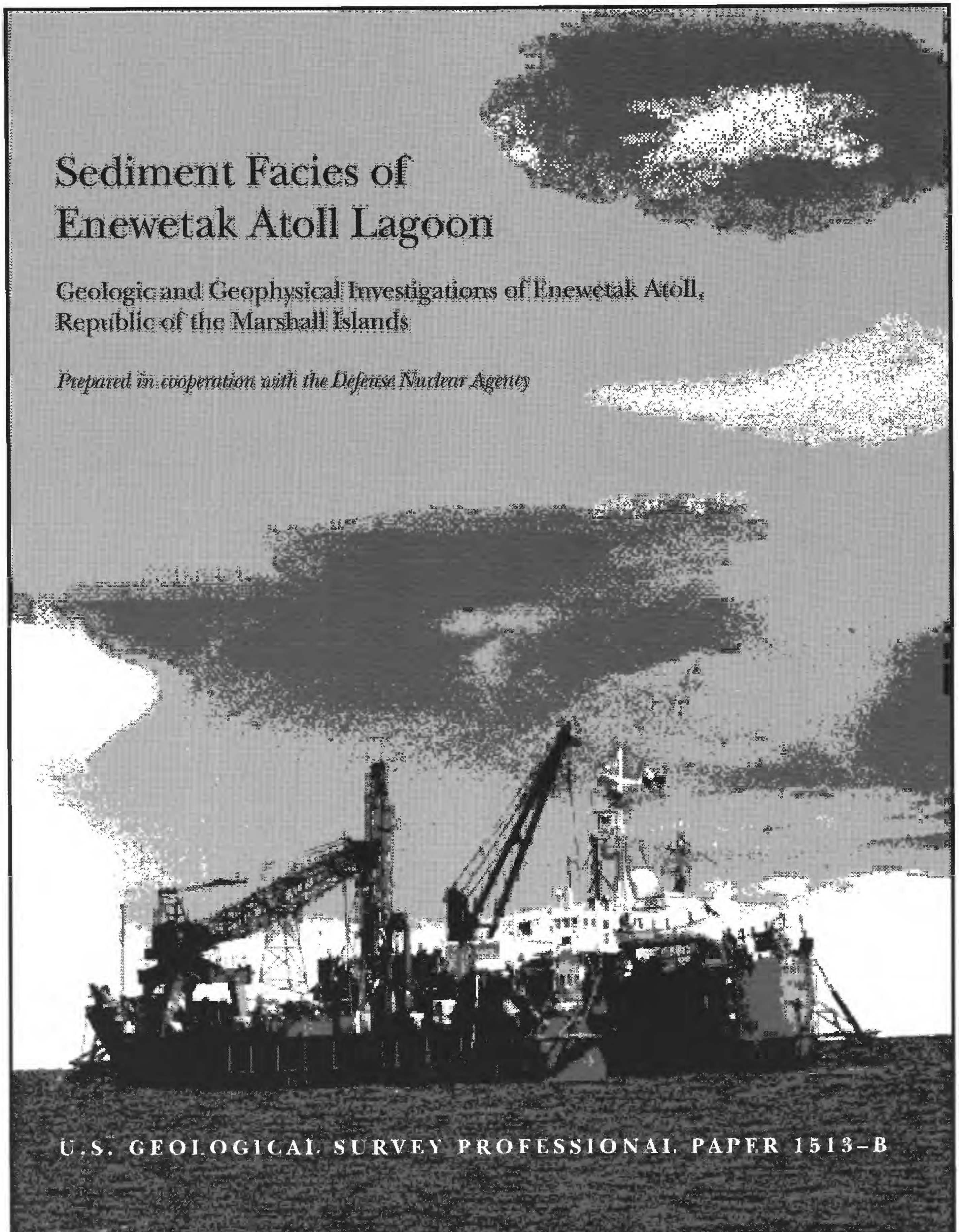
Sediment Facies of Enewetak Atoll Lagoon

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

Prepared in cooperation with the Defense Nuclear Agency



U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1513-B

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By BRUCE R. WARDLAW, THOMAS W. HENRY, *and* WAYNE E. MARTIN

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SEDIMENT FACIES OF ENEWETAK ATOLL LAGOON

By Bruce R. Wardlaw, Thomas W. Henry, and Wayne E. Martin

ABSTRACT

Eight sediment facies were distinguished for benthic (bottom-surface) samples from Enewetak Atoll lagoon on the basis of grain size: granule, granule-sand, sand-granule, granule-sand-mud, sand, muddy sand, sand-mud, and mud. These facies are represented as nonoverlapping fields on a tertiary plot of weight-percent of three constituents (mud, sand, and granule). Four of the facies are subdivided by relative degree of sorting. Facies recognized for the lagoon as a whole generally apply to nuclear craters in the lagoon, with the addition of mixed (or rubble) facies; this mixed facies includes fine-grained sediments that are ascribed to lagoon facies and, in addition, cobble- and larger sized rubble from crater-related slumps, margin collapse, and sand-piping. From the scant information on sediment distribution prior to nuclear testing on Enewetak, modification of the distribution due to testing is shown to include a general increase in fine-grained sediment throughout the lagoon and a marked increase in clay-sized carbonate near sites of larger near-surface tests.

INTRODUCTION

Two sets of benthic (bottom-surface) samples were taken from the lagoon on Enewetak Atoll, Republic of the Marshall Islands, during the PEACE Program (1984–1985) (fig. 1). One set of 117 samples was collected from aboard a small whaler (fig. 2*A*) during the Marine Phase. Another set of 49 samples was taken from aboard the North Sea class M/V *Knut Constructor* (fig. 2*B*) in the vicinity of KOA and OAK craters, in the northern part of Enewetak lagoon, during the subsequent Drilling Phase. These samples were collected to (1) familiarize project geologists with the distribution of sediment types and facies within Enewetak lagoon, (2) increase understanding of the distribution of modern microfaunas in the lagoon, and (3) supplement studies of the sea-floor features both within and near OAK and KOA craters. The benthic sample studies aided both evaluation of the stratigraphic sequence penetrated during the Drilling Phase and interpretation of the litho- and biostratigraphic framework used in analysis of OAK and KOA.

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TOPOGRAPHY AND PHYSIOGRAPHY OF LAGOON

Enewetak Atoll is circumscribed by a barrier reef and a chain of about 40 low, small sand islands bordering an acorn-shaped lagoon (fig. 1). The islands are concentrated on the northeastern, eastern (windward), and southern sides of the atoll. The lagoon is about 40 kilometers (km) (25 miles (mi)) long by 32 km (20 mi) wide and is elongated northwest-southeast. The total areas of the islands and the lagoon are about 6.7 square kilometers (km^2) (2.6 square miles (mi^2)) and 932 km^2 (360 mi^2), respectively. The barrier reef is cut by three passages or channels that lead from the open ocean into the lagoon.

The detailed bathymetry of the Enewetak lagoon was mapped primarily by the U.S. Navy from the U.S.S. *Bowditch* in 1944. Contour maps made from more than 180,000 soundings are presented in Emery, Tracey, and Ladd (1954, chart 5) and are greatly simplified as figure 3. The lagoon is characterized by four major bathymetric features (Emery and others, 1954): (1) lagoon terrace, (2) lagoon basin, (3) coral "knolls" or pinnacle reefs, and (4) reef channels or passages.

The lagoon terrace forms the rim of the lagoon everywhere except on the northwestern side (near OAK crater), where the rim is a relatively steep precipice from the reef tract to the deep lagoon floor, and on the southern side, where the rim is interrupted by the South Passage and the East Channel (fig. 3). The terrace attains a maximum width of about 3 km (1.9 mi) on the western side, north of Biken (LEROY) Island (fig. 1). Water depth on the terrace varies from 15 to 22 meters (m) (49 to 72 feet (ft)); the most frequently recorded depth is about 18 m (60 ft)—hence the term 10-fathom terrace (Emery and others, 1954). From the islands or

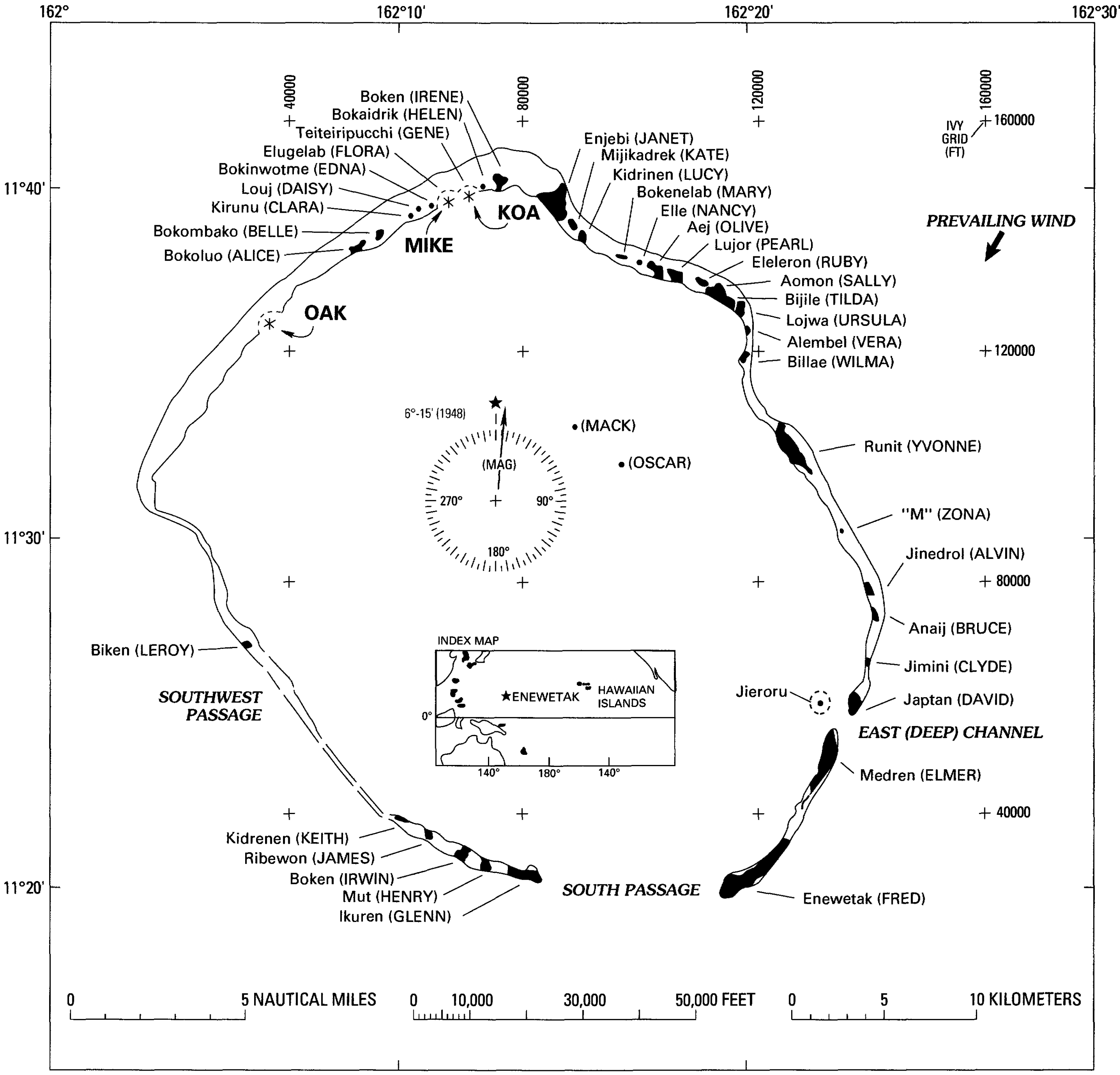

FIGURE 1.—Enewetak Atoll, Republic of the Marshall Islands, with locations of KOA, OAK, and MIKE craters, major channels (passages), principal islands (native names followed by military site names assigned during nuclear testing in parentheses), and coral pinnacles MACK and OSCAR. General location of Enewetak Atoll shown on inset map. (From Henry, 1988, fig. 12.)

reef tract, the terrace dips generally lagoonward, sloping at an average of about 2.5 degrees. The terrace surface is pockmarked with scattered, irregular depressions probably related to Pleistocene karst features (sinkholes). These depressions rarely are deeper than 3 to 4 m (about 12 ft) below the general terrace surface. The inner slope of the lagoon terrace, which separates the terrace from the lagoon basin, is less than 1.5 degrees. Patch reefs and small coral pinnacle reefs ("coral knolls") are common on the terrace.

The lagoon basin is an elliptical, gently undulating, nearly flat floored feature, with slopes averaging about 0.1 degree. According to Emery, Tracey, and Ladd (1954), the basin has a mean depth of about 55 m (180 ft) and attains a maximum depth of 62 m (200 ft) in its northwestern half. Enewetak lagoon is relatively deep

FIGURE 2A.—Sample-collecting crew and 21-foot Boston whaler used in August and early September 1985 during Marine Phase of PEACE Program (photograph courtesy of E.A. Shinn, USGS).

compared with lagoons of other Pacific atolls (Wiens, 1962). The floor of the lagoon basin is marked by several thousand coral pinnacle and patch reefs of varying sizes, about 10 percent of which rise abruptly from the floor to within a few meters of the water surface and several of which are awash at lowest tides (for example, OSCAR and MACK, fig. 1).

The three passages or channels that breach the barrier reef provide major access from the open-marine environment into the lagoon (figs. 1, 3). The East (Deep) Channel, between the islands of Japtan (DAVID) and Medren (ELMER), is the main marine connection on the windward side of the atoll. This channel is 1.5 km (0.9 mi) wide and 55 m (180 ft) deep. The South Passage is 9.5 km (5.9 mi) wide and 12 to 20 m (40 to 65 ft) deep, and the poorly defined Southwest Passage, between Kidrenen (KEITH) and Biken (LEROY) Islands, is a network of small passages 2 to 4 m (6.5 to 13 ft) deep.

LAGOON WATER AND CURRENT SYSTEMS

Windward and leeward cross-reef currents, channel currents, and tidal flow are major factors affecting the exchange of water between the lagoon and the surrounding open ocean (fig. 4A) (Atkinson and others, 1981; Atkinson, 1987). Enewetak lagoon is reasonably isolated from the general westward flow of the North Equatorial Current. However, the surf continually pounds the wind-

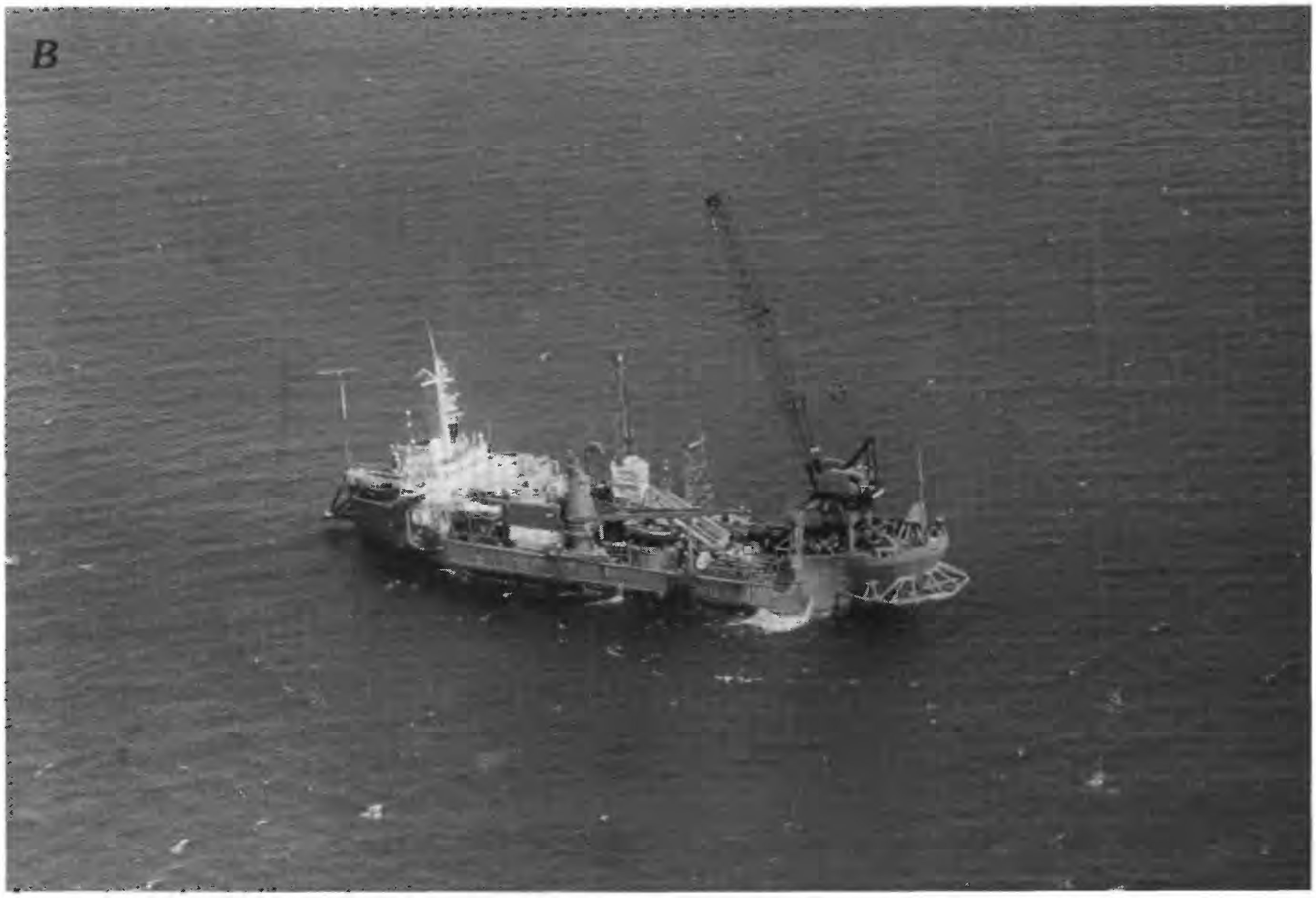

FIGURE 2B.—Portside aerial view of 237-foot drill ship M/V *Knut Constructor* photographed in OAK crater in early June 1985; ship is outfitted with a Failing-2000 rotary drill rig, located midship (photograph by Lt. Col. R.F. Couch, Jr., DNA/USAF; from Henry, 1988, fig. 13).

ward side, and, because the barrier-reef flats are shallow, water constantly spills over the reef into the lagoon. Most of the water coming into the lagoon enters over the windward reefs in this manner. Water cyclically flows into the lagoon through both the East (Deep) Channel and the Southwest Passage. Water flows out through the South Passage, the Southwest Passage, and the leeward reef. Because the amount of flow over the leeward reef from the lagoon is relatively small, most of the water ultimately moves south, exiting through the South Passage. Atkinson (1987, p. 68) estimated an average residence time of about 1 month for water in the lagoon; residence time of water entering the northern part of the lagoon is roughly 4 months.

Three current levels exist within the central lagoon—surface, mid-depth, and deep. The wind-driven surface currents (fig. 4*B*), 5 to 15 m (16 to 50 ft) thick and averaging 10 m (32 ft) thick, primarily facilitate internal circulation rather than "flushing" of lagoon waters. Surface-current velocities are slow, averaging about 10 centimeters per second (cm/s) (4 inches per second (in/s)); drift is generally downwind, to the southwest. The mid-depth currents (10 to 30 m (32 to 98 ft) deep) generally flow northeastward counter to the surface flow at velocities of 2 to 4 cm/s (0.8 to 1.6 in/s). The deep currents, generally 30 to 50 m (98 to 165 ft) deep, flow southward at rates of only 0.5 to 1.5 cm/s (0.2 to 0.6 in/s). Around the periphery of the lagoon, this general three-layer current system is modified or eliminated by tidal and cross-reef currents. The magnitude of the cross-reef currents varies seasonally. As shown in figure 4*C*, the windward cross-reef currents follow the configuration of the atoll along the northeastern side of the lagoon (flowing generally northwestward), and in the southeast between Medren (ELMER) and Enewetak (FRED) Islands (fig. 1) (southwestward flow). Between these two areas and centered on the East (Deep) Channel is a region where the currents also follow the lagoon margin but reverse in response to the tides (fig. 4*C*).

The water column in the lagoon is nearly isohaline and isothermal; salinity averages 34.4 parts per thousand (±0.20 ppt), and temperature averages 27 to 29 °C. Both values are only slightly higher than for surface waters of the North Equatorial Current. Concentrations of inorganic nutrients and dissolved gases show no vertical stratification within the lagoon waters. Thus, despite the three-layer circulation system, the waters exiting the lagoon are well mixed.

PREVIOUS BENTHIC SAMPLING AND ECOLOGIC STUDIES

The first benthic samples were collected from Enewetak lagoon and surrounding areas in 1946 during Operation CROSSROADS (Emery and others, 1954), prior to the period of nuclear testing (1948-1958). This suite of 365 samples was taken mainly from aboard the U.S.S. *Blish*, whose primary mission was gathering supplementary data for detailed bathymetric maps of the atoll. Most of these samples were taken with a small underway sampler ("scoopfish") along selected bathymetric-traverse lines (fig. 4*D*); fewer than 5 percent were collected with a dredge. The distribution and average weight percentages of the sedimentary components were described by Emery, Tracey, and Ladd (1954, p. 97–100; see figs. 5*A*–5*D* of this report). The principal grain components, in decreasing order of importance, were *Halimeda* (fig. 5*C*), coral, foraminifers (fig. 5*B*), mollusk shells and debris (fig. 5*A*), and other fine-grained biotic and bioclastic material (fig. 5*D*), defined as particles less than 0.25 millimeter (mm) in diameter (that is, fine sand and finer). This mix is similar to that of benthic samples taken from other Pacific atolls. According to J.I. Tracey (oral commun., 1986), the 1946 Enewetak lagoon samples were biased against the fine-grained components because of the tendency of the sampler to not close completely upon impact with the bottom and the consequent "streaming" of the finer materials out of the sampler as it was raised from the sea floor through the water column.

A number of the 1946 samples were included in a study of the Recent foraminifer faunas of the Marshall Islands by Cushman, Todd, and Post (1954). Some of the same samples were reexamined for the PEACE Program for both foraminifers and ostracodes by Cronin, Brouwers, and others (1986).

Additional surface and near-surface samples were taken from the atoll following nuclear testing on Enewetak, principally to determine the distribution of radionuclides in the sediments of the lagoon and islands to assess their potential long-term effects on the food chain and their consequent impact on relocated human populations. The most extensive of these programs was the Enewetak Radiological Survey of 1972. Identified in the report of the radiological survey (Nelson and Noshkin, 1973) were two areas of significant contamination (fig. 16*D*), a large area encompassing most of the northwestern part of the lagoon (downcurrent from where most of the nuclear testing was done) and a

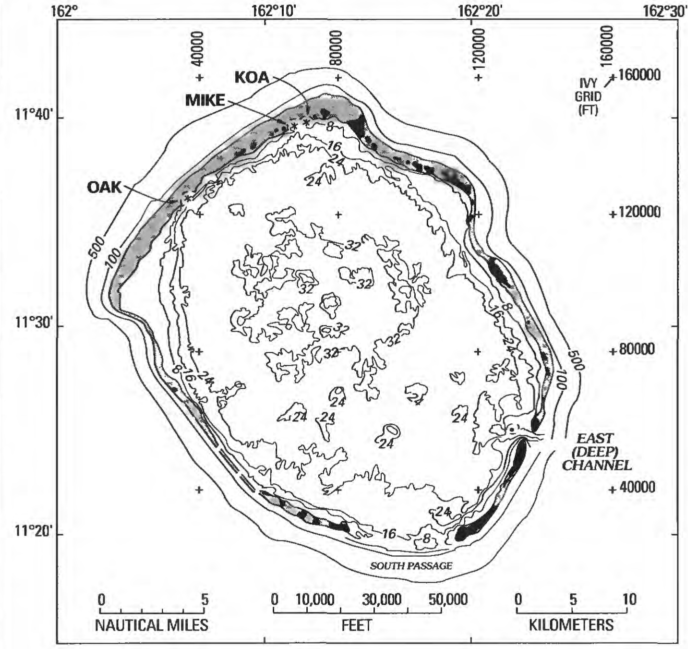

FIGURE 3.—Simplified bathymetric map of Enewetak lagoon. Sounding contours in fathoms (1 fathom equals 6 feet). (From Folger, Hampson, and others, 1986, fig. 1, generalized and simplified after Emery and others, 1954, chart 5.)

smaller area lagoonward from the island of Runit (YVONNE), on the eastern side of the atoll (see also Noshkin, 1980). More recently, McMurtry, Schneider, and others (1985) studied the vertical distribution of fallout radionuclides in shallow sediment cores—less than 244 cm (8 ft) in length—taken off Runit (YVONNE) Island near the HOLLY/MAGNOLIA/LINDEN/SEQUOIA composite crater. Subsequent studies of redistribution of radionuclides in the near-surface lagoon sediments by burrowing benthic organisms (bioturbation) were conducted by Suchanek and Colin (1986) and Suchanek, Colin, and others (1986).

The subtidal environments and biotic communities of Enewetak lagoon, with certain exceptions, are generally poorly known. This is particularly true of the deeper parts of the lagoon. Colin (1986, 1987) conducted a very general study of the subtidal lagoon environments based primarily on about 2,000 photographs taken with a submarine camera system. Supplementary information came from submersible dives in the deeper areas and scuba reconnaissances around the lagoon margin. Colin divided the subtidal area into (1) a lagoon-margin environment and (2) a deep-lagoon environment (the part exceeding 30 m (98 ft) in depth). The deep-lagoon environment is completely within the realm of the slow-moving, deep-current system. These environments were subdivided into a number of communities on the basis of substrate types and dominant organisms. For both environments, two general bottom types were recognized—hard and soft substrates. Conclusions about the nature of

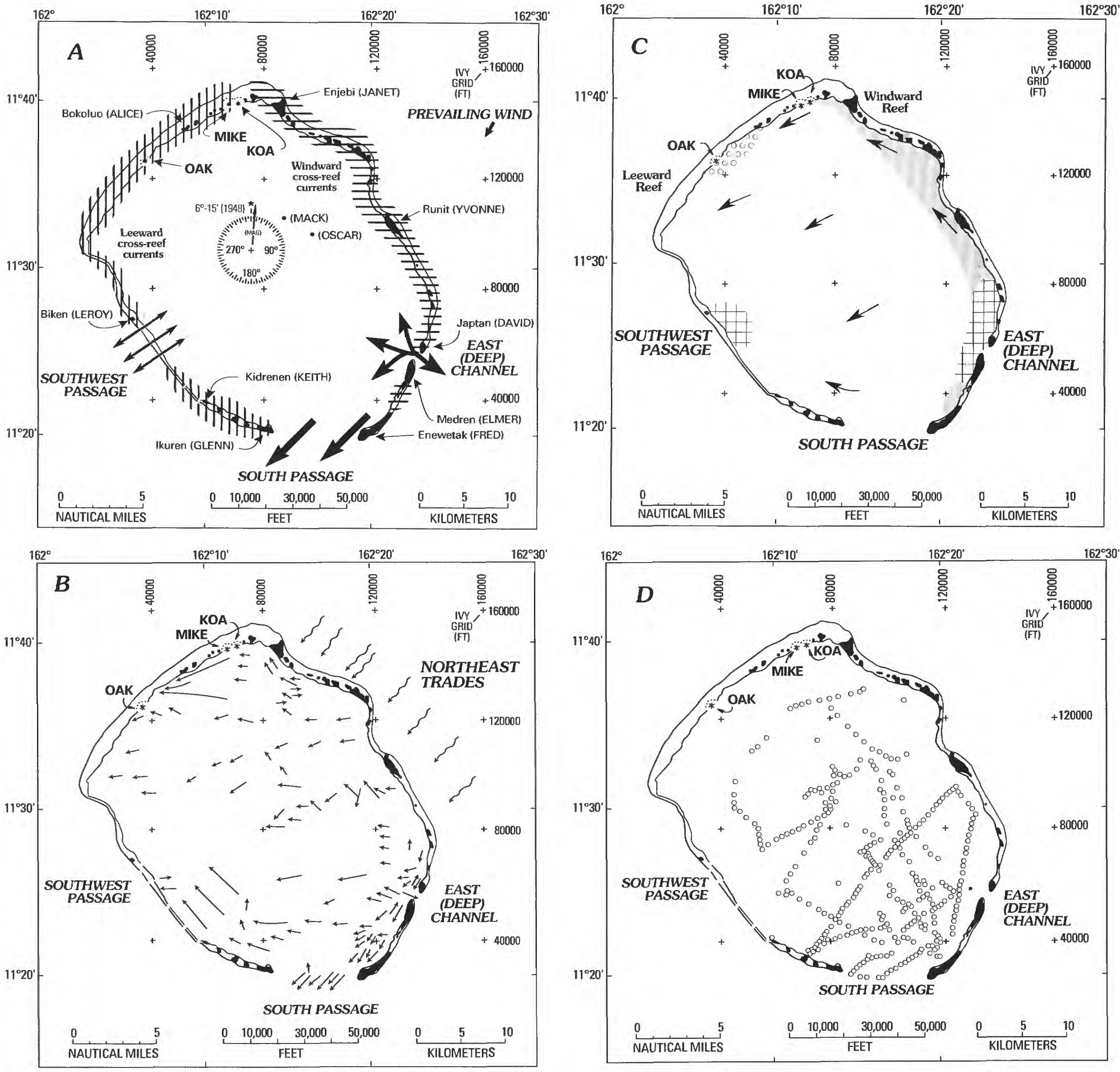

FIGURE 4.—Current systems in Enewetak lagoon. *A*, Major currents and passages; area influenced by windward cross-reef currents shown with horizontal hachures, area influenced by leeward cross-reef currents with vertical hachures; influx and outflux of water during tidal cycles shown with arrows (modified from Atkinson, 1987, fig. 2). *B*, Lagoon surface currents; arrows represent smoothed drogue trajectories over varying lengths of time (modified from Atkinson, 1987, fig. 4). *C*, General current patterns in lagoon; arrows indicate current direction, stippled areas are influenced by nonreversing cross-reef currents, cross-hachured areas are regions of reversing currents; circular pattern indicates convergence (modified from Atkinson, 1987, fig. 9). *D*, 1946 sample locations (modified from Emery and others, 1954, fig. 43).

the substrate and corresponding percentages were based on point counts from the photographic data.

