Engineer Intelligence Dossier
Strategic Study RYŪKYŪ-RETTŌ
Subfile 10 CONSTRUCTIONAL ASPECTS

MILITARY GEOLOGY OF OKINAWA-JIMA, RYŪKYŪ-RETTŌ

VOLUME I

INTRODUCTION AND ENGINEERING ASPECTS

PREPARED UNDER THE DIRECTION OF THE
CHIEF OF ENGINEERS, U. S. ARMY
BY THE
INTELLIGENCE DIVISION, OFFICE OF THE ENGINEER
HEADQUARTERS UNITED STATES ARMY JAPAN
WITH PERSONNEL OF
THE UNITED STATES GEOLOGICAL SURVEY

1957

MILITARY GEOLOGY OF OKINAWA-JIMA, RYŪKYŪ-RETTŌ

VOLUME I INTRODUCTION AND ENGINEERING ASPECTS

by

Allen H. Nicol, Delos E. Flint, and Raymond A. Saplis

Prepared under the direction of the
Chief of Engineers, U. S. Army
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FOREWORD

July 1957

Engineer Intelligence Study - Okinawa-jima, Ryūkyū-rettō

The Military Geology of Okinawa-jima, Ryūkyū-rettō is one of a series of reports resulting from detailed geologic and soil surveys conducted under the Pacific Geological Mapping Program, a part of the Corps of Engineers Post Hostilities Mapping Program. The purpose of these surveys is to produce information on the military geology of selected areas of the Pacific by field mapping and analysis of selected islands.

The Military Geology of Okinawa includes separate sections on Engineering Aspects (Vol. I), Water Resources (Vol. II), Cross-country Movement (Vol. III), Soils (Vol. IV), and Geology (Vol. V), of which this is Volume I.

This study was prepared in cooperation with the U. S. Geological Survey, Department of the Interior.

PHILIP F. KROMER, JR.
Brig Gen, USA
Engineer

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VOLUME I. INTRODUCTION AND ENGINEERING ASPECTS

INTRODUCTION

Present Studies

This series of military geology reports on Okinawa is part of the Corps of Engineers Post Hostilities Mapping Program. The purpose of this survey is twofold. The first is to collect scientific information through field study; the second is to publish it in a form that is usable by the United States Armed Forces and Civil Administrators.

The field party was composed of geologists and soil scientists of the U. S. Geological Survey and soil scientists of the U. S. Department of Agriculture assigned to the Office of the Engineer, U. S. Army Forces Far East. Members of the party and their principal contributions were as follows:

Geologists:

John Rodgers; initial field reconnaissance and first chief of party.
MacClelland G. Dings; field mapping of southern Okinawa and second chief of party.
F. Stearns MacNeil; field mapping of southern Okinawa and third chief of party.
Delos E. Flint; field mapping of northern Okinawa, principal author and fourth chief of party.
Gilbert Corwin; field mapping of northern Okinawa.
Warren P. Fuller; field mapping of southern Okinawa.
Allen H. Nicol; special field studies and author of section on engineering geology.
Raymond A. Saplis; field mapping and author.
Cornelia C. Cameron; water resources studies.

Soil scientists:

Clarence S. Coleman; field mapping.
Roy W. Simonson; field mapping.
Carl H. Stensland; field mapping and principal author.
Edward H. Templin; special field studies and author.
Joseph H. Vaden; field mapping.
Ray E. Zarza; field mapping.

The basic geologic and soils mapping was done in the field, between April 1946 and March 1949, on aerial photographs, scales 1:20,000 and 1:40,000, and the data were later transferred to planimetric base maps, scale 1:50,000, and photomaps, scale 1:25,000. All photos in this work were taken by members of the field party unless otherwise credited. The field data were assembled, interpretive studies were prepared, and the final report was written, incorporating supplemental information from previous reports and literature on the island, in the offices of the Military Geology Branch, U. S. Geological Survey, Washington, D. C. Numerous members of the Branch have

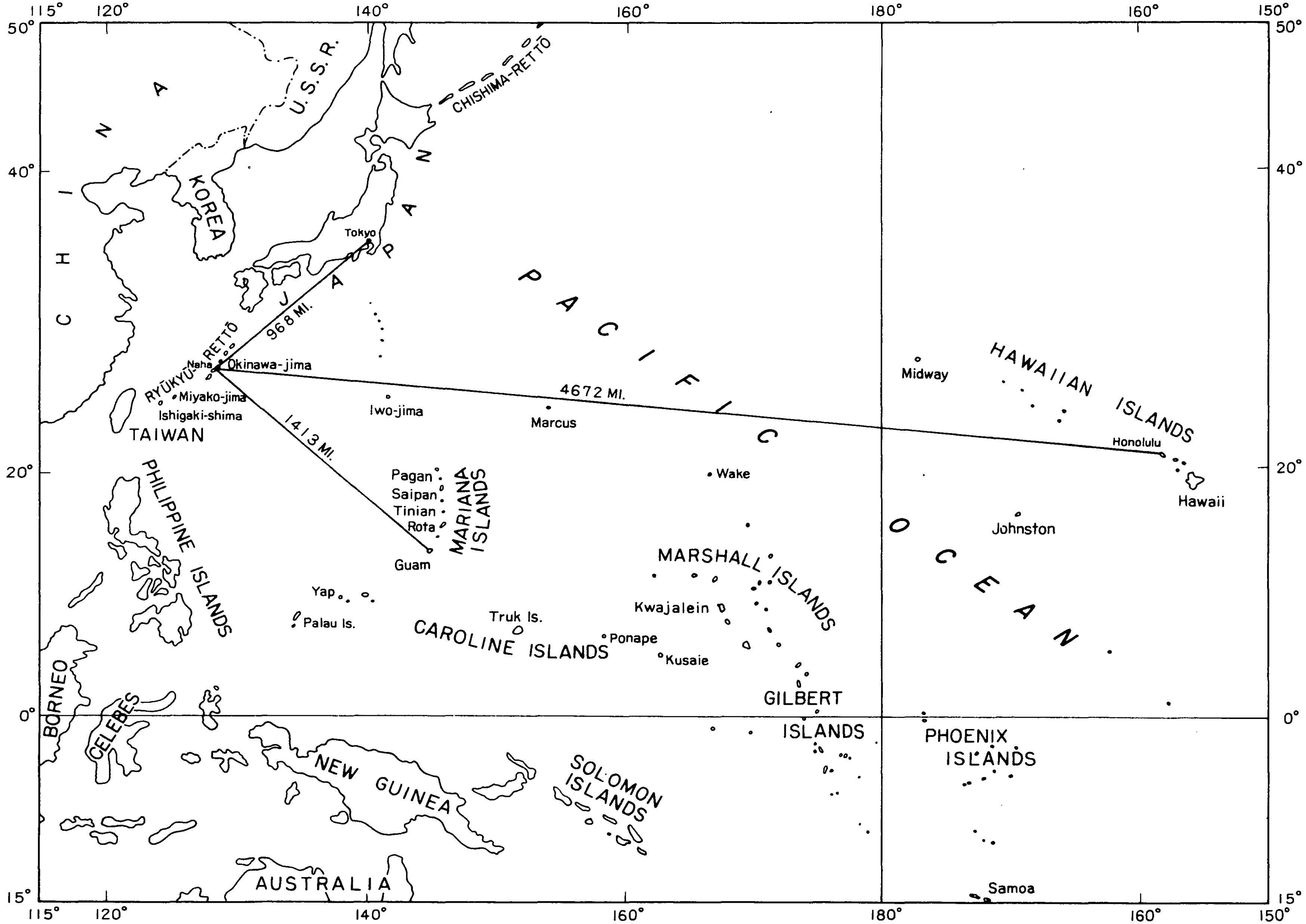


Figure 1. Index map of Okinawa-jima, Ryūkyū-rettō.

furnished ideas and criticism during preparation of the report. William E. Davies and Cornelia C. Cameron, geologists, U. S. G. S., reviewed the report and revised some sections. Final edit and review were accomplished in Tokyo by the Military Geology Branch, Intelligence Division, Office of the Engineer, U. S. Army Forces Far East and 8th U. S. Army (Rear).

Location and Physical Geography

Okinawa-jima, the largest island in the Ryūkyū-rettō, lies approximately 450 miles off the east coast of China at a point about equidistant between the islands of Taiwan and Kyushu, Japan (fig. 1). It is situated between 26° and 27° north latitude and at 128° east longitude. The island is 67 miles long in a northeast-southwest direction, ranges from 2 to 15 miles in width, and has an area of approximately 455 square miles. Sixteen small islands with a total area of about 18 square miles lie nearby and are included in this report.

Okinawa may be divided into two provinces on the basis of geography and geology. The boundary between the provinces is near the south end of a narrow isthmus at the village of Ishikawa. The northern portion, comprising about two-thirds of the island, is a mountainous area with high relief and deep dissection. Scattered small villages, farms, and narrow roads are largely confined to coastal areas. The southern portion, approximately one-third of the island, is lower, hilly country with moderate relief and only local deep dissection. The civil population (678,017 in Okinawa-guntō in 1955) and the U. S. military installations are concentrated in this portion.

Northern Okinawa is characterized by a discontinuous backbone ridge which runs from the isthmus at Ishikawa to the north end of the island. The highest elevation on the island, Yonaha Dake (1,650 feet), is near the north end of the ridge. Numerous peaks along the ridge and on mountainous Motobu-hantō, a peninsula to the northwest, are over 1,000 feet high.

Broad terraces flank both sides of the backbone ridge and the west and north sides of the uplands on Motobu-hantō. They are generally widest and most distinct on the east side of the island. The terraces slope gently seaward to the coast where they are cut off abruptly by high sea cliffs or are separated by steep slopes from narrow terraces at lower elevations. Large streams that are deeply incised into the upper terraces are alluviated near their mouths and commonly have extensive flats.

The backbone ridge, the mountains of Motobu-hantō, and the higher terraces consist chiefly of highly deformed, metamorphosed limestone, sandstone, shale, and volcanic rock overlain by a varying thickness of soil, and on the outer portions of terraces, coarse sand and gravel. Small masses of igneous rock are present within the older metamorphic rocks on Motobu-hantō and at a few places along the west coast. Recent gravels, sands, and clays form the alluvial flats of the larger streams, the surfaces of the lower terraces, and the low neck connecting Motobu-hantō to the mainland. Recent reef limestone forms the the outer edge of terraces on the north side of Motobu-hantō and along the central part of the east coast.

The southern one-third of Okinawa has a variety of terrain, but essentially is an erosional upland that is lower and less rugged than the northern part of the island. The highest elevations are less than 600 feet. Two rounded peaks north of Katena (Kadena) are the southern termination of the backbone ridge. The peaks are surrounded by deeply dissected terraces that are flanked to the east and west by lower limestone terraces and to the south by a relatively level limestone plateau on which Kadena Airfield has been constructed. Nakagusuku-wan, the large bay on the east side of the island, is bordered by a continuous coastal flat as much as a mile wide which is composed of beach deposits and clays from the adjacent slopes. Above the flats, the ground rises steeply to the crest of the island and then descends to the west in a series of broad terraces. A few deep, steep-walled valleys and sharp limestone ridges cross the terraces, but the terrain is mostly open and rolling. Discontinuous coastal flats lie along the shores of the East China Sea. A limestone upland of low relief bounded along much of the coast by steep, precipitous cliffs predominates the southernmost part of the island.

South of Katena, the uplands are composed of a thick sequence of compact gray to brown clays, silty clays, and sands. Porous, poorly lithified reef limestones mantle the clays on the lower terraces along the west coast and at the southern end of the island. Alluvium is confined to the flood plains of a few short streams and locally along the inner margins of the broad coastal flats. Soils are thin on the clays, are generally absent on the limestone ridges, and range up to about 20 feet thick on the limestone terraces and plateaus.

Summary Military Evaluation

Southern Okinawa is the most suitable part of the island for large scale military or civil development because the terrain is generally open and accessible. Level areas for the construction of airfields are present on the coastal flats and limestone terraces and plateaus. Limestone for surfacing and light construction is abundant. The dominant clays of the uplands are easily excavated and moved and provide good foundations on level surfaces and on slopes where they have been stabilized and are properly drained.

Because of mountainous terrain, northern Okinawa is generally unsuited for the construction of airfields and a comprehensive road network. Sites for army airstrips and heliports are available on some terraces and coastal flats. Narrow roads extend to all areas of present development except those along the northeast coast. Topographically, sites for large structures and underground installations are numerous.

Large quantities of rock suitable for heavy construction are available on Motobu-hantō. Most bedrock, however, is highly sheared and deeply weathered and therefore is a poor source of material for many construction uses.

Streams and adjacent alluvial deposits are the only sources of large quantities of water. The longest and largest streams are at the northern end of the island. Streams on the southern portion are short and flow becomes small during prolonged dry periods. Small quantities of ground water are available from subsurface streams within the limestone and from ground-water lenses developed in permeable limestone and coastal beach deposits.

Of the islands adjacent to Okinawa, only Ii-shima (Ie-shima) west of Motobu-hantō is suited for a large military installation. The island consists of a nearly level limestone plateau with a conical hill of metamorphic rocks rising above the surface near its east end. Because of its small size, water resources are limited.

Typhoons and Tropical Storms (by D. I. Blumenstock, U. S. Weather Bur.)

With the possible exception of one or two areas in the Philippines, Okinawa is more likely to be subjected to a typhoon than any other area of similar size. The high frequency of typhoons that hit the island or whose centers pass within 120 nautical miles is evident from the tabulation below. "Typhoon" refers to storms with winds of 65 knots or higher; "tropical storm" refers to storms with maximum winds between 33 and 64 knots, inclusive; and "probables" refers to storms that were probably of typhoon strength and probably followed the tracks indicated, but definite proof is lacking.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Typhoons & "probables"												
Hit Okinawa	0	0	0	0	2	2	11	15	8	4	0	0
Within 60 naut. m.	0	0	0	1	8	6	25	25	21	9	4	3
60 to 120 naut. m.	0	2	0	0	6	2	15	23	13	11	7	0
Tropical Storms												
Hit Okinawa	0	0	0	0	1	0	1	2	0	0	0	0
Within 60 naut. m.	0	0	0	0	0	5	1	3	0	1	0	1
60 to 120 naut. m.	0	0	1	0	2	2	1	2	2	3	2	0

(Data from 70 Years of Typhoon Tracks, 1884-1953, Royal Meteorological Observatory, Hong Kong. Pre-publication copy.)

