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Calvert Cliffs Slope Erosion Project
Phase II Final Report

Processes and Controls of Coastal Slope Erosion

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Executive Summary

More than 20 kilometers of the shoreline of Calvert County, Maryland consists of steep, actively eroding slopes 10 m to 35 m high. Coastal slope erosion produces a range of impacts, both positive and negative, on natural ecosystems and human activities of the Chesapeake Bay. Eroded sediments transport pollutants, reduce shellfish productivity, and create aesthetic problems. Bluff erosion damages coastal properties and mass movements may cause harm to people and animals. However, the Puritan Tiger Beetle, a federal threatened species, requires eroding slopes as habitat (Jacobs, 1993). And, along Calvert County, Maryland, the erosion of the Calvert Cliffs creates both scenic beauty and an excellent exposure of Miocene age sediments. A particular concern is the response of the cliffs to a rise in sea level, which would accelerate cliff recession by means of more frequent wave undercutting operating at higher elevations on the cliffs. An adequate prediction of the cliff response to sea level rise requires an understanding of the mechanisms by which the cliffs erode and the critical environmental factors that determine the type and rate of slope erosion.

This report presents the results of the second and terminal year of the Calvert Cliffs Slope Erosion Project (CCSEP), a collaborative effort between the Maryland Geological Survey and the Department of Geography and Environmental Engineering at the Johns Hopkins University. The goals of this report are (1) to summarize the field data collected in the project so that it may serve as a baseline for further monitoring of these cliffs, (2) to describe the environmental controlling factors of the coastal slope erosion along the Calvert County shoreline, (3) to combine these controls and our observations of slope erosion in a useful slope classification system, and (4) to discuss these observations in the context of possible slope response to natural and man-made environmental changes, such as sea-level rise and erosion protection measures. This report builds on the results of the first phase of the project, in which we characterized the slope materials and types of failures occurring along the Calvert County coastal slopes. In this report, we add information from a second field season and discuss (1) the wave climate for design storms, (2) piezometer records and groundwater regime at each site, (3) the mechanisms of slope erosion at each site, and (4) the frequency and controlling factors of large landslides..

The CCSEP field work was concentrated at four field sites chosen to represent the range of cliff types and erosion mechanisms found along the Calvert Cliffs. This report contains a summary of the geotechnical and hydrogeological properties of the cliff materials at each study site based on field observations, the logs of 22 groundwater observations wells, and laboratory testing of samples taken from the four cliff study sections. Direct observations of cliff erosion were supplemented with detailed surveys of 33 cliff sections, including 25 slope surveys added in the second year of CCSEP.

In a very general sense, the geometry and recession rate of individual slopes along the Calvert Cliffs are directly related to the rate of wave erosion. However, this relationship is subject to the influence of other environmental factors. For example, wave attack may produce rapid undercutting, shallow landsliding throughout the entire slope, and an overall steep cliff profile in a slope with relatively weak material at the base, whereas the same magnitude of wave attack may produce a vertical lower slope and a gently inclined upper slope in locations where the slope base is composed of more competent material. In general, we observe that slopes in areas subjected to relatively high wave undercutting rates are steep and the erosion is dominated by shallow and deep-seated slides. Slopes in areas with low levels of wave undercutting exhibit more gentle angles and are dominated by surficial erosion processes such as undercutting by groundwater seepage, surficial erosion by seepage discharge and surface wash, simple falling of material from near-vertical slopes, flow of saturated material during freeze/thaw cycles, and shallow sliding of saturated surface material.

A slope classification system developed in the first year of CCSEP has been modified and expanded based on our observations during the second year of the project. The classification system uses simple observations of slope geometry to identify the dominant erosion mechanisms operating on each slope. Because the system is based on the erosion mechanisms that occur on individual slopes, it provides the basis for designing and evaluating erosion mitigation projects and predicting slope response to changes in sea level and wave activity.

The slope classification system contains four basic types which are identified by unique and readily observable properties of the slope geometry. These types are also directly correlated to the relative rates of debris delivery to the slope toe, recession of the slope base, and recession of the midslope.

Toe erosion no longer occurs in Type I slopes. Debris gradually accumulates at the slope base and deposition progresses upslope over time. Eventually, Type I slopes will stabilize at angles less than 40 degrees. All observed Type I slope along the Calvert County Shoreline have angles less than 46 degrees.

Type II slopes experience a rate of wave erosion that is approximately equal to the rate at which debris is delivered to the slope toe by surficial erosion processes. Type II slopes exhibit relatively straight profiles and their slope angles range between 46 and 63 degrees.

Type III slopes also range between 46 and 63 degrees. They are distinguished from Type II slopes by a distinctive compound shape profile: Type III slopes are steep in the wave undercut toe zone and less steep along the midslope. The midslope is dominated by surficial erosion processes controlled by local hydrological inputs.

Type IV slopes are steeper than 63 degrees and are dominated by shallow sliding which progresses from the slope toe to the bluff top. On Type IV slopes, wave undercutting proceeds at a rate greater than the rate at which surficial processes can degrade the mid and upper slopes.

In general, individual slopes can be readily placed within the slope classification system based on the characteristic slope geometry associated with each slope type. The slope measurements we have made indicate that the characteristic slope angle and shape of the four basic slope types fall into distinct, nonoverlapping groups. This is a potentially important and useful result. The slope classification organizes groups of erosion processes and rates that typically occur together. If the dominant erosion mechanisms can be identified from the overall slope angle and shape, the environmental factors controlling that erosion can be readily estimated.

Type III slopes are the most common along unprotected sections of tall cliffs in Calvert County. Because recession of the middle and upper portion of Type III slopes is driven by hydrologic erosion processes related to seepage discharge and surface flow, it is clear that environmental factors other than wave undercutting can determine the type and rates of slope erosion acting at any one location. This point is particularly evident at two of our study sites, where direct wave undercutting has been prevented by man-made structures. At both sites, active erosion of the middle and upper slopes continues, despite the fact that toe erosion has been prevented for decades. An understanding of slope erosion along tall cliffs, such as those in Calvert County, clearly must include the erosion driven by seepage discharge and overland flow.

A discussion is given of design storms for cliff erosion and the impact on cliff recession of continued sea-level rise on the coastal slope erosion along the Calvert County shoreline. Wave run-up generated by storms and rising sea level are principal environmental factors that can drive changes in the dominant erosion processes and the rates at which they operate. A summary of erosion rates measured over the last 140 years is provided in this report and compared to the short term processes investigated here.

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1. Introduction

1.1. Overview

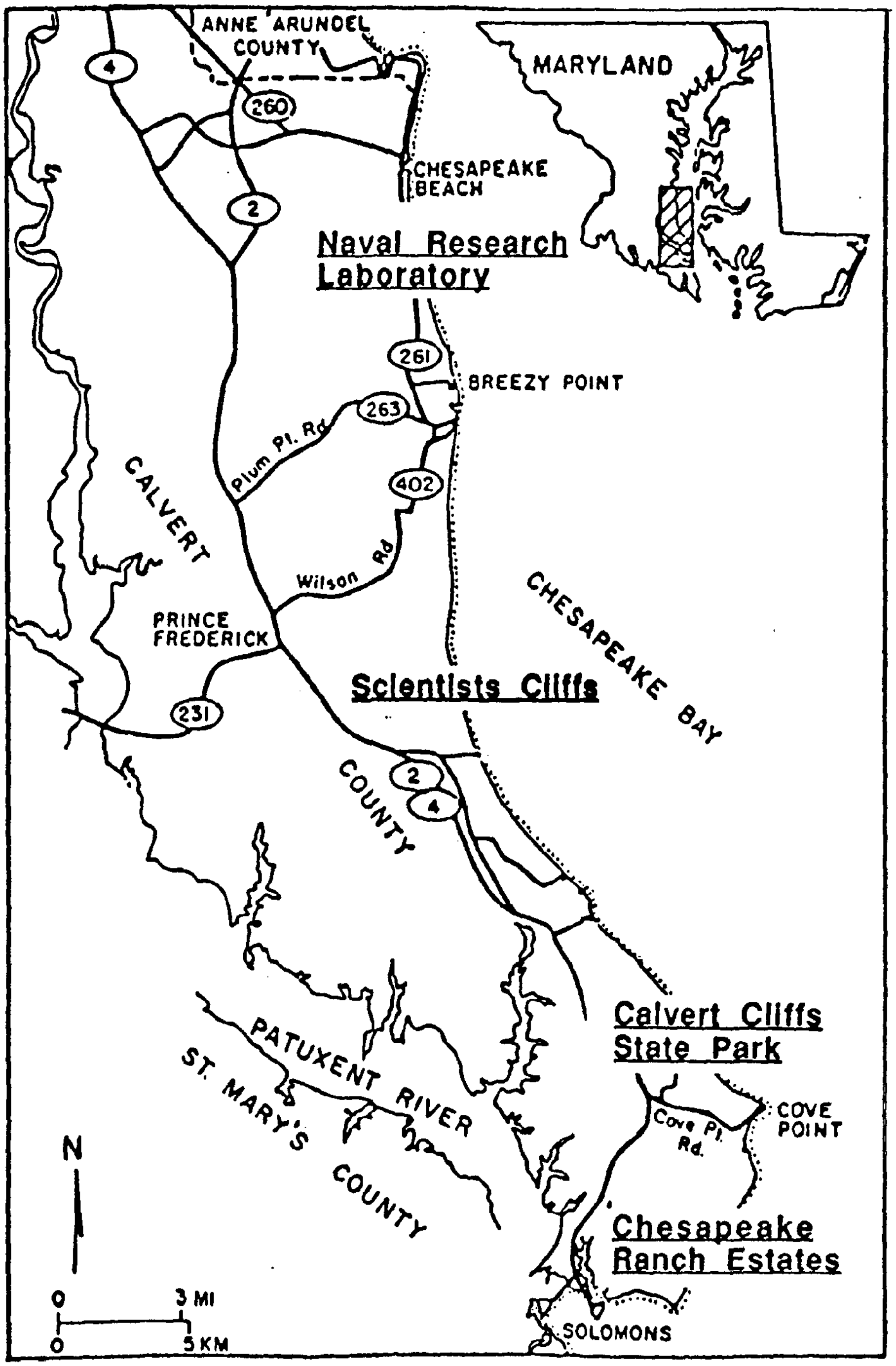
The open shoreline of Calvert County, Maryland extends 45 km along the western side of the Chesapeake Bay (Figure 1.1). Of this shoreline, 65% consists of steep slopes 10 m to 35 m high. Most of these slopes, well-known as the fossiliferous Calvert Cliffs, are actively eroding. Slope recession rates greater than 2.5 m/yr over a 96 year period have been measured along the Calvert Cliffs (Slaughter, 1949).

Tall, rapidly eroding cliffs present numerous important engineering, planning, and policy problems. Cliff-top recession eliminates shorefront property and threatens roads, dwellings, and other structures. Sediments eroded from the cliffs contribute to increased sedimentation and turbidity in the bay. Pollution from septic leachate is a growing problem where slope recession approaches septic fields. Landslides pose a direct safety problem in areas of public access, particularly because the cliffs are a popular site for fossil hunters. The cliff erosion also has some benefits. A portion of the eroded sediment is coarse sand that replenishes local beaches. Bare eroding cliffs provide exposure of stratigraphic units of international significance (Ward, 1993). Some bare cliffs provide habitat for the Puritan Tiger Beetle, a Federal Threatened species (Jacobs, 1993).

Decisions regarding the type and feasibility of erosion control practices require an understanding of the mechanisms by which particular cliffs erode. Effective planning, zoning, and policy decisions require an understanding of the rate of future cliff top recession, which depends on the cumulative erosion produced by the different erosion mechanisms. Identification of erosion mechanisms is particularly important when addressing questions concerning the response of the cliffs to changes in external variables such as climate and sea level, which can change not only the <u>rate</u> of erosion, but also the <u>types</u> of erosion that occur. Therefore, a rational assessment of the impact of such changes on coastal slope recession must be based on the dominant erosion mechanisms.

Identification of the dominant processes acting on eroding coastal slopes is often difficult. Not only may the slopes be eroding rapidly, but there are many mechanisms by which the cliffs can erode, many of which often operate simultaneously. Although wave undercutting of the slope toe (whether presently active or not) is a common feature of all of the receding cliffs, we will demonstrate below that it is often not the dominant erosion mechanism along many sections of the cliffs. The rate at which one erosion mechanism operates can directly depend on the particular combination of other active erosion mechanisms and their rates. The dominant erosion mechanisms at any particular site may not be immediately obvious, nor is the mix of mechanisms that may develop in response to a change in external forcing.

In this report, we describe the materials, hydrogeology, and slope geometry along four actively eroding sections of the Calvert Cliffs. We also describe the various erosion mechanisms operating on the cliffs and describe the external controlling factors of these mechanisms. We present a simple approach to classifying the cliffs according to the dominant erosion types. The classification uses readily observable properties of cliff geometry, stratigraphy, and



Study Site Locations

Figure 1.1

seepage to identify the dominant erosion mechanisms, thereby providing a basis for evaluating erosion control measures. We illustrate how the classification system may be used to provide guidance on planning and engineering decisions. The classification system also provides a basis for identifying threshold values of the external variables that would cause the suite of dominant erosion mechanisms to change in response to external forcing.

1.2. Erosion Mechanisms and Historical Shoreline Recession Rates

The classification of erosion mechanisms presented in this paper complements previous and on-going work in which long-term slope recession rates are determined from historical and modern maps and photographs of the shoreline (Slaughter, 1949; Downs and Leatherman, 1993; Conkwright, 1976). An historical approach provides the best currently available estimates of regional shoreline recession and sediment supply to the bay; it also can identify general locations of higher erosion. The historical approach is not as well suited as a planning tool at a site-specific level. For example, the timing and magnitude of slope failures contributing to slope recession may be highly variable and unresolvable using historical methods. It is difficult to make predictions of erosion for a period of, say, one year or one decade using information averaged over a century. In some locations, slope erosion may be shallow and continuous on a year-to-year basis. In other places, there may be little or no cliff-top recession for a long period of time as the slope is gradually undercut and steepened by toe erosion. Once the slope reaches a critical angle, or the combination of slope geometry and pore pressures within the slope become critical, a major failure may occur. Identification of such a potentially dangerous situation requires an understanding of the local erosion mechanisms.

Historical erosion rates also must be used with care when estimating future shoreline recession. For example, changes in sea level are likely to have an important influence on recession rates. Slope recession rate depends not only on the rates at which individual erosion mechanisms operate, but also on the particular mix of erosion mechanisms that would occur, the composition of which may change in response to a change in undercutting rate. For example, the recession of many of the Calvert Cliffs is presently dominated by erosion related to groundwater seepage. An increase in wave undercutting could cause the dominant form of cliff erosion to become one of rapid, shallow sliding, the controlling factors of which are the erosion rate of the slope toe and the supply of surface water to the slope. As a result of the complex interaction among wave undercutting and the other slope erosion mechanisms, a simple and direct relation between sea level change and historical recession rates cannot be made.

Work on erosion mechanisms and historical coastline recession form a useful complement; an understanding of mechanisms increases the utility of the historical recession rates by providing a means of interpreting the causes of shoreline recession; the historical rates provide well documented bounds for the investigation of mechanisms.

1.3. Background: Other Observations of Eroding Coastal Slopes

Several efforts have been made to outline the evolving processes and slope geometry typical of eroding coastal cliffs. The work presented here includes a further development and extension of these efforts, and an application to cliffs composed of sediments that are generally coarser grained and more subject to surficial erosion by running water.

Hutchinson (1973) identified three cases in which different rates of toe erosion produced distinctly different groups of erosion mechanisms and characteristic slope forms in cliffs of stiff, fissured Eocene London Clay located along the Thames River Estuary in southeast England. On slopes where toe erosion is no longer occurring, the slopes assume a "bilinear" form with a steeper upper slope eroded by shallow slips and soil creep and a stable lower slope at a gentler angle on which the upslope debris accumulates. These slopes can eventually flatten to a stable angle of repose if slope debris is allowed to deposit with no removal. A second slope type develops where wave action can remove slope debris at the same rate at which it is delivered to the slope toe. This results in a relatively straight and steeper slope form that mud flows and shallow slides cause to recede without major changes in slope geometry. A third characteristic geometry with a distinct cyclic component occurs at locations of still more rapid wave undercutting. Erosion of intact material can steepen the lower part of the slope to the point that a deep-seated rotational slide is initiated. If a slide occurs, the debris is deposited at the slope base and is eventually removed by wave erosion. While the toe debris is being eroded, the steep rear scarp of the slide scar is eroded by shallow slides and block falls, producing a gentler slope and making the slide topography more subdued. After the toe debris is completely removed, further erosion of intact material at the slope toe initiates a new cycle of steepening and deep-seated failure, followed by simultaneous erosion of the slide debris and degradation of the slide scar. Hutchinson observed that the cycle time of this pattern was hard to determine precisely, but was at least 30 years and often much longer.