The width of Colin's (1986, 1987) lagoon-margin environment—low tide to 30 m (100 ft) depth—varies from only a few hundred meters in the south (for example, near Enewetak (FRED) Island) to more than 1 km (0.6 mi) in the north and northwest (for example, near Engebi (JANET) and Biken (LEROY) Islands). This environment is highly variable and consists of soft- and hard-bottom communities, including numerous patch reefs and coral knolls. The types and distribution of the communities depend on their location (on the leeward or wind-

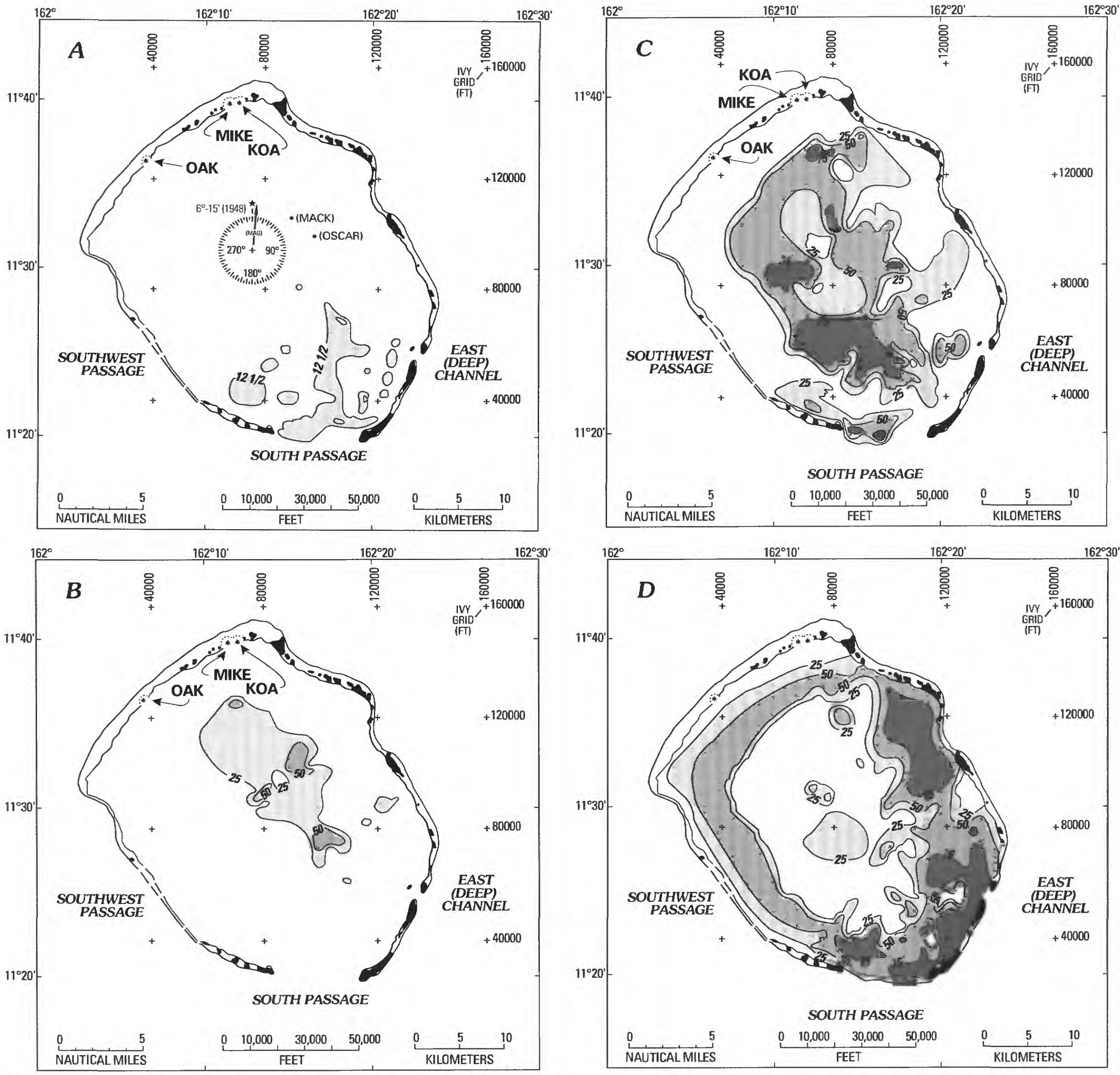

FIGURE 5.—Isopleth maps of Enewetak lagoon showing weight percentages of principal grain constituents of bottom sediments (data from 1946 (pretesting) survey; modified from Emery and others, 1954, fig. 43). *A*, Mollusk shells and debris. *B*, Foraminifera in benthic sediments. *C*, *Halimeda* debris and other green algae grains and flakes in benthic sediments. *D*, Fine debris (that is, fine sand and finer) in benthic sediments.

ward side of the atoll), the position and proximity of sheltering sand islands, and the community's proximity to the passages to the open ocean. The lagoon-margin environment in the vicinity of the South Passage has a particularly high concentration of mollusk shells and debris and *Halimeda* (figs. 5*A*, 5*C*).

Within the lagoon-margin environment, patch reefs are very well developed and (in some places) almost continuous on the western (leeward) side of the atoll, where the lagoon terrace is broad. Here, because of waves generated by the prevailing winds blowing across the lagoon and breaking on the lagoonward side of the main reef flat itself, a number of features (including spurs and grooves) are developed on the lagoonward side that resemble those found on the seaward side of the barrier-reef flats on the windward side of the atoll.

Colin (1986, 1987) estimated that about 85 percent of the deep-lagoon floor consists of soft substrates; the rest of the bottom is hard or a mixture of hard and soft. The hard-substrate communities are principally (1) pinnacle and patch reefs of very high diversity and of varying size and relief that are scattered throughout the basin and (2) so-called "coral pavements." The soft-substrate communities form four commonly intergrading types: (1) open-sand lagoon floor without a visible algal mat, (2) sand floor with a visible surficial microalgal mat ("algal film"), (3) sand floor populated by calcareous, green macroalgae (for example, *Halimeda* "flats" or "meadows"), and (4) sand floor populated by large numbers of unattached, solitary fungiid corals. (Note that the term "sand floor" is a misnomer; in a sedimentologic sense, these generally are not sand bottoms.)

The first soft-substrate "community" is self-explanatory. The microalgal mats (community 2) generally are composed of a diatom and blue-green algal film at the sediment-water interface. The algal-flat community (community 3), areas of high diversity and productivity, generally is made up of moundlike features composed of various kinds of calcareous algae and, commonly, stony corals. These mounds commonly project as much as several meters above the surrounding area because of the higher rate of production and accumulation of coarser grained skeletal material than the surrounding communities and because of the entrapment (baffling effect) by the algae of finer grained (muddy) particles being transported in suspension. Emery, Tracey, and Ladd (1954, p. 98–99) reported that in the 1946 study the highest percentage of *Halimeda* debris was in samples (fig. 4*B*) from the deep-lagoon environment; in places, *Halimeda* debris made up as much as about 80 percent of the sample. The fourth community (the fungiid coral community) is uncommon and seemingly is restricted to areas of the lagoon 50 m (about 160 ft) or more deep.

All four communities generally are highly bioturbated and studded with conical, callianassid shrimp mounds. Emery, Tracey, and Ladd (1954; fig. 5*B*, this paper) reported samples from the middle part of the lagoon to be particularly rich in smaller benthic foraminifers. This foraminifer-rich facies is in the deepest part of the deep-lagoon environment in waters dark enough that *Halimeda* cannot flourish and overwhelm the accumulation of foraminifer tests in the benthic sediments.

STORM EFFECTS ON THE LAGOON ENVIRONMENTS

Under normal conditions, sediment that is generated in the lagoon subtidal environments, or that is swept across the reef flats on the windward side and thus enters the lagoon, generally stays in the lagoon. These sediments are subject to reworking by cross-reef currents and waves around the shallower margins of the lagoon. Particles that enter the realm of the deep-lagoon floor (the part of the lagoon deeper than 30 m (98 ft)) by settling through the water column, or that are generated in situ by growth and death of calcareous organisms, generally stay on the lagoon floor or are reworked into the upper part of the sediment column by infaunal benthic organisms, such as the callianassids. Because of the shape of the deep-lagoon environment and the nature of the deep-current system, the possibility of this material being transported out of this environment into shallower parts of the lagoon or, indeed, out of the lagoon itself is slim.

Typhoons, tropical storms, and other tropical disturbances create wave and current conditions that disrupt normal sedimentary processes in shallow-water marine environments. Generally, in the western Marshall Islands, these disturbances occur during the wet season, particularly July through October (see Merrill and Duce, 1987, for data on the tropical storms and disturbances affecting Enewetak). The oceanward side of the normally leeward part of the atoll is particularly vulnerable to these storms. From the shallow subtidal part of the reef tract and reef flat on the side of the islands facing the storm, material can be broken up by the storm waves and piled up on the seaward side of the islands, forming so-called boulder ramparts consisting mainly of coral heads. Smaller carbonate particles can be driven across the islands by the storm waves and deposited on the stormward side of the lagoon. Some of the very fine suspended material ultimately settles in the deep-lagoon environment after the storm passes.

The impact of such storms on subtidal environments in the lagoon can be equally devastating, particularly on atolls (such as Enewetak) that have channels or passages large enough to admit ocean swells generated by these storms into the lagoon. The broad South Passage between Enewetak (FRED) and Ikuren (GLENN) Islands is deep enough to allow ocean swells from the southeast to southwest to enter the lagoon. According to Colin (1987), the swells are refracted at the channel so that wave trains moving from the west and southwest can travel across the lagoon and impinge on the opposite lagoon shoreline. To quote Colin (1987, p. 124): "These long period swells have no direct effect on the deep lagoon communities. However, when they reach the lagoon shore of windward islands or patch reefs, they can turn these shallow-water communities into churning maelstroms of breaking waves." Although it is probably true that these waves have no direct effect on the deep-lagoon communities, the shallower parts of the pinnacle reefs originating from the deep-lagoon bottom are affected, and some of the disrupted material is shed as talus into the deep-lagoon environment in the vicinity of the pinnacle reefs.

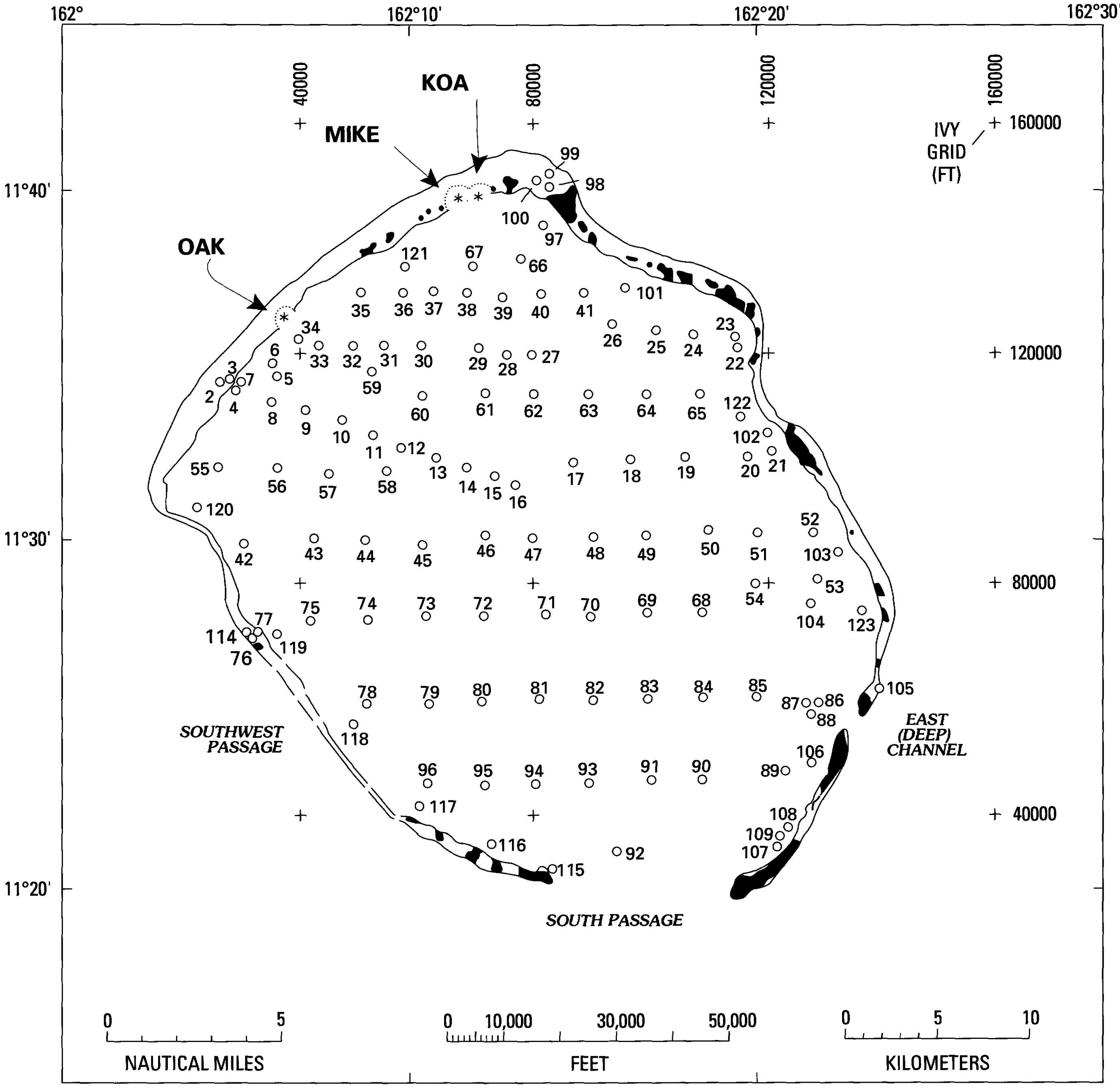

FIGURE 6. —Location of benthic samples taken in Enewetak lagoon during Marine Phase of PEACE Program (see table 1 for IVY-grid coordinates of samples).

Material churned up from the eastern and northeastern parts of the shallow lagoon margin by the impingement of these wave trains on the shores can also be exported from the lagoon by being swept across the islands and (or) reef flats. Colin (1987) also noted that the downslope movement of rubble on the oceanward parts of the reef during these storms is volumetrically significant.

PEACE PROGRAM DATA BASE AND PROCEDURES

The first set of 117 benthic samples taken during the PEACE Program was collected in September 1984, during the Marine Phase (fig. 6, table 1). The second set of 49 benthic samples was taken in the proximity of KOA and OAK from February through July 1985, during the Drilling Phase (table 1).

TABLE 1.—*Location of benthic samples taken during PEACE Program on Enewetak Atoll*

[IVY-grid coordinates in feet north and east. Sample 1 was lost in transit; samples 110–113 were not collected]

Sample	IVY-grid coordinates	
2	116,563 N.	025,625 E.
3	116,250 N.	026,250 E.
4	116,255 N.	027,500 E.
5	120,169 N.	034,022 E.
6	120,349 N.	033,675 E.
7	116,864 N.	028,860 E.
8	115,594 N.	033,997 E.
9	113,923 N.	039,437 E.
10	111,869 N.	045,446 E.
11	109,779 N.	051,012 E.
12	107,672 N.	056,308 E.
13	105,389 N.	062,053 E.
14	103,059 N.	068,016 E.
15	100,911 N.	072,994 E.
16	099,550 N.	076,310 E.
17	104,000 N.	087,200 E.
18	105,600 N.	096,400 E.
19	105,000 N.	105,700 E.
20	105,400 N.	114,700 E.
21	105,600 N.	123,500 E.
22	124,700 N.	117,700 E.
23	125,800 N.	117,700 E.
24	126,500 N.	108,400 E.
25	127,400 N.	102,400 E.
26	128,400 N.	094,100 E.
27	123,700 N.	079,571 E.
28	123,433 N.	075,155 E.
29	125,083 N.	070,078 E.
30	125,929 N.	059,865 E.
31	125,423 N.	053,733 E.
32	125,436 N.	047,996 E.
33	125,649 N.	042,008 E.
34	126,928 N.	038,264 E.
35	135,333 N.	048,432 E.
36	135,164 N.	056,891 E.
37	135,119 N.	062,314 E.
38	135,052 N. [1]	068,260 E.
39	134,957 N.	074,334 E.
40	134,474 N.	081,830 E.
41	134,750 N.	088,045 E.
42	089,900 N.	027,665 E.
43	090,339 N. [1]	040,438 E.
44	090,143 N.	049,953 E.
45	090,125 N. [1]	060,321 E.
46	090,278 N. [1]	070,766 E.
47	090,111 N.	079,886 E.
48	090,256 N. [1]	090,418 E.
49	089,847 N.	100,030 E.
50	090,269 N. [1]	110,628 E.
51	090,114 N. [1]	120,257 E.
52	090,051 N.	130,701 E.
53	081,528 N. [1]	131,360 E.
54	080,083 N.	120,271 E.
55	104,893 N.	023,570 E.
56	103,787 N.	034,358 E.
57	102,496 N.	043,504 E.
58	102,488 N.	053,802 E.
59	120,760 N.	050,924 E.
60	116,225 N.	060,082 E.
61	116,539 N.	071,146 E.
62	116,104 N.	079,923 E.
63	115,837 N.	090,031 E.
64	116,078 N.	100,618 E.
65	115,972 N.	100,092 E.
66	143,198 N.	077,635 E.
67	142,035 N.	068,681 E.
68	075,024 N.	110,040 E.
69	075,108 N.	100,323 E.
70	074,938 N.	090,070 E.
71	075,486 N.	081,692 E.
72	075,273 N.	070,622 E.
73	075,377 N.	060,633 E.
74	075,000 N.	050,359 E.
75	075,000 N.	040,038 E.
76	071,333 N. [2]	031,200 E.
77	072,200 N. [2]	031,817 E.
78	059,907 N.	050,165 E.
79	060,263 N.	060,919 E.
80	059,850 N.	070,209 E.
81	060,084 N.	080,327 E.
82	059,976 N. [1]	090,360 E.
83	059,899 N.	100,169 E.
84	060,122 N.	100,004 E.
85	060,078 N.	119,780 E.
86	058,730 N.	130,262 E.
87	059,790 N.	129,627 E.
88	056,721 N.	129,518 E.
89	046,609 N.	125,333 E.
90	044,985 N.	110,053 E.
91	045,356 N.	100,708 E.
92	032,115 N.	095,191 E.
93	045,006 N.	090,014 E.
94	045,034 N.	080,008 E.
95	045,159 N.	070,432 E.
96	045,553 N.	060,673 E.
97	147,500 N.	082,450 E.
98	151,300 N.	082,188 E.
99	153,125 N.	082,188 E.
100	151,563 N.	080,625 E.
101	135,625 N.	096,875 E.
102	106,250 N.	124,000 E.
103	086,563 N.	135,000 E.
104	076,563 N.	130,625 E.
105	062,188 N.	139,688 E.
106	048,120 N.	130,000 E.
107	035,156 N.	123,438 E.
108	037,500 N.	124,531 E.
109	037,344 N.	124,375 E.
114	072,033 N.	030,667 E.
115	031,250 N.	082,500 E.
116	034,688 N.	069,688 E.
117	041,250 N.	059,063 E.

TABLE 1.—*Location of benthic samples taken during PEACE Program on Enewetak Atoll*—Continued

[IVY-grid coordinates in feet north and east. Sample 1 was lost in transit; samples 110–113 were not collected]

Sample	IVY-grid coordinates	
118	056,250 N.	047,344 E.
119	072,656 N.	034,219 E.
120	096,875 N.	019,375 E.
121	140,625 N.	057,188 E.
122	112,188 N.	117,500 E.
123	075,313 N.	139,375 E.
KBZ-4S	149,290 N.	071,000 E.
KBZ-4B	149,382 N.	071,208 E.
KBZ-4C	149,350 N.	071,113 E.
KCT-5S	148,758 N.	070,971 E.
KCT-5B	148,828 N.	071,189 E.
KDT-6S	148,129 N.	071,018 E.
KDT-6B	148,240 N.	071,240 E.
KET-7S	147,985 N.	071,023 E.
KET-7B	148,049 N.	071,247 E.
OAM-3C	127,818 N.	039,450 E.
OBZ-4B	124,983 N.	036,211 E.
OCT-5S	125,434 N.	036,428 E.
OCT-5B	124,467 N.	036,652 E.
ODT-6S	126,109 N.	037,248 E.
ODT-6B	126,138 N.	037,472 E.
OET-7S	125,898 N.	036,973 E.
OET-7B	125,943 N.	037,195 E.
OFT-8S	125,768 N.	036,759 E.
OFT-8B	125,805 N.	036,982 E.
OGT-9S	125,723 N.	036,685 E.
OHT-10B	123,996 N.	037,295 E.
OIT-11S	124,214 N.	036,924 E.
OIT-11B	124,216 N.	037,150 E.
OJT-12S	124,031 N.	037,401 E.
OJT-12B	124,044 N.	037,627 E.
OKT-13S	124,327 N.	036,756 E.
OKT-13B	124,364 N.	036,979 E.
OLT-14S	123,561 N.	038,334 E.
OLT-14B	123,550 N.	038,573 E.
OMT-15S	123,956 N.	037,941 E.
OMT-15B	123,962 N.	038,167 E.
ONT-16S	124,204 N.	037,639 E.
ONT-16B	124,198 N.	037,865 E.
OOR-17S	119,843 N.	032,771 E.
OOR-17B	119,817 N.	032,996 E.
OPZ-18S	124,787 N.	036,255 E.
OPZ-18B	124,765 N.	036,480 E.
OQT-19S	123,631 N.	035,419 E.
OQT-19B	123,640 N.	035,644 E.
ORT-20S	123,281 N.	035,213 E.
ORT-20B	123,294 N.	035,439 E.
OSR-21S	120,304 N.	033,060 E.
OSR-21B	120,308 N.	033,297 E.
OSM-22S	120,282 N.	033,003 E.
OTG-23S	124,204 N.	035,771 E.
OTG-23B	124,180 N.	035,997 E.
OUT-24S	125,482 N.	035,552 E.
OUT-24B	125,538 N.	035,331 E.
RXNMASS	121,824 N.	033,363 E.

[1]"Average" location of multiple-grab sample.
[2]Location estimated from lagoon hydrographic map.

FIELD PROCEDURES

Sampling in Enewetak lagoon during the Marine Phase was done using a modified grid (fig. 6) from aboard a 21-ft Boston whaler (fig. 2*A*) equipped with a Motorola Falcon-IV Miniranger navigation computer. The number of sampling stations was limited by severe time constraints. A navigation specialist from Meridian Ocean Systems was aboard the whaler when the samples were collected. Thus, the network of five transponder stations established around the atoll for the program (see Folger, Hampson, and others, 1986, p. A2, and Henry and others, 1986, p. 32–39, for discussion) was used effectively, and the position recorded is highly accurate (±3 m (10 ft)). The whaler's location was recorded when the sampler struck the bottom. Although the heavy sampler dropped rapidly and almost vertically, minor allowance must be made for some drift, particularly on windy days in the deeper parts of the lagoon.

Most samples were taken with a 16-kilogram (kg) (35-pound (lb)), lead-weighted, snap-jaw, grab sampler (fig. 7). Generally, the jaws of the heavily sprung sampler closed cleanly, minimizing the loss of finer grained components as the sampler was retrieved. When the sampler did not close cleanly, the residual sample was discarded and another one was taken in the same area. Multiple samples were taken at many stations to obtain an acceptable volume of material for analysis, particularly in areas of predominantly hard bottoms or abundant fungiid corals. Thus, samples from such environments predominantly represent the soft-sediment component of the substrate. The location of multiple samples is given in table 1 as an "average" of the Miniranger locations for each grab. In shallower water, where the grab sampler was not effective, samples were obtained by diving from the surface and scooping the sediment into an approximately 2-liter (L) (2 quart (qt)) metal can. Samples taken with the grab-sampler generally weighed about 1 kg (2.2 lb); those taken with the metal can weighed about twice as much.

Onsite, no attempt was made to correlate the Marine Phase sample locations with depths or with bottom types. The depth of each sample was estimated from available bathymetric maps (Defense Mapping Agency charts).

All but three of the samples collected during the Drilling Phase were taken from the starboard bow and starboard stern of the *Knut Constructor* (fig. 2*B*), at most borehole sites using the same grab sampler (table 1). Two additional grab sampler samples were taken from starboard midship onboard. One additional sediment sample was scooped from the top of the reaction mass, after it was retrieved from the lagoon bottom at the end of the program. The borehole locations on KOA

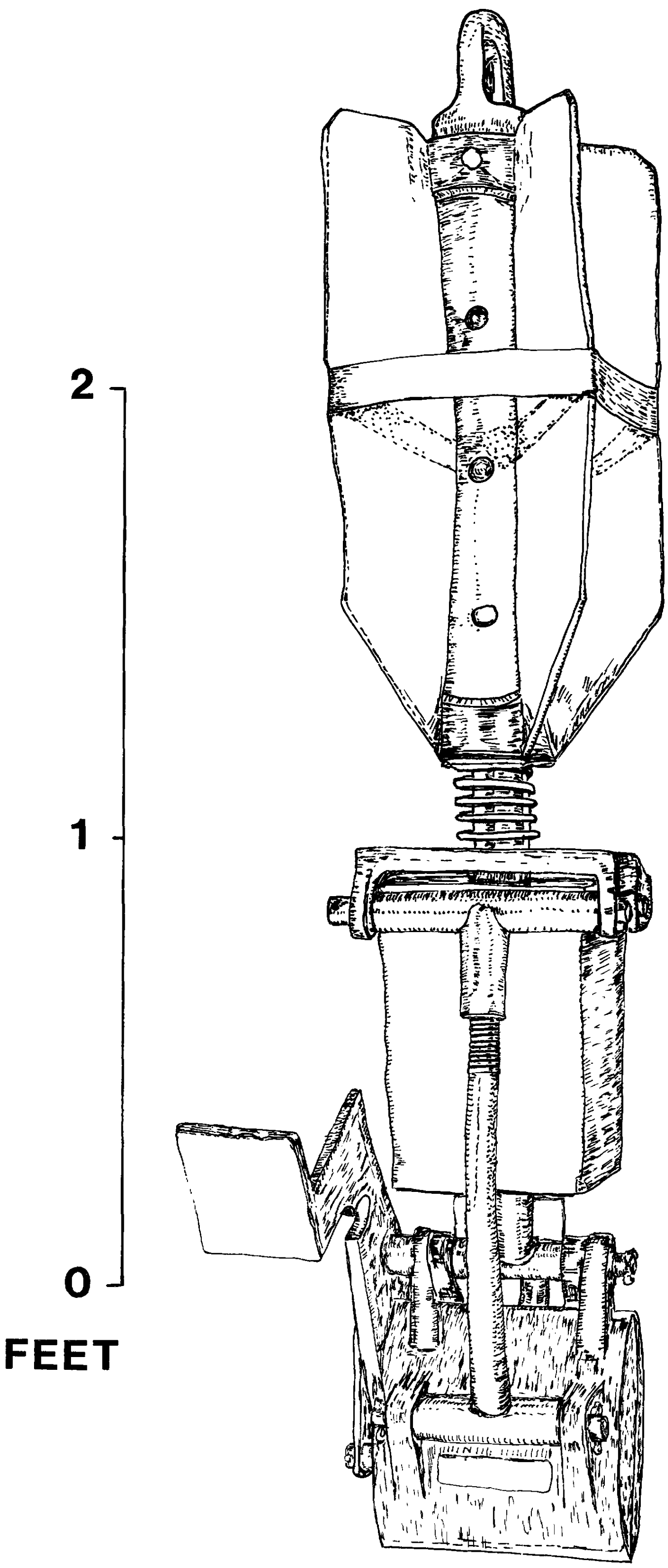

FIGURE 7.—Lead-weighted, snap-jaw grab (bottom) sampler used to collect most benthic samples during PEACE Program.

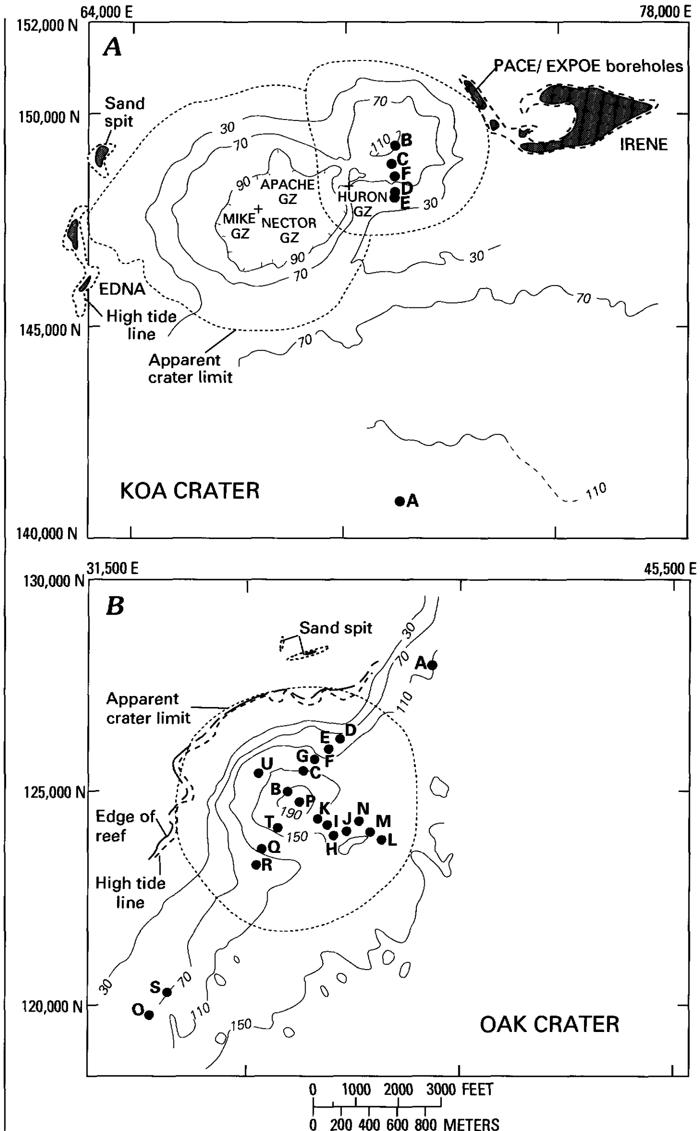

FIGURE 8.—Borehole sites (depicted by letters) and general bathymetric contours (in feet) in (*A*) KOA and (*B*) OAK craters (see fig. 1 for location of craters).

and OAK craters are shown in figures 8*A* and 8*B*, respectively. Samples taken from aboard the drill ship were located trigonometrically from the borehole site (determined by the shipboard navigational computer), the heading of the ship, and the distance from the moonpool to the sampling station. The depths are approximately those of the borehole or represent lead-line soundings made from the ship at the sample station.

For both sample sets, the material was scooped and (or) washed, with a spatula and squeeze bottle, from the sampler into sealable plastic bags and identified with the appropriate station. Marine Phase samples were transported to the University of Hawaii/DOE Mid-Pacific Research Laboratory on Enewetak (FRED) Island. Excess sea water was decanted from the samples after the sediment was allowed to settle. From 50 to 75 milliliters (mL) of 5-percent methanol and a few drops of buffered formaldehyde were added to each sample. The bags were then resealed, and inserted into larger plastic bags and sealed for shipment. Drilling Phase samples were sealed, labeled, and inserted into larger sealed bags for packing and shipment from the *Knut Constructor.*

LABORATORY PROCEDURES

The sediment samples were processed in U.S. Geological Survey (USGS) laboratories and in the Division of Sedimentology laboratory, Department of Paleobiology, at the Natural History Museum (Smithsonian Institution), Washington, D.C. The benthic samples were washed free of preservatives, if present, and then dried at low temperature (70 °C). After equilibration to standard conditions (room temperature and humidity), samples were weighed on a top-loading balance. Each sample was then split into paleontologic and sedimentologic fractions with a standard sediment splitter. Fragments (generally coral) too large for the splitter were weighed separately and retained with excess sedimentologic fractions as archival material.

The paleontologic split was transferred to USGS laboratories in Reston, Va., where selected samples were processed and picked for microfauna (benthic foraminifers and ostracodes) for study of the ecologic distribution of modern Enewetak lagoon microfaunas (Cronin and others, 1986, p. 36–37).

Twenty-three of the sedimentologic samples were split further and analyzed for total organic content (10 samples) and (or) for mineralogy (22 samples) by detailed X-ray analysis at the U.S. Air Force Weapons Laboratory, Kirtland Air Force Base, N. Mex. (Ristvet and Tremba, 1986b, and Tremba and Ristvet, 1986, respectively).

