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Farnella Cruise F7-86-HW, Cobalt-rich Ferromanganese Crust Data Report for Karin Ridge and Johnston Island, Central Pacific

by

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This report is preliminary and has not been reviewed for conformity with the U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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Introduction

Cruise F7-86-HW left Honolulu, Hawaii on 28 November 1986 aboard the R/V *Farnella* and arrived back in Honolulu on 14 December 1986 (Fig. 1), via Karin Ridge (Fig. 2) and south Johnston Island ridge (Fig. 3), which occur within the United States Exclusive Economic Zone (EEZ) of Johnston Island. This cruise was a multipurpose cruise funded by the U.S. Bureau of Mines (BOM), U.S. Geological Survey (USGS), Nuclear Defense Agency (NDA), National Oceanic and Atmospheric Administration (NOAA), and the Geological Survey of Japan (GSJ) in conjunction with the Japan Resources Association (JRA). The chief scientists were James R. Hein and William C. Schwab of the U.S. Geological Survey and 22 other scientific personnel participated in various phases of the work (Table 1). The objectives of the cruise included:

1. Collection of 5 tons of cobalt-rich ferromanganese crusts and associated substrate rocks from the Johnston Island EEZ for development of processing techniques, measurement of crust physical properties, and determination of bulk deposit chemical compositions (BOM).
2. Testing of a newly developed BOM dredge.
3. Bathymetric and bottom photographic surveys of a small area of the south Johnston Island ridge (hereafter referred to as SOJIR) (DNA).
4. Collection of 1 to 2 tons of cobalt-rich ferromanganese crusts and associated substrate rocks from the Johnston Island EEZ for development of processing techniques, measurement of crust physical properties, and studies of chemical composition of crusts (GSJ, JRA).
5. Test two newly developed JRA dredges.
6. Collection of cobalt-rich ferromanganese crusts and associated substrate rocks for scientific studies including origin and evolution of deposits, chemical and mineralogical compositions, and studies of paleoceanographic and volcanic edifice structure and morphology (USGS).

All of these objectives were met during the 16 day cruise; however, rough seas precluded detailed seafloor photographic surveys on SOJIR.

This report provides maps of camera and dredge stations and seismic reflection lines, description of the dredge hauls, seismic-reflection profiles, bathymetry, photographs of the sea floor, photographs of representative dredge hauls, and the bulk chemical composition of each dredge haul. Another report in preparation will provide detailed chemical and mineralogical compositions of individual crusts and substrates and other analytical data.

Summary of Past Research Activity, Johnston Island EEZ

The Johnston Island EEZ has been the most heavily surveyed EEZ for ferromanganese crusts within the ocean basins. The Federal Republic of Germany's R/V *Sonne*, under the direction of Dr. Peter Halbach, conducted four research cruises in that area starting with Midpac I in 1981, and with following surveys in 1984, 1985, and 1986. Their surveys concentrated on the area of the Johnston Seamount Group located south of Johnston Island, informally called Keli Ridge and Black Friday Ridge by the Germans (Halbach et al., 1982; Halbach et al., 1983; Halbach and Manheim, 1984; Puteanus, 1986). Under the direction of J.R. Hein and F.T. Manheim, the U.S. Geological Survey conducted one previous cruise to the area in 1983 which completed surveys on Horizon Guyot and the south flank of Johnston Island (Fig. 1; Hein et al., 1985a,b; Schwab, 1986). The University of Hawaii has recovered crusts in dredges taken within the Johnston Island EEZ, but has not had a cruise dedicated to crust studies within that area.

The resource potential of ferromanganese crusts is dependent on the high cobalt content, with other metals (Mn, Ni, Pt, Pb, Ce) as possible important byproducts. The Johnston Island EEZ has been given a high rating for crust resource potential as compared to other United States interests in the Pacific basin (Johnson et al., 1985; Hein et al., 1987). However, areas that have large average crust thicknesses are few.

Sample Collection and Descriptions

Thirty dredge attempts were made (Figs. 2, 3; Tables 2, 3, 4), 26 with the U.S. Geological Survey circular chain-bag dredge, one with the Bureau of Mines dredge sled, and 3 with Japanese designed experimental dredges. One dredge attempt (3%) resulted in a lost bag. All of the 29 dredges that recovered rocks also contained ferromanganese crusts (Tables 2, 3).

The total recovery of samples was 8637 kg (9.5 tons) of which about 1830 kg (26%) was ferromanganese crusts (Table 4). Samples were distributed as follows: Bureau of Mines, 5173 kg (5.7 tons); GSJ and JRA, 927 kg (1.02 tons); U.S. Geological Survey, 1039 kg (1.1 tons); discarded 1498 kg (1.6 tons of mostly substrate rocks). Most samples recovered were broken from outcrop rather than collected from talus debris (Table 2).

Crusts varied in thickness from a patina to 160 mm. CD29 has the thickest cobalt-rich crust known and the thickest crust average for any dredge haul known to the authors. All thicker crusts are composed of two or more layers, eight layers being the maximum number noted. Different layers may be laminated, massive, composed of crystallites oriented perpendicular to crust-growth layers, contain pillar structures, contain abundant fractures, contain abundant phosphorite veins, or are reddish-brown and minutely fractured. Phosphorite laminae occur in some crusts (as many as 5 laminae) and separate the crust from the substrate in other samples.

The surface textures of crusts are dominantly smooth or botryoidal (Table 2; Figs. 4, 5). Smooth surface textures are also flat (Fig. 4A), finely granular (Fig. 5D), or bulbous. Botryoidal textures consist of large to small botryoids, botryoids that were partially smoothed by current action (a complete gradation can be seen from unmodified botryoidal surface to smooth, Figs. 5C, 4C,D), modified botryoids that were eroded or dissolved at their base forming mushroom-like forms, botryoids that merged to form a rippled surface, and other modifications of the botryoidal surface (Fig. 5A).

Substrate rock types in decreasing order of abundance are volcanic breccia, basalt, mudstone, limestone, phosphorite, siltstone-tuff (Tables 2, 3). Thick crusts occur on all rock types, including limestone and mudstone, which have been noted in the past to support only thin crusts. Volcanic breccia consists dominantly of basalt clasts cemented by phosphorite, but matrix material may also be altered fine-grained volcanic debris or carbonate sediment. Manganese dendrites occur on some bedding planes in the mudstones. Limestones include weakly indurated foraminiferal sand, bioclastic siltstone and sandstone, and framework reefal limestone. Basalt is massive to highly vesicular and amygdaloidal and consists primarily of alkalic basaltic rocks.

The chemical composition of the homogenized bulk dredge hauls is listed in Table 5. These compositions would probably be equivalent to an ore collected by a rotary-rip-up mining system or a scraping mining system. The average cobalt content for all the bulk dredges listed is 0.21% and surprisingly, the average phosphate (P_2O_5) content is 4.27% (Table 5).

Bathymetry, Seismic-Reflection Profiles, Bottom Photographs, and Lithology

Karin Ridge is the northwest terminus of the Line Islands Ridge. The sinuous crest of the ridge varies in morphology (Figs. 2, 6, 7, 12-17). For example it is rounded in the area of profile 12 (Fig. 17) and razor-back in the area of profile 10 (Fig. 15). A wide variety of rocks were recovered from Karin Ridge, but dredging depth control was not good enough to distinguish the volcanic stratigraphy or changes in lithology with depth. Minor penetration (up to 0.15 sec.) on seismic profiles 1, 2, 11, and 12 (Figs. 6, 7, 16, and 17) along the crest of the ridge is probably due to the presence of reefal limestone and/or pelagic sediment. In general, the part of the ridge surveyed lacks significant sediment cover. No bottom photographs or video were collected on Karin Ridge.

South Johnston Island Ridge connects Johnston Atoll volcano to the Johnston Seamount Group (Keli Ridge). Bathymetry (Fig. 3) was constructed from a detailed 3.5 kHz profiling grid and dredging and transit profiles. Seismic profiles 3 through 6 (Figs. 8 through 11) demonstrate the rugged nature of the topography as indicated by little penetration and many hyperbolic echoes. Again, substrate lithologies are varied, but the length of dredge hauls preclude the determination of stratigraphy or specific outcrops; exceptions include CD17, CD20, and CD21.

Two camera stations were taken on SOJIR (Fig. 3) but rough seas limited the number of photographs and video coverage. About half of the photographs obtained are shown in Figures 18 through 21. Bottom photographs show a seafloor that varies from completely sediment-covered to completely rock-covered. Seismic-reflection records show that the sediment cover is thin and is rarely resolved on the records. Most photographs show ferromanganese oxide-encrusted volcanic rocks partly covered with a thin blanket of sediment. Some areas show degraded sediment ripples (Fig. 18B,C), while other areas show pebble- to cobble-sized encrusted talus debris (Fig. 20C,D). Photos show little evidence of macrobiota or trace evidence of organisms. Some burrowing structures are evident in Figure 18A-D and possibly feeding tracks in Figure 21D.

Discussion

Although remarkably thick crusts were recovered from both SOJIR and Karin Ridge, the overall average thickness is significant in terms of economic potential only for south Karin Ridge. Four centimeters has been suggested as the cut-off thickness for economic potential (see discussion in Hein et al., 1987). The overall average thickness for dredge hauls from SOJIR is 3.3 cm, central Karin Ridge is 2.8 cm, and south Karin Ridge is 4.5 cm. The high average thickness for south Karin Ridge may be partly the result of the small number of dredges taken in that area. Results from Karin Ridge suggest that additional work is warranted.

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Figure Captions

Figure 1. Track line and location map of Karin Ridge and Johnston Island area. The four solid circles are the bottom sampling areas. The dashed lines mark the 200 mile Exclusive Economic Zones of the Hawaiian Islands and Johnston Island. Isobaths are in fathoms and the base map is from Chase et al. (1972).

Figure 2. Bathymetry, seismic-reflection profiles, and dredge sites (CD, JOD, JTD), central and south Karin Ridge (modified from Chase and Menard, 1973).

Figure 3. Bathymetry, seismic-reflection profiles, camera stations (CS), and dredge sites (CD, BMDS, JOD), south Johnston Island ridge. Note that the isobaths are in meters on this figure.

Figure 4. Photographs of dredge hauls and individual rocks from dredge hauls: **A.** CD2, thick crust with a smooth surface texture; **B.** CD14, general view of dredge haul, U.S. Geological Survey chain-bag dredge and BOM dredge sled are in the background; **C.** CD21 general view of dredge haul; **D.** CD21, close-up of large boulder in lower left of C, showing a thick bulbous crust surface.

Figure 5. Photographs of dredge hauls and individual rocks from dredge hauls: **A.** CD23, modified botryoidal surface of crust on a large boulder; **B.** CD23, smoothed botryoidal surface of a crust on a large boulder; **C.** CD25, botryoidal surface of a thick crust on a large boulder; **D.** CD28, granular and partly smooth and partly botryoidal surface texture on a thick crust.

Figures 6 through 17. 3.5 kHz seismic reflection profiles. Profile locations can be found on Figures 2 and 3 where the profile numbers are indicated. A discussion of some of the profiles is given in the text.

Figure 18. Bottom photographs of south Johnston Island ridge, Camera Station CS1 (Fig. 3): **A.** Degraded ripples in foraminiferal sand blanketing crust-covered rocks; **B.** Degraded ripples in foraminiferal sand. Some burrow structures are present; **C.** Degraded ripples in foraminiferal sand blanketing crust-covered rocks; **D.** Burrowed carbonate sand blanketing crust-covered rocks. Vertical and horizontal scales vary between about 2.5 and 3.5 m depending on the height of the camera above bottom.

Figure 19. Bottom photographs of south Johnston Island ridge, Camera Station CS2 (Fig. 3): **A.** Ferromanganese oxide encrusted hard-rock outcrop; **B.** Dusting of carbonate sand on crust-covered rock outcrop; **C.** Same as B.; **D.** Light dusting of carbonate sand on rock outcrop with some talus debris. Vertical and horizontal scales vary between about 2.5 and 3.5 m depending on the height of the camera above bottom.

Figure 20. Bottom photographs of south Johnston Island ridge, Camera Station CS2 (Fig. 3): **A through D.** Ferromanganese oxide encrusted rock with varying amounts (increasing from A to D) of talus debris resting on the surface. Vertical and horizontal scales vary between about 2.5 and 3.5 m depending on the height of the camera above bottom.

Figure 21. Bottom photographs of south Johnston Island ridge, Camera Station CS2 (Fig. 3): **A.** Crust-covered rocks outcrop and pebbles and cobbles with carbonate sand resting in lows; **B.** Crust-covered pebbles resting on carbonate sand; **C.** Carbonate sand blankets crust-covered volcanic rocks; **D.**Carbonate sand blankets crust-covered rocks and fills depressions. Faunal feeding traces occur in the upper left oι the photo. Vertical and horizontal scales vary between about 2.5 and 3.5 m depending on the height of the camera above bottom.

Table 1. Scientific Personnel, R/V *Farnella* cruise F7-86-HW.

James R. Hein	Co-chief Scientist	U.S. Geological Survey
William C. Schwab	Co-chief Scientist	U.S. Geological Survey
David L. Barna	Observer, Watch Stander	Dept. of the Interior under the Assist. Sec. of Water and Science
Laura M. Benninger	Navigator, Photographer	U.S. Geological Survey
Robin Bonner	Airgun Technician	Research Vessel Service, Barry, Wales, U.K.
Edith Chave	Biologist	University of Hawaii
Henry Chezar	Photographer	U.S. Geological Survey
Edward Cooper	Navigator	Research Vessel Service
Alicé S. Davis	Watch Chief	U.S. Geological Survey
Charlaine L. Fleishman	Watch Chief	U.S. Geological Survey
Donald G. Foot	Watch Stander	U.S. Bureau of Mines
Kevin Kelley	Watch Stander	University of Hawaii
David A. Larson	Engineer, Watch Stander	U.S. Bureau of Mines
Colin Nichole	Engineer	J. Marr and Son, Hull, U.K.
Yoshio Masuda	Engineer, Watch Stander	Japan Resources Association
Charles L. Morgan	Observer	Hawaii Environmental Impact Statement Coordinator
James K. O'Toole	Mechanical Technician	U.S. Geological Survey
Ward R. Ozanne	Mechanical Technician	U.S. Geological Survey
Leda-Beth G. Pickthorn	Navigator, Watch Stander	U.S. Geological Survey
Peter Ruzzi	Engineer, Watch Stander	U.S. Bureau of Mines
Robert Turner	Engineer	Globe Engineering, Hull, U.K.
Akira Usui	Geologist, Watch Stander	Geological Survey of Japan, Marine Minerals Resource Section (MITI)
Rick W. Vail	Electronics Technician	U.S. Geological Survey
Robert F. Wallace	Airgun Technician	Institute of Oceanographic Sciences (IOS) Wormley, U.K.

Table 2. Location and description of dredge hauls from south Johnston Island ridge and Karin Ridge, *Farnella* cruise F7-86-HW.

