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CONTRIBUTIONS TO THE PETROGRAPHY of the GALÁPAGOS, COCOS, MALPELO, CEDROS, SAN BENITO, TRES MARÍAS, AND WHITE FRIARS ISLANDS

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CONTENTS

CONTENTS—Cont.

Introduction

For a period of several years, between 1905 and 1932, the California Academy of Sciences conducted extensive scientific expeditions to the Galápagos, Cocos, Malpelo, Cedros, San Benito, Tres Marías, and White Friars islands.

During the course of studies of these eastern Pacific Ocean islands, numerous volcanic rocks were collected by Washington Henry Ochsner from the Galápagos Islands (including Abingdon, Albemarle, Barrington, Bindloe, Charles, Chatham, Gardner, Hood, Indefatigable, Jervis, South Seymour and Tower islands); from Cocos, Malpelo, Tres Marías and White Friars islands by C. B. Perkins, Leo G. Hertlein, and G Dallas Hanna; and metamorphic and plutonic rocks from Cedros, San Benito and Tres Marías islands, by G Dallas Hanna. The volcanic rocks that were collected on these islands range in composition from basalt to rhyolite. Those lavas on the Galápagos Archipelego and Cocos Island are principally basaltic in composition, although a few are of andesitic composition (Richardson, 1933, p. 46). One lava from Cocos Island is a latite, and several collected from María Madre of the Tres Marías islands are rhyolitic in composition. Glaucophane schists were collected on Cedros and San Benito islands and several plutonic rock types were collected on María Madre Island.

Special thanks are due to Dr. Leo G. Hertlein for his encouragement and suggestions during the course of this investigation, and especially to Dr. G Dallas Hanna who made available the rock specimens and suggested that a petrographic study be made of them.

Galápagos Islands

Location and General Geology. The Galápagos Islands are on the equator about 650 miles west of Ecuador. They form an archipelago con-

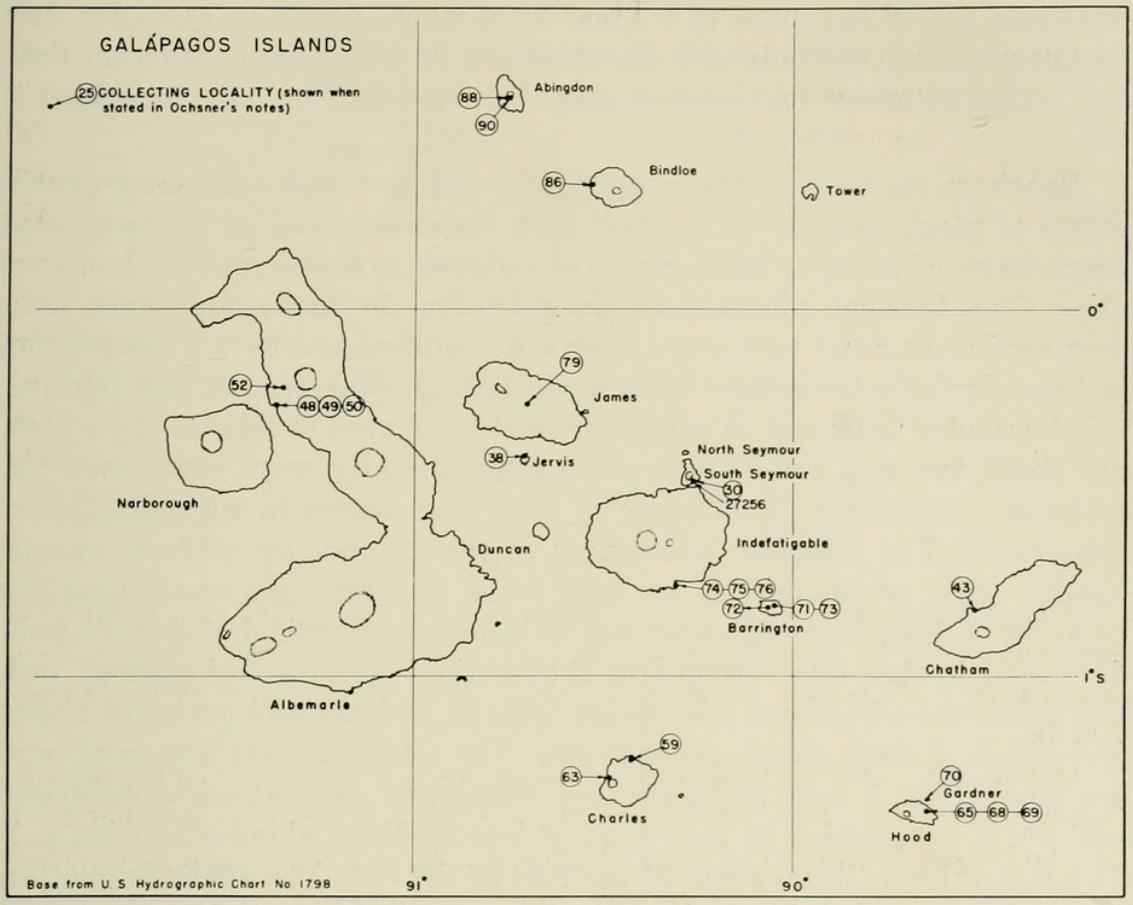

Figure 1. Map of the Galápagos Archipelago showing the major islands and the localities where rock specimens were collected.

sisting of 13 islands and many islets and projecting rock masses. The islands, except for minor amounts of sedimentary beds, are wholly of volcanic origin and contain at least 2000 cones and craters (Darwin, p. 110–131, 1891). This is a very conservative estimate for it has been shown that there are at least 2500 cones and craters alone on Albemarle Island (Banfield *et al.*, 1956, p. 222) which is the largest island in the archipelago. Some of the volcanoes have erupted during the last hundred years (Sapper, 1917, p. 95). In addition to the many craters, there are lava flows and deposits of tuffs and tuff-breccias.

PETROGRAPHY. Most of the crystalline rocks that make up the Galápagos Islands are basaltic in composition, and porphyritic with phenocrysts of basic plagioclase set in a microcrystalline groundmass. Olivine is not common, but when it is present it is more readily visible in lavas collected on Chatham, Charles, Gardner, Hood, Jervis, and Indefatigable islands.

ABINGDON ISLAND (Pinta; Geraldino). Two specimens of basalt were collected on Abingdon Island, the northernmost island in the archipelago.

Specimen no. 88 is typical of a great mass which forms an extensive flow that covers much of the island. Specimen no. 90 is from a more recent flow, and is less extensive in its occurrence than specimen no. 88 over which it lies.

Specimen no. 88 is a dark, porphyritic, vesicular rock containing phenocrysts of plagioclase up to one-half inch across enclosed in a fine-grained groundmass of feldspar laths, grains of colorless pyroxene and black opaque glass. The feldspar phenocrysts are subhedral in shape, and show well-developed zoning and twinning. They are unaltered and have a composition in the range of intermediate labradorite (An_{50}). The groundmass feldspar is in irregular laths and is seldom more than .2 mm. in length. They, too, are fresh, twinned and have a composition slightly more sodic than the feldspar phenocrysts. The augite is fresh and occurs in subhedral colorless grains. The principal constituent of the groundmass is dark, opaque basaltic glass which derives its dark color in part from small dust-like particles of magnetite. Specimen no. 90 is not porphyritic, but shows a well-developed hyaloophitic texture in thin-section. It is a fine-grained rock and under the microscope one can see laths of feldspar and grains of augite enclosed in a dark glassy groundmass. The feldspar laths are small and not more than .7 mm. in length, but reasonably accurate determinations indicate a composition in the range of intermediate labradorite (An_{45-50}). This mineral constitutes about 35 per cent of the rock. The augite is colorless and is in twinned, subhedral grains that constitute about 10 per cent of the rock. The remainder of the rock is dark basaltic glass.

BINDLOE ISLAND (Marchena; Torres). Of the three rock specimens collected on Bindloe Island, only one, no. 86, was available for study. This specimen was collected from a lava flow well exposed along the west coast of the island which appears to consist largely of pyroclastic deposits with a few narrow, smooth-surfaced lava flows.

