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SUSPENDED SEDIMENT DISTRIBUTION PATTERNS WITHIN AN ACTIVE TURBID-OUTWASH FIORD

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INTRODUCTION

This contribution is concerned with the characterization and dynamics of suspended sediment within an active, sub-arctic, turbid-outwash (1) fiord. The system studied is a discrete inlet within Glacier Bay National Monument in S.E. Alaska (Fig. 1). Queen Inlet is a typical uni-glacial fiord (approximately 1 x 6 miles) with high and steep rock-walls, a valley-type glacier (Carroll Glacier) and an out-wash fan laced by melt-water streams which enter the sea via an inter-tidal mud-flat area. The overall long-term climatic effect in S.E. Alaska is such as to cause a general glacial retreat, but Carroll Glacier appears to have advanced possibly by as much as one mile since these studies were initiated. The distance between the glacier-face and the marine fiord is now (1971) something in excess of one half-mile. The bedrock of the area is predominantly foliated granites and carbonates forming the steep sub-aerial walls typical of valley glaciation; the depth of recent sediment overlying the basement within the fiord is unknown at present.

The majority of the Glacier Bay fiords are "glacial" (1), i.e. the glacier front is in direct contact with the marine waters. Queen Inlet, by contrast, is a perfect example of a "turbid-outwash" fiord and as such has been studied and monitored annually since 1966. Slatt (2) has shown that the size distribution of the transported sediment is independent of the parent glacially-abraded bedrock. Likewise, the mineralogy of the clay-sized material is dependent more upon the indigenous sub-arctic weathering environment than the nature of the source rock. This latter mineralogy is simple; a preponderance of trioctahedral mica and Mg-rich chlorite which is closely comparable with adjacent Alaskan fiord localities (3,4). Other distinctive features of the clay-sized sediment include an abundance of primary mica and amphibole, an almost total absence of quartz below 1μ, and high cation exchange capacities (5). These characteristics are a function of the glacial origin and rapid transportation and deposition of the sediment under sub-arctic conditions.

Burrell and Hoskin (6) and Hoskin and Burrell (7) have considered the complete transport and accumulation portion of the sedimentary cycle within this fiord-estuary, including evidence for submarine turbidity-flow. Fig. 2 (from 7) is a physiographic representation of the fiord floor which includes the pronounced channels associated with the latter postulated flow. It should be noted that Queen Inlet is not terminated seaward by a complete entrance-sill. Such a barrier exists northwards from Composite Island (Fig. 3) but is entirely absent from the eastern channel. The bathymetry falls off dramatically from this latter passage into Glacier Bay proper, such that, if viewed sub-aerially, the inlet would have a classic truncated hanging-valley configuration. There is thus no question of sediment being deposited within a closed basin, or of the formation of stagnant bottom water masses.

HYDROGRAPHIC CYCLES

The principle fresh-water inflow into Queen Inlet is from Carroll Glacier melt-water during the short summer season. In the early part of the summer following break-up (June) one or two streams follow well-defined courses through the terminal moraine and across the inter-tidal mud-flat area. One such channel has always flowed between Triangle Island and the east wall but, in general, these channels vary from year to year, not least because the general glacial advance continually distorts the character of the terminal moraine. Through summer and early fall the volume of fresh-water inflow continually increases and the discrete nature of the streams is lost. By September, run-off usually covers the mud-flat area at low-tide from side to side. Several lateral valleys add fresh-water and sediment into Queen Inlet also but their combined volume is negligible in comparison to the principle glacial melt. Attempts have been made (Heggie, unpublished data) to calculate a summer freshwater accumulation value using both the method of Ketchum (8) and flood-tide quasi-synoptic salinity data. The former method, assuming a freshwater inflow of 4 x 10^8 cu. ft. per tidal cycle, gave (using a 50 m mixing depth) an accumulation of 10^{10} cu. ft. which was some five times greater than that calculated by the second method. The corresponding flushing times are 12 and 2 days respectively. It would appear that the value assumed for the freshwater inflow for this set of calculations is too high. From sedimentation dynamics discussed below, it is felt that a mean summer-time inflow of around 10^8 cu. ft. per tidal cycle may be reasonable.

Fig. 4 shows the density structure of the surface 50 m over a complete tidal cycle at the head of the inlet and at a time of maximum freshwater inflow. It should be noted that the pronounced shallow pycnocline is permanent but - as will be shown - the unflocculated sediment plume is maintained only in very low-salinity water. The annual salinity distribution at the same locality is given in Fig. 5. In April, prior to break-up and hence in the absence of freshwater inflow, the fiord is close to vertically iso-haline. At this time the surface waters are being warmed; in the middle of winter this trend is reversed and the waters are well-mixed throughout the fiord. From June through September the cold, freshwater entering at the head of the fiord (aided by surface warming) yields a stabilized surface stratification. Beneath this layer, the marine waters become colder and more saline in a regular fashion. This is a characteristic configuration; but it should be noted that the bottom waters do exchange during the summer months, becoming progressively warmer and less saline, and essentially following the contiguous Glacier Bay pattern (9). Fig. 6 (from 7) illustrates the quasisynoptic temperature structure for a standard longitudinal section (see Fig. 3; and 10) at the low water-flood tidal stage in July. Entrance-to-head conditions are shown to the right of the vertical dashed-line; the profile to the left is towards the sill between Composite Island and the north shore and thus represents a "back-water" area. The surface structure due to the glacial melt-water, and the core of Glacier Bay water ($>5.7°C$ and >30.7 °/₀₀ salinity) within the structure is well seen.

PARTICULATE SEDIMENT TRANSPORTATION

Fig. 7 illustrates the inter-tidal mud-flat area viewed towards Carroll Glacier. At low-water vast quantities of sediment are transported by the glacial melt-water into the fiord proper. Stream flows have not been directly measured, but velocities exceed the threshold values necessary to transport coarse silt-sized material. Suspended sediment concentrations exceed 1g/l at the seaward termination of the inter-tidal flats. Much of this material is re-cycled back to the latter area on the flood tide, and permanent losses are replenished from the moraine reservoir such that the system is very approximately in balance during the summer months. The mean unconsolidated clay-silt sediment deposit on the flats may exceed 2 m at this time. With the cessation of freshwater input during fall and winter, this cover is gradually lost. By spring, the inter-tidal surface consists largely of sand-sized and coarser material.

The summer freshwater input to the fiord forms a thin (few cm) prism of cold water upon the marine surface. In Queen Inlet this prism is, at least initially, an opaque sediment-laden plume. (In some adjacent nonturbid estuaries the initial fresh-marine boundary is sharp and clearly visible).

SEDIMENTATION: MECHANISMS AND RATES

Flocculation

At low-water, the sediment plume maintains its identity for several miles down the inlet, but biased toward the west side, as might be expected in this high-latitude environment. Fig. 8 (from 7) illustrates an approximately synoptic distribution of the plume between the low-water line (L.W.) and boundary A at this tidal-stage in early September. Boundary A is visually sharp and separates the principle plume from a diffuse plume zone which merges gradually into the non-turbid marine environment (very approximately the diffuse boundary B). It may be seen that the sediment loads collected from the surface 5-10 cm (S.L. in g/l) are not markedly different in these two defined plume zones. Boundary A represents the sediment flocculation front which occurs with mixing of the freshwater prism to approximately 4 $^\circ/_{\circ\circ}$ salinity. Once initiated, the flocculation proceeds rapidly because of the extremely high particulate concentration in the plume (e.g. 11). Flocculation at this salinity has been confirmed by laboratory experiment, and the aggregates appear to range up to at least 1 mm in size. The visually defined diffuse plume (between boundaries A and B of Fig. 8) is thus the zone of initial flocculation prior to settling of the sediment beyond surface observation. The concomitant exchange of non-structural ions (c.f. 12), while not considered to be the prime mechanism for initiating the aggregation process, undoubtedly adds stability to the resultant floc.