The data are if anything conservative. They minimize the typhoon odds because it is likely that some early storms were not recorded. Allowing for this, the chances in any one year are at least 3 to 1 that at least one typhoon will pass within 120 nautical miles of the island. Similar odds, by month, are as follows: The chances are at least 50-50 for a typhoon (center within 120 nautical miles) during any one July; at least 3 to 2 for one in August; and at least 1 in 2 for one in September. Similarly, the chances are 1 in 3 during October and are about 1 in 6 during November, May, and June. The only month during which there have been no typhoons or tropical storms within 120 nautical miles of Okinawa is January. Frequencies are, however, very low in February, March, April, and December.

A typhoon whose center passes within 60 nautical miles of Okinawa from May through November is virtually certain to yield winds of 65 knots or more in exposed locations since during this period typhoons are well-developed storms with very strong winds extending far outward from the storm center. Even if a typhoon passes at a distance of 120 nautical miles during May-November, the chances favor winds of 65 knots or more on the island itself. At the other extreme, a typhoon passing over or within 20 to 30 miles of the island may at any time of the year produce winds in excess of 120 knots, with gusts exceeding 150 knots in exposed localities, as along beaches, near the center of the storm. Typhoons also bring torrential rains and large waves. A typhoon passing within 120 miles of Okinawa will often bring rains of over 6 inches in 24 hours and have been known to produce rains of over 20 inches in that time. Finally, waves 5 to 20 feet high are certain to be produced in at least some shore areas whenever the typhoon approaches the island from the southwest along a SW-NE track or whenever it approaches from the east along a track generally oriented E-W. In the former instance the storm wave will inundate locations on the west and south coast; in the latter, on the east coast.

ENGINEERING ASPECTS

Introduction

This report on the engineering aspects of Okinawa is intended to provide a regional estimate of the general engineering properties of geologic materials and to serve as a guide in planning of engineering operations. The data presented are not intended to take the place of detailed field investigations for site selection or development, and in all cases of site selection or construction, intensive field and laboratory investigations should be conducted to determine the engineering properties of the rocks as they pertain to a specific project. Table 1 is a summary of the suitability of each rock type.

The information on engineering characteristics of rocks, either consolidated bedrock or unconsolidated surficial deposits, is based on laboratory tests of selected, representative samples of each rock type and covers only the more important engineering characteristics (table 2).

These data are supplemented by interpretations based on field observations. Interpretations of rock and soils data are generally confined to materials at or near the surface and are applicable to shallow quarries, excavations, and grading. Characteristics of rocks at depths of more than 150 feet have not been investigated.

The rock units used in this volume on Engineering Aspects and on the Engineering Materials Map (pl. 1) were established on the basis of physical and engineering characteristics of the rocks. No recognition is given to age or other stratigraphic data. As such, rocks of different ages or those of different regions may be included in the same rock units if they are similar from an engineering viewpoint. The data and descriptions of each map unit apply to the dominant characteristics of the unit. There are, however, minor variations which have not been included in the discussion.

Information on the engineering properties of the soil within 10 or 12 feet of the surface is given on the 11 sheet Soil Engineering Map, scale 1:50,000, which was published in 1951 by the Engineer Section, GHQ, FEC and is included as a part of this report (pl. 2). Detail contained on these maps supplement the information presented on the Engineering Materials Map and in the following text.

An unclassified, preliminary report on the engineering geology of Okinawa by A. H. Nicol, D. E. Flint, and R. A. Saplis was prepared and distributed to major headquarters throughout the Far East in April 1951 by the Intelligence Division, Office of the Engineer, GHQ, FEC. The present report incorporates the data contained in this 1951 report along with some additional information.

Construction Materials

In the following text and on Table 1, Engineering Use of Consolidated and Unconsolidated Rock and Table 2, Engineering Test Data, engineering geology units for Okinawa are defined and evaluated; the distribution of these units is indicated on Plate 1, Engineering Materials Map.

Table 2. Engineering Test Data 1/

Group	Unit No.	Unit Name	Test No. 2/	Depth of Sample	Mech. Analysis, Cum. % Passing: 2 in.	1½ in.	1 in.	3/4 in.	1/2 in.	3/8 in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Specific Gravity, Apparent, Coarse	Apparent, Fine	Bulk, Coarse	Bulk, Fine	Bulk (S.S.D.), Coarse	Bulk (S.S.D.), Fine	Absorption %, Coarse	Absorption %, Fine	L.A.R.T. Abrasion, 500 Rev. %	Unit Weight, lb./cu. ft., Rodded, Coarse	Rodded, Fine	Loose, Coarse	Loose, Fine	Soundness $MgSO_4$, 5 Cycles, Coarse	Soundness, Fine	Asphalt Film Stripping	Modified Proctor, Optimum Moisture %	Modified Proctor, Maximum Density lb./cu.ft.	California Bearing Ratio 4/, C.B.R. %	Swell %
Engineering tests on: Crushed ledge rocks	6	Coralline rubble	I	Surface to 60 ft. Channel sample.	100	98	73	58	44	38	27	22	18	14	10	7	4	2.54	2.62	2.10	2.02	2.27	2.25	8.40	11.23	44.18	73.36	85.17	66.70	70.84	36.47	22.15	Slight	-	-	-	-
	⊗3/	Well-cemented limestone	J	Quarry sample, representing upper 20 ft.	100	94	60	45	31	25	15	11	10	6	4	3	2	2.58	2.68	2.48	2.47	2.52	2.55	1.63	3.09	34.09	94.89	98.75	85.62	88.36	1.07	11.59	None	-	-	-	-
	9	Crystalline limestone	O	Surface to 15 ft.	100	95	55	39	26	21	12	8	5	3	3	2	2	2.71	2.70	2.69	2.63	2.70	2.66	0.27	1.11	29.45	100.80	113.78	92.75	95.24	0.39	11.92	None	-	-	-	-
	10	Greenstone	P	3 to 15 ft.	100	96	59	42	25	19	9	5	3	2	2	1	1	3.01	2.99	2.96	2.85	2.98	2.90	0.46	1.73	16.52	112.66	121.09	102.00	100.45	1.77	10.50	None	-	-	-	-
	12	Sandstone (fresh)	R	Across 85 ft. of outcrop.	100	92	48	35	24	19	11	8	5	4	3	2	1	2.71	2.72	2.69	2.58	2.70	2.63	0.27	1.93	18.45	96.72	115.33	84.50	92.18	0.11	7.20	None	-	-	-	-
	13	Porphyry dike rock	U	Pieces from quarry, representing 50-foot face.	100	93	59	42	29	24	14	11	6	4	3	2	1	2.62	2.61	2.31	2.29	2.43	2.42	5.01	5.41	35.00	91.35	99.76	82.18	86.42	15.33	45.80	None	-	-	-	-
Engineering tests on: Base course and granular materials	4	Clayey granular material (decomposed gravel)	G	3 to 15 ft. Channel sample.	99	97	90	85	75	68	51	40	29	21	16	12	8	2.66	-	2.40	-	2.50	-	4.1	-	39.00 Clay & lumps removed	94.40	98.20	84.24	86.27	-	-	-	10.8	122.7	10.0	0.32
	5	Limy granular material	H	Surface to 12 ft. Channel sample.	93	83	75	69	61	56	47	43	39	36	31	22	12	2.36	-	1.98	-	2.14	-	8.0	-	59.45	72.24	80.46	57.82	70.04	-	-	-	15.3	112.7	51.6	0.05
	11	Platy foliated rocks	Q	10 to 17 ft. Channel sample.	100	98	94	89	78	69	47	35	24	17	12	10	5	2.57	-	1.94	-	2.18	-	12.7	-	-	80.96	86.87	67.93	73.25	-	-	-	15.5	113.8	10.0	0.29

Group	Unit No.	Unit Name	Test No. 2/	Depth of Sample	Mech. Analysis, Cum. % Passing: No. 4	No. 10	No. 20	No. 40	No. 60	No. 140	No. 200	Larger than 2.0 mm. (No. 10)	Coarse Sand 2.0-0.25 mm. (Nos. 10-60)	Fine Sand 0.25-0.05 mm. (Nos. 60-270)	Silt 0.05-0.005 mm. (Nos. 270-400)	Clay Smaller than 0.005 mm.	Colloids Smaller than 0.001 mm.	Physical Test Constants: LL	PL	PI	SL	SR	Specific Gravity	Tests on Undisturbed and Remolded Samples: Optimum Moisture %	Field Moisture %	Optimum Density, lb./cu.ft.	Field Density, lb./cu.ft.	Consolidation with 0.341 tons/sq.ft.: Initial Void Ratio	Void Ratio after 24 hrs.	Direct Shear Test, 3000 lb./sq.ft. Vert. Load: Shear lb./sq.ft.	ø	Cohesion lb./sq.ft.	California Bearing Ratio 4/: C.B.R.%	Swell%	Soil Classification: Corps of Engrs. 6/	PRA
Soil mechanics tests on uncemented materials	1	Beach deposits	See footnote 5/	Surface to 30 in.	99.8	97.2	86.1	10.5	1.9	1.3	1.2	2.8	95.3	1.9 Includes silt and clay	-	-	-	Sand, nonplastic			-	-	-	-	-	-	-	-	-	-	-	-	-	-	SP	A-3
	2	Alluvium	A	18 to 26 in.	-	-	-	-	100	99	98	0	0	3	51	46	13	56.5	27.3	29.2	23.6	1.61	2.77	18.6	-	106.2	-	-	-	-	-	-	6.6	3.13	CH	A-6
			B	18 to 26 in.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	30.3	-	90.5	0.893	0.888	2404	21°	1220	2.7	0.39	CH	A-6
	3	Residual clay	C	30 to 144 in. Channel sample.	-	100	98	96	93	86	85	0	7	14	20	59	51	57.0	49.8	7.2	33.3	1.41	2.78	-	-	-	-	-	-	-	-	-	9.7	0.11	CH	A-7
			D	40 to 52 in.	-	-	-	-	100	99	99	0	0	9	40	51	1	70.2	48.0	22.2	30.9	1.46	2.85	-	47.3	-	74.6	1.481	1.472	2868	24°	1250	11.3	0.12	CH	A-7
	4	Clayey granular material (sandy clay)	E	30 to 156 in. Channel sample.	-	100	96	91	82	66	62	0	18	24	16	42	32	40.0	27.0	13.0	27.1	1.48	2.64	-	-	-	-	-	-	-	-	-	10.7	0.11	CL	A-7
			F	36 to 48 in.	-	-	100	97	88	74	70	0	12	21	17	50	33	49.1	33.5	15.6	29.7	1.53	2.79	-	30.6	-	85.4	0.884	0.878	2698	29°	1000	11.7	0	CL	A-7
	7	Silty sand	K	24 to 120 in. Channel sample.	-	-	-	100	99	64	43	0	1	69	24	6	3	Granular, noncohesive			27.5	1.47	2.73	-	-	-	-	-	-	-	-	-	9.0	0.30	SM	A-4
			L	170 to 180 in.	-	-	-	100	99	67	45	0	1	69	25	5	1	Granular, noncohesive			37.5	1.45	2.73	-	13.9	-	59.8	-	-	Too sandy for test			3.0	0	SM	A-4
	8	Compact gray clay	M	30 to 180 in. Channel sample.	-	-	-	100	99	95	94	0	1	14	45	40	18	55.0	23.7	31.3	21.3	1.60	2.73	-	-	-	-	-	-	-	-	-	2.3	0.76	CH 7/	A-6
			N	64 to 72 in.	-	-	-	100	99	96	94	0	1	7	51	41	11	54.0	25.1	28.9	33.4	1.35	2.81	-	23.4	-	103.2	-	-	3020	31°	1210	35.0	0.14	CH	A-6
	12	Sandstone (weathered)	S	24 to 180 in. Channel sample.	-	100	94	85	72	48	43	0	29	33	20	18	5	25.0	22.7	2.3	20.7	1.67	2.72	-	-	-	-	-	-	-	-	-	19.0	0.19	SM	A-2
			T	100 to 108 in.	-	100	97	88	74	47	39	0	26	39	17	18	5	Granular, noncohesive			19.6	1.68	2.74	-	11.7	-	116.8	0.596	0.575	Too sandy for test			29.7	0.57	SM	A-2

1/ All tests were made and data supplied (unless otherwise noted) by Materials Testing Laboratory, Dept. of the Army, Corps of Engineers, Office of the District Engineer, Honolulu, T.H. All tests were determined in accordance with the American Association of State Highway Officials and American Society for Testing Materials standard methods.

2/ Locations are shown on Plate 1. Some samples were taken from rock-type areas too small to be shown at the map scale and hence the sample's rock designation may differ from the map unit shown.

3/ Well-cemented limestone is found as isolated outcrops in Units 5 and 6, and although not large enough to map separately, significant differences warrant separate evaluation for engineering uses.

4/ All tests were made on soaked samples, using 10 lb. surcharge.

5/ Average of several tests on sand from Sobe beach. Data supplied by Dept. of the Army, Corps of Engineers, Office of the District Engineer, Okinawa.

6/ Corrected by D. Flint to accord with Unified Soil Classification, March 1949.

7/ This soil is on the border of CH, MH, and OH, but as it is neither micaceous nor organic, it is classed as CH.

Rock suitable for construction materials are widespread in Okinawa, but are generally only fair in quality. In the southern half of the island where weathering of the rocks is extensive, material suitable for crushed stone for surface or wearing courses of roads or airfields is scarce and of poor quality. In the northern half of the island, fresh bedrock is available, for use as crushed stone, but deep overburden of weathered material hampers quarrying.

In southern Okinawa detrital limestone (units 5 and 6) and calcareous beach sands and gravels (included in unit 1) are suited for use as surface or wearing courses. They are widely distributed and are easily excavated by light equipment. They compact well and after exposure and wetting they generally set to produce a well-cemented, pavementlike surface. However, the limestone particles lack compressive strength and are low in resistance to abrasion with the result that they break down under continued or heavy traffic; pitted, rough surfaces and extremely dusty conditions result. Application of bituminous binders retards the breakdown but does not stop it.

Within the detrital limestone are small zones of harder, more durable limestones that are slightly more suitable as surfacing material. However, even these limestones are subject to breakdown under heavy traffic.

Some metamorphic rocks of northern Okinawa are well suited for use as construction materials, but only a small quantity of this rock is fresh and unaltered. The most suitable source of crushed rock is crystalline limestone (unit 9). The rock is moderately tough, durable, and compact and occurs in very thick beds with only a thin mantle of overburden. Outcrops are common and easily accessible. Wide and high quarry faces can be opened and worked to produce rock that crushes to well-graded sizes. Numerous sites for quarries exist on Motobu-hantō and north of Shana-wan.