Specimen no. 86 is basalt. It is porphyritic, slightly vesicular, and contains phenocrysts of feldspar up to one-half inch across enclosed in a fine-grained, medium-gray colored groundmass.

The feldspar phenocrysts are euhedral to subhedral in shape, unaltered and constitute from 15–20 per cent of the rock. This mineral shows zoning, a combination of twinning, and a composition in the range of intermediate labradorite (An_{50}). The groundmass feldspar is in irregular-shaped laths that range up to .6 mm. in length. The laths are fresh and constitute as much as 45–50 per cent of the rock. They are twinned, but not zoned, and have a composition slightly more sodic than the feldspar phenocrysts, and are in the range of An_{45} to An_{50}. The augite is in angular grains which are seldom more than .2 mm. across. The mineral is slightly pleochroic in pale pinkish to pale greenish colors, unaltered, and is untwinned and unzoned.

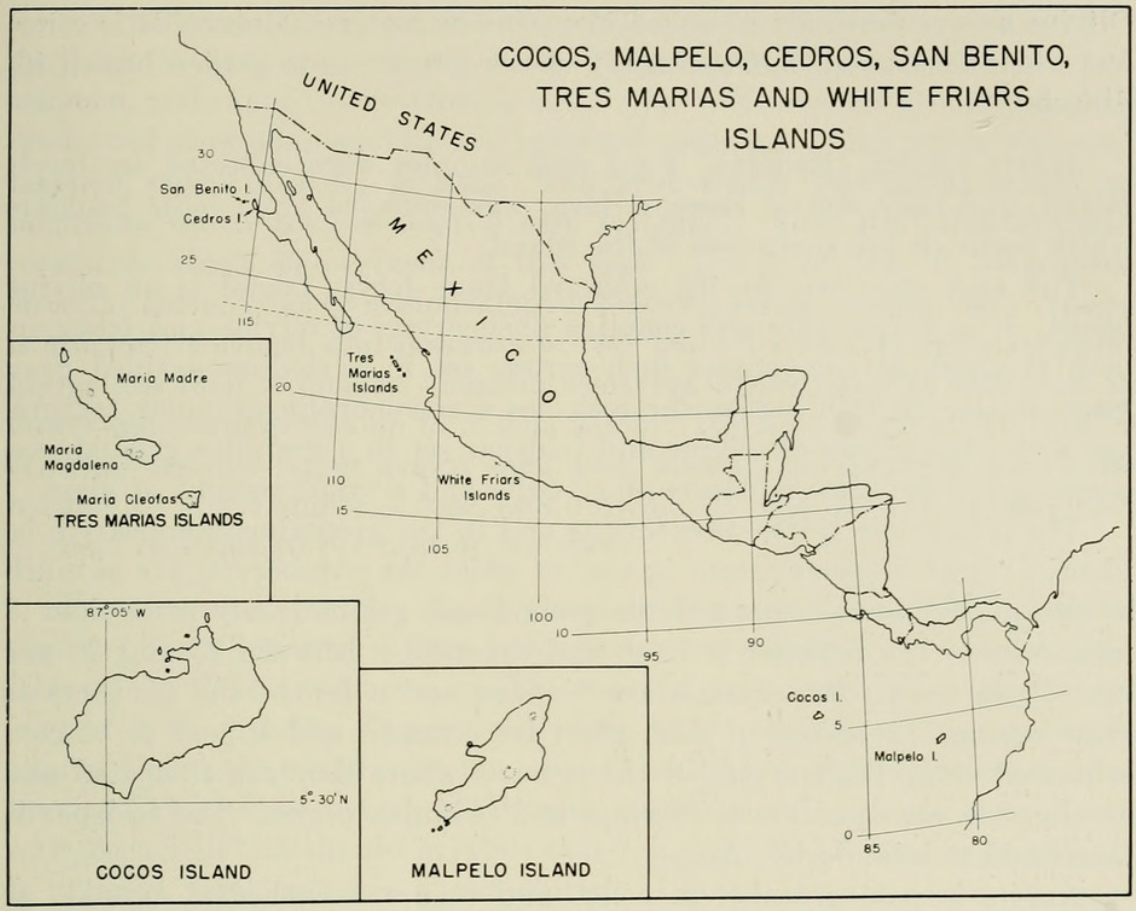

Figure 2. Map of the Pacific Ocean off the west coast of Central America showing the location of Cocos, Malpelo, Cedros, San Benito, Tres Marías and White Friars islands.

It constitutes about 35 per cent of the rock. Magnetite which occurs in irregular grains, scattered among the other minerals, constitutes about 5 per cent of the rock.

TOWER ISLAND (Genovesa, Ewres). Only one specimen was collected on Tower Island, and this is a basalt from one of several prominent lava flows well exposed in Darwin Bay. The basalt from Darwin Bay, is moderately vesicular and porphyritic, with phenocrysts of feldspar up to one-quarter inch across set in a fine-grained, dense, gray groundmass.

The feldspar phenocrysts are euhedral and subhedral in shape, and show well developed zoning and twinning. They are in the composition range of intermediate labadonite An_{50-55}. The crystals are slightly altered and contain small, dark, angular and irregular shaped inclusions. The groundmass feldspar occurs in poorly developed lath-shaped crystals. They are fresh and range in composition from An_{45} to An_{50}.

Augite occurs as euhedral phenocrysts and as anhedral grains in the groundmass. This mineral is common, fresh and lacks zoning and twinning.

Olivine occurs sparingly as euhedral grains in the groundmass. It is colorless where unaltered, but commonly shows alteration to golden brown iddingsite.

JERVIS ISLAND (Rábida). Four rock samples were collected on Jervis Island, and only one of these, a lava, was collected from loose boulders which occur on the north side of the island.

The rock specimen no. 38, collected from Jervis Island is an olivine basalt. It is porphyritic and contains phenocrysts of olivine and feldspar, both as much as one-quarter inch across, set in a medium-grained gray groundmass. In thin section the rock has a xenomorphic-granular texture, yet with phenocrysts of olivine and feldspar set in a granular groundmass composed of the same minerals plus augite and a small amount of glass.

The plagioclase in the phenocrysts and in the groundmass appear to be identical in all respects except in size, of which the phenocrysts are as much as one-quarter inch across and the groundmass grains rarely more than .3 mm. across. The feldspar is fresh and constitutes between 25 and 30 per cent of the rock. The crystals are twinned and a few of the phenocrysts show zoning. Inclusions of dark glass are common and appear to be concentrated along the margins of the crystals where they are elongated and arranged in rows parallel to cleavage and twinning planes. The feldspar is intermediate labradorite, An_{50-55}.

Augite is pale greenish in color, and occurs as anhedral crystals as much as .5 mm. across. This mineral, too, has dark glass inclusions, but in lesser amounts than the feldspar. The augite is fresh and constitutes about 50 per cent of the rock.

Olivine is in colorless anhedral crystals that show zones of yellow which are due to limonite and not the result of alteration to iddingsite.

SOUTH SEYMOUR ISLAND (Baltra). Three specimens were collected on South Seymour Island, and only two of these, nos. 27256 and 32, were available for study.

Specimen no. 27256 is fossiliferous limestone from one of beach terraces near the southern part of the island (no. 2 of Ochsner), and specimen no. 32 is from a lava flow that rests upon the fossiliferous terrace deposits, also in the southern part of the island.

Specimen no. 27256 should properly be called a fossiliferous tuffaceous sandstone. It contains white fossil shell fragments and dark brown, dark red and buff colored volcanic rock fragments enclosed in a medium-gray, fine-grained, dense groundmass.

Under the microscope one can see rounded grains of orange-red pumice containing phenocrysts of plagioclase, An_{50}, rounded grains of plagioclase, An_{45-50}, olivine altered almost wholly to orange-red iddingsite, and white shell fragments all enclosed in a murky matrix of secondary calcite.

