Geology and Petrography of Volcanic Rocks of the Truk Islands, East Caroline Islands

GEOLOGICAL SURVEY PROFESSIONAL PAPER 409

Stark and Hay—GEOLOGY AND PETROGRAPHY, VOLCANIC ROCKS OF THE TRUK ISLANDS—Geological Survey Professional Paper 409

Geology and Petrography of Volcanic Rocks of the Truk Islands, East Caroline Islands

By J. T. STARK *and* R. L. HAY

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A structural, stratigraphic, and petrographic study of the rocks of a highly dissected, partly submerged inactive shield volcano

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1963

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

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J. T. Stark and R. L. Hay

ABSTRACT

The Truk Islands are a near-atoll in the North Pacific Ocean at about 7°20′ north latitude and 151° east longitude. They consist of 12 volcanic islands and many low coral reef islands in a lagoon approximately 30 by 40 miles, enclosed by a coral reef. The volcanic islands range from 5 by 2 miles to islands less than a quarter of a mile in diameter. Several peaks on the volcanic islands rise more than 1,000 feet; the highest altitude is 1,453 feet, on Tol. Dense, jungle vegetation covers slopes and crests of the volcanic islands and many of the reef islands.

The Truk Islands are remnants of a large shield volcano, now inactive, which has been partly submerged. Lava flows predominate although pyroclastic deposits are locally interbedded with the flows. The Truk volcano extended about 16,000 feet from the ocean floor to the surface. No evidence of crater walls now exists, but geologic evidence indicates a central crater once erupted large volumes of pyroclastic ejecta. Most of the lavas issued from fissure vents now represented by dikes and dike swarms.

The petrography of the volcanic rocks of Truk is relatively simple except for breccia blocks in the pyroclastic deposits of the central islands. The lava flows and dikes consist of olivine-rich basalt, melilite-nepheline and nepheline basalt, nepheline basanite, andesite, and trachyte. The breccias of central Udot and Eot consist of angular fragments of rock in a fine-grained tuff matrix of crystal and rock fragments. Andesite, trachyte, and basalt blocks predominate in the breccias. Phaneritic blocks of gabbro are locally common, and blocks of hornfelsic, recrystallized gabbro, basalt, and breccia contain veins of fine-grained monzonite and quartz monzonite. Several blocks of monzonite have been found. Gabbro blocks contain dikes of andesite and basalt and inclusions of recrystallized basalt. A small number of limestone xenoliths were found.

The lavas of the Truk volcano clearly represent the alkalic-olivine-basalt-trachyte association common in the Pacific Ocean basin east of the andesite line. The undersaturated lavas of Hawaii are similar to those of Truk, but hypersthene-bearing tholeiitic lavas of Hawaii have no visible counterpart on Truk, either as lavas or pyroclastic ejecta. Unlike Hawaii, quartz trachyte occurs on the central islands of Truk. Most lavas and dikes of the central islands have been hydrothermally altered to some extent. Secondary chlorite and albite partly or entirely replace primary mafic minerals and plagioclase, respectively, and quartz and pyrite have been introduced into some of the rock.

Ejecta from the central crater include a number of rock types not found otherwise at the surface and supply information about rock types and processes at depth in the interior of the volcano. Gabbro was probably emplaced within the volcano, possibly as a stock. The gabbro is undersaturated and fundamentally similar to the basalt flows at the surface and was probably derived from the same magma. Monzonite and quartz monzonite form veins in the gabbro blocks and occur as individual xenoliths. The monzonite crystallized from a hydrous magma, apparently at temperatures high enough to melt and assimilate adjacent gabbro. The quartz monzonite may be the hypabyssal equivalent of the quartz trachyte which assimilated some gabbroic material during intrusion.

Foraminifera in limestone fragments from the central crater indicate a late Tertiary *e* age with a slight possibility that they could be early Tertiary *f*. In terms of the standard time scale, these Foraminifera are very likely early Miocene. Consideration of several factors suggests that this limestone was deposited when the volcano had grown approximately to sea level, prior to the development of the subaerial shield volcano of large size. After the growth of the shield volcano, erosion dissected the cone, and several flows of nepheline-bearing lavas were extruded. After these last eruptions the volcano subsided sufficiently to submerge most of the dissected subaerial shield. A barrier reef subsided relative to sea level as the volcano subsided and formed a lagoon enclosing unsubmerged remnants of the Truk shield volcano.

INTRODUCTION

This study of the geology and petrography of the volcanic rocks of the Truk Islands is based upon fieldwork and petrographic examinations of specimens collected during a survey of the islands for the purpose of a military geology report, made as a part of the Pacific Geological Mapping Program of the U.S. Geological Survey and Corps of Engineers of the U.S. Army. Introductory material here has been summarized from the military geology report (Stark and others, 1958).

LOCATION

The Truk Islands are between north latitudes 7°08′ to 7°41′, and east longitudes 151°26′ and 152°2′. They lie 2,100 miles southeast of Tokyo, 3,450 miles west and slightly south of Pearl Harbor, and 1,000 miles northeast of New Guinea (fig. 1).

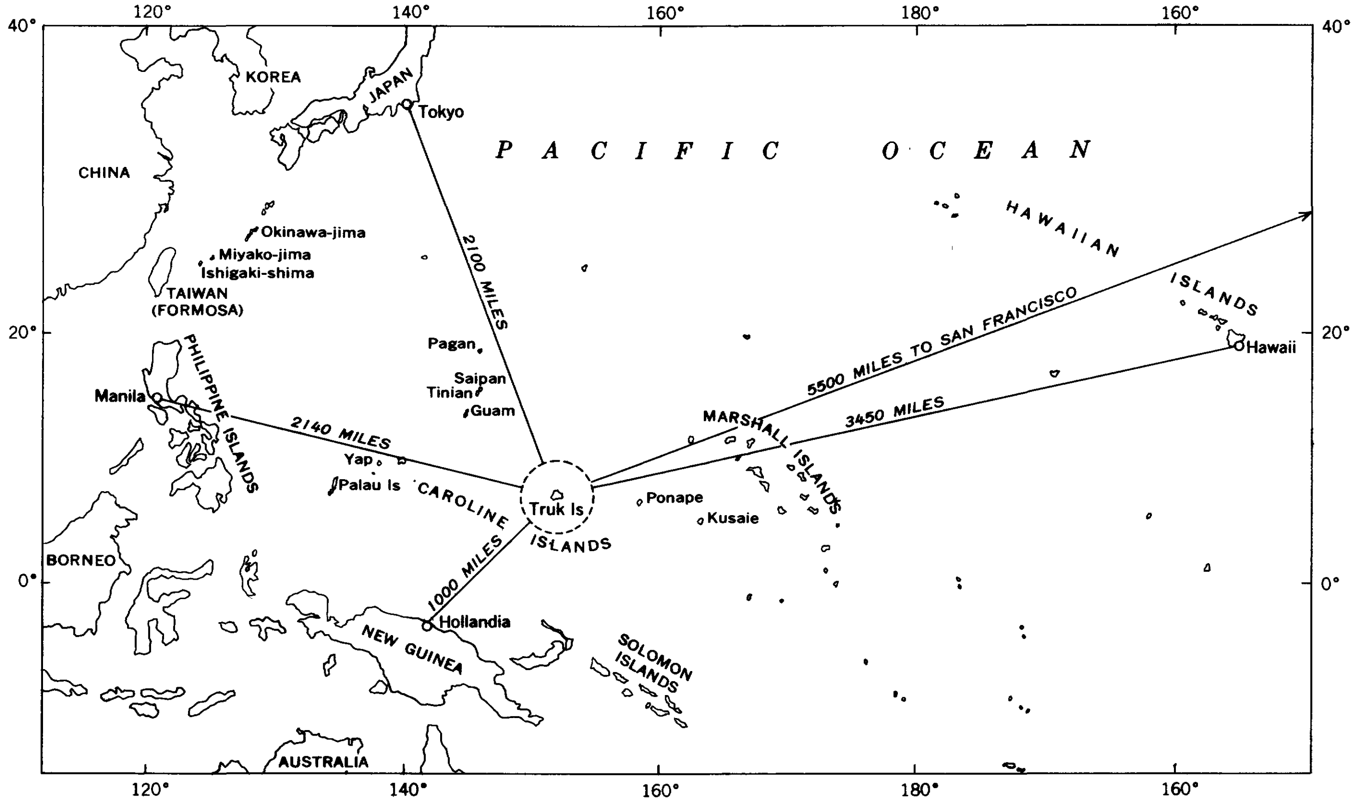

FIGURE 1.—Index map, showing location of Truk Islands.

TOPOGRAPHY AND DRAINAGE

Truk comprises small volcanic and reef islands in a lagoon, Truk Lagoon, formed by a coral reef (fig. 2). It has been termed a "near-atoll." The volcanic islands are separated more or less arbitrarily according to their location into an eastern group, including Moen, Uman, and Faneu (pl. 1); a central group, including Udot, Eot, and Eiol (pl. 1); and a western group, including Tol, Fala-beguets, and Ulalu (pl. 2). The high volcanic islands range in size from the two largest islands, Tol 5 by 2 miles and Moen 4 by 3 miles, to the two smallest islands, Eiol and Faneu, both less than one-quarter of a mile in diameter. The highest altitude is the crest of Mount Tumuital on Tol at 1,453 feet; Mount Tolomen on Dublon Island and Mount Teroken on Moen are both slightly more than 1,100 feet above sea level. Other prominent peaks, rising to nearly 1,000 feet, are on Fefan and Uman. The slopes in general average more than 30 percent, and slopes greater than 60 percent are common at higher altitudes.

Twenty-four low coral-reef islands are within the lagoon. The barrier reef is surmounted by 41 low coral islands. The largest is about 2 miles long and a quarter of a mile wide; most are much smaller. Altitudes on a few of these islands are as much as 8 feet, but most of the low islands are only 5 or 6 feet above mean sea level. Fringing reef flats surround most of the high and low islands.

The high volcanic islands are drained by many small streams during the rainy months, from April through December, but only a few streams persist throughout the dry period. The streams are not actively eroding the high islands, and little sediment is being carried to the lagoon.

Vegetation on the high volcanic islands is commonly more luxuriant than on the low reef islands. The upper slopes of such mountains as Mount Tumuital on Tol, Mount Teroken on Moen, and Mount Tolomen on Dublon Island are covered with dense forests of banyan and pandanus trees entwined with vines and shrubs. These forests were originally more extensive, but they have been replaced on the lower and middle slopes by breadfruit and coconut groves. A large percentage of the coconut groves, as well as additional forest areas, was cleared during the war because of the need for greatly increased food production and for lumber. These areas are now overgrown with grasses. Most of the low islands are covered with coconut palms, pandanus, and breadfruit trees.

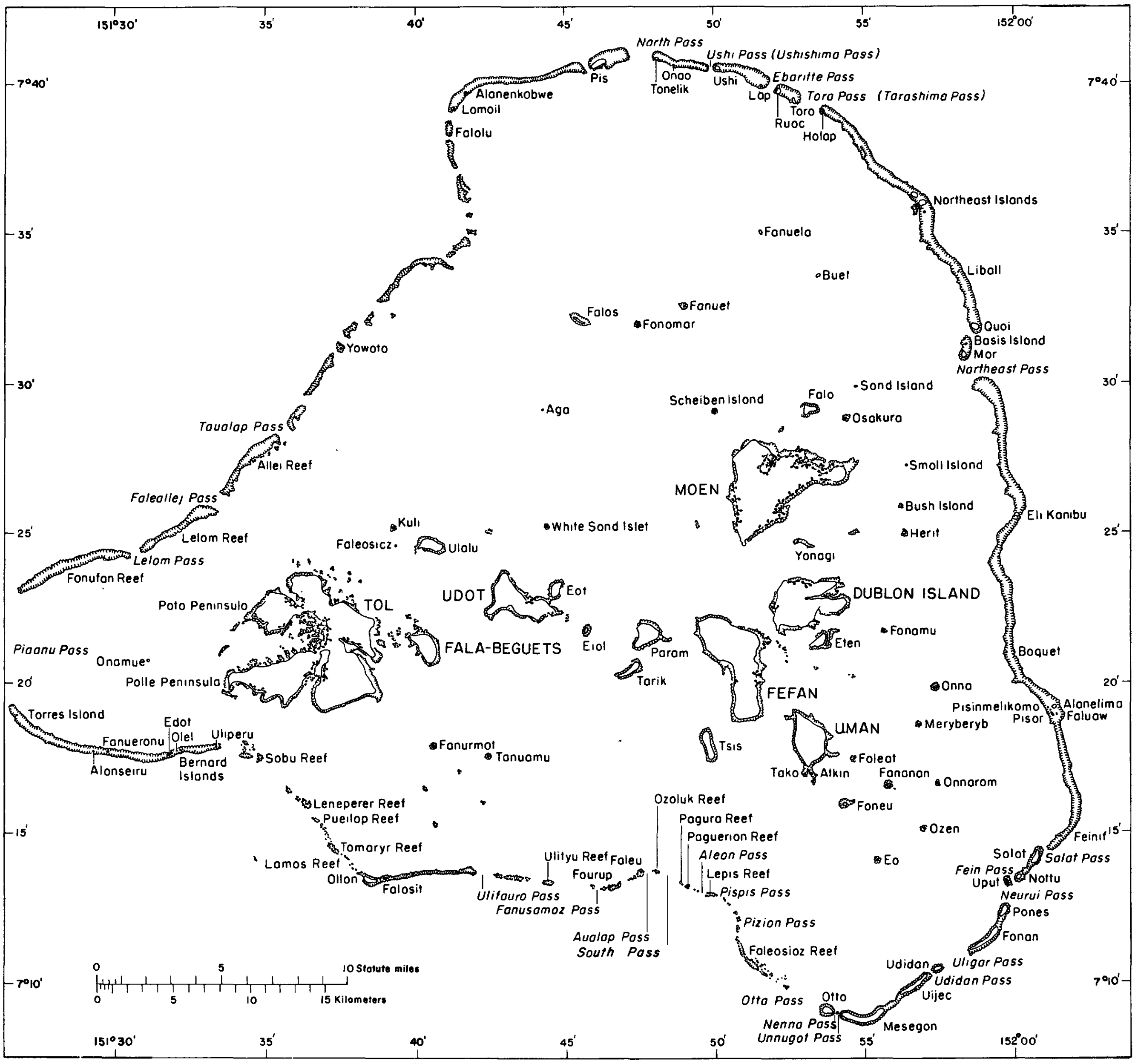

FIGURE 2.—Index map of Truk Islands.

ACKNOWLEDGMENTS

The field party was on the Truk Islands from early in October 1954 until the end of July 1955. Logistic support was furnished by the Corps of Engineers, U.S. Army. Fieldwork was supervised by C. G. Johnson, chief of the Pacific Geological Surveys section, Tokyo, on his several visits to the islands and throughout the progress of the work. Microscopic study of the rocks was started in Truk and completed in offices of the U.S. Geological Survey, Washington, D.C., and the Louisiana State University, Baton Rouge, La. Thanks are expressed to all members of the Truk field party, to W. C. Muller, district administrator for Truk, and to all members of the Trust Territory administration on Moen for their interest and helpful cooperation during the mapping of the islands. Dr. D. B. Stewart is thanked very much for X-ray study of a feldspar in several xenoliths from the islands.

GEOLOGY

The volcanic islands of the Truk Islands are the erosional remnants of a partly submerged large shield volcano, which has been long inactive. Although these remnants consist largely of lava flows, pyroclastic deposits are locally interbedded with the flows. The Truk volcano extends from the ocean floor, about 16,000 feet below to the water surface and was formerly at least several thousand feet above sea level.

Coral and reef rock now form a surrounding barrier, and fringing reefs border the islands of volcanic rock in the lagoon. Igneous rock of the old volcano almost certainly underlies the low reef islands within the lagoon and presumably forms the basement on which the coralline barrier reef was built. If so, the encircling barrier roughly marks the near-surface shape of the Truk volcanic mass.

At no place on any of the islands have traces of crater or caldera walls or remnants of a central volcanic vent been found. However, geologic evidence indicates that a central crater once erupted large volumes of pyroclastic ejecta, now consolidated as a volcanic breccia. Most of, if not all, the lavas very likely issued from fissure vents now represented by dikes and dike swarms. Many of the breccias were probably transported as mudflows. Some lavas and breccias were subjected to stream action and now form conglomerates, which consist largely of rounded boulders.

The lavas range in composition from olivine-rich basalts through andesites to trachytes and to extremely silica-deficient melilite-nepheline and nepheline basalts. Although the melilite-nepheline and nepheline basalt flows generally appear to have been the last to be erupted, the other types of flows, olivine basalt, andesite, and sodic trachyte, do not occur in any apparent sequence.

A detailed stratigraphic sequence of lava flows and pyroclastic breccia is difficult to establish on the larger islands because of the wide extent of dense vegetation and the thick soil cover that separate exposures of bare rock. Outcrops can be traced only for short distances horizontally or along the strike of the beds. A sequence of flows and breccias occurring in one vertical section may differ radically from the sequence in a section only a hundred yards away. Part of this is due to tonguelike projections of lava and to valley-filling flows and pryoclastic deposits that, in general, conform to the surface slopes existing at the time of extrusion. A further complicating factor in the western group of islands is the strong possibility that most of the flows issued from many separate fissures rather than from one or two well-developed craters. The general similarity of the flows mineralogically and texturally and the absence of distinguishing criteria, with the possible exception of nepheline basalt on Tol and Ulalu, make correlation of individual flows between islands impossible or extremely uncertain. There are, however, suggestive differences between groups of islands, which are discussed under headings of eastern, central, and western island groups.

CLASSIFICATION

In this report rocks are basically classified by color index of the rock, excluding phenocrysts; that is, by the sum of the normative femic minerals (wo+en+fs+fo+fa+mt+hm+il) as calculated from the chemical analyses of nonporphyritic rocks. Basalts will be considered those rocks having a color index greater than 37, and andesites are those rocks having an index between 10 and 37, following the usage of Kuno (1950, p. 958). Trachytes are those rocks consisting largely of alkali feldspar and having a color index less than 10. Rocks not chemically analyzed were classified by estimating the sum of the modal mafic minerals and comparing thin sections with those of texturally similar analyzed rocks. The basalts and andesites intergrade so completely that without chemical analyses about 10 percent of the borderline rocks may arbitrarily be placed in either category. Trachytes do not seem to intergrade with andesites, from which they generally can be separated without difficulty.

The lava flows of the Truk Islands are mineralogically rather simple. Most are undersaturated lavas consisting almost entirely of plagioclase, monoclinic pyroxene, olivine (or pseudomorphs after olivine), anorthoclase, and magnetite. Basalt is the dominant rock; of the nearly 500 specimens collected, 70 percent are basalt and 25 percent are andesite. The remaining 5 percent are sodic trachyte, nepheline basalt, melilite-nepheline basalt, and vitrophyric basalt containing normative nepheline. Nearly all the basalt flows contain more than 5 percent modal olivine and are olivine basalts in the classification of Macdonald (1949, p. 1544); a few of the andesites contain more than 5 percent olivine and are olivine andesites. The proportion of olivine in the finer grained rocks cannot be determined without microscopic study, and rocks will be discussed in the following text as basalt and andesite unless olivine is conspicuously abundant in the hand specimen. None of the olivine basalts contain sufficient mafic minerals (that is, 70 percent) to be classified as the picrite basalt of Macdonald (1949, p. 1544).

The basalts and andesites are almost uniformly dark gray. Both porphyritic and nonporphyritic basalt flows are common, but most of the andesites are nonporphyritic. Many basalts, particularly the finer gained ones, have a platy fracture that is due to planar orientation of plagioclase laths. Most of the andesites have a similar platy fracture and are impossible to distinguish in the field from the fine-grained platy basalts. The trachytes are medium to light gray and generally have a well-developed platy fracture that superficially resembles metamorphic foliation. A trachyte flow on Moen was, in fact, earlier misidentified as schist (Bridge, 1948, p. 217).

EASTERN ISLANDS

MOEN

Moen, largest of the eastern islands, is approximately 7.19 square miles in area (pl. 1). It is a mountainous mass of lava and indurated pyroclastic rocks bordered generally by unconsolidated organic marsh sediments, filled areas (reclaimed land), beach deposits, and mangrove swamps. The summit of Mount Teroken, the highest altitude on Moen, is approximately 1,223 feet.

The volcanic rocks consist of gently dipping lava flows and volcanic conglomerates. Locally, the volcanic conglomerates contain abundant angular debris and may be termed "volcanic breccia." The proportion of breccias and conglomerates to flows in the entire sequence cannot be estimated with accuracy because of the vegetation and soil cover, but the breccias and conglomerates probably form between 5 and 10 percent of the whole.

The flows consist largely of compact columnar-jointed lavas. Most are 35 to 100 feet in thickness and average an estimated 55 feet. The two thickest measure 150 to 200 feet. In general, flows can be traced only for short distances in continuous outcrop, but in southern and central Moen several flows are exposed almost continuously for slightly more than a mile. Olivine basalt is the predominant rock type, forming about 60 percent of the lavas. Moderately consolidated autobrecciated lava, generally from 3 to 10 feet thick, occurs at the top of many flows and less commonly at the base. The complete stratigraphic sequence is nowhere well exposed. The best exposures are on the south slope of Witipon, where nonprophyritic andesite is the only rock exposed from sea level to approximately 600 feet altitude. This andesite sequence is capped by a flow of sodic trachyte that measures at least 150 feet in thickness. Exposures on the jungle-covered slopes of Winifourer are basalt flows overlain by a thick sequence of nonporphyritic and slightly porphyritic andesite flows, which are capped in turn by flows of andesite and extremely porphyritic olivine basalt. As outcrops are separated by vegetation cover, it is not possible in many places to determine whether one or several flows are represented.

The sequence on the north spur of Mount Teroken differs from the exposures on Winifourer, less than half a mile away. Coarse conglomerate and breccia are interbedded in the lower part of the section with basalt lavas. Trachytic, andesitic, and basaltic debris occurs in these beds. They are overlain by several nonporphyritic andesite flows, which are in turn overlain by approximately 600 feet of extremely porphyritic olivine basalt flows, similar to those capping Winifourer. The porphyritic lavas on Mount Teroken extend downward from the crest to an altitude of approximately 600 feet; the base of those on Winifourer is between 900 and 1,000 feet. This difference in altitude between outcrops of similar lavas suggests that from 300 to 400 feet of andesite was eroded from the Mount Teroken area prior to the extrusion of the uppermost lava flows.

Three basalt flows, totaling at least 160 feet (tops are eroded and base not exposed), appear to be filling a valley cut in pyroclastic breccia in southwestern Moen. The slope of the valley wall ranges from 30° to 45°. The rarity of faulting elsewhere suggests that this contact is due to erosion and valley fill rather than to structural displacement.

Small unconformities occur between lava flows and breccia in a number of places. For example, on the north side of Mount Teroken at an altitude of approximately 350 feet, a lenticular body of breccia 20 to 30 feet thick fills a steep-walled narrow valley cut into an andesite flow. None of these unconformities are angular, rather they represent disconformities where valleys were eroded by streams between eruptions.

