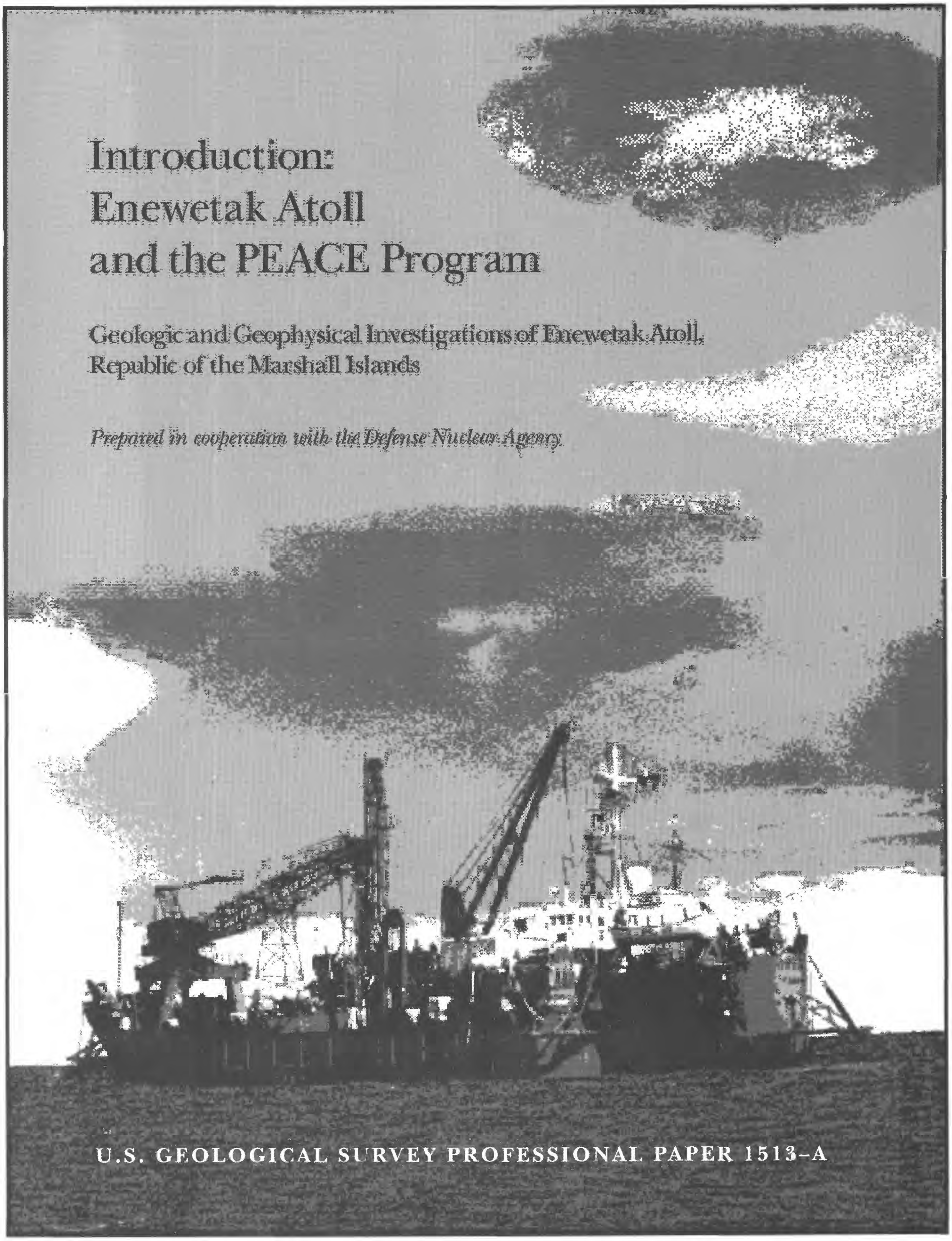
Introduction: Enewetak Atoll and the PEACE Program

Geologic and Geophysical Investigations of Enewetak Atoll, Republic of the Marshall Islands

Prepared in cooperation with the Defense Nuclear Agency



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Introduction: Enewetak Atoll and the PEACE Program

By THOMAS W. HENRY *and* BRUCE R. WARDLAW

GEOLOGIC AND GEOPHYSICAL INVESTIGATIONS OF ENEWETAK ATOLL, REPUBLIC OF THE MARSHALL ISLANDS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1513-A

A compilation of studies originating from the Pacific Enewetak Atoll Crater Exploration (PEACE) Program, prepared in cooperation with the Defense Nuclear Agency

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METRIC CONVERSION FACTORS

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply inch-pound units	By	To obtain metric units
foot (ft)	0.3048	meter (m)
nautical mile (nmi)[1]	1.852	kilometer (km)
nautical mile^2 (nmi^2)[1]	3.430	kilometer^2 (km^2)

[1]U.S. nautical mile.

ALTITUDE DATUM

Sea level: The term "sea level" generally refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929. The tidal datum used in this report was established in 1952 during Operation IVY jointly by the U.S. Coast and Geodetic Survey and Holmes and Narver, Inc. (H&N). The datum used is 0.5 ft below the mean-low-water-spring-tide level (MLWS), which is the datum used on the navigation charts of Enewetak Atoll produced by the U.S. Navy Hydrographic Office. Individual tidal datums for several of the northern islands were established in 1951 and 1952 by Holmes and Narver. These datums are 0.5 ft below *approximate*-mean-low-water-spring tide (AMLWS). In this report, "sea level" refers to the AMLWS datum of 1951–52, also called the H&N datum.

INTRODUCTION: ENEWETAK ATOLL AND THE PEACE PROGRAM

By THOMAS W. HENRY and BRUCE R. WARDLAW

ABSTRACT

An extensive study was made from June 1984 through August 1985 of the surface and subsurface configurations of two large nuclear craters on the northern side of Enewetak Atoll, Republic of the Marshall Islands. These craters, KOA and OAK, resulted from the near-surface detonation of two high-yield thermonuclear devices in 1958, when the atoll was part of the Pacific Proving Grounds. This multidisciplinary study was designed to produce a broad, well-documented geologic, geophysical, and materials-properties data base for use in answering critical questions concerning craters formed by high-yield bursts. The study was part of a larger research initiative by the U.S. Department of Defense to better understand high-yield, strategic-scale nuclear bursts and how Pacific Proving Grounds craters relate to the basing and targeting of nuclear-weapon systems and related national defense issues.

The data gathered during the study of the Enewetak craters are applicable to many scientific topics well beyond cratering mechanics and other related strategic concerns of the Department of Defense. These scientific topics include the geologic evolution of the Pacific Basin, the biologic and geologic history of a coral atoll, the fluctuation of sea level in response to glaciation and deglaciation, the diagenetic history of carbonate rocks in relation to sea-level changes and the differing substrate-water geochemistries thus produced, the speciation and migration of marine biotas, and the biostratigraphic succession of biotas through time and the calibration of these events with an absolute isotopic time scale, to name a few. The objective of this U.S. Geological Survey Professional Paper series is to provide a forum for these studies.

GENERAL REMARKS

From mid-1984 through mid-1985, the U.S. Geological Survey (USGS) conducted geologic and geophysical investigations of two craters formed by the detonation of high-yield, near-surface nuclear devices at Enewetak Atoll in the Marshall Islands (figs. 1, 2). These investigations are collectively referred to as the Pacific Enewetak Atoll Crater Exploration (PEACE) Program. The craters studied, KOA and OAK, resulted from 1.4- and 8.9-megaton (Mt)-yield detonations on May 12 and June 28, 1958, respectively, near the northern perimeter of Enewetak lagoon. At that time, Enewetak was administered by the U.S. Government through the Trust Territories of the Pacific Islands and was part of the Pacific Proving Grounds (PPG), where, on remote atolls and islands from 1946 through 1962, atmospheric nuclear testing was carried out. KOA and OAK are among the few craters produced by high-yield, near-surface bursts that are available for study.

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Few sedimentary geologic environments are more heterogeneous than a coral atoll. An analogy between a Pacific atoll and an inverted bucket filled with sediment is appropriate. The reef facies is the hard, competent, cemented exterior formed by an organic framework dominated by coralline algae and corals. The backreef environment, where the islands are generally located, consists of a spectrum of carbonate materials ranging from uncemented to well cemented. Here, a group of generally inorganic (marine) processes acts to cement the sediment in selected areas to form what generally is referred to as "beachrock." Thus, the reef and backreef environments are the hard rim of the bucket. The bucket is filled with finer grained, lagoonal sediment that generally is much less cemented or uncemented and consequently is less competent than the rim. Also scattered throughout the lagoon of any atoll the size of Enewetak are numerous patch or pinnacle reefs. These lagoonal reefs are structurally competent edifices. However, within the material inside the bucket (that is dominated by the finer grained sediment) are layers that have been more or less cemented by postdepositional nonmarine (ground water) geochemical processes during periods of atoll emergence. These periods of emergence were believed to have resulted from global lowstands of sea level during glacial periods. These cemented layers extend some distance inward toward the middle of the

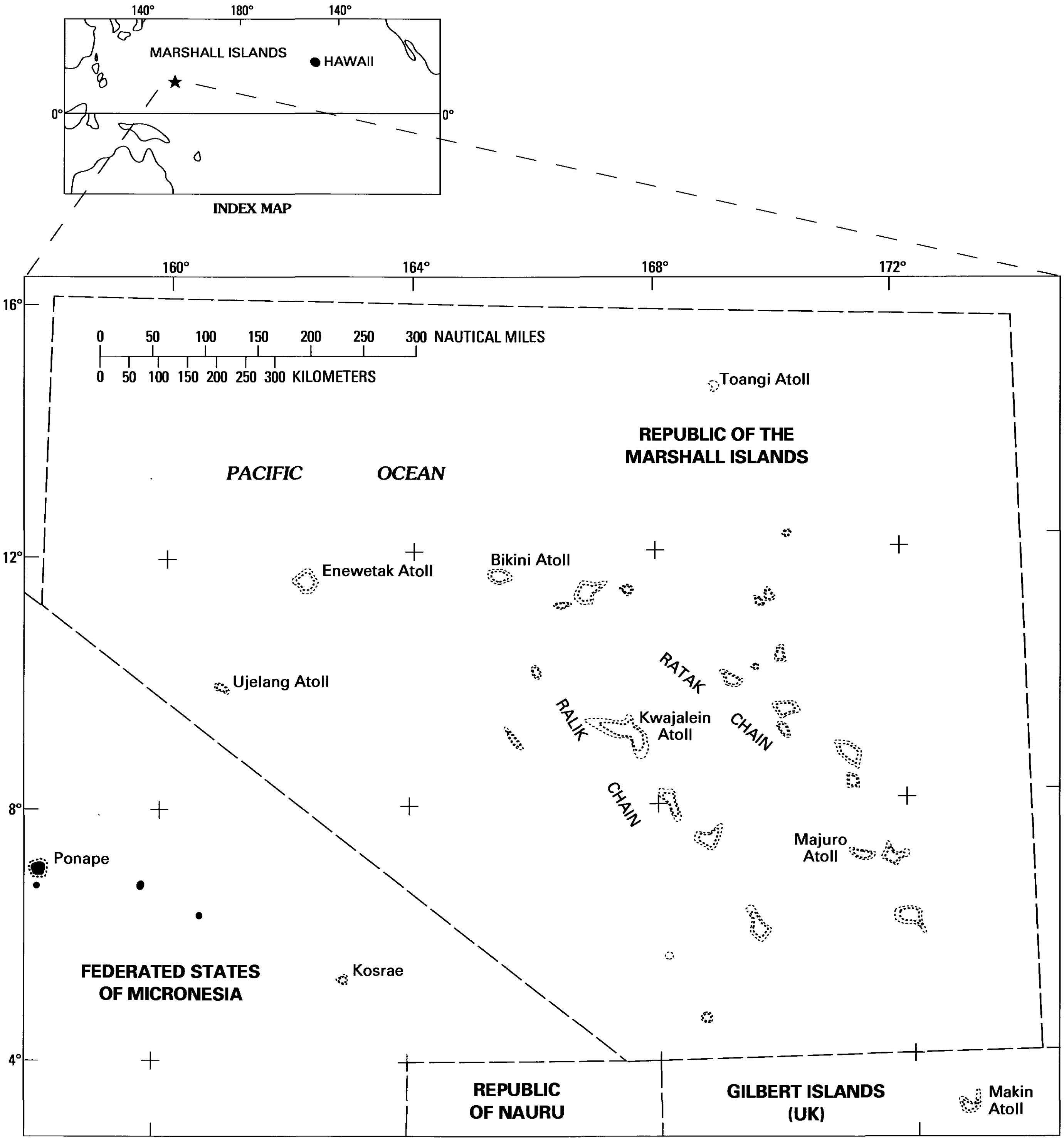

FIGURE 1.—Index map showing location of the Marshall Islands in the Pacific Ocean and geographic map of the Republic of the Marshall Islands.

