GEOLGY OF
THE SAN DIEGUITO
PYROPHYLITE AREA
SAN DIEGO COUNTY, CALIFORNIA

By
RICHARD H. JAHNS and JOHN F. LANCE
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RICHARD H. JAHNS* and JOHN F. LANCK**

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ABSTRACT

The San Dieguito area of west-central San Diego County, California, is one of the few localities in western North America where pyrophyllite has been produced in commercial quantities. The output from this area has been derived chiefly from one large deposit that was opened up for mining in 1845, and amounted to slightly more than 10,000 tons by mid-1940. Most of the pyrophyllite has been marketed as an insecticide carrier.

The deposits occur in the Santiago Peak volcanic series, which comprises flows, breccias, agglomerates, and tuffs of probable Jurassic age. A group of intrusive rocks, in which tonalite is the most abundant type, is closely related in space to the volcanic series, and probably is of later Jurassic age. A second, more widespread group of intrusive rocks cuts all the other crystalline types, and forms a part of the southern California batholith, which is Cretaceous in age. Stock-like bodies of Escondido Creek leucogranodiorite and larger masses of Woodson Mountain granodiorite are the principal batholith representatives in and near the San Dieguito area. Both the volcanics and the older of the intrusive rocks have been affected by regional metamorphism of low rank. This metamorphism appears to antedate the rocks of the batholith.

The crystalline rocks are unconformably over lain by poorly consolidated arkosic sands and interbedded siltts that probably are a part of the La Jolla formation of Eocene age. These sediments are in turn unconformably overlain by coarse-grained Quaternary terrace gravels.

The structure of the Santiago Peak volcanic series is essentially homoclinal. Shearing and schistosity are locally prominent, and commonly are subparallel with primary layering in the rocks. A low-angle discordance also is common. The intrusive rocks show little well developed planar structure. The Tertiary and Quaternary sediments have been very mildly deformed.

The pyrophyllite-bearing rocks are discontinuously exposed within an area of about one square mile. They represent progressive stages in the alteration of the volcanic rocks at some time distinctly later than the regional metamorphism. The original rocks were mainly flows, breccias, and tuffs that ranged in composition from andesite to rhyolite. Pyrophyllitization appears to have been guided chiefly by pre-metamorphism fracturing and shearing, and to a lesser degree by variations in the original composition of the rocks. A marked silicification preceded the pyrophyllitization, but much quartz that is associated with pyrophyllite probably formed contemporaneously with it. The most thorough pyrophyllitization appears to have taken place in the less silicified rocks.

The pyrophyllite-bearing rocks form elongate lenses that vary considerably in size and attitude and in general are conformable with the dominant planar structure of the host volcanics. Nearly all of the pyrophyllite mined to date has been obtained by open-pit methods from a single mass of high-grade schist at least 150 feet long and 15 feet in average thickness. Most of the other pyrophyllite-bearing rock in the area is of commercial grade.

Petrographic and chemical analyses indicate that the development of pyrophyllite was accompanied by the introduction of SiO2, Al2O3, and probably OH. A hypogene, rather than supergene, origin is indicated by (1) the localization of sulfide minerals in the pyrophyllite-bearing rocks, (2) alteration of an aggregate and non-selective, rather than a sequential type, (3) the occurrence of pyrophyllite and sulfides as consistently older minerals than those of...
Figure 1. Index map of a part of southern California
INTRODUCTION

General Statement. Several pyrophyllite deposits in west-central San Diego County were prospected in a small way at least 50 years ago, but no attempts were then made to exploit them commercially. Indeed, there is some doubt as to whether identification of the principal mineral as pyrophyllite had been made, and the early attention may well have been attracted instead by the boldness and whiteness of the outcrops, and by numerous prominent iron-stained fractures in the rock. The pyrophyllite was briefly described in 1912 by Rogers,1 and years later some of the occurrences were studied and tested by Richard,2 who pointed out possible commercial applications. Actual economic development, founded mainly upon use of the pyrophyllite as a carrier for dust-form insecticides, dates from the opening of the Pioneer mine in 1945.

The writers first visited the mine in 1947, at the suggestion of Roy M. Kepner, Jr., of the San Diego County Division of Natural Resources. Mr. Kepner had been observing the development of the property in some detail, and pointed out the desirability of geological study to determine the distribution, shape, and size of the deposits. Information also was sought concerning the probable downward extent of iron-oxide stains in the masses of high-grade pyrophyllite, and concerning the occurrence and distribution of inclusions, or "horses," of pyrophyllite-poor material.

The subsequent geologic investigations in the mine area have demonstrated the presence of several rock types that contain pyrophyllite. The details of their occurrence are of economic significance, and are inseparable involved in such genetic considerations as lithology and structure of the rocks from which the pyrophyllite was formed, the nature and source of the altering solutions, and structural features that controlled the distribution of these solutions. The pyrophyllite-bearing rocks are described in this report, and are discussed in terms of their origin and relations to the other rocks in the vicinity. Such treatment is aimed primarily at economic appraisal of the deposits, but the report also deals with general geology of the entire area.

Methods of Investigation. Approximately 35 man days was devoted to study of the Pioneer and nearby deposits during the period October 1946-April 1949. The mine area was mapped with plane table and telescopic alidade at a scale of 20 feet to the inch (pl. 2), and a much larger surrounding area was mapped at a scale of 660 feet to the inch (pl. 1). Enlargements of aerial photographs furnished by the Agricultural Adjustment Administration were used as a base for the latter map. A very small area of excellent exposure was mapped on a scale of 4 feet to the inch, principally to show in detail the relationships between some pyrophyllite-bearing and pyrophyllite-free rocks.

Emphasis was placed upon field recognition and discrimination of the various pyrophyllite-bearing rocks, and on the tracing of these units in detail. Field identifications and correlations were confirmed in the laboratory, chiefly by examination of 36 thin sections and numerous samples of crushed material under the microscope. This petrographic work also yielded much information concerning mineral textures and paragenesis. It was supplemented by four chemical analyses and by five semi-quantitative spectrographic analyses. Most of the petrographic studies were made by Lane, and the field mapping was chiefly the work of Jahus. Each of the writers participated in both phases of the project, however, and they share equally the responsibility for the conclusions advanced in this report.

Acknowledgments. The investigations were aided considerably by several discussions with Roy M. Kepner, Jr., of the San Diego County Division of Natural Resources, and with L. A. Norman, Jr., and L. A. Wright of the California State Division of Mines. These men contributed numerous ideas and suggestions. It also is a pleasure to acknowledge the friendly cooperation of Mr. Harold Smiley of Del Mar, who was operating the Pioneer mine during much of the present study. His many courtesies greatly facilitated the field work.

Special thanks are due to Joan T. Rounds, who drafted the maps and sections, and to Florence Wiltse, who aided in the preparation of the manuscript. The manuscript was critically reviewed by L. A. Wright.

The field and laboratory expenses of the project were met in large part by means of research grants from the California Institute of Technology.

GEOGRAPHY

The Pioneer mine, in the San Dieguito area of central-western San Diego County, is 2½ miles east-northeast of Rancho Santa Fe and 7½ miles southwest of Escondido (fig. 1). It lies about 1000 feet east of the San Dieguito River and 2 miles west-southwest of Hodges Dam, and it is 8 miles east of the coast line at Encinitas. The main deposit can be reached from Escondido or from Rancho Santa Fe over a paved highway, with which it is connected by a 0.6-mile dirt road (pl. 1). Most of the other deposits in the area are readily accessible by wagon road or trail. The nearest rail points are at Escondido to the northeast, and at Solana Beach, 9 miles by road to the west.

The pyrophyllite-bearing rocks are exposed in steep bluffs along the San Dieguito River, and on terraces and higher ridges east and southeast of the river. They lie at altitudes of 40 to 340 feet, and are well below the level of a broad, dissected terrace to the south. Steep-sided mountains rise to the north and east, generally to altitudes ranging from 500 to more than 1500 feet.

The area is drained by intermittent streams that form a rude trellis pattern with respect to the San Dieguito River (pl. 1). The river itself has a moderate flow during the wet season, but dwindles to a series of disconnected pools during the summer and fall months, when little water is released from storage behind Hodges Dam. Annual precipitation ordinarily is 12 inches or less, and the area supports only a sparse growth of grass and brush, with a few scattered clusters of eucalyptus trees. Very

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1Rogers, A. F., Notes on rare minerals from California: Columbia Univ. School of Mines Quart., vol. 20, p. 381, 1912.
little vegetation grows in the areas underlain by the pyrophyllite-bearing rocks, and such areas commonly appear as distinctively light-colored patches on the slopes and ridges (fig. 2).

**GEOLOGY**

**General Relations**

The pyrophyllite deposits are exposed near the eastern margin of the so-called coastal belt in San Diego County, chiefly in valleys cut beneath the level of an extensive marine terrace of Quaternary age. The oldest rocks in these valleys are mainly of volcanic origin, and probably date from Jurassic time. They are slightly metamorphosed, and in places have been further altered to various pyrophyllite-bearing rocks.

Intrusive into the volcanic sequence are dikes and stock-like masses of coarse-grained gabbro porphyry and fine- to medium-grained tonalite. These are best exposed north and east of the pyrophyllite area, where they form the western margin of the Peninsular Ranges province. A younger group of intrusive rocks, mainly granodiorite in the area studied, represents the southern California batholith, named and so well described by Larsen. This is a very large plutonic complex of Cretaceous age, and its rocks are the youngest of several crystalline types in the area.

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Coarse-grained white, buff, and greenish-gray arkosic sands overlie the pre-batholithic rocks, and in turn are capped by younger terrace gravels. The sands, which are poorly consolidated, probably are of early Tertiary age. They lap eastward against both the batholithic and older rocks of the Peninsular Ranges, and evidently were deposited on a surface that was very irregular in detail.

Terrace gravels of Quaternary age represent marine planation in the general coastal area. Several of the terrace surfaces are rather extensive, though considerably dissected. Some of the lower, more locally developed terraces are capped by gravels of marine origin, others by somewhat coarser material of fluviatile origin. Additional Quaternary deposits include alluvium, slump debris, talus, and fan gravels. The relations of these and the various older rocks are summarized in table 1.

The geology of this and nearby parts of western San Diego County has been described by several investigators, notably Fairbanks, Merrill, Ellis, Hanna, and Larsen. Numerous other papers and reports deal with such specific...
problems as petrology of the crystalline rocks in the Pen-
insular Ranges, paleontology and stratigraphy of the Cre-
taceous and Tertiary rocks in the coastal belt, regional geomorphology, and mineral deposits in specific districts. Occurrences of pyrophyllite in the region have been recorded by Rogers,9 Sanford and Stone,10 Kepner,11 and others, and high-grade material from the Pioneer deposit was tested and briefly described by Richard.12

Santiago Peak Volcanics

Distribution and General Features. The most abun-
dant crystalline rocks in the San Dieguito area are mildly
metamorphosed volcanic flows, breccias, agglomerates,
and tuffs, with some interlayered fine-grained argillaceous
sedimentary beds. This complex was termed the Black
Mountain volcanics by Hanna,13 and, more recently, the
Santiago Peak volcanics by Larsen.14 On a regional scale,
the rocks are exposed in a north-northwesterly trending
belt that is more than 80 miles long and as much as 10
miles wide. In most places, however, its width is less
than 5 miles. Much of the belt flanks the Peninsular Range
province on the west, but north of the San Dieguito area
the volcanic rocks commonly appear within the mountain
masses proper. In most areas these rocks are markedly
discontinuous in distribution, owing in part to the pres-
ence of younger masses of intrusive rock, and in part to
several eastward extensions of the cover of late Mesozoic,
Tertiary, and Quaternary sediments. Volcanic rocks charac-
teristic of the coastal belt.

Within the area investigated, the Santiago Peak vol-
canics are best exposed north of the Escondido-Rancho
Santa Fe road, and in the bottom and along the walls of
the San Dieguito River canyon. In general these rocks are
resistant to erosion, and form rough slopes with many
ragged, irregular cliffs. In some areas, however, they
underlie smooth, soil-covered hills. Both extremes of
topographic detail are well shown north of the Rancho
Santa Fe road (pl. 1), where there are broad transitions
from relatively fresh, knobly ledges high on the hills to
sultoned, soil-covered slopes farther down.

Where fresh, the rocks are light to dark gray, pale
greenish gray, and reddish to purplish brown. Tan, light
reddish to greenish brown, and very dark brown are char-
acteristic of weathered surfaces. Owing to a moderately
high content of pyrite and other sulfide minerals, many
of the volcanics are markedly stained by iron oxides, in
places to depths of 60 feet or more. In detail the rocks
weather into numerous angular fragments, which charac-
teristically are surrounded by both chemically and me-
chanically altered material. Some of the breccias also yield
nodular surfaces by differential weathering of the frag-
ments and matrix. Excellent transition zones between
weathered and underlying fresh rock are exposed in
several cuts along the Rancho Santa Fe road, and along
the bluffs that flank the San Dieguito River. The river
channel itself contains numerous outcrops that show little
or no weathering (figs. 4, 5).

Some of the volcanic rocks are marked by closely
spaced flow layers, and some of the tuffaceous types by
regular, well-defined bedding. Flow structure and other
planar elements are not readily discernible, however, on
many fresh exposures. A crudely developed sheet-like
structure, which appears on many weathered surfaces,
generally is parallel to the primary flow layers, to contacts
between recognizable units in the volcanic sequence, and
to clear-cut bedding in several of the tuffaceous units. It
is hence of considerable value in deciphering the structure
of these rocks. Also of value, but of very local occurrence,
are rows of large, angular to rounded fragments in masses
of breccia and agglomerate.

The rock types are interlayered, and grade into one
another or abruptly abut one another along their strike.
Most of the flow units are thinly tabular; in contrast, the
coarser breccia masses are thickly lenticular in form. In
most of the San Dieguito area the individual units and the
primary planar structures of the volcanic rocks strike

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Table 1. Generalized section of rocks exposed in
San Dieguito pyrophyllite area.

