nearly clear, crystalline masses closely associated with the pyrophyllite and with fine-grained sericite. These minerals were all identified by X-ray examination. The association of diaspore with pyrophyllite has also been observed by Edwin B. Eckel of the Geological Survey (written communication) in Paraguay.

The zone of hydrothermally altered rocks shown by dashed lines extending northwest of Cerro Marquesa west of the Río de Bayamón has been recentl (summer 1958) reported by M. H. Pease of the Geological Survey (oral communication) who believes that it is a northwest trending zone along which the Cerro Marquesa occurrence lies.

Lago de Cidra

The Lago de Cidra zone of light-colored rocks extends east-northeast from a point about 1 kilometer northwest of Cidra for a distance of at leas nine kilometers (8 on plate 6). Field examinations indicate that these roc are probably highly siliceous and a preliminary X-ray examination of two random samples shows that they consist predominantly of quartz and lesser amounts of sericite and kaolin group clays.

Other zones in southeastern Puerto Rico

Occurrences of hydrothermally altered rocks have been reported in the Cayey, Patillas, Caguas, Guayama, and Punta Tuna quadrangles by H. L. Berry and M. H. Pease, Jr. of the Geological Survey (oral communication). These occurrences are shown on Plate 6. Most notable is the Monte El Gato zone in the Cayey quadrangle. Mineralogical data on the rocks of these areas are not available.

Other occurrences of hydrothermally altered rocks will undoubtedly be found in the Gurabo, Caguas, Patillas and Guayama quadrangles which have not yet been systematically investigated.