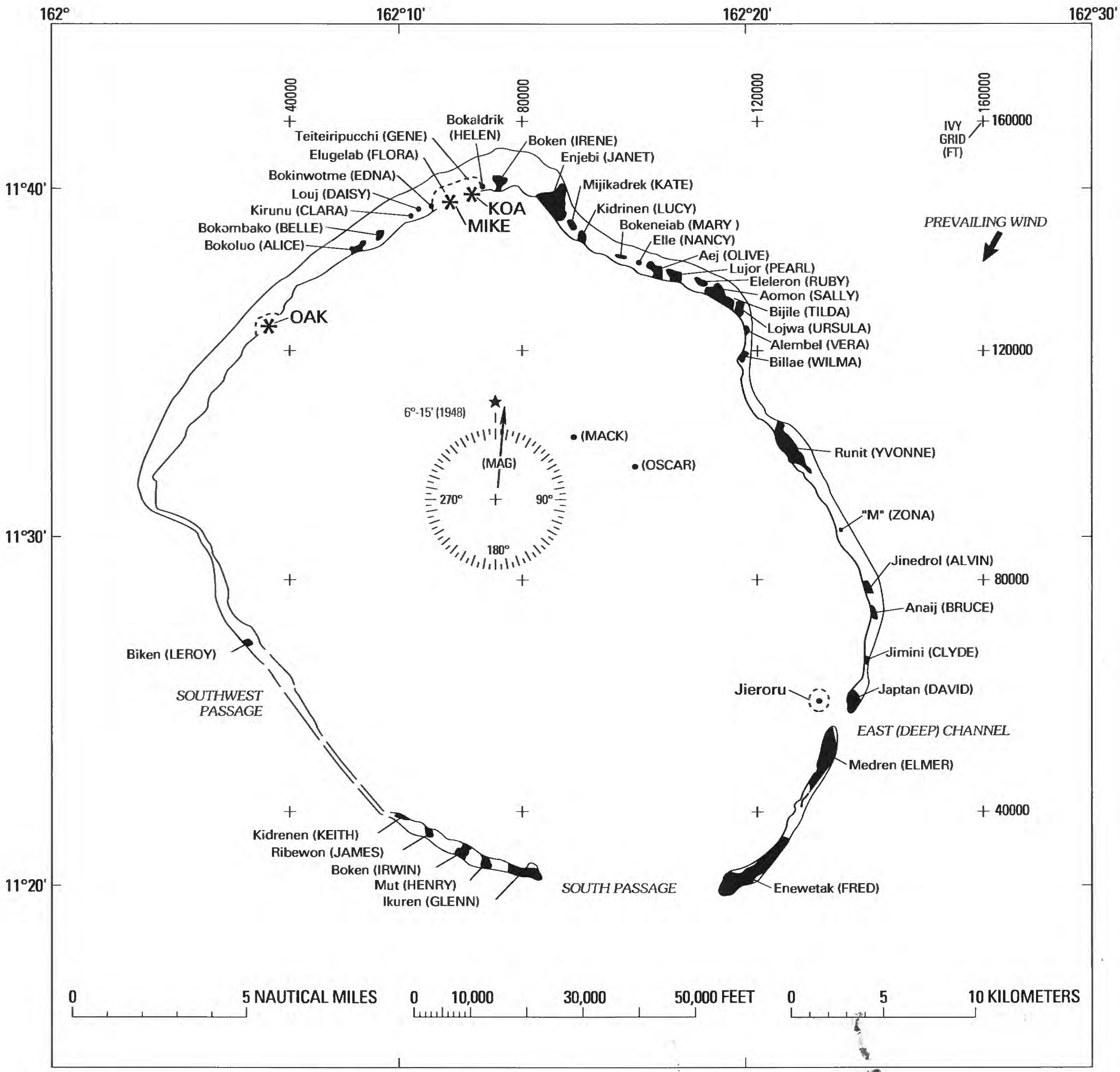

FIGURE 2.—Enewetak Atoll, Republic of the Marshall Islands, with locations of principal islands and other features (native names followed by military site names in parentheses), OAK, KOA, and MIKE craters, and MACK and OSCAR pinnacles. Jieroru is a small sand island inside the East Channel that was not given a site name. Magnetic declination (1948) shown in compass.

lagoon. This was the environment in which many of the high-yield, near-surface PPG nuclear bursts were detonated.

BASIC PROBLEM

Prior to the PEACE Program, the craters formed from near-surface bursts in the PPG were thought to differ in several critical ways from craters produced by both high-explosive and low-yield nuclear bursts in dry test beds at the Nevada Test Site[1] or, for that matter, elsewhere. The craters produced by high-yield bursts in the PPG were all formed in wet carbonate substrates. They have saucer-shaped apparent-crater profiles that are extraordinarily broad and shallow. The apparent

[1]These are generally referred to as continental United States (CONUS) sites.

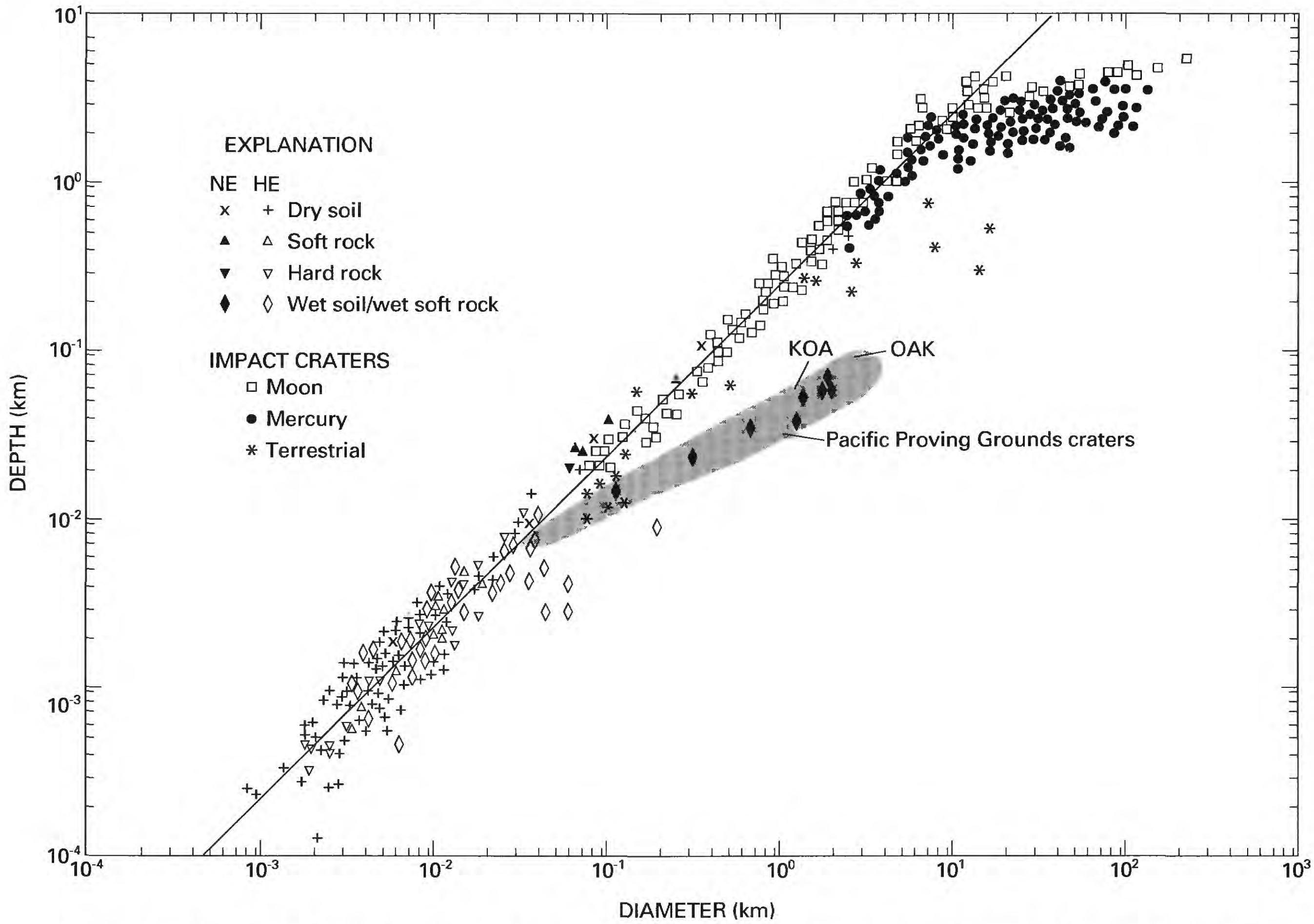

FIGURE 3.—Dimensions of explosion and impact craters (from Cooper, 1977). NE, nuclear explosive; HE, high-yield explosive.

craters[2] resulting from these high-yield PPG bursts have high aspect ratios[3] and, consequently, large volumes. The data base for PPG craters was extremely small and, because of the remoteness of the PPG and political considerations, difficult to augment. In contrast, the CONUS craters, for which a large data base was easily obtained and easily expanded, have bowl-shaped apparent-crater profiles that are small and proportionally deeper. These apparent craters have low aspect ratios and proportionally small volumes. In this sense, the CONUS craters are more similar to some impact (meteor) craters than to the PPG craters (see fig. 3).

Research in the PPG undertaken in the 1970's, principally by the Defense Nuclear Agency (DNA), suggested that geologic and hydrologic environments influence late-time cratering processes and, therefore, play a fundamental role in determining the *final* morphology and size of a crater (Knowles and Brode, 1977; Ristvet and others, 1978; Brode, 1979). To quote Cooper (1977, p. 20), "In general, the variation in cratering efficiency appears to correlate with media strength, i.e., the weaker the medium, the larger the crater." It was suggested that processes operating in response to the water-saturated, "weak" geologic substrates were responsible for significant "late-stage" modifications of the PPG craters and that the aspect ratios of the *excavational craters* (not the final apparent craters) resulting from PPG high-yield bursts were in fact much closer to aspect ratios predicted by first principle calculations and to aspect ratios at CONUS sites.

Computational models capable of simulating a wide variety of phenomena associated with high-explosive and low-yield nuclear bursts were available by the late 1970's. However, to summarize, the PPG craters (as observed and measured) formed by high-yield bursts and scaled to their CONUS counterparts were anomalous in shape and volume and could not be modeled confidently (Cooper, 1977; Knowles and Brode, 1977). The marked difference in crater volume between the predictions from

[2]Apparent crater is the locus of the zero-difference contour line surrounding a crater—that is, the locus of points along which the effects of an explosion can no longer be detected when the preevent contours are compared with the postevent contours (B.L. Ristvet, pers. commun., 1986).

[3]Aspect ratio is the ratio of crater depth to radius; the PPG craters typically have aspect ratios of about 3:5, CONUS craters, 1:2.

modeling and observations of existing PPG craters—a difference in the realm of an order of magnitude—and the lack of confidence in the fundamental data base itself resulted in considerable uncertainty about the Defense community's ability to predict the effectiveness of nuclear weapons against targets and the attendant capability of strategic installations to functionally survive a nuclear burst. Of particular concern were hardened, underground installations.

PACIFIC PROVING GROUNDS AND ENEWETAK NUCLEAR TESTING

The U.S. Government conducted atmospheric nuclear tests in the Pacific from 1946 through 1962, before the Limited Test-Ban Treaty of 1963 mandated that all further testing of nuclear weapons be conducted underground[4]. Enewetak and Bikini Atolls together constituted the western part of the PPG, which was created in 1948. The PPG, Amchitka in the Aleutian Islands, and Pahute Mesa on the Nevada Test Site were the only sites where the U.S. Government tested megaton-range nuclear devices. After the residents of Enewetak and Bikini Atolls were moved to nearby atolls, nuclear shots were conducted from 1946 through 1958—26 on Bikini Atoll and 43 on or in the vicinity of Enewetak Atoll (Hines, 1962; Defense Nuclear Agency, 1981; Bliss, 1982). On October 31, 1958, the United States and the Soviet Union began a joint moratorium on atmospheric testing of nuclear weapons. In fall 1961, however, the Soviets resumed atmospheric nuclear testing. The United States responded in 1962 with a series of 34 nuclear tests in the vicinity of Johnston Atoll and Christmas Island in the central Pacific and 4 low-yield tests at the Nevada Test Site.

The first PPG nuclear tests were conducted on Bikini Atoll in 1946 during Operation CROSSROADS. The first nuclear test on Enewetak Atoll was on April 14, 1948, as part of Operation SANDSTONE, a three-shot program staged from 200-foot (ft)-tall, island-based towers. The tests on Enewetak were primarily weapons related, although attempts were made to understand explosion phenomena and the blast effects on various types of manmade structures. Additional studies were conducted to measure biologic exposure and responses, to evaluate detection instruments, to compare nuclear-yield determinations, and so forth (Bliss, 1982, p. 1).

Table 1 lists the nuclear tests conducted on Enewetak Atoll. All but three of the Enewetak detonations occurred on or in the vicinity of the northeastern band of islands on the atoll (fig. 4).

[4]The Limited Test-Ban Treaty did allow near-surface nuclear explosions for peaceful purposes, such as excavations for harbors and canals.

OBJECTIVES OF PEACE PROGRAM

The PEACE Program was a broad research initiative formulated by the DNA for the U.S. Department of Defense (DOD) to answer a number of key questions about the dynamic properties of strategic-scale nuclear bursts and the relevance of the large craters of the PPG to strategic issues. The multidisciplinary study of KOA and OAK craters conducted by the USGS on Enewetak was part of the PEACE Program. These two craters were selected because of their accessibility and their differing source characteristics (see section on "Interim Events (1981–1984) Leading to PEACE Program").

The specific objectives of the DOD for the USGS portion of the PEACE Program were (1) formulation of a geologic and geophysical framework for the stratigraphic section (substrate or "test beds") in which the craters were formed, (2) identification and description of crater morphology, physiography, and structure, and measurement of the dimensions of primary crater features, (3) acquisition of new material-properties data from the PPG substrates, and (4) better understanding of the processes that both formed the excavational crater and altered that early-stage feature to the crater observed today (that is, the apparent crater). Establishment of a geologic framework in which to place the new PPG material-properties data was extremely important to the DNA for effective testing of computational modeling of a high-yield nuclear event (code validation). As stated simply by Cooper (1977, p. 14), the larger of two main sources of error in simulating high-yield nuclear events is the "state-of-ignorance of the dynamic response of geologic media."

ROLES, DATA BASES, AND DATA ACQUISITION

Enewetak Atoll lies in a geographically highly remote area. Successful operation of any large-scale research program in such an area requires careful thought and planning. Acquisition of data from Enewetak and the logistics were a collaborative effort between the USGS, the DNA, the U.S. Department of Energy (DOE), other Federal agencies, private contractors and research laboratories, personnel from several universities, officials of the newly formed Republic of the Marshall Islands (RMI), and the people of Enewetak.