<table>
<thead>
<tr>
<th>Age</th>
<th>General designation</th>
<th>Lithologic type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Alluvium</td>
<td>Laminated, talus, fan, and valley-fill deposits of unconsolidated sand, gravel, and rubble</td>
</tr>
<tr>
<td></td>
<td>Terrace gravel</td>
<td>Poorly to well consolidated gravel, with minor coarse sand</td>
</tr>
<tr>
<td>Tertiary</td>
<td>La Jolla formation</td>
<td>Coarse-grained granodiorite and medium- to coarse-grained leucogranodiorite</td>
</tr>
<tr>
<td>(Eocene?)</td>
<td>Torrey sand (?)</td>
<td></td>
</tr>
<tr>
<td>Cretaceous</td>
<td>Intrusive rocks of the southern California batholith</td>
<td>Coarse-grained granodiorite and medium- to coarse-grained leucogranodiorite</td>
</tr>
<tr>
<td>Jurassic</td>
<td>Pre-batholith (?) in-</td>
<td>Coarse-grained gabbro porphyry and fine- to medium-grained tonalite</td>
</tr>
<tr>
<td></td>
<td>trusive rocks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pre-batholith vol-</td>
<td>Chilled flows, breccias, agglomerates, and tuffs of andesite to quartz</td>
</tr>
<tr>
<td></td>
<td>canic rocks (Black Mountain and Santiago Peak volcanies)</td>
<td>latic composition; locally altered to pyrophyllite-bearing rocks</td>
</tr>
</tbody>
</table>

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* Rogers, A. F., op. cit., p. 381, 1913.
* Sanford, Samuel, and Stone, F. W., Useul minerals in the
* Kepner, R. M., Jr., Mining in San Diego County: San Diego
northwest to northeast, and dip moderately to very steeply north to northeast (pl. 1).

Some argillaceous sediments exposed in the area probably represent original tuffaceous shales. They are now splintery to platy, slightly schistose rocks of dark greenish-gray to black color. Most of them resemble rough, irregular slates. They contain abundant volcanic material similar to that in the tuffs already described, together with detrital grains of quartz, muscovite, and other minerals that are not clearly of immediate volcanic derivation.

Neither top nor bottom of the volcanic section is exposed in the area studied, but the thickness of these rocks plainly is many hundreds of feet. Hanna 15 reports a thickness well in excess of 2000 feet from the area immediately to the south.

The Santiago Peak volcanics are Mesozoic, and probably Jurassic, in age. They are cut extensively by plutonic rocks of Cretaceous age, and lie unconformably upon older series of metasedimentary and metavolcanic rocks in areas to the north and east. The older series has been variously designated as "basement complex," "schist complex," "Julian group," "Julian schist series," "Julian schist," "Santa Ana slates," and "Bedford Canyon formation." Some of these rocks are particularly well exposed in the Santa Ana Mountains,16 where they contain fossils of Triassic age; and others are exposed in the Julian district and surrounding areas,17 where they may be, in part, of Paleozoic age. Schist, phyllite, and quartzite of this older complex are exposed south of Bernardo Mountain, about 5 miles east of the Pioneer mine.

 Petrography. The Santiago Peak volcanics constitute the host rock for all the pyrophyllite deposits, and many of the minerals and structural features of these volcanic rocks are preserved, wholly or in part, in the pyrophyllite-bearing rocks.

The most abundant volcanic rock types in the mine area are dacite and quartz latite agglomerate and breccia. The fragments are angular to subrounded (figs. 4, 5), and range in diameter from less than 1/2 inch to 5 feet or more. Except in some extremely coarse "boulder beds," the average diameter of the fragments is less than one inch. The matrix is purplish to greenish gray, and generally is fine-grained, with seriate to distinctly porphyritic textures. Most of the fragments are irregularly scattered, but in some breccia units they form crudely planar elements that are parallel to flow structure. Distinct flow layering is best developed in the finest-grained facies of the breccias.

The phenocrysts in the matrix of the fragmental rocks are chiefly plagioclase, ranging in composition from calcic labradorite to median andesine. Most are euhedral, and are lath-shaped to nearly equant (figs. 6, 7). They are 0.5 mm. to 6 mm. in maximum dimension, with an average of about 2 mm. Many are distinctly zoned, generally with progressive increase in soda content from the cores outward. Oscillatory zoning, on the other hand, is by no means rare.

Subhedral to anhedral quartz phenocrysts also are widespread, but in general are somewhat smaller than the crystals of plagioclase. Most appear to have been in part resorbed, and many show overgrowths of later quartz. Orthoclase is fairly common in some rocks, but nowhere is it particularly coarse-grained or abundant. Other phenocryst minerals are green and brown hornblende, augite, and rare hypersthene. A little biotite also forms phenocrysts, but this mineral is much more common as finer-grained fringes around pyroxene and amphibole crystals, and as relatively coarse parts of the groundmass.

The groundmass is even grained to seriate, with an average grain size of about 0.05 mm. in the coarser rocks. Elsewhere it is commonly cryptocrystalline to microcrystalline. Recrystallization has altered the groundmass textures of many rocks, however, increasing the average particle size to as much as 1 mm. The principal groundmass mineral is plagioclase, which forms lath-shaped euhedra and smaller, more equant anhedral masses. Quartz, ortho-

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clase, hornblende, and biotite also are widespread. The most abundant accessory minerals are magnetite, ilmenite, and hematite. Pliotaxitic texture is shown by some of the plagioclase, hornblende, biotite, and other elongate mineral grains that are distinctly oriented by flowage around the phenocrysts.

Chlorite is abundant throughout both fragments and matrix, where it seems to have formed chiefly at the expense of hornblende, biotite, and other mafic constituents. Most of the phenocryst feldspars, as well as many of those in the groundmass, are altered to chlorite, quartz, pyrophyllite, zeolites, sericite, carbonate minerals, and to abundant and widespread albite (figs. 6, 7). Quartz also appears in the groundmass as microgranular aggregates, in veinlets cutting across breccia fragments, and as a few relatively large metacrysts.

Under the microscope, many of the breccia fragments are little different from the porphyritic matrix material. Indeed, these essentially cognate fragments are very difficult to recognize in the field, especially on fresh surfaces. They appear clearly on most weathered surfaces, however, possibly because of slight textural differences that controlled the rate of weathering. Other breccia fragments, coarser grained and slightly darker in color, are in general of andesitic composition. Some of the breccias contain numerous fragments of silicified quartz latite and rhyolite, which are fine-grained, dense, and light gray to almost white. Such leucocratic rocks are particularly well exposed in the northeast corner of the area (pl. 1).

The breccias and agglomerates grade into tuffaceous rocks, in many places so uniformly that it is impossible to draw a boundary between them. The matrix of the coarsely elastic rocks is commonly tuffaceous, and many of the tuffs are themselves unusually inequigranular, containing some fragments of andesite and dacite an inch or more in diameter.

The maximum diameter of individual fragments in the tuffs generally is less than 2 mm., with an average of less than 0.5 mm. Primary layering is well shown by differences in mineral composition, and by sharply contrasting variations in texture. Most of the tuffs are lithic, but some consist wholly of closely packed crystals of plagioclase and other minerals. The fragments of rocks and minerals ordinarily are set in a very fine-grained groundmass that constitutes less than 25 percent of the rock. It appears to consist of feldspar and devitrified glass. The alteration of both fragment and groundmass minerals in the tuffs is similar to that described for the breccias and agglomerates above.

Another common gradation in the area is from pyroclastic rocks to simple flow rocks. Both porphyritic and non-porphyritic types occur, and most are strikingly similar to the matrix material of adjacent agglomerates and flow breccias. The phenocrysts are typically altered, and consist mainly of fine-grained quartz, chlorite, albite, and pyrophyllite. Phenocrysts of altered amphibole and pyroxene also are present. Orthoclase appears as tiny grains in the groundmass of some rocks, where it commonly is associated with fine-grained quartz. Quartz also occurs as phenocrysts, and more abundantly as metaocrysts with sugary texture. Some of the latter are plainly the result of growth from a fine-grained mosaic of secondary quartz.

Figure 6. Phenocryst of calcic plagioclase in part altered to quartz and minor chlorite, dacite breccia. Groundmass is mainly lath-like plagioclase, with quartz, orthoclase, biotite, and magnetite. Ordinary light, X 110

Amygdaloidal structure is preserved in several of the flows, and is represented chiefly by aggregates of recrystallized epidote and quartz. Zeolites, carbonate minerals, and chlorite are common associates. Chlorite, serpentine, and epidote also are widely scattered through the groundmass and phenocrysts of the nonamygdaloidal rocks. Such rocks also are cut by numerous stringers and veinlets of subhedral quartz and epidote (fig. 5).

Fine-grained, strikingly light-colored varieties of quartz latite and rhyolite are well exposed in several parts of the area. Some of these are flows and flow breccias, others are distinctly tuffaceous. All are leucocratic, and are moderately to almost completely silicified. They are so fine-grained and dense in appearance that they resemble some arenaceous metasedimentary rocks, especially where flow-layers are preserved. Some rocks of this type appear to have been included by Hanna in the


Figure 7. Phenocryst of calcic plagioclase partly replaced by pyrophyllite, quartz, and epidote, dacite flow rock. Groundmass mainly lath-like plagioclase and partly devitrified glass. Crossed nico, X 110
general designation of quartzite, and in places they are
indeed associated with typical sedimentary material.
They do not form continuous or throughgoing units, but
occur instead as lenticular masses a few feet to as much as
300 feet in maximum dimension.

Though dense and very fine-grained, these light-
colored rocks are commonly porphyritic, mainly with
tabular phenocrysts of plagioclase and orthoclase 1 mm.
to 4 mm. long. The phenocrysts constitute 5 percent to
more than 60 percent of the original rock. Quartz also
occurs as coarse individual masses, many of which appear
to be secondary growths. The groundmass evidently was
crystalline in some of the rocks, and originally glassy in
others; all is now recrystallized and much silicified.

The feldspar phenocrysts have been partly or wholly
replaced by finely crystalline quartz, much of which evi-
dently was introduced along fractures, cleavage cracks,
twin planes, and even along directions of crystal zoning.
Sericite and clay minerals are common associates, and
well formed crystals of pyrite and magnetite are wide-
spread minor constituents. Epidote and carbonate min-
erals are the most abundant alteration products, and some
masses of very pale yellowish-green rock consist almost
wholly of fine-grained epidote. Most of the leucocratic
quartz lattes and rhyolites, however, are so much silicif-
ed that quartz is by far the most abundant constituent.

Metamorphism. Many of the volcanic rocks evi-
dently were somewhat altered by deuteric processes,
chiefly with development of such amygduoidal minerals
as calcite, epidote, and zoéites, and with corrosion and
partial replacement of primary mafic minerals. Nearly all
of the alteration now visible in the rocks, however, is
plainly ascribable to subsequent metamorphism, mild in
degree but very widespread. This caused devitrification
of glassy constituents; obliteration of vesicles, some
amygduoids, and the most delicate representatives of
other structural features; recrystallization of quartz,
feldspar, and other minerals of both phenocryst and
groundmass occurrence; and the attack of older minerals
by chlorite, epidote, clinozoisite, serpentine, albite,
quartz, ankerite, calcite, and sulfide minerals. As a result
of this alteration, most of the andesitic, dacitic, and latitie
rocks could well be classified under the general term
"greenstone."

The plagioclase phenocrysts are partly or wholly
replaced by quartz and albite in the more siliceous rock
types, and by very fine-grained aggregates of albite,
chlorite, serpentine, carbonate minerals, quartz, epidote,
and clinozoisite in the rocks of intermediate composition.
Pyrophyllite, chloritoid, and chloritoid are locally abundant as well.

Various stages of alteration are clearly visible (figs. 6, 7),
but in very few rocks are the phenocrysts completely
fresh. The finest-grained parts of the groundmass appear
to have been selectively replaced, so that in many rocks
sheaves of small, lath-like plagioclase crystals are sur-
rounded by much finer-grained aggregates of the altera-
tion minerals. Many of the rocks are impregnated with
carbonate minerals, and both calcite and ankerite pseudo-
morphically replace some euhedral phenocrysts of augite
and hornblende (fig. 8).

The biotite is commonly bleached, and in some rocks
is altered to pale green chlorite. Most of the ilmenite is
altered to leucoxene. Quartz and pyrite are the chief meta-
cryst minerals, and are scattered through the rocks as sub-
hedral to euhedral crystals and crystal aggregates 1 mm.
to 10 mm. or more in diameter. Many of these metacrysts
are cracked and "healed" by veinlets of quartz, chlorite,
clinozoisite, and epidote. Similar veinlets occur in the
remainder of the rock, as well.

Most of the volcanic textures are well preserved, even
though the groundmass of nearly all rock types has been
recrystallized and is distinctly coarser than its original
form. Where alteration was most severe, the original
phenocryst minerals are no longer present; the porphy-
ritic texture, however, is clearly shown by the pattern of
the alteration minerals. In general, the alteration during
metamorphism was rather simple, and probably did not
represent introduction of much new material. As pointed
out by Larsen,19 there is abundant evidence for addition
of water during metamorphism, but otherwise there proba-
belly was no great change in bulk composition of the rocks.

Other Crystalline Rocks

Older Intrusive Rocks

The oldest intrusive rocks in the area are exposed
on the high ground north and northeast of the Pioneer
mine. The most extensive rock type, a fine- to medium-
grained non-porphyritic tonalite, is in contact with the
Santiago Peak volcanics north of the San Dieguito
River (pl. 1). It is more resistant to erosion than the
volcanic rocks, and forms numerous bold outcrops. It also
yields rounded boulders of disintegration, which gene-
rally occur in scattered but well-defined groups.

A contact zone, discontinuously exposed along and
above the aqueduct northeast of the Pioneer mine, dem-

19 Larsen, E. S., Batholith and associated rocks of Corona, Eids-
more, and San Luis Rey quadrangles, southern California; Geol. Soc.
medium-grained, light gray to greenish-gray tonalite contains subangular to well-rounded fragments of partly digested volcanic rocks. The matrix is similar to the normal tonalite, except that it contains abundant needles of hornblende 1 inch to 2 inch long. The fragments range in diameter from less than an inch to 3 feet, with an average of about 4 inches. They consist of fine-to-medium-grained andesitic and dacitic volcanic rocks, some of which are coarse breccias, and they show all degrees of impregnation with younger igneous material.

Many of the fragments are discoidal, but they show no distinct or consistent orientation. In most exposures they form a subordinate part of the contact breccias, but locally they are so abundant that the entire rock resembles a "puddingstone."