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59-54
plate 4

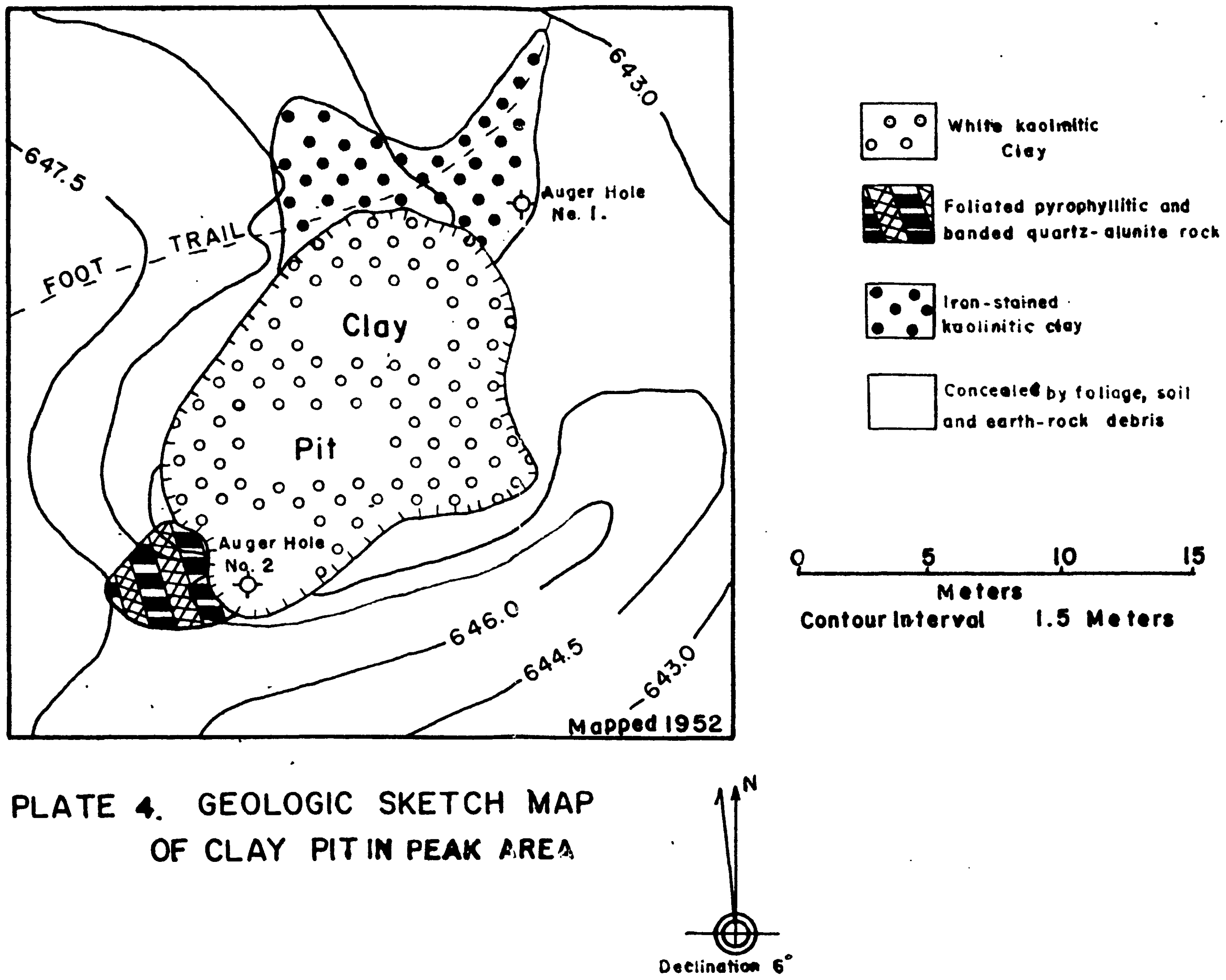

PLATE 4. GEOLOGIC SKETCH MAP OF CLAY PIT IN PEAK AREA

Contours by R.J. Smit

PLATE I.--- INDEX MAP SHOWING LOCATION OF CERRO LA TIZA AREA

Plate 2.--- Geologic map of the Cerro La Tiza Area, Puerto Rico

Plate 3.— Sketch map of Cerro la Tiza Area showing 1) central axis(red) of major mineralized zone 2) axis of smaller mineralized zone(red) bearing N75 - 80W, northeast of major zone and 3) principal drainages and access roads.

△ Outcrop areas of known pyrophyllitic rocks.

○ Locations at which five analyzed alunitic rocks (409, 530, 362, 576A and 604 - plate 2) were collected.

Contours(in meters) and culture were traced from geologic map (plate 2).