Dredge No.	Location	Latitude (°N)	Longitude (°W)	Water Depth (m)[3]	Total Recovery (kg)	% Broken From Outcrop	% Talus	Description of Ferromanganese Oxides	Substrate Description
CD1[1]	KE[2]	17°05.9′ 17°06.2′	168°19.4′ 168°22.39′	2255(?)- 1800	725	70	30	Surface texture smooth to small botryoidal. Maximum crust thickness 50 mm, average 10 mm. 50% of rock covered by crust. ≤1% nodules present, 0.5 to 4 cm diameter, botryoidal surface.	Cream to yellowish-tan bioclastic limestone with abundant gastropods and pelecypod shells. Phosphorite layers common. Some limestone is phosphatized. A few limestones with manganese crust have much iron oxidation. Porphyritic basalt and hyalobasalt altered completely to iron oxides and clays. Phosphorite. Of total dredge recovery ≥40% basalt, ≤55% limestone, ≤2% mudstone, ≤1% nodules. All limestone and mudstone broken from outcrop. Most but not all basalt is talus cobbles.
CD2	J	16°26.4′ 16°24.4′	169°31.8′ 169°32.7′	2300- 2900	500	80	20	Surface texture smooth to elongate botryoidal. Maximum crust thickness 110 mm, average 50 mm. 90% of rock covered by crust. <1% nodules present, 0.5 to ~3.0 cm diameter, botryoidal surface.	Sedimentary rock, mostly conglomerate and sandstone. Sandstone is yellowish-brown, poorly to moderately indurated with subrounded and angular volcanic clasts to 2-5 cm. Conglomerate (or breccia) is well indurated with well-rounded basaltic clasts, some with manganese crusts of their own in white, pinkish to reddish-tan phosphatized matrix. Chalk cobbles are well-rounded and bioturbated. Three boulders—two basalt and one volcanic breccia. ≥30% crust with little or no substrate, ~25% volcanic breccia or conglomerate, ~43% volcaniclastic sandstone, <1% nodules, <<1% chalk.
BMDS3	J	16°26.46′ 16°27.21′	169°31.55′ 169°31.90′	2340- 2730	20	100	0	Surface texture smooth to botryoidal. Maximum crust thickness ~25 mm, average ~10 mm. 95% of rock covered by crust.	Basalt, minor limestone and volcanic breccia. Seafloor shavings—basalt and manganese shaved off by the teeth on the dredge.
JOD4	J	16°26.6′ 16°27.0′	169°29.7′ 169°35.0′	>3100- 2380	70	<5	~95	Surface texture botryoidal (large and small botryoids). Smooth on basalt substrates. Maximum crust thickness 30 mm, average 20 mm. ~90% of rock covered by crust. <<1% nodules present.	~85% volcanic breccia composed of basaltic clasts, angular to subrounded, mm to 5-cm-sized in greenish and tan colored phosphatized matrix. ~15% basalt, aphyric, highly vesicular, amygdaloidal. Minor chalk. Pale brown pelagic ooze in fractures and covering some surfaces. One phosphorite.
CD5	J	16°23.0′ 16°24.5′	169°31.5′ 169°33.5′	2420- 2750	200	95	5	Surface texture botryoidal. Maximum crust thickness 100 mm, average 45 mm. 50% of rock covered by crust.	Greenish to pale brown mudstone, probably the dominant crust substrate. Reefal limestone, without crusts. One large basalt boulder, two large mudstone cobbles with crust, two volcanic breccia substrates. Large amounts of thick ferromanganese crusts broken off the mudstone substrate.
CD6	KW	16°58.5′ 16°59.8′	168°35.2′ 168°34.2′	2300- 1330	365	90	10	Surface texture varies from botryoidal to smooth to granular. Maximum crust thickness 60 mm, average 28 mm. 95% of rock covered by crust.	Three substrate types nearly equivalent in abundance: volcanic breccia, brown basalt, and mudstone. Two types of volcanic breccia: (1) angular to subrounded clasts in a greenish-gray sandy matrix, and (2) red-brown mostly angular volcanic clasts in pale beige calcareous matrix. One small limestone fragment. A few gray basalt samples. Volcanic breccia has thickest crusts, mudstone less thick, basalt least thick.

Table 2. continued.

Dredge No.	Location	Latitude (°N)	Longitude (°W)	Water Depth (m)	Total Recovery (kg)	% Broken From Outcrop	% Talus	Description of Ferromanganese Oxides	Substrate Description
CD7	KW	16°58.7′ 16°58.62′	168°34.5′ 168°32.99′	3100- 1800	270	95	5	60% of crusts have smooth surface texture, 40% botryoidal. At least one crust with granular surface texture. Maximum crust thickness 72 mm, average 35 mm. 85% of rock covered by crust.	Greenish-brown and reddish-brown mudstone dominant, basalt and volcanic breccia minor. Basalt is altered, calcitized and phosphatized to various degrees, and has some unusual textures, including swirly flow textures. Some vugs in basalt filled with dog-tooth spar calcite.
CD8	KW	17°02.15′ 17°05.17′	168°34.92′ 168°32.43′	2675- 1685	30	100	0	Surface texture smooth to smoothed botryoidal. Maximum crust thickness 70 mm, average 40 mm. 100% of rock covered by crust.	Gray basalt and volcanic breccia.
JTD9	KW	16°58.1′ 16°57.9′	168°34.5′ 168°33.5′	3050- 2100	450	95	5	Dominant surface texture smooth to modified botryoidal. Maximum crust thickness 70 mm, average 40+ mm. 100% of rock covered by crust.	Primarily mudstone, minor highly vesicular basalt, very minor volcanic breccia. Mudstone is greenish-brown and bored in places.
JOD10	KW	16°58.7′ 16°59.1′	168°36.2′ 168°33.5′	2830- 1800	20	50	50	Surface texture smooth. Maximum crust thickness 50 mm, average 30-40 mm on breccia and 10 mm on basalt. ~95% of rock covered by crust.	Predominantly volcanic breccia, minor basalt. One large slab of volcanic breccia (10-12 kg) has thick crust. Basalt is all talus debris with thin crusts. Volcanic breccia has angular to subrounded clasts of altered basalt ranging from mm to several cm in size in gray-green sandy matrix. Basalt highly altered and plagioclase phyric.
CD11	KE	17°08.5′ 17°08.4′	168°18.8′ 168°19.5′	2530- 2240	300	90	10	Dominant surface texture is botryoidal-glassy to almost knotted. Also common is smooth, bulbous, and combinations of the three types. The glassy textures have several subvarieties and look like fresh glassy basalt flows. Maximum crust thickness is 30 mm, average 15 mm. 90% of rock covered by crust.	60% volcanic breccia, 30% muddy volcanic breccia, 10% basalt pebbles and small cobbles. The basalt cobbles are subrounded to angular clasts that were removed from the volcanic breccia during dredging—not from basalt outcrop on seafloor.
CD12	KE	17°06.28′ 17°07.97′	168°17.34′ 168°20.02′	2550- 2110	400	90	10	Surface texture irregular botryoidal to smooth. Maximum crust thickness ~50 mm, average ~25 mm. 80+% of rock covered by crust.	Dominantly volcanic breccia, 2 or 3 different types, like CD11. 30% subangular to rounded basalt cobbles, most of which are probably clasts from the breccias. Some calcareous mud coats the breccias. One large breccia boulder (~70 kg) is cemented by calcite pore fill (druzy calcite). Much secondary carbonate in the breccias. Breccias contain mudstone, porphyritic basalt, and phosphorite clasts.
CD13	J	16°26.2′ 16°25.2	169°31.4′ 169°32.9′	2700- <2100	500	70	25 nodules 5 other	Dominant surface texture is smoothed botryoidal, smooth to irregular; some botryoidal. Maximum crust thickness 70 mm, average 40 mm. 98% of rock covered by crust. 25% of total recovery is nodules, ranging from 5-100 mm in diameter.	Dominantly tuff or tuffaceous siltstone, highly altered, gray-green in color. Two volcanic breccia boulders and several cobbles broken from outcrop. One large almost complete silicosponge.

Table 2. Continued.

Dredge No.	Location	Latitude (°N)	Longitude (°W)	Water Depth (m)	Total Recovery (kg)	% Broken From Outcrop	% Talus	Description of Ferromanganese Oxides	Substrate Description
CD14	J	16°26.8′ 16°26.2′	169°32.3′ 169°33.6′	2390- 2290	545	40	60	Smooth to granular surface texture. Maximum crust thickness 60 mm, average 25 mm. 80% of rock covered by crust. <5% nodules present.	Dominant substrate is basalt, highly vesicular. Minor volcanic breccia and tuffaceous siltstone or tuff. Very large basalt boulders with variable crust thickness, very thick to thin.
CD15	J	16°25.0′ 16°24.9′	169°31.0′ 169°33.6′	2850- <2100	115	35	65	Surface texture small botryoidal. Maximum crust thickness 60 mm, average 20 mm. 90% of rock covered by crust. <5% nodules present.	Mudstone, basalt, greenish-gray tuffaceous siltstone and mudstone. One large vesicular, porphyritic basalt boulder.
CD16	J	16°26.4′ 16°25.27′	169°32.0′ 169°33.5′	2650- 2140	455	95	5	Surface texture smooth to smoothed botryoidal. Maximum crust thickness 120 mm, average 65 mm. 98% of rock covered by crust.	Highly altered reddish-brown and yellowish-brown volcanic breccia with phosphorite and manganese oxide veins, commonly mixed.
CD17	J	16°26.68′ 16°27.07′	169°32.07′ 169°32.59′	2620- 2460	775	75	25	Surface textures smooth and bulbous. Maximum crust thickness 70 mm, average 30 mm. 90+% of rock covered by crust. <5% nodules present.	Primarily moderately vesicular, strongly altered basalt. Also volcanic breccia, tuffaceous siltstone, phosphorite. Many bulbous cobbles that are either pure manganese or thick manganese surrounding breccia rich with phosphorite. Several varieties of volcaniclastic rocks.
CD18	J	16°25.6′ 16°25.8′	169°31.1′ 169°33.2′	2660- 2170	130	100	0	Surface texture smooth, also bulbous and rippled. Maximum crust thickness 60 mm, average 40 mm. 100% of rock covered by crust. 20% of dredge is manganese crust rubble.	Altered volcanic breccia and highly altered basalt. Very little substrate overall. One large boulder (0.5 m by 0.25 m) accounts for most of the substrate.
CD19	J	16°26.7′ 16°26.9′	169°32.0′ 169°33.6′	2880- 2380	25	80	20	Smooth and botryoidal surface textures. Maximum crust thickness 25 mm, average 10 mm. 80% or rock covered by crust. <10% nodules present.	Primarily limestone, minor volcanic breccia and basalt cobbles and pebbles. Limestone very poorly consolidated. Basalt highly vesicular. Volcanic breccia contains volcanic and limestone clasts, some with their own manganese coatings.
CD20	J	16°25.0′ 16°24.8′	169°31.5′ 169°31.9′	2610- 2340	70	>99	<1	Granular to smooth surface texture. Maximum crust thickness 15 mm, average 2 mm. 70% of rock covered by crust.	Volcanic breccia, two types: (1) brick-red clasts of altered basalt in yellowish-brown calcite (?) and clay cement, and (2) yellow, fine-grained altered volcanic debris in calcite cement. Two small basalt cobbles.
CD21	J	16°26.0′ 16°25.1′	169°31.0′ 169°30.9′	2890- 2350	570	85	15	Surface texture smooth undulatory to bulbous. Maximum crust thickness 130 mm, average 45 mm. 100% of rock covered by crust.	60% volcanic breccia, 40% basalt, some with amphibole phenocrysts. Few phosphorites. Many large slabs with coarse-grained breccia substrates.
CD22	J	16°25.5′ 16°26.0′	169°30.2′ 169°33.4′	>3100- 2290	12	100	0	Surface texture smooth to granular. Maximum crust thickness 60 mm, average 45 mm. 100% of rock covered by crust.	Gray basalt, some massive, some vesicular.
CD23	J	16°26.0′ 16°26.20′	169°31.06′ 169°33.75′	2740- 2290	230	85	15	Surface texture of 60% of crusts is botryoidal, 40% smooth. Maximum crust thickness 60 mm, average 30 mm. 100% of rock covered by crust.	Reddish-brown volcanic breccia. Highly vesicular basalt cobbles.

Table 2. Continued.

Dredge No.	Location	Latitude (°N)	Longitude (°W)	Water Depth (m)	Total Recovery (kg)	% Broken From Outcrop	% Talus	Description of Ferromanganese Oxides	Substrate Description
CD24	J	16°25.58′ 16°25.9′	169°30.9′ 169°33.1′	3160- 2250	155	90	10	Surface texture modified botryoidal, mushroom-type to smooth. Maximum crust thickness 65 mm, average 40 mm. 85% of rock covered by crust.	Dominant substrate type is reddish-brown volcanic breccia. One small boulder of yellowish-brown volcanic breccia. Relatively fresh gray basalt cobble.
CD25	J	16°26.0′ 16°26.7′	169°32.3′ 169°33.0′	2320- 2450	550	80	20	Dominant surface texture is smooth. Some smoothed botryoidal. Maximum crust thickness 90 mm, average 45 mm. 90% of rock covered by crust.	Dominantly gray slightly vesicular, aphyric basalt. Basalt breccia. One large boulder is a slab with 9-cm-thick crust.
CD26	J	16°25.6′ 16°25.2′	169°27.8′ 169°32.8′	>3100- ~2100	600	80	20	Surface textures are irregular porous, smooth, and bulbous. Maximum crust thickness 60 mm, average 30 mm. 100% of rock covered by crust. <1% nodules—manganese cobbles with manganese nuclei.	Basalt is dominant. Three or four types of volcanic breccia. Phosphorite. Six large boulders and slabs, five with basalt substrate and one with volcanic breccia substrate.
CD27	KS	Lost Dredge Bag							
CD28	KS	16°39.6′ 16°40.3′	168°11.6′ 168°10.5′	1950- 2210	40	100	0	Surface texture granular rippled to granular bulbous. Maximum crust thickness 95 mm, average 45 mm. 100% of rock covered by crust.	Basalt.
CD29	KS	16°41.7′ 16°43.1′	168°14.5′ 168°14.0′	1950- 2400	295	95	5	Surface texture rippled botryoidal. Maximum crust thickness 160 mm, average 75 mm. 100% of rock covered by crust.	Volcanic breccia and highly vesicular basalt with calcite lining vesicles and fractures.
CD30	KS	16°33.19′ 16°33.47′	168°16.83′ 168°16.38′	3050- 1920	220	60	40	Surface textures are granular, irregular, and botryoidal. Maximum crust thickness 70 mm, average 15 mm. 90% of rock covered by crust.	Primarily porphyritic basalt and basaltic flow breccia containing highly vesicular basaltic clasts.

[1]CD = USGS circular chain-bag dredge
BMDS = Bureau of Mines dredge sled
JOD = Japanese oval dredge
JTD = Japanese toothed dredge

[2]J = south Johnston Island ridge
KW = west-central Karin Ridge
KE = east-central Karin Ridge
KS = south Karin Ridge

[3]Water depth is for dredge on and off bottom. The shallowest depth in each pair is taken from Figures 2 and 3 and deepest from Table 3. Figures 2 and 3 were constructed from bathymetric surveys of the area with the closest track-line spacing for the area of Figure 2. The depths from Table 3 were those recorded using satellite navigation and 3.5 and 12 kHz seismic recorders during the dredging operation.

Table 3. Summary of ferromanganese crusts recovered from south Johnston Island ridge and Karin Ridge, R/V *Farnella* cruise F7-86-HW.

Dredge Number	Water Depth[1]	Water Depth[2]	Total Recovery (kg)	Crust Recovery (kg)	Percent Crust	Maximum Thickness (mm)	Average Thickness (mm)	Dominant Substrate	Location
CD1	2255(?)-2200	?	725	70	10	50	10	Basalt, limestone	KE
CD2	2900-2650	?	500	100	20	110	50	Volcanic breccia	J
BMDS3	2700-2340	2460-2340	20	10	50	25?	10?	Basalt?	J
JOD4	3175-3200*	3175-2430	70	35	50	30	20	Volcanic breccia	J
CD5	2750-2350	2750	200	40	20	100	45	Mudstone	J
CD6	2300-2150	2240-2150	365	40	11	60	28	Volcanic breccia, basalt, mudstone	KW
CD7	3100-1990	2340-2120	270	35	13	72	35	Mudstone, basalt, volcanic breccia	KW
CD8	2675-1685	1910-1850	30	10	33	70	40	Basalt	KW
JTD9	2980-2600	2910-2260	450	100	22	70	40+	Mudstone, basalt	KW
JOD10	2830-2160	2830-2160	20	5	25	50	30	Volcanic breccia, basalt	KW
CD11	2530-2240	2530-2240	300	50	17	30	15	Volcanic breccia	KE
CD12	2550-2110	2280-2100	400	70	18	~50	~25	Volcanic breccia	KE
CD13	2310-2140	2310-2140	500	140	28	70	40	Tuff, siltstone	J
CD14	2370-2340	2370-2340	545	60	9	60	25	Basalt, volcanic breccia, tuff	J
CD15	2350-2250	2350-2250	115	25	22	60	20	Mudstone, basalt	J
CD16	2650-2520	2540-2520	455	150	33	120	65	Volcanic breccia	J
CD17	2620-2600	2620-2315	775	125	16	70	30	Basalt, volcanic breccia	J
CD18	2560-2420	2560-2420	130	40	31	60	40	Volcanic breccia, basalt	J
CD19	2880-2530	2530-2430	25	10	40	25	10	Limestone	J
CD20	2340-2100	2280-2070	70	5	7	15	2	Volcanic Breccia	J
CD21	2775-2350	2775-2370	570	180	32	130	45	Volcanic breccia, basalt	J
CD22	2630-2320	2430-2340	12	3	25	60	45	Basalt	J
CD23	2740-2340	2370-2340	230	50	22	60	30	Volcanic breccia	J
CD24	2380-2290	2380-2290	155	30	19	65	40	Volcanic breccia	J
CD25	2450-2320	2450-2320	550	115	21	90	45	Basalt	J
CD26	2440-2220	2350-2220	600	90	15	65	30	Basalt	J
CD27	Lost Dredge Bag		—	—	—	—	—	—	—
CD28	2210-1950	2210-2070	40	22	55	95	45	Basalt	KS
CD29	2400-1950	2390-2290 and 2120-1970	295	193	65	160	75	Volcanic breccia, basalt	KS
CD30	2000-1920	1950-1920	220	30	14	70	15	Basalt, volcanic breccia	KS
Total	—	—	8637	1833	26 (ave.)	—	—	—	—

* Went up and over a hill
J = south Johnston Island ridge
KE = east-central Karin Ridge
KW = west-central Karin Ridge
KS = south Karin Ridge
CD = USGS circular chain-bag dredge
BMDS = Bureau of Mines dredge sled
JOD = Japanese oval dredge
JTD = Japanese toothed dredge

[1]Water depth of dredge on and off bottom as determined from 3.5 and 12 kHz seismic recorders and satellite navigation.