Beds of chert that occur interbedded with the platy foliated rocks (unit 11) of Motobu-hantō are suitable as high-quality surfacing material. Most individual chert beds are thin and generally separated by thick zones of foliated rock. Locally, however, the chert beds are 50 feet thick and could be exploited for small quantities of surfacing materials.

Sandstone (unit 12), porphyry dike rock (unit 13), and greenstone (unit 10), which are extensive in northern Okinawa, are suitable as construction materials where the rock is fresh and hard. However, these rocks are generally covered by an overburden of weathered rock up to a hundred feet or more thick, and suitable quarry sites are lacking.

Material for use as aggregate in concrete is scarce in Okinawa. The best source for aggregate in southern Okinawa is the well-cemented limestone that occurs locally in the areas of limy granular material (unit 5) and coralline rubble (unit 6). This limestone is available in small quantities and is poor quality because of its low crushing strength. Coralline rubble (unit 6) and limy granular material (unit 5) could furnish large quantities of material for coarse aggregate, but such aggregate would have a very low crushing strength and would rapidly disintegrate under heavy use. In northern Okinawa, crystalline limestone (unit 9) is a source for concrete aggregate. The limestone has good strength, stability, and moderate hardness. Outcrops are well suited for quarry development, and the limestone crushes readily to produce a well-graded aggregate. Chert beds in the platy foliated rocks (unit 11) on Motobu-hantō, are opal-free and have excellent physical properties for aggregate. However, the chert is difficult to quarry because most of the chert beds are thin and widely spaced within the foliated rocks. Sandstone (unit 12) and porphyry dike rock (unit 13) are suitable for aggregate where the rock is fresh, but throughout Okinawa these rocks are covered by a thick overburden of weathered material that makes quarrying difficult and uneconomical. Greenstone (unit 10) has a high pyrite content which makes it unsuited as concrete aggregate.

Suitability for Construction of Roads

Northern and southern Okinawa present quite different problems in road location and construction (pl. 3, Suitability for Construction of Roads). All-weather roads may be built rapidly and with little difficulty in most of southern Okinawa, whereas roads of any type are difficult to construct in northern Okinawa. Surfacing is necessary on all roads intended for all-weather use. In the south, an excellent network of paved roads exists. In the north, the existing network of roads is along the coast while most of the interior is inaccessible to vehicles.

In southern Okinawa, which is open country with generally moderate relief and only locally rugged terrain, suitable alignments for roads can be established with a minimum of engineering effort (pls. 6 A and 6 B). In some places steep slopes (pl. 7 A) may require moderate to heavy construction.

Cuts are easily excavated in the soft materials that underlie most of southern Okinawa, and the excavated material is suitable for use as fill. Cuts in limestone may require some blasting, but excavation by power equipment is generally possible. Vertical-cut faces of limestone will stand with no support. Cut faces in silty clay (pl. 1, unit 8, Compact gray clay), are subject to continuous raveling (pl. 7 B), or small-scale surface sloughing of material. Old cut faces develop a cover of loose, cracked, silty clay, which permits absorption of water during rains. After heavy rains, small slides, generally of less than two or three tons of mud, may take place from large cut faces. The cut faces become stable when the slope reaches about 2 1/2 or 3:1 and is covered with vegetation. Vegetative cover on steeper slopes will not stabilize the slope as both the cover and the soil will slide together, on the surface of the underlying bedrock, when waterlogged; common occurrence after heavy rains. Soil slides occur on steep natural slopes and along the upper edges of cuts, sometimes causing damage to structures and blocking roads. Silty sand, which is present in a few localities, will stand in very steep to vertical slopes without vegetative cover.

Fills on slopes of silty clay must be well drained and well anchored to the bedrock if possible, because the thin layer of natural clay soil that covers bedrock is very slippery when wet. When slope runoff and rain soak through both the fill and soil layer, impregnating and lubricating the clay soil, the fill, though stable itself, may slide on the original ground surface due to the reduced cohesion of the saturated clayey soil. A slide of this type occurred in 1951 on Highway 13 near the town of Tomai (Tomari); 5,000,000 cubic yards of fill were estimated to have moved.

A. Aerial view of limestone terrace, southern Okinawa, on which Yontan Airfield is located. Large quarries at terrace edge furnish paving material for the airstrips, taxiways, and hard standings.

B. Aerial view of Yonabaru Airfield, built on coastal flat. Rock for paving this airfield came from borrow pits in the coastal flat.

A. Aerial view of limestone terrain, southern Okinawa. The high point in the left foreground is Yaeju-dake. Steep fault scarps are obstacles to road construction.

B. Road cut, west of Awase Airfield, where exposed compact gray clay is raveling.

Drainage presents few problems other than the providing of drains for the low-lying clayey soils. No troublesome or deep bogs are known. Bridges and culverts must have sufficient capacity to allow rapid runoff following heavy rainstorms and typhoons.

All roads in southern Okinawa require surfacing if uninterrupted all-weather use is desired. Roads constructed on silty clay are very slick and slippery when wet and become morasses of mud under traffic. Roads on the reddish residual clay soils (pl. 1, unit 3, Residual clay) formed over limestone are slippery and soft when wet, but they dry rapidly. Moist red clays are very sticky and ball on the tracks of some tracked vehicles. Weasels, especially, are troubled with thrown tracks owing to sticky clay.

Rubbly detrital limestone for road surfacing is available in southern Okinawa both from the limestones (pl. 1, unit 5, Limy granular material and unit 6, Coralline rubble) and from the calcareous beach gravels (pl. 1, unit 1, Beach deposits). This material can be excavated and spread on the roads with little or no crushing. After compaction and exposure to wetting and drying, the limy material cements itself on the surface to form a hard pavement which is excellent for lightly used roads but which breaks down rapidly under heavy traffic. Unless covered by black topping the pavement also dusts very badly during dry weather. This road material, the best in southern Okinawa, is well suited to the construction of combat roads and airfields where rapidity of construction is important. It is not well suited for permanent roads which must carry heavy traffic, because constant maintenance is necessary to preserve the surface. Better aggregates for wearing courses may be obtained from northern Okinawa.

Alignment of roads in northern Okinawa involves sharp curves, steep grades, deep cuts or tunnels, and numerous bridges (pl. 8 A). Because of the difficulty of construction in most of the area, existing roads are few and narrow. Trunk roads are restricted to the coast where they follow raised beaches as much as possible (pl. 8 B). Where beaches are absent, roadbeds have been blasted in the sea cliffs (pl. 9 A). These roads are narrow and sinuous, but improvements, such as widening or straightening, would be costly and time consuming, especially in the area north of Shana-wan. Cross-island roads may be built without great difficulty where terraces merge with gaps through the backbone ridge of mountains. On the north and west sides of Motobu-hantō and in the vicinity of Kin and Jinoza, detrital limestone underlies extensive terraces and road-building problems in these areas are similar to those in southern Okinawa.

In northern Okinawa, soft, weathered rock extends downward as much as 100 feet below the level of the wide terraces but is thin in the mountain areas and absent over crystalline limestone. Cuts can be excavated in weathered rock with power machinery, but fresh rock requires drilling and blasting. Cuts in the hard rock will stand well except where the plane of bedding or foliation dips into the cut (pl. 9 B). Locally, shattered zones may require retaining walls or moderately sloping cut faces to prevent large slides of rock over the road. Vegetative cover is required to prevent gullying in the walls of cuts in gravels and sands.

Unweathered rocks of northern Okinawa generally are suitable for fill. Clayey sands and gravels (pl. 1, unit 4, Clayey granular material) require protection against gullying (pl. 10 A) as does the more weathered part of the bedrock. Most difficulties in building fills in the mountains and dissected terraces arise from the steep slopes and great relief and not from the characteristics of the bedrock.

Drainage presents no unusual problems in northern Okinawa. Roads require drains to reduce the erosive effect of the surface runoff, but the relief of the area makes it easy to construct such drains. Flood conditions should be considered in planning all culverts and bridges as all streams rise rapidly during and after heavy rains.

Most roads in northern Okinawa require surfacing to protect the roadbed; unsurfaced roads wear badly, with the formation of ruts and gullies. Where the road is constructed on fresh solid rock little subgrade is required. Good surfacing materials are not readily available in northern Okinawa as most of the surficial, weathered rock is too soft to stand up under the wear of traffic. Excellent, hard aggregate can be obtained from exposures of fresh sandstone (pl. 1, unit 12), greenstone (pl. 1, unit 10), chert and crystalline limestone (pl. 1, unit 9), but most of the rocks with the exception of the limestone have a deep overburden of weathered material which would have to be stripped before quarrying. Because of this, crystalline limestone is the most accessible source of high-quality road material. Exposures of crystalline limestone are limited to Motobu-hantō and the west coast of mainland Okinawa north of Shana-wan.

Suitability for Construction of Airfields

Sites suitable for the construction of airfields are mainly on Ii-shima (Ie-shima) and the southern third of Okinawa; only a few usable sites are on the mainland north of Ishikawa (pl. 4, Suitability for Construction of Airfields). Most of the suitable locations were utilized during World War II when 11 airfields were built.

High relief and rough dissected terrain (pl. 8 B) make most of Okinawa unsuitable for airfields, but the coastal flats (pl. 6 B) and undissected terrace levels of southern Okinawa (pl. 6 A) furnish areas of low relief on which airfields can be built.

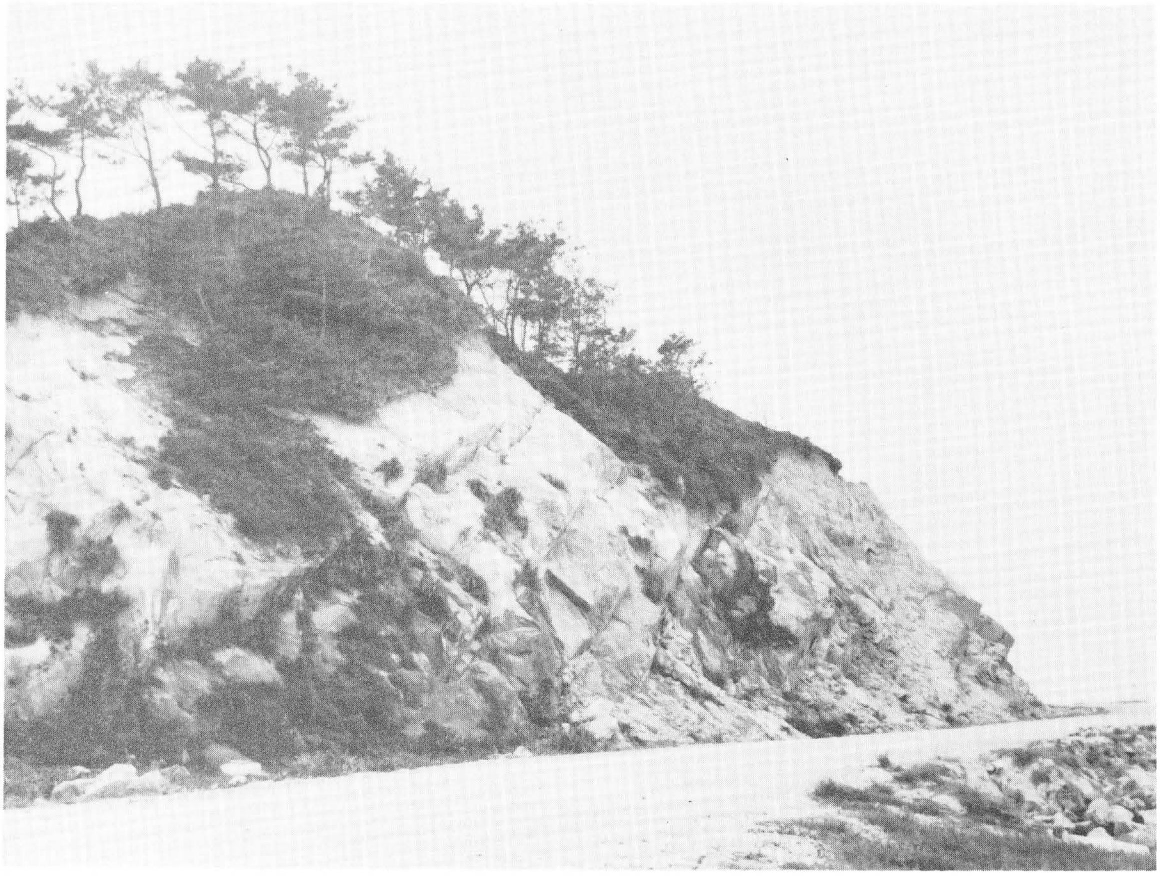
In only a few places are 10,000-foot runways possible, without large amounts of cutting and filling. Extensive sand and reef tidal flats furnish a suitable foundation for airfields at several places in southern Okinawa. Where these flats are shallowly covered by the sea, they could be utilized by using sufficient fill to raise the ground surface above sea level and constructing the airfield facilities on the filled ground. Fill may be obtained by dredging or scraping the nearby sea floor or by utilizing borrow pits on dry land.

Plentiful supplies of limy granular material (pl. 1, unit 5), suitable for surfacing material, are located near areas of suitable topography. Springs or streams are not found in most of these suitable areas, and water must be pumped or hauled to the sites.

Subgrade conditions in Okinawa are generally suitable for heavy-duty runways with the exception of those on limestone. The detrital limestones (pl. 1, unit 5, Limy granular material and unit 6, Coralline rubble) comprise a thin formation overlying dense rock of low

A. Aerial view of the southern side of Ōura-wan. In this terrain of dissected flanking terraces, road alignments require many cuts, fills, and sharp curves.