The USGS conducted the geologic, paleontologic, and geophysical investigations of OAK and KOA and worked closely with DNA contractors on analysis of the downhole geophysical logging, on the borehole gravimetry, and on parts of the other material-properties studies. As originally planned, all field operations on Enewetak were to be conducted concurrently. However, the fieldwork later was divided into two major phases, the Marine

TABLE 1.—*Dates and locations of nuclear detonations on Enewetak Atoll*

[ft, feet; kt, kiloton; Class., classified; Mt, megaton. 1 Mt = 1,000 kt]

Event name	Date	Burst type/ height	Yield	General location[1]	IVY-grid coordinates	
	1948					
X-RAY	Apr. 14	Tower, 200 ft	37 kt	JANET	147,330 N.	083,569 E.
YOKE	Apr. 30	Tower, 200 ft	49 kt	SALLY	130,907 N.	111,993 E.
ZEBRA	May 14	Tower, 200 ft	18 kt	YVONNE	106,120 N.	124,364 E.
	1951					
DOG	Apr. 7	Tower, 300 ft	Class.	YVONNE	106,178 N.	124,318 E.
EASY	Apr. 20	Tower, 300 ft	47 kt	JANET	147,382 N.	083,515 E.
GEORGE	May 8	Tower, 200 ft	Class.	RUBY	130,947 N.	111,929 E.
ITEM	May 24	Tower, 200 ft	Class.	JANET	148,985 N.	086,450 E.
	1952					
MIKE	Oct. 31	Surface	[2]10.4 Mt	FLORA	147,754 N.	067,789 E.
KING	Nov. 15	Airdrop, 1,500 ft	500 kt	YVONNE	108,150 N.	124,130 E.
	1954					
NECTAR	May 13	Barge	1.69 Mt	MIKE crater area	147,750 N.	067,790 E.
	1956					
LACROSSE	May 4	Surface	40 kt	YVONNE, N. end	106,885 N.	124,515 E.
YUMA	May 27	Tower, 200 ft	Class.	SALLY	130,603 N.	112,155 E.
ERIE	May 30	Tower, 300 ft	Class.	YVONNE	102,060 N.	127,930 E.
SEMINOLE	June 6	Surface	13.7 kt	IRENE	149,897 N.	075,237 E.
BLACKFOOT	June 11	Tower, 200 ft	Class.	YVONNE	104,435 N.	126,080 E.
KICKAPOO	June 13	Tower, 300 ft	Class.	SALLY	132,295 N.	114,018 E.
OSAGE	June 16	Airdrop	Class.	YVONNE	102,851 N.	126,647 E.
INCA	June 21	Tower, 200 ft	Class.	PEARL	133,540 N.	105,300 E.
MOHAWK	July 2	Tower, 300 ft	Class.	RUBY	132,165 N.	109,737 E.
APACHE	July 8	Barge	Class.	MIKE crater area	148,063 N.	069,227 E.
HURON	July 21	Barge	Class.	MIKE crater area	148,304 N.	070,015 E.
	1958					
CACTUS	May 5	Surface	18 kt	YVONNE	106,370 N.	124,215 E.
BUTTERNUT	May 11	Barge	Class.	SW. of YVONNE	080,812 N.	123,319 E.
KOA	May 12	Surface	[2]1.37 Mt	GENE	149,360 N.	071,120 E.
WAHOO	May 16	Underwater, 500 ft	Class.	HENRY, oceanside	029,550 N.	061,515 E.
HOLLY	May 20	Barge	Class.	SW. of YVONNE	101,834 N.	124,943 E.
YELLOWWOOD	May 26	Barge	Class.	SW. of JANET	143,994 N.	078,161 E.
MAGNOLIA	May 26	Barge	Class.	SW. of YVONNE	101,344 N.	124,161 E.
TOBACCO	May 30	Barge	Class.	SW. of JANET	145,137 N.	079,779 E.
ROSE	June 2	Barge	Class.	SW. of YVONNE	080,811 N.	123,315 E.
UMBRELLA	June 8	Underwater[3]	Class.	N. of GLENN	042,615 N.	076,029 E.
WALNUT	June 14	Barge	Class.	SW. of JANET	143,996 N.	078,168 E.
LINDEN	June 18	Barge	Class.	SW. of YVONNE	101,877 N.	125,012 E.
ELDER	June 27	Barge	Class.	SW. of JANET	145,136 N.	079,790 E.
OAK	June 28	Barge	[2]8.9 Mt	SW. of ALICE	124,981 N.	036,108 E.
SEQUOIA	July 1	LCU	Class.	SW. of YVONNE	101,871 N.	125,000 E.
DOGWOOD	July 5	LCU	Class.	SW. of JANET	145,135 N.	079,786 E.
SCAEVOLA	July 14	Barge	Class.	SW. of YVONNE	102,638 N.	126,227 E.
PISONIA	July 17	Barge	Class.	W. of YVONNE	103,212 N.	114,678 E.
OLIVE	July 22	LCU	Class.	SW. of JANET	145,138 N.	079,790 E.
PINE	July 26	Barge	Class.	SW. of JANET	142,549 N.	076,110 E.
QUINCE	Aug. 6	Surface	Class.	YVONNE, middle	103,950 N.	126,185 E.
FIG	Aug. 18	Surface	Class.	YVONNE, middle	103,950 N.	126,185 E.

[1]Locations shown in figure 4.
[2]Thermonuclear device.
[3]Shot 5 ft off bottom in 150 ft of water.

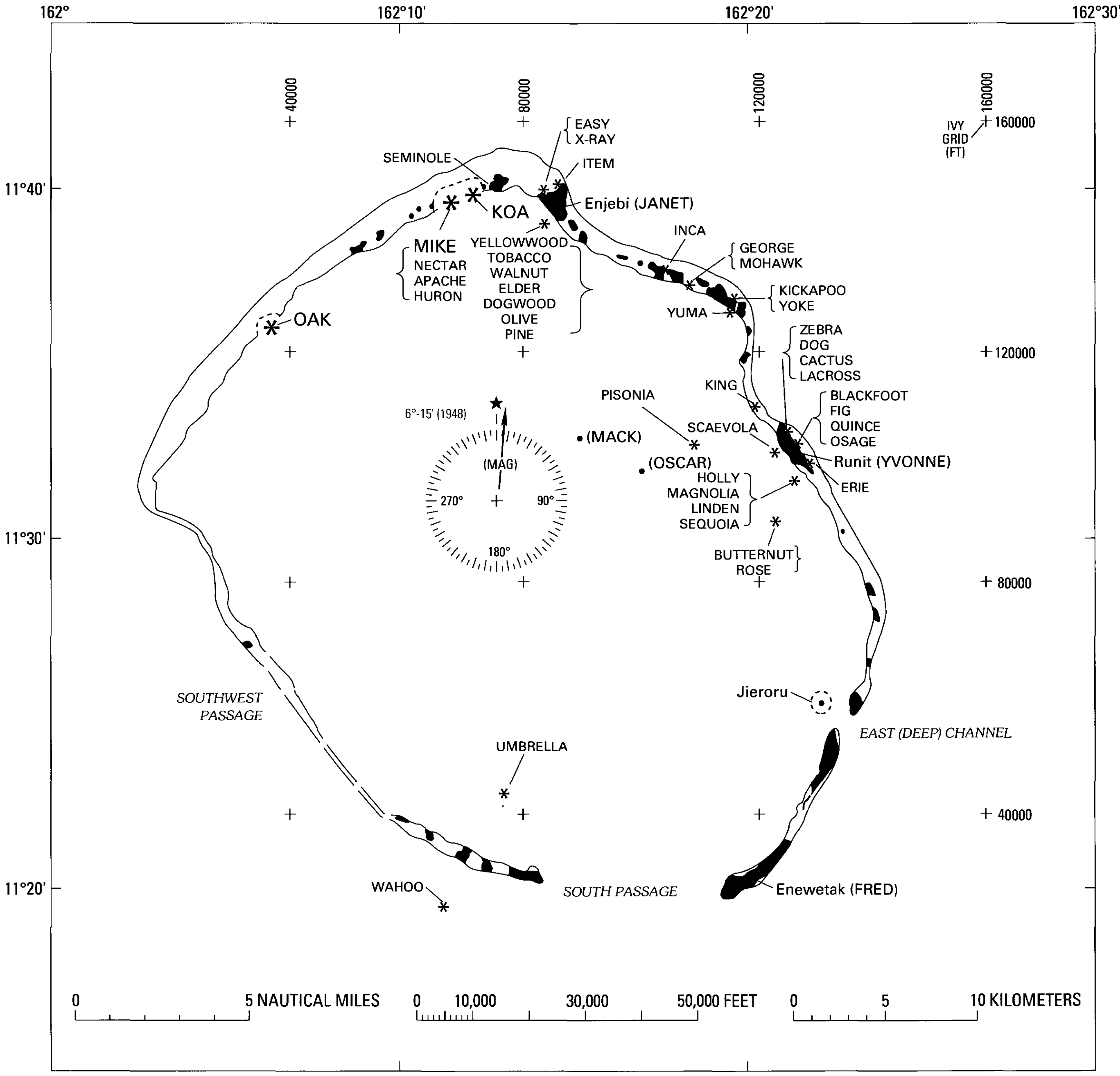

FIGURE 4.—Sites of detonations on Enewetak Atoll. Detonations having the same or approximately the same ground-zero location are grouped with brackets. Generally, large asterisks indicate thermonuclear bursts, and small asterisks nonthermonuclear nuclear detonations.

Phase and the Drilling Phase. The Marine Phase consisted of geophysical and geologic investigations of surface and subsurface characteristics of the two craters and environs. The Drilling Phase consisted of complementary geologic and geophysical assessments of borehole data.

PRE-PEACE PROGRAM DATA BASES

A wide array of pre-PEACE Program data from the PPG was reexamined during the USGS studies. Included were the following:

1. Published accounts in the USGS Professional Paper 260 series (Emery and others, 1954) from the initial geologic, geophysical, biologic, and oceanographic investigations in the Marshall Islands associated with the early phases of nuclear testing. Some of the original geologic samples and core were examined also.
2. Published reports and raw data from the geologic and geophysical studies of the PACE, EXPOE, and EASI Programs[5], sponsored by the DNA and conducted on Enewetak by the Air Force Weapons Laboratory (AFWL) (Henny and others, 1974a, 1974b; Couch and others, 1975; Ristvet and others, 1978; Tremba and others, 1981; Tremba and others, 1982; Tremba, 1987). Some of the multichannel seismic lines from EASI were reprocessed by Grow, Lee, and others (1986), and selected PACE/EXPOE boreholes were redescribed and analyzed petrographically, biostratigraphically, and isotopically before the Drilling Phase started (Cronin and others, 1986; Halley, Major, and others, 1986; Henry and others, 1986).
3. Other published scientific (biologic, geologic, oceanographic, radiologic) and general interest articles on Enewetak, the Marshall Islands, the PPG, and Pacific atolls. Included were the series of papers in the two-volume "The Natural History of Enewetak Atoll" edited by Devaney and others (1987) and released by the DOE.
4. Unpublished archival material from the PPG made available to USGS investigators by the DNA and the DOE. These data included pre- and postshot survey maps of the OAK and KOA crater areas, both black-and-white and color stereographic aerial photographs, other types of aerial photographs, and photographs made (both pre- and posttesting) from ground level of various crater features and manmade structures. Pre- and postshot maps of OAK crater prepared by Holmes and Narver, Inc., were digitized and form an essential part of the volumetric analysis for the PEACE Program (Peterson and Henny, 1987).

PREPARATORY ONSITE WORK

Navigational accuracy for locating point data for the PEACE Program was extremely important. The navigation network was controlled by five transponder stations placed on towers on the islands of Biken (LEROY), Bokoluo (ALICE), Enjebi (JANET), Lojwa (URSULA), and Enewetak (FRED) (fig. 2). Navigation specialists from Meridian Ocean Systems of Ventura, Calif., assembled the towers, set up the transponders, and tied them into the IVY-grid[6] net using Motorola Satellite Navigation Systems in January 1984. The tie-in of these stations to the IVY-grid was verified by specialists from the Defense Mapping Agency by geodetic surveys using a laser theodolite (Woodworth and Crothers, 1985; Folger, 1986a). Meridian Ocean Systems operated the Motorola Falcon-IV Miniranger system (accuracy about 10 ft) during both phases of the program.

In April 1984, just prior to the arrival of the main group of scientists and technicians for the Marine Phase, the USGS and the DNA conducted a successful pilot borehole-gravity study in an old, deep drill hole (E-1) on Medren (ELMER), one of the southern islands of the atoll (Beyer and others, 1986; Beyer, 1987).

MARINE PHASE OF PEACE PROGRAM

The Marine Phase (June 17 to September 20, 1984) was carried out by USGS personnel principally from the Office of Energy and Marine Geology. It involved onsite observers from the DNA (and their contractors) and substantial logistic support from the Pacific Area Support Office of the DOE. Lists of key personnel and responsibilities and a detailed discussion of the Marine Phase are given in Folger (1986a).

Basically, this phase was designed to study both sea-floor and subbottom characteristics of KOA and OAK by using overwater geophysical techniques, scuba teams, and surveys from a submersible. Studied were (1) the bathymetry, physiography, and character and distribution of bottom or near-subsurface materials and (2) the depth, distribution, continuity, and disruption of acoustic reflectors in the craters and their proximity. Geophysical studies generated data from sidescan-sonar surveys, single- and multichannel seismic-reflection surveys, and a seismic-refraction survey of OAK. Geologic studies gathered data from sea-floor observations from the submersible and scuba operations, from six shallow (that is, less than 40 ft deep) boreholes drilled by the scuba teams, and from lagoonwide benthic sampling.

The primary support vessel for the Marine Phase was the DOE research vessel *Egabrag II* (fig. 5*A*), operated by U.S. Oceanography out of San Diego; the two-man submersible was MARFAB, Inc.'s, *Delta* (fig. 5*B*), operating out of Los Angeles.

[5]PACE is an acronym for Pacific Atoll Cratering Experiments Program, EXPOE for Exploratory Program on Enewetak, and EASI for Enewetak Atoll Seismic Investigation Program.