[2]Depth interval samples were probably recovered from as determined by 3.5 and 12 kHz seismic recorders at the times of high tensiometer readings on the wire.

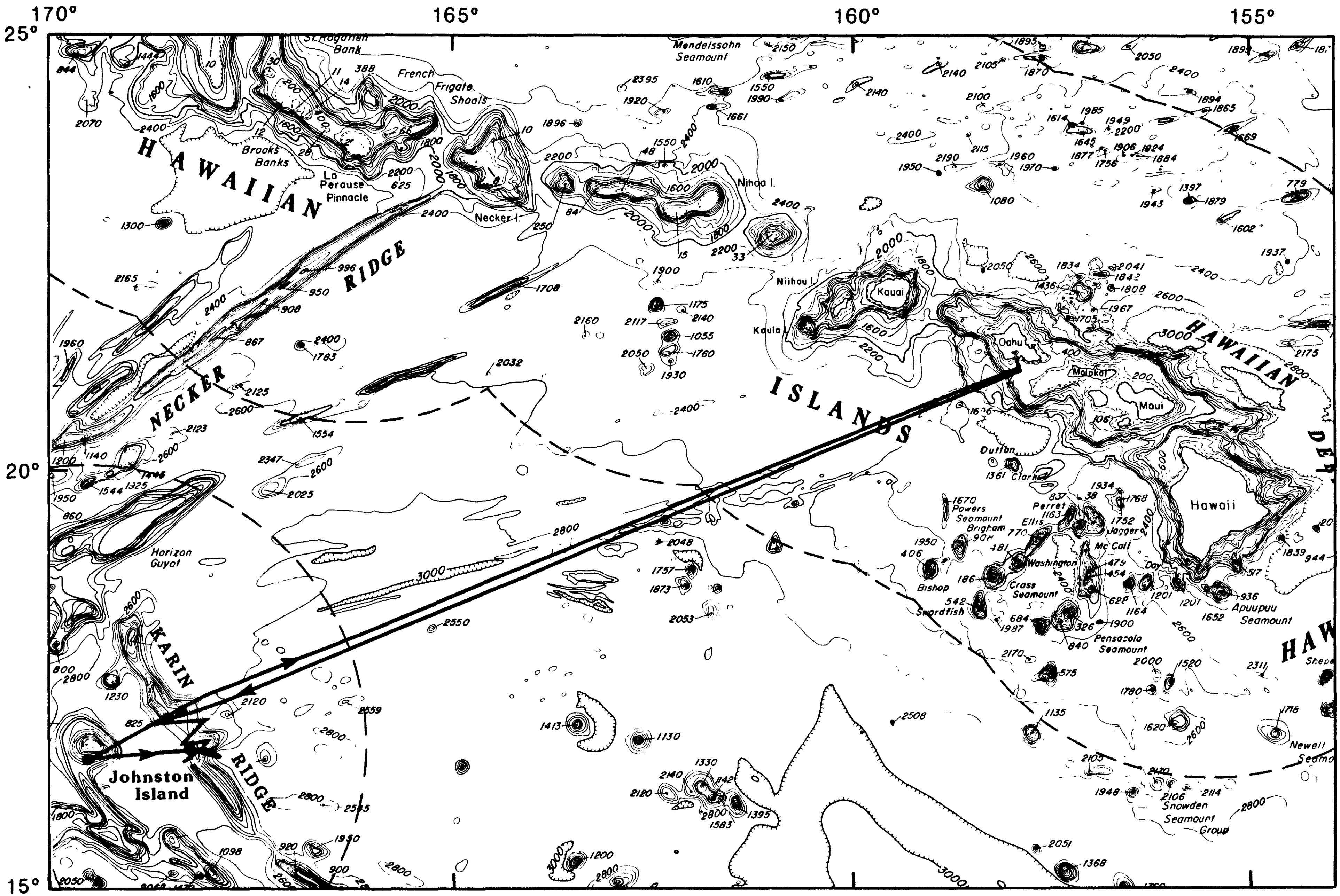
Table 4. Chemical composition of representative splits of homogenized dredge hauls, substrates plus crusts, R/V *Farnella* cruise F7-86-HW. Elements and oxide are in weight percent.

Dredge No.	Dry Weight (gms)	Mn	Co	Ni	Cu	P_2O_5	Ti	Location
CD1	402.6	4.2	0.168	0.1	0.02	4.06	1.11	KE
CD2	428.8	10.8	0.38	0.26	0.07	5.95	1.08	J
CD5	138.8	10.2	0.28	0.19	0.06	3.6	1.5	J
CD6	357.6	5.6	0.17	0.116	0.04	2.69	1.74	KW
CD7	418.6	5.2	0.18	0.102	0.04	2.4	1.74	KW
CD8	31.6	8.4	0.34	0.22	0.04	9.36	0.892	KW
JTD9	308.6	6	0.178	0.11	0.05	1.6	1.37	KW
CD11	397.6	2.6	0.094	0.05	0.02	1.97	1.59	KE
CD12	706.4	3	0.124	0.06	0.02	2.07	1.73	KE
CD13	858.8	12	0.34	0.24	0.07	4.43	1.36	J
CD14	540.8	2	0.076	0.042	0.02	3.45	2.59	J
CD15	204.8	5.6	0.14	0.136	0.04	3.55	1.17	J
CD16	399.4	15.6	0.48	0.3	0.10	3.89	0.965	J
CD17	733	4.8	0.166	0.106	0.04	3.51	2.09	J
CD18	218	6.4	0.24	0.128	0.05	3.42	1.99	J
CD19	21.2	5.6	0.186	0.116	0.03	8.43	0.981	J
CD20	52.6	1.2	0.052	0.054	0.03	2.22	1.65	J
CD21	938.2	5.6	0.186	0.116	0.04	4.53	0.915	J
CD22	28	6	0.24	0.118	0.03	4.24	0.87	J
CD23	326	7.2	0.24	0.144	0.06	4.18	1.4	J
CD24	196.6	5.8	0.138	0.106	0.05	4.59	0.947	J
CD26	1332	3.6	0.132	0.076	0.03	4.63	0.845	J
CD26[1]	29.8	1.8	0.058	0.052	0.02	26.7	0.206	J
CD29	193.8	10.2	0.34	0.26	0.07	5.95	0.917	KS
CD30	135.2	2.2	0.092	0.056	0.02	7.8	1.25	KS

Mn, Co, Ni, and Cu analyzed by atomic absorption, P_2O_5 analyzed by molybdenum vanadate colorimetric method, and Ti analyzed by induction-coupled plasma emission spectroscopy. All analyses by Bureau of Mines. Analysts were Carl Paystrup (Mn, Cu), Merle Shurtz (Co, Ni), Dwight Hammargren (P_2O_5), and William Lockman (Ti).

[1] phosphorite-rich zone from CD26.