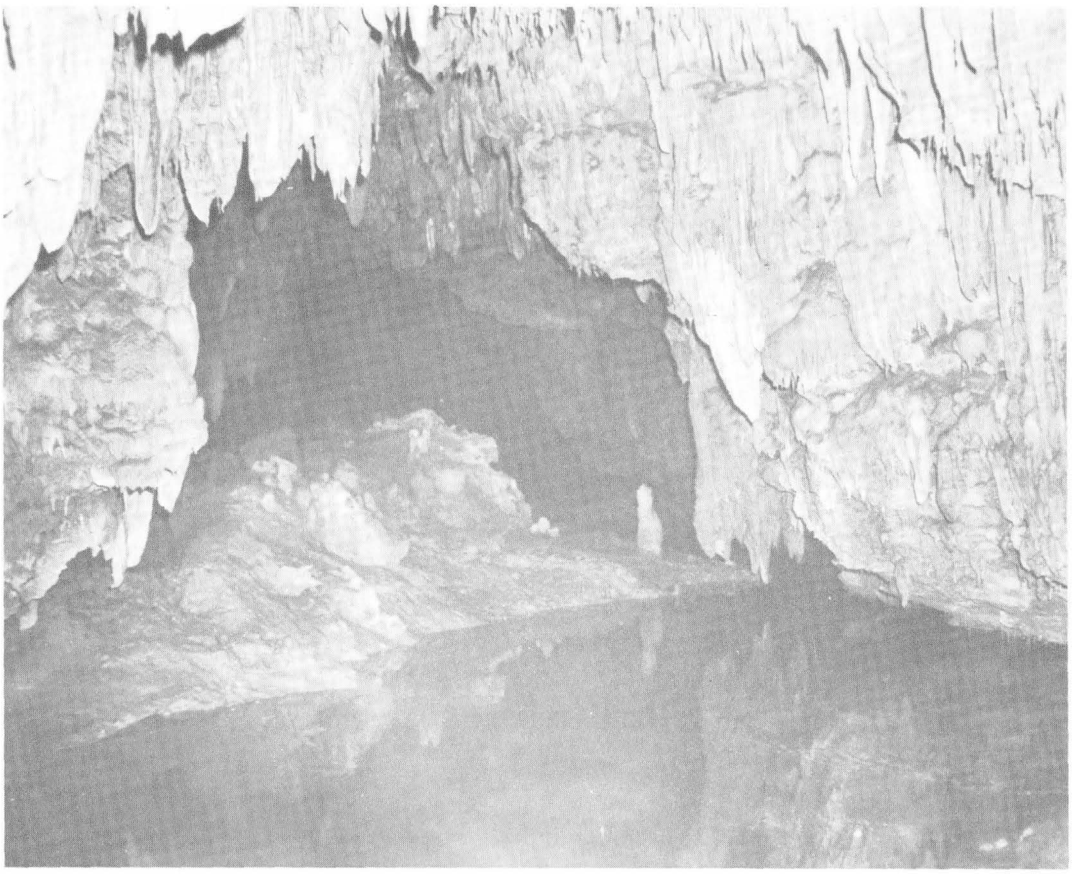
B. Aerial view south of Shuya, showing the mountains and flanking terrace on the west coast of northern Okinawa.



A. Road cut on Highway 1 near Nakama. Deeply weathered porphyry dike rock is exposed here, but a well-developed blocky joint pattern is discernible.

B. Road cut on Highway 13 north of Inubi. The foliation of the platy foliated rock, in which this cut is made, dips toward the road and the face is subject to much slumping.

A. Road cut on Highway 13 near Ishikawa. Gullies have cut the clayey granular material. Dark-colored material at top is residual clay.



B. Cavern on Chinen plateau formed in limy granular material. The stream has been dammed to form the pool of water. Photo by U. S. Army.

permeability, generally compact gray clay (pl. 1, unit 8). Because of the solubility and permeability of the limestone, there are caverns, tubes, and cavities developed in it (pl. 10 B). Surface runoff through these openings enlarges the underground openings. Collapse of these caverns is common and is caused normally by the excessive enlargement of subterranean openings or the removal of fine-grained interstitial supporting material. Collapse may be brought about by application of additional load over a cavern, by drainage disturbance, or by weakening the roof of the cavern by grading or other surface alterations (pls. 11 A and 11 B). In some cave-ins the collapse extends to the surface to form sinkholes (pl. 12 A).

Cavities (pls. 12 B and 13 A) also occur in the red-brown clayey soils, which are very thick over the detrital limestones. Some of these cavities, up to 10 feet in diameter, are formed by the chemical solution and removal of lime and residual concentrations of impurities in the soils. The others are formed by drainage through subterranean openings in the detrital limestone which mechanically removes large quantities of the residual overlying soil. Cavities in soil, that extend nearly to the surface, collapse to form "swallow holes" (small, funnel-shaped sinkholes).

Those cavities and caverns that do not visibly affect the surface are serious problems in engineering as they are difficult to detect, and they collapse under loads imposed upon them by construction. Geologic and hydrologic studies, test drilling, and the use of geophysical prospecting methods (mainly seismic, sonar, gravimetric, and electrical resistivity) may be used to detect and locate the cavities, but no one method can be depended upon to give continuous, reliable results.

Suitability for Construction of Underground Installations

The distribution of units referred to in this section is shown on Plate 5, Suitability for Construction of Underground Installations. Hard rocks suitable for tunneling are restricted to northern Okinawa. Tunnels in these rocks will stand with wide, unsupported roofs. Great thicknesses of protective cover are possible. In southern Okinawa, where the rocks are easily excavated, only the silty sand (pl. 5, unit 1; pl. 13 B) and the detrital limestone (pl. 5, unit 2; pl. 14 A) are capable of standing with moderately wide spans of roof; support for all such spans is mandatory for safety. Cut and fill installations may be constructed in many places in southern Okinawa but in only a few places in northern Okinawa.

Sandy clay and silty sand are well suited for rapid development of underground storage or shelter facilities by tunneling (pl. 5, unit 1). The material is easily excavated and stands fairly well in both walls and roof, though support is required for wide openings. There is a tendency for slabs to fall from the walls and roof in some tunnels in this material. The permeability of the rock may allow rainwater to seep into underground installations, but such seepage will probably be small and can be prevented by lining the installations. The areas most suited are in dissected terrain in the vicinity of Yonabaru Airfield, Oroku, and Awase, where numerous locations for horizontal entries are easily accessible by roads.

The detrital limestone (pl. 5, unit 2) stands very well in tunnels but is more difficult to excavate than the sandy clay and silty sands (pl. 5, unit 1) described above and the silty clay (pl. 5, unit 3). This limestone will, however, allow wider chambers with less support than any other rock in southern Okinawa. It is very permeable and seepage may occur following rains; installations in this unit should be lined to prevent seepage. The limestone is also suitable as a roof for excavations made in underlying, softer material.

The silty clay (pl. 5, unit 3) is moderately suited for tunnels. Many steep slopes provide protective cover for short entries. This material is more difficult to dig than the sand, and it does not stand as well because it tends to slough from the cut surface. However, it is impermeable, so little water will seep into installations. Because of the impermeability any water that does get into a tunnel is retained; drainage is essential. Japanese tunnels in this silty clay were damp, and in some, the floors were slippery, ankle-deep morasses of mud.

Crystalline limestone (pl. 5, unit 4) and sandstone (pl. 5, unit 5) are suitable for installations in northern Okinawa. Tunneling problems in these rocks, as well as in the foliated rocks (pl. 5, unit 6), are essentially those of hard-rock mining; all the rocks require drilling, blasting, and standard mining practices. The massive nature of the crystalline limestone and sandstone make them superior to the foliated rocks.

The alluvium and beach deposits (pl. 5, unit 7) are not suitable for underground installations of any type because of their lack of relief and their high water table.

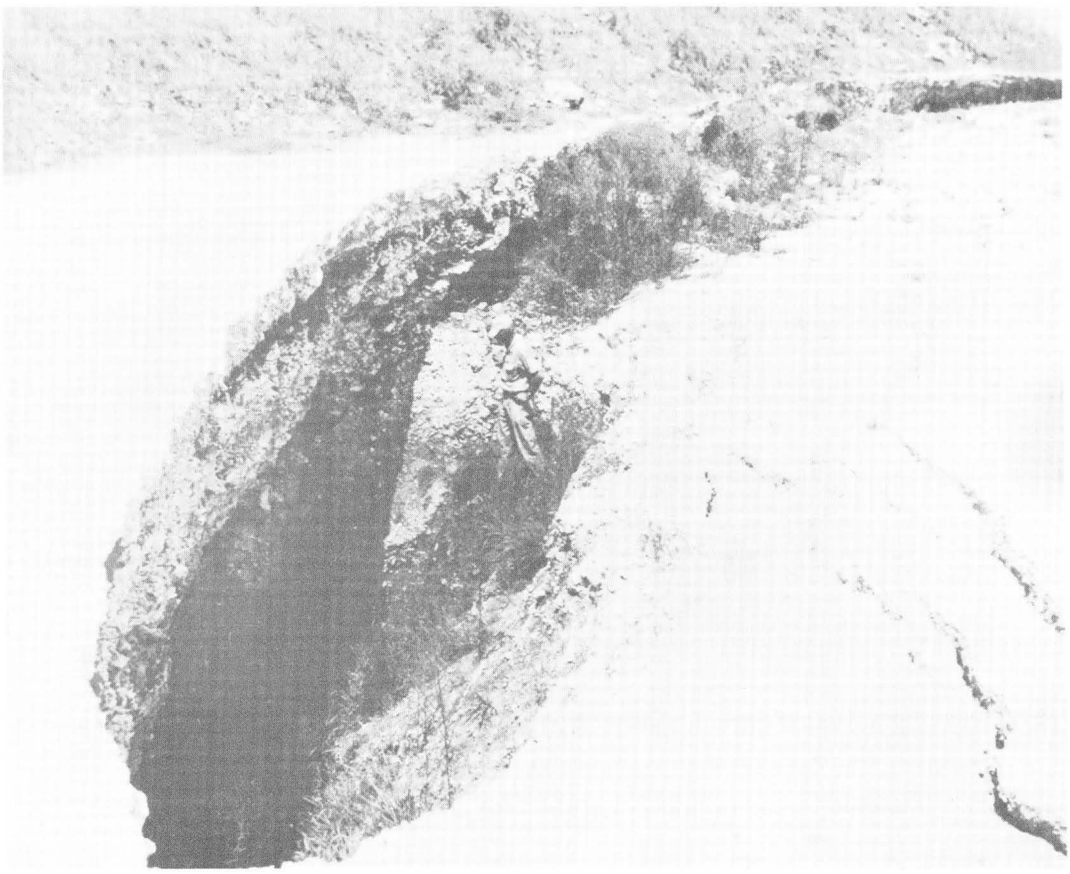
Silty clay (pl. 5, unit 3) and the silty sand and sandy clay (pl. 5, unit 1) are the only rocks recommended for cut and cover installations. These rocks are easily excavated to a depth sufficient for constructing installations. The silty clay (pl. 5, unit 3) is the only unit suited for the underground storage of petroleum products. The permeability of the other rocks allows leakage to contaminate ground water. Such contamination is improbable with the clay.

Natural caves

All known natural caves on Okinawa occur in the Tertiary and Quaternary detrital limestone (pl. 5, unit 2). Other natural caves may occur in the crystalline limestone (pl. 5, unit 4), but none have been found to date. Two general types of caves are known: those formed by solution due to the channelized movement of underground water, and those formed in cliffs along the sea and later elevated. The latter type is known only from Ie-shima and the south coast of Okinawa.

All the large and many of the small natural caves on Okinawa are developed along the contact of the detrital limestone and the basement rocks. Many of these caves are large drip-stone lined caverns decorated with stalactites hanging from the ceiling and walls (pl. 10 B). Such caves may continue for a mile or more, but rockfalls from the roof commonly block the cavern a comparatively short distance from the entrance. Some caves which are large in total area

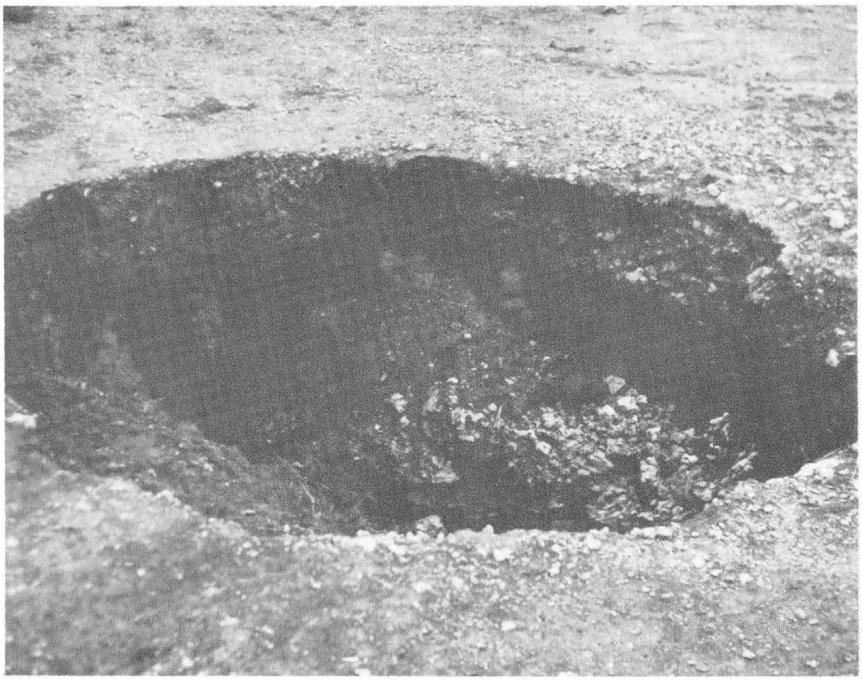
A. Aerial view of subgrade collapse on taxiway at southern end of Bolo Airfield. Collapse resulted from weakened roof over an underground cavern in the limestone bedrock.



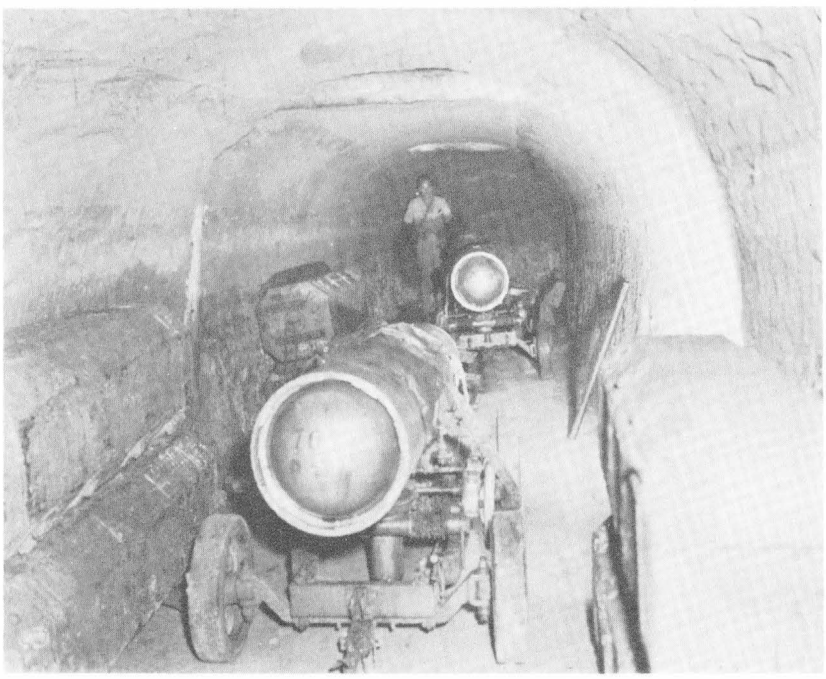
B. Closeup of sinkhole at Bolo Airfield shown on Plate 11 A. A 12- to 14-inch layer of pavement is exposed at the top of the overhanging wall. Thin, clayey soil layer underlain by coral-line rubble is below pavement.