From the remaining fraction of the 23 samples just described and from all the other sedimentologic samples, 100- to 200-gram (g) (3.5- to 7-ounce (oz)) portions were weighed and cleaned of organics by oxidation with a 30-percent hydrogen-peroxide solution. From each, an approximately 50-g (1.8-oz) split was taken for grain-size analysis. These samples were wet-sieved to separate the silt and clay fraction from the sand and small-granule fraction by flooding the sample with less than a liter of 0.03 percent "Calgon" water and washing it through a 4-phi- (no. 230-) mesh brass screen. The sample retained on the screen was dried, weighed, transferred into a set of nested sieves, and placed in a sediment shaker for 15 minutes. Sieve sizes were selected for the major sediment-size categories, which include -1, 0, 1, 2, 3, and 4 phi (fig. 9). Material retained on each sieve screen then

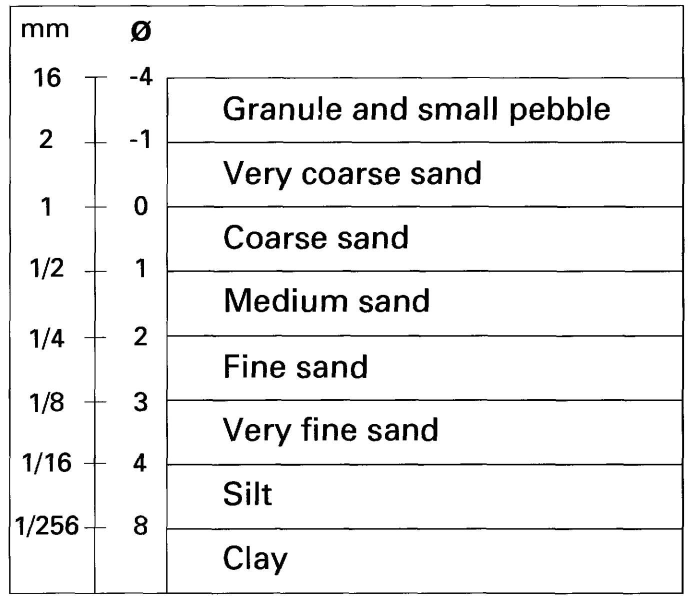

FIGURE 9.—Grain-size scale (Wentworth scale) used for the sedimentologic samples.

was weighed, and the size fractions recombined and archived.

Pipette analysis in 1-L graduated cylinders was done on the material in the bottom pan after wet sieving, using the method described by Folk (1974). Pipette samples were dried, allowed to equilibrate to standard room conditions, and weighed on an analytic balance.

The ratio of granule:sand:mud was calculated for each sample (table 2) in the manner described by Folk (1974) (granule, -4 to -1 phi; sand, -1 to 4 phi; mud, >4 phi). For samples containing 65 weight-percent or greater sand, the sand size was differentiated into very coarse and coarse, medium, and fine and very fine fractions (see fig. 9). Histograms of the size fractions for each sample are given at the end of the text (figs. 17, 18).

Noncarbonate fractions of the Enewetak lagoon samples make up very small percentages of the total sediment. Nonorganic insoluble residues are negligible in PEACE Program borehole samples (Ristvet and Tremba, 1986a), including subbottom samples from the Holocene section. Although the lagoon-bottom samples were not analyzed for insoluble residues, certainly a paucity of noncarbonate components is expected. On the other hand, the organic content of the modern lagoon benthic sediments averages 3.3 percent by weight, and the Holocene core samples only slightly less (3.0 percent) (Ristvet and Tremba, 1986b). Note that the organic fraction was *not* measured in the present study, and that the percentage values given in the sedimentologic table (table 2) reflect *only the total weight of the carbonate material.*

TABLE 2.—*Sedimentologic analyses of benthic samples from Enewetak lagoon*

[Analyses are ratios, in weight-percent, as follows: Entire sample, granule:sand:mud; Sand portion of sample: very coarse and coarse:medium:fine and very fine. Some ratios do not add to 100 owing to rounding. See text for determination of depths, given in meters and feet below Holmes and Narver datum (0.5 feet below approximate mean low water spring) for all samples except those marked with "+," which were taken above that datum. Samples marked with "x" were split for mineralogic (X-ray diffraction) analysis (Tremba and Ristvet, 1986); those marked with "o" were analyzed for organic content (Ristvet and Tremba, 1986b). "S" indicates stern sample, "B" bow sample, and "C" midship sample; "RXNMASS" is from reaction mass. Location of samples 1–123 shown in fig. 6; coordinates of all samples given in table 1]

Sample	Sediment facies	Entire sample	Sand portion of sample[1]	Depth	
				Meters	Feet
Lagoon samples taken during Marine Phase					
1	—	(Sample lost in transit)		—	—
2	Granule-sand	44.3:54.0: 1.7		+0.6	+2
3	Granule-sand	35.1:63.1: 1.7		0.6	2
4	Sand	2.0:96.2: 1.8	32.4:60.5:17.2	0.9	3
5	Sand-granule	15.3:82.3: 2.4	52.4:34.9:12.7	22.0	72
6	Granule-sand-mud	25.9:52.4:21.7		9.1	30
7	Sand-granule	17.5:80.7: 1.8	34.3:51.5:14.2	4.6	15
8	Granule-sand-mud	23.3:61.6:15.1		32.9	108
9 xo	Mud	2.5:45.0:52.5		49.4	162
10	Mud	7.2:35.0:57.8		56.7	186
11	Sand	4.1:92.7: 3.2	42.7:28.3:29.0	48.5	159
12	Sand	8.5:88.8: 2.7	54.7:28.4:16.9	58.5	192
13	Sand-mud	1.0:63.7:35.3		56.7	186
14	Sand	8.7:89.3: 2.0	43.3:30.7:26.0	51.2	168
15	Granule	82.7:15.7: 1.6		36.6	120
16 x	Sand-granule	18.4:74.5: 7.1	71.0:15.4:13.6	58.5	192
17 xo	Sand-granule	11.0:87.0: 2.0	54.9:26.8:18.3	29.3	96
18	Muddy sand	6.8:80.3:12.9	45.1:20.9:34.0	31.1	102
19	Sand-mud	2.5:70.5:27.0	39.8:22.4:37.7	54.9	180
20	Sand	4.1:94.3: 1.6	52.9:32.3:14.8	18.3	60
21	Sand	0.1:98.8: 1.1	31.2:56.8:12.0	5.5	18
22	Sand	5.1:93.7: 1.2	51.1:40.3: 8.6	3.4	11
23	Granule	70.7:28.1: 1.2		1.8	6
24	Sand-mud	1.0:71.2:27.8	25.4:21.7:52.9	18.0	59
25	Granule-sand-mud	25.2:61.0:13.8		22.0	72
26 x	Muddy sand	3.5:81.2:15.3	23.8:32.3:43.9	43.9	144
27	Sand-mud	7.8:60.0:32.2		40.2	132
28	Sand-mud	2.2:75.5:22.3	46.6:21.2:32.2	53.0	174
29 x	Sand-mud	2.5:63.9:33.6		53.0	174
30 xo	Muddy sand	8.4:78.3:13.3	59.3:18.9:21.9	53.0	174
31	Muddy sand	8.7:79.2:12.1	50.4:22.2:27.4	53.0	174
32 x	Mud	0.8:36.0:63.2		53.0	174
33	Granule-sand-mud	32.7:50.6:16.7		42.1	138
34	Sand	3.3:92.0: 4.7	22.3:20.3:57.5	15.2	50
35	Sand	3.3:95.3: 1.4	24.3:23.8:52.0	6.4	21
36	Mud	18.1:41.5:40.4		40.2	132
37 xo	Mud	3.6:53.2:43.2		45.7	150
38 x	Mud	6.1: 8.2:85.7		36.6	120
39 x	Mud	0.1: 9.1:90.8		34.8	114
40	Muddy sand	9.2:79.6:11.2	32.3:24.2:43.6	38.4	126
41	Granule	50.3:37.1:12.6		29.3	96
42	Sand	7.3:91.4: 1.3	69.1:23.0: 7.9	3.7	12
43 x	Mud	2.3:46.5:51.2		40.2	132
44	Sand-mud	5.6:71.5:22.9	52.7:20.2:27.1	18.3	60
45	Muddy sand	11.1:75.9:13.0	52.6:21.1:26.4	51.2	168
46	Muddy sand	8.6:74.5:16.9	48.5:21.6:29.9	43.9	144
47	Sand-mud	3.4:72.7:23.9	47.0:21.9:31.0	54.9	180
48	Granule	54.8:40.6: 4.6		54.9	180
49	Muddy sand	3.7:86.1:10.2	57.8:19.5:22.7	38.4	126

TABLE 2.—*Sedimentologic analyses of benthic samples from Enewetak lagoon*—Continued

Sample	Sediment facies	Entire sample	Sand portion of sample[1]	Depth	
				Meters	Feet
Lagoon samples taken during Marine Phase—Continued					
50	Granule	47.9:40.1:12.0		18.3	60
51	Sand-granule	10.8:80.4: 8.8	48.8:25.2:26.1	43.9	144
52	Sand	3.9:88.0: 8.1	42.2:16.0:41.9	13.4	44
53	Muddy sand	0.2:83.9:15.9	22.5:29.1:48.4	38.4	126
54	Sand-granule	15.7:80.7: 3.6	55.8:26.4:17.8	9.0	29
55	Sand-mud	3.4:74.3:22.3	9.5: 7.9:82.7	6.1	20
56 o	Mud	0.5:59.8:39.7		38.4	126
57	Mud	2.9:51.8:45.3		38.4	126
58 x	Muddy sand	7.1:83.6: 9.3	62.3:19.2:18.5	58.5	192
59	Sand-granule	10.5:85.6: 3.9	63.2:22.0:14.9	42.1	138
60	Sand-mud	1.5:65.2:33.3	45.4:20.2:34.4	45.7	150
61	Sand-granule	22.9:73.4: 3.7	67.6:21.2:11.2	36.6	120
62	Sand	6.4:89.7: 3.9	43.6:27.6:28.8	54.9	180
63 x	Sand-granule	12.1:82.6: 5.3	65.5:18.1:16.4	54.9	180
64	Sand-mud	2.0:78.5:19.5	43.9:22.9:33.2	34.8	114
65 xo	Sand-mud	2.1:72.7:25.2	18.4:21.0:60.6	36.6	120
66	Mud	0.0:42.9:57.1		29.3	96
67	Sand-mud	0.2:77.0:22.8	14.4:13.5:72.1	38.4	126
68	Sand	8.8:90.6: 0.6	77.2:13.3: 9.5	43.9	144
69	Sand-granule	17.5:78.7: 3.8	53.1:20.5:26.4	49.4	162
70	Granule	54.9:41.5: 3.6		43.9	144
71	Muddy sand	7.5:81.1:11.4	71.1:14.5:14.4	58.5	192
72	Sand-granule	14.2:77.3: 8.5	57.5:22.3:20.2	51.2	168
73	Sand-granule	14.9:79.2: 5.9	51.8:24.1:24.1	51.2	168
74 x	Granule-sand-mud	18.7:68.2:13.1	43.3:24.6:32.0	38.4	126
75	Sand-mud	13.0:57.6:29.4		40.2	132
76	Granule-sand	41.7:57.0: 1.3		+1.5	+5
77	Granule-sand	45.3:53.6: 1.1		+0.3	+1
78 xo	Sand	7.0:85.3: 7.7	34.1:29.4:36.6	36.6	120
79	Granule-sand-mud	21.6:67.6:10.8	49.4:24.5:26.1	40.2	132
80	Sand-granule	19.3:73.5: 7.2	45.9:25.5:28.6	38.4	126
81	Granule-sand-mud	21.1:67.2:11.7	39.1:21.1:39.8	51.2	168
82	Sand	7.1:87.0: 5.9	51.8:23.4:24.8	43.9	144
83 x	Sand-granule	15.8:77.8: 6.4	53.3:21.7:25.0	43.9	144
84	Sand-granule	18.4:72.9: 8.8	42.5:24.2:33.3	51.2	168
85	Sand	8.5:89.4: 2.1	38.1:31.0:30.9	40.2	132
86	Sand-granule	20.6:77.2: 2.2	47.1:44.7: 8.2	18.3	60
87	Sand	4.5:93.9: 1.6	26.6:54.3:19.1	36.6	120
88	Sand-granule	14.5:84.3: 1.5	53.2:39.2: 7.6	32.9	108
89 xo	Sand-mud	2.2:69.9:27.9	13.9:21.0:65.1	42.1	138
90	Sand	6.6:90.8: 2.6	49.3:27.6:23.1	45.7	150
91 x	Sand	4.8:91.3: 3.9	38.1:34.7:27.2	42.1	138
92	Sand	1.3:97.2: 1.5	24.2:36.0:39.8	31.1	102
93	Sand-granule	14.5:78.6: 6.9	39.5:28.2:32.2	38.4	126
94	Sand	7.0:89.9: 3.1	40.6:33.0:26.4	34.8	114
95	Granule-sand-mud	21.6:67.5:10.9	43.1:23.7:33.2	34.8	114
96	Sand-granule	23.5:71.6: 4.9	59.8:20.6:19.6	29.3	96
97	Sand	0.9:98.6: 0.5	8.6:20.2:71.2	1.8	6
98	Granule	54.2:44.5: 1.3		1.2	4
99	Granule	56.9:41.4: 1.7		0.3	1
100	Sand-granule	16.3:82.3: 1.4	64.9:31.0: 4.1	0.9	3
101	Sand	9.0:90.1: 0.9	84.0:15.0: 1.0	3.0	10
102	Granule-sand	34.7:64.6: 0.7		3.0	10
103	Sand-granule	24.5:73.5: 2.0	83.9:10.8: 5.3	4.9	16

TABLE 2.—*Sedimentologic analyses of benthic samples from Enewetak lagoon*—Continued

Sample	Sediment facies	Entire sample	Sand portion of sample[1]	Depth	
				Meters	Feet
Lagoon samples taken during Marine Phase—Continued					
104 x	Sand	0.2:92.1: 7.7	6.3:16.7:77.0	38.4	126
105	Sand-granule	27.7:71.2: 1.1	76.8:18.6: 4.6	9.1	30
106	Sand	1.2:97.0: 1.8	69.7:26.1: 4.3	3.0	10
107	Sand	0.0:98.8: 1.2	1.2:67.0:31.8	3.0	10
108	Granule-sand	31.9:67.0: 1.1	83.4:14.8: 1.8	3.0	10
109	Sand	7.2:91.9: 0.9	65.6:32.6: 1.8	4.3	14
		(Samples 110–113 not collected)			
114	Granule	57.5:40.5: 2.0		1.2	4
115	Sand	0.7:98.1: 1.2	7.5:81.7:10.8	3.0	10
116	Sand-granule	19.6:78.4: 2.0	46.8:33.3:19.9	3.7	12
117	Sand-granule	16.7:81.6: 1.7	50.9:42.6: 6.5	4.3	14
118 xo	Sand-granule	13.6:85.3: 1.1	67.7:29.9: 2.4	32.9	108
119	Sand-granule	23.3:74.6: 2.1	35.4:27.5:37.1	9.1	30
120	Sand	5.6:92.0: 2.4	63.3:27.1: 9.6	3.7	12
121	Sand	0.1:97.6: 2.3	3.8:54.0:42.2	3.7	12
122	Sand-granule	13.8:84.5: 1.7	83.6:12.4: 3.9	4.6	15
123 xo	Sand	9.8:89.1: 1.1	57.4:40.9: 1.7	4.3	14
Crater samples taken during Drilling Phase					
KBZ-4S	Mud	0.0:34.7:65.3		33.2	109
KBZ-4B	Mud	0.0:25.1:74.9		33.2	109
KBZ-4C1	Mud	0.8:19.8:79.4		33.2	109
KBZ-4C2	Mud	0.1:16.5:83.5		33.2	109
KCT-5S	Muddy sand	1.5:88.7: 9.9	32.9:31.9:35.2	30.2	99
KCT-5B	Muddy sand	0.0:87.3:12.7	9.7:28.7:61.6	30.2	99
KDT-6S	Granule	60.5:34.2: 5.3		17.1	56
KDT-6B	Sand-mud	0.1:74.6:25.3	13.3:17.9:68.8	17.1	56
KET-7S	Sand	0.4:90.6: 9.0	9.7:21.3:69.0	15.5	51
KET-7B	Sand-mud	0.3:73.0:26.8	5.2:11.9:82.9	15.5	51
OAM-3C	Muddy sand	11.8:75.0:13.2	17.8:11.8:70.4	32.9	108
OBZ-4B	Sand-mud	0.0:62.5:37.5		60.7	199
OCT-5S	Sand-mud	0.2:66.8:33.0		50.0	164
OCT-5B	Granule-sand-mud	31.9:60.6: 7.5		50.0	164
ODT-6S	Muddy sand	0.9:89.0:10.1	27.0:31.1:41.9	26.5	87
ODT-6B	Sand	0.6:94.2: 5.3	37.4:44.0:18.5	26.5	87
OET-7S	Sand	0.7:93.7: 5.6	25.2:38.8:36.0	32.6	107
OET-7B	Sand	0.1:91.8: 8.1	8.3:33.3:58.5	32.6	107
OFT-8S	Muddy sand	0.0:84.2:15.8	14.5:39.0:46.5	39.9	131
OFT-8B	Sand	0.3:94.1: 5.6	19.6:35.2:45.1	39.9	131
OGT-9S	Muddy sand	0.2:79.4:20.5	7.6:28.0:64.4	41.2	135
OHT-10B	Sand-mud	0.1:68.8:31.2	6.8:19.3:73.9	41.8	137
OIT-11S	Sand-mud	0.5:68.5:31.1	12.6:20.2:67.1	47.3	155
OIT-11B	Sand-mud	0.0:64.5:35.4		47.3	155
OJT-12S	Sand-mud	0.0:71.4:28.6	10.3:20.6:69.1	43.9	144
OJT-12B	Granule-sand-mud	34.0:54.4:11.6		43.9	144
OKT-13S	Sand-mud	0.0:62.5:37.5		50.3	165
OKT-13B	Sand-mud	0.4:80.1:19.5	15.0:32.3:52.7	50.3	165
OLT-14S	Granule-sand	42.6:52.3: 5.1		42.7	140
OLT-14B	Sand	1.7:88.8: 9.4	33.8:40.1:26.1	42.7	140
OMT-15S	Sand-mud	0.5:62.6:37.0		33.8	111
OMT-15B	Granule	65.6:31.0: 3.6		33.8	111
ONT-16S	Sand-mud	8.3:53.4:38.2		41.2	135
ONT-16B	Granule	90.7: 6.2: 3.1		41.2	135
OOR-17S	Granule-sand-mud	29.9:62.3: 7.8		16.8	55

TABLE 2.—*Sedimentologic analyses of benthic samples from Enewetak lagoon*—Continued

Sample	Sediment facies	Entire sample	Sand portion of sample[1]	Depth	
				Meters	Feet
Crater samples taken during Drilling Phase—Continued					
OOR-17B	Granule-sand-mud	28.5:54.7:16.8		16.8	55
OPZ-18S	Sand-mud	0.1:63.9:36.0		61.6	202
OPZ-18B	Mud	0.1:43.5:56.4		61.6	202
OQT-19S	Muddy sand	3.9:82.0:14.1	25.4:27.2:47.3	36.0	118
OQT-19B	Sand-mud	0.1:78.2:21.7	15.8:22.8:61.4	36.0	118
ORT-20S	Muddy sand	0.2:90.0: 9.9	25.9:33.1:40.9	30.8	101
ORT-20B	Muddy sand	8.7:79.9:11.4	28.6:29.2:42.3	30.8	101
OSR-21S	Granule-sand-mud	33.9:49.3:16.8		25.6	84
OSR-21B	Granule-sand-mud	29.1:46.7:24.2		25.6	84
OSM-22S	Sand-mud	14.8:54.7:30.5		23.2	76
OTG-23S	Sand-mud	0.3:67.3:32.4	8.3:19.8:71.9	50.0	164
OTG-23B	Mud	0.0:54.6:45.4		50.0	164
OUT-24S	Sand	0.0:95.6: 4.4	21.7:33.2:45.1	44.8	147
OUT-24B	Sand	0.0:93.7: 6.3	13.1:31.5:55.4	44.8	147
RXNMASS	Granule-sand-mud	24.0:58.5:17.5		?	?

[1]Sand portion of original samples containing 65 weight-percent or greater sand.

SEDIMENT FACIES OF ENEWETAK LAGOON

Eight sediment facies can be distinguished for the samples from Enewetak lagoon using a tertiary plot of mud, sand, and granules (figs. 10, 11). These facies are defined in table 3.

Halimeda plates, small corals, coral fragments, and mollusk (mainly gastropod and pelecypod) shells and fragments make up most of the granule-size (and coarser) fraction, and *Halimeda* plates also make up the bulk of the very coarse sand fraction. Foraminifers and skeletal elements constitute most of the remaining sand fraction. Sand- to granule-sized fragments of calcareous red algae are common only in the sediments near the reef flat and sand islands on the windward side of the atoll and are absent from the other lagoon samples. Ostracodes, also sand sized and important biostratigraphically, make up far less than 5 percent of most samples taken from the lagoon (E.M. Brouwers, oral commun., 1987). The silt and clay (mud) fraction is dominated by broken and biodegraded skeletal grains or biogenic grains, including tunicate spicules.

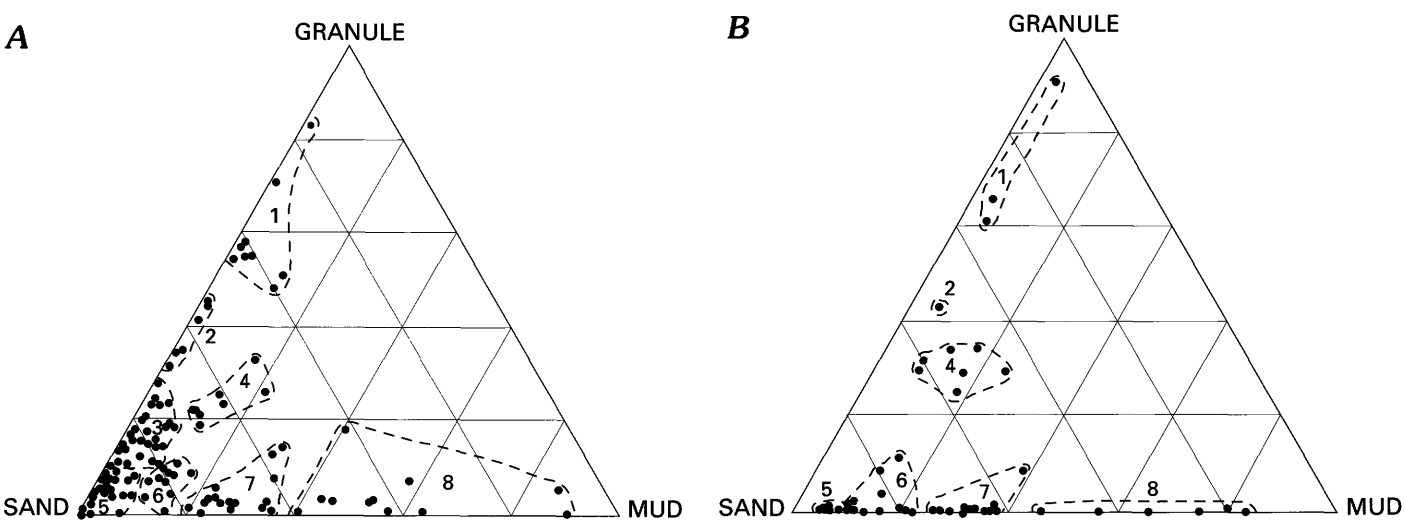

FIGURE 10.—Plot of benthic samples from (*A*) Enewetak lagoon and (*B*) OAK and KOA crater areas on tertiary diagrams of weight-percent granule (and coarser), sand, and mud (silt plus clay). Sediment facies are enclosed by dashed lines: 1, granule; 2, granule-sand; 3, sand-granule; 4, granule-sand-mud; 5, sand; 6, muddy sand; 7, sand-mud; 8, mud. (Grain-size limits described in table 3.)

TABLE 3.—*Sediment facies and grain-size limits for benthic samples from Enewetak lagoon taken during PEACE Program (see fig. 10)*

[The term "granule," as used here, is any particle granule sized or larger (that is, diameter 2 millimeters or greater)]

	Facies	Grain-size limits
COMPOSITE	1. Granule	Greater than 47 percent granules, less than 13 percent mud, 6–45 percent sand
COMPOSITE	2. Granule-sand	32–45 percent granules, less than 6 percent mud, 52–67 percent sand
COMPOSITE	3. Sand-granule	11–28 percent granules, less than 9 percent mud, 71–87 percent sand
	4. Granule-sand-mud	19–34 percent granules, 8–24 percent mud, 47–68 percent sand
	5. Sand	Less than 10 percent granules, less than 9 percent mud, greater than 85 percent sand
MUDDY	6. Muddy sand	Less than 12 percent granules, 9–17 percent mud, 75-90 percent sand
MUDDY	7. Sand-mud	Less than 15 percent granules, 20–38 percent mud, 53–80 percent sand
MUDDY	8. Mud	Less than 19 percent granules, greater than 39 percent mud, 8–60 percent sand

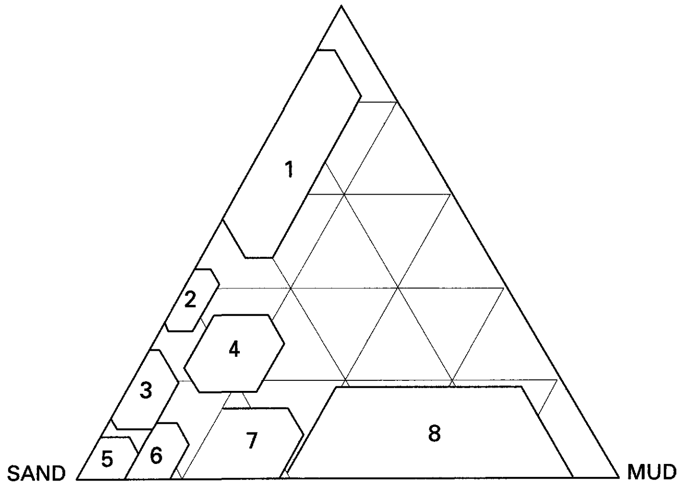

FIGURE 11.—Fields defined for facies of all Enewetak benthic samples. 1, granule; 2, granule-sand; 3, sand-granule; 4, granule-sand-mud; 5, sand; 6, muddy sand; 7, sand-mud; 8, mud.

DISTRIBUTION OF SEDIMENT FACIES

The distribution of sediment facies in Enewetak lagoon is shown in figure 12. The granule, granule-sand, and sand-granule facies (facies 1–3, table 3) intergrade over short distances on the floor of the lagoon and on the islands. Thus, for mapping purposes, these facies are treated as one composite facies, termed the "granule-coarse sand facies."

GRANULE-COARSE SAND FACIES

The composite granule-coarse sand facies forms a band around the edge of the lagoon around most of the reef tract (fig. 12). Even coarser grained facies (that is, facies containing substantial quantities of granules, pebbles, cobbles, and boulders) dominate the oceanward side of the islands, particularly on the windward side of the atoll (see Emery and others, 1954, p. 91–95, and plates referenced therein). These commonly include large coral heads and blocks of cemented reef plate or beach rock ripped up during storms. These coarser grained facies are not separated from the composite granule-coarse sand facies in this report and thus occupy the islands, reef plates, and parts of the lagoon-terrace areas of the atoll.

The composite granule-coarse sand facies also dominates the sediments in the vicinity of the coral knolls or patch reefs; the majority of large knolls and reefs that represent local distribution of this facies are shown in figure 12. A large area in the south-central part of the lagoon (fig. 12) that contains many large coral knolls that profusely shed sediment also is dominated by this facies.

GRANULE-SAND-MUD FACIES

The granule-sand-mud facies (facies 4, table 3) is mapped in three general areas (fig. 12). The largest area is in the southwest lagoonward from the composite granule-coarse sand facies in the vicinity of the Southwest Passage. The second area is lagoonward from OAK crater in the northwestern part of the atoll, and the third is in the northeastern part of the lagoon.

SAND FACIES

The sand facies (facies 5, table 3) forms a very narrow belt around the lagoonward edge of much of the atoll and includes some of the lagoon beaches (fig. 12) on the eastern and southern margins. These coarse to very coarse sands are generally foraminifer rich (Emery and others, 1954, p. 99; fig. 5*B*, this report). The foraminifers in the subfacies on the northeastern, eastern, and southern sides of the lagoon are dominated by the large, heavy-walled benthic forms *Calcarina*, *Amphistogina*, and, to a lesser extent, *Marginopora*. The lagoon-beach sands, which contain as much as 65 percent of these taxa, and the shallow subtidal lagoon sediments adjacent to these beaches from Enewetak (FRED) to Runit (YVONNE) Islands are tinted grayish orange because of the superabundance of these foraminifers.

