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WATER-COLUMN STUDIES NEAR A MELTING ARCTIC ICEBERG,(U)
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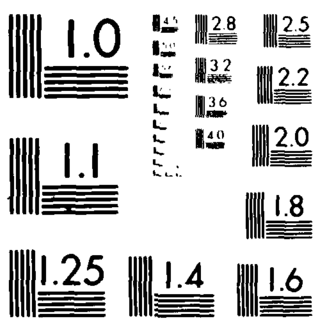

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WATER-COLUMN STUDIES NEAR

A MELTING ARCTIC ICEBERG

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P. O. Box 1390

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ABSTRACT

Glacial icebergs contain large amounts of nitrate, an important phytoplankton nutrient. Low density iceberg meltwater, in rising, mixes with euphotic zone water nearby, wherein NO_3 is in low concentration. Rising meltwater may also entrain nutrient-rich deeper waters and raise them to sunlit depths. Sixteen vertical profiles of nutrients (PO_4, NO_3, SiO_2), chlorophyll-a, and physical parameters were taken near a Greenland iceberg at ~50°N, 50°W in May–June 1980. Chlorophyll profiles show very pronounced maxima at or just below the maximum rate of change of water density vs. depth; profile forms are heterogeneous (no "typical" form is evident). No enhancement of chlorophyll concentration was found re distance from or direction to the iceberg. Effects of mixing on NO_3 concentrations are marginally detectable, but no 'wake' or 'downwind' effects were observed. The iceberg does not appear to grossly perturb water column plant biology nearby, but measures of rates of productivity might show otherwise, particularly near larger (e.g. Antarctic) icebergs.

Key words: icebergs, chlorophyll, nutrients, melting

INTRODUCTION

Glacial icebergs are a prominent feature of some high-latitude waters. Such icebergs contain significant amounts of nitrate (NO_3), an important nutrient for phytoplankton (Parker *et al.*, 1978). This NO_3 is apparently produced in the outer atmosphere (Wilson and House, 1965; Parker *et al.*, 1978); any NO_3 that enters the lower atmosphere at high latitudes may be washed out of the atmosphere in snowfall. Because ambient temperatures preclude plant growth in some of those areas (e.g. central Antarctica and the Greenland interior), such NO_3 accumulates in snowpack and eventually reaches the ocean incorporated into glacial icebergs.

Most annual Arctic iceberg production melts within a year, although a few individual Arctic icebergs take longer. Much of an iceberg's melting takes place on the surface of the berg which is above the thermocline, and especially in the surf zone. All melting of bergy bits and growlers produced by mass wastage of icebergs also takes place in the uppermost few tens of m of water. Iceberg melting could have important effects upon growth of phytoplankton nearby. Much or most iceberg melting takes place during warm parts of the year, when sunshine is brightest, and in areas where growth rate of phytoplankton is light-limited most of the year (Dunbar, 1968). The time of year when icebergs are melting fastest also has the calmest weather and strongest thermocline development, hence has minimal upwards mixing of plant nutrients into the top few 10s of m of water (the euphotic zone, where phytoplankton growth is possible) from nutrient-rich, but unlit, deeper waters. Thus at least four factors suggest the possibility of an "iceberg effect" on water-column biology near melting icebergs: (1) depth of maximum melting (thermocline to surface); (2) time of year of maximum melting (summer, with bright sunlight); (3) iceberg-borne nutrients (especially NO_3); and (4) possible upwards flow of fresh, low density meltwater, which could entrain nutrient-rich deeper water and carry nutrients into the euphotic zone (see Neshyba, 1977; Josberger, 1978). Meltwater from icebergs may contribute to the gross vertical temperature and salinity structure of large areas such as the Weddell Sea (Huppert and Turner, 1978), and in parts of the ocean where icebergs are common, biological effects, if they exist, could have in the aggregate a significant effect upon the general biology of a large area.

I report here on a preliminary search for possible strong effects of iceberg melting on plant biology nearby.

MATERIALS AND METHODS

An iceberg ~160 m in plan-view diameter, with maximum exposed height ~25-30 m, was located from USCGC Evergreen on 27 May 1980 at 49°30'N, 50°W (Fig. 1). The Evergreen followed the iceberg for several days, never moving off farther than about 2 km. Sixteen 20-bottle hydrocasts were obtained between 1111 (local time) 28 May 1980 and 2130 01 June 1980 (Fig. 1, Table 1). Cast #1 was a partial failure and is often not included in analyses. Each cast went to either 134 m (Nansen bottles @ 7 m intervals: casts #1-6) or 190 m (bottles @ 10 m intervals: casts #7-16) (Table 1). On each cast, all bottles were sampled for chlorophyll-a concentration (per Strickland and

Parsons, 1968). Nansen bottles were shaken before samples were drawn; phytoplankton were vacuum filtered onto Whatman GFC glass fibre filters, and chlorophyll was extracted by immersing each filter in 10 ml of 90% acetone/10% distilled water solution for 24-48 hours at 4°C. Chlorophyll-a was determined   with a Turner model 110 fluorometer; samples were serially diluted when necessary.

Every Nansen sample was also analyzed for concentrations of dissolved phosphate, nitrate, silicate, and nitrite (nitrate data are not treated here). Each 125 ml sample was preserved by acidification with 0.5 ml of 17<u>M</u> HCl and sealed in a washed polyethylene bottle. Chemical analyses were completed within three months at Scripps Institution of Oceanography Physical and Chemical Oceanographic Data Facility. Hydrographic data were obtained with a U.S.C.G. Plessey CTD. Nansen bottles were deployed on the CTD wire in order to obtain simultaneous CTD/bottle data.

We established two crossed lines of stations, centered on the iceberg. One line extended down the line of drift, with stations ahead of and in the wake of the iceberg: the other extended at approximately right angles to the first (Fig. 2). Each arm of the pattern included stations at 'near' (60-100 m), 'middle' (100-300 m), and 'far' (300-8[illegible] m) distances (Fig. 2). Two stations (#15, 16) were occupied about 2000 m ahead of the iceberg to provide information on conditions beyond its influence (i.e., "far-field" conditions). Winds were calm throughout. The iceberg drifted generally eastward for the first 10 stations, then went south and west: positions in Figure 1 were obtained with satellite navigation.

RESULTS

CHLOROPHYLL. At all stations there were pronounced chlorophyll maxima; most occurred at about 30 m (e.g. Fig. 3: station #10). Concentrations above this abrupt maximum were uniform and low relative to the maximum (e.g. Fig. 3, stations 4-13). On several stations there was a clear second maximum at much greater depth (~100 m: Fig. 3, stations 2, 3, 15). At stations 3 and 15, chlorophyll concentration at the deeper maximum was > that at the shallower maximum. Analyses of CTD data, nutrient data, and cast records from double-maximum stations suggest that the double maxima are not results of sampling problems (e.g. pre-tripping of Nansen bottle strings).

Abrupt increases in chlorophyll concentrations at the maxima occur nearly depth-coincident with abrupt changes in density (as sigma-t: Fig. 4). In the clearest profiles (e.g. Fig. 4) the sample with the highest chlorophyll concentration always occurs at or immediately below the depth of maximum vertical gradient in sigma-t (Fig. 5: see also Shulenberger and Reid, 1981).

There was no relation between bearing to the iceberg and strength of chlorophyll maximum (Fig. 6) or between bearing and depth of chlorophyll maximum (Fig. 7). There was no discernable tendency for increasing dissimilarity of chlorophyll profiles ($p > 0.20$, Kolmogorof-Smirnof test; Sokal and Rohlf, 1969) with increasing station separation (Fig. 8). There was no tendency for profiles taken on a particular bearing to be more similar than were profiles taken on different bearings (Fig. 9). There was no tendency for samples taken close together in time to have more similar profiles than samples taken further apart in time (Fig. 10).

<u>NUTRIENTS</u>. NO_3, PO_4 and SiO_2 all showed much lower concentrations above than below the pycnocline; all showed sharp changes in concentration at the pycnocline, and all varied simultaneously and in the same direction (Fig. 11).

<u>1. Nitrate</u>. Concentrations of nitrate in surface samples ranged from 0.16 to 0.86 $\mu M\ l^{-1}$. There was no significant correlation between surface concentration and distance from the iceberg (Spearman's rank difference correlation r_d = .031, $P \gg 0.20$; Tate and Clelland, 1957) (Fig. 12). Figure 13 shows no obvious relationship between surface concentrations and direction to the berg.

At each station, mean NO_3 concentration was calculated for all samples from above the thermocline; these values showed no correlation with distance from the iceberg (r_d = 0.25; $P > 0.25$) (Fig. 14), and no relation to direction from the iceberg (Fig. 15).

<u>2. Phosphate and silicate</u>. For PO_4 and SiO_2, the same calculations were made as for NO_3; similar results were obtained. For both SiO_2 and PO_4 there was no significant correlation (both $P > 0.20$) between distance to the iceberg and either surface values or mean concentration above the thermocline. For both nutrients neither parameter showed any relation to direction from the iceberg.

3. Nutrients in Iceberg Ice. Two samples of iceberg ice were analyzed: nutrient concentrations were much higher than those in surface water samples (all in $\mu M\ l^{-1}$):

	Iceberg sample 1	Iceberg sample 2	0m average (n 16)
NO_3	9.50	9.27	0.33
PO_4	1.14	1.65	0.40
SiO_2	6.35	6.75	0.97

WATER-COLUMN DENSITY STRUCTURE. Table 2 presents the mean of the absolute values of changes of σ_t between successive CTD data points ("$\overline{\Delta\sigma}_t$") for each 5 m depth increment on each cast. At ten (of 16) stations, CTD data were obtained both above and below the chlorophyll maximum (Table 3). In eight of those 10 profiles, the chlorophyll maximum and maximum $\overline{\Delta\sigma}_t$ ("$\overline{\Delta\sigma}_t$-max") coincided or were in adjacent 5 m intervals (Table 2). The chlorophyll maximum never occurred shallower than did $\overline{\Delta\sigma}_t$-max. There are also six stations (#s 3, 4, 7, 11, 13, 15) where at least two 5 m intervals shallower than $\overline{\Delta\sigma}_t$-max were successfully sampled for CTD data. At all six stations, the break between $\overline{\Delta\sigma}_t$ values shallower than $\overline{\Delta\sigma}_t$-max and $\overline{\Delta\sigma}_t$-max is abrupt (e.g. stations 4, 15), as is the return to lower $\overline{\Delta\sigma}_t$ values at greater depths (Table 2).

Table 3 results from a search for effects of distance from the iceberg on depth and strength of the break in σ_t. The three strongest breaks in σ_t occur in the three profiles taken closest to the iceberg. This is probably not due to chance ($P = 3!/10!$, about 2×10^{-6}, given random rankings), and indicates a 'distance effect' upon strength of $\Delta\sigma_t$ (i.e., on sharpness of the pycnocline). There appears to be no correlation between depth at which $\Delta\sigma_t$-max occurs and either distance to the iceberg (Table 3) or strength of $\Delta\sigma_t$-max (Table 3). There is no relation between strength of $\Delta\sigma_t$-max and bearing to the iceberg (Fig. 16).