Vertical distribution of suspended sediment

The suspended sediment load distributions within the marine column have been monitored at the head of the fiord at various times during the June - September period of freshwaters in-flow. At all times during this season, sediment is concentrated in distinct horizontal bands. In June - July immediately following break-up, and in late September - October, at the time of cessation of freshwater flow, these bands are widely spaced in the column; e.g. Fig. 9. During the period of maximum freshwater in-flow (e.g. Fig. 10) the sediment bands are more closely spaced. It is believed that such layers represent individual tidal flocculations, and these data thus indicate vertical sediment velocity vectors of around 3-10 m/hr. At the beginning and end of the summer season, surface freshwater and entrained saline out-flow, and in-flow at depth, are both minimal so that the settling rate of the sediment is greatest. Values for this parameter in excess of 10 m/hr would be consistent with the observed floc sizes (e.g. 13). Conversely, the enhanced advective flow in early September slows the effective sedimentation rate. The substitution of continuous transmissiometer profiles for the more tediously obtained and non-continuous direct load determinations has been shown to not bias these results.

The enhanced sediment loads adjacent to the bottom sediment boundary (e.g. Fig. 9) were commonly observed and are considered to be due to re-suspension of deposited sediment by flow at depth up the inlet. Direct current measurements have given mean velocities around 0.1 kt (surges to 0.5 kt), sufficient to transport silt-range particles by turbulent flow.

Size spectra

The upper clay- to silt-sized fraction of the suspended sediment has been studied using Coulter Counter techniques (14). This method necessitated prior removal of particles in excess of 64 μ, and the data are open-ended at the lower size range and limited in accuracy by machine noise. Fig. 11 shows volume concentrations (ppm; closed circles) together with total load values (mg/l; crosses). These volume and weight concentration trends determined by two totally independent methods are closely similar, suggesting that the silt fraction is reasonably well representative of the total sample.

These techniques measure the primary particle sizes, not the aggregated flocs. The principle suspended sediment mode measured at 7.6 ϕ is close to (but does not exactly duplicate) the major mode of the deposited sediment ("flat bottom" facies of 7). This discrepancy may be due to the totally different size analysis methods utilized, but the "flat bottom" sediment size distribution is, in any case, mesokurtic, and the modes are diffuse. The silt-size spectra of the major suspended sediment bands are identical.

Deposition rates

Utilizing the maximum plume concentration data for the standard station at the head of Queen Inlet (referenced frequently above), an indicated deposition rate at that locality of around 30-40 cm/yr is given when tenuously extrapolated over an idealized "open season". A mean inlet value of around 10 cm/yr may be calculated assuming a freshwater in-flow (carrying a standardized load) of 10^8 cu. ft. per tidal cycle and total deposition over only 10% of the fiord surface area.

Bottom sediment profiles all contain very thin layers of fine-grained black material. These marker horizons are repeated on an approximately regular pattern within individual cores, with band spacings decreasing seawards (Fig. 12 from 7). It would appear that these layers are produced on a regular cyclic basis, and annual production would, *a priori*, appear most feasible. If so, then deposition rates in excess of 1 m/yr are indicated.

These deposition rate data estimated by various methods are not incompatible considering the severe assumptions made. It is believed that the calculations derived from empirical load measurements are likely to produce minimal values and they do not, in any case, take acccount of sedimentation by other mechanisms. Evidence for bottom turbidity flow has been noted elsewhere. Likewise, there is no direct evidence at this time for the assumption of annual production of the marker horizons described above; although subsequent removal of deposited sediment is a negative factor to be considered also. Queen Inlet is not, as noted, a closed basin system. The rate of deposition/accumulation decreases seaward and it would appear that the equilibrated system includes systematic sediment losses to Glacier Bay.

DEPOSITED SEDIMENT FACIES

A basic two-fold subdivision of the deposited fiord bottom sediment has been described by Hoskin and Burrell (7). The uniformly distributed "flat bottom" sediment type may be correlated with the flocculated suspended sediment as described. This material has a mesokurtic size distribution, with major modes in the silt size-range. Such size distribution descriptions are, of course, open-ended since no data exist for the sediment finer than 10 ϕ. This amounts, an average, to some 40% w/w of this facies. The deposited sediment texture is shown in Fig. 13 (O'Brien, unpublished data) which well illustrates the structure of the primary particle aggregates.

SUMMARY

Vast quantities of glacially derived sediment are transported during the short summer season within this turbid-outwash fiord system. It is suggested that some material flows periodically via turbidity currents at the sediment surface into the basin area, but the major sedimentation mechanism appears to be flocculation from the highly distinctive freshwater plume. This thin freshwater prism spreads over the marine surface and extends several miles seaward at low-water. Flocculation of the highly concentrated silt-clay sized suspended sediment occurs rapidly following mixing with the underlying saline water to around 4 ‰ salinity, and primary particle aggregates in the mm. Size range may be produced. This latter material settles in distinct tidal bands through the water column at velocities varying between approximately 3-10 m/hr depending upon seasonal horizontal advection rates. Mean deposition rates of 10-40 cm/yr have been calculated, and marker horizons within the bottom sediment suggest that values in excess of 1 m/yr may be possible at the extreme head of the inlet. Deposition decreases seawards. The deposited sediment exhibits a remarkably uniform and distinctive texture and mineralogy which is characteristic of this sub-arctic fiord environment, rather than of the source material.