Within the sand facies, a small band just inside the lagoon extending from the reef tract on the northwestern side of the atoll westward and southward from OAK crater is dominated by well-sorted medium sand characterized by large ripple marks. This subfacies, the largest subtidal concentration of well-sorted sediment on the

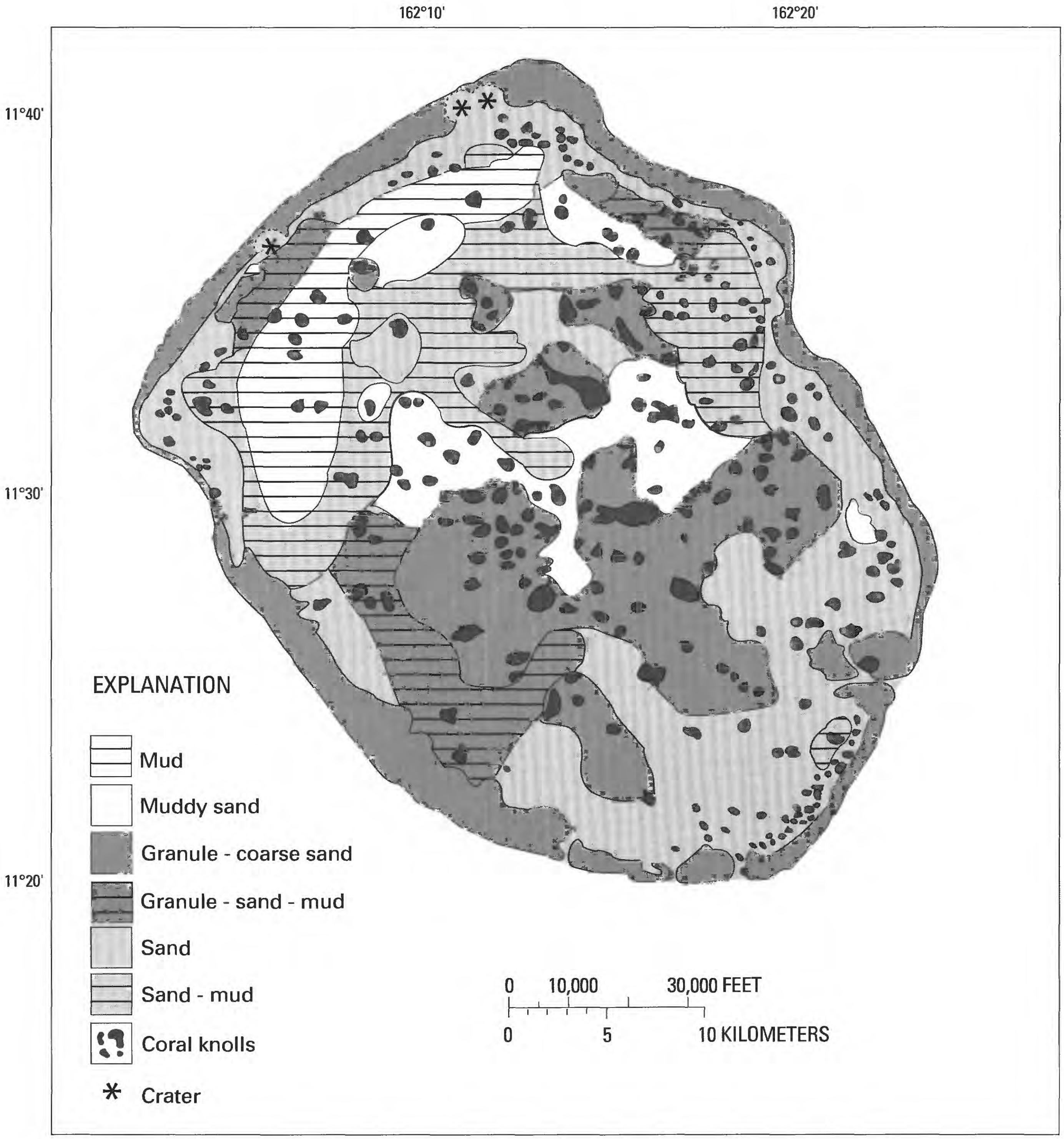

FIGURE 12.—Distribution of sediment facies in Enewetak lagoon. (See table 3; facies 1–3 in table 3 have been combined to make up granule-coarse sand facies.)

atoll, occurs in water generally less than 7.6 m (25 ft) deep on the broad terrace that rims this part of the lagoon. Referred to as the "sand slope" in Halley, Slater, and others (1986, their figs. 4A–4B), this area is within easy reach of waves generated by the fetch of the winds blowing across the lagoon and is dominated by the leeward cross-reef currents. Here, few coarse-grained components are generated locally or transported into the area, and fine-grained components (very fine grained sand and silt) are constantly being winnowed and transported out. This "sand slope" subfacies is downcurrent from the part of the lagoon—extending from Enjebi (JANET) to Bokoluo (ALICE) Islands (fig. 1)—that has the highest productivity and concentration of phyto- and zooplankton in the lagoon (Colin, 1987, p. 92). This part of the lagoon is the only area in which phytoplankton blooms have been reported.

The sand facies also occurs peripherally to some large coral knolls and knoll clusters (fig. 12).

MUDDY FACIES

Mud-rich sediments (muddy sand, sand-mud, and mud facies (facies 6–8, table 3)) dominate the bottom in the northern half of the lagoon (fig. 12). A true mud facies (facies 8, table 3) occurs in only one area, in the northwest, extending from near Enjebi (JANET) toward Biken (LEROY) Islands (fig. 1).

Undoubtedly, some of the fine-grained constituents were produced naturally and incorporated in the modern lagoon sediments. The source of the rest of the muddy sediments is related to the cratering effects of the near-surface nuclear bursts and is discussed in a succeeding section.

SEDIMENT FACIES OF SUBMARINE NUCLEAR CRATERS

From 1948 through 1958, 43 nuclear tests were conducted on and in the vicinity of Enewetak Atoll. Most of the detonations occurred on the islands and on barges in the lagoon on the northern and northeastern sides of the atoll (fig. 13). Most of the near-surface bursts, ranging in yield from fractions of a kiloton to the 10.4-megaton (Mt) MIKE, created craters. A substantial volume of material was ejected physically from these sites during the bursts. However, in these water-saturated test beds, ejection does not account for either the final size and configuration of the crater or the total volume of material displaced into the lagoon.

Only a handful of these tests created substantial craters that potentially modified the distribution of sediments in the lagoon. These include OAK, KOA, MIKE (which includes several large tests), BUTTERNUT, and the composite crater area of YELLOWWOOD (fig. 13).

The craters produced by OAK and KOA thermonuclear devices (8.9 and 1.4 Mt, respectively) were selected for study for the PEACE Program by the Department of Defense (DOD). The physiographic features of these craters and environs were mapped in detail by the USGS during the program. The reader is referred to Folger, Robb, and others (1986) for detailed discussions of the sidescan sonar mosaics of OAK and KOA craters and to Halley, Slater, and others (1986) and Slater, Roddy, and others (1986) for details of the bottom features of the craters as observed and mapped from a submersible during both phases of the program. A summary of the features, cratering processes and dynamics, and timing of various stages of crater development is given in Wardlaw and Henry (1986) and Wardlaw (1987). MIKE crater was transected by the submersible *Delta* during the program, but it was not mapped with sidescan sonar, drilled, or sampled benthically.

Benthic samples for sediment analysis of OAK and KOA craters are sparse (bow and stern samples from most borehole sites, table 2). However, the benthic sample information combined with observations from the submersible and seafloor image interpretation can be used to provide a general sediment facies breakdown of the crater seafloor.

Both OAK and KOA craters are strongly negative topographic features. The center of the crater floor of OAK is approximately 61 m (200 ft) below the tidal datum; KOA is 37 m (120 ft) below that datum. The inner bowls (crater floors) of KOA and OAK are essentially flat bottomed features. The inner bowl of KOA is an oval feature measuring 244 by 425 m (800 by 1,400 ft), and that of OAK is circular with a diameter of 402 m (1,320 ft). Characteristically, surface and near-surface sediments from within the craters of KOA and OAK are markedly enriched in mud-sized grains (silt and clay), in contrast to the rest of the lagoon (contrast figs. 10*A* and 10*B*). The submersible traverses demonstrated that the floor of both craters is very fine grained, extensively bioturbated, and, like that of the deep-lagoon floor, covered with callianassid mounds 15 to 30 cm (0.5 to 1 ft) high (Halley and others, 1986; Slater and others, 1986). Bottom sediments of the inner bowl of KOA belong to the mud facies, whereas those of OAK are assignable to the sand-mud facies (fig. 14).

The inner bowls are surrounded by a series of steplike features (scarps and slopes) and terraces, described by Folger, Robb, and others (1986) and Halley, Slater, and others (1986). From the muddy facies of the inner bowl of both craters, the benthic sediments on these features generally coarsen outward to sandy facies, confirming the observations made from the submersible (see Halley and others, 1986, figs. 5 and 12). This transition appears to be much more abrupt in KOA crater. In OAK, a muddy sand facies can be recognized in the northeast and southwest "wings" of the crater (fig. 14). Coarser grained sediments are found in three general environments in the area of the slopes and terraces in OAK and KOA; these are referred to as "mixed facies" because the coarser material appears mixed in with finer, "normal" lagoon facies.

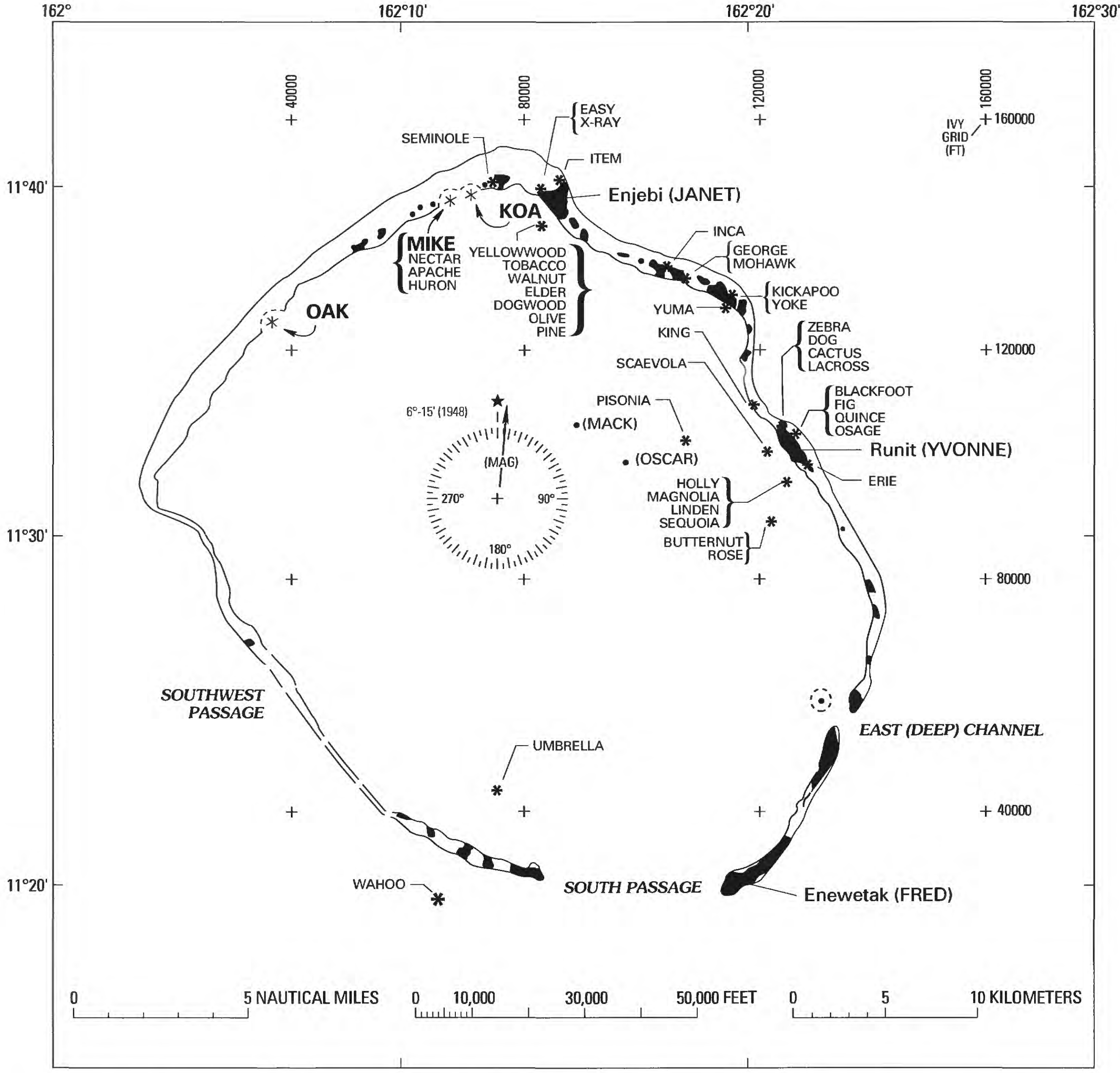

FIGURE 13.—Nuclear-detonation sites on Enewetak Atoll. Nuclear shots with same or approximately same ground-zero location are grouped together with brackets. (Data from Defense Nuclear Agency, 1981, fig. 1.53, and Freisen, 1982, table 1.3.)

MIXED-1

Heterogeneous agglomerations (slump deposits) consisting of blocks and boulders of reef plate, coral heads, beachrock, and cobble- and pebble-sized materials mixed with sand and occurring in a patchy distribution within sand are particularly common on the reefward side of OAK and the islandward side of KOA (fig. 14).

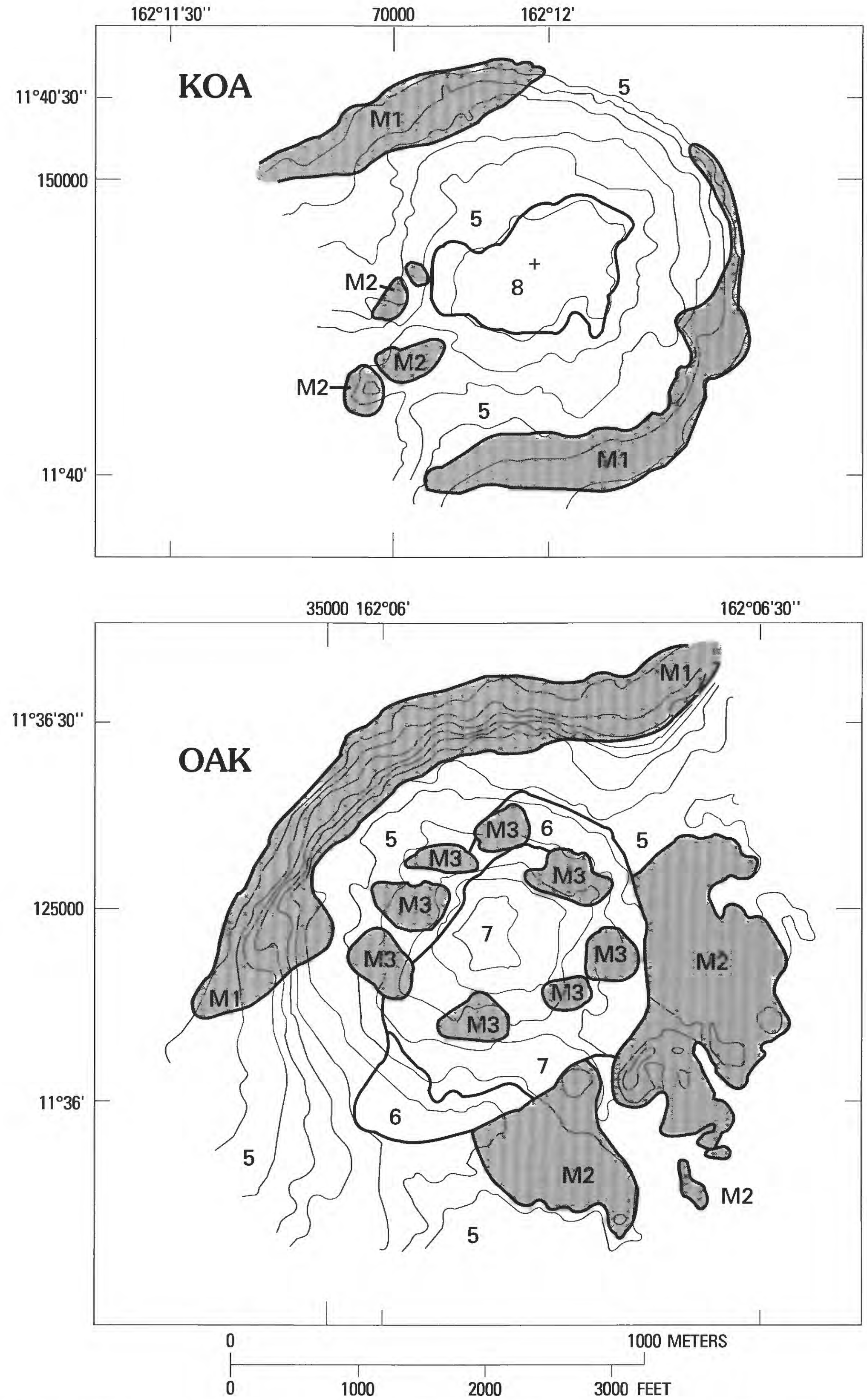

FIGURE 14.—Distribution of sediment facies in KOA and OAK craters. Facies are as follows: 5, sand; 6, muddy sand; 7, sand-mud; 8, mud; M1, mixed facies 1 (slumps); M2, mixed facies 2 (debris); and M3, mixed facies 3 (sand volcano swarms).

MIXED-2

Debris deposits occur on the lagoon (southeastern) side of OAK crater and toward MIKE crater in KOA. On the lagoon side of OAK, the "debris blanket" of Folger, Robb, and others (1986) is a patchwork of areas characterized as sand-mud facies and various granule-dominated (granule-and-coarser) facies. On the MIKE side of KOA, crater granule-sized and coarser sediments were observed on apparent debris mounds by the submersible. Unfortunately, these mounds were not sampled.

MIXED-3

Samples from the slopes of "sediment hills" or "sand volcanoes," which occur in clusters or "swarms" on the terraces, at least of OAK (see Halley and others, 1986, p. F8; Wardlaw, 1987, fig. 14) consist of coarse sand and granule-, pebble-, and (sparse) cobble-sized material stained moderate brown. The swarms of sand volcanoes occur within the sand, muddy sand, and sand-mud facies of OAK. Paleontologic analyses (Brouwers, Cronin, and Gibson, 1986; Cronin and others, 1986; Wardlaw and Henry, 1986; Cronin and Gibson, 1987; Wardlaw, 1987) confirm that much of this material was transported to the surface from stratigraphic intervals far below the excavation craters themselves. Similar clusters of "sand boils" or "sand volcanoes" are seen in photographs of KOA and MIKE taken soon after these detonations (Ristvet and others, 1978, figs. 7.24, .31, .32, .34). Many of these features in the MIKE and KOA area were obliterated by subsequent sedimentary and geologic processes (particularly slumping).

KOA is covered by a more extensive sand facies than OAK, which has a more widespread muddy facies. This agrees with the general observation of Halley, Slater, and others (1986) that KOA sediment is slightly coarser than OAK sediment. However, sediment analysis clearly shows that the central bowl of KOA is covered by finer grained sediment than the central bowl of OAK. The absence of the mixed-1 facies along the northeastern rim of KOA probably indicates active sand transport to the crater and deposition obscuring any probable underlying slump deposits. In general, the windward cross-reef currents are stronger than the leeward cross-reef currents. The windward cross-reef currents bring sediment from the fore-reef and reef-flat environments into the lagoon. Net water (and sediment) movement by the weaker leeward cross-reef currents is greater from the lagoon oceanward than from the ocean lagoonward. Consequently, the crater floor of KOA currently receives both more sediment and coarser grained sediment swept from the fore-reef and reef-flat environments and moved from the northeast into the crater.

SORTING AND SUBDIVISION OF FACIES

The crater benthic sediments generally are finer than the lagoon benthic sediments but conform to the general facies described for the benthic samples except for the mixed deposits described above, which were established largely by seafloor observations. Therefore, the crater benthic samples are ascribed to lagoon facies and subfacies on the basis of sorting (table 4). Each sample was plotted on a cumulative curve, and the median diameter (second quartile, Q_2) and sorting coefficient were determined. The sorting coefficient (S_o, Trask, 1932) is the square root of the ratio of the first quartile (Q_1, the 25 percent value) to the third quartile (Q_3, the 75 percent value):

$$S_o=\sqrt{Q_1/Q_3}$$

These values are summarized into facies in table 4 and are listed for each sample in table 6.

Analysis of median diameter and sorting coefficient allows close comparison of crater and lagoon benthic samples. It also provides additional information about each facies and a clearcut subdivision of four of the eight facies.

1. Granule facies. The few crater samples assigned to the granule facies appear to have a larger median diameter than the lagoon samples; however, the sorting is extremely variable, from well sorted to unsorted in both suites of samples. No subfacies were differentiated on the basis of sorting characteristics.
2. Granule-sand facies. All samples assigned to the granule-sand facies are well to moderately sorted (S_o=1.62–2.18), and the suite is not subdivided on the basis of sorting characteristics.
3. Sand-granule facies. The sand-granule facies does not include any crater samples and is divided on the basis of sorting characteristics into two nonoverlapping subfacies: (a) moderately well to moderately sorted (S_o=1.58–2.09) and (b) poorly sorted (S_o=2.18–2.92).
4. Granule-sand-mud facies. The granule-sand-mud facies is generally poorly sorted to unsorted and is not subdivided on the basis of sorting characteristics.
5. Sand facies. The sand facies is divided into four subfacies on the basis of sorting characteristics: (a) well sorted (S_o=1.24–1.44), (b) transitional from well to moderately sorted (S_o=1.51–1.72), (c) moderately to poorly sorted (S_o=1.81–2.24), and (d) very poorly sorted (S_o=3.02).

TABLE 4.—*Diameters and sorting coefficients of sediment facies and subdivisions of facies based on sorting*

Sediment facies	Number of samples	Average median diameter	(Range)	Average sorting coefficient	(Range)
1. Granule					
Lagoon	9	2.52[1]	(1.90 –4.0)	2.18[1]	(1.41–3.32)
Crater	3	5.70[1]	(3.70 –9.5)	3.53[1]	(2.28–5.16)
Total	12	3.31[1]	(1.90 –9.5)	2.52[1]	(1.41–5.16)
2. Granule-sand					
Lagoon	6	1.54	(1.30 –1.75)	1.91	(1.62–2.18)
Crater	1	1.7		1.89	
Total	7	1.56	(1.30 –1.75)	1.90	(1.62–2.18)
3. Sand-granule					
Lagoon	27	0.71	(0.43 –1.15)	2.17	(1.58–2.92)
Crater	0				
Moderately sorted	15	0.77	(0.46 –1.15)	1.89	(1.58–2.09)
Poorly sorted	12	0.62	(0.43 –0.93)	2.51	(2.18–2.92)
4. Granule-sand-mud					
Lagoon	8	0.72	(0.43 –1.2)	3.41	(2.69–5.33)
Crater	7	0.89	(0.40 –1.3)	4.23	(2.34–6.04)
Total	15	0.80	(0.40 –1.3)	3.79	(2.34–6.04)
5. Sand					
Lagoon	31	0.46	(0.15 –1.02)	1.73	(1.24–3.02)
Crater	8	0.27	(0.16 –0.40)	1.64	(1.57–1.72)
Total	39	0.42	(0.15 –1.02)	1.71	(1.24–3.02)
Well sorted					
Lagoon	10	0.43	(0.20 –0.80)	1.36	(1.24–1.44)
Crater	0				
Transitional					
Lagoon	6	0.61	(0.15 –1.02)	1.54	(1.51–1.60)
Crater	8	0.27	(0.16 –0.40)	1.64	(1.57–1.72)
Total	14	0.42	(0.15 –1.02)	1.60	(1.51–1.72)
Moderately to poorly sorted					
Lagoon	14	0.42	(0.20 –0.58)	1.97	(1.81–2.24)
Crater	0				
Very poorly sorted					
Lagoon	1	0.32		3.02	
6. Muddy sand					
Lagoon	11	0.46	(0.20 –0.78)	2.49	(2.09–2.93)
Crater	9	0.23	(0.13 –0.31)	2.04	(1.70–2.53)
Total	20	0.36	(0.13 –0.78)	2.29	(1.70–2.93)
Moderately sorted					
Lagoon	0				
Crater	6	0.24	(0.15 –0.31)	1.88	(1.70–1.98)
Poorly sorted					
Lagoon	11	0.46	(0.20 –0.78)	2.49	(2.09–2.93)
Crater	3	0.21	(0.13 –0.275)	2.35	(2.21–2.53)
Total	14	0.41	(0.13 –0.78)	2.46	(2.09–2.93)
7. Sand-mud					
Lagoon	15	0.19	(0.083–0.37)	3.49	(1.41–5.48)
Crater	16	0.11	(0.075–0.18)	2.19	(1.55–4.60)
Total	31	0.15	(0.075–0.37)	2.82	(1.41–5.48)
Poorly to moderately and well sorted					
Lagoon	5	0.11	(0.083–0.13)	2.10	(1.41–2.87)
Crater	14	0.10	(0.075–0.18)	1.94	(1.55–2.14)
Total	19	0.10	(0.075–0.18)	1.98	(1.41–2.87)
Poorly to unsorted					
Lagoon	10	0.24	(0.160–0.37)	4.19	(2.97–5.48)
Crater	2	0.14	(0.092–0.18)	3.94	(3.27–4.60)
Total	12	0.22	(0.092–0.37)	4.15	(2.97–5.48)
8. Mud					
Lagoon	11	0.057	(0.015–0.098)	4.38	(2.27–7.24)
Crater	6	0.039	(0.019–0.070)	2.46	(1.88–2.90)
Total	17	0.051	(0.015–0.098)	3.70	(1.88–7.24)

[1]Averages only approximate.

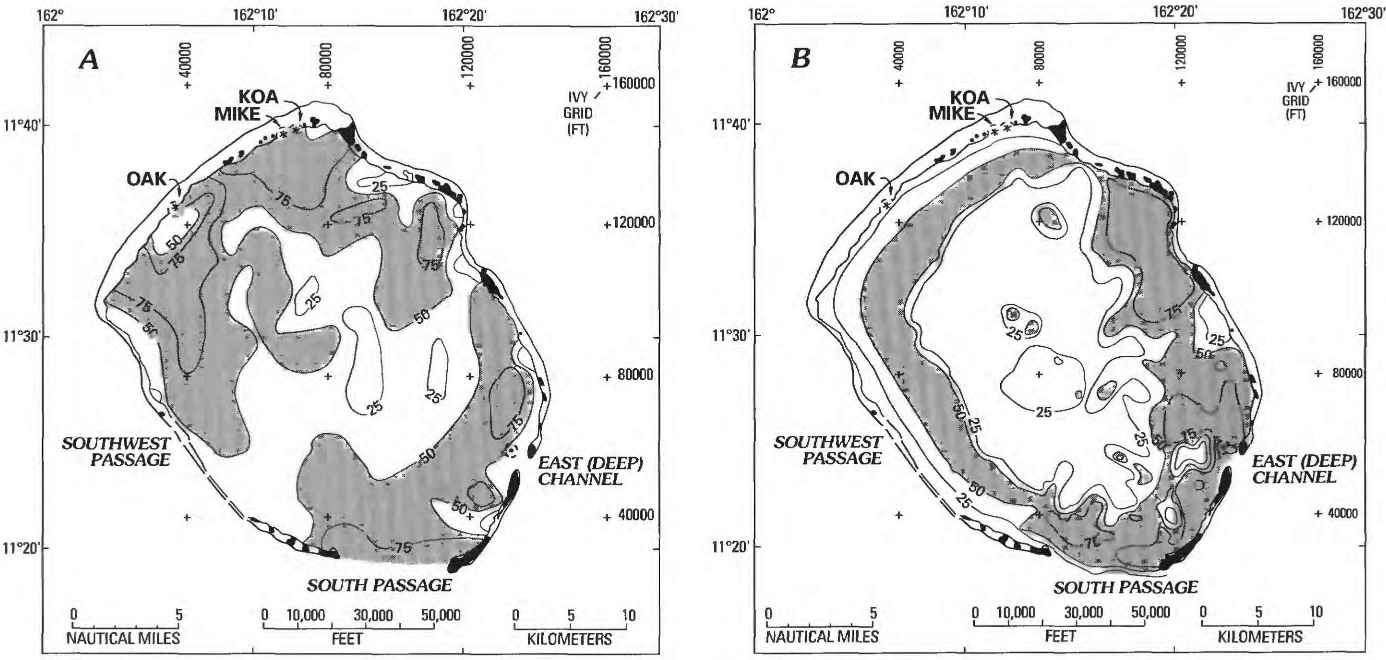

FIGURE 15.—Isopleth maps showing distribution of fine debris (fine sand, silt, plus clay) in Enewetak lagoon: *A*, Data from PEACE Program survey (1984–1985); *B*, Data collected in 1946 and reported in Emery, Tracey, and Ladd (1954), replotted on PEACE Program sample grid. Shading indicates area with greater than 50 weight-percent.

6. Muddy sand facies. The muddy sand facies is divided into two subfacies on the basis of sorting characteristics: (a) moderately sorted (S_o=1.70–1.98) and (b) poorly sorted (S_o=2.09–2.93).
7. Sand-mud facies. The sand-mud facies shows a wide range in sorting, from very well sorted to unsorted, and is divided into two subfacies: (a) poorly to moderately and well sorted (S_o=1.41–2.87), composed of mostly moderately sorted samples, and (b) poorly sorted to unsorted (S_o=2.97–5.48), composed of mostly very poorly sorted samples.
8. Mud facies. The mud facies shows a wide range in sorting, from moderately sorted to unsorted, but the majority of samples are very poorly sorted and the facies is not subdivided on the basis of sorting characteristics.

MODIFICATION OF SEDIMENT FACIES BY NUCLEAR TESTING

Unfortunately, detailed sediment size-fraction analysis or sampling was not carried out before nuclear testing. Emery, Tracey, and Ladd (1954) did report the distribution of sediments less than 1/4 mm ("fine debris" of their report). We have constructed a similar diagram based on the PEACE Program samples and replotted the 1946 data on our sample grid (figs. 15*A*, 15*B*). Even though the 1946 sampling was very sparse in the northern part of the lagoon (fig. 4*D*) and was biased against fine-grained sediments, as discussed previously, a modification of the distribution of "fine debris" is apparent. The entire lagoon shows a general increase in fine sediment, best illustrated by the decrease in area of less than 25 weight-percent distribution. The northern lagoon shows a marked increase in area and percentage of fine sediments. The difference between the data sets in the distribution in the southeast and east is thought to be relatively minor and due largely to differences in the sampling grids and in contouring those points. The distribution of mud in the lagoon (fig. 16*A*) is largely responsible for the noted change in the northern part of the lagoon (compare figs. 15*A* and 16*A*). Some of the mud in the lagoon is naturally produced sediment (for example, whole tunicate spicules, holothurian sclerids) or bioclastic particles created from physical abrasion and (or) biotic breakdown ("bioerosion") of coarser grain particles (for example, fine silt-sized "chips" created by the boring sponge *Cliona*). However, some of the mud, probably a substantial volume, was produced by the direct and indirect effects of the nuclear tests.

Why is the mud concentrated in the northern part of the lagoon? One reason, also discussed previously, is that the deeper part of the lagoon is a natural trap for fine-grained sediments. Any material that enters the realm of the deep-current system (that is, the deep-lagoon environment) is not likely to escape the area, even during storm conditions. Second, the direct effects of the

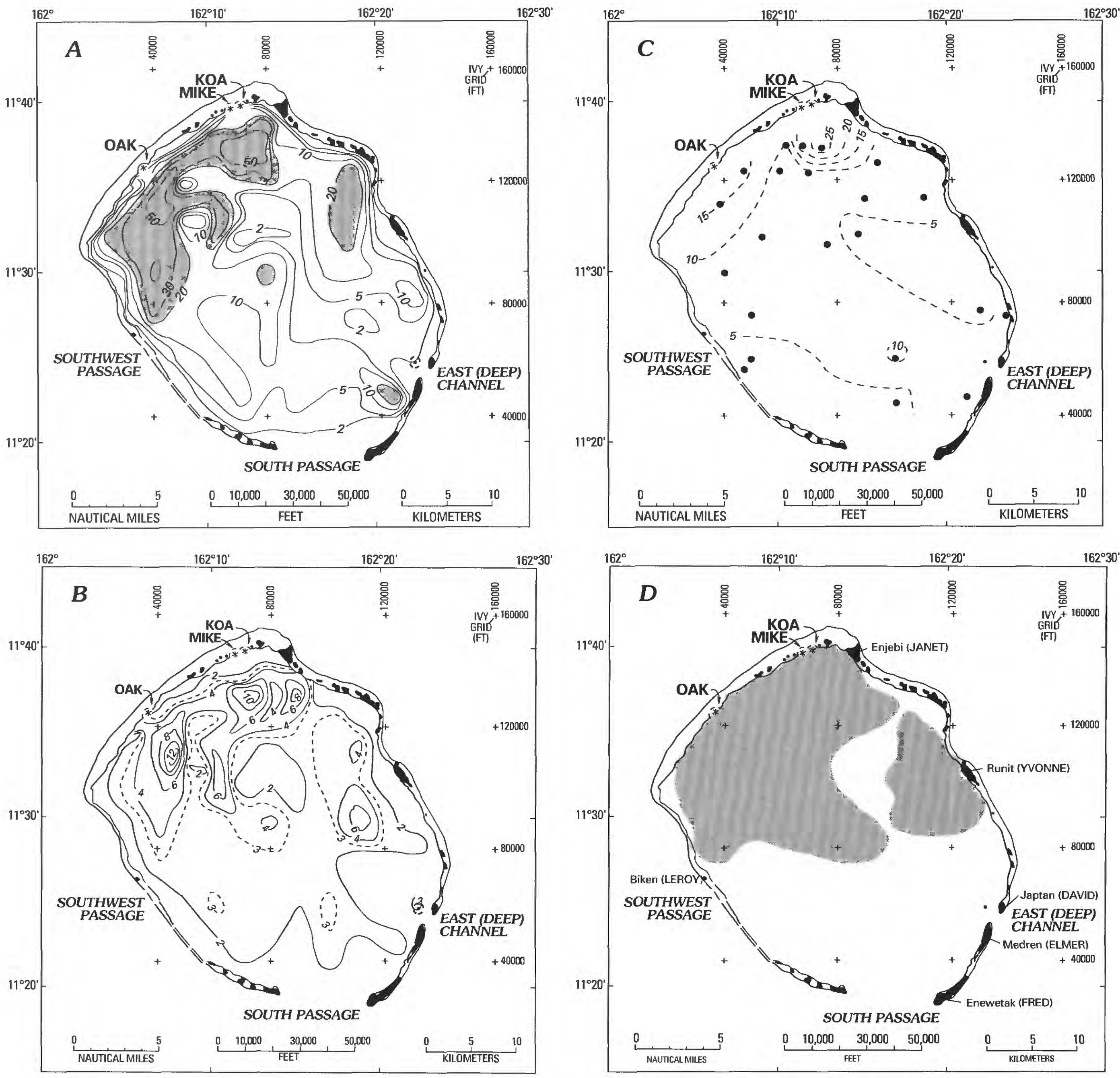

FIGURE 16.—Isopleth maps showing distribution (in weight-percent) of (*A*) mud (silt plus clay; greater than 20 weight-percent shaded), (*B*) clay, and (*C*) low-magnesium calcite, and (*D*) distribution of elevated radionuclide concentration in Enewetak lagoon (shaded) (modified from McMurtry and others, 1985).