J = south Johnson Island ridge
KE = east-central Karin Ridge
KW = west-central Karin Ridge
KS = south Karin Ridge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HAWAIIAN RIDGE
NECKER RIDGE
HAWAIIAN ISLANDS
KARIN RIDGE
Johnston Island
French Frigate Shoals
Brooks Banks
La Perouse Pinnacle
Necker I.
Nihoa I.
Niihau I.
Kaula I.
Kauai
Oahu
Molokai
Maui
Hawaii
Mendelssohn Seamount
Horizon Guyot
Dutton
Clark
Powers Seamount
Brigham
Ellis
Perret
Jagger
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Washington
Day
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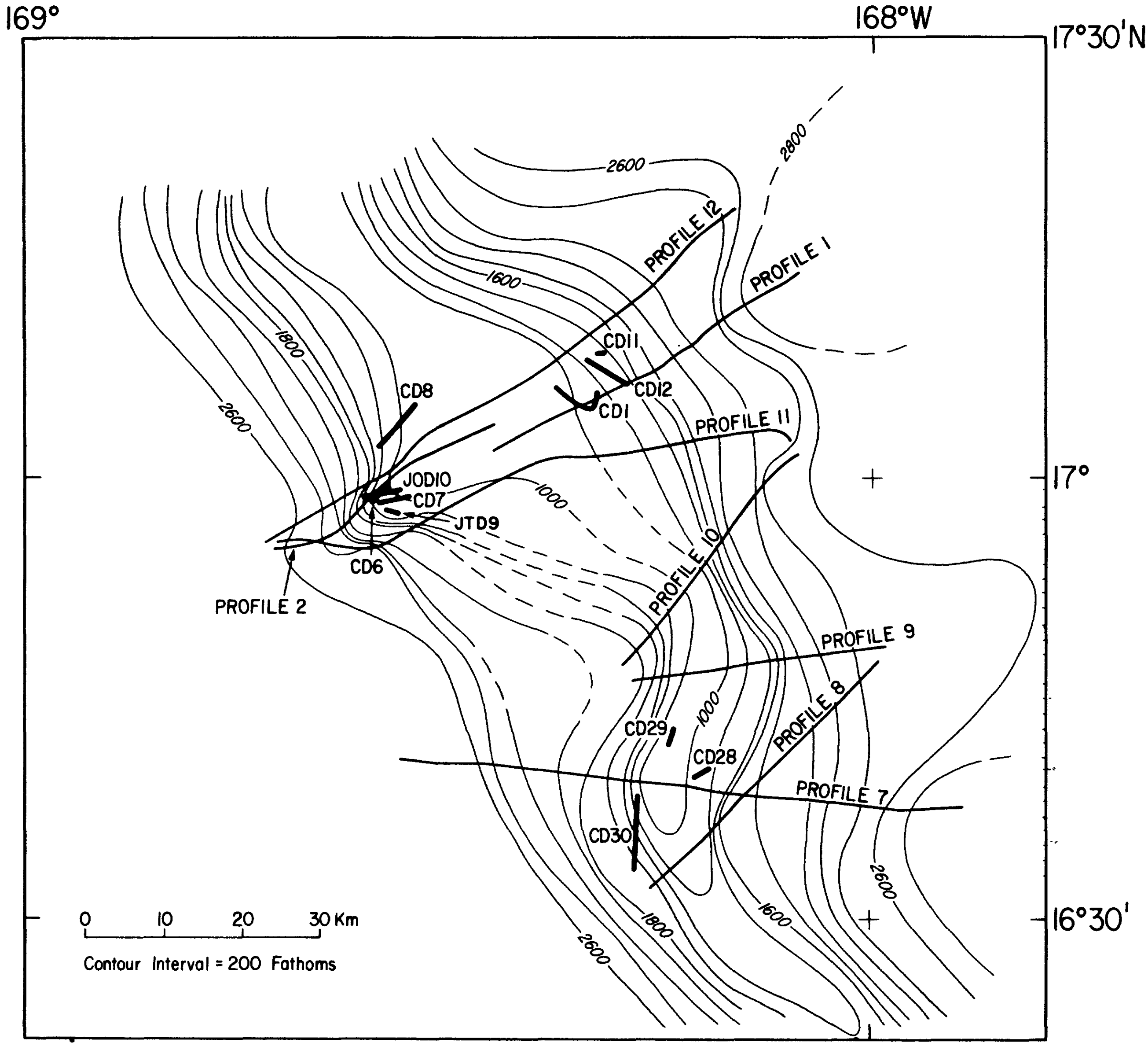
Bishop
Swordfish
Pensacola Seamount
Apuupuu Seamount
Snowden Seamount Group
Newell Seamount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PROFILE 12
PROFILE 1
PROFILE 11
PROFILE 10
PROFILE 9
PROFILE 8
PROFILE 7
PROFILE 2
CD11
CD12
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CD8
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CD7
JTD9
CD6
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CD28
CD30
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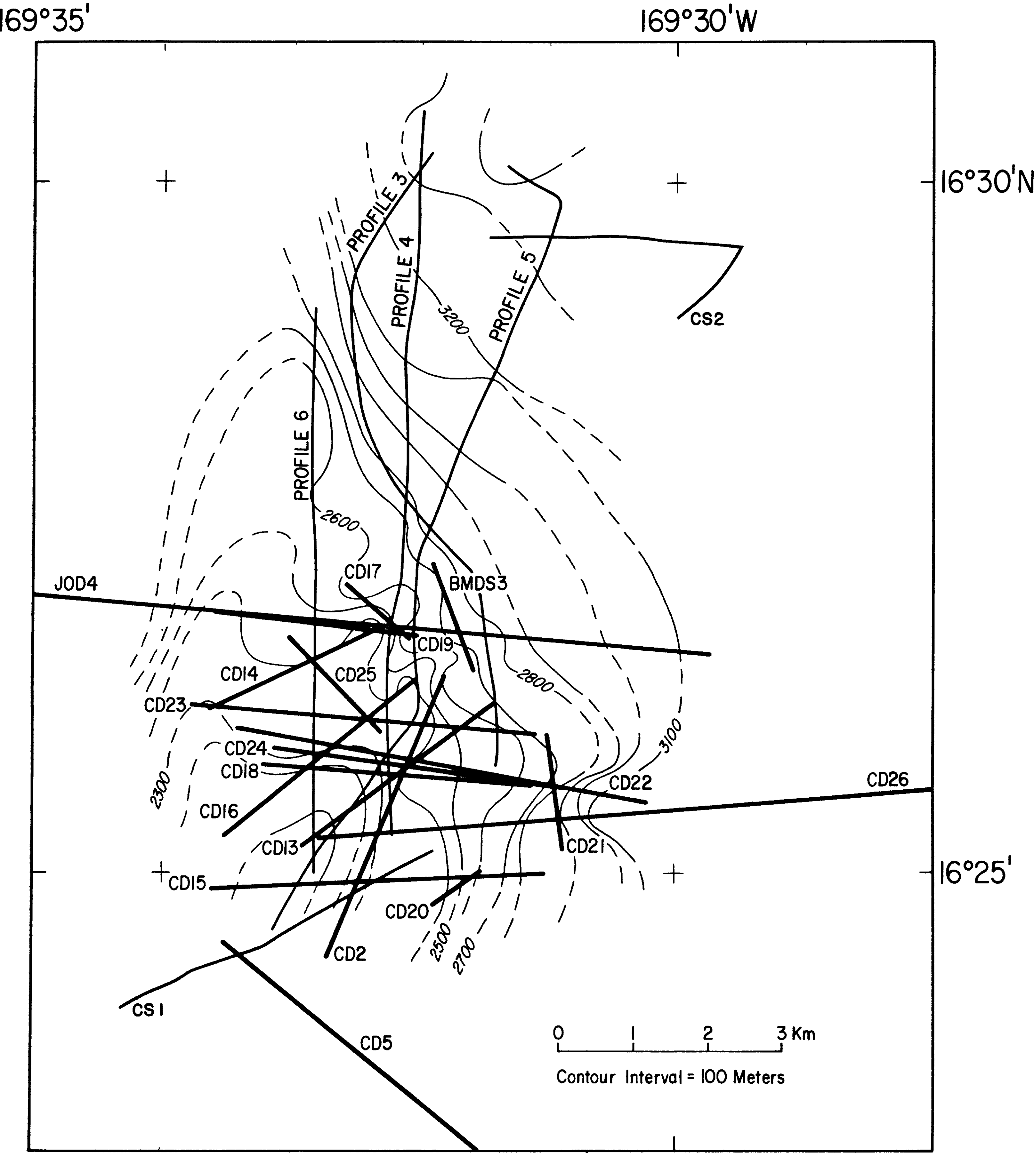
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PROFILE 5
PROFILE 6
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BMDS3
CD19
CD14
CD25
CD23
CD24
CD18
CD16
CD13
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1
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3 Km
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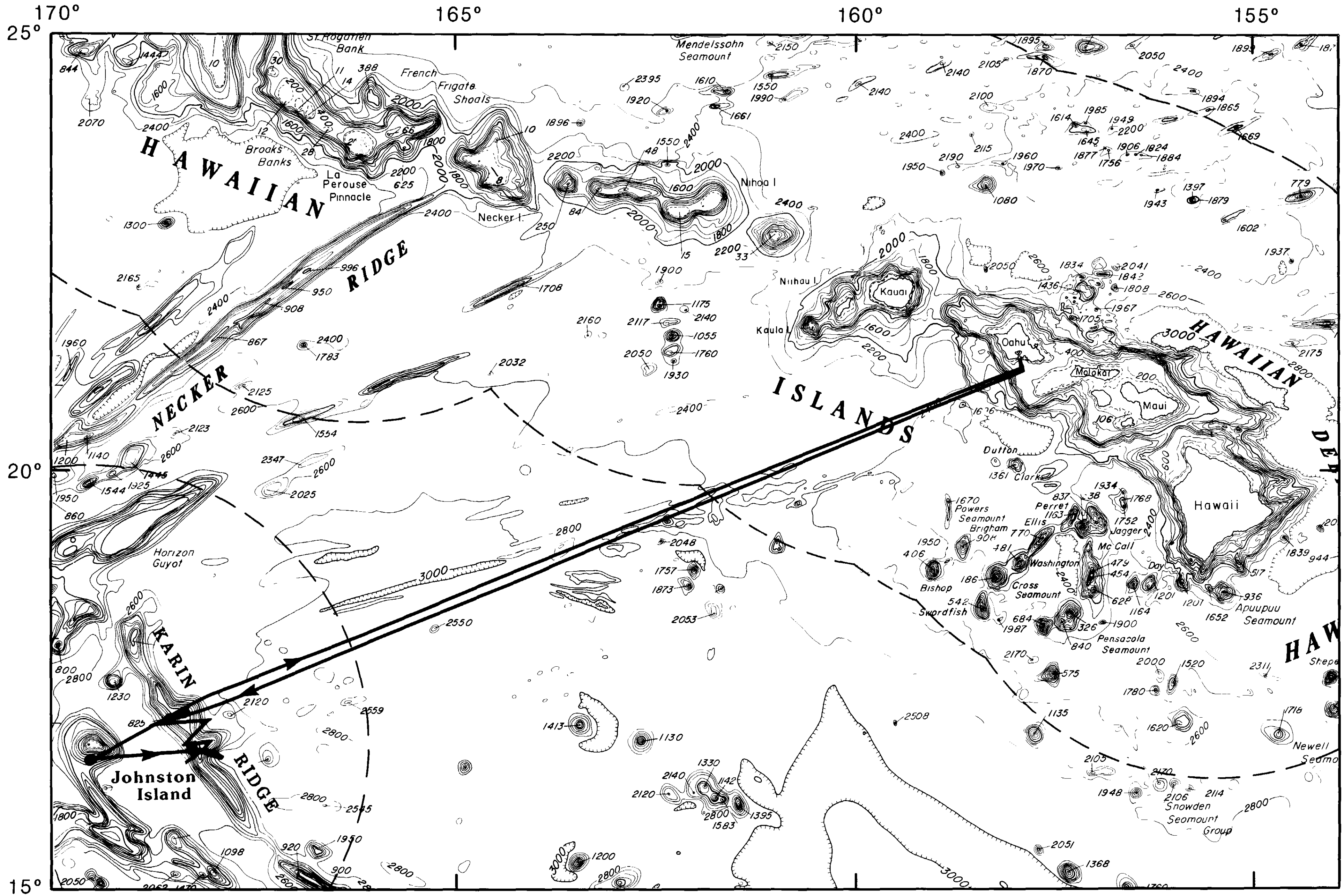
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ISLANDS
HAWAIIAN
NECKER
RIDGE
KARIN
RIDGE
Johnston Island
Horizon Guyot
St. Rogatien Bank
French Frigate Shoals
Brooks Banks
La Perouse Pinnacle
Necker I.
Nihoa I
Mendelssohn Seamount
Niihau I.
Kauai
Kaula I.
Oahu
Molokai
Maui
Hawaii
Dutton
Clark
Powers Seamount
Brigham
Ellis
Perret
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Bishop
Swordfish
Day
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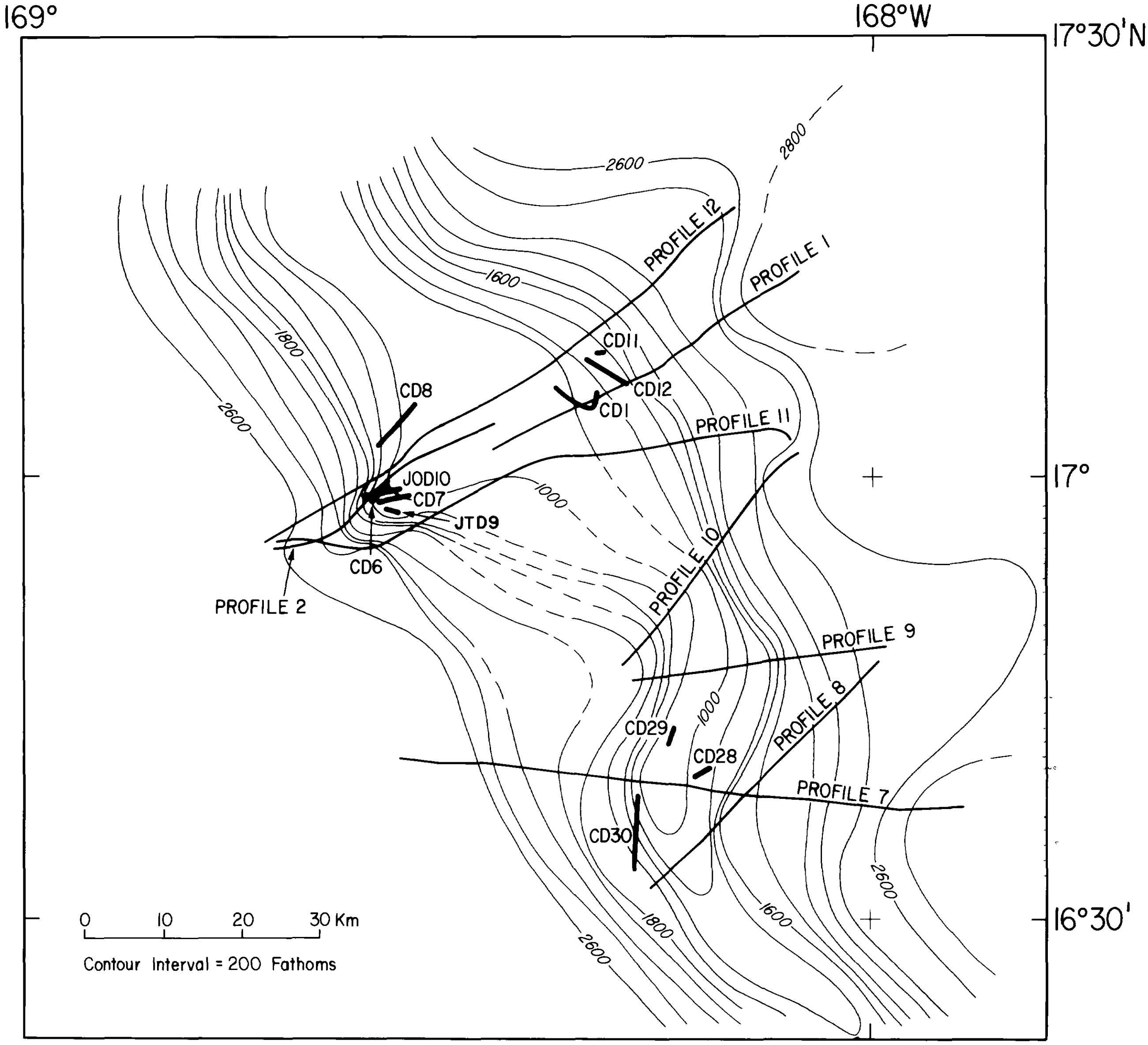
Apuupuu Seamount
Snowden Seamount Group
Newell Seamo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2600
PROFILE 12
PROFILE 1
CD11
CD12
CD1
CD8
PROFILE 11
JOD10
CD7
JTD9
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PROFILE 10
PROFILE 9
PROFILE 8
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CD28
PROFILE 7
CD30
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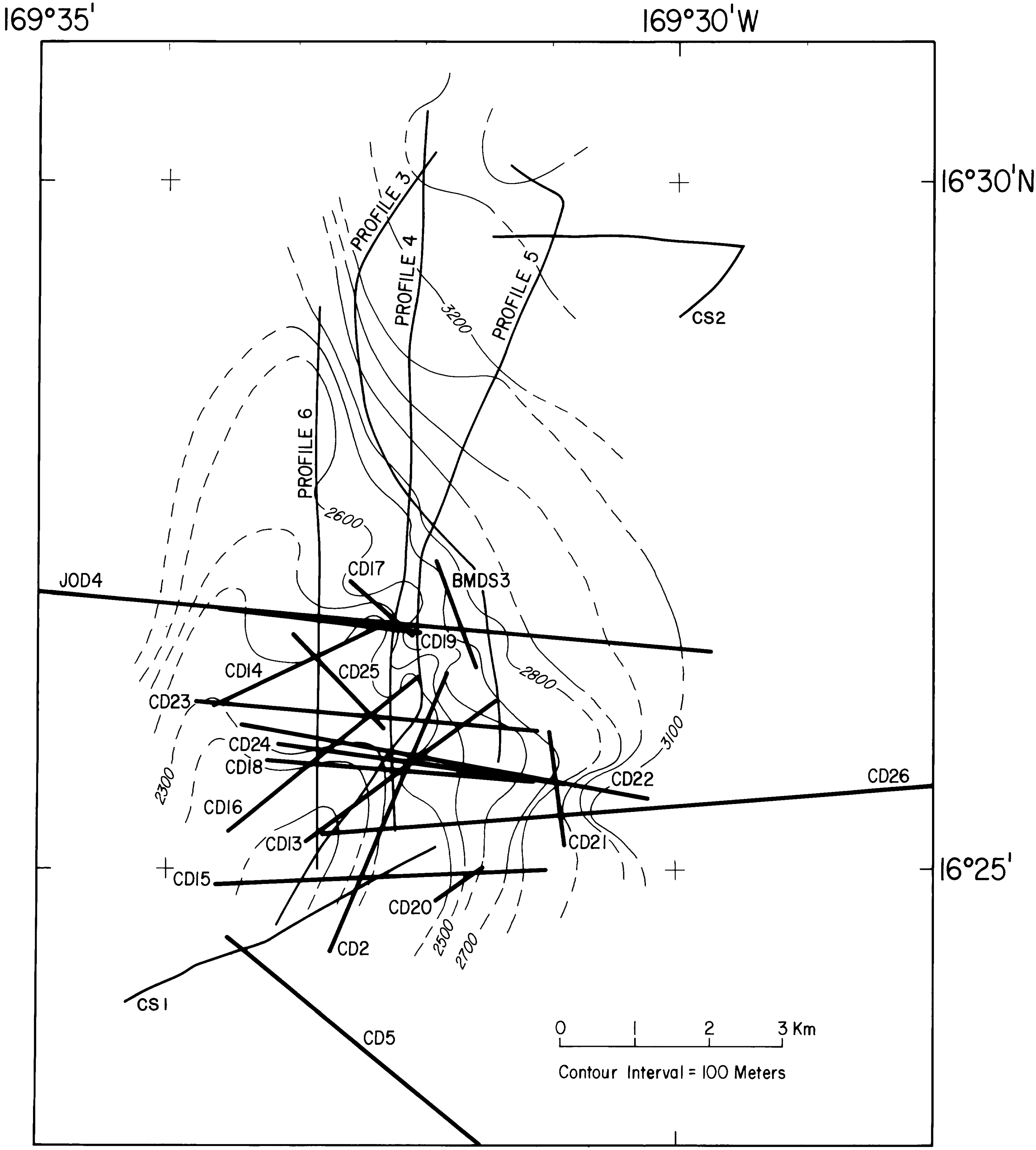
Contour Interval = 200 Fathoms