Volcanic sedimentary deposits are widespread on Moen. They consist predominantly of unstratified pyroclastic breccia in which angular blocks are enclosed in a finer grained unsorted matrix of volcanic detritus. In places, the breccias grade into conglomerates that contain cobbles aand boulders showing the effect of rounding by water. The thickest deposits are in the northeast and central parts of the island. On the northeast slope of Tonaachau, the cobble and boulder conglomerate is 50 feet thick and pinches out laterally to the east and south. In the valley of the Wichen River, the breccia is 300 feet in thickness. In general, the breccia is more thoroughly indurated than the conglomerate. Many beds are only from 2 to 8 feet thick. Fine tuffaceous material is estimated to form between 20 and 50 percent of the beds. The coarse fragments, ranging from a few inches to 6 feet in diameter, are composed of all types of the Moen lavas: basalts, andesites, and trachytes.

The upper and lower contacts of the flows are nearly horizontal, as far as can be determined from the small areas of exposures, except for the few irregularities due to channeling and the uneveness that might be expected from varying thickness of the flows. An attempt was made to measure the altitude of the flows exposed in steep escarpments with aneroid readings along the outcrops. A general dip to the northeast and possible east is indicated. The sodic trachyte flow capping Witipon appears to strike northwest and dips approximately 2½° E. One extremely porphyritic olivine basalt flow was mapped for a distance of 1½ miles on the north side of Moen with strike of N. 45° W., and dips of 3° to 3½° NE. The andesite series of flows exposed on the southern slopes of Mount Teroken and Witipon dips 2° to 2½° E. Based on correlation of the conglomerate exposed at an altitude of approximately 500 feet on Tonaachau with the thick breccia unit 1 mile to the south, a solution of the three-point problem suggests that the top of the conglomerate strikes northward and dips 3½° E. As the breccia may not be equivalent to the conglomerate, the inferred northly strike of the pyroclastic unit is probably not as reliable as the northwest strike measured on the porphyritic olivine basalt flow.

No conclusive evidence of faulting was found on Moen. Either faulting or filling of a steep-walled valley is, however, indicated by relations on the northern corner of Moen. A 160-foot flow of oligoclase andesite, which lies adjacent to the airfield on the north corner of Moen, forms a narrow band terminating abruptly against a flow of olivine basalt along the southern margin of the andesite outcrops. This abrupt termination may represent faulting or the lateral margin of a valley-filling flow. The unusually great thickness of this flow, the thickest andesite flow measured in Truk, can be explained by origin of the flow as a valley filling. However, fault displacement along the contact of the basalt and andesite is a possible explanation of lithologically similar, coarse volcanic conglomerate north of the contact at an altitude of about 6 feet and on the hillside south of the contact at an altitude of about 350 feet. Present data are inadequate to demonstrate faulting or to prove cut-and-fill origin of the steep contact. Similarly, three basalt flows on the southwest part of Moen lie against volcanic breccia along a contact having a dip of 30° to 45°. As volcanic breccia has been clearly observed elsewhere to fill a steep-walled canyon cut in a lava flow, it is likely that the flows in question fill a steep-walled valley cut in breccia. The possibility of faulting, however, cannot be eliminated at this time.

The source of the Moen lavas can only be inferred as no dikes or vents have been found on the island. The general northeast dip suggests a source to the southwest. This suggestion is supported by the northeast trend of the valley-filling lava flows at the southwest end of Moen. The inferred unconformity between nonporphyritic andesite and porphyritic basalt on Mount Teroken and Winifourer indicates a southern source for the upper porphyritic lavas.

FALO

Falo, a small island 1¾ miles north of Moen, is an upland plateau of approximately 140 feet altitude, consisting of several olivine basalt flows surrounded by patches of fresh-water marsh deposits and calcareous beach sands. The total surface area is 0.13 square mile (pl. 1).

The olivine basalt flows are well exposed in cliffs on the north side of Falo and in separate outcrops on top of the plateau. They range in texture from massive and even grained to porphyritic with abundant olivine and pyroxene phenocrysts.

YANAGI

Yanagi, 500 feet long and 250 feet wide, lies approximately half way between Moen and Dublon Island (pl. 1). It rises about 45 feet above its fringing reef and is composed entirely of coarse pyroclastic breccia. The fragments are andesite and olivine basalt similar in composition to the flows on Moen to the north and Dublon Island to the south. No indication of the attitude of the breccia beds on Yanagi was observed.

DUBLON ISLAND

Dublon Island, third largest of the islands in the eastern group (pl. 1), consists of lava flows and pyroclastic deposits. Detailed traverses across Dublon Island's four prominent uplands—Mount Tolomen and Foukenau and the northeast and southeast peninsulas—show no agreement in sequence of flows and interbedded pyroclastic deposits that might suggest specific correlations.

There are only isolated outcrops of olivine basalt and andesite in the western half of the island, and more than three-fourths of the area is mapped as undivided volcanic rocks (pl. 1). On Mount Tolomen the single mapped flow of andesite appears to dip about 3½° E. Olivine basalt and andesite form most of the northeast and southeast peninsulas; however, a nepheline basalt flow is interbedded with olivine basalt at the southeast end of the northeast peninsula and is the only nepheline basalt identified in islands of the eastern group. This flow on Dublon Island is of especial interest in its occurrence as it is interbedded near the base of a series of olivine basalt and andesite flows, in contrast to the nepheline basalt flows on Tol, which occur as the uppermost and last phase of volcanic activity recorded in the Truk Islands.

A thick porphyritic flow of olivine basalt underlies the upper surface of the northeast peninsula. This flow appears to strike N. 30° W.; the angle of dip varies but averages 4° E.

Fragmental deposits were mapped at several places on Dublon Island. A bed of conglomerate from 8 to 10 feet thick, penetrated by manmade caves, lies beneath the two flows capping Foukenau. The conglomerate is poorly sorted, and the coarsest debris is about 4 feet in diameter. Locally, the fragments have been rounded by stream action. Lapilli tuff crops out in a 12-foot-high roadcut, stratigraphically about 100 feet below the conglomerate, and a 4-inch-thick bed of well-laminated fine-grained tuff is interbedded with the lapilli tuff. Unstratified, unsorted breccia forms several lenticular beds in the southwest part of Dublon Island, the thickest of which is at least 75 feet thick. Blocks in the breccia are of olivine basalt and andesite of various textures, accompanied locally by blocks of laminated tuff. There is no obvious indication of a nearby vent, and these breccias may have been deposited by a mudflow.

A dike of andesite cuts an olivine basalt flow in a roadside outcrop on the west side of Dublon Island. The dike is 15 feet wide, strikes N. 40° W., and dips 52° S. It is one of the very few dike exposures in the eastern islands.

Olivine basalt is the predominant rock type on the islands, averaging about 65 percent of the flows; it is nearly twice as common as the andesite. Nepheline basalt forms far less than 1 percent of the island.

ETEN

Eten, 3,500 feet long and 1,500 feet wide, is a small northeast-trending island just half a mile south of Dublon Island (pl. 1). Reclaimed land forms a large part of the island, but volcanic rocks compose a hill about 180 feet high on the south side, and a small knoll, 15 to 20 feet high, at the east end of the island.

The hill consists of olivine basalt flows, conglomerate, and breccia. The conglomerate is made up largely of basalt boulders from 1 to 4 feet in diameter. It crops out at the southwest corner of the hill, where it forms the basal unit. This conglomerate is separated by a steep-walled erosional unconformity from a valley-filling flow of olivine basalt ranging in thickness from 50 feet to about 5 feet where it overlaps the conglomerate. Rudely stratified volcanic breccia and lapilli tuff with interfingering flows of olivine basalt, about 130 feet thick, form the upper parts of the hill. Complexly contorted lower pyroclastic beds and lava flows, overlain by pyroclastic breccias and lapilli tuff that are nearly horizontal and undisturbed, suggest that the lower beds were deformed by a mudflow prior to deposition of the undisturbed beds.

The volcanic rocks of Eten appear to dip gently to the north or northeast. A 20-foot-thick flow, cropping out for approximately 300 feet on the north-central side of the large hill, dips 5° NE. The thinness of the lava flows and the coarseness of the breccia constituents suggest a nearby source. The lack of water stratification in the pyroclastic rocks indicates an eruptive rather than a detrital origin. Their thickness also is suggestive of a local source of eruption. The northeasterly dips of one flow and the pinching out of the lower olivine basalt flow toward the west and the northwest, that is, against the west side of a north-south valley, argue for a local source to the south or southwest. The probable major center of eruption for the eastern group of islands is shown in figure 3. All flows on Eten are olivine basalt.

FEFAN

Fefan consists of a mountainous ridge with four prominent peaks (pl. 1), a mangrove swamp that fringes most of the volcanic upland, and locally, a few areas of lowland marsh and sand. Porphyritic olivine basalt greatly predominates over andesite flows in ratio of about 9 to 1. Maximum thickness of the lava flows is best exposed on the northwest side of Mount Iron, where there is 1,000 feet of interbedded basalt and andesite. The thickest single flow observed is porphyritic olivine basalt, which forms a cliff 80 feet high.

Pyroclastic deposits are rare on the island, having been found only on the middle west slope of Witunumo. Here a 1-foot-thick bed of volcanic tuff rests on the brecciated tops of the undivided flows, and grades upward into 8 feet of pyroclastic breccia containing angular blocks as much as 4 feet in length.

The attitude of the Fefan flows shows a persistent dip to the south. The outcrops of slightly porphyritic basalt on the east and west sides of the central part of the island strike eastward and dip from 1° to 1½° S. The thick porphyritic olivine basalt flow on the northwest corner of the island apparently dips more steeply southward.

PARAM

Param consists of deeply weathered lava flows bordered by fresh-water marsh deposits and calcareous beach sands (pl. 1). On the southern side of the island, reclaimed land was used by the Japanese as an airfield. Scattered exposures of fine-grained andesite and porphyritic olivine basalt can be seen in roadcuts and in small excavations on the north side of the island. Four flows are exposed on the east end of the island in borrow pits, up to an altitude of about 140 feet. At the base of the sequence is weathered porphyritic lava, probably olivine basalt. Slightly porphyritic platy basalt crops out at altitudes between 40 and 50 feet and is overlain by 40 feet of weathered porphyritic olivine basalt. No outcrops are exposed above the olivine ba-

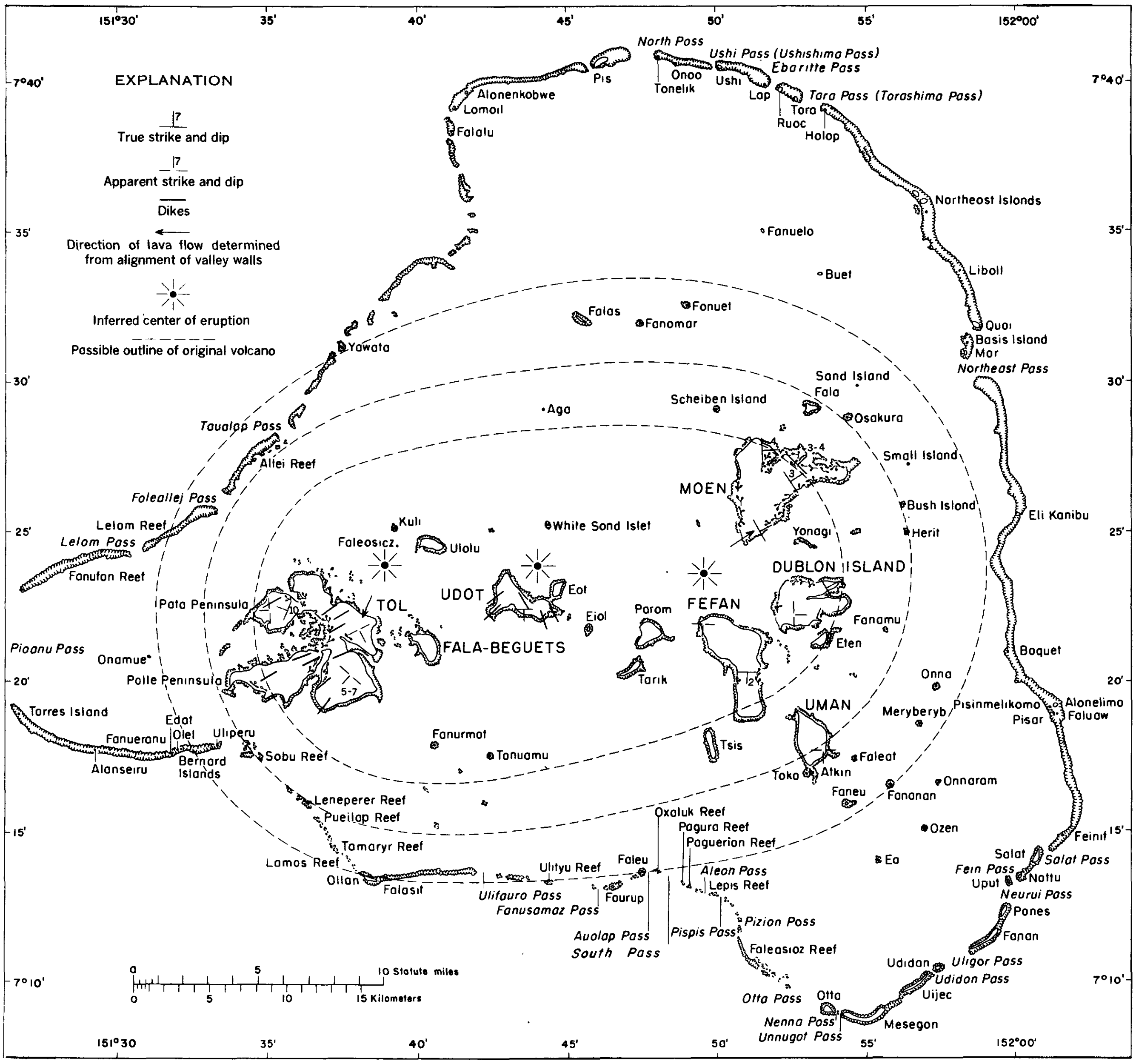

FIGURE 3.—Probable centers of eruption, Truk Islands, and possible outlines of original volcano.

salt to the highest point on the island, about 180 feet; however, abundant float blocks of fine-grained andesite above the olivine basalt suggest that an andesite flow almost certainly formed the uppermost unit on Param.

Rock types on Param are andesite and olivine basalt which occur in almost equal amounts.

TARIK

The surface slopes and crests of the eastern, central, and western peaks of Tarik are covered with loose blocks of olivine basalt. Although bedrock exposures are rare (pl. 1), two outcrops are exposed near sea level in the east-central part of the island: a highly weathered flow crops out at the water's edge, and 10 feet upslope is a small ledge of fine-grained olivine basalt. The top and bottom of the flows are not exposed, and erosion of the water-level outcrop obscures any indication of dip. No andesite was found on the island.

TSIS

Tsis, an island southwest of Fefan, is composed entirely of porphyritic olivine basalt flows and is fringed on the north by fresh-water swamp deposits and calcareous beach sands. Exposures are not continuous enough to map separate flows. The apparent direction of dip of one small outcrop is S. 25° E.

UMAN, TAKO, AND ATKIN

Uman is a conical mass of volcanic rock rising to a central peak about 850 feet above sea level, with several smaller peaks around the lower slopes (pl. 1). Only flows of olivine basalt were observed in outcrop. One bed of volcanic breccia, 4 feet thick, is the only pyroclastic rock exposed. A thick olivine basalt flow on the middle eastern slope of Uman appears from topographic relations to be dipping very gently to the south. A fault with a vertical displacement of 5 to 10 feet on the southeast side of Uman is suggested by an unusually straight valley with a difference in altitude of benchland surfaces on either side.

Tako and Atkin are small islets of volcanic rock, 900 feet south of Uman. Both are surrounded by coral reefs that are continuous with the fringing reef that surrounds Uman. Tako and Atkin are composed of olivine basalt flows that show well-developed columnar jointing. The flows are believed to be continuous, beneath the reef rock, with the olivine basalt flows of Uman.

FANEU

Faneu is a nearly circular island 2 miles south-southeast of Uman (pl. 1). It is approximately 750 feet in diameter and consists of a hill of volcanic rock 75 feet high, fringed by a sand beach and older beach deposits. Brecciated olivine basalt is exposed several feet above sea level in the base of an old Japanese torpedo cave on the south side of the island. This autoclastic breccia is overlain by a columnar-jointed olivine basalt flow. The lowermost 5 to 10 feet are sparsely porphyritic and grade upward into highly porphyritic rock which extends 30 to 40 feet higher. The hill is capped by sparsely porphyritic lava that may be the same flow.

CENTRAL ISLANDS

Numerous dikes and predominance of pyroclastic breccia over lava flows characterize the central islands of Udot, Eot, and Eiol (pl. 1). The volcanic rocks here differ significantly from those of other Truk islands and deserve detailed description.

PYROCLASTIC DEPOSITS

Volcanic breccia is the most abundant type of pyroclastic rock. In places the tuff matrix (that is, fragments less than 4 mm in diameter) is sufficiently abundant to form tuff-breccia facies of the volcanic breccia. Most coarse fragments in a few beds are less than 3.2 cm in diameter, and the rock is termed "lapilli tuff." All the pyroclastic deposits consist of angular to subangular, rarely rounded fragments of rock in a finer grained tuff matrix. Generally the blocks are between 1 and 12 inches in diameter, but blocks as long as 6 feet have been found. Some breccias consist almost entirely of blocks from 1 to 3 feet in diameter. The tuff matrix ranges from 5 to 75 percent, but generally averages about 25 percent. The pyroclastic deposits are uniformly well indurated and break across fragments and matrix alike. Nearly all the breccia is unstratified, and it commonly forms smooth, rounded cliffs as much as 50 feet high. The breccia usually weathers into blocks and boulders, some 20 feet in diameter, that locally are difficult to distinguish from bedrock. Boulders of breccia as much as 50 feet long occur along the south-central seacoast of Udot.

Fragments in the pyroclastic breccia include a wide range of rock types. Both porphyritic and nonporphyritic andesite, basalt, and trachyte are common. Many blocks are either vesicular or amygdaloidal. A small percentage of the trachyte blocks lack flow texture and are somewhat coarser than the trachyte forming dikes, flows, and autoclastic breccias. Also, some blocks of andesite and basalt are texturally dissimilar to the andesite and the basalt of dikes and flows exposed in the central islands. Blocks of fine- to coarse-grained gabbro are widely distributed in the breccia on Udot. Individual crystals in the gabbro are generally 1/8 to 1/4 inch in diameter, but 1/2-inch crystals characterize pegmatitic zones. Plagioclase forms between 50 and 80 percent of the gabbro, which is commonly pale gray. Many of the gabbro blocks contain veins of coarse-grained latite and quartz latite. A few of the gabbro blocks contain dikes of andesite and basalt. Other blocks contain inclusions of recrystallized volcanic rock. Blocks of hornfelsic, recrystallized gabbro, basalt, and volcanic breccia have also been found in the breccia. Several small blocks of quartz monzonite and fragments of limestone were collected from the breccia on Eot and Udot.

LAVA FLOWS AND AUTOCLASTIC BRECCIAS

Lava flows are widely distributed on Udot and Eot, and one flow occurs on Eiol. Andesite and basalt flows are about equally common, and a few trachyte flows are present. Single lava flows do not form prominent scarps as in the eastern islands, and although flow thicknesses could not be accurately determined, most flows are probably 20 feet thick or somewhat less. In a number of places the lava is intermixed with pyroclastic breccia in irregular tongues and stringers and does not form well-defined flows.

Autoclastic breccia is abundant and widespread on Udot and Eot. Some is vesicular and occurs at the top and base of flows as on the other islands; most, however, forms entire flows that consist largely of angular fragments of nonvesicular lava in a lava matrix. Angular fragments range from a fraction of an inch to more than 6 feet in diameter but most commonly are several inches in diameter. The matrix enclosing the angular fragments is generally nonvesicular lava, but a well-indurated tuff matrix occurs in places. Several autoclastic breccias grade, owing to the increase of tuff matrix and the addition of accessory volcanic blocks, into breccia which appears truly pyroclastic in all respects.

DIKES

The central islands are characterized by numerous dikes, generally between 1 and 5 feet thick. Trachyte and andesite dikes are about equally abundant; basalt dikes are less common. Texture ranges from nonporphyritic to extremely porphyritic. Pyrite is commonly disseminated throughout the dikes as small grains and forms coatings on fracture surfaces. Most dikes have a general uniform thickness and attitude, but some are irregular in shape and vary both in strike and dip. Small dikes, about an inch thick, commonly branch from irregular-shaped dikes and penetrate the country rock for distances of several feet. Multiple dikes, side by side, are exposed in several places. Where two dikes of different attitude intersect, the older dike is commonly irregular in width and sinuous in strike; the younger dike is generally uniform in trend and thickness. Dips of dikes range from 10° to vertical, and strikes represent all points of the compass. Statistically, however, the dikes form a radial pattern having a projected center north of Udot and west of Eot (fig. 3).

UDOT

Udot consists of three major upland segments connected by low narrow divides and is widely fringed by fresh-water swamps, mangrove swamps, and calcareous beach deposits. The three uplands are at altitudes of about 439, 472, and 793 feet, from east to west, and several small peaks rise from the lower slopes of the upland areas. The large conical mass forming the western, highest upland segment is composed largely of andesite flows, basaltic flows, and autoclastic breccias. Elsewhere, breccia and related pyroclastic deposits predominate over the lava flows and autoclastic breccias.

The proportion of different types of blocks in the pyroclastic breccias varies throughout Udot but fragments of andesite generally predominate over other types although trachyte is more abundant in places. Vesicular and amygdaloidal fragments are widespread, and scoriaceous fragments are abundant in some beds. Gabbro fragments have been found locally in breccia from sea level to altitudes of about 750 feet and from the east to the west end of Udot, but much breccia contains no gabbro. The gabbro fragments in most beds range from 1/4 to 3 inches in diameter. Gabbro fragments are largest and most abundant in a bed in central Udot where they locally form as much as 10 percent of the breccia. Many gabbro blocks in this bed are a foot in diameter, and a few have average diameters of as much as 2 feet. The gabbro-rich breccia forms an 80-foot-thick bed on the south side of the island but thins northward, pinching out at one place. Blocks of recrystallized basalt and quartz monzonite were found only in the bed richest in gabbro blocks.

Several poorly exposed lava flows have diverse dips of as much as 30° over outcrops of several tens of feet. A small exposure of rudely stratified tuff beds on the west side of the eastern segment, at approximately 400 feet altitude, appears to be nearly horizontal. Much more reliable is the attitude of the bed of gabbro-rich breccia on the central segment; this unit strikes east and dips from 5° to 10° S.

Dikes are numerous in all parts of Udot. They differ considerably in attitude; but dips are generally steep, and most of the strikes fit into the radial orientation pattern with a projected center a mile northeast of east-central Udot (fig. 4). The dikes average approximately 40 percent andesite, 40 percent trachyte, and 20 percent basalt.

EOT

Eot is a small island one-quarter of a mile north of the east end of Udot. It is approximately 3,000 feet long and 1,500 feet wide and trends northward. Fresh-water swamps and calcareous sands fringe parts of the west and east sides of the island.

Limestone at sea level and 4 feet above sea level forms a thin plaster on pyroclastic bedrock at the north point of Udot. Both coral and rounded, waterworn volcanic detritus are cemented by fine-grained calcite. This limestone may be a remnant of a coral reef that formed during a period of slightly higher sea level.