DISCUSSION

CHLOROPHYLL. Maximum chlorophyll values (Table 1) break into two obvious groups: stations 1-11 and 12-16. Stations' water depths also seem to break into the same groups (Table 1). Rank-difference correlation (Tate and Clelland, 1957) of water depth with maximum chlorophyll value (16 stations) gives $r_d = -0.626$ ($P < 0.01$), suggesting a strong relationship. However, one may use the *a-priori* knowledge that there is an obvious grouping of values to further investigate the relationship. There are 16! possible rankings of stations by depth (given no ties, per Table 1). The sum of ranks (for water depths) of stations 12-16 = 17. Fewer than 6! of the 16! possible rankings could have produced a sum of ranks ≤ 17 for those stations, hence the probability that such an extreme sum occurs due to random rankings is exceedingly small ($P < 2(6!/16!)$, $\approx 6 \times 10^{-4}$). Ranking depth and maximum chlorophyll values only within stations 1-11 gives $r_d = -0.$[illegible] (nonsignificant, $P \gg 0.20$). This suggests that the depth-chlorophyll relationship is indeed dichotomous (per Table 1) rather than linear, and that almost all significance seen in the overall data set (i.e., $r_d = -0.626$, $P \sim 0.01$) is caused by the dichotomy.

The five lowest values of integrated chlorophyll (i.e., per m^2 surface area from Ø to Z_{max}) are stations 12-16 (Table 1). Given the two *a-priori* groups (above), the probability of getting Σ ranks = 15 for stations 12-16 with random rankings is 5!/16! ($P \sim 6 \times 10^{-12}$). Clearly the two groups suggested by maximum chlorophyll values (Table 1) are real.

Total water-column chlorophyll and maximum chlorophyll value at a station are closely related (16 stations: $r_d = 0.91$, $P << 0.01$): whatever is causing variations in chlorophyll concentrations appears to be affecting the chlorophyll structure of the entire water column in a coherent manner. This effect is probably not a simple function of some parameter related to water depth, because the rank correlation of maximum chlorophyll value with water depth is only marginally significant ($r_d = 0.51$, $P \sim 0.05$). Depths are not so clearly dichotomized (Table 1) as are maximum chlorophyll values and integrated chlorophyll totals (Table 1).

There was no obvious change in non-oceanographic factors (e.g. wind, station plan, observational techniques) which can account for the sharp between-group dichotomies in chlorophyll. It also seems unlikely that any change in iceberg behavior could account for the dichotomies: changes in hydrography (below) appear to be more likely candidates.

The occasional double maxima of chlorophyll (Fig. 3) may be due to either lateral advection, at depth, of chlorophyll-enriched water or to residual effects of pronounced mixing events. The latter is unlikely: Dillon and Caldwell (1978, 1979) found that a wind of ≥40 kts (≥20 m sec^{-1}) blowing for ≥2 days appeared to mix surface waters only down to about 30 m, and the second maxima in station 2, 3, and 15 are all at Z ≥100 m. The wide variation in form of chlorophyll profile is suggestive of forms which might be produced by variable lateral advection: profiles range from single (e.g. stations 4, 6, 7, 10) to 'split maxima' as in #s 5 and 12, to obvious double maxima (#s 2, 3, 15), and to stations with pronounced but broad maxima (#s 13, 14, 16). Cast 15 seems to combine all these types. On our sampling scale the environment is clearly heterogeneous in regard to chlorophyll profiles, and no one profile may safely be considered 'typical'.

HYDROGRAPHY. Starting with station 12, the iceberg changed direction radically (Fig. 1); in stations 1-11, its overall path was roughly ESE; in stations 12-16, the path was nearly due west. Although surface hydrography of the region is variable and not well known, and our incomplete near-surface CTD data do not allow detailed analyses, it seems probable that the iceberg drifted across a hydrographic boundary (e.g. front, rift, or eddy) between stations 11 (2100 hrs, 31 May) and 12 (1300 hrs, 01 June). Such a boundary is not unlikely when moving from considerably shallower water (stations 1-11; Table 1) into much more variable depths (stations 12-16; Table 1).

Data from stations 2-16 show a strong trend [illegible] increasing salinity at 100 m (Table 4), but [illegible] groups of stations. This suggests that any feature [illegible] only (i.e., <100 m thick).

Mixing. A number of papers have argued that [illegible] should rise to the surface (Foldvik and [illegible], 1974; [illegible], 1977; [illegible], 1978), sink ([illegible], 1978), or spread laterally at [illegible] (Huppert and Turner, 1978). Observations on natural [illegible], [illegible] Josberger (1978) described apparent [illegible]. Laboratory studies using dyed freshwater [illegible] equivocally showed that meltwater spreads laterally [illegible], with little or no meltwater [illegible] rising to the surface [illegible] (Huppert and Turner, 1978). Although the use of [illegible] may have influenced the observed mixing [illegible] by volume compressed air, as bubbles: [illegible], hydrographic studies along the edge of the [illegible] Shelf ([illegible] et al., [illegible]) [illegible] show lateral meltwater spreading at depth. Foldvik and [illegible] (1977) suggest that the shallow salinity [illegible] (Carmack, 1976) may result from lateral spreading of glacial meltwater [illegible]. Extrapolation of Huppert and Turner's (1978) [illegible] icebergs suggests certain vertical density structures in [illegible] water, due to lateral spreading. Our CTD data are inadequate to resolve such structures however, the data do include frequent sudden changes in T and S with depth that are suggestive of vertical layering, and these changes are more frequent in profiles nearest the iceberg.

We were unable to detect meltwater or mixing effects in the wake of the iceberg, where maximum effects were expected. Our far-field stations generally resemble those near the iceberg. Physical effects of meltdown and mixing are probably marginally present in our CTD data but below our threshold of reliable detection: Josberger (1978) did detect a cool, low salinity wake behind an Arctic iceberg (see also Donaldson, 1978). Nevertheless, we may have detected some general effects of meltwater mixing. Over half the stations closer than 2000 m to the iceberg (#s 1, 6, 8-12, 14) had integrated NO_3 (0 to pycnocline, per m^2) greater than either far-field station. However, these stations ranged from 60 to 800 m from, and in most directions from, the iceberg (Fig. 2): generalized lateral mixing of NO_3-rich iceberg water could produce such an effect. In addition, Table 3 shows that the strongest breaks in σ_t profiles occurred near the iceberg, a result expected if meltwater were spreading and mixing laterally.

Many biological effects probably have too long lag times to be detected with the single techniques used here. Considering the generation time of even rapidly-growing marine phytoplankton (about 1-2 days), the rate at which the iceberg moved (rapidly) and melted (relatively slowly), the probable mixing ratio of meltwater to surface seawater (very low), and the uncertain direction of meltwater movement, it is not surprising that we detected no obvious biological effect of meltwater even close alongside the iceberg. Our primary indicator of biological activity was chlorophyll concentration: chlorophyll is a time-integral of plant growth rate and concentration, and of numerous other factors. Better indicators of biological activity would be assays for rates of primary productivity, or rates and amounts of microbiological growth. High concentrations of chlorophyll occur at the interface between mixed layer and deeper water at all distances from the iceberg and are probably a general feature of the region rather than a result of iceberg meltdown. The chlorophyll maximum is probably a function of nutricline location; even a small amount of mixing across the thermocline/nutricline (e.g. by breaking internal waves) would provide a much larger nutrient [illegible], integrated over the area, than could [illegible] meltwater from this iceberg.

In essence, we found no striking effects of the iceberg's presence on [illegible] either nutrient concentrations or chlorophyll concentrations nearby. The system in which the iceberg was situated is quite variable on the spatial scales we measured, and that system seemed to be undergoing no obvious temporal evolution over the observation period. The iceberg seems, simply, to have been set into that system without biologically perturbing it in any major way (but see Josberger, 1978: 256 m. near iceberg fine scale T and S modifications). Such may not be the case in Antarctic regions, where much larger bergs are much more common. There, large tabular bergs may well be sufficiently massive and long-lasting to yield the sort of signatures which we sought near the present, much smaller Arctic iceberg (see note added in press, Zeller et al., 1978).

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TABLE CAPTIONS

Table 1. Data from each hydrocast. * = station positions shown in Fig. 1

Table 2. Mean absolute value of change in σ_t ("$\overline{\Delta\sigma}_t$") between successive CTD measurements. Means were calculated for every 5 m interval for which there were N>2 points. Tabled values are $\overline{\Delta\sigma}_t \times 10^3$. () = depth of chlorophyll maximum. Casts 1-6 went only to 140 m; other blanks are missing CTD data. Station #15 had three chlorophyll maxima (Fig. 3)

Table 3. Distance *vs.* strength of break in $\overline{\Delta\sigma}_t$. Only hydrocasts which yielded adequate CTD data are included. †: strength = difference between $\overline{\Delta\sigma}_t$ values (see text) for consecutive 5 m intervals at the break in $\overline{\Delta\sigma}_t$ profiles: units used are of σ_t

Table 4. Temperature and salinity at 100 m at each station

FIGURE CAPTIONS

Figure 1. Progressive vector plot of iceberg positions at successive stations (numbered). Positions were obtained using satellite navigation.

Figure 2. Station positions relative to drifting iceberg.

Figure 3. Profiles of chlorophyll-a concentration (mg m^{-3}) at stations #2-16. Distance to iceberg is given for each profile. Dots represent Niskin-bottle depths. Note scale change in stations 12-16. Additional station data are provided in Table 1. Note pronounced maxima at about 30 m, and occasional double maxima.

Figure 4. Concentration of chlorophyll-a (mg m^{-3}) and density (as σ_t) vs. depth. Note sudden, pronounced chlorophyll maximum and its relation to the maximum density gradient.

Figure 5. Concentration of chlorophyll-a (mg m^{-3}) vs. $\overline{\Delta\sigma_t}$. Note relation of chlorophyll maximum to gradient in σ_t. $\overline{\Delta\sigma_t}$ = mean of $|\Delta\sigma_t|$ values calculated by difference of successively deeper σ_t values (from CTD data). σ_t was calculated at 1 m increments where possible; no interpolations were made for missing values. Averages were over 5 m or 10 m increments depending upon sampling success. For each plotted point $N \geq 3$, usually 4-6.

Figure 6. Concentration of chlorophyll-a (mg m^{-3}) at the chlorophyll maximum vs. bearing from the iceberg. Distance from origin is proportional to chlorophyll concentration, not to distance from iceberg.

Figure 7. Bearing to iceberg vs. depth of chlorophyll maximum. Distance from origin is proportional to depth, not to distance from iceberg.

Figure 8. Similarity of stations' chlorophyll profiles vs. spatial separation of compared stations. Dots = stations with bottles at 10 m intervals (45 comparisons); triangles = stations with 7 m bottle spacing (10 comparisons). Distances taken from Lagrangian plot of positions relative to iceberg (Fig. 2). Λ max = maximum difference, in percent, between compared stations' cumulative percentage curves of chlorophyll vs. depth (Kolmogorov-Smirnov test: see text). Increasing Λ max indicates decreasing similarity. No trend, $P > 0.20$ (Tukey Corner Test: Sokol and Rohlf, 1969).

Figure 9. Similarity of stations' chlorophyll profiles (as cumulative percentage vs. depth) vs. angular separation of stations relative to drifting iceberg (Fig. 2). No trend, $P > 0.20$ (see legend, Fig. 8).

Figure 10. Similarity of stations' chlorophyll profiles (as cumulative percentage vs. depth) vs. temporal separation (in hours) of compared stations. Profiles were compared only between stations with the same bottle spacing (i.e., stations 2-6 and stations 7-16: see text). No trend, $P > 0.20$ (see legend, Fig. 8).

Figure 11. Concentrations of NO_3, PO_4, and SiO_2 *vs.* depth at station 4. Some stations showed even more pronounced breaks in profiles at ~30 m.

Figure 12. Surface concentrations of NO_3 and PO_4 as functions of distance from iceberg.

