STRESS HISTORY IN THE BEAUFORT SEA: AN INITIAL STUDY

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August, 1983

SUMMARY

LIST OF FIGURES

1. INTRODUCTION

In order to understand the complex stress history in the Beaufort Sea, a review of all avaiable consolidation data is necessary. Therefore, an initial study of the consolidation properties was undertaken to investigate two areas of the Beaufort Sea: Kringalik Plateau (O'Connor, 1983) and Tingmiark Plain. A determination of the state of consolidation of the sediment was made within each area. As expected, in general, the top few meters are apparently overconsolidated, and below 10 to 15 meters the soils tend to be normally consolidated. For the Kringalik Plateau data, a comparison is made with the results and conclusions from O'Connor (1983). A complete review of the consolidation data for the Tingmiark Plain is presented. Also, the factors that could affect the state of consolidation of the soil (lithology, organic content, temperature etc.) are discussed.

2. KRINGALIK PLATEAU

2.A. SETTING

2.A.1. LOCATION

The Kringalik Plateau (O'Connor, 1983) is located in the Beaufort Sea between latitude N 69°40'00" and N 70°30'00", and longtitude W 138° 00'00" and W 136°00'00". Kringalik is east of the Mackenzie Trough, an area which may significantly influence the sedimentation properties on the plateau. Figure K-1 is a map of the physiographic provinces of the Beaufort Sea (O'Connor, 1982). Table K-1 lists the position of each borehole used in this study and the water depth. The water depth over the area varies from 20.7m to 23.8m. This province has small water depth variations.

2.A.2. GENERAL DESCRIPTION OF LITHOLOGY

O'Connor (1983) presents a two unit model for the Kringalik Plateau. The two units are:

Unit 1 (from 0 to 15 meters below sea bottom) is comprised of recent soft clay and silt with very low shear strength and high overconsolidation ratio (OCR). This unit can be related to Unit A of the general geologic model (O'Connor, 1982).

Unit 2 (from 15 to 150 meters from sea bottom) consists of overconsolidated to normally consolidated fine sediments containing some sandy layers. These sediments have a moderatly high shear strength. This unit can be related to Unit B and part of Unit C of the general model (O'Connor, 1982).

TABLE K-1

LOCATION	BOREHOLE	LATITUDE	LONGTITUDE	WATER DEPTH(M)
N-44 1981	F-TAR 1:2	69°53′13.69"	136°04′21.19"	21.3
	F-TAR 1:3	69°53′44.86"	136°14′32.37"	21.4
	F-TAR 1:6	69°54′03.28"	136°12′28.50"	23.4
	F-TAR 1:9	69°53′31.14"	136°11′37.39"	21.6
	F-TAR 1:10	69°53′43.13"	136°12′43.30"	21.8
	F-TAR 1:18	69°53′42.30"	136°11′38.78"	23.8
N-44 1980	1	69°53′49"	136°11′36"	20.9
N-44 1981 DEEP CORE	F-TD 1:1	69°53′48.76"	136°11′38.77"	21.1
A-25 1978	2	69°54′12.11"	136°20′20.20"	23.2
D-14 1980	1	69°53′14"	136°04′18"	20.7

2.B. METHOD OF DETERMINATION OF Pc AND Po

2.B.1. INTRODUCTION AND GENERAL DESCRIPTION OF ONE-DIMENSIONAL CONSOLIDATION THEORY

Consolidation is the reduction in void ratio when sediment is subjected to an increase in pressure. This reduction in void ratio is a time dependent process which is a function of the sediment permeability. Because of the low permeability of cohesive soils (clays), when a surcharge or pressure is applied over a very large surface, the pore water pressure of the clay will increase immediately to $P = U$,

Where P: Increase in total stress
U: Increase in pore water pressure

At that instant, there is no increase of effective stress ($P' = 0$). With time, the increase in pore water pressure, U, decreases, and P′ (effective stress) increases. Figure K-2 shows the change in pore water pressure and effective stress in a clay layer or sample. Based on this theory, two related definitions have been proposed:

Consolidation: Process involving a decrease of the water content of saturated soil without replacement of water by air. (Terzaghi, 1943)

Consolidation: The gradual process of increase of

effective stress in a clay layer due
to a surcharge which will result in
a time-dependent settlement.
(Das, 1983)

The ideal case does not occur in nature. Therefore, assumptions are made to explain the deviation from the ideal behaviour. The assumptions are:

- -The sediment layer is homogenous.
- -The sediment layer is saturated.
- -The water and soil particles are incompressible.
- -Darcy's law is valid.
- -The compression of the soil layer is due to the change in volume only, which, in turn, is due to the squeezing out of water from the void spaces.
- -Deformation of soil occurs only in the direction of the load application.
- -The coefficient of consolidation, Cv, is constant during consolidation.

(after Das, 1983)

Three stages of deformation can be distinguished as a soil layer or sample deforms with time. The stages are shown in Figure K-3 for one load increment. Stage I represents the deformation due to precompression of the sample. Stage II is a linear portion representing primary consolidation. At the end of this stage, most of the excess pore water pressure (caused by the load increment) is dissipated. Stage III is a gentler sloping linear portion representing the secondary consolidation. During this stage the sample has very little excess pore water pressure, so only very small deformations occur. These deformations can be attributed to particle rearrangements or creep.

It is even more relevant to study the void ratio (e) versus log of effective stress (P') relationship because an estimate of the state of consolidaton of the soil can be made. A typical e versus log P' curve is shown in Figure K-4. Initially, the soil will undergo small changes in void ratio as long as the load stress does not reach the maximum effective stress that was applied on the soil in the past (Pc). After this point, the sample void ratio will decrease rapidly under an increase of effective stress, following a close to linear path (virgin compressin curve). Based on the e vs. log P' relationship, three states of consolidation can be defined where Po' is the present overburden stress and Pc is the preconsolidation stress:

- -Normally consolidated: Where Po' = Pc
- -Overconsolidated: Where Po' < Pc
- -Underconsolidated: Where Po' > Pc

The ratio of Pc to Po' is called the overconsolidation ratio (OCR). A soil is overconsolidated if OCR>1, normally consolidated if OCR =1, and underconsolidated if OCR<1.

2.B.2. CASAGRANDE METHOD FOR THE DETERMINATION OF Pc

Many methods can be used to evaluate Pc from an e vs. log P′ graph. The most common one is the Casagrande method and it is the method used for this study (Casagrande, 1936). The technique is described below. Refer to Fig. K-5.

1. Determine the point T of maximum curvature (minimum radius) on the curve.
2. From T, draw two lines: one horizontal, and one tangent to the compression curve. The angle (θ) between the two lines is bissected.
3. Extend the straight-line portion of the compression curve. The point of intersection C of the extension with the bissector line is the estimated value of Pc.
4. Pc can be considered as a range. The minimum value is the intersection of the virgin curve extension and horizontal line that passes by point E (value of initial void ratio); the maximum value is the point where the straight-line portion of the curve begins (point M).

2.B.3. PROBLEMS

The exact determination of Pc is quite difficult. Many problems due to the nature of clay soils, method of sampling, accuracy of data, etc. can be encountered.

When the e vs. log P′ curve has no distinct break, it is difficult to accurately pick the point of maximum curvature. Flat curves can be caused by many factors of which sample disturbance and high coarse-grained (sand) content are significant.

Perfect sample recovery is almost impossible to achieve. However, sample disturbance can be minimized so that good data can be determined from the consolidation test. For a normally consolidated clay, the in-situ curve should look like curve I, the virgin curve (Figure K-6 a). A carefully recovered sample tested in the lab would result in a curve similar to curve II in Figure K-6 a. The top section of the curve is due to the release of pressure during sampling. For a remolded (highly disturbed) sample, the curve (curve III in Figure K-6 a) flattens and it becomes difficult to determine the point of maximum curvature. For an overconsolidated clay, the in-situ curve would be similar to curve I on Figure K-6 b, where ab is the recompression part of the curve and bc is part of the virgin curve. The curve of an undisturbed overconsolidated sample would be like curve II on Figure K-6 b. It should be noted that the change of curvature is more pronounced for an overconsolidated clay than for a normally consolidated one. As in the normally consolidated case, the curve for a disturbed sample would be flatter than for the undisturbed one (curve III Figure K-6 b). (Das, 1983)

A consolidation test performed on a sand (coarse-grained sediments) sample typically results in a very flat curve. So, if a sample contains a large amount of coarse-grained sediment, the shape of the curve will change. This is probably associated with the difficulty in sampling coarse-grained material without disturbance.

A "young" normally consolidated clay is one that has not undergone secondary compression and is only capable of carrying its own overburden weight (Bjerrum, 1973). Any additional load would result in significant settlement. Young normally consolidated clays are characterized by Po′ = Pc. As the clay ages, i.e. is left under a constant overburden for a long time (thousands of years), it continues to consolidate under secondary compression (stage III, Fig. K-3), and it develops a more stable structure that reduces its compressibility and increases its strength. If a normally consolidated "aged" clay is tested, the e vs. log P′ curve looks like Figure K-7 where Pc > Po. This situation (Pc > Po) can be a cause of confusion, because when Pc > Po the soil is usually interpreted as overconsolidated. It is important to note that aging (long secondary consolidation) can act simultaneously with actual overconsolidation to produce a significant increase in strength (Bjerrum, 1973).

2.B.4. CALCULATION OF OVERBURDEN PRESSURE (Po′)

The value of Po′ is a function of the unit weight, the state of saturation, and the height of sediment above the identified layer or depth below sea bottom. In the marine environment, the bouyant unit weight (γ_b) is used in the calculation:

$$\gamma_b = \gamma_{sat} - \gamma_w$$

where:

γ_{sat} = saturated unit weight in g/cm3 or Mg/m3
γ_w = unit weight of salt water : 1.03g/cm3

In this study, the overburden (in kPa) was calculated by:

$$Po' = \gamma_b * H * 9.81$$

where: H = height of sediment above the sample in meters
γ_b = bouyant unit weight in g/cm3 (Mg/m3)
9.81 = conversion from Mg/m3 to kPa

2.C. RESULTS

2.C.1. Preconsolidation Stress (Pc)

In general for the top 10 to 15 meters, Pc increases with depth below seabed. Within this range, the maximum value of Pc is 260 kPa at 5.58m and the minimum value is 14 kPa at 0.3m. For deeper samples, the values do not generally increase with depth. The range Pc was quite wide between 15 and 150 m. The maximum value is 1900 kPa at 94.47m (this value was very uncertain-a better maximum value is 1650 kPa at 155.7m). The minimum value is 125 kPa at 39.47m. It should always be kept in mind, though, that the Casagrande construction gives an estimate of Pc, not an absolute value. In fact, major differences (up to 75%)

have been found between the reevaluated values of Pc (presented in this report) and those from the contract reports. A range of value of Pc has sometimes been established to check the variation in Pc. These ranges can help in evaluating more acurately the state of consolidation of the soil.

2.C.2. Overconsolidation Ratio (OCR)

The main objective of this study is to establish the stress history of the sediments in the Beaufort Sea. In order to do so, all the raw consolidation data has been reevaluated and plotted for each borehole. From those graphs, a few interesting observations can be made.

1. Figures K-8, K-9 and K-10 clearly shows that the surface sediments are highly overconsolidated. These very high OCR's are primarily within the top 10 meters of sediments. For deeper samples, the OCR decreases and the soils tend to be normally consolidated.

2. As revealed by Figures K-9 and K-10, the values of OCR for the very top samples (first two meters) can be as high as 15 to 20 (for some specimens). This magnitude cannot be simply explained by the usual loading-unloading cycle (e.g. erosion) that can cause overconsolidation. In fact, other factors (cementation, dessication, cyclic freeze-thaw etc.) must contribute to this stress history. The influence of these factors will be discussed in the conclusion.

3. Figure K-11 displays the results for the deeper samples. As mentioned before, the soil becomes normally consolidated to slightly underconsolidated below 35 meters. It should be noted that a zone of high OCR (2.5 to 3.5) between 25 to 30 meters does not follow this trend.

4. Figure K-12 to K-16 are the plots of each borehole included in this interpretation. Actual values are listed in Table K-2 for Pc and OCR values for all boreholes.

All results agree quite well with the ones presented in O'Connor (1983). However, O'Connor (1983) does not consider samples deeper than 30 meters. This report includes sample test results from depths over 150 meters.

TABLE K-2

Location	Borehole	Depth (m)	Pc (kPa)	OCR
TARSIUT N-44 1981	F-TAR 1:2	0.39	47	15.7
		0.49	51	13.4
		0.59	83	18.0
	F-TAR 1:3	0.30	14	7.4
		0.50	28	8.0
	F-TAT 1:6	0.37	32	12.3
	F-TAR 1:9	0.76	42	7.6
		2.3	81	4.3
		2.65	28	1.5
		4.33	102	2.9
	F-TAR 1:10	0.72	42	7.8
		1.32	39	4.0
		3.18	48	1.9
		4.72	110	3.1
		5.58	260	5.0
	F-TAR 1:18	0.78	86	14.6
		1.35	152	13.3
TARSIUT N-44 1980	1	2.32	91	5.1
		5.42	195	3.8
		8.27	132	1.8
		12.02	110	1.1
		18.22	242	1.6
		27.02	660	2.7
TARSIUT N-44 DEEP CORE 1981	F-TD 1:1	22.12	760	3.53
		34.24	842	2.66
		35.40	470	1.44
		56.62	520	0.99
		74.40	480	0.72
		85.15	490	0.64
		97.19	1390	1.61
		103.28	780	0.85
		122.82	1340	1.21
		142.75	1280	0.97
		155.72	1650	1.15
TARSIUT (A25) 1978	2	9.30	354	4.05
		50.75	766	1.39
		78.18	651	0.92
		108.81	642	0.59
TARSIUT D-14 1980	1	3.55	220	6.5
		6.57	250	4.6
		7.12	140	2.2
		8.40	280	3.8

10.02	220	2.6
10.16	250	3.0
12.05	620	6.0
21.07	530	2.6
33.12	490	1.6
39.32	540	1.6
39.47	125	0.35
51.52	540	1.2
54.80	48	0.1
76.10	640	0.95
94.47	1900	2.6
99.90	610	0.7
110.40	300	0.3
119.47	480	0.45

3. TINGMIARK PLAIN

3.A. SETTING

3.A.1. LOCATION

The Tingmiark Plain is located in the Canadian Beaufort Sea between latitude N 70°00'00" and N 71°00'00", and logtitude W133°30'00" and W131° 00'00". The plain is in the eastern part of the Beaufort Sea and is bounded on the west side by the Kugmallit Channel and on the east side by the Niglik Channel. The Tingmiark Plain is shown in Figure K-1 (O'Connor,1982). Table T-1 lists the name, position, and water depth of each borehole used in this part of the study.

3.A.2. GENERAL DESCRIPTION OF LITHOLOGY

In order to represent the structure of the soil a simple statigraphic model has been established. The model has three main units which are described below and schematically shown in Fig. T-1.

Unit I is found from 0 to between 35 and 45 meters below the sea bottom. It consists of an olive grey to grey-brown fine to medium sand. The sand contains varying amounts of silty sand, silt and gravel. These sediments have been observed as thin layers, laminae etc. The bottom of this unit (40-45m) in some boreholes is ice bonded sand or silt. Unit II is found from around 45m to 70-90m. This unit is an olive grey to dark grey clay with variable organic content. The soil is generally frozen throughout this unit. Unit III extends from between 70m and 90m to 120m. It is composed of brown to dark grey sand and silt. The sediments are generally well ice bonded, but the bonding decreases with depth, so that at the bottom of the unit the sediment is unfrozen.