Quigley and Gelinas (1976) observed similar combinations of slope erosion and geometry for slopes along the northern shore of Lake Erie, even though these cliffs are composed of a Pleistocene clay till of substantially different composition than the London Clay examined by Hutchinson (1973). Slopes with little or no toe erosion were observed to have a bilinear form similar to that described by Hutchinson. Such slopes were observed to occur in locations protected by substantial beaches, or over a broader area during periods of low lake level. Slopes experiencing moderate toe undercutting were observed to retreat in a parallel fashion with little change in slope form, representing some critical equilibrium between the cliff erosion mechanics and wave erosion. Such an equilibrium is similar to the second slope type defined by Hutchinson for the case of a balance between wave erosion and the rate of debris delivery to the slope toe, but differs in that the slope type defined by Quigley and Gelinas clearly involves some active wave erosion of intact material at the slope toe. The resulting slope geometry has a scalloped pattern of embayments with a relatively straight slope at a lower angle separated by steeper sections with a convex form (the angle of the lower slope is steeper than that of the upper slope). At locations with the most rapid toe erosion, Quigley and Gelinas observed a cyclic variation of erosion mechanism and slope geometry that is very similar to the corresponding slopes identified by Hutchinson. Quigley and Gelinas suggest that the cycle time is on the order of 20 years.

Edil and Vallejo (1977) studied eroding slopes in fine-grained, unconsolidated Pleistocene glacial tills and glacial-lacustrine sediments along the western shore of Lake Michigan. They noted that characteristic groups of erosion processes can be associated with the lower, middle, and upper segments of a cliff profile, an observation we develop further in this paper. They also described two different sequences of slope evolution: one involving rotational slides and the other shallow translational slides, mudflows and surface wash related to freeze/thaw cycles. Cliffs of greater height were observed to undergo a cycle in which the slope toe is steepened by wave erosion, thereby precipitating a sequence of successive rotational slides, none of which involves the entire slope, that gradually work their way to the slope top. Edil and Vallejo note that a system for classifying slope evolution would provide a useful tool in coastal slope studies.

Although many different erosional processes may act simultaneously on a slope, one erosion mechanism (or a group of similar mechanisms) is often responsible for most of the erosion on a specific segment of a slope, which can then take on a form that is characteristic of that process (Parsons, 1988). Edil and Vallejo (1977) implicitly use this distinction to distinguish between slopes dominated by rotational and translational slides. Hutchinson (1973) and Quigley and Gelinas (1976) also distinguish slopes by a characteristic geometry that could be correlated with a particular suite of erosional processes acting on particular segments of the slopes. We will build on this approach in developing a classification of the eroding Calvert Cliffs that is based on characteristic slope geometries and that may be used to identify the dominant erosion process.

1.4. Calvert Cliffs: Erosion Mechanisms and Their Controlling factors

The erosion mechanisms operating along the Calvert Cliffs are varied and complex (Leatherman, 1984; Pomeroy, 1990). They include direct erosion by wave action, detachment and transport of individual soil grains by both gravity and running water, sediment flows from thawing of ice lenses near the slope surface, separation and sliding or toppling of large blocks along nearly vertical fractures, and the failure of large slump blocks along a deep surface of material weakness. Most of these mechanisms operate to some degree on all of the bare, eroding slopes, and more than one erosion mechanism generally contributes significantly to the observed slope form and slope recession at any one site.

The environmental factors that control each mechanism are different. Surficial erosion requires a water source such as direct precipitation, snow melt, or groundwater seepage, and is most effective when acting on bare soil. Vegetation and drainage controls are important controlling factors. Direct erosion by seeping groundwater depends primarily on the local groundwater supply and the presence of a less permeable zone within the slope. Erosion from sliding or falling of large blocks is controlled by the rate at which saturated intact slope material is undercut. If undercutting is sufficiently rapid, the slope becomes very steep, producing near-vertical tension cracks in response to the rapid unloading at the slope. Surface and subsurface water may enlarge the tension cracks and reduce frictional strength along the remaining contact, but the influence of water is secondary to the gravitational stresses related to rapid slope retreat. Wave undercutting initiates block falls in the lower slope; these, in turn, may undercut upper portions of the slope and initiate block falls upslope. In portions of the slope that are not saturated, wetting and drying cycles can enlarge tension cracks, producing columnar blocks that topple when undercut by block falls lower in the slope or by erosion along groundwater seepage zones. Deep-seated failures typically occur when a weak material at depth, such as a clay, fails due to its inability to support the stresses imposed on it by changing enviromental conditions. The environmental conditions which may produce such failures include steepening of the slope face by wave erosion or surficial processes and rising water pressure within the weak material. Steepening by erosion forces a smaller portion of the weak zone to carry a greater portion of the slope load. As the water table rises above the weak material, the increasing weight of the water causes the pressure in the pores between the material grains to rise. Rising pressure tends to reduce the frictional strength of the contacts between the grains and results in a reduction of the the material's ability to resist failure. The timing of deep failures is controlled primarily by groundwater drainage at a local to regional scale.

Undercutting by wave activity, whether currently active or not, is a common factor in the development of all coastal slopes. Wave erosion initiates and, in some cases, dominates the slope erosion. In some cases, particularly where the undercutting rate is very rapid, undercutting is the dominant environmental controlling factor of both erosion mechanisms and rates for the entire slope. In other cases, including most of the Calvert Cliffs, wave undercutting is only one of several factors controlling the type and rate of slope erosion. This is particularly true in the middle and upper portions of the slopes, for which the recession rate is often more rapid than, and therefore relatively independent of, the wave-driven recession of the lower slope. In these cases, a characteristic slope profile is formed in which the middle portion of the slope is more gentle (has receded back from) than the steeper lower slope. We take advantage of this characteristic profile in our classification system in which we identify the erosion mechanisms from the slope geometry. An important point is that the erosion mechanisms producing these slopes and, therefore, the factors controlling that erosion, are not a direct function of the lower slope erosion. Wave action is needed to initiate slope erosion and to remove the debris shed from the slope, but the mechanisms and rates of erosion of the middle and upper slopes are controlled by local surface water and groundwater, slope geometry, and material strength, and not by toe undercutting.

The complexity of rapid coastal erosion is augmented by the fact that the types of erosion processes acting on any individual slope may not be constant in time. For example, a cyclic variation in both erosion mechanism and slope geometry, similar to that described by Hutchinson (1973), occurs in the Calvert Cliffs. A period of direct toe undercutting and slope steepening can produce a deep-seated landslide. At the Calvert Cliffs, these slides appear to be limited to locations where a soft clay layer is found within a seepage zone. A minimum slope height of 15 m above the clay layer is apparently necessary to produce sufficient shear stress to produce failure within the clay layer. The landslide is followed by a period during which the failure debris protects the slope toe from further erosion, while surficial erosion processes continue to degrade the middle and upper parts of the slope. The cycle begins again when the slope debris is removed from the slope base and erosion of the intact toe resumes. Removal of the debris at the slope base occurs over a period of generally less than one or two years, depending on the elevation of the slope base and the sequence of storm water levels following the landslide. The overall cycle period is difficult to estimate based on observations over a few years. The period is likely to vary between a few years and a few decades; the longer cycle period is similar to that observed by Quigley and Gelinas (1976) for Lake Erie and much shorter than that observed by Hutchinson (1973) for cliffs in the London Clay.

2. Field Observations and Methods

2.1 Methods

Slope Surveys

Surveying instruments used during the course of the CCSEP included:

1) Lietz/Sokkisha SET3 - electronic total station (serial # 84121)

Vertical Accuracy	5"
Horizontal Accuracy	2"
EDM* Accuracy	± (5mm + 3ppm x distance (m))

*(Electronic Distance Measurer)

2) Lietz/Sokkisha DT20E Theodolite - electronic digital theodolite (serial # 60619)

Vertical Accuracy	20"
Horizontal Accuracy	20"

3) Topcon AT-F6 Auto Level (serial # X60457)

Accuracy in 1 Km in double run leveling	±2.0 mm

Horizontal control

Horizontal control was not referenced to a general horizontal network. Instead, it was maintained locally at each study site, typically referenced to a unique, obvious, and permanent feature. Each horizontal reference feature is documented within the field notes.

Elevation Surveys

All elevations were established relative to the 1929 National Geodetic Vertical Datum. The double run leveling method was used to perform all elevation transects. Elevations were established for the well heads and surveying reference stations using the Topcon level and a level rod. Elevations for slope survey instrument stations were established from surveying reference stations using the SET3 total station distance ranging feature.

U.S. Coast and Geodetic Survey benchmarks were used directly for all of the elevation transects except the transect at the Chesapeake Ranch Estate site. There, the elevation of a public water supply well head at well site No. 3 was used. The elevation at this well head was established in reference to 1929 NGVD by the Maryland Department of Natural Resources, Technical Services Division and designated "Ca-Fe 18". A list of the benchmarks used to establish elevation at each site follows.

Site	Benchmark
Naval Research Lab	Navy (reset 1971)
Scientists' Cliffs	U133 (reset 1971)
Calvert Cliffs State Park	Cove B.M.
Chesapeake Ranch Estates	Ca-Fe 18

Mean Water Levels Relative to NGVD

Elevation measurements must be referenced to a datum. Typically a vertical datum is referenced to a statistically defined mean ocean surface or to an imaginary 3-dimensional geoid surface. In regions affected by tidal waters, mean tidal water surfaces serve as useful horizontal data for local elevation measurements. The water surfaces referred to in this report were established for the tidal gauging station at Ft. McHenry in Baltimore, MD. These data have been referenced to the 1929 National Geodetic Vertical Datum (NGVD) (Balazs, 1991). Figure 2.1 shows the relationship of mean lower low water (MLLW), mean tide level, mean sea-level for the 1960-1978 epoch (MSL), and mean higher high water (MHHW). The tidal water surfaces are defined in the following manner (NOAA, 1992): All elevations mentioned in this report use the 1929 NGVD as the elevation datum.

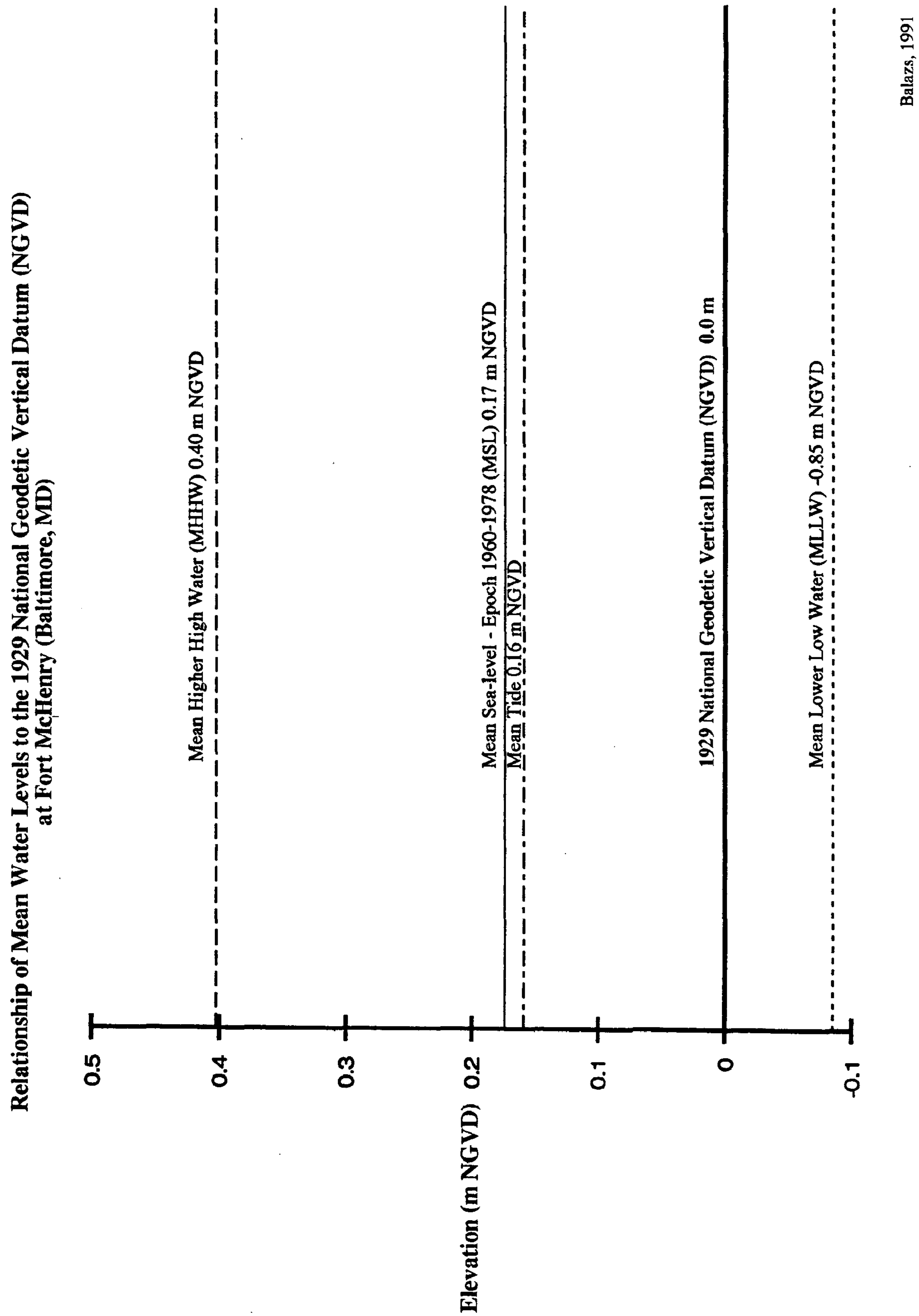

Relationship of Mean Water Levels to the 1929 National Geodetic Vertical Datum (NGVD)
at Fort McHenry (Baltimore, MD)
Elevation (m NGVD)
0.5
0.4
0.3
0.2
0.1
0
-0.1
Mean Higher High Water (MHHW) 0.40 m NGVD
Mean Sea-level - Epoch 1960-1978 (MSL) 0.17 m NGVD
Mean Tide 0.16 m NGVD
1929 National Geodetic Vertical Datum (NGVD) 0.0 m
Mean Lower Low Water (MLLW) -0.85 m NGVD
Balazs, 1991

Figure 2.1

Mean sea-level (MSL) - "A tidal datum. The arithmetic mean of hourly water elevations observed over a specific 19-year Metonic cycle (the National Tidal Datum Epoch)."

Mean Lower Low Water (MLLW) - "A tidal datum. The arithmetic mean of the lower low water heights of a mixed tide observed over a specific 19-year Metonic cycle (the National Tidal Datum Epoch). Only the lower low water of each pair of low waters, or the only low water of the tidal day is included in the mean."

Mean Higher High Water (MLLW) - "A tidal datum. The arithmetic mean of the higher high water heights of a mixed tide observed over a specific 19-year Metonic cycle (the National Tidal Datum Epoch). Only the higher high water of each pair of high waters, or the only high water of the tidal day is included in the mean."

Mean Tide Level - "Also called half-tide level. A tidal datum midway between mean high water and mean low water.

Slope Profile Surveys - all sites

Site by site discussions of the slope profiles are provided in sections 2.2, 2.3, 2.4, and 2.5. The slope angle is mentioned frequently. Unless otherwise stated, the slope angle refers to the overall angle formed between a horizontal plane and a line drawn between the intact slope toe and bluff top.

Open traverses were used to establish baselines along the shoreline for the horizontal control used in slope surveys. Accurate and efficient closed traverses were virtually impossible to complete due to the nature of the slope topography. Except for slope survey instrument stations on protected slope toes, instrument stations could only be temporarily established due to washover by high tides. Therefore, baselines had to be established each time a survey was made.

A typical slope survey was performed using both the SET3 total station and the DT20E theodolite. The instruments were set up two to three meters apart. Both instruments sighted on identical points along a slope profile. Triangulation was used to establish the horizontal and vertical position of individual points on the slope. The distance ranging feature of the total station was not used because safe access for positioning the reflector was restricted to the slope toe and bluff top region. One instrument was located along a profile line and the horizontal angle was set for that machine so that it was perpendicular to the slope toe. This angle remained unchanged during the course of the survey. Points along the slope surface and on this profile line were selected and the angles to each point from both machines were recorded.

During Phase II, 25 slope profiles were completed using only the SET3 total station. The instrument station for one or several profiles was referenced to previously established reference stations. A pulley and rope system was used to tow a reflector array along the slope surface. The slope distance, horizontal angle, and vertical angle was recorded for each measured point on each profile.

Field Observations and Photo Stations

In addition to repetitive slope surveys, regular site visits are made to observe changes in the slope geometry, seepage condition, and shoreline configuration. During each slope survey and when visual inspection indicates significant changes have taken place, the slopes are photographed from fixed stations established during the initial baseline surveys.

