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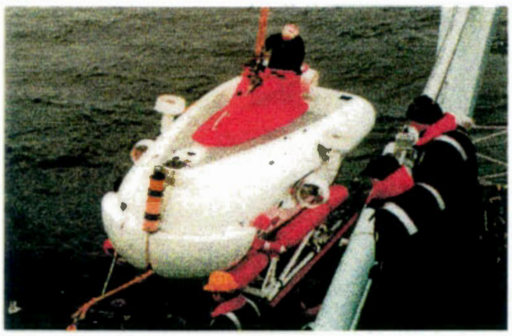
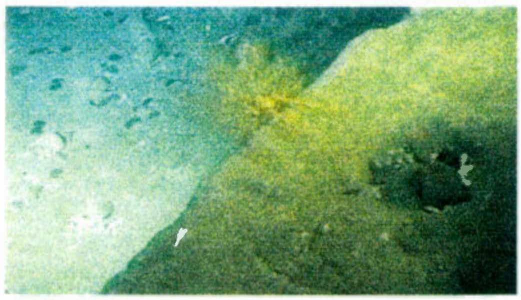
Seabed Characterization and Soil Response at the Terra Nova O-90 Glory Hole: Observed Changes, 1990-1995

GSC OPEN FILE # 3681

April, 1996





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Canada

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centre to the NE in relation to the drill rig and centre of drill stem.

(August, 1990).

Figure 25: Image of a bucket resting on what is interpreted as a thin accumulation of gravel overlying the original substrate of unconsolidated sandy material (unit 1). The gravel is interpreted to represent the coarser component of the material jetted out during the excavation. Note that the material all appears to be of a uniform gravel size with no larger cobbles or boulders present. Location is along the northwestern edge of the excavation. The gravel appears to extend right to the edge of the steep Unit 2 outcrop. Image is a frame grab from Hysub 5000 ROV VHS colour video (August, 1990). (Parrott and Sonnichsen, 1990).

Figure 26: Plan view of the Glory Hole five years after excavation (March, 1995).

Figure 27: Generalized representation of the glory hole almost five years after completion. Hi-8 and VHS colour imagery, visual observations from the manned submersible, SDL-1 provided exceptional resolution and unique insight into the physical character of the exposed sediments.

Figure 28: The upper flat lying surface of the Unit 2 "hardpan" has cracks, fissures and dissolution holes that are interpreted to have formed prior to the emplacement of the upper unit. This surface may represent a desiccated layer probably formed during subaerial exposure or in a higher energy shallow water environment Image scanned from 35mm still photograph collected using the SDL (March, 1995).

Figure 29: By 1995 Unit 1 has migrated back exposing 1-2m of Unit 2 and has stabilized at a substantially lower angle than observed during 1990 (from 40+ to ~15). Sub-angular boulders (0.1 to 0.4m diameter) along the exposed rim of the hole indicate that clasts larger than gravel were present during the excavation but were not lifted to where the coarser grained spoils were deposited (Figures 21 and 25). Image scanned from 35mm still camera photograph collected using SDL-1 (March, 1995).

Figure 30: Along the base of the southwestern exposure of the "hardpan" scarp sediment removal by preferential excavation suggests prolonged hydraulic jetting at this level. This has produced an overhang of up to 0.2m. The material above and below this overhang appears to have the same composition and consolidation. Image collected using the SDL-1 externally mounted VHS colour camera and derived as a frame grab from the original video (March, 1995).

Figure 31: At the base of the southern edge of the sand ramp along the western side of the glory hole are blocks of Unit 2 material. Along the edge of the sand ramp and grading into the glory hole are bifurcating ripples with smaller 2nd generation ripples are oriented normal to and superimposed on the larger ripples. Image collected using the hand-held HI-8 video camera inside the SDL and derived as

a frame grab from the original video tape (March, 1995).

Figures 32: Shelly "hardpan" of Unit 2 was sampled at this site on the SW edge of the glory hole. Note the angular fresh character of the material. Cliff face could not be penetrated by sub's hydraulic samplers. Image collected using the SDL externally mounted VHS colour camera and derived as a frame grab from the original video tape (March, 1995).

Figure 33: Same as figure 30

Figure 34: "Shelly hardpan" of Unit 2 sample. The block was recovered from the base of Unit 2 (see Figure 31).

Figure 35: View of the sample site on the northwestern edge in Unit 2 at approximately the same stratigraphic level as Figure 30. Note the darker colour, absence of shelly material and the more rounded , massive (degraded) character of the material in comparison to Figure 15.Cliff top was penetrated by sub's hydraulic samplers but mud was too cohesive to remain in sampler. Image collected using the hand-held HI-8 video camera inside the SDL and derived as a frame grab from the original video tape (March, 1995).

Figure 36: Similar view as Figure 35 obtained at the same location but with a 35mm handheld camera from a different angle.

Figure 37: Close up of sample site 2 indicating the Unit 2 northwestern outcrop. Note degraded character and sub manipulator arm. Image collected using the hand-held HI-8 video camera inside the SDL and derived as a frame grab from the original video tape (March, 1995).

Figure 38: Similar view as Figure 37 obtained at the same location but with a 35mm handheld camera from a different angle.

Figure 39: Bifurcating ripples with a 0.3-0.5 m wavelength with the crests trending downslope (0900) on the large sandy ramp on the W edge of the glory hole. Smaller 2nd generation ripples are oriented normal to and superimposed on the larger ripples. These bedforms were only observed in March,1995 and not on any of the August data (1990,1995). Image collected using the hand-held HI-8 video camera inside the SDL and derived as a frame grab from the original video tape (March, 1995).

Figure 40: Large bifurcating wave-formed ripples (>0.5m wavelength, 0.3 m amplitude) with crests trending downslope on a sand ramp along the N edge of the glory hole. They were observed only on the March, 1995 data. These features are interpreted as having formed during the winter storm season. Image collected using the SDL externally mounted VHS colour camera and derived as a frame grab from the original video tape (March, 1995).

Figure 41: Sidescan sonogram of the O-90 glory hole CSS Dawson, 1990. Fine angular lines at the glory hole site indicate 1994 video-grab transect.

Figure 42: Sidescan sonogram of the O-90 glory hole CSS Hudson, 1994.

Figure 43: Sidescan sonogram of the O-90 glory hole HMCS Cormorant, 1995.

SECTION 1 - EXECUTIVE SUMMARY

This report details observations on sediment response to the drilling of the Terra Nova O-90 glory hole derived from the available data at the Geological Survey of Canada (Atlantic) (GSCA). This data includes an observer's engineering report on the operation of the Tornado drill (Poorooshasb, 1990) and video, sample and visual observations collected from June 1990 - August 1995.

The glory hole stratigraphy can be subdivided into four units of which the response to drilling can be described for the upper three.

Unit 1 response

Unit 1 at O-90 is described as loose sand with small stones (Peter Hampton, pers. comm, 1990). The unit was approximately 1.5 m thick. Where exposed during drilling there was little change observed in the short term (ie June - August 1990): The unit maintained a steep angle of repose (20->40^0) right up to the glory hole edge (Section 5).This suggests collapse of Unit 1 into the hole was not a factor affecting drill response. Based on the angle of repose of the unit 1 sediments it is inferred that over the 3 month period there was little infilling. Coarse material (ie coarse, approximately 8 cm) excavated during the drilling process was preferentially deposited over Unit 1 in the NW perimeter. In 1995, retreat of Unit 1away from the Unit 2 scarp edge exposed boulders interpreted to have been present within Unit 1 (Section 6). Thus it is likely at least some boulders accumulated at the base of the hole during drilling.

Unit 2 response

Unit 2 was described as a unit of variable thickness composed of a green-grey,well cemented "mudstone" with numerous shell fragments, and similar material with only moderate cementation and sandy colour (Peter Hampton, pers. comm, 1990). The unit was described as a "hard pan" layer. Visual observations from March 1995 suggests the initial description is a hybrid derived from cuttings from two different Unit 2 sediment types which are at the same stratigraphic level and which change abruptly over short distances (< 10 m). Unit 2 can be divided into two distinct materials- greenish-grey, cemented "shelly hardpan" along the southwestern edge of the hole and dark grey, stiff massive mud along the north and northwestern edge (Sections 6 and 7). The "shelly hardpan" displays a smooth, vertical face and an angular fresh character; the stiff mud has a much lower concentration of shelly material and a more irregular edge, rounded and blockier character. The upper surface of this entire unit appears to have been subaerially exposed (dissolution holes) (Section 6). The walls of Unit 2 where observed in 1990 and 1995 were always vertical (Sections 6 and 7).

Preliminary geotechnical analysis completed by the GSCA Geotechnics Group indicate the southwestern exposure "shelly hardpan" sample is an order of magnitude more consolidated (<200kPa) than the stiff mud sample from the northwestern exposure (< 20 kPa)(Section 7).

Initial response of Unit 2 to the drilling activity was variable (based upon subsequent detailed video and sampling analysis) (Section 7). The shelly hardpan seems to have collapsed as cohesive blocks based on 1) a triangular collapsed block (6-10m^2) towards the southern margin (Section 4), 2) the presence of smooth, sheer scarps around the southwestern perimeter of the hole (Sections 4-7), and 3) highly, reflective material in the centre of the hole toward the centre of the hole interpreted as segments of the hardpan layer (Section 4).

Based on ROV measurements of the hole centre and the resulting hole shape and dimensions, it appears the mud on the northeastern side of the hole was preferentially removed. This may reflect a more sensitive reaction the hydraulic jets on the drill arms. Alternatively, a cusp like feature on the northern edge (Section 5) could represent an offset in the hole centre caused by the extracting and redeploying the Tornado drill during the drilling program.

Unit 3 response

Unit 3 consists of an approximately 5m thick unit described as fine-grained sand with a clay matrix and numerous igneous stones, displaying a good initial strength and very mobile once fluidized; possibly glacial till (Petro-Canada, 1990).Video evidence could not confirm either the presence of boulders or glacial till in Unit 3. The 1990 ROV data indicates that there are only a few boulders present at the base of the hole. Fluidizing of the Unit 3 sediment likely undermined Unit 2 hard pan, and removed the Unit 2 mud causing the collapse features observed and enlargement of the hole to the northwest from a nominal drill diameter of 7.4m to an oval depression of 20x24m (Poorooshasb, 1990).

Unit 4 response

Unit 4 was encountered at the base of the hole during drilling and was described as a stiff grey green clay. This unit has not been observed in any later observations. It is inferred to correspond to a prominent seismic reflector at 9 m below seafloor which dips NE. This suggests the stiff clay would be encountered closer the seafloor south and southwest of O-90.

It appears from the brief description of the Tornado Drill available to GSCA (Poorooshasb, 1990) that the rate of drill rotation, the water pressure and the airflow within the airlift system can all be controlled. The principal cutting method is hydraulic (Poorooshasb, 1990). High pressure water (13.8MPa at the rig head) is jetted out at various points on the drill assembly fluidizing the sediments. Fluidizing the Unit 3 sediments probably undermined the Unit 2 causing the collapse features observed and caused enlargement of the hole. The amount of boulders identified in the hole from video and visual observations did not appear to be great. However mechanical failure of the Tornado Drill was attributed to the damage of the drive hydraulics by the lodgement of a boulder within the drive unit, it therefore appears that at least some boulders were concentrated at the base of the excavation.

With control over the drill/hydraulic behaviour it would suggest that coupled with a very detailed pre-drilling knowledge of the substrate characteristics that a specific methodology could be developed/pre-planned for each site.

Changes to the O-90 Glory Hole (1990-95)

The glory hole is a small feature on a sandy seafloor that is occasionally mobilized by the effects of long period surface waves. The hole has experienced approximately 1.5 m of infill but can still be clearly recognized visually and on sidescan.

The seafloor has been reworked on at least one occasion by the effects of long period ocean waves, creating oscillatory ripples up to 0.4m high and 1.5m in wavelength (Section 8). The oscillatory motion has also swept Unit 1 sands into the O-90 glory hole from the perimeter. No evidence for large scale unidirectional transport is seen.

It is expected that the hole will very gradually continue to be infilled and buried, until the grades are sufficiently gentle for it to be in equilibrium with the surrounding seafloor (Section 9).

SECTION 2 - INTRODUCTION

This report summarizes observations from a series of geological and engineering surveys completed by the Geological Survey of Canada (Atlantic) and Petro-Canada at the Terra Nova 0-90 glory hole site.

The Terra Nova oil field was discovered by Petro-Canada in 1984. In June, 1990, Petro-Canada attempted to drill and case a glory hole at the O-90 well site (Figure 1) for wellhead and BOP protection from iceberg scouring (Figure 2). The glory hole was excavated from the semi-submersible SEDCO 710 with a Tornado drill, developed by Tornado Drilling of Calgary.

After two attempts, the Tornado drill had not reached the target depth and was retrieved without deploying the caisson.Tentative reasons (Poorooshasb, 1990) suggested for the failure include:

- inability of the drill to remove spoils, especially boulders which would have concentrated at the base of the hole.
- progressive collapse of the vertical sides of the hole due to the presence of noncohesive sediments.

Understanding the soil characteristics and their variability will assist in establishing the installation specifications for the "cased glory hole" for the Terra Nova development project if the "cased glory hole" technology is selected by Petro-Canada. GSC interest in the glory hole is related to three main issues:

- “Hard pan”sediment, occasionally described in past drilling operations, has only been sampled and visually observed at this site. Determining its age, nature and distribution will provide insight into the recent geological history of the seabed in the Jeanne d’Arc Basin and any potential constraints to sub-sea engineering design.
- It is a large, monitoring site of known age to observe evidence of sediment infill, transport and erosion.
- The O-90 glory hole can also be considered a quantitative analog for a seafloor ice scour (pits and furrows); repetitive surveys will provide insight in the processes affecting them and their preservation on the seafloor.

Section 2.1 - Objectives

The objective of this report are to document the observations and interpretations from video, geophysical, and geotechnical sample data collected at or near the O-90 glory hole excavation from 1990 to 1995 in order to:

- qualitatively describe the glory hole created by the Tornado drill, and the surface/subsurface sediment response.

- characterize physical properties of the "hard pan" strata observed and sampled in the glory hole.

- describe visually observed changes to the hole since 1990 including sediment infill and erosion.

Section 2.2 - Input data

Interpretations presented in this report were based primarily on observations documented from:

- vertically mounted SIT camera video (collected immediately after excavation, June 1990) provided to the GSC by Petro-Canada.

- HySub 5000 ROV video with SIT, VHS colour and sector scanning sonar (collected August, 1990).

- a SDL-1 manned submersible dive with visual observations, VHS and HI-8 colour video, sector scanning sonar and 35mm still photography (collected March, 1995). Bottom samples were also collected at two sites.

Valuable background information were extracted from a C-CORE external review of the operation of the Tornado drill (Poorooshasb, 1990), from an earlier analysis of the 1990 GSC HySub video (Cameron and Sonnichsen, 1992) and from various GSC geophysical and geotechnical reports (Parrott and Sonnichsen, 1990; Sonnichsen, 1995; Sonnichsen, 1996; Moran and Mosher, 1989).

Documentation of the seabed setting for the O-90 glory hole, and for relative seabed changes was obtained from sidescan sonar imagery collected in 1990 and again in 1994 and 1995.

Section 2.3 - Seabed Geology in the Terra Nova Region

Section 2.3.1 - Surficial geology

The immediate seafloor surficial geological unit is part of the regional surficial unit informally called the Grand Banks Sand and Gravel (Unit 1). This unit is described by King (1989) as a "basal lag deposits with moderately regular surface formed during the Late-Wisconsinan-Holocene transgression; occurs in present day water depths <105-110m; Overlying sand usually comprises various bedforms such as sand ridges (thickest deposits), sand ribbon, megaripples and wave formed ripples; in part relict features with surficial sands presently undergoing reworking. Texturally the unit consists of rounded to subrounded gravels (pebble to boulder) overlain by clean well sorted, coarse to fine grained sand with variable gravel; many clasts have Avalonian affinity."

The Terra Nova discovery site is located in water depths ranging from 92 to 98 m.The seafloor is composed of unconsolidated medium grained sand with shell hash and pebbles and cobbles overlying a coarser lag surface with cobbles and gravels.The seafloor is relatively flat but complex bedforms including sediment-starved sand ridges, sand waves and megaripples cover one-third of the area, while lag gravels are exposed elsewhere.The sand is less than 2 m thick in areas of sand bedforms, and 1 metre or less in areas of exposed gravels (CSR, 1996). Low amplitude (<10 cm) sand ripples (wavelength ~1-2 m) appear to be periodically generated.

Section 2.3.2 - Subbottom seismic character

On seismic reflection profiles, the surficial sand and gravel (Unit 1) is too thin to resolve.The subsurface at O-90 is characterized by low angle,seaward dipping reflections with an interval spacing of approximately 10 metres (Figure 3). The reflections are truncated by an angular unconformity (A in Figure 3) at the Unit1/Unit2 boundary which represents the erosional surface of a low stand of sea level approx 12,000 years before present (BP) (Sonnichsen et al., 1994).

The shallowest reflection in the subsurface is at about 9 m bsf (B in Figure 3). Above the 9 m reflector there are no coherent reflections but there is some evidence for energy scattering from point source reflections such as boulders or cobbles and possibly from subsurface irregularities such as channelling or unconformities.

Section 2.3.3- Seabed geotechnics

There have been five geotechnical boreholes drilled in the Terra Nova area. The nearest geotechnical borehole to the site is 88-400-04 (Figure 1) 2.4 km to the SW,(NGL, 1988). While it gives some indication as to the likely soil conditions at O-90 (Figure 4,5), it should be noted that the five boreholes drilled in 1988 indicate a high degree of local variability in grainsize and soil strength in the upper 20 m of the seafloor (Moran and Mosher,1988). Only 6 samples were recovered at 88-400-04 in the upper 9 metres. Also, it should be noted it is slightly up dip from O-90.

Section 2.4 - Pre-excavation Site Conditions

The seafloor at O-90 is typical of the Terra Nova region (Figure 1); it is composed of unconsolidated medium grained sand (Figures 6,7) less than 2 m thick with shell hash and pebbles and cobbles overlying a coarser lag surface with cobbles and gravels. Thickness of this unit is approximately 1.5 m; it is not resolvable on Figure 3. The seafloor is largely flat and featureless (Figure 14) but with occasional low amplitude (<10 cm) sand ripples (wavelength ~1-2 m) and gravel regions (CSR, 1996, Cameron and Sonnichsen, 1992).

Figures 8 and 9 represent a generalized distribution of the upper geological units as determined from a preliminary borehole (Poorooshasb, 1990) and the 88-400-04 borehole (Figure 4,5) approximately 2400m to the southwest (Figure 1). The unit descriptions are quoted from correspondence to AGC from Roy Hodgkinson at Petro-Canada (1992).

Figure 1: Terra Nova oil field surficial geology (Prepared for Petro-Canada by Canadian Seabed Research, 1990). Well locations and the positions of geotechnical boreholes (NGL, 1988) are shown. The light green pattern depicts areas of wave-formed ripples.