The upland of Eot consists of pyroclastic breccia and one outcrop of an andesite lava flow, on the west-central point of the island. The pyroclastic breccia contains a few small fragments of light-gray and reddish-brown tuffaceous limestone having abundant organic detritus, including Foraminifera of Tertiary age (W. S. Cole, written communication, July 14, 1955).

The breccia and lava flows are cut by many dikes, as on Udot. They differ in attitude, but are generally steeply dipping, and their strikes conform to the same radial pattern exhibited by the dikes on Udot. The dikes are of basalt, trachyte, and possibly andesite.

EIOL

Eiol is about 1,200 feet long and 600 feet wide and trends northward (pl. 1). The island consists of a small hill of volcanic rock approximately 90 feet high, bordered by calcareous beach sand at altitudes of less than 5 feet. The hill is composed of breccia overlain by 15 to 20 feet of fine-grained andesite, probably representing a single flow. The breccia is moderately well indurated where unweathered and consists largely of angular fragments of lava ranging from less than an inch to 15 inches in diameter. The tuff matrix forms from 20 to 50 percent of the breccia.

WESTERN ISLANDS

TOL

Tol is an island formed by four upland blocks of volcanic rock, separated by deep embayments (pl. 2), two of which are joined by narrow channels, which are crossed by a wooden bridge and a rock causeway. Mangrove swamps are more extensively developed around Tol than around any other of the Truk Islands, and muck and peat deposits occur in isolated patches between mangrove swamps and the base of the uplands. Calcareous beach sands form a few narrow strips along the north and south shores of the island. The highest altitude in Truk Lagoon is on southeast Tol where Mount Tumuital rises to 1,453 feet.

The geology of the Tol uplands differs from that of both the eastern and the central islands. Tol consists almost entirely of olivine basalt and andesite flows that are cut by steeply dipping fractures and dikes whose dominant strike is northeast. The flows are generally thinner and more vesicular than those of the eastern islands. This series of flows is unconformably overlain on northeast Tol by a thick unfractured flow of melilite-nepheline basalt and one of nepheline basalt.

Most olivine basalt and andesite flows are between 20 and 60 feet in thickness, but flows as thin as 2 feet have been observed. The tops and bottoms of flows are commonly characterized by vesicular texture and scoriaceous autoclastic breccia. A high proportion of the flows is vesicular or amygdaloidal throughout, and many flows consist largely of vesicular and amygdaloidal autoclastic breccia. Owing to the relative thinness of the flows, the lack of columnar jointing, and possibly, the less resistant character of the porous lavas, single lava flows do not make prominent scarps such as are found in the eastern islands.

Plagioclase, augite, and olivine are commonly recognizable as phenocrysts. The basaltic and andesitic flows are generally very similar in appearance, and field distinctions between them are difficult. Except for the plateaulike summits on northeast Tol, exposures are so limited that no flows were mapped singly. Pyroclastic beds are rare, volcanic breccia having been found only in one place.

Dikes have been observed on all the volcanic uplands and are undoubtedly much more abundant than shown on the geologic map (pl. 2). The most prominent exposures are on the southeast half of northeast Tol. Andesite dikes predominate, but olivine basalt dikes are common, and several sodic trachyte dikes were also found. The width of the dikes ranges from 15 inches to 8 feet. Dike swarms show separate intrusions side by side with a total thickness of as much as 10 feet. The dikes are vertical or nearly so and show a uniform strike; the most prevalent direction is N. 60° E. Fractures in the lavas paralleling the dikes are conspicuous in most outcrops in which dikes are present.

It is very likely that these dikes were feeders for lavas of the western islands. The northeast trend of the fractures and the dikes is probably responsible for the dominant northeast orientation of valleys and scarps on northwest and southwest Tol. Faulting may have been an additional factor in controlling valley trends, but fault displacement was nowhere observed along the fractures.

Two dikes, one 3 and one 12 inches thick, may have originated in a way different from the thicker dikes previously described. These dikes of olivine basalt cut the basal part of an andesite flow. The olivine basalt is lithologically similar to the underlying basalt flow and may represent lava squeezed upward from the unsolidified basalt flow during emplacement of the overlying andesite.

Two lava flows on northeast Tol form relatively flat upland surfaces and unconformably overlie the dikes and fractured lavas. The two flows are exposed in palisades around the east and southeast sides of this upland area. The southern flow, of melilite-nepheline basalt, trends 1½ miles northwest and averages a quarter of a mile in width. The surface slopes about 2° SW. The exposed thickness ranges from 150 feet at the south end to 50 feet at the north. The northern flow, of nepheline basalt, is now a relatively small erosional remnant (a mesa) and averages 100 feet in thickness. At one exposure the nepheline basalt flow unconformably overlies a steeply dipping surface eroded in fractured dike-intruded lavas. This surface strikes N. 20° E. and dips 40° to 50° W. It is probably part of one side of a former valley filled by the lava flow.

Unusual pegmatitic zones characterize the upper part of the nepheline basalt flow In the exposed upper 5 feet of the outcrop, pegmatitic segregations are extremely abundant, and a few segregations occur as much as 30 feet below the uppermost exposures. On the eroded surface of the upland, pegmatitic areas range from a few inches to tens of feet in length and are of extremely irregular and varying width. They form slightly more than 50 percent of the eroded surface outcrops of the flow. Small dikelike veins and stringers occur, but in general the pegmatitic areas are very irregular. Some crystals are as much as ½ inch long but average from ⅛ to ¼ inch in their longer dimension. The pegmatite areas grade into the fine grain size that characterizes most of the flow. The lava surface is weathered into fluted pinnacles ranging from several inches to several feet in height (fig. 4).

Most of the volcanic rocks on Tol appear to dip westward, but definite measurements are possible only in a few outcrops because of poor exposures. On northwest Tol interbedded lava and autoclastic breccia strike north and dip 15° W. Autoclastic breccia beds in the eastern part of this northwest block strike N. 25° E. and dip 10° W. The uppermost flows on Mount Tumuital, observed from the southeast, show apparent dips of 5° to 7° SW. The melilite-nepheline basalt flow dips 2° SE., nearly at right angles to the older lavas. This flow may fill a valley eroded in the older lavas.

A

B

FIGURE 4.—*A*, Fluted pinnacles on nepheline basalt flow, northeast Tol (1956). *B*, Detail of fluted pinnacles on nepheline basalt flow, northeast Tol (1956).

The volcanic rocks of Tol are predominantly olivine basalt, estimated at 75 percent of the total—the andesites are about 20 percent; nepheline basalt, melilite-nepheline basalts, and trachyte dikes form the rest.

FALA-BEGUETS

The elongated dome-shaped island of Fala-beguets lies 1½ miles east of Tol; it is 1½ miles along its northwest axis and averages slightly less than half this in width (pl. 2). Mangrove swamps border the west shore of the island. Calcareous sandy beach deposits extend half a mile westward from the north tip and are represented by two narrow bands on the mangrove-free east shore.

The volcanic rocks of the upland are largely olivine basalt flows. Pyroclastic breccias, if present, are not exposed. The slopes are covered with lava blocks; outcrops are few and so limited in extent that at no place could separate flows be mapped.

ULALU

The small oval island of Ulalu is 3.3 miles northeast of Tol (pl. 2). It trends east and is 4,000 feet long and averages 2,000 feet in width. The altitude of a small peak at the east end is 190 feet, but most of the island is less than 100 feet above sea level. Calcareous beach sands surround all but the northeast and east shores.

The volcanic rock on Ulalu is a single flow of nepheline basalt. The flow is unfractured and is not cut by dikes. Because of its similarity to the nepheline basalt flow on Tol, Ulalu is geologically included with the western rather than the central islands.

WEATHERING

Most volcanic bedrock is intensely weathered to depths ranging from a few inches to an observed 30 feet in one lava flow and to as much as 50 feet in the pyroclastic breccia and volcanic conglomerate. Bedrock exposures comprise only about 5 percent of the volcanic terrain; the remainder is covered by soil from weathering of underlying flows. Fresh, unaltered specimens are obtainable chiefly from ledges, palisades, and stripped surfaces on gently dipping lava flows.

In the deeply weathered flows, the residual centers of joint blocks are of hard, unaltered olivine basalt and andesite in a matrix of limonite-stained clay formed from weathering of the igneous rock. Boulders and cobbles of lava in the pyroclastic breccia and conglomerate show exfoliation and alteration to limonitic clay.

Plagioclase, augite, and magnetite are unaltered in most specimens of basalt and andesite. Fresh olivine occurs in a few weathered flows, but more commonly it is altered in varying degrees to serpentine and saponite. Alteration of interstitial glassy material to chlorite and saponite(?) is common in some flows.

Bauxite is developed in soil overlying the summit flow of sodic trachyte on Witipon, Meon. The bauxite consists of nodules ¼ to 4 inches in longer diameters and superficially resembles dried sponges in shape. The nodules are pale brown on the fresh surface and weather to moderate brown (fig. 5A and 5B). Where most completely developed, the soil profile is about 3 feet thick. The nodules form a 6-inch layer about 4 inches below the surface (fig. 6). Where soil is absent, the nodules locally lie scattered on the bedrock surface.

This occurrence of bauxite was described by Bridge (1948), who mentioned "200 acres" of bauxite exposures. This is evidently a misprint as the exposures are less than one-third of the total summit area of 63 acres of Witipon. Chemical analyses showed the bauxite to be so low in Al_2O_3 (42.78 percent in the Bayer process) that Bridge concluded it was of no commercial importance at the present time. There is nothing in the present survey that modifies his conclusions.

Chemical analyses of the weathering products of the Truk Islands are shown in table 1.

Concentrations of limonite in the form of concretionary nodules (fig. 5–B) cover the surface of olivine-rich basalt lavas on several of the volcanic islands and are especially well developed on Fefan and Ulalu. The nodules are generally ¼ to 1 inch in diameter. Locally the nodules are cemented by a limonitic matrix and are exposed as ledges and blocks. Position of the nodules in the soil profile is illustrated in figure 6–B.

TABLE 1.—*Chemical analyses of weathering products of Truk Islands*

	1. *Paseur 7–1*	2. *Ul. 10–1*	3. *Moen*
SiO_2	0.78	13.58	----------
Al_2O_3	16.47	23.00	53.08
Fe_2O_3	51.63	39.80	7.26
FeO	1.22	.60	----------
MgO	.23	.07	----------
CaO	.39	.24	----------
Na_2O	.28	.24	----------
K_2O	.06	.07	----------
TiO_2	5.36	5.63	.66
P_2O_5	3.88	..85	----------
MnO	.14	.07	----------
SO_3	.13	----------	----------
CO_2	.05	----------	----------
H_2O^-	----------	4.82	----------
H_2O^+	----------	11.71	----------
Insoluble	----------	----------	9.37
Loss on ignition	----------	----------	29.68
	80.62	100.68	100.05

1. Concretionary ferruginous laterite, Fefan. Analysis does not include H_2O. This material is similar to that forming upper part of Ulalu profile, fig. 6–B. Analysts, Asari and Ikawa.
2. Soft ferruginous laterite from center of profile shown in fig. 6–*B*, Ulalu. Analysts, Asari and Ikawa.
3. Bauxite nodule from Witipon, Meon, given by Josiah Bridge, Pacific Sci., v. 2, no. 3, July 1948.

A

B

FIGURE 5.—*A*. Profile of soil on trachyte flow near summit of Witipon, Moen (1956). Nodules of hydrated aluminum oxide form layer in upper part of profile. *B*. Gravelly surface of soils overlying nepheline basalt flow on Ulalu (1956). Ferruginous nodules form surface layer visible in photograph.

ORIGIN, AGE, AND PHYSIOGRAPHIC DEVELOPMENT

ORIGIN

The lava flows and pyroclastic beds of the Truk Islands dip gently away from the central part of Truk Lagoon and are remnants of either a single large volcano or several volcanoes. The volcanic flows on Moen dip northeastward from 2½° to 3½°. Dips of the flows on Dublon Island are generally eastward from 3½° to 4°. The dips of the flows on Fefan are southward from 1° to possibly 5°. A breccia unit on Udot dips 5° to 10° S. Most of the volcanic rocks on Tol dip west and southwest from about 5° to as much as 15°. An exception to these attitudes on Tol is the flow of melilite-nepheline basalt, which dips south or southeast. No evidence favoring deformation was discovered in the course of the fieldwork, and these dips very likely represent the original attitudes of the lava flows and pyroclastic beds. The gentle dips and great preponderance of lava flows over pyroclastic deposits suggest that the volcanic islands of Truk are erosional remnants of a shield volcano. Marine deposits are absent within the volcanic sequence, supporting lithologic analogy with other subaerial shield volcanoes such as those of the Hawaiian Islands.

No traces of crater or caldera walls have been found on any of the Truk Islands; however, field data provide a basis for postulating three main centers of eruption on the shield volcano (fig. 3). The presence of coarse, unstratified pyroclastic breccia and autoclastic breccia flows on Udot and Eot suggest a nearby source. The breccia contains a high proportion of accessory and accidental blocks and was probably explosively erupted from a large crater rather than from the lava-filled dikes of this area. The dikes of Udot and Eot have a radial pattern outward from a point in the lagoon about a mile north of Udot and half a mile west of Eot. By analogy with the radial dikes surrounding the central craters of many volcanoes, the central crater of the Truk shield volcano was probably north of Udot and west of Eot. The southward dip of the breccia beds on Udot is additional evidence that the crater lay to the north of Udot. The innumerable dikes on Tol are petrographically similar to the basalt and andesite flows of Tol and were probably the source for most of, if not all,

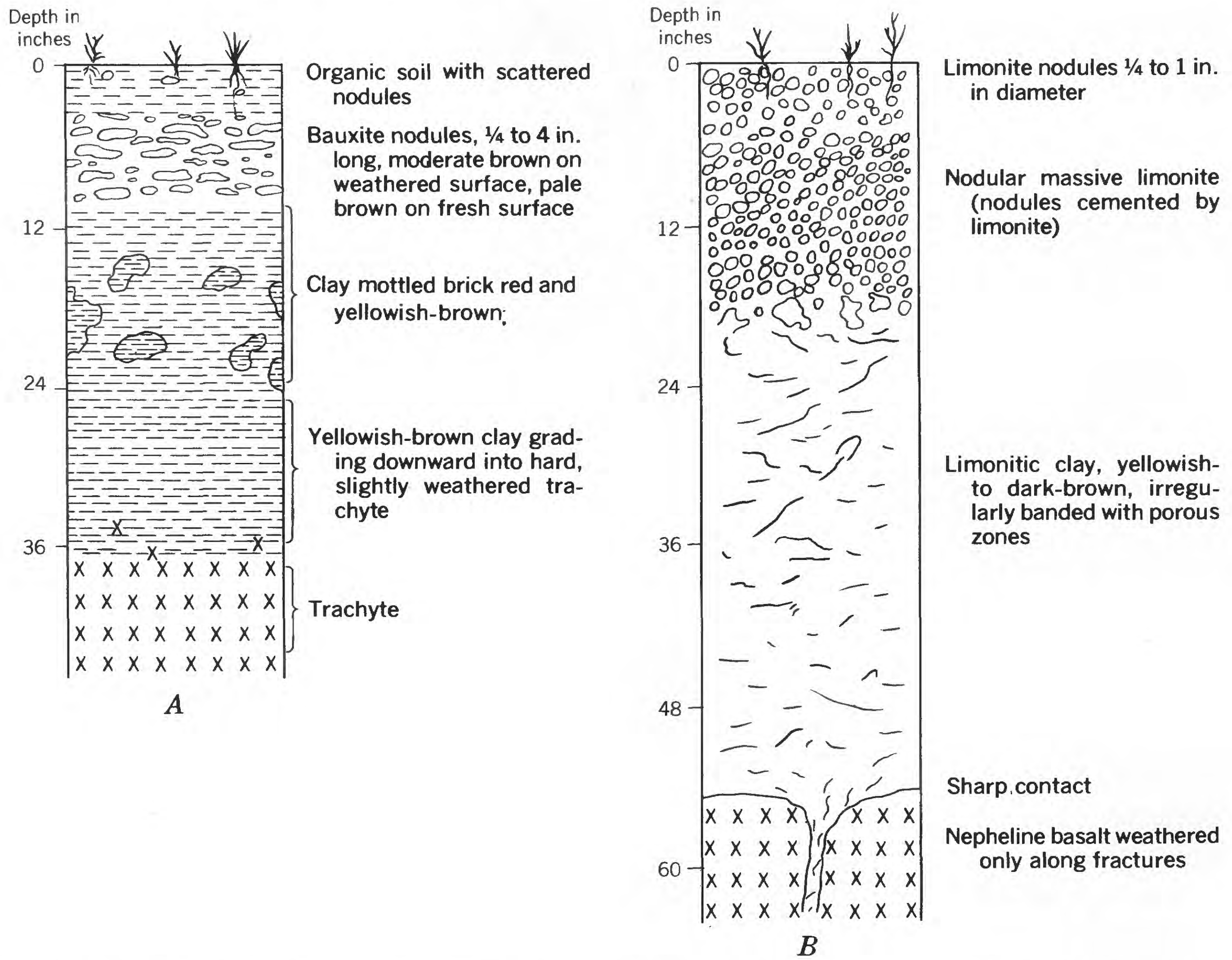

FIGURE 6.—Lateritic soil profiles on Moen and Ulalu illustrating relation of bauxite nodules to trachyte bedrock and limonite nodules to nepheline basalt bedrock.

these lavas. An analogous dike complex is believed to have been the source for the thick sequence of lava flows forming the primitive shield volcanoes of Oahu (Stearns and Vaksvik, 1935, p. 95–96). Updip projections of the flows of Moen, Dublon Island, and Fefan suggest another center of eruption between Fefan and Moen.

The northeast alinement of valley-filling flows within the volcanic sequence on Moen suggests that the source lay southwest of Moen. Dikes are rare in the eastern islands, and these flows may have been erupted from a large crater rather than from a linear fissure system. The flows of the eastern islands are generally thicker, less vesicular, and more continuous in outcrops downdip than those of the western islands; further suggesting a relatively distant vent rather than a source at fissures of a nearby dike complex.

Other vents (that is, parasitic volcanoes) were undoubtedly present. The thin lava flows and abundance of pyroclastic material on Eten, in the eastern islands, is evidence for a parasitic volcano in the eastern part of the Truk shield volcano.

The nepheline basalt and melilite-nepheline basalt flows on Tol unconformably overlie the dikes and fractured lavas of the shield volcano and originated from another source. Lava flows forming the crest of Mount Tumuital, highest point in the Truk Islands (1,453 feet altitude), are fractured and cut by dikes that suggest that 1,400 feet or more of shield lavas was eroded prior to extrusion of nepheline basalt and melilite-nepheline basalt flows, which filled valleys cut in the shield volcano. These flows were apparently analogous to nepheline basalt and melilite-nepheline basalt flows of Oahu, which represent the latest phase of volcanic activity on that island. Two thousand feet of relief was developed on the Koolau shield volcano of Oahu before the valley-filling flows of nepheline basalt and melilite-nepheline basalt were extruded (Winchell, 1947, p. 3). The melilite-nepheline basalt flow on Tol dips to the south and southeast, and the nepheline basalt flow appears to fill a valley trending N. 20° E. Thus the vent(s) which erupted the nepheline basalt and melilite-nepheline basalt of Tol—and probably the nearby nepheline basalt on Ulalu—most likely lay to the north or northeast of Tol.

AGE

The most exact information about the age of the shield volcano is provided by fossiliferous limestone xenoliths of Udot and Eot. Tayama (1952, p. 84) reported that these xenoliths contain *Cycloclypeus* and *Miogypsina,* which indicate a Miocene age. About a handful of limestone xenoliths was collected from Udot and Eot in the course of the present study. They were examined by W. Storrs Cole, who identified the larger Foraminifera and kindly supplied the following information (written communication, July 14, 1955).

Lepidocyclina (*Nephrolepidina*) *sumatrensis* (Brady), which ranges from Tertiary *e* into Tertiary *f*.

Flosculinella sp., a poor specimen. Range of this genus is upper Tertiary *e* through Tertiary *f*.

Miogypsina (*Miogypsina*), whose range is same as *Flosculinella.* "* * * Certain features of the vertical section compare favorably with *M.* (*M.*) *eccentrica* Tan, an upper Tertiary *e* species; therefore, I am inclined to believe that these samples represent upper Tertiary *e* with the slight possibility that they could be Tertiary *f*."

In terms of the standard time scale, these Formaminifera are probably early Miocene (Irving, 1952, p. 448).

The fossiliferous limestone xenoliths are interpreted to indicate that the volcano had grown approximately to sea level by early Miocene time. The limestone was probably deposited in shallow water near a coral reef. It must have been deposited on or near the central part of the volcano in order for the xenoliths to be ejected later from the central crater. Thus, the limestone was probably deposited when the volcano had grown from the ocean floor, at a depth of about 15,000 feet, to sea level and was temporarily covered by a coral reef. The fossils do not date the later subaerial growth of the shield volcano, and it is not known when the shield volcano reached its maximum size.

PHYSIOGRAPHIC DEVELOPMENT

Physiographic data and comparison with other volcanoes affords some basis for inferring the later history of the Truk volcano. Modification of the shield volcano to the present number of small islands scattered within a large lagoon is most easily explained by subsidence of the extinct volcano after dissection by erosion. Oahu, Hawaiian Islands, and Ponape, Caroline Islands, provide analogies to earlier stages of dissection and submergence. Oahu consists largely of a deeply dissected pair of shield volcanoes that have subsided several hundred meters since volcanic activity ceased (Stearns, 1946). Ponape, a single dissected shield volcano, has subsided even farther to drown a number of valleys, which are now fiordlike bays. Numerous islands have been formed adjacent to Ponape by partial submergence of coastal hills. Additional subsidence of Ponape would produce a number of rugged islands, the larger of which would be deeply indented by irregular bays and similar in shape to the island of Tol, the highest of the Truk Islands. The present concentration of volcanic islands in eastern and western parts of the Truk Lagoon suggests that the former shield volcano was elongated eastward. The barrier reef enclosing the Truk Lagoon probably originated as a reef fringing the shield volcano, as visualized by Darwin (1909). The reef continued to grow upward as the volcano subsided and gradually became the barrier reef that exists today.

The amount of subsidence can be estimated only between broad limits. Sinking of 1,000 to 2,000 feet is probably necessary to account for the individual Truk islands, formerly peaks on a single dissected shield volcano, but now widely scattered throughout the lagoon. Submarine slopes on the outside of the barrier reef are steep to depths of at least 700 to 800 fathoms, probably reflecting the reef structure. The volcanic platform has not necessarily subsided this much, however, for the lower third or half of the reef edifice may be reef-flank talus below the level of the reef itself.

The volcano may have commenced sinking either during or after active volcanism and may have subsided slowly enough for the reef growth to keep pace with subsidence. Analogy with Eniwetok atoll, which overlies a submerged Eocene or pre-Eocene volcano of the western Pacific (Ladd and others, 1953), suggests that the Truk Islands may continue sinking until the volcanic islands are submerged and only an atoll remains.