Geotechnical Methods

Stratigraphic Description, Piezometer Installation and Logging, and Sample Collection

Prior to establishing groundwater monitoring wells, a preliminary survey of the slope profile adjacent to each well site was conducted. A detailed stratigraphic description was then made at the cliff face along the surveyed profile. For those stratigraphic units buried by debris or located in the inaccessible upper cliff, descriptions were made of the same unit as close as possible to the surveyed profile. The stratigraphic description of each unit included information on the strength, color, thickness, grain size, moisture content, hydrology, paleontology, sedimentary structures, and vegetative surface cover. All elevations are referenced to the 1929 National Geodetic Vertical Datum and elevations associated with stratigraphic intervals are given where they occur in the sampled borehole at each site.

A total of twenty-two groundwater monitoring wells were drilled over the period from 6 December 1990 to 1 February 1991; six at the NRL, five at SC, six at the CCSP, and five at the CRE. They were drilled using a rotary drill rig owned and operated by the State of Maryland, Department of Natural Resources, Water Resources Administration, Technical Services office. The drilling was done using a hollow stemmed auger through which a standard penetration test (SPT) was performed and a split-spoon sample obtained, each at five foot intervals. The penetration tests and sampling were done in the first (and deepest) well drilled at each site.

Each piezometer measures the water pressure present within the material located at the base of the well. The water level within the piezometer is known as the piezometric surface which represents the total head available to drive groundwater flow at that point. Groundwater flows from locations of higher head to locations of lower head. A rise in the piezometric surface indicates a rise in the head within the target material. The measurements made of the water levels since the completion of the wells provides a time series of piezometric surfaces for each targeted stratigraphic horizon (Figures 2.13, 2.27, 2.42, and 2.52).

The Standard Penetration Test (SPT) is a reliable, widely used method for estimating the relative variations of in-situ, undrained shear strength of subsurface cohesionless materials. For strongly cohesive materials it provides a somewhat less reliable, but useful, estimate of the stiffness (cohesive strength) of the unit. The results of the SPT are reported as the number of blow counts required to drive the split-spoon sampler the final twelve inches of each sampling interval. The blow count is corrected for overburden pressure as specified in the procedure for the SPT.

The SPT data is presented graphically on the geotechnical diagram for each site. These diagrams permit an immediate evaluation of the relative strength of each stratigraphic unit at each site.

Split-spoon samplers were driven 1.5 feet vertically downward, ahead of the auger bit. Upon retrieval, each sample was described and a representative portion or portions obtained for laboratory analysis. The field description includes information on the color, grain-size, fossil content, and moisture content.

Laboratory Analysis

The samples collected during the drilling process form the basis for the geotechnical profiles provided in descriptions of each site (Figures 2.4, 2.16, 2.30, and 2.45). A grain size analysis was performed at the Maryland Geological Survey's sediment laboratory on 70 samples taken from the split-spoon. For split-spoon samples which spanned more than one stratigraphic unit, each unit was analyzed. The information is graphically presented on the geotechnical diagram for each site as percentages of gravel, sand, silt and clay . A tabular presentation of the grain size analysis is provided in Appendix A.

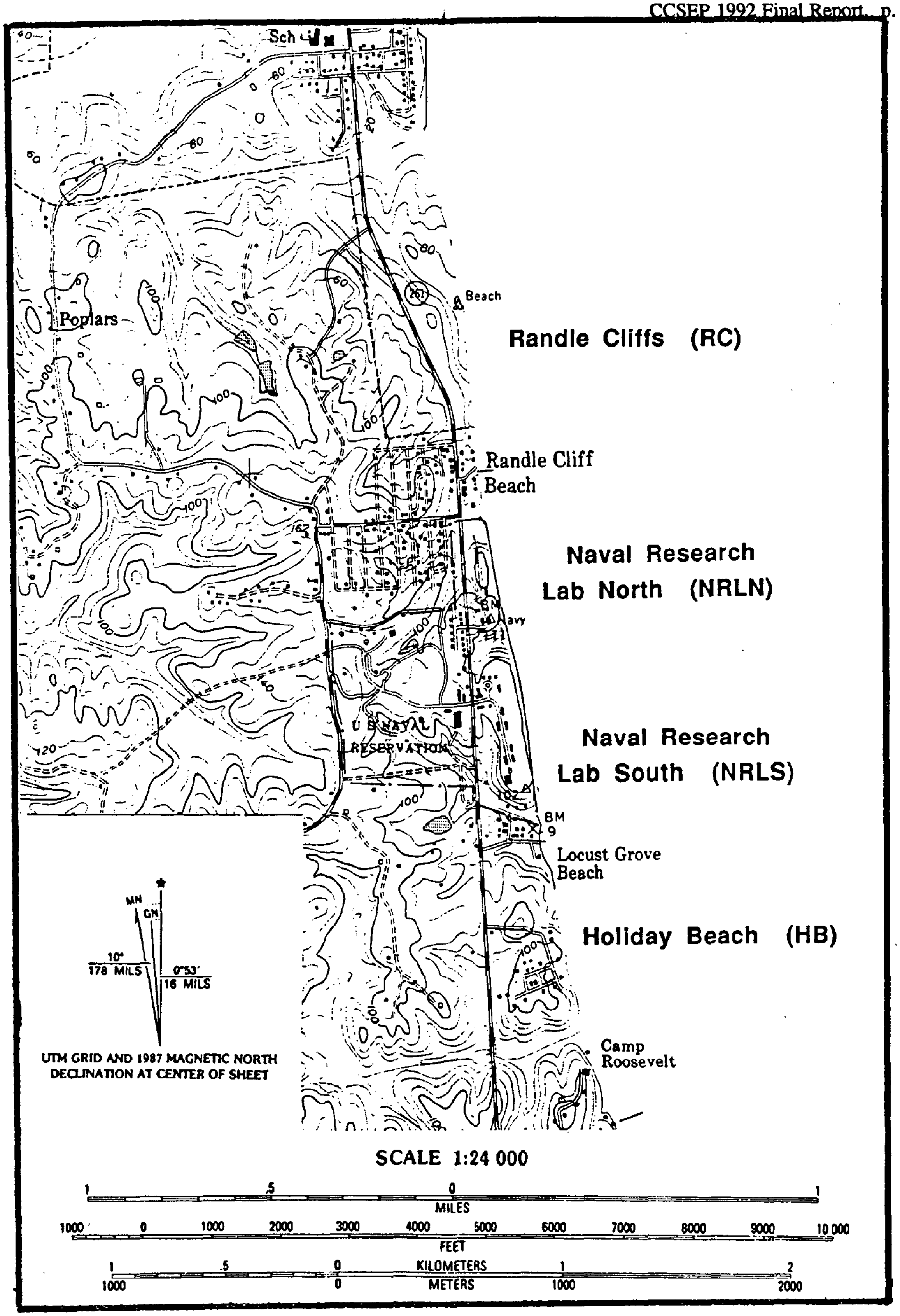
2.2 Naval Research Laboratory (NRL)

General Site Description

The NRL site encompasses the shoreline and cliffs from Randle Cliff to Holiday Beach (Figure 2.2). The subsites are Randle Cliff (RC), Naval Research Lab North (NRLN), Naval Research Lab South (NRLS), and Holiday Beach (HB).

The cliffs uniformly face east-northeast, except at RC where they face due east. Shore protection exists in the form of a seawall in front of the Naval Research Laboratory (subsites NRLN and NRLS). The seawall has been in place for approximately 60 years. The shoreline is unprotected at the northern and southern ends of the site (subsites RC and HB). A series of sub-parallel longshore sand bars is present at both the northern and southern ends of the site, but the bars are not evident along the portion of shoreline protected by the seawall.

The cliff height varies gradually across the site ranging between 18 and 34 m. The elevation of the slope toe also varies. At RC the slope toe is steep and generally extends below MLLW except where large debris falls have temporarily accumulated. The mid and upper slopes at RC are also quite steep, in some places nearly vertical. Slope toes at subsites NRLN and NRLS are protected by a seawall and are all above 2 m. The slope toes at these two subsites are not composed of intact slope material. Instead, debris carried from upslope is deposited behind the seawall and a wedge shaped feature thickening upslope is formed.. Here, the slope toe angle is shallow, typically less than 32 degrees. The midslopes at NRLN and NRLS are also gently inclined. Sometimes the toe debris extends the debris wedge upslope it until meets the steep upper slope. At other locations, the upper edge of the debris of the midslope intersects intact slope material inclined at a shallower angle than the upper slopes. The resulting composite profiles are concave, two-part and three part slopes, respectively. The slope toe at HB is unprotected.



Study Site NRL:
Naval Research Laboratory

Figure 2.2

During Phase I of the CCSEP project, a small beach was present under most tide conditions at this site. However, observations made during 1992 indicate that the condition of this beach is transient. Even when a beach is present, the intact material of the slope toe is very near the surface and extends beneath MSL at an angle of 60 to 65 degrees. The overall slope angles of HB slopes range between 60 and 70 degrees.

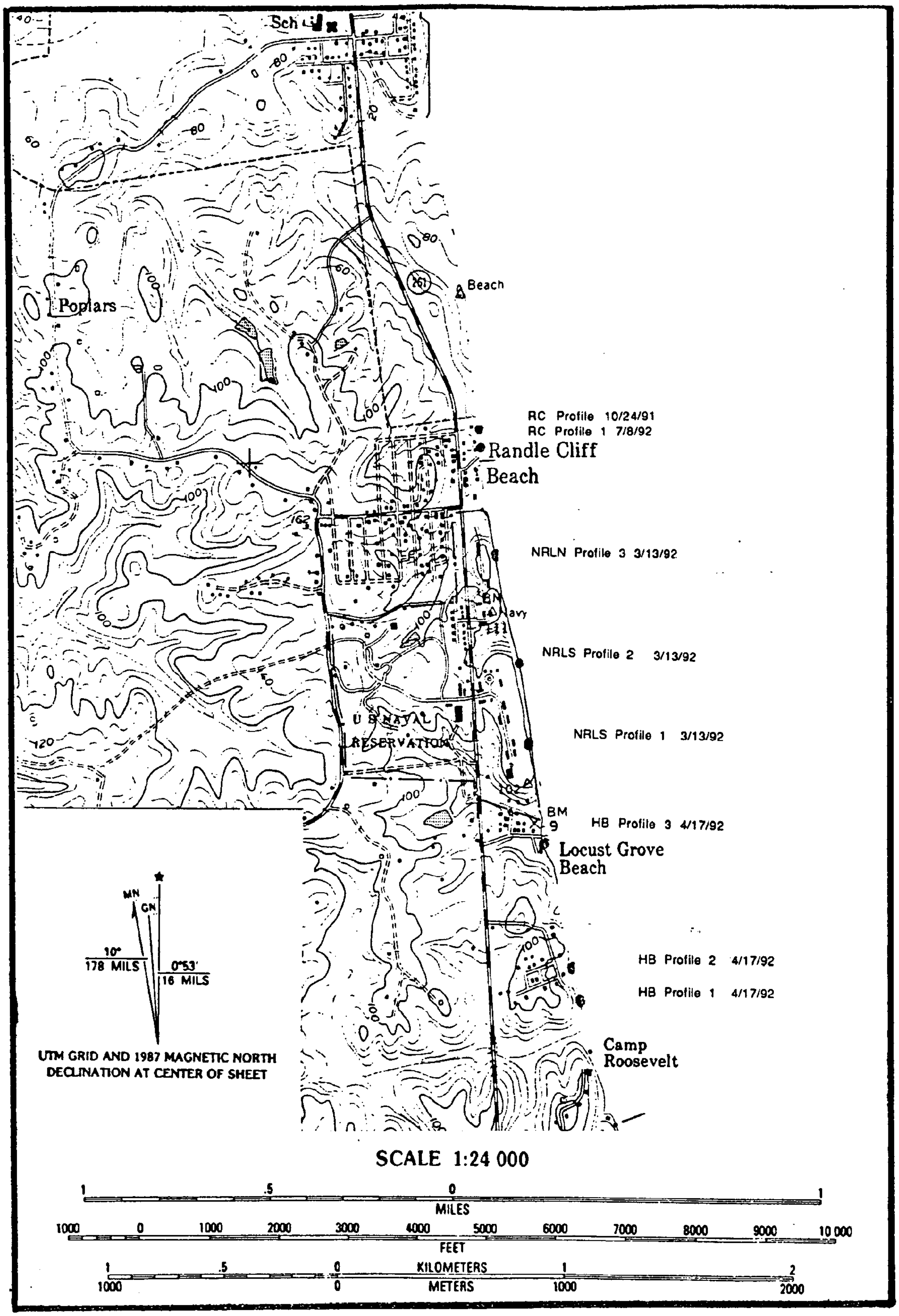
Geotechnical Properties

Six piezometers were installed at the NRLN subsite. They are designated NRL1, NRL2, NRL3, NRL4, NRL5, and NRL6 (see Figure 2.4). During the drilling, NRL1 was sampled and SPTs were performed. Sampling was performed to an elevation of -1.6 m.

The cliffs at NRL are 12 to 34 m high. The slope may be divided into four major groups: a fine grained root zone with well developed soil horizons, two extensive vertical segments composed primarily of sands, and a 4.3 m thick series of silts and clays separating the two sand units.

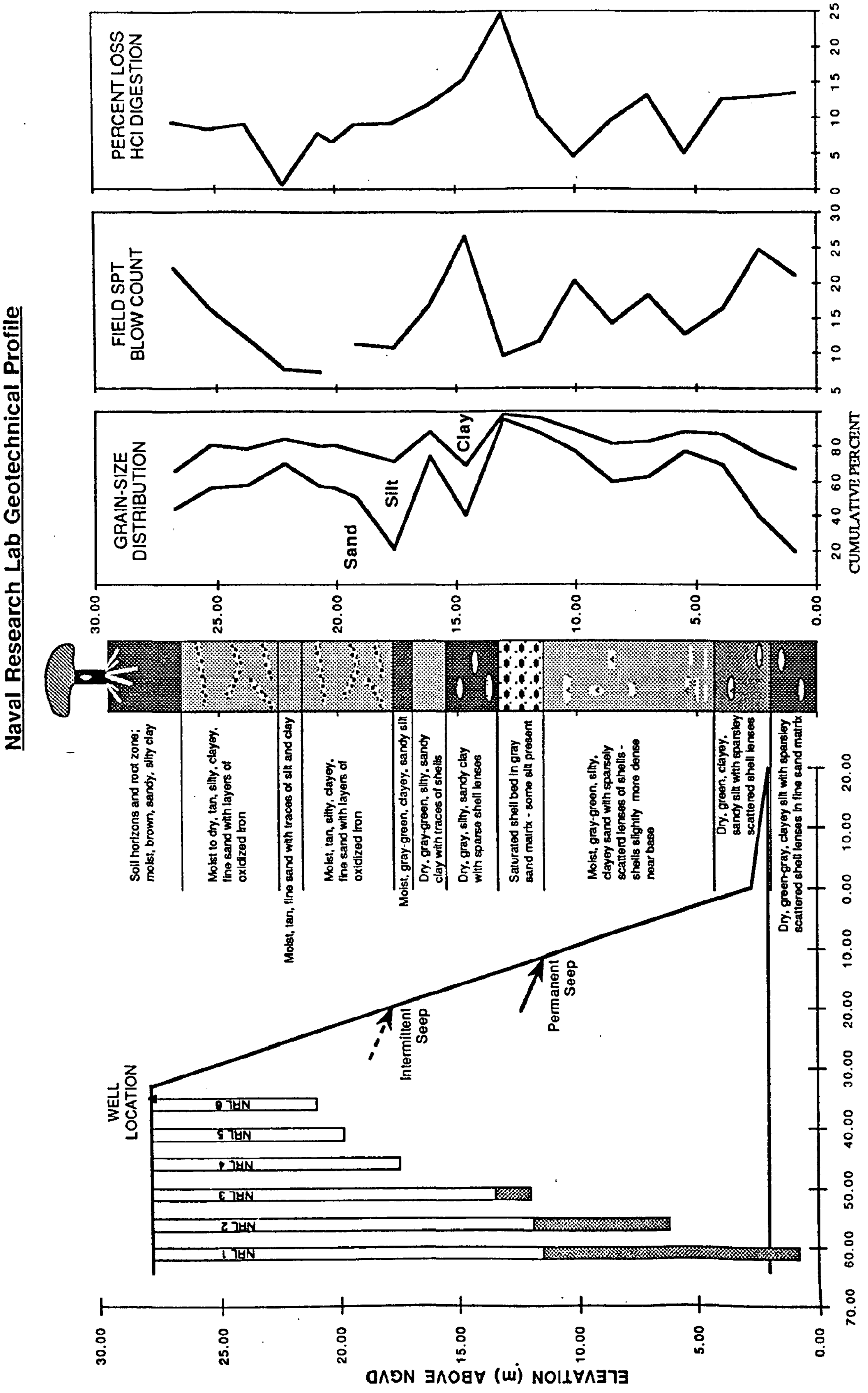
The site lies entirely within the Miocene Calvert Formation. The general dip of the formation is gently to the southeast. Stratigraphic units located near the cliff top at the north end of the site gradually descend toward beach level at the southern end. The Fairhaven member, a heavily diatomaceous silt, occurs in the lower slopes. Its upper surface is disconformable with the overlying Plum Point member (Kidwell, 1984). A discomformity is a type of discontinuity between materials and usually represents a significant break in time between the deposition of the lower and upper units. The upper surface of the Fairhaven member does not vary with the regional dip. Instead, where exposed, it gradually rises from near MSL at the northern end of the RC subsite to an elevation of approximately 2 m at the northern end of the HB subsite. The overlying Plum Point member extends to the bluff top along the entire NRL site. It is lithologically heterogeneous consisting of alternating beds of fossiliferrous sands and sandy, clayey, silts.