ACKNOWLEDGEMENTS

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FIGURES

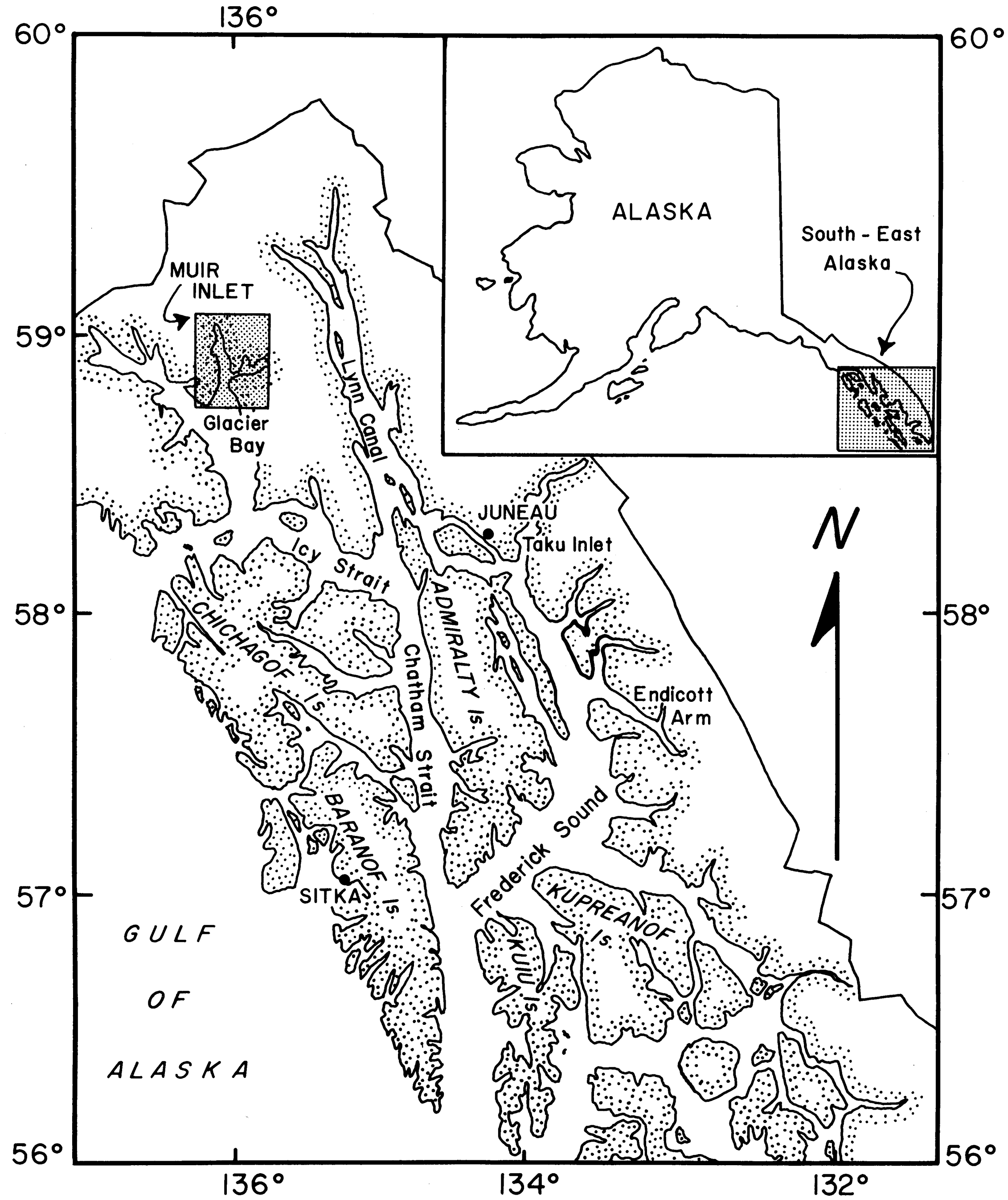

136°
60°
60°
59°
58°
58°
57°
57°
56°
56°
136°
134°
132°
ALASKA
South - East
Alaska
MUIR
INLET
Glacier
Bay
Lynn Canal
JUNEAU
Taku Inlet
N
Icy Strait
CHICHAGOF Is.
Chatham Strait
ADMIRALTY Is.
Endicott
Arm
Frederick Sound
BARANOF Is.
SITKA
KUPREANOF Is.
KUIU Is.
GULF
OF
ALASKA

Figure 1.

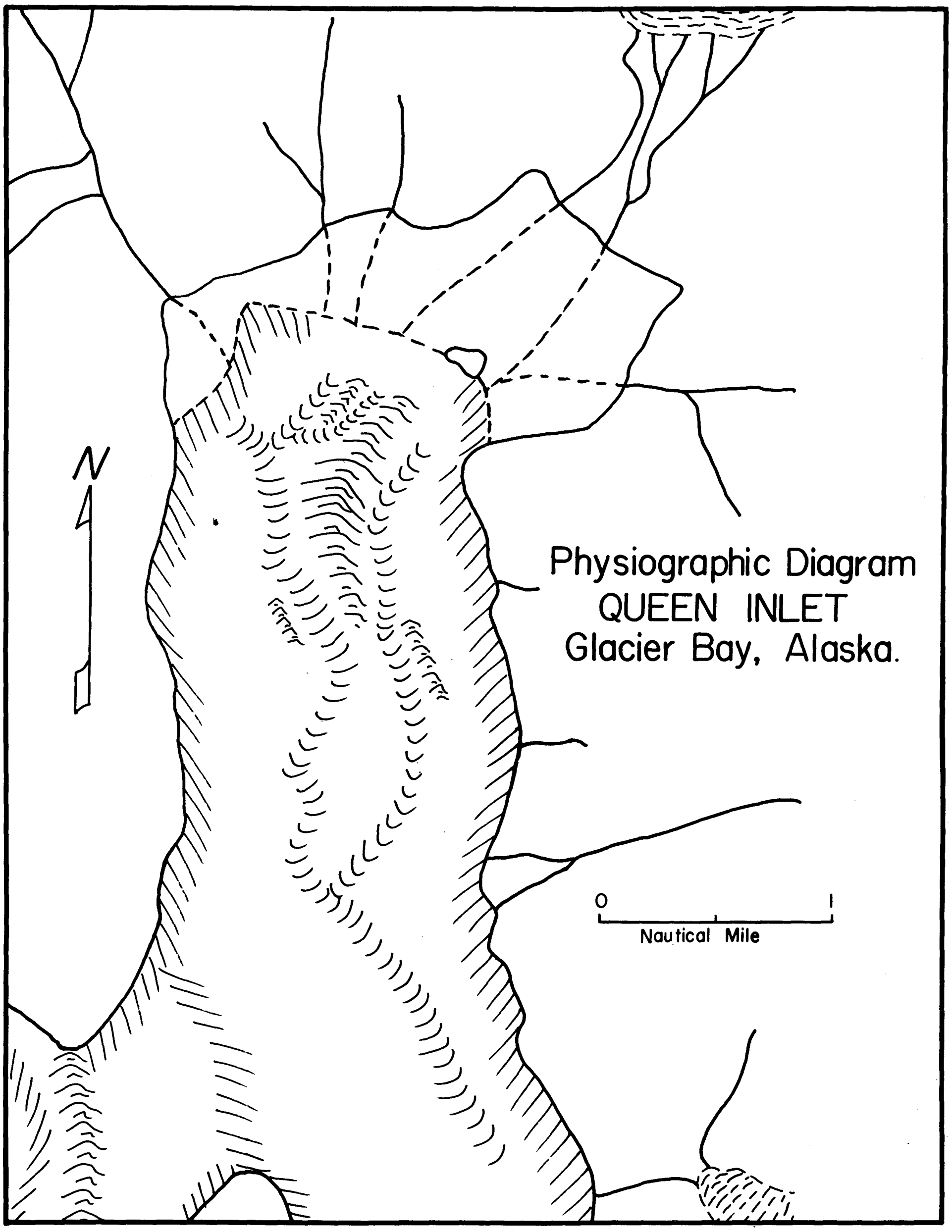

N
Physiographic Diagram
QUEEN INLET
Glacier Bay, Alaska.
0
1
Nautical Mile

Figure 2.