169°35'
169°30'W
16°30'N
16°25'
PROFILE 3
PROFILE 4
PROFILE 5
PROFILE 6
CS2
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2600
CD17
BMDS3
JOD4
CD19
CD14
CD25
2800
CD23
CD24
CD18
CD22
CD26
3100
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CS1
CD5
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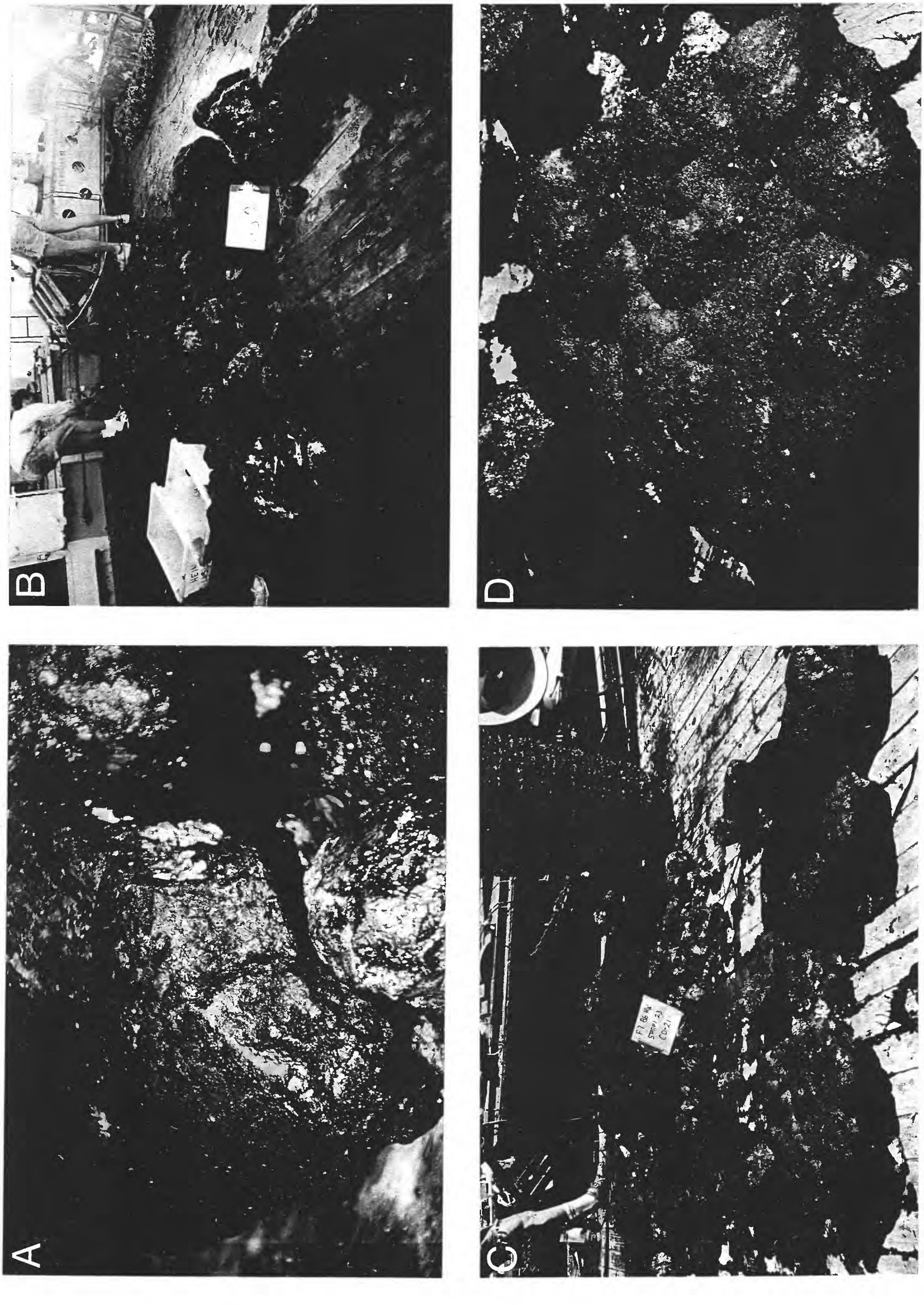
Contour Interval = 100 Meters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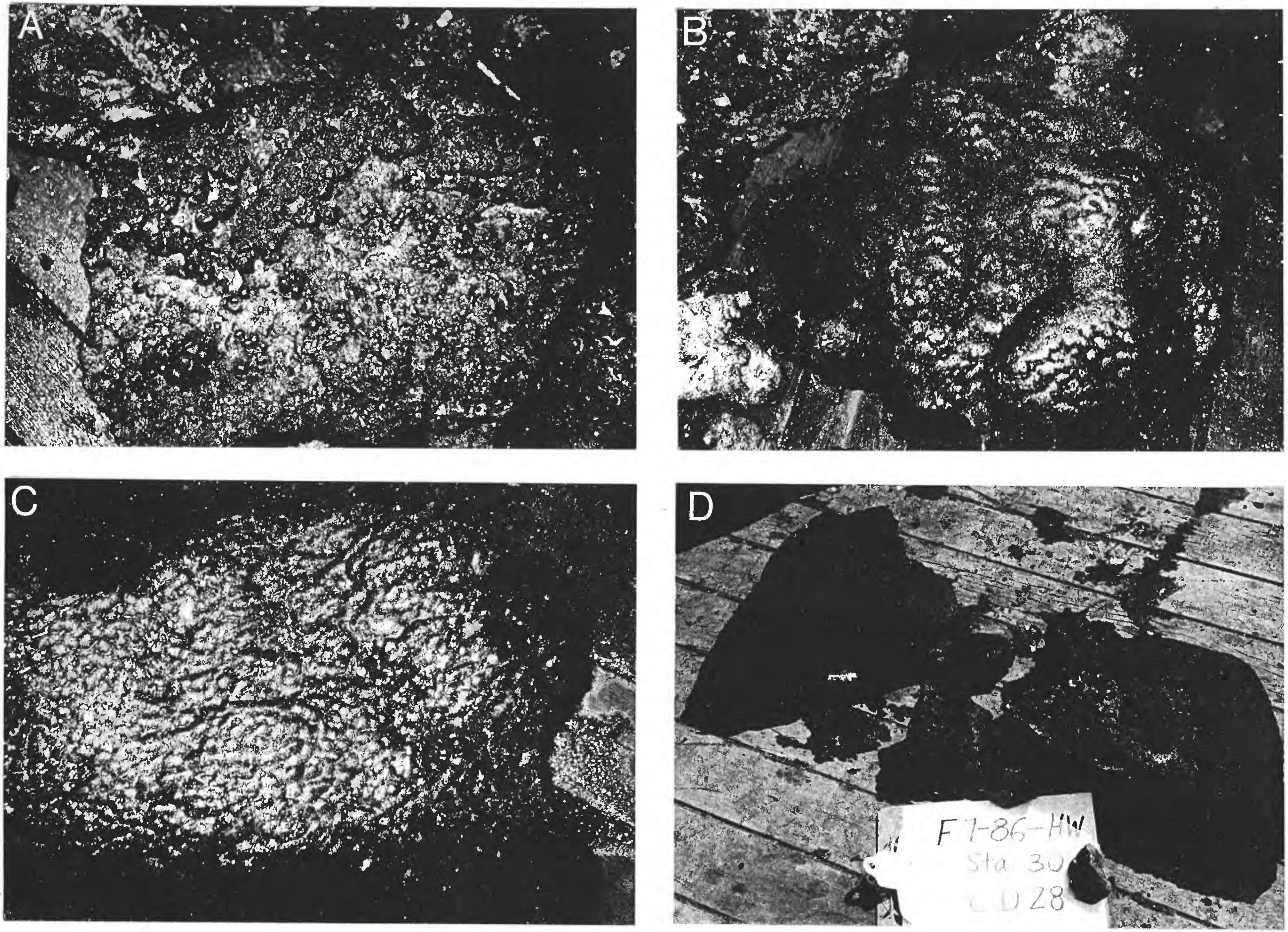
B
C
D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B
C
D
F7-86-HW
Sta 30
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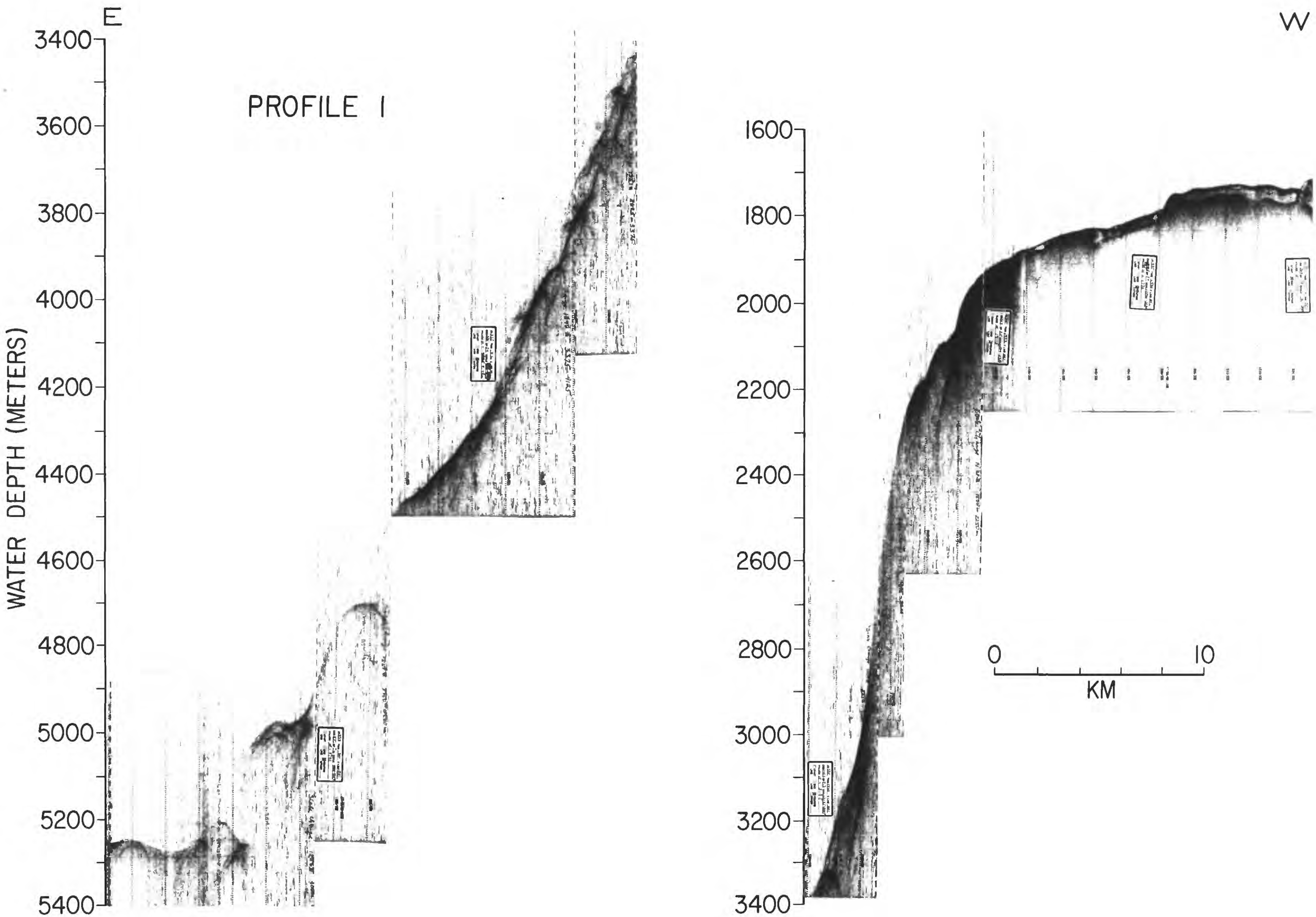

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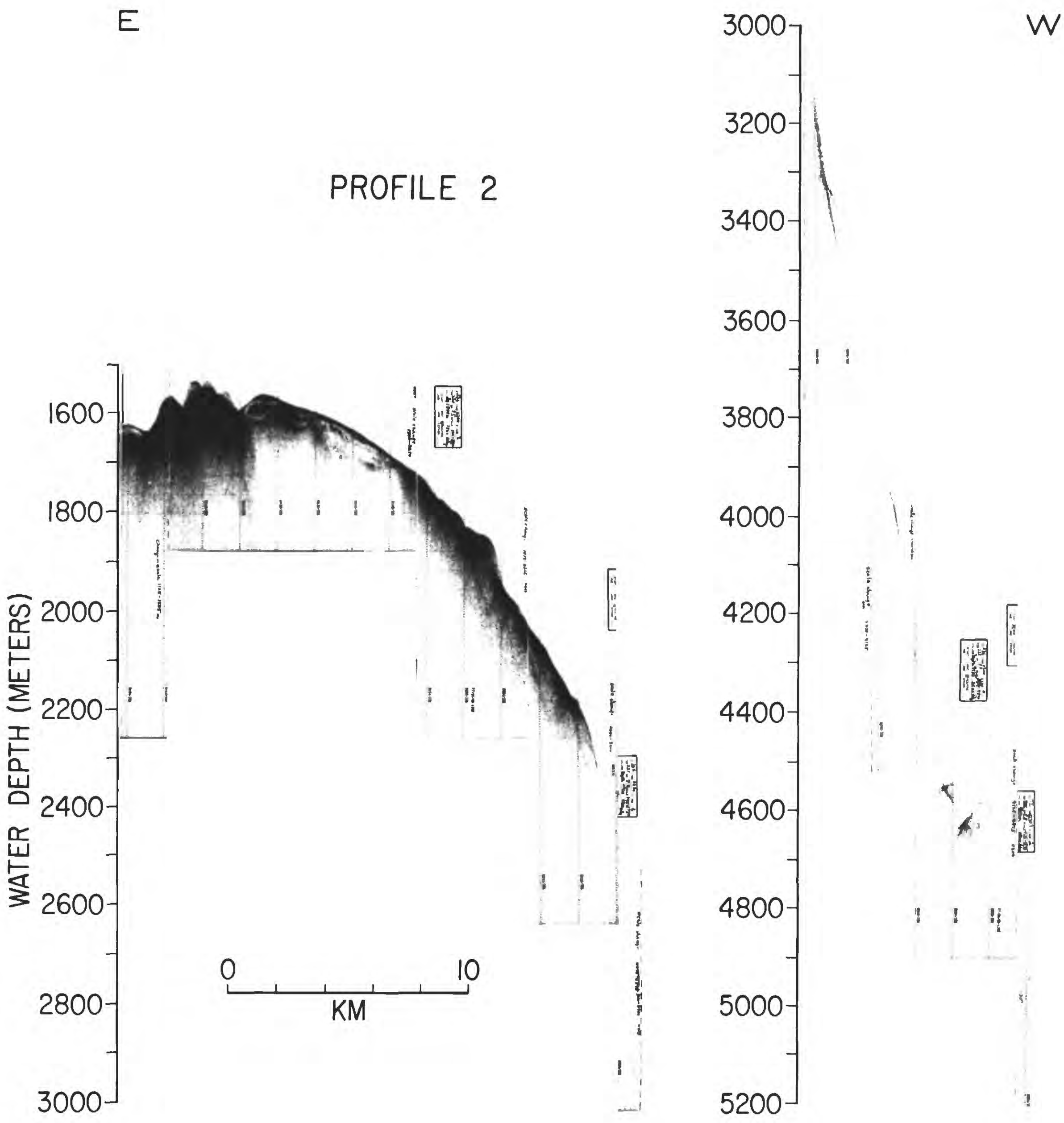
3400
0
10
KM



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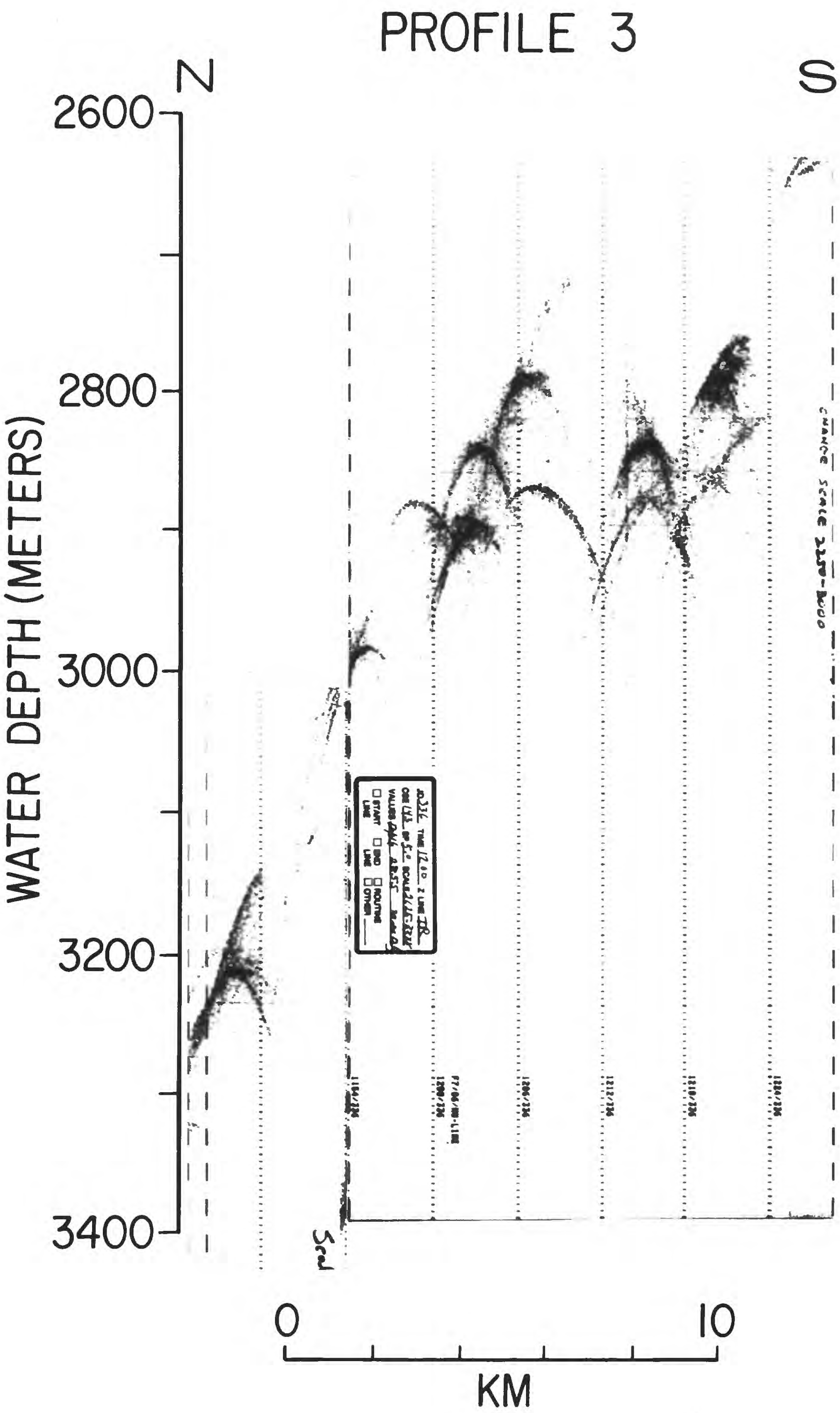