The present diameter of the barrier reef suggests a shield volcano roughly the size of Oahu. The outline of the Truk barrier reef probably does not coincide exactly with the margin of the former shield volcano. If the reef grew only upward and the volcano subsided uniformly, then one should expect the reef to be about equally distant from the outermost volcanic islands in the lagoon; yet, the reef lies only 2½ miles from Tol, largest single land mass in the Truk Lagoon, whereas the northern part of the barrier reef lies as much as 18 miles from the nearest volcanic island. The western part of the barrier reef, thin and discontinuous, may have grown inward towards the volcano during subsidence. The reef bordering the northeastern part of the lagoon is thicker and more luxuriant than the western part and may have grown outward as the volcano sank. Asymmetric development of the reef would be expected in this climatic zone, where the northeast trade winds predominate during most of the year.

Most of the coral islands and reefs in the Truk Lagoon probably originated as fringing reefs on volcanic hills, now submerged. Seventy-five feet of subsidence would submerge the reef-fringed island of Faneu and form a coral islet similar to the nearby islets of Fananan and Faleat. Assuming that most lagoonal coral reefs in the lagoon grew on volcanic platforms, then the distribution of reefs and coral islands should afford some indication of the area once covered by the former shield volcano, probably after some dissection. The area in which lagoonal reefs and coral islands are concentrated is indicated in figure 3. This evidence supports the earlier mentioned inference that the reef has grown outward towards the east and northeast beyond the margin of the volcano.

Evidence of Pleistocene change in sea level was sought throughout the Truk Islands. Japanese observers (for example, Tayama, 1952 p. 206) have reported marine terraces as occurring widely in Truk at altitudes of 1 to 2 meters, 30 to 50 meters, and 100 meters. These observers also noted that the presence of "mushroom rocks" of dead coral at places 3 to 5 feet above sea level implies erosion of preexisting reef rock caused by a drop in sea level of 1 to 2 meters. The "mushroom rocks" were studied briefly in the course of the present study and would indeed seem to indicate a relatively recent drop of 3 to 5 feet in sea level. Furthermore, wave-cut notches at an altitude of about 3 feet above sea level were found on the southeast coast of Udot, and a small exposure of reef limestone cemented to volcanic bedrock was found about 4 feet above sea level on the north point of Eot. The present study found no reliable evidence for widespread marine terrace surfaces, however. Flattish surfaces are widespread, but they occur at many horizons and almost certainly represent the upper surfaces of massive lava flows stripped by stream erosion. Most of the flattish surfaces have the same inclination as the base of the underlying flows, a feature not to be expected of marine abrasion terraces. Tayama (1952) reported the occurrence of limonite pebbles and basalt gravel on the terrace surfaces. The present writers believe the "pebbles" are limonitic nodules produced by weathering; the gravel may represent residual cores of spheroidal-weathered basalt.

PETROGRAPHY

The Truk Islands lie east of the andesite line (fig. 7), the zone that follows the highly deformed island-arc belt along the oceanward side of the Aleutians, the Japanese Islands, and the Mariana group, through the Caroline Islands, southward around Fiji along the Tonga Islands to New Zealand (Betz and Hess, 1942; Hobbs, 1944). This zone is a major structural and physiographic boundary that separates the region of continental-type rocks—the basalt-andesite-dacite-rhyolite kindred of the Pacific margin—from the Pacific basin region of oceanic type rocks—"predominantly olivine basalts, nepheline basalts, and smaller amounts of their differentiation products" (Hess, 1948). The

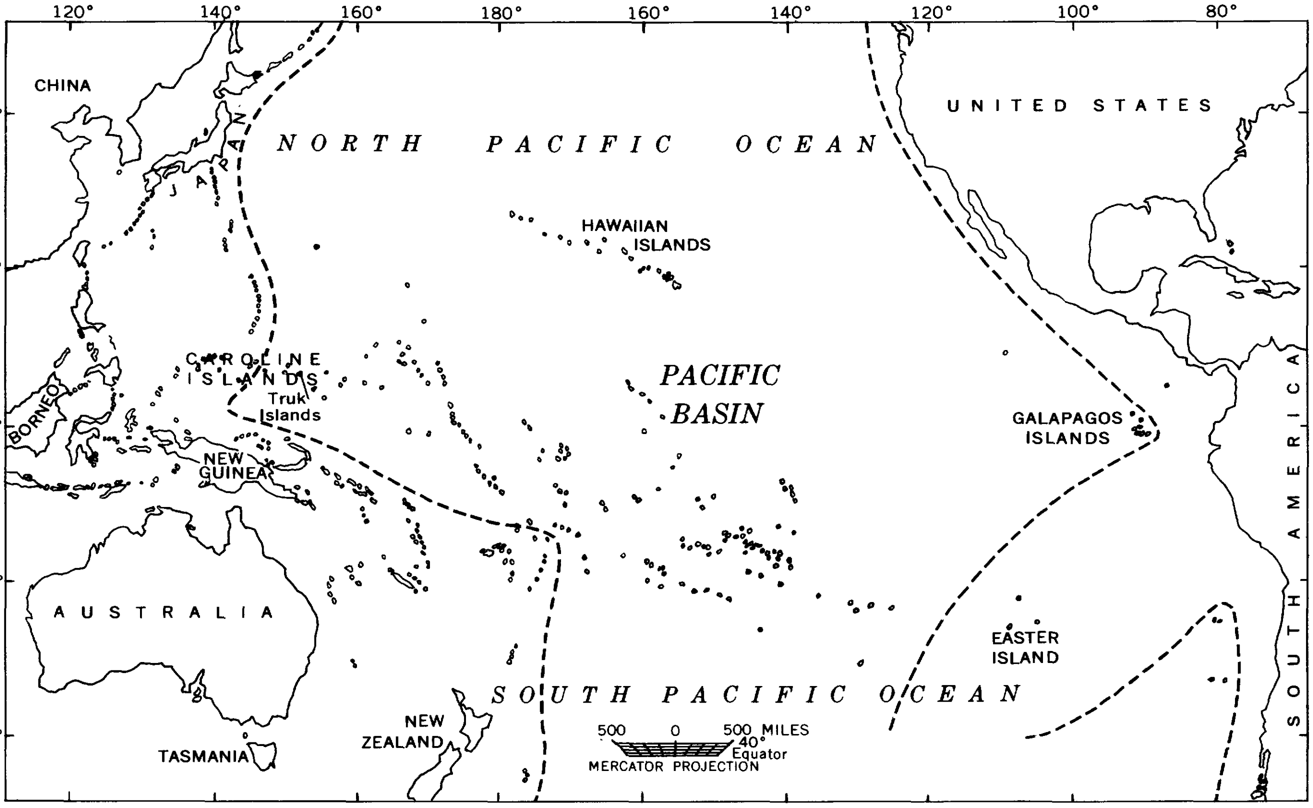

FIGURE 7.—Map of the Pacific Ocean showing location of the Truk Islands. Boundary of the Pacific basin (dashed line) characterized by oceanic crust, is taken from Macdonald (1949, p. 1590, fig. 11). Western boundary of the Pacific basin corresponds to the andesite line.

volcanic rocks of the Truk Islands are chiefly oceanic in type with olivine basalt forming approximately 70 percent, and andesite approximately 25 percent, of all the lava flows. The remaining 5 percent includes nepheline basalt, melilite-nepheline basalt, nepheline basanite, glassy basalts, and sodic trachytes.

This classification, as previously stated, is based on the color index of the rocks excluding phenocrysts; that is, upon the sum of the normative femic minerals (wo+en+fs+fo+fa+mt+hm+il) as calculated from chemical analyses of nonporphyritic rocks. In the absence of chemical analyses, the rocks are classified on the basis of comparison to analyzed rocks and the percentage of modal mafic minerals. In general the results of the classification closely approximates that used by Macdonald (1949, p. 1544) for the Hawaiian petrographic province, which is based primarily on the composition of the feldspars. The coarse blocks in the pyroclastic breccia of the central islands are called gabbros on the basis of mineral composition although their color index is generally less than percentages used to distinguish basalts. The petrography of the central islands of the Truk Lagoon is sufficiently different from that of the eastern and western islands to justify treating the groups separately.

PETROGRAPHY OF EASTERN AND WESTERN ISLANDS

OLIVINE BASALT

The most abundant rock type, both as flows and dikes, is olivine basalt. On fresh surfaces it is black to dark gray and varies through shades of brown and red to light gray, according to the degree of oxidation and weathering. Many outcrops are of hard, unaltered rock; others are reduced to a soft, claylike rubble with only residual boulders fresh enough to be recognized. Textures range from aphanitic to medium-coarse phaneritic and from nonporphyritic to extremely porphyritic, where phenocrysts form as much as 40 to 50 percent of the whole. The tops and bottoms of the flows are commonly vesicular, amygdaloidal, and slightly finer grained than the interior of the flow. Pronounced chilling at the edges is present in narrow selvages of some of the dikes and at the base of a few flows. Generally, however, the difference in grain size between edges and the interior of the flows is slight. Scoriaceous and amygdaloidal basalt characterize many of the autoclasitic breccia zones at the tops and bottoms of flows. Vitrophyric olivine basalt forms a small proportion of basalt flows and a few small dikes in the western islands. Most of the olivine basalts have an intergranular texture, but ophitic to subophitic textures occur. In many flows the lath-shaped plagioclase crystals show typical trachytoid orientation. Such rocks break readily into slabby blocks and present shining surfaces that are due to reflections from parallel crystal and cleavage faces. This rock cleavage, due to flow orientation of elongate and platy minerals, is especially common in andesite flows, but microscopic examination is often necessary before distinction between basalt and andesite can be made.

The conspicuous phenocrysts of the olivine basalts are pyroxene, plagioclase, and olivine. Magnetite occurs as a phenocryst in a few of the extremely porphyritic flows. The predominance of any one or any combination of phenocrysts differs widely from flow to flow, and within a few flows the proportion of phenocrysts differs strikingly from bottom to top. The lower 6 to 7 feet of one flow is nonporphytic and grades upward through a vertical distance of several feet into extremely porphyritic lava, which forms the remaining 30 feet of the flow. In many outcrops the olivine is so completely altered that its presence is detected only under the microscope, where it is seen as very small relicts of fresh olivine or as alteration pseudomorphs of serpentine with euhedral outlines of the original olivine preserved. In some flows, pyroxene is the only megascopic mineral; in others olivine is the only recognizable phenocryst. More rarely plagioclase is the only apparent phenocryst, but there are very few of the porphyritic basalts in which plagioclase is wholly unrecognizable in hand specimens. The megascopic minerals range in size from tiny laths of plagioclase up to phenocrysts three-quarters of an inch long. Two generations of phenocrysts are apparent in many sections under the microscope, and, less commonly, three generations occur. Flow orientation is generally evident. The phenocrysts are fractured and torn apart and show embayments and rounded edges that are due to resorption. In many of the flows, there are glomeroporphyritic clusters that may have formed from floating together of anhedral crystals. Most generally they are formed from the same mineral, plagioclase, pyroxene, or olivine, although some clusters contain mixtures of all three.

Plagioclase in the olivine basalts averages between 45 and 50 percent of the rock and ranges from bytownite to andesine. Sodic labradorite is the dominant feldspar in most of the flows, but several flows contain chiefly calcic andesine. The phenocrysts in some flows have bytownite cores with peripheral zones of less sodic plagioclase. Although euhedral and subhedral phenocrysts are common, many are anhedral owing to fracturing and resorption. There is no evidence of saussuritization, but in some flows resorption embayments filled with fine-grained groundmass leave only small, irregular remnants of the original crystals. Many feldspar phenocrysts contain small inclusions of pyroxene and olivine. Zoning is not especially common, and the bands where present are only faintly outlined. Plagioclase laths of the groundmass show random orientation in a few flows, but these are greatly subordinate to textures showing some degree of parallel orientation that is due to flow. In many flows small laths are closely matted together and are molded by flow around the larger phenocrysts.

Alkali feldspar is present in small amount in some of the olivine basalts. It occurs as fine interstitial material having lower refractive index than the plagioclase. As much as 8.5 percent of normative orthoclase is present in some basalts, a further suggestion that this interstitial feldspar is potassic (probably anorthoclase).

The pyroxene content of the olivine basalts ranges from 25 to about 40 percent. It is monoclinic and ranges from colorless augite, with maximum extinction angles ($C \wedge Z$) between 39° and 45°, to faintly tinted pink and stronger shades of violet and reddish tan, in varieties of augite rich in titanium. The titaniferous augites are by far the most abundant. They show strong birefringence and faint pleochroism. Optic angles measured by universal stage range from 50° to 58°, average less than 54°, and α in a typical specimen is 1.695. These data indicate an augite having the composition of Wo_{45}, En_{21} Fs_{34} (tables of Hess, 1949). No orthorhombic pyroxene has been recognized.

The pyroxene phenocrysts are angular to rounded, owing to absorption, and commonly form glomeroporphyritic clusters. Deep resorption embayments have reduced many of the larger crystals to extremely irregular relicts. They are generally fresh although in a few flows both phenocrysts and groundmass grains are completely changed to fibrous pseudomorphs of chlorite. In the groundmass the augite occurs in slightly elongated flakes and equigranular grains between the plagioclase grains.

Olivine occurs in all the basalt flows as phenocrysts and in small grains in the groundmass. It generally ranges from about 4 to 20 percent and averages 5 to 10 percent of the basalts. No completely olivine-free flows were observed, and in flows where no olivine is visible its former presence is detected from pseudomorphs of serpentine or saponite(?). Some show typical euhedral outlines, but more commonly the phenocrysts are subhedral to anhedral, and many are deeply embayed. Pyroxene was nowhere found to form reaction coronas around olivine crystals. Rims of serpentine surround fresh relicts of olivine, and larger grains show fibrous alteration to antigorite and chlorite along partings and around grains. Pseudomorphs of these alteration minerals are common. Some flows on Tol are rich in fresh olivine, and its alteration is limited to narrow peripheral fringes and discolorations along partings that are due to incipient development of serpentine. Iddingsite is prominent as an alteration product of olivine, and in many of the flows on Tol, numerous crystals are completely altered to pseudomorphs of iddingsite. Other olivine grains show bands of yellowish-green antigorite surrounding centers of iddingsite. In some places this relation is reversed, with cores of serpentine and chlorite surrounded by peripheral zones of iddingsite.

Magnetite is always present in the olivine basalts. It occurs most commonly as small octahedra and irregular grains from 0.01 to 0.05 mm in diameter that are distributed more or less evenly throughout the rock. In a few flows elongated rods up to 1 mm long appear to be of later growth than the equidimensional grains. In other flows large grains 1 to 2 mm long show extremely irregular vermicular borders. Only rarely, in specimens fresh enough for thin sectioning, do the grains show oxidation to hydrous iron oxides.

Iddingsite is conspicuous in many flows as alteration after olivine. It ranges from light yellow and orange, where it is incipiently developed around edges and in fractures of olivine grains, to deep reddish brown, reddish orange, and bright red in many of the pseudomorphs. A faint pleochroism is discernable in some of the iddingsite, but more generally pleochroism is absent or masked in the darker varieties.

Biotite occurs in small amounts as rods and flakes, generally less than 0.05 mm in length. It ranges from yellow to olive to dark brown and shows faint to strong pleochroism. In a few flakes it is well enough developed to show the typical "bird's eye maple" appearance. It occurs as isolated interstitial crystals of yellow to orange brown.

Serpentine, largely yellow and greenish-yellow antigorite, is a common alteration product of olivine and of some pyroxenes. In a few specimens it forms as much as 10 percent of the rock. Chlorite is a common associate of serpentine in the alteration of olivines and pyroxenes. In some specimens it is the chief constituent of fibrous pseudomorphs after augite. Light-green chlorite is present as an alteration of glass in the glassy groundmass of some aphanitic and scoriaceous flows. Calcite is common in a few flows as amygdules and cavity linings and is irregularly developed interstitially throughout some rocks. It occurs sparsely in the alteration of the plagioclase, but none of the feldspar shows typical saussurization. Zeolite occurs as vesicle fillings in a few glassy and aphanitic basalts. It is generally in the form of radiating rosettes. The fibers show parallel extinction and are length slow. Apatite forms swarms of elongated acicular needles, commonly included in the feldspars. It is generally more abundant in flows near the basalt and andesite borderline but occurs to some degree in all flows.

A light-yellow to dark-brown and black mineral occurs in small amounts in many of the olivine basalts. It forms poorly developed rods and flakes and occurs interstitially in angular areas between plagioclase laths. Other grains appear to be discrete mineral flakes showing an incomplete hexagonal outline and a complete gradation from subtransparent brown to opaque according to thickness of plates. It is similar to ilmenite and to the isomorphous mixture of hematite and ilmenite described by Kuno as being in the basalts of the Hakone volcano (1950, p. 983).

NEPHELINE BASALT

A flow of nepheline basalt occurs interbedded with olivine basalt and andesite flows on Dublon Island and as a capping flow on the upland plateau of northeast Tol. The small island of Ulalu, just northeast of Tol, is entirely composed of nepheline basalt. These rocks differ from the olivine basalts by having feldspathoid in place of feldspar. They are generally porphyritic with small phenocrysts of pyroxene and olivine, which in some specimens form as much as 50 percent of the rock. The holocrystalline groundmass consists of nepheline, magnetite, pyroxene, apatite, and biotite.

The nepheline basalt on Tol is characterized by conspicuous pegmatitic segregations in the upper part and to a lesser extent throughout the flow. The coarsest grains are half an inch long; most average between one-eighth and one-quarter of an inch. The pegmatitic areas are extremely irregular, have gradational boundaries with finer grained parts of the flow, and in places are connected by pegmatitoid veins. Numerous vugs occur in the pegmatitic segregations. Minerals of the pegmatite are the same as in the country rock, predominantly nepheline, pyroxene, olivine, and magnetite. In general the nepheline is subordinate to the pyroxene and olivine. It occurs as poikilitic phenocrysts half an inch in diameter, and as anhedral, irregularly rounded grains in the groundmass. Very small grains of magnetite and olivine are commonly present as inclusions.

Augite is extremely abundant in some of the specimens, ranging from 20 to 50 percent. It occurs commonly as very irregular to euhedral prismatic crystals arranged rudely in radiating pattern. The optic angle measured on the larger grains ranges from 45° to 52°; 2 V of the smaller crystals studied is 48° to 52°. The coarse pyroxene of the pegmatite area is light to dark pink in thin section and is probably highly titaniferous. The pink titanaugite grades outward into a peripheral zone of pleochroic green aegirine-augite. Small amounts of light-green aegirine-augite with lower extinction angles ($C \wedge Z$) than augite also occur as discrete crystals in the groundmass.

Olivine is always present, averaging between 20 and 25 percent. It is generally fresh with only incipient discoloration that is due to serpentinization along partings and around edges of the grains. Some crystals are euhedral, and others show deep resorption embayments. A few grains show the beginning of alteration to iddingsite.

The amount of magnetite ranges considerably, from 1 to 5 percent. It occurs as small octahedral grains sprinkled throughout the groundmass and as a few microphenocrysts. Small grains are commonly enclosed in the nepheline. Ilmenite occurs as small irregular grains in the groundmass and as subhedral grains similar to its occurrence in the olivine basalts.

Mica is present as discrete light- to dark-brown crystals of biotite and as partly formed flakes closely associated with olivine and magnetite. It is generally more abundant in the nepheline basalt than in the olivine basalt and andesite flows but never forms as much as 1 percent of the rock. Specimens from the nepheline basalt flow on Ulalu contain a few grains of pink to pale-brown garnet, probably andradite (var. melanite). In other specimens, highly refractive isotropic grains suggest garnet but are too poorly formed to be positively identified. Apatite occurs in small acicular needles embedded in other minerals.

Small irregular brown opaque areas of ilmenite occur interstitially in discrete flakes. They are similar to the ilmenite in the olivine basalts.

MELILITE-NEPHELINE BASALT

Melilite-nepheline basalt was recognized only on Tol, as a flow capping the southern part of the upland plateau of northeastern Tol. It is similar in most respects to the nepheline basalt described above and differs chiefly by containing melilite as well as nepheline. The melilite is largely confined to the groundmass, but a few microphenocrysts are present in some specimens, always subordinate in amount to the nepheline. The flow displays excellent examples of clathrate texture.

NEPHELINE BASANITE

One flow of nepheline basanite is known to occur on Moen. This lava is similar to the nepheline basalt previously described except that a small amount of feldspar takes the place of some nepheline and a groundmass of dark-brown glass is present.

VITROPHYRIC BASALTS

A few flows consist largely of olivine and pyroxene in a groundmass of brown glass. These petrographically resemble the nepheline basalts except that glass forms the groundmass in place of nepheline. These flows may be nepheline basalts chilled before the nepheline crystallized.

ANDESITE

The andesites of the Truk Islands are mineralogically similar to the olivine basalts. Much of the foregoing description of the olivine basalt applies equally well to the andesites, and only the differences will be stressed.

The andesites generally show trachytoid orientation of the plagioclase laths and are nonporphyritic. The flow structures are so well developed that many andesites fracture into platy slabs with glistening surfaces that are due to parallel crystal faces and cleavages of tabular minerals. As some basalts also exhibit this platy fracture, accurate field determinations are often impossible.

The andesites are composed primarily of the same four types of minerals that are dominant in the olivine basalts: plagioclase feldspar, monoclinic pyroxene, olivine, and magnetite. All four occur as phenocrysts, but generally the andesites are fine grained, and megascopic minerals are relatively few and widely scattered. Microporphyritic textures are seen in thin sections, and some specimens show three generations of mineral growth. The phenocrysts are most commonly between 1 and 2 mm, but may be as much as 3 or 4 mm in diameter. Glomeroporphyritic clusters of phenocrysts and fragments of phenocrysts are common. Euhedral outlines of crystals are partially preserved in some flows, but commonly they are subhedral to anhedral and may show extremely irregular edges that are due to resorption.

Andesine is the most common plagioclase although oligoclase is the predominant feldspar in some of the andesites. Zoning in the plagioclase crystals is less obvious than in those of the olivine basalt. Peripheral bands of some of the zoned crystals show extinctions that indicate a slightly more sodic composition than the central cores. The parallel orientation of the groundmass laths and the fragmentation of phenocrysts, owing to flow, are strikingly developed in many specimens. Plagioclase of the groundmass averages between 60 and 70 percent. Small amounts of anorthoclase occur as fine interstitial crystals in the groundmass.

Augite is the most abundant pyroxene. It ranges from typical colorless grains in the groundmass to pink and violet-tinted varieties of titaniferous augite. The darker augite is conspicuous in rocks transitional from andesite to basalt. Optic angles in the pyroxene range from 48° to 53° and average about 50°; α is 1.698 to 1.699. These data indicate an augite of composition Wo_{40}, En_{33}, Fs_{27}, somewhat more iron rich than that of the basalts. Small equigranular grains in the groundmass appear fresh in most rocks. In other rocks the pyroxene has weathered to fibrous masses of chlorite and antigorite.

Olivine is generally present in the andesites in amounts as much as 8 percent. It occurs as phenocrysts and in the groundmass and commonly shows relicts of fresh olivine surrounded by zones of granular and fibrous antigorite, chlorite, iddingsite, and more rarely, small flakes of saponite(?). In some places these alteration minerals form pseudomorphs with euhedral outlines of the original olivine crystals. In the more sodic andesites, fresh olivine is not recognized although its former presence is suggested by the shape of the pseudomorphs of chlorite and other alteration products. Pyroxenes may give similar alterations, but there is little doubt that olivine was once present in all the andesites examined.