[6]The IVY-grid is a second- and third-order plane coordinate system based on true meridian and established for the PPG (Holmes and Narver, 1952) for operation IVY, a series of nuclear tests conducted in 1952 for the development of a hydrogen (thermonuclear) bomb. The origin of coordinates for Enewetak is a triangulation station with arbitrarily assigned values of North 100,000 ft and East 100,000 ft.

A

B

FIGURE 5.—*A*, DOE research vessel *Egabrag II* (photographed by authors, June 1985); *B*, MARFAB, Inc.'s, two-man submersible *Delta* (photograph courtesy of B.L. Ristvet, Defense Nuclear Agency).

DRILLING PHASE OF PEACE PROGRAM

The Drilling Phase had three primary field objectives: (1) to acquire samples of rock and sediment in as undisturbed condition as possible for geologic studies of the litho- and biostratigraphic framework and for material-properties studies of soil and (or) rock mechanics; (2) to conduct downhole geophysical logging for additional geologic, material-properties, and radiologic information on the two craters; and (3) to verify and complete the description and identification of the major crater features and dimensions begun during the Marine Phase.

Detailed discussion of the Drilling Phase (January 14 through July 25, 1985), including lists of personnel, tours, and duties, is given in Henry, Wardlaw, and others (1986) and in U.S. Department of Energy (1985). Fieldwork was a cooperative effort between three Federal agencies, the USGS, the DNA, and the DOE. The drill ship was the North-Sea class *Knut Constructor*, owned by Knutsen O.A.S. Shipping and based out of Singapore (figs. 6*A*, 6*B*).

The chief scientists and onsite program managers for the Drilling Phase were from the DNA, which also provided experts in downhole geophysical logging, material properties, and gravimetry.

Logistic and technical support from the DOE was through the Pacific Area Support Office of the Nevada Operations Office (U.S. Department of Energy, 1985). Through DOE's contractors, Holmes and Narver (H&N) and Fenix and Sisson, the drilling, downhole geophysical logging, borehole gravimetry, navigation, submersible, and communications were subcontracted. The DOE also arranged the radiologic monitoring, supply and resupply, personnel transportation, and core and sample shipment stateside.

The role of the USGS during the Drilling Phase was essentially geologic, and most of the USGS personnel, including the chief geologists, were from the Office of Regional Geology. The USGS was solely responsible for stratigraphic analysis of the borehole data, including description and paleontologic studies of the core and samples, and was jointly responsible with the DNA for interpretation of the downhole geophysical logging and the borehole gravimetry. The USGS assisted the DNA in development of the initial drilling plan and worked with both the DNA and the DOE in constant onsite modification of that plan, including placement of boreholes, geologic and material-properties sampling, downhole geophysical logging, and borehole gravimetry.

Thirty-two boreholes were drilled overwater in the northern part of the lagoon (fig. 2) from the *Knut Constructor* (fig. 6). These consisted of 27 geologic, 4 material-properties, and 1 cone-penetrometer borehole. Eight boreholes were in the KOA area (fig. 7*A*), the rest in the OAK area (fig. 7*B*). Borehole penetrations below the sea floor ranged from 41 to 1,605 ft, and the composite linear footage was 14,189 ft. The deepest borehole (the OAK crater ground-zero borehole, OBZ-4), drilled in the deepest water (slightly in excess of 200 ft), penetrated lower Miocene strata. In addition to the integrated suite of conventional geophysical logs that was run (table 2), shallow, borehole-gravity surveys were done in selected boreholes on the southwestern transect of OAK crater (Beyer and others, 1986; Beyer, 1987). Tables 2 and 3 present technical details of the Drilling Phase boreholes, including water depth, total footage, and types of logs run.

This group of boreholes formed the primary data base for the geologic framework for the program. It also formed the ground-truth for interpretation of the single-channel and multichannel seismic profiles that provided the primary three-dimensional subsurface picture of the craters and environs.

Two other activities occurred on Enewetak during the Drilling Phase: (1) an additional set of benthic samples was taken from the drill ship in the vicinity of OAK and KOA and (2) because of the value of the information obtained from the submersible during the Marine Phase the previous summer, the *Delta* was brought back to Enewetak for further sea-floor investigations.

PEACE PROGRAM REPORTS

Table 4 lists the PEACE Program data groups and analyses with corresponding references for all the reports published by the USGS for the DNA and for some additional reports and papers by other groups. Most of the Marine Phase information appears in USGS Bulletin 1678 (Folger, 1986b), although some is included in three of the subsequent four USGS open-file reports for the Drilling Phase—Open-File Reports 86–159 (Cronin and others, 1986), 86–555 (Henry and Wardlaw, 1986), and 87–665 (Henry and Wardlaw, 1987). The remaining open-file report (86–419; Henry and others, 1986) documents the drilling operations, strategies for selecting borehole locations, rationale for downhole logging, and procedures for core and sample handling and sampling and gives detailed lithic descriptions. Also included in this volume is an appendix (Holloway and Young, 1986) summarizing technical aspects of the drill ship and drilling system, strategies for drilling and sampling, procedures for core and sample handling, the geotechnical (material-properties) investigations conducted onsite by McClelland Engineers, Inc., and engineering rock ("soils") descriptions of the boreholes.

Most of the material-properties studies were not conducted by the USGS, nor was our close collaboration

A

B

FIGURE 6.—237-foot-long drill ship *Knut Constructor*. Drill rig is mounted amidship (photographed in OAK crater in June 1985 by Lt. Col. Robert F. Couch, Jr., Defense Nuclear Agency). *A*, Port side view from surface; *B*, Starboard side view photographed from air.

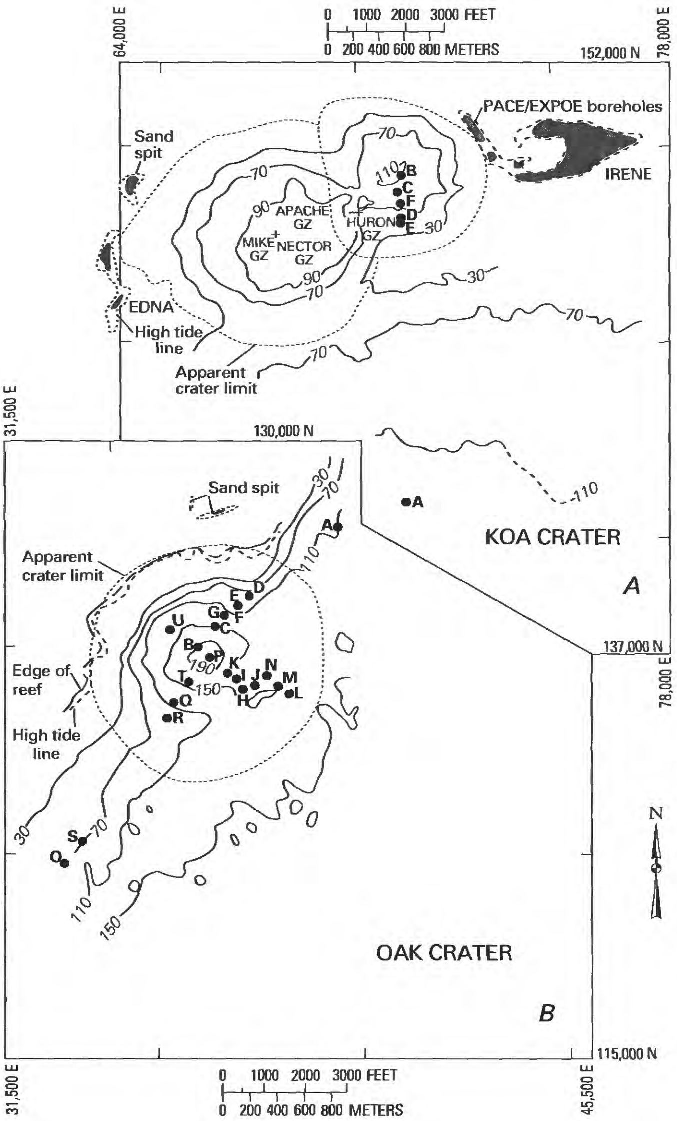

FIGURE 7.—Borehole sites and general bathymetric contours in (*A*) KOA crater area and (*B*) OAK crater area. General locations shown in figures 2 and 4; specific sites (depicted by letters) described in table 3. Contour lines in feet. (Modified from Henry and others, 1986, figs. 27, 29.)

requested or required for these. The results of these investigations have been reported elsewhere for the DNA (Akers, 1986; Borschel and others, 1986; McClelland Engineers, Inc., 1986; Blouin and Timian, 1987; Mueller, 1987; Patti and Schatz, 1987). The USGS did collaborate closely with the X-ray diffraction (mineralogic), organic-content, and insoluble-residue studies and the analyses of the downhole geophysical logs and the borehole gravimetry—all of which provide primary physical and numeric data for computational modeling. These are reported in two of the USGS open-file reports cited previously (table 4) and in Oberste-Lehn (1989).

CURRENT SERIES OF PAPERS

In a multidisciplinary investigation of this scope and scale, data bases are created that are applicable to research activities far beyond the original objectives and scope of the program. The PEACE Program is no exception. These "spinoffs" include studies of the geologic history and evolution of the Pacific Basin, the biologic and geologic evolution of a coral atoll, the petrographic and geochemical diagenesis of carbonate rocks, fluctuations in sea level as a response of the global ocean to major climatic events (glaciation, deglaciation), and the speciation (evolution) and migration of marine biotas, to name but a few topics of interest. Several papers that exploit this new information already have been published in other journals (Hudson, 1985; Halley and Ludwig, 1987; Ludwig and others, 1988; Quinn and others, 1989; Quinn, in press).

In the spirit of Professional Paper 260, "Bikini and Nearby Atolls," which marked the first involvement of the USGS in the Marshall Islands, the purpose of the current series is to provide a forum for more of these geologic and biologic studies and for expansion of several topics summarized but not completely covered—primarily because of time and space constraints—in the initial USGS reports to the DNA.

ACKNOWLEDGMENTS

We, as editors of this Professional Paper series and chief geologists for the Drilling Phase of the PEACE Program, extend a special note of appreciation to the following people, without whom this program would not have been possible. Lt. Col. Robert F. Couch, Jr. (U.S. Air Force, Washington, D.C., and DNA manager for the PEACE Program), Byron L. Ristvet and Edward L. Tremba (both DNA subcontractors from S–Cubed Division of Maxwell Laboratories, Albuquerque, N. Mex., during the program and currently with the DNA in Las Vegas, Nev., and Alexandria, Va., respectively), and Robert W. Henny (Air Force Weapons Laboratory (AFWL), Kirtland Air Force Base, N. Mex.) were full collaborators with us during the PEACE Program. All four of these geologists had logged extensive onsite experience in the PPG and with various problems of nuclear-weapons effects prior to the current program and were principal investigators in all or various phases of the earlier AFWL investigations on Enewetak. In a real sense, they represent a vital component of the record of cratering studies on Enewetak. Their expertise and geotechnical knowledge were invaluable to the PEACE Program, and we owe them a profound debt of gratitude. Couch, Ristvet, and Tremba served

TABLE 2.—*Downhole geophysical logs from PEACE Program drilling*
[X indicates that log was made]

Borehole	Log type[1]						
	MCS	GR/NU	GR/DN/CP	TAC	SRS	GR/CP	BHG
			KOA crater				
KAR–1	X	X	X	–	X	–	–
KAM–2	–	–	–	–	–	–	–
KAP–3/KAM–2A	–	–	–	–	–	–	–
KBZ–4	X	X	X	–	X	–	–
KCT–5	X	X	X	–	X	–	–
KDT–6	–	X	X	–	X	–	–
KET–7	–	–	–	–	–	–	–
KFT–8	–	X	X	–	X	–	–
			OAK crater				
OAM–1/OAR–2	–	X	X	X	X	–	–
OAR–2A	X	X	X	–	–	–	–
OAM–3	–	X	X	–	–	–	–
OBZ–4	X	X[2]	X	–	X	–	–
OCT–5	X	X[2]	X	–	X	–	–
ODT–6	–	–	–	–	–	–	–
OET–7	X	X	X	–	–	–	–
OFT–8	X[3]	X	–	–	–	–	–
OGT–9	–	X	–	–	–	–	–
OHT–10	–	X	–	–	–	–	–
OIT–11	X	X	X	–	–	–	–
OJT–12	–	X	–	–	–	–	–
OKT–13	X	X[2]	X	–	–	–	–
OLT–14	–	–	–	–	–	–	–
OMT–15	–	X	–	–	–	–	–
ONT–16	–	X	–	–	–	–	–
OOR–17	X	X	X	–	X	–	X[4]
OPZ–18	–	X[2]	X	–	–	–	X[4]
OQT–19	X	X[2]	X	–	–	–	X[4]
ORT–20	–	–	X	–	–	–	X[4]
OSR–21	–	–	X	–	–	–	X[4]
OSM–22	–	–	–	–	–	–	–
OTG–23	–	–	–	–	–	X[4]	X[4]
OUT–24	–	X	–	–	–	–	–

[1]Log type: MCS, multichannel sonic; GR/NU, gamma-ray/neutron-neutron; GR/DN/CP, gamma-ray/density/caliper; TAC, three-arm caliper; SRS, seismic reference survey; GR/CP, gamma-ray/caliper; BHG, borehole gravimetry.

[2]Run in open hole only.

[3]Run in drill pipe only.

[4]Run in casing.

as chief scientists aboard the *Knut Constructor* during legs of the Drilling Phase of the program, and all three were onsite part of the time during the Marine Phase.

David J. Roddy (USGS, Flagstaff) set up the initial USGS involvement in the PEACE Program and helped guide and advise the program through many of its stages.

L. Stephen Melzer and John F. Schatz of Science Applications International Corporation provided us with constructive scientific, engineering, and technical information during the program. Melzer was onsite with us as a chief scientist during part of the Drilling Phase fieldwork.