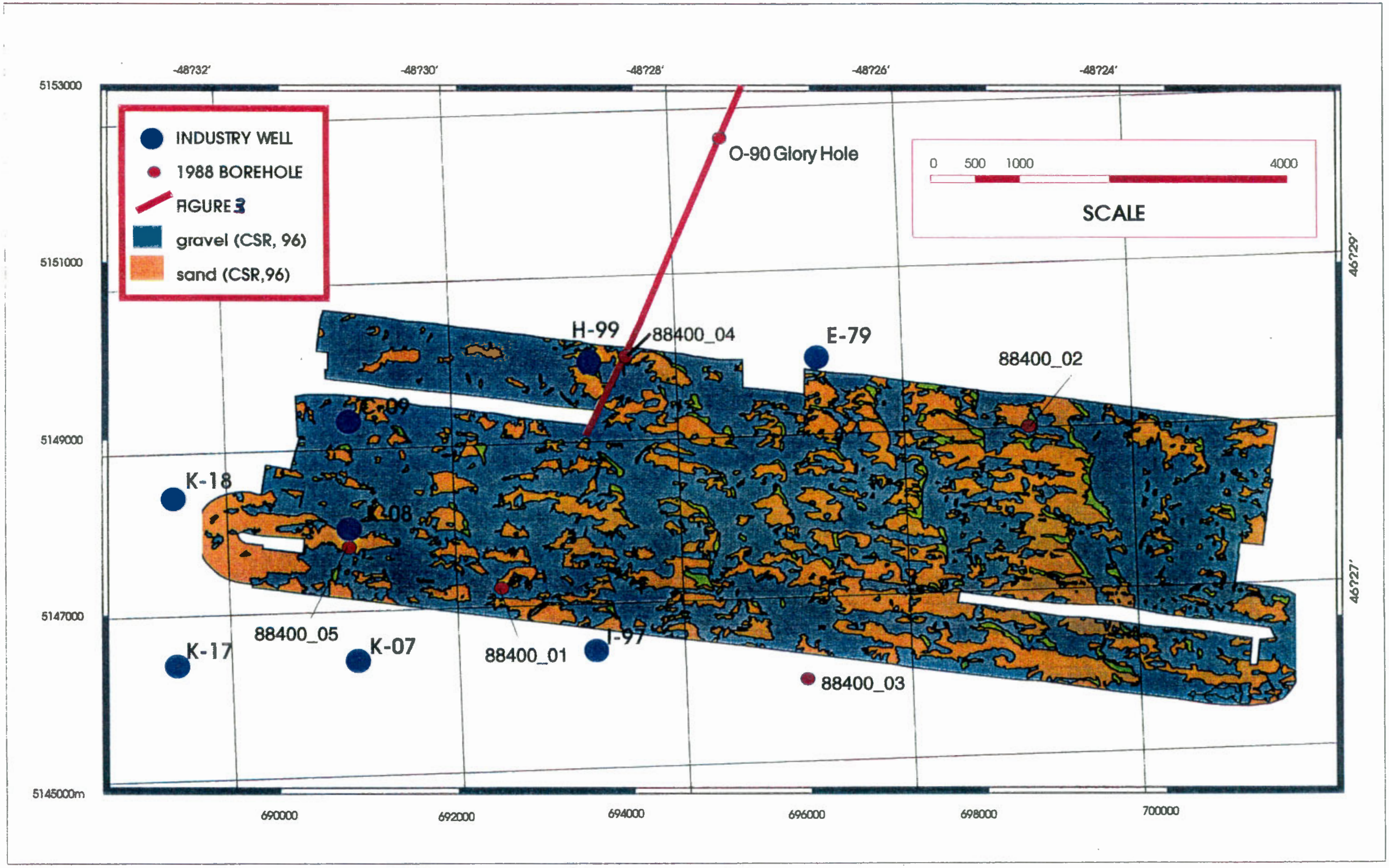

INDUSTRY WELL
1988 BOREHOLE
FIGURE 3
gravel (CSR, 96)
sand (CSR,96)
O-90 Glory Hole
0
500
1000
4000
SCALE
H-99
88400_04
E-79
88400_02
K-18
K-08
88400_05
K-17
K-07
88400_01
88400_03
5153000
5151000
5149000
5147000
5145000m
690000
692000
694000
696000
698000
700000

Figure 1

Figure 2: Protective cylindrical caisson which will form the "cased glory hole" (image scanned from Petro-Canada et al, 1995. Terra Nova, a Petro-Canada operated energy project)

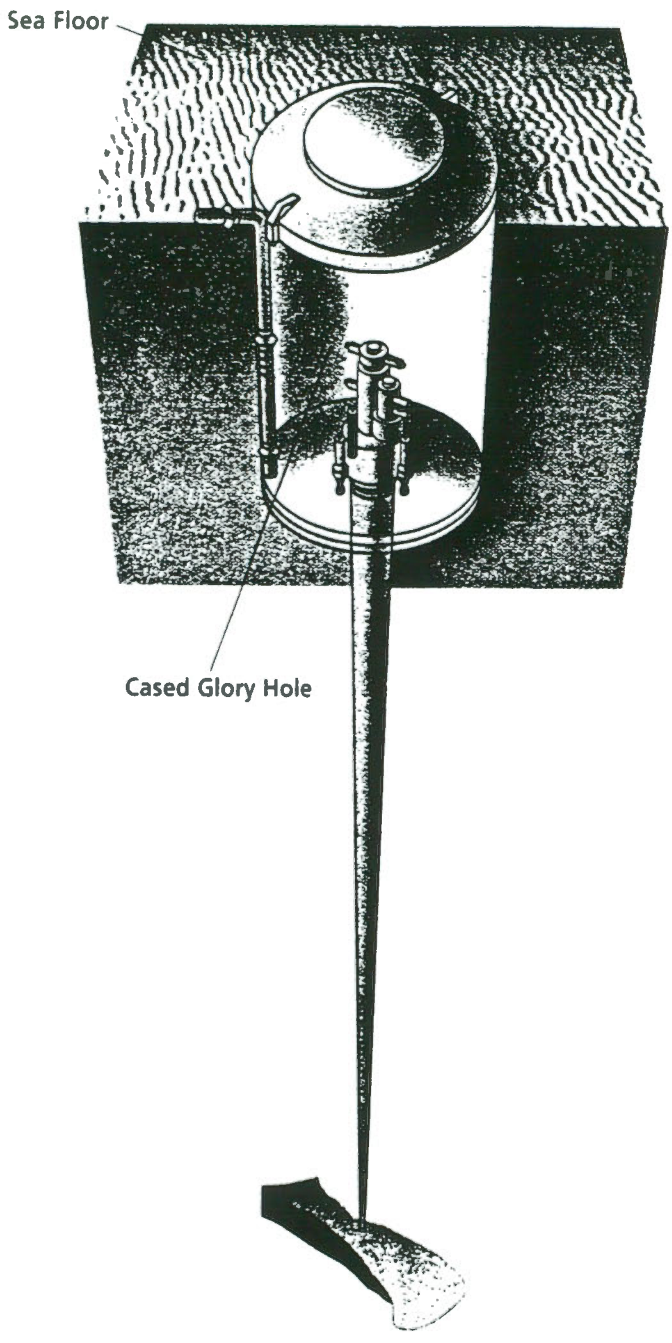


Figure 2

Figure 3: 10 cubic inch sleeve gun profile SW to NE through 88-400-04 (NGL, 1988) and the O-90 glory hole site. For location see Figure 1.

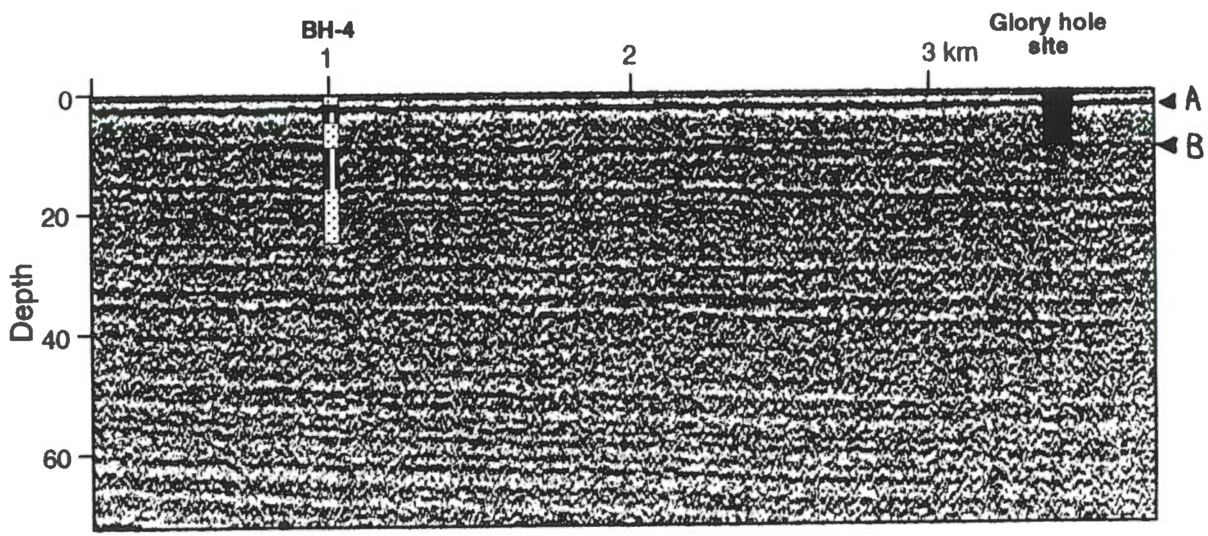
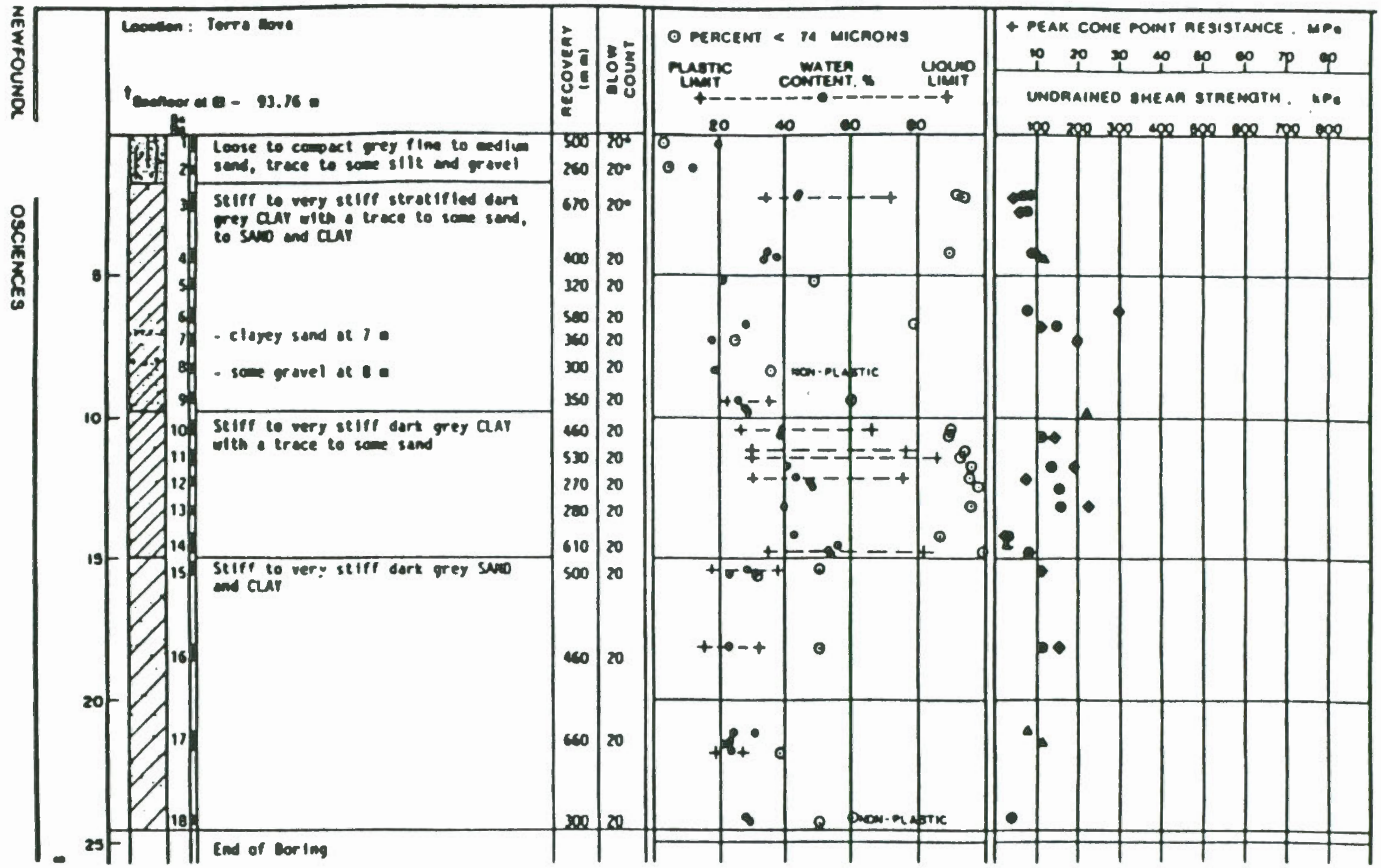


Figure 3

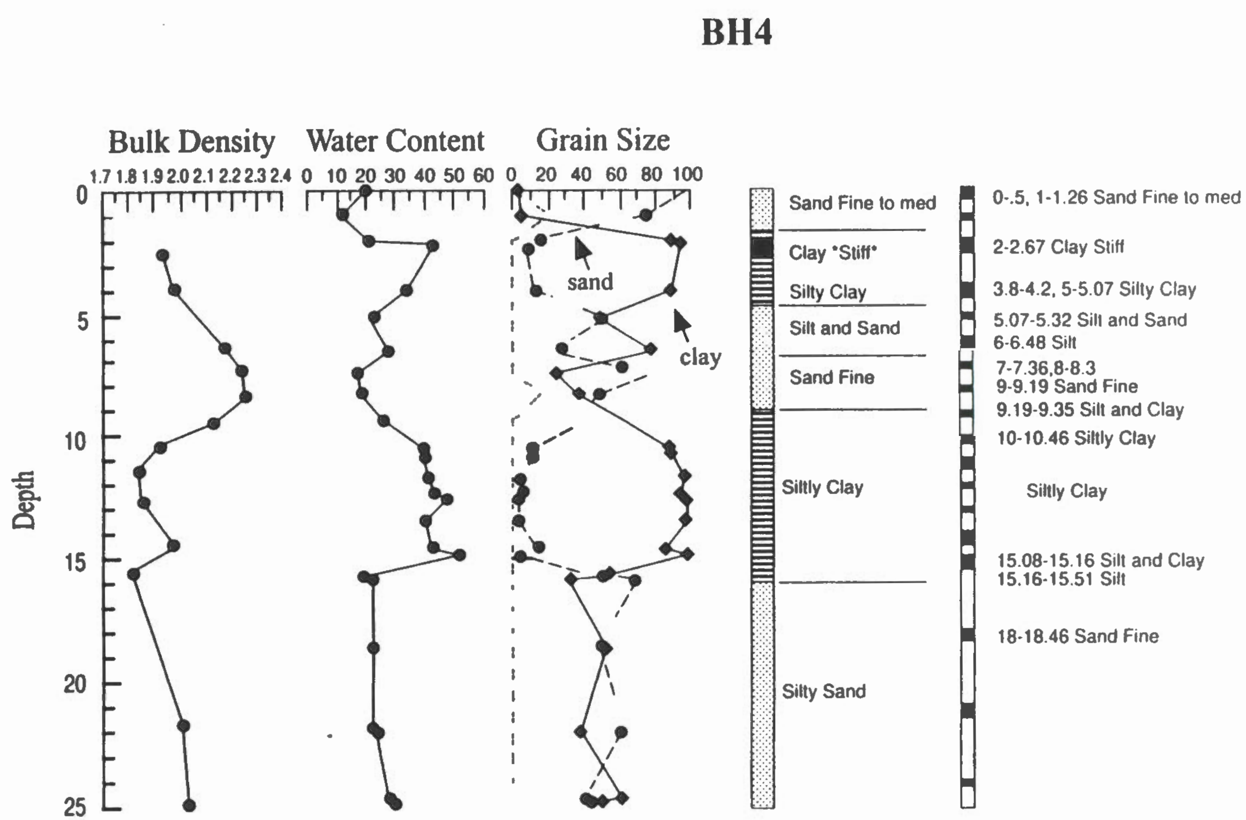
Figure 4: Borehole 88-400-04 (Newfoundland Geosciences Ltd, 1988). For location see Figure 1.



Location : Terra Nova
Seafloor at EL - 93.76 m
RECOVERY (mm)
BLOW COUNT
Loose to compact grey fine to medium sand, trace to some silt and gravel
Stiff to very stiff stratified dark grey CLAY with a trace to some sand, to SAND and CLAY
- clayey sand at 7 m
- some gravel at 8 m
Stiff to very stiff dark grey CLAY with a trace to some sand
Stiff to very stiff dark grey SAND and CLAY
End of Boring
O PERCENT < 74 MICRONS
PLASTIC LIMIT
WATER CONTENT, %
LIQUID LIMIT
NON-PLASTIC
+ PEAK CONE POINT RESISTANCE , MPa
UNDRAINED SHEAR STRENGTH , kPa

Figure 4

Figure 5: Borehole 88-400-04 bulk density, water content, grain size data analysis and recovery rates (Geological Survey of Canada (Atlantic)). Note that only 7 samples were collected in the upper 9m. For location see Figure 1.



sea 96

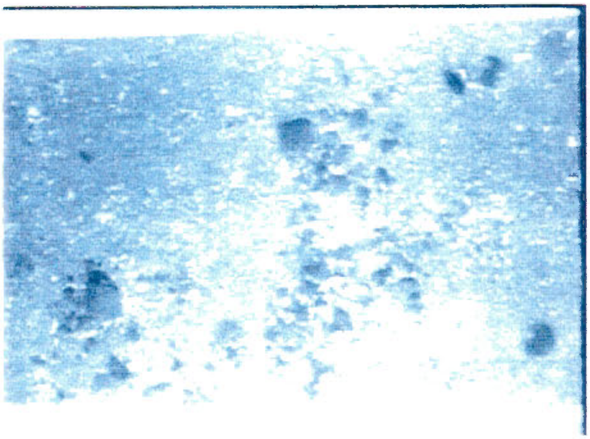
Figure 5

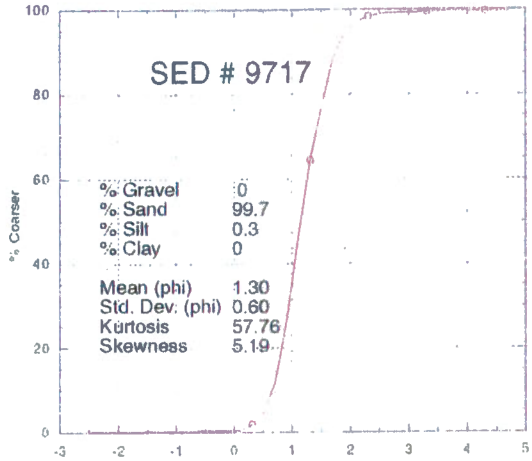
Figure 6: Representative grain size analysis and bottom photographs from the Terra Nova site (Sonnichsen, 1994).

Appendix 2 Grainsize Data

Station 18 Terra Nova
water depth 96 metres

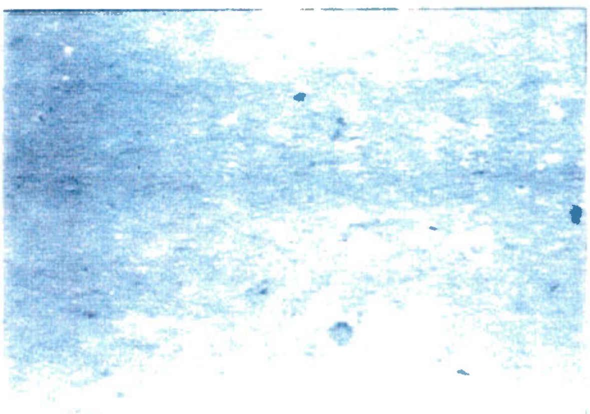
46 30.3 N
48 27.53 W





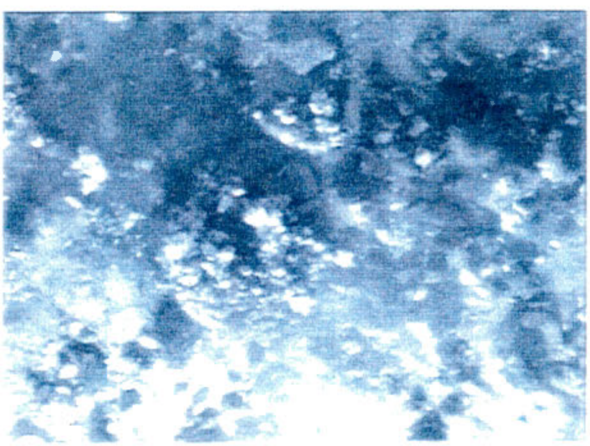
Station 19 Terra Nova
water depth 92 metres

46 28.51 N
48 28.43 W



Station 20 Terra Nova
water depth 93 metres

46 27.10 N
48 29.56 W



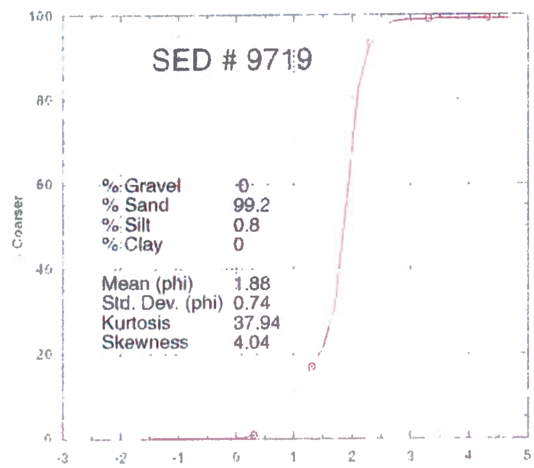


Figure 6

Figure 7: Representative undisturbed seafloor consisting of predominantly sand with occasional gravel, cobbles and shell hash. Image was collected during the 1995 SDL dive with a 35mm camera.

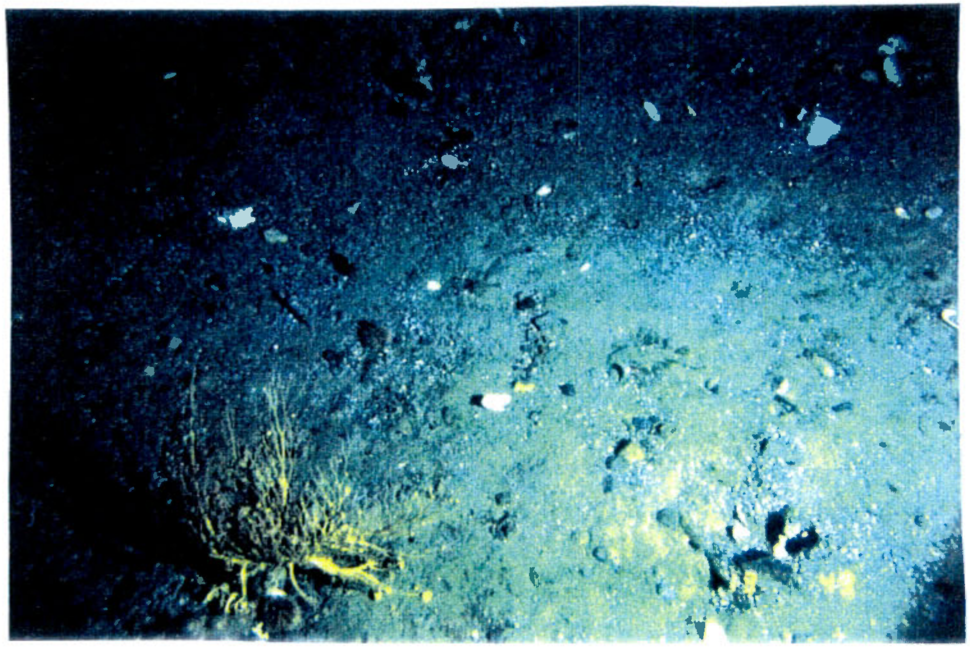


Figure 7

Figure 8: Plan view of the Terra Nova O-90 glory hole site before excavation.