Where fresh, the normal tonalite is light gray to moderately dark greenish gray. It is seriate in texture, with minerals ranging in diameter from 0.5 mm to 6 mm. The principal constituent is plagioclase, mainly in zoned crystals of labradorite to median andesine. The largest grains are euhedral, the others are subhedral. Quartz also occurs as large grains, and in addition forms micropegmatitic intergrowths with orthoclase and oligoclase. Some orthoclase also is present as anhedral crystals that bear no systematic relation to the quartz.

Green hornblende occurs as prismatic crystals scattered throughout the rock, with albite and epidote in fracture-filling veinlets, and in fine-grained, felt-like aggregates that corrod quartz and feldspar. Biotite is a sparse but widespread constituent, and the chief accessory minerals are sphene, apatite, magnetite, ilmenite, and pyrite. Epidote and chlorite are abundant alteration minerals, and appear to give the rock its greenish color.

Much coarser-grained intrusive rocks are exposed on the mountain side less than a mile northeast of the Pioneer mine, where they form prominent knobby outcrops. A felsic gabbro, with laths of calcic labradorite 4 mm. to more that 12 mm. long, is closely associated with a gabbro porphyry that has an unusual "blotchy" appearance, especially on weathered outcrops. The "blotches" are bundles and rosettes of pencil-like hornblende crystals, some two inches or more long. Locally this rock also has a pillow-like appearance, caused in part by closely spaced rounded inclusions of partly digested volcanic rocks. The host material is relatively felsic, and has a rude planar structure that wraps around the inclusions. It consists of labradorite, epidote, and hornblende, with some biotite, quartz, and orthoclase. The quartz and orthoclase commonly form micropegmatitic intergrowths, which also contain some muscovite. Calcite and epidote are widely scattered alteration minerals.

Though younger than the Santiago Peak volcanics, these intrusive rocks appear to be closely related to them. They evidently were affected by the same metamorphic processes, and contain abundant epidote, chlorite, and carbonate minerals. As pointed out by Larsen,\(^{20}\) they are intimately associated in space with the volcanic rocks, and, in some areas, with the pre-volcanic metamorphic complex, and they differ markedly in petrography from the more widespread younger intrusive rocks. They are therefore tentatively assigned to the Jurassic, along with the Santiago Peak volcanics.

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20 Larsen, E. S., op. cit., p. 27, 1948.

\(\text{Rocks of Southern California Batholith}\)

The youngest crystalline rocks in the area studied are representatives of the southern California batholith. The principal type is a medium- to coarse-grained, very light gray rock termed the Escondido Creek leucogranodiorite by Larsen.\(^{21}\) It is very resistant to erosion, and forms bold cliffs with angular to rounded, somewhat boulder-like projections. It is best exposed on the north side of the San Dieguito River canyon, north-northeast of the pyrophyllite area.

The granodiorite is texturally uniform in most places, but is distinctly porphyritic near its contacts, particularly contacts with the Santiago Peak volcanics. Inclusions of the older rocks also are present in these marginal zones. The average grain size of the granodiorite is about 1 mm. Its mineral constituents, in order of decreasing abundance, are oligoclase, quartz, microcline and orthoclase microperthite, hornblende, biotite, magnetite, pyrite, apatite, and zircon.

The rock occurs both as large, stock-like masses and as dikes that transect the Santiago Peak volcanics, the pre-batholith tonalites, and the tonalite-matrix contact breccias described above. It also cuts the earlier, in general more basic units of the batholith, chiefly in areas several miles north and northwest of the mine.

Large masses of Woodson Mountain granodiorite, a coarse-grained, light gray member of the batholith sequence,\(^{22}\) form bold hills 4 to 5 miles east and east-northeast of the mine. These hills are characterized by a cover of large, bare, closely spaced boulders of disintegration.

The southern California batholith is of Lower Cretaceous or Upper Cretaceous age,\(^{23}\) and its rocks appear to post-date the folding and metamorphism that affected the Santiago Peak volcanics and associated intrusive rocks.\(^{24}\)

\(\text{Younger Rocks}\)

A complex section of Upper Cretaceous and Tertiary rocks is known from the coastal region of southern California, but is represented in the area of present study only by sediments of probable Eocene age. These are poorly consolidated arkosic sands and interbedded silts that probably correspond to a part of the Torrey sand member of the La Jolla formation.\(^{25}\) They underlie the southwestern part of the area studied, and project eastward into its central, central-eastern, and southeastern parts (pl. 1). In general, they are poorly exposed, but they appear very clearly in several areas of actively developing gullies and small badlands.

Evidently these sediments were laid down on a surface of considerable local relief, perhaps amounting to as much as 500 feet in some places. They lap abruptly onto moderately steep slopes of pre-Tertiary crystalline rocks (fig. 9), some of which now are exposed as "islands."

\(\begin{align*}
21 & \text{Larsen, E. S., op. cit., p. 57, 1948.} \\
25 & \text{Larsen, E. S., op. cit., pp. 135, 1948.} \\
26 & \text{Larsen, E. S., op. cit., pp. 32-33, 1948.} \\
\end{align*}\)
Figure 9. Sketch section of San Dieguito River valley southwest of Hodges Dam
entirely surrounded by the younger, unconsolidated rocks.

Most of the sands are white, buff, or greenish gray in color. They are characterized by a coarse, open texture, and contain abundant fresh feldspar grains and moderate quantities of hornblende, muscovite, and biotite. Some beds are rich in magnetite and ilmenite. In general the sands are well stratified, with very gentle dips to the south and southeast. Cross bedding, ordinarily in 2-inch to 10-inch layers, is widespread.

No fossils were found in these sediments during the course of the present investigation, and their correlation with the Torrey sand to the south is founded chiefly upon their lithology and their relative position in the section as inferred from their altitude and areal distribution. Evidently they represent conditions of rather rapid deposition, possibly in a fluviatile or brackish water environment. The thickness of the section is not known, but probably is 220 feet or more, as suggested by known exposures and the logs of several wells.

Overlying the Eocene (?) rocks with distinct unconformity are coarse-grained terrace gravels of Quaternary age (fig. 4). The oldest of these deposits cap broad surfaces of marine erosion, remnants of which are preserved above the 300-foot contour south and southwest of the mine area. The gravels and their associated coarse, arkosic sands are about 10 feet in average thickness, but locally reach thicknesses of 30 feet or more. The constituent rock fragments are rounded, and range in diameter from less than an inch to nearly 2 feet. Most are Santiago Peak volcanics, but many others consist of batholithic rocks and older crystalline types. Owing to the occurrence of widespread hematite in the cementing material, most of the gravels are distinctly reddish in color.

At least 3 younger terraces are present at lower levels in the pyrophyllite area, where they appear to have been cut by the San Dieguito River. Some were developed in bedrock of pre-Tertiary age, as in the immediate vicinity of the mine, and may well represent exhumed parts of an extensive pre-Eocene surface of erosion. The exposed rocks are deeply weathered, and are discolored by fracture-controlled stains of iron oxide to depths of 60 feet or more.

In places these terraces are veneered with nearly horizontal bedded sands and coarse gravels (fig. 9), locally as much as 25 feet thick. The gravels are composed mainly of well rounded, poorly to well-sorted fragments of batholithic and older crystalline rocks. They are loosely cemented except locally along their contacts with underlying pre-Tertiary rocks, where abundant iron and manganese oxides hold the pebbles firmly in their matrix. Such cemented gravel is exposed in the vicinity of the Pioneer mine (pl. 2).

The youngest deposits in the area include colluvium, valley fill, and local talus, landslide, and fan accumulations. These consist of interbedded sand, gravel, and ill-sorted rubble. All are unconsolidated, and range in thickness from less than a foot to 25 feet. Well sorted gravels are present along the course of the San Dieguito River, although in many places this stream is actively cutting into bedrock (pl. 1).

Structure

The structure of the Santiago Peak volcanics seems to be rather simple, even though individual flow and pyroclastic units lie nearly on edge in many places. This essentially homoclinal series is disturbed in detail, however, by some moderately open to very close folding and crumpling. Some of the rocks are much sheared, and locally are distinctly schistose, with irregular subparallel planes of recrystallization ½ inch to 2 inches apart.

In places the shearing and schistosity are subparallel to the primary layering of the volcanic rocks, but elsewhere they dip more gently and strike northwestward across the north-northwest trend of individual horizons. This divergence is well shown on several low knobs that project above Tertiary sediments north of the San Dieguito River and about ¼ mile west-southwest of the Pioneer mine (pl. 1). In general, the schistosity is most nearly parallel to original planar elements where it occurs in thin, relatively incompetent units between thick masses of breccia or other relatively competent rock. In contrast, such planar features transect the noses of folds in the primary layering, regardless of the relative thicknesses and degrees of competency of the host units.

Poorly defined lineation is shown by elongate phenocrysts in the flow rocks, and by the intersections of primary and secondary planar elements. Most of the linear elements plunge moderately to steeply north to north-northeast, and another, much less widespread set plunges very gently. The total number of measurable linear features observed in the area is so small, however, that little statistical value can be attached to interpretations of their orientation.

Faults, shear zones, and tectonic breccia layers are exposed at many places. Ordinarily these features are unidirectional in a given outcrop, but in some places two sets of shear planes intersect at acute angles. Some of the faults appear to have involved rather small offsets, but the amount of movement in most is not determinable. The shearing, faulting, and schistosity antedate the youngest metamorphic minerals in the rocks, but some postmetamorphism movement also has taken place along numerous faults and shear zones.

Little planar structure is present in most of the intrusive rocks, except locally near their walls. Here flowage of the groundmass around phenocrysts is particularly evident, and in places the phenocrysts themselves are distinctly oriented parallel to the contacts. Several prominent joint sets appear in the granodiorite rocks of the batholith complex, in which their trends are emphasized by the distribution of residual boulders. Most of the joints trend northerly, with dominantly steep dips, and east to east-northeast, with moderate north to north-northwest dips. In the northwest part of the area, the volcanic rocks are transected by fractures that trend east-northeast; many of these are filled with dikes that dip steeply south-southeast.

The structure of the Tertiary rocks is rather simple. They are gently tilted, as shown by distinct components of dip away from the ocean, and in places they are cut by faults of small displacement. The principal irregularity, however, is one of original sedimentation on a very uneven surface.
Summary of Geologic History

The geologic history of the San Dieguito area comprises the following major episodes:

Volcanism and concomitant sedimentation, leading to accumulation of considerable thicknesses of flow and pyroclastic rocks, with minor interlayered argillaceous sediments. These were laid down, probably in Jurassic time, over a surface cut in part on Triassic metasedimentary and metavolcanic rocks, and in part on older rocks.

Emplacement of stocks and dikes of tonalite and gabbro porphyry.

Tilting, folding, faulting, and shearing, with widespread low-rank metamorphism of the volcanic and associated intrusive rocks.

Emplacement, in Cretaceous time, of granodioritic rocks representing the southern California batholith. This was accompanied locally by contact metamorphism of the pre-batholith rocks.

Profound and widespread erosion, with development in Upper Cretaceous time of a broad surface of low relief.

Deposition and subsequent removal by erosion of Upper Cretaceous clastic sediments.

Deposition of Eocene (?) sands over a surface of moderate relief, developed on the Mesozoic crystalline rocks.

Sedimentation and erosion throughout the remainder of Tertiary time, with ultimate complete erosion of all Tertiary beds younger than Eocene (?).

Development of Pleistocene terraces at successively lower levels, chiefly by marine planation, with concomitant development of fluvialite terraces along some streams.

Development of the present topography, with deposition of valley fill and accumulation of talus, fan, and other unconsolidated deposits.

PYROPHYLLITE-BEARING ROCKS

Distribution and Occurrence

The pyrophyllite-bearing rocks constitute altered parts of the Santiago Peak volcanic series. They are readily recognized in the field, mainly because of their characteristic white, buff, tan, or light gray color. Many of them are distinctly weathered, and are marked by widespread iron-oxide stains. These rocks are prominent in the bottom and along both sides of the San Dieguito River for a distance of nearly a mile, and they also crop out on ridges and slopes east and southeast of the river. With the other rocks of the volcanic series, they appear in an area that is surrounded by sediments of Tertiary and Quaternary age (pl. 1). This area is elliptical in plan, with a maximum, or northeast-southwest dimension of about 1 1/2 miles. Additional volcanic rocks are exposed a short distance to the north and east.

In general, the pyrophyllite-bearing rocks crop out plainly, and most continuously so along the river. They also have been well exposed by stripping along several ridges and hillsides. In the southwestern part of the area, most of these rocks form outcrop belts a few inches to 150 feet wide, and a few feet to at least 1500 feet long. Their depth dimensions appear to be of the same order as their lengths, so that most are probably thinly discoidal masses. They trend northwest and dip steeply to very steeply northeast, in essential conformity with the layering of the enclosing volcanic rocks.

Much thicker masses of pyrophyllite-bearing rocks are present farther northeast in the area. Here they are 3000 feet or more long, and as much as 1300 feet in outcrop breadth. The ends of the longest masses are covered by younger rocks, so that their shape is not accurately known. The Pioneer mine lies within the largest single body of pyrophyllite-bearing rock, a thick, bulbous mass that trends west-northwest. Much of this rock terminates abruptly east-southeastward against dacitic volcanics, but some continues to the southeast as a relatively thin "tail" more than 1300 feet long (pl. 1).

Rock Types

Classification

Several different types of pyrophyllite-bearing rocks can be recognized in the San Dieguito area on the basis of their texture, color, and pyrophyllite content. As discussed in some detail farther on, these rocks were developed by alteration of pyrophyllite-free volcanic flows, breccias, and tuffs that ranged in composition from andesite to rhyolite. There is complete gradation from one kind of altered rock to another, but most individual types are readily distinguishable as such. Even so, the detailed drawing of boundaries between any two of the principal pyrophyllite-bearing rock types is necessarily somewhat arbitrary, particularly where there are gradations along the strike of lenticular masses.

In the mapping of the Pioneer mine area (pl. 2), six kinds of crystalline rocks were distinguished on the basis of megascopic examination and supplementary study under the microscope. In order of decreasing pyrophyllite content, these units are: (1) Pyrophyllite schist. (2) Pyrophyllite-quartz schist. (3) Andesitic to quartz latitic flows and pyroclastic rocks, moderately pyrophyllitized. (4) Andesitic to quartz latitic flows and pyroclastic rocks, slightly pyrophyllitized. (5) Andesitic to quartz latitic breccia, slightly pyrophyllitized. (6) Leucocratic quartz latitic and rhyolitic flows and pyroclastic rocks, locally much silicified.