TABLE T-1

LOCATION	BOREHOLE	LATITUDE	LONGTITUDE	WATER DEPTH (M)
UVILUK P-66 1981	UVI 1:1	70 15'48.28"	132 18'47.48"	22.9
GEOCON 1975	1	70 10'36.43"	132 58'50.86"	29.0
KOGYUK 1981	1	70 07'36.59"	133 14 49.90"	28.0
UKALERK 1978	1	70 09'36.56"	132 42'30.99"	30.2
WEST TINGMIARK 1981	1	70 14'19.02"	133 27'40.04"	39.5

3.B. METHOD

The same method and calculations to determine Pc and Po have been used for Tingmiark Plain. For more detail, refer to section B of Kringalik Plateau.

3.C. FACTORS INFLUENCING THE STATE OF CONSOLIDATION

In order to make a good evaluation of the consolidation state in the Tingmiark Plain sediments, a review of some properties (salinity,organic content, permafrost) has been undertaken.

3.C.1. SALINITY

The pore water salinity can have an important effect on the stress state because it can change the physico-chemical bonding within the double layer, and can reduce the freezing point of pore water. It is also, therefore, directly related to the amount and type of permafrost. In the Tingmiark Plain sediments, the salinity varies from 4 ppt to 37 ppt. The average value is 22. This is slightly lower then normal for sea water (30-35ppt) but can be explained by the flow of Mackenzie River fresh water into the Beaufort Sea. It is also interesting to point out that lower salinities are found in frozen sediment, and higher salinities in unfrozen sediment.

3.C.2. ORGANIC CONTENT

Some organics have been seen in most of the clay layers. But the organic contents are quite low and should not significantly influence the conslolidation process. It should be noted that organic contents as high as 15% have been found.

3.C.3. PERMAFROST CONDITION

Permafrost is the term used to indicate that the temperature of the soil is permanently below 0°C. But if a soil is under permafrost conditions, it does not imply necessarily that the soil is frozen. In fact, because of the salt contained in the pore water and the type of clay material, some soils with temperature below 0°C, are not frozen. The results about permafrost presented in this report were deduced from soil observation rather than from soil temperature. By definition, most of the sediments of the Tingmiark Plain are permafrost. However, as shown in the model(Fig. T-1), the top 40 meters or so are not frozen. Going down the stratigraphic column, the temperature decreases, and most of the sediments (sand, silt and mainly clay) become ice bonded. Below 105m, the soil is usually unfrozen. Some ice lenses and crystals have been observed throughout layers in the boreholes.

3.C.4. SAMPLE DISTURBANCE

All the samples seemed to have been recovered well with the exception of those from Uviluk P-66. In fact, these samples displayed unusual curves and it was difficult to estimate Pc. This might have been caused by possible disturbance to the Uviluk samples. A characteristic Uviluk P-66 curve is shown in Fig. T-2. The curve is quite flat, suggesting sample disturbance or remoulding.

3.D. RESULTS

As seen in the stratigraphic model, the primary clay sequence is found between 40 and 90m. Due to the difficulty of sampling coarse-grained sediment for consolidation testing, all of the experimental data compiled comes from samples within this sequence. Therefore, the consolidation data is limited to Unit II.

3.D.1. PRECONSOLIDATION STRESS (Pc)

For the depths considered (40-90m), Pc does not increase with depth. In fact, the results have a quite random behaviour. The minimum value is 220 kPa at 53.27m (Uviluk) and the maximum value is 960 kPa at 46.10m (Kogyuk). As in the Kringalik Plateau, some problems in determining Pc were encountered particularly for the curves of Uviluk P-66 (see section 3.C.4).

3.D.2. OVERCONSOLIDATION RATIO

The samples tested from the Tingmiark Plain were from depths between 40m (39.30m) and 90m, which, based upon our current understanding of the recent geological history, are expected to be normally consolidated. As shown in Table T-2, the values of OCR range from a maximum of 2.4 to a minimum of 0.51. The average value is 1.2 . As one can see on Figure T-3, the linear least square fit for the OCR versus depth graph of Tingmiark Plain has a maximum value of 1.6 for OCR at 40m and a minimum value of 0.8 for OCR at 90m. Figure T-4 is a plot of OCR versus depth for Uviluk P-66. The OCR average (0.95) is close to 1 or normally consolidated.

3.D.3. SHEAR STRENGTH and Cu/Pc RATIO

Values of shear strength (Cu) are reported in Table T-2 with preconsolidation stress (Pc). For the depths considered, quite high values of shear strength and Cu/Pc ratio are expected. The values of Cu vary from 30 kPa to 170 kPa, with an average value of 97 kPa. Low shear strengths are noted for most samples from Uviluk P-66 and Geocon,1975 (Tingmiark). For Uviluk, the low values can be explained by possible sample disturbance. For the Geocon samples, the quite low shear strength can be explained by the fact that the samples, unlike most of the others, were unfrozen. The Cu/Pc ratios follow the same trend; quite high values for Ukalerk, Kogyuk, West Tingmiark, and low values for Geocon and most Uviluk samples. The maximum value for Cu/Pc is 0.355 and the minimum value is 0.062 (Table T-2).

3.D.4. INDEX PROPERTIES

The natural water content over the Tingmiark Plain area is almost constant; it varies from 28% to 33%. The liquid limits range between

29% and 60%, and the plastic limits, which are more constant, vary from 21% to 30%. The index of plasticity, for the region, is quite low (minimum value is 8% and maximum value is 30%) with an average of 17%. Table T-3 lists the index properties. Empirically, the apparent OCR has been shown to increase with index of plasticity (Das, 1983). The results from Tingmiark Plain do not follow this empirical relationship perfectly, but the trend shows slightly higher OCR's correspond with higher indices of plasticity. There is one exception for Kogyuk where 2.4 is the highest OCR the index of plasticity (12%) is below the average.

TABLE T-2

LOCATION	BOREHOLE	DEPTH (m)	Pc (kPa)	OCR	Cu(kPa)	Cu/Pc
Uviluk P-66	UVI 1:1	50.10	480	1.27	30	0.062
		50.23	440	0.98	30	0.068
		53.27	220	0.51	50	0.222
		54.93	420	0.88	70	0.167
		64.02	540	0.97	68	0.126
		80.61	730	1.11	135	0.185
		89.43	660	0.86	110	0.167
Geocon	1	53.64	766	1.56	67.1	0.087
	1	55.17	862	1.71	71.8	0.083
Kogyuk	1	46.10	960	2.4	169	0.176
Ukalerk	1	55.47	575	1.11	141.3	0.246
West Tingmiark	1	39.30	480	1.38	155-170	0.322-0.335

TABLE T-3

LOCATION	BOREHOLE	DEPTH (M)	Wo(%)	Wl(%)	Wp(%)	Ip
Uviluk P-66	F-UVI 1:1	57.90	33	36	25	11
		62.80	30	40	24	16
		89.75	31	29	21	8
Geocon	1	53.64	28	46	27	19
		55.17	30	46	26	20
Kogyuk	1	46.10	30	39	27	12
Ukalerk	1	55.47	32	60	30	30
West Tingmiark	1	39.30	32	49	28	21

4. DISCUSSION AND CONCLUSION

4.A. KRINGALIK PLATEAU

The Kringalik Plateau sediments display a similar behaviour to deep sea clays: the surficial sediments (0-15m) behave overconsolidated and then become normally consolidated to slightly underconsolidated with depth. The overconsolidation is unusually high and will be discussed below.

4.A.1. CAUSES OF HIGH OVERCONSOLIDATION

The normal process that causes overconsolidation is the removal of overburden by some mechanism such as erosion. For example, when soil is exposed to an aerial environment (e.g.,lowering of sea level), the soil may be eroded and the overburden is reduced. If the sea level rises again to submerge the soil, the actual overburden (Po′) will be lower than the maximum past pressure (Pc) and the OCR will be greater than 1. This process is probably not the cause of the high overconsolidation encountered in the surficial sediments at the Kringalik Plateau. First, there are no traces of surficial erosion in the top few meters of these sediments; second, it is impossible to explain OCR as high as 20 by this process (it would mean that at least half of the sediment column would have been eroded!). Consequently, these soils are interpreted to be "apparently" overconsolidated, because the possible processes causing the overconsolidated behaviour are not loading and unloading mechanisms. Some of the possible processes are explained and discussed below.

As mentionned in section 2.B.3, when a sediment is left with an overburden stress for a very long period of time, its structure changes increasing its strength. This process, called aging, implies that the soil undergoes a prolonged secondary consolidation. During this period, physico- chemical bonds may change and cementation may begin. In fact for clays, the double layer around the clay particles becomes thinner as the secondary compression takes place, promoting stronger bonds between particles. For deeper samples, the "aging" effect may be counterbalanced by the very high overburden stress (Chamberlain, 1979).

One of the most common explanations for overconsolidation is the freeze-thaw cycle. The soil can be submitted to significant temperature variations throughout its stress history. The freeze-thaw process can cause a cyclic expansion-contraction that decreases the void ratio (refer to section 2.B.1. for definitions of consolidation) and increases the permeability (Chamberlain, 1979).

Another possible explanation for the "apparent" overconsolidation in the surface sediments is based on the inherent problems in one dimensional consolidation theory. By definition, a recently deposited sediment is normally consolidated. For normally consolidated material, the overconsolidation ratio is 1. If it is assumed that the preconsolidation stress (Pc) is equivalent to the undrained shear strength (Cu), then Cu = Po. In this case, the overburden stress, Po is very low due to recent deposition and, therefore, Cu should correspondingly be low. However, the shear strength is not as low as the overburden stress due to the physico-chemical bonding which occurs upon deposition which is a function of the clay mineralogy and pore water chemistry, not the overburden stress. Thus, the sediment appears to be overconsolidated when in fact it is only "apparently" overconsolidated. In order to substantiate this explanation, the surficial sediment stress history should be studied for various sediment types. For example, sediments with a high smectite content should display more apparent overconsolidation than equivalently deposited sediments with lower smectite content. Similarly, coarser grained deposits should display less apparent overconsolidation.

4.A.2. OVERCONSOLIDATION

As mentionned in section 2.C.2, high OCRs (values between 2.5-3.0) were found at depths of 25m to 30m below sea bottom (or 40-50m below sea level). The best explanation for this state of overconsolidation is that the soil has undergone a loading and unloading process. It is possible that during the last sea level lowering, the sediment may have been emerged or in shallow enough water to be exposed to erosion and unloading. Then when the sea level again increased, more sediments were accumulated, but the actual overburden remained lower than the maximum past pressure.

4.A.3. UNDERCONSOLIDATION

As stated above, some of the deep samples (more than 100m below sea bottom) are slightly underconsolidated, i.e. have an OCR lower than 1. Different hypotheses have been proposed to explain this phenomenon. As defined by Sangrey (1983), underconsolidation is the occurence of excess pore water pressure. The accumulation of excess pore water pressure can be caused by the following:

1- rapid rate of sedimentatation
2- pressure associated with artesian water or gas in a deep formation
3- shallow free gas in sediments
4- residual pore pressure resulting from cyclic loading.

Pore pressures generated by 1, 3 and 4 probably do not explain the underconsolidation observed in some of the Beaufort Sea sediments, because these conditions generally occur in the surficial sediments. In fact, high sedimentation rates usually only influence the surficial sediments; free gas can be found in the upper sediments where the overburden is not too high; and cyclic loading doesn't have an important influence at depths greater than 100m below seabed. Consequently, artesian water or gas is the most probable explanation. Similarly, Silva et al. (1982) mentions that high overburden pressure can cause an upward fluid migration that increases pore pressure and reduces sediment strength.

Another explanation has been proposed by Nacci (1969) who states that the very high overburden acting on these sediments might provoke the breakdown of some physico-chemical bonds, which could cause a decrease in the sediment resistance to overburden (softening of the sediment). The sediment at depth may also appear to be underconsolidated because the ratio of preconsolidation stress to overburden stress may not remain linear at higher stresses. This phenomenon has also been observed in samples of deep sea clays (Silva et al., 1982).

4.B. TINGMIARK PLAIN

The soil tested at the Tingmiark Plain were situated between 40 and 90m. The Tingmiark Plain samples are normally consolidated. However, some of the samples are also underconsolidated. See section 4.A.3 for a discussion of underconsolidation.

4.C. COMPARISON BETWEEN KRINGALIK PLATEAU AND TINGMIARK PLAIN

Figure C-1 is a plot of the data from the two regions. Because of the lack of data from Tingmiark Plain for the top few meters, it is not possible to make a comparison on the overconsolidated zone. However, for deeper samples (between 40-90m), a good relationship can be established. In fact, those two physiographic provinces display normally consolidated to slightly underconsolidated behaviour within the same depth intervals.

4.D. COMPARISON BETWEEN THE CANADIAN AND THE U.S. BEAUFORT SEA

A report from the USGS (1979) gives some results of geotechnical tests performed on Alaskan Beaufort Sea samples. Special attention was given to the consolidation data. Some results are summarized here. The Pc values vary from 527 kPa (at a depth of 10.97m) to 34 kPa (at 5.03m). The OCR values vary from 0.3 (at 67.06m) to 45.7 (at 1.34m). The top 15 meters of sediments are largely overconsolidated (average value of OCR is 7.6) and the sediment becomes normally consolidated (to slightly underconsolidated) below 15m (average value of OCR is 1.1). Table C-1 is a summary of the data and Figure C-2 and C-3 are plots of OCR versus depth.

The consolidation results correspond suprisingly well with those from the Canadian Beaufort Sea (Kringalik Plateau and Tingmiark Plain). In fact, both regions can be characterized by an "apparently overconsolidated" zone in the top 15 meters and normally consolidated to slightly underconsolidated sediments below 15m (see Figure C-4).

4.E. FURTHER STUDIES

A new method to find the maximum past pressusure (Pc′) consisting of calculating the strain energy has been recently developed (Tavenas, et al., 1979). However this method was not properly adapted at the time of this study, so no evaluation of the method or comparaison with our results have been included in the present report.