Figure 13. Surface concentration of NO_3 *vs.* bearing from iceberg. Numbers are station numbers. Distance from origin is proportional to concentration, not to distance from iceberg.

Figure 14. Mean NO_3 concentration above the thermocline at a station *vs.* distance of station from iceberg. Mean concentration was figured as mean of all data from samples collected above the thermocline at a station.

Figure 15. Mean NO_3 concentration (per Fig. 14) above the thermocline *vs.* bearing to iceberg. Distance from origin is proportional to mean concentration, not to distance from iceberg.

Figure 16. Bearing to iceberg *vs.* strength of break in profiles of $\overline{\Delta\sigma}_t$. $\overline{\Delta\sigma}_t$ = mean absolute value of change in $\Delta\sigma_t$ between successive CTD measurements. A mean was calculated for every 5 m interval. Strength of break = maximum change between successive $\overline{\Delta\sigma}_t$ values. Distance from origin is proportional to strength of break, not to distance from iceberg. Units are units of σ_t. Missing stations lacked CTD data sufficient to yield meaningful results.

Table 1.

Stn # *	Water Depth	Distance from Berg	Bearing to Berg	Chlor-a Max mg m^{-3}	Depth of Chlor Max	Chl-a mg m^{-2}	Time of Day (Local)	Date (Local)
1	[illegible] m	60 m	220°	5.88	42 m	19.52	1111	28 May
2	261	300	210	3.08	35	19.29	1350	28 May
3	[illegible]	340	220	5.85	98	32.38	1540	28 May
4	310	150	340	4.95	28	21.08	1430	29 May
5	[illegible]	400	240	4.50	21	17.30	1812	29 May
6	287	340	340	2.07	35	11.92	2150	29 May
7	174	100	90	2.74	30	8.27	1355	30 May
8	263	340	90	1.87	30	7.71	1730	30 May
9	329	600	90	2.40	30	8.80	1900	30 May
10	[illegible]	170	60	[illegible]	30	15.80	1800	31 May
11	[illegible]	300	270	5.47	40	15.71	2100	31 May
12	891	50	200	[illegible]	40	5.83	1243	01 June
13	893	150	270	[illegible]	90	5.19	1430	01 June
14	[illegible]	300	270	.60	70	4.30	1800	01 June
15	341	2000	270	.86	100	7.06	1945	01 June
16	337	2000	270	.61	40	4.39	2130	01 June

Table 8.

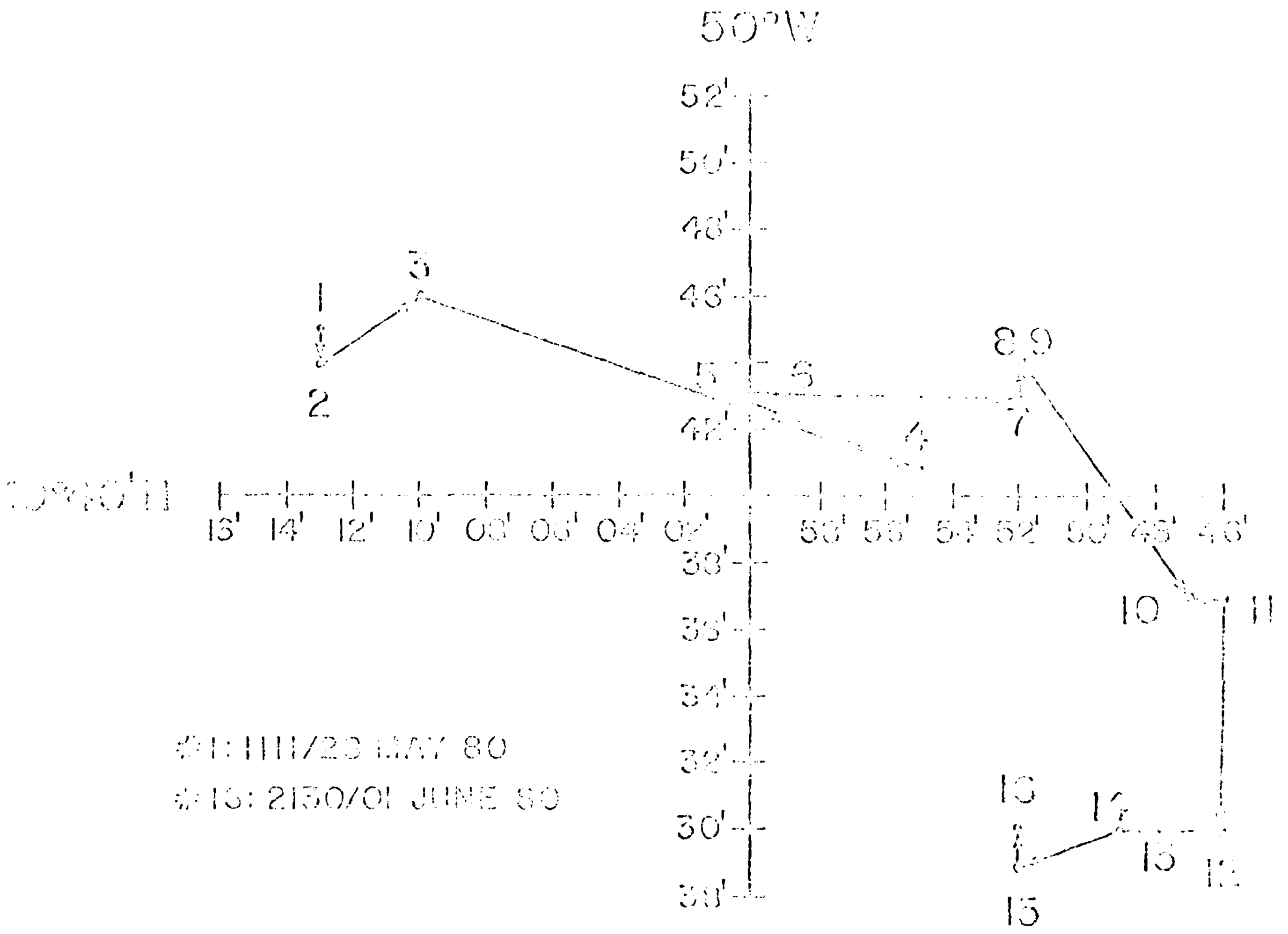
Depth (metres)	Station # 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0 - 5				4									13		19	
-10			15	46							29		29		52	
-15			34	18							40		14		55	
-20			13	40	64			72			39		36		72	
-25			95	203	(140)		25	107			39		7		64	
-30		( )	(143)	(45)	13	( )	102	(74)	( )	( )	31		12		160	
-35		(58)	10	26	32		(287)	32	34	30	97		13		37	32
-40		42	20	19	14		72	37	106	69	(49)	( )	120		116	(153)
-45	( )	15	40	16	20		29	25	31	28	37		32		80	65
-50		61	24	11	63		13	55	11	51	33		72		43	30
-55		47	29	67	22	43	9	35	13	31	28		52	19	21	22
-60		23	19	41	4	45	161	30	34	11	10		15	36	20	15
-65		37	17	15	16	14	62	22	14	11	24		41	33	31	69
-70		27	34	15	2	30	98	14	43	18	41		16	(60)	28	20
-75		17	44	61	10	20	8	15	14	38	16		18	27	14	67
-80		10	34		3	14	10	27	3	17	60	9	(68)	42	13	80
-85		3	12	30	12	9	13	29	13	13	41	11	38	21	15	42
-90		16	15		33	10	13	25	12	16	32	8	--	20	30	57
-95		14	40	7	6	16	59	31	9	12	35	6	11	30	13	[illegible]
-100		14	15	7	25	16	7	4	14	30	10	9	36	47	20	11
-105		12	25	22	13	5	7	3	13	20	10	[illegible]	15	14	[illegible]	20
-110		4	[illegible]	44	12	7	3	13	14	34	[illegible]	9	41	[illegible]	16	7
-115	17	13	10	30	17	15	22	14	66	13	17	26	47	13	15	22
-120	7	14	17	51	42	10	17	20	5	10	17	13	7	7	12	10
-125	20	11	13	47	25	30	10	12	22	12	14	11	14	3	13	9
-130	37	15	14	4	21	16	14	1	10	21	51	23	4	[illegible]	[illegible]	20
-135	24	31	20	[illegible]	28		29	20	21	17	[illegible]	[illegible]	10	[illegible]	[illegible]	11
-140	12	77		14			11	24	20	8	3	11	7	[illegible]	11	10
-145				4			11	17	15	15	7	[illegible]	[illegible]	1	11	
-150							12	10	[illegible]	30	7	6	10	1	[illegible]	17
-155							16	4	70	14	10	6	41	31	[illegible]	22
-160							22	11	7	27	6	14	20	21	21	27
-165							7	9	7	31	31	5	7	4	7	23
-170							10	12	[illegible]	7	4	9	16	16	11	13
-175							15	5	3	8	5	7	24	25	5	18
-180							17	17	21	13	13	43	[illegible]	27	[illegible]	[illegible]
-185							7	11	[illegible]	20	5	7	11	12	[illegible]	15
-190							10		14		5	6	[illegible]	14	6	7

Table 3.

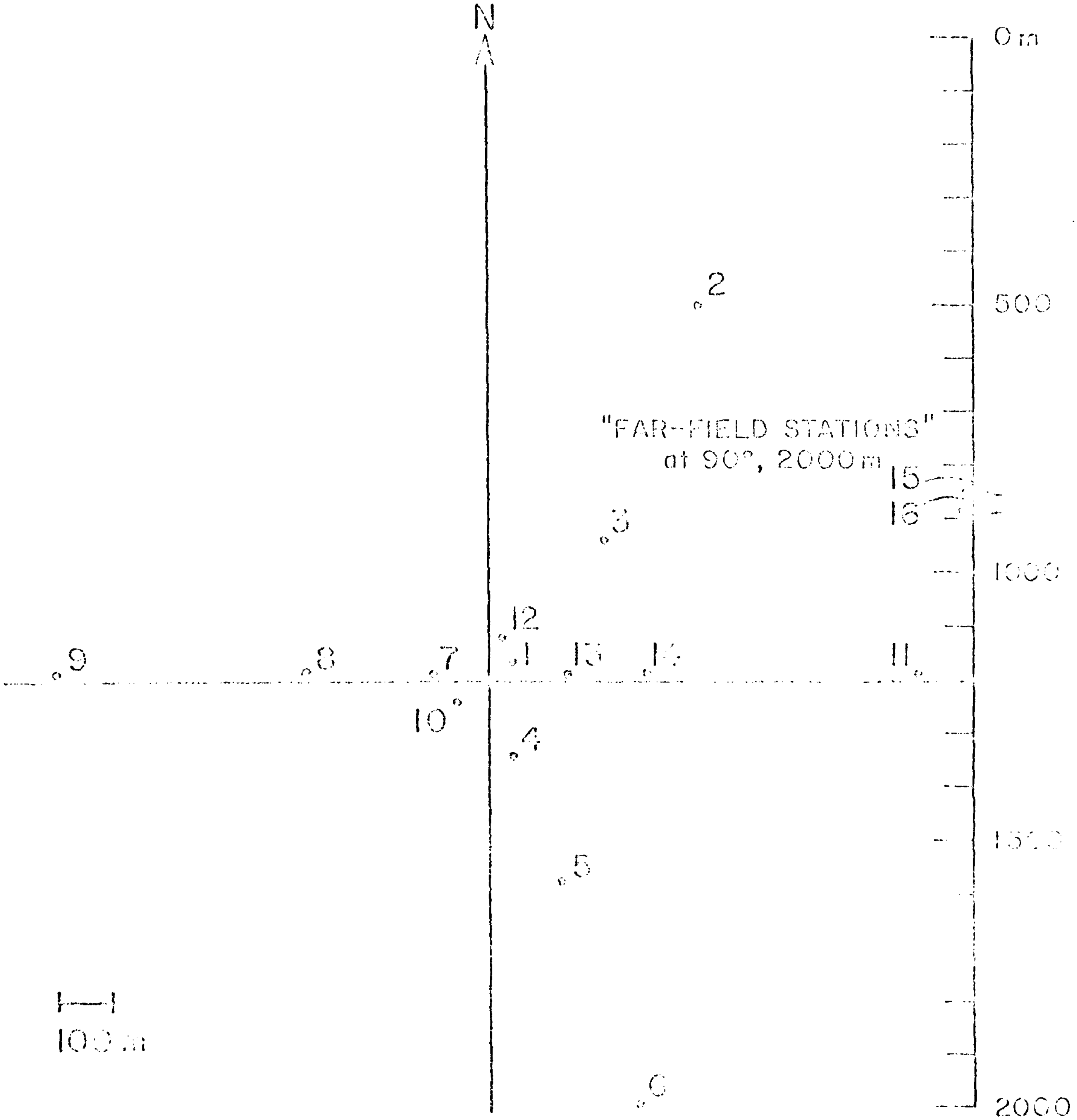
Distance From Berg	Cast #	Depth of Break in $\Delta\sigma_t$	Strength of Break, $\Delta\sigma_t$	Bearing to Berg
60 - 130 m	4	25 m	.159	340°
	7	35	.135	90
	13	40	.130	270
300 - 400 m	3	30	.048	220
	5	25	.076	340
	8	25	.035	340
800 - 2000 m	9	40	.072	90
	11	[illegible]	[illegible]	270
	15	30	[illegible]	270
	16	40	[illegible]	270