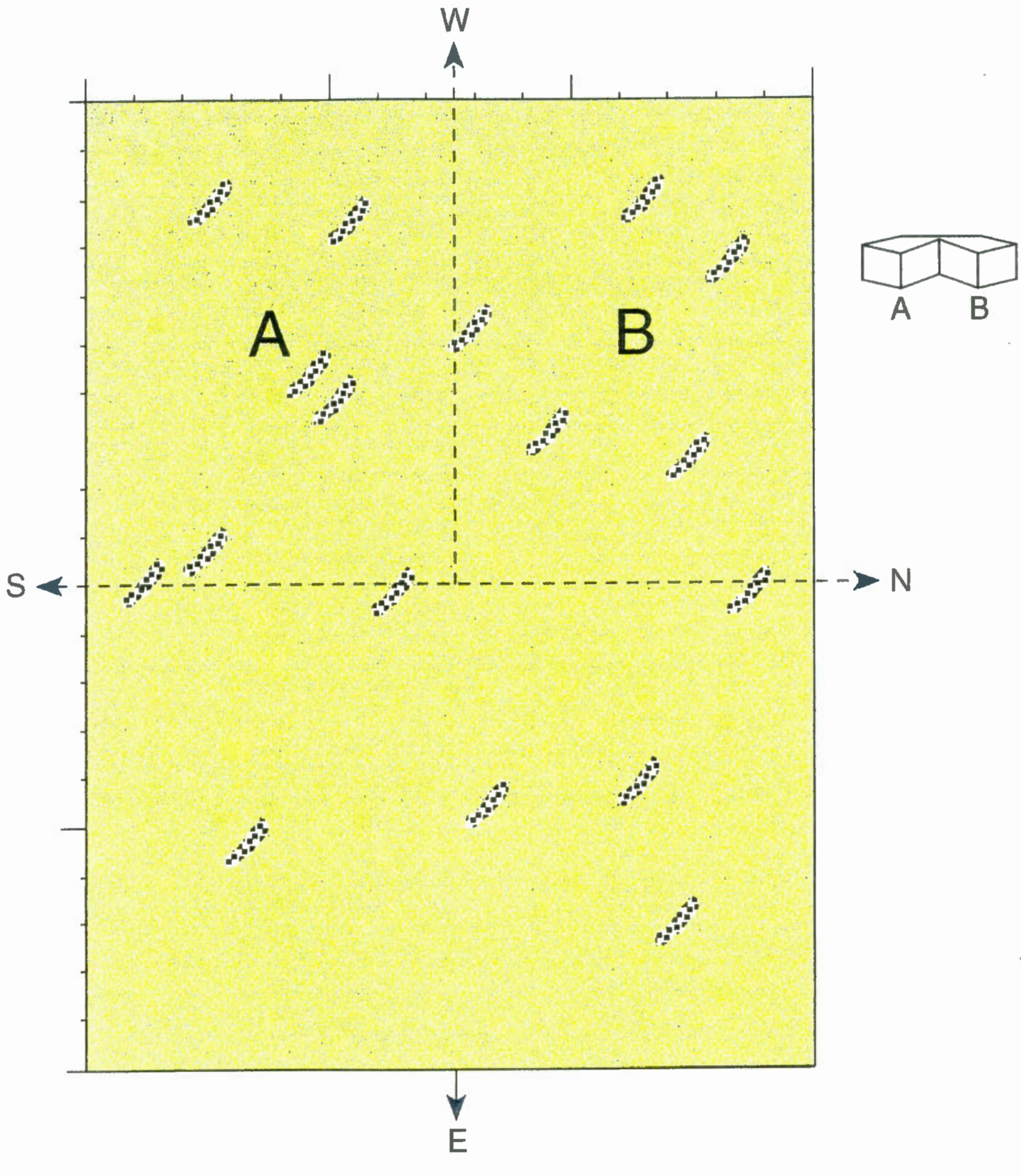
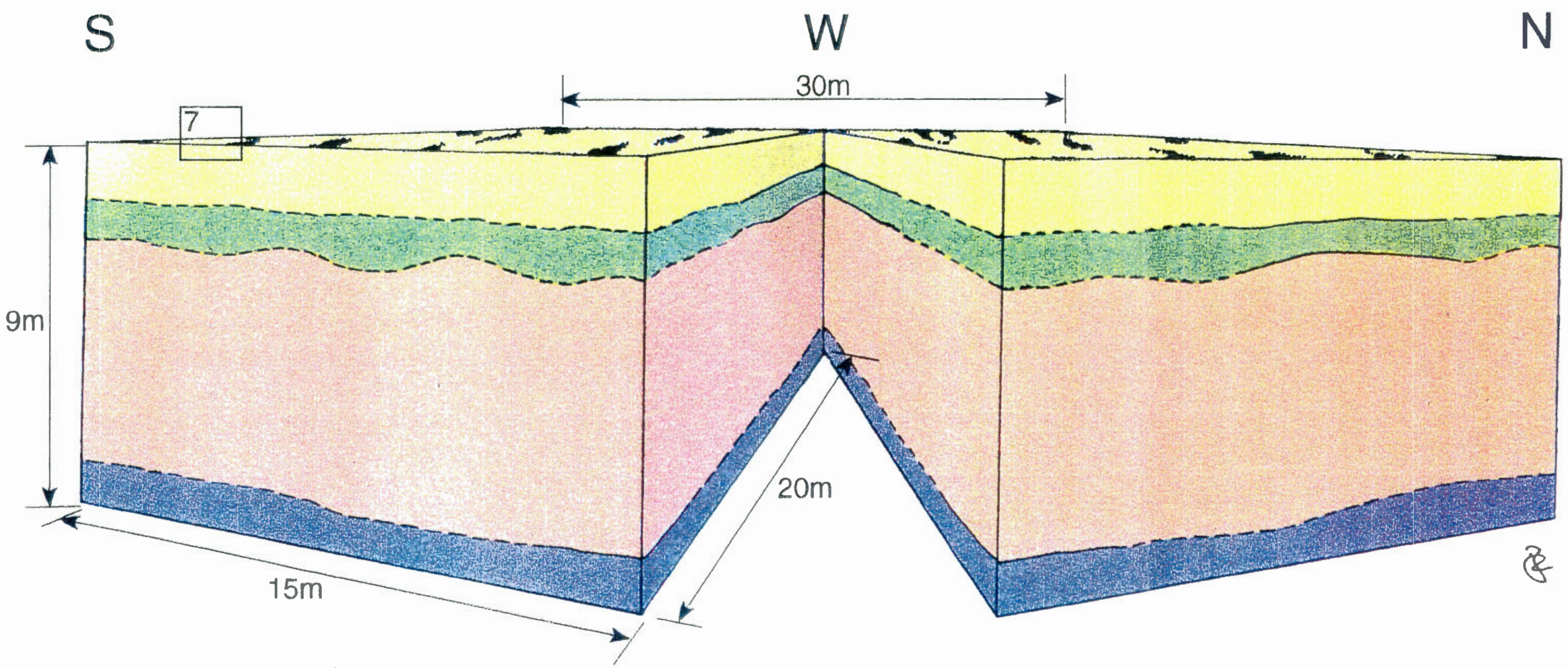


Figure 8

Figures 9: Generalized 3 dimensional representation of the upper geological units. When facing the block diagrams the angle of view is a low angle oblique view slightly above the seafloor looking from the east towards the west.



UNIT 1 - Loose sand with small stones

UNIT 2 - Mudstone, well cemented with abundant shell fragments

UNIT 3 - Fine grained sand with a clay matrix with numerous igneousstones

UNIT 4 - Stiff grey green mud

7 Figure location, number and approximate field of view

Figure 9

SECTION 3 - TORNADO DRILL OPERATION

Section 3.1- Tornado Drill Description

The drilling equipment is summarized below from Poorooshasb (1990). The Tornado Drill used at the Terra Nova O-90 glory hole consisted of two sections. The component were the drilling mechanism and the caisson (Figure 11). These two sections are attached to each other during the drilling process. Once the hole has been created, the drill is detached from the caisson and retracted, leaving the caisson in the hole (Figure 2). Combined weight of the equipment is 75 ton.

The drill consists of a hydraulic system housing overlying the cutting mechanism (Figures 10,11,12). The cutting mechanism consists of three arms of unequal length which rotate slowly about the axis of the drill (~12 revolution per hour or 5 minutes per revolution or 4.65m/minute or 0.07m/s for the outer edge of the longest arm). At the end of each of these arms is a cutter head, which contains a series of teeth and high-pressure nozzles. The principal cutting method is hydraulic (13.8MPa at the rig head). Each cutter head itself rotates with an angular velocity three times that of the three arms.

Centrally located below the arms is a spear which extends approximately 2 metres below the cutter heads. This spear contains two high pressure nozzles (one aimed downward and one aimed laterally) and has four stubby fins welded to it. The spear rotates at the same rate as the arms (~12 revolutions per hour).

Section 3.2- Tornado Drill Operation

The Tornado drill was operational for approx. 26 hours over two deployments. During the first deployment, it was raised once without vacating the hole. After repairs it was redeployed into nominally the same hole. At the end of drilling, ROV inspections identified an oval shaped crater 20x24m, 6m deep (Figure 10) - an estimated 1050m^3 material was removed (P.Hampton,PCI,pers. Comm., 1990).

Figures 8 and 9 (Section 2) represent a generalized distribution of the upper geological units as determined from a preliminary borehole (Poorooshasb, 1990), the Tornado rotary drill cuttings (Figures 14-16) and the 88-400-04 borehole (Figure 4,5) approximately 2400m to the southwest (Figure 1). The unit descriptions are quoted from correspondence to Russell Parrott at AGC from Roy Hodgkinson at Petro-Canada (1992).

UNIT 1- Loose sand with small stones

UNIT 2 - Mudstone,well cemented with abundant shell fragments

UNIT 3 - Fine grained sand with a clay matrix with numerous igneous stones

UNIT 4 - Stiff grey green mud

Figure 10: Photograph of the Tornado Drill and nose ring (bottom section of caisson) (Poorooshasb, 1990)

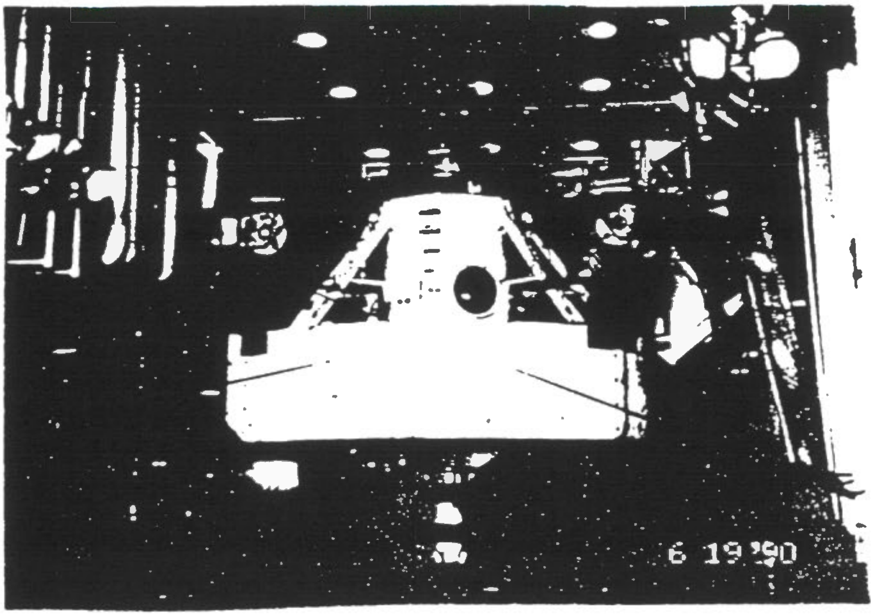


Figure 10

Figure 11: Schematic diagram of the Tornado Drilling Tool (Poorooshasb, 1990) illustrating s plan view of the drill arms and the connection of the caisson to the drill assembly.

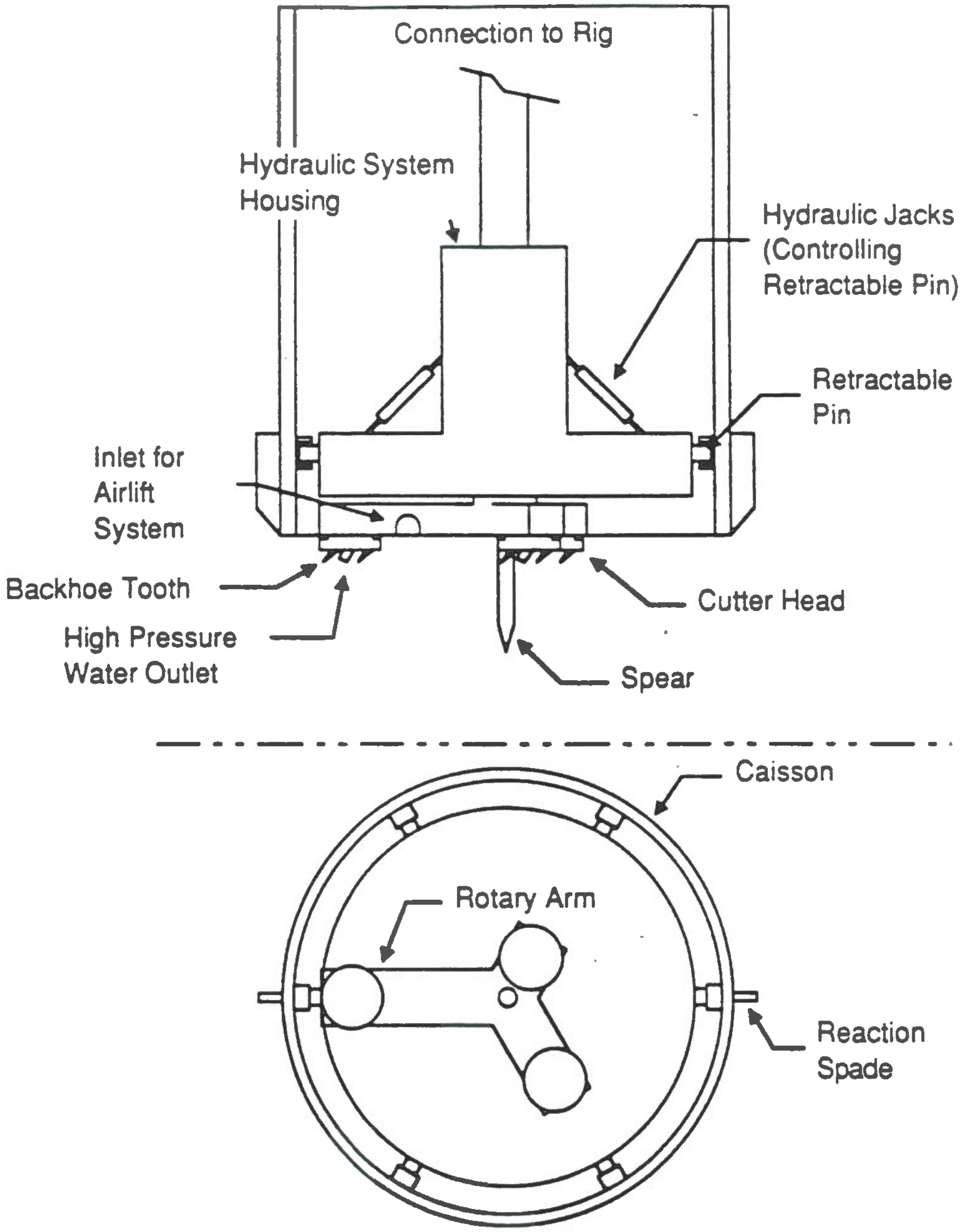
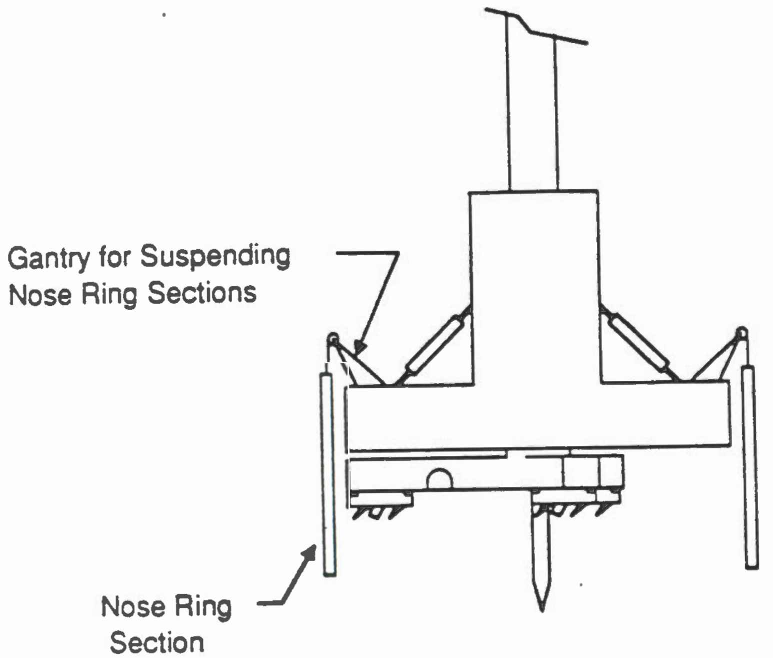

Connection to Rig
Hydraulic System
Housing
Hydraulic Jacks
(Controlling
Retractable Pin)
Retractable
Pin
Inlet for
Airlift
System
Backhoe Tooth
Cutter Head
High Pressure
Water Outlet
Spear
Caisson
Rotary Arm
Reaction
Spade

Figure 11

Figure 12: Suspension System for easing assembly of nose ring sections in limited space.



· Suspension System for Easing Assemby of Nose Ring
Sections in Limited Space
Additional Ease of Assembly can be Acheived By Threading
Hawser Through Boltholes and Tightening

Figure 12

Figure 13: Glory hole survey by ROV, video inspection/Honeywell tracking (from letter from Peter Hampton to Russell Parrot, 90-10-15). Note the resulting hole is off centre to the NE in relation to the drill rig and centre of drill stem.

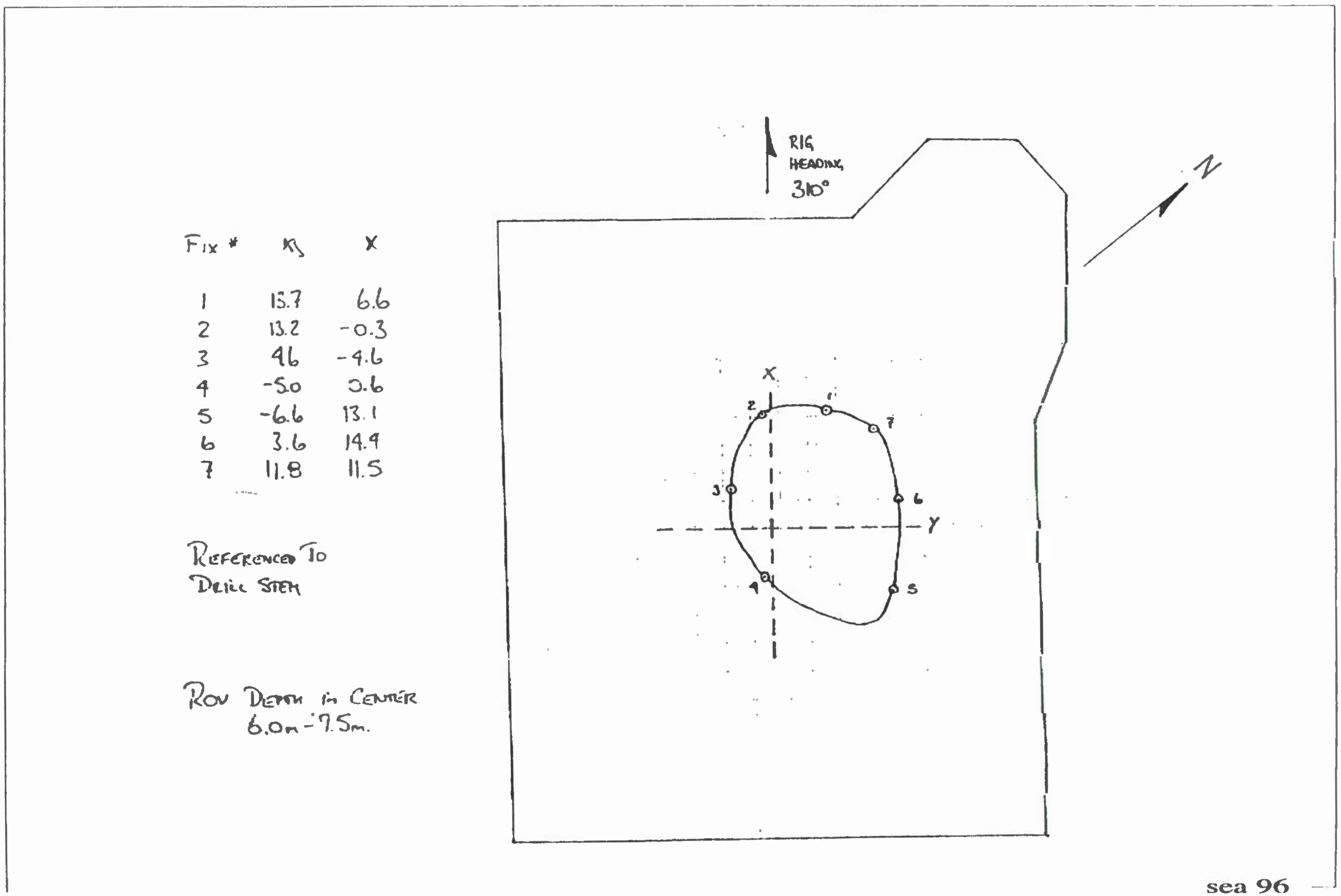

Fix # y x
1 15.7 6.6
2 13.2 -0.3
3 4.6 -4.6
4 -5.0 0.6
5 -6.6 13.1
6 3.6 14.9
7 11.8 11.5
Referenced To
Drill Stem
Rov Depth in Center
6.0m - 7.5m.
Rig
Heading
310°
N
X
Y
1
2
3
4
5
6
7
sea 96