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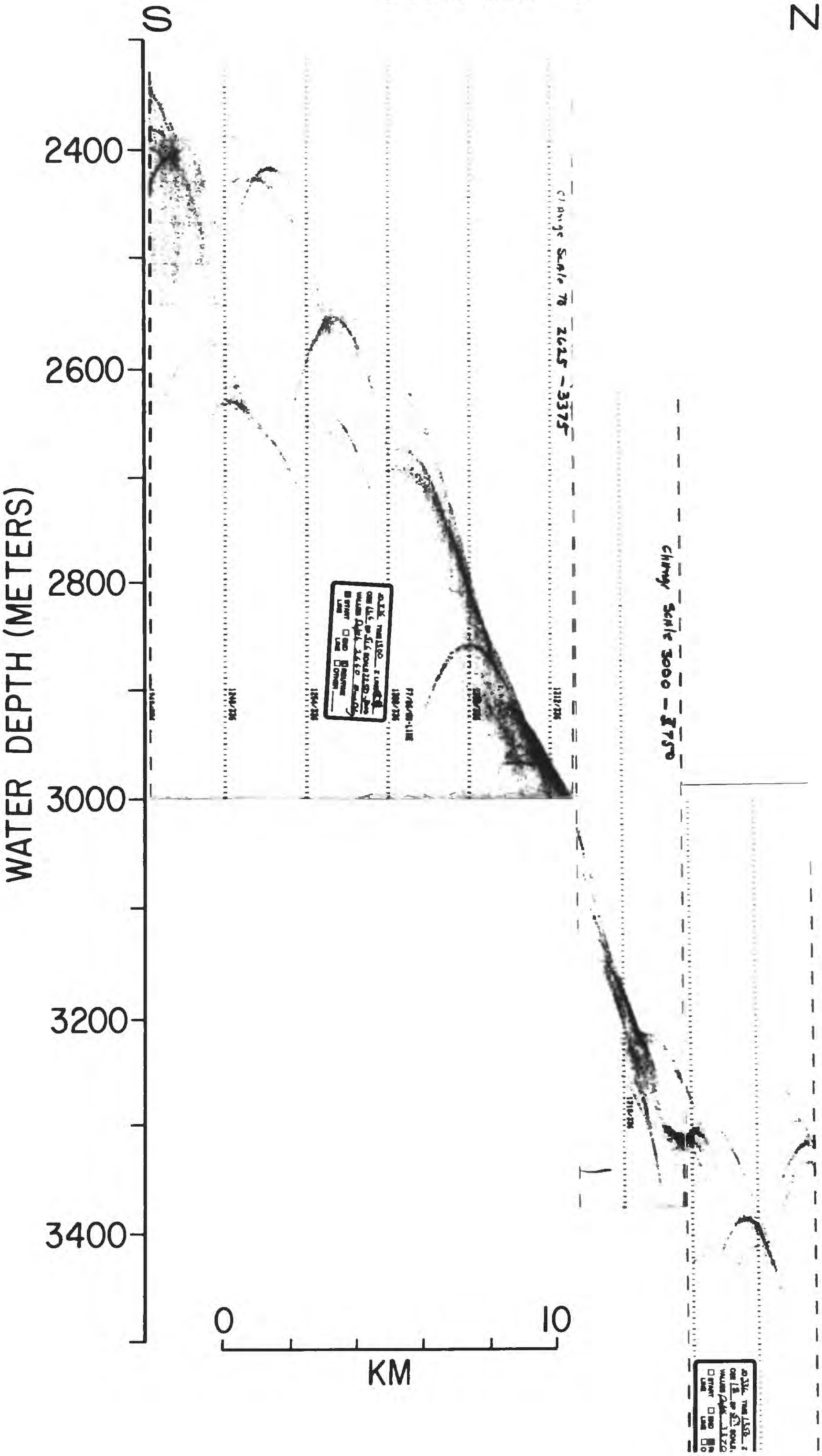
PROFILE 4



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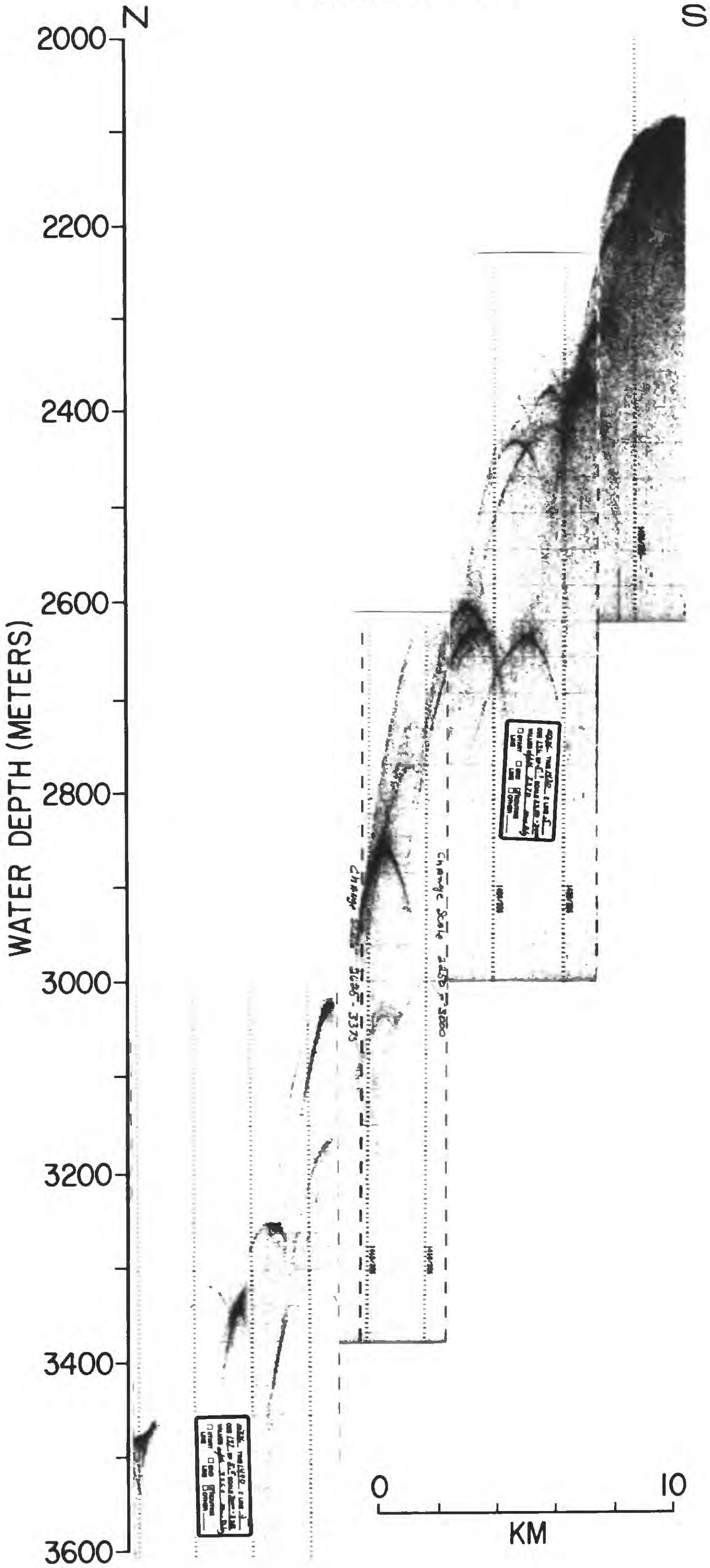
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3600
WATER DEPTH (METERS)
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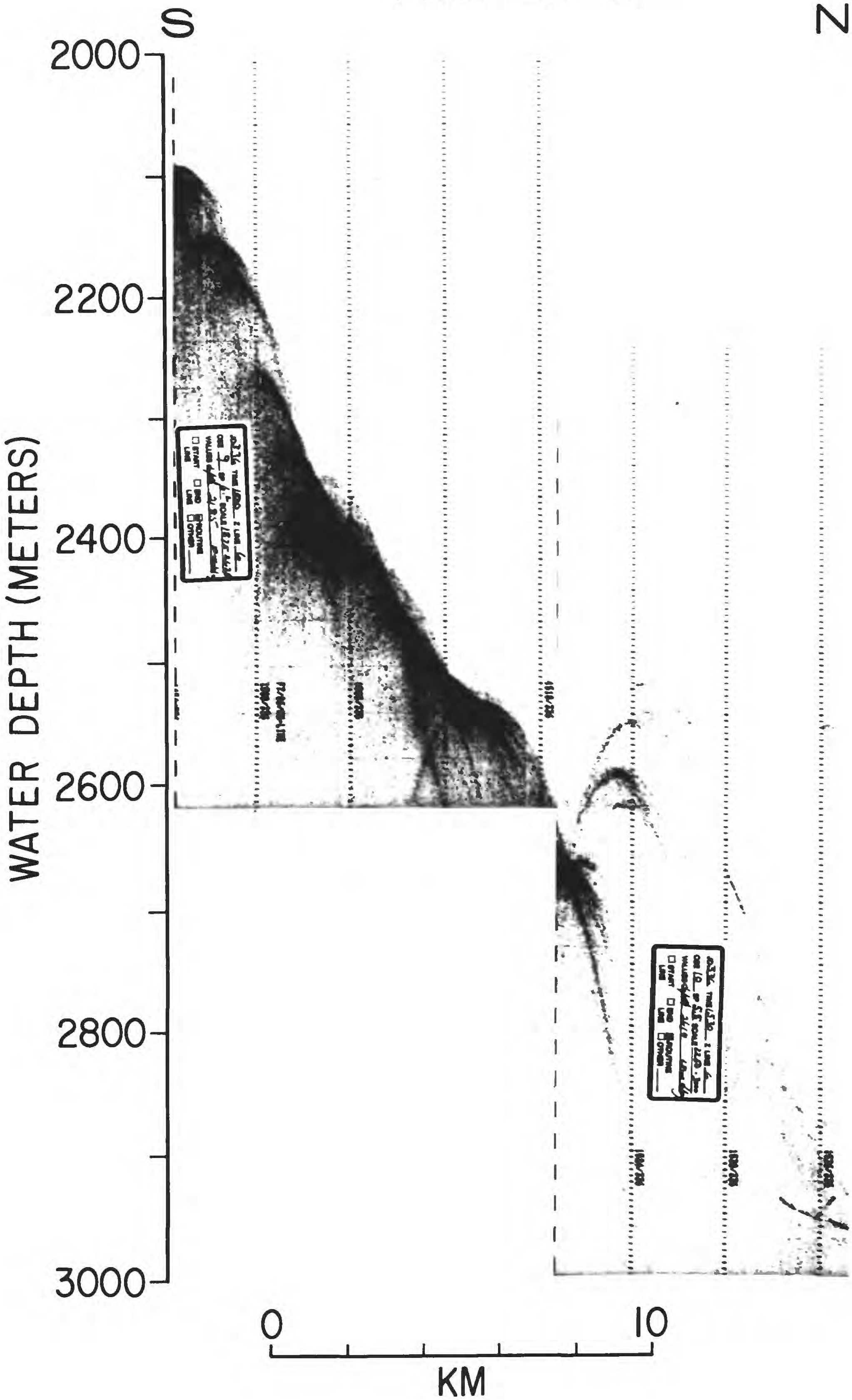
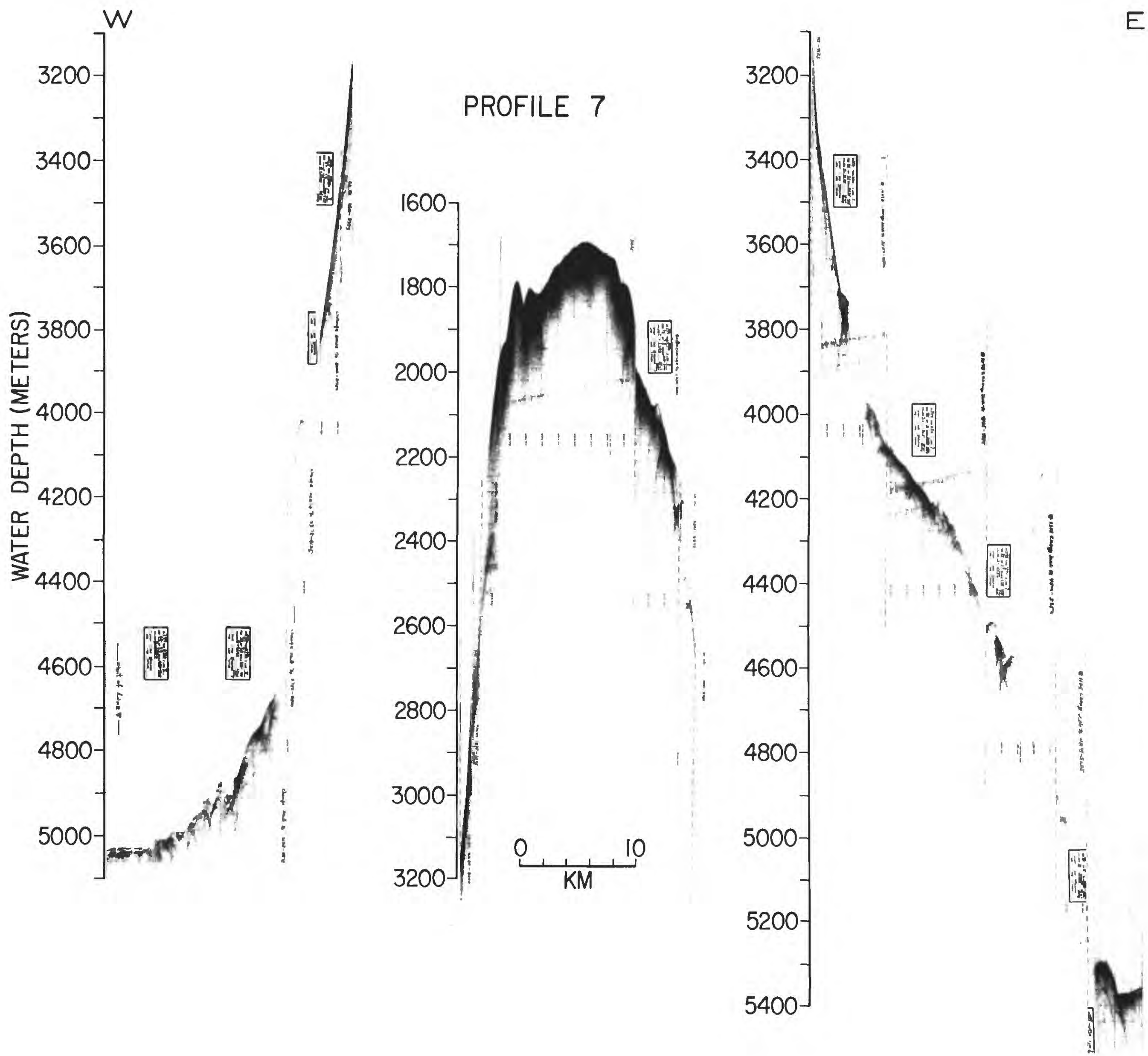
10
KM

PROFILE 6





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3000
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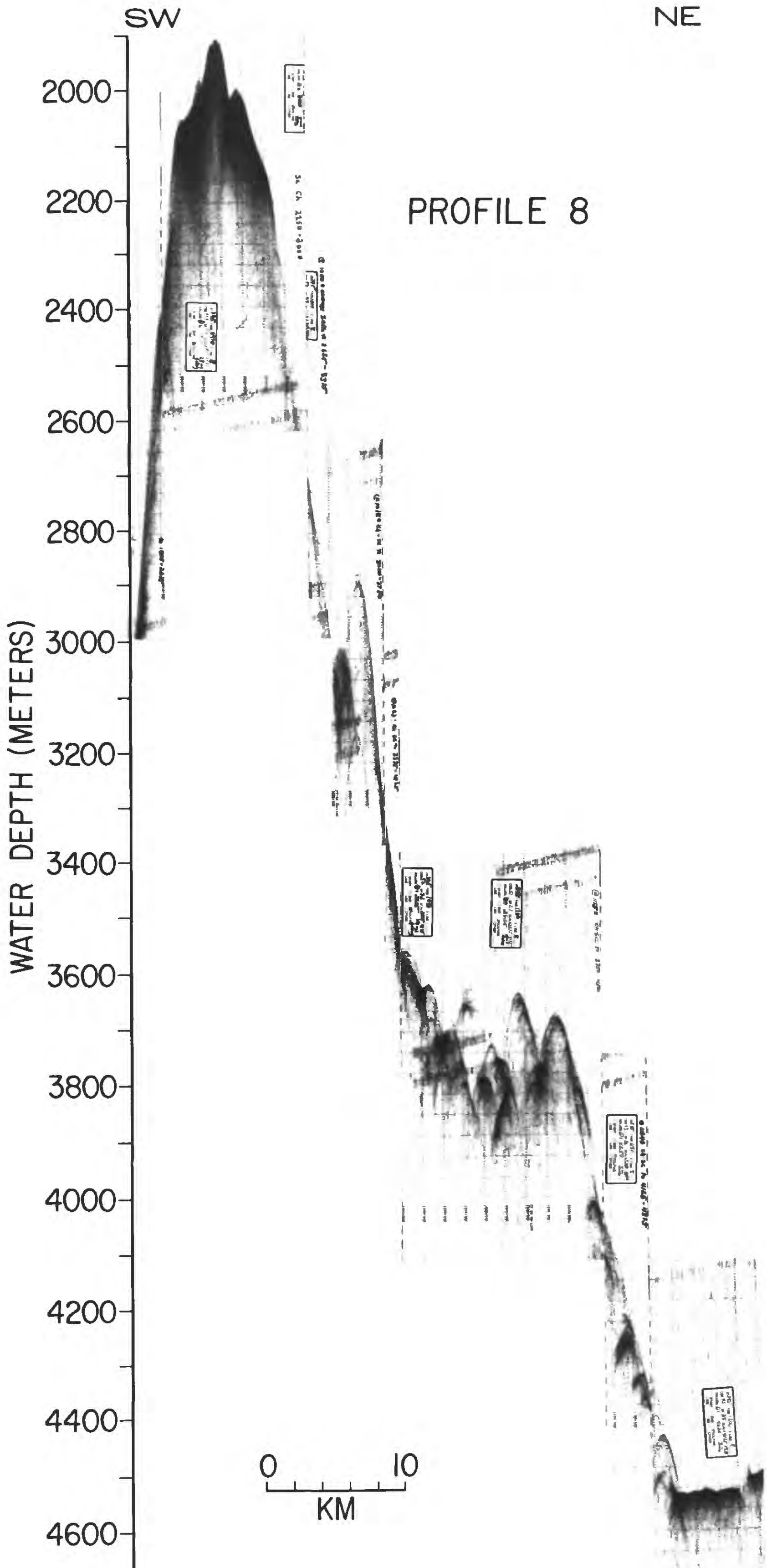
5400
0
10
KM