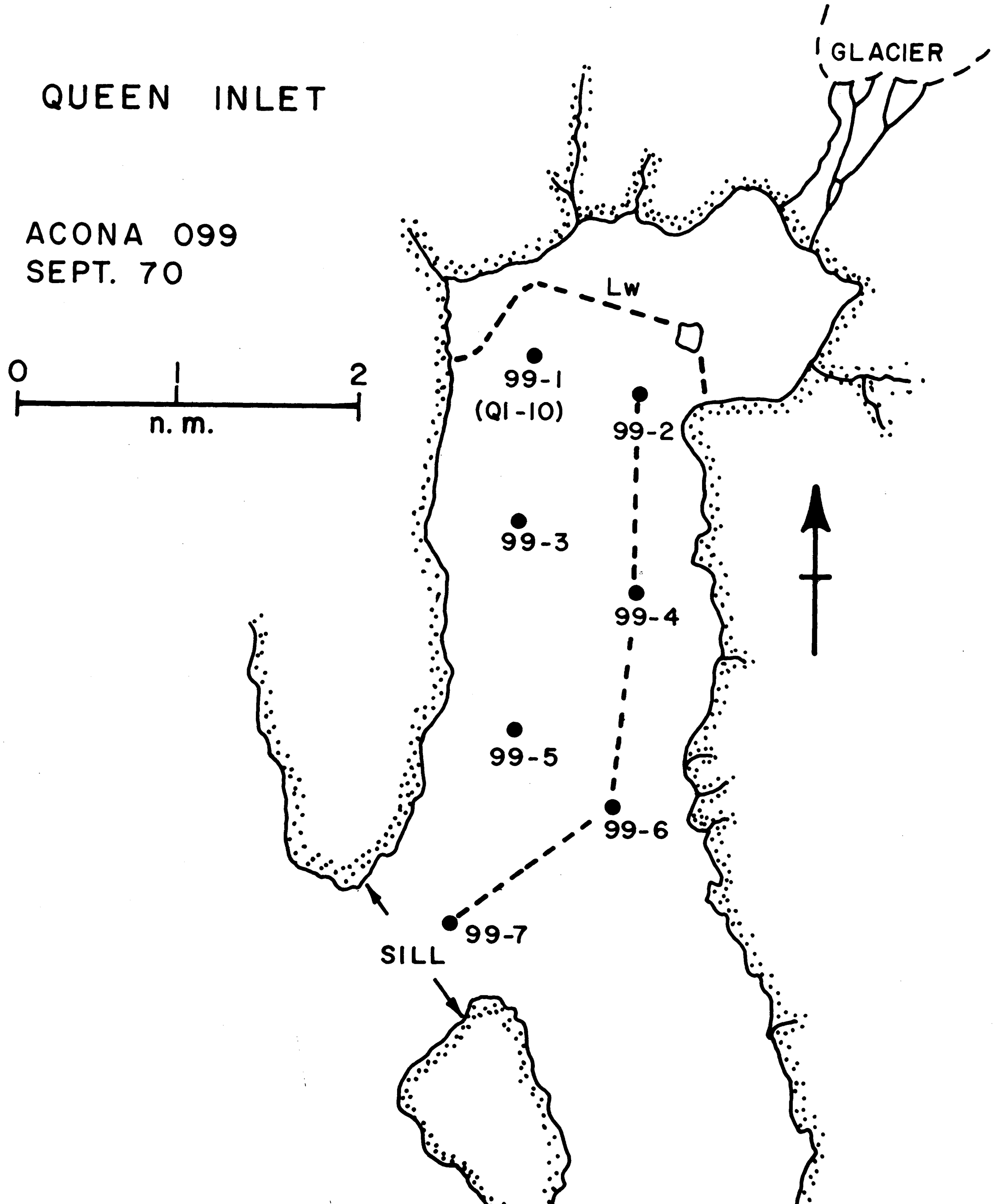
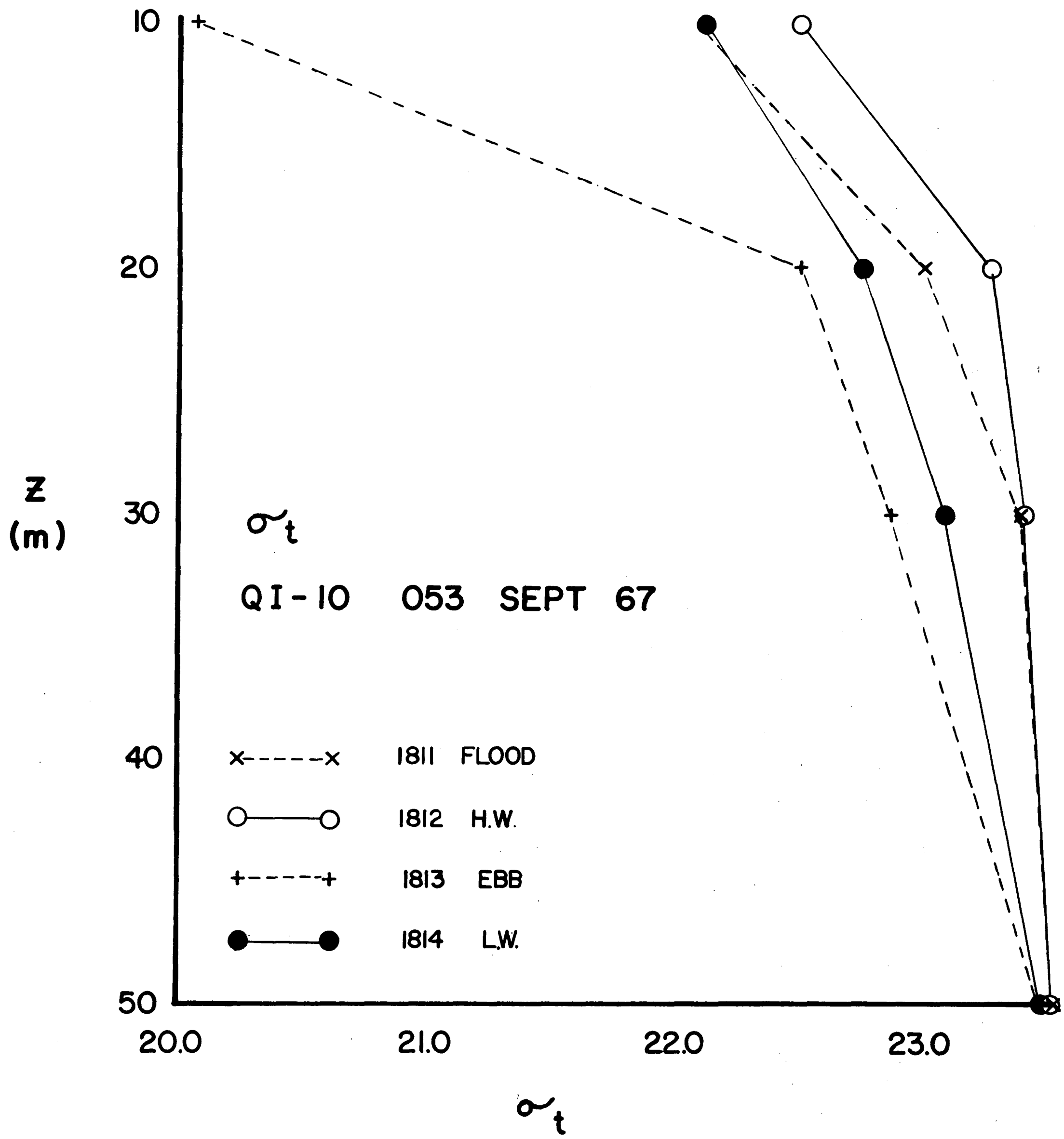
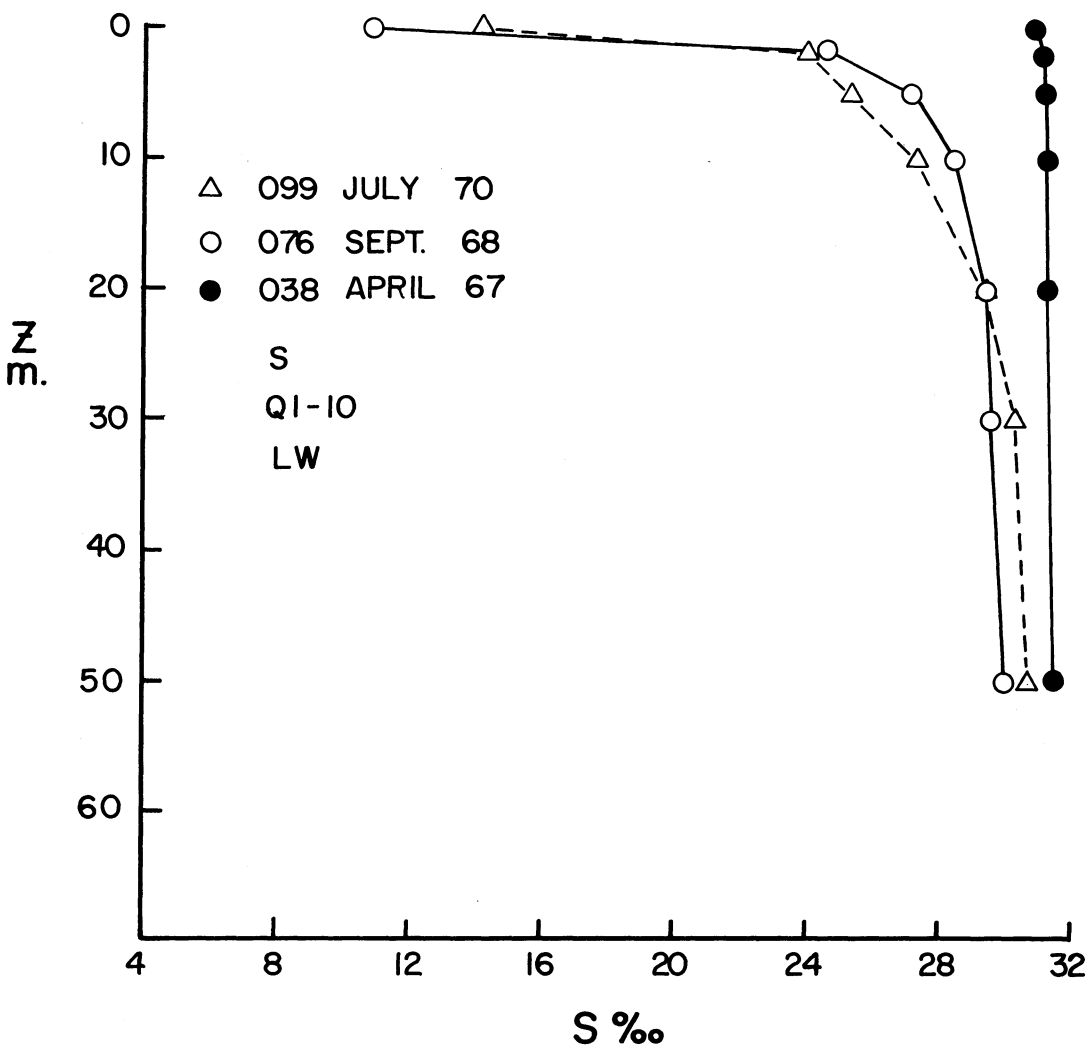