The silicified leucocratic rocks are the only ones in the mine area that are essentially pyrophyllite-free.
little dacite- and dacite breccia also appears within the pyrophyllite-bearing rocks as relatively unaltered residua, but these masses are too small to be shown on the map. Much larger bodies of only slightly altered volcanic rocks crop out not far beyond the limits of the mine area, especially to the north and northwest, where they contrast sharply with the relatively soft, 'punky' pyrophyllite-bearing rocks. They are tough and fresh appearing, and ring when struck with a hammer.

Volcanic Breccias

**General Features.** The volcanic breccias, as described in preceding pages, are low-rank metamorphic rocks characterized by coarsely clastic structure, porphyritic texture in both fragments and matrix, and an average composition of dacite. These rocks include numerous representatives from the last four map units indicated above, and are particularly abundant in the south and southeastern parts of the Pioneer mine area (pl. 2). They also occur in the surrounding area, where they form a substantial part of the unit designated in plate 1 as "pyrophyllite-bearing volcanic flows and pyroclastic rocks." They typically form lenticular bodies oriented in conformity with subparallel shear zones.

The quartz latite and rhyolite breccias contain very little pyrophyllite, and the breccias of more basic composition also contain less pyrophyllite than the other rocks of the mine area. Where slightly pyrophyllitized, the andesite and dacite breccias are white, gray, tan, or greenish gray, and locally are stained reddish brown or black along fractures. Most are hard, and silicification appears to be widespread. Weathered outcrops of these rocks commonly have a nodular appearance, as if containing many pebbles. This nodular weathering is not characteristic of all exposures, however, and on the geologic map some masses of this rock may well have been included with ordinary flows.

**Petrography.** The least pyrophyllitized dacitic breccias in the Pioneer mine area consist chiefly of quartz, with 10 to 20 percent of pyrophyllite. Most of them evidently were originally porphyritic, but the textures are difficult to decipher in detail because of widespread silicification. The groundmass contains nearly all the pyrophyllite in those rocks in which this mineral is a relatively minor constituent (figs. 10, 11).

In one type of partly silicified rock, both phenocrysts and groundmass are extensively replaced by quartz. The groundmass is mainly a semi-opaque aggregate of fine-grained pyrophyllite, clinozoisite, and albite, with dust-like hematite and leucoxene. It contains veins of quartz in small satured grains; in some irregular areas these grains reach a diameter of 1 mm. The age relations of quartz and pyrophyllite are well shown in numerous specimens, where mosaics of small quartz grains in the groundmass are in part replaced by stringers of pyrophyllite (fig. 12). These stringers are similar in general appearance to those of serpentine in altered masses of olivine. A slight schistosity appears wherever the proportion of pyrophyllite increases considerably.

Quartz replaces most of the feldspar phenocrysts, forming aggregates of grains distinctly coarser than those in the groundmass. Mosaic texture is characteristic of both occurrences, however. Some of the quartz grains are partly clear, with the clearer portions commonly rimmed with inclusions that may represent material rejected from minerals replaced by the quartz. The clear quartz is itself corroded and partly replaced by pyrophyllite flakes. In addition, scum-like aggregates of pyrophyllite and hematite form numerous replacement veins in the quartz of both phenocryst and groundmass occurrence. The original mafic groundmass minerals do not appear to have been entirely removed, but instead are intimately mixed with the pyrophyllite. There is no such contamination in the areas of clear quartz.

Quartz also occurs as lens- and pod-like aggregates of anhedral grains (fig. 10). Many of these contain coloform silica that appears to represent open-space filling contemporaneous with or slightly later than development of the lenses. Some of this fine-grained silica might have been arsenopyrrhotoid in origin, and hence originally formed much earlier in the history of the rock.

Most breccias also contain hornblende, biotite, chlorite, epidote, ilmenite, pyrite, and leucoxene. The chlorite,
chloritoid, and epidote are plainly earlier than the pyrophyllite, which replaces them and occurs within them as fracture-filling veinlets. In some thin sections, the pyrophyllite is clearly pseudomorphous after chlorite, Ilmenite is widespread as small skeletal crystals, in large part altered to leucoxene. Flakes of clear pyrophyllite occur adjacent to ilmenite and leucoxene grains, occupying the corners of the "eyes" formed by bending of the groundmass structure around these grains.

In the more highly pyrophyllitized breccias, the fragments and matrix are difficult to distinguish from each other. On the other hand, palimpsest porphyritic textures are readily recognized. With increasing pyrophyllitization, the pyrophyllite-quartz ratio ordinarily increases, and the proportions of epidote, chlorite, chloritoid, albite, and original labradorite-andesine, biotite, hornblende, and pyroxene decrease. In some specimens widespread silification appears to have preceded development of pyrophyllite, and even in moderately pyrophyllitized rocks the proportion of quartz is high.

Progressive pyrophyllitization of the breccias is well shown by several samples obtained from the bed of the San Dieguito River north of the Pioneer mine. One light gray to white rock, a typical very slightly pyrophyllitized breccia, is chiefly an aggregate of quartz and albite, with rather uniformly scattered finer-grained pyrophyllite. The pyrophyllite occurs as tiny equant grains, rather than flakes, and replaces the quartz and feldspar. It is virtually confined to the groundmass, and the original feldspar phenocrysts are almost completely silicified.

In contrast, a second variety of breccia, distinctly richer in pyrophyllite, shows a much coarser-grained groundmass. Here the pyrophyllite occurs as distinct flakes, many of which appear to have developed by progressive overgrowths on tiny grains of the type described above. Although the pyrophyllite is most abundant in the groundmass, irregular patches and vein-like aggregates also occur in most of the silicified phenocrysts. The original porphyritic texture is only faintly preserved, but is plainly recognizable under low magnifications.

Other, still more pyrophyllite-rich breccias show further development of these same trends. The pyrophyllite forms flakes and thin blades that are scattered through both phenocrysts and groundmass of the host rock. The groundmass texture is distinctly coarser than that of the breccias, with lower pyrophyllite content.

The most silica-rich and pyrophyllite-poor types of breccia evidently were developed from leucocratic rocks of original quartz latitic to rhyolitic composition. They form irregularly lenticular bodies that ordinarily are surrounded by relatively pyrophyllite-rich rocks. One large pod-like mass, with a maximum exposed dimension of 110 feet, forms the hill southwest of the open cuts of the Pioneer mine, and another mass, at least 70 feet long, forms another hill east of these cuts (pl. 2). In general, these masses are elongated in the direction of most pronounced shearing in the area, and have lengths 2 1/2 to 3 1/2 times their average widths.

The leucocratic breccias weather to blocky boulders and small, angular fragments. Bluish gray to greenish gray and pale buff colors are typical of fresh surfaces, and greenish brown, reddish brown, and black are most common on weathered and stained surfaces. Some parts of the exposures are porous, owing to leaching of unsilicified material during weathering.

These rocks are distinctly porphyritic under the microscope. Here and there in the fine-grained mosaic of groundmass quartz are shreds and ragged shred groups of pyrophyllite. In the phenocrysts there are all gradations from individuals of primary plagioclase and orthoclase to pseudomorphs of granular, anhedral quartz. Variations in texture of the quartz and in distribution of fine-grained accessory minerals preserve the outlines of the phenocrysts, even where silification is almost complete.

In many specimens there are appreciable quantities of epidote, residual feldspars, and pyrite. Both quartz and epidote generally are of the same age, and occur together in numerous late-stage fracture-filling veinlets. A little of the quartz is still younger, however, and ordinarily is associated with grains of pyrophyllite.

Volcanic Flows and Tuffaceous Rocks

Slightly to moderately pyrophyllitized volcanic flows and tuffaceous rocks, along with the volcanic breccias described above, constitute more than 95 percent of the pyrophyllite-bearing rock shown in plate 1. They occur in all areas in which pyrophyllite has been identified, and are particularly abundant south and southeast of the main Pioneer mine workings. These flows and tuffaceous rocks are interlayered with the volcanic breccias, and wherever all the types contain abundant pyrophyllite they are not easily distinguished from one another.

Slightly pyrophyllitized rocks. The slightly pyrophyllitized flow and porphyroclastic rocks are white, tan, or pale greenish gray on fresh surfaces, and purplish to reddish brown on weathered surfaces. They are hard, and although some pyrophyllite is present in most, they cannot be scratched with the fingernail. These rocks ordinarily contain less quartz than the altered breccias, and hence do not have such a gritty feel under the fingernail.

Some outcrops are essentially massive, but closely spaced fractures cause a sheeted appearance in others. Weathered surfaces are typically rough in detail, and locally there is a slight suggestion of pebblyness, similar to that so common in the breccias. Most of the rock is finely

![Figure 12. Partly pyrophyllitized dacite. Relict zoning in plagioclase phenocrysts. Groundmass mainly quartz, pyrophyllite, and opaque minerals. Crossed nicols, X 45.](image-url)
granular in appearance, with little schistosity evident in hand specimens. A porphyritic texture, characteristic of a few outcrops, presumably is due to selective weathering of numerous mineral grains. Small, limonitic masses of highly calcified limestone rock, similar to much larger breccia masses already described, are scattered irregularly in most areas of exposure.

In thin section the slightly pyrophyllitized volcanic flows show well preserved original textures. Both porphyritic and nonporphyritic types are represented, with the former best shown by differences in orientation of pyrophyllite flakes and variations in coarseness of quartz mosaics. Both zoning and twinning of original plagioclase are evident in some specimens, even where no feldspar is now present (fig. 13).

Quartz and pyrophyllite are about equally abundant in most of the slises examined, although accurate determinations are made difficult by the fineness of the groundmass and by local iron-oxide stains. Quartz occurs both as very fine-grained aggregates and as metacrysts 0.2 mm. to 1.5 mm. in diameter. The latter are clearest, and seem to have been formed chiefly at the expense of groundmass minerals. Pyrophyllite replaces the quartz, both in the smaller and the larger grains (fig. 14); thus most of the phenocrysts appear to have been altered to quartz and then to pyrophyllite.

The pyrophyllite forms tiny flakes, as well as scattered shreds and flakes 0.5 mm. to 1.5 mm. in maximum dimension. Mesh-like aggregates of the larger shreds also occur in the coarsest quartz, where they were introduced along networks of fractures. Such aggregates stand out prominently from the much finer-grained pyrophyllite mosaics of the groundmass.

As in the slightly pyrophyllitized breccias, other, generally minor minerals include hornblende, biotite, chlorite, chloritoid, epidote, clinzoisite, and pyrite. Irregular grains of leucoxene are scattered through most of the rocks, and evidently were formed from ilmenite. Hematite is present as tiny, pinkish opaque grains and dust-like particles in the groundmass, and also in later veins as blood-red translucent to opaque anhedral. The earlier hematite apparently was formed by hypogene alteration of mafic minerals in the original volcanic rock, whereas the vein-forming crystals are of supergene origin.

A somewhat different rock type, represented only in a few exposures, is tan to light brown and has a blocky appearance on weathered surfaces. It is chiefly an extremely fine-grained aggregate of pyrophyllite and quartz, with widespread cloudy masses of nearly opaque material. No porphyritic texture is evident, and the original rock may have been a fine-grained tuff, perhaps with a glassy base.

Another rock type resembles a reddish-brown sandstone with a few relatively large, well-rounded sand grains. Under the microscope it consists mainly of reddish-brown translucent to opaque material, both in extremely fine-grained aggregates, and locally in spherical grains with faintly discernible radiating structure. Some of these grains have cores of intergrown quartz and pyrophyllite. Granular aggregates of these minerals also are scattered through the groundmass. Originally, this rock may have been a latite or quartz latite, with a fine-grained or even a glassy groundmass. It may well have been weathered prior to metamorphism, with development of iron oxides and clay minerals.

**Modestly pyrophyllitized rocks.** Exposures of the moderately pyrophyllitized flow rocks are confined to the vicinity of the Pioneer mine, the banks of the San Dieguito River west of the mine, and to a few localities on the hill slopes south of the mine area. These rocks are interfingered with less pyrophyllitized types and with more pyrophyllitized types. They occur as lenses within larger masses of other rock, and smaller masses of such rock are present as lenses within them. Nearly all these lenses are aligned in accord with the prevailing direction of shearing (pl. 2).

The moderately pyrophyllitized flow rocks are similar in color, texture, and structure to those with smaller proportions of the mineral. They ordinarily contain less silica, however, and their outcrops are not so bold. Though distinctly softer, they are scratched by the fingernail only with difficulty, and in many places not at all. Porphyritic texture is evident in most hand specimens. Small grains of quartz are present, but are neither as numerous nor as prominent as in the less pyrophyllitized rocks. Most fresh exposures show no well-defined planar structure, but enough of the mineral grains in the rock are arranged in layers to give a crudely platy appearance to most weathered surfaces.

In thin section these rocks contain more pyrophyllite than quartz. Porphyritic textures are well preserved, despite the complete alteration of most feldspar phenocrysts to these two minerals. The groundmass is a fine-grained aggregate of quartz grains and clear flakes of pyrophyllite. Some relatively coarse-grained mosaics of quartz are embayed and replaced by pyrophyllite. A few specimens contain as much as 30 percent of oligoclase and subordinate orthoclase, which appear in the groundmass rather than as phenocrysts. These feldspars form less than 5 percent of most specimens, however.

Much of the pyrophyllite occurs as tiny rosettes, both in the groundmass and in the altered phenocrysts. Distinct alignment of abundant pyrophyllite flakes forms a well defined schistosity in a few places, and in others the
flakes are oriented parallel to or normal to the margins of original feldspar phenocrysts. Crystals of leucoxene are scattered through most of the rocks. Some of these crystals contain residual "islands" of ilmenite, a mineral that may have developed in part during the pyrophyllitization process. The largest ilmenite grains appear in those rocks with the most pyrophyllite.