Figure 13

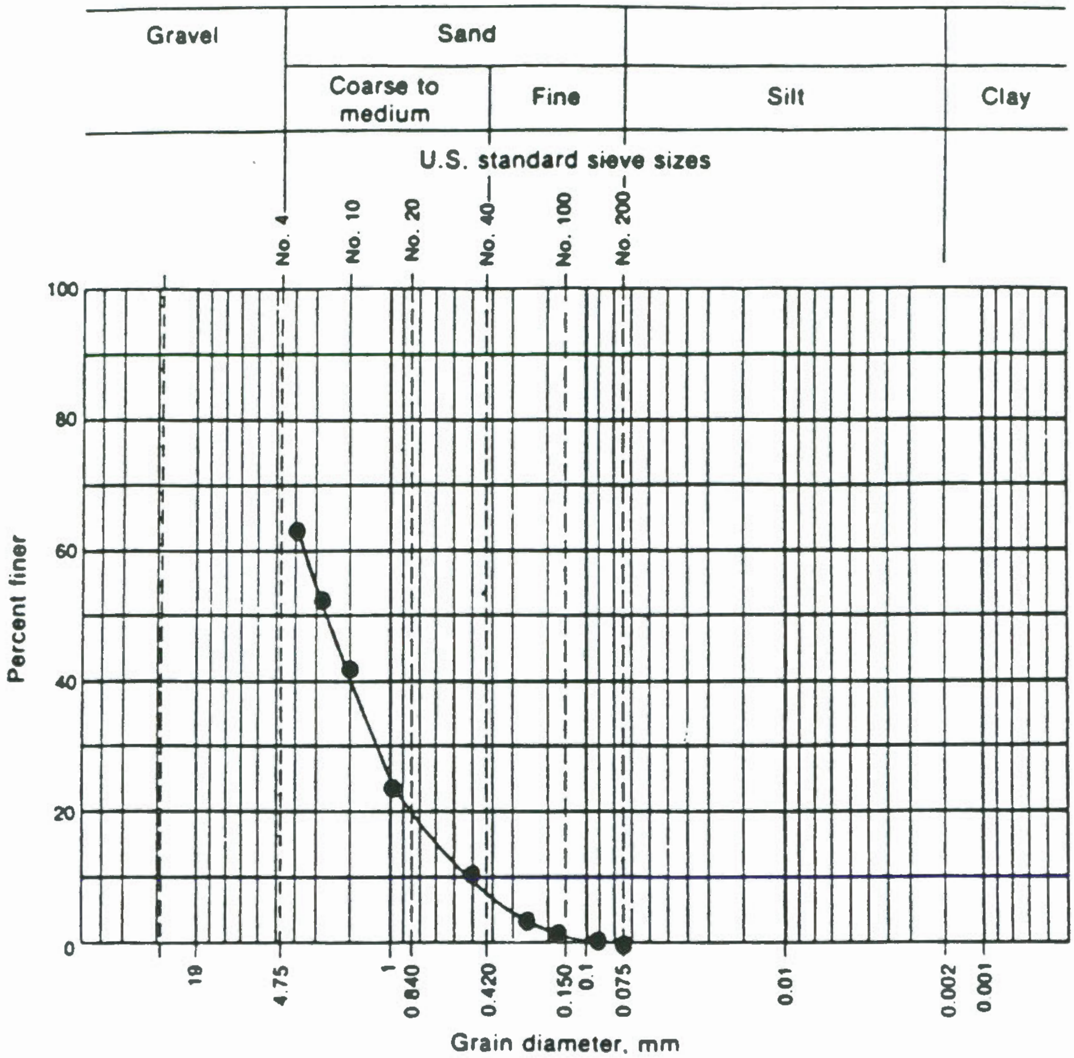


Figure 14: Grain Size Analysis of Cuttings from Drill Top
(Cuttings 1)
Carbonate Content = 16.9%

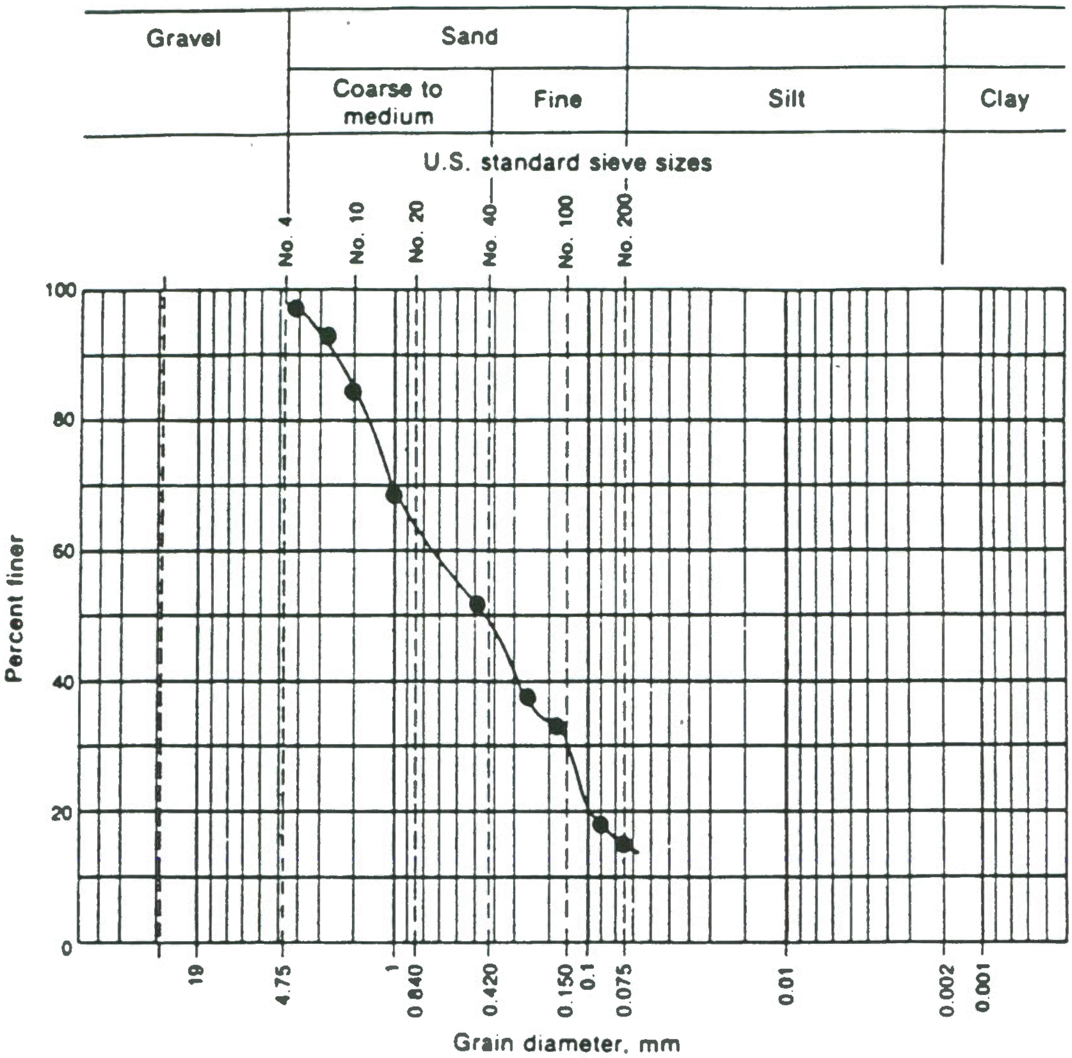


Figure 15: Grain Size Analysis of Clay/Sand Mixture Undisturbed by Drilling (Cuttings 2) Carbonate Content = 55.5%

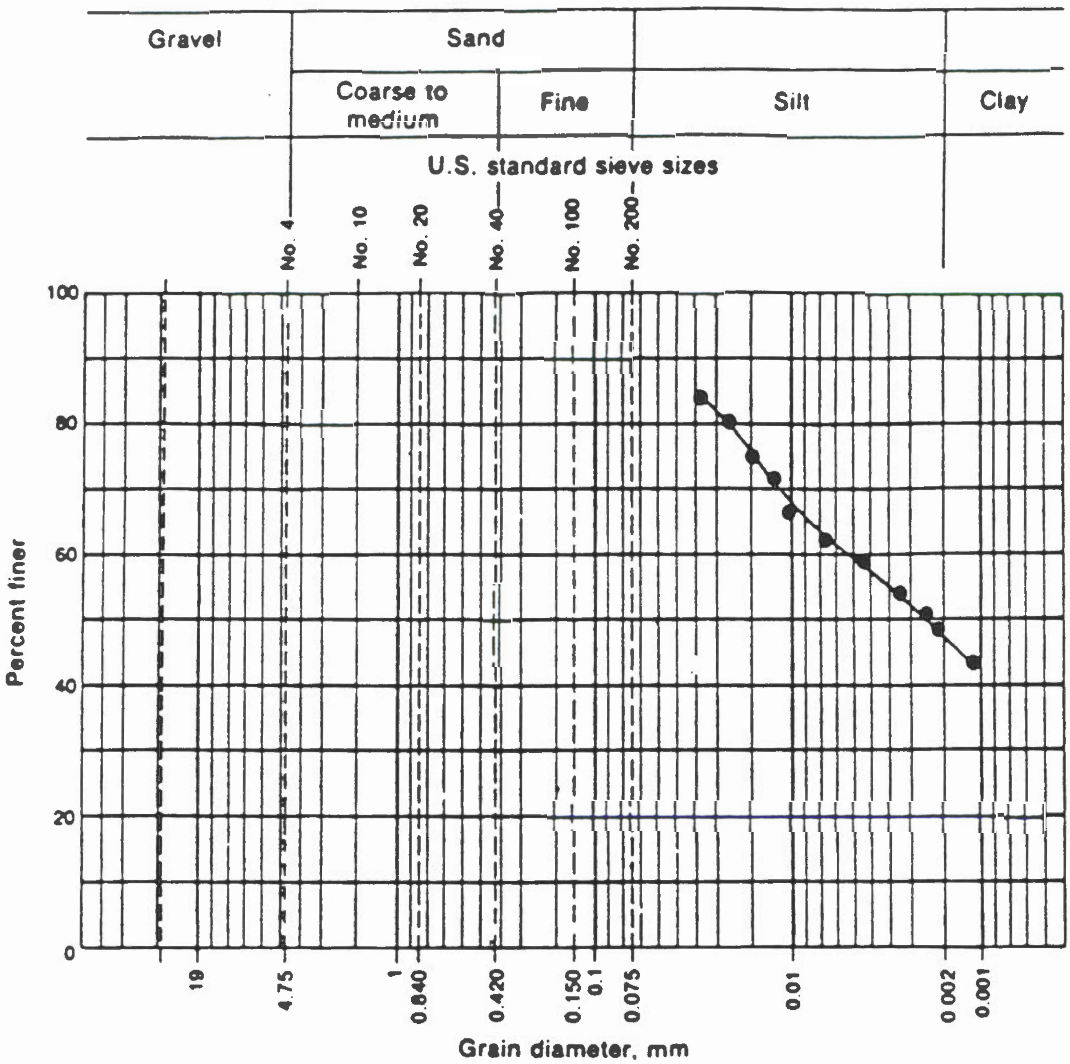


Figure 16: Grain Size Analysis of Material from Bottom of Hole (Cuttings 3) Carbonate Content = trace

SECTION 4 - IMMEDIATELY POST-EXCAVATION

Review of the Petro-Canada SIT video and GSCA sidescan sonograms (Figure 17) support Petro-Canada's estimates for the overall size and shape of the hole. The video did not provide detail on the type of sediment outcropping in the hole, but the shape and character of the walls and rim suggests the sediments behaved differently around the hole edge (Figures 18 and 18A)).

- On the southern edge, a prominent, smooth scarp with a sheer face ~ 1 metre in height is evident. This was interpreted to be the "hardpan" identified during drilling.
- The northern edge is more irregular with prominent cusp-like features.
- A large sandy ramp separates the N and S wall exposures; it apparently developed during or just after drilling. It likely occurred through collapse of the hole perimeter and/or increased removal of material by the drill's hydraulic jetting.
- A prominent triangular zone (Figure 19) towards the S margin represents a collapse of the S wall during or immediately after drilling, possibly due to undercutting. Approximate surface area of the section is 6-10 m2 and this block appears to stand proud of the seafloor 0.2-0.4m.
- Reflective areas are seen at the base of the southern scarp face.
- A few highly reflective features are observed toward the centre of the hole suggesting either blocks of excavated material or boulders.
- Some cobbles and pebbles were identified on the SIT near the base of the hole.

Figure 17: Klein 100 kHz sidescan sonogram of the O-90 glory hole from August, 1990 (Parrott and Sonnichsen, 1990). Slant-range and scale- corrected.

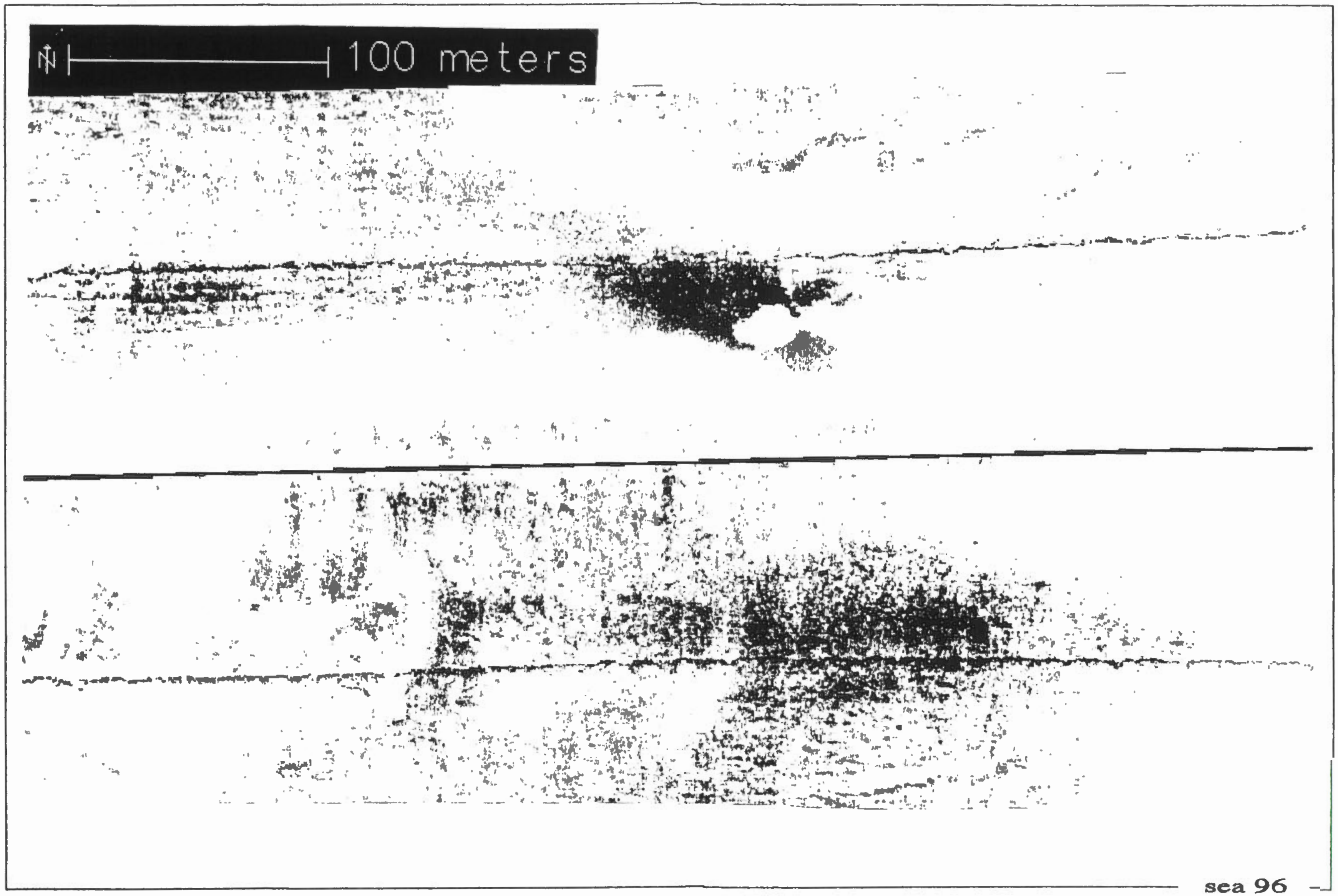


Figure 17

Figure 18: Generalized representation of the initial O-90 Glory Hole excavation into the upper geological units. Features were drawn from vertical SIT camera data collected by Petro-Canada after the completion of the glory hole with description derived from comments by Poorooshasb (1990).

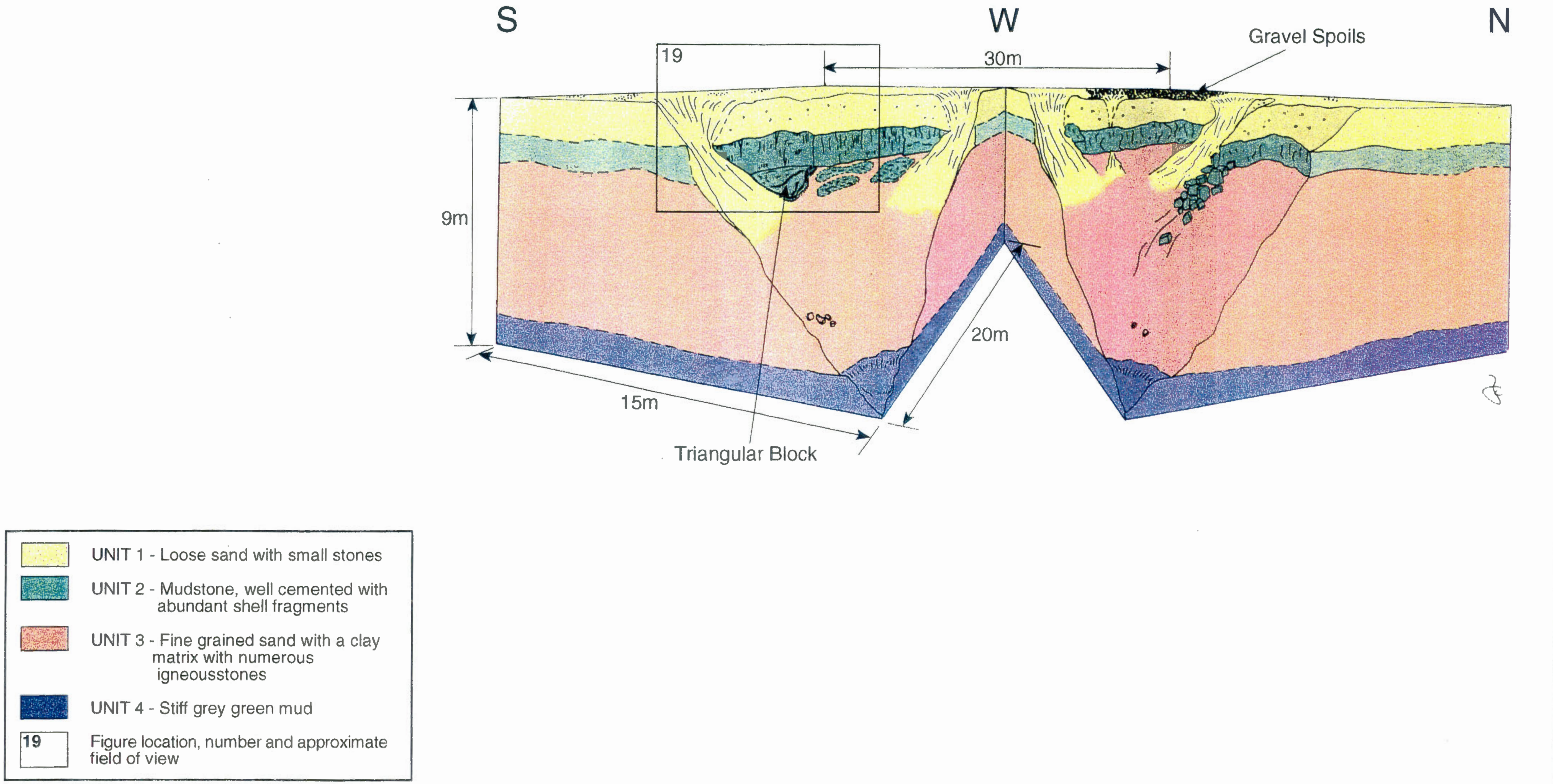
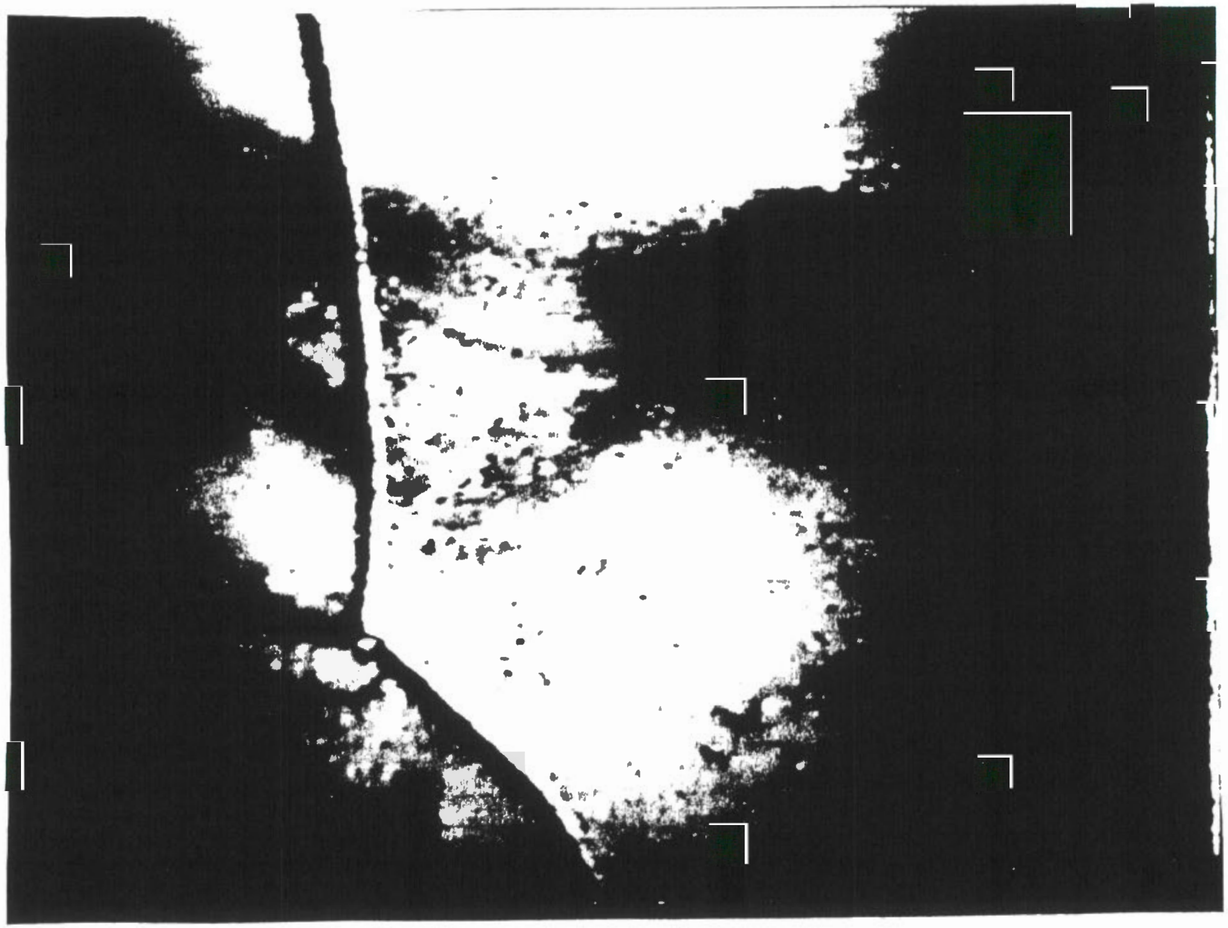