Our appreciation is extended to all the members of the Marine Phase, particularly David W. Folger, PEACE Program coordinator for the USGS Office of Energy and Marine Geology, John A. Grow and his crew for the superb multichannel seismic profiles, James C. Robb and his group for the single-channel sections, and Folger, Robb, and J.C. Hampson and company for the sidescan-sonar images of both craters. These images, digitally processed at the USGS laboratories in Flagstaff, Ariz., were enhanced by airbrush techniques and were instrumental in the critical identification of many surficial crater features. The sidescan-sonar images and the seismic-reflection profiles greatly aided the selection of the borehole sites during the Drilling Phase.

TABLE 3.—*Summary of PEACE Program borehole data from KOA and OAK craters*

Site[1]	Borehole[2]	IVY-grid coordinates (feet)		Water depth (feet below Holmes and Narver datum[3])	Borehole depth (feet below sea level)	Recovery	
						Footage	Percentage
				KOA crater			
A	KAR–1	140,851 N.	071,192 E.	105.1	1,146.3	710.0	62
A	KAM–2	140,816 N.	071,157 E.	105.7	80.8	(5)	(5)
A	KAP–3[4]	140,874 N.	071,106 E.	111.1	[5]78.0	(5)	(5)
A	KAM–2A[4]	140,874 N.	071,106 E.	111.1	[5]482.9	(5)	(5)
B	KBZ–4	149,350 N.	071,113 E.	109.1	1,045.9	388.8	37
C	KCT–5	148,815 N.	071,087 E.	98.9	306.6	135.0	44
D	KDT–6	148,178 N.	071,140 E.	56.2	123.8	55.1	45
E	KET–7	148,034 N.	071,147 E.	51.1	41.1	13.1	32
F	KFT–8	148,490 N.	071,107 E.	77.8	317.9	126.1	40
GZ	---	149,360 N.	071,120 E.	163.0	---	---	---
				OAK crater			
A	OAM–1[4]	127,784 N.	039,575 E.	114.2	[5]401.6	(5)	(5)
A	OAR–2[4]	127,784 N.	039,575 E.	114.2	885.6	366.3	76
A	OAR–2A	127,861 N.	039,566 E.	110.5	410.5	188.1	46
A	OAM–3	127,873 N.	039,569 E.	111.0	[5]93.0	(5)	(5)
B	OBZ–4	124,980 N.	036,115 E.	198.7	1,605.2	967.8	60
C	OCT–5	125,467 N.	036,552 E.	163.7	851.5	260.6	31
D	ODT–6	126,140 N.	037,372 E.	90.1	164.2	86.8	53
E	OET–7	125,938 N.	037,095 E.	106.9	231.7	113.4	49
F	OFT–8	125,803 N.	036,882 E.	130.8	283.5	104.0	37
G	OGT–9	125,754 N.	036,809 E.	134.8	75.0	28.3	38
H	OHT–10	124,003 N.	037,195 E.	137.3	162.5	64.5	40
I	OIT–11	124,230 N.	037,051 E.	155.0	286.5	111.5	39
J	OJT–12	124,053 N.	037,527 E.	143.8	97.3	53.4	57
K	OKT–13	124,362 N.	036,879 E.	164.7	765.3	248.5	32
L	OLT–14	123,569 N.	038,473 E.	139.7	49.2	27.1	55
M	OMT–15	123,974 N.	038,068 E.	110.9	76.6	36.7	48
N	ONT–16	124,215 N.	037,767 E.	135.1	152.3	73.1	48
O	OOR–17	119,843 N.	032,899 E.	75.1	1,091.1	563.5	52
P	OPZ–18	124,789 N.	036,383 E.	201.9	748.6	188.1	26
Q	OQT–19	123,651 N.	035,545 E.	117.5	701.5	126.0	18
R	ORT–20	123,303 N.	035,339 E.	101.4	491.8	73.3	15
S	OSR–21	120,320 N.	033,197 E.	84.0	354.3	63.9	18
S	OSM–22	120,313 N.	033,127 E.	76.0	[5]127.5	(5)	(5)
T	OTG–23	124,204 N.	035,899 E.	164.0	[5]587.3	(5)	(5)
U	OUT–24	125,499 N.	035,424 E.	147.0	351.4	56.8	16
GZ	---	124,981 N.	036,108 E.	195.6	---	---	---

[1]Site locations shown in figure 7; GZ, ground zero.

[2]In borehole identifiers, first character stands for the crater area (O, OAK; K, KOA), second character for the site, and third character for the type of borehole (R, reference; M, material properties; P, cone penetrometer; Z, ground zero; T, transition zone; and G, borehole gravimetry). The numbers to the right of the hyphen designate the sequential number drilled.

[3]Holmes and Narver datum is 0.5 ft below approximate-mean-low-water-spring tide (AMLWS).

[4]KAP–3 and KAM–2A are the same hole; OAM–1 and OAR–2 are the same hole.

[5]Not used in summary for geologic total footage and recovery.

We thank the authors of the chapters of the current Professional Paper series and of the previous set of open-file reports for their timely response to our needs in compiling and editing their chapters for this Professional Paper and for their cooperation and stimulation earlier in synthesizing the diverse data bases for the open-file reports.

A profound debt of gratitude is owed to Thomas R. Clark, manager of the Nevada Operations Office (NVO) of the DOE, and Roger Ray, deputy manager for Pacific operations, NVO, and their staff, and to William J. Stanley, director of the Pacific Area Support Office of the DOE in Honolulu, and his staff, particularly Harry U. Brown, DOE program manager for this project, for contracting the drilling, downhole logging, navigation, and related activities, for arranging for support from a number of Government and subcontractor personnel to manage the operations and logistics for the fieldwork,

TABLE 4.—*Summary of reports from the PEACE Program*

Data group	Phase	Publication[1]	Chapter	Reference
Bathymetric maps	Marine	Bull. 1678	A	Folger, Hampson, and others (1986).
		OF–87–665	5	Peterson and Henny (1987).
Sidescan sonar and imagery	Marine	Bull. 1678	B	Folger, Robb, and others (1986).
Single-channel seismic reflection	Marine	Bull. 1678	C	Robb and others (1986).
Multichannel seismic reflection	Marine	Bull. 1678	D	Grow and others (1986).
Seismic refraction	Marine	Bull. 1678	E	Ackermann and others (1986).
Submersible observations	Marine	Bull. 1678	F	Halley, Slater, and others (1986).
	Both	OF–86–555	13	Slater and others (1986).
Debris/ejecta studies	Marine	Bull. 1678	G	Halley, Major, and others (1986).
	Marine	OF–86–555	3	Ludwig and others (1986).
	Drilling	OF–87–665	4	Polanskey and Ahrens (1987).
Scuba observations	Marine	Bull. 1678	H	Shinn and others (1986).
Benthic samples	Both	OF–86–555	10	Wardlaw and others (1986).
Boreholes	Drilling	OF–86–419	–	Henry and others (1986).
Lithostratigraphic framework	Drilling	OF–86–555	2	Wardlaw and Henry (1986b).
		OF–87–665	7	Wardlaw (1987).
Biostratigraphic framework and mixing studies	Drilling	OF–86–159	–	Cronin and others (1986).
		OF–86–555	11	Brouwers and others (1986).
		OF–87–665	3	Cronin and Gibson (1987).
		"Geology"	v. 17	Wardlaw (1989).
Geophysical logs	Drilling	OF–86–555	7	Melzer (1986).
		OF–87–665	6	Trulio (1987).
Seismic reference survey	Drilling	OF–86–555	9	Tremba and Ristvet (1986a).
Borehole gravity	Drilling	OF–86–555	8	Beyer and others (1986).
		OF–87–665	2	Beyer (1987).
		OF–87–665	6	Trulio (1987).
	Drilling	TR–161605–002	–	Oberste-Lehn (1989).
Petrography, diagenesis	Drilling	Brown Univ.	–	Quinn (1989).
	Drilling	GSA Abstr.	–	Quinn and others (1989).
	Drilling	"Sedimentology"	–	Quinn (in press).
Sr-isotope framework	Marine	Bull. 1678	G	Halley, Major, and others (1986).
	Drilling	OF–86–555	3	Ludwig and others (1986).
		"Geology"	v. 16	Ludwig and others (1988).
X-ray mineralogy	Drilling	OF–86–555	4	Tremba and Ristvet (1986b).
Organic geochemistry	Drilling	OF–86–555	5	Ristvet and Tremba (1986c).
Insoluble residues	Drilling	OF–86–555	6	Ristvet and Tremba (1986a).
Radiation chemistry	Drilling	OF–86–555	12	Ristvet and Tremba (1986b).
Electron-spin resonance	Drilling	OF–87–665	4	Polanskey and Ahrens (1987).
Crater-area benthic samples	Drilling	OF–86–555	4	Tremba and Ristvet (1986b).
		OF–86–555	10	Wardlaw and others (1986).
Crater synthesis	Marine	Bull. 1678	A	Folger (1986a).
	Both	OF–86–555	14	Wardlaw and Henry (1986a).
	Both	OF–87–665	7	Wardlaw (1987).

[1]Bull., USGS Bulletin; OF, USGS Open-File Report; TR, Technical Report.

and for obtaining necessary approval from the U.S. Air Force at Hickam Field in Honolulu, from the U.S. Army Missile Base at Kwajalein Atoll, and from Government officials of the Republic of the Marshall Islands and the Trust Territory of the Pacific Islands.

Emit L. Herbst (H&N, Las Vegas) and George Krosnbein, Judy Honda, Jack H. Matthewman, and Pat R. Haggerty (all H&N, Honolulu) orchestrated transportation and supply logistics throughout the Drilling Phase. In addition, we thank Stan S. Miyasato (H&N) and his staff at the University of Hawaii/DOE Mid-Pacific Research Laboratory on Enewetak Island for providing every assistance throughout the drilling and logging operations.

The program is indebted to members of the staff and management of McClelland Engineers, Inc., and particularly to McClelland's project director, Alan G. Young, and his deputy, Tom Hamilton. Peter Gemeinhardt, vice-president for international operations and operations director for this program, served onsite as a crewman during mobilization and the early phases of drilling. The response of McClelland's field superintendents (Chuck Rivette and Glenn L. Holloway), chief drillers (Glen Mooney and Charlie Peltier), multinational drilling crew, and support personnel to program needs and technical problems was outstanding and often innovative. The program would have not been possible without their expertise, enthusiasm, and cooperation.

We also acknowledge the support of the officials of the Republic of the Marshall Islands and the people of Enewetak, many of whom piloted the whalers and LCM6 landing craft used as resupply vessels between the islands and the drill ship (in all kinds of weather) and assisted us in many other project operations. All of these individuals freely and warmly extended their hospitality to program participants.

Last but not least, we express our appreciation to the officers and crew of the drill ship, the *Knut Constructor*, for their role in this program. We salute the "Jolly Knut," as she became affectionately known to us, for her fine service during the PEACE Program.

LOCATION AND SETTING

Enewetak and Bikini are "coral" atolls in the equatorial Pacific Ocean located roughly 2,500 nautical miles (nmi) southwest of Hawaii (fig. 1). Both Enewetak and Bikini are part of the Republic of the Marshall Islands, formed in 1987. The approximate center of Enewetak Atoll is 11°30′ N. 162°15′ E.; Bikini is about 220 nmi east of Enewetak, with a center at about 11°35′ N. 165°23′ E.

The Marshall Islands are located principally on two subparallel chains of extinct volcanoes (the Ralik and Ratak Chains) that formed as the Pacific tectonic plate moved northwestward over a hot spot in the upper mantle known as the Darwin Rise. Enewetak Atoll is at the northwestern end of a third chain, which is principally submerged. Reefs made primarily from corals and coralline algae became established on the volcanic bases and, in the cases of atolls such as Enewetak and Bikini, reef growth generally kept pace with subsidence and (or) eustatic sea-level rises.

Enewetak Atoll is acorn shaped, with a long axis approximately 22 nmi long and oriented in a northwest-southeast direction. The short axis is about 17 nmi long (fig. 2). Like most of the Marshall Islands, Enewetak's approximately 40 islands are very low lying (maximum elevation about 13 ft above sea level) and are restricted to the atoll margin. Enewetak thus is dominated by the lagoon, which has three principal outlets to the open ocean (fig. 2). The islands constitute only about 2.75 square nautical miles (nmi^2) of the atoll's almost 300 nmi^2 and are concentrated primarily on Enewetak's northeastern margin, facing the prevailing trade winds. The islands have been called by different names. As many as four "native" names or variations in English phonetic spellings have been applied to some. To avoid confusion, most of the islands were assigned a military site name during the period of nuclear testing. In both Folger's (1986a) report and the USGS open-file reports, and in the current series, the Marshallese names identified by Tobin (1973) and reported in Freisen (1982) are used. The military site names are given in parentheses in capital letters after the preferred island name.

PREVIOUS GEOLOGIC INVESTIGATIONS

Scientific studies were conducted sporadically in the Marshall Islands prior to the end of World War II. The first geologic observations of the islands were made in 1816 and 1817 by Albert Chamisso, a naturalist with one of the Russian Pacific expeditions. Chamisso described the reefs, islands, and lagoons of the Ratak (eastern) Chain of the Marshalls. From 1918 through 1944, the Marshall Islands were part of the Pacific territories controlled by the Japanese. Although the Japanese conducted scientific studies on the atolls during this period, most of their data has been lost (Emery and others, 1954). Some general comments were published by Stearns (1945) concerning possible damage to the Enewetak reefs during the 1944 American invasion when the Japanese were defeated.