**Pyrophyllite-Quartz Schist**

*General features.* Most of the pyrophyllite-quartz schist is exposed in and around the main open cuts of the Pioneer mine, on the hill to the east and southeast, and in the vicinity of a vertical shaft about 300 feet south of the cuts. The rock is white, pinkish, or greenish gray, but where weathered it is stained tan to dark reddish brown along numerous fractures. It can be scratched by the fingernail in most outcrops, although commonly with some difficulty. It is distinctly schistose, both in fresh and weathered masses, but chalky white phenocryst phantoms are visible in some hand specimens. On weathering, the schist breaks down into small wedges and plates. Some of these contain residual lenses, an inch or less in maximum dimension, of silicified flows and breccias. Elsewhere, lenses of similar rock reach maximum dimensions of 10 feet or more.

*Petrography.* Under the microscope, the quartz-pyrophyllite schist is a fine-grained aggregate of pyrophyllite flakes with a little micocrystalline quartz and much larger, clearer grains of quartz. Most of these grains are embayed and transsected by aggregates of fine-grained pyrophyllite (fig. 15). A well defined schistosity, formed by coarser flakes and shreds of pyrophyllite, is interrupted only by individual crystals and some large crystal-line masses of quartz. Many of these are characterized by exploded-bomb texture, with quartz fragments in a matrix of fine-grained pyrophyllite. Some pyrophyllite flakes in the schist are large enough to show very clearly their cleavage, although no interference figures could be obtained. Instead of sharp extinction, these larger grains have a "curly maple" appearance similar to that in micas.

![Figure 15. Pyrophyllite-quartz schist. Exploded bomb texture in quartz-grain cut and embayed by fine-grained pyrophyllite. Crossed nicols, X 40](image)

**Pyrophyllite Schist**

*General features.* Most of the exposed pyrophyllite schist occurs as a long, relatively thin lens, in which the main cuts of the Pioneer mine have been developed. It is in part surrounded by pyrophyllite-quartz schist, with which it intergrades on both large and small scales. The two rocks intergrade along the strike of their schistosity, but are sharply bounded in a direction normal to the schistosity. Here and there the pyrophyllite-rich rock contains lenses of silicified rhyolite and quartz latite, as well as residual "boulders" of partly pyrophyllitized dacitic breccia and flow rock.

The pyrophyllite schist is white to very light gray where fresh, but near the surface it is stained along and adjacent to fractures by iron oxides. A few dark spots consist chiefly of manganese oxides. Schistosity is well developed, and the rock breaks into long splinters, slabs, and rough rhombohedral blocks. It splits fairly smoothly in the direction of schistosity, but commonly forms hackly surfaces when broken across the schistosity. Megascopically, the pyrophyllite is fibrous to massive, and in general does not form clearly recognizable rosettes. It has a faintly soapy feel, and most of it is readily scratched with the fingernail. In general appearance it resembles compact talc.

*Petrography.* Under the microscope the pyrophyllite schist is similar to the pyrophyllite-quartz schist, except that it contains much less quartz. Ilmenite, leucoxene, and pyrite are the chief accessory constituents. Ghosts of phenocrysts are clearly preserved, even though all the feldspar has been replaced by pyrophyllite. A few aggregates of anhedral quartz are scattered through the rock. The grains, about a millimeter in average diameter, are clear and fresh in appearance. They are embayed and partly replaced by pyrophyllite, which forms little shreds and flakes with rather consistent orientation (fig. 16). Some pyrophyllite occurs as tiny flattened rosettes that are oriented in accord with adjacent blades and flakes of greater size. So fine-grained is all the pyrophyllite, however, that the entire rock is homogeneous in general texture.

**Structural Relationships**

The occurrence of pyrophyllite appears to have been governed mainly by pre-metamorphism fracturing and
shearing in the host volcanic rocks, both in a broad way and in detail. It also is related in some degree to variations in original composition of these rocks, but appears to have been little influenced by their identity as breccias or as flows. Relatively little pyrophyllite is present in those rocks that were most silicified prior to pyrophyllitization.

The various rock types are sharply bounded from one another, as followed across the trends of primary planar structures or later shearing, but they are typically gradational along these trends. The presence of folds is suggested in a few places by the broad, nose-like traces of faintly recognizable primary layers. In the eastern part of the mine area (pl. 2), layering appears to represent an original feature of the volcanics that can be traced northward around the axis of a west-plunging syncline before passing beneath a thin mantle of terrace gravels.

In the vicinity of the Pioneer mine the rocks are sheared along northwest-trending zones that are vertical or dip very steeply. Here and there these zones depart from the prevailing direction, as near the east end of the main open cuts, where their trend swings to the east, and near the southern end of the mine area, where their trend is southwest. Prominent shear zones also lie normal to the major trends, and in some places the rocks are transected by fractures and shear planes without systematic orientation. In general, the rocks richest in pyrophyllite are most sheared, and those with relatively little pyrophyllite show little well-defined shearing.

Typical relations between shearing and mineralization are shown along the margins of an elongate mass of slightly pyrophyllitized dacite breccia 3000 feet south of the Pioneer open cuts. Here a well defined set of shear planes and joints trends northwest and dips very steeply northeast, essentially parallel to the primary flow structure of the volcanic series. A second set trends nearly due west and dips steeply north. As shown in figure 17, the contact between pyrophyllite-free and pyrophyllite-bearing rock trends northwest, or parallel to one shear set, whereas the other shear set controls the contact in detail. This relation is characteristic of a rather large area, and appears on both large and small scales. Moreover, the mineralizing solutions evidently circulated through both sets of shear planes and fractures, so that there is a transition from pyrophyllite-bearing rock into pyrophyllite-free rock through a zone in which block-like masses of pyrophyllite-free rock are outlined by a network of pyrophyllite-bearing stringers.

The planar structure in the pyrophyllite-quartz schist and in the pyrophyllite schist might have been developed by selective replacement of minerals already possessing a schistosity, by application of stresses during formation of the pyrophyllite, or by recrystallization of the pyrophyllite under stress. Some of the schistosity may well have been inherited, as there are zones of discernible schistosity in the less altered rocks. On the other hand, the presence of widespread palimpsest porphyritic textures in rocks that extend to the boundaries of the pyrophyllite-schist masses suggests that pre-pyrophyllite shearing must not have been very extensive. Moreover, thin sections of the slightly altered rocks indicated that pyrophyllite is the only mineral with a preferred orientation; the more abundant the pyrophyllite, the more pronounced is this orientation. It seems probable that the schistosity in the pyrophyllite-rich rocks dates from the time of mineralization, or from some subsequent period of deformation during which only the pyrophyllite was reoriented.

If much shearing had postdated pyrophyllitization, the quartz and leucoxene grains within the schist probably would have been rolled or fractured to some degree. They show no evidence of rolling or cataclasis, and only a few grains contain fractures at all. That the stresses causing mineral orientation probably were not severe is suggested by the unaltered primary textures of rocks in which a slight schistosity is shown solely by concentrations of pyrophyllite flakes and shreds.

Pyrophyllite

Mineral Relationships

The pyrophyllite, as observed in hand specimens of high-grade schist, is rather uniform in color. Most is white to creamy white, but is stained along numerous fracture surfaces by iron and manganese oxides. The mineral is softer than the fingernail, and probably lies between 1 and 2 on the Mohs scale. It has a greasy feel and an earthy to distinctly pearly luster. The specific gravity of the purest pyrophyllite aggregates that could be separated under binoculars ranges from 2.81 to 2.86.

Under the microscope the pyrophyllite appears as tiny anhedral grains, anhedral to subhedral shreds and flakes, and, rarely, as tiny rosettes and fibrous aggregates of radial pattern. Many of the smaller flakes have a cloudy appearance, owing to admixed opaque material. In the least pyrophyllitized rocks the flakes are extremely small, but some of those in the pyrophyllite schist are several millimeters long. None are large enough to yield interference figures. The preferred orientation of such flakes gives a mass birefringence effect, however, with definite positions of maximum and minimum illumination, over relatively large areas. The median index of refraction of the mineral, Na., is 1.588 ± 0.001.

Other Minerals

Most of the mineral relationships in the pyrophyllite-bearing rocks already have been described, and the following data are presented in summary.

Plagioclase, chiefly in the labradorite-andesine range, is the most abundant phenocryst feldspar, and is a widespread groundmass constituent as well. Phenocrysts of orthoclase are rather rare, but potash feldspar is abundant in the groundmass of several rock types, both as
Figure 18. Geologic map of a small area in channel of the San Dieguito River, San Diego County, California.
small anhedral crystals and in micropegmatite intergrowths with quartz. Fine-grained aggregates of albite and oligoclase are scattered through most of the volcanic rocks, in which they evidently were formed by alteration of earlier, much coarser feldspars.

Quartz is present in coarsest form as phenocrysts, many of which were embayed and partly curved. All now appear as recrystallized aggregates. Quartz also forms large, clear grains of secondary origin. These and much finer-grained aggregates replace feldspar phenocrysts and parts of the groundmass in many rocks. Numerous aggregates of microcristalline quartz occur in the finest-grained groundmass mosaics, where they are intimately associated with orthoclase, oligoclase, iron oxides, ilmenite, leucoxene, sphene, chlorite, and serpentine. Many of these aggregates appear to have been formed through devitrification of a glassy volcanic groundmass.

The mosaics of quartz, both old and relatively young, are transected by still younger quartz veins in many places. This youngest quartz appears to be essentially contemporaneous with most of the pyrophyllite in the rocks, whereas the quartz that replaces original phenocryst and groundmass minerals is distinctly older than the bulk of the pyrophyllite.

Hornblende, augite, biotite, and other original mafic constituents are not common in the pyrophyllite-bearing rocks. Evidently these minerals were in part replaced by epidote, chlorite, serpentine, and sodic plagioclase during the mild metamorphism of the rocks, and in part removed during the earliest stages of the subsequent pyrophyllitization.

Ilmenite appears to be more abundant than magnetite in most of the rocks, and the moderately to highly pyrophyllitized types contain more titanium oxide than total iron oxides. The ilmenite forms anhedral to subhedral grains, a few of which show skeletal structure. Nearly all are extensively altered to leucoxene, which is one of the most common opaque minerals in these rock types. Magnetite occurs as an alteration product of the original mafic minerals, and possibly also as a primary constituent of the volcanic rocks. It forms small anhedral masses and very abundant dust-like aggregates. Some of it has been altered to hematite.

Hematite is intimately associated with magnetite and ilmenite as a hypogene alteration product. Some of it may have been derived from pyrite and pyrrhotite as well. A much younger, supergene generation of hematite occurs along fractures, where it is commonly associated with manganese oxides. In a few specimens of pyrophyllite-quantz schist obtained from the deepest parts of the Pioneer mine workings, numerous partial pseudomorphs of hematite contain unreplaced cores of pyrite. Pyrite and other sulfide minerals probably are abundant and widespread accessory constituents, although they have been largely removed by oxidation from the near-surface rocks thus far exposed.

Much epidote is present in the slightly pyrophyllitized rocks as tiny anhedral to euhedral grains and aggregates of grains, most of which were derived from primary mafic constituents of the volcanic flows and breccias. It also is an associate of quartz in many cross-cutting veinlets, and as such is younger than all other abundant minerals except pyrophyllite.

Chlorite, like epidote, is widely scattered as a flaky alteration product in both phenocrysts and groundmass of those rocks that contain relatively little pyrophyllite. It forms shreds and patches, as well as large, fan-shaped grains with sweeping extinction under the microscope. It appears to be one of the minerals most readily altered to pyrophyllite, and pseudomorphs of pyrophyllite after chlorite are common.

Serpentine, another of the metamorphic minerals in the volcanic rocks, occurs in the groundmass as mesh-like aggregates and as tiny veinlets characterized by transverse fibrous structure. It also appears to be readily altered to pyrophyllite, and is not present in the pyrophyllite schist or pyrophyllite-quantz schist. The occurrence of chloritoid is similar, in that much of this mineral is attacked and replaced by pyrophyllite. In the pyrophyllite-poor rocks it forms little bundles of fibres, commonly alongside such opaque minerals as pyrite, magnetite, and hematite.

Calcite, though not generally abundant, occurs in many of the slightly pyrophyllitized rocks. In some it appears to be pseudomorphs after pyroxene, and contains numerous inclusions of magnetite, ilmenite, leucoxene, and pyrophyllite. Most of the pyrophyllite, however, appears to be younger than the calcite, which it veins and corrodes along cleavage planes. In other rocks the calcite replaces plagioclase, chiefly the phenocrysts. Most of the rocks also contain supergene calcite, which is distributed along fractures and commonly is associated with hematite.

Some extremely fine-grained, cloudy masses of redish color are present in many of the rocks. They may consist mainly of eliachite or some related aluminum hydroxide. Other rocks contain tiny spherulitic masses that may be gibbsite. Boehmite may be present in small quantities in some of the more highly pyrophyllitized rocks. Additional minor constituents include apatite, sphene, ilelite, and at least two varieties of zeolites.

**Paragenetic Summary**

Three well defined generations of hypogene minerals occur in the pyrophyllite-bearing rocks of the San Diego area. The earliest of these includes quartz, plagioclase, orthoclase, biotite, hornblende, augite, and some magnetite and ilmenite, which appear to represent the chief original constituents of the volcanic rocks. In contrast, such minerals as chlorite, serpentine, epidote, albite and sodic oligoclase, calcite and other carbonates, pyrite, and some quartz are distinctly younger, and appear to have developed during mild regional metamorphism. A third generation of minerals, younger than the other two, is represented mainly by quartz and locally abundant pyrophyllite. The only minerals younger than these are supergene, and include such species as hematite, kaolinite, and some calcite.

In more detail, pyrophyllitization appears to have followed a marked silicification of many of the volcanic rocks, although the two processes must have overlapped considerably in time. That they probably were very closely related genetically is suggested by the intimate association of pyrophyllite and late-stage quartz in all parts of the area, and by the general congruence of the boundaries of silicified and pyrophyllitized masses of rock. Silicification was far from complete in most places, although quartz is now the principal constituent of some lenses of leuocratic
quartz latite and rhyolite. In general the less silicified rocks appear to have been more thoroughly pyrophyllitized than those with very high proportions of secondary quartz. On the other hand, nearly all the pyrophyllite is closely associated with relatively clear quartz that appears to have developed at essentially the same time.

Chemical Composition

The chemical composition of 5 samples of pyrophyllite-bearing rock from the Pioneer mine area, together with the composition of theoretically pure pyrophyllite, are shown in Table 2. Sample A represents a rock mapped as silicified and slightly pyrophyllitized dacite. Most of this unit comprises flows, but layers of breccia and tuff also are present. Sample B, collected from a point near the south rim of the main Pioneer open cut, shows abundant altered, chalky-appearing phenocrysts in hand specimen, but evidently contains much pyrophyllite. Sample C is a pyrophyllite-quartz schist from the north wall of the same cut, and sample D is pyrophyllite schist obtained from the central part of the cut. The sample corresponding to analysis E probably was collected from the main lens of pyrophyllite schist prior to development of the cut.