TABLE C-1

CONSOLIDATION DATA FROM THE ALASKAN BEAUFORT SEA

BOREHOLE	DEPTH (M)	Pc(kPa)	OCR
1	0.46	81	20.2
	3.35	115	3.0
	7.92	88	1.4
2	5.03	134	3.3
4	5.79	287	5.4
	7.77	101	0.6
	11.34	240	2.4
5	2.50	101	4.8
	67.06	182	0.3
	72.85	311	0.4
6	2.59	359	17.1
	17.22	335	2.1
7	2.10	187	10.4
	12.86	359	2.9
8	6.86	215	4.0
	13.41	249	1.8
9	1.98	374	17.8
	4.11	216	5.1
	7.77	86	1.0
10	3.41	168	5.4
	6.61	359	5.4
	19.05	192	0.9
	21.34	378	1.7
11	3.96	431	10.0
	8.69	406	4.5
	12.19	335	2.4
12	1.37	168	12.0
	6.40	335	5.2
13	1.98	134	5.2
	5.64	383	7.0
14	2.23	77	2.5

15	5.03	34	1.3
	75.74	263	0.3
16	2.59	125	3.9
	5.49	134	2.4
	9.45	240	2.3
	14.63	431	2.5
	20.57	335	1.7
17	0.91	378	34.4
	2.29	455	19.0
	5.33	359	6.4
	10.97	527	4.6
18	1.98	228	10.9
	4.30	55	1.2
	6.55	393	6.1
	11.13	275	2.5
19	1.34	503	45.7
	8.38	335	4.7
	15.88	132	0.7
	23.29	479	1.9
20	1.65	383	22.5

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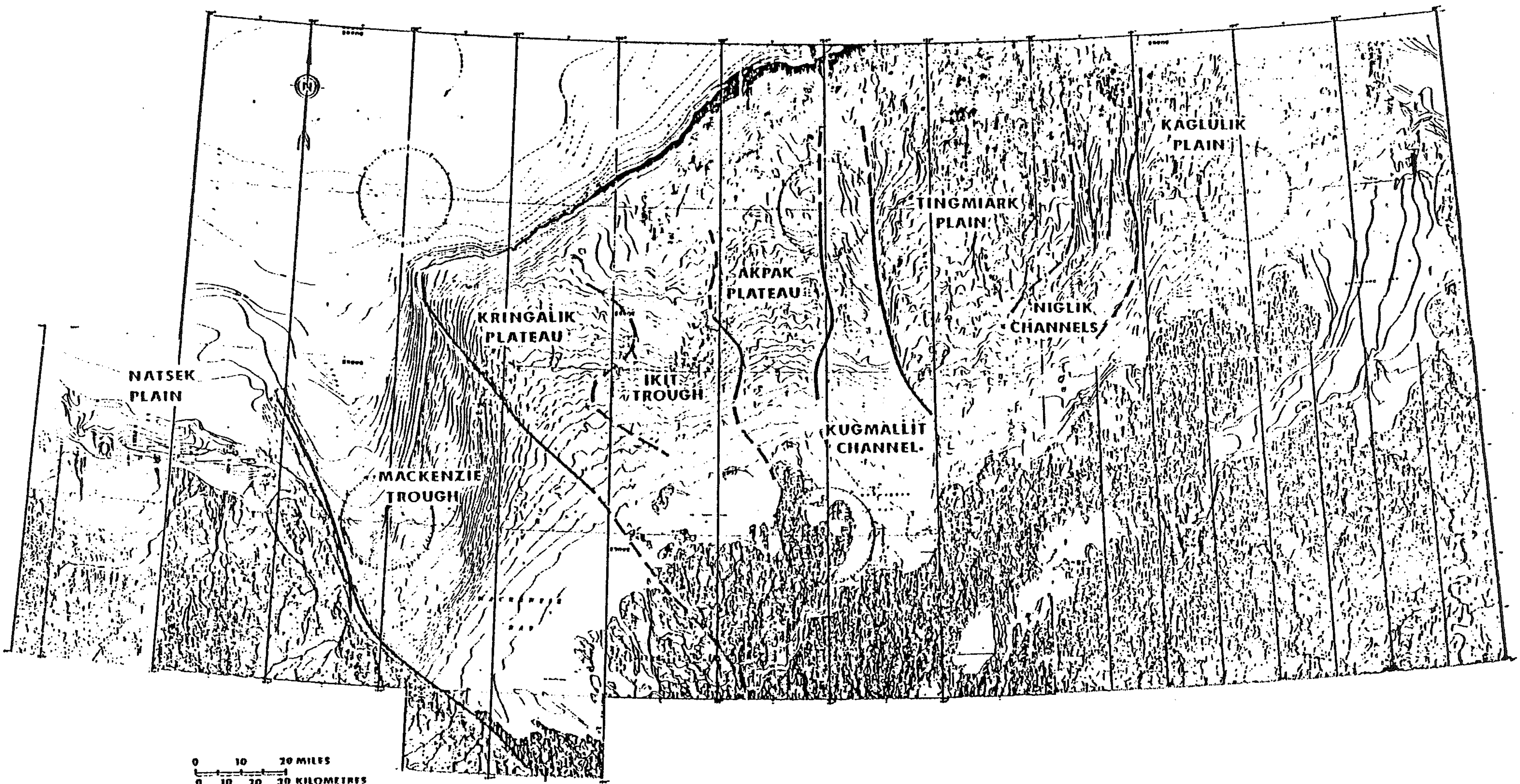

Figure K-1 Physiographic Provinces of the Beaufort Sea

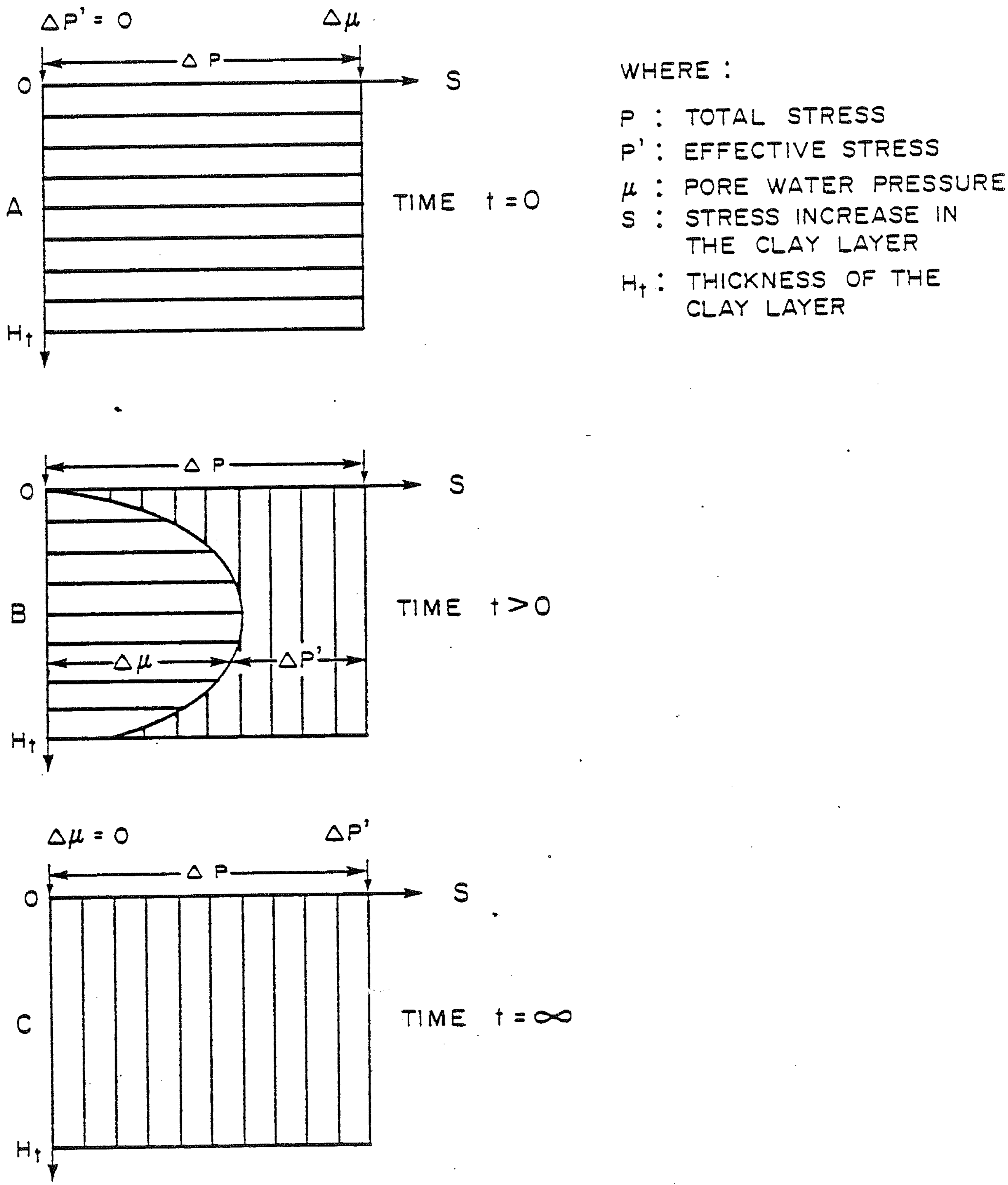

FIGURE K-2 Change in pore water pressure and effective stress versus time
(modified from DAS, 1983)

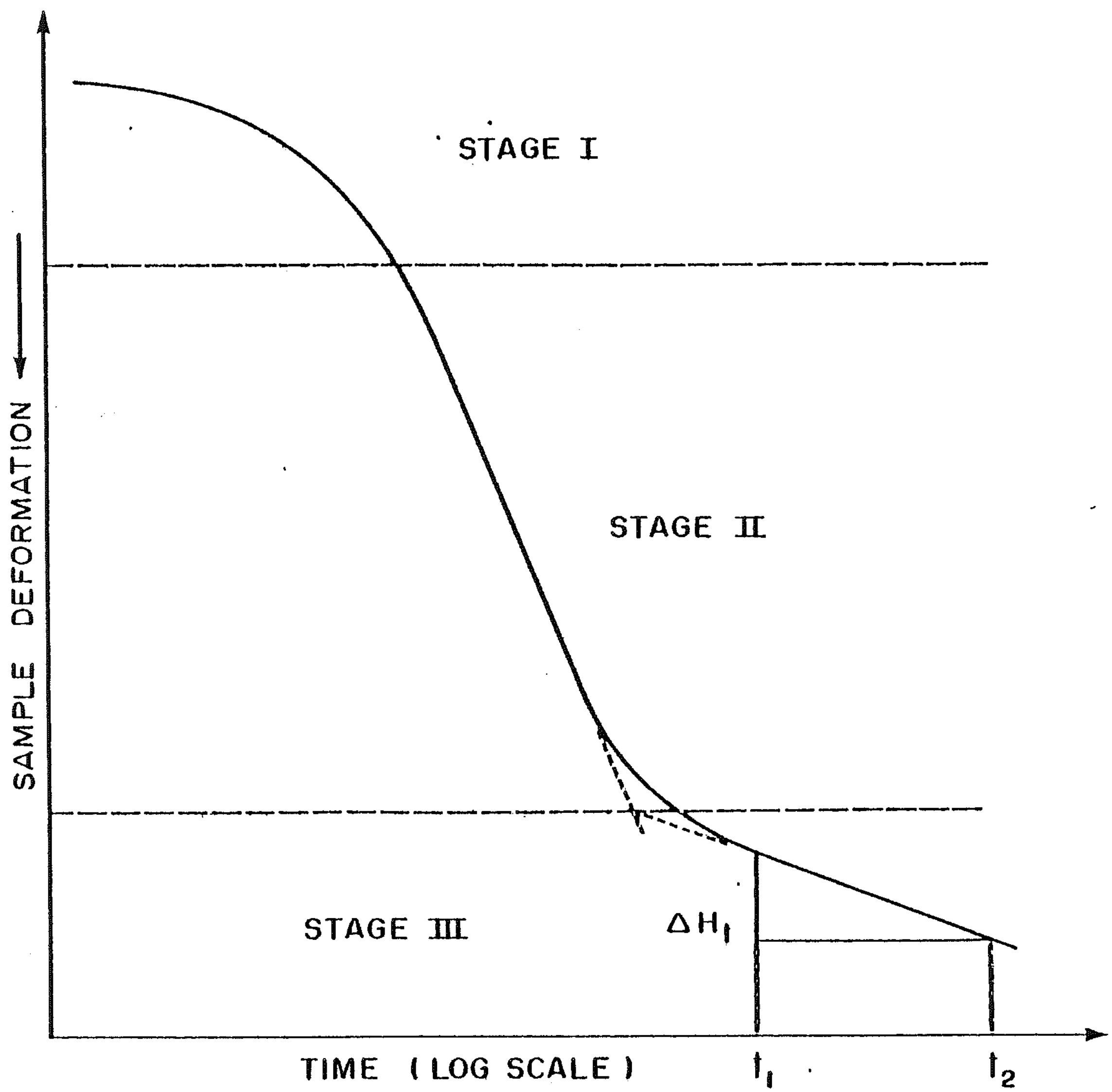

FIGURE K-3 Deformation versus log time graph (from DAS, 1983)

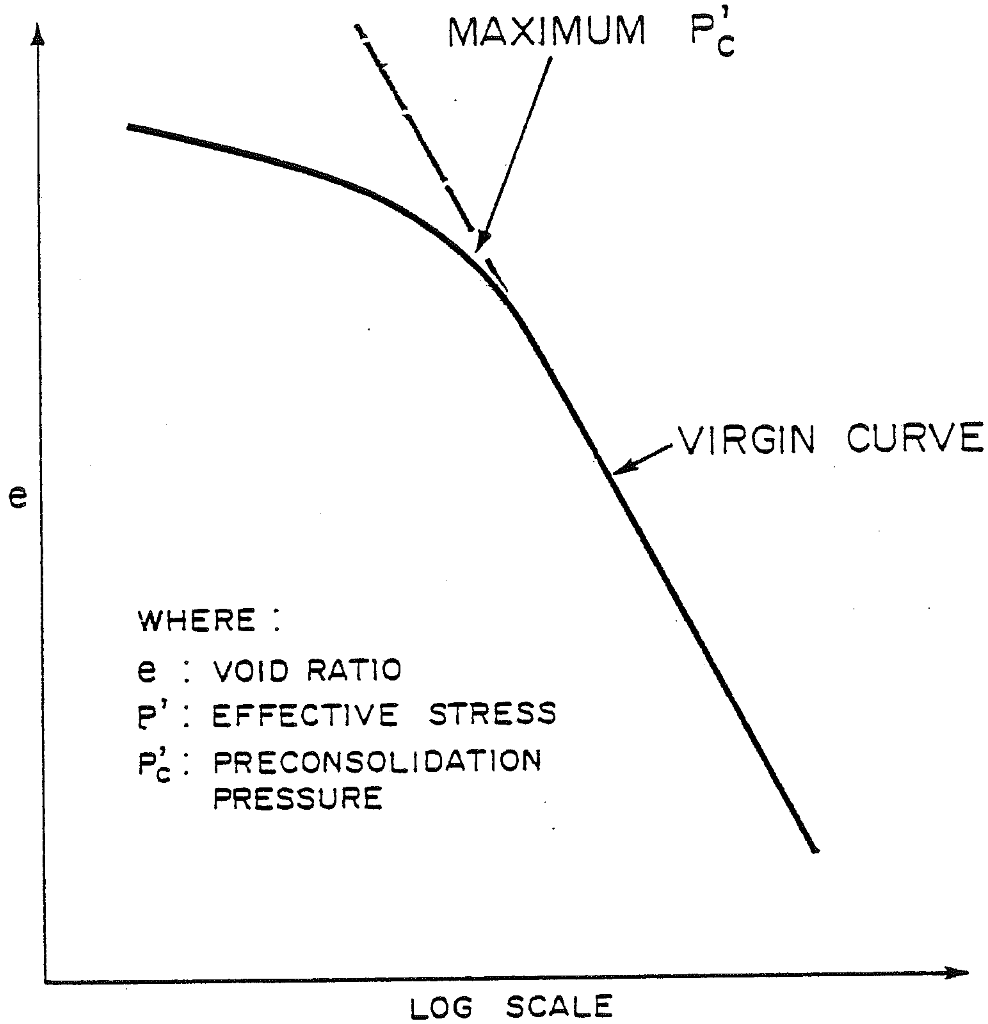

FIGURE K-4 Typical e versus log P' curve (modified from DAS, 1983)