S
W
N
Gravel Spoils
19
30m
9m
20m
15m
Triangular Block
UNIT 1 - Loose sand with small stones
UNIT 2 - Mudstone, well cemented with abundant shell fragments
UNIT 3 - Fine grained sand with a clay matrix with numerous igneousstones
UNIT 4 - Stiff grey green mud
19
Figure location, number and approximate field of view

Figure 18

Figure 19: Triangular material on the southern interior margin is interpreted as a block of "hardpan" which broke away from the excavation edge. There is insufficient resolution to determine whether highly reflective features at the base of the hole represent blocks of "hardpan" material or boulders.



sea 96

Figure 19

SECTION 5 - THREE MONTHS POST EXCAVATION (AUGUST, 1990)

The GSC's HySub 5000 ROV SIT and color video provided enhanced detail on the shape and character of the O-90 Glory Hole and identified subtle changes that had occurred in the 3 months since excavation (Figure 18).

Figures 21 and 22 are generalized representations of the excavation three months after completion. Angle of view remains the same throughout the series of block diagrams but there is a substantial increase in resolution for this diagram when compared to Figure 18. Figure 20 represents the best oblique view available of the glory hole. This view shows the steep walled exposure of the "hardpan" unit and looks towards the prominent sandy ramp on the western edge. Another prominent feature is the very angular distinct cusp-like feature protruding from the middle of the northern edge of the excavation (Figure 23). This cusp like feature shows Unit 2 outcrop overlain by unconsolidated material at a steep angle of repose with this material extending right to the edge of the steep "hardpan" scarp (Figure 24). Also there is an accumulation of gravel on the northwest margin of the hole (Figures 21 and 25). This gravel is interpreted to represent the coarser component of the material jetted out during the excavation process. From the video data the material all appears to be gravel size with no larger cobbles or boulders present. The video data did not show any bedforms or erosional features present during the August, 1990 reconnaissance.

As observed the edge of the excavation is sharp (Figures 23 and 24). The unconsolidated upper unit grades at a steep angle (20->40^0)(Figure 24) into the hole and unconformably overlies the near vertical, fresh looking and angular "hardpan" scarp. This scarp is frequently dissected by both large and small "crevasse splays" where the unconsolidated sediments of the upper unit have slumped and formed debris fans. There are angular blocks present around both the perimeter of the "hardpan" scarp and towards the centre of the hole. Video observations indicate that these are semi-consolidated sediment blocks and not angular boulders. The glory hole has not been colonized by larger sessile benthic organisms and the centre of the hole appears to have been slightly infilled when compared to the immediate post-excavation data (Figure 22).

HYSUB ROV video observations summarized

- The unconsolidated Unit 1 grades at a steep angle (20->40 degrees) of repose to the very edge of the glory hole (Figure 24). Unit 1 unconformably overlies Unit 2.

- The edge of the glory hole is occasionally buried by large and small ramps of sand where Unit 1 sediments have cascaded into the hole and formed debris fans.

- The differing character of the N and S walls is confirmed in the HySub imagery. Views of the southern exposure reveal the near vertical, fresh looking and angular "hardpan" scarp (Figure 22). Northern exposures are more irregular, blocky and characterized by angular cusp-like features (Figure 20).

- The triangular zone (Figure 19) is present but appears more degraded.

- The reflective patches noted in the hole on Figure 19 appear as well preserved blocks in Hysub SIT video data.

- Reflective features present around the base of the "hardpan" scarp and towards the centre of the hole are consolidated sediment blocks of excavated material that fell into the hole and not angular boulders.

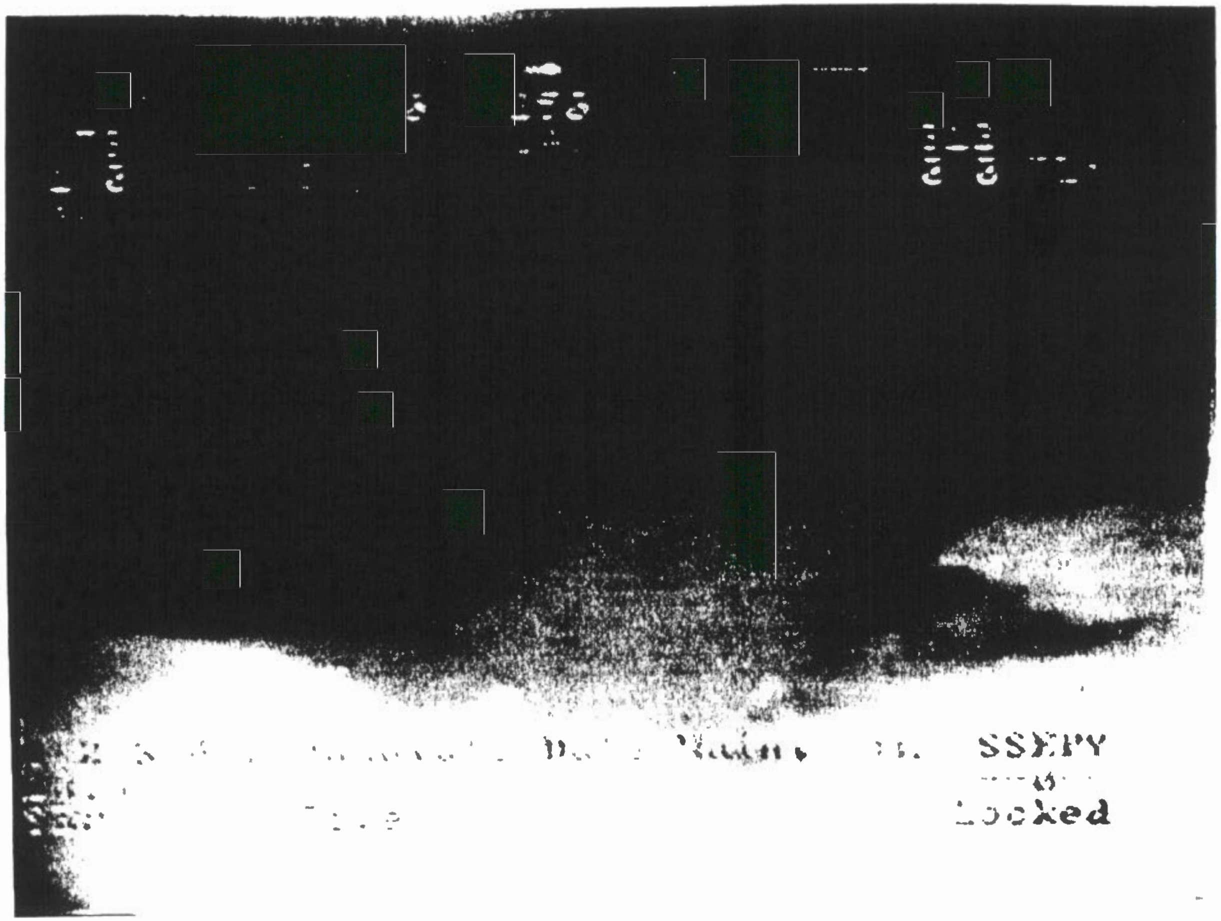
- An accumulation of gravel on the NW margin of the hole (Figures 21 and 25) is the coarser component of the material jetted out during the excavation process. The material appears to be gravel (approx. 8 cm) with no larger cobbles or boulders present.

- The glory hole has not been colonized by sessile benthic organisms.

- The centre of the hole appears to have been slightly infilled compared to the June post-excavation data (Figure 22).

- The video data do not shown any bedforms or erosional features present during the August, 1990 reconnaissance.

Figure 20: This image represents the best oblique view available of the glory hole. The ROV is positioned on the eastern edge of the excavation with the view towards the prominent sandy ramp on the western edge. Image is a frame grab from August, 1990 Hysub 5000 ROV.



sea 96

Figure 20

Figure 21: Plan view of the excavation three months after completion. Note the location of the ROV for point from which Figure 20 image was obtained.

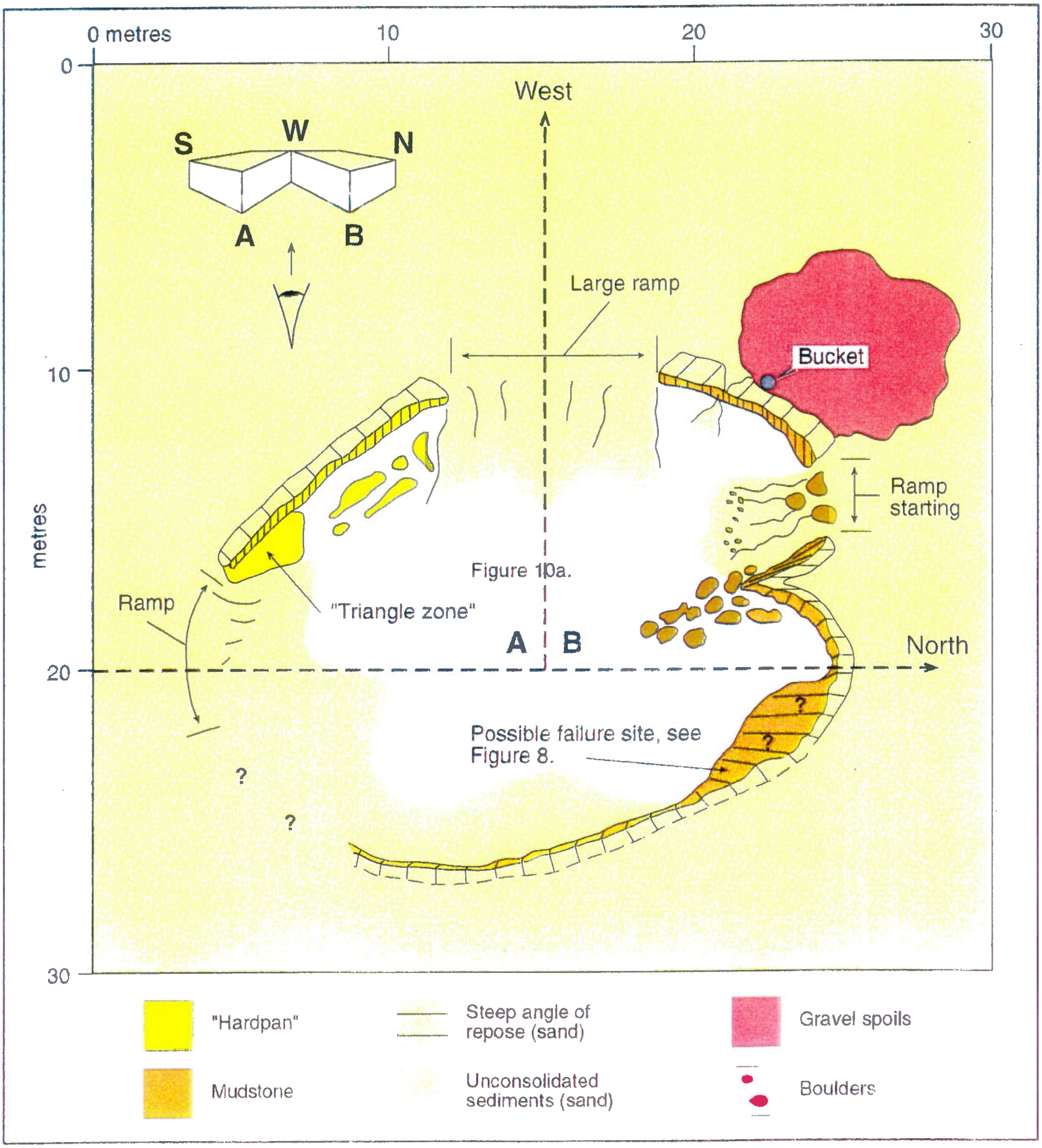
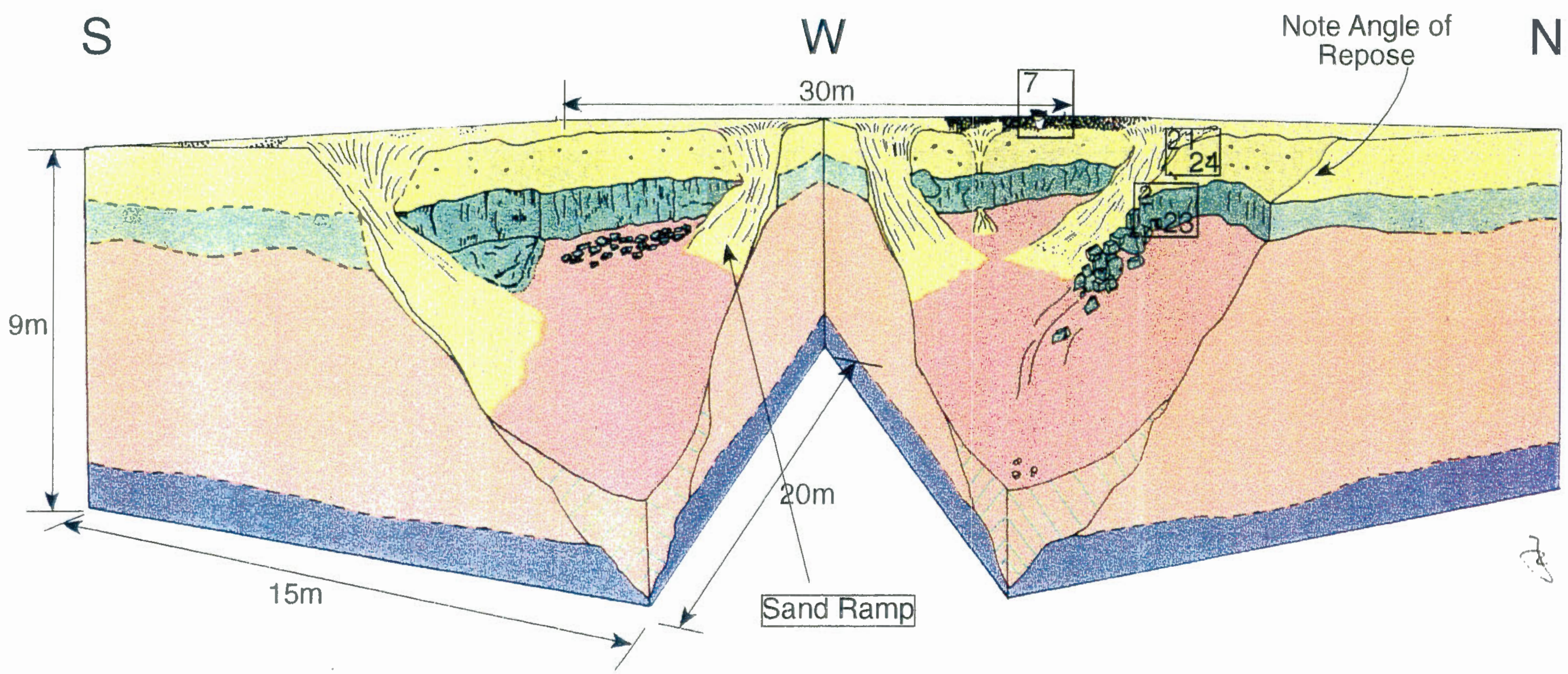

0 metres
10
20
30
0
10
20
30
metres
West
North
S
W
N
A
B
Large ramp
Bucket
Ramp starting
Figure 10a.
"Triangle zone"
Ramp
A
B
Possible failure site, see Figure 8.
?
?
"Hardpan"
Mudstone
Steep angle of repose (sand)
Unconsolidated sediments (sand)
Gravel spoils
Boulders

Figure 21

Figure 22: Generalized representation of the excavation three months after completion. SIT black and white, VHS colour and colour scanning sonar data collected from the Hysub 5000 ROV provided increased resolution when compared to Figure 18.



UNIT 1 - Loose sand with small stones

UNIT 2 - Mudstone, well cemented with abundant shell fragments

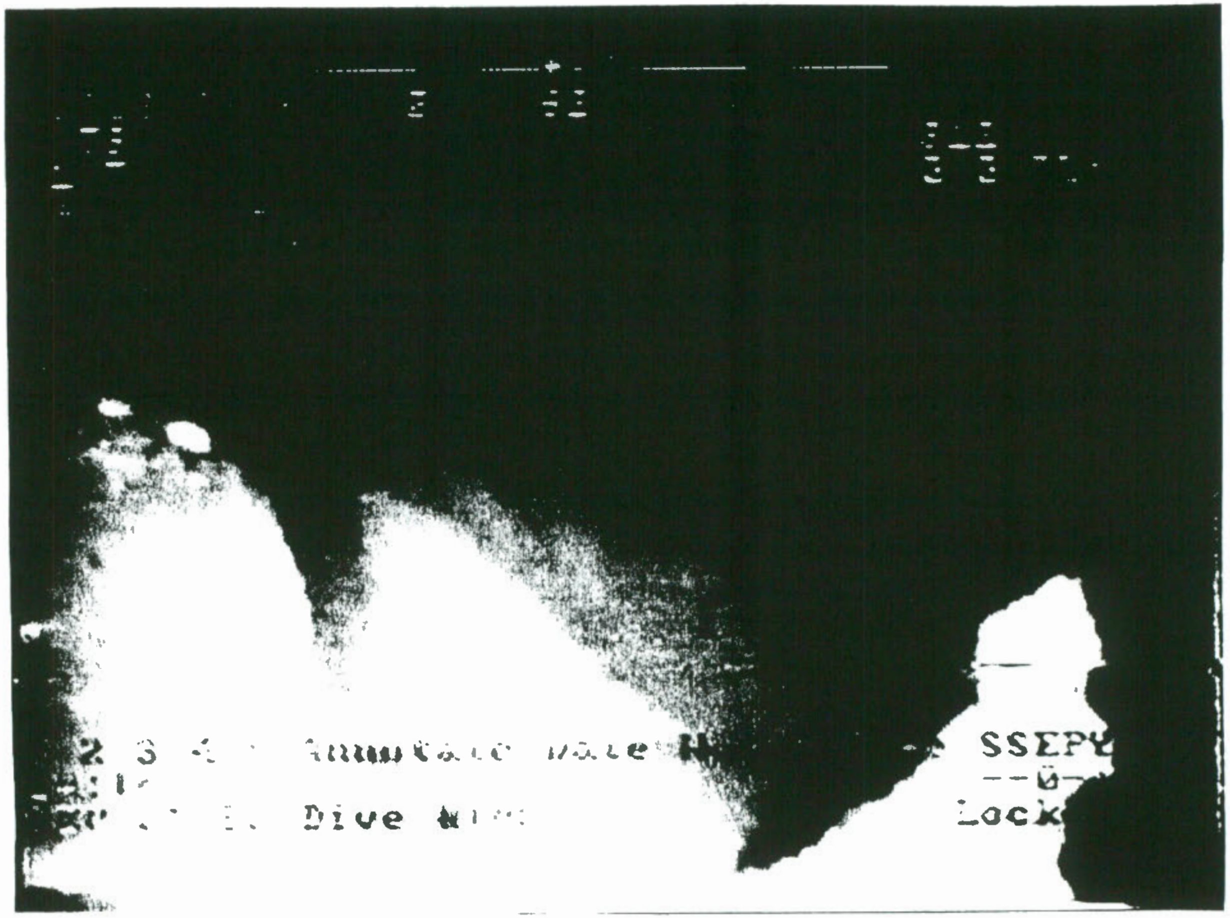
UNIT 3 - Fine grained sand with a clay matrix with numerous igneousstones