At the piezometer site (elevation 25.7 m), the Plum Point member may be divided into four major zones, defined by grain-size characteristics (Figure 2.4). The zone at the surface, containing the root zone and developed soils is composed of nearly equal parts of sand, silt, and clay and is approximately 1.5 m thick. Below the root zone, the materials contain an average of 58 percent sand, 22 percent silt, and 20 percent clay. The SPT indicates that the materials reach a minimum in undrained shear strength within this sandy zone at an elevation of approximately 20.5 m. At an elevation of 15.4 m, a silty and clayey unit is encountered. This sequence is 4.3 m thick at the piezometer site. On average, it contains 55 percent silt and clay with the uppermost layer of this zone being nearly 80 percent silt and clay. The materials reach a peak strength in the silt and clay materials; however, it should be noted that the materials were dry when tested and are composed of cohesive materials which may behave very differently when saturated. Two clay layers within this zone form columnar pillars which either topple or disintegrate into angular fragments. Below the 4.3 m thick fine-grained unit and extending to the Fairhaven member, is a very thick, sandy zone composed of 76 percent sand, 14 percent silt, and 10 percent clay.



Study Site NRL:
Locations of Slope Surveys

Figure 2.3



Naval Research Lab Geotechnical Profile
GRAIN-SIZE DISTRIBUTION
Sand
Silt
Clay
CUMULATIVE PERCENT
FIELD SPT BLOW COUNT
PERCENT LOSS HCl DIGESTION
Soil horizons and root zone; moist, brown, sandy, silty clay
Moist to dry, tan, silty, clayey, fine sand with layers of oxidized iron
Moist, tan, fine sand with traces of silt and clay
Moist, tan, silty, clayey, fine sand with layers of oxidized iron
Moist, gray-green, clayey, sandy silt
Dry, gray-green, silty, sandy clay with traces of shells
Dry, gray, silty, sandy clay with sparse shell lenses
Saturated shell bed in gray sand matrix - some silt present
Moist, gray-green, silty, clayey sand with sparsely scattered lenses of shells - shells slightly more dense near base
Dry, green, clayey, sandy silt with sparsley scattered shell lenses
Dry, green-gray, clayey silt with sparsley scattered shell lenses in fine sand matrix
WELL LOCATION
NRL 6
NRL 5
NRL 4
NRL 3
NRL 2
NRL 1
Intermittent Seep
Permanent Seep
ELEVATION (m) ABOVE NGVD
DISTANCE FROM CLIFF BASE (m)

Figure 2.4

At the RC and NRLN subsites, surface water drains toward the cliffs over an area extending almost one km west of the cliff top. The NRLS and HB subsites are located on hilltops which cause the surface water to drain in all directions. Across the entire site, groundwater infrequently seeps from the cliff face at the interface between the upper sandy zone overlying the silt and clay zone. Water slowly seeps from entire cliff face in the sandy zone above the Fairhaven formation. Immediately below the silty, clayey zone is a sandy shell bed which, over the past 24 months, has been observed to have the strongest and most constant seepage. There appears to be a greater volume of seepage where topographic lows intersect the cliff face.

At the RC subsite, the top of the lower sandy zone occurs at 9.1 m and the zone extends to 2.0 m. The materials are composed of gray-green to green, dry to moist, sandy sediments that contain increasing amounts of fine-grained material with depth. During field mapping, this zone was observed to be strongly jointed along nearly vertical planes parallel to the slope face. It is thought that the planes, technically known as exfoliation surfaces, develop near the slope face as lateral confining pressure is relieved by slope erosion. The joint surfaces were visibly wet, acting as preferential flow paths for groundwater and creating planes along which block spalling takes place. Where this unit is exposed, it has been observed to spall year-round, although the frequency of spalling increases during freeze-thaw periods and immediately after periods of intense wave undercutting. The spalling tends to terminate near the contact of this unit with the shell bed above causing the shell bed to form an overhang in many places.

Slope Profiles (Figures 2.5 to 2.12)

(Note: A dashed line representing the position of the intact slope is provided only on the profile figures where the slope toe is buried by debris. The lower portions of the slopes profiled in Figures 2.7, 2.8, and 2.9 are largely composed of debris and the intact slope surface could not be ascertained. All other profiles without the dashed line may be assumed to represent the intact slope material.)

Eight slope profiles were surveyed at the NRL site. Two at subsite RC, one at subsite NRLN, two at subsite NRLS, and three at subsite HB. The surveyed slopes at the RC subsite are both over 19 m high, steep (>76^{o}), and the slope toes are below MHHW and are subject to constant wave erosion (Figures 2.5 and 2.6). Variations in slope angle within the profile are generally small and, where present, occur at the boundaries between different materials. The slope toes of all of the slopes at the NRLN and NRLS sites have been completely protected from erosion by a bulkhead for over sixty years. Here, despite being relatively tall (26 m to 33 m), the slopes display much gentler, three-part profiles (Figures 2.7, 2.8, and 2.9). In each case, the slope angle increases with increasing elevation creating a concave shape. The upper slopes tend to be quite steep. Typical slope angles range between 43 degrees and 46 degrees. South of the Navy bulkhead, at subsite HB, the slope toes are once again subjected to wave erosion (Figures 2.10, 2.11, and 2.12). Typically, there is a small beach along HB. However, during Tropical Storm Danielle (25 September 1992) the beach was completely submerged (or eroded) and the slope toe was actively attacked by waves. The heights of the profiled slopes at subsite HB range between 20 m and 30 m. The slope toe to bluff top angles of the profiled slopes range between 60 degrees and 69 degrees. As at subsite HB, variations in angle within the profiles are minor and are due to changes in the materials comprising the slopes.

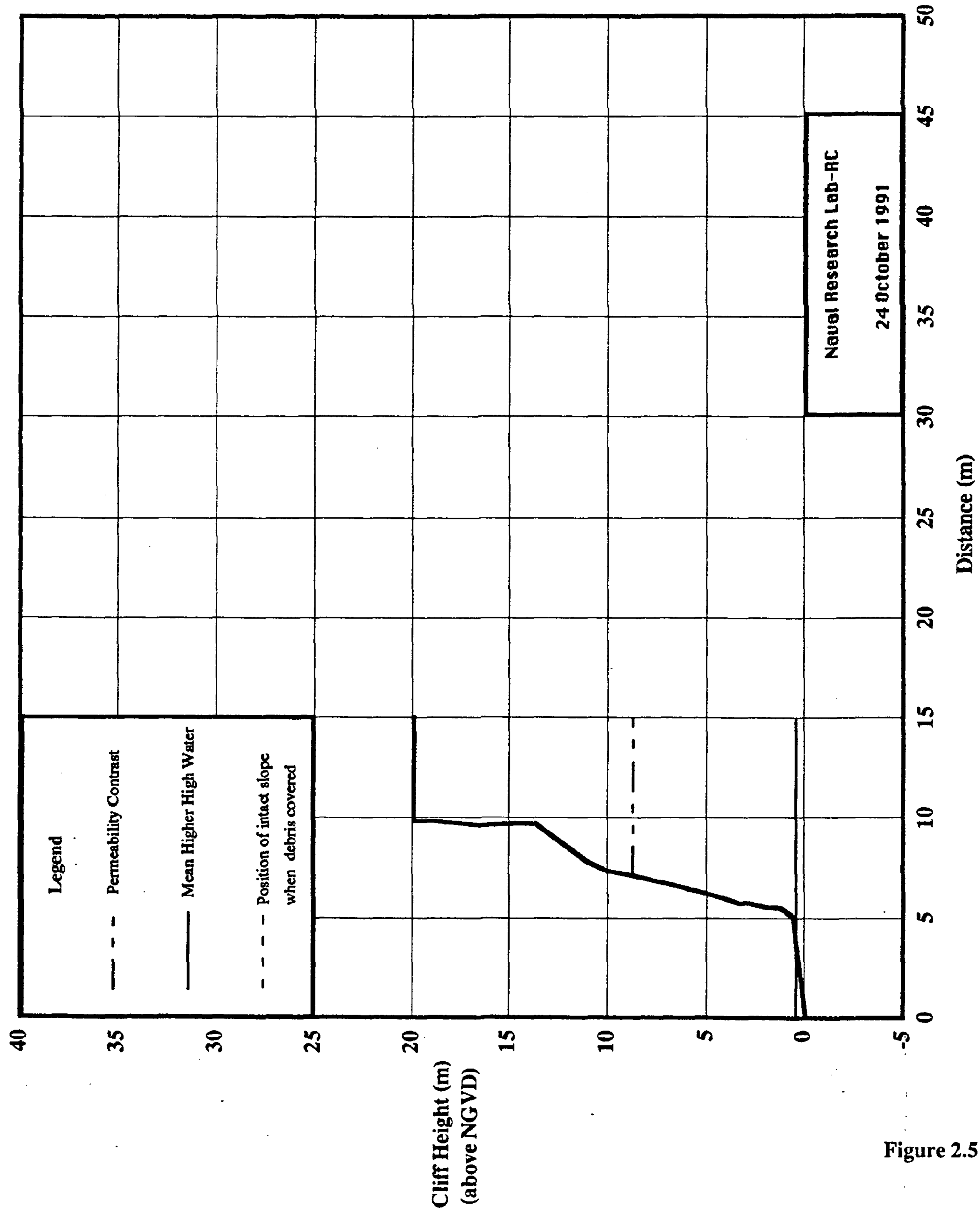

Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Naval Research Lab-RC
24 October 1991
Distance (m)
0
5
10
15
20
25
30
35
40
45
50
Cliff Height (m) (above NGVD)
40
35
30
25
20
15
10
5
0
-5

Figure 2.5

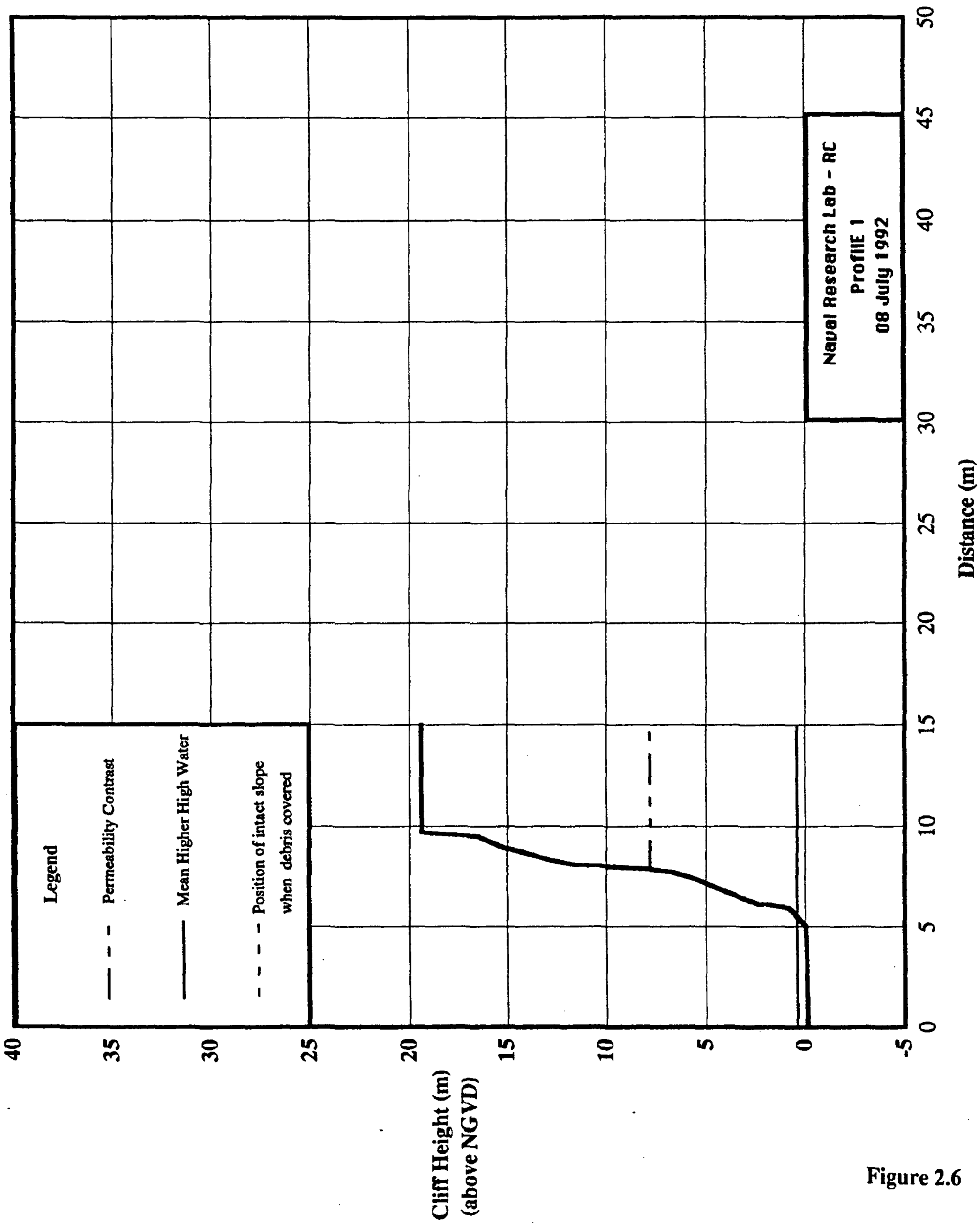

Naval Research Lab - RC
Profile 1
08 July 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Cliff Height (m)
(above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.6

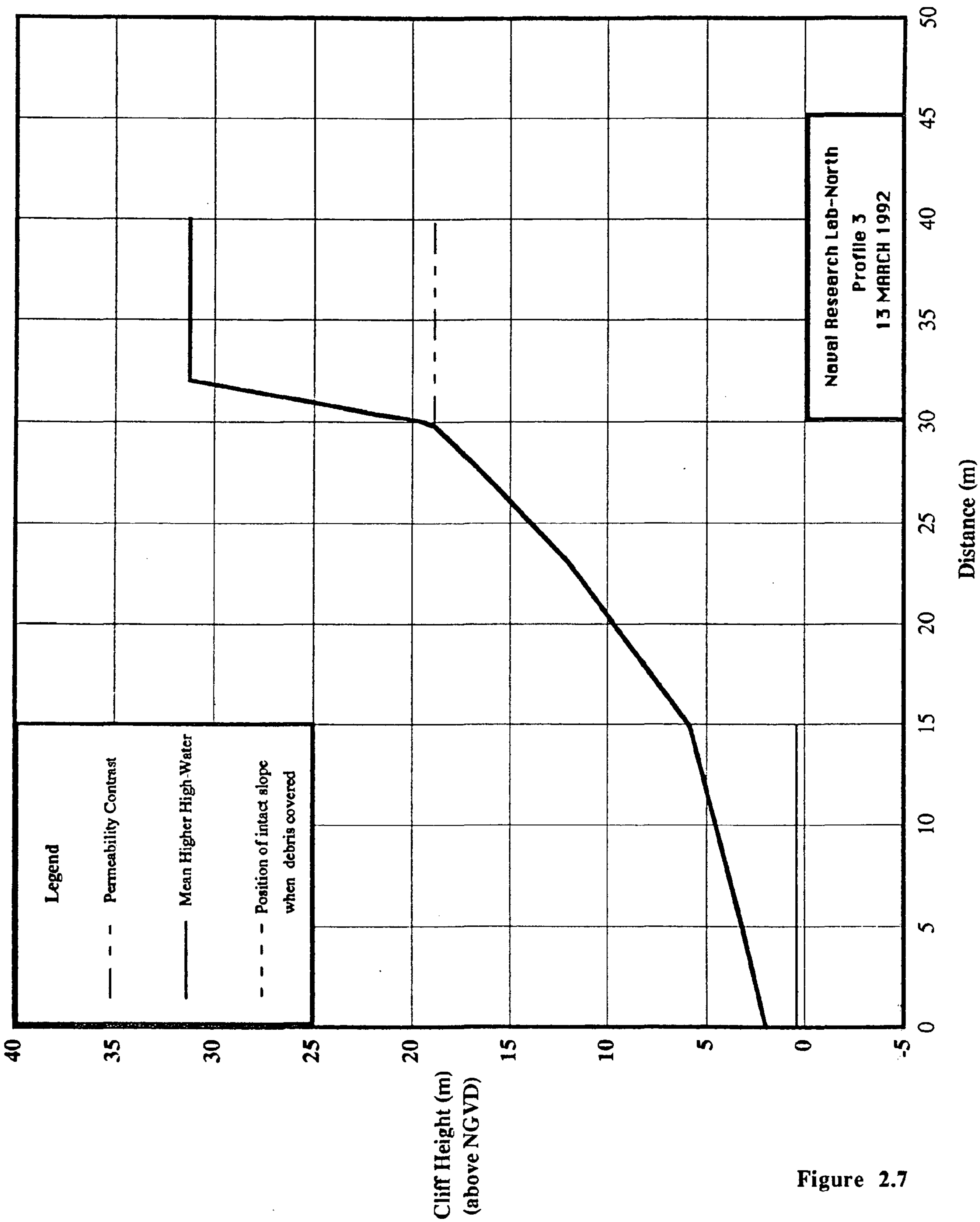

Naval Research Lab-North
Profile 3
13 MARCH 1992
Legend
Permeability Contrast
Mean Higher High-Water
Position of intact slope
when debris covered
Distance (m)
0
5
10
15
20
25
30
35
40
45
50
Cliff Height (m)
(above NGVD)
40
35
30
25
20
15
10
5
0
-5