Specimen no. 32 is andesite. It is a fine-grained, weakly prophyritic, medium- to dark-gray colored rock. Phenocrysts of plagioclase are uncommon, and range in size from .6 to 1.0 mm. The crystals are lath-shaped, fresh, and show simple albite and carlsbad twinning. They are in the composition range of An_{35} to An_{40}. The groundmass plagioclase occurs as microlites which are less than .5 mm. in length. They are abundant and constitute about 30 per cent of this rock. The microlites of plagioclase have the same range in composition as the plagioclase phenocrysts. Augite is also very common, and it occurs in two distinct sizes: as small anhedral grains less than .1 mm. in diameter scattered throughout the rock and as larger subhedral grains up to .5 mm. across. The smaller grains are nearly colorless and the larger grains show pale pinkish and greenish pleochroic colors. All of the augite is fresh and untwinned. Magnetite is common and constitutes about 10 per cent of the rock.

Indefatigable Island (Santa Cruz; Bolivia; Norfolk; Porter; Valdéz; Chavez; San Clemente). Five specimens were collected on Indefatigable Island. Of these specimens, no. 28, was the only specimen available for study. It is a dense, fine-grained, dark gray, slightly vesicular olivine basalt. Under the microscope, the olivine basalt has a diabasic-intergranular texture. Plagioclase, which constitutes approximately 40 per cent of the rock, occurs in lath-shaped crystals that range up to 1.0 mm. in length. It is twinned, fresh and has a composition of An_{50}. Augite occurs in large irregular-shaped crystals and constitutes approximately 45 per cent of the rock. It is weakly pleochroic in shades of pale purple and light green. Olivine is colorless when fresh, but golden-yellow when altered to iddingsite. It occurs in subhedral-shaped grains and constitutes about 15 per cent of the rock. Both magnetite and ilmenite are present. Magnetite is in angular and rounded grains whereas the ilmenite is in small skeletal crystals, usually enclosed in the feldspar.

Albemarle Island (Isabela; Santa Gertrudis). Eleven specimens were collected on Albemarle Island. Specimens numbered 44, 47, 48, 51, 52, and 54 are volcanic rocks, and of these specimens only nos. 48, 49, 50, and 52 were available for study. Specimen no. 48 is basalt. It is non-vesicular, porphyritic, and contains phenocrysts of feldspar and augite up to one-eighth inch in length enclosed in a dense, fine-grained, medium-gray colored groundmass. The phenocrystic feldspar, in the composition range of An_{55} to An_{60}, occurs as anhedral and subhedral shaped grains. They are completely twinned, but not zoned or altered. Augite occurs as small granular inclusions in the larger feldspar phenocrysts. The groundmass feldspar, whose composition is approximately An_{50}, occurs as irregular-shaped laths that are slightly more sodic than the feldspar phenocrysts. The groundmass feldspar constitutes about 25 per cent of the rock. Augite, although ocur-

ring as phenocrysts and in the groundmass too, is more abundant in the groundmass. It is pale-greenish in color and shows twinning but no zoning. The phenocrysts are euhedral in shape, whereas the groundmass grains are subhedral and anhedral in shape. Few of the phenocrysts of augite are rimmed with dust-like particles of magnetite, and a few of the grains in the groundmass are almost completely clouded by magnetite.

Specimen no. 49 is a crystal-lithic-vitric tuff. It contains pyroclasts of plagioclase, porphyritic basalt and andesite, and pumice set in a groundmass of fine-grained, partly altered glass. The feldspar pyroclasts are subhedral and anhedral in shape, and range in composition from An_{40} to An_{50}. The larger grains contain bleb-shaped inclusions of pale-yellowish glass, arranged parallel to twinning planes. The larger grains are unaltered, but a few of the smaller feldspar grains have a narrow rim of pale-yellowish opal. Augite pyroclasts are colorless, and are rimmed by yellowish nontronite. The lithic pyroclasts consisting essentially of andesite and basalt, are rounded and also rimmed by opaline silica. The pumice pyroclasts are rounded and contain a few crystals of potash feldspar (sanidine) as well as some yellowish colored nontronite. A small amount of secondary calcite is present.

Specimen no. 50 is tuff-breccia. It consists of angular and rounded, dark-gray pumice fragments up to one-half inch across enclosed in a medium- to fine-grained, grayish- and greenish-brown matrix of partly altered volcanic ash.

Specimen no. 52 is a porphyritic basalt from Tagus cove. It contains phenocrysts of plagioclase and augite up to one-quarter inch across enclosed in a fine-grained, dense, dark-gray, vesicular groundmass. The plagioclase phenocrysts are in the composition range of An_{55} to An_{60}, and occur in subhedral and anhedral grains that are well twinned and show zoning. Inclusions of dark glass are present, and especially noticeable at the interior of the feldspar grain where they are arranged in elongated clots parallel to the twinning planes. The groundmass feldspar occurs in microlites that constitute about 30 per cent of the rock. They are twinned and range in composition from An_{50} to An_{55}. Augite occurs as euhedral phenocrysts and as anhedral grains scattered among the feldspar microlites. The augite is fresh, though in places it is stained yellowish-orange by limonite. It constitutes about 30 per cent of the rock. The remainder of the rock is dark basaltic glass.

BARRINGTON ISLAND (Santa Fé). Three specimens were collected on Barrington Island; and only one of these (no. 73), a specimen of olivine basalt, was available for study. It is said to be characteristic of the lava flows in the northern part of the island. This olivine basalt is a fine-grained, slightly vesicular rock containing phenocrysts of olivine and plagioclase set

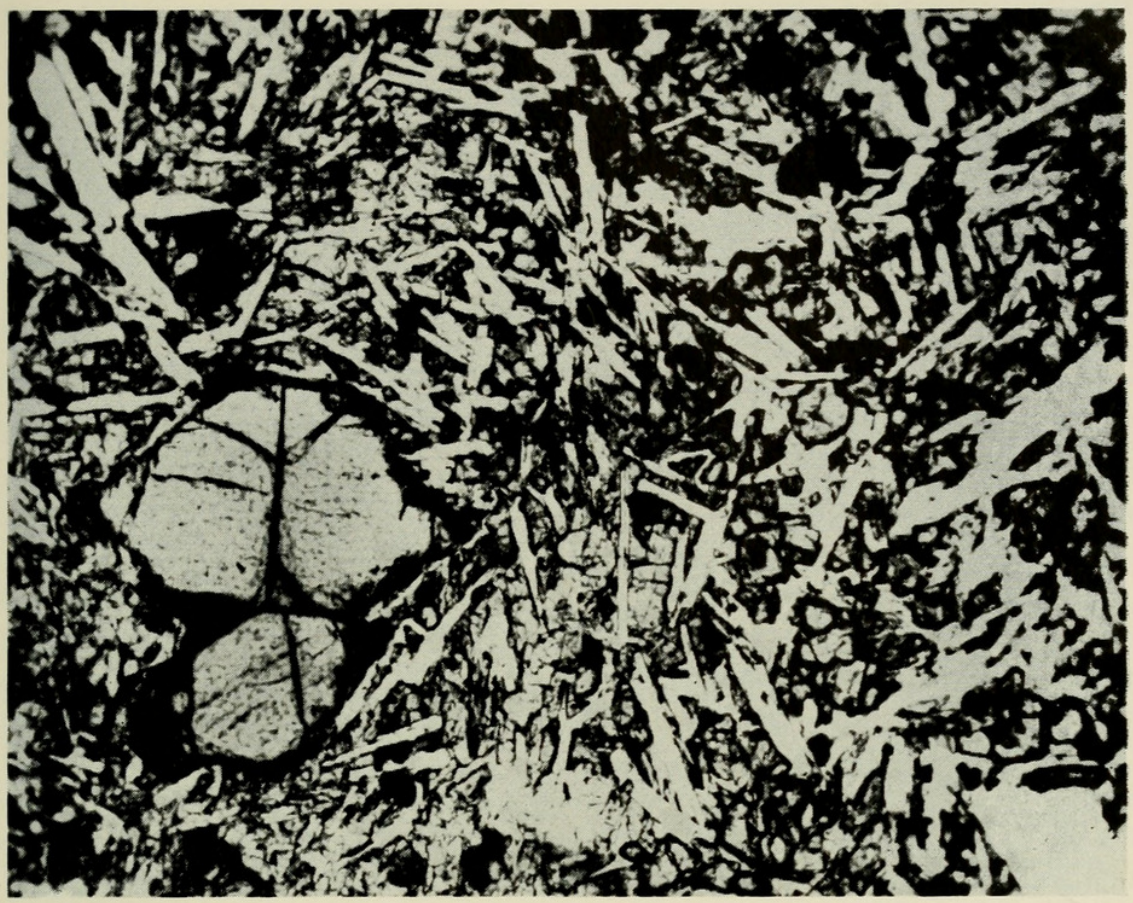

Figure 3. Olivine basalt from Barrington Island, Galápagos Achipelago. Phenocrysts of olivine are rimmed by yellow iddingsite and are enclosed in a groundmass composed of plagioclase laths (An_{60}) and granular augite. Plain light. × 30.