59-54
plate 5

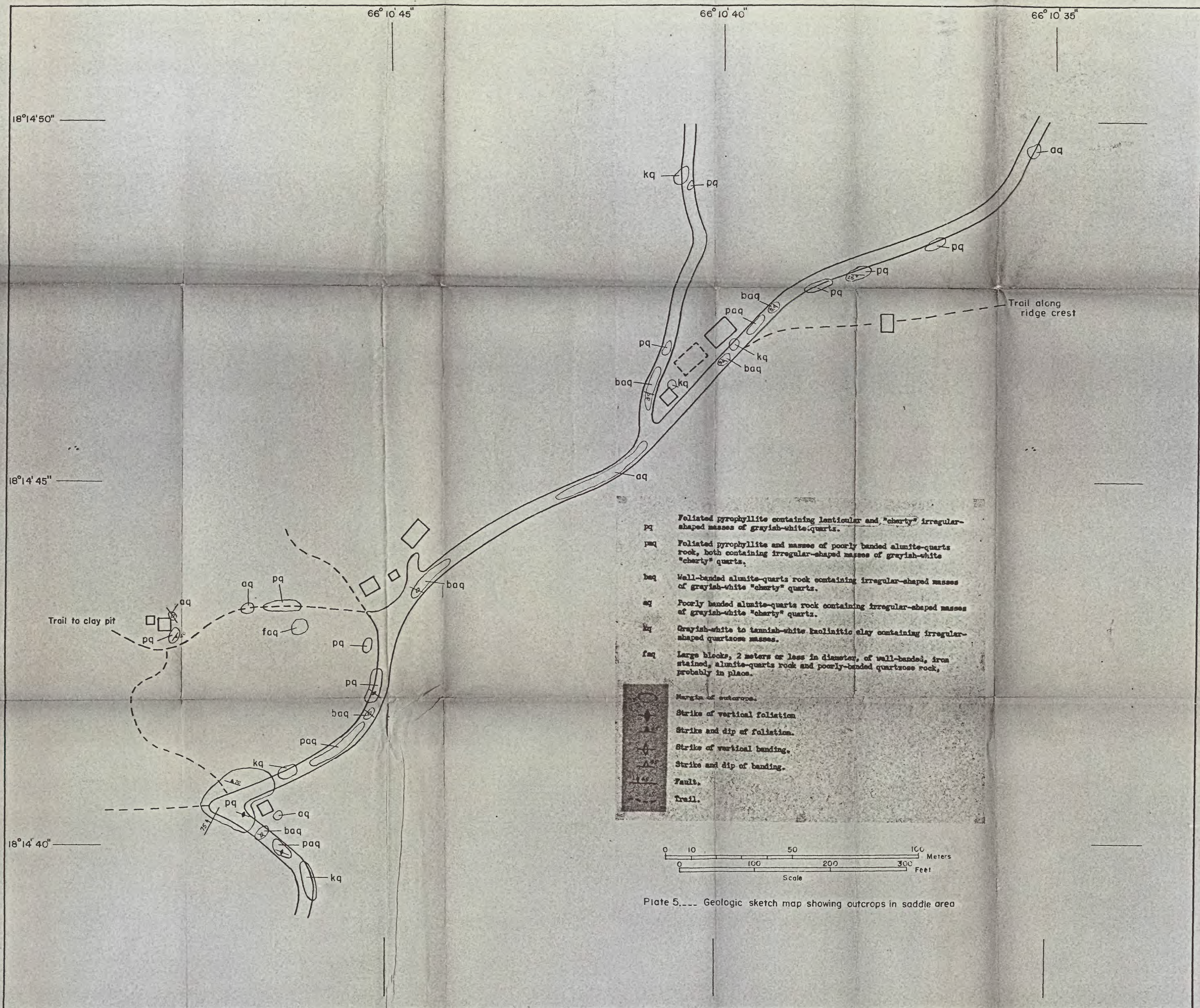

Plate 5.--- Geologic sketch map showing outcrops in saddle area

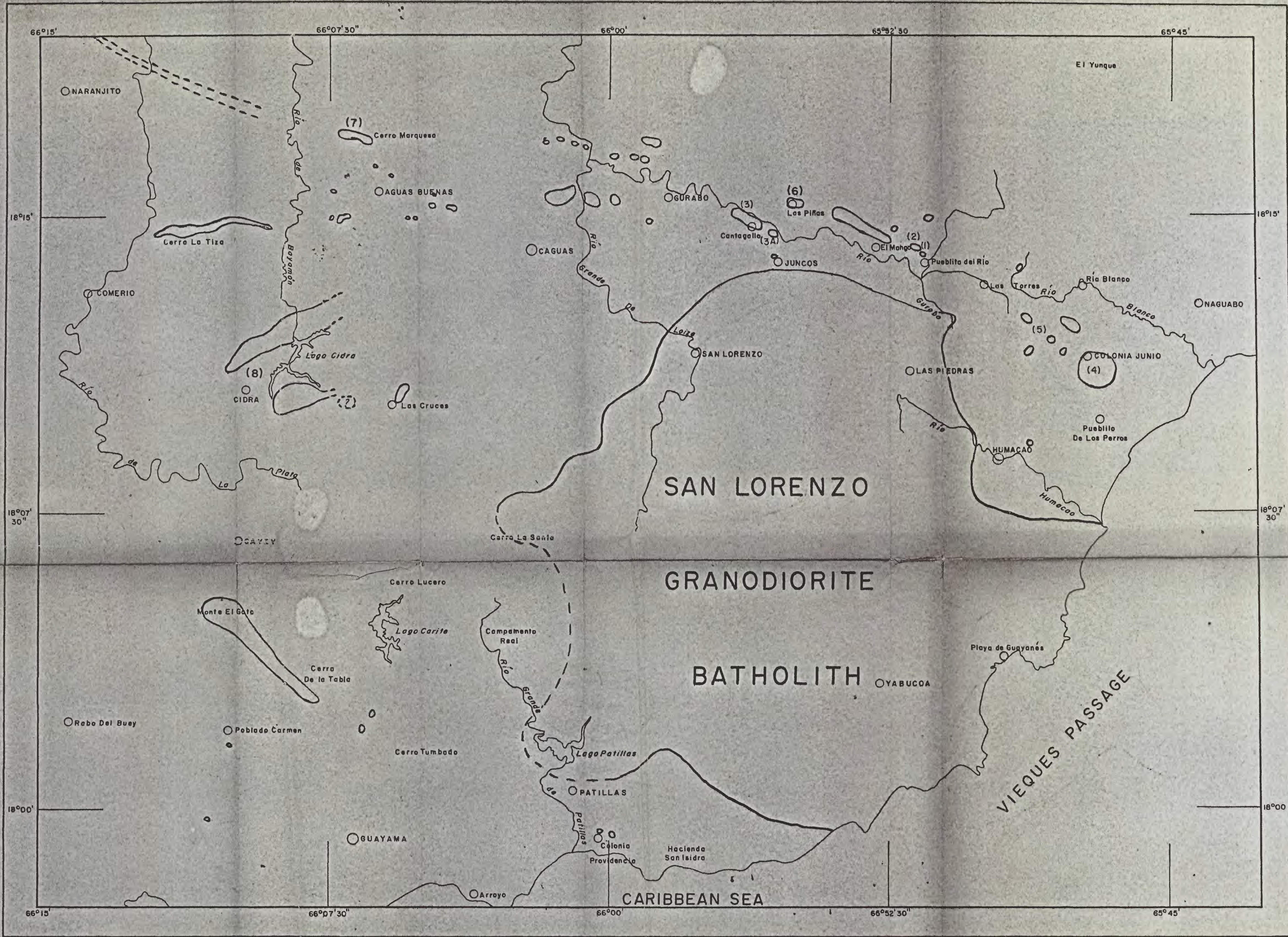

Plate 6.--- Distribution of hydrothermally altered rocks in East-Central Puerto Rico

Scale 1:120,000

0 5 10 Kilometers

0 5 Miles

— Outline of San Lorenzo pluton - dashed where uncertain

— Occurrences of hydrothermally altered rocks - dashed where uncertain