UNIT 4 - Stiff grey green mud

7 Figure location, number and approximate field of view

Figure 22

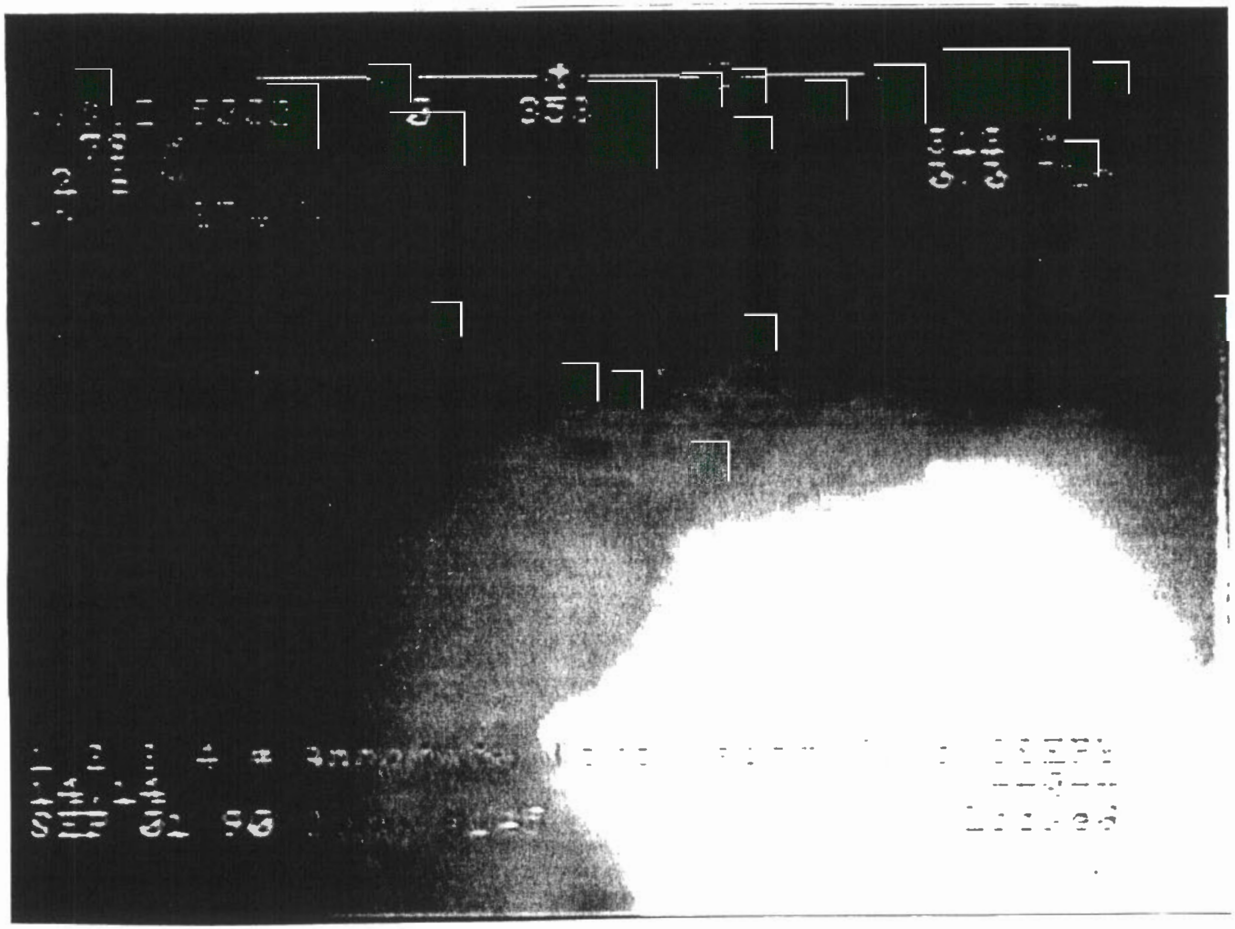
Figure 23: Very angular distinct cusp like feature protruding from the middle of the northern edge of the excavation displays Unit 2 outcrop fractured into a series of large blocks sloping down towards the base of the hole. Image collected using the ROV SIT camera and derived as a frame grab from original video tape (August, 1990).



sea 96

Figure 23

Figure 24: Very angular distinct cusp like feature protruding from the middle of the northern edge of the excavation displays Unit 2 outcrop overlain by unconsolidated material at a steep angle of repose. Note that this material extends to the edge of the steep Unit 2 outcrop. Image collected using the ROV SIT camera and derived as a frame grab from the original video tape (August, 1990).



sea 96

Figure 24

Figure 25: Image of a bucket resting on what is interpreted as a thin accumulation of gravel overlying the original substrate of unconsolidated sandy material (unit 1). The gravel is interpreted to represent the coarser component of the material jetted out during the excavation. Note that the material all appears to be of a uniform gravel size with no larger cobbles or boulders present. Location is along the northwestern edge of the excavation. The gravel appears to extend right to the edge of the steep Unit 2 outcrop. Image is a frame grab from Hysub 5000 ROV VHS colour video (August, 1990). (Parrott and Sonnichsen, 1990).

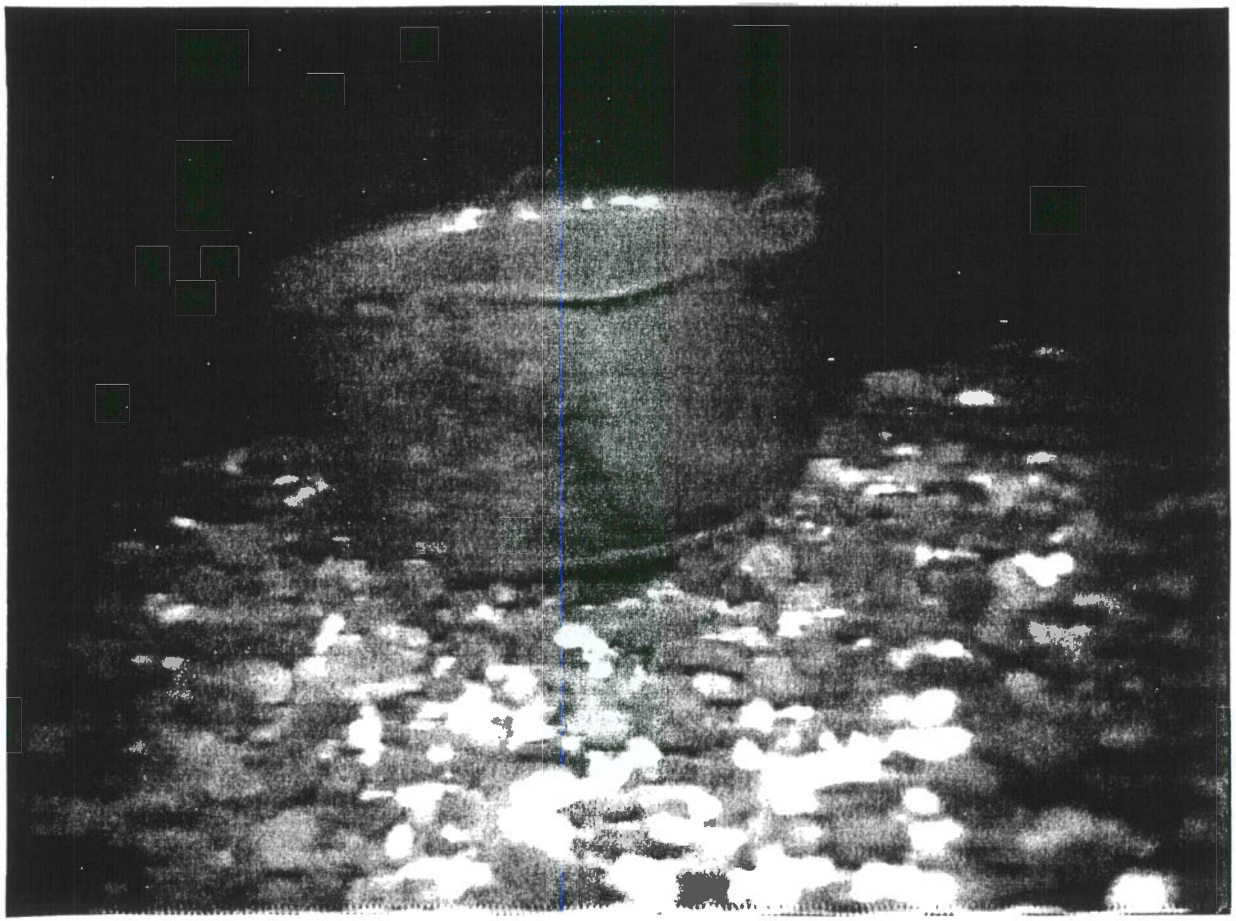


Figure 25

SECTION 6 - FIVE YEARS POST EXCAVATION (MARCH, 1995)

This section represents a summary of the SDL-1 manned submersible dive observations and sampling completed in March, 1995. The following describes the changes observed between the 1990 post-excavation data and March 1995 with a minimal comparison to the BIO Video Grab observations completed in August 1995.

The main change noted between 1990 and 1995 was the change in Unit 1. Unit 1migrated away from the hole exposing a 1-2m wide rim of the upper flat lying surface of Unit 2 (Figures 26,27). In the 1990 data the edge of this unit was emplaced immediately over the scarp top at high angles of repose (at times exceeding 40^0). The 1995 data shows a gradual slope and return to grade of the overall seafloor.

The migration of the upper unit away from the hole and the subsequent exposure of the upper surface of Unit 2 on the southwestern rim shows the presence of cracks, fissures, and dissolution holes (Figure 28). As this unit was up until 5 years ago blanketed by 1.5m of unconsolidated sediment these features are interpreted to have been formed prior to the emplacement of the upper unit. This surface could therefore represent a desiccated layer probably formed during subaerial exposure (Adshead, 1990,). Two "hardpan' outcrop sites were sampled during the SDL-1 dive (March 1995). One along the southwestern edge of the glory hole and the other along the northern edge. The material at the southwestern site had an angular fresh character and the northwestern sample displayed a more rounded (degraded) character.

Observation from the Hysub 5000 ROV in August 1990 (Figure 18) indicated that there were a few angular boulders present towards the centre of the glory hole but that there was no major concentrations. The 1990 data set also indicated that the smaller coarse gravel component was preferentially deposited along the northwestern margin of the hole during excavation (Figures 21 and 25). Exposure of the upper surface of the "hardpan" layer observed in the 1995 data revealed angular boulders along this ledge ranging from 0.08-0.4m diameter (Figure 29). Five larger boulders were observed along the 6-10m of exposed rim on the southwestern edge of the hole. This indicates that larger than gravel size material was present during the excavation but the emplacement of this size fraction was not evident in the area where much of the coarser grained material was deposited (Figures 21 and 25) during the excavation.

Sediment at the base of the glory hole consists only of fine grained material with abundant shell hash with no blocks of unconsolidated material or angular boulders observed. Depth measurements completed during the dive indicate that maximum depth of the glory hole below seabed is less than 5m versus the 6-7m observed upon the completion of the hole in 1990 (Poorooshasb, 1990). This indicates some infill but could also reflect from what base level the hole was measured ie. from the top of the "hardpan" layer or the surface of the overlying unconsolidated silty sand unit.

In summary by March, 1995, significant changes had occurred to the O-90 glory hole (Figure 12).

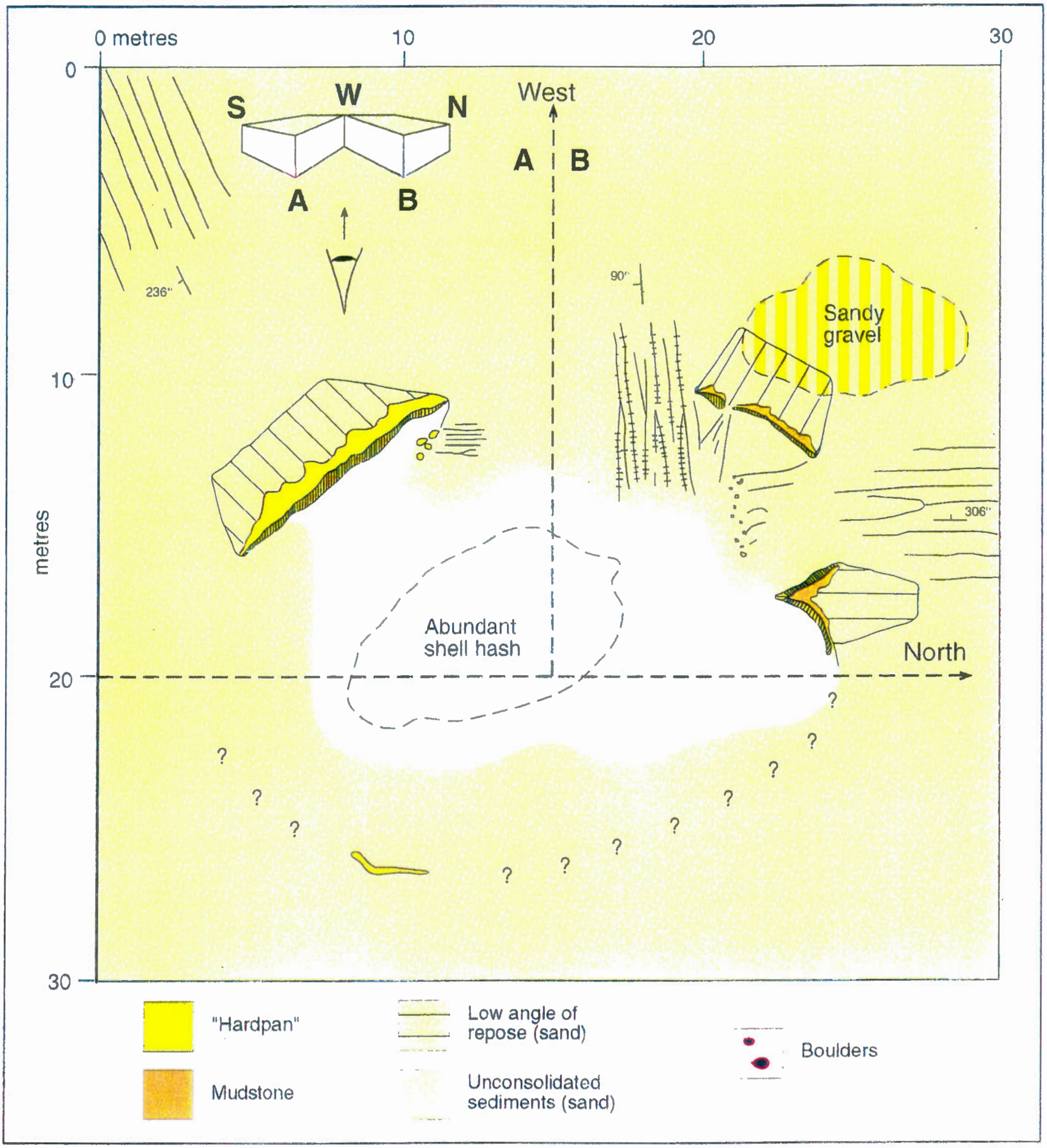
- The depth of the glory hole has decreased to less than 5 m from 6-7 m (Poorooshasb, 1990) assuming measurements were from the top of Unit 1 in both cases.

- Outcrop of the walls of O-90 has been greatly reduced due to sand infill. The original ramp on the western side of the hole has expanded towards the north and a new ramp has split the N exposure into two isolated outcrops. Also, sand has completely covered the eastern side of the hole ("cut away"portion of the hole in Figures 19, 22 and 27)

- Angular to sub-rounded gravels and boulders ranging from 0.08 to 0.4 m are visible on the surface of Unit 2 (Figure 29). This suggests that boulders and cobbles were encountered by the Tornado drill but were not deposited with the gravel spoils (Figure25). They may be buried under the sand infill.

- By 1995 the edge of Unit 1has retreated away from the hole, exposing a 1-2 m wide rim of the upper surface of Unit 2 (Figures 28 and 29). The 1995 data also show a more gradual angle of repose for Unit 1.

Figure 26: Plan view of the Glory Hole five years after excavation (March, 1995).



0 metres
10
20
30
0
10
20
30
metres
S
W
N
A
B
West
A
B
236°
90°
Sandy gravel
306°
Abundant shell hash
North
?
"Hardpan"
Mudstone
Low angle of repose (sand)
Unconsolidated sediments (sand)
Boulders

Figure 26

Figure 27: Generalized representation of the glory hole almost five years after completion. Hi-8 and VHS colour imagery, visual observations from the manned submersible, SDL-1 provided exceptional resolution and unique insight into the physical character of the exposed sediments.

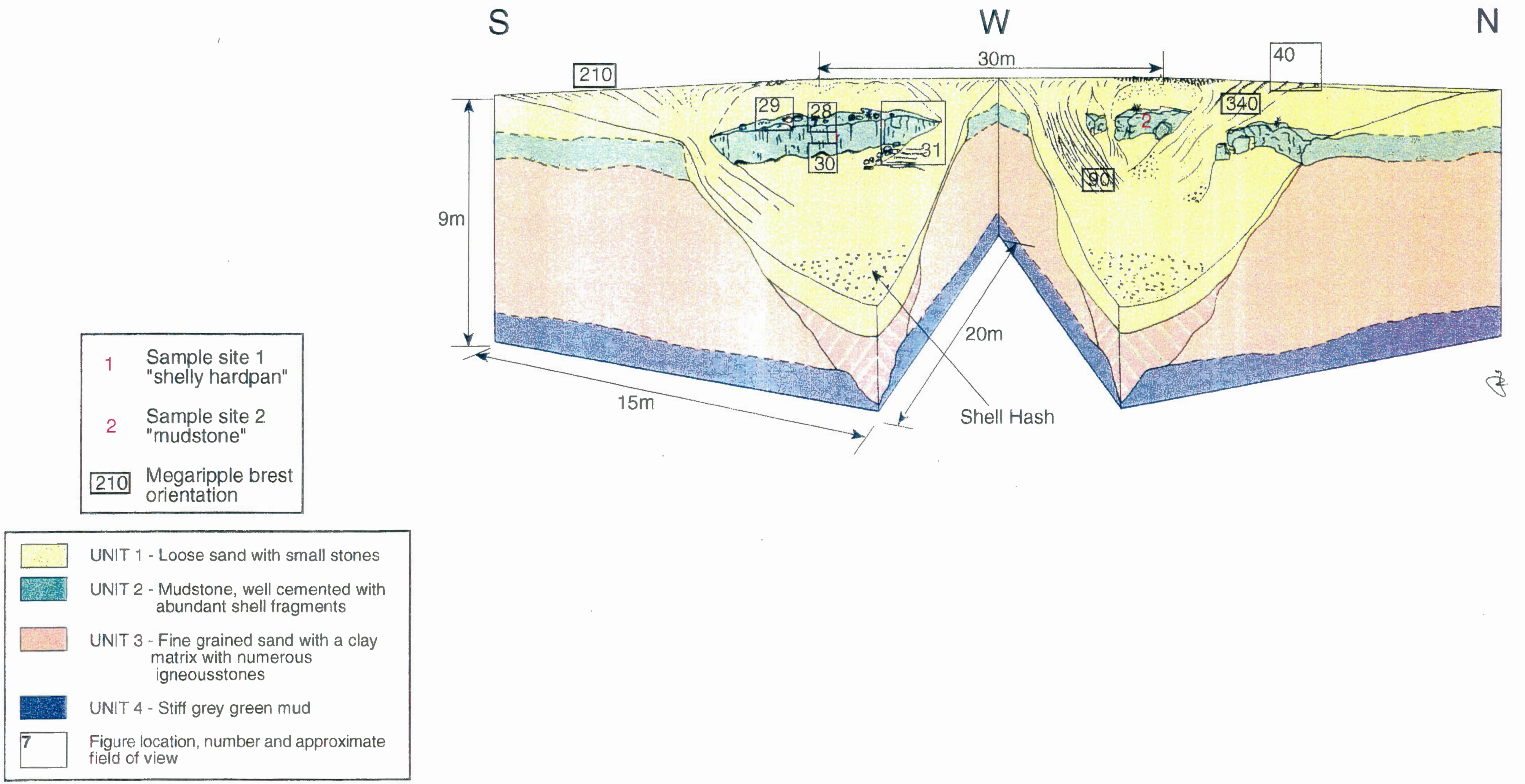
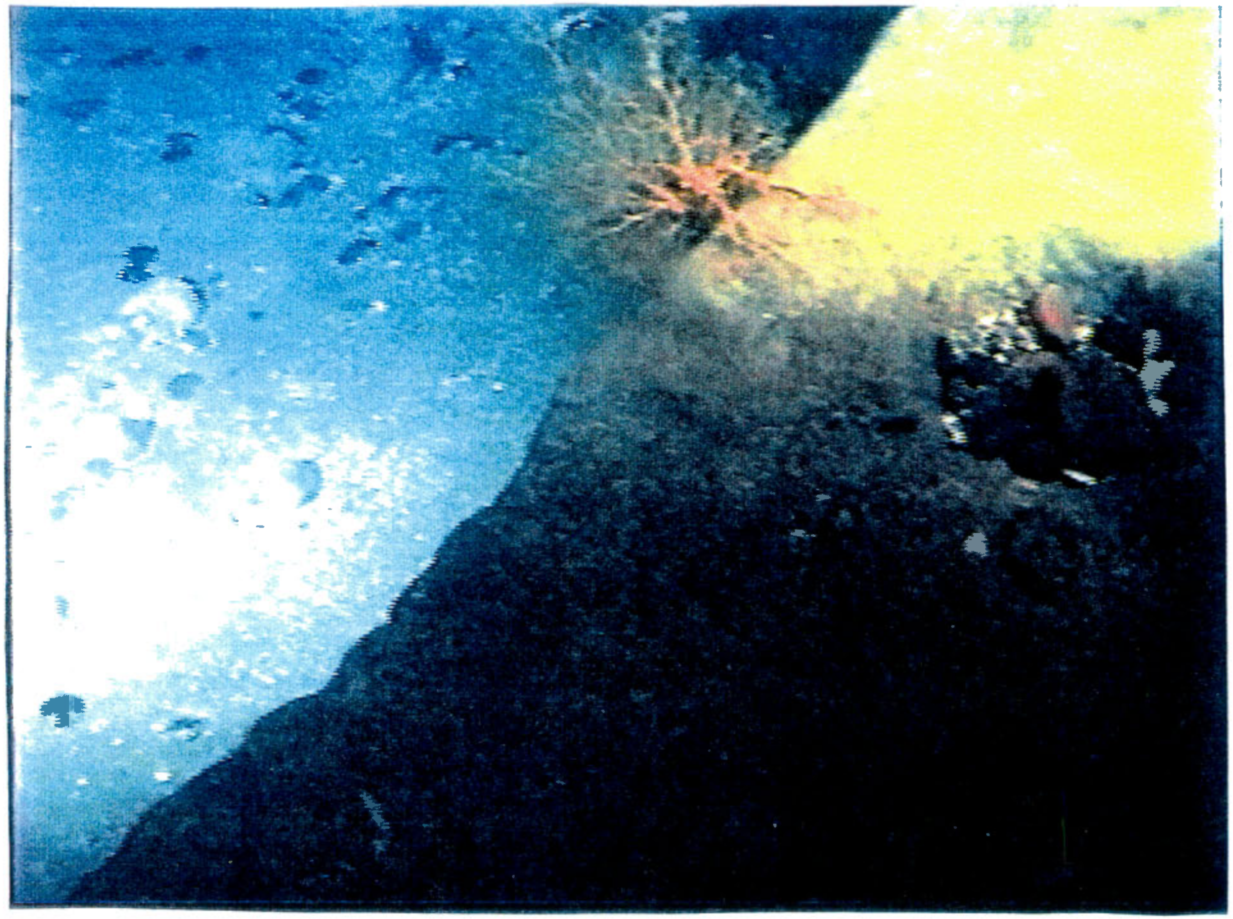