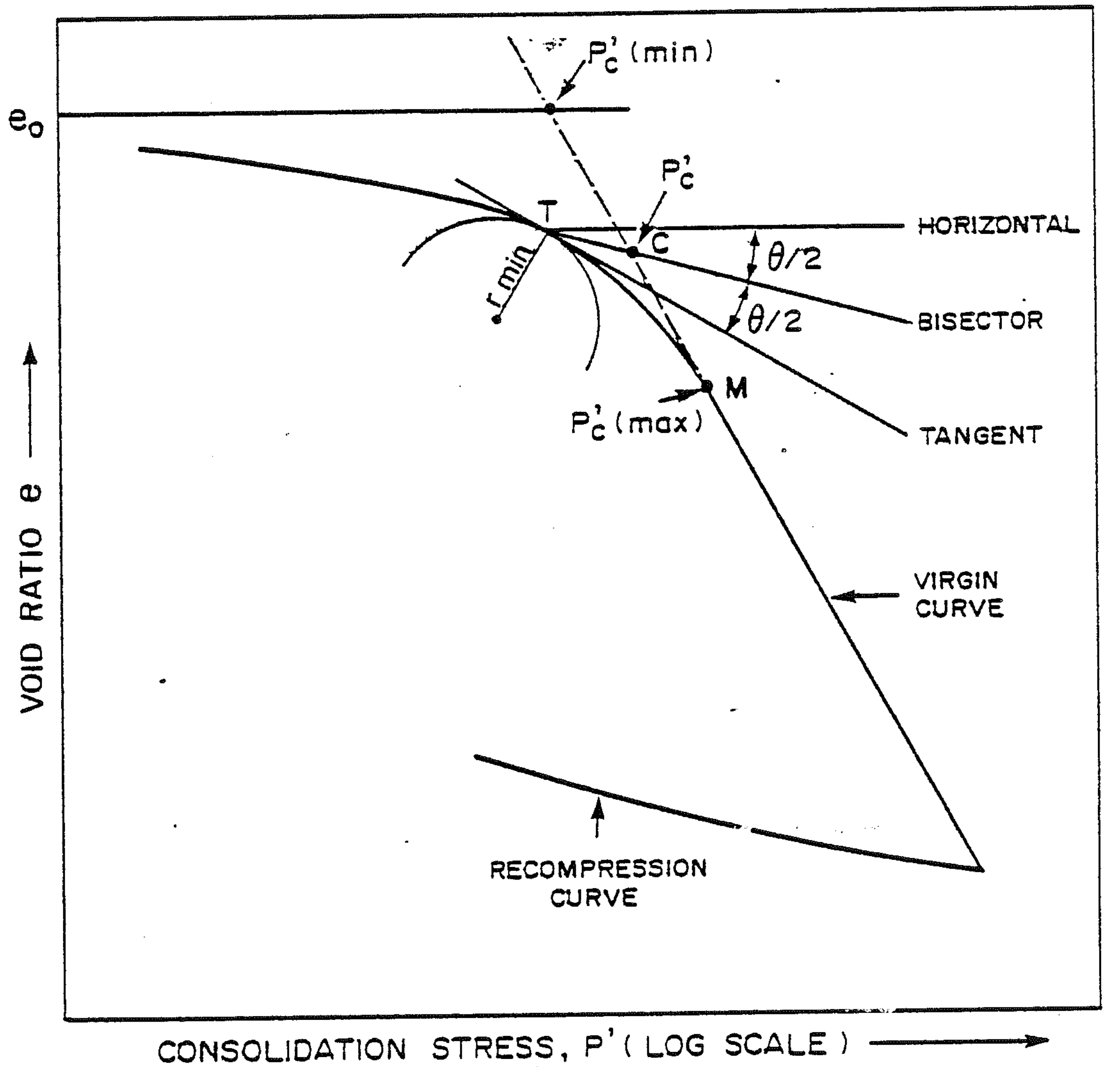

FIGURE K-5   Casagrande Method for estimating P'c
(modified from BRUMUND, 1976)

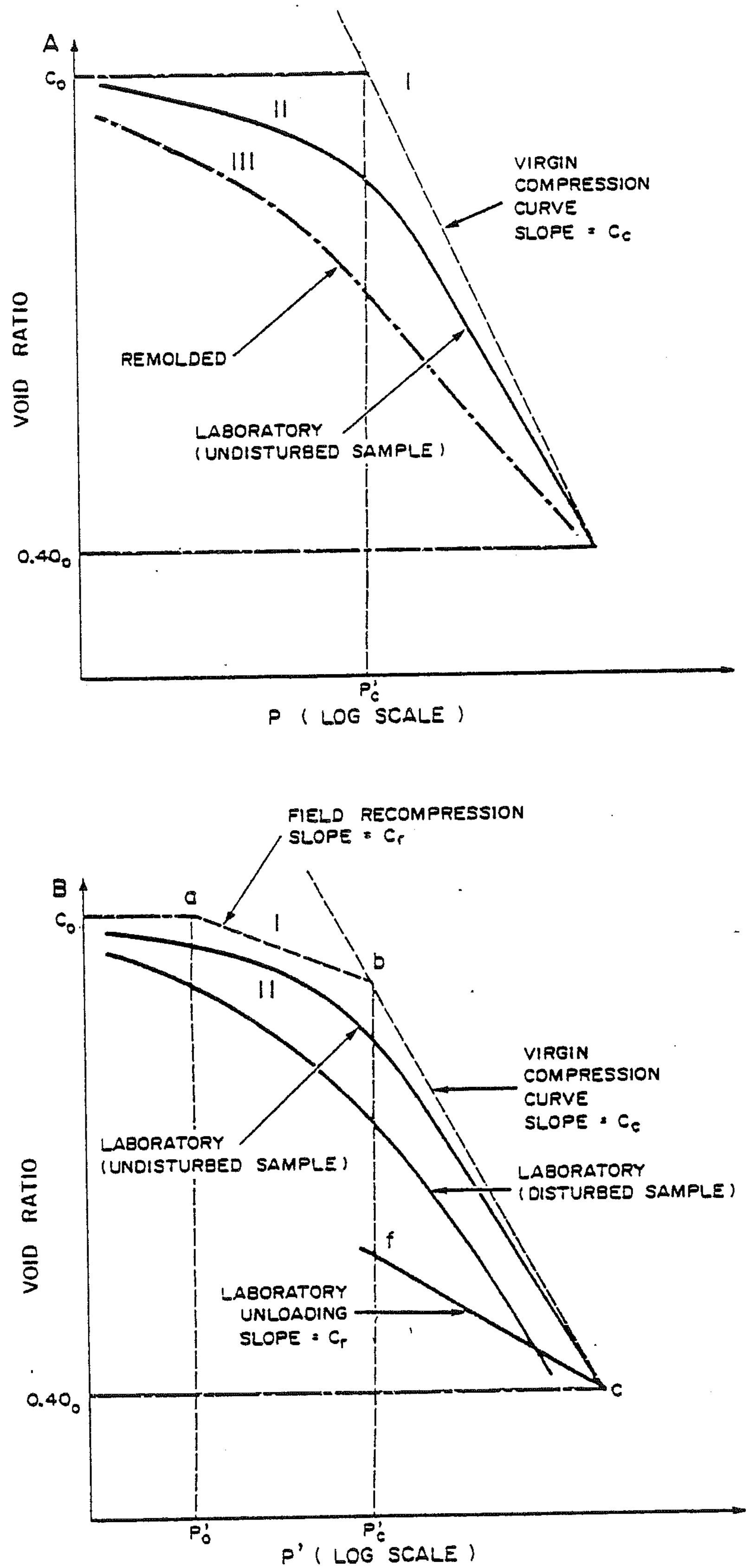

FIGURE K-6 Effect of sample disturbance
A. Normally consolidated clay
B. Overconsolidated clay
(modified from DAS, 1983)

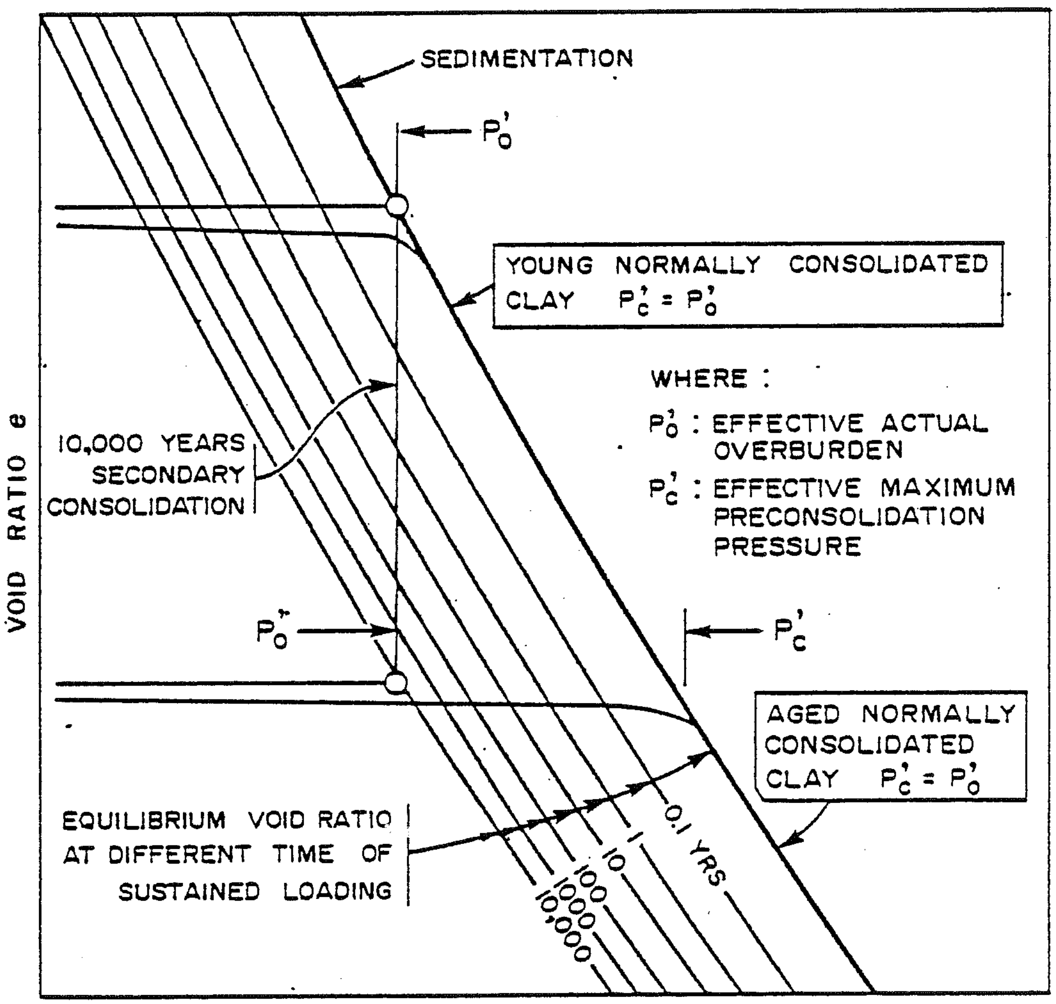

Figure K-7 EFFECTIVE VERTICAL PRESSURE IN LOGRITHMIC SCALE (modified from BJERRUM, 1973)

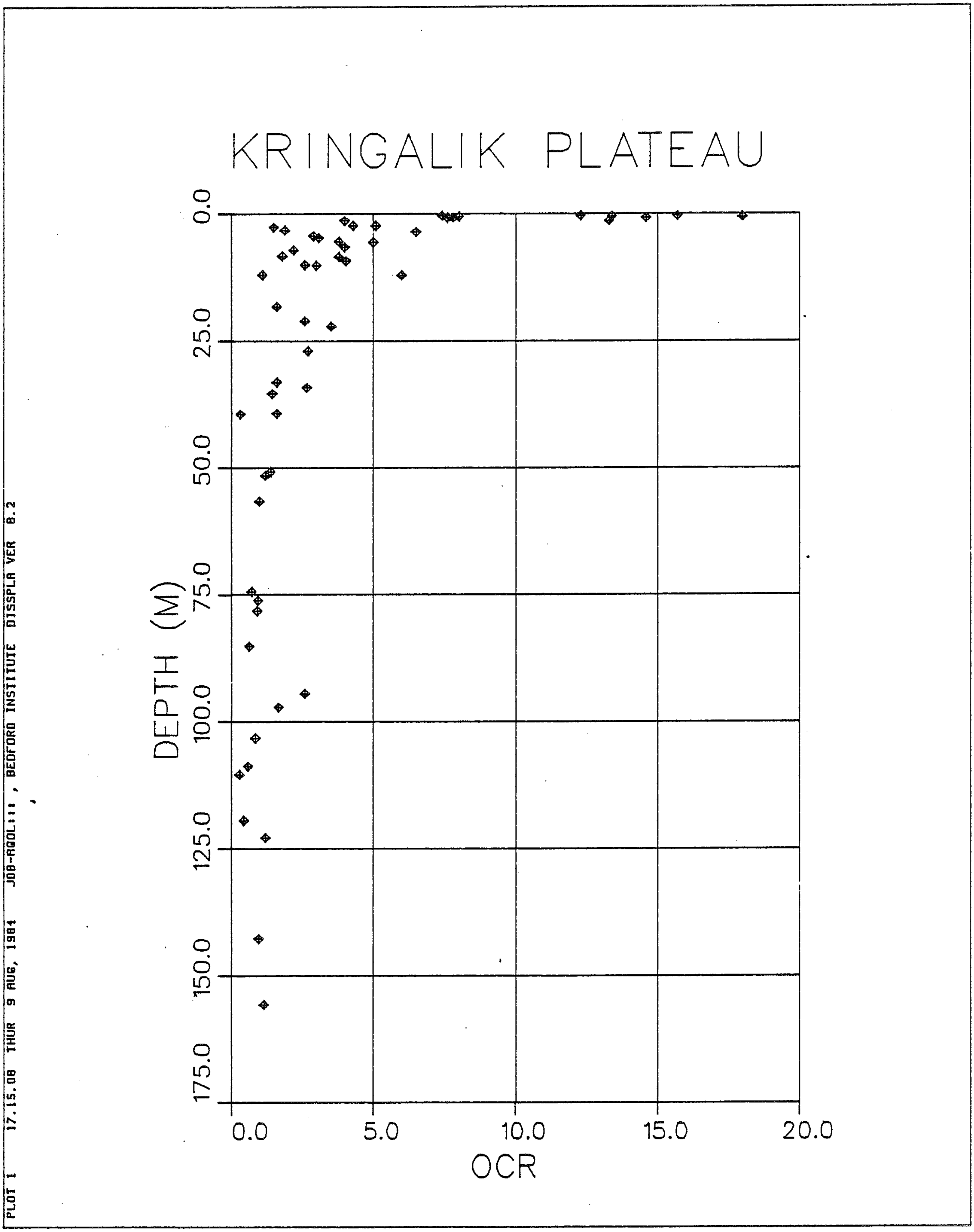
KRINGALIK PLATEAU
DEPTH (M)
0.0
25.0
50.0
75.0
100.0
125.0
150.0
175.0
0.0
5.0
10.0
15.0
20.0
OCR
PLOT 1 17.15.08 THUR 9 AUG, 1984 JOB-AQOL::: , BEDFORD INSTITUTE DISSPLA VER 8.2