in a groundmass of feldspar laths and augite grains. The plagioclase phenocrysts are labradorite (An_{60}) and occur as slightly rounded, twinned, unzoned crystals as much as .2 mm. across. The feldspar phenocrysts are fresh and constitute about 5 per cent of the rock. The groundmass feldspar occurs in lath-shaped crystals not more than .5 mm. in length. They are fresh, twinned, not zoned and are in the composition range of An_{45} to An_{50}.

Olivine occurs as subhedral and anhedral grains up to .2 mm. in diameter. They are colorless and slightly altered to golden-yellow iddingsite. Olivine also makes up part of the groundmass where it occurs in rounded grains scattered among the feldspar laths. It constitutes approximately 20 per cent of the rock. Augite occurs in irregular-shaped crystals that include small laths of feldspar. It is weakly pleochroic from pale pinkish-purple to pale greenish, and constitutes about 40 per cent of the rock.

CHATHAM ISLAND (San Cristóbal; Dassigney; Grande). Five rock specimens were collected on Chatham Island. Only one of these specimens,

Figure 4. Olivine basalt from Chatham Island, Galápagos Archipelago. Phenocrysts of olivine enclosed in a groundmass of plagioclase (An_{50}) and augite. Plain light. × 30.

no. 43, an olivine basalt collected at the terminus of a lava flow south of Sappho Cove, was available for study. The olivine basalt from Sappho Cove is a fine-grained, finely-vesicular, medium-gray porphyritic rock which contains phenocrysts of augite and plagioclase enclosed in an intergranular groundmass of feldspar laths and grains of augite and olivine. The feldspar phenocrysts, intermediate labradorite An_{55}–An_{60}, occur in subhedral and anhedral crystals up to .5 mm. across. They are fresh, well-twinned and constitute about 10 per cent of the rock. The groundmass plagioclase (An_{50}) is slightly more sodic than the feldspar phenocrysts, and occurs as lath-shaped crystals partly enclosed in the augite and partly forming a mesh structure which is infilled by smaller augite crystals. The groundmass feldspar constitutes about 50 per cent of the rock. The augite occurs in colorless and pale-purplish, irregular-shaped crystals that measure as much as .6 mm. across. This mineral is unaltered and constitutes between 35 and 40 per cent of the rock. Olivine is in euhedral to subhedral grains. It is colorless where fresh, but is altered in part to golden-yellow iddingsite,

especially around the margins of the crystals. Olivine constitutes between 10 and 15 per cent of the rock.

Charles Island (Santa María; Floreana). Eight rock specimens were collected on Charles Island. Two of these specimens numbered 59 and 63, were available for study. Specimen no. 59 was collected from an exposure on Cormorant Bay and is a crystal-vitric-lithic tuff. In hand specimen this rock is dark, greenish-black to black in color and contains angular pyroclasts set in a fine-grained, dense matrix of dark-brown colored glass.

Under the microscope one can see angular pyroclasts of colorless augite and irregular grains of basic andesine An_{45}, and rounded pyroclasts of slightly vesicular, amygdaloidal, and vitrophyric glass. These pyroclasts of glass constitute a bulk of the rock. They are yellow in color, with the interior part being canary-yellow and the rims a golden-yellow. The amygdules are ovoid in shape and more or less completely filled with secondary calcite. Augite and andesine are the crystalline constituents in the glassy pyroclasts. The augite is colorless and is in angular crystals. The andesine (An_{40} to An_{45}) occurs in lath-shaped as well as in irregular-shaped crystals. The matrix is a glass. It is grayish in color and contains finely divided magnetic as well as microlitic laths of andesine and angular grains of colorless augite.

This tuff is similar in many respects to the tuffs found on Albemarle Island, excepting the tuff from Cormorant Bay on Charles Island contains very small amounts of lithic material such as pyroclasts of andesite and basalt. Specimen no. 63 is said to be representative of a lava flow which reached the ocean at Black Beach Road (Ochsner, unpublished manuscript). The rock is basaltic in composition. It is porphyritic and contains phenocrysts of plagioclase and pyroxene set in a sub-ophitic groundmass of plagioclase microlites and intergranular augite.

The plagioclase phenocrysts (An_{55} to An_{60}) occur in subhedral and anhedral grains. They are completely twinned, zoned and show a slight amount of alteration. The larger phenocrysts, up to .5 mm. across, contain numerous inclusions of glass, augite, and alteration products of the pyroxene, all localized more toward the interior of the crystal and oriented parallel to the twinning planes. The plagioclase phenocrysts constitute about 25 per cent of the rock.

The plagioclase in the groundmass has the composition of An_{55} and occurs in subhedral and irregular-shaped crystals up to .4 mm. in length. They are twinned, but not altered, and constitute about 30 per cent of the rock. The pyroxene is hypersthene which occurs in slightly colored euhedral grains that exhibit weak pleochroic colors. Many of the larger crystals of hypersthene have a rim of iddingsite; the smaller grains are almost completely altered to iddingsite.

Small amounts of magnetite and colorless glass are present in the rock.

HOOD ISLAND (Española). Three rock specimens were collected on Hood Island. Specimen no. 65 is from a lava flow exposed in the cliff southwest of Gardner Bay, and specimen no. 69 from a lava flow exposed due west of Gardner Bay. Specimen no. 65 is olivine basalt. It is porphyritic and contains phenocrysts of olivine and plagioclase set in a dense, fine-grained, dark-gray groundmass composed of plagioclase microlites and grains of augite. The plagioclase phenocrysts are in rounded, zoned crystals that range in composition from An_{45} to An_{55}. They contain numerous inclusions of very small crystals of apatite and augite which tend to be concentrated in the outer zone of the phenocrysts. The plagioclase microlites are slightly more sodic than the phenocrysts and have a composition of approximately An_{45}.

Augite is in small, colorless, subhedral and anhedral grains. It is very common and constitutes about 25 per cent of the rock. Olivine occurs as anhedral crystals, of which many of them have been altered in part to iddingsite. Olivine constitutes about 20 per cent of the rocks. Specimen no. 69, too, is olivine basalt, and is similar in many respects to specimen no. 65, excepting the augite which in specimen no. 69 is pale purplish in color, indicates the presence of titanium in more than normal amounts.

COCOS ISLAND

Cocos Island, governed by Costa Rica, is located on latitude 5° 32′ N., about 650 miles west of Cape Corrientes, Colombia. It is a volcanic island approximately 4 miles long and slightly more than 2 miles wide, with a maximum elevation of 1932 feet* above sea level. Six rock specimens were collected on Cocos Island by W. H. Ochsner in 1905, and by Dr. Leo G. Hertlein, California Academy of Sciences, February, 1932. Specimen nos. 14–1 and 17 are basalt, no. 12–1 is latite, no. 13–1 is tuff-breccia, and no. 18–1 is andesite (oligophyre).