STUDIES FROM 1946 TO 1952

Operation CROSSROADS was initiated by the U.S. Government in 1946 just prior to the detonation of two atomic bombs over and under naval warships in the lagoon at Bikini Atoll. This scientific study was conducted to establish a baseline against which to assess the impact of the Nuclear Weapons Testing Program in what was to become the PPG. The Operation CROSSROADS study of Bikini included (1) surficial geologic investigations of the reef complex, the lagoon floor, and the outer slopes of the atoll and (2) a seismic-refraction study of the subsurface structure of the atoll (Emery and others, 1954). To paraphrase Hines (1962, p. 31, 32), Operation CROSSROADS was unquestionably the most thoroughly documented, reported, and publicized peacetime military/scientific program in history. This study set the stage for the extensive scientific investigations of the northern Marshall Islands that followed. Those of geologic and geophysical importance are the Bikini Resurvey (1947), the Mid-Pacific Expedition (1950), the Atomic Energy Commission (AEC)-Los Alamos Scientific Laboratory (LASL) Drilling Program (1950–1951), and the USGS/AEC Drilling Program (1951–1952). Under these programs from 1946 to 1952, extensive geologic, paleontologic, geophysical, biologic, radiologic, oceanographic, and atmospheric studies were conducted by the DOD, the USGS, the U.S. Fish and Wildlife Service, the AEC, the LASL, the Woods Hole Oceanographic Institution, the Scripps Institution of Oceanography, the Smithsonian Institution, other Federal agencies, the Bishop Museum, and various American universities. Summaries of many of these investigations were published as the 35-volume USGS Professional Paper 260, beginning in 1954 (Emery and others, 1954, Professional Paper 260-A) and ending in 1969 (Leopold, 1969, Professional Paper 260-II). To quote Ristvet (1987, p. 39), "This...series comprises the most comprehensive single body of geologic, geophysical, and oceanographic data ever assembled on a group of atolls."

FIRST ATOLL BOREHOLES

Coral atolls have been of intensive interest to geologists and biologists since before the publication by Charles Darwin of "Voyage of the *Beagle*" in 1837. From the data base assembled during the expedition to the South Pacific (1831–36) of the H.M.S. *Beagle*, Darwin (1837, 1842) constructed a threefold classification of coral reefs—fringing reefs, barrier reefs, and coral atolls—and postulated that atolls were formed on the foundation of subsiding islands that evolved (with subsidence and upward growth of the reef complex) through the fringing-reef and barrier-reef stages. This sparked a number of alternative theories about atoll formation, as well as the scientific impetus to drill into the volcanic basement on a coral atoll.

The first major attempt to drill through the carbonate cap of a coral atoll was made by the Royal Society of

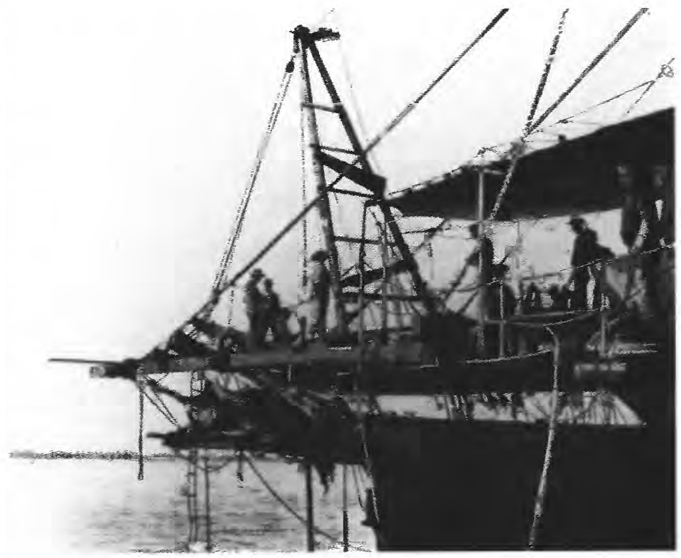

FIGURE 8.—Drill ship H.M.S. *Porpoise* showing bow and the hydraulic (steam) rig used to drill the two overwater boreholes in the lagoon at Funafuti Atoll in 1898. (From Halligan, 1904, p. 161, fig. 20.)

London at Funafuti Atoll, in the Ellice Islands (about 1,300 nmi south of the Marshalls), in 1896–98 (Coral Reef Committee, 1904). During this expedition, in 1897–98, one borehole was drilled on Funafuti Atoll to a depth of 973 ft (David, 1904, p. 56), and, in 1898, two boreholes were drilled with a steam rig from the H.M.S. *Porpoise* (fig. 8) in the lagoon in about 200 ft of water to depths of 114 and 113 ft below the bottom (Halligan, 1904). These two boreholes were the first ever drilled overwater in a coral atoll lagoon. All three boreholes penetrated only carbonate sediments, and no volcanic rock, and therefore only partly confirmed Darwin's (1837, 1842) subsidence theory.

The first conclusive demonstration of deep subsidence on open-ocean atolls was made a little more than 50 years later in the northern Marshall Islands in conjunction with the onset of nuclear testing in the Pacific. Activities in 1946 on Bikini Atoll under Operation CROSSROADS included surficial geologic studies of the reef, lagoon floor, and outer slopes and a seismic-refraction study of the subsurface of the atoll (Emery, 1948; Dobrin and Perkins, 1954; Emery and others, 1954; Raitt, 1954). In 1947, two boreholes were drilled on Bikini Atoll, borehole 2-A to a depth of 1,346 ft and 2-B to a depth of 2,556 ft (Ladd and others, 1948; Ladd and others, 1950; Emery and others, 1954); neither reached the volcanic basement. In 1950, a few deep-sea cores were obtained from the southeastern flank and lower slope of Bikini Atoll and one core was obtained from the adjoining guyots and atoll slopes (Emery and others, 1954), and volcanic rocks were dredged from the southeastern slopes of Bikini from depths of 6,000 to 12,060 ft (Ladd and others, 1953).

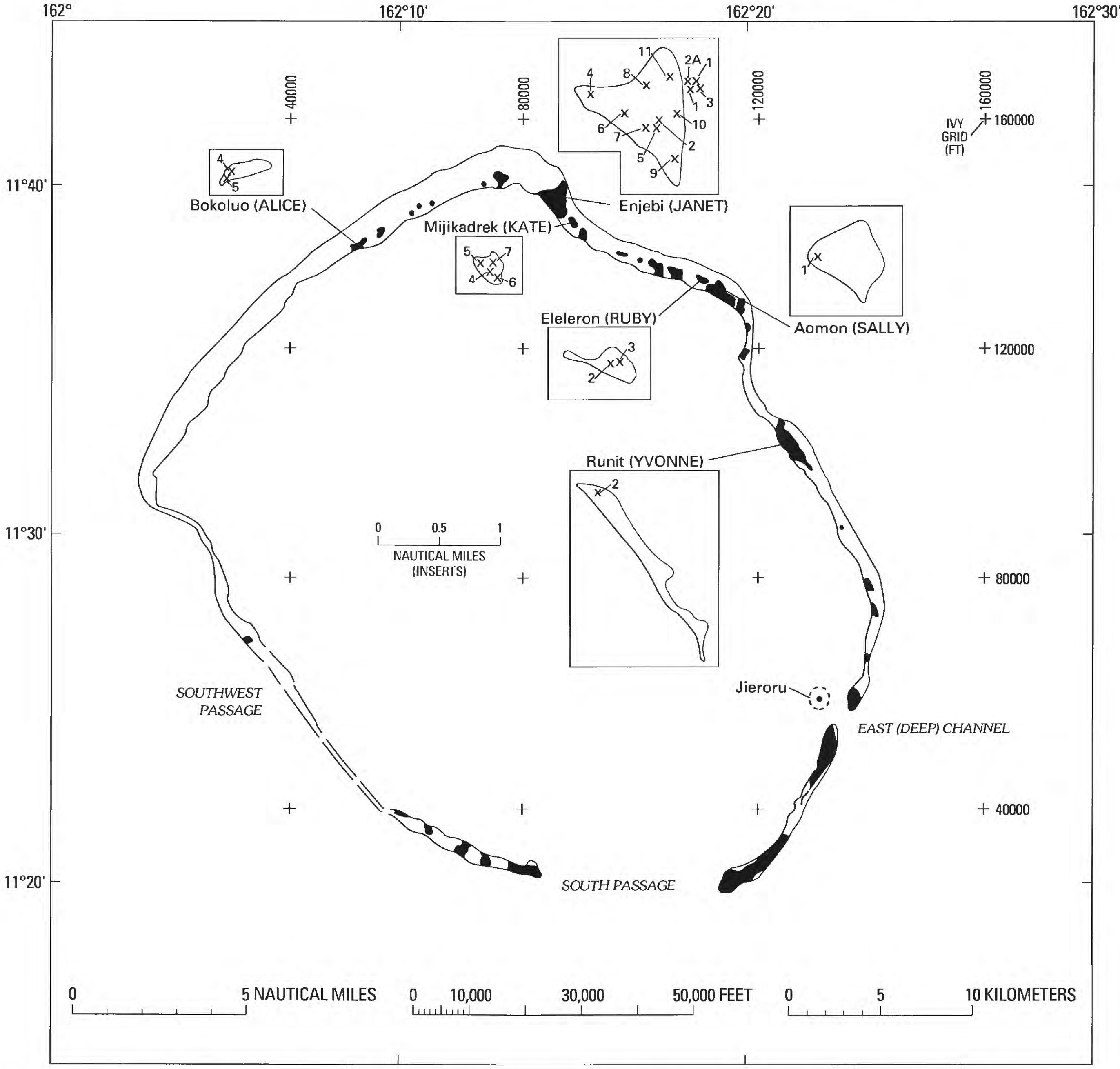

FIGURE 9.—Location of AEC-LASL (1950–1951) boreholes (modified from Ladd and Schlanger, 1960, fig. 260). On original map and in accompanying text, Bokoluo (ALICE) is called Bogallua, Enjebi (JANET) is Engebi, Mijikadrek (KATE) is Mujinkarikku, Eleleron (RUBY) is Eberiru, and Aomon (SALLY) is Aranit.

AEC-LASL DRILLING PROGRAM (1950–1951)

Drilling on Enewetak Atoll commenced in 1950, with four very shallow boreholes (maximum depth 15.9 ft) drilled under the sponsorship of the AEC and the LASL and the supervision of the USGS. These holes were drilled on the seaward side of Enjebi (JANET), Mijikadrek (KATE), Eleleron (RUBY), Aomon (SALLY), and Runit (YVONNE) on the northeastern side of the atoll (fig. 9). These boreholes and subsequent ones were described in Ladd and Schlanger (1960).

USGS-AEC DRILLING PROGRAM (1951–1952)

Three deep holes were drilled on Enewetak Atoll in 1951 and 1952 by the USGS and the AEC (fig. 10) from heavy truck- and trailer-mounted rotary rigs. K-1B was

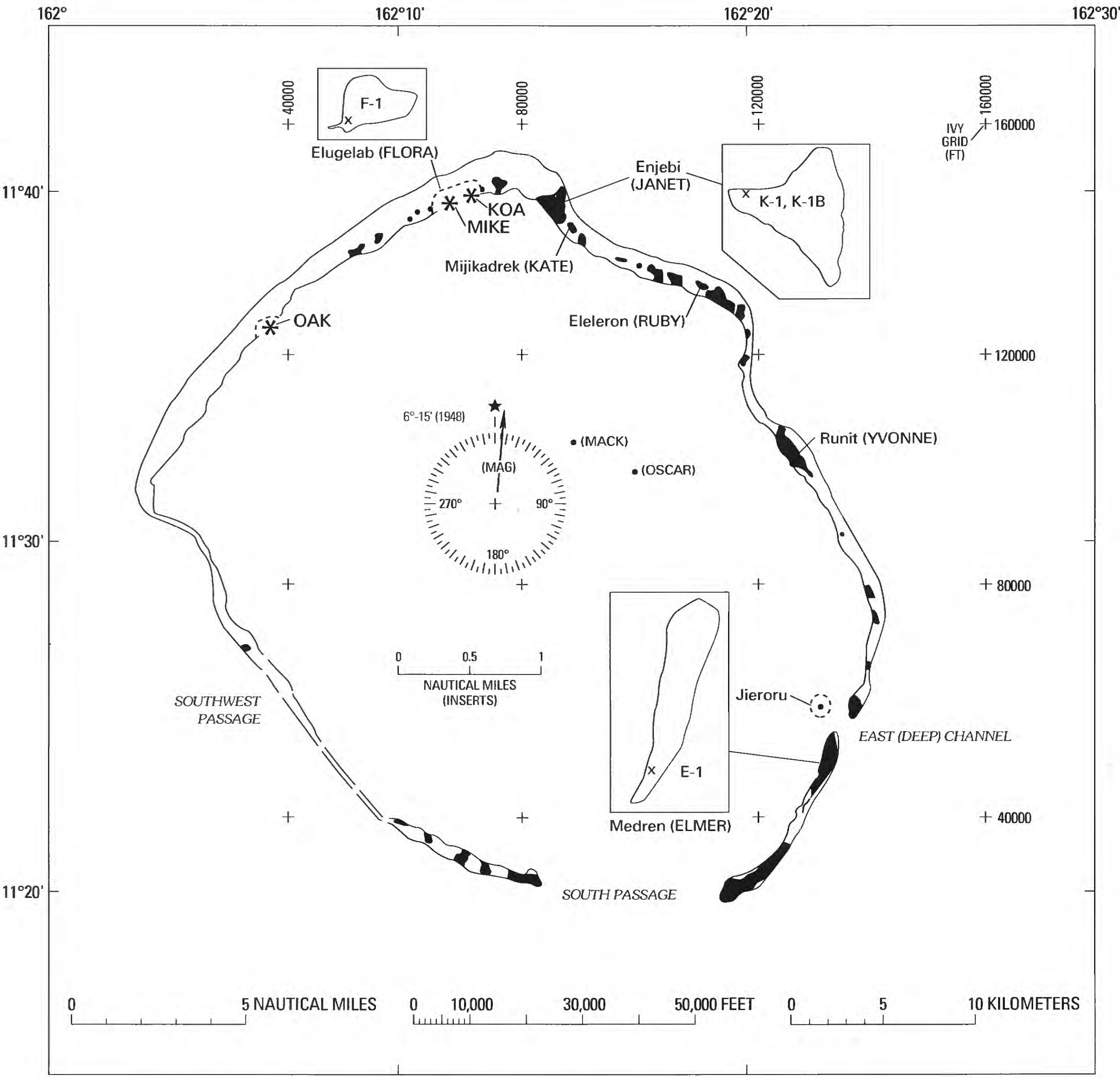

FIGURE 10.—Location of USGS-AEC (1951–1952) deep boreholes (modified from Ladd and Schlanger, 1960, fig. 261). On original map and in accompanying text, Enjebi (JANET) is called Engebi and Medren (ELMER) is called Parry Island.

drilled on Enjebi (JANET) to a depth of 1,280 ft, F-1 was drilled on Elugelab (FLORA) to 4,630 ft, and E-1 was drilled on Medren (ELMER) to 4,222 ft (Ladd and others, 1953; Ladd and Schlanger, 1960). Boreholes E-1 and F-1 (fig. 10) penetrated through the limestone cap of the atoll into the volcanic, olivine-basalt basement at depths of 4,610 ft and 4,158 ft, respectively (fig. 11). About 15 ft of the basalt was recovered in the latter borehole. In general, recovery was poor in these boreholes (see fig. 11), and only relatively small portions of F-1 and E-1 were actually cored. However, cuttings were carefully evaluated and provided invaluable information about the stratigraphy. Of these three deep boreholes, only E-1[7] was not destroyed by the direct effects of nuclear testing (Couch and others, 1975).