S
W
N
30m
210
40
340
29
28
30
31
2
90
9m
20m
15m
Shell Hash
1 Sample site 1 "shelly hardpan"
2 Sample site 2 "mudstone"
210 Megaripple brest orientation
UNIT 1 - Loose sand with small stones
UNIT 2 - Mudstone, well cemented with abundant shell fragments
UNIT 3 - Fine grained sand with a clay matrix with numerous igneousstones
UNIT 4 - Stiff grey green mud
7 Figure location, number and approximate field of view

Figure 27

Figure 28: The upper flat lying surface of the Unit 2 "hardpan" has cracks, fissures and dissolution holes that are interpreted to have formed prior to the emplacement of the upper unit. This surface may represent a desiccated layer probably formed during subaerial exposure or in a higher energy shallow water environment Image scanned from 35mm still photograph collected using the SDL (March, 1995).



sea 96

Figure 28

Figure 29: By 1995 Unit 1 has migrated back exposing 1-2m of Unit 2 and has stabilized at a substantially lower angle than observed during 1990 (from 40+ to ~15). Sub-angular boulders (0.1 to 0.4m diameter) along the exposed rim of the hole indicate that clasts larger than gravel were present during the excavation but were not lifted to where the coarser grained spoils were deposited (Figures 21 and 25). Image scanned from 35mm still camera photograph collected using SDL-1 (March, 1995).

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Figure 29

Figure 30: Along the base of the southwestern exposure of the "hardpan" scarp sediment removal by preferential excavation suggests prolonged hydraulic jetting at this level. This has produced an overhang of up to 0.2m. The material above and below this overhang appears to have the same composition and consolidation. Image collected using the SDL-1 externally mounted VHS colour camera and derived as a frame grab from the original video (March, 1995).

Figure 30

Figure 31: At the base of the southern edge of the sand ramp along the western side of the glory hole are blocks of Unit 2 material. Along the edge of the sand ramp and grading into the glory hole are bifurcating ripples with smaller 2nd generation ripples are oriented normal to and superimposed on the larger ripples. Image collected using the hand-held HI-8 video camera inside the SDL and derived as a frame grab from the original video tape (March, 1995).

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Figure 31

SECTION 7 - UNIT 2 SAMPLING RESULTS

The migration of the upper unit away from the hole and the subsequent exposure of the upper surface of the "hardpan" layer shows the presence of cracks, fissures, and dissolution holes (Figure 28). As this unit was up until 5 years ago blanketed by 1.5m of unconsolidated sediment these features are interpreted to have been formed prior to the emplacement of the upper unit. This surface could therefore represent a desiccated layer probably formed during subaerial exposure (Adshead, 19**). Two "hardpan' outcrop sites were sampled during the SDL dive (March 1995). One along the southwestern edge of the glory hole (Figures 32-34) and the other along the northern edge (Figures 35-38). The material at the southwestern site had angular fresh character and the northwestern sample displayed a more rounded (degraded) character.

On the southwestern edge of the glory hole hardpan sampled from the cliff face and a large angular block that had collapsed into the hole (Figure 35) were described as;

> *very hard, blackish grey, poorly cemented shelly conglomerate or coquina; massive with subtle colour banding.*

The material was impossible to penetrate with a tube sampler pushed by the sub's 6-function arm. Lab tests of unconfined compressive strengths on the hardpan were >200kPa.

On the northwestern edge of the glory hole the material was more irregular and blocky but at the same stratigraphic level. This sample was described as;

> *dark brown, very stiff, cohesive mud; massive, occasional coarse clasts imbedded.*

This material was penetrated by the tube sampler but the sediment was too cohesive and did not separate from the outcrop; it was not recovered. Unconfined compressive strength on the non-cemented Unit 2 "mudstone" was an order of magnitude less than the "shelly hardpan" (<20kPa).

Observations Unit 2:

- Visual and sampling observations indicate that Unit 2 varies substantially over short distances (< 10 m). At O-90, cemented calcareous "hard pan" appears to be restricted to the southern half of the hole; the northern side exposed stiff greenish mud. Previous hard pan descriptions did not distinguish the two Unit 2 sediment types.

- Cemented "hard pan" was 1.5 m thick at O-90 and is part of the regional unconformity surface beneath Unit 1: it is not associated with the outcrop of a specific horizon. This suggests there is a strong possibility that hard pan will be encountered at other sites in the Terra Nova region.

- "Hard pan" likely occurs as isolated patches where carbonate conditions are favourable. These may represent storm deposited mounds or lagoonal type concentrations of broken shell material deposited and cemented under shallow marine conditions.

Preliminary geotechnical analysis completed by the GSC(Atlantic) Geotechnology Group March, 1995 on the southwestern exposure "shelly hardpan" sample and the northwestern exposure mudstone sample are listed below.

	Unit 2 -"shelly hardpan"	Unit 2 -mudstone
Bulk density	2.242 gr/cc	1.955 gr/cc
Grain density	2.662 gr/cc	2.781 gr/cc
Water content	12.7 %	31.1 %
Shear strength	>215 kPa	4-6 kPa

The shear strengths of both samples should be treated with caution because the "shelly hardpan" was too hard and the mudstone too soft to measure accurately with a hand-help instrument (Kate Moran, pers comm). However, it is accepted the two samples indicate an order of magnitude difference.

Figures 32: Shelly "hardpan" of Unit 2 was sampled at this site on the SW edge of the glory hole. Note the angular fresh character of the material. Cliff face could not be penetrated by sub's hydraulic samplers. Image collected using the SDL externally mounted VHS colour camera and derived as a frame grab from the original video tape (March, 1995).

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Figure 32

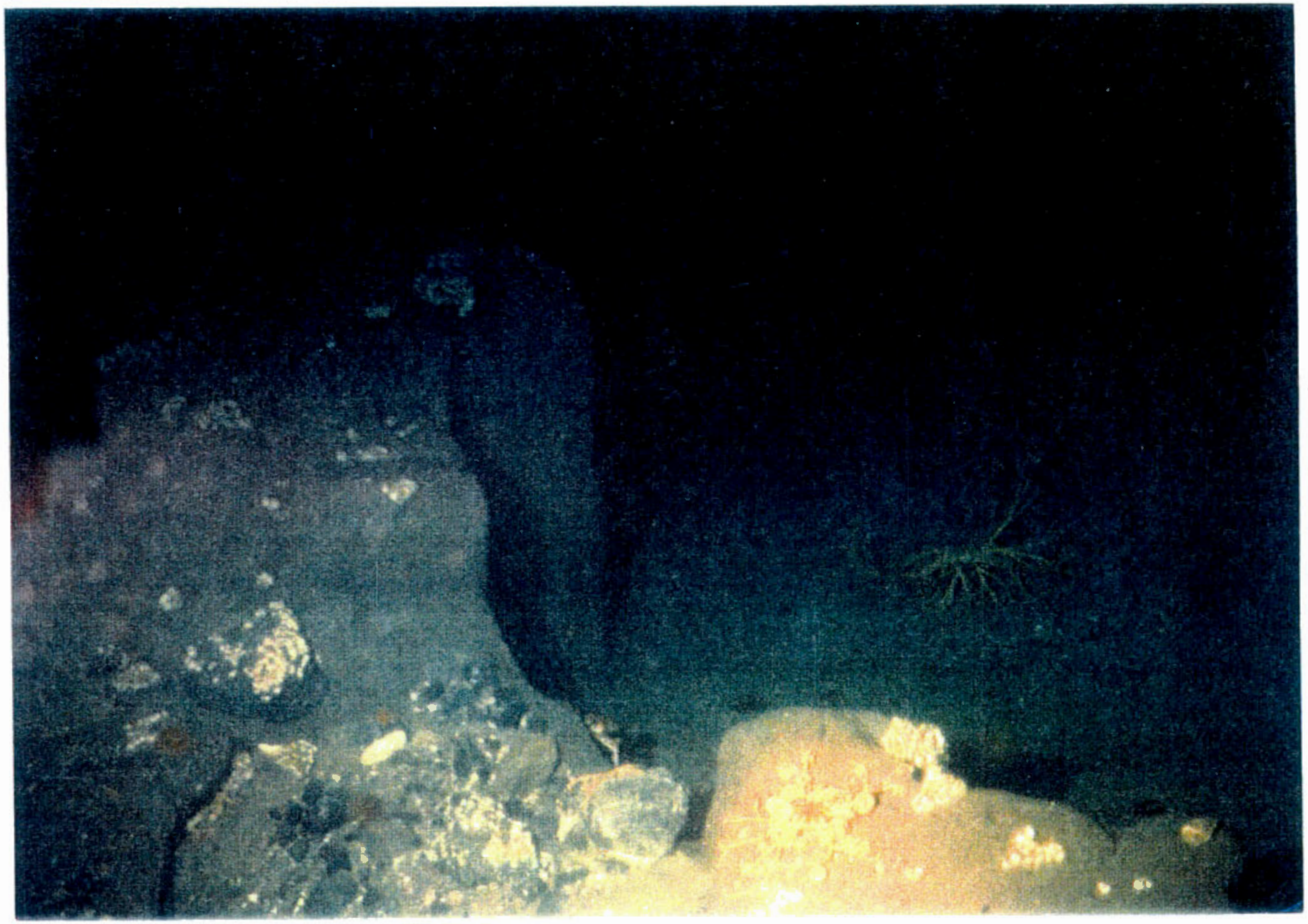
Figure 33: Same as figure 30

Figure 33

Figure 34: "Shelly hardpan" of Unit 2 sample. The block was recovered from the base of Unit 2 (see Figure 31). Scale bar units is in centimetres.

Figure 34

Figure 35: View of the sample site on the northwestern edge in Unit 2 at approximately the same stratigraphic level as Figure 30. Note the darker colour, absence of shelly material and the more rounded , massive (degraded) character of the material in comparison to Figure 15.Cliff top was penetrated by sub's hydraulic samplers but mud was too cohesive to remain in sampler. Image collected using the hand-held HI-8 video camera inside the SDL and derived as a frame grab from the original video tape (March, 1995).



sea 96

Figure 35

Figure 36: Similar view as Figure 35 obtained at the same location but with a 35mm handheld camera from a different angle.

Figure 36

Figure 37: Close up of sample site 2 indicating the Unit 2 northwestern outcrop. Note degraded character and sub manipulator arm. Image collected using the hand-held HI-8 video camera inside the SDL and derived as a frame grab from the original video tape (March, 1995).

Figure 37

Figure 38: Similar view as Figure 37 obtained at the same location but with a 35mm handheld camera from a different angle.

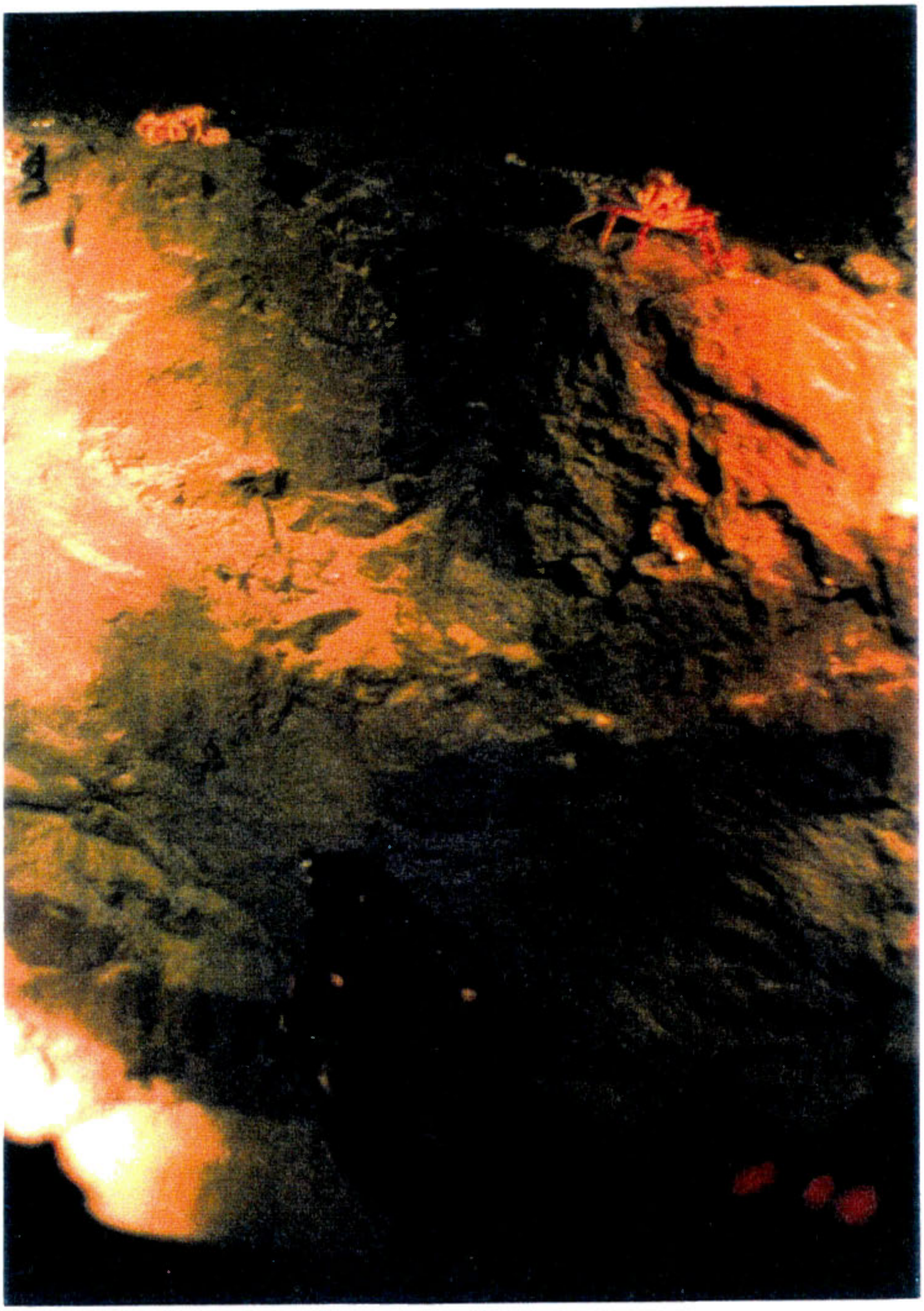


Figure 38

SECTION 8 - BEDFORM OBSERVATIONS AND SEDIMENT TRANSPORT

In 1995, the first evidence for sediment transport is seen:

- presence of small and medium to large oscillatory ripples (Figures 39,40)

  The megaripples were only observed in March, 1995 and not on the August 1990 or 1994 data.They are interpreted as having formed during the winter storm season with subsequent infill/degradation over the summer.

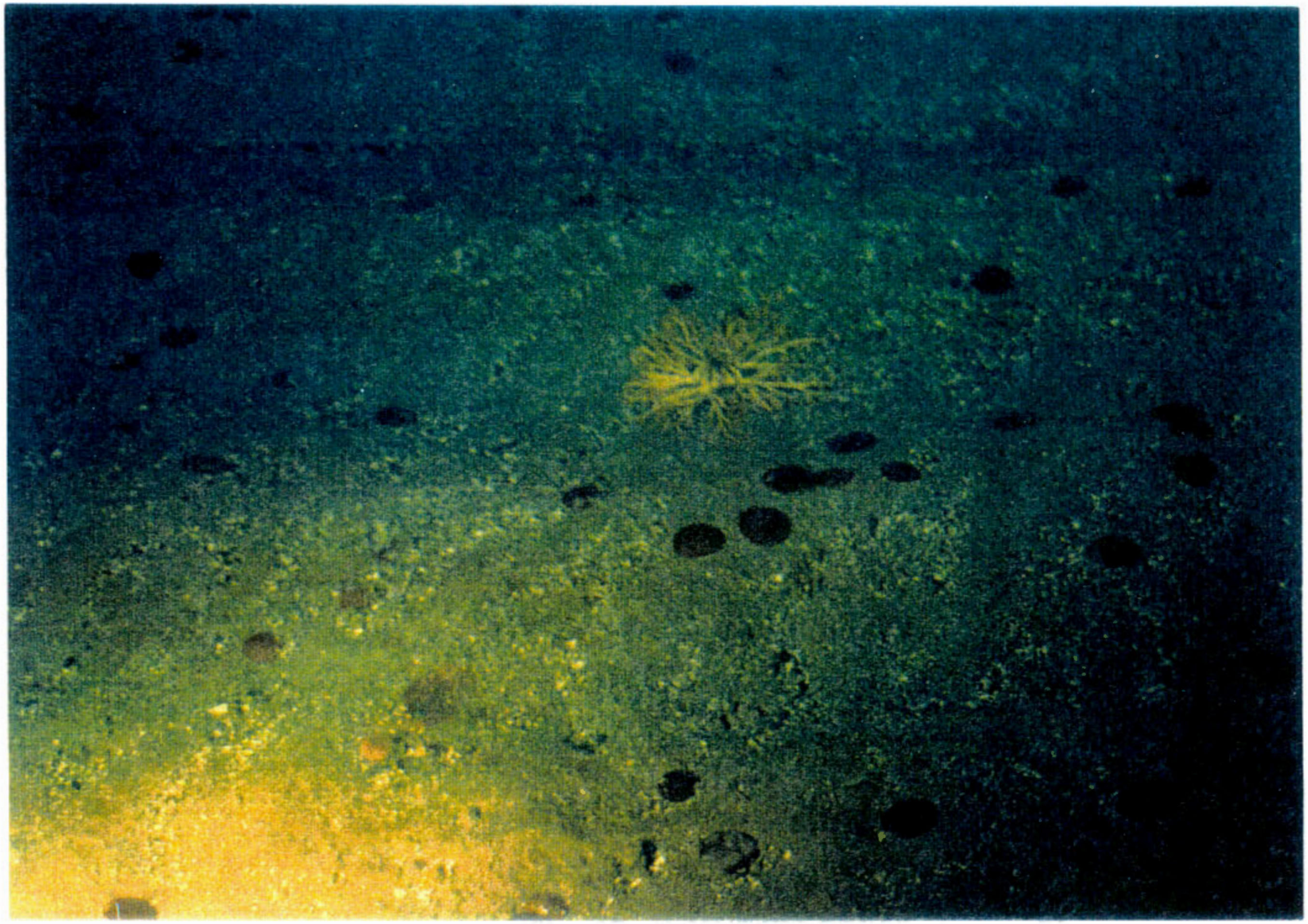
- removal of 1 to 2 m of Unit 1 sand from the perimeter of the hole (Figures 28,29).

  Removal of Unit 1 around the glory hole suggests an oscillatory particle motion (created by long period surface waves) "swept" the sand into the hole where it could not be reactivated. On a larger scale, there is only infrequent net or unidirectional transport of sands at Terra Nova as evidenced by the stability of seafloor sediments and large bedforms over almost 7 years (CSR, 1996).

Figure 39: Bifurcating ripples with a 0.3-0.5 m wavelength with the crests trending downslope (0900) on the large sandy ramp on the W edge of the glory hole. Smaller 2nd generation ripples are oriented normal to and superimposed on the larger ripples. These bedforms were only observed in March,1995 and not on any of the August data (1990,1995). Image collected using the hand-held HI-8 video camera inside the SDL and derived as a frame grab from the original video tape (March, 1995).

Figure 39

Figure 40: Large bifurcating wave-formed ripples (>0.5m wavelength, 0.3 m amplitude) with crests trending downslope on a sand ramp along the N edge of the glory hole. They were observed only on the March, 1995 data. These features are interpreted as having formed during the winter storm season. Image collected using the SDL externally mounted VHS colour camera and derived as a frame grab from the original video tape (March, 1995).



sea 96

Figure 40

SECTION 9 - SUMMARY OBSERVATIONS ON THE O-90 GLORY HOLE

Section 9.1 Soil Response

The glory hole is a relatively small feature in a region with an active seabed surface of silty sand (unit 1) (Cameron and Sonnichsen, 1992). The hole has experienced some infill but can still be clearly recognized both on sidescan sonar as well as video data and does not appear to have either increased or decreased in aerial extend over the 5 year period based on sidescan sonar data (see Figures 21,26).