SW
NE
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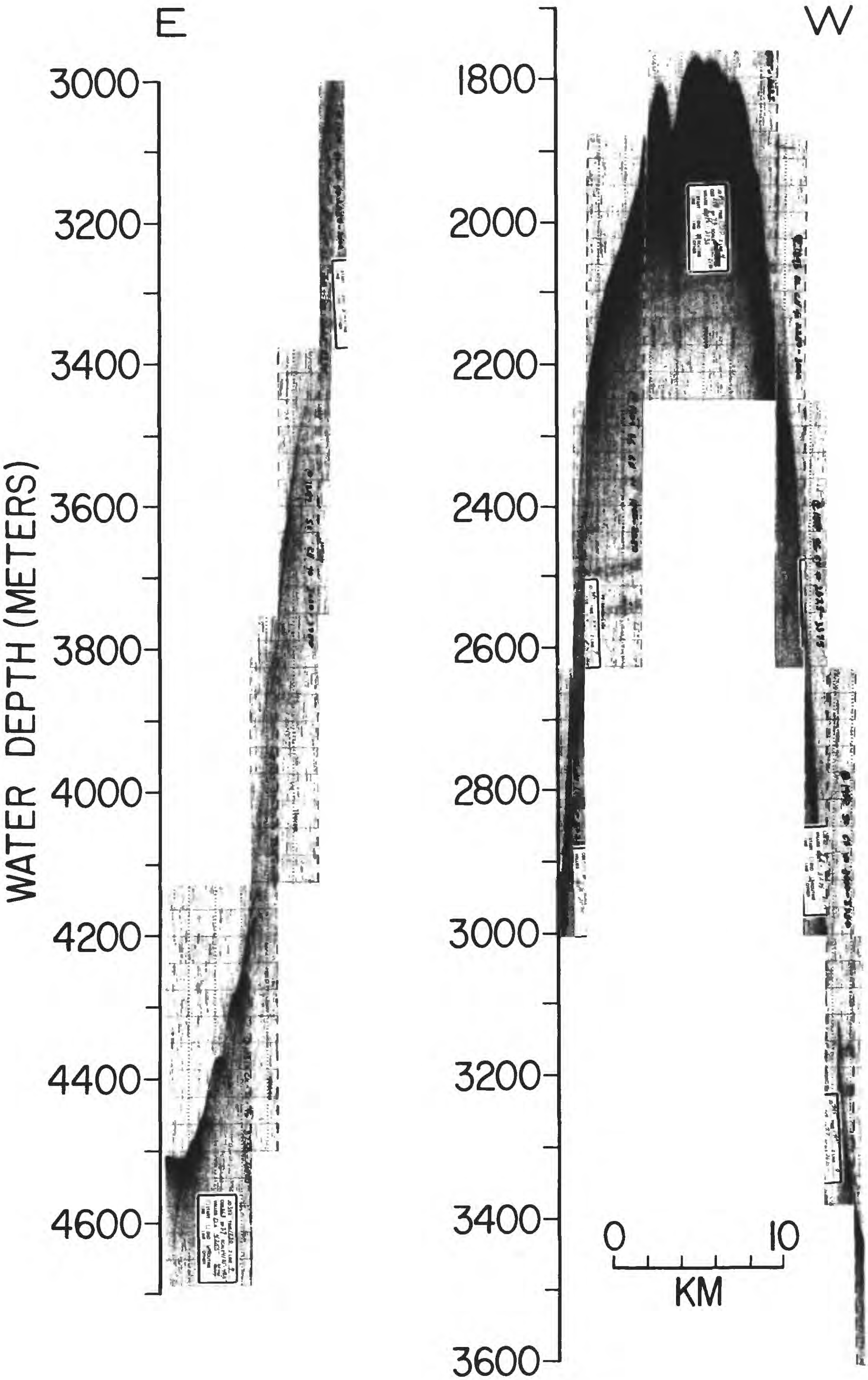
0
10
KM

PROFILE 9



E
W
WATER DEPTH (METERS)
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3600
3800
4000
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2400
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3600
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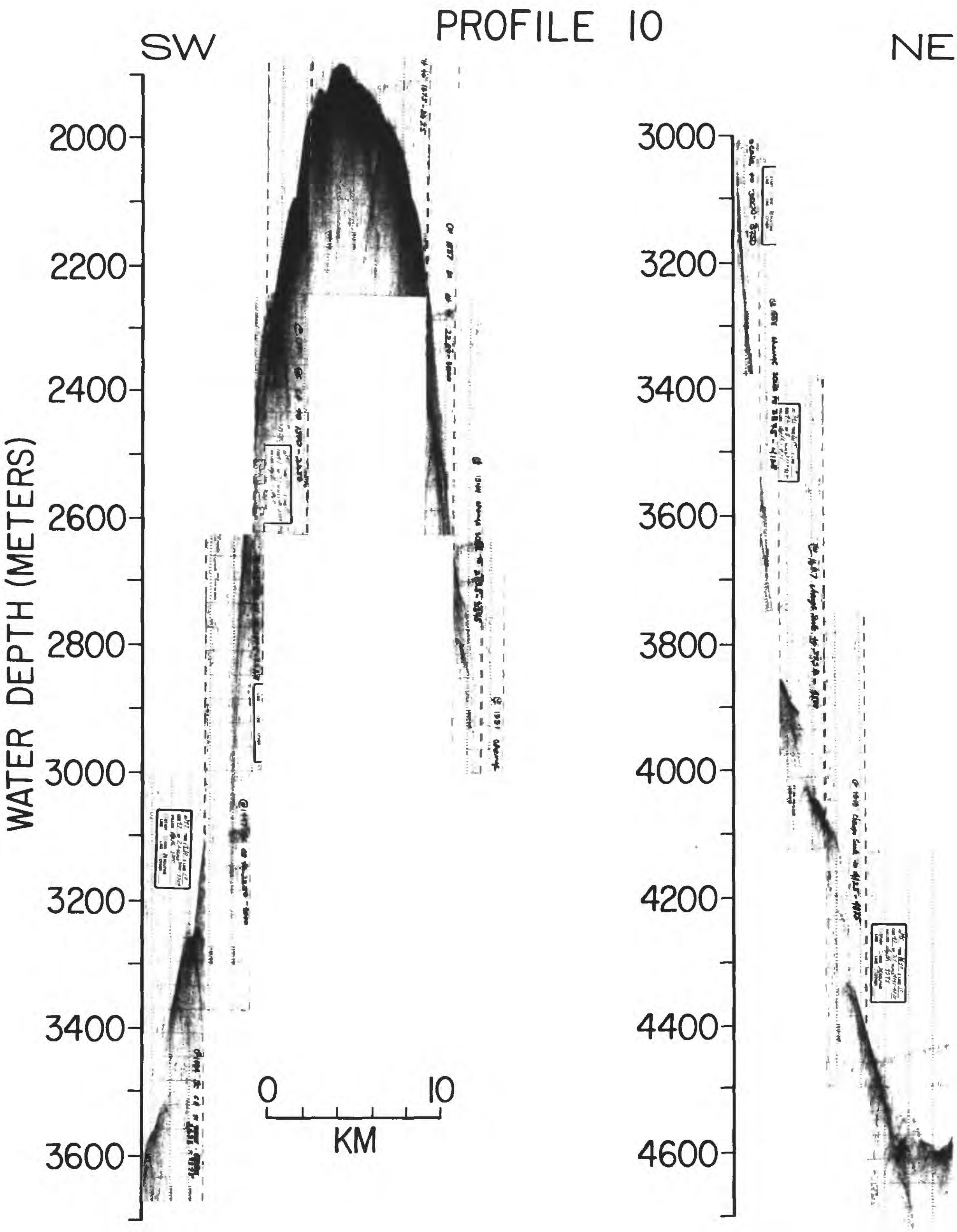
10
KM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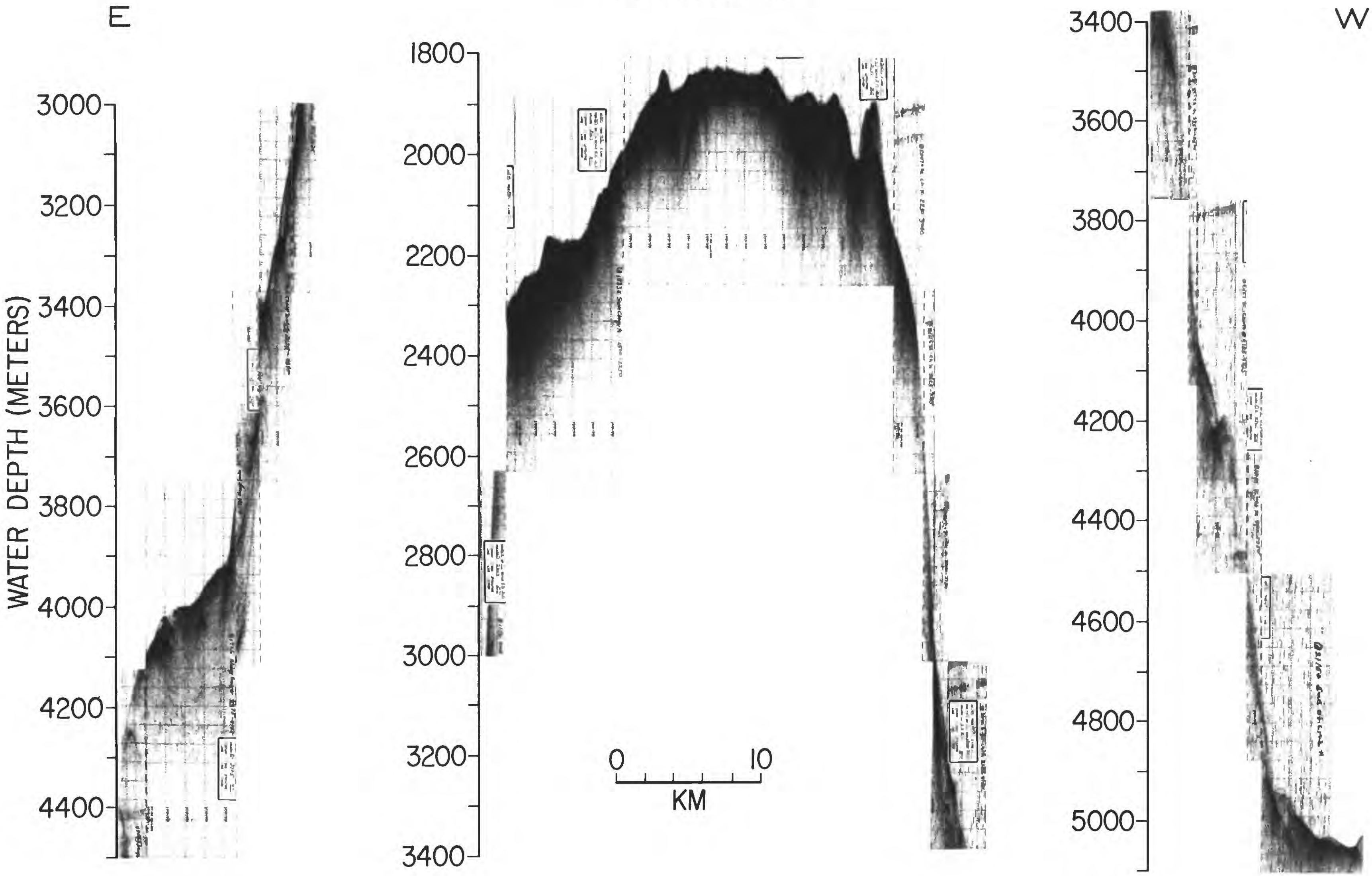
10
KM

PROFILE 11


E
W
WATER DEPTH (METERS)
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1800
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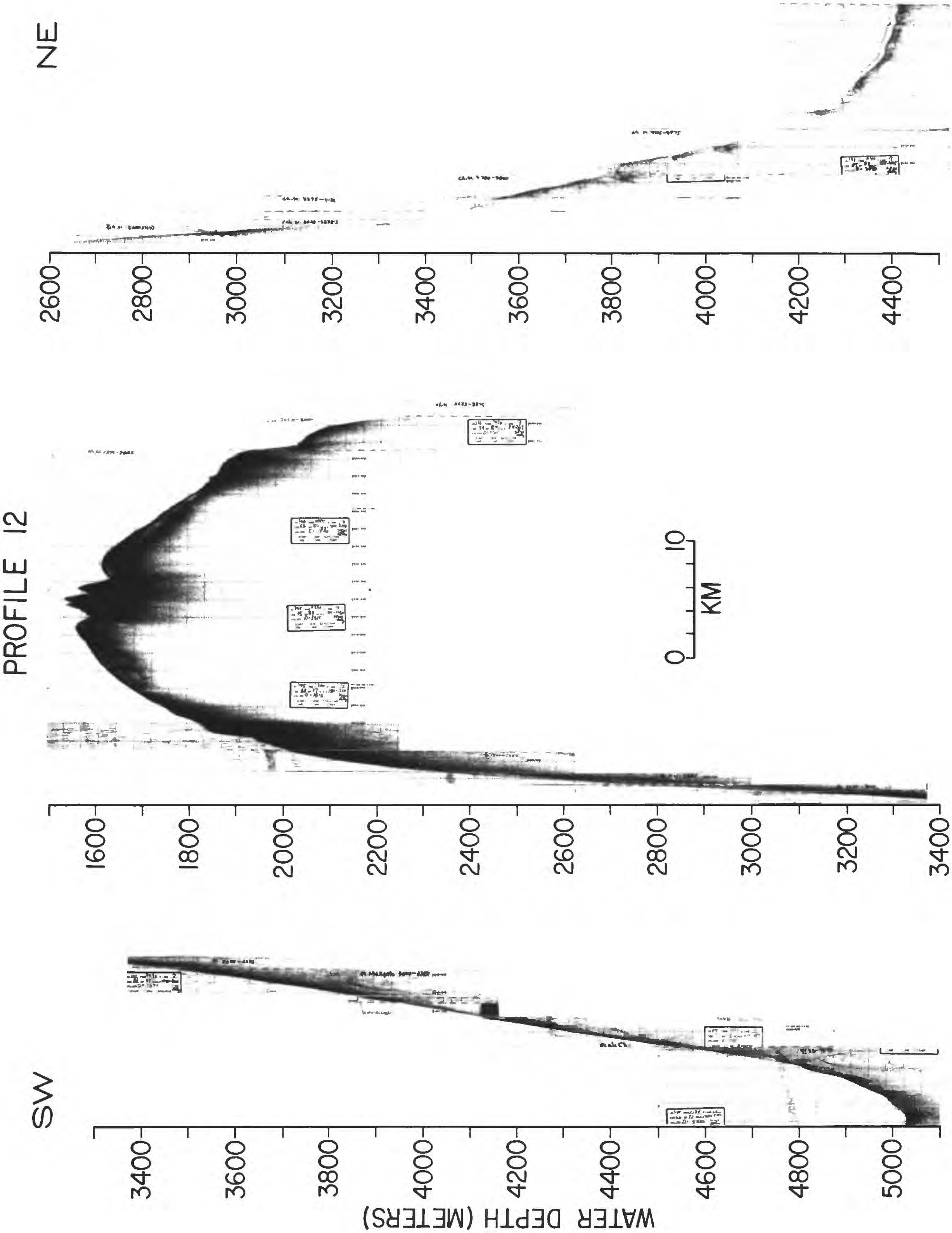
4800
5000
0
10
KM