QUEEN INLET
ACONA 099
SEPT. 70
0
1
2
n. m.
GLACIER
Lw
99-1
(QI-10)
99-2
99-3
99-4
99-5
99-6
99-7
SILL

Figure 3.



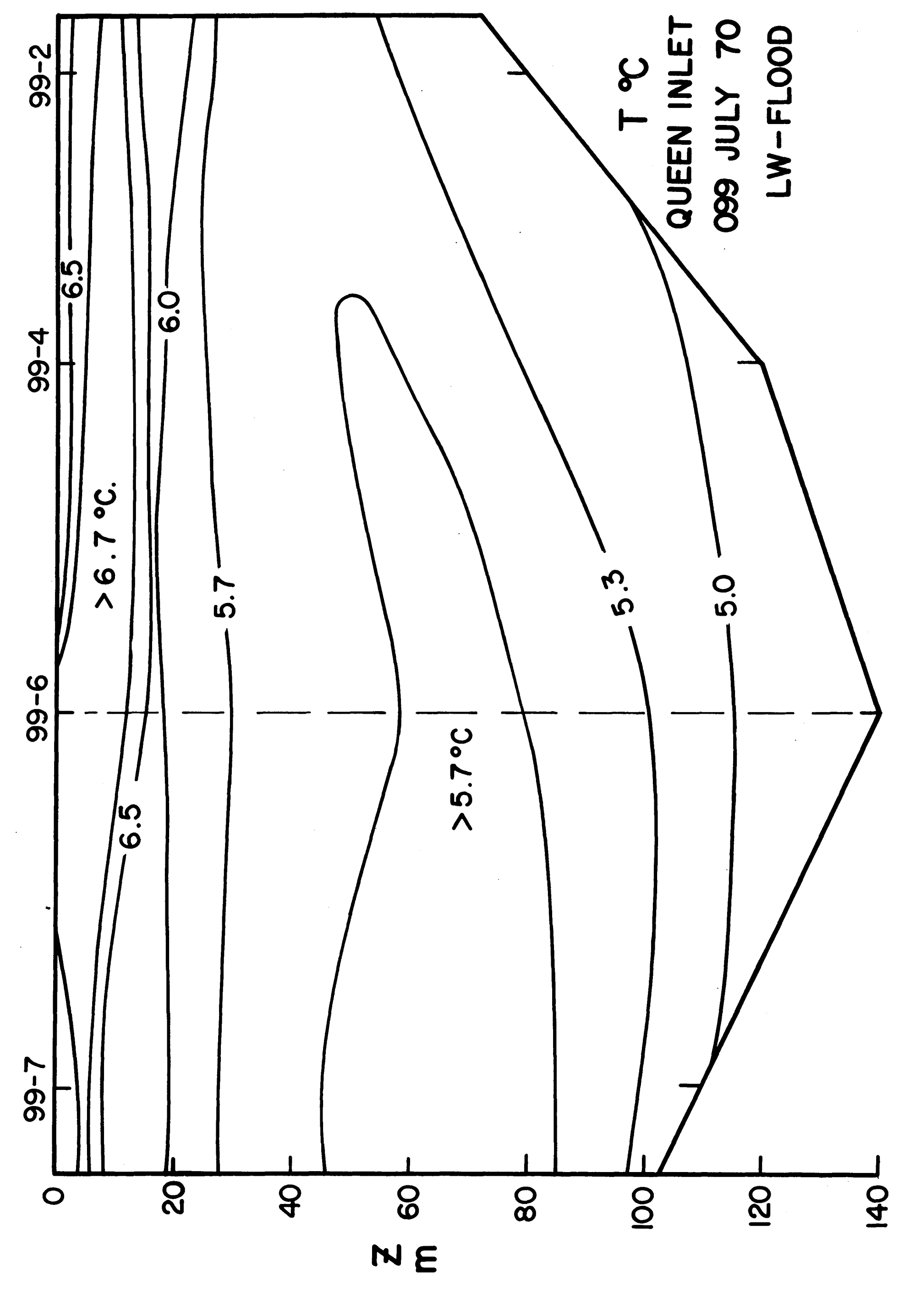
10
20
30
40
50
Z
(m)
σt
QI-10 053 SEPT 67
×-----× 1811 FLOOD
○——○ 1812 H.W.
+-----+ 1813 EBB
●——● 1814 L.W.
20.0
21.0
22.0
23.0
σt

Figure 4.



△ 099 JULY 70
○ 076 SEPT. 68
● 038 APRIL 67
S
Q1-10
LW
Z
m.
0
10
20
30
40
50
60
4
8
12
16
20
24
28
32
S ‰

Figure 5.



T °C
QUEEN INLET
099 JULY 70
LW-FLOOD
99-2
99-4
99-6
99-7
Z
m
0
20
40
60
80
100
120
140
6.5
6.0
5.7
5.3
5.0
>6.7 °C.
>5.7°C
6.5

Figure 6.