Figure K-8

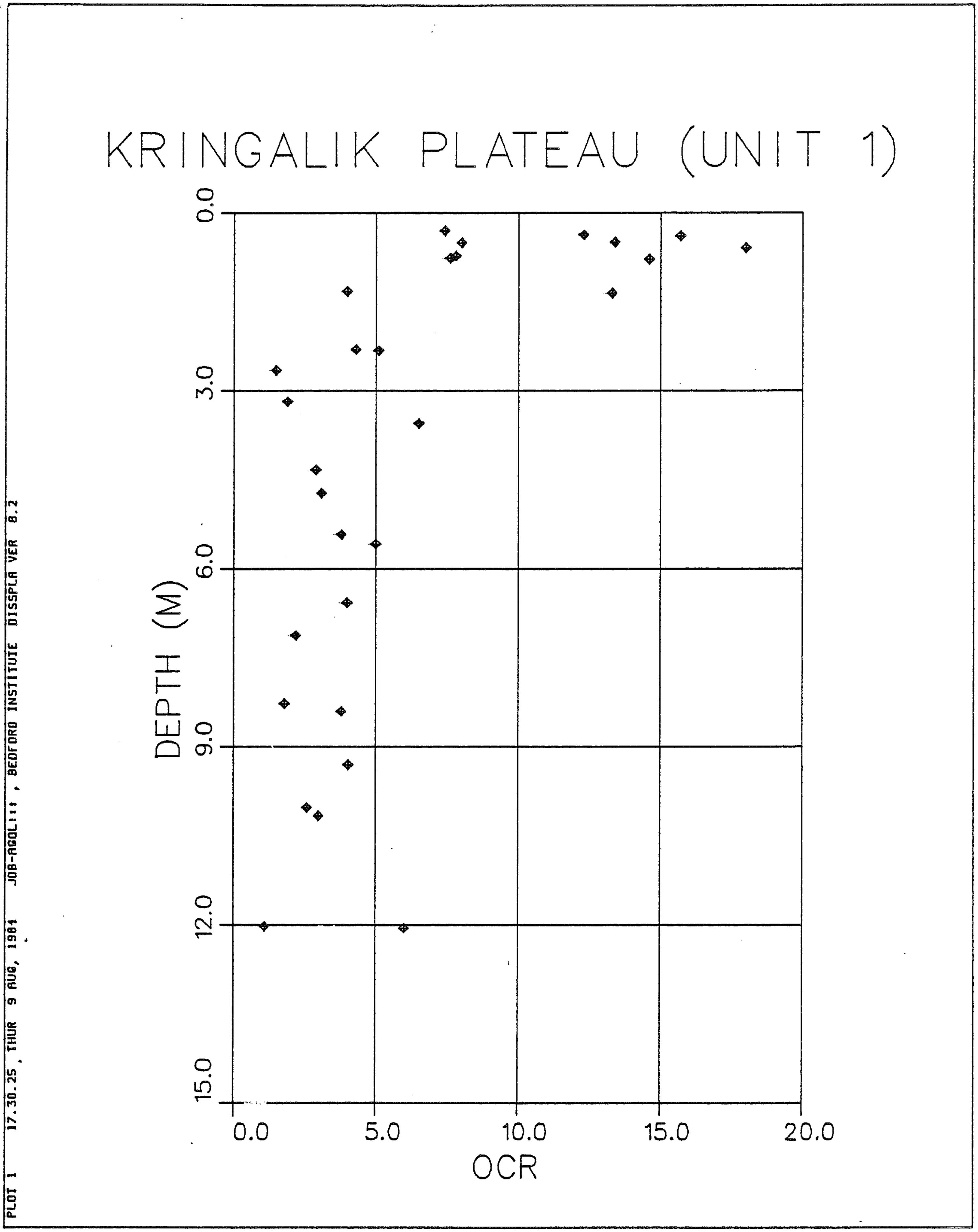
KRINGALIK PLATEAU (UNIT 1)
DEPTH (M)
0.0
3.0
6.0
9.0
12.0
15.0
0.0
5.0
10.0
15.0
20.0
OCR
PLOT 1 17.30.25, THUR 9 AUG, 1984 JOB-AGOL::: , BEDFORD INSTITUTE DISSPLA VER 8.2

Figure K-9

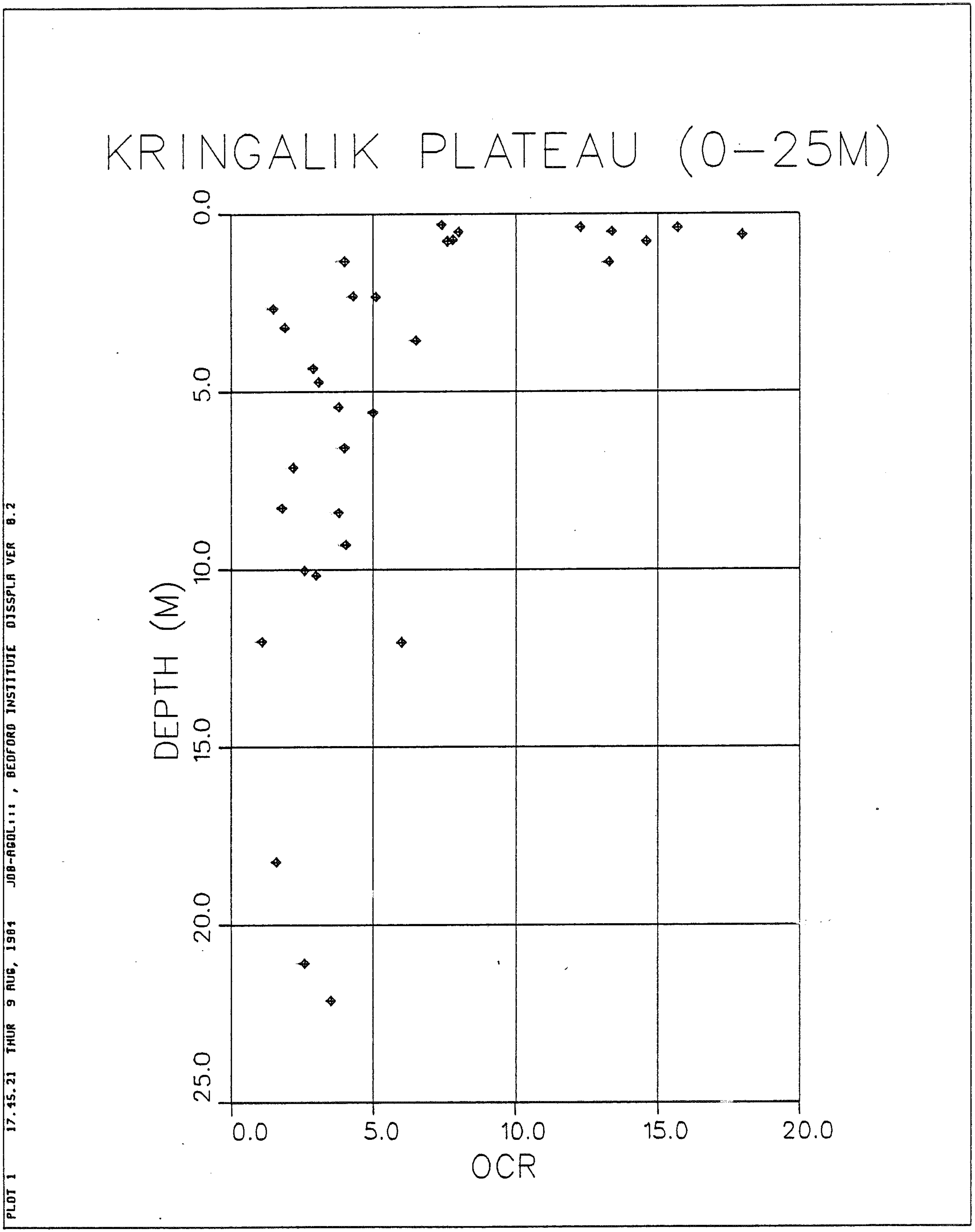
KRINGALIK PLATEAU (0-25M)
DEPTH (M)
0.0
5.0
10.0
15.0
20.0
25.0
0.0
5.0
10.0
15.0
20.0
OCR
PLOT 1 17.45.21 THUR 9 AUG, 1984 JOB-AGOL:::, BEDFORD INSTITUTE DISSPLA VER 8.2

Figure K-10

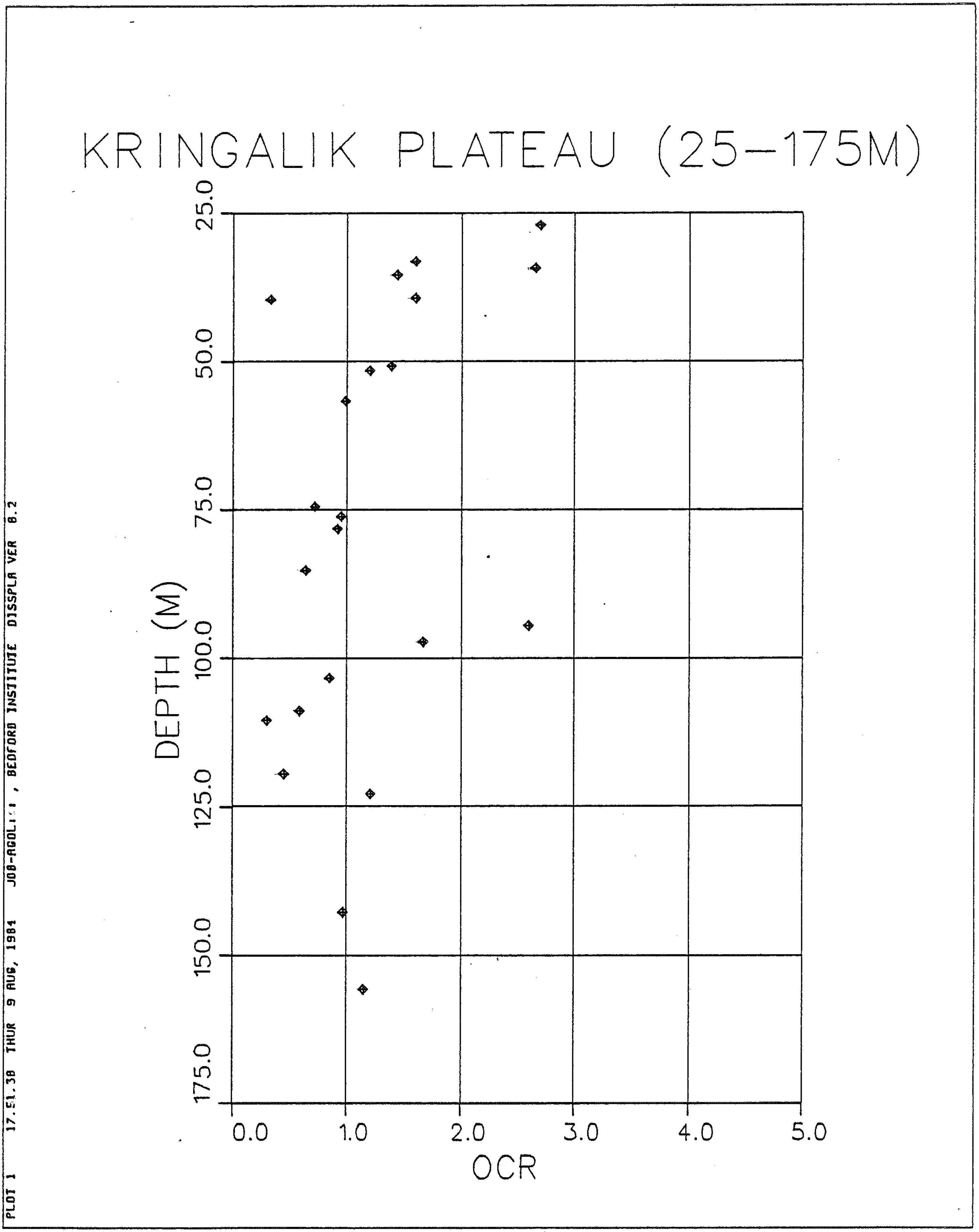
KRINGALIK PLATEAU (25-175M)
DEPTH (M)
25.0
50.0
75.0
100.0
125.0
150.0
175.0
0.0
1.0
2.0
3.0
4.0
5.0
OCR
PLOT 1 17.51.38 THUR 9 AUG, 1984 JOB-AGOLI , BEDFORD INSTITUTE DISSPLA VER 8.2

Figure K-11

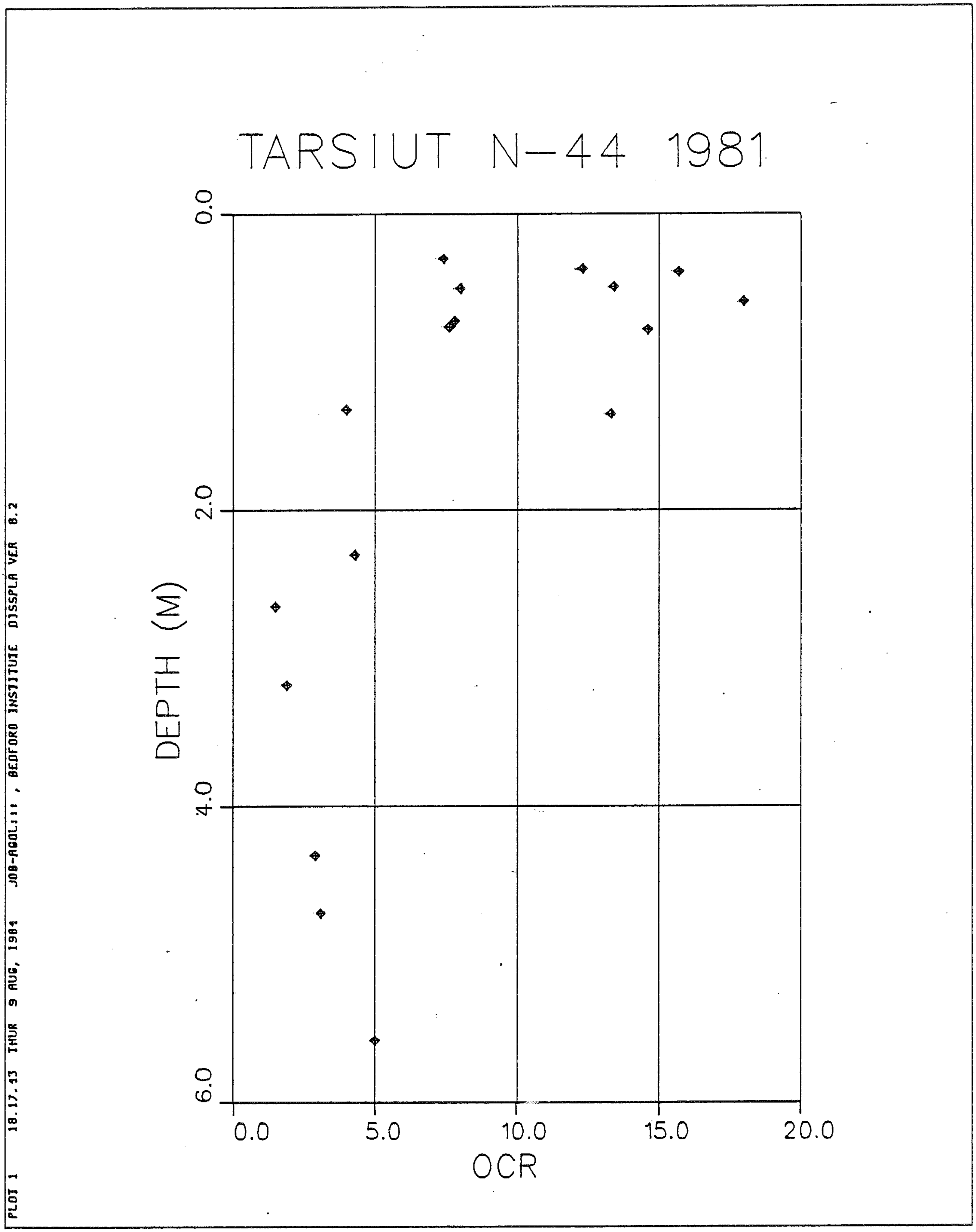
TARSIUT N-44 1981
DEPTH (M)
0.0
2.0
4.0
6.0
0.0
5.0
10.0
15.0
20.0
OCR
PLOT 1 18.17.43 THUR 9 AUG, 1984 JOB-AGOL::: , BEDFORD INSTITUTE DISSPLA VER 8.2