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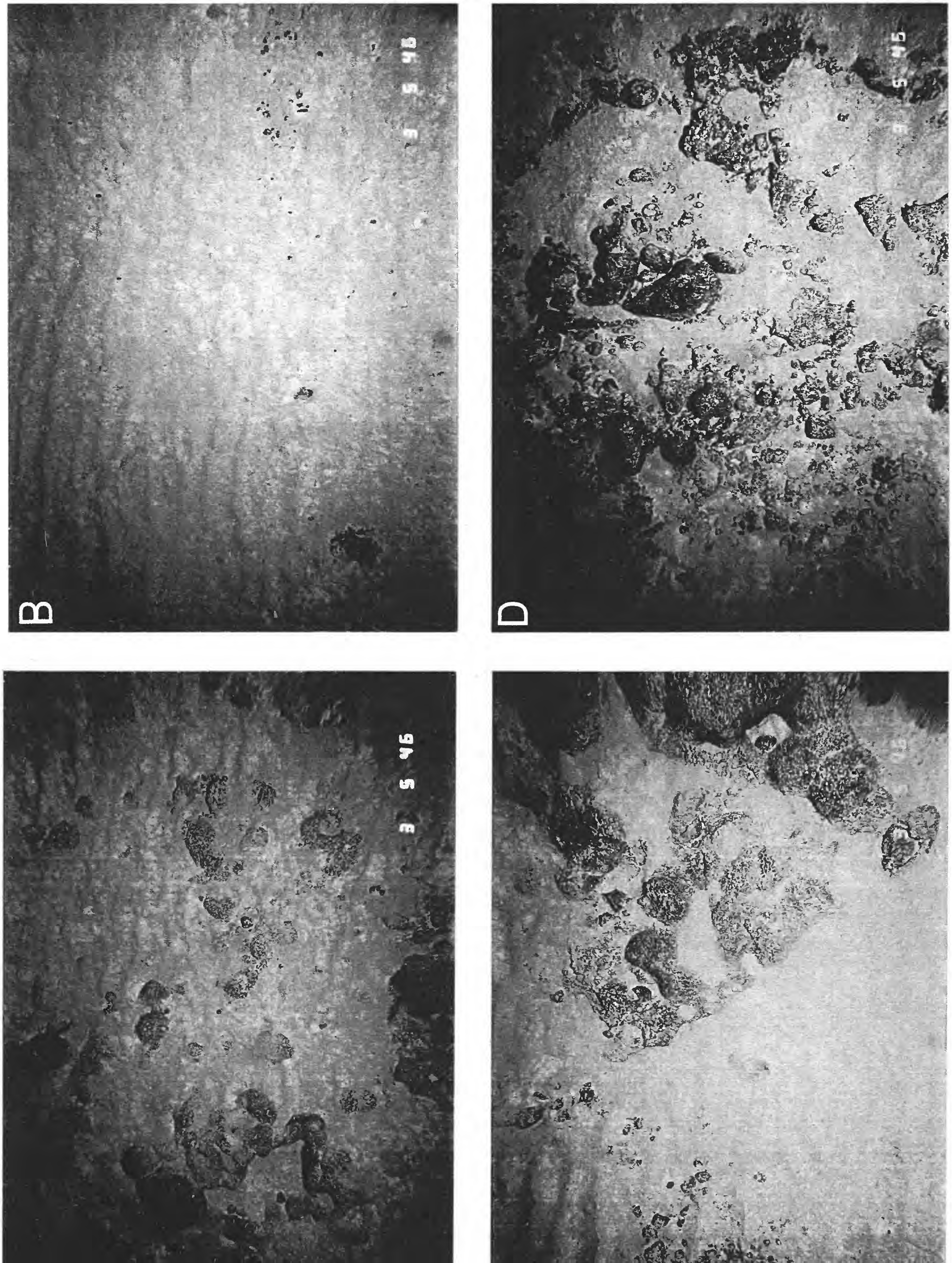
2600
2800
3000
3200
3400
2600
2800
3000
3200
3400
3600
3800
4000
4200
4400
0
10
KM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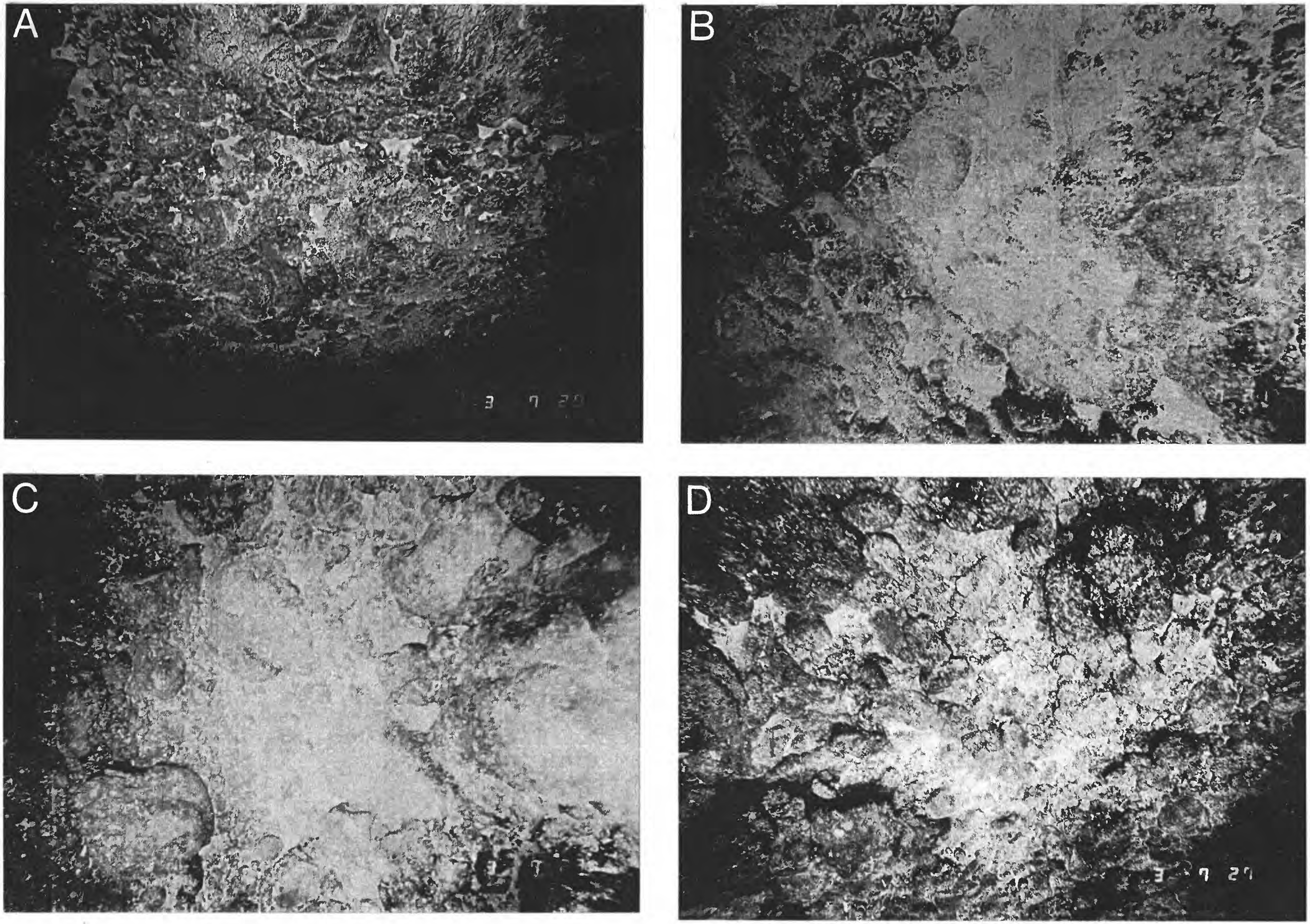
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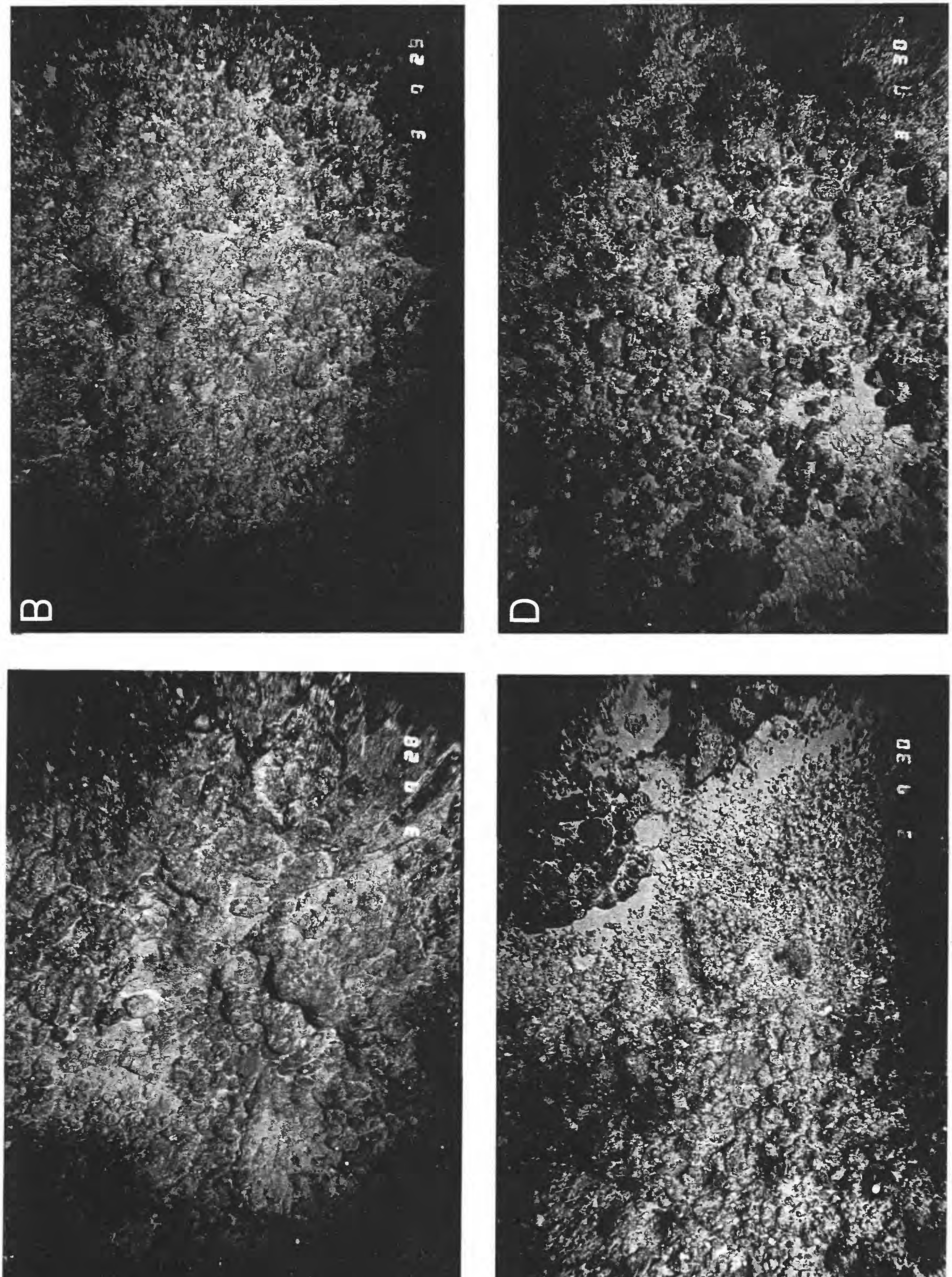
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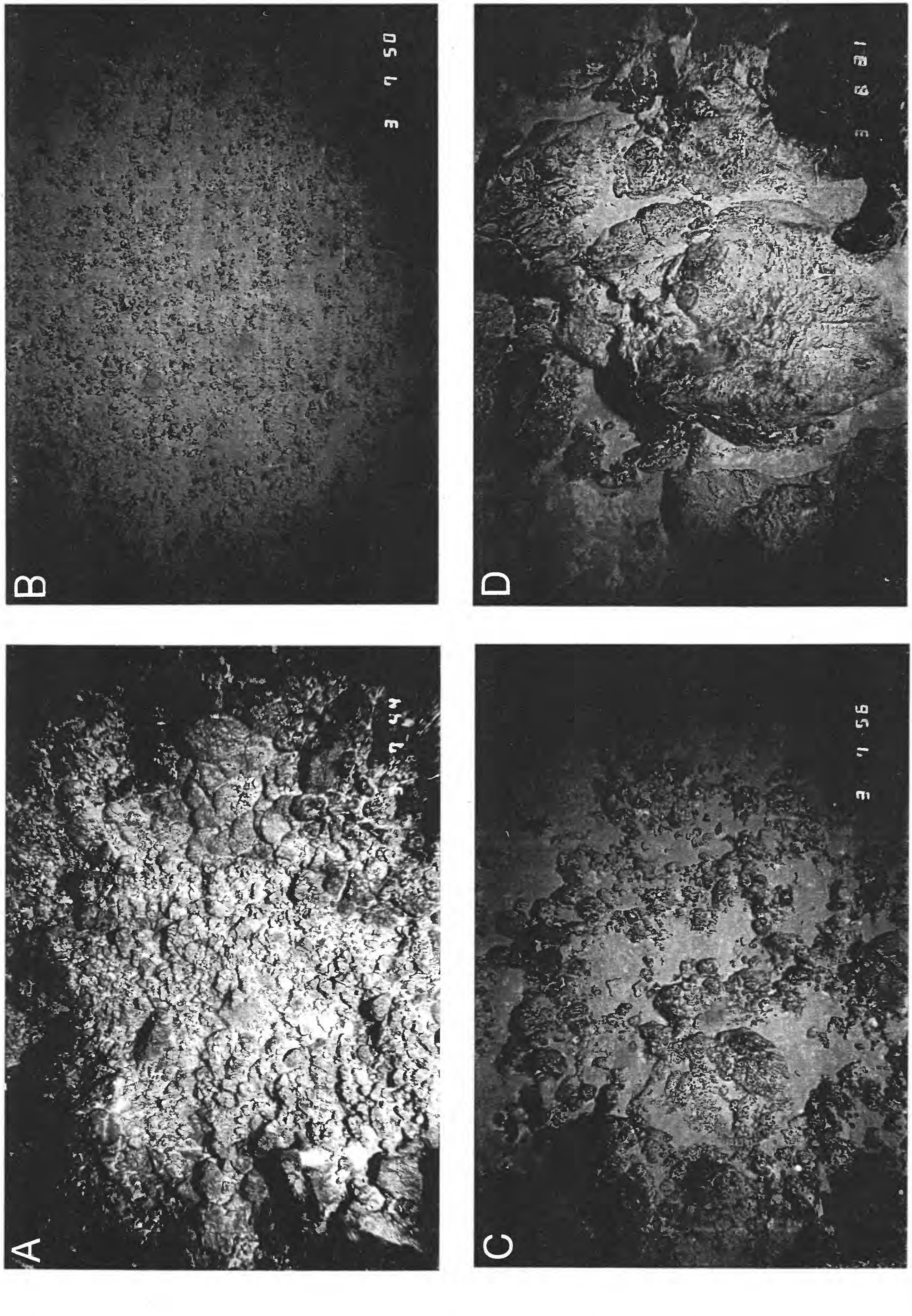
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