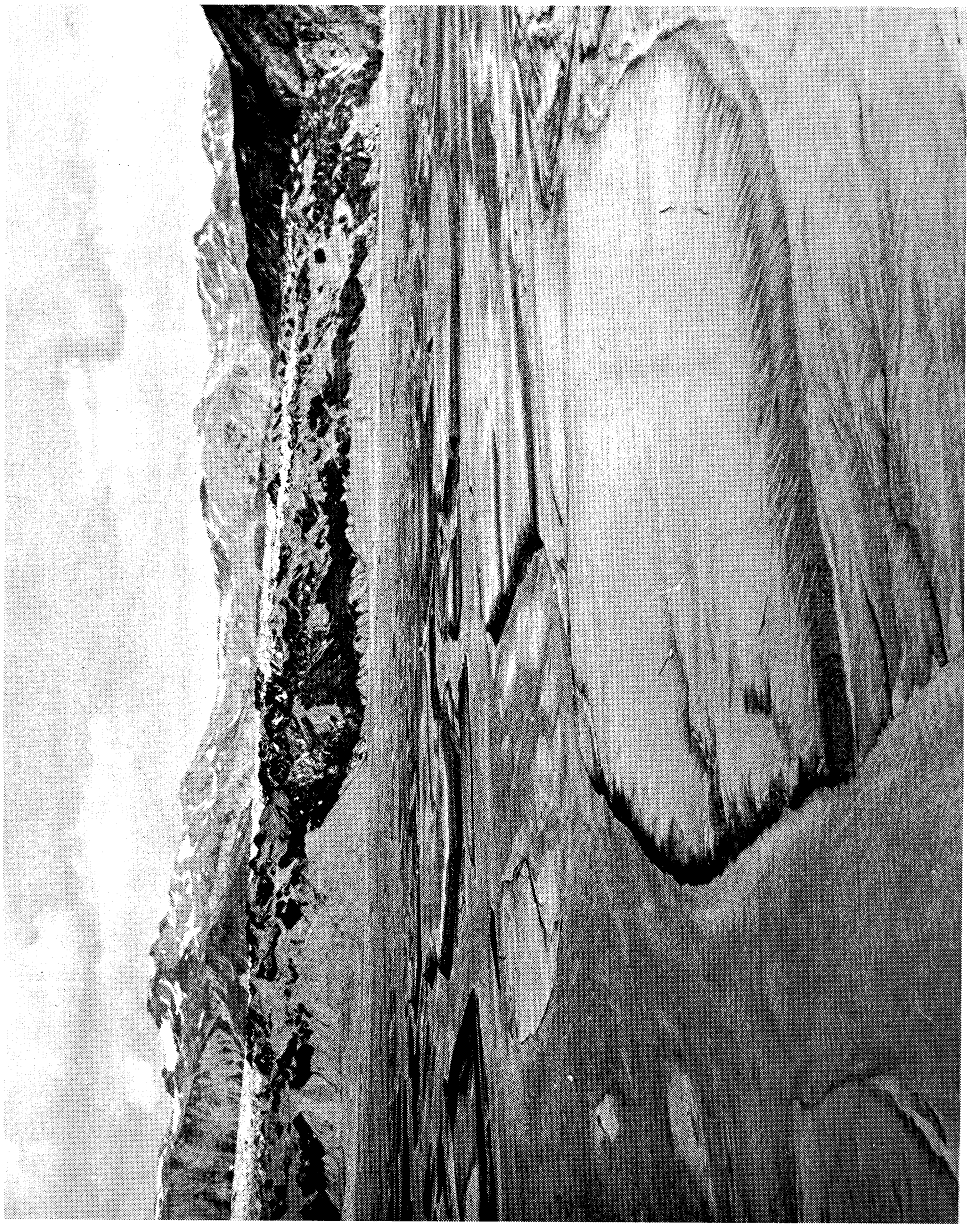


Figure 7.

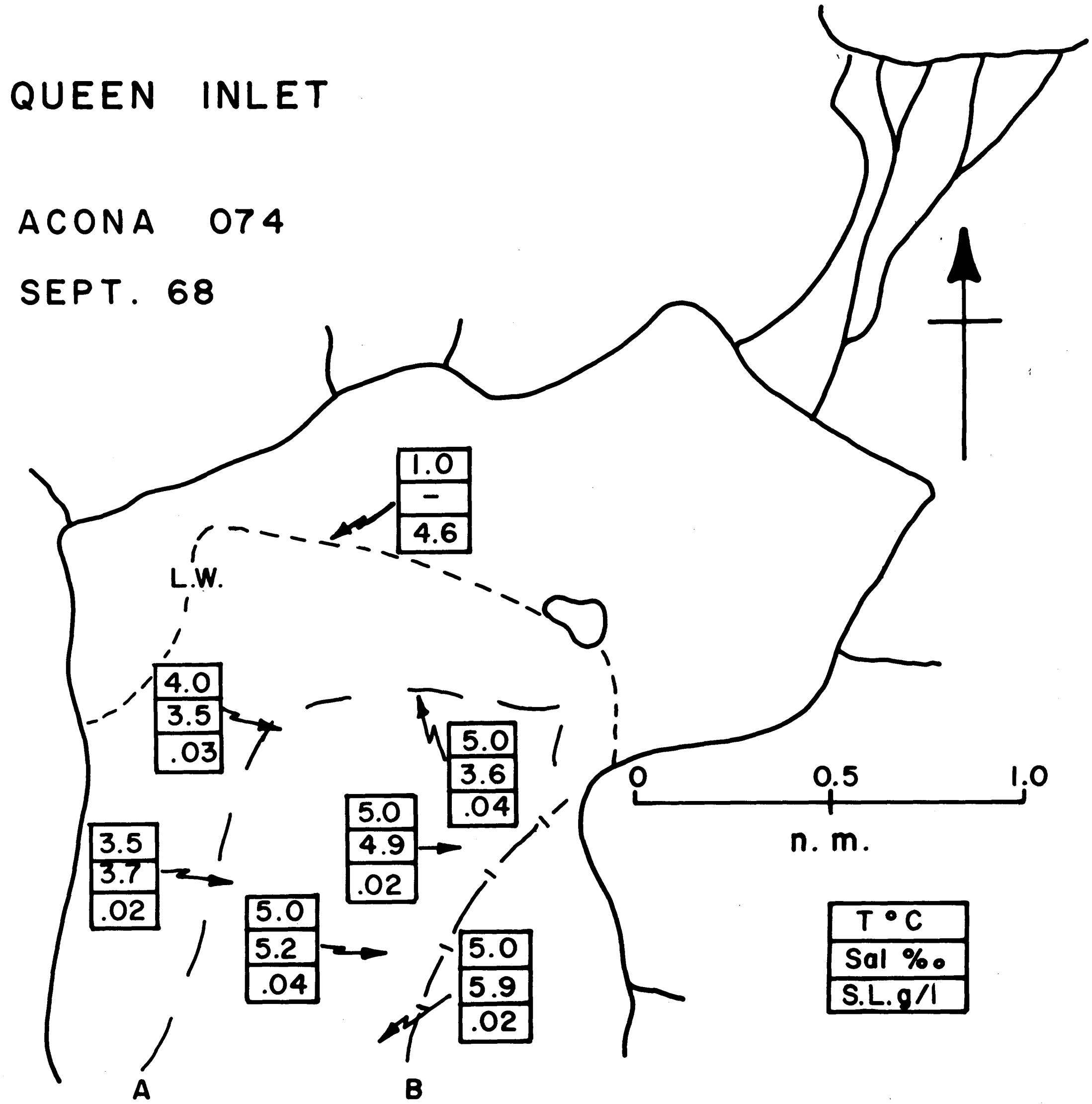

QUEEN INLET
ACONA 074
SEPT. 68
1.0
–
4.6
L.W.
4.0
3.5
.03
5.0
3.6
.04
5.0
4.9
.02
3.5
3.7
.02
5.0
5.2
.04
5.0
5.9
.02
A
B
0
0.5
1.0
n. m.
T °C
Sal ‰
S.L. g/l

Figure 8.