Figure K-12

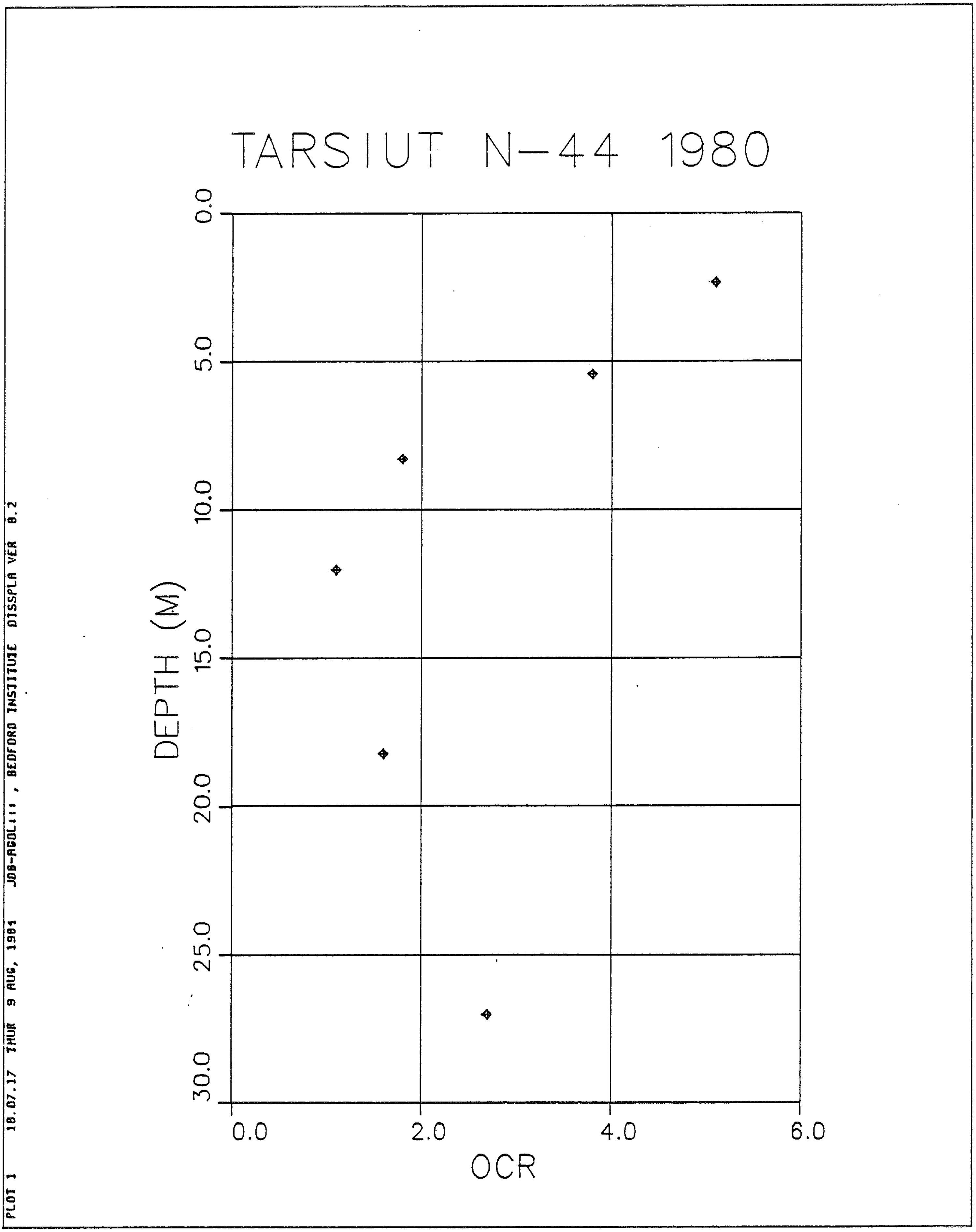
TARSIUT N-44 1980
DEPTH (M)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
OCR
0.0
2.0
4.0
6.0
PLOT 1 18.07.17 THUR 9 AUG, 1984 JOB-AGOL::: , BEDFORD INSTITUTE DISSPLA VER 8.2

Figure K-13

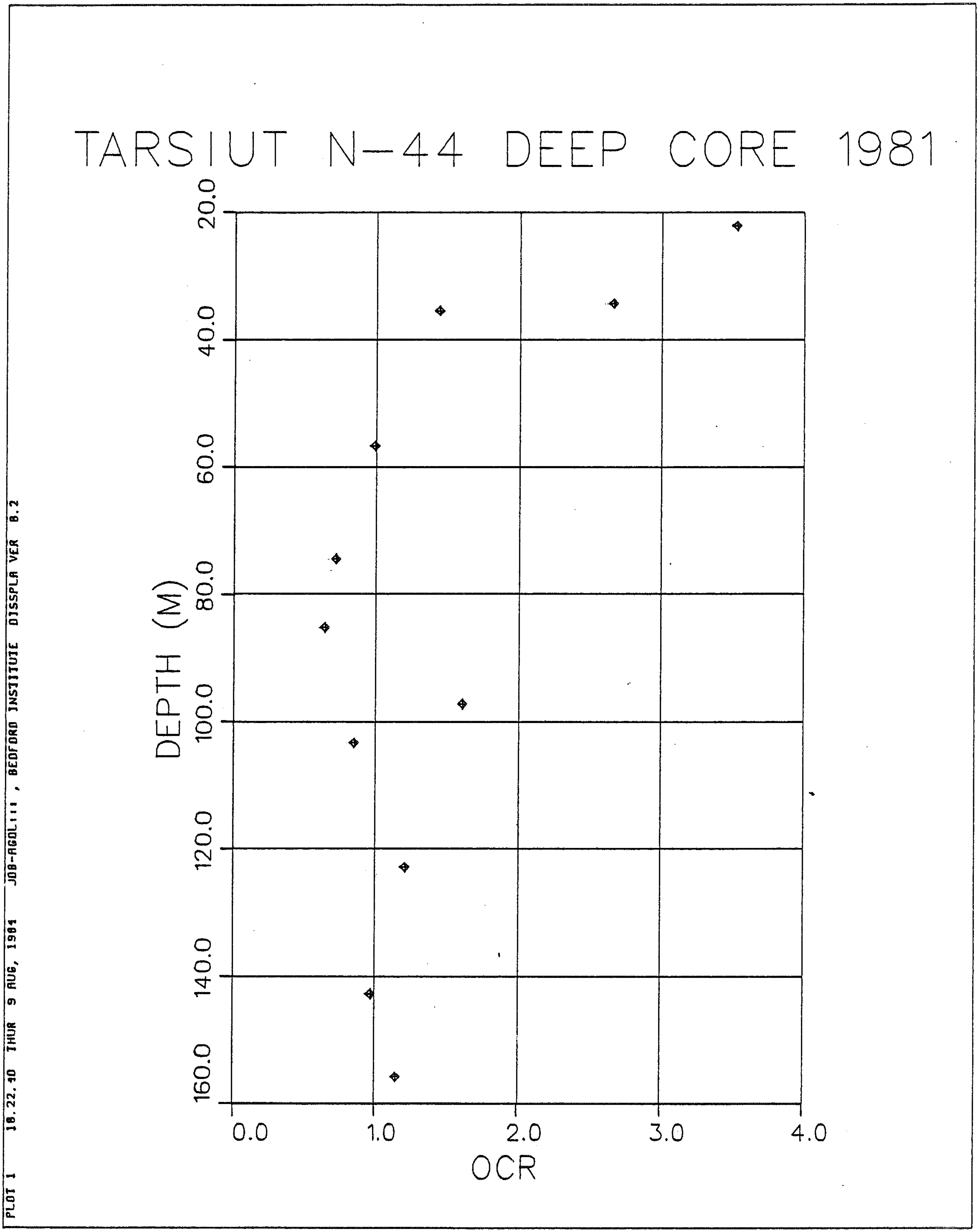
TARSIUT N-44 DEEP CORE 1981
DEPTH (M)
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
0.0
1.0
2.0
3.0
4.0
OCR
PLOT 1 18.22.40 THUR 9 AUG, 1984
BEDFORD INSTITUTE DISSPLA VER 8.2

Figure K-14

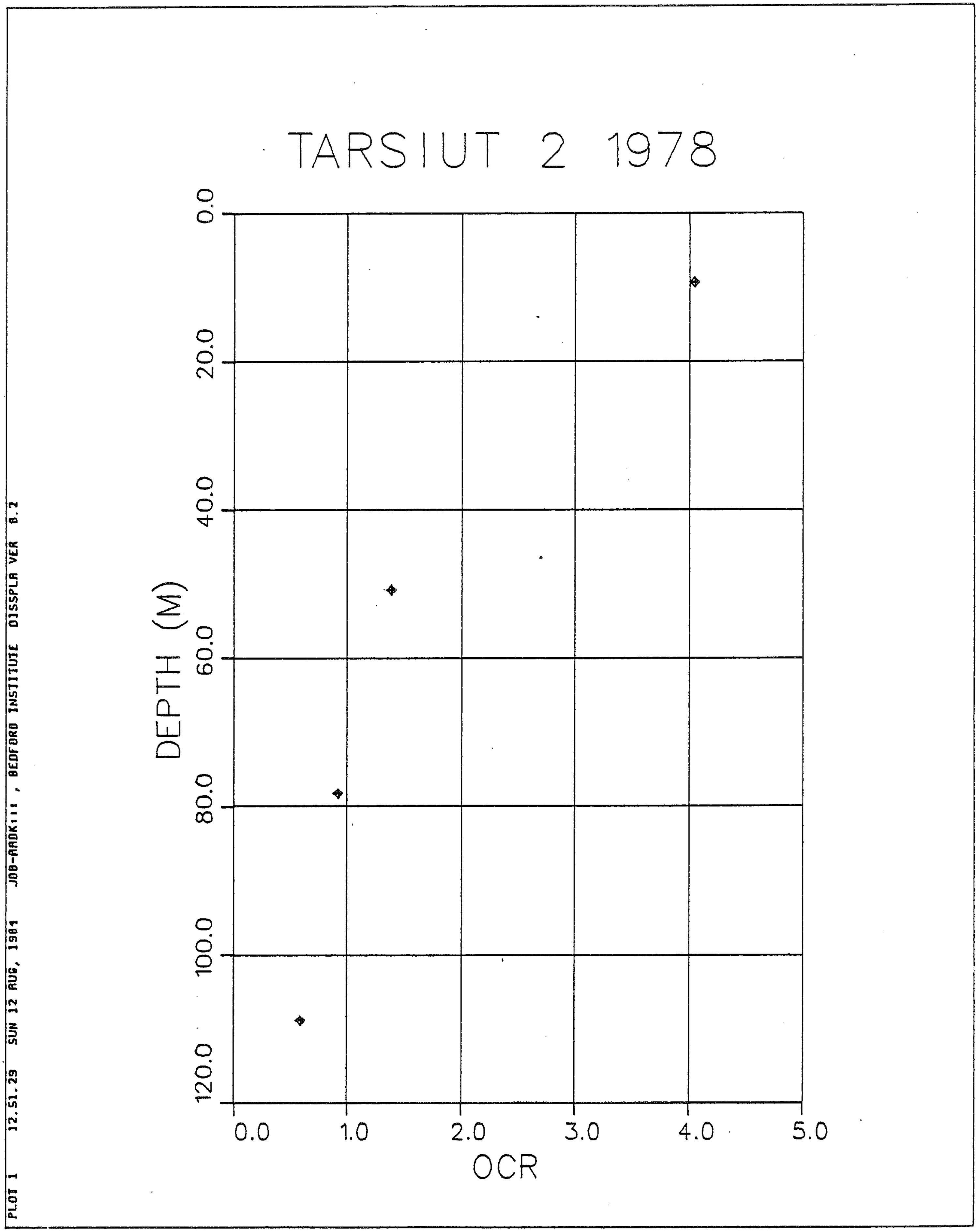
TARSIUT 2 1978
DEPTH (M)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
OCR
0.0
1.0
2.0
3.0
4.0
5.0
PLOT 1   12.51.29   SUN 12 AUG, 1984   JOB-AADK:::, BEDFORD INSTITUTE   DISSPLA VER 8.2

Figure K-15

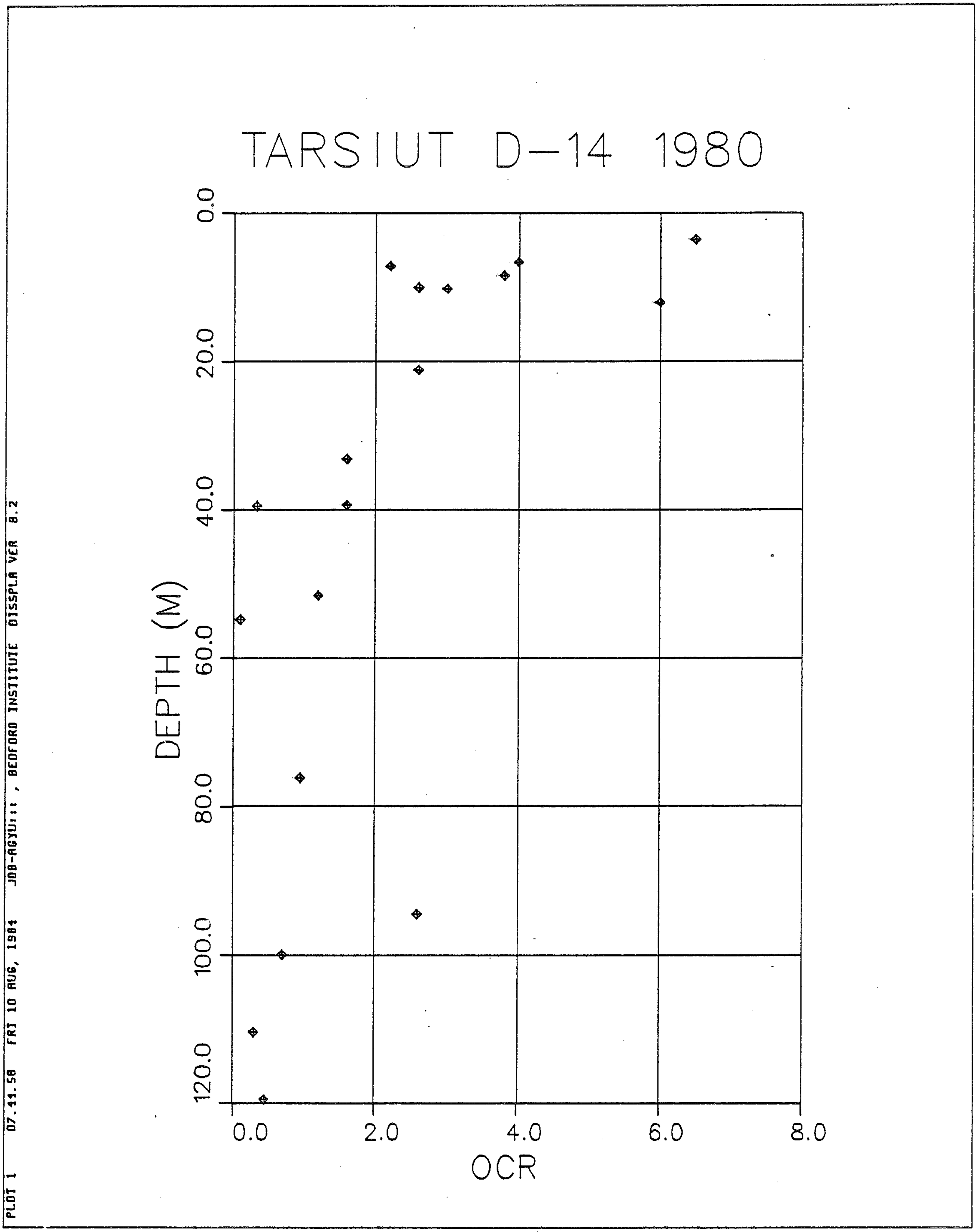
TARSIUT D-14 1980
DEPTH (M)
OCR
0.0
20.0
40.0
60.0
80.0
100.0
120.0
0.0
2.0
4.0
6.0
8.0
PLOT 1 07.41.58 FRI 10 AUG, 1984 JOB-AGYU , BEDFORD INSTITUTE DISSPLA VER 8.2