A. Aerial view of sinkhole, northeast of Kiyan, formed on a limestone terrace. Sinkholes such as this commonly form by collapse of the roofs over caverns.

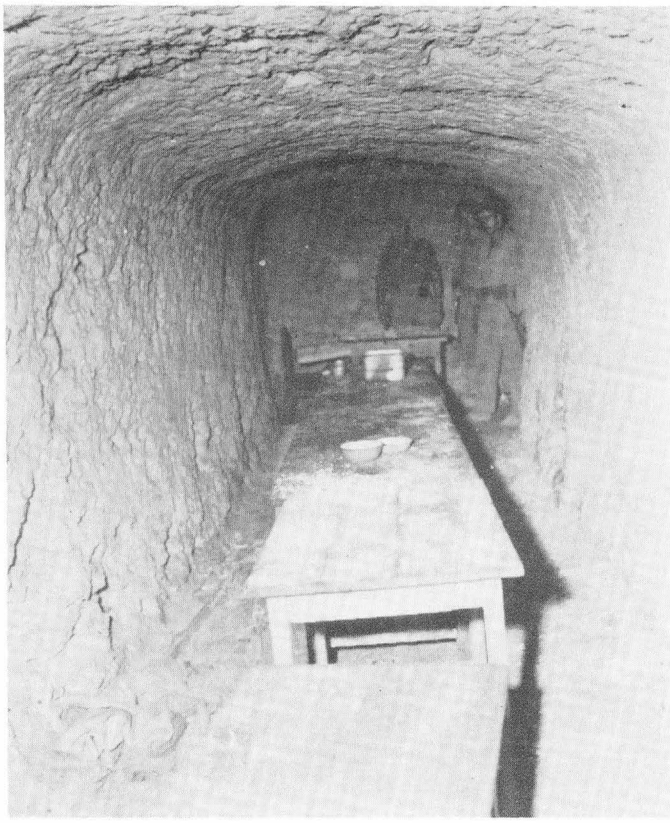
B. Sinkholes at Futema Airfield on the northeast extension of the runway. They were formed by subgrade collapse during typhoon Gloria, 10-12 October 1948.



A. Closeup of sinkhole at Futema Airfield, the larger of the two shown on Plate 12 B.



B. Tunnel near Naha Airfield, which stands with only a minimum of support. It was dug in silty sand by the Japanese.



A. Tunnel on south side of Naha-kō, in cliff of detrital limestone. The limy granular material stands well without support.

B. Raised beach deposits, northeast of Tengan, along the coast of Chin-wan. Material in scarp is uniform calcareous sand which is stained by iron oxide in upper part. Coral boulders in foreground.

are very irregular, both in plan and cross section. Streams are common in these caves and, like surface streams, they vary in size with the amount of rainfall; during periods of heavy rain flooding of the caves may occur. Caves of this type, though large, are not suitable for either permanent storage or personnel shelter because of the irregularity of passages, the seepage of water from the roof, and the danger of flooding during and after rains.

A series of irregularly shaped caves occur in the detrital limestone exposed in the rocky scarps which separate terrace levels both on the north coast of Ie-shima and on the south coast of Okinawa. These caves were formed as sea caves during higher stands of the sea, in part by the solution of limestone by sea water and in part by solution due to fresh water moving through the rock into the ocean. All are now high and generally dry owing to the relative elevation of the land, but seepage may follow heavy rains. These caves are highly irregular in shape, both in plan and section, and are up to 40-feet long, 25-feet wide, and 6-feet high. Many have been altered by the construction of walls across their entrances and the leveling of floors. Others have been enlarged by excavation. Caves in the upper terrace walls on Ie-shima are accessible with little difficulty; those in the present sea cliff are accessible but with difficulty. The caves on Ie-shima served as shelters for the civilian population during fighting for the island in 1945.

Existing artificial openings

Two principal types of underground installations are found on Okinawa: those excavated as military installations and those excavated as mines. There are many Japanese-excavated tunnel fortifications and shelters. These range in size from short hillside burrow holes to complex tunnel systems large enough to house hospitals and command posts. Tunnels are found throughout the island, but most are in southern Okinawa where they are concentrated in areas organized as defensive units. In such an area almost every hill is honeycombed by tunnels, each offering a field of fire that covers part of an integrated, mutually supporting system. As a result of combat, the entrances of most of the tunnels as well as parts of the tunnels themselves have been blasted shut.

The excavated tunnels on Okinawa were reported in combat reports to be damp, vermin-infested, foul-smelling installations that commonly were exceedingly muddy. In the years since World War II, most of the timber supports have been removed from the tunnels, and the resulting sloughing of walls and ceilings renders the tunnels unsafe. Because of the high humidity and warm temperature, fungi flourish on any vegetable or animal matter within the tunnel.

The larger tunnels, dug for defensive positions or command posts, have considerable underground area, but most of it is distributed in tunnels with few or no chambers. Ventilation and drainage are poor. Many of the short tunnels remain in fair or good condition, requiring only a little cleaning and repair to make them usable for emergency shelters and command posts. Most are too small to afford much storage space.

There are no large mines now open on Okinawa. The largest mine, located at Yamadadōbaru northeast of Nago, has not been operated for about 50 years and is caved so it cannot be entered. Other smaller mines and prospect tunnels are scattered throughout northern Okinawa, mostly in remote spots, far from roads and military installations. Most are short tunnels excavated in hard metamorphic rocks, which stand well without support, and many are in excellent condition.

Engineering Characteristics of Geologic Materials

In the following descriptions the units refer to Plate 1 and Tables 1 and 2.

Beach deposits (unit 1)

Occurrence and topographic characteristics: Beach deposits are located along the coast and at the mouths of principal stream valleys; they include beach ridges, tidal zones, and beaches. Extensive coastal flats of southern Okinawa are included in this unit, although they are partly overlain by alluvial deposits. Sandy beach ridges are common in northern Okinawa; they generally merge inland with estuarine and alluvial deposits (unit 2).

Description of material: Deposits on beaches and coastal flats contain various mixtures of unconsolidated sand, silt, and gravel. Beach sands are fine to coarse grained, composed primarily of fragments of shells, corals, and other limy organic material. Gravels in southern Okinawa consist of coral and shell fragments; in northern Okinawa gravels also contain schist, sandstone, quartz, limestone, and porphyry fragments. Deposits of durable beach gravel are limited to small patches along the shoreline. Cemented beach rock, in beds up to 2- or 3-feet thick, occurs locally in the tidal zone. Locally, raised beach deposits, primarily of calcareous sand, are present. Fringing coral reefs border most of the coast; some reefs are elevated and cemented along the shoreward margin. Maximum thickness of this unit is over 50 feet.

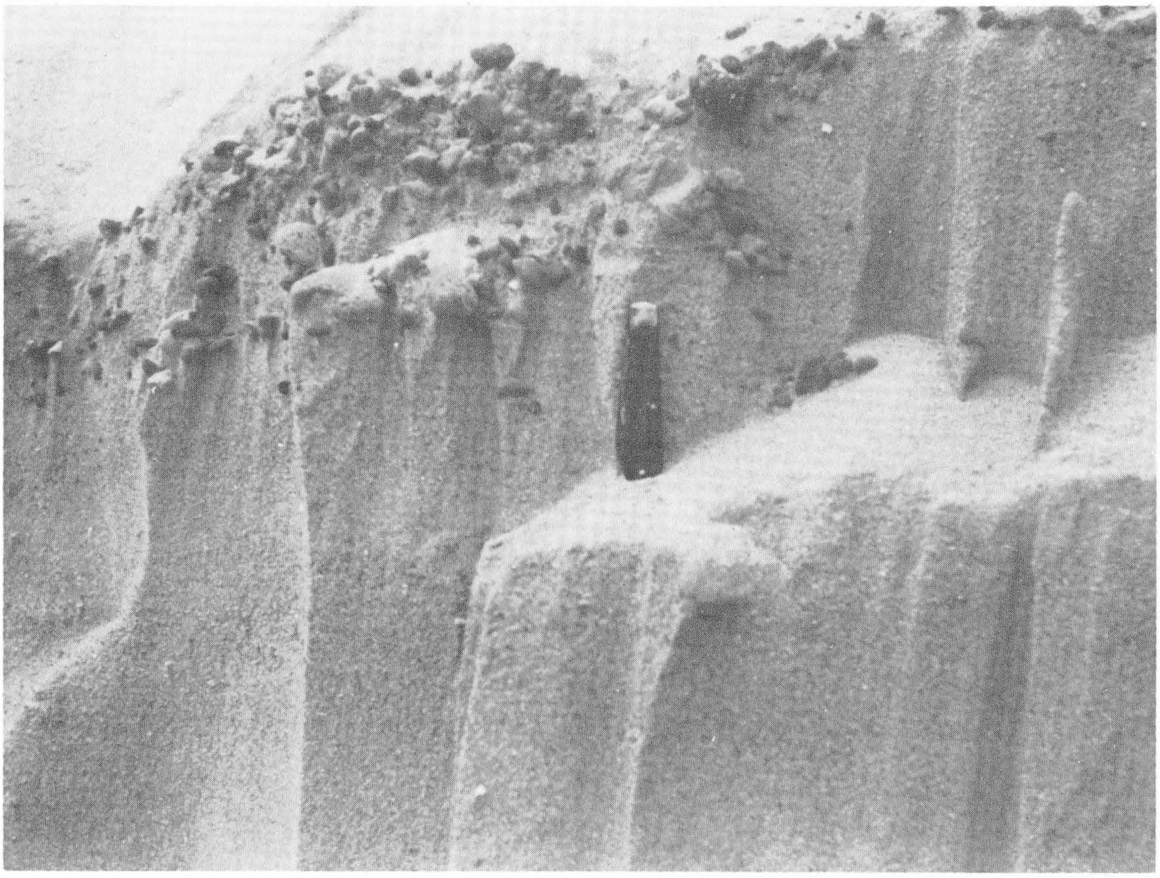
Fragmentation and crushing characteristics: No crushing is required for most beach material (pls. 14 B and 15 A) as it is soft and easily cut or broken when fresh. Reef rock and calcareous beach material commonly harden on removal and exposure to weather. Crushing of beach rock and reef rock produces much fines.

Tunneling and underground storage: Low relief and high water table make tunneling and underground storage impractical.

Suitability for road construction: Long, level tangents are possible. Cuts are negligible and fills are necessary only locally. Stabilization and drainage are required for fills on tidal flats, but elsewhere subgrade conditions are generally good. Protection against marine erosion is required in areas close to the sea, especially on tidal flats.

Pit and quarry exploitation: High water table interferes with quarry operations. Beach-ridge sand is suitable as blending sand in fine aggregate. Sand from tidal flats and beaches is used as fill. Cut beach rock and coral-reef rock for dimension stone are produced locally.

Method and facility of excavation: Loose sand and gravel are easily



A. Closeup of raised beach deposits northeast of Tengan shown on Plate 14 B. Pebbles are of pumice.

B. Steep-walled valley at Uku. The flat valley floors of alluvial sands and gravels are common in northern Okinawa.

excavated. Drilling and blasting aid in the excavation of beach rock and coral-reef rock. High water table hinders deep excavations.

Slope stability and erosion protection required: Estimated angle of repose of unconsolidated materials is 1 1/2:1 1/(pl. 14 B). Cemented beach rock and coral-reef rock stand vertically. Beach ridges have a maximum naturally stable slope of 3:1. Unconsolidated materials will run if slope is oversteepened. Sea walls are required for protection, against erosion, of installations near the shore. Revetments are required where streams cross this unit. Vegetative cover is needed to hold the sand against wind erosion.

Drainage: Depth to water table ranges from surface to 15 feet. Natural surface drainage and subsurface drainage are very rapid. Agricultural practices locally induce poor drainage. Pumping is necessary for adequate drainage in areas below the water table.

Remarks: Beach rock and coral-reef rock harden when they are cut and exposed to the weather. Beach deposits which contain much finely divided calcium carbonate cement themselves when compacted and exposed to the weather.

Alluvium (unit 2)

Occurrence and topographic characteristics: Alluvium is most extensively developed in northern Okinawa. It occupies broad, flat-floored valleys, especially in the lower courses of major streams (pl. 15 B). Alluvial areas are highly cultivated, many of them being in paddy land, where agricultural practices have developed a surficial layer of muck 1- to 2-feet deep.

Description of material: Unit 2 consists of unconsolidated clay, silt, sand, and gravel, with local accumulations of organic muck. In northern Okinawa it contains a high percentage of gravel derived from platy foliated rocks, sandstone, greenstone, crystalline limestone, and porphyry. Most of the gravel is weathered but not severely. Alluvium in southern Okinawa is mainly clay and silt. The maximum thickness of alluvium probably exceeds 100 feet.

Fragmentation and crushing characteristics: Crushing characteristics of gravel and other coarse fragments vary but are essentially the same as the moderately weathered bedrock from which the fragments came.

Tunneling and underground storage: High water table makes unit unsuitable.

Suitability for road construction: Possible alignments are nearly level with moderate-radius curves and good visibility. Fills or bridges are required where the water table is high. Clayey subgrades may require stabilization for heavy fills.

Pit and quarry exploitation: Alluvium is used locally for fill. Existing developed pits are scattered, mostly in inland alluvial areas.

1/ In this report, all slope ratios are given in the sequence horizontal:vertical.

Method and facility of excavation: Above the water table the material is easily excavated with hand or machine tools. High water table impedes deep excavations.

Slope stability and erosion protection required: Unit 2 is generally flat. The angle of repose of unconsolidated gravels and sand is estimated to be 1 1/2:1. River banks as much as 6-feet high stand in slopes of 1/2:1; except where protected by plant roots, the slopes will probably retreat to 1 1/2:1. Unconsolidated material will slump and slide on oversteepened slopes. Vegetative cover or retaining walls are required for cuts and fills, and revetments are needed along stream banks.

Drainage: Depth to water table ranges from surface to 10 feet. Seepage is rapid but surface drainage is generally artificially inhibited for rice culture. Deep excavations require pumping because of high water table and rapid seepage.

Remarks: Sites for construction on this unit should be carefully selected to avoid flood hazard.

Residual clay (unit 3)

Occurrence and topographic characteristics: Residual clay occurs on deeply weathered areas of upland limestone plains and thoroughly leached limestone remnants capping ridges in dissected terrain. Topography is generally flat to subdued rolling, on upland areas, but erosion of underlying units may produce rough terrain locally.