Table 4.

Cast #	°C	‰
2	.31	34.00
3	.22	33.97
4	.24	33.96
5	.45	33.98
6	.34	34.00
7	.40	34.06
8	.50	34.02
9	.51	34.03
10	.82	34.07
11	1.08	34.05
12	.91	34.07
13	.76	34.01
14	1.34	34.00
15	.98	34.09
16	1.10	34.03



50°W
52'
50'
48'
46'
42'
34'
32'
30'
#1: 1111/20 MAY 80
#15: 2130/01 JUNE 80


N
0 m
500
1000
1500
2000
"FAR-FIELD STATIONS"
at 90°, 2000 m
15
16
2
3
12
1
13
14
11
9
8
7
10°
4
5
6
100 m

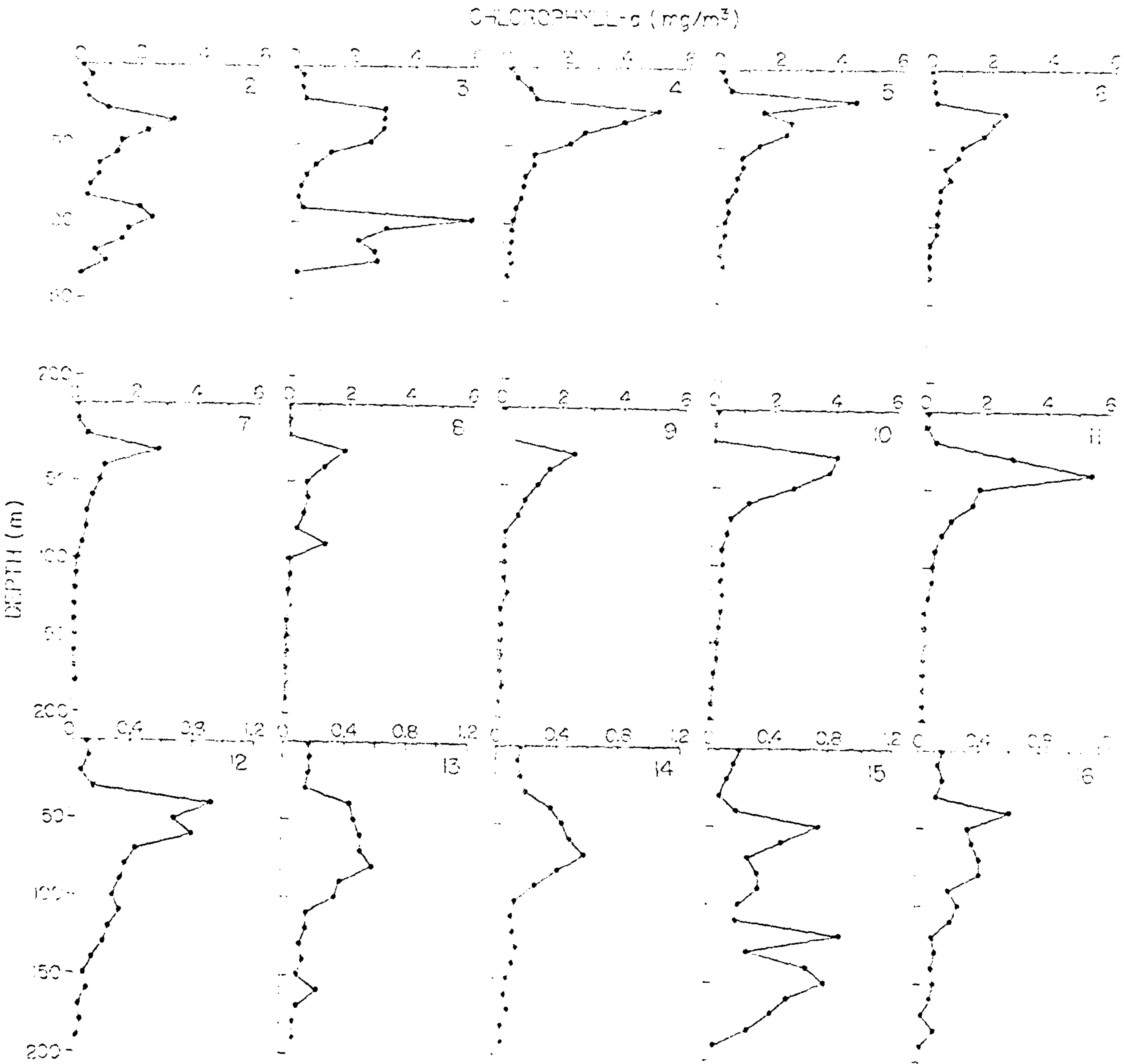
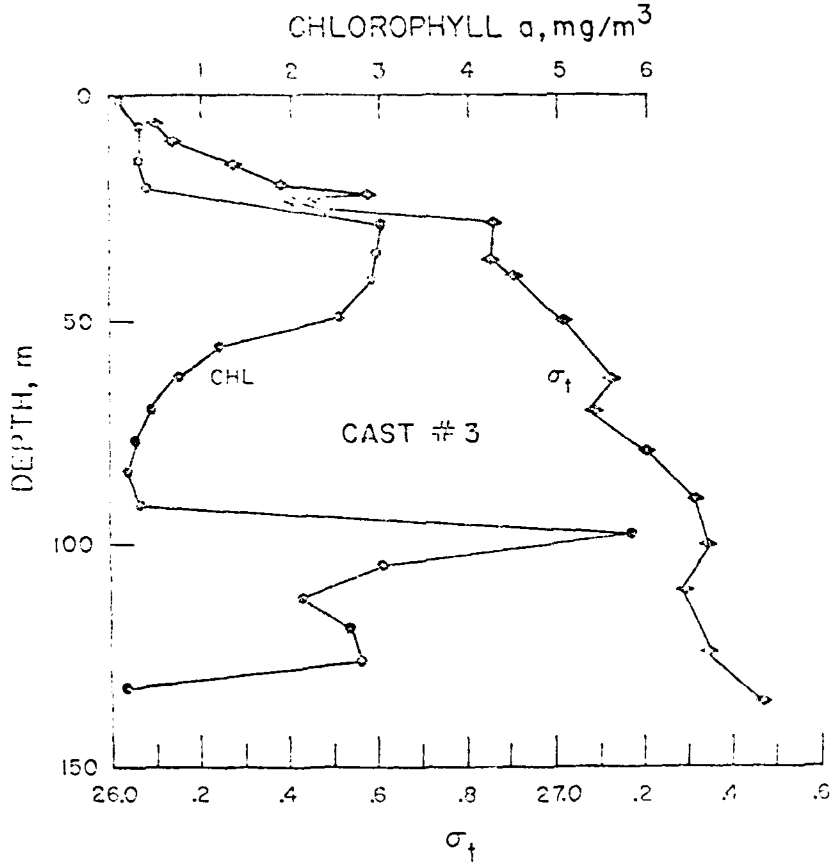
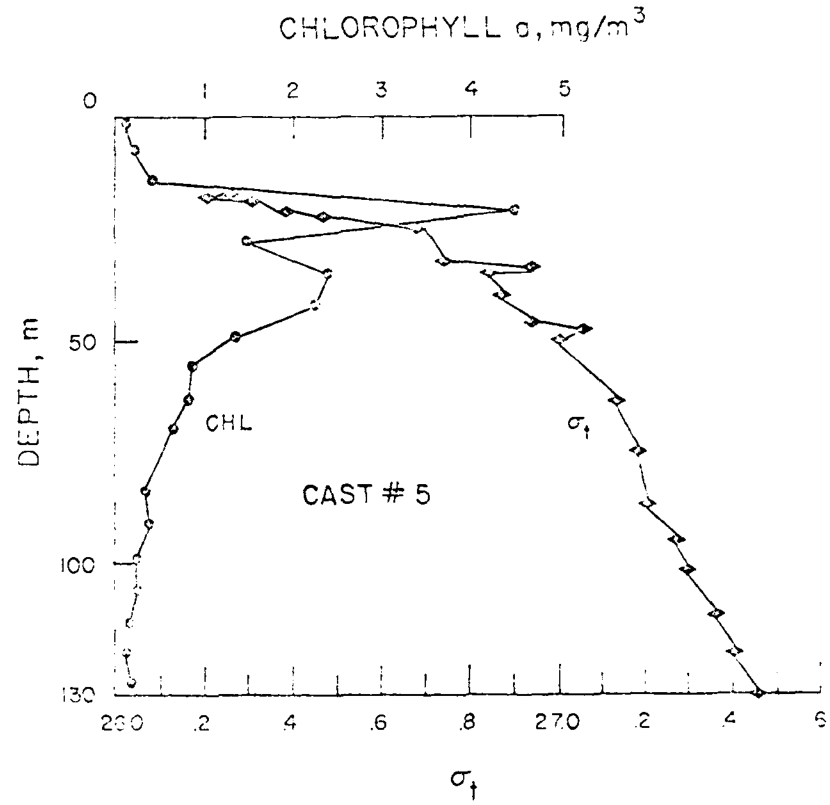