Magnetite is ubiquitous and ranges from 3 to 6 percent of the andesite flows. It occurs as very small octahedra and irregular grains, more or less widely distributed throughout the rock, and there are a few larger grains as much as 1 mm in diameter. Around the edges the larger crystals commonly show vermicular extensions, similar to vermicular grains in the olivine basalts. In a few specimens the magnetite occurs almost entirely as small slender rods as much as 1 mm long. Apatite rods ranging from 0.1 to 0.5 mm long are fairly abundant in the andesite flows. Some are enclosed by the feldspar.

Antigorite, chlorite, and olive-green saponite(?) occur as alteration products after olivine and pyroxene. Biotite is more common in the andesites than in the basalts. It occurs as discrete plates scattered throughout the groundmass, rarely forming as much as 1 percent of the rock. Biotite is most common in the basalts of Dublon Island. Later deposits of natrolite and of calcite are present in a few flows as vesicle fillings and irregular deposits along fractures.

Small irregular opaque areas of interstitial ilmenite occur in the groundmass of many of the andesites and appear similar in every way to the ilmenite of the basalts.

TRACHYTE

The trachyte forms only a small part of the volcanic rocks of the Truk Islands, probably less than 2 percent judging from present exposures. On Witipon, a hill on Moen, 150 feet of relatively flat lying trachyte is the youngest flow and forms the caprock. Other exposures occur in a small isolated outcrop on the west slope of Tonaachau (Moen) and in dikes on Tol. The trachyte on Moen was reported as amphibolite schist by Kramer (1908); Bridge (1948) made a restudy of the outcrops, identifying them correctly as trachyte. On the slope of Tonaachau the small exposure is interbedded with andesitic and basaltic flows, and on Tol the trachyte dikes cut both basalt and andesite flows.

The trachyte in hand specimens shows only a few phenocrysts, but most sections under the microscope are microporphyritic with a few oligoclase microphenocrysts in a groundmass of lath-shaped anorthoclase(?). α is 1.527 to 1.528; β is 1.530 to 1.532. The optic angle is estimated between (−) 50° and 60°. The normative plagioclase calculated from one analysis is $Or_{22}Ab_{77}An_1$. Most of the specimens show trachytic textures with closely matted anorthoclase(?) forming approximately 80 percent of the rock. It is this parallel flow structure that gives the megascopic schistose appearance and a rock cleavage resembling that of a metamorphic schist. In a few specimens the trachytic orientation gives way to more intergranular textures. In general, the crystals show much less resorption than those of the andesites and basalts, and in spite of the weathered appearance in outcrops, the trachyte appears remarkably fresh when seen in thin sections.

The pyroxene content is low and rarely forms as much as 1 percent. It is pale-yellowish-green augite with maximum extinction angles averaging around 40°. It occurs interstitial to the feldspar laths and only rarely as phenocrysts.

Small phenocrysts of fresh olivine are present in most specimens. They are generally surrounded by thick rims of alteration products. Serpentine and chlorite are recognized in small patches, but mostly the character of the rims is masked by iron oxide staining.

Magnetite is always present as widely scattered octahedra throughout the groundmass and as a few microphenocrysts. It is never as abundant as in the andesite and averages only between 1 and 2 percent of the rock.

Light-yellow to light-brown biotite is present in small amounts in many of the trachyte specimens. It occurs as poorly developed flakes, interstitial to the feldspar laths and commonly parallel to them. Amphibole also occurs chiefly as pleochroic green and brown hornblende. A few grains show small extinction angles and may be oxyhornblende. Both biotite and amphibole are in small amounts of less than 1 percent.

Apatite occurs as small acicular needles enclosed in other minerals of the groundmass. Small amounts of brown, opaque ilmenite are also present in the groundmass.

The trachytes differ from the andesites by the smaller amounts of dark minerals, by the dominant feldspars being albite and oligoclase rather than oligoclase and andesine as in the andesites, and by the distinct color contrast between the light-gray trachytic flow and the dark-colored andesites. Flows transitional between the andesite and trachyte have not been found, in contrast with those showing the transition from andesite into basalt.

PETROGRAPHY OF THE CENTRAL ISLANDS

LAVA FLOWS AND DIKES

The basalts and andesite flows of the central islands are fundamentally similar to those of the other Truk Islands but are more highly altered. The least altered flows consist largely of plagioclase (oligoclase, andesine, and labradorite), augite, chlorite pseudomorphs after olivine, anorthoclase, and magnetite. Poikilitic hornblende crystals, pinkish brown to brown in pleochroism, are common in one andesite flow; small rodlike crystals of dark-brown hornblende were identified in several other andesites.

Plagioclase and pyroxene are altered to varying extents in most basalts and andesites. Plagioclase phenocrysts of many basalts and andesites are albitized along fractures and througout irregular areas. In some flows the plagioclase is entirely albitized and has a dusty, altered appearance. No slides of basalts and andesites were stained for identification of potassic feldspar. The pyroxene is commonly unaltered in andesites and basalts in which the plagioclase is albitized; conversely the plagioclase is largely unaltered in several andesites in which the pyroxene is entirely replaced by secondary minerals. The pyroxene is extensively replaced by chlorite or calcite or both. Epidote and actinolite less commonly replace the pyroxene. Interstitial chlorite and small irregular crystals of sphene are abundant in the completely altered rocks. Amygdules generally consist of chlorite and calcite. Quartz is present in a few amygdules, and pyrite occurs in some dikes.

All the trachyte flows and dikes are highly altered and consist largely of albite and potassic feldspar having a dusty, altered appearance. Many contain several percent of quartz. The optic angle of the albite is estimated to lie between +70° and +80°; this angle suggests that the albite does not contain potassic feldspar in solid solution. The albite is widely mantled by and intergrown with potassic feldspar, as shown by staining of slides with sodium cobaltinitrite as described by Chayes (1952). In some slides potassic feldspar is concentrated in the marginal part of the albite laths; elsewhere entire crystals consist largely of potassic feldspar. Plagioclase is locally sericitized in a few thin sections. Quartz is present in most trachytes and occurs as anhedral interstitial crystals and as polycrystalline aggregates that form as much as 5 percent of the rock. Some polycrystalline aggregates of quartz, as much as 1.5 mm in diameter, appear to fill pores in the trachyte. Euhedral outlines or "ghost crystals" are common in the crystals of a few pore-filling quartz aggregates, probably representing euhedral nuclei about which later growth of quartz took place. Quartz replaces some small irregular areas of adjacent feldspar crystals, and quartz pseudomorphs after plagioclase phenocrysts are present in one specimen studied. Textural relations indicate that most quartz is primary, but evidence of secondary growth and replacement relations suggest that some quartz is secondary (probably hydrothermal). No primary, unaltered mafic minerals other than magnetite are present in the trachytes, but secondary chlorite is abundant, probably replacing the primary mafic minerals. Sphene is disseminated throughout most trachytes. Pyrite occurs commonly as disseminated crystals and as coatings on fractured surfaces.

PYROCLASTIC BRECCIA

The breccias on Udot and Eot consist of fragments of rock in a fragmental finer grained matrix of rock, crystals, and fine tuff. Locally, these breccias appear to grade into flows of autoclastic breccias in which the matrix is composed of both lava and tuff. In thin section some of the rock fragments can be seen surrounded by smaller chips derived from larger fragments. These fragments were immobilized in the process of autobrecciation, probably during mudflow or some other type of mass movement.

Blocks of andesite, trachyte, quartz trachyte, and basalt predominate in the breccias. Phaneritic gabbro blocks are locally common, and blocks of hornfelsic recrystallized gabbro, basalt, and breccia occur in the bed in which gabbro blocks are most abundant. Several small quartz monzonite blocks were found, and several gabbro blocks contain dikes of monzonite and quartz monzonite. Other gabbro blocks contain dikes of andesite and basalt and inclusions of recrystallized basalt. A few limestone xenoliths were also collected.

ANDESITE, BASALT, AND TRACHYTE BLOCKS

Most of the blocks of andesite, basalt, and trachyte are lithologically similar to the lava flows and dikes, and the pyroxene and plagioclase in most blocks are similarly altered.

One block of quartz trachyte similar to the quartz trachyte of the dikes and flows was studied in detail to determine the nature of the alterations. The rock consists largely of feldspar, which occurs as oriented laths of plagioclase peripherally mantled and partly replaced by potassic feldspar. Both feldspars have a dusty, altered appearance (fig. 8A). Refractive indices indicate that the plagioclase is nearly pure albite. The large optic angle suggests that albite is not significantly potassic. The X-ray diffraction pattern indicates that albite is structurally similar to "low" plagioclase (D. B. Stewart, written communication, 1956). Quartz occurs as anhedral crystals forming an estimated 5 percent of the rock (fig. 8A–B). No primary mafic minerals are present but a chloritic-appearing mineral forms angular interstitial fillings which may replace primary hornblende. Chlorite(?) also replaces plagioclase.

Some trachyte and quartz trachyte blocks are coarser than the trachyte of flows and dikes observed at the surface. The plagioclase of the coarser blocks is albite which lacks the trachytic orientation of dikes and flows. The albite has a turbid appearance, however, and appears similar to the plagioclase of the dikes and flows now exposed. Irregular areas of orthoclase are present within most plagioclase crystals. Brown hornblende that is zoned outward to blue-green riebeckitic amphibole occurs in some blocks. Chlorite, sphene, and, less commonly, epidote form interstitial fillings and locally replace plagioclase. Amygdules consist of calcite, chlorite, and quartz, either singly or in combination. These trachyte blocks probably represent trachyte magma that crystallized below the surface and was altered by hydrothermal solutions and gases(?) similar to those which altered the dikes and flows.

Several blocks of andesite and basalt, coarser in texture than surface flows and dikes, were found. Pyroxene in these blocks is generally altered to pseudomorphous actinolite(?) in which small crystals of sphene are embedded. Less commonly, epidote replaces the pyroxene. The plagioclase is replaced by albite and by potassic feldspar. Quartz occurs in some amygdules of these blocks. One relatively unaltered block of olivine basalt (or olivine dolerite) porphyry was found. The block consists of subhedral to euhedral phenocrysts of olivine, generally 2 to 4 mm long, in an ophitic groundmass of augite (poikilitic crystals, generally 3 mm long), calcic labradorite or bytownite laths, generally 0.4 to 1.5 mm long, and magnetite. Olivine forms 40 percent of the rock, feldspar 30 percent, augite 28 percent, and magnetite 2 percent. The olivine is partly altered to chlorite, and the plagioclase is locally sericitized.

Two blocks of vitrophyric olivine-rich basalt containing amygdules of nearly pure albite were collected. Much of the albite is clear, but more commonly it has a dusty, altered appearance similar to that of the albite in the altered flows and dikes. The albite is structurally "low," according to D. B. Stewart (written communication, 1957). Olivine phenocrysts, formerly abundant in these blocks, are now represented by pseudomorphs of chlorite, serpentine, and, less commonly, albite.

GABBRO BLOCKS

The gabbro blocks are fine to coarse grained and hypidiomorphic granular and consist largely of labradorite, augite, brown hornblende, magnetite, apatite, and both magnetite-chlorite and actinolite-magnetite pseudomorphs after olivine crystals. Reddish-brown hornblende occurs in some of the gabbro. The proportion of mafic minerals (including pseudomorphs after mafic minerals) ranges greatly but is generally between 20 and 35 percent of the total. The grain size of most blocks averages about 5 mm, but it is 1 to 2 mm in some blocks and as much as 1 cm in a few others. The grain size is rather uniform in most blocks but ranges considerably in some. The minerals most commonly lack orientation, although the plagioclase displays excellent planar orientation in a few blocks. The plagioclase in one block has linear as well as planar orientation. The labradorite has an average composition of An_{60-65} but is commonly zoned to more sodic margins.

The pyroxene is uniformly augite. α ranges from 1.688 to 1.696 and 2 V was found to be 45° to 53°. The composition of the pyroxene ranges from wo_{43}, fe_{17} en_{40} to wo_{40} fe_{25} en_{35}, on the basis of tables of Hess (1949). Some augite is pink and is probably titaniferous.

Brown hornblende is present in most thin sections. It occurs as crystals both intergrown with augite and mantling augite and magnetite.

Brown biotite having an altered appearance fringes magnetite in several thin sections. It is most common in blocks which display evidence of thermal recrystallization and may be largely, if not entirely, metamorphic in origin.

A few gabbro blocks have been locally to completely recrystallized to a granoblastic rock similar in composition to the parent gabbro except for olivine which was not found. The gross texture of primary gabbro is preserved in some blocks in which the individual primary igneous crystals are represented by fine-grained monomineralic aggregates of the same composition. The recrystallized plagioclase crystals are commonly 0.4 to 0.7 mm long and about 0.2 to 0.4 mm wide. The recrystallized augite is more variable in size, and in some rocks the small crystals are optically continuous. The augite is recrystallized in some blocks in which the plagioclase is clouded with abundant dustlike inclusions but not otherwise recrystallized. The dusty appear-

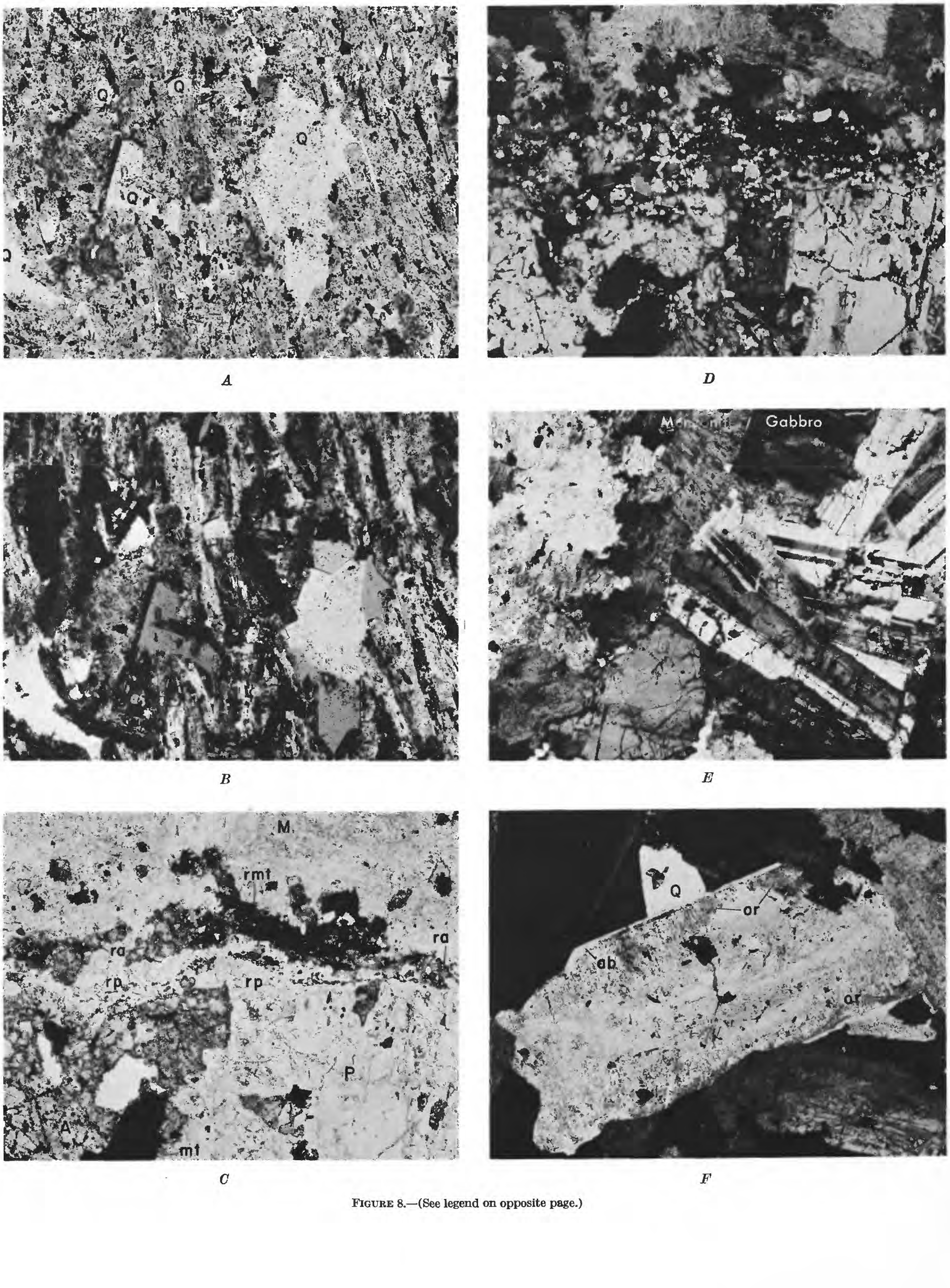

FIGURE 8.—(See legend on opposite page.)

ance of the labradorite was probably caused by heating below the melting point of the plagioclase (MacGregor, 1931). Veinlets of recrystallized augite that cut dusty labradorite crystals in some blocks suggest that the augite was melted and flowed into fractures in the plagioclase crystals. Clouded plagioclase crystals are the only evidence of heating in a few blocks.

All the gabbro blocks are altered to some extent. In the freshest blocks only olivine is altered (to pseudomorphs of magnetite-chlorite and actinolite-magnetite). Augite is partly to wholly altered in many blocks to pale-green actinolite, in which small crystals of sphene are embedded. Epidote replaces some augite, and much of the biotite is partly altered to chlorite. Brown hornblende is replaced by pseudomorphous actinolite and less commonly by epidote in the more altered blocks. Plagioclase of most blocks is partly replaced by alkali feldspar. Albitization has occurred along narrow fractures in some gabbro, but some labradorite of other blocks is entirely replaced by sodic plagioclase and potassic feldspar. Augite is commonly recrystallized but otherwise unaltered in some blocks in which the labradorite is entirely replaced by alkali feldspar. Calcite and quartz are present in many altered blocks, and a veinlet of quartz is contained in one block of gabbro. Some gabbro has been converted by these alterations to an aggregate of epidote and actinolite; other gabbro has been altered to a composition approaching quartz monzonite.

RECRYSTALLIZED BASALT BLOCKS

Blocks of recrystallized basalt as much as 8 inches in diameter occur both as inclusions in the gabbro blocks and as individual xenoliths. The degree of recrystallization varies. The more recrystallized basalt is a plagioclase-augite-hornblende-magnetite hornfels in which biotite may be present. The hornblende is brown and forms poikilitic crystals enclosing the magnetite. All the plagioclase is clear and unzoned (that is, recrystallized) except for zoned relict cores of cloudy appearance in some larger crystals. In less recrystallized blocks, clouded relict plagioclase phenocrysts are commonly embedded in a granoblastic groundmass. Only augite is recrystallized in some blocks. Coarse-grained seams or veinlets are present in one of the hornfels blocks. The granoblastic and clouded appearance of relict plagioclase suggests thermal recrystallization of these basaltic blocks.

BRECCIA BLOCKS

A small proportion of breccia blocks occur within the breccias on Udot and Eot. Many of these blocks consist of fragments of gabbro and volcanic rock in a fragmental matrix. In a few blocks, fragments of gabbro are more abundant than fragments of volcanic rock. Half of one block is gabbro that abuts with a sharp contact against the pyroclastic breccia. The gabbro in this block is sheared adjacent to the breccia, which contains fragments of gabbro, suggesting primary emplacement of the pyroclastic breccia against the gabbro.

A few breccia blocks are recrystallized, and individual lithic fragments display granoblastic textures and grade into the recrystallized tuff matrix. Most breccia blocks, including those recrystallized, are extensively altered to epidote, alkali feldspar (chiefly albite), chlorite, actinolite(?), and calcite.

DIKES OF BASALT AND ANDESITE IN GABBRO BLOCKS

A few gabbro blocks contain dikes of fine-grained basalt and andesite. Nearly all these dikes are between ⅛ and 2 inches wide; the thickest is 6 inches wide. They are commonly finely crystalline to vitrophyric oligoclase andesite. A few dikes of crystalline basalt and andesite having granoblastic textures also cut the gabbro of several blocks. Poikiloblastic biotite crystals as much as 1 mm in diameter are common in one granoblastic dike, and smaller biotite crystals are common in another. A narrow selvage of gabbro adjacent to one basalt dike is recrystallized in a fashion that suggests the gabbro was melted by the invading basalt. Later thermal recrystallization probably accounts for granoblastic textures and biotite poikiloblasts in the dike rock.

VEINS OF MONZONITE IN GABBRO BLOCKS

Veins and veinlets of fine-grained monzonite and quartz monzonite are contained in several gabbro blocks. A similar vein cuts a dike of recrystallized basalt contained in a gabbro block. The veins and veinlets range in width from about 0.04 mm to about 2.5 cm but are most commonly between 2 and 10 mm wide. The thin

FIGURE 8.—Photomicrographs of quartzose rocks from Udot, Truk Islands. *A,* quartz trachyte block chemically analyzed (analysis 23, Ud 187). Note quartz crystals (Q) and dusty, altered appearance of feldspar laths. (Plane-polarized light, × 43). *B,* same as *A* under crossed nicols. Note polycrystalline quartz aggregate at right × 43. *C,* selvage of recrystallized plagioclase (rp), augite (ra), and magnetite (rmt) between vein of monzonite (M) and gabbro. The gabbro consists of plagioclase (P), augite (A), and magnetite (mt). Note augite of selvage partly engulfed in monzonite. (Plane-polarized light, × 29). *D,* same as *C* under crossed nicols × 29. *E,* contact of gabbro inclusion with vein monzonite. Outer zone of one labradorite crystal (P) is partly albitized (crossed nicols, × 31). *F,* feldspar crystal in quartz monzonite block. Core of crystal in An_{10-15} plagioclase, mantled by albite and perthitic(?) orthoclase (or). Outer zone of albite (ab) encloses orthoclase. Note quartz crystal (Q). (Crossed nicols, × 25).

veinlets branch from the veins. The veins are pale gray (almost white) to medium gray. Average grain size is generally between 0.5 and 1.0 mm, and crystals in the veinlets average between 0.04 and 0.5 mm. Single crystals commonly extend the full width of the thinner veinlets. Marginal chilled zones are lacking, but average crystal size is somewhat smaller on one side of several veins than on the opposite side.

The vein rock is largely a mosaic of irregularly shaped sodic oligoclase crystals, but albite (An_{0-5}), orthoclase, augite, magnetite, and zircon are usually present. Labradorite, quartz, biotite, chlorite, epidote, actinolite, pyrite, and calcite occur in one or more veins.

Most of the vein oligoclase is An_{10-15} in composition, but An_{25} oligoclase is common in one vein. The oligoclase is clear where unaltered but contains irregular patches and veinlets of orthoclase having a dusty, altered appearance. The orthoclase may be a result of exsolution or replacement. Dusty albite (An_{0-5}) and orthoclase extensively replace the primary plagioclase of most veins. X-ray diffraction patterns indicate that the sodic plagioclase is structurally similar to the "low" plagioclase of plutonic rocks; the bulk composition of the orthoclase in the veins is not more sodic than $Or_{85}An+Ab_{15}$ (Stewart, written communication, 1956).

Labradorite xenocysts and inclusions can be seen in several thin sections of the veins (fig. 8E). Most labradorite crystals are albitized marginally and along a network of veinlets.