Figure 2.7

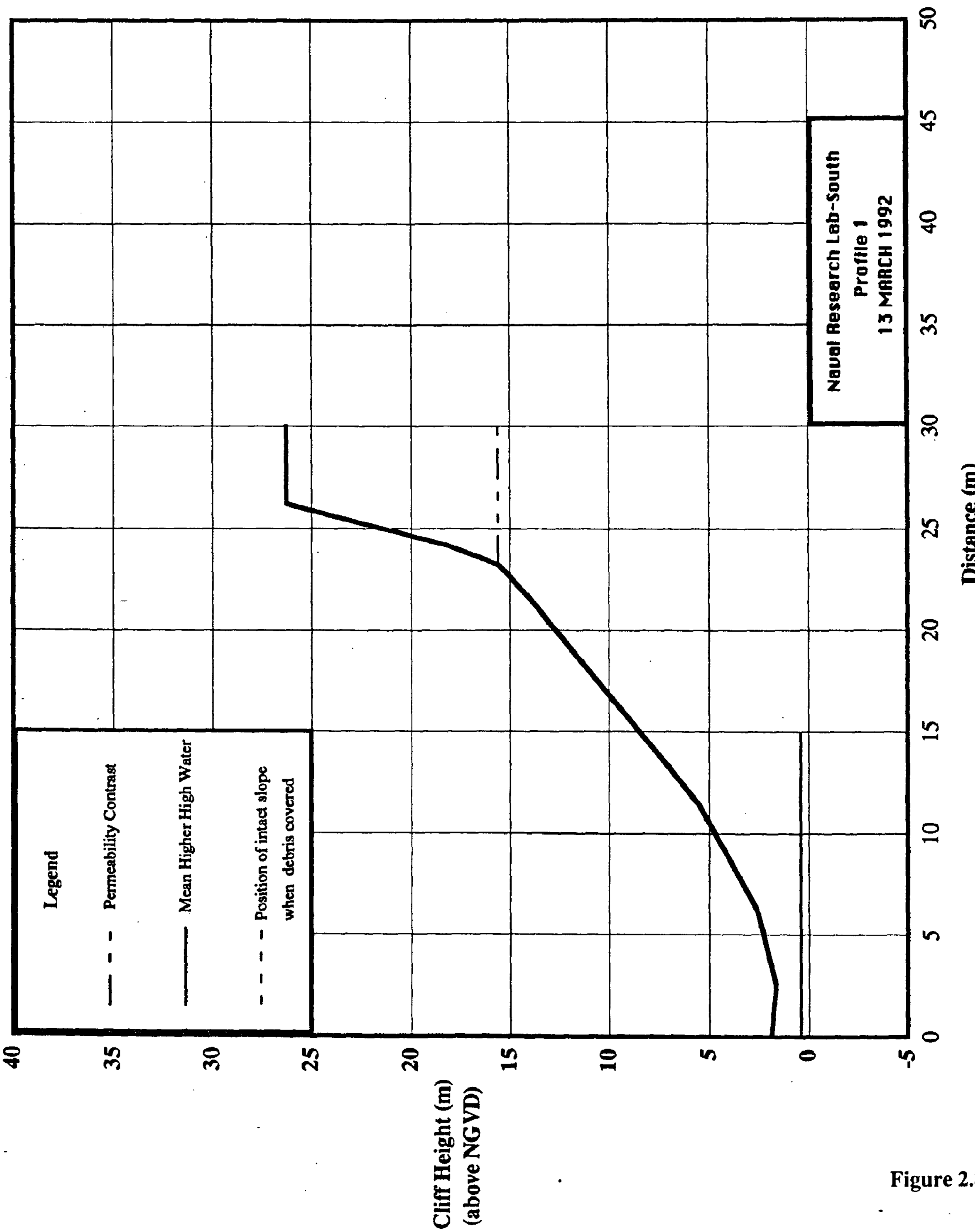

Naval Research Lab-South
Profile 1
13 MARCH 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Distance (m)
0
5
10
15
20
25
30
35
40
45
50
Cliff Height (m)
(above NGVD)
40
35
30
25
20
15
10
5
0
-5

Figure 2.8

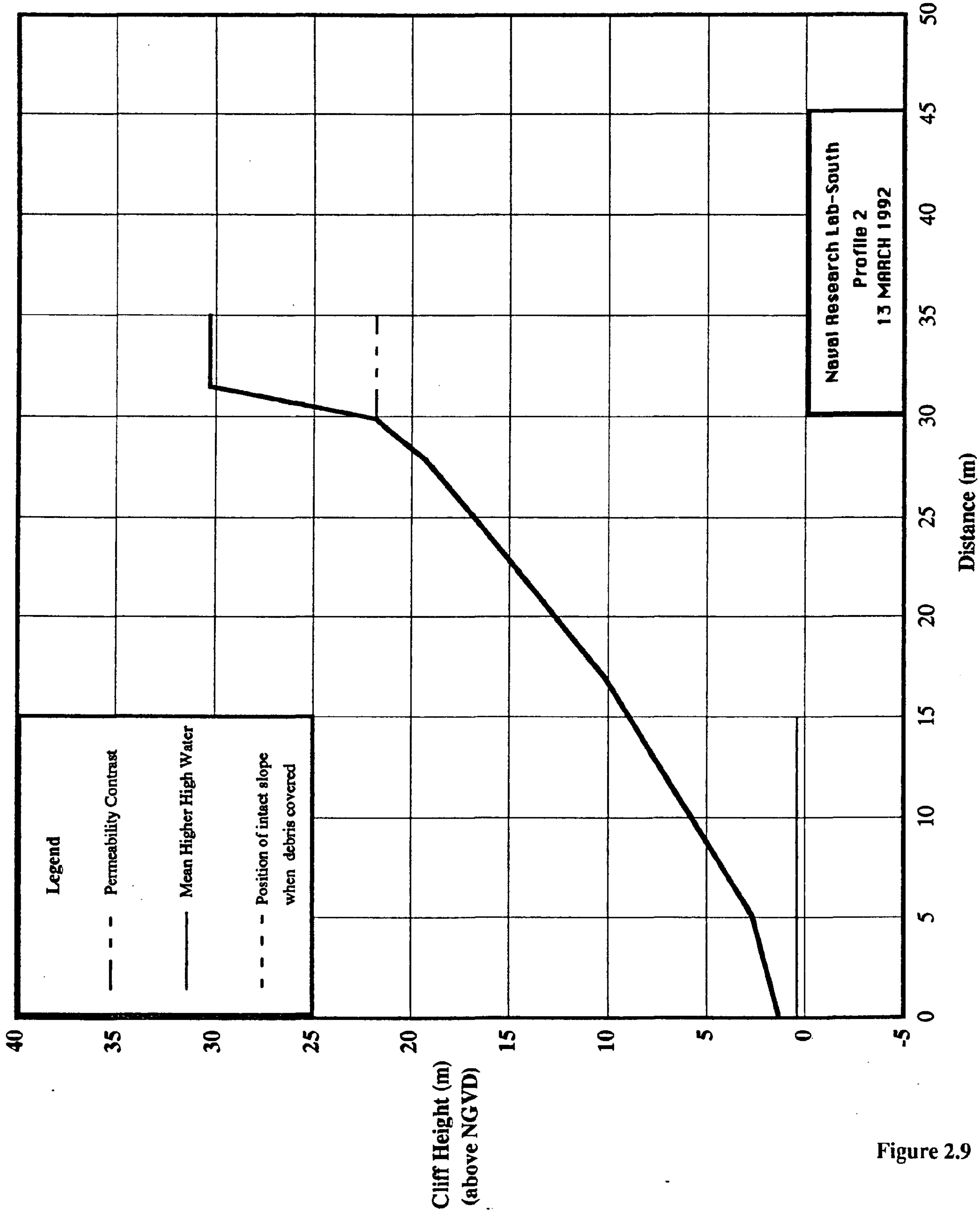

Naval Research Lab-South
Profile 2
13 MARCH 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Distance (m)
Cliff Height (m) (above NGVD)
0
5
10
15
20
25
30
35
40
45
50
-5

Figure 2.9

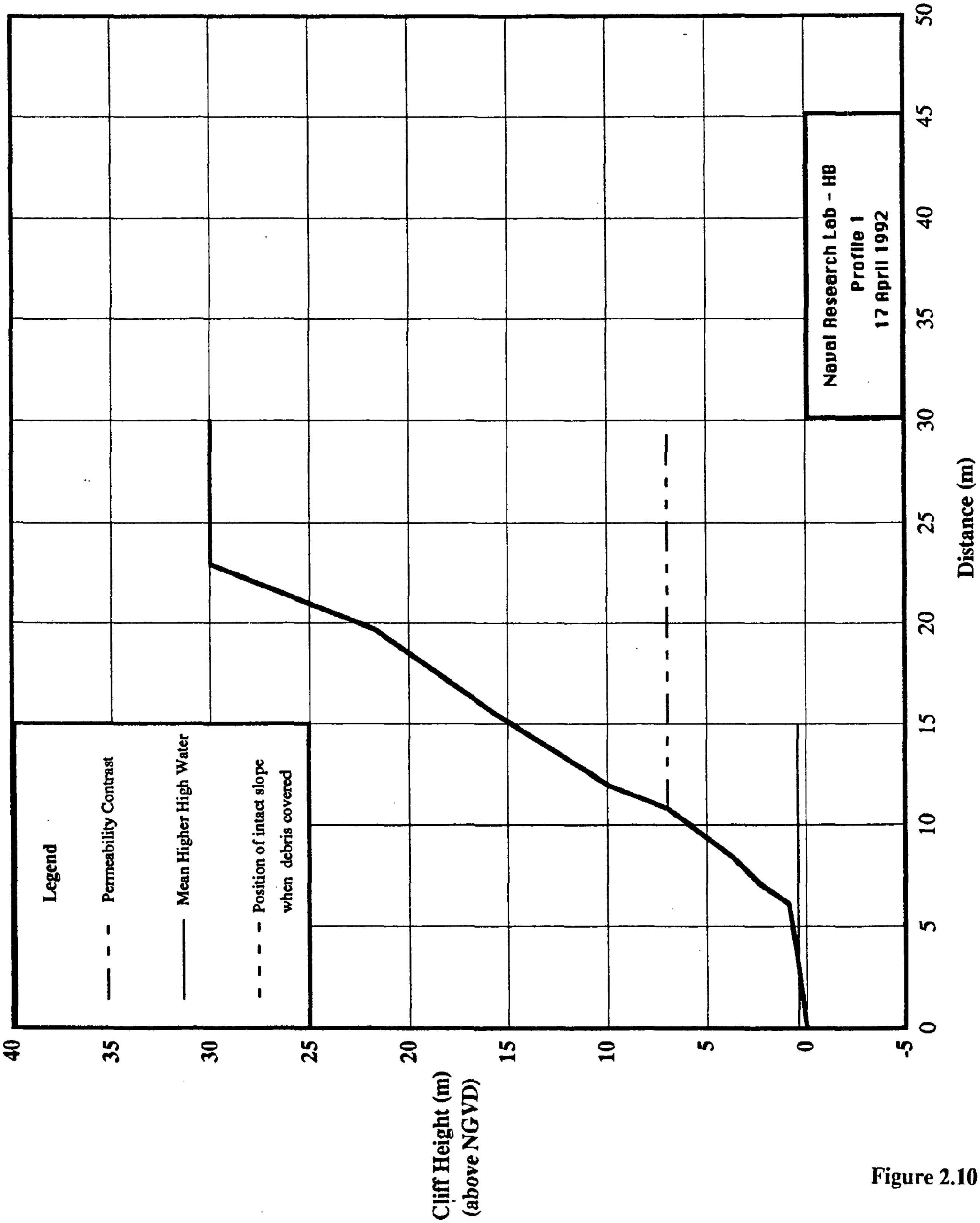

Naval Research Lab - HB
Profile 1
17 April 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Distance (m)
Cliff Height (m)
(above NGVD)
0
5
10
15
20
25
30
35
40
45
50
-5
0
5
10
15
20
25
30
35
40

Figure 2.10

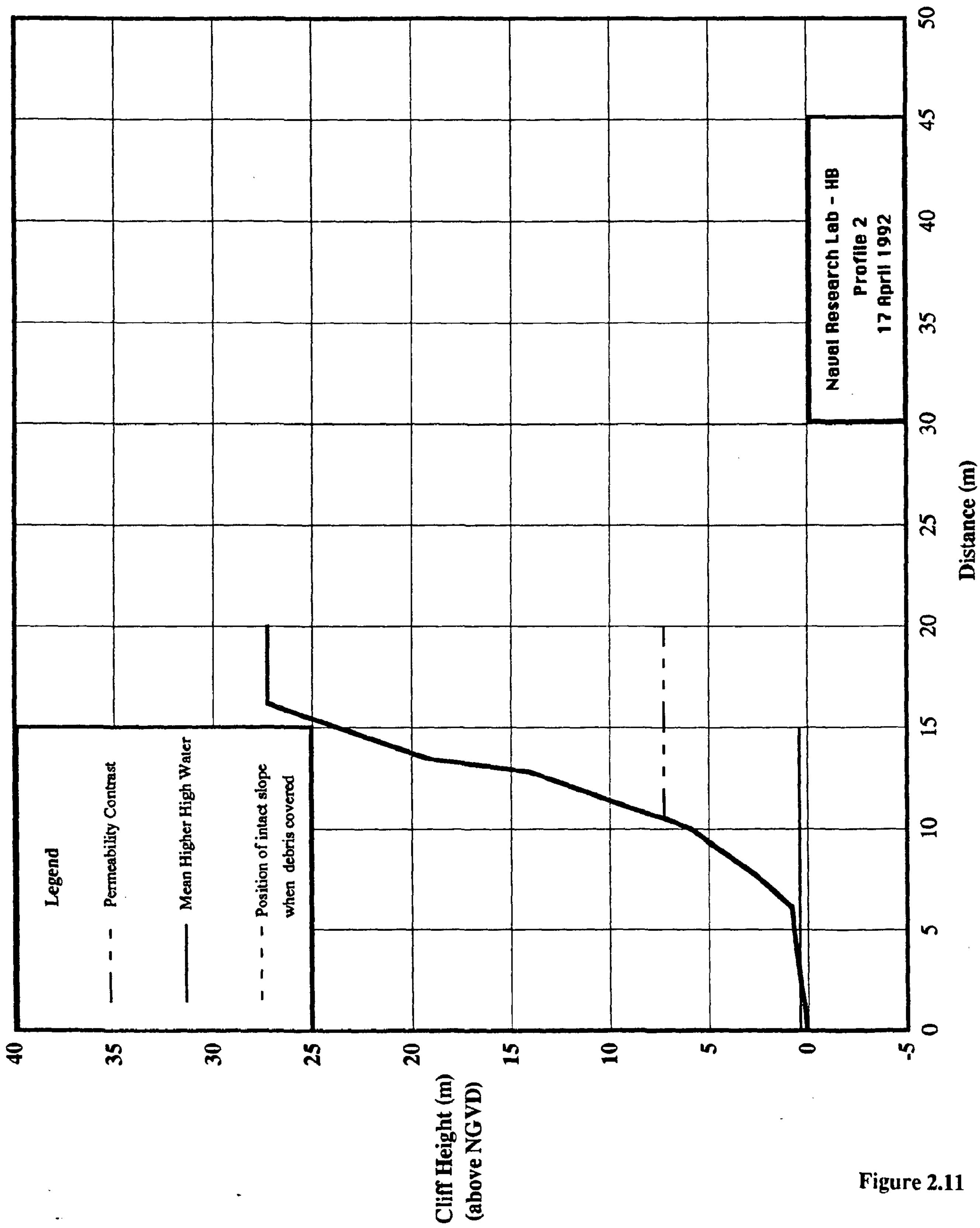

Naval Research Lab - HB
Profile 2
17 April 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Distance (m)
0
5
10
15
20
25
30
35
40
45
50
Cliff Height (m)
(above NGVD)
40
35
30
25
20
15
10
5
0
-5