[7]E-1 was the borehole in which the borehole-gravimetry pilot study was conducted for the PEACE Program.

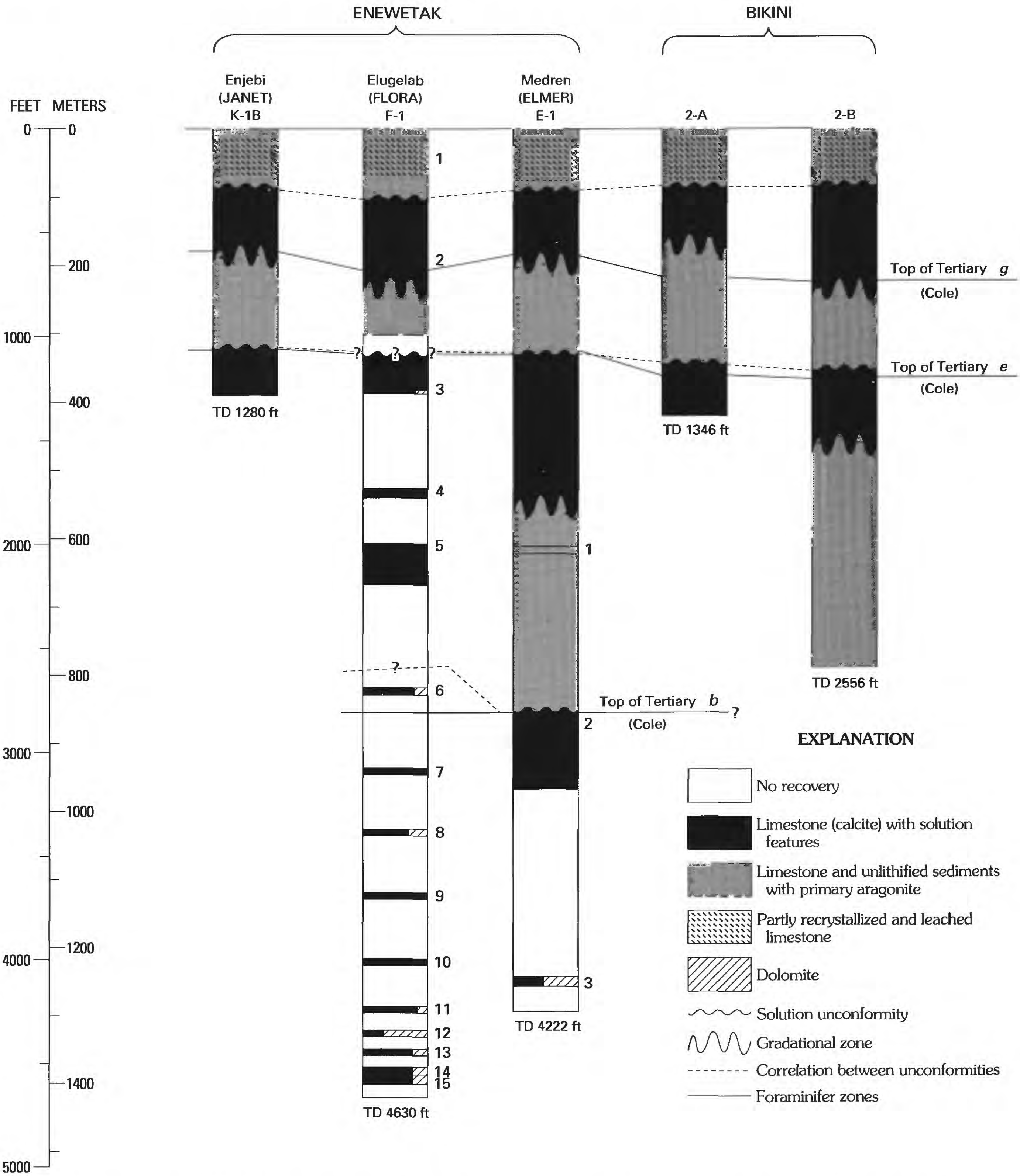

FIGURE 11.—Correlation of USGS-AEC deep boreholes drilled on Enewetak and Bikini Atolls, showing zones of unaltered material and recrystallized and partly dolomitized intervals (modified from Schlanger, 1963, fig. 308). Numbers along sides of drill holes F-1 and E-1 indicate cored intervals. Tertiary *g*, Tertiary *e*, and Tertiary *b* are "standard" biostratigraphic zones based on larger foraminifers, developed and picked by Cole (1957). TD, total depth.

E-1 and F-1 were the first boreholes on any atoll to reach the volcanic "basement." The three deep Enewetak holes and the two deep Bikini holes provided the first general litho- and biostratigraphic framework for these atolls and demonstrated that they had remarkably similar geologic histories. The subsurface sedimentary sequence at both Enewetak and Bikini is characterized by relatively thick intervals of leached, altered, cemented (lithified), calcite-rich carbonate rock (predominantly limestone) alternating with generally thick intervals of unleached, unaltered, uncemented (unlithified), aragonite-rich carbonate sediments (fig. 11). The cemented, altered zones grade downward into unaltered, uncemented intervals that in turn sharply overlie another cemented zone. Because the tops of the leached and cemented zones are sharp and the rocks immediately underlying them commonly contain dissolution features, they were referred to by Schlanger (1963, p. 994) as "solution unconformities," interpreted to have formed during periods when sea level was lower and the atolls emergent (Ladd and others, 1948; Emery and others, 1954; Schlanger, 1963). That these unconformities generally coincide with major microfaunal breaks (fig. 11) indicated to these geologists that periods of nondeposition or perhaps even erosion had interrupted the formation of the carbonate sequence.

INTERIM PERIOD (1952–1970)

The original experiments, observations, and data base that were obtained from the PPG just after World War II were oriented toward military application and weapons development rather than the physics of ground shock and cratering phenomenology. Between 1952 and 1970, after the flurry of geologic studies in the early post-World War II period, several major problems surfaced that required additional information from the PPG. Specifically, additional data were needed to better understand crater geometry, material properties, and ground-shock phenomena associated with high-yield nuclear explosions (Circeo and Nordyke, 1964; Henny and others, 1974a; Couch and others, 1975; Ristvet and others, 1978; Tremba and others, 1981; Tremba and others, 1982; and Tremba, 1987).

In addition to the problems of geologic heterogeneity, the PPG high-yield craters did not scale with their high-explosive and low-yield nuclear counterparts at other test sites, as discussed in a preceding section. It was postulated (at various times) that some of these deviations resulted from (1) the differences in the material properties of the test-site environment (for example, the water-saturated carbonate environment of the PPG versus the air- and gas-saturated silicate environment of the other test sites), (2) primarily the yield of the energy source (device), (3) the manner in which the energy source was coupled to the substrate, (4) massive washback of the water evacuated by the explosion in the lagoon, or (5) failure of the weak geologic matrix induced by the ground shock.

These concerns resulted in four research programs based on Enewetak, all funded by the DNA. The first three of these—the PACE, EXPOE, and EASI Programs (see Pyrz, 1973; Henny and others, 1974a, 1974b; Couch and others, 1975; Tremba, 1987)—were directed by the AFWL. The last one is the PEACE Program.

AIR FORCE WEAPONS LABORATORY STUDIES (1970–1981)

PACE PROGRAM (1970–1972)

As originally formulated, the Pacific Atoll Cratering Experiment (PACE) Program consisted of two interrelated subprograms, PACE 1 and PACE 2 (Tremba and others, 1982). PACE 1 was designed to examine the nuclear craters on Enewetak and to provide information on the near-surface geology of the atoll and the physical and structural characteristics of selected craters and related ejecta fields. PACE 2 was to concentrate on the cratering and ground-motion response of the water-saturated carbonate substrate to a series of high-explosive TNT tests, culminating in a 500-ton blast. However, the program was terminated prematurely through legal and political action before all of the objectives were achieved (see Tremba and others, 1981; Kiste, 1987). Consequently, PACE 2 yielded little valuable new geologic and physical information.

Fieldwork for PACE 1 was conducted in 1971 (Couch and others, 1975), when 128 shallow boreholes (total of 8,200 linear ft of hole) were drilled on seven of the northeastern islands (fig. 12). Most boreholes were concentrated on Runit (YVONNE) (35 holes) and Aomon (SALLY) (80 holes). In addition to the drilling program, 60 shallow trenches were dug to determine the distribution of the beachrock beneath six of the islands, and 50,000 ft of land-based seismic-refraction surveys were run, mainly in the vicinity of Aomon (SALLY) and on Runit Island (YVONNE) (Henny and others, 1974a, 1974b).

EXPOE PROGRAM (1973–1974)

To model the geologic and material-properties heterogeneity of the subsurface of Enewetak Atoll, the strategy of the EXPOE Program (the successor of PACE 1) was to (1) delimit the general geologic differences between the leeward, windward, and transitional islands

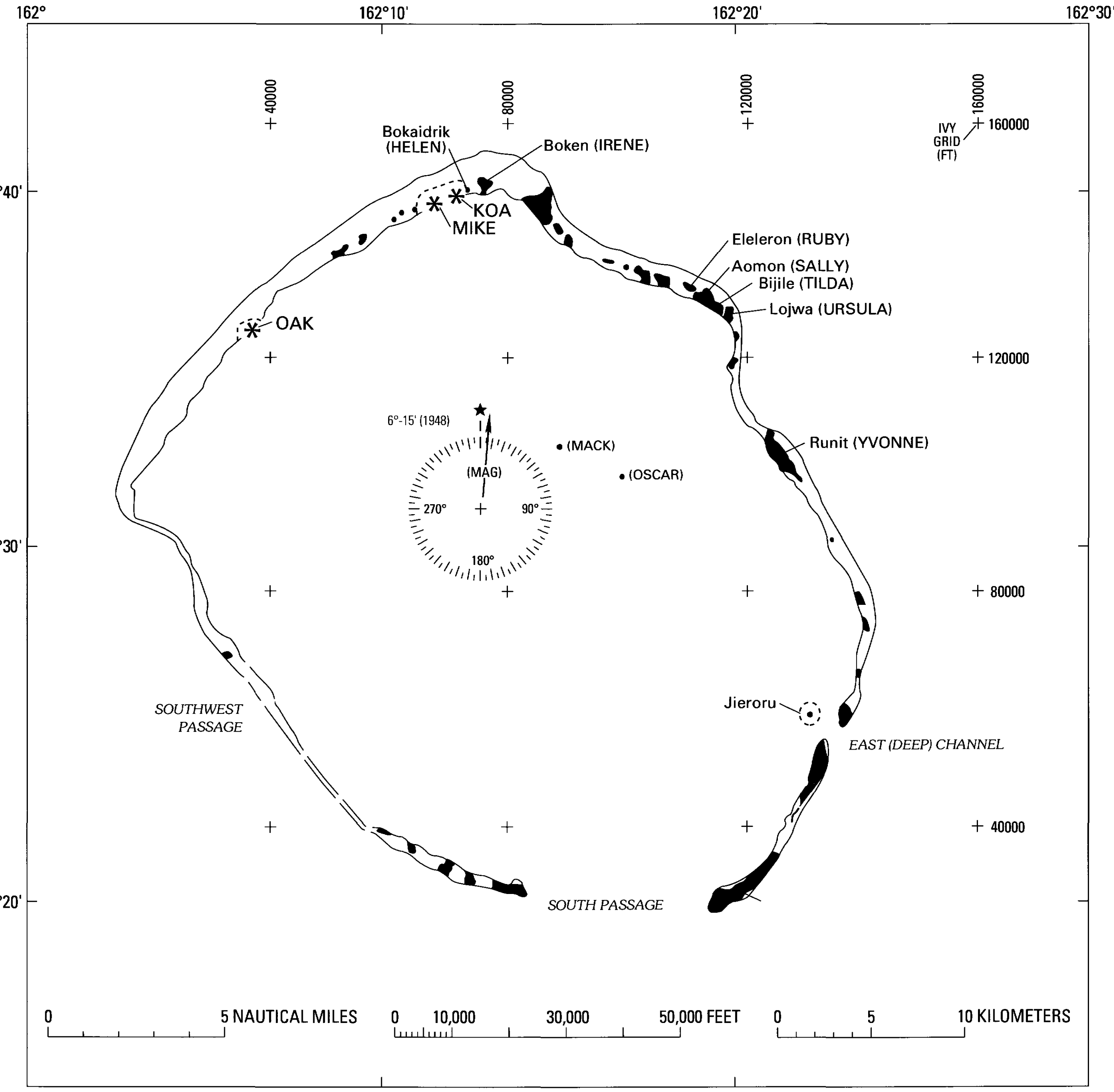

FIGURE 12.—Location of PACE Program (1970–1972) boreholes (modified from Couch and others, 1975, fig. 4). Only islands drilled are identified; for individual sites, see Couch and others (1975).