Initial shape and dimensions of the glory hole was an oval shaped hole 20x24m, >6m deep. An estimated 1050m^3 material was removed (Poorooshasb, 1990). If the hole had vertical or near vertical sides total volume removed would have exceeded 2000m^3 . If the hole would have been as planned (with a diameter of approximately 8m and total depth of 11m) the volume removed would be approximately 500m^3. The glory hole did not reach the required depth of 10m; this was attributed to the presence of a shelly "hardpan" layer and boulders in the hole which accumulated during the excavation preventing the air jet lifting of material from the hole (Poorooshasb,1990).

Section 9.1.1 - Unit 1 response

Unit 1 is described as loose sand with small stones (Peter Hampton, pers. Comm, 1990). The unit is 1.5 m thick. Little change was observed in this unit over the short term (ie June - August 1990). From June to August, Unit 1 maintained a steep angle of repose to the edge of the excavation with minimal sloughing into the hole. This suggests collapse of Unit 1 into the hole was not a factor affecting drill response. Based on the angle of repose of the unit 1 sediments it is inferred that over the 3 month period there was little infilling.Boulders and cobbles would have been encountered within Unit 1. It does appear that the coarser material (ie coarse but not exceeding 10-15cm) from the drilling process was preferentially deposited on the NW segment. No bedforms were observed on the August 1990 data.

Over the long term (August, 1990 - March, 1995) Unit 1 migrated well away from the hole, supplied sediment to the hole and revealed the presence of boulders within Unit 1. The boulders would have contributed at least some of the boulders that ultimately responsible On the March, 1995 data substantial evidence for sediment transport were observed which was not observed on the August 1994 data. Sediment transport therefore appears to have been associated with winter, 1995 conditions.

Section 9.1.2 - Unit 2 response

Initial descriptions of this unit were based on a pre-drilling borehole (Peter Hampton, pers. Comm to Russ Parrott) and the 88-400-004 borehole. Unit 2 was described as a unit of variable thickness composed of a green-grey,well cemented "mudstone" with numerous shell fragments, and similar material with only moderate cementation and sandy colour (Peter Hampton, pers. comm, 1990). The unit was described as a "hard pan" layer. Visual observations from March 1995 suggests the initial description is a hybrid derived from cuttings from two different Unit 2 sediment types which are at the same stratigraphic level and which change abruptly over short distances (< 10 m). Unit 2 can be divided into two distinct materials- greenish-grey, cemented "shelly hardpan" along the southwestern edge of the hole and dark grey, stiff massive mud along the north and northwestern edge (Sections 7 and 8). The "shelly hardpan" displays a smooth, vertical face and an angular fresh character; the stiff mud has a much lower concentration of shelly material and a more irregular edge, rounded and blockier character. The unit appears to be cemented along the southwestern edge of the hole due to the presence of carbonate material. The upper surface of this entire unit appears to have been subaerially exposed (dissolution holes) (Section 7). The walls of Unit 2 where observed in 1990 and 1995 were always vertical (Sections 7 and 8).

Preliminary geotechnical analysis completed by the GSCA Geotechnics Group indicate the southwestern exposure "shelly hardpan" sample is an order of magnitude more consolidated (<200kPa) than the stiff mud sample from the northwestern exposure (< 20 kPa) (Section 8).

Initial response of Unit 2 to the drilling activity was variable based upon video and sampling analysis (Section 8). Prominent features to be noted in this unit immediately and three months after excavation were; 1. a triangular collapsed block (6-10m^2) towards the southern margin, 2. the presence of "hardpan" scarps around the perimeter of the hole, 3. highly reflective material toward the centre of the diagram interpreted as segments of the hardpan layer and 4. a cusp like feature on the northern edge. The cusp feature on the northern edge could possible represent the separation between the drilling events and was marked at the leading edge by a train of blocks and pinnacle type structures oriented towards the centre of the hole -this is postulated only as there is no reference to actually moving the drilling equipment or platform,:offset of the centre position would be approximately 10m). Also at the base of the southwestern exposure the Unit 2 sediments have been preferentially excavated which has produced an overhang of up to 0.2m.

Based on the 1990 Petro-Canada sketch of the hole (Figure *, Peter Hampton, PCI, pers. comm) there is a distinct offset between the centre of the drill string and the resulting glory hole.This seems to indicate there was preferential removal of the stiff Unit 2 mud on the northeast side of the hole causing enlargement of the hole in that direction. This implies the mud was either senstiive to the hydraulic drilling and was jetted away during drilling or it too was undercut and collapsed into the hole. Assuming that Unit 3 if of relatively consistent texture and properties, the former scenario is more likely: the Uni2 muds which are uncemented, and much less consolidated thatn the Unit2 hardpan were preferentially jetted away causing enlargement of the hole in a NE direction.

In summary the features identified in Unit 2 include a large triangular collapse feature,sharp vertical scarps and cusps , and numerous angular blocks of Unit 2 intact n the hole. This suggests that much of the Unit 2 hardpan failed and collapsed in blocks rather than being desegregated by the drill jets. Collapse likely occurred as the underlying sediment was preferentially removed. This would explain the large circumference of the glory hole. In addition, based on ROV measurements of the hole centre and the resulting hole shape and dimensions (Figure 6), it appears the mud on the northeastern side of the hole was preferentially removed. This may reflect a more sensitive reaction to the hydraulic jets on the drill arms.

Section 9.1.3 - Unit 3 response

Unit 3 consists of an approximately 5m thick unit described as fine-grained sand with a clay matrix and numerous igneous stones, displaying a good initial strength and very mobile once fluidized; possibly glacial till (Petro-Canada, 1990).Video evidence could not confirm either the presence of boulders or glacial till in Unit 3. The 1990 ROV data indicates that there are only a few boulders present at the base of the hole. Observation in 1995 indicated that the sediments at the base of the glory hole consist only of fine grained material with abundant shell hash with no blocks of unconsolidated material or angular boulders observed. Blocks of unconsolidated material originating from the southwestern scarp of Unit 2 were observed only along the base of this scarp (Figure 31).

The sand component of Unit 3 would have been highly susceptible to the hydraulic action of the drill jets and could have been removed to a much greater distance than the 7 m diameter of the drill. This would have increased the collapse of Unit 2 by undermining it and causing both the collapse features observed as well as the overhang observed in 1995. Fluidizing the Unit 3 sediment likely undermined Unit 2 hard pan, and removed the Unit 2 mud causing the collapse features observed and enlargement of the hole to the northwest from a nominal drill diameter of 7.4m to an oval depression of 20x24m (Poorooshasb, 1990). Relatively similar soil conditions should be expected in Unit 3 throughout the Terra Nova region.

Section 9.1.4 - Unit 4 response

This unit was encountered at the base of the hole during drilling and was described as a stiff grey green clay. It was only sampled and observed during the initial pre-excavation boring. It was never observed in the hole. However it is postulated to coincide with reflector B in Figure 4. If that is the case stiff clay may be encountered closer to the seabed as one moves SW to Terra Nova.

Section 9.2 - Observed Changes to the O-90 glory hole (1990-1995)

The glory hole is a small feature on a sandy seafloor that is occasionally mobilized by the effects of long period surface waves. The hole has experienced some infill but can still be clearly recognized visually and on sidescan.

The seafloor at the O-90 glory hole has been reworked on at least one occasion by the effects of long period ocean waves, creating oscillatory ripples up to 0.4m high and 1.5m in wavelength. The oscillatory motion has also swept Unit 1 sands into the O-90 glory hole from the perimeter. No evidence for large scale unidirectional transport is seen.

The main change noted between 1990 and 1995 was the change in the upper unit. This unit migrated away from the hole exposing a 1-2m wide rim of the upper flat lying surface of the 'hardpan" (Figures 28,29). In the 1990 data the edge of this unit was emplaced immediately over the scarp top of the "hardpan" at high angles of repose (at times exceeding 40^0) (Figures

23,24). The 1995 data shows a gradual slope and return to grade of the overall seafloor.

The migration of the upper unit away from the hole and the subsequent exposure of the upper surface of the Unit 2 hardpan shows the presence of cracks, fissures, and a dissolution hole (Figure 28). As this unit was up until 5 years ago blanketed by 1.5m of unconsolidated sediment these features are interpreted to have been formed prior to the emplacement of the upper unit. This surface could therefore represent a desiccated layer probably formed during subaerial exposure (Adshead, 1991).

Observation from the Hysub 5000 ROV in August 1990 (Figure 22) indicated that there were a few angular boulders present towards the centre of the glory hole but that there was no major concentrations. This data set also indicated that the smaller coarse gravel component was preferentially deposited along the northwestern margin of the hole during excavation (Figures 21.25). Exposure of the upper surface of the "hardpan" layer observed in the 1995 data revealed angular boulders along this ledge ranging from 0.08-0.4m diameter. Five larger boulders were observed along the 6-10m of exposed rim on the southwestern edge of the hole (Figure 29). This does indicate that larger than gravel size material was present during the excavation but the emplacement of this size fraction was not evident in the area where much of the coarser grained material was deposited during the excavation.

Sediment at the base of the glory hole consist only of fine grained material with abundant shell hash with no blocks of unconsolidated material or angular boulders observed. Depth measurements completed during the dive indicate that maximum depth of the glory hole below seabed is less than 5m versus the 6-7m observed upon the completion of the hole in 1990 (Poorooshasb, 1990). This indicates some infill but could also reflect from what base level the hole was measured ie. from the top of Unit 2 or the surface of the overlying Unit 1.

Increased current activity and modern seabed processes affecting the glory hole are the presence of megaripples and the undercutting/slumping along the "hardpan" scarp (Figure 30). The megaripples were observed only on the March, 1995 data and not on any of the August data (1990,1995). These features are therefore interpreted as having formed during the winter storm season with subsequent infill/degradation over the summer season.

It is expected that the hole will continue to be infilled and buried, until the grades are sufficiently gentle for it to be in equilibrium with the surrounding seafloor.

Figure 41: Sidescan sonogram of the O-90 glory hole CSS Dawson, 1990. Fine angular lines at the glory hole site indicate 1994 video-grab transect.

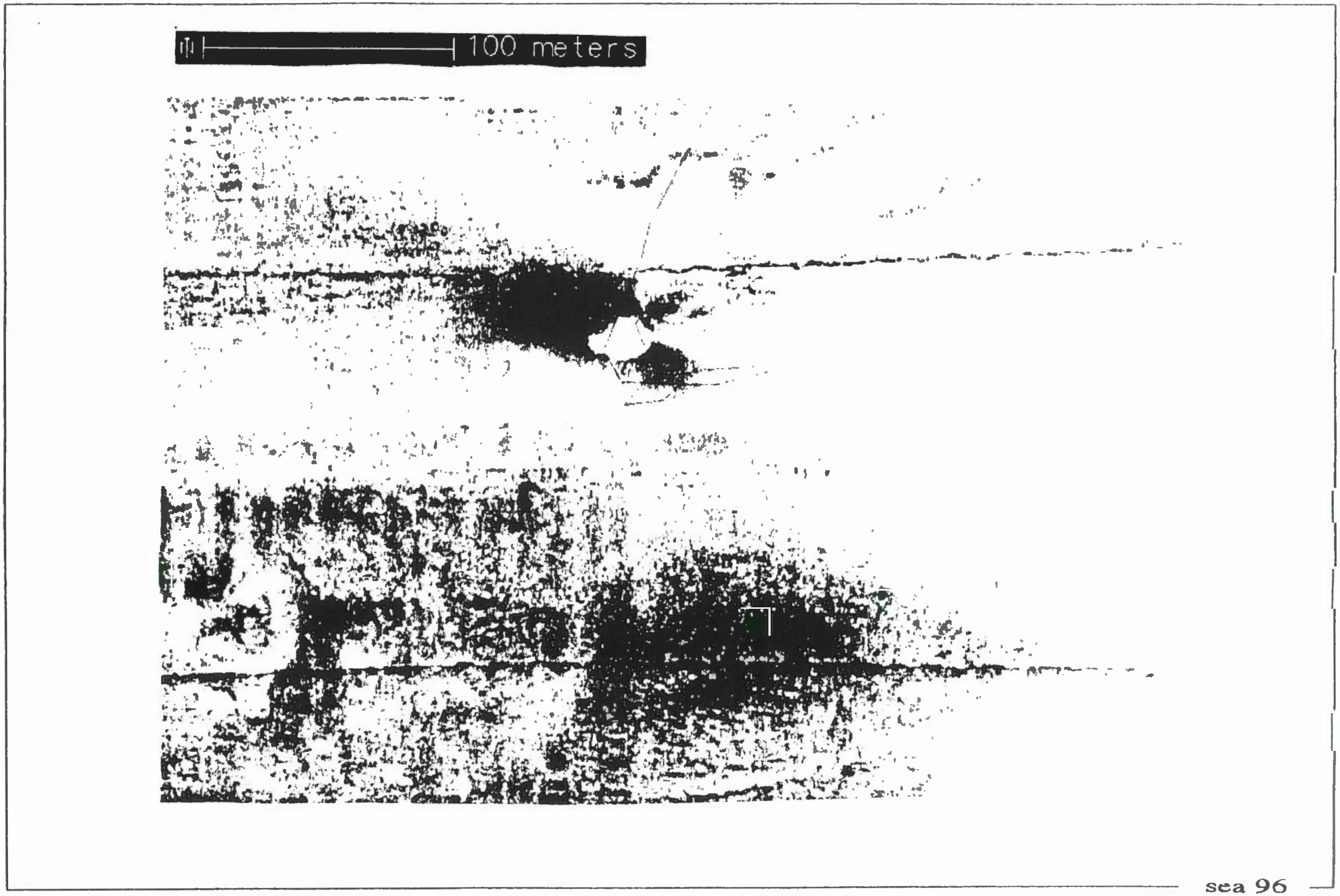


Figure 41

Figure 42: Sidescan sonogram of the O-90 glory hole CSS Hudson, 1994.

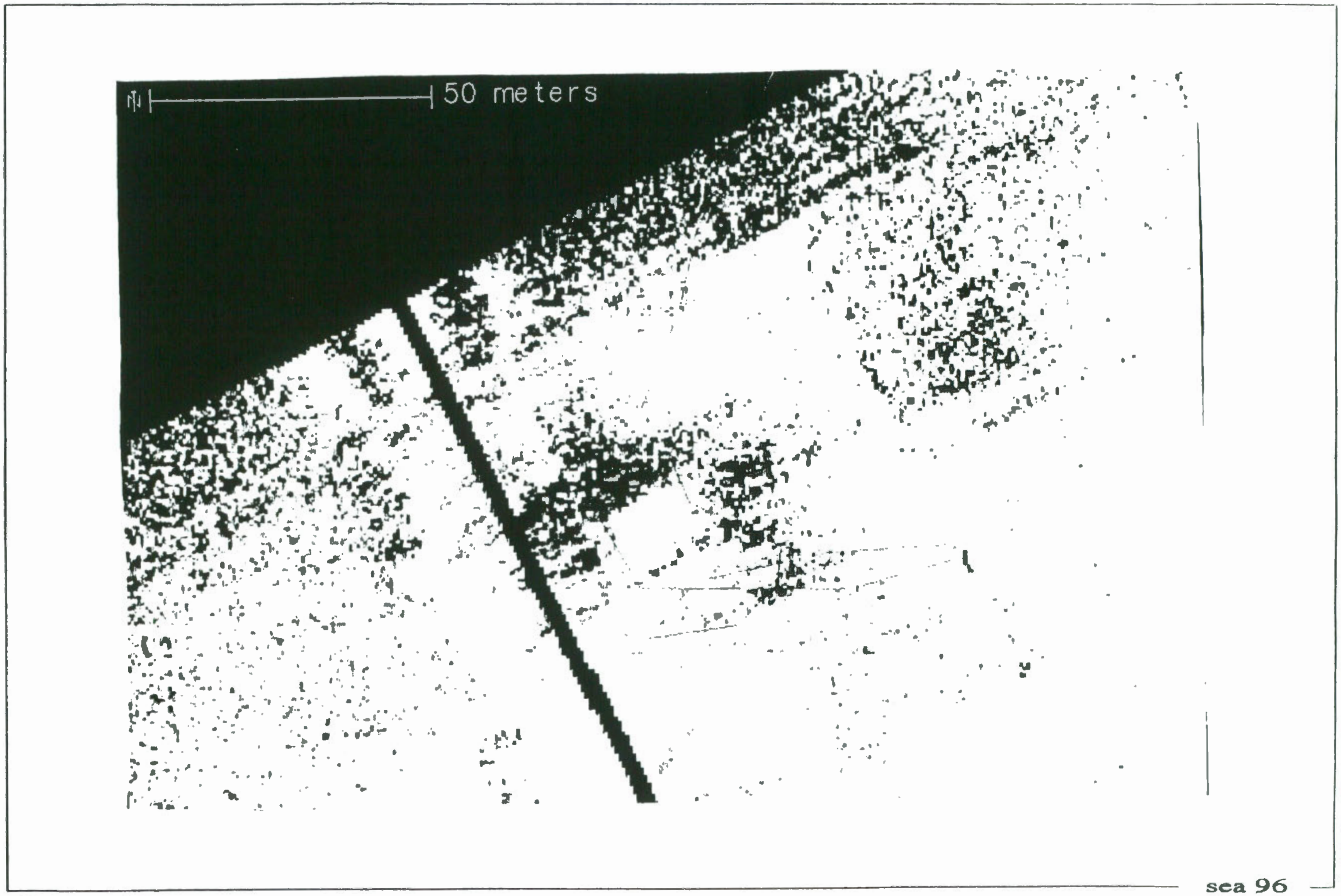


Figure 42

Figure 43: Sidescan sonogram of the O-90 glory hole HMCS Cormorant, 1995.

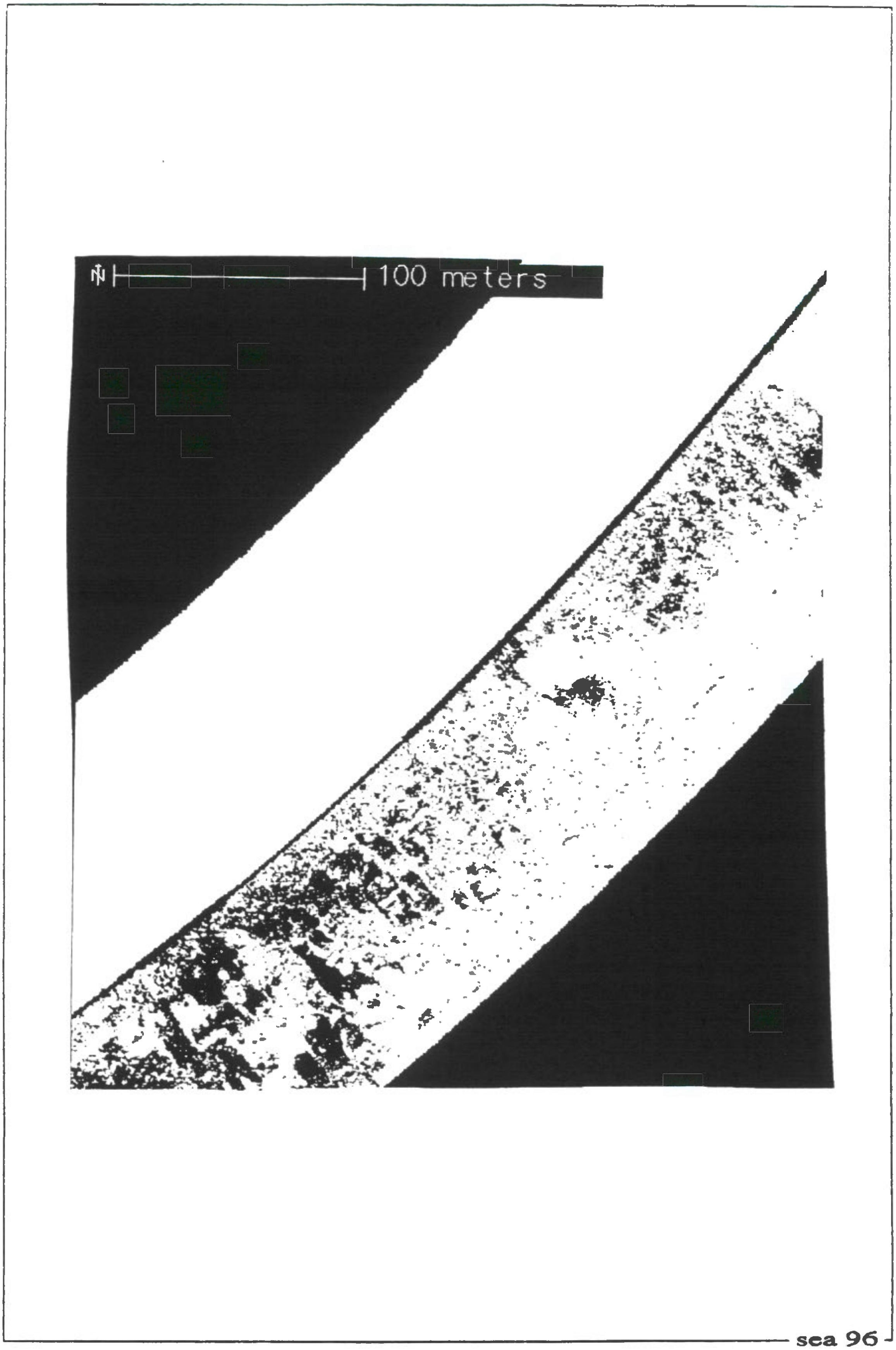


Figure 43

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