Figure K-16

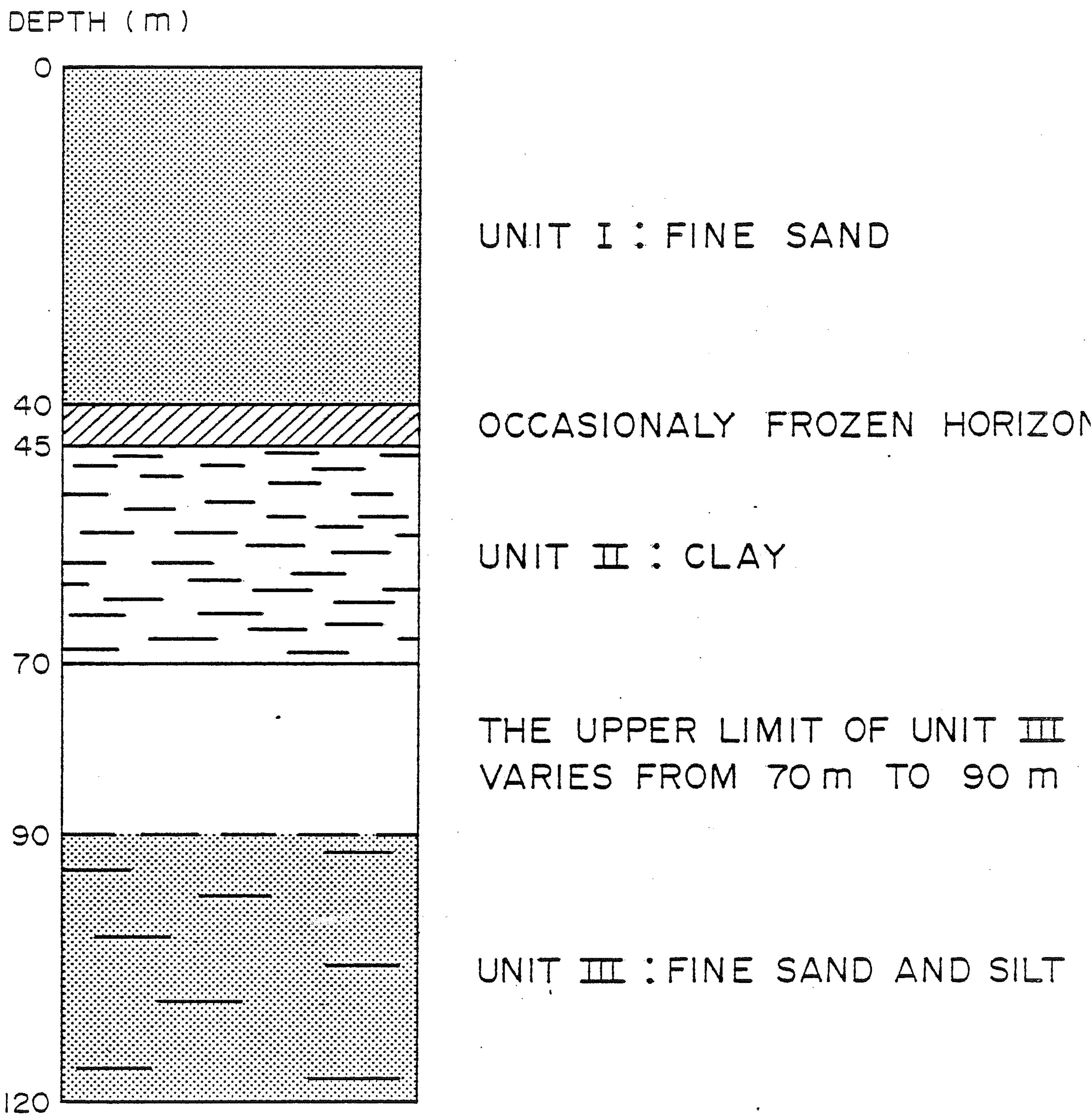

FIGURE T-1 Stratigraphic model of the Tingmiark Plain

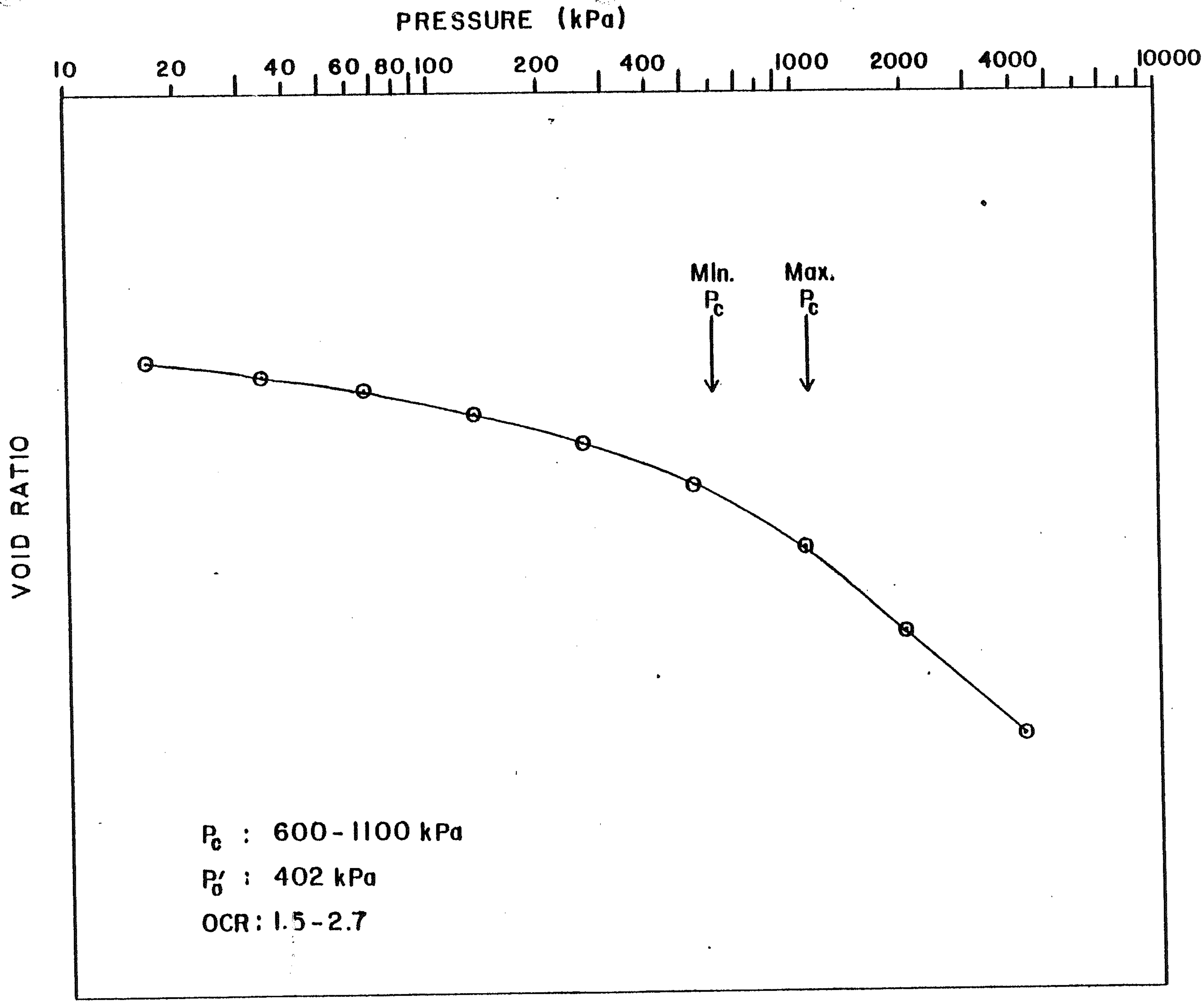

FIG.T-2 VOID RATIO vs. LOG PRESSURE for A SAMPLE FROM UVILUK P-66

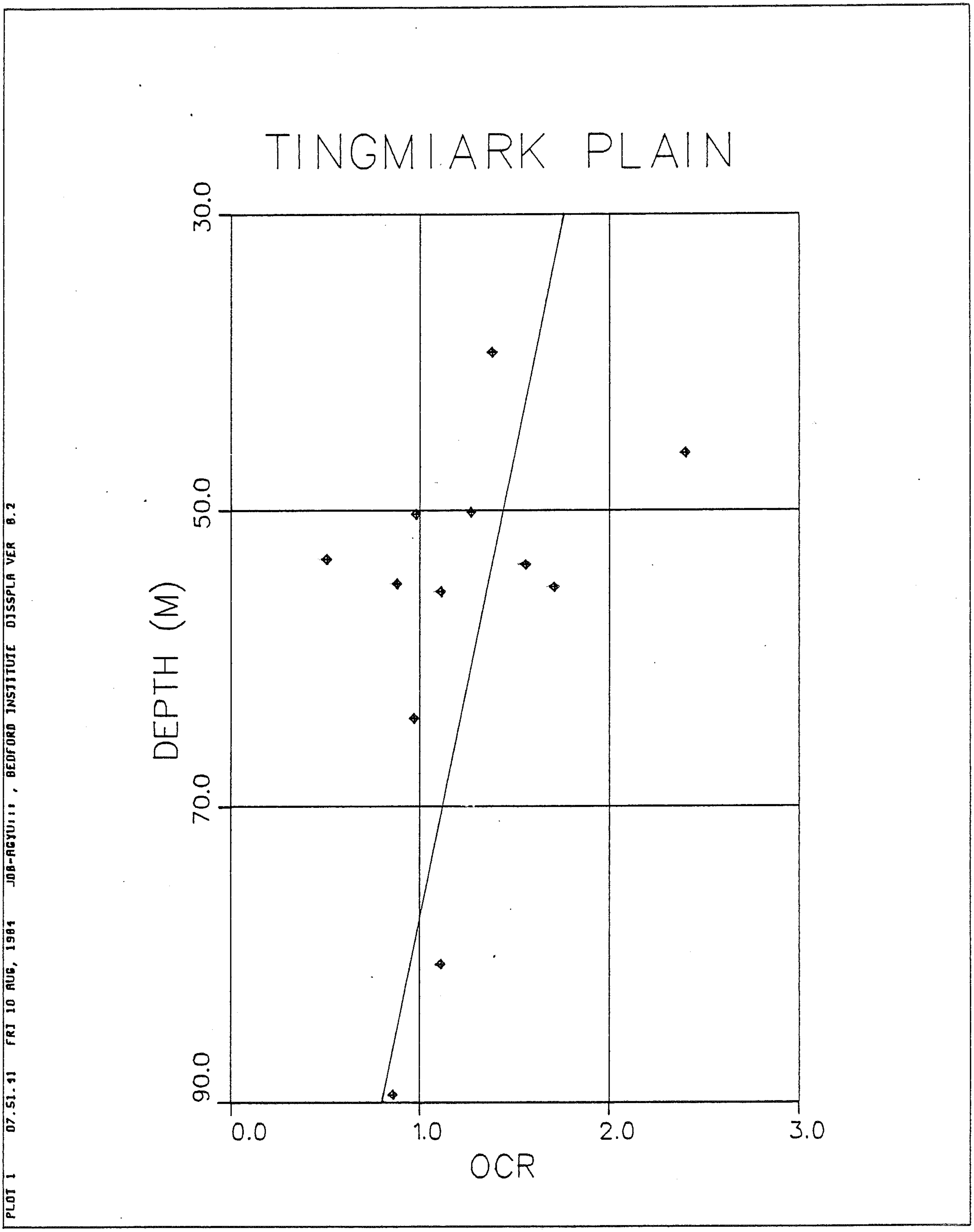
TINGMIARK PLAIN
30.0
50.0
70.0
90.0
DEPTH (M)
0.0
1.0
2.0
3.0
OCR
PLOT 1 07.51.41 FRI 10 AUG, 1984 JOB-AGYU111 , BEDFORD INSTITUTE DISSPLA VER 8.2

Figure T-3

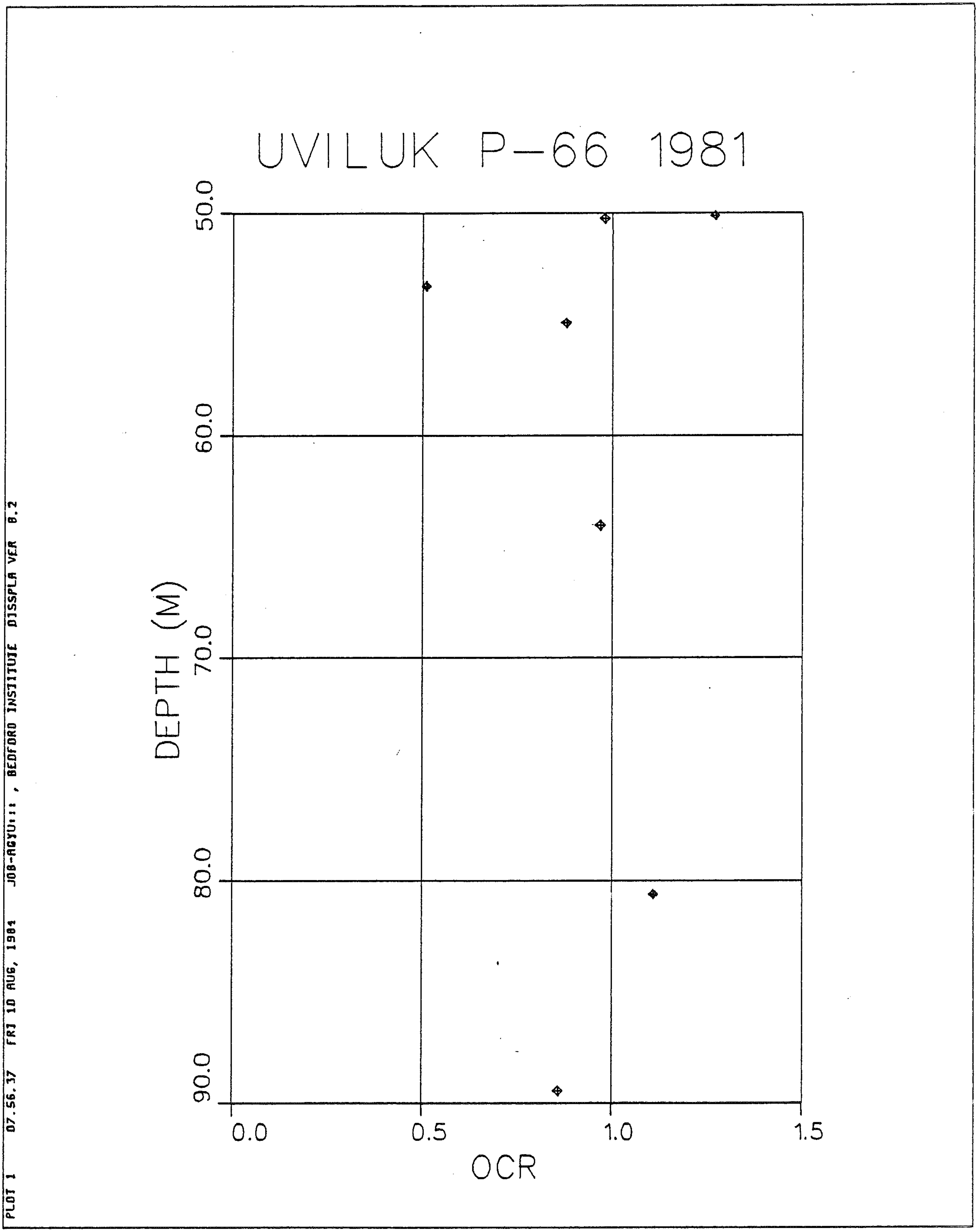
UVILUK P-66 1981
DEPTH (M)
50.0
60.0
70.0
80.0
90.0
0.0
0.5
1.0
1.5
OCR
PLOT 1 07.56.37 FRI 10 AUG, 1984
BEDFORD INSTITUTE DISSPLA VER 8.2