Figure 2.11

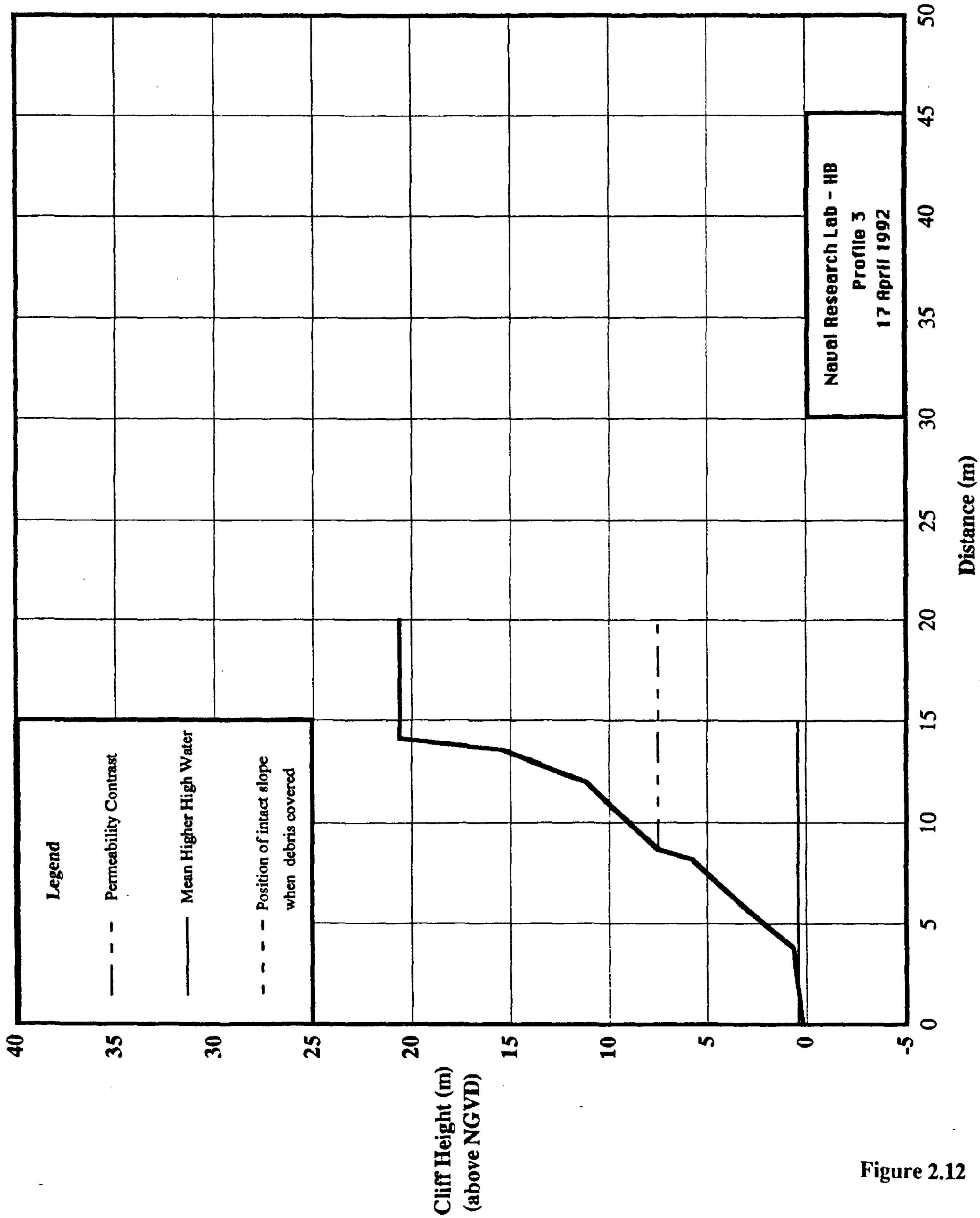
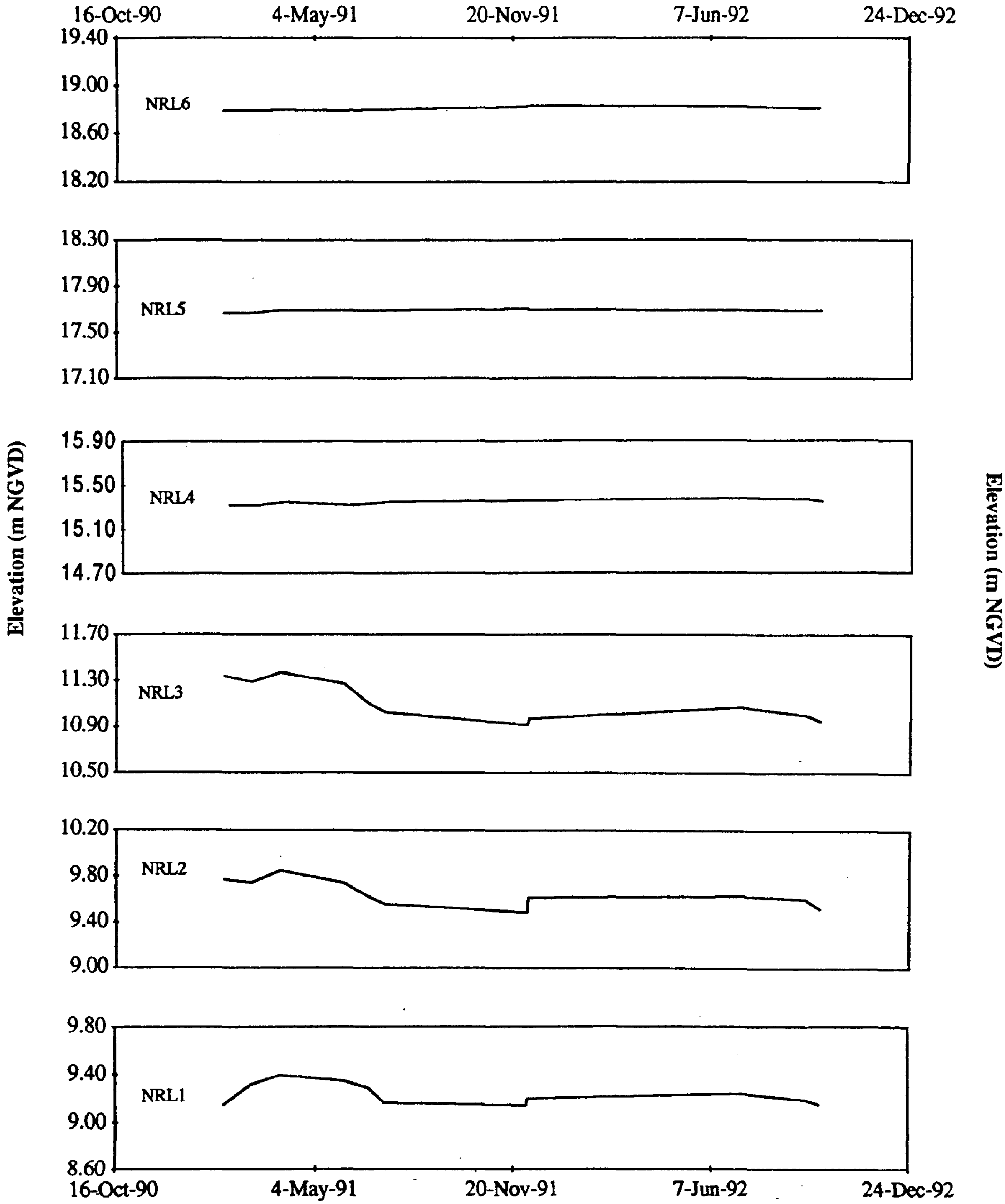

Naval Research Lab - HB
Profile 3
17 April 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Cliff Height (m)
(above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.12



Time Series of Water Levels at NRL Piezometers

Figure 2.13

Groundwater Levels (Figures 2.4 and 2.13)

Figure 2.4 shows the position of the NRL piezometers and the mean water level relative to the stratigraphy at the NRL site. Figure 2.13 is a time series of the piezometric levels for each well since its installation.

As with all of the CCSEP sites, the presence and movement of groundwater at the NRL site is controlled by the heterogeneity of the materials composing the slopes and the surface topography of the groundwater recharge area. Two relatively independent groundwater systems exist at this site. An ephemeral, perched water table exists above 15.4 m for short periods of time after extended rainy periods (stratigraphic elevations correspond to those measured at the piezometer site at NRLN). Water moving downward from the surface travels through relatively sandy materials until it is impeded by a silty, clayey horizon at 15.4 m. Only a narrow segment of the bluff top is able to contribute infiltrated water to this perched water table because, at short distances away from the bluff edge, the surrounding land surface is dissected to elevations at or below 16 m. As a result, the perched water drains into nearby streams and from the slope face until the rather limited supply is exhausted. However, when this water table exists it can cause considerable seepage erosion along the slope face. It is this seepage zone that is responsible for undercutting the steep upper slopes along the NRL property. Piezometers NRL4, NRL5, and NRL6 were installed to monitor the groundwater conditions occurring above 16 m (Figure 2.4). Since the installation of the piezometers in January, 1991, precipitation has been substantially below normal and no water has been present in any of the three wells. However, during drilling, the sandy materials between 15.4 m and 20.3 m were noted to be moist. It can be inferred from field observations made along the length of the NRL property that ephemeral seepage has occurred at the base of the sandy materials causing undercutting of the slope above.

The spatial occurrence of this transient groundwater body is also highly variable and depends strongly on the patterns of surface drainage. Despite the lack of water above 15.4 m at the piezometer site, a perched water table may exist at this elevation for short periods of time at other locations on the NRL site. The Navy property is served by a sewage collection system so that near surface materials do not receive septic leachate. However, the Randle Cliff and Holiday Beach communities dispose of their wastewater via leachate fields and septic tanks which may contribute considerable quantities of water to localized, near-surface groundwater bodies.

As discussed in the section on geotechnical properties, a 4.3 m thickness of clays and silts occurs between 11.1 m and 15.4 m. This relatively impermeable sequence of materials effectively isolates the ephemeral groundwater bodies occurring in the near surface materials from the deeper, permanent, regional groundwater regime. During the geotechnical investigation of the Calvert Cliffs Nuclear Power Plant site (BG&E, 1967), a laboratory hydraulic conductivity test was performed on material from the same stratigraphic horizon that occurs between 15.4 m and 19.3 m at the NRL piezometer site. Grain-size analyses from both sites indicate that the materials are very similar, both being silty very-fine sands. The test results indicate that the hydraulic conductivity for the material between the ground surface and the relatively impermeable zone occurring at 15.4 m has an hydraulic conductivity of 10^{-6} m/s. This value is within the bounds that may be expected for the observed grain size distribution (Freeze and Cherry, 1979). Grain-size analyses for the materials between 11.1 m and 15.4 m indicate that the maximum hydraulic conductivity is likely to be at least three orders of magnitude smaller than the units above and below, ranging from approximately 10^{-9} m/s to 10^{-11} m/s.

The sandy units below 11.1 m are fully saturated and are recharged from surface waters up to a kilometer away from the slope face. Piezometers NRL1, NRL2, and NRL3 are located within the permanent groundwater flow system (Figure 2.4). The plot of water surface positions over time shows that the regional groundwater regime does not fluctuate rapidly, but varies gradually in response to the long-term hydrologic conditions of the NRL region (Figure 2.13). A particularly permeable, fossiliferrous sand occurs between the elevations of 9.1 m and 11.1 m at the piezometer site. A laboratory hydraulic conductivity test conducted on similar material indicates that a minimum value of 10^{-5} m/s should be expected in this material. The contact between the top of this unit and the base of the overlying fine-grained sediments forms the horizon below which the slope surface is distinctly darkened. The darkening results from continuous seepage beginning in this unit and extending below sea level. The rate of seepage depends on the permeability of each unit below this horizon. Vegetation is able to grow along zones on the slope face where sufficient seepage discharge is available, even on the steepest of slopes. Exfoliation surfaces provide preferential flow paths for seepage near the slope face in the silty, clayey sands below 9.1 m. In turn, seepage along these surfaces widens and weakens the material jointing.

Erosion Mechanisms

Site/Subsite: Naval Research Lab/ Randle Cliff (RC)

Lower Slope. The toe zone is composed of a green-gray clayey silt. The elevation of the toe material is below MLLW and it is subjected to nearly continuous wave undercutting. This results in spalling of large blocks along nearly vertical exfoliation joints in the lower slope. Removal of the slope debris is generally quite rapid; only debris from the largest slope failures remains on the beach for periods longer than a month. Approximately half of the toe zone is devoid of slide debris at any time.

Midslope. The active wave undercutting and retreat of the lower slope steepens the midslope and initiates further spalling and shallow sliding in the midslope. This process of failures in the lower slope triggering additional failures in the overlying material, leading to a series of retrogressive failures at higher elevations has been described for other coastal slopes (Edil and Vallejo, 1977; Quigley et al., 1977). Typically, spalls work their way up the steep slope face to the perennial seepage zone where the lower sandy shell bed is located. Some spalls are sufficiently large that they extend from beach level to the perennial seep approximately 10 m above the beach. Undercutting and spalling tend to keep the slope face straight and nearly vertical. Above the seep, columnar slope sections separate from the face along tensional fractures and topple or fall to the beach. The columnar joints form in response to desiccation in the unsaturated materials. Columns topple and fall when undercut by retreat of the slope below.

Upper Slope. Weathered and leached materials near the bluff top tend to fail in undercut slumps that bury earlier spalled material beneath. Undercut root zones eventually collapse in cantilever type failures.

Site/Subsite: Naval Research Lab/ NRL North and South (NRLN and NRLS)

Lower Slope. The entire length of the shoreline along the Navy property has been protected by a bulkhead for a period of 60 years. The slope toe is completely protected. The result is that toe debris has been allowed to accumulate at angles of less than 35 degrees and become vegetated.

Midslope. Typically, the middle portion of cliffs along the Navy property is vegetated and inclined at a gentle angle and composed primarily of unconsolidated upper slope debris. At the top of the mid-slope incline is an ephemeral seepage zone where a densely fossiliferous shell bed with a fine sand matrix overlies a green-gray, clayey, silty, very fine sand. Here, sapping erosion is prevalent but intermittent. This erosion undercuts overlying units, causing them to fall. Field inspection of this seepage zone indicates that it is subject to both piping and sapping erosion when the seepage is active. Field strength tests indicate that the shear strength of the materials comprising the cliffs is a minimum at the seepage interface. Seepage from the shell bed produces surficial erosion of weathered material from the slopes below. In this way, bluff top recession continues despite significant toe protection.

Upper Slope. The slope break between the midslope and upper slope is defined by an intermittent seepage zone. The bluff top recedes by undercutting due to seepage, surficial erosion of weathered materials, and toppling of columns of material that separate from the slope along vertical stress-relief fractures.

Site/Subsite: Navy Research Lab/Holiday Beach (HB)

Lower Slope. On the slopes with angles of approximately 60 degrees or less, most of the toe zone is covered with a light mantle of loose debris delivered from the upper slopes. The debris forms laterally continuous, wedge-shaped deposits or larger triangular debris fans. Sparse, herbaceous vegetation has become established on the unconsolidated debris along most of the toe zone. Physical and chemical weathering produce disintegration of the silt which comprises the intact slope material along the toe zone. Daily waves and tides do not remove toe zone debris at this site. However, wave action due to strong winds and storms periodically removes the unconsolidated debris and erodes the intact slope. During Tropical Storm Danielle, the slope toe was directly exposed to wave action to a height of nearly two meters above mean high water. All of the debris that had accumulated in the toe zone at this site was removed by waves during this storm.