Specimen no. 14–1 is basalt. It is a dense, fine-grained, medium-gray, slightly porphyritic rock containing phenocrysts of plagioclase and hypersthene enclosed in a sub-ophitic groundmass of plagioclase laths and microlites and intergranular hypersthene. The plagioclase phenocrysts are anhedral in shape and are in the composition range of An_{55} to An_{60}. Both zoning and twinning are common, and a few of the crystals are partly altered. The larger phenocrysts contain many inclusions of glass, hypersthene, and its alteration products. The inclusions tend to be localized more at the central portion of the crystal and in a few crystals they are oriented somewhat parallel to the twinning planes. The plagioclase phenocrysts constitute about 25 per cent of the rock. The groundmass plagioclase

*This elevation is given in Sailing Directions for the west coasts of Mexico and Central America. United States Naval Oceanographic Office, H.O. No. 26, p. 26, January, 1962.

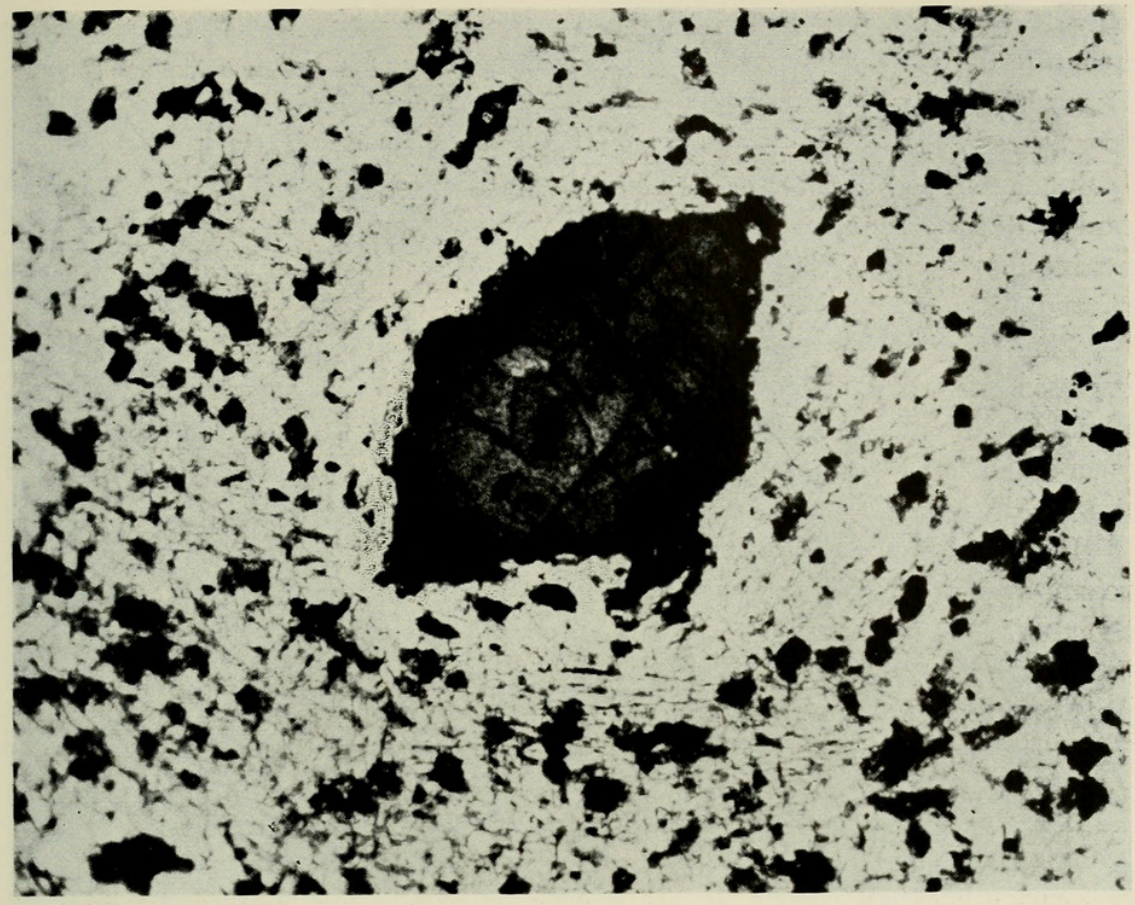

Figure 5. Oligophyre from Cocos Island. The euhedral phenocryst of olivine which has been altered entirely to iddingsite, is enclosed in a trachytic groundmass of oligoclase laths and grains of olivine. Plain light. × 30.

occurs in microlites and subhedral, irregular-shaped laths, of which the latter are no more than .4 mm. in length. The laths are twinned, but not altered and are slightly more sodic than the phenocrysts. The groundmass feldspar constitutes about 30 per cent of the rock. Hypersthene occurs in euhedral crystals, of which a majority are phenocrysts. The large hypersthene crystals have a narrow rim of yellow iddingsite, whereas, the small-grains of hypersthene are altered largely to yellowish-orange iddingsite. Minor accessory materials include colorless glass and grains of black magnitite. Specimen no. 16, olivine basalt, is porphyritic and contains phenocrysts of olivine and plagioclase set in a groundmass of plagioclase laths and grains of augite.

The plagioclase phenocrysts are subhedral to euhedral and exhibit well developed twinning and zoning. Their composition is in the range of An_{50} to An_{55} and most of the alteration is at the interior of the crystals where they are more calcic. The groundmass plagioclase occurs in irregular, lath-shaped crystals. Because of their small size their composition is difficult to determine, but it is in the range of An_{45}–An_{50}. The olivine is in

euhedral-shaped crystals which are altered largely to iddingsite, especially around the margins of the crystals. Augite is present in small colorless grains. Secondary materials include iddingsite, limonite, and sericite. A small amount of dark glass occurs interstitially between the feldspar laths.

Specimen no. 17 is also an olivine basalt. It has a porphyritic texture and contains phenocrysts of plagioclase and hypersthene enclosed in a fine-grained groundmass of feldspar laths and grains of olivine and hypersthene.

The plagioclase phenocrysts are in anhedral and subhedral-shaped crystals and are in the composition range of An_{45} to An_{50}. They are completely twinned, zoned, and remarkably fresh. The groundmass plagioclase is in small, lath-shaped crystals and is in the composition range of An_{40} to An_{45}. They are twinned, unaltered and show no zoning.

Hypersthene occurs in euhedral-shaped crystals that show faint pleochroism, and are rarely twinned. Olivine is in euhedral-shaped crystals that show almost complete alteration to yellowish-orange iddingsite.

Specimen no. 12–1 from Cocos Island is latite. It is slightly vesicular, purplish-gray in color, and porphyritic with phenocrysts of plagioclase set in a fine-grained groundmass. The plagioclase phenocrysts occur as euhedral and subhedral grains of which some are skeletal and contain inclusions of magnetite and glass. Their composition is oligoclase, in the range of An_{20} to An_{25}. The crystals are zoned and complexly twinned and constitute about 10 per cent of the rock. The plagioclase in the groundmass is slightly more sodic than the phenocrysts and have an An content of about 20 per cent. The grains are anhedral and show slight alteration, twinning, and zoning. They are very abundant and constitute about 80 per cent of the rock. The pyroxene is diopsidic-augite and it occurs in pale, yellowish-green anhedral grains. It makes up about 5 per cent of the rock. Magnetite occurs in irregular-shaped grains which are commonly surrounded by yellow limonite.