Augite is the dominate mafic mineral. In one vein the optic angle of the pyroxene is 53°, and α is 1.691, indicating a composition identical (within limits of accuracy measurements) with the augite of the gabbro in the same block. Proportion of quartz ranges from 1 or 2 percent to as much as 10 percent. The quartz commonly occurs as interstitial anhedral crystals, some of which are elongated and irregular in shape. Quartz forms a micrographic intergrowth with the oligoclase of one dike which resembles granophyre in petrographic appearance. Quartz occurs in one vein as lenticular crystals between cleavage lamellae of biotite.

Magnetite, apatite, and zircon are common accessory minerals. Biotite is the principal mafic mineral in one dike. Epidote, calcite, chlorite, and less commonly pyrite are present in altered dikes.

Contact relations of the veins generally appear sharp to the naked eye but are more complex in detail. The gabbro is commonly recrystallized in a discontinuous selvage 0.15 to 0.75 mm wide adjacent to the veins (fig. 8*C–D*). Recrystallized plagioclase crystals in the selvage are clear and generally between 0.01 and 0.03 mm in diameter; they seem to be more sodic (An_{45}) than the plagioclase of the gabbro (An_{60}), which is clouded as if heated (MacGregor, 1931). Augite is also recrystallized in the selvage. Distribution of pyroxene and plagioclase crystals in the recrystallized selvage indicate that the selvage represents melted gabbro. The recrystallized plagioclase of the selvage grades outward into the coarser plagioclase of the veins. Magnetite in the gabbro adjacent to the recrystallized selvage is commonly fringed by reddish-brown biotite that extends the width of the selvage. The gabbro is not appreciably recrystallized adjacent to a few veins and most veinlets. Where the selvage is absent, plagioclase crystals of the gabbro commonly extend as much as 0.05 mm out into the veins. These extensions of the gabbroic plagioclase are generally albitized and have a dusty, altered appearance characteristic of the vein albite. Recrystallized selvages indicate that most veins were emplaced at temperatures high enough to melt gabbro; labradorite xenocrysts and augite similar in composition to most of the gabbro indicate that the veins incorporated some gabbroic material.

The thin veinlets consist almost entirely of albite and orthoclase and generally lack a border zone of recrystallized gabbro. Where a recrystallized selvage is absent, the veinlets lack augite. Where cut by a veinlet, labradorite crystals are albitized and form part of the veinlet. Veinlets of albite fill fractures in pyroxene crystals of the gabbro and indicate that albite is not solely a replacement of labradorite.

MONZONITE BLOCKS

Three small blocks of fine-grained quartz monzonite, 2 to 3 inches in diameter, were found in the breccias on Udot. All blocks consist largely of sodic plagioclase and orthoclase but also contain quartz, hornblende, zircon, apatite, and opaque ores. Quartz forms between 2 and 5 percent of the monzonite.

The finest grained block is somewhat coarser but is otherwise similar to the monzonite veins cutting the gabbro. The average grain size is about 1 mm. The block consists largely of dusty-appearing albite, in which a few ragged unreplaced cores of oligoclase remain. Orthoclase is abundantly distributed throughout the albite as fine veinlets and small areas of irregular shape. The plagioclase is structurally similar to the "low" plagioclase of the plutonic rocks (D. B. Stewart, written communication, 1956). Quartz occurs both as interstitial anhedral crystals and as thin finely crystalline veinlets. Partly assimilated inclusions of volcanic rock are present in the block.

Another block is biotite-hornblende-quartz monzonite, with a grain size of 1 mm, in which largely assimilated inclusions of volcanic rock are common. The hornblende is pleochroic (from pinkish brown to green) and locally grades into marginal hornblende of deep bluish green. Most of the augite and biotite is altered to chlorite. Albite having a dusty, altered appearance is the dominant feldspar, but larger crystals have clear cores of more calcic plagioclase (one found to be labradorite) that are veined with albite, particularly adjacent to quartz, which occurs as anhedral interstitial crystals and polycrystalline aggregates. A zone of dusty albite forms an outer mantle enclosing orthoclase and inner plagioclase.

The third and coarsest block is biotite-augite-hornblende-quartz monzonite having a porous, somewhat miarolitic character and an average grain size of about 2 mm. The larger feldspar crystals consist of clear, unaltered cores of oligoclase (An_{10-15}) veined and enclosed by a thick mantle of albite (An_{0-5}) having a dusty, altered appearance. Orthoclase, which forms about 10 percent of the feldspar, occupies irregular areas within the mantle of dusty albite and is most abundant adjacent to a thin outer mantle of albite about 0.015 mm thick (fig. 8). The quartz occurs chiefly as interstitial crystals and forms an estimated 2 to 3 percent of the rock. Euhedral feldspar and quartz crystals protrude into small miarolitic cavities. Most hornblende crystals are pleochroic from brown to brownish green, but marginal zones and some whole crystals are deeply pleochroic from dark violet to blue green and are probably sodic. Most of the biotite and much of the augite are altered to chlorite.

LIMESTONE FRAGMENTS

A handful of limestone fragments were collected from the breccia in the course of the present study. Most are pale reddish brown, and a few are pale gray. Stylolites are present in most limestone fragments, which are bioclastic (that is, largely organic detritus) and consist largely of sand-size debris. Most detritus is algal, individual fragments of which are as much as 1.5 cm long. Both larger and smaller Foraminifera are common. The larger Foraminifera, identified by W. Storrs Cole, comprise the genera *Lepidocyclina*, *Flosculinella*, and *Miogypsina*. (See earlier discussion on p. 15.) Bryozoan and gastropod detritus has also been identified, and echinoderm(?) spicules are common. One fragment of limestone consists largely of intergrown algae and colonial coral and may be a fragment of a reef. Abundance of bioclastic debris, particularly coarse algal detritus, suggests that this limestone was deposited in shallow water, very probably near a reef.

Sand-size grains of volcanic rock are scattered throughout most of the limestone; the proportion of the volcanic detritus ranges from a few percent in most limestone to about 25 percent in one. Most of the volcanic rock fragments consist of calcite pseudomorphs after plagioclase and primary mafic minerals in a matrix of dark-brown glass. It is not known whether the volcanic detritus is pyroclastic or whether is was washed in as derital sediment. The latter possibility is favored by the similar grain size of volcanic and organic debris, and the dissemination of the volcanic detritus throughout the limestone.

PETROGENESIS

CHEMICAL COMPOSITION AND VARIATION DIAGRAMS

Chemical analyses and norms of representative rocks of the Truk Islands are shown in table 2, together with two previously unpublished analyses of basalt from Ponape. They fall into four main classes: olivine basalt, nepheline and nepheline-melitite basalt, andesite, and trachyte. The transition from basalt to andesite is so gradual that sharp distinctions are not possible. No such transitional zone between andesite and trachyte is apparent. The melilite-nepheline and nepheline basalts are characterized by the presence of feldspathoids. These relations are well shown on the variation diagram (fig. 9) where the weight percent of various oxides are plotted as ordinates against the weight percent of silica. The melilite-nepheline basalts with silica about 39 percent show at the low silica side of the diagram. Olivine basalts and andesites fall closely together near the middle part of the diagram, between 42 and 48 percent silica. In general, there is a close association between silica percentages and color index distinction between basalt and andesite. There are exceptions, however, such as specimen 5 (Du–105), which appears to be a typical olivine basalt with a silica percentage of 44.35 and a color index slightly below 37. There is a wide gap between andesites with silica between 45 and 50 percent and the trachyte with 65 percent silica.

The low silica content of the analyzed andesites and basalts in relation to other oxides is again shown in figure 10.

Figure 10, a triangular *SKM* diagram, shows the composition of the rocks in terms of three components where *S*, *K*, and *M*, are molecular amounts: $S=SiO_2-2CaO$, $K=6(Na_2O+K_2O)$, and $M=MgO+FeO-Fe_2O_3-TiO_2-CaO-Na_2O-K_2O+Al_2O_3$. The diagram is a modification of the von Wolff (*OLM*) triangle by Prof. J. B. Thompson, of Harvard University (Schmidt, 1957, p. 152). The median horizontal line represents silica saturation; all rocks that fall above this line contain an excess of silica (oversaturated

TABLE 2.—*Chemical composition and norms*

	Melilite-nepheline basalt		Olivine basalt						Andesite						
	1 To-315	2 To-316	3 Mo-134a	4 Fe-118	5 Du-105	6 Mo-153	7 To-18	8 Mo-8	9 Fe-10	10 Mo-9	11 Mo-160	12 Mo-159	13 To-5	14 Ud-135	15 Mo-13
Bulk															
SiO_2	38.62	38.80	42.00	44.24	44.35	44.70	46.03	46.39	46.80	47.47	47.56	48.10	48.59	48.59	55.55
Al_2O_3	13.03	10.00	11.12	13.23	18.05	11.80	15.22	13.93	15.96	14.73	15.87	14.40	14.82	14.84	16.76
Fe_2O_3	3.21	3.70	4.42	5.10	1.92	1.80	1.84	2.07	1.76	3.31	1.48	4.30	2.89	4.50	3.10
FeO	7.93	7.50	10.31	9.74	7.05	11.10	9.77	10.60	9.02	8.25	8.00	8.00	8.49	6.88	4.41
MgO	10.72	12.50	11.44	8.68	5.59	12.00	8.55	11.22	5.04	4.57	4.34	6.40	4.23	3.90	2.67
CaO	13.80	14.70	9.68	8.82	10.14	10.20	9.91	9.11	9.48	8.52	8.28	9.50	8.39	8.45	4.64
Na_2O	3.16	3.30	2.65	2.48	6.36	1.90	3.64	2.44	4.99	5.39	3.88	3.20	5.93	5.39	5.99
K_2O	1.19	1.20	1.35	.90	1.12	.54	.90	.38	1.12	1.17	1.19	.69	1.18	1.13	2.13
H_2O-	1.14	2.50	.24	.40	.56	2.30	.69	.44	.99	.76	.88	2.20	.88	.66	1.09
H_2O+	2.84		2.90	3.20	1.85		1.30	1.11	1.73	1.72	3.90		2.40	1.61	.76
TiO_2	3.58	3.10	2.86	2.57	1.20	2.60	2.00	1.70	2.30	3.15	3.33	2.50	2.21	2.91	1.83
CO_2	--	.05	--	--	--	.05	--	.12	--	--	--	.05	--	--	.03
P_2O_5	.64	1.10	.82	1.03	1.13	.42	.53	.21	.07	.71	.90	.51	.34	.62	.75
MnO	.18	.20	.19	.17	.23	.16	.29	.19	.30	.24	.19	.19	.30	.24	.24
S	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total	100.04	98.65	99.98	100.56	99.55	99.57	100.67	99.91	99.56	99.99	99.80	100.04	100.65	99.72	99.95
Niggli															
Q	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1.3
or	--	--	8.5	5.5	6.5	3.0	5.5	2.5	7.0	7.0	7.5	4.0	7.0	7.0	12.5
ab	--	--	12.3	23.5	12.8	17.0	24.8	22.5	25.5	35.5	37.0	29.5	32.5	38.0	54.5
an	18.3	9.3	15.3	20.8	17.5	23.0	22.5	26.0	18.0	13.0	23.3	24.0	10.7	13.2	12.5
lc	6.0	6.0	--	--	--	--	--	--	--	--	--	--	--	--	--
ne	17.4	18.0	7.1	--	26.5	--	5.5	--	12.0	9.0	--	--	13.2	7.2	--
di wo	13.8	16.3	11.9	7.6	10.2	10.6	7.5	7.2	10.0	10.4	6.6	9.0	11.9	10.4	.6
di en	11.6	14.2	9.2	5.6	6.8	7.6	5.1	5.0	6.0	6.5	4.1	6.6	6.9	8.0	.4
di fs	2.2	2.1	2.7	2.0	3.4	3.0	2.3	2.2	4.0	3.9	2.5	2.4	5.0	2.5	.2
hy en	--	--	--	10.0	--	4.8	--	4.6	--	--	1.3	9.6	--	--	7.0
hy fs	--	--	--	3.4	--	1.9	--	1.7	--	--	.7	3.9	--	--	2.4
ol fo	14.3	16.1	17.8	7.5	10.3	16.5	21.0	16.5	10.8	4.9	5.5	1.6	5.5	3.5	--
ol fa	2.6	2.3	5.1	2.7		6.2		7.0			3.4	.6			
mt	4.1	5.1	4.6	5.7	2.0	2.0	--	2.2	1.8	3.6	1.5	4.6	3.1	4.8	3.3
il	3.5	3.9	4.0	3.6	1.6	3.6	2.8	2.2	3.2	4.6	4.8	3.4	3.2	4.2	2.4
hm	1.3	2.4	--	--	--	--	1.9	--	--	--	--	--	--	--	--
ap	5.0	4.4	1.6	2.1	2.4	.8	1.1	.5	1.6	1.6	1.8	.8	.8	1.3	2.9
C	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Ru	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pr	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total	100.1	100.1	100.1	100.0	100.0	100.0	100.0	100.1	99.9	100.0	100.0	100.0	99.8	100.1	100.0

1. Melilite-nepheline basalt flow south side of north Tol, near top of mesa. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
2. Melilite-nepheline basalt flow south side of north Tol, near top of mesa. Analysts, P.L.D. Elmore and K. E. White, U.S. Geol. Survey.
3. Olivine basalt flow 60 ft. altitude at southeast edge American base, Moen. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
4. Olivine basalt flow 200 ft. altitude, west Fefan. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
5. Biotite-bearing olivine basalt flow 150 ft. altitude, Mount Tolomon, Dublon Island. Analysts. Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
6. Olivine basalt flow; thick flow at east end Moen. Analysts, P. L. D. Elmore and K. E. White, U.S. Geol. Survey.
7. Olivine basalt flow, south coast of south Tol. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Toyko.
8. Olivine basalt flow, west side Wichap village, Moen. Analyst, Lois Trumbull, U.S. Geol. Survey.
9. Andesite flow, base of trail, Feurep village, Fefan. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
10. Andesite flow, Elelup village, Moen. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
11. Andesite flow, Mount Tonaachau, Moen. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
12. Andesite flow, east end of old Japanese airfield, south end Moen. Analysts, P. L. D. Elmore and K. E. White, U.S. Geol. Survey.
13. Andesite dike, trail above Wonip village, Tol. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
14. Hornblende-bearing andesite flow. Udot. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.

rocks) and all rocks below it are deficient in silica (undersaturated rocks) and contain one or more minerals with less silica than is required for saturation. The end points of this line represent normative alkali feldspar and total normative pyroxene of the von Wolff triangle. The *SKM* triangle has the advantage that lines connecting normative minerals become valid phase boundaries with removal of the calcic feldspars and pyroxenes. The diagram becomes a partial graphic solution of the norm, and the composition of any rock can be expressed in terms of a combination of three normative mineral components depending on where it falls in the diagram. All the analyzed Truk rocks fall below the silica saturation line. All but the melilite-nepheline basalts, specimens 1(To–315) and 2(To–316) fall into subsidiary triangles, alkali feldspar-olivine-hypersthene or alkali feldspar-olivine-nepheline.

Figures 11 and 12 are triangular diagrams or–ab–an and wo–en–fs to show, respectively, the composition of the normative feldspar and the normative pyroxene of the volcanic rocks of the Truk Islands, plotted with normative feldspar and normative pyroxene of Daly's average rock types. Both diagrams reflect the low silica percentage of the Truk rocks. The apparent undersaturation in the diagrams, plus the abundance of modal olivine in all the basalts (averaging from 10 to 15 percent), and the presence of olivine in all the andesites and in many of the trachytes indicate that the Truk flows were deficient in silica. The lavas exposed at the surface in Truk represent only the upper *of volcanic rocks of Truk Islands and Ponape*

Sodic trachyte	Hornfelsic block	Gabbro block	Basalt in gabbro block	Gabbro block	Granophyre gabbro block	Monzonite block	Trachyte block	Pumice	Basalt	
16 Mo-208	17 Ud-141a	18 Ud-122a	19 Ud-139c	20 Ud-125	21 Ud-126	22 Ud-146	23 Ud-187	24 Ud-138	25 Po-18	26 Po-15
analysis										
65.00	41.24	45.62	46.32	48.50	58.22	63.60	67.61	69.16	42.42	45.70
17.50	16.50	19.08	15.75	22.70	19.59	16.90	15.68	13.53	13.64	15.45
2.10	7.51	5.44	6.68	3.90	1.00	3.09	3.02	.97	3.60	1.82
.93	8.31	4.93	7.11	3.50	2.65	1.72	1.53	2.83	7.88	9.36
.52	6.03	4.63	5.30	3.10	1.12	.61	.85	.39	11.06	6.48
1.20	12.54	13.51	10.40	11.40	3.20	1.30	.36	2.04	11.71	9.46
8.10	1.41	2.30	3.11	3.50	5.62	5.54	5.42	4.92	2.64	2.84
3.60	.15	.25	.34	.35	4.36	3.58	2.51	2.99	.82	1.23
} .38	.18	.06	.04	} 1.00	.26	.48	.34	.14	.82	.42
	1.66	2.71	2.10		1.51	1.91	1.51	1.90	3,49	3.53
.79	3.68	.77	2.40	1.70	1.27	.49	.42	.43	1.79	3.05
.05	--	--	--	.86	--	--	--	tr	--	--
.23	.03	.24	.61	.30	.96	.03	.05	.24	.73	.79
.12	.19	.12	.22	.13	.07	.06	.06	.09	.19	.18
--	--	--	.10	--	--	.03	--	--	--	--
100.52	99.43	99.66	100.48	100.94	99.83	99.31	99.36	99.63	100.79	100.31
Norms										
2.4	0.5	2.7	2.1	0.2	1.7	13.9	23.9	22.0	--	--
20.5	1.0	1.5	1.5	2.0	26.0	21.5	15.0	18.0	5.0	7.5
70.5	13.0	22.5	28.5	31.5	50.5	50.5	50.0	45.0	8.1	27.0
.8	41.0	32.0	29.0	46.0	10.0	4.3	--	6.2	22.7	26.8
--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	9.8	--
1.2	9.7	15.9	8.0	3.7	--	--	.2	1.1	10.7	6.8
1.2	8.3	13.0	7.2	3.3	3.2	--	.2	.2	13.8	4.6
--	1.4	2.9	.8	.4	1.7	--	--	.9	3.0	2.2
.2	9.5	1.2	7.8	5.3	--	1.6	2.2	1.0	--	2.2
--	1.6	.3	.8	.7	--	.4	--	3.7	--	1.2
--	--	--	--	--	--	--	--	--	15.5	9.0
--	--	--	--	--	--	--	--	--	8.0	4.5
.9	8.4	6.3	7.2	4.1	1.1	3.5	3.0	.9	3.9	2.0
1.0	5.4	1.2	3.4	2.2	1.8	.6	.6	.6	2.4	4.4
.8	--	--	--	--	--	--	.2	--	--	--
.6	.2	.6	1.3	.6	1.9	.5	.3	.6	1.6	1.6
--	--	--	--	--	2.1	2.6	--	--	--	--
--	--	--	--	--	--	--	4.5	--	--	--
--	--	--	2.4	--	--	.7	--	--	--	--
100.1	100.0	100.1	100.0	100.0	100.0	100.1	100.1	100.2	100.0	99.8

15. Andesite, quarry east end of north Moen, airstrip. Analyst, Lois Trumbull, U.S. Geol. Survey.
16. Trachyte flow, top Mount Witipon, Moen. Analysts, P.L.D. Elmore and K. E. White, U.S. Geol. Survey.
17. Hornfelsic block in breccia, Udot. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
18. Gabbro block in breccia, Udot. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
19. Basalt in gabbro block, breccia, Udot. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
20. Gabbro block from breccia bed, south side of central Udot. Analysts, P.L.D. Elmore and K. E. White, U.S. Geol. Survey.
21. Granophyre block, breccia, south side Udot. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
22. Monzonite block, breccia, Udot. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
23. Trachyte block, breccia, Udot. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
24. Recent pumice, beach on north side Udot. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
25. Basalt flow, Ponape. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.
26. Basalt flow, Ponape. Analysts, Drs. Ikawa and Asari, Japan Insp. Co., Tokyo.

part of the shield volcano and do not necessarily prove that the principal mass of the volcano, now submerged, consists of undersaturated lavas. The flows in Truk are nearly horizontal and represent but a small fraction of the volcano during its final stages of growth.

COMPARISON WITH ROCKS OF OTHER AREAS

Powers (1955, p. 80) in discussing the composition and origin of the basaltic magmas of the Hawaiian Islands points out that olivine basalt is a product of the declining phase of the shield-building eruptions and that the volume of such flows is insignificant compared with that in primitive shields. He concludes that the concept that the parent magma of the primary Hawaiian magma was undersaturated is not justified and that the composition of the olivine basalt in the primitive shields indicates that the primary Hawaiian magma is approximately saturated with silica and should not be called an olivine basalt magma (as recognized earlier by Tilley, 1950, p. 40). The lavas of the Truk Islands are petrographically and chemically similar to the lavas of the declining phase on Hawaii. Whether tholeiitic lavas form the primitive shield of Truk is unknown, as only the upper part of the shield is now above sea level.

Previous studies of the volcanic rocks of Saipan (Schmidt, 1957, p. 153–163) and of Guam by Stark show comparisons of the compositions of the lavas of these islands with those of Palau, Bonin, and Volcano Islands, the Hakone volcano and Izu Peninsula region

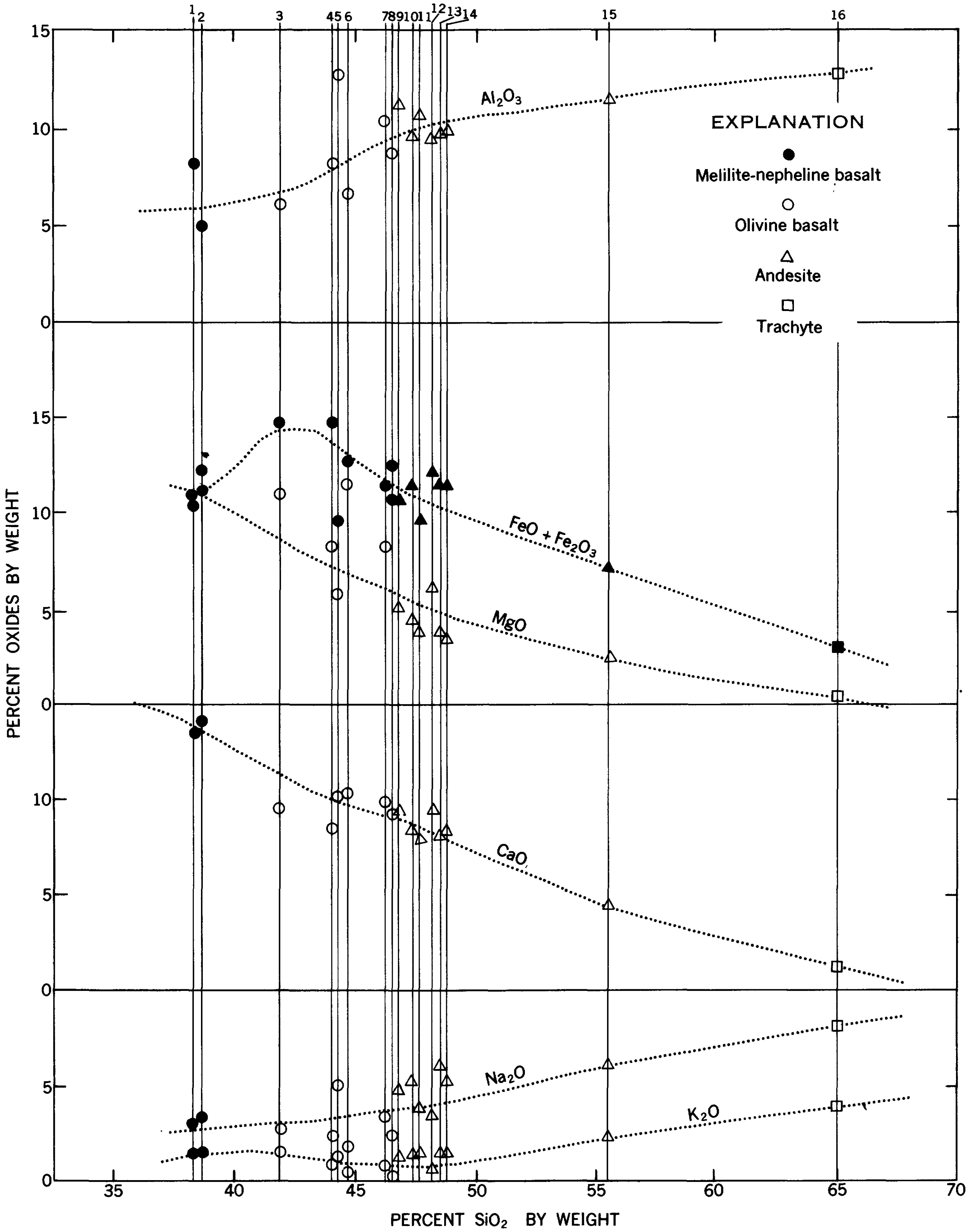

FIGURE 9.—Variation diagram for volcanic rocks of Truk Islands (Numbers refer to analyses and corresponding rock specimens in table 2).