A nearly uniform incline occurs from the base of the debris fans at the toe to the base of the root zone. A perennial seepage zone occurs at approximately 5 m above the beach where a shell bed with a gray, medium to fine sand overlies a gray-green clayey, silty, very fine sand. This is the same sandy, fossiliferrous zone that is found between 9.1 m and 11.1 m at the piezometer site. At locations where the topographic surface behind the cliffs is low, groundwater seepage tends to be strong and keeps the slope face below moist. Below the seepage zone, the face is covered with a thin veneer of weathered debris. The debris appears to form a uniform planar surface when viewed from a distance, although closer inspection reveals that it is slightly rilled, indicating some erosion by overland flow.

On slopes steeper than 65 degrees, the intact material is exposed and eroded directly by waves.

Midslope Above the shell bed seepage zone is a drier face composed of a gray, silty, sandy clay which coarsens upward to become a clayey, sandy, silt and is prone to fragmental disintegration primarily due to desiccation. Further upslope, an ephemeral seepage zone is encountered where the clayey, sandy, silt meets a silty, clayey, fine sand. This seep periodically supplies water to the slope face below and, when active, undercuts the bluff top by sapping erosion. (Sapping erosion is the erosion of slope materials by groundwater flow along a laterally continuous seepage zone).

Upper Slope. The bluff top is nearly vertical along this site with very little undercutting. The bluff top retreats by surficial erosion of weathered sediments and some root mass failures.

2.3 Scientists Cliffs

General Site Description

The site encompasses the shoreline and cliffs from Parker Creek to Governor Run. The subsites are Parker Creek South (PCS), Scientists' Cliffs North (SCN), Scientists' Cliffs South (SCS), and Governor Run (GR) (Figure 2.14).

The cliffs face east-northeast along the entire site. Beach protection exists in the form of uniformly spaced gabion groins in front of the Scientists Cliffs Community (SCN and SCS). These groins have produced a beach up to one meter higher than that found at the subsites to the immediate north and south (PCS and GR). The beach at SCS and SCN appears to offer a significant degree of slope toe protection.. Slope toes to the north and south, PCS and GR respectively, have either low, seasonal beaches or none at all. Active toe erosion is common at these subsites. PCS slopes are virtually devoid of vegetation, SCN and SCS are generally well vegetated, predominantly with small herbaceous plants, and GR slopes lightly vegetated with small herbaceous plants and grasses concentrated along groundwater seepage zones.

The slopes are relatively steep along the PCS subsite, standing at angles between 70 and 80 degrees. Slope height varies between 15 and 30 meters. The subsite at GR has slope angles of 65 to 80 degrees and cliff heights between 18 and 36 meters. At both the SCN and SCS subsites, the slopes are thickly vegetated and slope angles vary between 50 and 60 degrees. However, the cliffs are generally taller at the southern subsite, ranging from 20 to 29 meters, while at the northern subsite, they range from 15-28 meters.

The sediments of this site consist of interbedded clays, silts, and sandy fossiliferous units of Miocene age. The Calvert Formation is found in the lower portions of the slopes and the Choptank Formation in the upper portions. The regional stratigraphy dips gently to the southeast, although individual stratigraphic thicknesses and dips at SC are less uniform than elsewhere along the Calvert Cliffs. Spalling occurs near the cliff base at the PCS subsite in a thick blue-gray silty clay unit. Stratigraphic horizons in the upper sections of the cliff tend to be leached and less cohesive than those below.

The surface topography of the site is characterized by a highly dissected drainage consisting of a series of hilltops separated by drainage channels. Groundwater seepage is evident along exposed cliff faces and tends to occur at the base of a sandy fossiliferous stratigraphic unit. Seepage rates tend to be higher where topographically low surface areas intersect the cliff face.

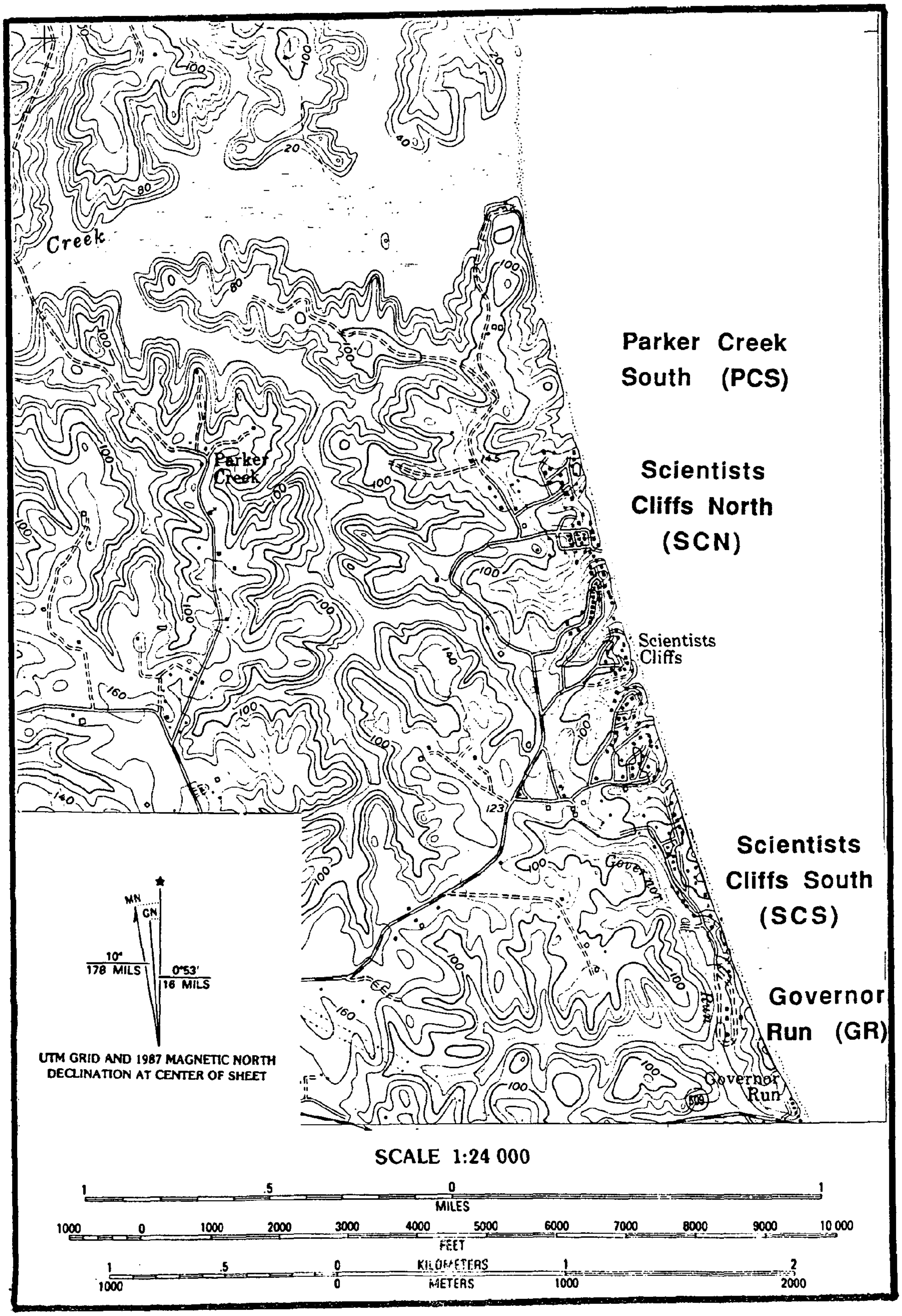

Creek
Parker Creek
Parker Creek South (PCS)
Scientists Cliffs North (SCN)
Scientists Cliffs
Scientists Cliffs South (SCS)
Governor Run (GR)
Governor Run
MN
GN
10°
178 MILS
0°53'
16 MILS
UTM GRID AND 1987 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET
SCALE 1:24 000
MILES
FEET
KILOMETERS
METERS

Figure 2.14

Geotechnical Properties

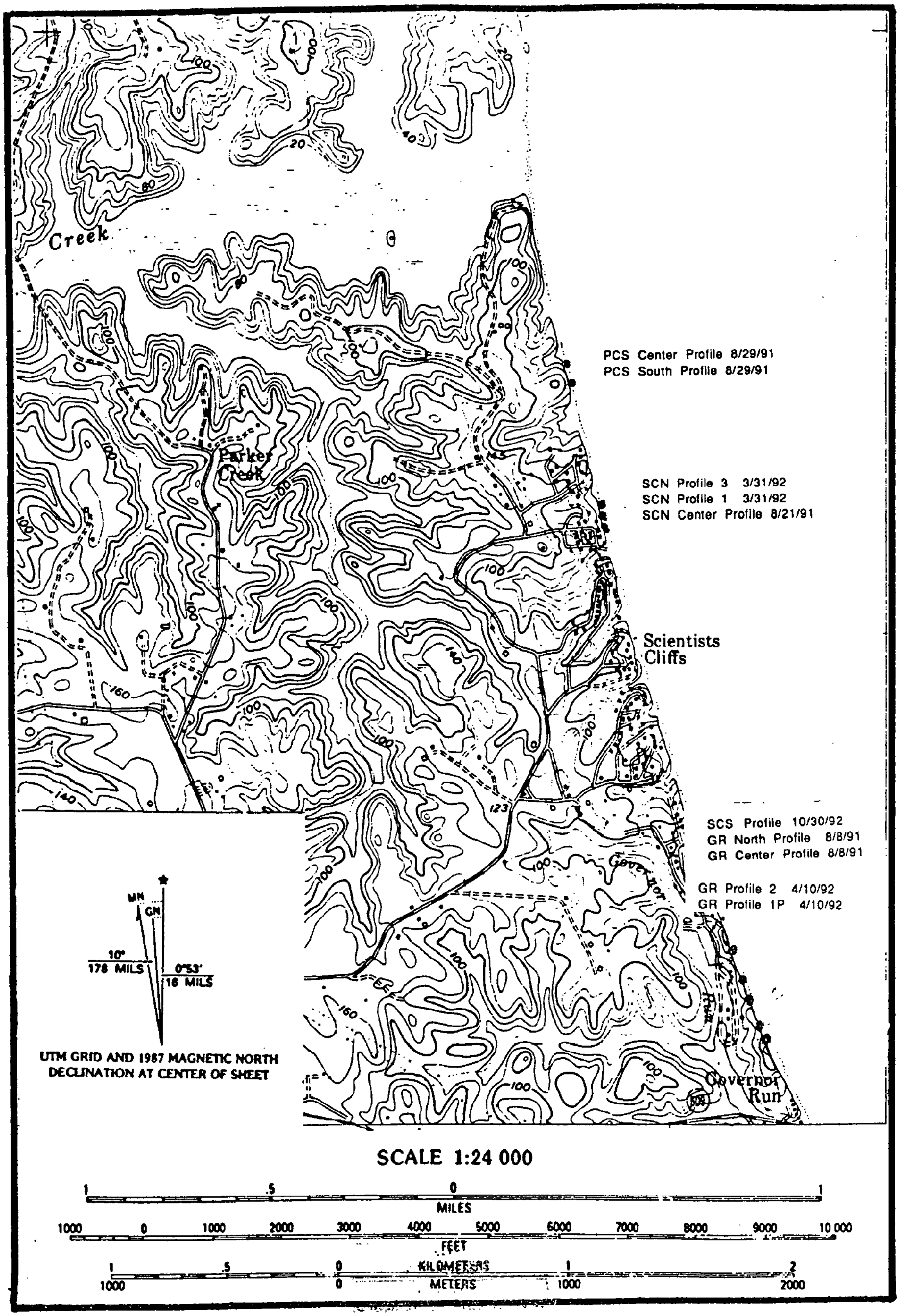
The geotechnical profile (Figure 2.14), constructed from data acquired during the drilling of the wells is representative of the entire Scientists' Cliffs site, although the exact elevations of stratigraphic contacts and unit thicknesses will vary due to the regional dip and local irregularities. Five piezometers were installed at the SCS subsite. They are designated SC1, SC2, SC3, SC4, and SC5 (see Figure 2.14). During the drilling, SC1 was sampled and SPTs were performed. Sampling was performed to an elevation of -0.6 m.

The stratigraphic profile consists of five material groups at this site. The root zone and soils are developed in a silty, very fine sand. A weathered clay separates the sandy soils above from another thick sequence of sands containing shell beds below. About mid-slope the sands are interrupted by a thick, clayey, sandy silt. Beneath the silt lies another shell bed and series of fine to very fine sand units. This sequence continues uninterrupted to the cliff base and below.

The surface elevation at the well head is 26.9 m. The matrix in the soil horizons and root zone is composed of an orange, very fine sand. The amount of silt and clay increases with depth to an elevation of 23.4 m where a unit composed predominantly of clay is present. It consists of a series of tan and gray clays and extends to 21.7 m where a sandy shell bed is encountered.

The shell bed is the Boston Cliffs member of the Choptank Formation (Kidwell, 1984). SPT blow counts indicate that it has the highest strength of all the stratigraphic units in the entire Scientists' Cliffs profile (Figure 2.16). The 4.2 m thick shell bed is quite porous and permeable. At its base the shell bed grades into a non-fossiliferrous, brown, medium sand, approximately 0.5 m thick. The base of the brown sand lies at an elevation of 17 m on a noticeably finer grained, dry, gray, silty sand, the grain-size of which becomes finer in a downward direction. At 14.6 m a permeability contrast gives rise to intermittent seepage on the cliff face. Erosion due to seepage is responsible for undercutting the bluff top, causing it to fail under its own weight. The brown sand and silty sands immediately below the Boston Cliffs member are the weakest materials at the Scientists' Cliffs site as indicated by the SPT. Non-fossiliferous sandy silts continue to an elevation of 13.4 m. A massively bedded sandy, silty clay extends from the base of the sands and silts at 13.4 m to 10.0 m.

Below the clay is a material composed of numerous shells in a brown, medium to fine sand matrix. This unit is the Drumcliff member of the Choptank formation and is found between 10.0 and 8.5 m. This unit is indicated to be relatively strong by the SPT (Figure 2.16). It is followed by 4.1 m of gray green, silty, medium to fine sand. Kidwell, 1984 informally designated the sandy material as the "Governor Run sand-clay interbeds" and noted that it is a stratigraphic exception relative to the Choptank stratigraphy elsewhere in the Calvert Cliffs. Kidwell interpreted this unit as the fill in a broad channel, extending from Governor Run to Parker Creek. At the well site, near the middle of the channel structure, the fill is a gray, medium to fine sand. Toward the channel flanks, sandy clay interbeds are present. It exhibits decreasing strength with depth and reaches a local strength minimum at its base.