KOA and OAK detonations (and the numerous other nuclear bursts in the northern part of the atoll) caused a tremendous amount of existing finer grained material to be excavated and stirred up from the bottom and subbottom. Even more was created by shattering, breaking, or "blast pulverizing" of individual coarser grains and "framework failure" of the cemented subbottom strata. Third, numerous independent lines of evidence indicate that liquefaction and piping of slurries consisting of water plus sediment from mud-rich (mostly silt), unlithified (uncemented) sediments played a role in adding mud to crater-fill sediments and crater environs (Henry and Wardlaw, 1986; Trulio, 1987; Wardlaw, 1987). Some of this piped material came from strata far below the excavation craters themselves. Aerial photographs taken by the DOD 8 and 10 hours after the OAK burst

TABLE 5.—*Results of X-ray diffraction analyses of benthic samples from Enewetak lagoon*

[In weight-percent. Calcite is low-magnesium calcite; Mg-calcite is high-magnesium calcite. Location of samples shown in fig. 6. Modified from Tremba and Ristvet, 1986]

Sample number	Sedimentary facies	Calcite	Mg-calcite	Aragonite
9	Mud	15	15	70
16	Sand-granule	8	17	75
17	Sand-granule	2	5	93
26	Muddy sand	6	12	82
29	Sand-mud	8	24	68
30	Muddy sand	8	12	80
32	Mud	16	21	63
37	Mud	10	13	77
38	Mud	23	19	58
39	Mud	27	18	55
43	Mud	8	15	77
58	Muddy sand	7	15	78
63	Sand-granule	8	20	72
65	Sand-mud	9	16	75
74	Granule-sand-mud	7	11	82
78	Sand	2	6	92
83	Sand-granule	10	10	80
89	Sand-mud	7	8	85
91	Sand	3	4	93
104	Sand	3	22	75
118	Sand-granule	3	7	90
123	Sand	7	25	68

show a large plume of turbid water containing suspended, finer grained particles (silt and clay) extending southwestward downcurrent from the crater (Ristvet and others, 1978, fig. 8.10). Similar current-driven plumes existed after the other high-yield bursts, particularly MIKE (B.L. Ristvet, oral commun., 1987).

That some of this mud-rich sediment is derived from nuclear detonations also is clearly substantiated by the following lines of evidence. (1) X-ray analysis shows that the normal lagoon sediments and Holocene sediments contain less than 10 weight-percent low-magnesium (low-Mg) calcite (Tremba and Ristvet, 1986; table 5, fig. 16*C*). However, the mud facies in the northwestern part of the lagoon is anomalously high in low-Mg calcite, the common to predominant carbonate mineral in the diagenetically altered Pleistocene sequence beneath the Holocene lagoon sediments (Videtich and Tremba, 1978; Tremba and Ristvet, 1986). (2) Modern, naturally produced lagoon carbonate muds normally contain only a tiny fraction of true clay-sized material (that is, particles less than 1/256 mm). However, in the northern part of the atoll, the mud facies contains a significant percentage of true clay-sized carbonate (fig. 16*B*). (3) McMurtry and others (1985) concluded for the barge-based bursts off Runit (YVONNE) Island that radionuclides are concentrated in the clay-sized carbonate sediment. They refer to this material as "blast-pulverized." They and Noshkin (1980) show an area of radioactive contamination in the northern lagoon extending from Runit on the east to Biken (LEROY) Island on the west (fig. 16*D*), although Noshkin did not attempt to associate concentration levels of transuranics in specific sedimentary components. The only sediments exhibiting levels of radiation above background outside the craters noted during the PEACE Program were from benthic samples from the mud facies near MIKE and KOA craters.

Clearly, the nuclear testing on Enewetak disrupted the benthic sedimentary patterns and facies. Most telling is the comparison of the isopleth map of weight-percent clay (fig. 16*B*) and the distribution of elevated radionuclide concentration (fig. 16*D*). The distribution of values greater than 3 weight-percent clay in the northern part of the lagoon mimic the radionuclide distribution. McMurtry and others (1985) and Wardlaw (1987) have pointed out the affinity of radionuclides and clay-sized sediment. The very similar distributions of elevated clay content and radionuclide concentration suggest that the majority of clay was derived from nuclear testing. The insensitivity of pretest benthic sampling techniques for silt and clay recovery and analysis precludes further development of this line of reasoning.

The benthic samples from the OAK reference boreholes (OAM-3, OOR-17, OSR-21, table 6) apparently are enriched in mud and poorly sorted, suggesting that the surface sediments have been affected by the nuclear testing, as previously suggested by Wardlaw (1987).

SUMMARY

Benthic samples from Enewetak Atoll can be subdivided by sediment-size analysis into eight facies: granule, granule-sand, sand-granule, granule-sand-mud, sand, muddy sand, sand-mud, and mud. The granule, granule-sand, and sand-granule facies intergrade laterally over short distances and were combined into a composite granule-coarse sand facies for mapping purposes. The composite granule-coarse sand facies dominates the reef tract, small areas adjacent to the coral knolls, and much of the south-central portion of the lagoon. The mud, sand-mud, and muddy sand facies dominate the northern part of the lagoon.

Samples from within the apparent craters of KOA and OAK are depleted in coarser grained components compared with the rest of the lagoon floor. Furthermore, the samples apparently are enriched in mud and fine sand.

Sorting analysis was used to subdivide four of the sediment facies. The sand-granule facies was divided into moderately well to moderately sorted and poorly sorted subfacies. The sand facies was divided into well sorted, transitional from well to moderately sorted, moderately to poorly sorted, and very poorly sorted subfacies. The

TABLE 6.—*Summary of samples and sediment facies from Enewetak lagoon*

[Analysis is ratio, in weight-percent, of granule:sand:mud; ratios may not add to 100 owing to rounding. Median diameter is in millimeters. Location of lagoon samples shown in fig. 6; coordinates of all samples given in table 1]

Sample	Ratio	Median diameter	Sorting coefficient
1. Granule facies			
Lagoon samples			
15	83:16:02	4.0	~1.73
23	71:28:01	3.5	~2.43
41	50:37:13	2.0	~2.76
48	55:41:05	2.2	~1.79
50	48:40:12	1.9	~3.32
70	55:42:04	2.1	~1.41
98	54:45:01	2.2	~2.20
99	57:41:02	2.5	~2.36
114	58:41:02	2.25	~1.61
Crater samples			
ONT-16B	91:06:03	9.5	~2.28
OMT-15B	66:31:04	3.9	~3.16
KDT-6S	61:34:05	3.7	~5.16
2. Granule-sand facies			
Lagoon samples			
2	44:54:02	1.7	2.18
3	35:63:02	1.4	1.88
76	42:57:01	1.6	1.94
77	45:54:01	1.75	2.03
102	35:65:01	1.5	1.62
108	32:67:01	1.3	1.78
Crater sample			
OLT-14S	43:52:05	1.7	1.89
3. Sand-granule			
Moderately sorted			
Lagoon samples			
5	15:82:02	0.60	1.93
7	18:81:02	0.46	1.83
16	18:75:07	0.97	2.09
17	11:87:02	0.64	1.95
59	11:86:04	0.78	2.01
61	23:73:04	0.97	2.02
63	12:83:05	0.84	2.08
86	21:77:02	0.60	2.07
88	15:84:02	0.64	1.90
100	16:82:01	0.70	1.74
103	25:74:02	1.15	1.71
105	28:71:01	0.98	1.93
117	17:82:02	0.59	1.80
118	14:85:01	0.80	1.76
122	14:85:02	0.88	1.58
No crater samples			
Poorly sorted			
Lagoon samples			
51	11:80:09	0.52	2.41
54	16:81:04	0.70	2.18
69	18:79:04	0.74	2.52
72	14:77:09	0.66	2.41
73	15:79:06	0.63	2.45
80	19:74:07	0.57	2.70
83	16:78:06	0.66	2.49
84	18:73:09	0.48	2.92

TABLE 6.—*Summary of samples and sediment facies from Enewetak lagoon*—Continued

[Analysis is ratio, in weight-percent, of granule:sand:mud; ratios may not add to 100 owing to rounding. Median diameter is in millimeters. Location of lagoon samples shown in fig. 6; coordinates of all samples given in table 1]

Sample	Ratio	Median diameter	Sorting coefficient
3. Sand-granule—Continued			
93	15:79:07	0.43	2.44
96	24:72:05	0.93	2.40
116	20:78:02	0.63	2.34
119	23:75:02	0.50	2.83
No crater samples			
4. Granule-sand-mud			
Lagoon samples			
6	26:52:22	0.70	5.33
8	23:62:15	0.70	3.40
25	25:61:14	1.10	2.83
33	33:51:17	1.20	2.69
74	19:68:13	0.46	3.22
79	22:68:11	0.62	2.85
81	21:67:12	0.43	3.58
95	22:68:11	0.52	3.36
Crater samples			
OCT-5B	32:61:08	0.76	3.72
OJT-12B	34:54:12	1.0	4.20
OOR-17B	29:55:17	0.9	4.29
OOR-17S	30:62:08	1.2	2.34
OSR-21S	34:49:17	1.3	4.24
OSR-21B	29:47:24	0.7	6.04
RXNMASS	24:59:18	0.4	4.76
5. Sand			
Well sorted			
Lagoon samples			
4	02:96:02	0.40	1.31
21	00:99:01	0.39	1.37
87	05:94:02	0.375	1.39
97	01:99:01	0.20	1.29
101	09:90:01	0.80	1.44
106	01:97:02	0.62	1.37
107	00:99:01	0.30	1.31
115	01:98:01	0.35	1.24
121	00:98:02	0.27	1.43
123	10:89:01	0.58	1.48
No crater samples			
Transitional			
Lagoon samples			
22	05:94:01	0.52	1.51
42	07:92:01	0.68	1.51
68	09:91:01	1.02	1.58
104	00:92:08	0.15	1.52
109	07:92:01	0.66	1.51
120	06:92:02	0.65	1.60
Crater samples			
KET-7S	00:91:09	0.16	1.59
ODT-6B	01:94:05	0.40	1.57
OET-7S	01:94:06	0.31	1.64
OET-7B	00:92:08	0.20	1.64
OFT-8B	00:94:06	0.25	1.69
OLT-14B	02:89:09	0.35	1.66

TABLE 6.—*Summary of samples and sediment facies from Enewetak lagoon*—Continued

[Analysis is ratio, in weight-percent, of granule:sand:mud; ratios may not add to 100 owing to rounding. Median diameter is in millimeters. Location of lagoon samples shown in fig. 6; coordinates of all samples given in table 1]

Sample	Ratio	Median diameter	Sorting coefficient
5. Sand—Continued			
OUT-24S	00:96:04	0.27	1.72
OUT-24B	00:94:06	0.22	1.63
Moderately to poorly sorted			
Lagoon samples			
11	04:93:03	0.41	2.05
12	09:89:03	0.58	1.85
14	09:89:02	0.48	2.00
20	04:94:02	0.55	1.81
34	03:92:05	0.20	2.00
35	03:95:01	0.245	1.89
62	06:90:04	0.44	2.09
78	07:85:08	0.34	2.23
82	07:87:06	0.53	2.24
85	09:89:02	0.41	1.97
90	07:91:03	0.53	1.97
91	05:91:04	0.40	1.81
92	01:97:02	0.30	1.81
94	07:90:03	0.44	1.90
Very poorly sorted			
Lagoon sample			
52	04:88:08	0.32	3.02
6. Muddy sand			
Moderately sorted			
No lagoon samples			
Crater samples.81			
KCT-5S	02:89:10	0.31	1.98
KCT-5B	00:87:13	0.175	1.81
ODT-6S	01:89:10	0.27	1.96
OFT-8S	00:84:16	0.255	1.70
OGT-9S	00:80:21	0.15	1.89
ORT-20S	00:90:10	0.27	1.96
Poorly sorted			
Lagoon samples			
18	07:80:13	0.38	2.77
26	04:81:15	0.24	2.09
30	08:78:13	0.57	2.66
31	09:79:12	0.48	2.60
40	09:80:11	0.29	2.43
45	11:76:13	0.52	2.83
46	09:75:17	0.42	2.93
49	04:86:10	0.54	2.41
53	00:84:16	0.20	2.21
58	07:84:09	0.66	2.28
71	08:81:11	0.78	2.20
Crater samples			
OAM-3C	12:75:13	0.13	2.53
OQT-19S	04:82:14	0.225	2.31
ORT-20B	09:80:11	0.275	2.21
7. Sand-mud			
Poorly to moderately and well sorted			
Lagoon samples			
24	01:71:28	0.12	2.87
55	03:74:22	0.083	1.41

TABLE 6.—*Summary of samples and sediment facies from Enewetak lagoon*—Continued

[Analysis is ratio, in weight-percent, of granule:sand:mud; ratios may not add to 100 owing to rounding. Median diameter is in millimeters. Location of lagoon samples shown in fig. 6; coordinates of all samples given in table 1]

Sample	Ratio	Median diameter	Sorting coefficient
7. Sand-mud—Continued			
65	02:73:25	0.13	2.22
67	00:77:23	0.10	1.74
89	02:70:28	0.10	2.24
Crater samples			
KDT-6B	00:75:25	0.11	1.91
KET-7B	00:73:27	0.10	1.69
OBZ-4B	00:63:38	0.09	1.98
OCT-5S	00:67:33	0.105	1.96
OHT-10B	00:69:31	0.10	1.99
OIT-11S	01:69:31	0.10	2.14
OIT-11B	00:65:35	0.09	2.10
OJT-12S	00:71:29	0.10	1.96
OKT-13S	00:63:38	0.075	1.55
OKT-13B	00:80:20	0.18	2.04
OMT-15S	01:63:37	0.084	2.03
OPZ-18S	00:64:36	0.08	1.70
OQT-19B	00:78:22	0.135	2.07
OTG-23S	00:67:32	0.096	2.04
Poorly to unsorted			
Lagoon samples			
13	01:64:35	0.20	5.48
19	03:71:27	0.20	3.75
27	08:60:32	0.16	4.07
28	02:76:22	0.28	3.33
29	03:64:34	0.22	5.48
44	06:72:23	0.37	3.73
47	03:73:24	0.28	3.56
60	02:65:33	0.17	5.14
64	02:79:20	0.29	2.97
75	13:58:29	0.20	4.39
Crater samples			
ONT-16S	08:53:38	0.092	3.27
OSM-22S	15:55:31	0.18	4.60
8. Mud			
Lagoon samples			
9	03:45:53	0.052	5.82
10	07:35:58	0.038	5.46
32	01:36:63	0.033	3.95
36	18:42:40	0.098	7.24
37	04:53:43	0.096	4.70
38	06:08:86	0.017	2.34
39	00:09:91	0.015	2.27
43	02:47:51	0.06	3.94
56	01:60:40	0.089	3.70
57	03:52:45	0.089	5.54
66	00:43:57	0.044	3.23
Crater samples			
KBZ-4B	00:25:75	0.03	2.34
KBZ-4S	00:35:65	0.041	2.56
KBZ-4C1	01:20:79	0.021	2.90
KBZ-4C2	00:17:84	0.019	2.49
OPZ-18B	00:44:56	0.052	2.56
OTG-23B	00:55:45	0.07	1.88

muddy sand facies was divided into moderately sorted and poorly sorted subfacies. The sand-mud facies was divided into poorly to moderately and well sorted and poorly sorted to unsorted subfacies.

The nuclear testing on Enewetak Atoll disrupted the natural sediment patterns of the lagoon and contributed a large volume of fine sediment (particularly clay-sized carbonate) to the lagoon.

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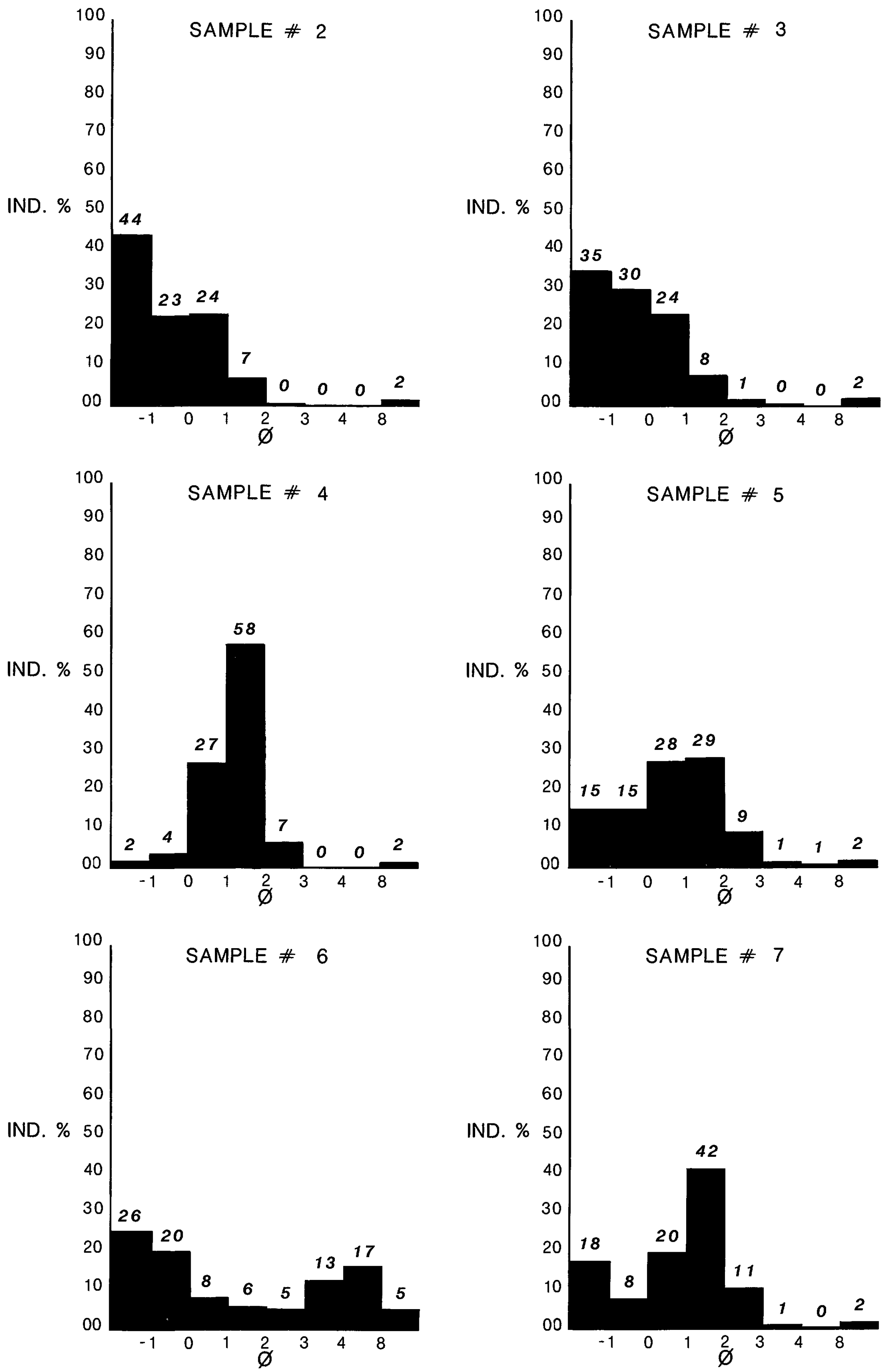
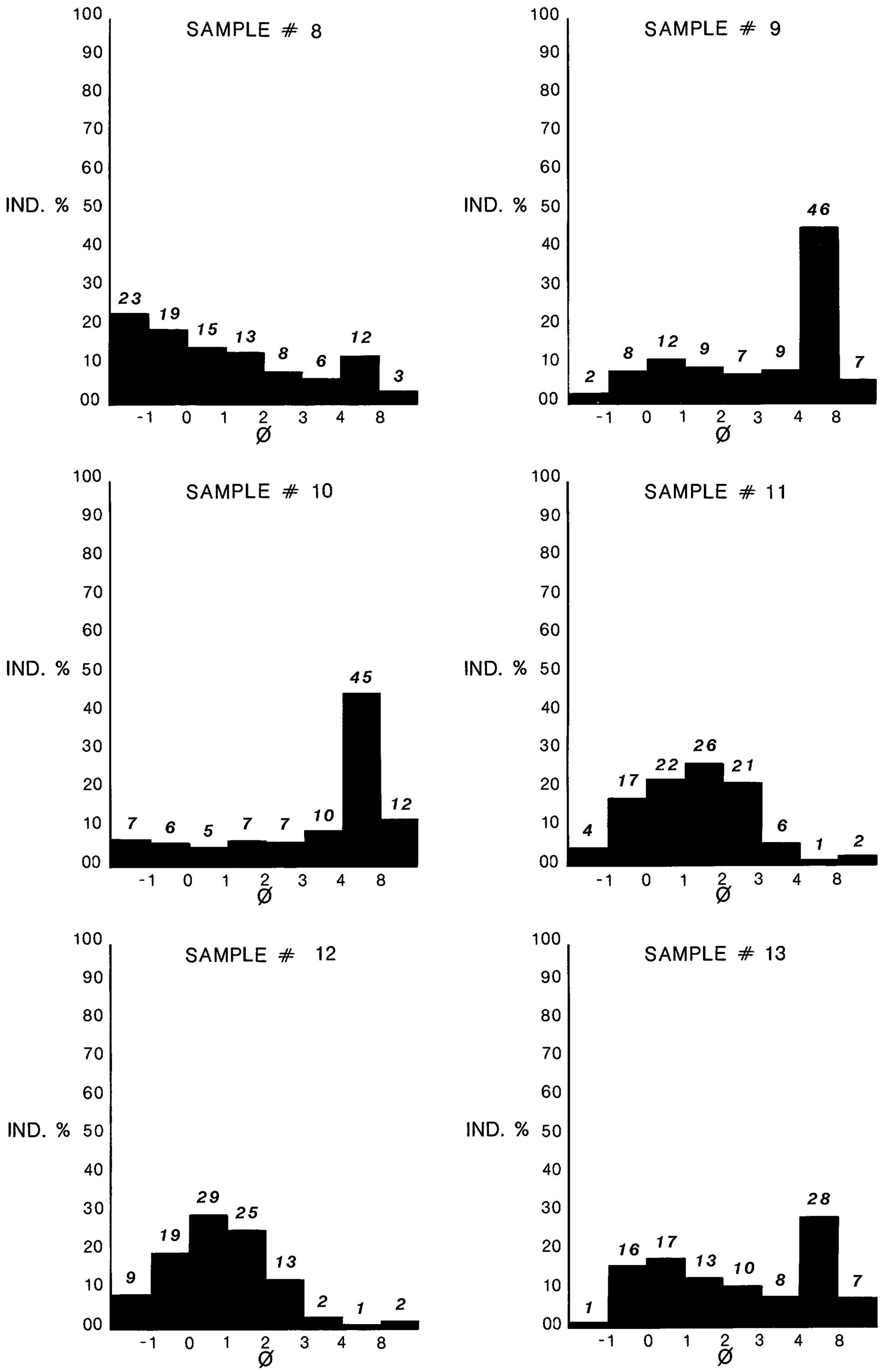


FIGURE 17.—Histograms showing weight-percent of grain-size fractions (see fig. 9) of benthic samples from Enewetak lagoon. Percentages are rounded. IND., individual.



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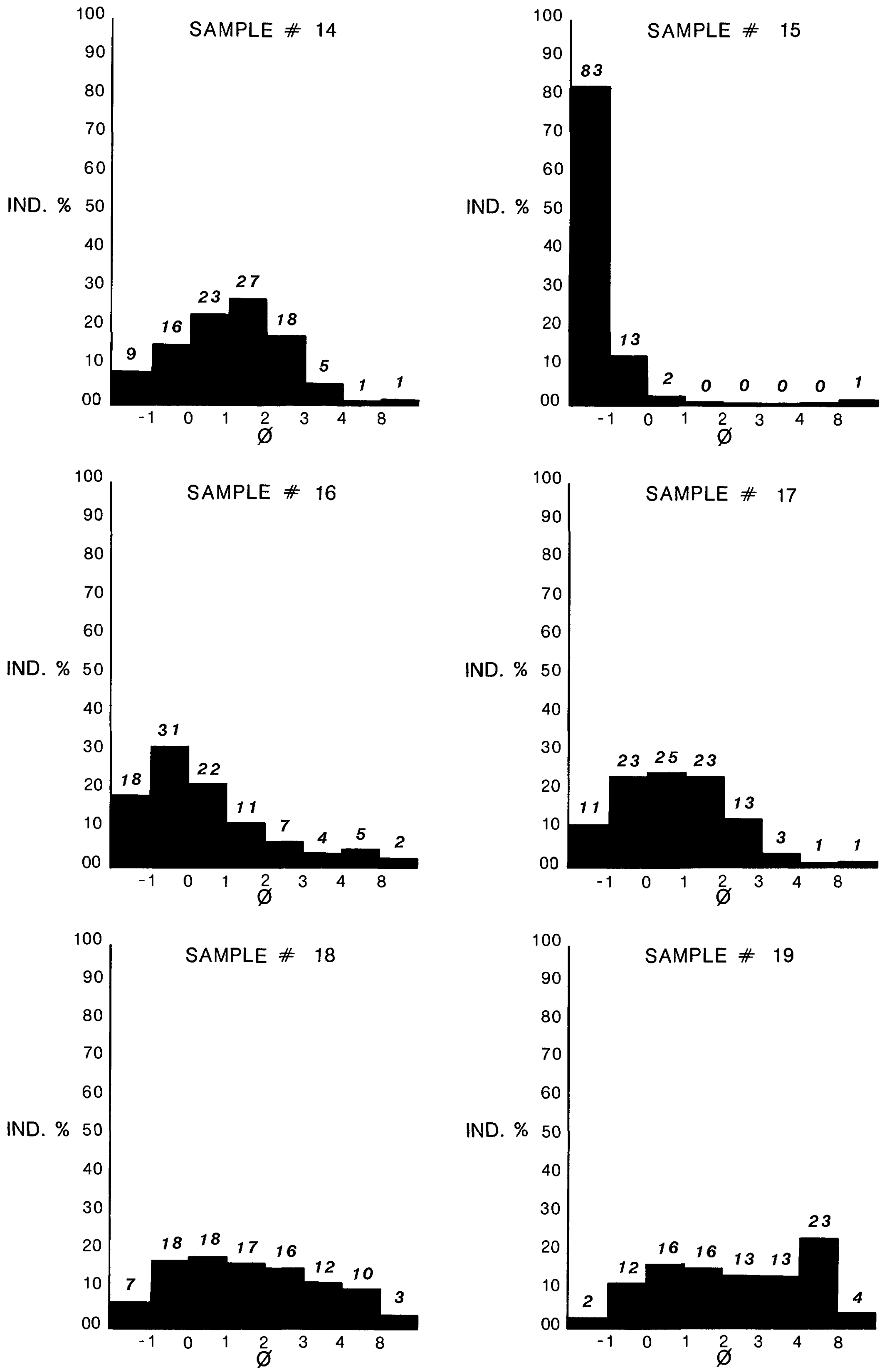

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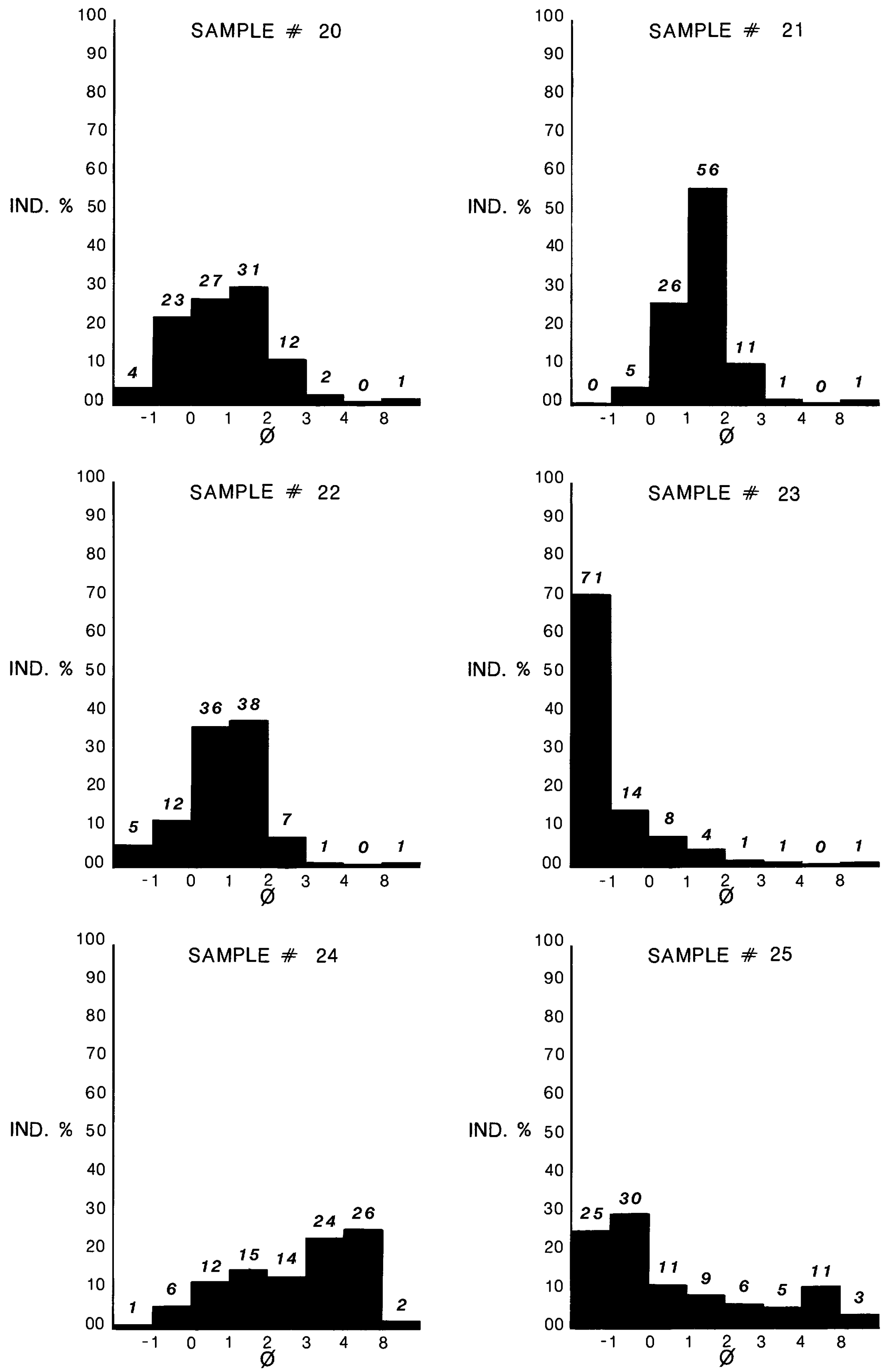