(fig. 13) and (2) drill groups of boreholes both parallel and perpendicular to the reef front in the areas of the selected craters. According to Couch and others (1975, p. 23), (1) the general lack of lithofacies variation in the transects parallel to the reef front and (2) the marked lateral facies changes between the transects perpendicular to the reef front indicated the validity of modeling the entire atoll subsurface on the basis of a few sections perpendicular to the reef trend and by comparing the geology of the reefward area with that of the lagoonward area.

During the EXPOE Program, 46 additional shallow boreholes were drilled (8,413 linear ft) with truck-mounted rotary rigs on Enewetak (FRED), Medren (ELMER), Japtan (DAVID), Runit (YVONNE), Lojwa (URSULA), Aomon (SALLY), Enjebi (JANET), Boken (IRENE), Bokaidrik (HELEN), Bokinwotme (EDNA), Kirunu (CLARA), Bokombako (BELLE), and Biken

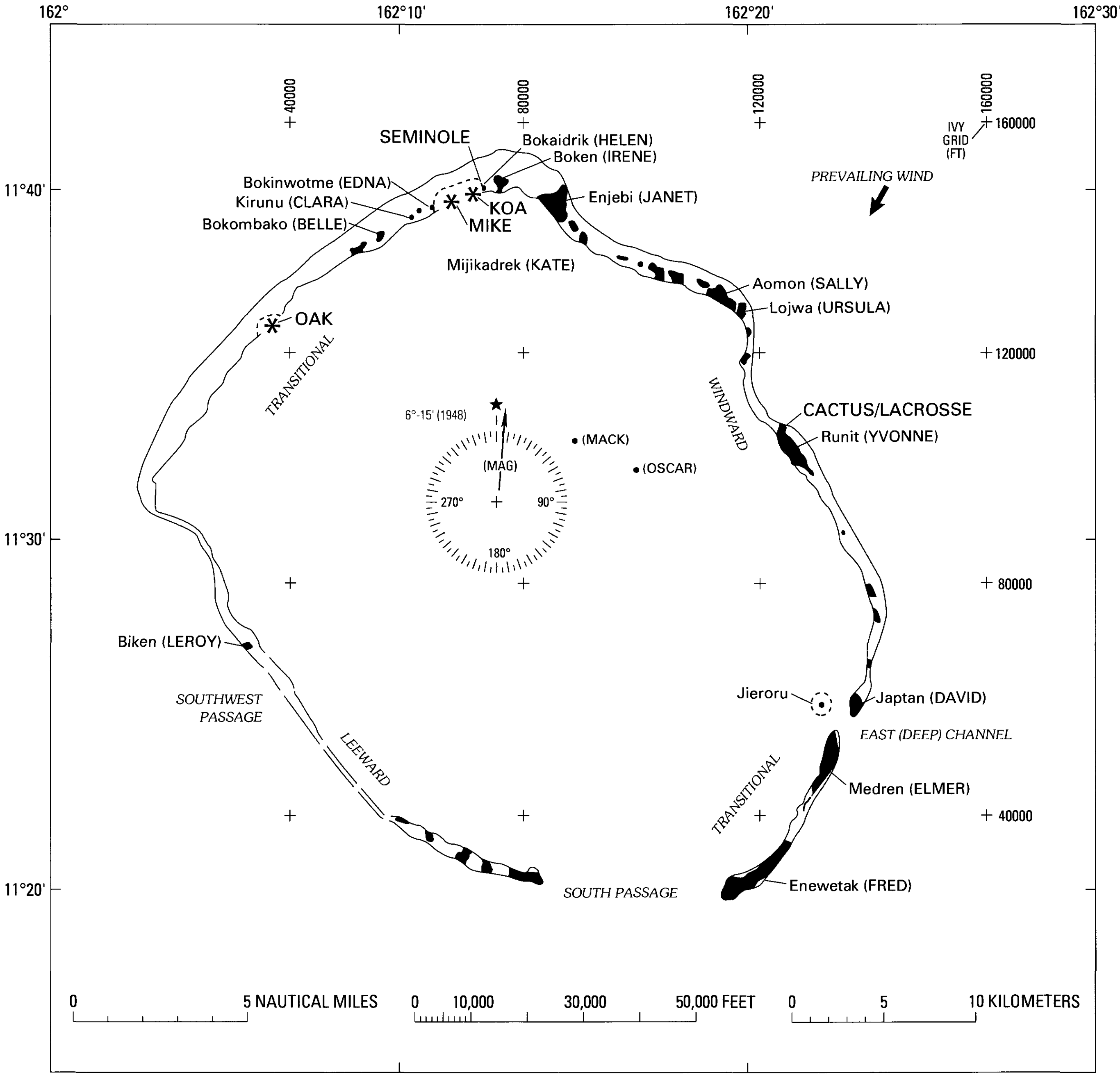

FIGURE 13.—Location of EXPOE Program (1973–1974) boreholes (modified from Couch and others, 1975, fig. 8). Only islands drilled are identified; for individual sites, see Couch and others (1975). Drilled islands are identified as transitional, windward, or leeward, with respect to prevailing wind.

(LEROY) (fig. 13). The deepest of these holes, 298-ft XEN-3, located on Enjebi (JANET), is part of the first lagoon-to-reef geologic cross section of an atoll island (fig. 14). Similar lagoon-to-reef cross sections for Boken (IRENE) and Aomon (SALLY) appear in Ristvet, Tremba, and others (1978, p. 167, fig. 6.5) and in Szabo, Tracey, and Goter (1985, p. 56, fig. 2), respectively.

Because of improved core and sample recovery (approximately 80 percent) and more detailed analysis, five major, gently lagoonward dipping unconformities were identified in the upper 300 ft of section on Enewetak (FRED) in the PACE/EXPOE stratigraphic synthesis (Ristvet and others, 1974; Tracey and Ladd, 1974; Couch and others, 1975). After analysis of subsequent seismic work, Ristvet, Couch, and Tremba (1980) were able to confirm a sixth solution unconformity, corresponding to a major unconformity at a depth of about 300 ft postulated by Schlanger (1963) and by

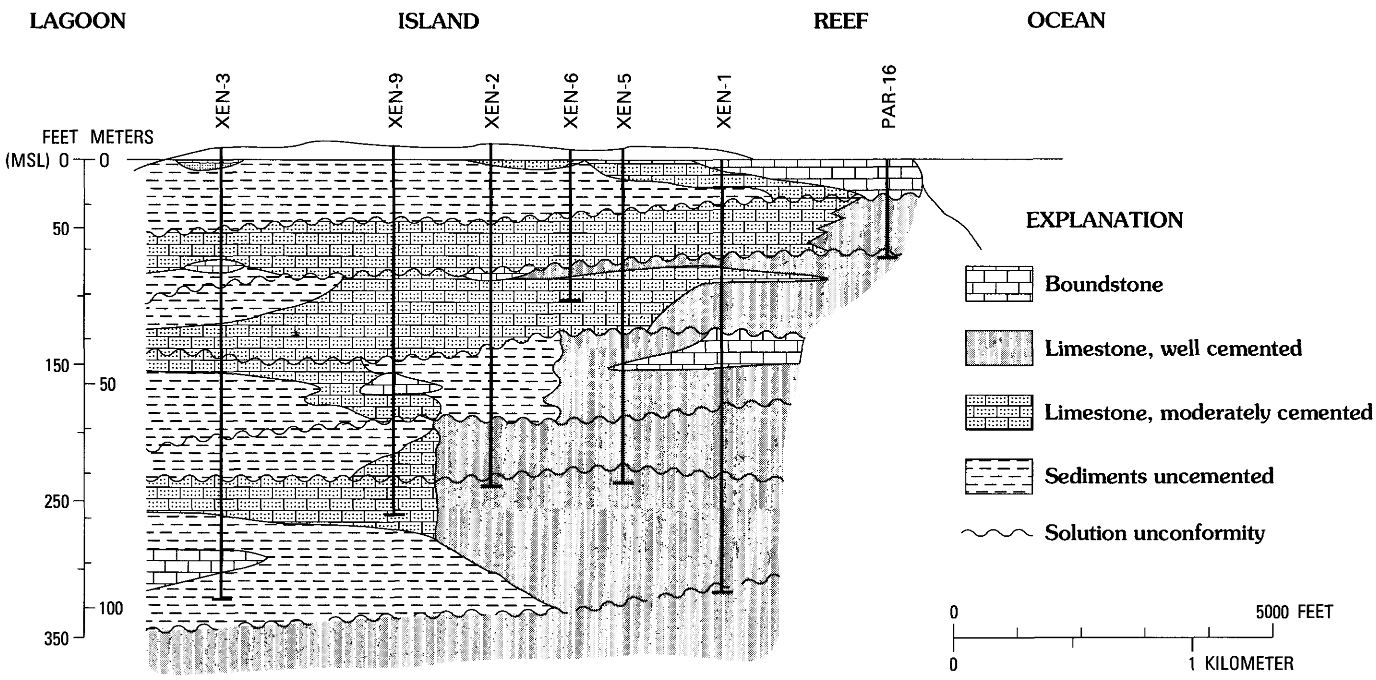

FIGURE 14.—Subsurface geologic cross section of Enjebi (JANET) Island (modified from Couch and others, 1975, fig. 15).

Tracey and Ladd (1974) on the basis of correlation with the Bikini sections. As in earlier studies, these unconformities were interpreted as former subaerial-exposure surfaces marked by terra-rosa types of paleosols (reddish-brown stain, reddish-brown fine silty clay, light-brown laminated crusts), black manganese coatings in pores and cavities, and dissolution features. The unconformities were thought to correlate with similar unconformities produced during glacial lowstands of sea level in other carbonate sections of late Cenozoic age elsewhere in the world.

The first attempts to drill boreholes overwater in nuclear craters also were made during EXPOE (Couch and others, 1975; Ristvet and others, 1978). Although sample recovery was poor, two small, water-filled craters were successfully probed to depths of 153.3 ft and 200.0 ft from a Failing-314 drilling rig mounted on an anchored pontoon barge. The craters, SEMINOLE and CACTUS (fig. 13), were produced by surface bursts of 13.7 and 18 kilotons (kt) on Boken (IRENE) and Runit (YVONNE) in 1956 and 1958, respectively (table 1). An attempt had been made to drill the much larger KOA crater, which resulted from the 1.4-Mt device detonated in a water tank (fig. 13, table 1). Although water filled, SEMINOLE and CACTUS are essentially landlocked craters, whereas KOA is in much deeper water, is not landlocked, and is exposed to waves and currents generated in the open lagoon. The EXPOE drilling barge proved to be unstable and unsafe as a drilling platform in KOA, and the effort was abandoned after only setting surface casing (Couch and others, 1975, p. 38).

Geophysical studies were an integral part of EXPOE (Pyrz, 1973). As summarized by Ristvet, Tremba, and others (1978), EXPOE obtained about 280,000 linear ft of seismic-refraction profiles for the near-surface section (less than 200 ft thick) from the islands, about 100,000 ft of overwater seismic-refraction lines for the near-surface areas (less than 300 ft) of the large craters OAK, KOA, and MIKE, overwater seismic-refraction and seismic-reflection profiles for the noncratered areas of the lagoon, and downhole geophysical logs for many of the boreholes drilled during the program. Unfortunately, the seismic-reflection data from the lagoon were not of good quality because of high noise levels aboard the ship, the data-reduction techniques, and inaccuracies in navigation. Most downhole geophysical logs were also poor because of casing problems in the boreholes.

EASI PROGRAM (1979–1981)

Although the PACE and EXPOE Programs provided greater understanding of the importance of geologic factors controlling crater formation on a coral atoll and greater definition of crater parameters and other features for the small craters SEMINOLE, CACTUS, and LACROSSE, these programs did not answer fully the major questions regarding the large craters—OAK, KOA, and MIKE—and many of the questions about material properties presented by the lagoonward location of OAK ground zero.

By 1979, research on nuclear-weapons effects funded by the DNA generated renewed interest in resolving the remaining major PPG cratering issues. Another two-phase seismic and drilling program was proposed by the AFWL in July and August 1979. However, only the seismic and geophysical phase of the proposed study received funding by the DNA; the funded study was designated the EASI Program. About 140 nmi of over-water, high-resolution seismic lines were run in 1980 (Tremba and others, 1982; Tremba, 1987). These were concentrated mainly in grids over OAK, MIKE, and KOA craters but included profiles in areas of the lagoon not affected by the nuclear detonations. A limited number of dives and traverses in the OAK and KOA areas were made in 1981 with the submersible R/V *Makalii*, sponsored jointly by the University of Hawaii and the National Oceanic and Atmospheric Administration, the Bishop Museum, and the DNA.

The EASI seismic study and associated submersible observations, coupled with detailed direct and quantitative calculations of the results, provided the DNA and DOE weapons-effects community the first direct evidence that the Pacific high-yield nuclear craters were dominated by late-time processes rather than excavation and ejection. According to Tremba, Couch, and Ristvet (1982, p. 74–80), the evidence strongly suggested that a small, bowl-shaped excavational crater existed prior to the formation of the much larger, broader, dish-shaped crater for OAK, and that the major factors in the difference between the excavational crater and the final crater could be explained plausibly by a combination of shock-induced liquefaction and subsidence responses, compaction, and slope failures of the crater walls. They also stated that it was essential to verify these tentative conclusions with an extensive drilling program.

INTERIM EVENTS (1981–1984) LEADING TO PEACE PROGRAM

The DNA embarked on a three-pronged program in 1981 to better understand near-surface nuclear events. This program consisted of computer-calculation efforts supporting underground nuclear testing, high-explosive simulation, and a detailed site survey of two PPG craters, OAK and KOA, produced by megaton-sized detonations. The two craters were selected for study because of their differing high-yield nuclear-source characteristics, the relative isolation of one of them (OAK) from other nuclear bursts, accessibility by a shallow-water drill ship, and a support base (Mid-Pacific Research Laboratory) at Enewetak Island (FRED). In 1983, an outline of the program was formulated by David J. Roddy of the USGS and Maj. J.B. Jones of the DNA, with the assistance of DNA contractors. This program, which included a drilling plan, was presented to the DNA and later to the USGS. Thus, the PEACE Program came into being.

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