Specimen no. 13–1 is a lapilli-tuff-breccia. This rock is well consolidated and consists of angular and rounded fragments of dark-gray and brownish vesiculated glass, lithic material, and mineral grains set in a fine-grained ashy matrix. The vesiculated glass fragments range up to three-eighths of an inch across. They are relatively unaltered, and contain very few phenocrysts, but refractive index determinations made on the glass indicate an andesitic composition. In addition to the vesiculated glass fragment, the rock contains also dark pyroclasts of vitrophyre which have phenocrysts of intermediate andesine, (An_{45}) enclosed in a dark glass. The lithic fragments are of three types: hornblende andesite, andesite, and basalt. The hornblende andesite contains strongly pleochroic, needle-shaped crystals of hornblende and fresh andesine (An_{40-45}). The andesite is composed of andesine phenocrysts (An_{45-50}), set in a groundmass of small andesine

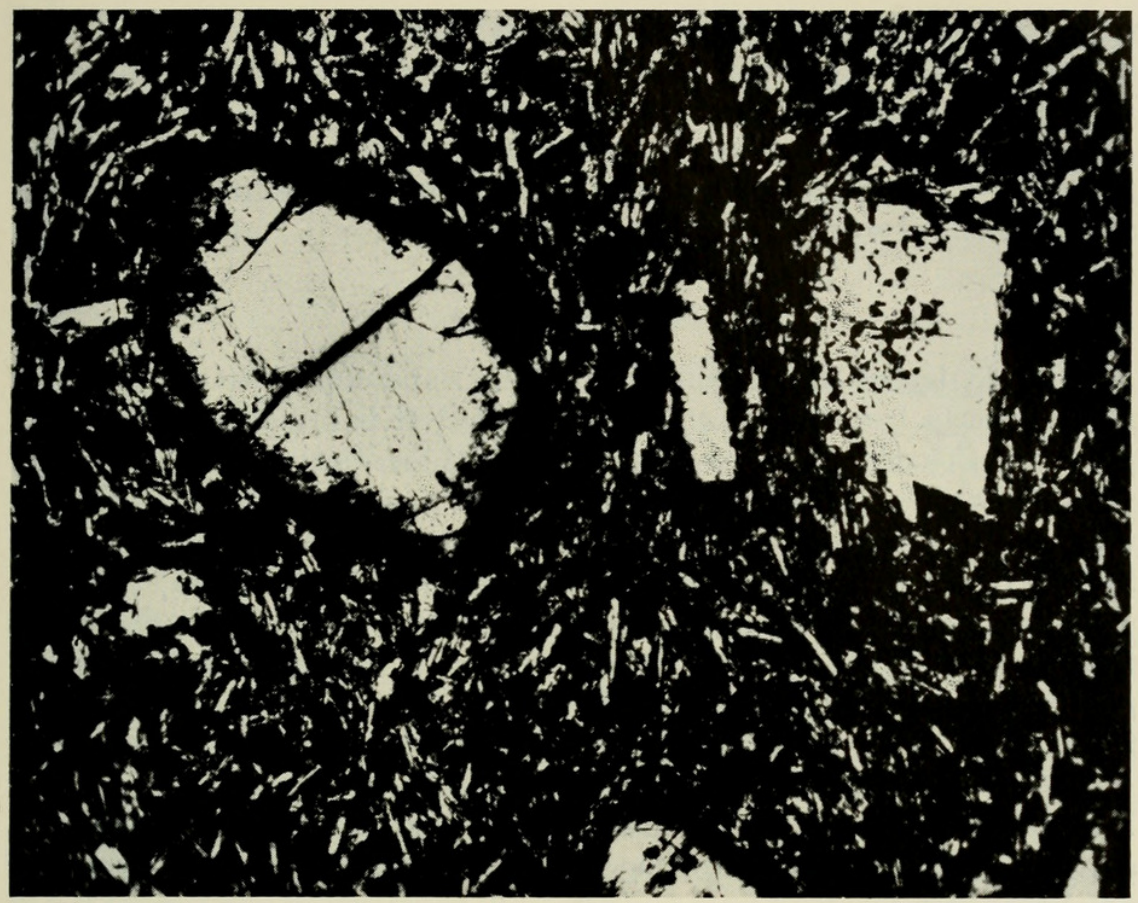

Figure 6. Olivine basalt from Cocos Island. Phenocrysts of plagioclase (An_{45} to An_{50}) and olivine enclosed in a fine-granied groundmass of feldspar laths and grains of olivine and hypersthene. Plain light. × 30.

grains and colorless diopsidicaugite. The basalt pyroclasts, on the other hand, are much darker in color than either of the andesite pyroclasts and contains phenocrysts of labradorite (An_{60-65}), enclosed in a fine-grained groundmass of plagioclase microlites and small, anhedral grains of augite. Olivine, too, is present in the basalt and this mineral is in small, anhedral grains which are altered largely to iddingsite. Mineral pyroclasts include euhedral grains of plagioclase in the composition range of An_{40} to An_{45}, subhedral, fresh and colorless grains of hypersthene, rounded and corroded grains of brown hornblende, and a few rounded grains of quartz.

Specimen no. 18–1 is by far the most interesting rock collected on Cocos Island. The rock is called an oligophyre for want of a better name. It is fine-grained, buff-colored, and has a poorly defined flow banding. Under the microscope one can see that the rock is weakly porphyritic. It is composed largely of oligoclase. The phenocrysts of oligoclase are anhedral and are in the composition range of An_{30} to An_{35}. The groundmass oligoclase (An_{20-25}) is in lath-shaped grains that are arranged in zones around the

oligoclase phenocrysts. Diopsidic-augite is present in colorless, subhedral grains. Biotite is in dark brown, strongly pleochroic, anhedral grains. Both of these ferromagnesian minerals are present in about equal amounts. Magnetite occurs in cubic-shaped grains. Secondary minerals include limonite, which is probably derived either from the biotite or from the small amount of pyrite that is present in the rock.

MALPELO ISLAND

Malpelo Island is on latitude 3° 59′ N., and lies about 250 nautical miles westerly from Buenaventura, Colombia. It is a territory of the Republic of Colombia and was known as early as 1530. The island is of volcanic origin and is approximately one and one-half miles long, one-half mile wide, and has a maximum elevation of 854 feet above sea level. Very little has been written regarding the geology of Malpelo Island, and only a limited amount is known about the rocks that are exposed there. McConnell (1943) gives an excellent description of the fresh lava and phosphatized rocks that were collected by Comandante Eduardo Fallon of the Colombian Navy in December, 1940 (Murphy, 1941, p. 57).

Two rock specimens were collected by C. B. Perkins, herpetologist, San Diego Zoo, in December, 1931, and the following comments are based upon a study of these specimens. One is pyroxene andesite and the other is phosphate rock.

The pyroxene andesite is greenish-gray in color, dense, and fine-grained. Under the microscope the rock is holocrystalline, microporphyritic, and has a pilotaxitic texture. The plagioclase phenocrysts are fractured, twinned, slightly altered, and range in composition from An_{35} to An_{40}. The plagioclase that comprises a bulk of the groundmass is in microlites whose composition based upon limited determination is in the range of An_{20} to An_{25}. The plagioclase phenocrysts and groundmass microlites combined constitute about 50 per cent of the rock. The pyroxene, diopsidic-augite, occurs in colorless, anhedral grains usually no more than .05 mm. across, and occasionally in larger grains up to .1 mm. across. It constitutes about 20 per cent of the rock. Chloritic material is present, especially in close association with the plagioclase phenocrysts and the larger pyroxene grains. It is grass-green in color, moderately pleochroic, and locally stained brown by limonite. Both quartz and chalcedony are present, but as secondary minerals, and in small amounts. Scattered uniformly throughout the rock are black, slightly angular, needlelike crystals. They are opaque and could possibly be ilmenite. The phosphate rock is dark brownish-black, mottled, and fine- to medium-grained. Under the microscope it is dark brown in color with scattered irregular, colorless areas, composed of quartz and chalcedony. Calcite is present in narrow, curved veinlets.

Because of the lack of relict mineral grains in the phosphate rock, it is exceedingly difficult to determine whether it was originally a pyroclastic or flow rock. One could speculate, on the basis of lack of crystalline constituents, that the original rock was a vitric-crystal tuff in which the crystalline constituents were titanium and iron-bearing minerals, or titaniferous magnitite.

CEDROS ISLAND

Cedros (Cerros) Island is situated just outside of Sebastian Vizcaino Bay, on the west side of Baja California, midway between San Diego and Cape San Lucas. The island is elongated in a north-south direction, and measures about 22 miles long and 7 miles wide. The highest peak is Cedros Mountain whose elevation is 3950 feet. Very little is known about the geology of the island, but from observers (Hanna, 1925, p. 268) who have visited the island we learn that it is composed largely of cherts, sandstones, schists, and serpentine, all similar in many respects to the Franciscan rocks (upper Jurassic) that are exposed so well in the San Francisco Bay area. In addition there are Miocene and Pliocene sedimentary rocks on the eastern side of the island and some volcanic rocks of presumably Tertiary age at the southwest corner of the island.