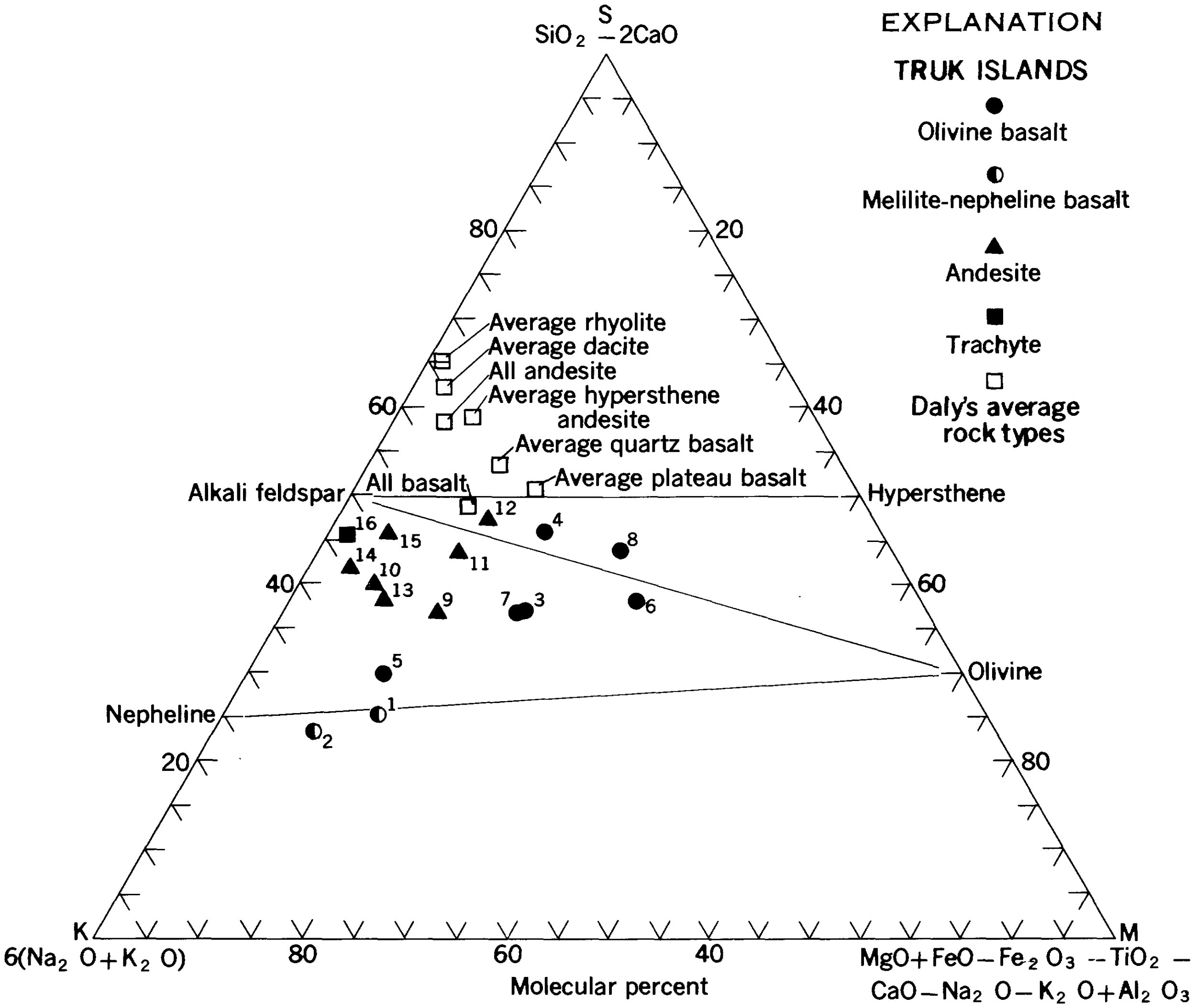

FIGURE 10.—*SKM* diagram of specimens of volcanic rocks of Truk Islands and Daly's average rock types.

of Japan, and the Hawaiian Islands. All except the Hawaiian Islands lie west of the andesite line, in the zone of continental-type rocks of the Pacific margin. A close relation was pointed out between the islands of Saipan and Guam, and to the similarity in composition of their lavas with those of the Izu Peninsula region of Japan. The Truk Islands lie east of the andesite line and are closely related to the oceanic-type rocks of the Pacific basin. A comparison of the average composition of rocks of the Truk Islands with average compositions of the rocks of Guam (Stark, in prep., table 2) and Hawaii (Macdonald, 1949, table 5) is shown in figure 13. The analyses of two basalts from Ponape are also shown.

In the triangular *SKM* diagram (fig. 13), there is a close relation shown between the average andesite of the Truk Islands and the average andesine andesite of Hawaii. The average olivine basalt of Truk is slightly more mafic than the average olivine basalt of Hawaii, and both fall below the median alkali feldspar-hypersthene join. The melilite-nepheline basalts of Truk and Hawaii fall close to each other on the diagram, just below the nepheline-olivine join. The average andesite and average basalt of Guam fall well above the median alkali feldspar-hypersthene join or above the line of silica saturation. The trachyte of Truk and Hawaii fall close together just below this line and close to the alkali feldspar side of the *SKM* triangle.

Figures 14 and 15 are triangular diagrams or–ab–an and wo–en–fs, respectively, and show the relations of the normative feldspar and normative pyroxene of the rocks of Truk, Hawaii, Guam, and Ponape. In each diagram the similarity in composition between the lavas of Truk and Hawaii is indicated; however, certain significant differences occur. Macdonald (1949, p. 1545–1549) reports abundant pigeonite in the olivine

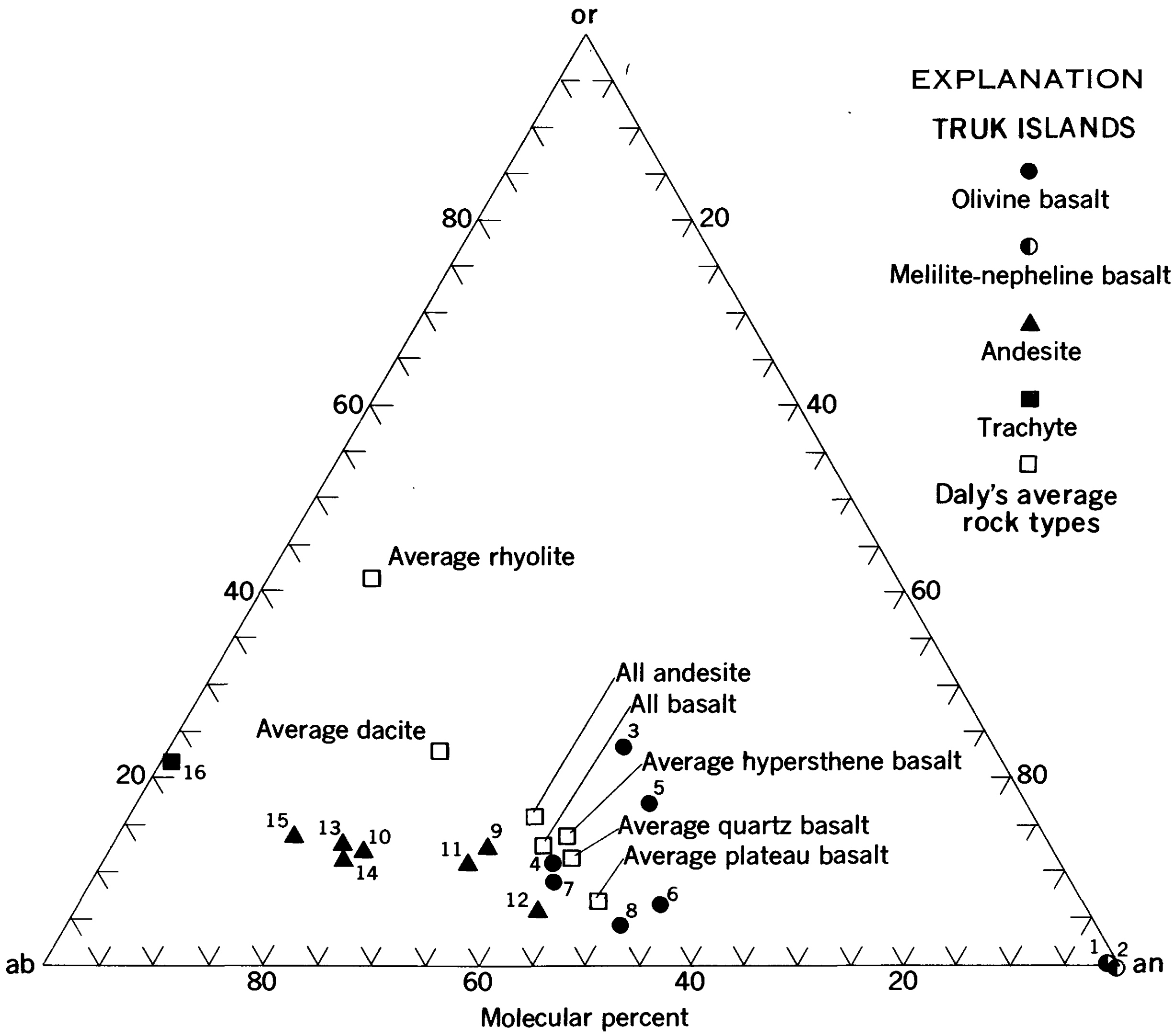

FIGURE 11.—Composition of normative feldspars of volcanic rocks of Truk Islands and Daly's average rock types.

basalt, basalt, and andesine andesite of Hawaii. Although some of the pyroxene in the Truk rocks have optic angles slightly lower than typical augites, in none of the measurements made is the optic angle small enough to identify pyroxene as pigeonite. Figure 16 is a triangular FeO–alkali–MgO diagram, with total iron plotted as FeO. The curve represented is similar to the curves of olivine basalt-trachyte series plotted elsewhere by Nockolds and Allen (1954, p. 246, 248). The nonporphytitic basalt lying closest to the MgO point represents the liquid closest in composition to the primary magma of the Truk Islands lavas. Chemically this basalt is essentially similar in all respects to the parental magmas of the olivine basalt-trachyte series as shown by Nockolds and Allen. (See table 3.)

CONCLUSIONS

EASTERN AND WESTERN ISLANDS

Various origins have been suggested to account for the parent magma of the olivine basalt-trachyte series. Some have advocated derivation from tholeiitic magma, a view recently reiterated by Powers (1955). Others (Kennedy, 1933) have postulated two basaltic layers in the crust, one of which yielded the alkalic olivine basalt magma series. Seismologists have recently shown that the Pacific Ocean is underlain by a basaltic layer only 3 to 5 kilometers thick (Raitt, 1956); this figure throws doubt on the feasibility of deriving oceanic volcanoes from a basaltic layer. Kuno and others (1957, p. 212–216) have summarized evidence that sug-

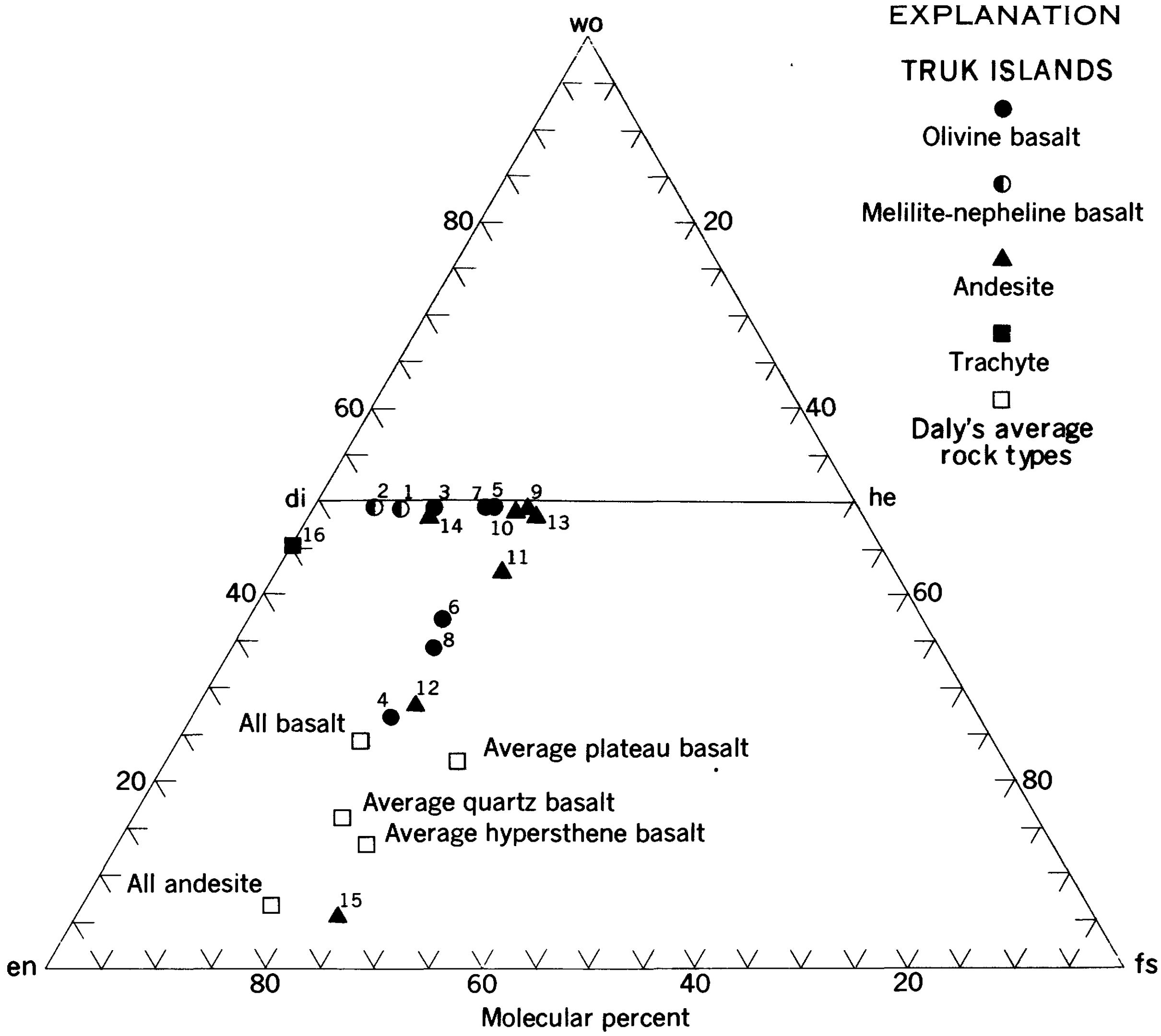

FIGURE 12.—Composition of normative pyroxenes of volcanic rocks of Truk Islands and Daly's average rock types.

TABLE 3.—*Chemical composition of nonporphyritic basalt of the Truk Islands, compared with basalts assumed by Nockolds and Allen (1954, p. 282) to represent primary magma of the olivine basalt-trachyte magma series*

	Truk Islands [1]	Scottish Tertiary	Hawaiian	Polynesian
SiO_2	47.2	46.1	46.7	46.0
TiO_2	1.7	2.5	3.0	2.9
Al_2O_3	14.2	15.1	15.3	16.9
Fe_2O_3	2.1	3.0	3.8	4.6
FeO	10.8	10.4	8.2	7.4
MnO	.2	.3	.1	.2
MgO	11.4	10.4	8.5	7.3
CaO	9.3	9.3	10.5	10.9
Na_2O	2.5	2.5	2.6	2.5
K_2O	.4	.3	1.0	1.0
P_2O_5	.2	.2	.3	.3

[1] Analysis by Lois Trumbull, calculated on a water-free basis.

gests the olivine basalt parent magma originated by fractional melting of peridotite at considerable depth in the earth's mantle. The present study offers little evidence if any on this controversial and fundamental problem.

CENTRAL ISLANDS

ANDESITE AND BASALT

The andesite and basalt lavas and dikes of the central islands are petrologically similar to those of other Truk Islands and indicate derivation from a similar (or the same) alkalic, undersaturated olivine basalt magma. Hornblende, however, is more common in andesite on Udot and Eot than elsewhere, a difference possibly reflecting a higher content of volatiles in the andesite erupted from the central conduit than in that erupted from lateral fissures. Some of the andesites and basalts are albitized, and a few contain quartz amygdules.

Most andesite and basalt blocks in the breccia resemble the lavas and dikes, but some are different. A small proportion of the blocks are more highly altered than the surface dikes and flows, and a few are coarser. The coarser rock crystallized below the surface, prob-

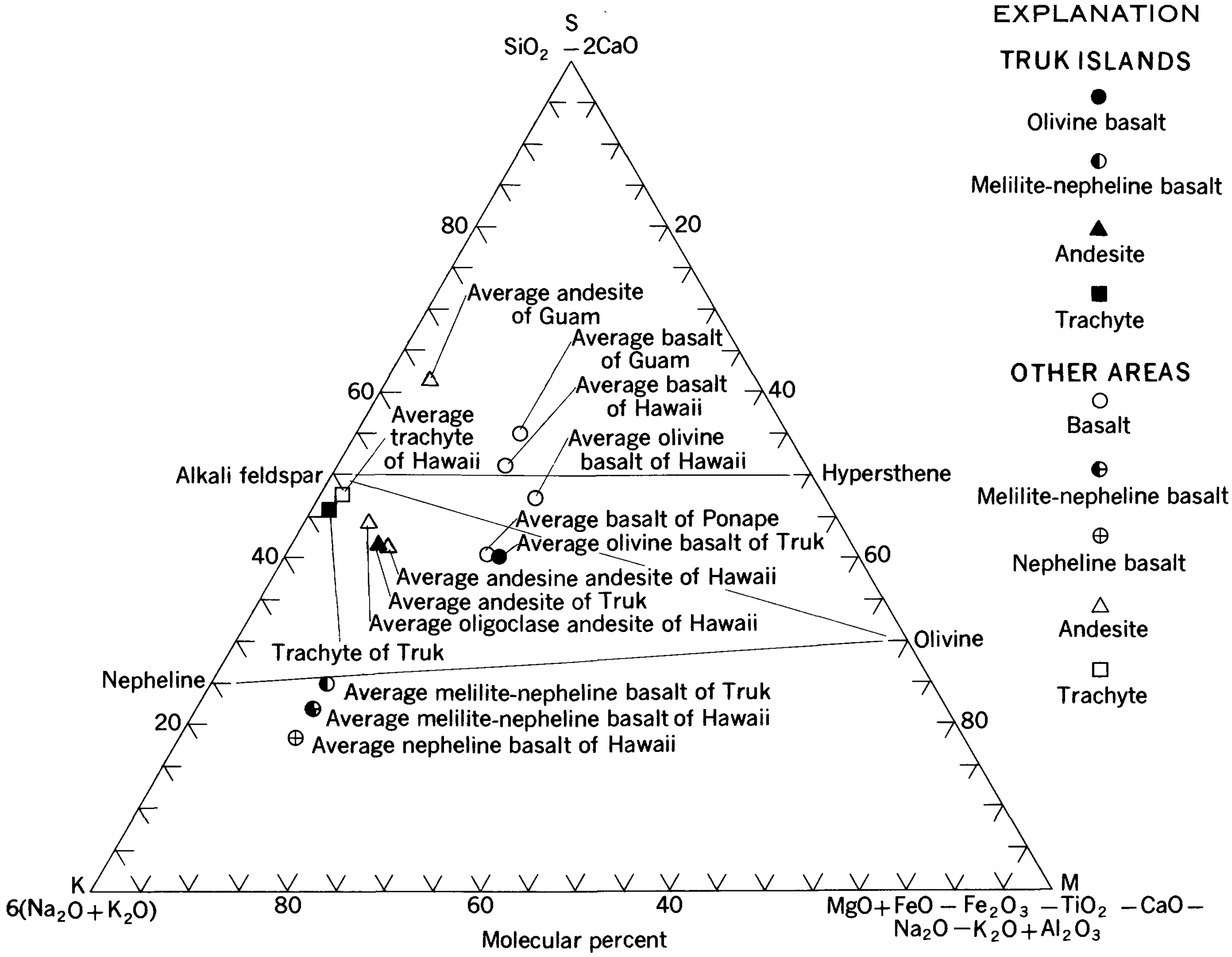

FIGURE 13.—SKM diagram of average volcanic rocks of Truk Islands and other areas.

ably in the central conduit. One block of coarse olivine basalt (or olivine dolerite) porphyry contains a higher proportion of olivine and plagioclase more calcic than any surface dikes or flows studied. This block may have been broken from a layer of settled crystals in the lower part of either the conduit or a magma chamber.

TRACHYTE AND QUARTZ TRACHYTE

Many of the trachyte lava flows, dikes and ejected blocks of the central islands contain quartz that is almost certainly primary, and thus they represent a magma oversaturated in silica. Texturally, these trachytes resemble the quartz-free trachytes of the eastern and western groups of the Truk Islands. The feldspar of the trachytes of the central islands is, however, a dusty complex of "low" albite and potassic feldspar (probably orthoclase), in contrast to the anorthoclase of trachytes on the other islands. Orthoclase mantles and replaces plagioclase in the Udot trachyte, but this fact does not prove that the orthoclase was postmagmatic. The normative plagioclase and content of normative orthoclase is about the same in the analyzed trachytes of Udot and Moen; hence, the "low" albite and potassic feldspar in the trachyte of Udot may have exsolved from anorthoclase under the influence of gases or solutions. The potassic feldspar may have been redistributed to mantle and replace plagioclase.