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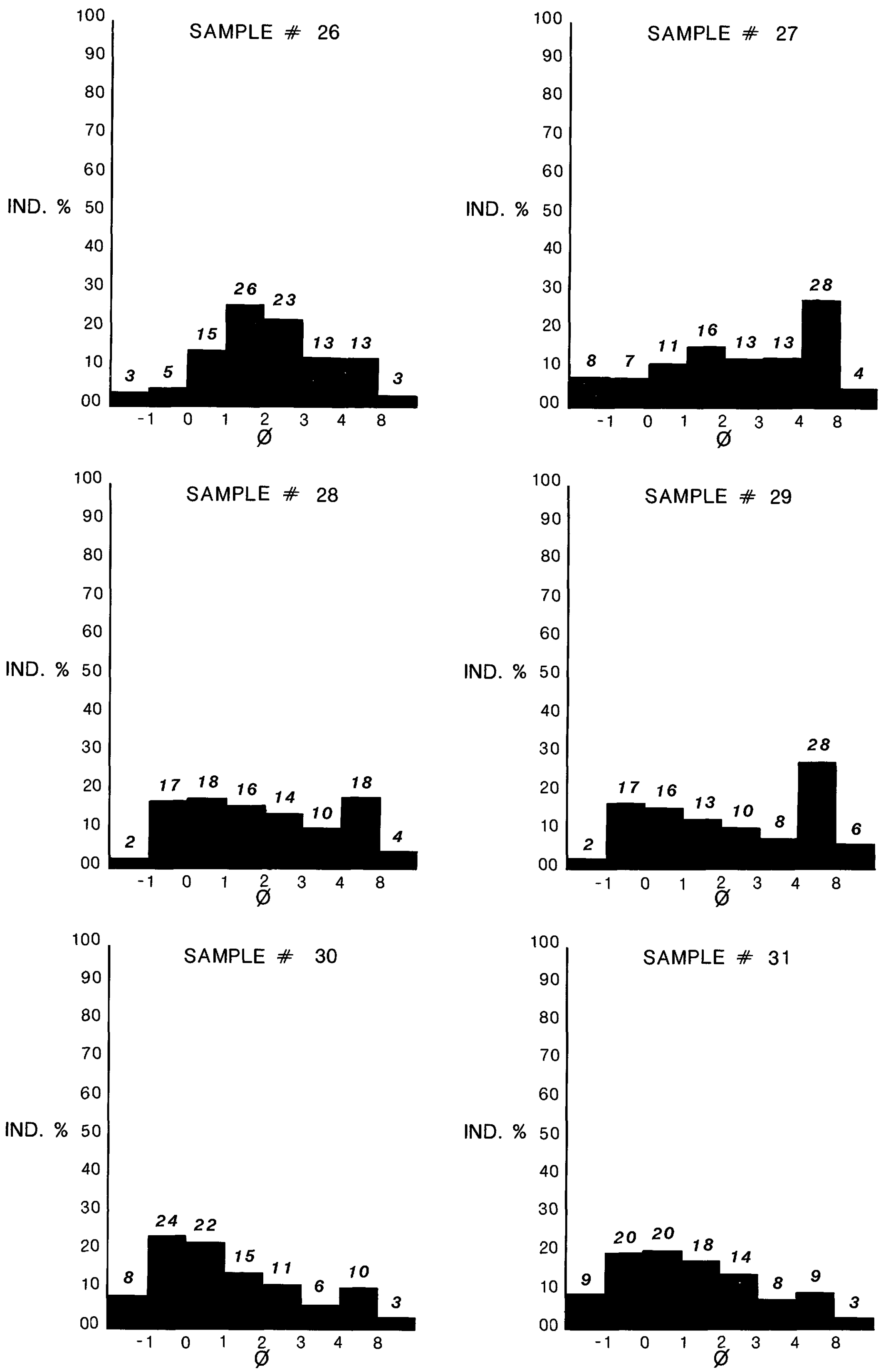

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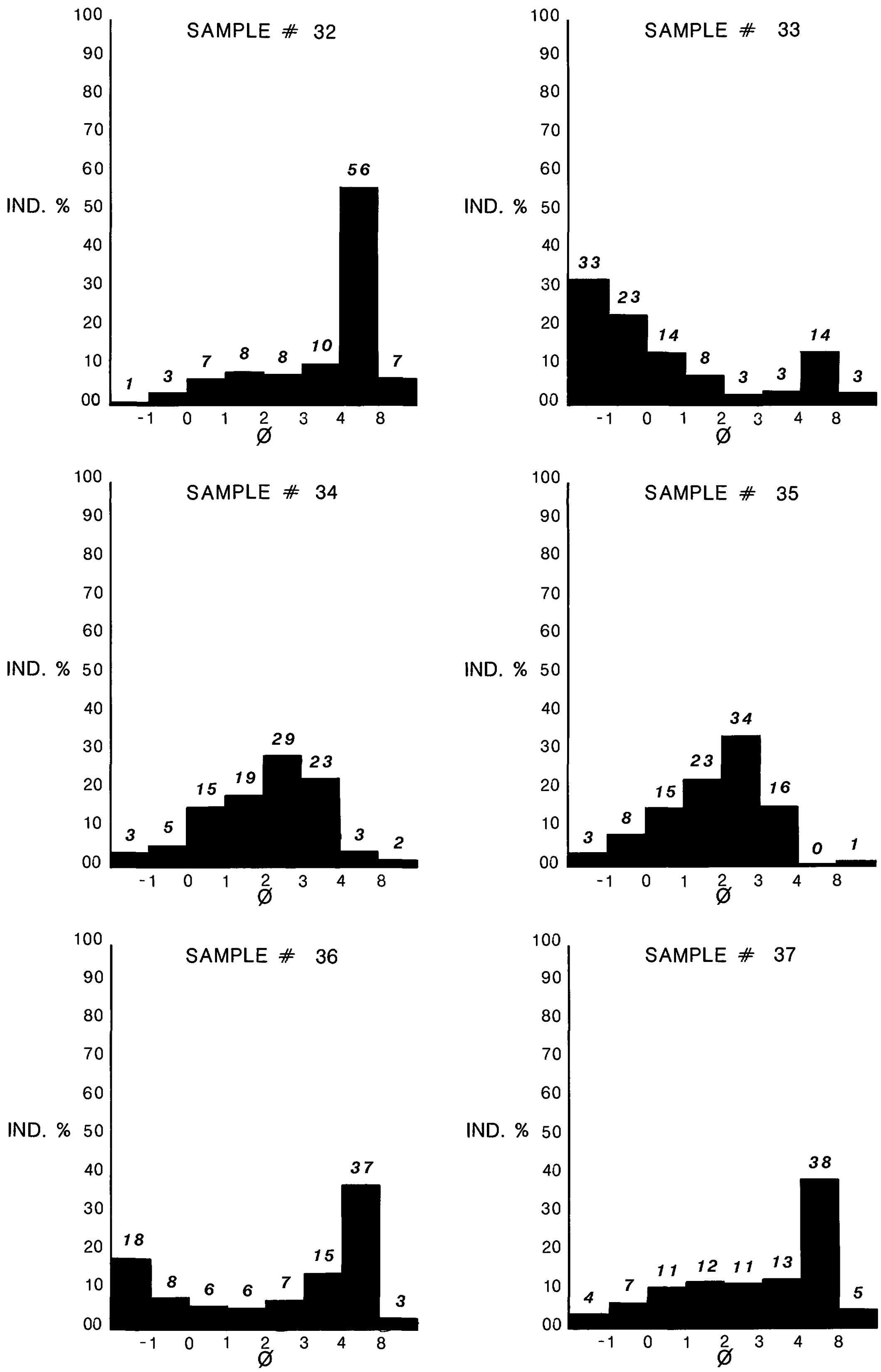

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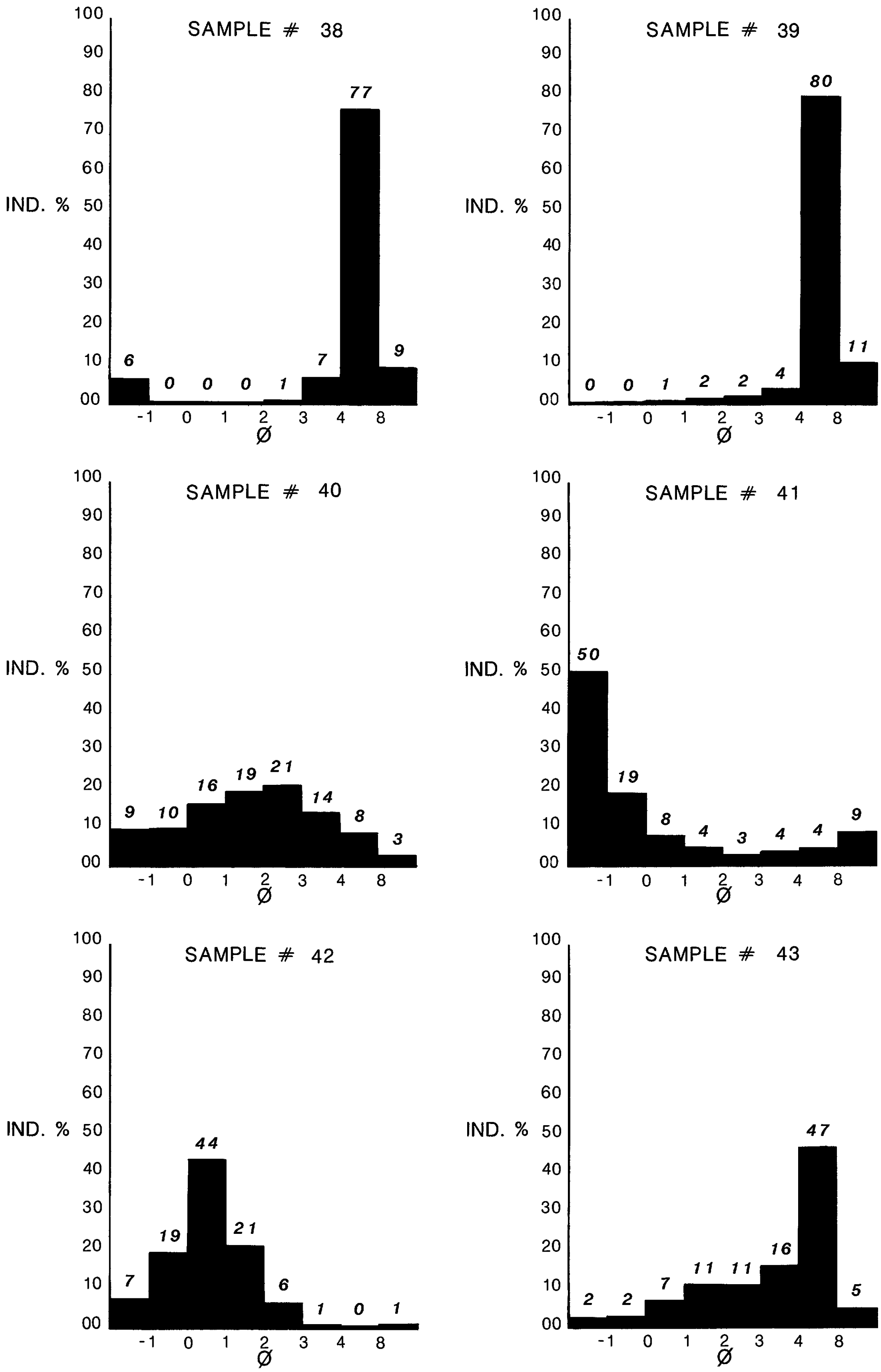

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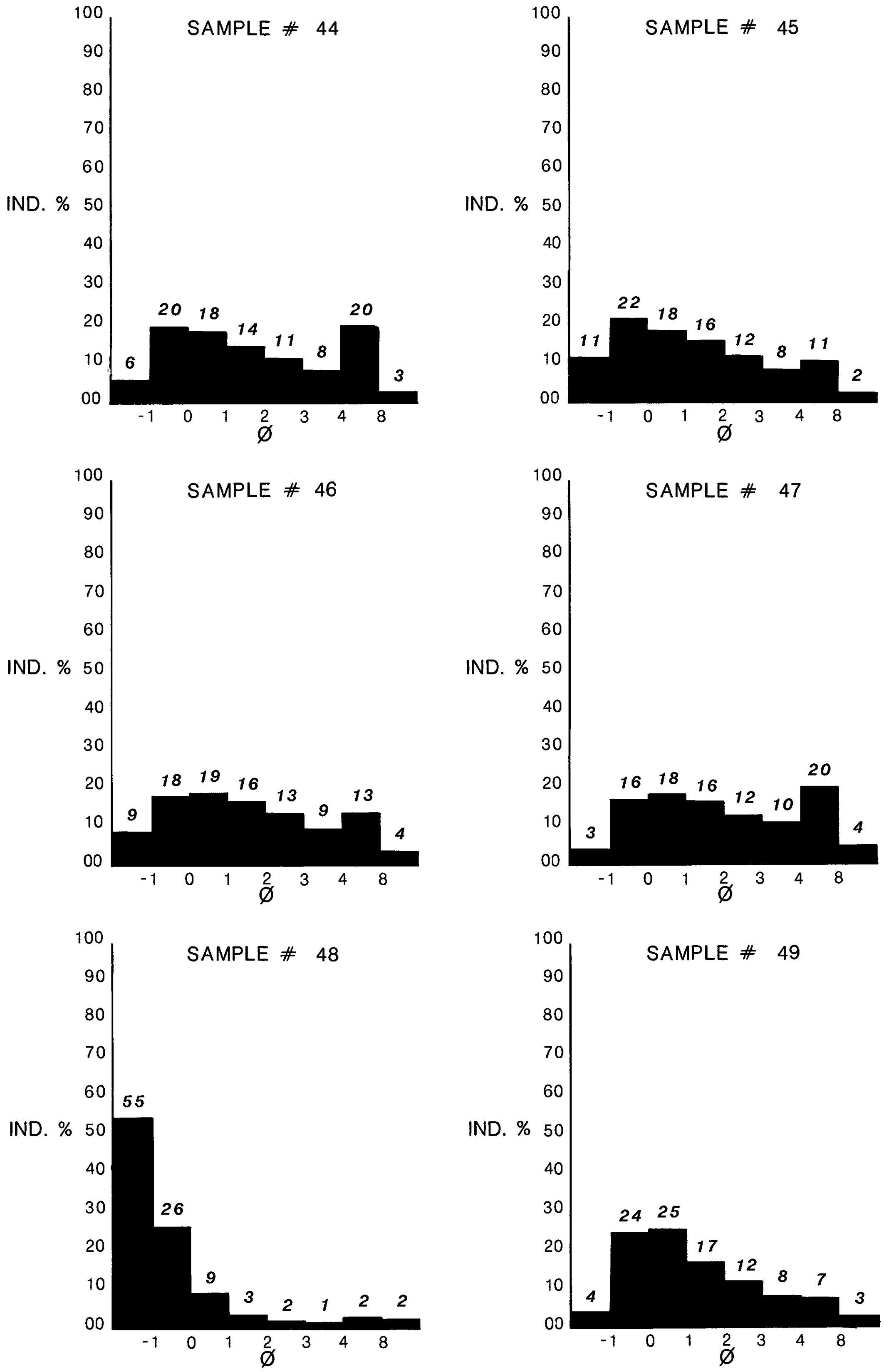

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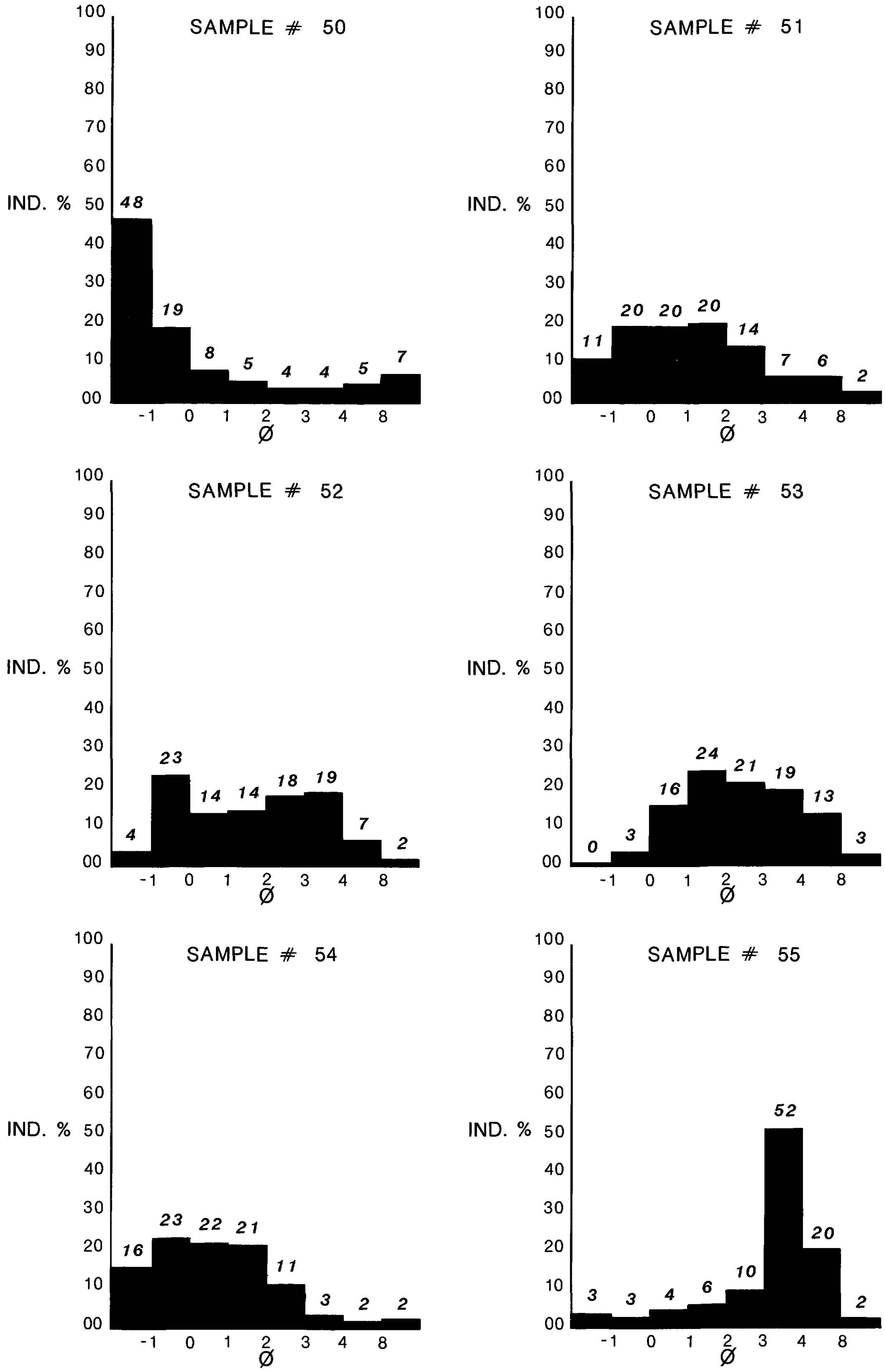

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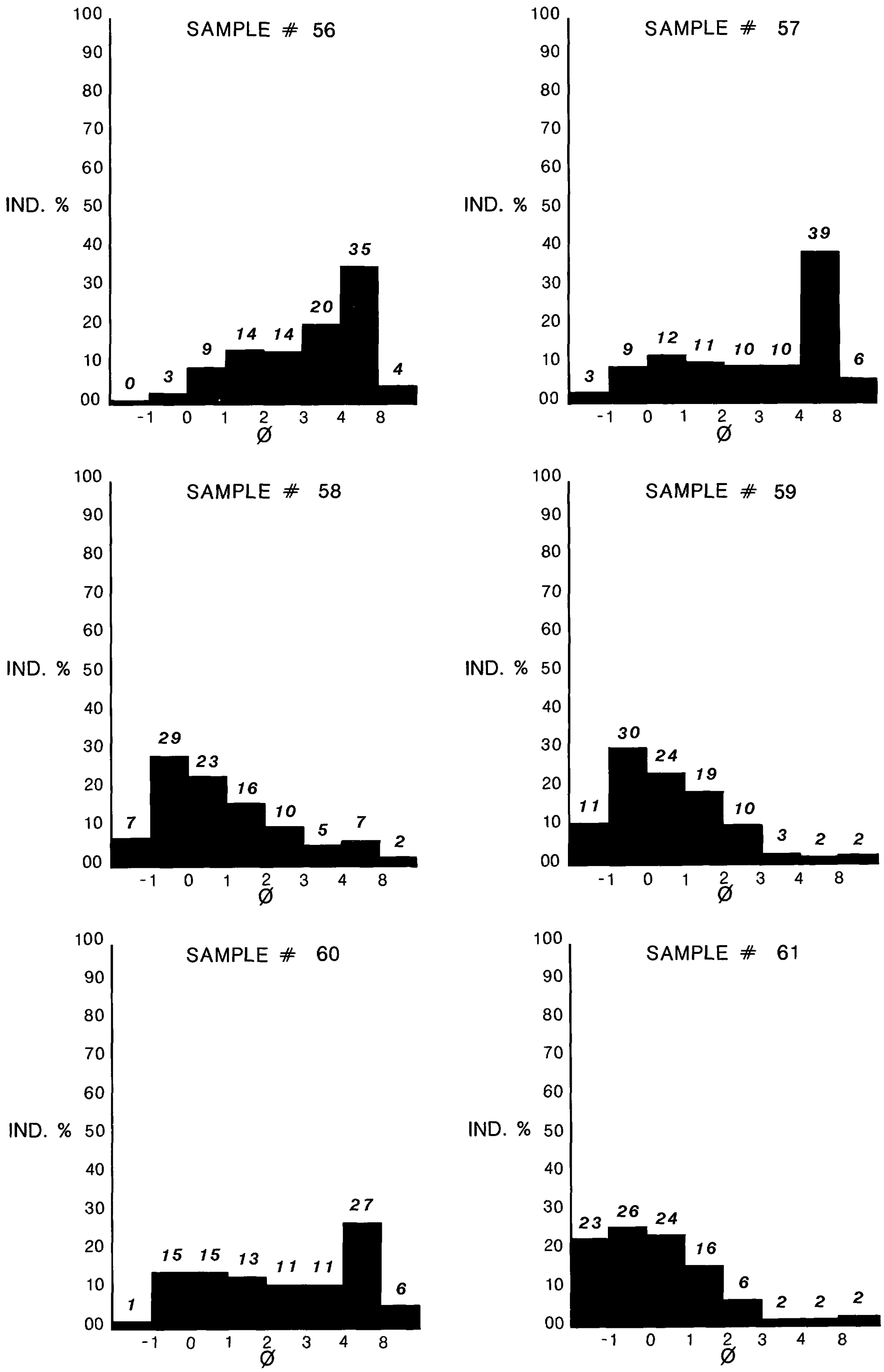

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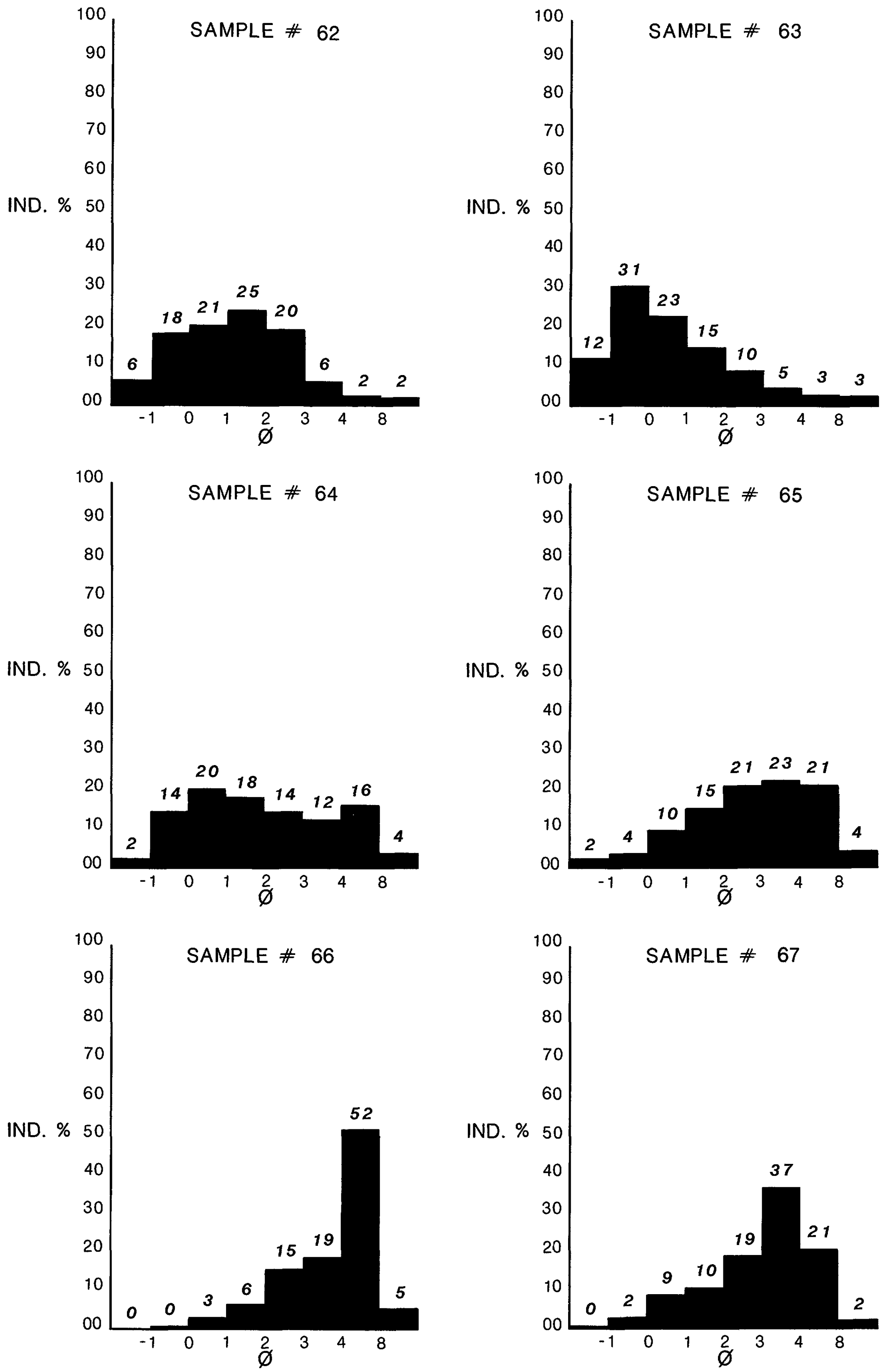

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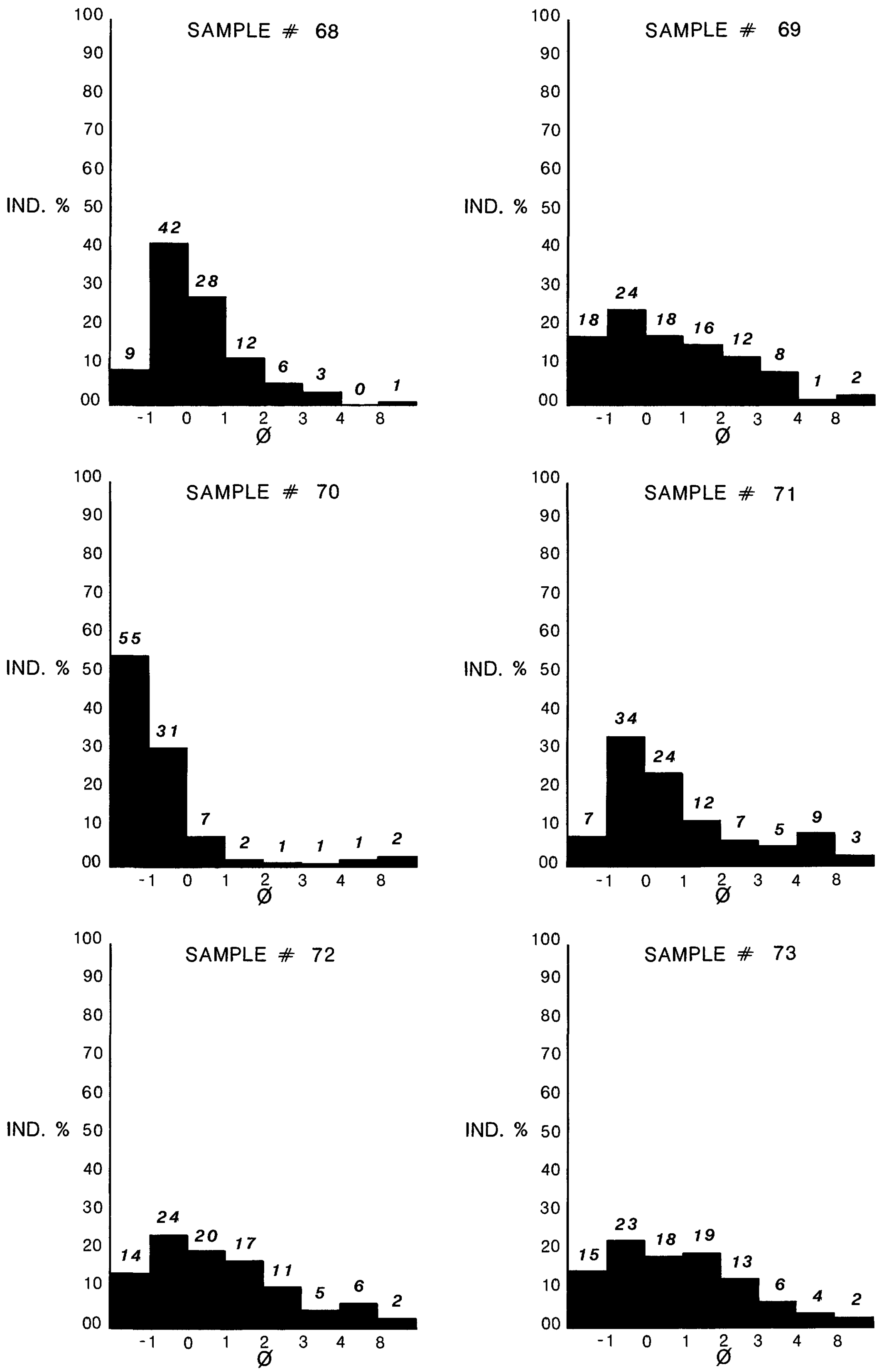