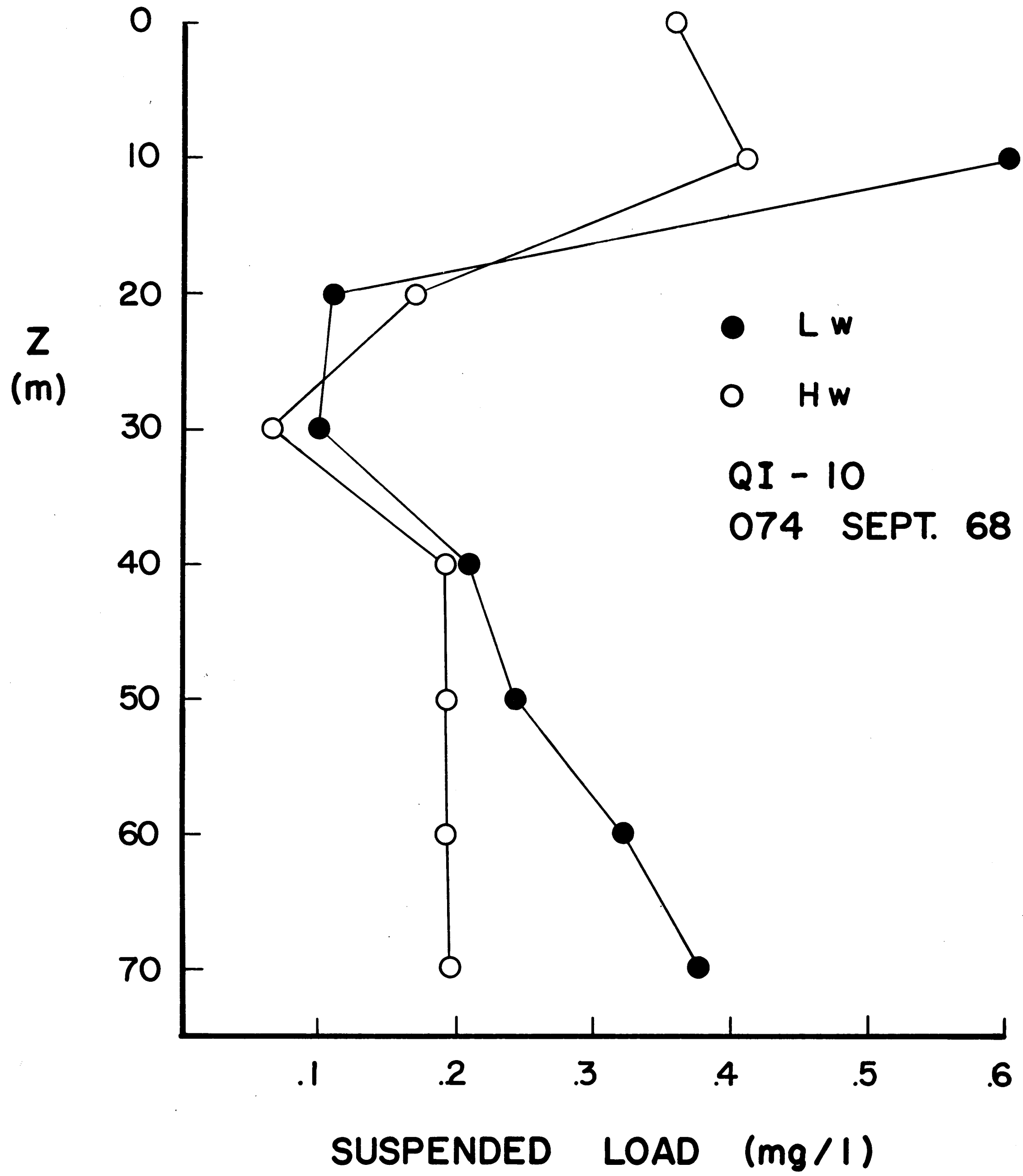

Z
(m)
0
10
20
30
40
50
60
70
.1
.2
.3
.4
.5
.6
SUSPENDED LOAD (mg/l)
L w
H w
QI - 10
074 SEPT. 68

Figure 9.

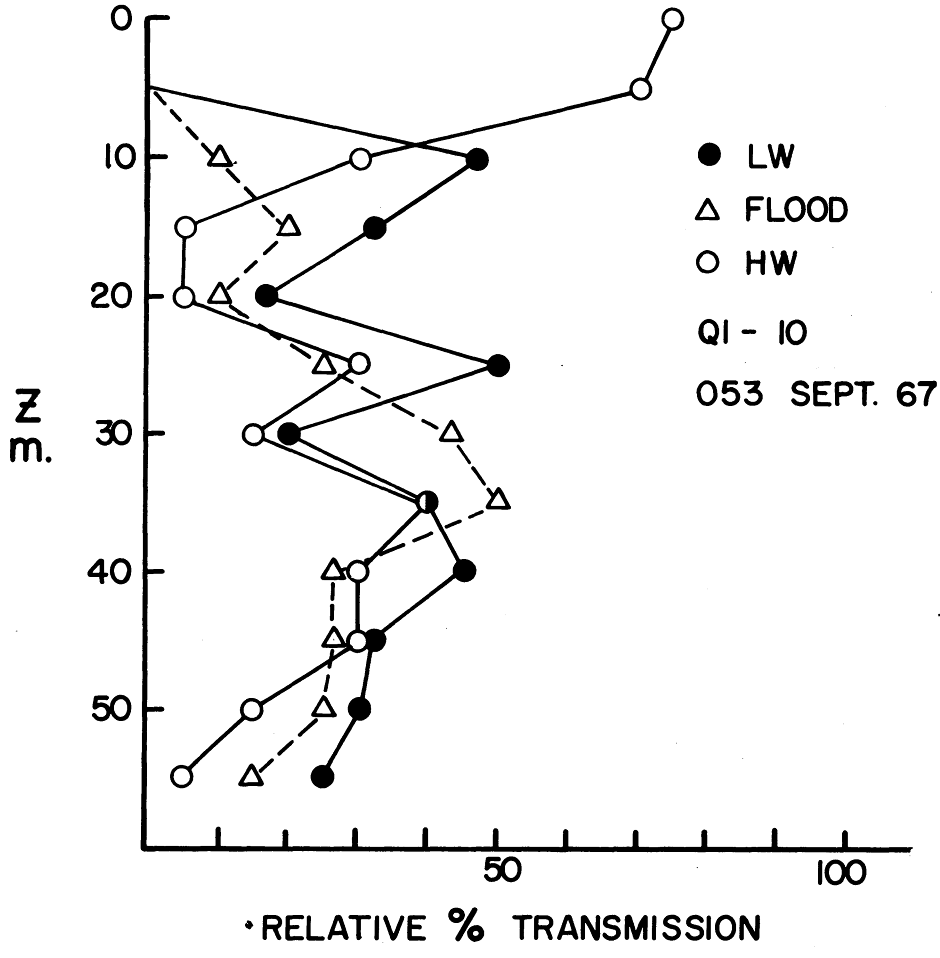

0
10
20
30
40
50
Z
m.
LW
FLOOD
HW
QI - 10
053 SEPT. 67
50
100
RELATIVE % TRANSMISSION

Figure 10.