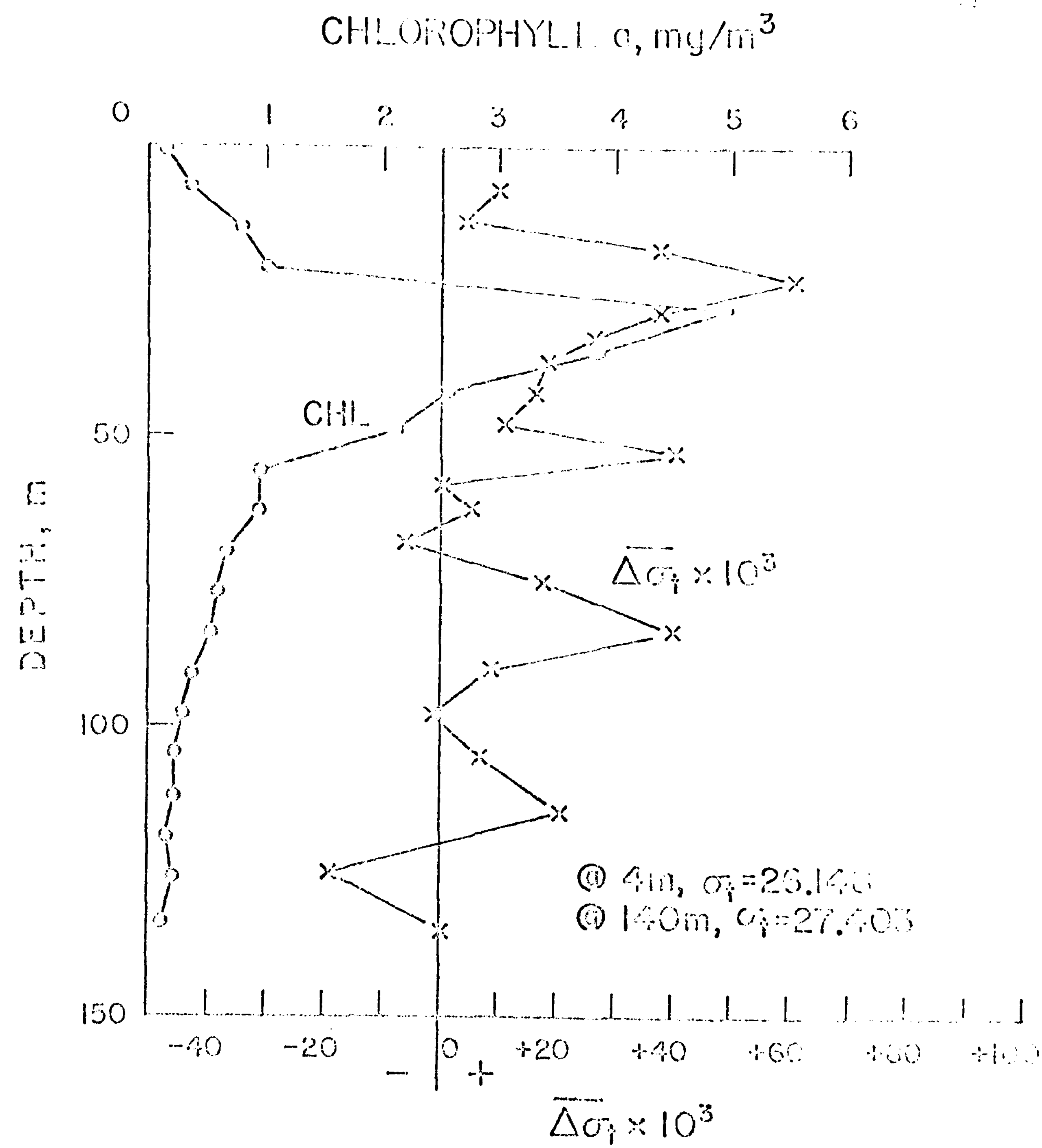
Fig. 3



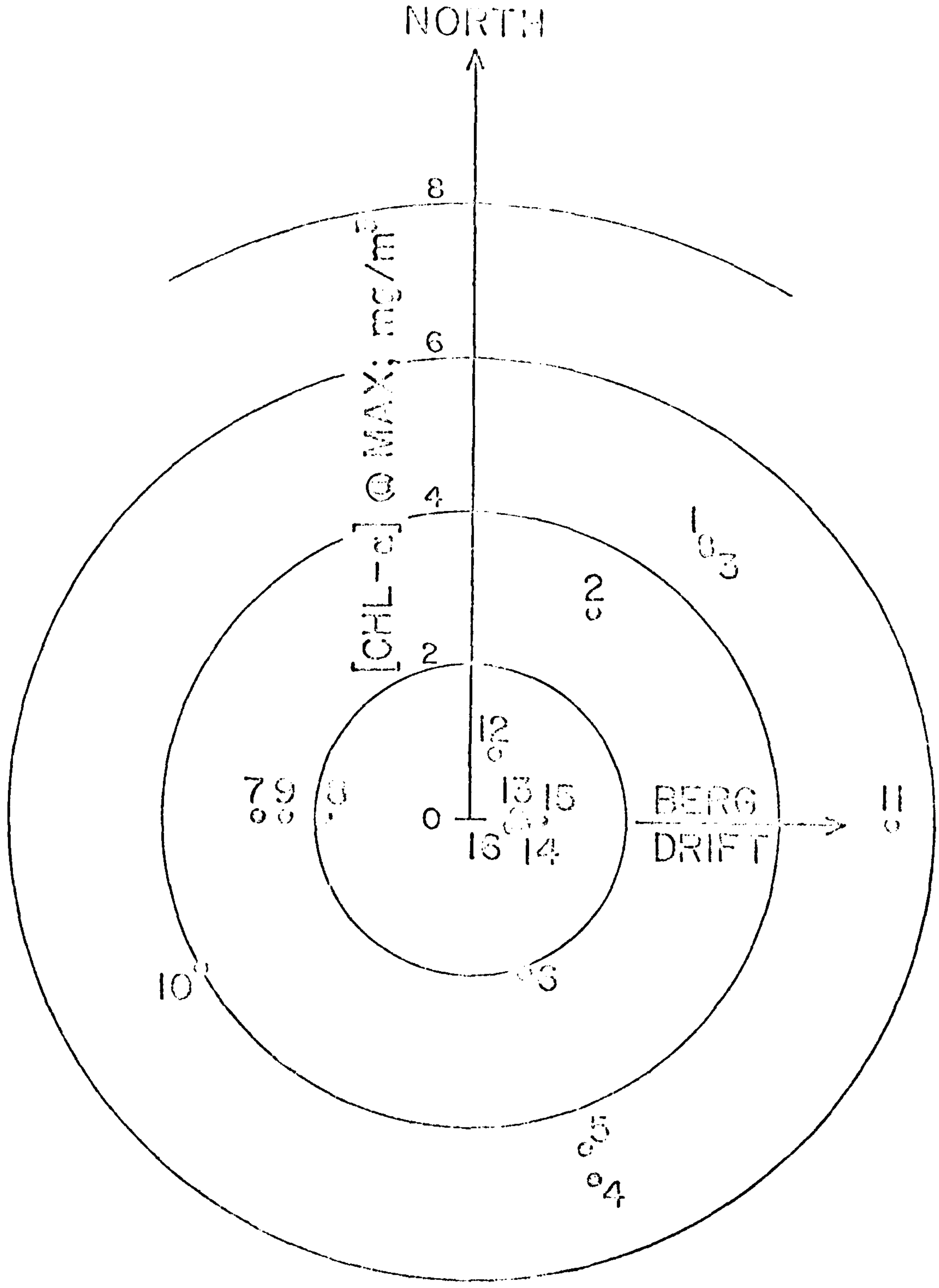
CHLOROPHYLL a, mg/m3
DEPTH, m
CHL
σt
CAST # 3



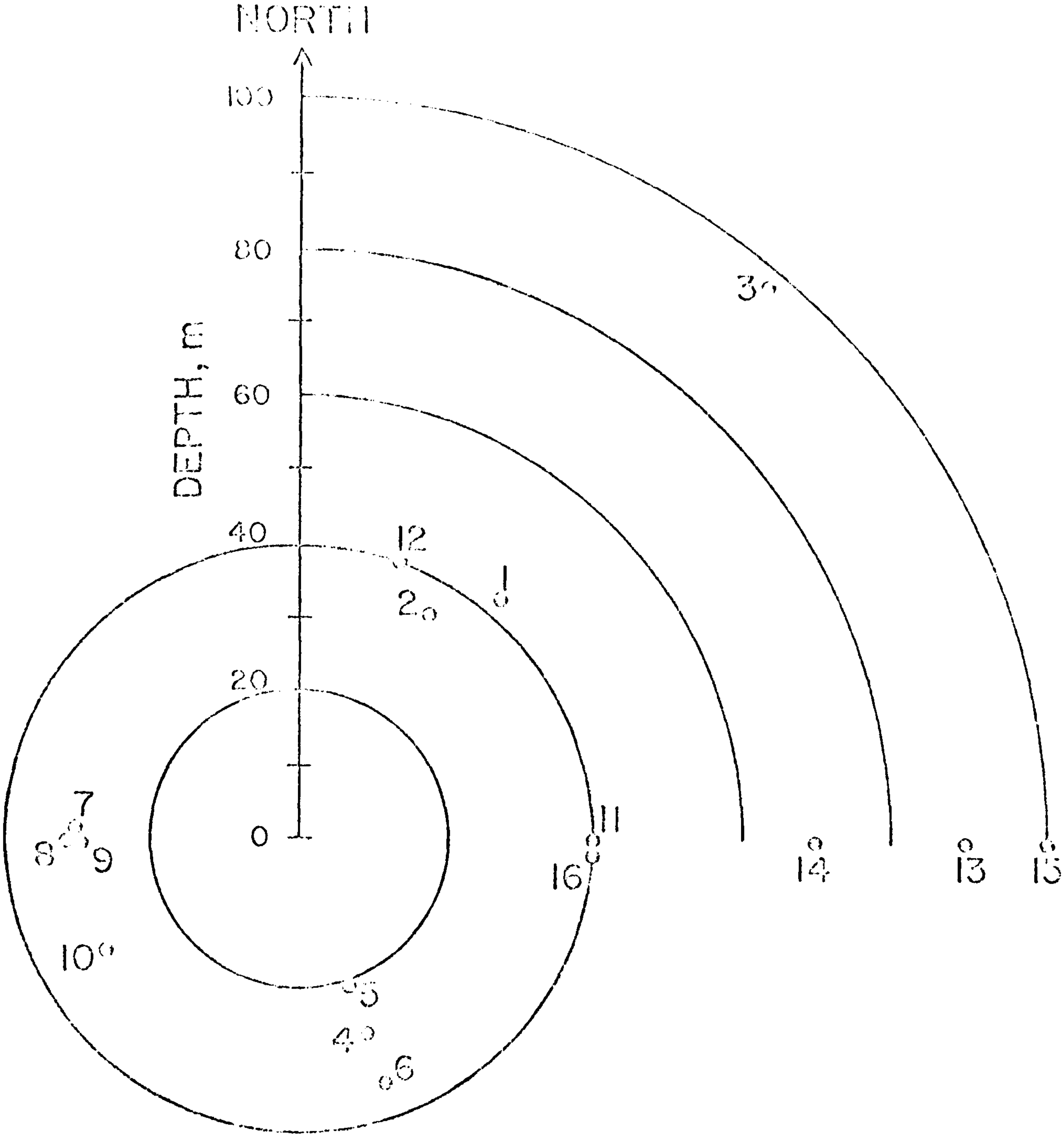
CHLOROPHYLL a, mg/m3
DEPTH, m
CHL
σt
CAST # 5