Description of material: The residual clay is reddish brown and plastic. It was derived from weathered limy granular material and coralline rubble (units 5 and 6) and is generally underlain by these parent materials or by compact gray clay (unit 8) and silty sand (unit 7). Total thickness of unit is generally 20 feet or less.

Boundaries of this unit are arbitrary, as the mappable areas of residual clay grade into overburden on limestone (units 5 and 6) and into clayey granular material (unit 4). The basis of distinction is whether residual clay is estimated to be thick enough to be of engineering significance other than as overburden.

Fragmentation and crushing characteristics: The material is a plastic clay and crushing is not necessary.

Tunneling and underground storage: Material is easily excavated, but support is required for roofs and walls. Tunneling is not practicable because of limited thickness of unit. Cut and cover installations could be constructed easily. Tunnels and excavations would require drainage to prevent puddles and ponds. Clay will adhere to tools when wet. Caverns occur in limestone bedrock (units 5 and 6), which underlies this unit.

Suitability for road construction: Possible alignments have long-radius curves with shallow cut and fill. Subgrade is good if well compacted; otherwise poor. Compacted clay has poor drainage and requires close control of moisture content. The clay is unsatisfactory as a base directly below wearing course. Unsurfaced roads are slick, sticky, and easily rutted when wet; rough and dusty when dry.

Pit and quarry exploitation: This clay is worked in a few small pits for brick and tile manufacture.

Method and facility of excavation: Excavation is easy with hand or machine tools. Wet clay will cling to equipment.

Slope stability and erosion protection required: Steepest naturally stable slopes and estimated stable slopes are 2 1/2:1. Plastic clay will slump on oversteepened slopes. Vegetation cover and drainage control are necessary to prevent stripping of material by wind and water.

Drainage: Generally the entire thickness of this unit is above the water table. Drainage is moderately rapid in undisturbed clay. Disturbing of material by such means as excavation and compaction reduces the natural permeability with resultant puddling and ponding. Control of surface drainage is necessary to prevent erosion.

Clayey granular material (unit 4)

Occurrence and topographic characteristics: The clay granular material occurs on upland plains and dissected terraces and is generally restricted to the area north of RYCOM. Valleys are closely spaced on the dissected terraces and are separated by steep, flat-topped ridges.

Description of material: The materials forming this unit are dissimilar geologically but similar in engineering characteristics. Most of unit is a mantling layer of poorly bedded to structureless sandy and gravelly clay. Near most areas of hard bedrock (units 10, 11, 12, and 13) this unit consists of irregular lenses of clay, clayey silt, sand, and decomposed gravel; individual lenses rarely are more than 4 or 5 feet thick. Maximum thickness of the unit is about 150 feet.

Fragmentation and crushing characteristics: The material is unconsolidated and does not require crushing.

Tunneling and underground storage: Material is easily dug. Tunnels stand well without support in most of unit; gravels with low clay content need support. Installations with wide ceiling spans require support throughout unit. Dissected terrain allows short entry for adits but restricts size of underground installations. Drainage is generally no problem although puddles may form in low spots in the floor of tunnels owing to destruction of the natural permeability. Tunnels may require lining to prevent seepage.

Suitability for road construction: Much cutting and filling of unconsolidated material is required to cross the dissected terrain. Material is good subgrade when properly compacted; drainage of puddles required in areas where compaction has been made. All cuts and fills require erosion protection to prevent formation of gullies (pl. 10 A). Material is unsatisfactory as base directly under wearing course. Unsurfaced roads are slick, sticky, and easily rutted when wet; very dusty when dry.

Pit and quarry exploitation: Unit has limited potential for development of borrow pits for fills, but construction practice balances cuts and fills so that borrow pits are not necessary. A few clay pits have been developed for brick and tile manufacture.

Method and facility of excavation: Materials are easily dug by hand and machine tools. Clay will stick to equipment when wet.

Slope stability and erosion protection required: Stable slope ratio is estimated to be 1 1/2:1 to 2:1; steepest naturally stable slopes are 1 3/4:1. Clayey granular material slumps in large masses on oversteepened slopes. Benching is necessary in deep cuts to prevent slumping. Vegetative cover is necessary in all cuts to prevent development of gullies (pls. 10 A and 16 A).

Drainage: Depth to water table is variable; generally more than 30 feet; locally at surface. In undisturbed material, seepage and drainage are moderate to rapid. Where material is disturbed drainage is slow and puddles may form. Surface drainage requires careful planning to prevent erosion. Excavations with compacted surfaces will collect water which will drain slowly or not at all.

Remarks: Okinawa's most severely gullied areas are in this unit. Gullies form readily in unprotected material (pl. 10 A).

Limy granular material (unit 5)

Occurrence and topographic characteristics: Limy granular material forms gently sloping, undulating terraces separated by steep, rocky slopes (pls. 6 A, 7 A, and 16 B). These terraces are developed best on the west coast of southern Okinawa and on the north coast of Motobu-hantō. Within the area of this unit some streams are subterranean (pl. 10 B). Surface streams, where present, flow in vertical-walled canyons. Sinkholes are found only locally (pl. 11 A). Jagged pinnacles (pl. 17 A) and steep rocky ridges stand above the level of the terraces in parts of this unit (pl. 7 A).

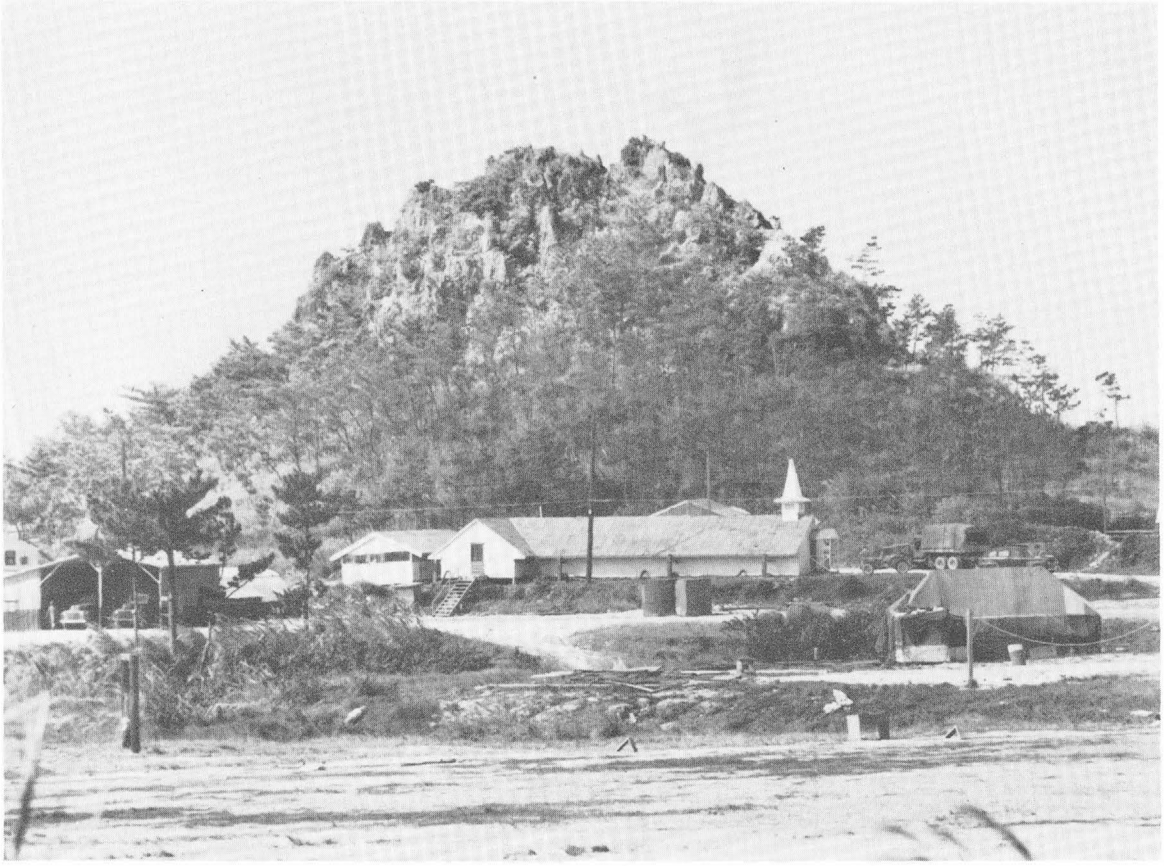
Description of material: The material is composed chiefly of calcium carbonate in the form of light buff to yellow, poorly bedded, fine- to medium-grained sand containing irregular lumps and gravel-sized fragments. Most of the material is soft and friable, but individual fragments are tough and fairly hard. The unit contains cemented zones and layers of hard limestone. Thick cemented zones (shown by symbol, as well-cemented limestone, on plate 1) are most common along exposed surfaces; cemented zones or layers also occur along joints, crevices, caverns, and water courses. This unit also contains clay, silt, and quartz sand in its basal portion; it contains much noncalcareous debris near masses of hard bedrock (units 9, 10, 11, 12, and 13). Maximum thickness is about 100 feet. In some small areas of low relief a mantle of red residual clay as much as 20 feet thick is common. Areas of thick residual clay are mapped as Units 3 and 4.

Fragmentation and crushing characteristics: Pit-run material is usable for fill and base course without processing. Hardened zones crush easily to give concrete aggregate but produce much powdery fines.

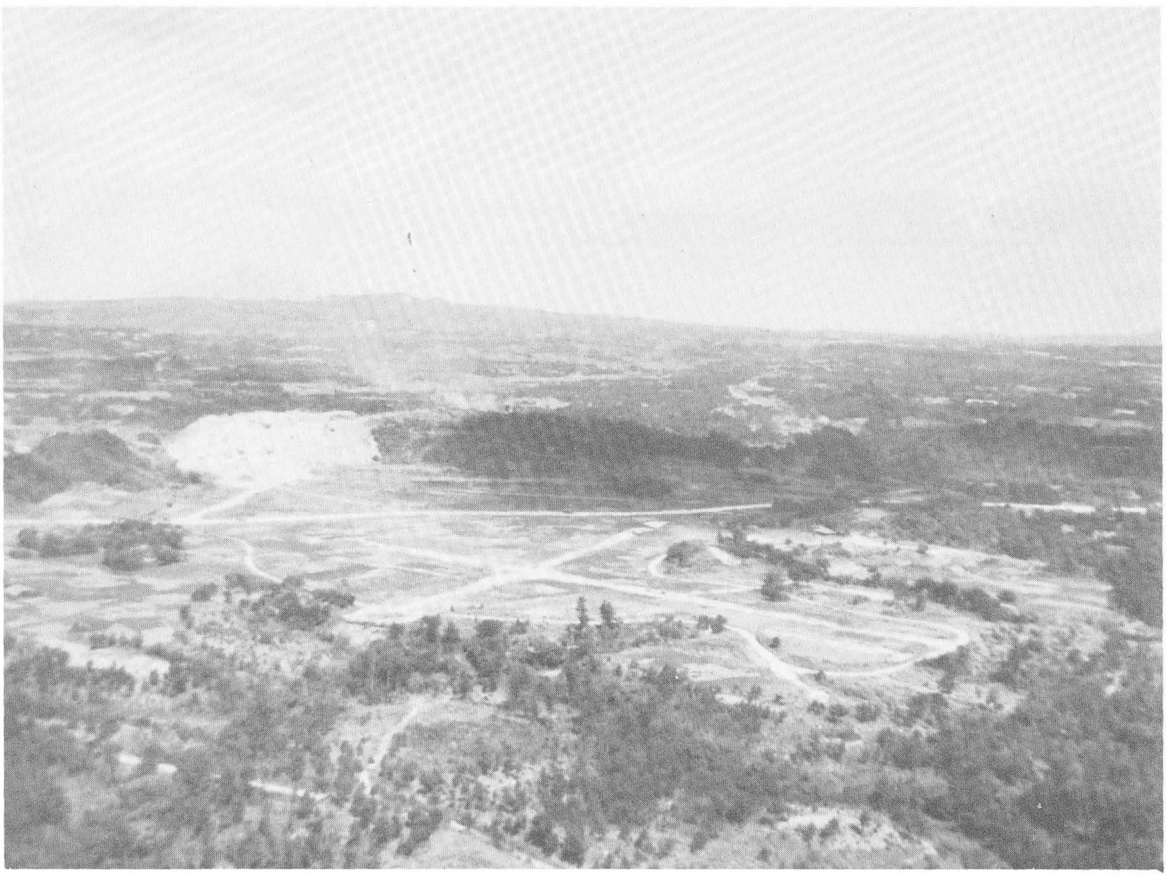
Tunneling and underground storage: Tunnels are easily excavated by hand tools, but hard zones require blasting. The material stands well and commonly cements itself on exposure to air. Wide underground chambers require roof support. The steep slopes, common in the west,

A. Road cut east of Yontan Airfield. The exposed material is a remnant of impure limestone in clayey granular material derived by the weathering of the limestone.

B. Aerial view of the terrain near Ishikawa. This is typical terrain on limy granular material. The camp at the left is built on a flat terrace level underlain by poorly lithified, granular limestone. The quarry at the right was opened in the edge of the terrace as a source of road metal.



A. Pinnacle at Kadena Airfield composed of well-cemented limestone. Masses such as these are good quarry sites.



B. Aerial view of Chibana quarry. This quarry is developed in a pinnacle of well-cemented coralline limestone. Other pinnacles remain in a line to the left and right of the quarry.

are suitable for short entries. Natural caverns are common in this unit, generally along the base. Seepage and drainage are rapid and may necessitate lining of tunnels. The limy granular material is poor for petroleum storage because of leakage.

Suitability for road construction: Alignments are easy on plains (pl. 6 A) but difficult on steep rocky slopes (pl. 7 A). Subgrade conditions on the limy granular material generally are excellent, except in areas of local accumulation of residual clay. The limy material makes excellent base course and is widely used in southern Okinawa. The possibility of surface subsidence due to collapse of underground caverns makes detailed route investigations imperative in establishing road alignments.

Pit and quarry exploitation: Limy granular material, most widely used for base and wearing course in road and airfield construction on Okinawa is abundant. There are many pits developed in it, especially in the vicinity of airfield sites (pl. 17 B). Several large quarries (pl. 18 A) have been worked for hardened rock for crushing as aggregate, but good material for aggregate is rare.

Method and facility of excavation: Hand tools and power machinery can work all but the hardened zones. Thick, hardened zones require drilling and blasting; thin layers may be broken by tractor-drawn rooters.