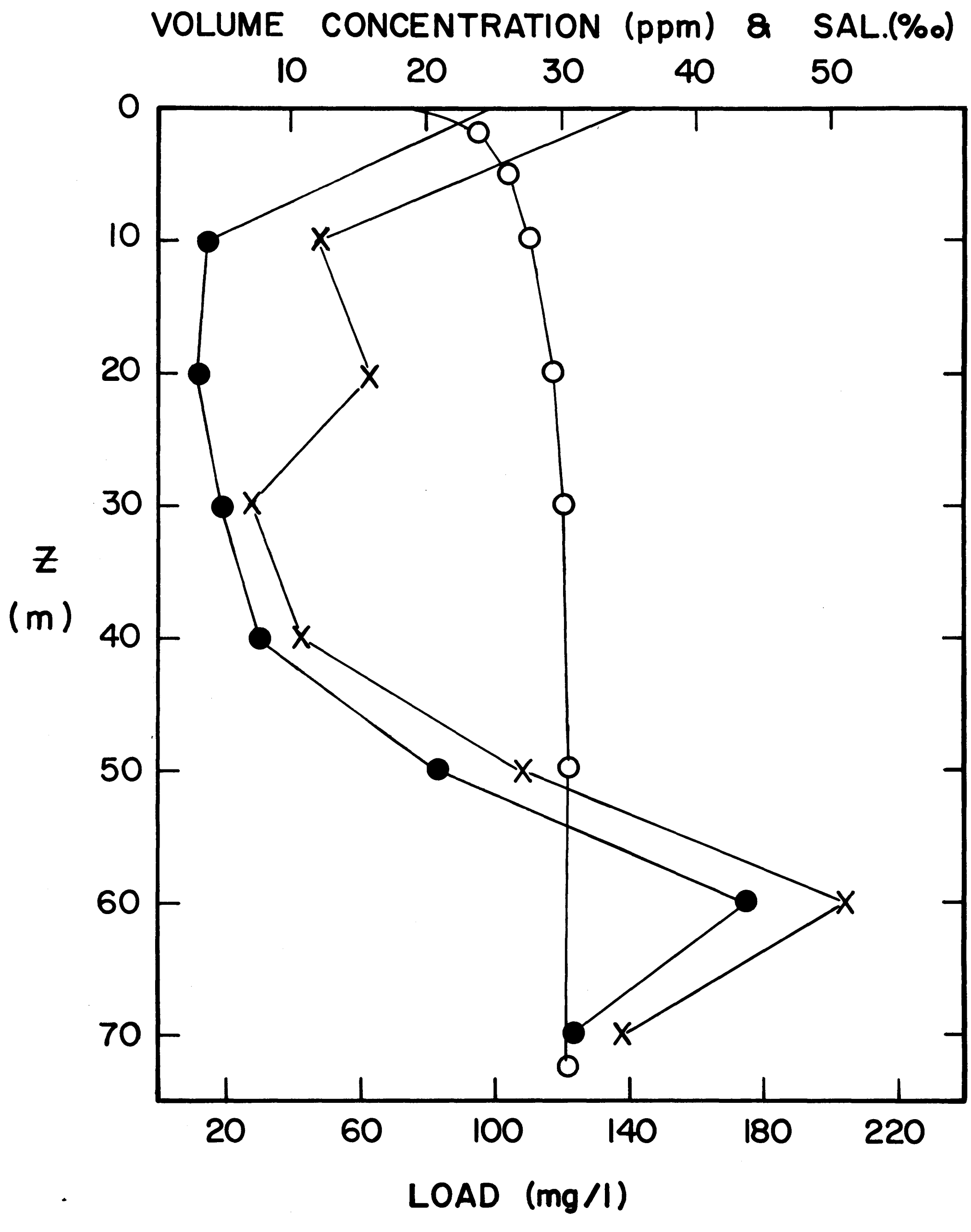

VOLUME CONCENTRATION (ppm) & SAL.(‰)
10 20 30 40 50
0
10
20
30
40
50
60
70
Z
(m)
20 60 100 140 180 220
LOAD (mg/l)

Figure 11.

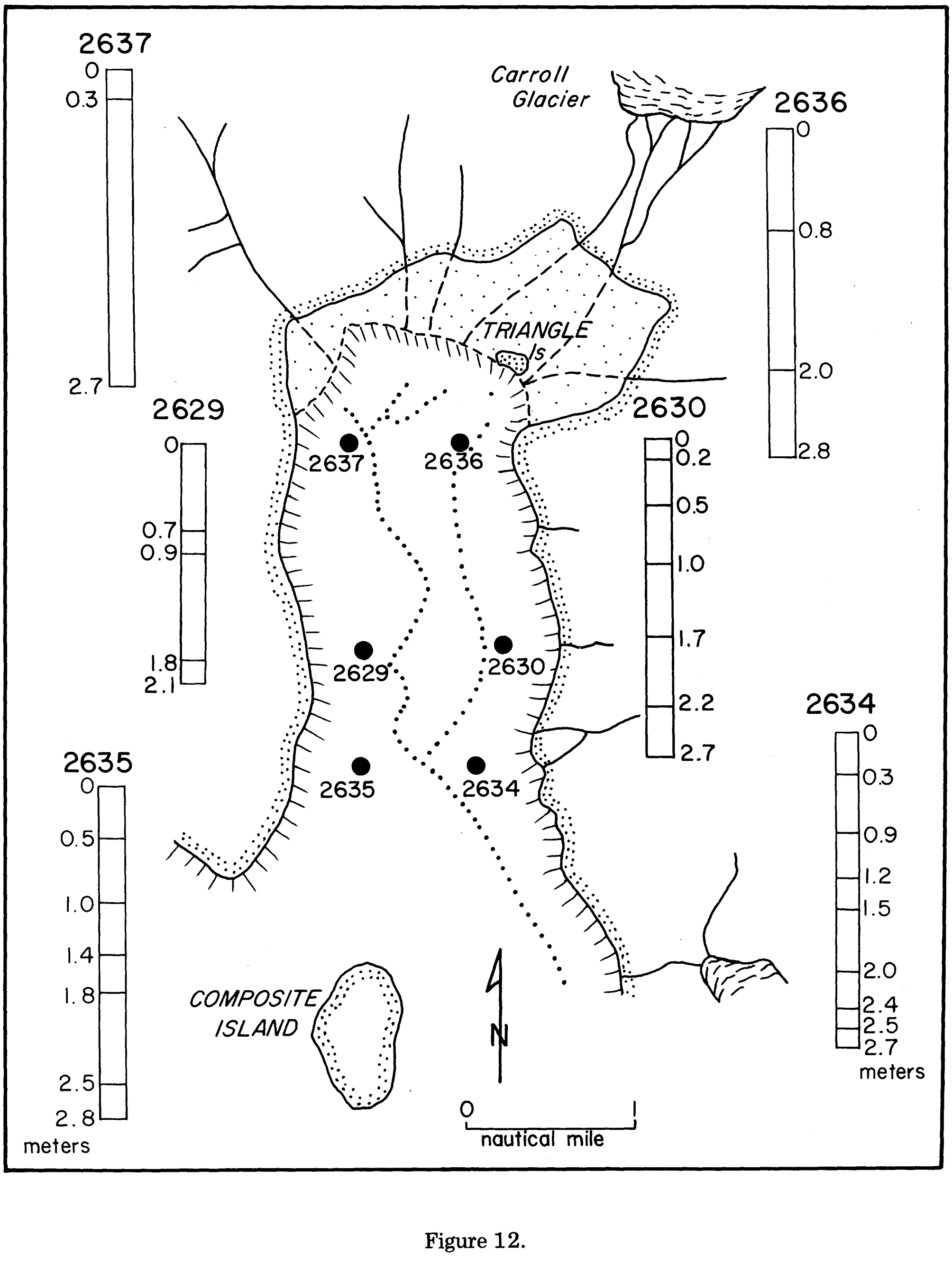

2637
0
0.3
2.7
Carroll
Glacier
2636
0
0.8
2.0
2.8
TRIANGLE
Is
2629
0
0.7
0.9
1.8
2.1
2630
0
0.2
0.5
1.0
1.7
2.2
2.7
2637
2636
2629
2630
2635
2634
2635
0
0.5
1.0
1.4
1.8
2.5
2.8
meters
2634
0
0.3
0.9
1.2
1.5
2.0
2.4
2.5
2.7
meters
COMPOSITE
ISLAND
N
0
1
nautical mile

Figure 12.

Figure 13.