Normative minerals were calculated for these rocks, on the basis of certain assumptions that are compatible with known mineral occurrences under the microscope. Owing to extreme fineness of grain and to extensive iron-oxide staining in some of the thin sections, it was not possible to make a satisfactory micrometric study of sample B. This sample, which is not readily calculable into a norm on the basis of analytical data now available, is discussed in detail farther on.

The analyses of samples A, B, C, and D are not complete; in that ferrous iron and the alkalis were not determined. That these constituents are conspicuously rare or absent, however, is indicated by the summation of other constituents in samples A, C, and D. In calculations of the norm for these three samples, the calcium was used as a basis for estimating spherule (to account for leucozene), the excess TiO₂ was computed as rutile (although actually present as ilmenite), and the Fe₂O₃ was assigned to hematite. So little P₂O₅ is present that it is reported as a trace of apatite, without apportioning any calcium to it.

All Al₂O₃ was assigned to pyrophyllite, and excess silica was calculated as quartz. The MgO was disregarded, in part because it is present in such small proportions in samples A, C, and D, and in part because it may well be present in the pyrophyllite, as a proxy for aluminum. The amounts of H₂O in the analyses are in close agreement with the amounts required for normative pyrophyllite, especially in samples C and D.

The normative mineral assemblages for samples A, B, C, and D are shown in Table 3. The individual proportions are fully compatible with the results of field observations and with micrometric data obtained from thin sections.

As traced through successive stages of pyrophyllitization from slightly metamorphosed and moderately silicified volcanic flows and breccias to pyrophyllite schist, the rocks show a progressive decrease in proportion of free silica and an increase in the proportion of pyrophyllite. There also is a general decrease in proportion of titanium minerals. The amount of hematite varies somewhat, but this is scarcely surprising for a mineral whose occurrence is in part supergene.

Petrographic study shows that the apparent sequence of mineral development indicated by these analyses cannot be accepted wholly at face value. Although the increase in pyrophyllite content is real enough, the inverse relationship of quartz is not. Sample A, for example, is a distinctly silicified rock, as shown by both chemical and microscopic evidence. In contrast, samples C and D appear to represent rocks that never were so strongly silicified. Sample B appears to present an anomaly, inasmuch as it contains less silica and more alumina than either sample A or sample C. Evidently it was not as much silicified as the other samples.

The data at hand indicate that silicification antedated pyrophyllitization in some, but not in all, the rocks; that pyrophyllite replaced silica in some, but not in all; and that pyrophyllitization of feldspar was an early process in most rocks, but not in all of them. With respect to the last point, sample B provides interesting information. This rock must have escaped both silicification and pyrophyllitization of the degrees typical in adjacent rocks, despite its occurrence in a highly pyrophyllitized part of the Pioneer deposit. In some respects it is chemically more

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Table 2. Chemical composition of pyrophyllite-bearing rocks from Pioneer mine area.

|       | A | B | C | D | E
|-------|---|---|---|---|---
| SiO₂  | 80.13 | 65.38 | 77.16 | 66.74 | 66.80 | 66.70 |
| Al₂O₃ | 11.79 | 24.07 | 18.29 | 26.68 | 28.20 | 28.30 |
| Fe₂O₃ | 0.28  | 0.38  | 0.16  | 0.44  | 0.14  | 0.14  |
| MgO   | 0.06  | 0.43  | 0.05  | 0.06  | 0.06  | 0.06  |
| CaO   | 0.74  | 0.30  | 0.10  | 0.05  | 0.20  | 0.20  |
| H₂O   | 3.10  | 3.43  | 3.13  | 4.65  | 5.00  | 5.00  |
| H₂O⁻  | 1.00  | 0.46  | 0.21  | 0.16  | 0.16  | 0.16  |
| TiO₂  | 1.00  | 0.08  | 0.05  | 0.70  | 0.62  | 0.62  |
| Fe₂O₃ | 0.24  | 0.07  | 0.05  | 0.02  | 0.06  | 0.06  |
| Totals| 99.19 | 95.42 | 99.80 | 99.50 | 100.27 | 100.00 |

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Table 3. Normative mineral composition of pyrophyllite-bearing rocks from Pioneer mine area.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrophyllite</td>
<td>41.4</td>
<td>54.4</td>
<td>64.4</td>
<td>94.3</td>
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<tr>
<td>Quartz</td>
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<tr>
<td>Albite</td>
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<td>11.7</td>
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</tr>
<tr>
<td>Anorthite</td>
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<td>0.6</td>
</tr>
<tr>
<td>Orthoclase</td>
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<td>2.6</td>
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<tr>
<td>Biotite</td>
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</tr>
<tr>
<td>Apatite</td>
<td>Tr.</td>
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<td>Tr.</td>
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</tbody>
</table>

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like the original volcanic rocks than any of the three other types analyzed for the present investigation.

Owing to the very fine-grained and locally opaque nature of the rock in sample B, its constituent minerals could be determined only semi-quantitatively under the microscope. It contains some quartz, pyrophyllite, and feldspar, with an opaque to translucent material that is white in reflected light and has a more pearly luster than the flaky pyrophyllite. The excess AI₂O₃ in the analysis over the quantity required for the minerals specifically determined in thin section might be accounted for by assignment to kaolinite, to sericite, or to an aluminum hydroxide such as boehmite. Calculation of any appropriate amount of kaolinite would not leave sufficient silica to form the quartz that plainly is present in thin section. The most careful examination yielded no positive evidence of fine-grained mica, but there is a possibility that some sericite may indeed be present, having been mistaken for pyrophyllite. The norm for the sample was estimated by allotting to boehmite 10 percent of the alumina remaining after calculation of feldspar. To further simplify matters, all TiO₂ was assigned to rutile and all Fe₂O₃ to hematite. A small amount of CaO was assigned to anorthite.

The calculation for sample B is in approximate agreement with the estimated mode, which is about 50 percent pyrophyllite, 15 percent quartz, and 35 percent feldspar, chiefly albite-oligoclase and orthoclase. Potash and soda, assumed to account for most of the difference between the analysis total and 100 percent, were apportioned in accordance with the quantitative relations of feldspars in the less altered dacies of the area. The assumed alkali content of the sample may be too high; if so, any appropriate correction would decrease the proportion of normative feldspar, and hence would bring the amount of normative quartz into closer correspondence with the higher modal percentage.

The results of spectrophotographic analyses of samples A, B, C, and D, as well as a sample of dacite considered to be less pyrophyllitized, are shown in table 4. These analyses are only semi-quantitative, and the reported quantities are approximately accurate only to the nearest factor of 10. The data were obtained in part to confirm the assumption of moderately abundant alkalis in sample B, and in part to determine the presence and respective proportions of minor constituents in all the samples, and in fine-grained groundmass material that could not be identified with confidence under the microscope. Moderate quantities of sodium and potassium evidently are present in sample B, as already suggested. These alkalis occur in relict feldspars, and some potassium may be present in sericite, as well.

The magnesium indicated in both the chemical and spectrophotographic analyses probably reflects the presence of chlorite and serpentine, particularly in samples X and B. The relatively high lime content of sample A seems best correlated with its relatively high proportion of TiO₂, as previously suggested. A little lime may be present as calcite, also. In contrast, the calcium in sample B probably reflects the occurrence of plagioclase and some epidote. The barium in this sample probably is present in feldspar.

Such constituents as calcium and magnesium appear to decrease progressively with increasing pyrophyllitization. The proportion of titanium also appears to decrease, but not markedly beyond the stage represented by pyrophyllite-quartz schist. The progressive decrease in strontium may reflect the removal of the last traces of feldspars in which it is a minor constituent. Other minor elements show no clear-cut trends that are beyond the limits of error of the analyses themselves. Moreover, the trends of such constituents as copper and manganese lack meaning because of their dominantly supergene origin in these rocks.

### Conditions of Pyrophyllite Formation

The mode of occurrence of the San Dieguito pyrophyllite, particularly its distribution with respect to fractures and shear zones in the host volcanic rocks, indicates that it was formed by replacement of these rocks. Its development was accompanied by introduction of SiO₂, Al₂O₃, and probably OH. The pyrophyllite-bearing rocks, including those of highest grade, contain fresh pyrite and other sulfide minerals at depths in excess of 20 feet in most parts of the area. Both pyrophyllite and the sulfides appear to be hypogene, and are plainly earlier than the widespread iron oxides, manganese oxides, and clay minerals of supergene origin.

Under the microscope, both pyrophyllite and quartz replace feldspars and other original minerals of the volcanic rocks, and in many places the two replacing minerals are of the same general age. As pointed out by Bastin and others, 20 aggregate, rather than sequential replacement, is characteristic of hypogene processes. Zonal distribution of replacing minerals with respect to remnants of earlier minerals, a feature so common in supergene replacement, is conspicuously absent from the pyrophyllite-bearing rocks. Moreover, the replacement is not particularly selective: the pyrophyllite, although first attacking parts of the groundmass in the volcanic rocks, is generally distributed throughout the phenoecryl and groundmass minerals.

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**Table 4. Minor constituents of pyrophyllite-bearing rocks from Pioneer mine area.**

<table>
<thead>
<tr>
<th>Mineral</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>W</th>
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<tbody>
<tr>
<td>Fe₂O₃</td>
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<td>0.5</td>
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<tr>
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<td>0.3</td>
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</tr>
<tr>
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<td>0.5</td>
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<td>0.5</td>
</tr>
<tr>
<td>MgO</td>
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<td>0.08</td>
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</tr>
<tr>
<td>Al₂O₃</td>
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<td>0.03</td>
<td>0.5</td>
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<tr>
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<td>0.005</td>
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</tr>
<tr>
<td>MnO</td>
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<td>0.005</td>
<td>0.005</td>
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<tr>
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<td>0.005</td>
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<tr>
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<tr>
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<td>TiO₂</td>
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</table>

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* a Qualitative spectrophotographic analyses by Smith-Emery Co., Los Angeles. Quantities reported are approximately accurate to nearest factor of ten.

X—Dacite

| A—Silicified and slightly pyrophyllitized dacite (sample A in tables 2 and 3). B—Moderately pyrophyllitized dacite (sample B in tables 2 and 3). C—Pyrophyllite-quartz schist (sample C in tables 2 and 3). D—Pyrophyllite schist (sample D in tables 2 and 3).
Additional, more specific data on the conditions of pyrophyllite formation are provided by the results of numerous geochemical investigations. According to reports quoted by Morey and Ingerson, the development of pyrophyllite under experimental conditions is accomplished in the temperature range 250°-540° C. The upper limit was determined by Schwarz and Trægner, who treated feldspars with acid in pressure bombs. In these and other experiments, it was found that with progressively increasing temperatures the amount of pyrophyllite formed from the feldspar alteration increased up to a temperature of 470° C, and then decreased. Kaolinite was formed in the temperature range 200° to 400° C, pyrophyllite and boehmite from 400° to 540° C, and corundum above 600° C. The kaolinite-pyrophyllite point at 400° C was suggested as a meaningful one in geologic thermometry.

Slightly different techniques were used by Noll, who also found that pyrophyllite was formed in the higher temperature ranges and kaolinite in the lower temperature ranges. He, too, suggested that the 400° C temperature is one of considerable significance, and that the Al₂O₃/SiO₂ ratio appears to be critical in the experiments producing pyrophyllite. He concluded that kaolinite forms through the reaction of alumina and silica in neutral alkali-free solutions, or in acidic alkali-bearing solutions, at temperatures below 400° C; that pyrophyllite forms from similar solutions, but at temperatures above 400° C; that kaolinite forms in nature from alkali feldspars when much of the alkali is removed or when the active solutions are acidic; and finally, that pyrophyllite forms under similar conditions but at higher temperatures, a feature held to be in accord with its known natural occurrences.

The lower temperature limit of experimental pyrophyllite formation originally was suggested as 250° C by Norton, but subsequent investigations have cast some doubt on this figure. On the basis of extensive experiments involving alteration of feldspars in solutions of hydrochloric acid, Gruner concluded that feldspars will yield kaolinite, pyrophyllite, sericite, and boehmite in acid-solution alteration, and that the concentration of K ions and the aluminum-silicon ion ratio determine which mineral will form at a given temperature. He further suggested that pyrophyllite can be formed through alteration of feldspars at temperatures as low as 300° C, although it may be only metastable below 350° C.

The results of these and other experiments were summarized by Folk, and more recently O’Neill made additional experiments along the lines of those performed by Gruner. He obtained pyrophyllite as an alteration product of albite and labradorite, under conditions not at variance with those previously reported. The results of his work again emphasize the importance of pH value and K-ion concentration in determining whether pyrophyllite or some other mineral will form as an alteration product of various feldspars. As pointed out by Ross and Hendricks, pyrophyllite probably is formed in nature at moderately high temperatures, and is yet to be found as a constituent of soils that characteristically are formed by low-temperature weathering.

The metamorphism of the volcanic rocks in the San Diego area, and the subsequent introduction of silica and pyrophyllite almost certainly took place during late Jurassic or Cretaceous time. A considerable thickness of volcanic rocks was removed by erosion prior to deposition of the latest Cretaceous sediments in the region, so that it is impossible to establish a maximum depth at which the pyrophyllite deposits were formed. At no place is the total thickness of the Santiago Peak volcanics known, but it may well have amounted to several thousand feet. On the basis of the general geologic relations and the indirect evidence from laboratory investigations, it seems likely that the San Diego pyrophyllite deposits were formed hydrothermally under conditions of intermediate temperatures and pressures. This is in accord with conclusions reached by Buddington for somewhat similar deposits in the Conception Bay region of Newfoundland, and by Stuckey for the deposits in the Deep River region of North Carolina. In contrast, the deposits on Vancouver Island, British Columbia, appear to have been formed under near-surface conditions.