Slope stability and erosion protection required: Stable slope ratios range from 1/4:1 to vertical. Removal of underlying clay material causes large slump blocks. Quarry faces do not slump. No protection is needed in cuts that are solely in this unit. Large slump blocks are commonly formed where compact gray clay (unit 8) is exposed beneath this unit (pl. 7 A).

Drainage: Depth to water table is variable. There is no surface drainage system; seepage and subsurface drainage are very rapid. Surface drainage from airfields and roads should be carefully handled to prevent subgrade material from washing into subsurface watercourses.

Remarks: This unit is very cavernous and the danger of cavern collapse is always present. Cavern collapse is not solely a factor of applied load but is most common during torrential rains.

Coralline rubble (unit 6)

Occurrences and topographic characteristics: Coralline limestone forms terraces with gently sloping, undulating surfaces separated by steep, rocky slopes. Terraces are best developed on west coast of southern Okinawa and on the west tip of Motobu-hantō. Areas of this unit have subsurface drainage in which streams flow in caverns or in tubes in the underlying rock. Sinkholes are present only locally. Jagged pinnacles and steep, rocky ridges stand above terraces in parts of the unit.

Description of material: Coralline-limestone rubble is composed of firm, white, porous fragments up to several inches in diameter, in a matrix of limy sand. Bedding is very poorly developed and commonly is absent. Unit is mainly unconsolidated but contains hard, cemented zones up to 20 feet thick. These cemented zones are most common along exposed surfaces; other zones occur along joints, crevices, caverns, and watercourses. Near the boundary with other units (units 9, 10, 11, 12, and 13) the basal portion contains debris from those units. Maximum thickness of the unit is approximately 100 feet. On fairly flat, gentle slopes this unit is overlain by residual red-brown clay formed by leaching of lime; the clay mantle may be as deep as 10 feet, but generally is much less. On steeper slopes, clay occurs in pockets between outcrops of hardened limestone. Clay washes down into underlying limestone, so that local pockets and zones of clay in the rock are common.

Within the coralline rubble are small patches of dense, white to buff, well-cemented limestone. Surfaces are highly irregular, with clay pockets extending as much as 10 feet into the hard rock; small caverns and openings are common. This well-cemented limestone is restricted to the southern two-thirds of Okinawa where it forms jagged pinnacles (pl. 17 A) and rocky hills. The location of this material is shown on Plate 1 by special symbol.

Fragmentation and crushing characteristics: Pit-run material can be used without crushing for base and wearing course. Hard, cemented layers can be crushed easily to give aggregate. The well-cemented limestone is moderately tough and resilient but not hard enough to wear crusher jaws. Crushing of the limestone produces much powdery fines which coat fragments.

Tunneling and underground storage: Tunnels are easily excavated by hand tools, in most of unit, but hard zones require blasting. Material stands well (pl. 14 A) and commonly cements itself upon exposure to air. Wide underground chambers require roof support. Slopes offer many locations for short entry adits. Natural caverns are common in this unit but are not as well developed as in limy granular material (unit 5). Seepage and drainage are rapid and may necessitate lining of tunnels. Coralline rubble is poorly suited to petroleum storage because of leakage.

Suitability for road construction: Alignments are good on plains but poor on steep, rocky slopes. Subgrade conditions are generally excellent, but local accumulations of residual clay may present problems. Limy material is excellent as base course; widely used in southern Okinawa. Investigation of foundations is imperative in order to avoid surface subsidence from collapse of underground caverns. Cavities developed in residual clay may collapse where surface water drains into underground watercourses.

Pit and quarry exploitation: Material is suitable for base and wearing course in road and airfield construction. Many pits have been developed in coralline rubble especially around airfields. One large quarry was worked for crushed rock for use as aggregate for bituminous mix (pl. 18 A). Good aggregate is rare, but surfacing material for roads and airfields is abundant. In the hard limestone several large quarries are worked for crushed rock, but the supply is limited. Drilling and blasting are necessary for excavation of the hard limestone.

Method and facility of excavation: Hand tools and power machinery can work all but the hardened zones which require drilling and blasting; thin layers may be broken by tractor-drawn rooters.

A. Aerial view of Nagahama quarry. This face exposes about 200 feet of well-cemented coralline limestone. Direction of photo is southeast.

B. Tunnel east of Naha Airfield. This tunnel was dug in silty sand, by the Japanese, and completely lined to prevent material from sloughing.

Slope stability and erosion protection required: Naturally stable slopes range from 1/4:1 to vertical. Removal of underlying material causes large slump blocks. No slumping occurs on quarry faces. No protection is needed in cuts solely in this unit. Cuts which expose easily eroded material below this unit require retaining walls or vegetative cover.

Drainage: Unit drains into underlying rocks. Locally a basal water table may form, generally within a few feet of sea level. There is no surface drainage system; seepage and subsurface drainage are very rapid. Surface drainage from airfields and roads should be carefully handled to prevent washing of subgrade material into subsurface courses.

Remarks: Though this unit is not as cavernous as limy granular material (unit 5), the danger of collapse is always present. Large slump blocks are common where compact gray clay (unit 8) is exposed below the limestone.

Silty sand (unit 7)

Occurrence and topographic characteristics: The silty sand occurs only in southern Okinawa. Large areas, in which the silty sand is exposed, are dissected terrain with very steep valley walls and flat floors. Local masses form prominent hills with steep slopes. The areas of silty sand are commonly covered with pine and dense vegetation.

Description of material: The silty sand is fine grained and compact with thin layers of silty clay. It is brown in most exposures but may be gray in fresh cuts. The material is porous and friable, with little or no cementation. Certain layers contain cemented concretions ranging in size from a few inches to 2 or 3 feet. Maximum thickness of the unit is about 250 feet. Quartz is the important constituent. Most of the sand passes No. 40 mesh sieve and contains as much as 30 percent silt and 10 percent clay. Compact gray clay (unit 8) is in close association with this unit.

Fragmentation and crushing characteristics: Crushing is unnecessary as material is not cemented.

Tunneling and underground storage: Tunnels are easily driven by hand tools, and the material stands well without support; thinly bedded zones and large installations, however, require support throughout. Seepage and drainage are rapid in most places.

Suitability for road construction: Alignments through hills and ridges of this unit require moderate to deep cuts and fills. Locally steep grades and short-radius curves are necessary. Fills of this material require protection to prevent erosion. Vertical cuts need no protection. Subgrade conditions are moderately good. Ditches in unit will undercut and clog.

Pit and quarry exploitation: No pits or quarries are developed in this unit.

Method and facility of excavation: The sand is easily excavated by hand and machine tools, without blasting.

Slope stability and erosion protection required: Vertical cuts, less than 30 feet, are stable. Naturally stable slopes of 1/2:1 are known. Vertical cuts stand without slumping, but slides are probable if clay seams dip into the cuts. Vegetative cover is necessary to prevent gullying. Bare vertical cuts will gully less than gentle slopes.

Drainage: Position of water table varies greatly. Seepage and drainage are generally moderately rapid but retarded by clay layers. Drainage may be a problem in low areas and may require special construction.

Compact gray clay (unit 8)

Occurrence and topographic characteristics: Extensive areas of compact gray clay are confined to southern Okinawa where they form rolling to fairly flat areas with occasional knolls and low mounds. Abrupt changes of slope, ridges, and steep-sided knolls are usually caused by outcropping of sand (unit 7) or capping of limestone (units 5 and 6).

Description of material: The material forming this unit is dense, impermeable, compact gray clay and silty clay, with interbedded thin layers of silt and very fine-grained sand. Bedding is well developed but generally obscured by surface weathering. Jointing is irregular. Maximum thickness of the unit exceeds 4,000 feet. Cuts in the clay develop finely spaced fractures across the entire face and individual pieces develop conchoidal fractures (pl. 7 B). Moist clay is slippery and plastic; wet clay slakes and loses consistency. Wetting is accompanied by expansion. The clay contains up to 14 percent calcium carbonate, mostly as small shells. Slopes are covered by a mantle of clay soil about 1 foot thick. Alluvial concentrations of clay soil, accumulated in valleys, reach thicknesses of several tens of feet.

Fragmentation and crushing characteristics: Unit is unconsolidated sediment and requires no crushing.

Tunneling and underground storage: Tunnels can be driven by hand tools in the clay, without blasting. When moist, clay may adhere to equipment and thus hinder operations. All tunnels and underground chambers require support and lining (pl. 18 B). Undisturbed compact gray clay is impermeable; interbedded silty sand layers may allow some seepage. This unit is suitable for petroleum storage as leakage will not contaminate ground water or seep into other installations.

Suitability for road construction: Alignments with long-radius curves and minimum cut and fill are possible in flat to gently rolling areas; moderate to deep cuts may be required in some hilly areas. Subgrade conditions and drainage are poor; adequate base course is necessary, unless moisture is kept out of subgrade by a blanket course. The material will not repack to original density after being disturbed. Unsurfaced roads are slippery when slightly wet and become quagmires when thoroughly wet; they are very dusty and full of ruts when dry.

Pit and quarry exploitation: There are practically no developed quarries or pits. Some clay is used in brick and tile manufacture.

Method and facility of excavation: Easily excavated by power machinery without blasting. Excavation by hand equipment is possible. Wet clay adheres to equipment.

Slope stability and erosion protection required: Fresh cuts stand at 1/2:1, but cut faces work back by raveling and minor slumping until a naturally stable slope of 2 1/2:1 is reached. Soil slides over clay bedrock are common. Benching is needed on deep cuts. Vegetative cover and gentle slopes required for all cuts.

Drainage: Undisturbed clay is impermeable. Overburden may have a perched water table locally, within 2 or 3 feet of the surface. Seepage and drainage are imperceptible except along scattered sand beds. Excavations have to be pumped or drained. Ditches and drains clog rapidly.

Remarks: All cuts on slopes of this unit are likely to cause soil slides. Construction on this unit should be limited to gentle slopes, and the vegetation cover should be preserved as much as possible. Fills on slopes of this unit will slide on the clay layer if it becomes saturated with water.

Crystalline limestone (unit 9)

Occurrence and topographic characteristics: Crystalline limestone occurs only in northern Okinawa, on Motobu-hantō and north of Shana-wan. It forms distinctive terrain of high, rugged mountains with deep, steep- to vertical-walled stream canyons and many rocky projections (pl. 19 A) and outcrops of bare limestone. Ridges and slopes commonly are covered with thick growth of shrubs, grass, and trees (pl. 19 B).

Description of material: The crystalline limestone is bluish gray to white, dense, fine to medium grained, and locally is veined with white to black calcite. The limestone is bedded, although bedding often is not discernible. Maximum thickness is about 1,000 feet. The rock is jointed and locally has incipient fractures that cause it to break into small, angular, wedge-shaped fragments. The joints allow good internal drainage. Loose, fragmented rock occurs in fault and shear zones. This unit contains some lenses of highly squeezed platy rocks. In addition the limestone is interbedded with platy, foliated rocks (unit 11), especially where it borders areas of the latter type of rock. Overburden is brown clay soil that locally may exceed 10 feet in depth and has small cavities.

Fragmentation and crushing characteristics: Blasting is required to remove this rock. The rock is fairly brittle and shatters readily under impact. It crushes to cubical particles with less waste than the well-cemented coralline limestone of Units 5 and 6.

Tunneling and underground storage: All tunneling requires drilling and blasting. Tunnels stand well, but sheared zones, loose bedding, and jointing may necessitate local support. Large underground installations would require moderate support. Seepage and drainage are rapid in fractured zones. This unit is poor for petroleum storage, as leakage may contaminate ground water.

Suitability for road construction: Alignments of existing roads have short-radius curves. Widening and straightening of existing roads, or construction of new roads, require much excavation, some tunneling and bridge building. Subgrade and drainage conditions are excellent. Excavated rock can be used for aggregate and riprap.

Pit and quarry exploitation: A few quarries have been worked in the crystalline limestone. Potential quarry sites are numerous, especially on Motobu-hantō (pl. 19 B). Crystalline limestone is the best source of good-quality aggregate on Okinawa, but it is generally distant from population centers.

Method and facility of excavation: Drilling and blasting are required. Large working faces could be operated in quarries. Drainage is no problem above the water table.

Slope stability and erosion protection required: Steepest naturally stable slopes range from 1/4:1 to vertical. Slump blocks have formed in the geologic past, but rate of formation is too slow to constitute a problem in excavation. No erosion protection is required.

Drainage: Depth to water table varies with topography; usually very deep. Seepage and drainage are very rapid along joints and shears. Tunnels may require lining and pumping in fractured zones.

Greenstone (unit 10)

Occurrence and topographic characteristics: Greenstone is found in the mountainous terrain of the highly dissected terraces of Motobu-hantō and the western slope of the backbone ridge of northern Okinawa.

Description of material: The greenstone is a fine-grained, greenish, crystalline rock composed principally of amphibole or chlorite with some epidote and feldspar, and minor amounts of pyrite. Most of this unit is soft and friable from weathering to a depth of 20 or 30 feet; weathering is severe in shear zones adjacent to faults, and concentrations of pyrite accelerate decomposition. Moderately hard, fairly fresh, strong rock is scarce and confined mainly to canyons and some sea cliffs along the coast. The unweathered rock is fractured, somewhat platy and easily broken along innumerable weak cleavages.

Fragmentation and crushing characteristics: This rock is sufficiently jointed and fractured to greatly facilitate fragmentation. Recovery of firm blocks larger than 8 or 10 inches is difficult. Moderately fresh rock is fairly tough but is crushed without difficulty to very angular and somewhat elongate particles with a high percentage of fines. Crushing the weathered rock produces a high percentage of waste material.

Tunneling and underground storage: Drilling and blasting are required. Tunnels stand moderately well without timbering, but large galleries require support, especially in the closely jointed, highly fractured zones. Seepage is rapid in shear zones. Concrete linings should be sulfate resistant as weathering of pyrite makes water slightly acid.

Suitability for road construction: Most existing roads are narrow, have short-radius curves, and poor visibility; widening requires deep cuts and fills. New alignments would also require deep cuts, fills, and possibly bridges. Subgrade and drainage conditions are good.

A. Pinnacle near Awa, on the south coast of Motobu-hantō, composed of crystalline limestone.

B. Terrain near Sugā on the south coast of Motobu-hantō. The vegetation-covered slope is underlain by crystalline limestone. Steep hills in the background are massive limestone; terrace in the foreground is covered with large blocks of limestone.

Residual soils and extremely weathered rock are slippery when wet. Below depths of 20 or 30 feet much of the excavated rock can be used for concrete and asphalt aggregate, wearing course, surfacing, and possibly light riprap.