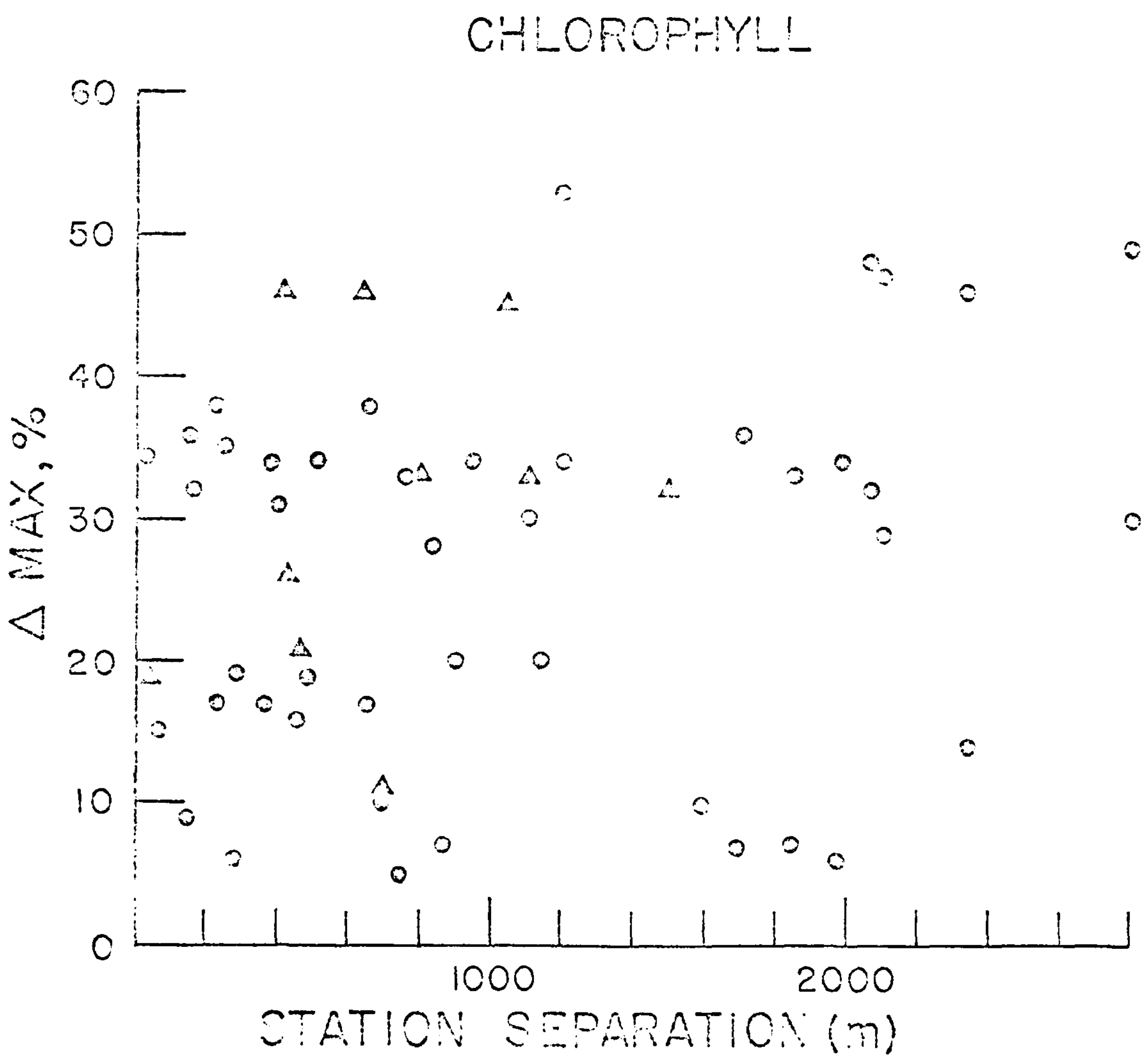
CHLOROPHYLL a, mg/m3
0
1
2
3
4
5
6
CHL
DEPTH, m
50
100
150
$\overline{\Delta\sigma_t} \times 10^3$
@ 4m, σ_t=26.14
@ 140m, σ_t=27.40
-40
-20
0
+20
+40
+60
-
+
$\overline{\Delta\sigma_t} \times 10^3$