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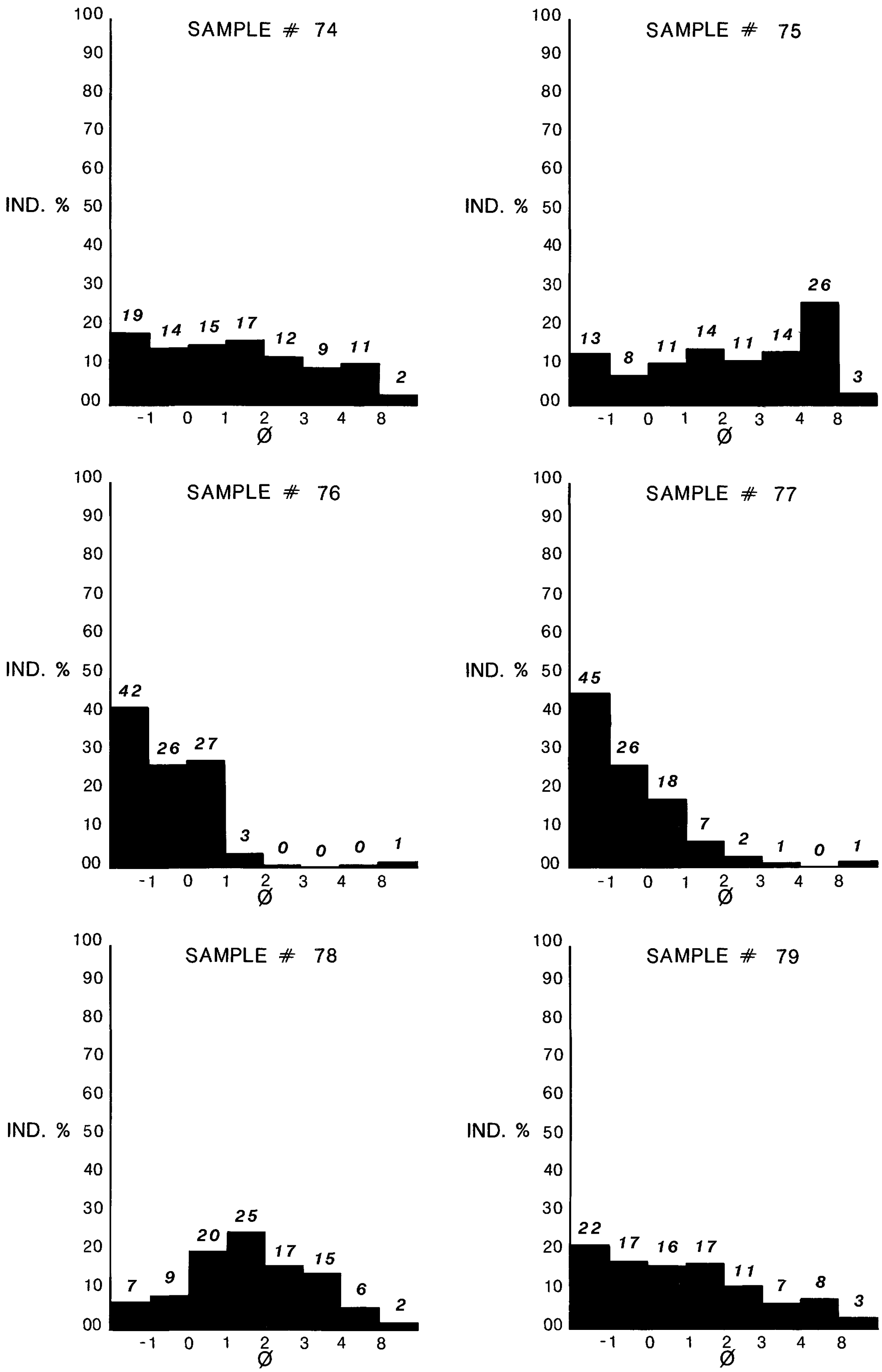

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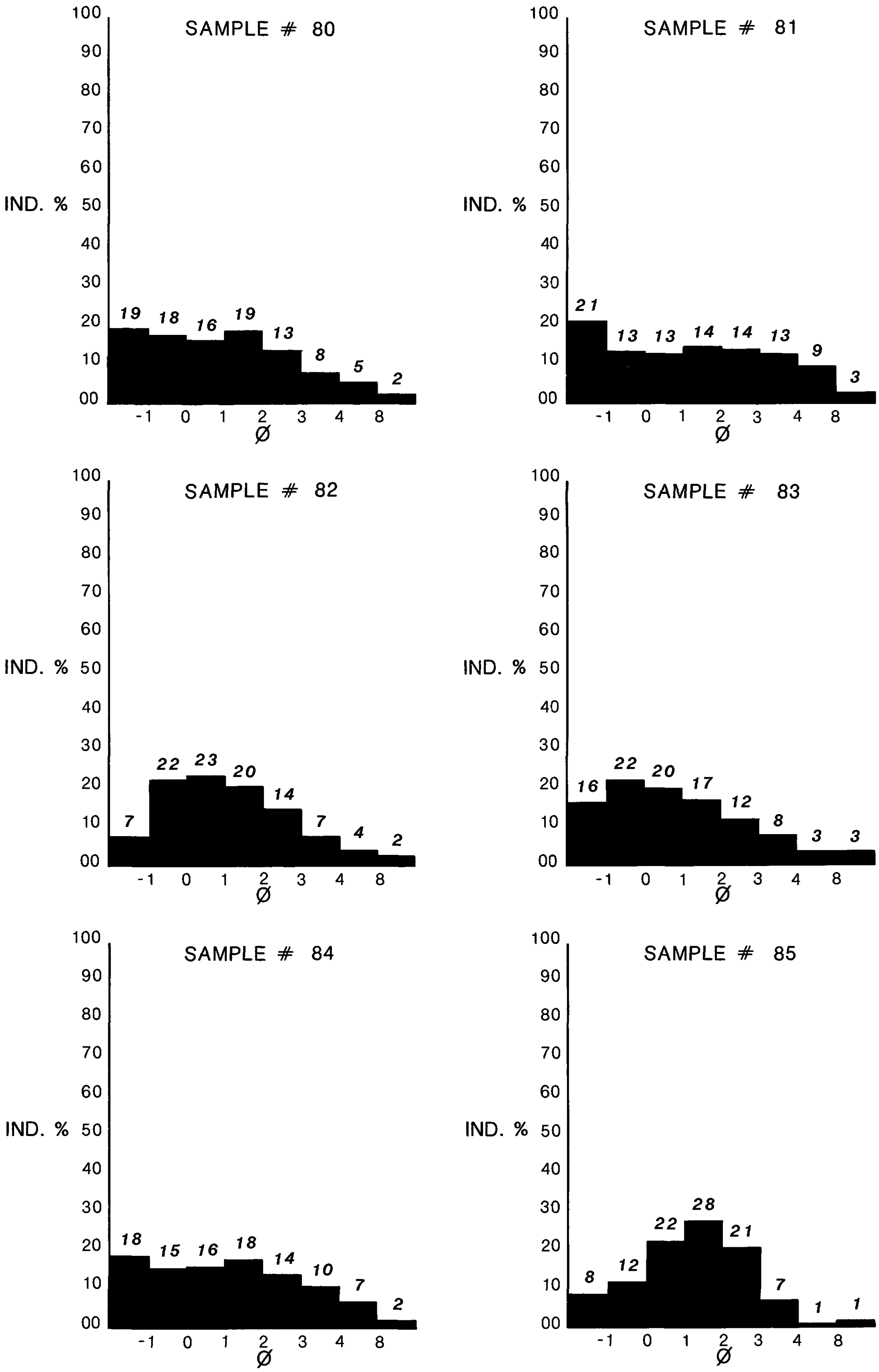

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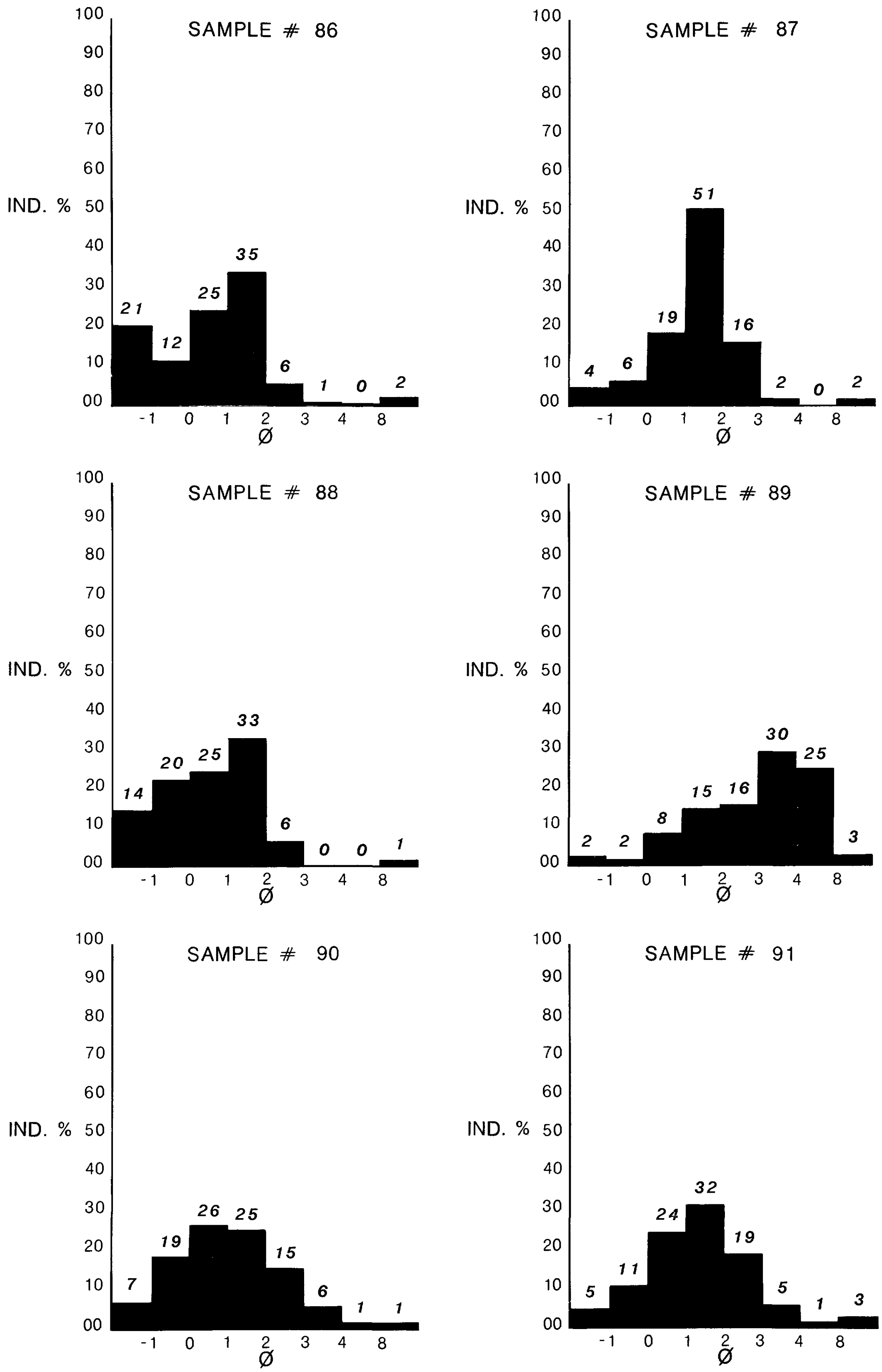

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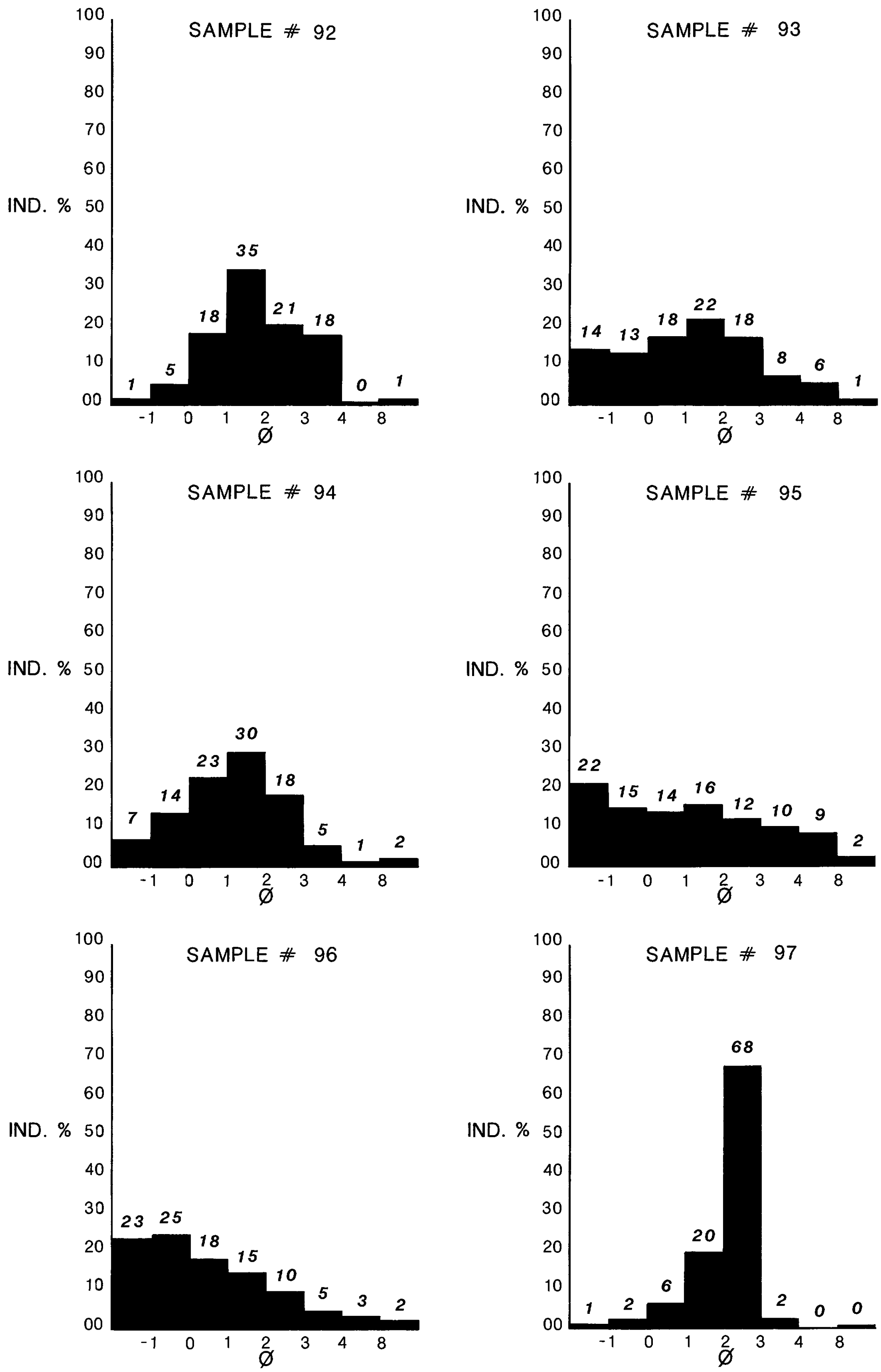

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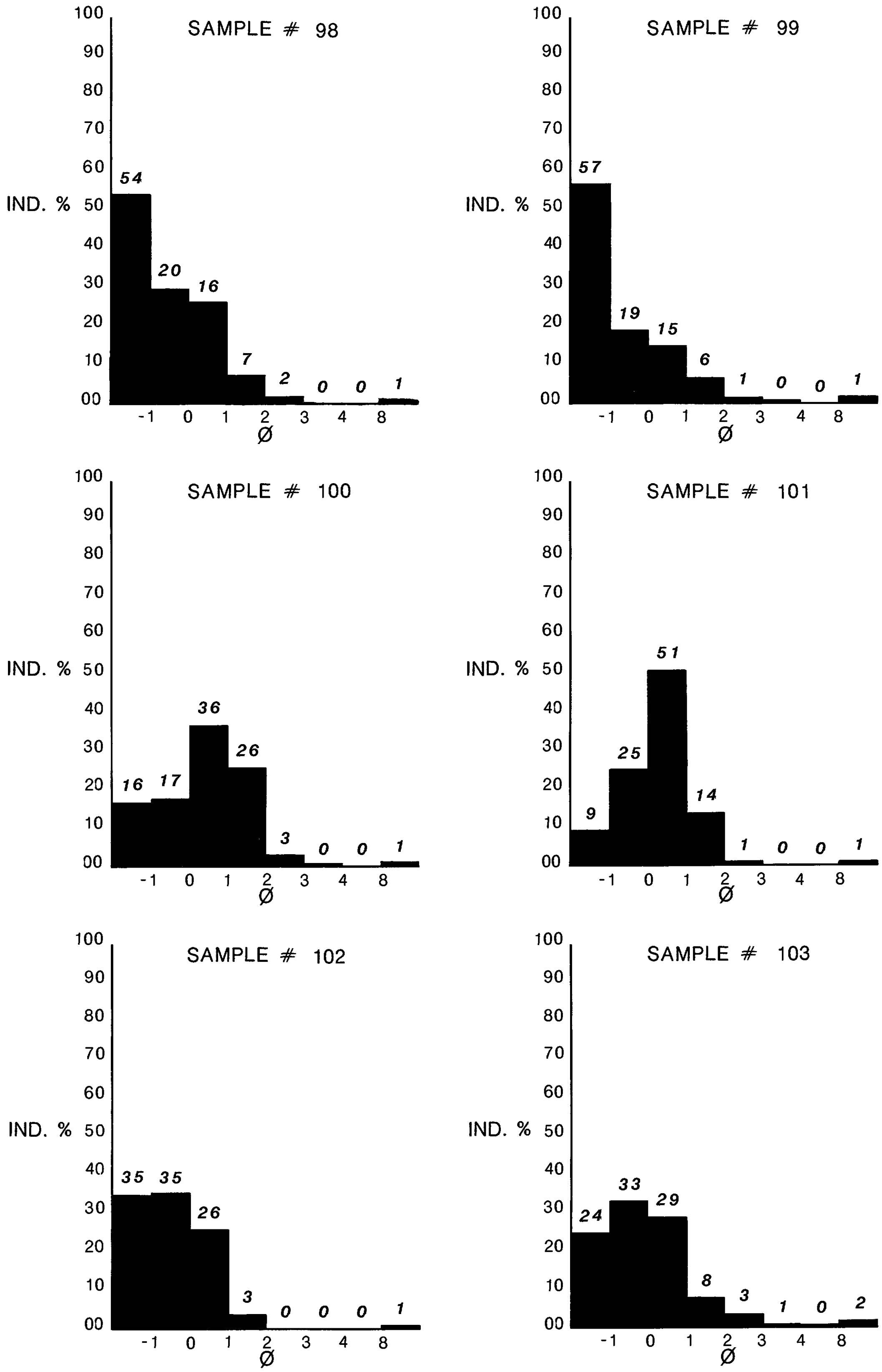

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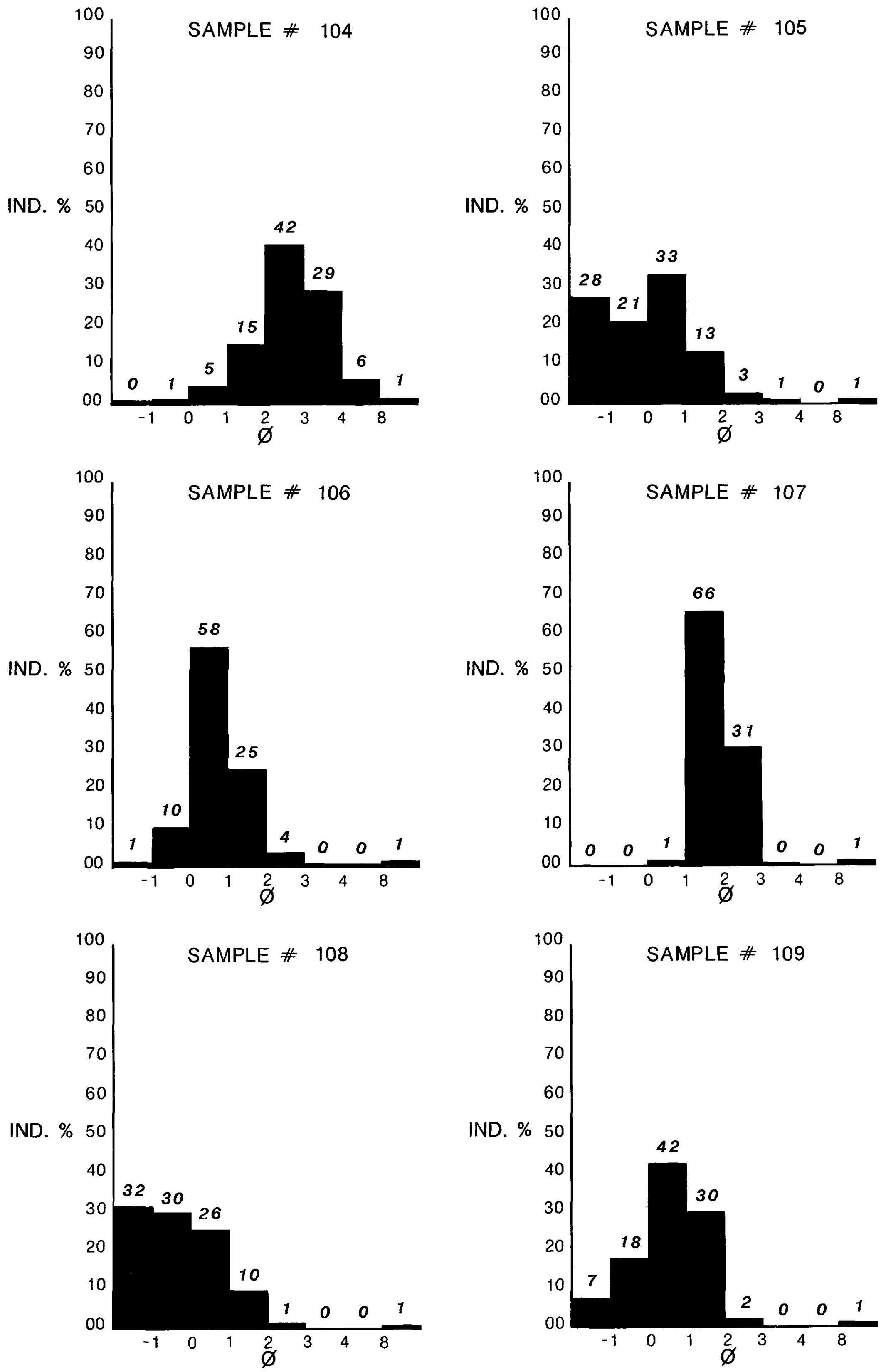

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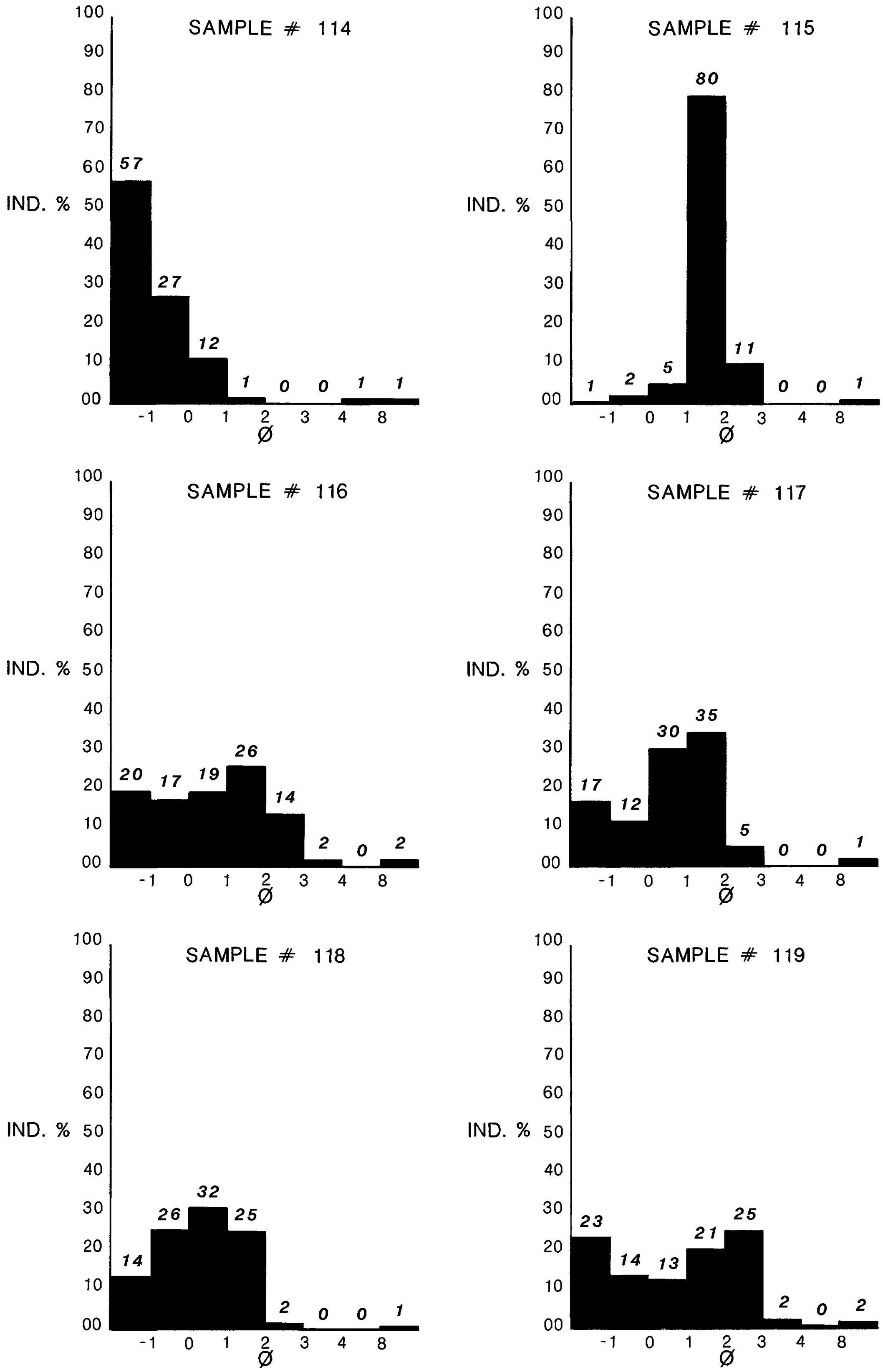

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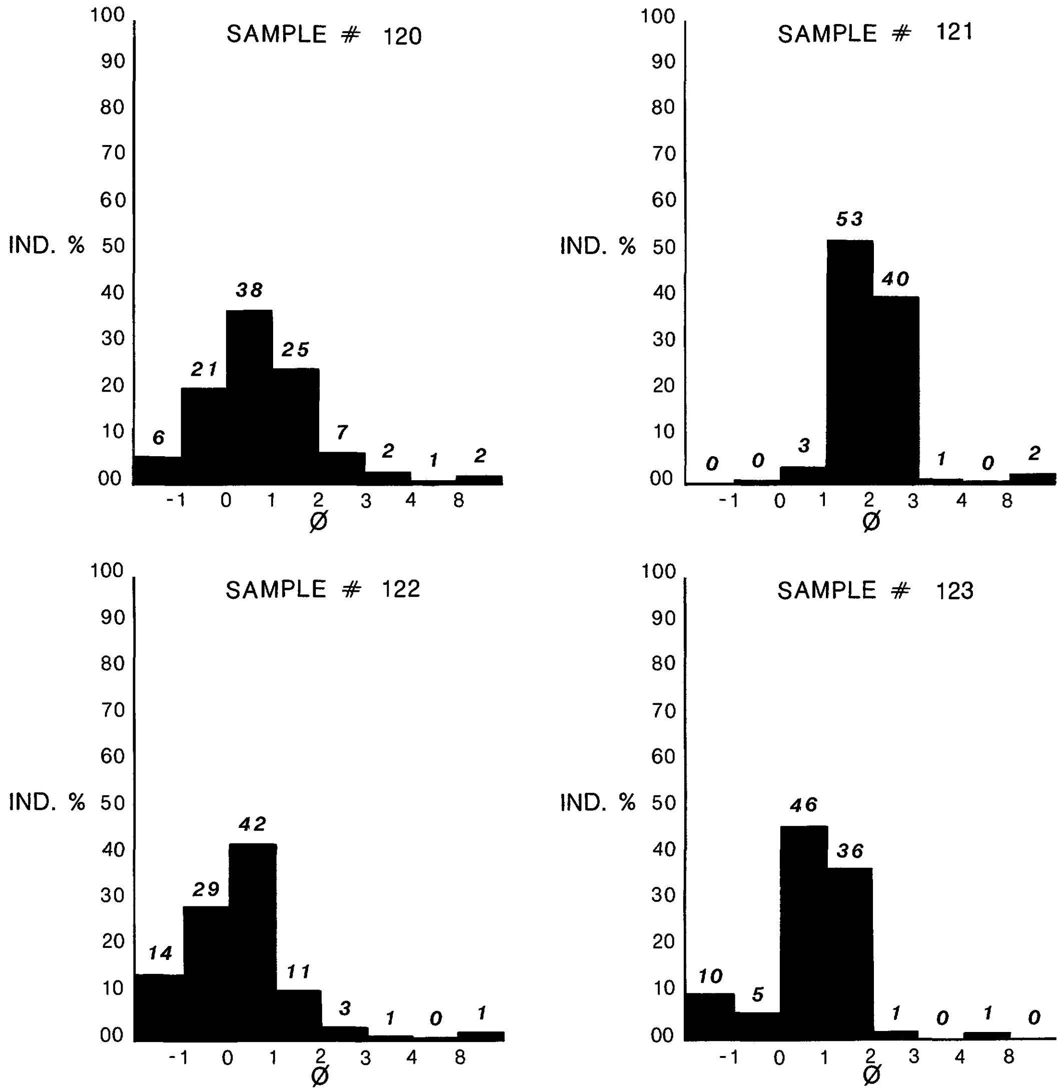