Origin of the quartz in these rocks is a petrologic problem, as all evidence points to an undersaturated alkalic olivine basalt primary magma for the Truk volcano. Crystallization of olivine and pyroxene in magma of this composition is eutectic (Hess and Poldervaart, 1951, p. 477) and lacks the reaction relation that enriches the residual magma in silica during fractional crystallization of tholeiitic basalt. This view has been recently reiterated by investigators of the

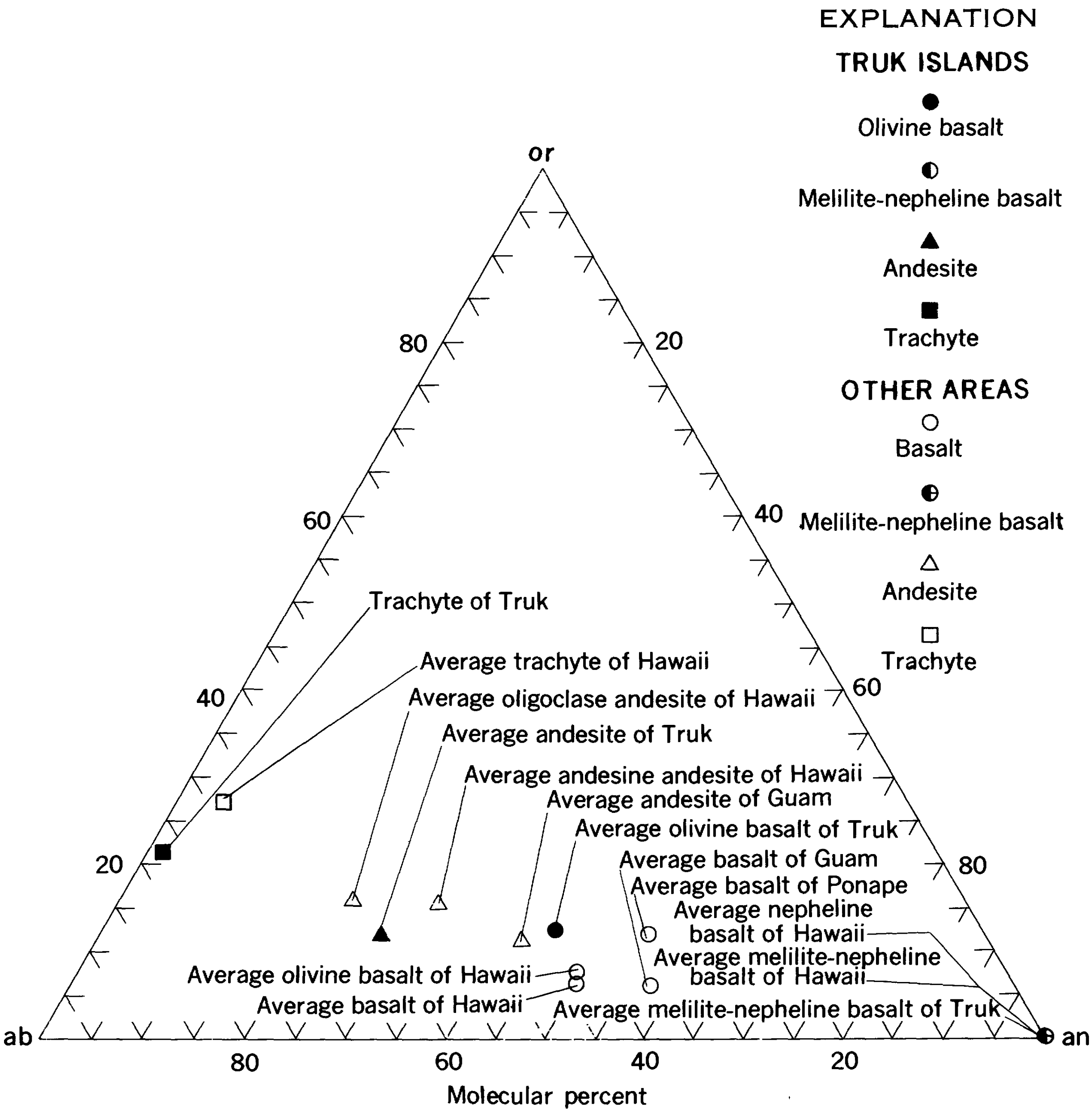

FIGURE 14.—Composition of average normative feldspar of volcanic rocks of Truk Islands and other areas.

Geophysical Laboratory (Geophysical Laboratory, 1956, p. 169; Thornton and Tuttle, 1956). Despite this theoretical objection, Tilley (1950 p. 43) has maintained that small amounts of a siliceous alkalic residuum are produced by differentiation of undersaturated alkalic olivine basalt magma. In support of Tilley's argument, the average trachyte of the Hawaiian Islands contains 4 percent normative quartz (Macdonald, 1949, table 5, p. 1571), and one trachyte contains nearly 20 percent normative quartz. Tholeiitic basalt is now believed to form the bulk of the Hawaiian shield volcanoes, but the trachytes are more closely related in time, space, and chemical composition to undersaturated alkalic lavas than to the tholeiitic ones. Two other possible origins of the oversaturated magma on the Truk Islands will be considered as crystallization differention meets with a strong theoretical objection. The silica may have been concentrated in the magma by volatile transfer or thermal water (Fenner and Day, 1931). Secondary quartz in altered lavas and dikes was indeed transferred by gases or hydrothermal solutions, but this transfer does not prove volatile or hydrothermal concentration of the quartz. Conceivably the silica in rocks of the central islands was liberated

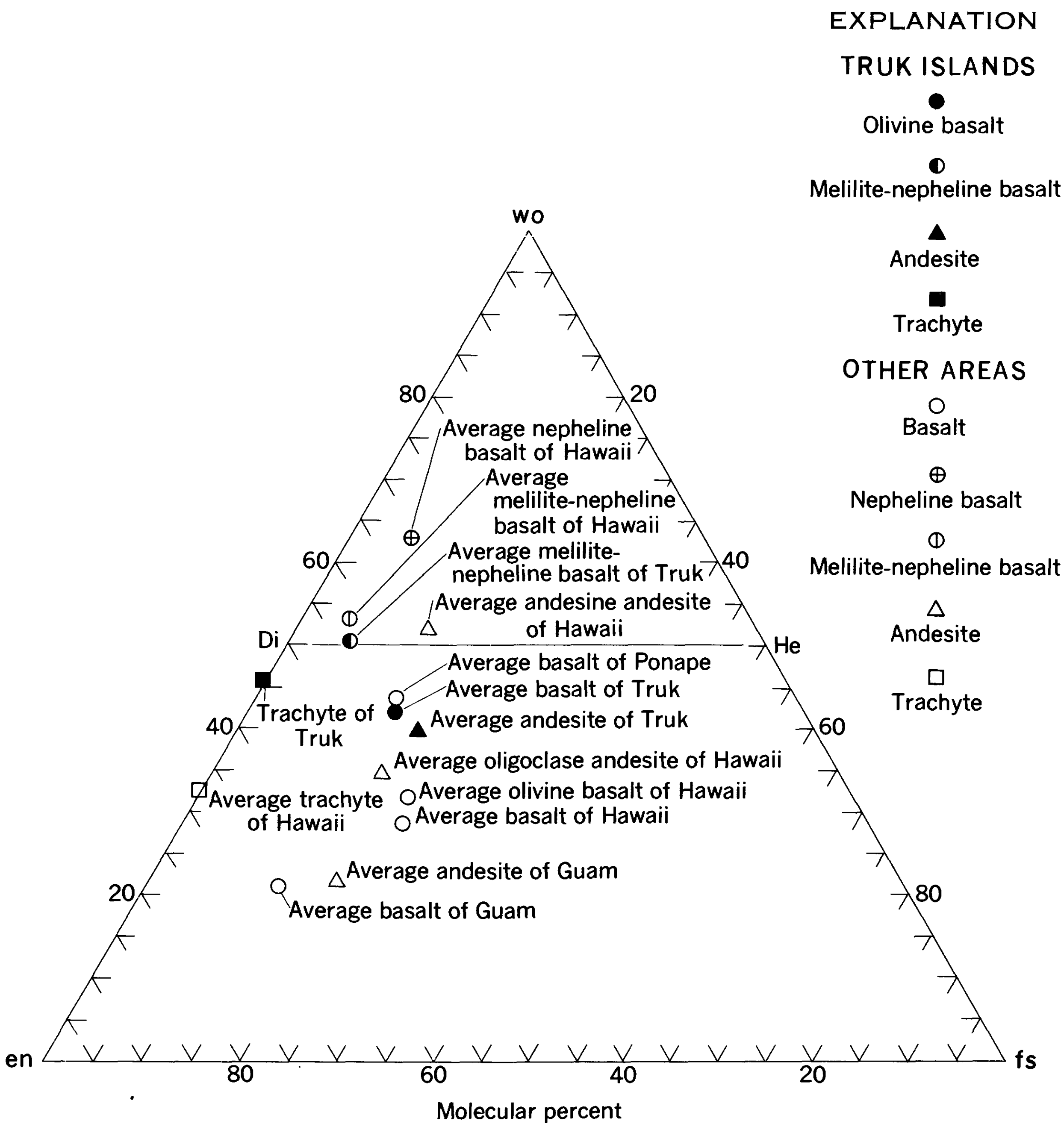

FIGURE 15.—Composition of average normative pyroxenes of volcanic rocks of Truk Islands and other areas.

by oxidation of ferrous ion (in silicates) and by the recombination of the ferrous ion into magnetite during thermal recrystallization of rocks adjacent to a magma chamber or the central conduit. This suggestion apparently receives some support from the abnormally low silica and high magnetite content of one block of recrystallized basalt that was chemically analyzed (specimen 17–Ud 141a). In conclusion, the writers believe that present data are inadequate to determine the process by which oversaturated alkalic magma of the central islands has been produced from the primary undersaturated parent magma.

GABBRO BLOCKS

Origin of the gabbro blocks on Udot and Eot is of interest in view of recent conclusions that peridotite in some lavas of the Hawaiian Islands may represent fragments of a peridotite mantle within the earth (Ross and others, 1954). Geologic evidence suggests, how-

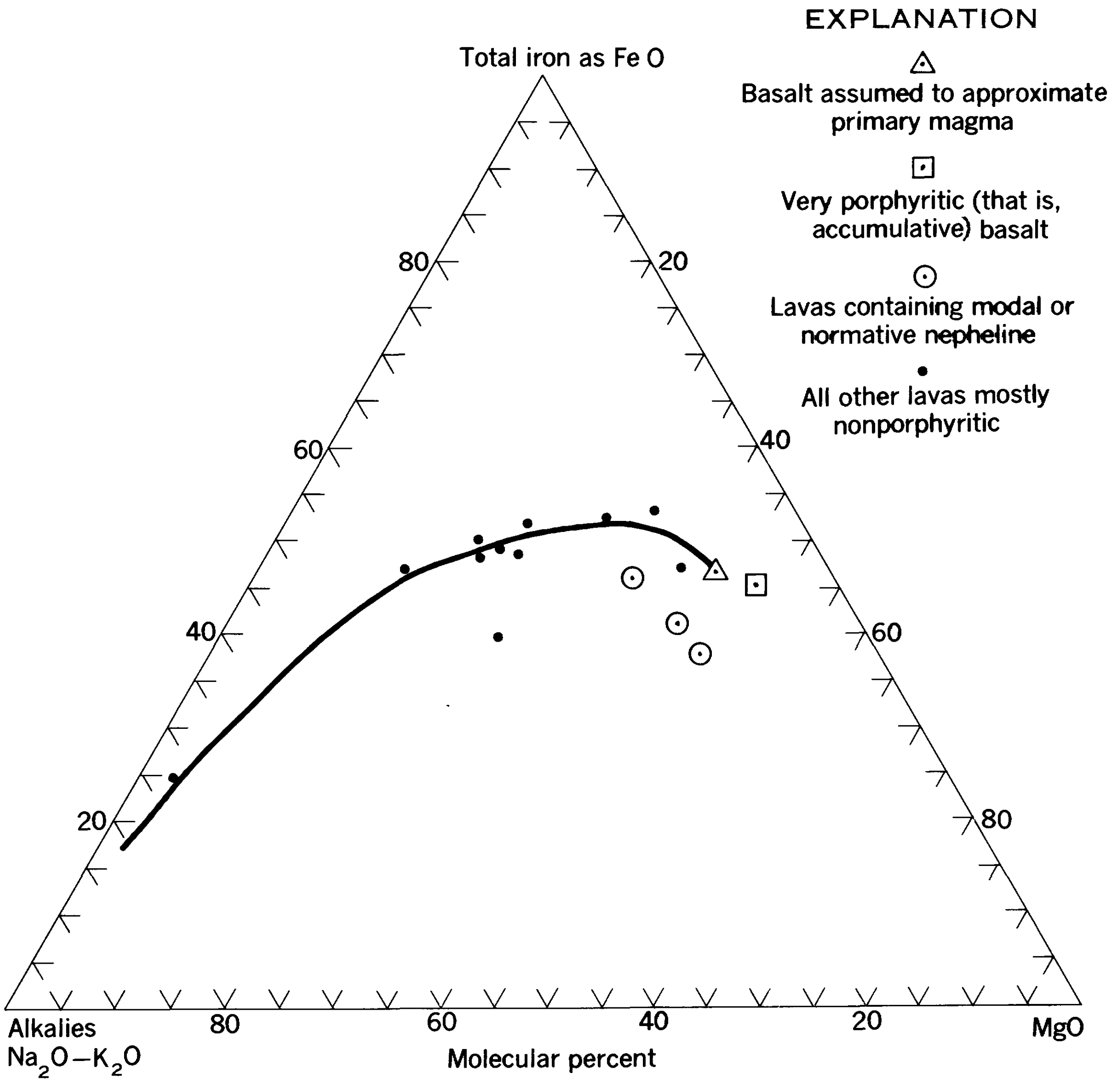

FIGURE 16.—Triangular FeO–alkali–MgO diagram of Truk Islands lavas. Total iron plotted as FeO.

ever, that the gabbro xenoliths of the Truk Islands were torn from an intrusion within the volcano itself.

The gabbro blocks contain nearly all the same minerals as do the basaltic lavas of Truk and indicat^ that the gabbro was olivine bearing and hence undersaturated in silica (as are the basalts). Some of the pyroxene in both basalt and gabbro is titaniferous, and the nontitaniferous pyroxene of both is augite of similar composition. These facts suggest the same or a similar primary magma for both basalt and gabbro. The color index (that is, proportion of mafic minerals) of the gabbro is, however, lower than that of basalts having the same plagioclase composition; this relation suggests some settling of mafic minerals from gabbro magma before intrusion. Chemical analyses of slightly altered gabbro are given in table 2.

Zoned plagioclase crystals indicate that cooling was too rapid for establishment of chemical equilibrium in the cooling magma; this rapid cooling favors interpretation as an intrusive stock rather than a crustal layer within the earth.

The fine- to coarse-grained texture and general lack of mineral orientation can most easily be explained by assuming the gabbro blocks to be fragments of an intrusive stock rather than a crustal layer. Linear orientation of plagioclase in a few blocks suggests magmatic flow rather than crystal settling.

Gabbro fragments occur only in the breccia; none were observed in the lavas. Intrusive relations of pyroclastic breccia to gabbro were observed in composite xenoliths; these relations suggest that the breccia was formed at or below the level of the gabbro. Pyroclastic breccia was more likely formed in the throat of the volcano than in a crustal layer 16,000 or more feet below the surface; hence, the gabbro is probably present in the volcano rather than in a crustal layer.

The hornfelsic, recrystallized gabbro and probably the gabbro in which the plagioclase is turbid were heated, possibly by magma rising in the central conduit penetrating the intrusive gabbro body. Some of the gabbro was actually remelted.

The epidote and actinolite of altered gabbro are probably hydrothermal in origin and were probably produced by aqueous solutions in and near the central conduit. Sodic plagioclase, potassic feldspar, and quartz were introduced in some blocks lacking alteration to epidote and actinolite, but may also be of hydrothermal or pneumatolytic origin.

RECRYSTALLIZED BASALT BLOCKS

The blocks of recrystallized basalt are probably fragments of lava flows that were adjacent to the central conduit and heated by rising magma. Inclusions of recrystallized basalt in the gabbro blocks are probably xenoliths incorporated by the gabbro magma during intrusion. A chemical analysis of recrystallized basalt is given in table 2, specimen 17 (Ud–141a). The chemical composition and normative minerals suggest that this rock was formerly olivine basalt. The silica percentage is considerably lower than that of any of the analyzed lavas, however, and suggests the block became desilicated (through oxidation of iron?) during recrystallization. Possibly release of silica during thermal recrystallization may have been a source of some secondary silica on the Truk Islands.

DIKES OF ANDESITE AND BASALT IN GABBRO BLOCKS

These dikes indicate that magma similar to that of the dikes and flows at the surface penetrated fractures in the gabbro at depth. A chemical analysis of a partly recrystallized andesine basalt dike contained in a gabbro block is given in table 2 (specimen 19, Ud–139c). The dike is similar in most respects to an andesine basalt flow of Moen, table 2 (specimen 12, Mo–159). As previously discussed, gabbro was melted adjacent to some of the dikes; the melting suggests intrusion of the dike rock at high temperature. Many of these dikes are recrystallized, indicating later heating of the dike rock. Biotite was formed in some dikes during thermal recrystallization.

MONZONITE AND QUARTZ MONZONITE

The monzonite and quartz monzonite veins and blocks crystallized from a magma more calcic than but otherwise similar to that of the quartz trachytes. Partly assimilated labradorite xenocrysts are present in several monzonite specimens; hence, lime has probably been added beyond that present in the melt before intrusion. In other words, a quartz trachyte (that is, quartz syenite) magma may have been modified to a quartz monzonite magma by the assimilation of labradorite. In support of this suggestion, labradorite crystals of the gabbro are albitized where protruding into the monzonite veins, and recrystallized labradorite bordering the monzonite veins grades out into the coarser vein oligoclase. Pyroxene of the monzonite veins is similar in composition to that of the adjacent gabbro and was probably incorporated from the gabbro.

The oligoclase in the monzonite is extensively mantled and veined by albite (An_{0-5}), which was probably introduced by late magmatic or deuteric solutions. Some irregular areas of orthoclase resemble exsolution perthite, but other orthoclase appears to be a massive replacement of the primary plagioclase. The replacing orthoclase may have been a secondary introduction (as in the altered gabbro), but it may be that the orthoclase mobilized and concentrated after exsolution by "stewing" in the late magmatic or deuteric solutions which deposited the albite.

The marginal selvages of recrystallized gabbro adjacent to the monzonite veins indicate that the monzonite magma was emplaced at a temperature sufficiently high to melt the gabbro. Under anhydrous conditions a temperature of about 1,200° or 1,300° C would be required to melt gabbro, but the temperature may have been as low as 700° or 800° C under a high H_2O pressure (Yoder and Tilley, 1956, p. 170, fig. 6). Melted augite of the gabbro was incorporated in the monzonite veins to form the dominant ferromagnesian mineral. Apatite and magnetite of the veins may have been incorporated from the melted gabbro, but quartz and zircon probably crystallized from the melt as they do not occur in the gabbro. The fringe of biotite enclosing magnetite in the contact zone of the monzonite and gabbro resulted from deuteric reaction of the magnetite with the hydrous monzonite magma or related deuteric solutions or gases. Lenticular quartz crystals between the lamellae in biotite crystals of one vein suggest that the albitic deuteric solutions contained silica as well.

Siliceous veins such as granophyre are commonly associated with sills of tholeiitic basalt and gabbro, from which they can be shown to have originated by fractional crystallization. Consequently, the possibility that the quartz monzonite may be the residuum produced by fractional crystallization of the gabbro stock(?) within the Truk volcano requires consideration. This possibility seems unlikely, as one of the monzonite veins contained in a composite basalt and gabbro xenolith cuts both fine-grained basalt and gabbro. The basalt is a dike chilled against the gabbro during intrusion at depth and is andesine basalt similar in composition to lavas exposed at the surface; hence, the basalt was emplaced after the gabbro had cooled sufficiently to chill intruded basalt. The interval of cooling and of basalt intrusion between the gabbro and the monzonite suggests that the latter are unrelated in origin.

The quartz monzonite veins and blocks of the Truk Islands shed no new light on the origin of oversaturated magma outside the andesite line. This quartz monzonite is, however, similar in some respects to the alkalic granite blocks of Ascension Island, which Tilley (1950, p. 43) believes a differentiation product of undersaturated alkalic olivine basalt magma. As already pointed out, the quartz monzonite blocks of Truk may represent contaminated quartz alkalic syenite magma (perhaps more accurately an alkalic granite magma). The blocks of Ascension Island are characterized by alkalic pyroxenes or amphiboles, and some of the quartz monzonite in Truk contains amphibole. Pyroxene in blocks of the latter is not alkali rich, probably because it was incorporated from gabbro.

HYDROTHERMAL ALTERATION

The secondary minerals in dikes, flows, and blocks include albite, potassic feldspar (probably orthoclase), chlorite, calcite, quartz, sphene, and less commonly epidote, actinolite, sericite, hematite, and pyrite. This overall assemblage suggests a hydrothermal or pneumatolytic origin. The hydrothermal minerals are restricted to the islands near the former central crater. Altered blocks in otherwise unaltered breccia prove that the alteration occurred during the active magmatic history of the volcano. The sodium and potassium are easily explained as residual materials concentrated in the magma chamber during crystallization. Origin of the silica is a problem that is presently unsolved.

SUMMARY OF CONCLUSIONS

The lavas of the Truk Islands are, excepting the quartz trachyte, an undersaturated assemblage ranging from nepheline-melilite basalt to trachyte; this assemblage resembles lavas of the declining phase in the Hawaiian Islands. Most of the lavas of Truk can be explained by fractional crystallization of undersaturated olivine basalt parent magma. This study supplies no new evidence on the origin of the olivine basalt magma.

Gabbro xenoliths in pyroclastic breccia of the central islands were probably torn from an intrusive body in the volcano. The gabbro is undersaturated and may have been derived from the same source as the Truk Islands lavas.

Quartz trachyte lavas, dikes, and ejected blocks were formed by the crystallization of magma oversaturated in silica. This silicic magma was probably produced from the same undersaturated magma that gave rise to the undersaturated lavas on Truk. The process by which this silica-rich magma was produced from an undersaturated magma is not known.

Monzonite and quartz monzonite xenoliths and dikes contained in gabbro xenoliths crystallized from a quartz syenite magma which had assimilated pyroxene and labradorite from adjacent gabbro in the volcano. The quartz syenite magma is probably the same magma that erupted to form the quartz trachyte just discussed.

Many blocks in breccias of the central islands were hydrothermally altered before they were erupted, and all rocks of the central islands have been subsequently altered to a lesser extent. Calcic plagioclase is extensively albitized, and primary anorthoclase in the trachytes is now represented by intergrowths of "low" albite and orthoclase. Orthoclase extensively mantles the albite of some trachyte and suggests redistribution of alkalies by hydrothermal solutions or volatiles. Minerals deposited by hydrothermal solutions include albite, potassic feldspar (probably orthoclase), chlorite, calcite, quartz, and pyrite. Epidote, actinolite, sphene, sericite, and hematite have been formed by alteration of the primary igneous minerals. The soda and potash of the hydrothermal solutions are readily explained as residual materials concentrated in the magma chamber during crystallization. Origin of the silica is an unsolved problem.

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