Two rock specimens were collected on Cedros Island: Specimen no. 7 is tuff-breccia and specimen no. 9 is glaucophanized volcanic rock.

Specimen no. 7 tuff-breccia, is orange red in color, somewhat friable, and contains partly altered pumice fragments, pyroclasts of basalt, and grains of augite, altered olivine, biotite, hornblende, and plagioclase (An_{50}), all enclosed in a matrix of partly devitrified, brownish colored glass. The basalt pyroclasts are of two types, one which is composed wholly of a felted mat of plagioclase (An_{50}) laths, and the other which contains plagioclase microlites (An_{50-55}) set in a dark brownish glass which constitutes at least 50 per cent of the rock.

Specimen no. 9, glaucophanized volcanic rock, the first of two metamorphic rocks to be mentioned in this paper, is a dense, fine-grained bluish gray rock. Distinct foliation is lacking and the rock has a cataclastic texture. Glaucophane is common and contributes largely to the bluish coloration imported to the rock. It occurs in ragged and irregular-shaped grains that are strongly pleochroic with $\times$ = pale greenish-colorless, y = lavender blue, z = blue. The glaucophane appears to have formed in part from a colorless pyroxene, and it is altered locally to a fibrous mineral of low birefringence. Tremolite is very abundant and constitutes at least 45 per cent of the rock. It occurs in small, lath-shaped crystals and fibrous needles, usually arranged in angular and subangular clots.

Both calcite and aragonite are present. The calacite is colorless and is

in veins, whereas the aragonite, which, too, is colorless, is present as discrete grains forming a mineral phase in the rock. A pyroxene of diopsidic-augite composition occurs as rounded grains that have altered in part to glaucophane and to pale-green chlorite. Quartz is not abundant, but this mineral is present as small rounded grains scattered irregularly throughout the rock.

Because of the lack of distinct foliation, the irregular distribution of the glaucophane and tremolite, and the presence of relict pyroxene, it is believed that the glaucophane rock was derived from a basic volcanic rock.

San Benito Islands

The San Benito Islands are about 18 miles west of Cedros Island. There are three islands in the group. West San Benito (the largest), Middle San Benito (smallest), and East San Benito (next largest); all lie close together in an east west line. West and middle San Benito are composed largely of Franciscan chert, and East San Benito, the most rugged of the three islands, contains schist and marble in addition to chert (Hanna, 1924, pp. 373–374) (Van West, 1959, pp. 8–13). Only one specimen was available from San Benito Islands for study, and it is a glaucophane schist, collected on East San Benito Island.

The glaucophane schist is a medium-to-fine-grained, grayish-blue rock that shows well developed foliation. Under the microscope one can see wispy muscovite plates curved around earlier formed grains of glaucophane and plagioclase. Glaucophane occurs in irregular-shaped to xenoblastic crystals that show distinct pleochroism: $=$ colorless, $y =$ purplish blue, $z =$ ultramarine blue. The crystals appear broken as though they had developed early and were fractured and disrupted during shearing stages of metamorphism. Plagioclase (An_{5-10}) occurs as rounded and angular grains, usually closely associated with quartz which, too, is in rounded grains. The quartz shows undulatory extinction. Muscovite is present as wispy-shred-like aggregates of small plates. It apparently developed late. Van West (1958, pp. 535–37) describes glaucophane schists from San Benito Islands similar to that mentioned immediately above and states that this is ". . . a common variety among the glaucophane schists formed on East San Benito Island."

Tres Marías Islands

The Tres Marías Islands, consisting of Maria Madre, Maria Magdalena, and Maria Cleofas, lie about 55 miles off the west coast of Mexico, west of San Blas, Nayarit, between latitudes 21° and 22° N., and longitudes 106° and 107° W. (see fig. 2).

Much has been written of the paleontology of these islands as a result

of expeditions by the California Academy of Sciences. However a few remarks about some of the rocks collected in 1925 by G D. Hanna and E. K. Jordon, and other rocks collected and reported upon by Hertlein and Emerson (1959, p. 4) will help to explain further the geology of these islands.

All of the rock specimens were collected on María Madre Island which, according to Hanna (1926, p. 69) is stated as consisting ". . . of granite, chiefly, with a rim of diorite around the edges." It is apparently from this granitic core and dioritic rim that the specimens of biotite granite and hornblende-quartz diorite porphyry were collected. The biotite granite (CAS–35) is a medium-grained, light-colored rock which is speckled by biotite and hornblende. Under the microscope the rock has a hypidiomorphic-granular texture, the texture common to most plutonic rocks of this composition. Both orthoclase and plagioclase feldspars are present and where they occur adjacent to another a myrmeketic border has developed on the orthoclase. The orthoclase is in anhedral grains which constitute about 40 per cent of the rock. It is fresh for the most part and contains a small amount of sericite along fractures. Plagioclase, in the composition range of An_{10} to An_{15}, occurs in subhedral and anhedral grains which, too, contain some sericite. Zoning is absent, but the twinning in the plagioclase is complex. This mineral constitutes about 20 per cent of the rock. Quartz is in rounded, slightly fractured grains. It constitutes about 10 per cent of the rock. Biotite is present in strongly, pleochroic, dark greenish-brown subhedral grains. This mineral has been altered locally to deep-green chlorite and contains small inclusions of zircon and apatite. Hornblende is in short prismatic crystals. It is fresh, grass-green in color, and too contains inclusions of apatite and zircon.

CAS–39, the hornblende-quartz diorite porphyry, is considerably darker colored than the biotite granite. It has a distinct porphyritic texture and contains phenocrysts of plagioclase, quartz, and hornblende enclosed in fine, granular groundmass of the same materials.

The plagioclase phenocrysts are subhedral in shape and range up to .4 mm. in size. They are zoned and complexly twinned and range in composition from core to rim, from An_{30} to An_{25}. Alteration is present, principally to sericite and calcite, with the cores being more highly altered than the rims. This mineral constitutes about 40 per cent of the rock. The groundmass feldspar is in small lath-shaped crystals that average less than .5 mm. in length. They range in composition from An_{20}–An_{25}, show slight alteration to sericite, and locally form diabasic intergrowths with the quartz. The groundmass plagioclase constitutes about 20 per cent of the rock. Quartz occurs as angular phenocrysts up to .4 mm. across and as rounded grains in the groundmass. It constitutes about 10 per cent of the rock. The horn-

blende is in pale-green crystals that have a moth-eaten appearance. It is weakly pleochroic, contains inclusions of apatite and magnetite, and constitutes about 5 per cent of the rock. A small amount of deep-green biotite is present. It is strongly pleochroic in shades of green and brown, and contains inclusions of apatite and magnetite. Several specimens of rhyolite (CAS–37 and 38) were collected as float in the first main canyon southwest of the village on María Madre Island. The rhyolite is a fine-grained, dense rock and ranges in color from purplish-gray to gray. It shows flow banding and contains white, rounded phenocrysts and small cavities of which the latter now contain small, well-formed quartz crystals. The rock is porphyritic and contains altered phenocrysts of plagioclase and green biotite enclosed in a fine-grained groundmass which shows a micrographic structure. The plagioclase phenocrysts are subhedral in shape, show simple twinning, and are in the composition range of An_{15} to An_{20}. Alteration of the plagioclase is principally to sericite and calcite. The phenocrysts constitute about 10 per cent of the rock. The groundmass feldspar is orthoclase and is in anhedral, untwinned, slightly altered grains. It forms microscopic intergrowths with quartz and constitutes about 50 per cent of the rock. Excepting for a few scattered ragged-appearing, green-colored phenocrysts of biotite, quartz comprises the remainder of the rock. It occurs both as distinct anhedral grains and in micrographic intergrowths with the groundmass feldspar. In the same canyon where the rhyolite was collected and upstream from the contact between the Pliocene sedimentary rocks and the underlying granite, a specimen (CAS no. 36) of rhyolite granophyre was collected from an outcrop of this rock. The granophyre resembles the rhyolite in hand specimen. It lacks the flow banding which is so characteristic of the rhyolite, but does show phenocrysts of feldspar and has a dull gray color. The texture of the rock is granophyric and porphyritic, and the rock contains rounded phenocrysts of plagioclase and quartz set in a granophyric intergrowth of quartz and orthoclase. The plagioclase, though slightly altered is in the composition range of An_{10} to An_{15}. It is subhedral in shape and measures up to .3 mm. in size. The groundmass feldspar, orthoclase is less altered than the phenocrystic, and constitutes about 45 per cent of the rock. Quartz occurs sparingly as rounded phenocrysts. However, it is more abundant in the groundmass where it is much coarser grained when intergrown with the orthoclase. The quartz constitutes about 40 per cent of the rock. The biotite is green, strongly pleochroic, and occurs in sponge-like crystals with irregular outlines.