**Chemical Changes**

The average silica content of most of the pyrophyllite-bearing rocks probably was within the range of 61 to 68 percent prior to their alteration, as suggested by several modal analyses of unaltered rocks in the San Diego and adjacent areas. The marked silicification of such slightly pyrophyllitized rocks as that represented by sample A (table 2) is thus evident from their chemical analyses. It is equally clear, however, that there is little difference in silica content between the most pyrophyllitized-rich rocks and the original volcanic rocks. There appears to have been considerable redistribution of silica during alteration of the rocks in the area studied, with perhaps some additions from a hypogene source; on the other hand, the pyrophyllitization process itself did not necessarily involve the introduction of abundant silica.

The average alumina content of the metamorphosed but unpyrophyllitized volcanic rocks is 16 to 17 percent. It is of course less in those rocks that have been silicified, and much greater in those containing abundant pyrophyllite. Considerable alumina must have been added to the rocks in the vicinity of the Pioneer mine; perhaps much of it was derived from nearby rocks that are now highly silicified. The amount introduced from more distant

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**References**

sources is difficult to determine, but it may well have been large.

The proportion of alkalis, chiefly soda and potash, in the original volcanic rocks probably ranged from 6.5 to as much as 8 percent. Nearly all these constituents were removed during the alteration, and mainly during its early stages. Nothing is known concerning their ultimate disposition.

Source of Mineralizing Solutions

The pyrophyllite-forming solutions were clearly of hypogene origin, but their source is by no means so evident. It is difficult to correlate the deposits with any igneous rock exposed in the surrounding area. They might be genetically associated with the masses of pre-batholith intrusive rocks, notably the gabbroic and tonalitic types. On the other hand, they might be related to the younger and more abundant rocks of the southern California batholith, although there is no systematic relation between them and individual plutons or groups of plutons that represent the batholith.

All the known pyrophyllite deposits lie near intrusive masses that appear to be closely related to the volcanic rocks, and that have been interpreted as pre-batholith in age. These masses probably were formed at intermediate depths, a feature in accord with the presumed conditions of pyrophyllite development. On the other hand, the total number of pyrophyllite deposits exposed in the coastal belt is so small that their systematic relation with respect to the older series of intrusive rocks might be fortuitous. No pyrophyllite concentration in the San Dieguito area has been recognized within an intrusive mass, nor even within the anreole of contact metamorphism associated with such a mass.

In the absence of definitive data, it can be concluded only that the pyrophyllite depositing solutions were hypogene, and that they were most likely related to the intrusive rocks that are closely associated with the Santiago Peak volcanics.

Comparisons With Other Occurrences

The best known and economically most important deposits of pyrophyllite in the United States occur in the Deep River region of North Carolina. These have been described in some detail by Stuckey. The pyrophyllite occurs as concordant elongate lenses in shear zones developed in a series of tightly folded and metamorphosed volcanic and sedimentary rocks. These rocks include slates, acid tuffs and breccias, rhyolite, andesites, and diabases, but only the acid tuffs and breccias contain noteworthy masses of pyrophyllite. Stuckey suggested that the shear zones along which pyrophyllitization took place were developed principally in the most siliceous volcanic rocks because these rocks were less competent than the others in the area. Thus lithology appears to have been an indirect but important control in localizing the deposits. Pyrophyllitization was preceded in most places by marked silicification, with attendant decrease in the feldspar content of the rocks. Pyrite and chloridot were developed during or shortly after introduction of silica, but prior to formation of pyrophyllite.

The San Dieguito deposits closely resemble those described by Stuckey, although they are much smaller and more localized. They show about the same degree of structural control in their development, but considerably less lithologic control. The replaced rocks in the California deposits were less silicic in average composition, and the mineralogy of the deposits themselves is somewhat simpler than that of the North Carolina deposits. The development of silica prior to pyrophyllitization appears characteristic of both occurrences, except that it evidently was more extensive and consistent in the Deep River region.

The pyrophyllite deposits in the Conception Bay Region of Newfoundland have been described in detail by Buddington and Vhav. They occur in a thick series of pre-Cambrian rhyolite and basalt flows, with interlayered breccias, tuffs, and some water-laid material. This volcanic series was altered regionally, with development of abundant chlorite and silica. On a more local scale, some of the rocks were pyrophyllitized, some pinitized, and some silicified.

A few of the pyrophyllite concentrations occur in rhyolite breccias and congolomates, but most are confined to the rhyolite flows. The pyrophyllite itself forms single, well defined veins, as well as series of anastomosing veins, pockets, and lenses. The development of the mineral evidently involved introduction of large quantities of alumina, replacement of alkalis by hydroxyl, and the solution of silica, both that occurring as free quartz and that in other minerals. Much of the pyrophyllitized rock may once have been a relatively homogeneous glass.

It was concluded by Buddington that the deposits were formed through metasomatic replacement of previously silicified rhyolites by thermal waters, under conditions involving dynamic stress and moderate temperatures and pressures. The solutions evidently gained access along fault or shear zones, and the deposits themselves are markedly schistose. In a subsequent study, Vhav concluded that the individual flakes of pyrophyllite have a random orientation, and that the schistosity of the deposits is an inherited feature preserved by differential replacement along planar structures already established.

The pyrophyllite at Conception Bay and in western San Diego County was localized along shear zones, and occurs in lentieular masses. The structural control in both localities was very similar in detail. Indeed, numerous exposures in the San Dieguito area are strikingly like that shown in Buddington’s photograph of “lenticular structure in rhyolite.” The general introduction of silica prior to pyrophyllitization, and the replacement relations of the pyrophyllite also are similar features.

On the other hand, the volcanic rocks in the California occurrences were less silicic in original composition than those in the Newfoundland area. Further, much of the silification in the San Dieguito area appears to have been contemporaneous with pyrophyllitization, rather than wholly earlier, and there is no evidence that rocks now rich in pyrophyllite were once wholly or in large part silicified.

13Stuckey, J. L., op. cit., pp. 448, 1925.
14Buddington, A. F., Pyrophyllitization, pinitization, and silicification of rocks around Conception Bay, Newfoundland: Jour. Geol., vol. 24, pp. 139-152, 1916.
16Buddington, A. F., op. cit., p. 159, 1918.
Finally, there is little extensive development of white mica in the Pioneer and adjacent deposits.

A third series of pyrophyllite deposits has been described by Clapp \(^{19}\) from Kyyunot Sound, on the west side of Vancouver Island, British Columbia. Both alunite and pyrophyllite occur in andesite, dacite, and associated pyroclastic rocks of Triassic and Lower Jurassic age. This series, and in particular its fragmental parts, has been metasomatically altered to quartz-sericite-chlorite rocks, quartz-sericite rocks, quartz-pyrophyllite rocks, and quartz-aluminate rocks. Pyrite is widespread, and appears to have been introduced after alunization and pyrophyllitization, and perhaps during sericitization and silicification. The alteration is plainly related to shear zones.

Clapp \(^{20}\) concluded that most of the mineralization was caused by hot sulfuric-acid solutions of volcanic origin which were active during the accumulation of the pyroclastic rocks, and hence at relatively shallow depths. Little change in bulk composition of the original volcanic rocks was postulated, and most of the new minerals were interpreted as having been developed from feldspars. In detail, however, the quartz-pyrophyllite rocks show a net gain in alumina, a loss in potash, and either a loss or gain in silica. There seems to have been little replacement of quartz by pyrophyllite.

The original volcanic rocks of the Vancouver Island occurrences apparently were more similar to those in the San Diego area than to those in the other areas described above. However, there are noteworthy differences in the alteration. The occurrence of alunite and sericite has not been established in the California deposits, which are not thought to have been developed under conditions of low temperature and pressure. Further, silicification in part antedated pyrophyllitization in these deposits, and there appear to have been distinct changes in bulk composition of the rocks.

**ECONOMIC FEATURES**

**Commercial Pyrophyllite**

**Properties.** Pyrophyllite is an hydroxyl-bearing aluminum silicate, with the formula Al\(_2\)Si\(_4\)O\(_{10}\)(OH)\(_2\). As first shown by Paunling, \(^{21}\) the mineral has a platy-crystal structure similar to that of talc, Mg\(_2\)Si\(_4\)O\(_{10}\)(OH)\(_2\). It is hence not surprising that these two species are markedly similar in physical properties, even though quite different in chemical composition and general mode of origin. Both are so soft that they have a greasy feel, and both are characterized by micaceous habit, perfect basal cleavage, pearly luster, and light color. Owing to these and other points of similarity, the two minerals are interchangeable for most uses, and ordinarily are treated together in discussions of mineral technology.

Pyrophyllite occurs in several common habits. Best known, perhaps, are rosette-like aggregates of radially disposed fibers and elongate flattened crystals. Such pyrophyllite is relatively coarse grained, with fiber lengths commonly \(\frac{1}{4}\) inch or more. Many of the commercial deposits, in contrast, consist of much finer-grained material. Some comprise thin, regular layers of oriented or unoriented tiny plates and fibers, whereas other aggregates lack both orientation and layering. In some of the finer-grained occurrences, the pyrophyllite individuals are rosette-like in detail, although this rarely is apparent megascopically.

Some very compact, massive varieties of pyrophyllite, used chiefly in the Orient for carving, are known as agatalite, but in recent years this term also has been applied to similar forms of tale and to some fine-grained aggregates of other soft minerals.

Pyrophyllite loses its water when heated, with attendant expansion and loss in weight. According to the findings of Stuckey, \(^{22}\) this loss proceeds at a rate slower and more uniform than that for similarly hydrated seirecite, which is practically dehydrated at 750° C. Distinctly higher temperatures are required for complete dehydration of pyrophyllite. The amount and rate of expansion vary with different varieties of crude pyrophyllite, with the type of grinding and pressing used if the material is processed, with the amounts and kinds of impurities (notably sericite), with the rate of temperature rise during heating, and with the duration of heat treatment at a given temperature.

Although the chemical formula of the theoretically pure pyrophyllite is rather simple, most commercial pyrophyllites contain appreciable, though very small quantities of such elements as iron, calcium, magnesium, titanium, and the alkalis. Several of these, like magnesium, iron, and some titanium, sodium, and potassium, may be present in the pyrophyllite crystal lattice. Others, like calcium and some of the alkalis, probably represent residual material from the rocks at whose expense the pyrophyllite was formed. Still others, notably iron and manganese, are of supergene origin.

Chemical composition can be useful in predicting the behavior of pyrophyllite where exacting control is required in the manufacture of certain products. In ceramics, for example, such properties as color, shrinkage, and absorption of tile bodies can be in part predicted in terms of the composition of the raw pyrophyllite used in them. Many other factors are involved in the control of such features, however, and hence there are numerous exceptions to generalizations founded upon trends of composition. Largely for this reason, most pyrophyllite is currently selected for ceramic use by empirical methods.

The nature and commercial applications of several types of pyrophyllite from North Carolina have been effectively summarized in a small booklet published by the R. T. Vanderbilt Company of New York. \(^{23}\) For discussion of fundamental chemical and structural properties of pyrophyllite and related minerals, the reader is referred to contributions by Gruner, \(^{24}\) Hendricks, \(^{25}\) and by Ross and Hendricks. \(^{26}\)

**Uses.** Most uses of pyrophyllite are similar to those of tale, and depend mainly upon the remarkable physical properties of the mineral. In the field of ceramics, where much pyrophyllite is being used and is being tested for new uses, its behavior upon heating also is very important. The various commercial applications of tale and pyrophyllite are summarized in Table XXII.

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are discussed in the published record by Ladoo,\textsuperscript{37} Gilson,\textsuperscript{38} Johnson,\textsuperscript{59} Burgess,\textsuperscript{59a} and others.

A large part of the domestic output of pyrophyllite is incorporated into paints, and particularly into non-reflecting and other special types in which flake pigments of light color are desired. High oil absorption of ground pyrophyllite and its freedom from grit also are desirable properties for paint use. Ground material is employed as a filler in rubber goods, certain roofing and flooring materials, special plasters, plastics, insecticides, textile products, paper, linoleum and oilcloth, rope and string, several types of soap, and in some fertilizers. It serves as a "loader" in paper and textile fabrics, where its whiteness and resistance to the effects of fire and weather are particularly desirable. This resistance also partly accounts for its use in roofing papers and other asbestos and asphalt goods. Its corrosion resistance makes it an especially satisfactory filler in battery cases. There are indications that it also may serve effectively as a low-noise filler in phonograph records.\textsuperscript{50}

With a low bulk density and slight acidity in ground form, high absorptive characteristics, and superior qualities as a flake-form dusting agent, pyrophyllite is an excellent carrier for such active insecticides as DDT, nicotine, pyrethrum, and rotenone. The flakiness of the mineral leads to desirable adhesion on leaves and other parts of dusted plants, and its softness and freedom from grittiness when finely ground make for reduction of wear on nozzles and other parts of mechanical insecticide dispersers.

Pyrophyllite of great purity and whiteness has been used as a base for cosmetics and toilet preparations, but the total amount is not large. The lubricating properties of the mineral underlie its use in some greases, in tires and other rubber goods, on machine-driven box nails, and in various kinds of dies. On the other hand, it also is employed as a fine, "soft" abrasive in the scouring and polishing of certain foodstuffs, as well as some painted or lacquered surfaces. It serves as a high-quality packing and insulating material, as a constituent of adhesive, corrosion-resistant covering compounds, and as an absorbent for oily substances in a wide variety of products. It also can be processed for use in crayons and pencils.

As a constituent of ceramic bodies, pyrophyllite is being more and more widely used. It is a good substitute for feldspar and quartz in wall-tile bodies, as it decreases their shrinkage and their crazing by thermal shock or moisture expansion.\textsuperscript{61} It also is employed as a source of aluminum in enamels, and is a raw material for semivitreous dinnerware and some types of refractories.\textsuperscript{62}

More than three-quarters of domestic talc and pyrophyllite production during 1946 was used in paints, rubber goods, roofing materials, ceramic products, and insecticides.\textsuperscript{63} Most pyrophyllite mined in the United States has been obtained from deposits in North Carolina. The domestic output for the period 1942-1946 is summarized in Table 5. In general, prices during recent years have averaged about $7.00 per short ton of crude pyrophyllite at the mine, $10.20 per short ton for 200-mesh ground pyrophyllite at the mill, and $12.20 per short ton for material ground to 325 mesh.