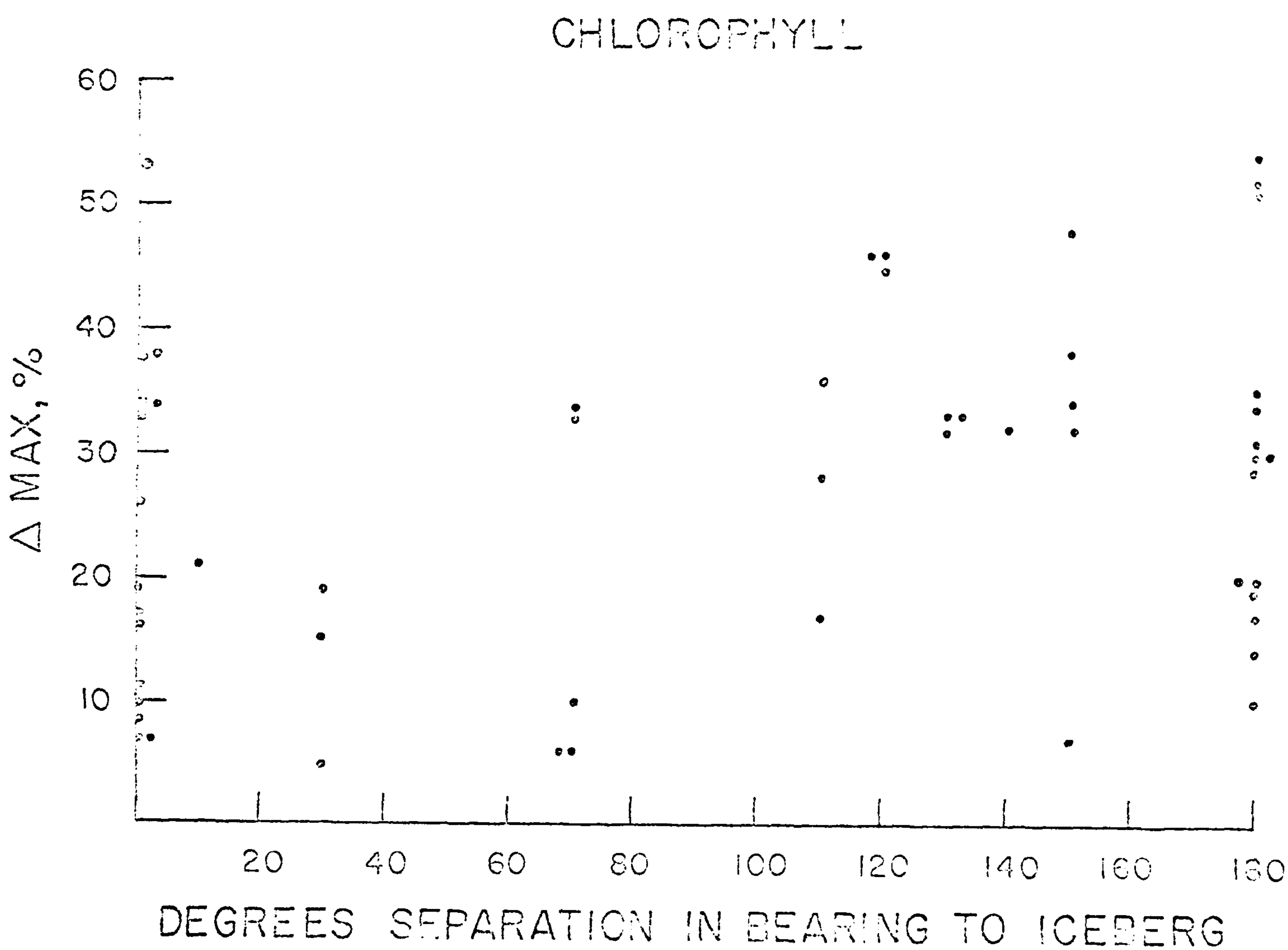
BEARING VS CONCENTRATION OF CHLOROPHYLL @ MAXIMUM

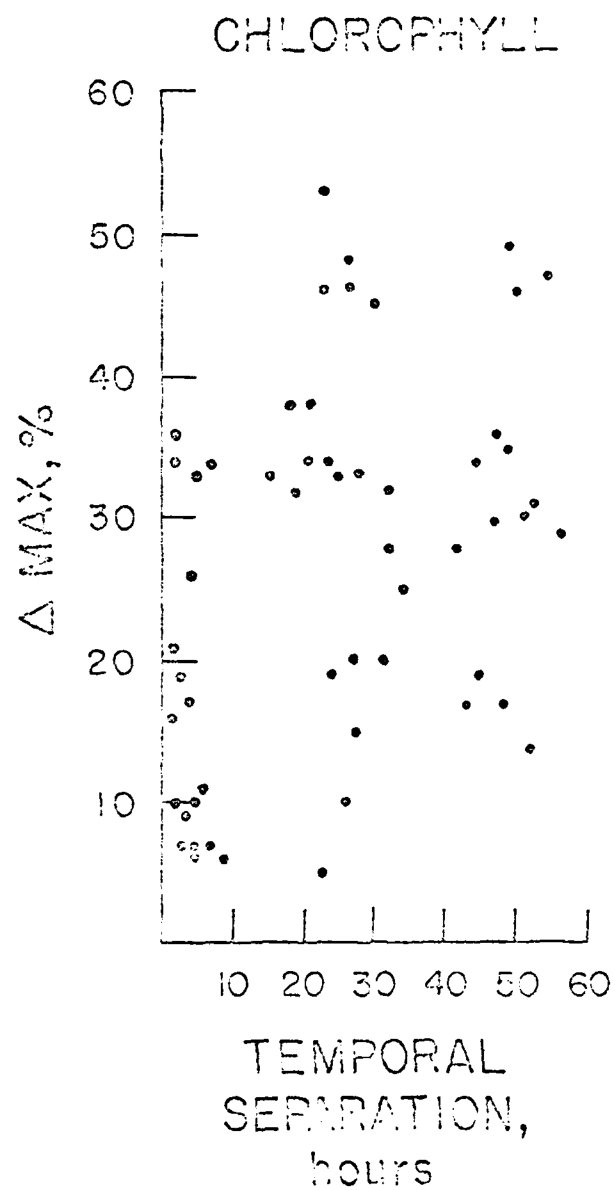


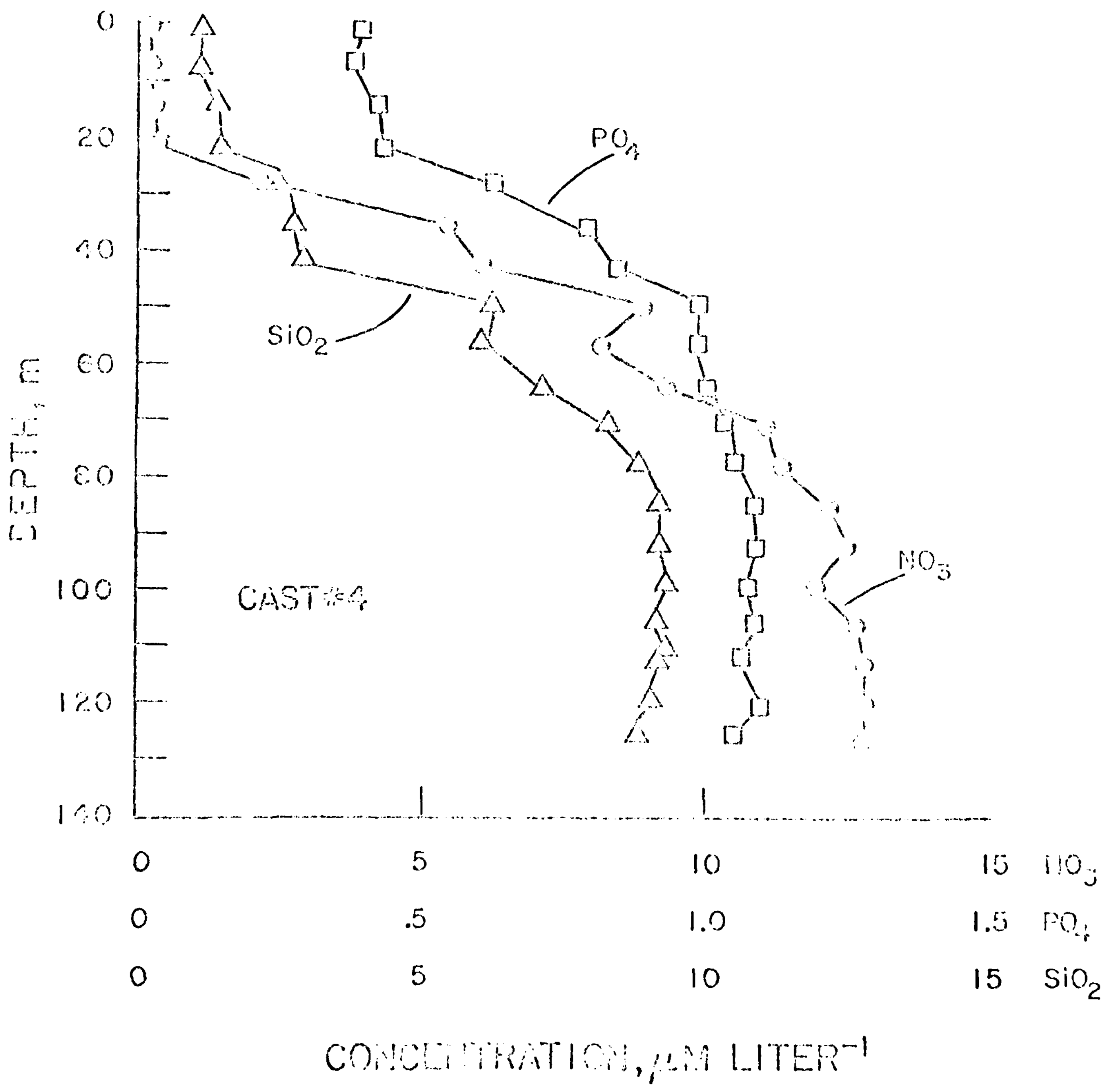
BEARING vs DEPTH OF CHLOROPHYLL MAXIMUM



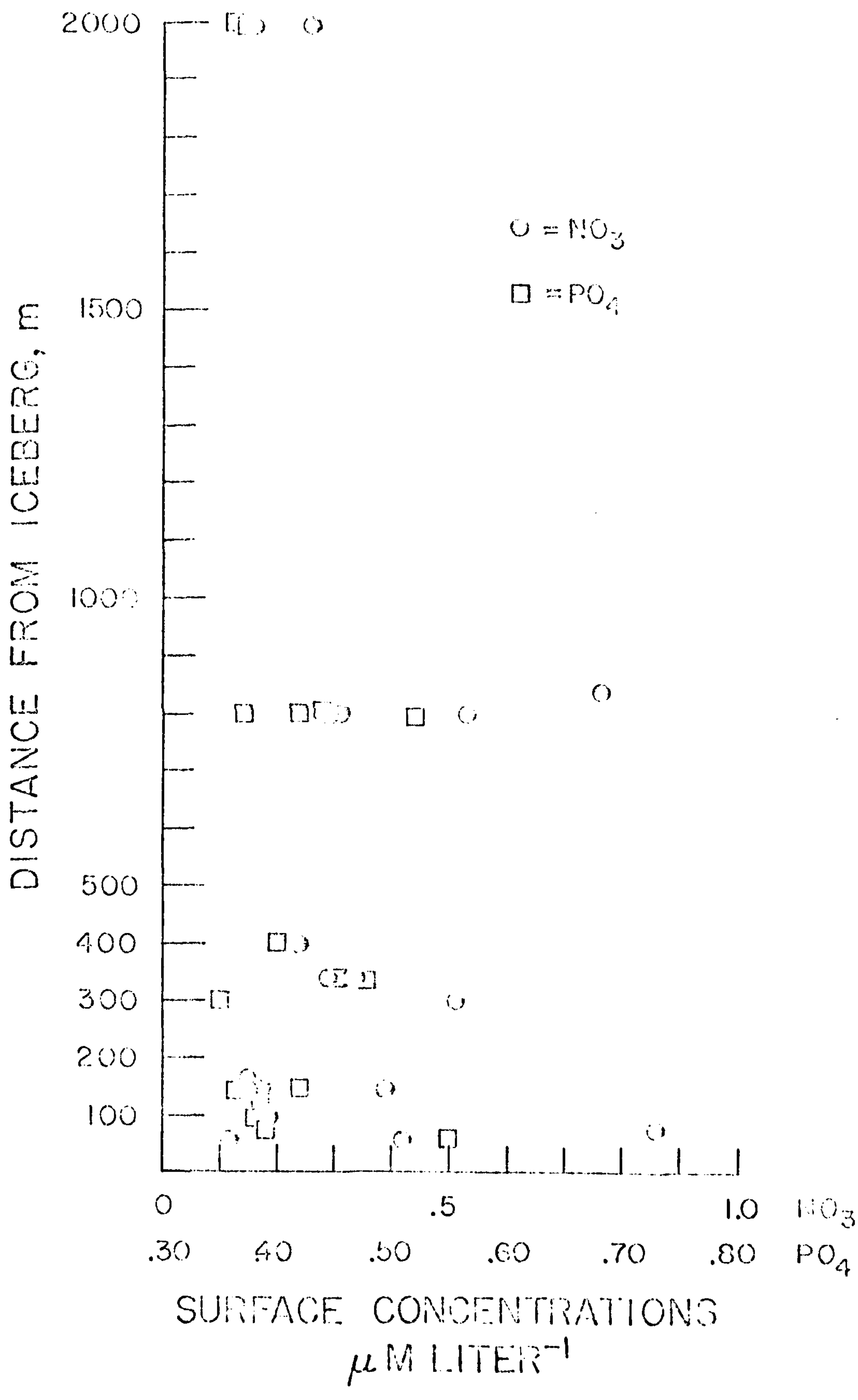
CHLOROPHYLL
Δ MAX, %
0
10
20
30
40
50
60
1000
2000
STATION SEPARATION (m)