Pit and quarry exploitation: No quarries are developed in the greenstone. Potential sites are few and access to them is difficult. Fracturing and jointing are favorable for quarry operation. Greenstone is not suitable as stone for heavy riprap or masonry.

Method and facility of excavation: Extremely weathered and highly shattered rock may be removed with difficulty by hand or machine tools. Drilling and blasting are necessary for effective excavation of large quantities of unweathered rock.

Slope stability and erosion protection required: Cuts should stand vertically in little-broken rock; 1:1 to 2:1 in shattered rock. The steepest naturally stable slope is 1:1. Shattered zones run badly in cuts. Unfavorably oriented foliation and fracture may cause slides of large masses. Retaining walls or low slopes are needed to prevent this. In areas lacking shattered zones and unfavorably oriented fractures no protection is required.

Drainage: Depth to water table varies with the topography; ranges from surface to several hundred feet deep. Seepage is rapid in shattered zones; elsewhere slow. Drainage or pumping is required to prevent flooding and ponding in all excavations because clay or rock floor from weathered or excavated greenstone impedes drainage. Tunnels require lining to prevent seepage.

Remarks: This unit contains many prospect tunnels for copper ore and one formerly productive copper mine.

Platy foliated rocks (unit 11)

Occurrence and topographic characteristics: Platy, foliated rocks occur only north of Katena. They underlie the backbone range of mountains and the broad dissected terraces of northern Okinawa. The terrain is rugged, with deep, steep-sided canyons and dense forest growth. Streams have steep gradients with many cascades and falls. Linear valleys form along faults and shear zones.

Description of material: This unit contains several types of platy, foliated metamorphic rocks, including chlorite and sericite schist, phyllite, greenstone, and schistose feldspathic sandstone, in a mixed, interbedded sequence. Beds of very fine-grained quartzitic rock are present on Motobu-hantō. All types are severely folded, fractured, and faulted. Jointing is poorly developed. Thin quartz veins and lenses are common, especially along the west side of the island. Weathering extends as deep as 50 feet below the surface. Sulfate coatings are locally developed by decomposition of pyrite. Fresh surface rock is limited to sea cliffs and the walls of deep, actively eroding streams.

Fragmentation and crushing characteristics: Fracturing and foliation induce high fragmentation. Most fresh rock is weak with low resistance to shearing stress parallel to the foliation. Fresh rock crushes without difficulty to flaky, elongate fragments with a very high percentage of fine waste material.

Tunneling and underground storage: Driving of tunnels in fresh rock requires drilling and blasting; in weathered zones blasting aids in tunneling. Tunnels require support, as rock breaks along foliation or bedding. Acid water in weathering zones necessitates sulfate-resistant cement for linings. Lining is required as seepage is fairly rapid during the wet season. Drainage is rapid above the water table, except when floors become impermeable with accumulated clay. The rough terrain provides many possible sites for adits.

Suitability for road construction: Existing roads along coast are narrow with sharp curves and poor visibility. Road widening and new alignments, over most of this unit, would require many deep cuts and fills, tunnels, and bridges. Alignments along ridge tops are less difficult. Subgrade and drainage conditions are good except in severely weathered, clayey zones. Unsurfaced roads rapidly develop ruts.

Pit and quarry exploitation: No quarries or pits are developed in this unit as rock is unsuited for construction material.

Method and facility of excavation: Deeply weathered layer, which attains maximum depth of about 50 feet, can be removed by hand tools and power equipment. All fresh and moderately fresh rock requires drilling and blasting.

Slope stability and erosion protection required: Estimated stable slope ratio for this unit is 1/2:1 in fresh rock; 1:1 in weathered rock. Unfavorably oriented foliation will lower the ratio. Ratio of steepest naturally stable slopes is 1:1. Large masses of rock may slide on planes of foliations or fracture, especially when wet. Roads on weathered rock need drains to prevent development of gullies.

Drainage: Water table is generally near the elevation of valley bottoms, but it varies with the topography; ranges from surface to more than 50 feet deep. Seepage and drainage are fairly rapid, especially in shear zones. Excavations may require lining to prevent seepage. Deep excavations will require pumping or draining.

Remarks: Permeability and strength of rocks vary with relation to plane of foliation.

Sandstone (unit 12)

Occurrence and topographic characteristics: Sandstone occurs north of Katena and is extensive only north of Kin, generally along the east side of the island. It underlies the backbone range of mountains and the broad dissected terraces of northern Okinawa. The terrain is rugged with deep, steep-sided canyons and dense forest growth. Streams have steep gradients with many cascades and falls. Linear valleys form along fault and shear zones.

Description of material: Sandstone is medium grained, feldspathic, interbedded with lesser amounts of clay slate and phyllite. Fresh sandstone composed of feldspar and quartz grains in a matrix of chlorite and sericite, is gray to gray green, tough, and fairly hard. Highly weathered rock, composed of fine quartz grains in a clayey matrix, is buff to brown, friable, and soft. Exposed rock shows gradations in weathering. Intense weathering is encountered as far as 50 feet below terrace surfaces; most exposures of the unit are moderately weathered. Fresh rock crops out only in deep stream canyons and at the base of high sea cliffs. Individual beds are a few inches to about 10 feet thick. Total thickness of unit is several hundred feet. Thin veins of quartz are disseminated through the sandstone. Pyrite is present in small amounts.

Fragmentation and crushing characteristics: Fresh sandstone is tough and similar in many respects to trap rock. Fairly high fragmentation will be obtained only in thin-bedded, closely jointed zones and not in thick beds with wide joint spacing. Fresh rock crushes with difficulty to cubical fragments. Most of the surface rock is weathered and moderately soft; not suited for crushing or construction purposes.

Tunneling and underground storage: Tunnels can be driven easily in weathered rock; in fresh or little-weathered rock, blasting is required. Tunnels stand well without support except for large chambers and tunnels in thin-bedded and fractured zones where timbering is required. Seepage and drainage are moderately rapid. Steep slopes provide many possible sites for adits, but most are inaccessible from present roads.

Suitability for road construction: Existing roads along coasts are narrow with sharp curves and poor visibility. Widening and straightening them would require excessive excavation, bridges, and perhaps tunnels. New alignments over most of this unit would require deep cuts and fills, bridges, and tunnels. Subgrade and drainage conditions are good in fresh to moderately weathered rock but fair in well-weathered material.

Pit and quarry exploitation: No pits or quarries have been developed. Potential quarry sites occur within the unit but are inaccessible from existing roads except along the northwest coast.

Method and facility of excavation: Well-weathered rock can be removed by hand tools and power equipment. Excavations in fresh rock require drilling and blasting.

Slope stability and erosion protection required: Cuts will stand vertically in fresh rock. In weathered rock, for cuts of 25 feet or less, the estimated stable slope ratio is 1/2:1. Unfavorable orientation of bedding planes may necessitate gentler slopes. Steepest naturally stable soil-covered slopes are 1 1/2:1. Large masses may move along bedding planes, especially when wet. Weathered rock stands well with little erosion on steep faces. Gentler slopes, and slopes where runoff is concentrated, gully rapidly.

Drainage: Water table is generally near the elevation of valley bottoms but varies with the topography and ranges from surface to more than 50 feet deep. Seepage and drainage are moderate to rapid, depending on the degree of fracturing and weathering of material. Excavations may require lining to prevent seepage. Deep excavations may require pumping or drainage.

Porphyry dike rock (unit 13)

Occurrence and topographic characteristics: Porphyry dikes are most common on the west side of northern Okinawa (pl. 9 A) and Motobu-hantō.

Description of material: Porphyry dike rocks are massive, gray, and finely crystalline containing large phenocrysts of feldspar with less-abundant quartz, biotite, and hornblende. There is a marked variation in mineral composition; some dikes have no quartz, some no biotite, some no hornblende. Dikes range from a few feet to a third of a mile in width and are as much as several miles long. Only large dikes are shown on Plate 1. Jointing is well developed (pl. 9 A). Narrow dikes generally have well-developed columnar jointing; wider dikes have blocky, more widely spaced jointing. Biotite is commonly oriented parallel to the tabular shape of the dike. Weathering is marked and some dikes are completely altered to clay minerals. All gradations from slightly weathered to completely weathered rock are exposed. Exposures of fairly fresh rock are rare and most are inaccessible.

Fragmentation and crushing characteristics: Fragmentation is induced by well-developed joints. In several quarries, columnar jointing produces six-sided columns of rock up to 2 feet long. Moderately weathered rock crushes without difficulty to chip-shaped, elongated particles, with a high percentage of waste material. Most of the unit is too soft for use as aggregate.

Tunneling and underground storage: Excavation characteristics depend on the amount of weathering. Excavation by hand tools is possible in weathered material; tunnels stand well and are not bothered by seepage. Moderately weathered and fresh rock require drilling and blasting; tunnels stand well, except where joints are well developed, close, and loose. Seepage may occur in jointed rock.

Suitability for road construction: Most dikes are too small to be important in road building. The large dike on the west coast furnishes good subgrade with comparatively little drilling and blasting but will furnish poor material for base course and wearing course.

Pit and quarry exploitation: There is limited development of quarries for dimension stone and monuments. Existing quarries utilize weathered rock. Potential quarry sites for fresh, hard rock are rare and difficult to reach. Highly weathered dikes with low iron content have been exploited for china clay.

Method and facility of excavation: Deeply weathered material easily removed by hand tools or power equipment. Moderately weathered and fresh rock require drilling and blasting.

Slope stability and erosion protection required: Estimated stable slope ratio is nearly vertical in fresh rock, if not badly jointed (pl. 9 A); vertical in deeply weathered material. Steepest naturally stable slopes are vertical to 1:1. Blocks break out along columnar joints and fall from steep exposures. Weathered rock erodes and gullies but not severely. Vegetation stabilizes gentle slopes.

Drainage: Depth to water table varies with the topography, but generally is near the elevation of the valleys. Seepage and drainage are slow to rapid, depending on the amount of jointing. Drainage control is required for extremely weathered rock.

Glossary

amphibole - A common rock forming mineral; a silicate of calcium and magnesium and usually iron and magnesium.

basal water table - Ground water in hydrostatic equilibrium with sea water. Compare with artesian (under hydrostatic pressure) and perched (trapped at higher subsurface levels by impermeable rock).

base course - Specially selected soils, treated soils or aggregates, placed and compacted on the subgrade to increase the wheel-load capacity.

basement rocks - As used in this report, a general term referring to the hard-rock foundation of a region; may occur at the surface or under any thickness, up to thousands of feet, of sediments.

beach rock - Bedded rock formed by the consolidation of beach materials.

bench - A narrow, approximately horizontal, terrace or steplike ledge.

blanket course - A 1- to 2-inch layer of sand or screenings spread over a plastic and cohesive soil subgrade to prevent it from mixing with the base course.

bog - A wet, spongy morass, chiefly composed of decayed vegetal matter.

chert - A very fine-grained dense rock primarily consisting of opal or chalcedony. It is usually associated with limestones, either as entire beds or as isolated, included masses. It has a homogeneous texture and a white, gray, or black color.

chlorite - A silicate of aluminum with ferrous iron and magnesium and chemically combined water, characterized by its green color.

columnar jointing - Jointing where the fissures form polygonal columns.

conchoidal fracture - A break having faces with elevations and depressions resembling a bivalve shell; like the surface of a piece of broken glass.

concretion - A spherical to disc-shaped or irregular body ranging in size from a pebble up to several feet in diameter, formed by the segregation and precipitation of some soluble material; generally in rock of a composition different from its own and from which it separates on weathering.

detrital - Pertaining to rock debris formed by natural mechanical processes.

dike - A wall-like intrusion of igneous rock, which cuts across the bedding or other layered structure of the country rock.

drip stone - The stalactites and stalagmites of caves formed by the precipitation of calcium carbonate from dripping water.

epidote - A yellowish-green mineral composed of a basic orthosilicate of calcium, aluminum, and iron.

fault - A break or shear along which there has been observable displacement.

feldspar - Any of a group of crystalline minerals, aluminum silicates with either potassium, sodium, calcium, or barium. An essential constituent of nearly all granitelike rocks.

foliation - The structure of a rock showing characteristically parallel layers or lines of one or more of the conspicuous minerals of the rock.

friable - Easy to break, or crumbling naturally.

hornblende - A dark aluminous variety of the mineral amphibole.

interstitial - Pertaining to the voids or spaces in a rock or soil.

joint - A parting, crack, fissure, or fracture in rock along which there has been no observable displacement.

massive - Occurring in thick layers, if stratified at all, and free from minor fractures and planes of separation.

matrix - The general mass of a rock in which isolated crystals or larger fragments are embedded.

metamorphic - Altered by geologically great age, heat, or pressure.

parent material - In soil science, the rock material from which soil was or is now being formed.

phenocrysts - Term applied to isolated or individual crystals, usually visible to the naked eye, which are embedded in a finer grained matrix of rock.

phyllite - A compact lustrous finely foliated rock with its minerals less well defined than in a mica schist.

platy - Structure of a rock, characteristically thin plates or tabular sheets, which gives it a stratified appearance.

pumice - A variety of volcanic glass, full of minute cavities and very light.

pyrite - A hard, heavy, shiny yellow mineral composed of sulfur and iron, generally in cubic crystals.

Quaternary - The latest period of geologic time. One of the two periods comprising the Cenozoic Era.

raised beach - A shelf or terrace of gravel and sand higher than present-day beaches. May be the result of land uplift or lowering of the sea or both.

raveling - The process of flaking or spalling that occurs in material after it has been exposed.

schist - Those foliated metamorphic rocks, whose individual folia are mineralogically alike, and whose principal minerals are so large as to be visible to the naked eye.

schistose - Pertaining to or having the nature of schist.

sericite schist - Mica schist with mica in a more or less fibrous form.

shear zone - In geology, a zone in which shearing has occurred on a large scale, so that the rock is crushed and brecciated.

sinkhole - A vertical hole worn by water into limestone along a joint or fracture. Also called swallow hole.

slake - To become slack and loose.

sloughing - To shed or castoff an outer layer.

slump block - Large detached, isolated mass or block of rock that falls, slides, or rolls down steep hillside slopes, sometimes for a considerable distance from the parent bed.

stalactite - Columnar deposits, generally of calcite, formed on the roof of a cavern by the drip of mineral solutions.

subgrade - Applies to the natural soil in place or to fill, upon which a pavement or base is constructed.

surface course - The top portion of a road structure, which comes into direct contact with the wheeled load or tracked load. It is intended to resist wear and dusting and to prevent surface water from infiltration into the road structure.

swallow hole - See sinkhole.

Tertiary - The earlier of the two geologic periods comprising the Cenozoic Era. See Quaternary.

wearing course - See surface course.