\textbf{Occurrence.} The pyrophyllite deposits in the Piedmont region of North Carolina, in the Conception Bay region of Newfoundland, and on Vancouver Island, British Columbia, already have been noted. In addition, economically important deposits are present in the Transvaal, South Africa, and in the southern Ural Mountains of Russia. Other occurrences of relatively minor or potential commercial interest are known from China, Hungary, Korea, Saxony, Scotland, Tasmania, and Turkestan. Pyrophyllite also has been reported from many localities where it is of mineralogical interest only. That it is a far from uncommon mineral is indicated by its occurrences in the State of California alone. It has been recorded\textsuperscript{64} from Alameda, Amador, El Dorado, Imperial, Inyo, Madera, Mariposa, Mono, Plumas, San Diego, and San Luis Obispo Counties.

Although most of the commercial deposits were formed by alteration of volcanic rocks, pyrophyllite is by no means restricted to deposits of this origin. In some places it is associated with andalusite, dumortierite, and other aluminous minerals, and in many others it occurs in or along gold-quartz veins. It also is a major constituent of schists that appear to be mainly of dynamic metamorphic origin. All these types of occurrence are known from San Diego County alone.

Pioneer Deposit

General Features. The Pioneer pyrophyllite deposit is exposed on an irregularly dissected terrace surface about 1000 feet east of the San Dieguito River (pl. 1), chiefly at altitudes of 200 feet to 310 feet. The principal mass of pyrophyllite-bearing rock appears immediately north of a small draw, and occupies the south side of a prominent bare knob (fig. 2). The main workings of the Pioneer mine, which have been developed primarily in this mass of pyrophyllite schist, lie in the south-central part of the N \( \frac{3}{4} \) sec. 23, T. 13 S., R. 3 W. To the south and east are other knobs, which owe their topographic expression to resistant lenticular masses of silicified volcanic rock (pl. 2).

Several types of pyrophyllite-bearing rocks, representing progressive stages in the alteration of original volcanic rocks, crop out from beneath a discontinuous cover of terrace gravels, alluvium, talus, and other unconsolidated deposits. As shown in plate 2, the pyrophyllite-bearing rocks occur as elongate lenses that range considerably in size. They trend west-northwest to north-northwest in most of the mine area, but swing broadly to the west in the east part of the main open cuts, as well as in the south part of the mine area. Most dips are steep to the north or northeast. In general the lenses are conformable with primary layering in the volcanic sequence, but in the south half of the mine area they locally lie athwart the broadly curving traces of primary flow planes (pl. 2).

The mass of highest grade pyrophyllite schist is at least 150 feet long, 10 feet to 22 feet in outcrop breadth, and about 15 feet in average thickness. To the west-northwest it is interlayered with pyrophyllite-quartz schist and with moderately pyrophyllitized dacite rocks, but its other end is concealed by alluvium and mine waste. The high-grade rock is flanked on the north by pyrophyllite-quartz schist that contains nodular masses of moderately pyrophyllitized dacite and some highly silicified rocks. These masses range in maximum dimension from less than 2 inches to as much as 18 feet. Most of the relations south of the main open cuts are concealed by waste material.

Lenses of pyrophyllite-quartz schist and pyrophyllite schist also are exposed on the knob southeast of the main cuts, at a pit 300 feet to the south, in a shaft 150 feet east of this pit, and in a pit on the north side of a small ravine still further south (pl. 2). These lenses, as well as prominent shearing and schistosity within them, dip steeply north to northeast.

Mine Workings. The principal workings of the Pioneer mine are two open cuts that are coalesced along their strike (pl. 2, figs. 2, 3). The larger of these, the Long Cut, is 15 feet to 45 feet wide, 140 feet long, and 10 feet to 25 feet deep. The New Cut, which was developed at a lower level immediately west of the Long Cut, is a bench-like opening 50 feet wide, 70 feet long, and slightly more than 20 feet deep at the face (fig. 19). Thus far, these two workings have yielded all the commercial output from the deposit.

An old shaft 300 feet south-southeast of the cuts is approximately 90 feet deep, but is not accessible. It appears to have been sunk chiefly in pyrophyllite-quartz schist. Shallow pits and small cuts are scattered over the remainder of the mine area, and attest numerous past efforts to develop other masses of pyrophyllite-bearing rock. Several areas of poor exposure southeast and south of the mine have been explored by means of bulldozer stripping (pl. 2). The overburden also has been removed from the top and sides of the knob in which the main cuts were excavated.

Mining Operations. The main pyrophyllite deposit was first explored years ago by means of several small, shallow cuts. The vertical shaft to the south-southeast was sunk at about the same time. Little but exploratory work was done until 1945, when extensive stripping was followed on a small scale by open-cut mining. The crude pyrophyllite schist was first shipped to Los Angeles for grinding, but the mine operators acquired a small mill in Chula Vista later in the year, and began to process some of the rock there. Haulage to Los Angeles was stopped entirely when this mill was subsequently enlarged and improved.
The crude material is broken in hammer mills, passed through blowers, and then generally is ground to 325-mesh in a large Raymond mill. The final product is shipped to the Mefford Chemical Company in Los Angeles for use as a dust-form insecticide carrier. The operators currently are enlarging the mill, and expect to obtain a capacity of at least 100 tons of pyrophyllite schist per day.

The rock is mined by very simple methods. It is drilled mechanically, blasted, and loaded by means of a small power shovel. Most of the large fragments are readily broken by hand into lumps less than a foot in maximum dimension, chiefly along well-developed cleavage and shear planes. The schistosity in the deposit has caused some operational inconvenience along the north face of the open cuts, where large masses of rock have split off and slumped into the workings on several occasions.

A reasonably good grade of product is maintained by selective mining, and by both hand and mechanical sorting in the piles of freshly broken rock. The coarsest of the undesirable material is loaded with the power shovel onto trucks, from which it is dumped on the slope a short distance to the west. The remainder is periodically bull-dozed from the floor of the cuts. The coarsely broken ore is hauled to Chula Vista by means of two heavy trucks. The output of the mine since it was opened in 1945 is not known, but is reported to be slightly in excess of 10,000 tons.

Properties and Grade of Mined Rock. Where fresh, the pyrophyllite schist is white to a very pale creamy white. The pyrophyllite itself is platy to shred-like in habit, but nearly all is so fine-grained that its aggregates appear compact and homogeneous. A definite orientation of the mineral grains, however, shows megascopically as a pronounced schistosity or cleavage, along which the rock splits readily (fig. 20). Most of the schist is very soft, and is readily scratched with a fingernail.

The best grades of pyrophyllite schist contain very little finely dispersed foreign material, but where the rock is closely associated with quartz-pyrophyllite schist it contains scattered small veinlets and lenticular masses of quartz. Also present are remnants of other, older minerals that represent the igneous rocks from which the pyrophyllite was derived. These include epidote, ilmenite, chlorite, and locally abundant and very fine-grained clayey material. Well-formed crystals of pyrite, pyrrhotite, and other sulfide minerals are scattered through the pyrophyllite schist and pyrophyllite-quartz schist, and locally are rather abundant.

Iron oxides constitute the most widespread impurity in the deposits as now exposed. They appear to have been derived from the alteration of pyrite, and form an extensive reddish-brown discoloration in all near-surface parts
of the deposit (figs. 2, 3). This stain is strikingly pervasive
and uniform in appearance to depths of 2 feet to 15 feet
beneath the surface, but farther down it forms ramifying
fracture-controlled veins in white to tan pyrophyllite
(figs. 3, 19). It is present to depths of 30 feet or more in
much of the deposit, but little of the rock exposed on the
floor of the main cuts is discolored.

The highest grade of pyrophyllite schist contains pod-
like masses of quartz and silicified volcanic rocks, as
well as masses of relatively unaltered dacite and dacite breccia.
These range from a few inches to 4 feet or more in
maximum dimension, and most are thick and distinctly
rounded. One of them, a lens of dark green, slightly altered
dacite about 4 feet in diameter, was uncovered on the
east wall of the New Cut during the summer of 1948
(fig. 21). Similar small masses of pyrophyllite-poor rock
are said to have been encountered during earlier phases of
the mining. Such masses are easily broken away from the
pyrophyllite-rich rocks, and hence are readily removed
prior to loading and hauling of the ore.

The highest-grade pyrophyllite schist is rather free
from grit, and on grinding yields a smooth, even-grained
product. It has high oil absorption capacity, as compared
with other ground pyrophyllites, and has a relatively
low density in loose or packed form. When tested, the
ground pyrophyllite had an average pH value of 6.6. These
properties, together with the reportedly good adherence
and wettability of the pyrophyllite, indicate that it is well
suited for insecticide use. The light color of the material
that is not stained by iron oxides should make it suitable
for use in the manufacture of such products as paints,
ceramic goods, paper, and textiles. Its freedom from grit
should make the highest-grade material suitable for lubri-
cants.

Table 6. Chemical analyses of representative commercial pyrophyllites.

<table>
<thead>
<tr>
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<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
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<td>Al₂O₃</td>
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<td>n.d.</td>
<td>n.d.</td>
<td>0.03</td>
<td>n.d.</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.70</td>
<td>0.02</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.71</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.02</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>S</td>
<td>n.d.</td>
<td>0.06</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

Totals 99.50 100.27 100.74 100.27 100.48 100.57 100.00

As shown by the chemical analyses, the best grades of
schist in the Pioneer deposit consist almost wholly of
pyrophyllite. Analyses of this schist are compared with
those of other commercial pyrophyllites in table 6. Depart-
ures from the theoretical values are due mainly to admixed quartz or sericite. Little of either is present
in much of the Pioneer deposit, although moderate quanti-
ties of quartz appear in the poorer grades of schist along
the margins of the open cuts.

The physical properties of interest to ceramic industries
have been recorded for the Pioneer pyrophyllite by
Richard as follows:

- Mechanical analysis: Consists of fibrous pyrophyllite
- Working properties: At 40-mesh, fair; at 80-mesh, good
- Water of plasticity (%): 14.3
- Dry shrinkage (%): 2.2
- Making: Does not shake down in water
- Odor: Argillaceous
- Hardness: 1.2
- Drying properties: Dries fast; no warping
- Specific gravity: 2.9
- Tensile strength: 148-160 lb.

Sample bars, made up and fired at four different
temperatures, yielded the following information:

<table>
<thead>
<tr>
<th>Cone</th>
<th>Color</th>
<th>Shrinkage (%)</th>
<th>Absorption (%)</th>
<th>P.C.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>White</td>
<td>0.1</td>
<td>18.5</td>
<td>29.3</td>
</tr>
<tr>
<td>6</td>
<td>White</td>
<td>0.1</td>
<td>18.4</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>White</td>
<td>0.2</td>
<td>17.6</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>White to cream</td>
<td>2.1</td>
<td>10.7</td>
<td></td>
</tr>
</tbody>
</table>

Reserves. The Long Cut and New Cut effectively
outline the lateral boundaries of high-grade pyrophyllite
schist. In a sense these are indefinite boundaries, and have
been determined during mining by relative amounts of
pyrophyllite-poor material encountered. Indeed, some of
the pyrophyllite-quartz schist actually has been mined
and shipped. The bottoms of the cuts generally are con-
cealed by waste rock, but over an operational period of
several months the writers had opportunity to observe
most of the bedrock on the floors of both main workings.
Pyrophyllite schist was exposed rather continuously, and
evidently extends downward to points well below the level
of the present workings. It is known to be interlayered
with pyrophyllite-quartz schist and with other rocks of
lower pyrophyllite content to the west-northwest, and its
along-strike relations probably are similar in the opposite
direction.

The high-grade pyrophyllite appears to form a lens
6 to 8 times as long as its average thickness. Its third
dimension is not known, but the form and attitude of
other lenticular units in the area suggest a rather steep
plunge and a down-dip continuity of at least the same
order of magnitude as its strike length. A steep plunge
also would be in accord with observed plunges of linear
elements formed in the surrounding volcanic rocks by
the intersections of shear zones and foliation planes with
primary planar structures, or by intersections of two sets
of shear or foliation planes. Linear elements plunge gently
eastward in the north end of the mine area, however
(pl. 2). Here they appear to be formed by the intersecti-
ons of primary flow layers and a faint schistosity, prob-

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ably where the layers outline the noses of gentle folds. Nevertheless, a distinct set of shear planes, which intersect the bedding and the faint foliation, forms much more steeply dipping linear elements.

On the basis of the dimensions of the open cuts relative to the estimated original contour of the hill, the amount of stripping done, and the tonnage of dump material in the immediate vicinity, it seems probable that 10,000 to 11,000 tons of pyrophyllite schist and subordinate associated pyrophyllite-quartz schist has been removed during mining operations to date. Another 10,000 tons is indicated to an additional depth of 20 feet by present exposures. On the basis of an inferred discoidal shape for the principal lens of pyrophyllite schist prior to its partial removal by erosion, the reserves may well amount to 75,000 tons or more. A considerable reserve of pyrophyllite-quartz schist also is present, mainly along the margins of the higher-grade mass being mined. Other, smaller masses of high-grade pyrophyllite schist, chiefly in the area south and southeast of the main cuts, might contain as much as 6,000 tons of inferred reserves.

As mining operations are carried to greater depths, the proportion of supergene iron oxide should decrease markedly. In its place, however, will be scattered crystals of pyrite and other sulfide minerals. Unless removed from the pyrophyllite, these will militate against its satisfactory application to certain uses.

Other Deposits

Other lenticular bodies of slightly and moderately pyrophyllitized rocks are exposed in the San Dieguito area, as already described and as indicated in plate 1. Most of these masses lie along and on both sides of the river southwest and south of the Pioneer mine. Few of them appear to be rich in pyrophyllite, although in some places there are small masses of rock that could well be termed pyrophyllite-quartz schist and locally even pyrophyllite schist.

It seems likely that other masses of high-grade pyrophyllite schist are present in the area, but these have not been encountered as yet. Perhaps this is due in part to their softness and consequent poor exposure, and in part to concealment by terrace gravels or other younger deposits. In general, the high-grade lenses occur in the largest and thickest masses of slightly to moderately pyrophyllitized volcanic rocks. The main Pioneer deposit is an excellent example of this relation (pl. 1). Further prospecting for pyrophyllite schist and pyrophyllite-quartz schist therefore might best be confined to areas of altered rock, such as those shown in plate 1. Most promising for such prospecting are the area along the west bank of the San Dieguito River west and southwest of the Pioneer mine, the hillside south of the mine, and the slopes underlain by the largest lenses of pyrophyllite-bearing rock 2,000 feet or more southwest of the mine.