Figure T-4

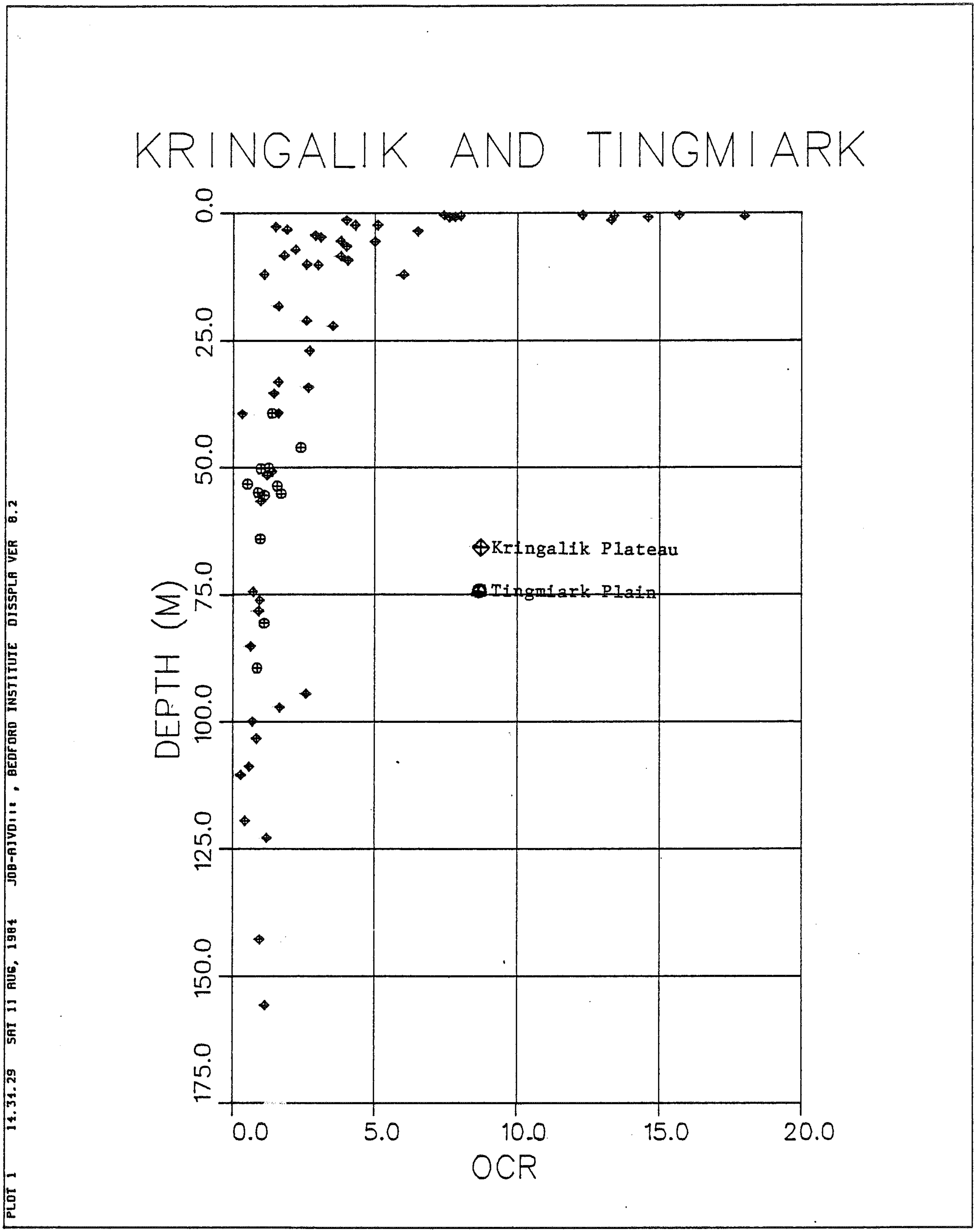
KRINGALIK AND TINGMIARK
DEPTH (M)
0.0
25.0
50.0
75.0
100.0
125.0
150.0
175.0
OCR
0.0
5.0
10.0
15.0
20.0
Kringalik Plateau
Tingmiark Plain
PLOT 1
14.34.29
SAT 11 AUG, 1984
BEDFORD INSTITUTE
DISSPLA VER 8.2

Figure C-1

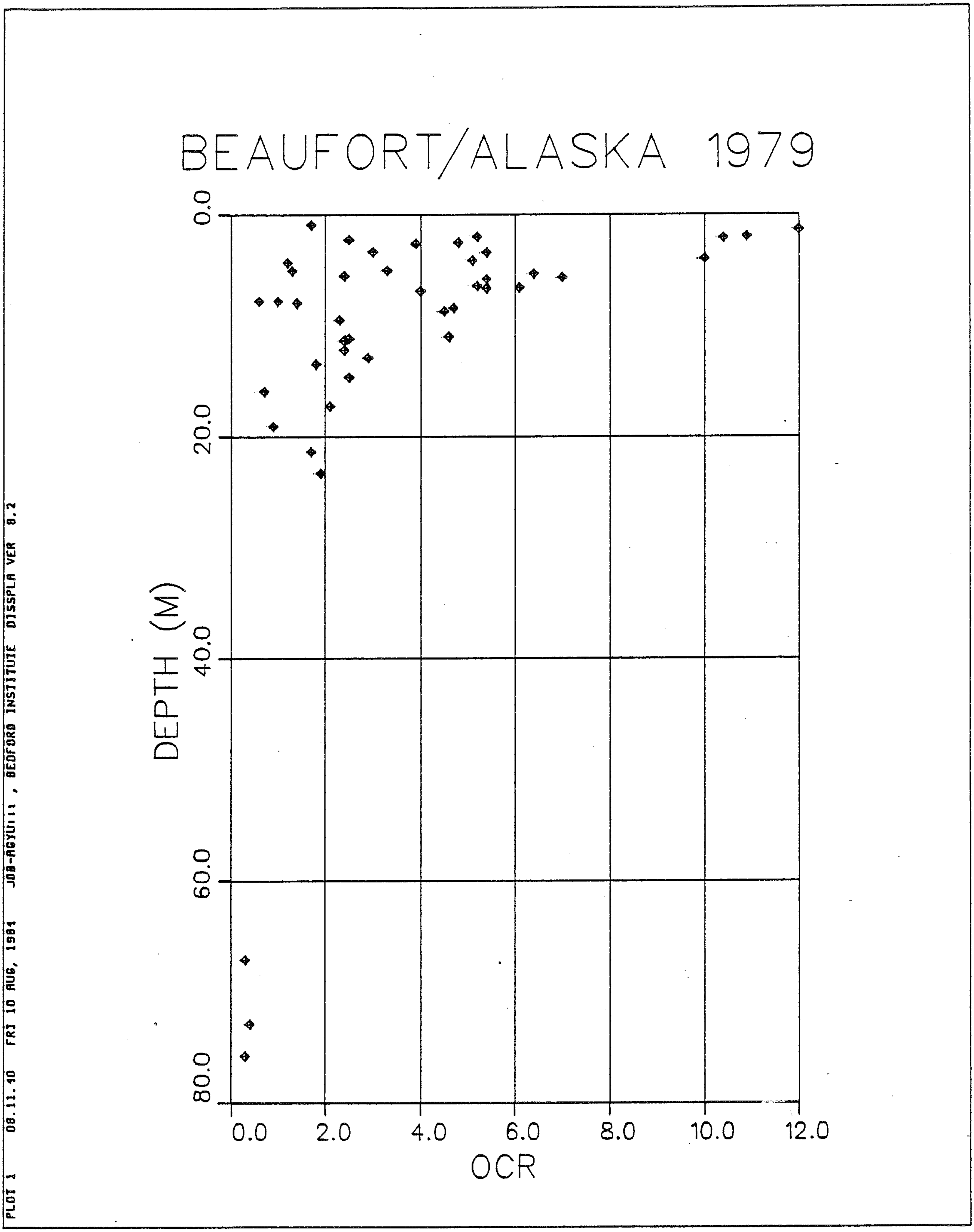
BEAUFORT/ALASKA 1979
DEPTH (M)
0.0
20.0
40.0
60.0
80.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
OCR
PLOT 1 08.11.40 FRI 10 AUG, 1984 JOB-AGYU111 , BEDFORD INSTITUTE DISSPLA VER 8.2

Figure C-2

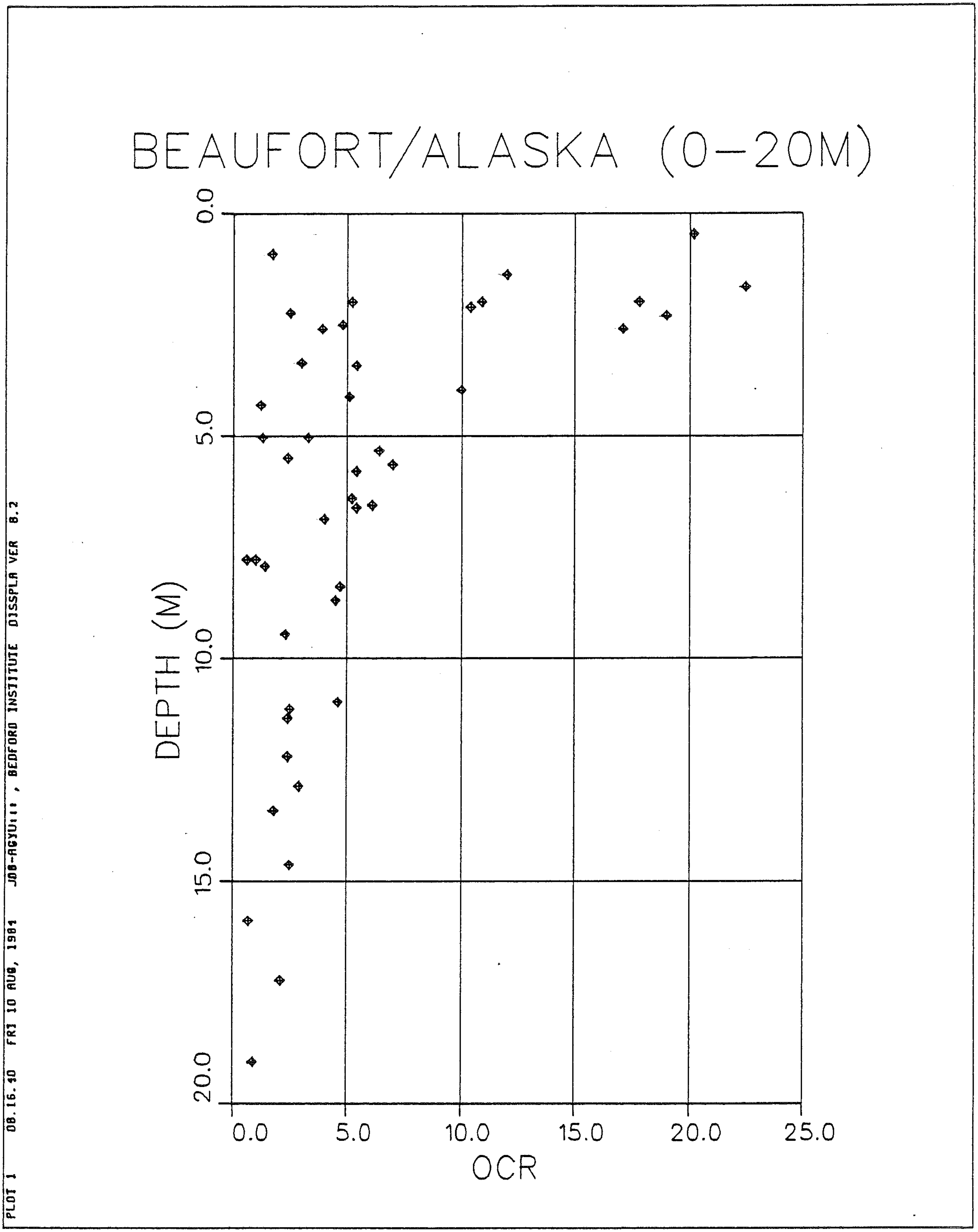
BEAUFORT/ALASKA (0-20M)
DEPTH (M)
0.0
5.0
10.0
15.0
20.0
OCR
0.0
5.0
10.0
15.0
20.0
25.0
PLOT 1
08.16.40 FRI 10 AUG, 1981
BEDFORD INSTITUTE DISSPLA VER 8.2

Figure C-3

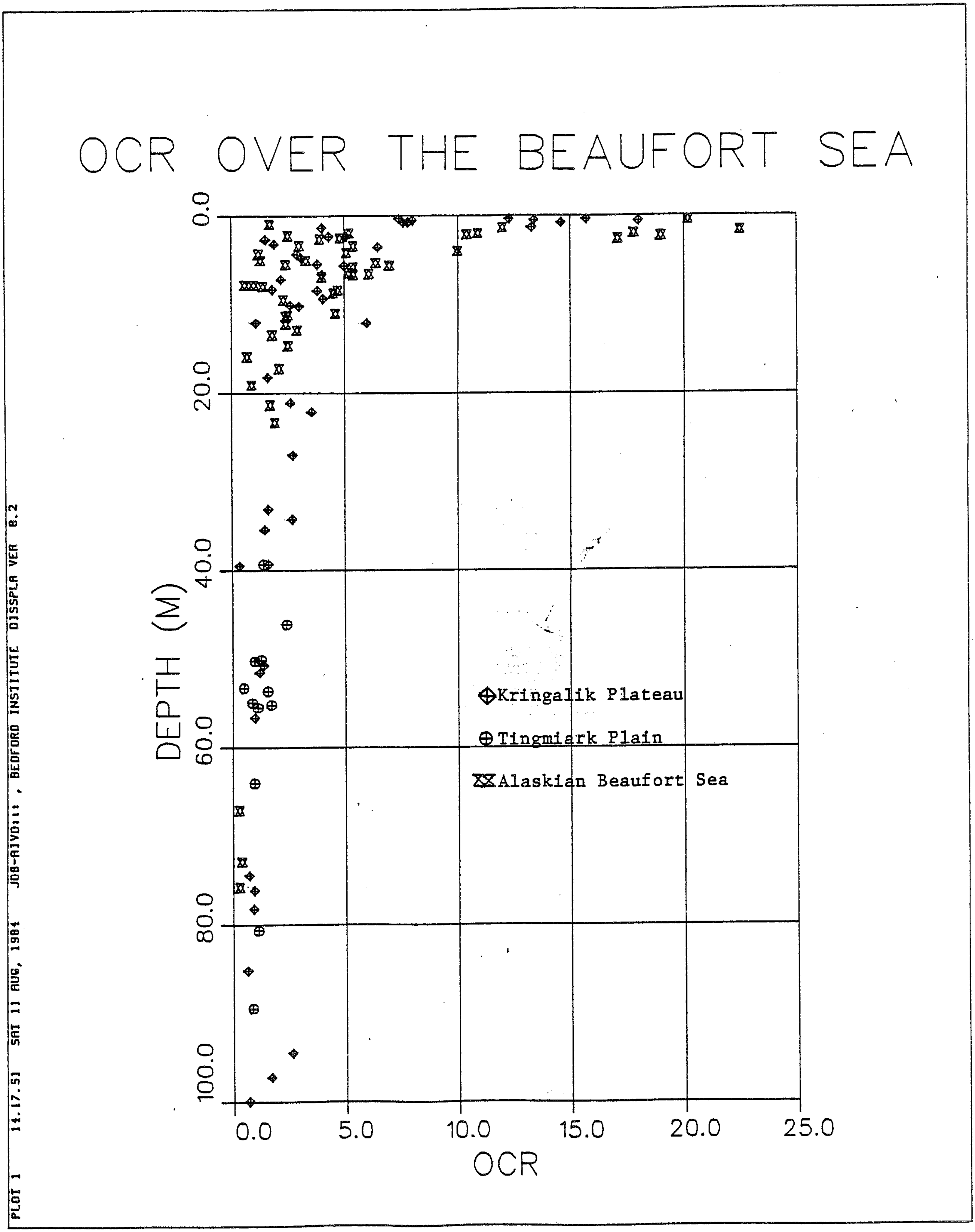
OCR OVER THE BEAUFORT SEA
DEPTH (M)
0.0
20.0
40.0
60.0
80.0
100.0
0.0
5.0
10.0
15.0
20.0
25.0
OCR
Kringalik Plateau
Tingmiark Plain
Alaskian Beaufort Sea
PLOT 1 14.17.51 SAT 11 AUG, 1984 JOB-AIVD::: , BEDFORD INSTITUTE DISSPLA VER 8.2

Figure C-4