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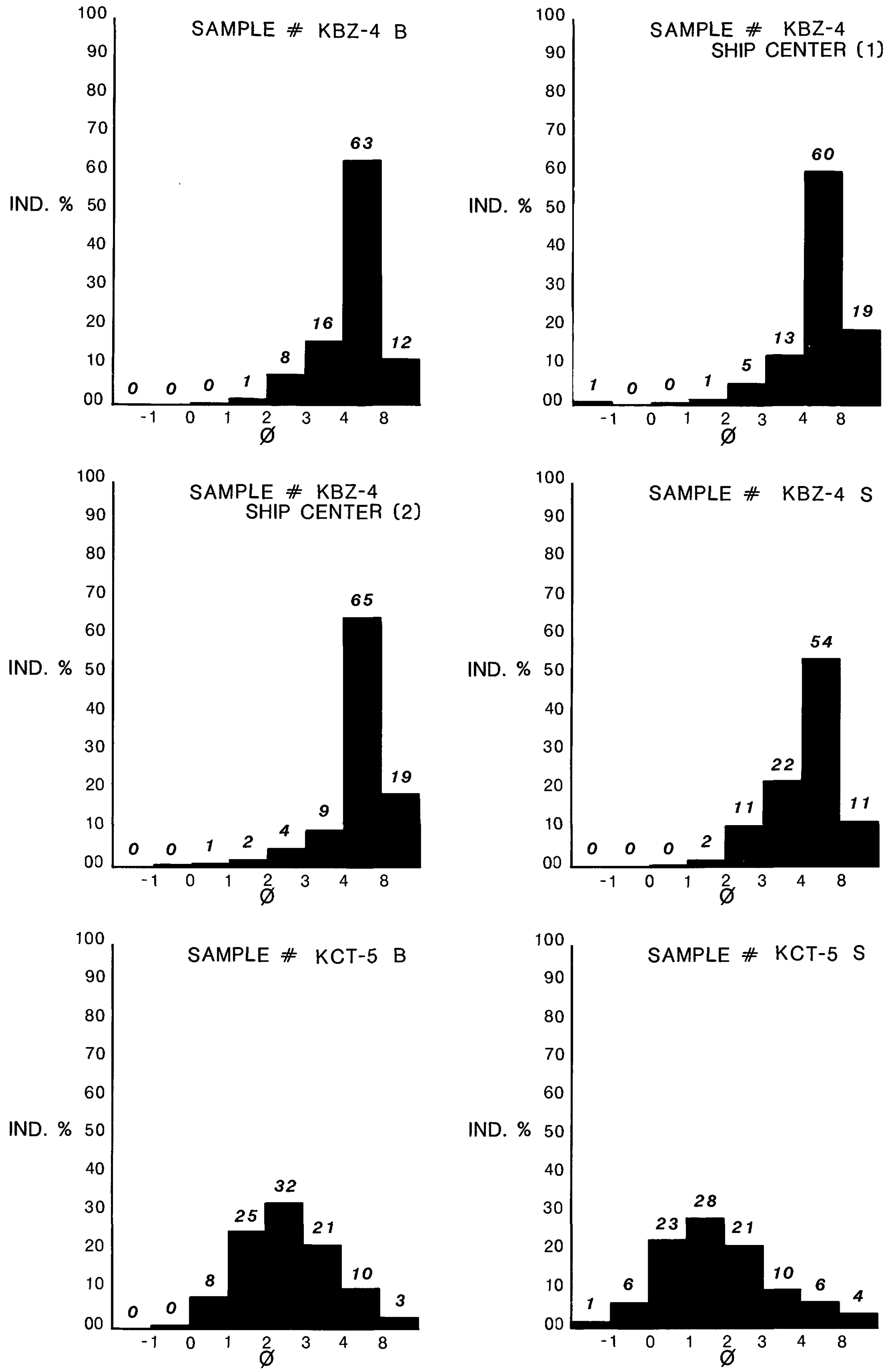
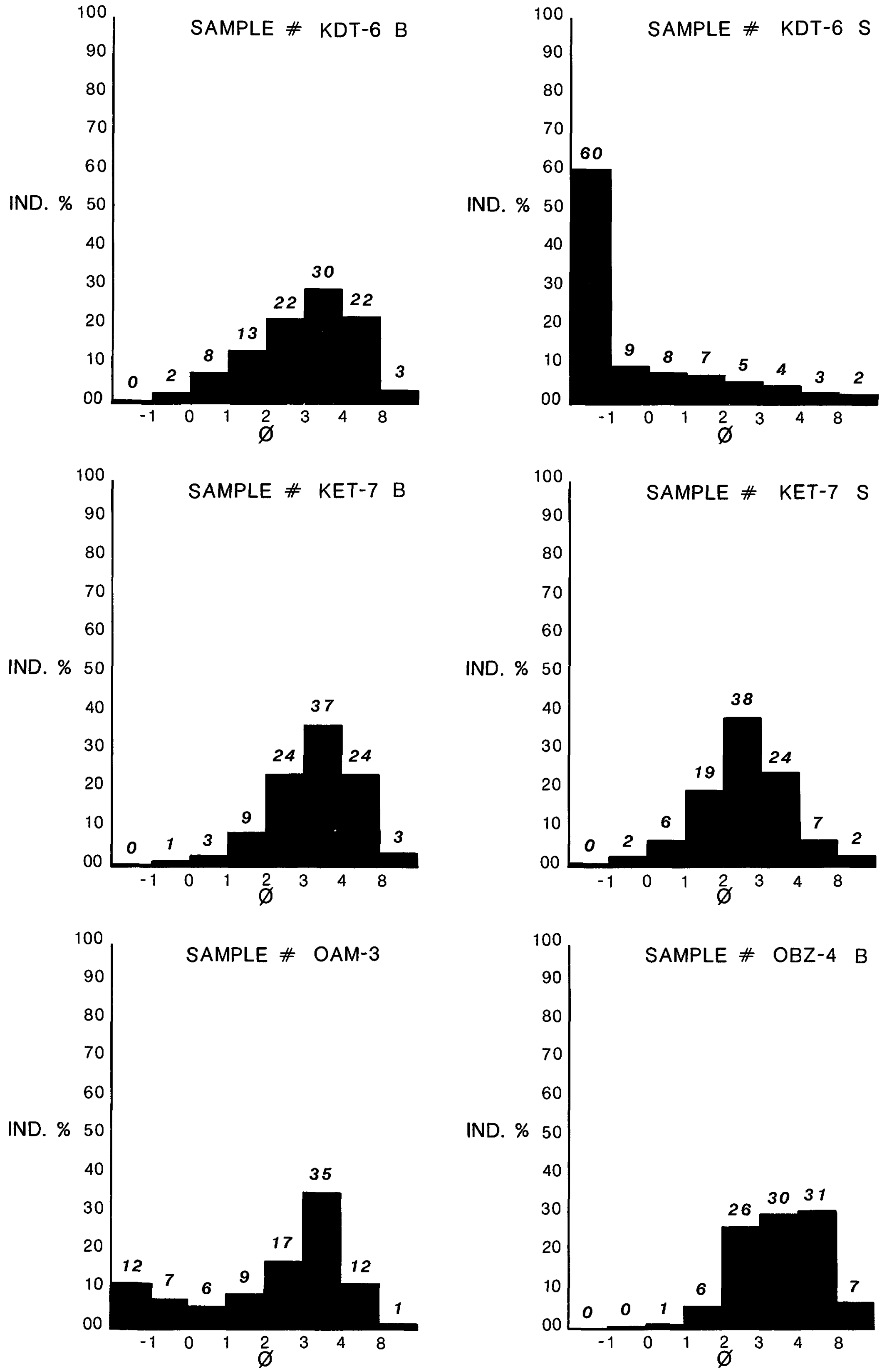


FIGURE 18.—Histograms showing weight-percent of grain-size fractions (see fig. 9) of benthic samples from KOA and OAK crater areas. Percentages are rounded. IND., individual.



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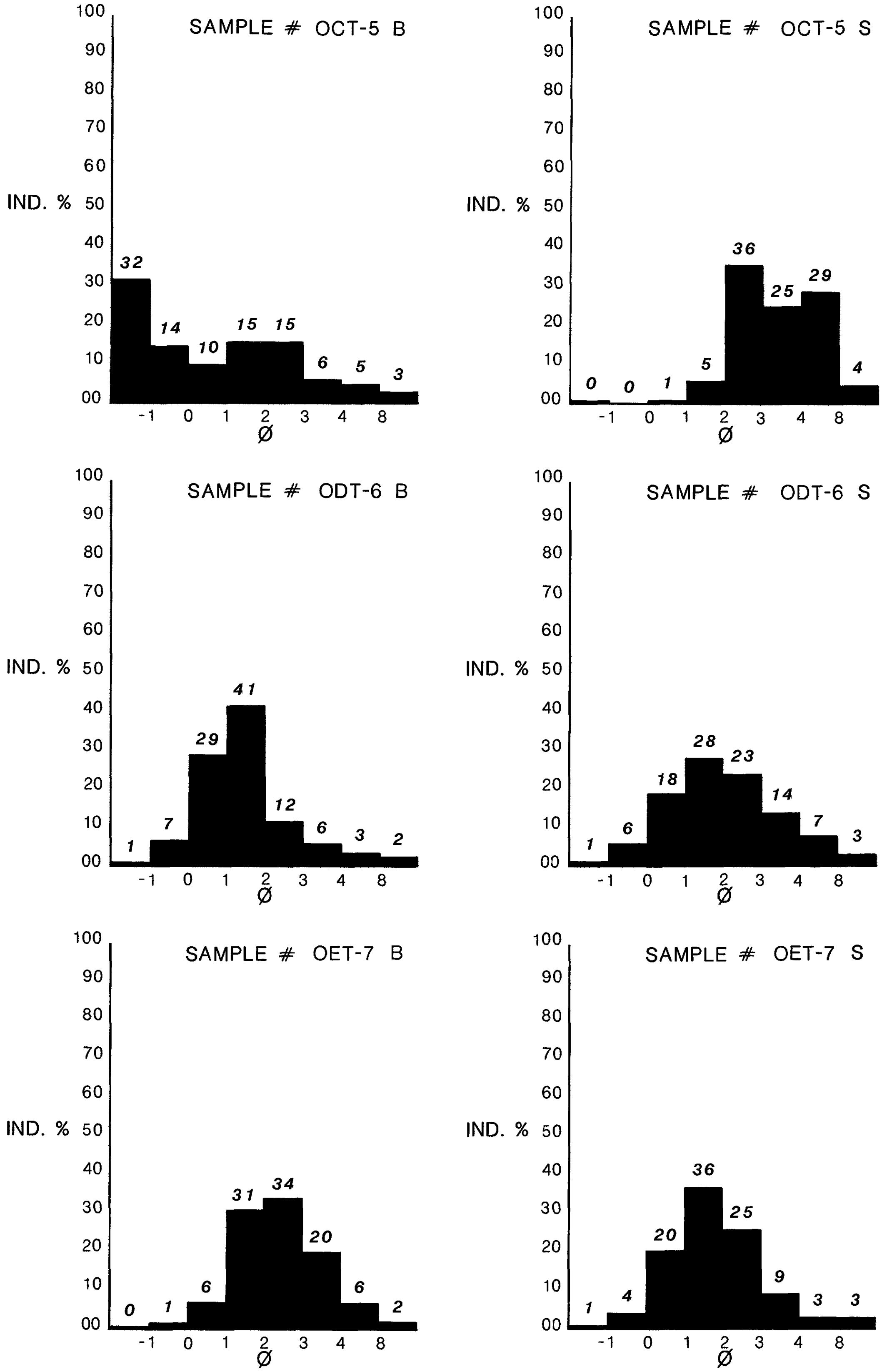

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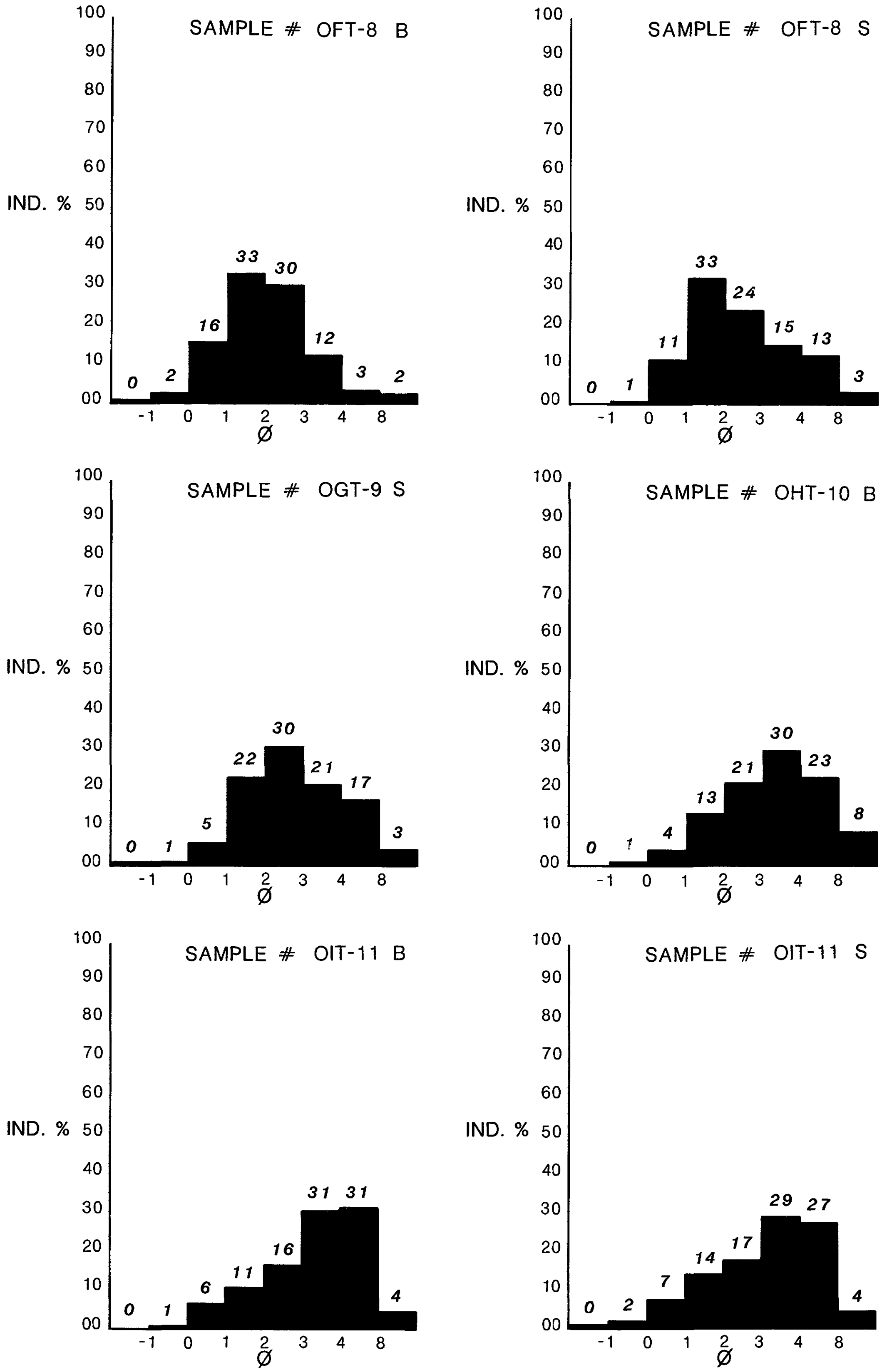

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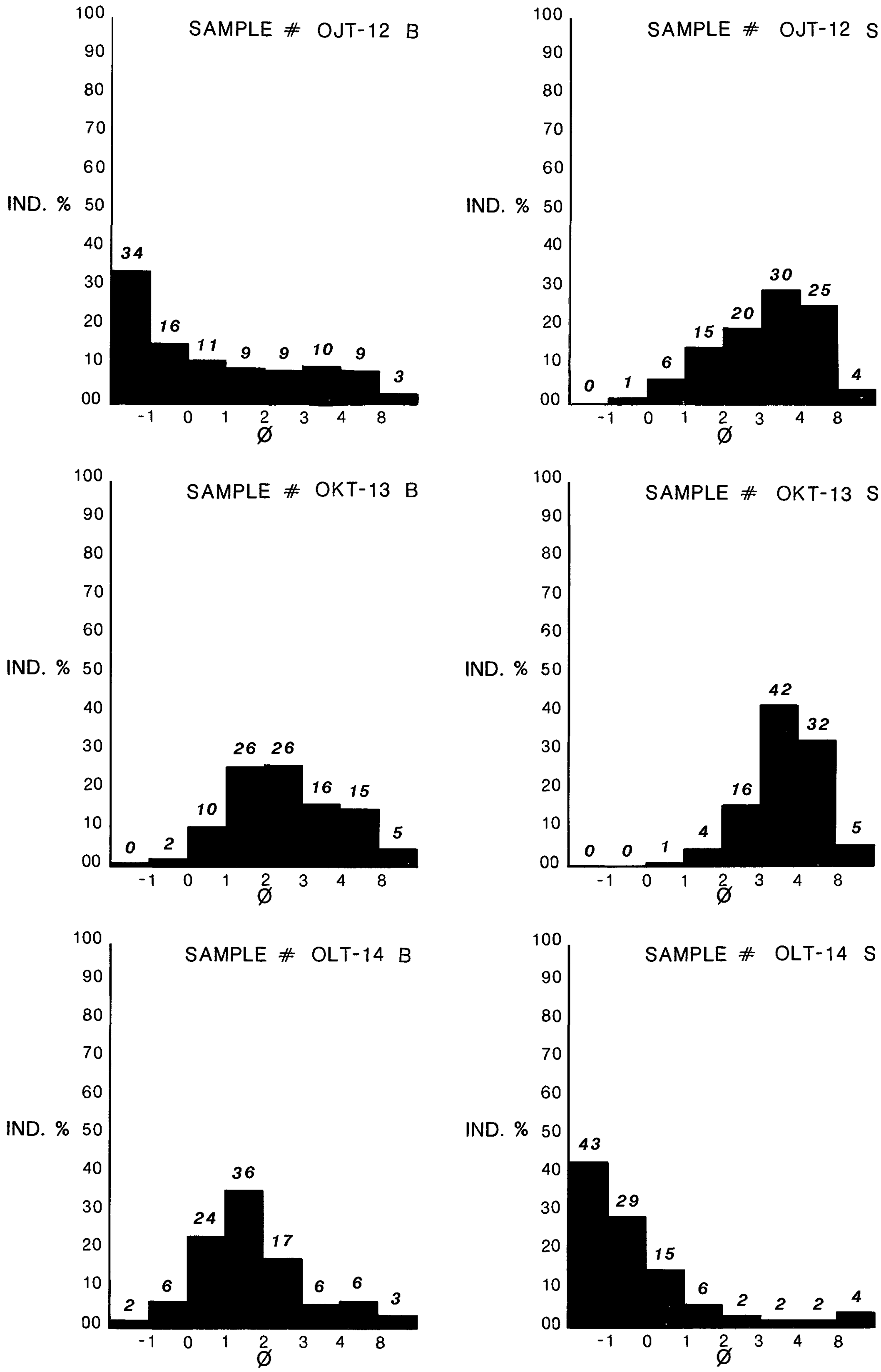

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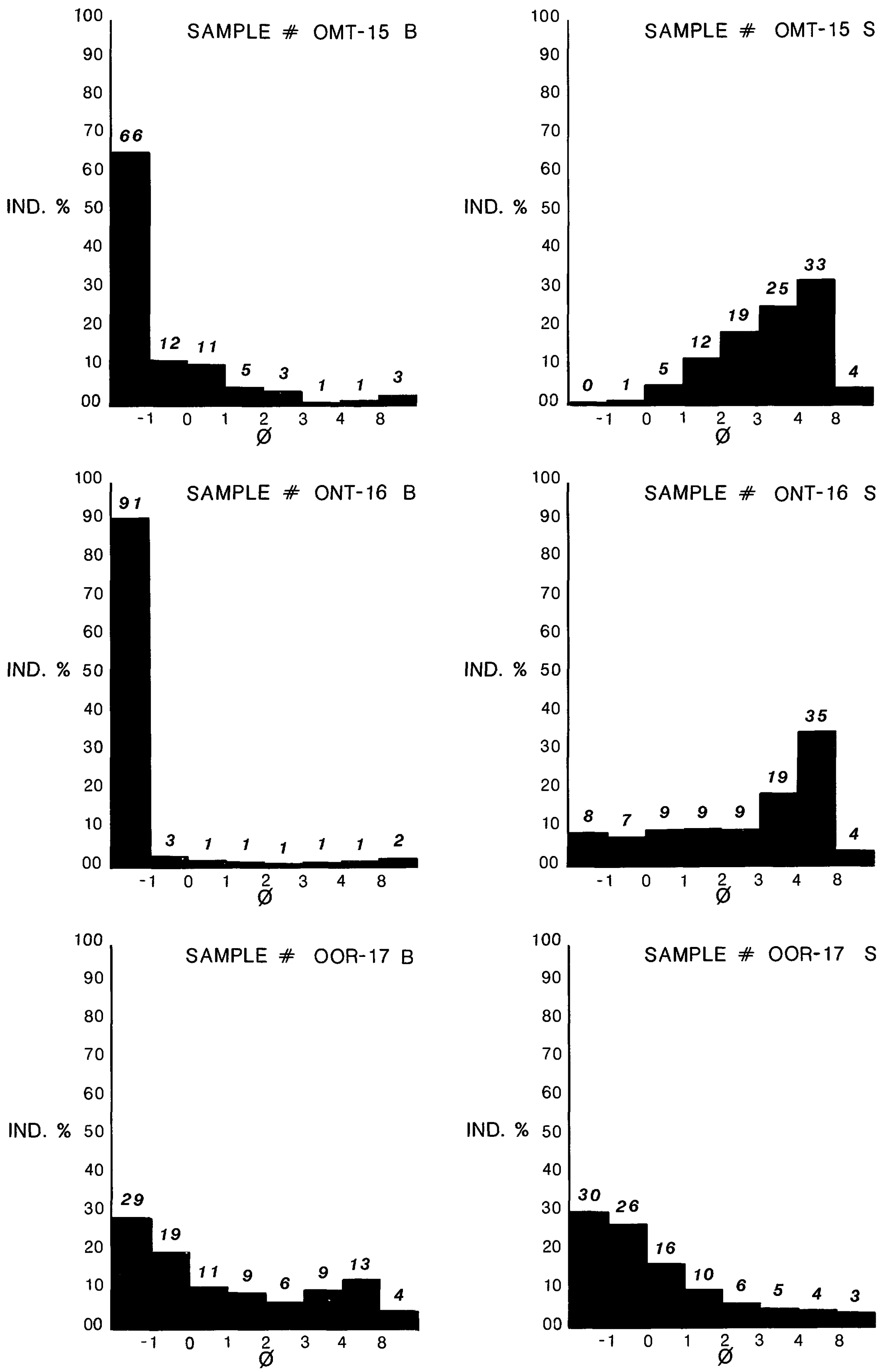

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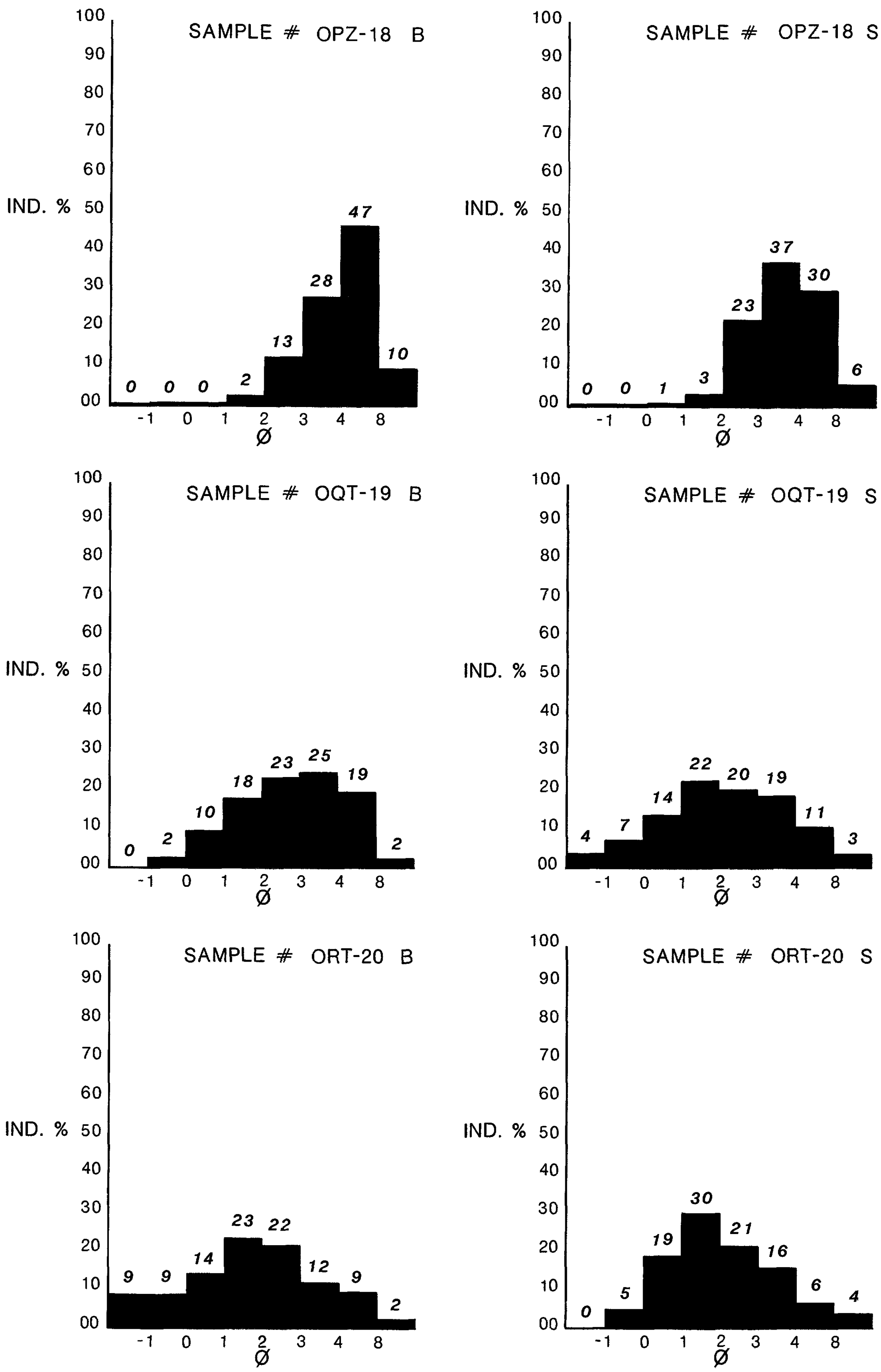

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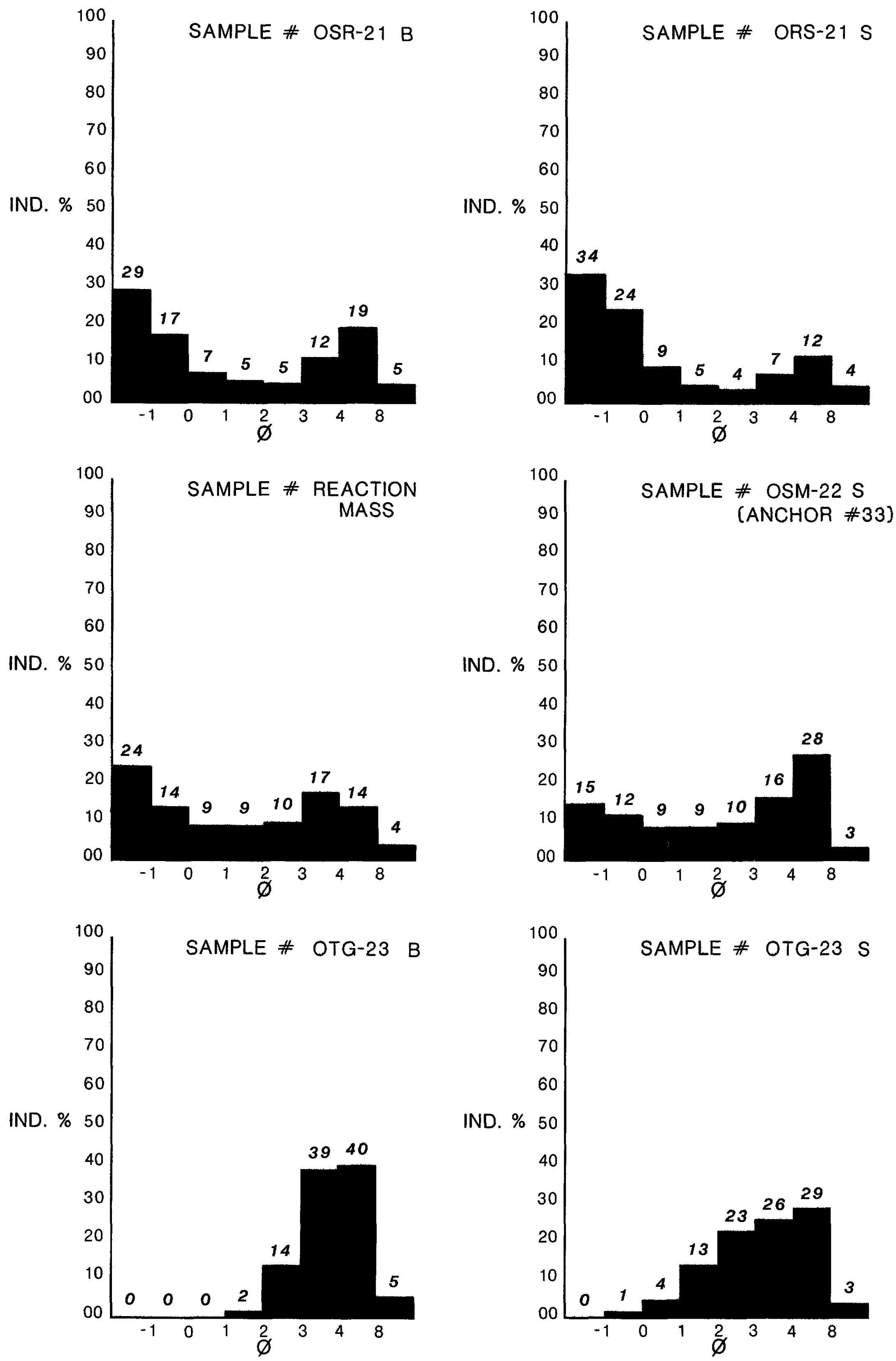

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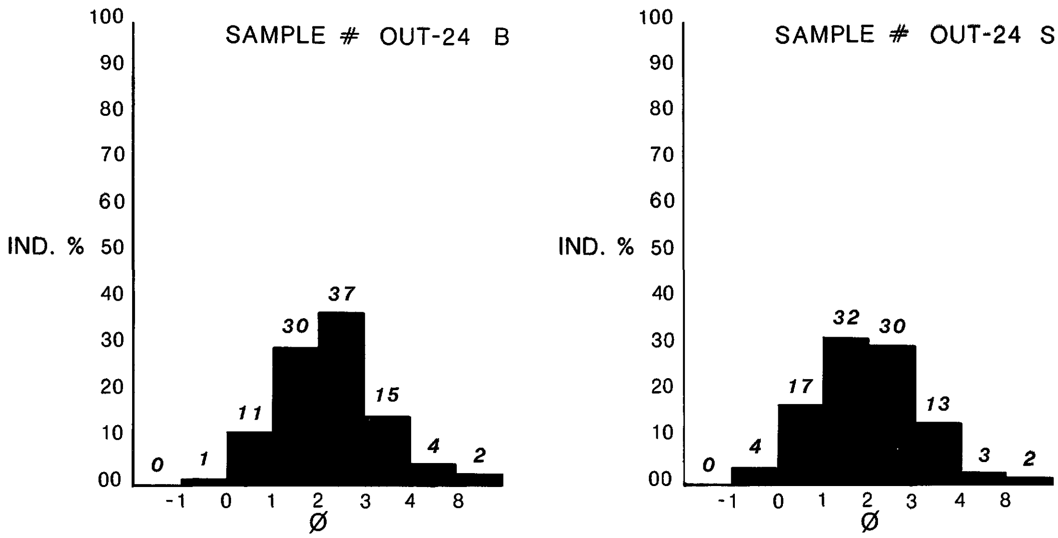

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