Specimen CAS–40 is fossiliferous siltstone and was obtained from a large boulder in the first main canyon southwest of the village on María Madre Island. The siltstone is fine-grained and contains rounded and angular grains of quartz and shell fragments, and fossil foraminifera in a matrix consisting of calcite and chalcedonic silica. C. C. Church (written

communication, January, 1963) kindly examined the siltstone and identified the following genera:

Peneroplis sp.
Bolivina sp.
Bulimina sp. similar to *B. ovata*
Frondicularia sp.
Globigerina sp.

These fossils indicate late Tertiary (possibly Pliocene) age for the siltstone.

WHITE FRIARS ISLANDS (MORRO DE PAPANOA)

During the course of later excursions off the west coast of Mexico by the California Academy of Sciences, several rock specimens were collected by Dr. Leo G. Hertlein from a group of small islands which lie some 5 to 6 miles south of Zihuatenejo, State of Guerrero. These islands are referred to as the White Friars and are said to resemble members of that monastic order in a kneeling position.

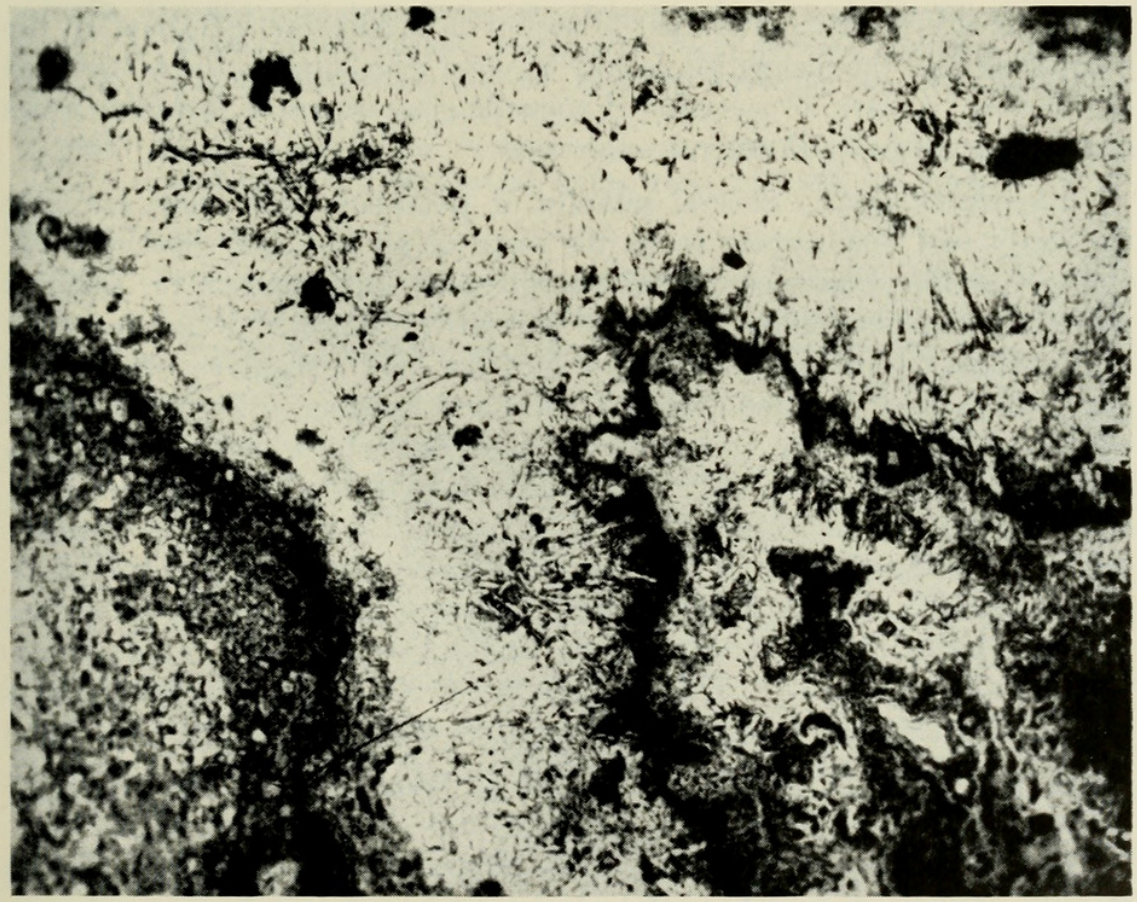

Figure 7. Phosphate rock from the White Friars Islands. Veins of white metavariscite in collophane. Plain light. × 30.

Most of the rock specimens collected by Dr. Hertlein are highly phosphatized volcanic rock, but one (CAS–42) is reasonably unaltered and is identified as hornblende andesite. The andesite is porphyritic and contains plagioclase phenocrysts set in a granular matrix of feldspar, hornblende, volcanic glass, and minor quartz. The plagioclase phenocrysts are subhedral, twinned, and zoned; a few are bent. Those phenocrysts that show the best zoning are euhedral in shape. Many of the phenocrystic plagioclases are of a pale, pinkish-brown color. These colored feldspar crystals have a composition in the range of An_{30} to An_{35}. The remaining, non-colored plagioclase phenocrysts are in a composition range of An_{45} to An_{50}. The phenocrystic plagioclase constitutes about 45 per cent of the rock. The groundmass plagioclase is in subhedral and anhedral grains which show twinning, but lack zoning. They are relatively unaltered, range in composition from An_{35} to An_{40}, and constitute about 40 per cent of the rock.

Hornblende occurs as pale-green, weakly pleochroic, prismatic and skeletal crystals. Biotite is in irregular pleochroic crystals. The hornblende and biotite constitute less than 10 per cent of the rock. The quartz present in this rock is scarce, and occurs in rounded grains that show wavy extinction and contain tiny prismatic crystals of zirion. Both apatite and magnetite are present. The apatite occurs as needle-like inclusions in the plagioclase and the magnetite usually in close proximity to the biotite and hornblende. A dark, brown-colored volcanic glass occurs in irregular areas scattered irregularly throughout the rock.

PHOSPHATE ROCK. Several samples of phosphate rock were available for study and they appear to be the same in all respects. Specimen no. CAS–44 is the largest and offers the greatest opportunities for detailed petrologic and mineralogic study. It is relatively smooth, dense, and light brownish-gray to beige in color. Cut surfaces show irregularly distributed open voids as well as a well developed colloform banding which in some cases conforms to the outline of the void. Under the microscope the colloform banding shows up fairly well and one can see that the rock consists principally of two distinct materials: (1) a pale-buff to brown-colored, weakly birefringent isotropic mineral whose refractive index and structure indicate collophane and (2) a crystalline, colorless mineral which has moderate to strong birefringence, moderate axial angle, optically positive and an extinction of $Z' \wedge C = 27°$. This latter mineral is metavariscite in which a small amount of iron isomorphously replaces some of the aluminum. The metavariscite occurs as small prismatic crystals and in crusts that show a radial-fibrous structure.

The phosphate rock from the White Friars resembles in many respects the phosphate rock found on Malpelo Island, yet they differ somewhat in their mineralogical content. The phosphate rock on Malpelo consists largely

of phosphosiderite and strengite (McConnell, 1943, p. 713) whereas that on the White Friars Islands is collophane and metavariscite.

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