CHLOROPHYLL
60
50
40
30
20
10
Δ MAX, %
20
40
60
80
100
120
140
160
180
DEGREES SEPARATION IN BEARING TO ICEBERG

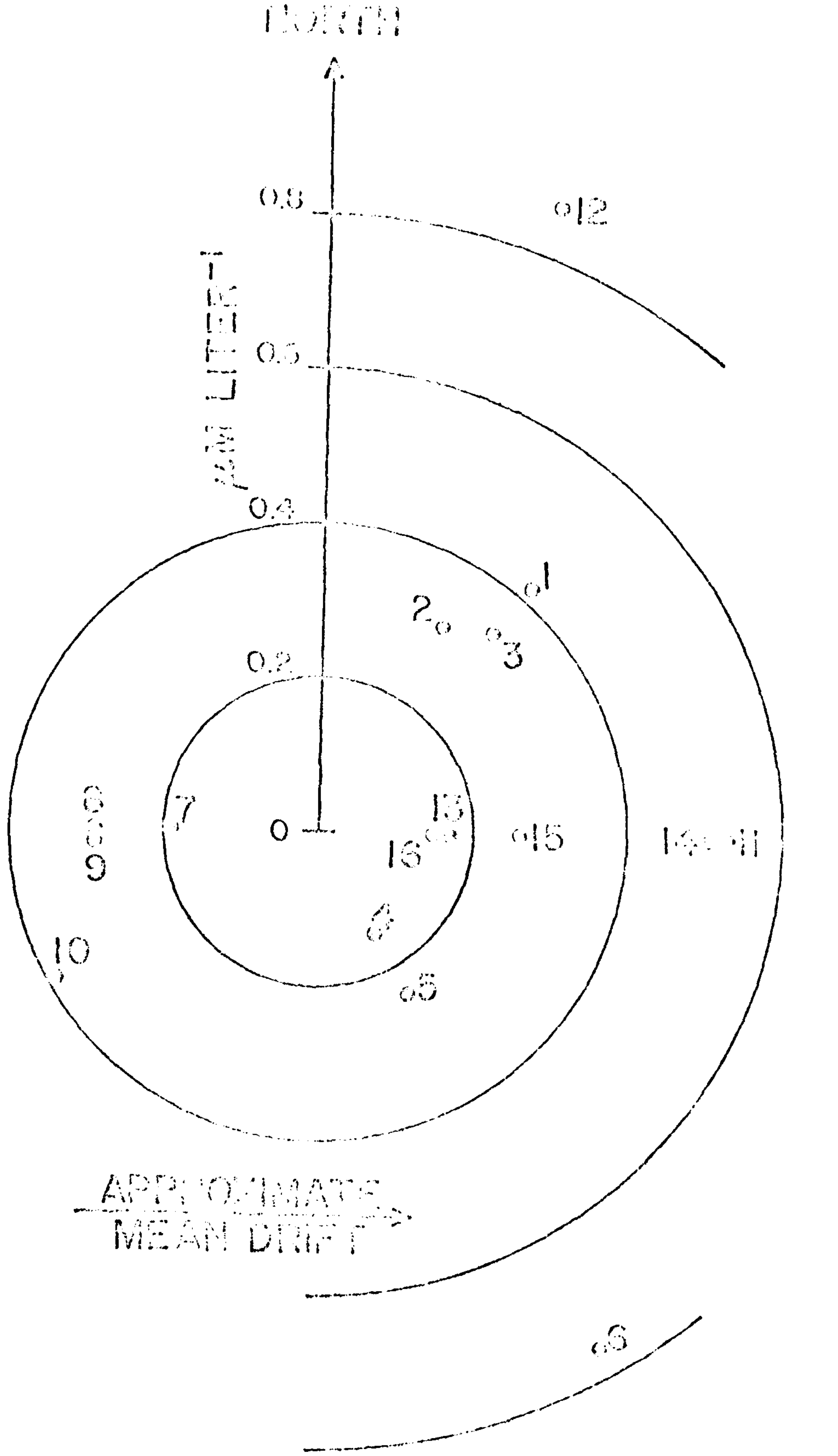

CHLOROPHYLL
Δ MAX, %
60
50
40
30
20
10
10 20 30 40 50 60
TEMPORAL SEPARATION, hours



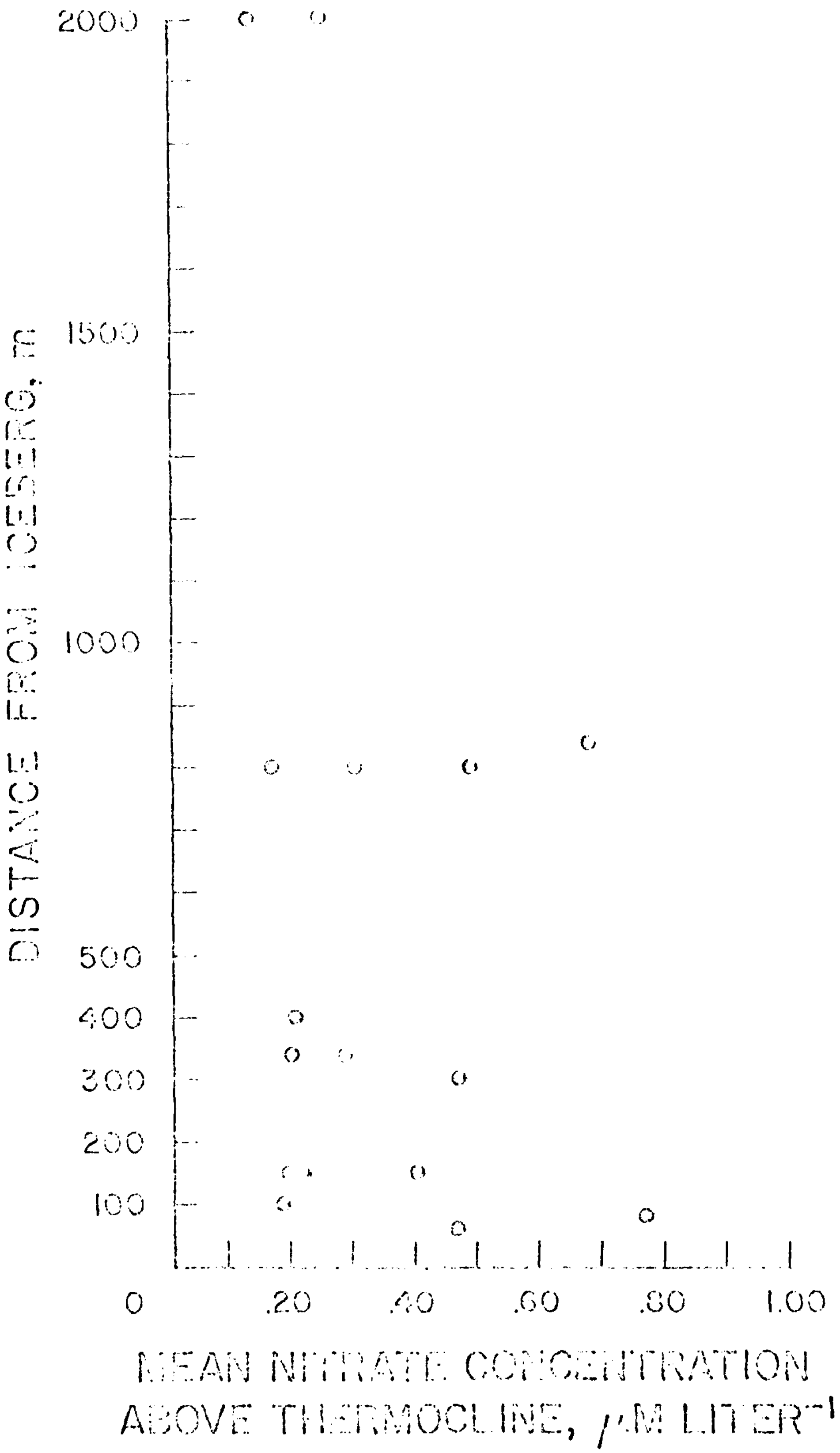
DEPTH, m
0
20
40
60
80
100
120
140
PO4
SiO2
NO3
CAST#4
0 5 10 15 NO3
0 .5 1.0 1.5 PO4
0 5 10 15 SiO2
CONCENTRATION, µM LITER⁻¹



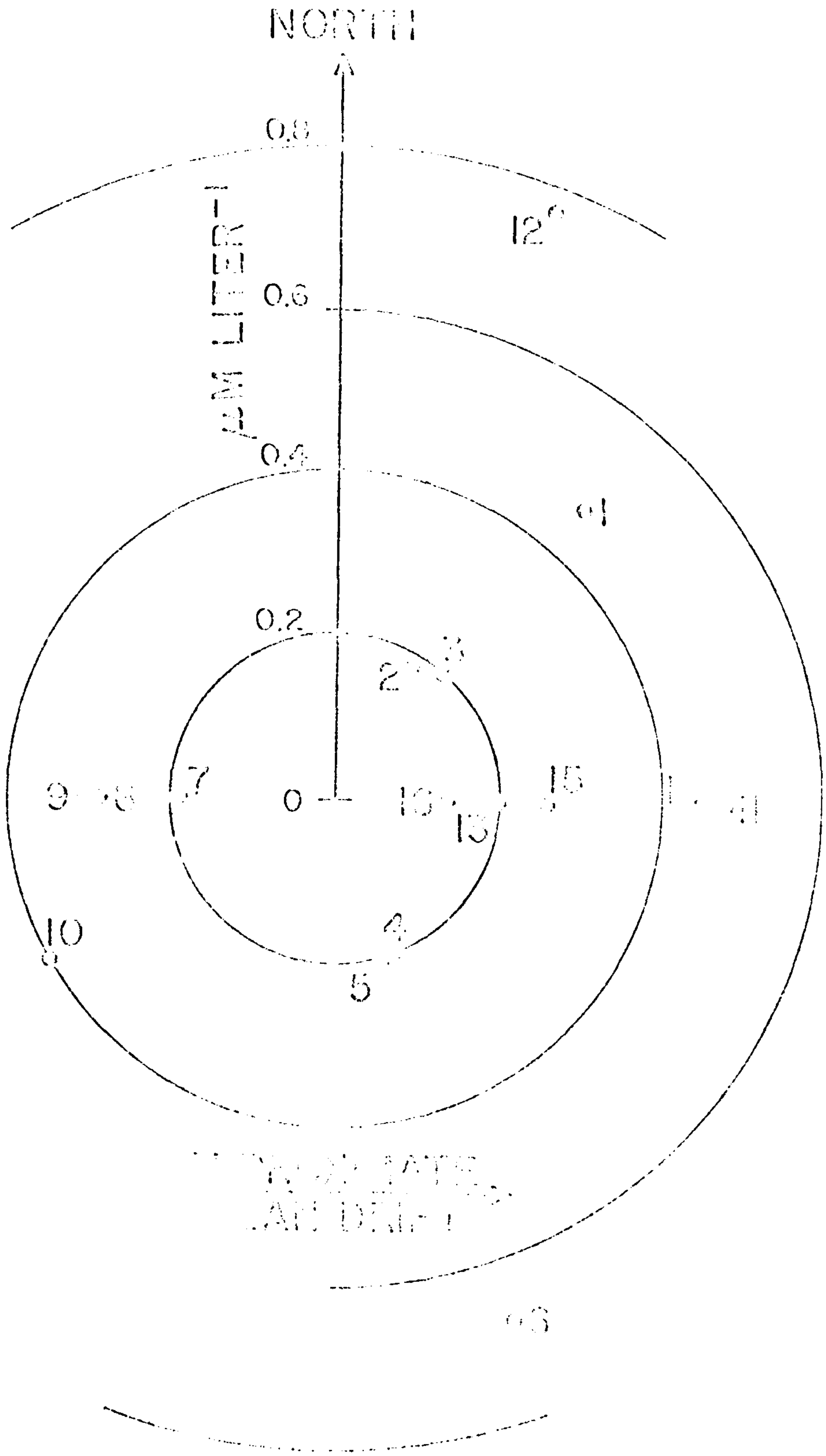
DISTANCE FROM ICEBERG, m
2000
1500
1000
500
400
300
200
100
O = NO_3
□ = PO_4
0
.5
1.0
NO_3
.30
.40
.50
.60
.70
.80
PO_4
SURFACE CONCENTRATIONS
μM LITER^{-1}



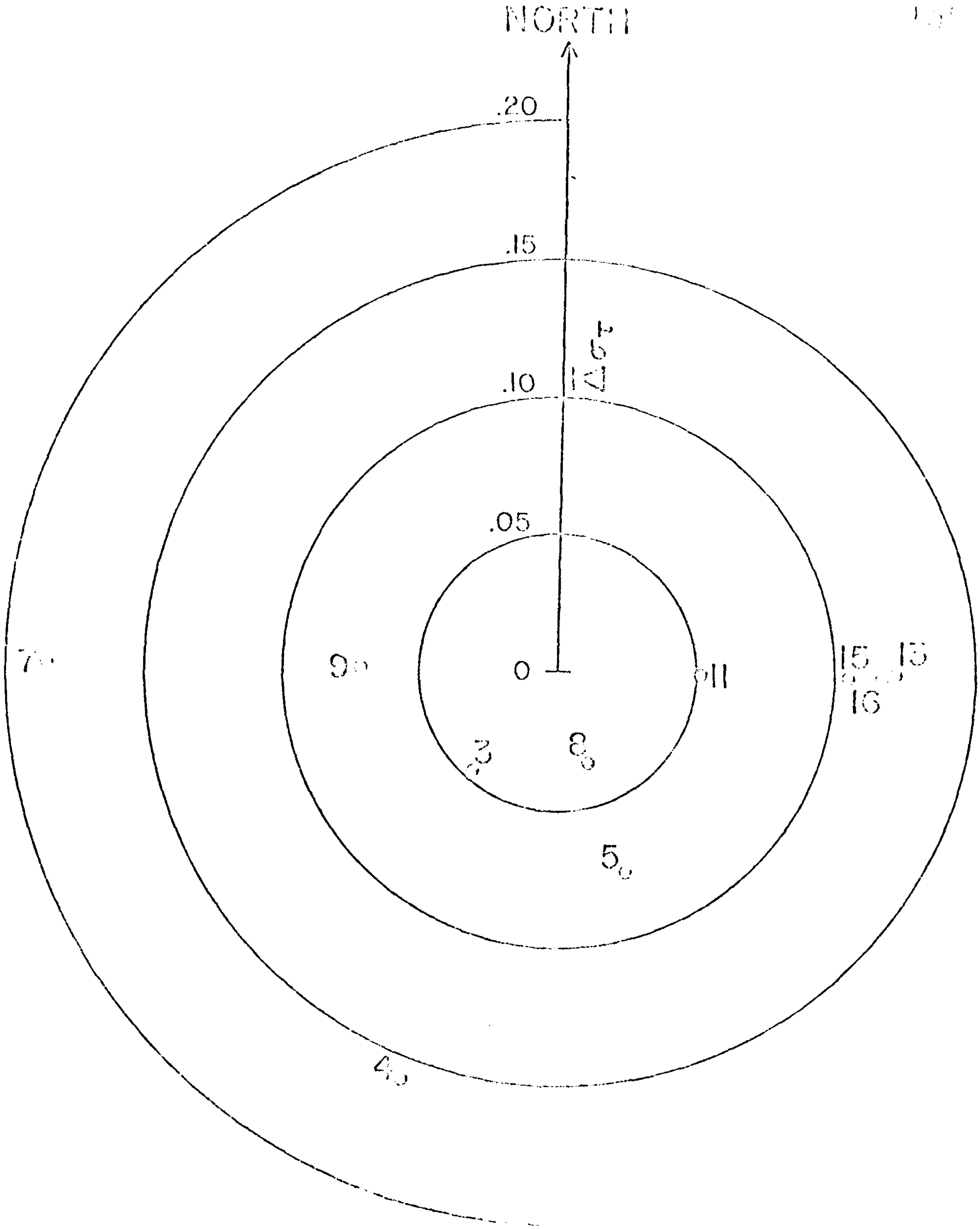
BEARING TO ICEBERG vs SURFACE NITRATE



DISTANCE FROM ICEBERG, m
2000
1500
1000
500
400
300
200
100
0
.20
.40
.60
.80
1.00
MEAN NITRATE CONCENTRATION
ABOVE THERMOCLINE, μM LITER⁻¹



MEAN NITRATE CONCENTRATION ABOVE
THE THERMOCLINE VS FLARING



BEARING TO HERO vs. STRENGTH OF BREAK IN $\overline{\Delta}\sigma_t$


FILMED
8