Study Site SC
Locations of Slope Surveys

Figure 2.15

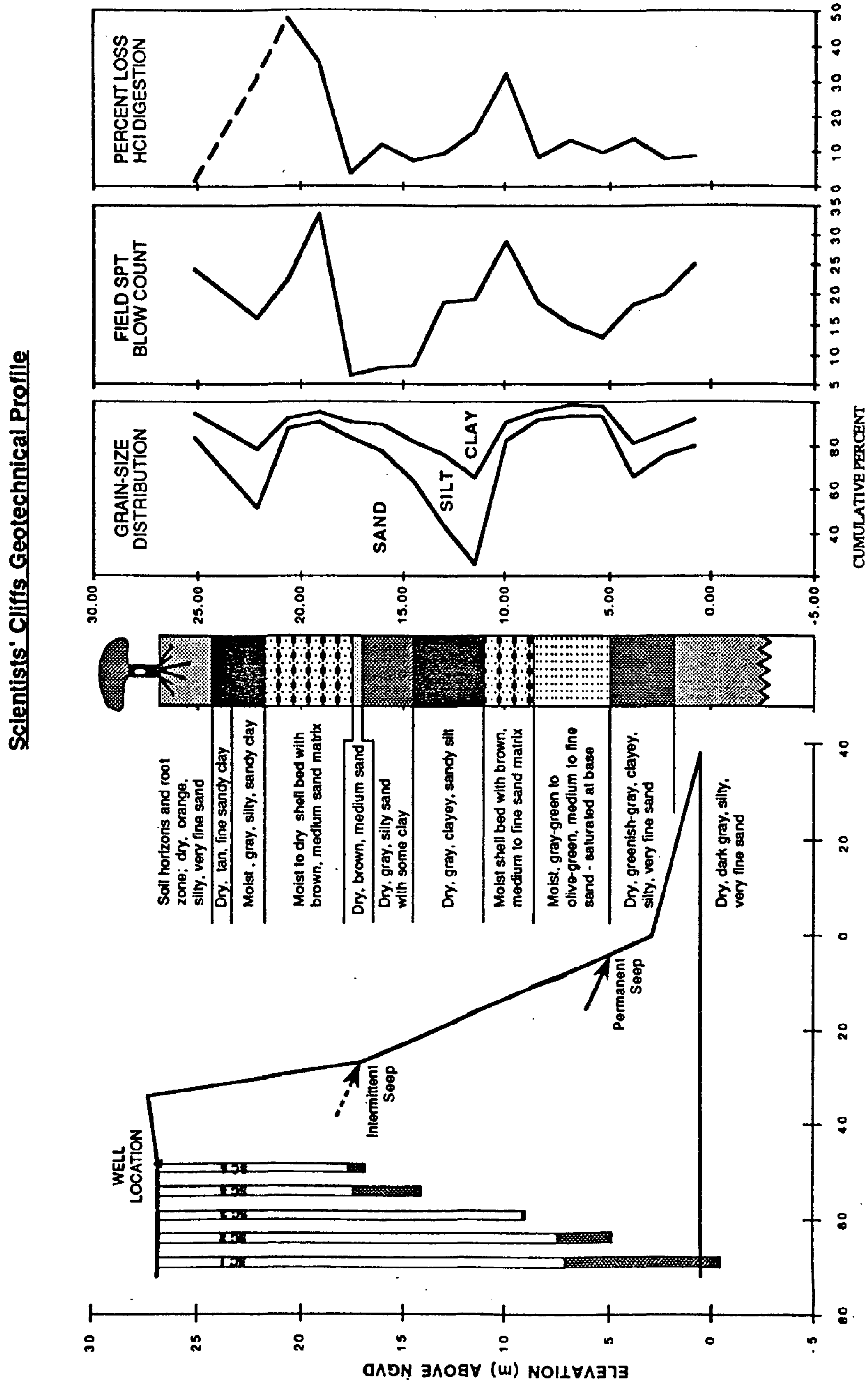

Scientists' Cliffs Geotechnical Profile
PERCENT LOSS
HCl DIGESTION
FIELD SPT
BLOW COUNT
GRAIN-SIZE
DISTRIBUTION
SAND
SILT
CLAY
CUMULATIVE PERCENT
Soil horizons and root zone; dry, orange, silty, very fine sand
Dry, tan, fine sandy clay
Moist, gray, silty, sandy clay
Moist to dry shell bed with brown, medium sand matrix
Dry, brown, medium sand
Dry, gray, silty sand with some clay
Dry, gray, clayey, sandy silt
Moist shell bed with brown, medium to fine sand matrix
Moist, gray-green to olive-green, medium to fine sand - saturated at base
Dry, greenish-gray, clayey, silty, very fine sand
Dry, dark gray, silty, very fine sand
WELL
LOCATION
Intermittent
Seep
Permanent
Seep
DISTANCE FROM CLIFF BASE (m)
ELEVATION (m) ABOVE NGVD

Figure 2.16

The Governor Run sand-clay interbeds terminate at 4.4 m at the disconformity between the Choptank and Calvert formations. At the well site, the top of the Calvert formation is a gray sandy silt which grades below MSL into a clayey silt. Along the PCS subsite, the Choptank formation contacts the Calvert formation disconformably on the sandy Parker Creek bone bed (Kidwell, 1984). At the southern end of the PCS subsite, the bone bed is at MSL and rises to an elevation of approximately 1 m at the extreme northern end of the site. Below the Parker Creek bone bed and extending below tide at the north end of the PCS subsite is a massive, clayey silt.

Slope Profiles (Figures 2.17 to 2.26)

(Note: A dashed line representing the position of the intact slope is provided only on the profile figures where the slope toe is buried by debris. The lower portion of the slope profiled in Figure 2.22 islargely composed of debris and the intact slope surface could not be ascertained. All other profiles without the dashed line may be assumed to represent the intact slope material.)

Ten slope profiles were surveyed at the SC site; two at subsite PCS, three at subsite SCN, one at subsite SCS, and four at subsite GR. The surveyed slopes at the PCS subsite (Figures 2.17 and 2.18) are both over 18 m high and steep (>76°). The toes of these slopes are at an elevation at or below MHHW and the slopes are subject to daily wave erosion. Tall slopes with steep angles are common at the PCS site. Lack of access to the property required that surveying stations be set up along a narrow zone of beach between high and low tide. From this vantage point, it was possible to survey only slopes shorter than 20 m. Variations in slope angle within the profile occur at material contacts and are most dramatic where the material contrast is great.

Since the 1930s, the slope toes of all of the slopes at the SCN (Figures 2.19, 2.20, and 2.21) and SCS (Figure 2.22) sites have been partially protected from erosion by a beach which has developed between a series of gabion groins. The slopes along SCN and SCS display relatively straight profiles at angles between 50 and 56 degrees. At SCS, the slope toe is completely protected by a parking area and the slope has a composite shape, because slope debris has built a gentle lower and middle slope, while the upper slope remains steep. The angle for this slope is approximately 37 degrees. Along the GR subsite (Figures 2.23, 2.24, 2.25, and 2.26), the slope toes are once again subjected to wave erosion. A small beach was present along this subsite from 1990 to 1991, but has subsequently been removed and the slope toe exposed to direct wave erosion. During Tropical Storm Danielle (25 September 1992) the slope toe was actively attacked by waves. The heights of the profiled slopes at GR range between 24 m and 30 m. The slope toe to bluff top angles of the profiled slopes range between 55 degrees and 65 degrees. The GR slopes display gentle slope changes at material contacts.

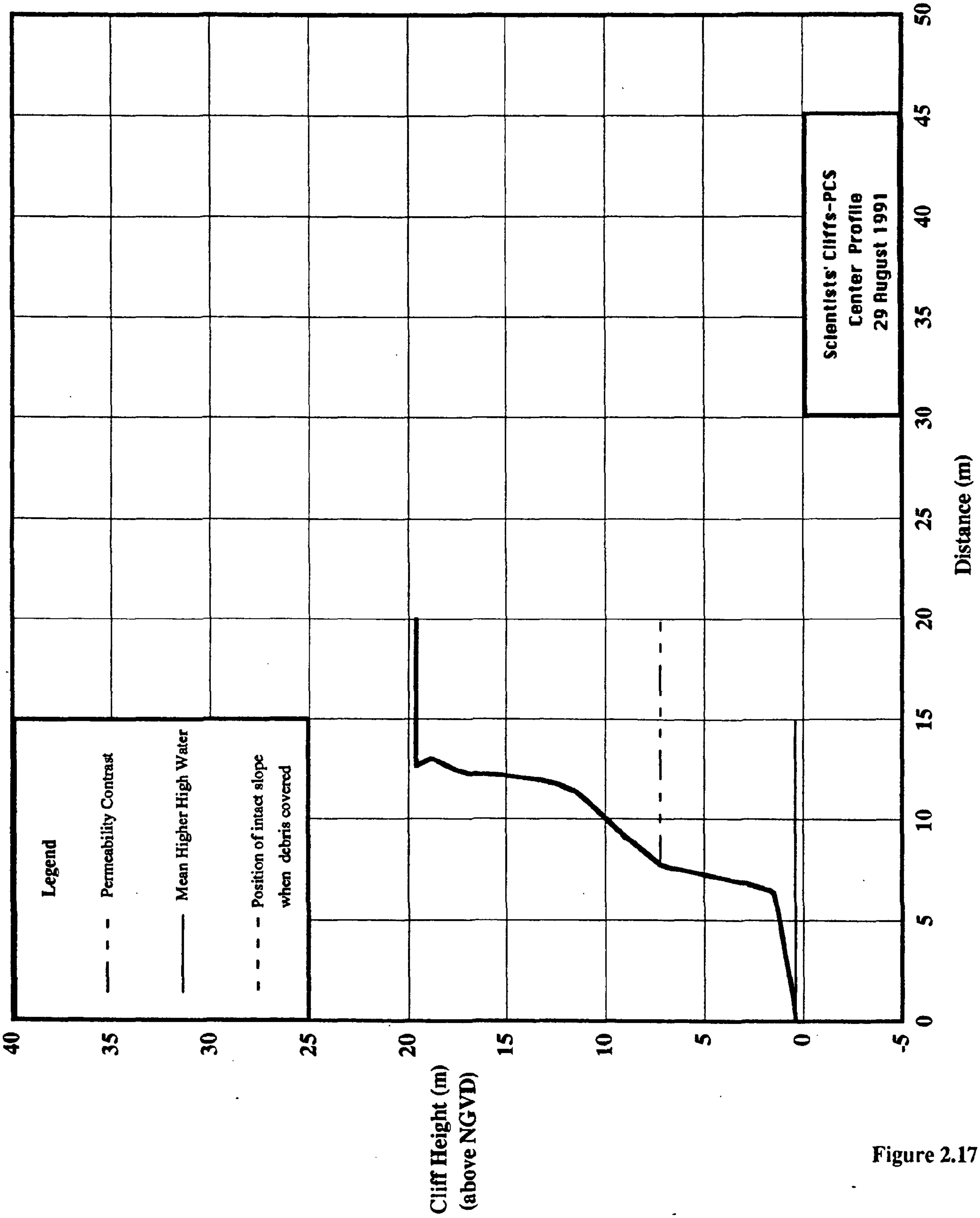
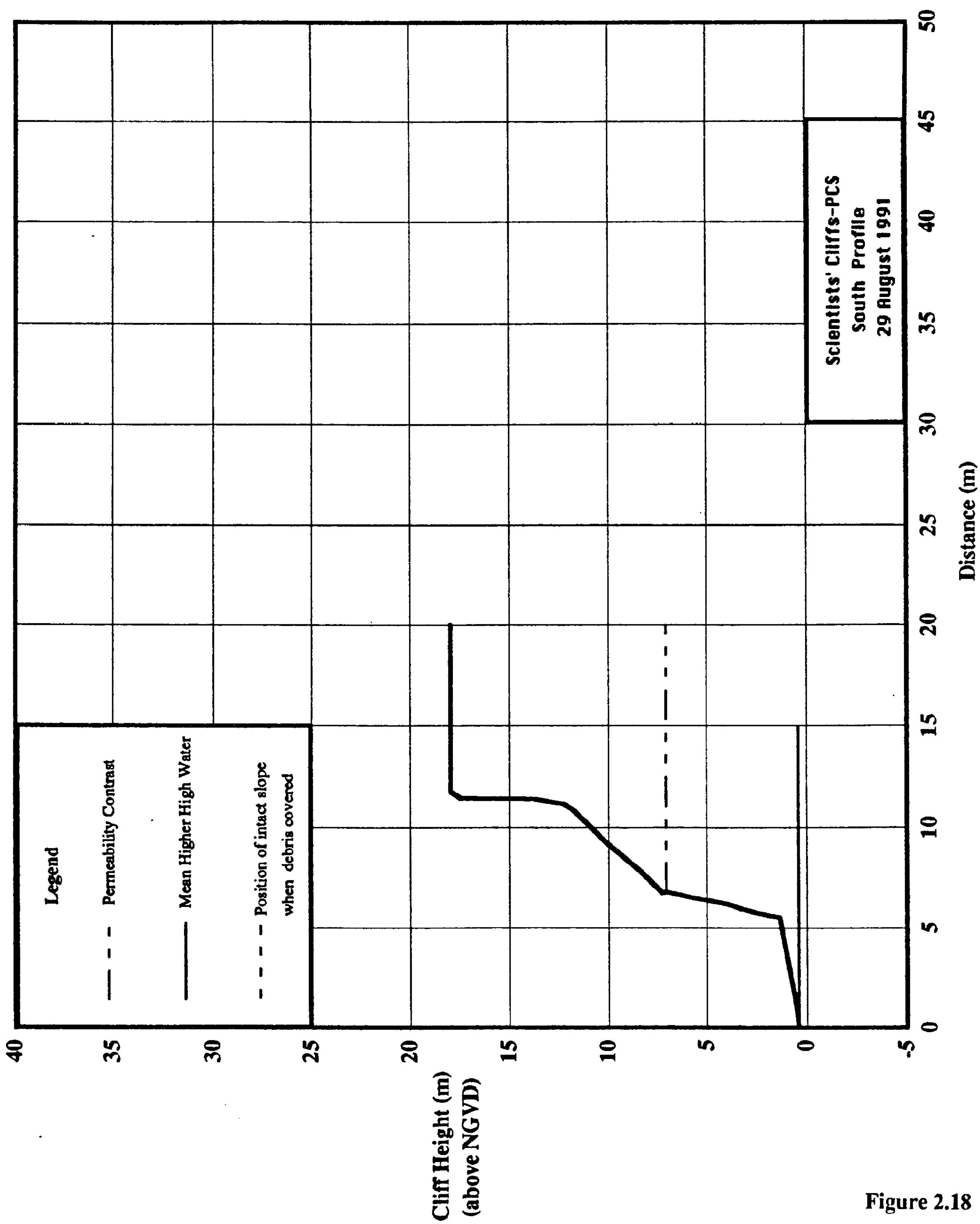

Scientists' Cliffs-PCS
Center Profile
29 August 1991
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Cliff Height (m)
(above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.17



Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Scientists' Cliffs-PCS
South Profile
29 August 1991
Distance (m)
0
5
10
15
20
25
30
35
40
45
50
Cliff Height (m)
(above NGVD)
40
35
30
25
20
15
10
5
0
-5

Figure 2.18

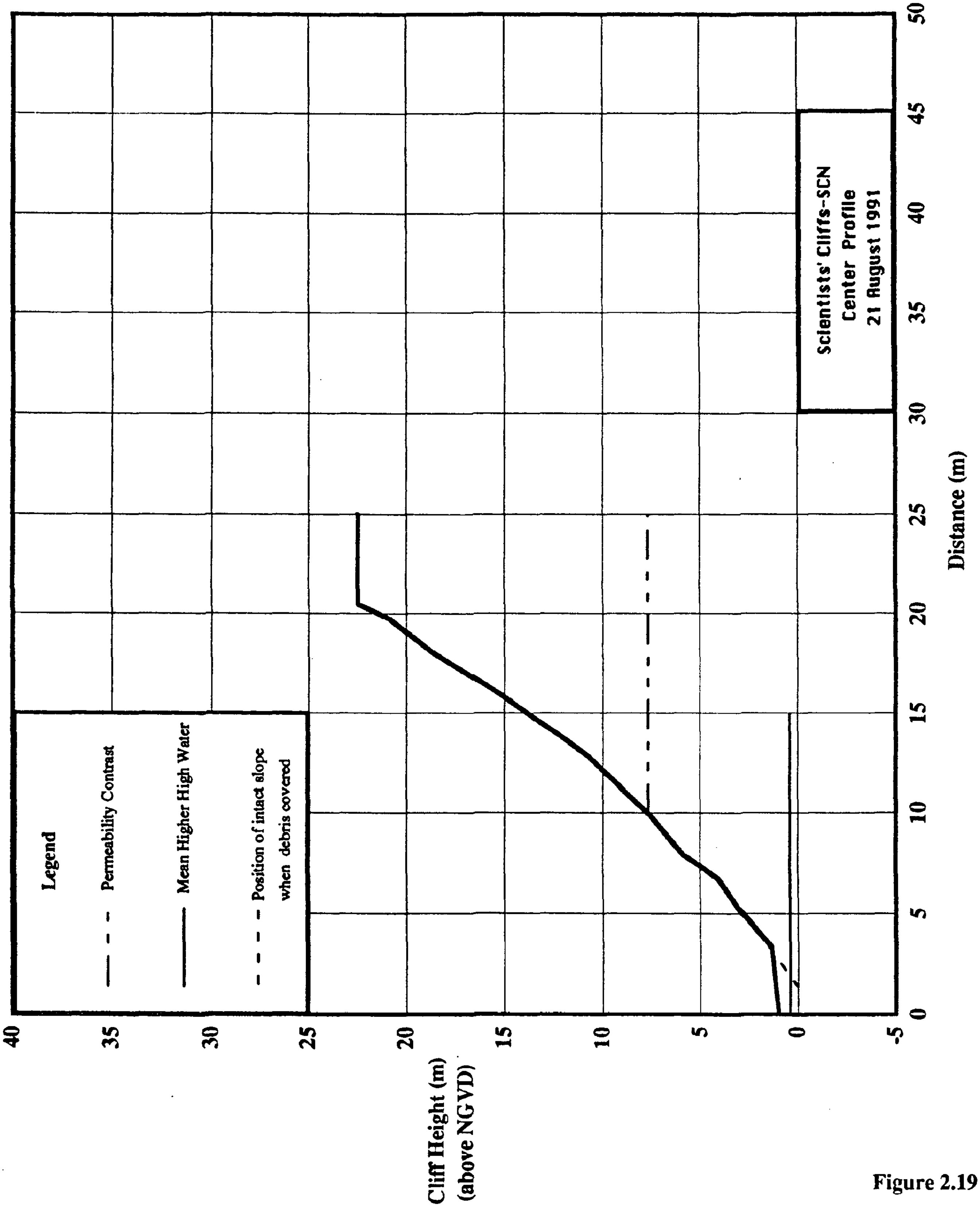

Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Scientists' Cliffs-SCN
Center Profile
21 August 1991
Distance (m)
0
5
10
15
20
25
30
35
40
45
50
Cliff Height (m)
(above NGVD)
40
35
30
25
20
15
10
5
0
-5

Figure 2.19

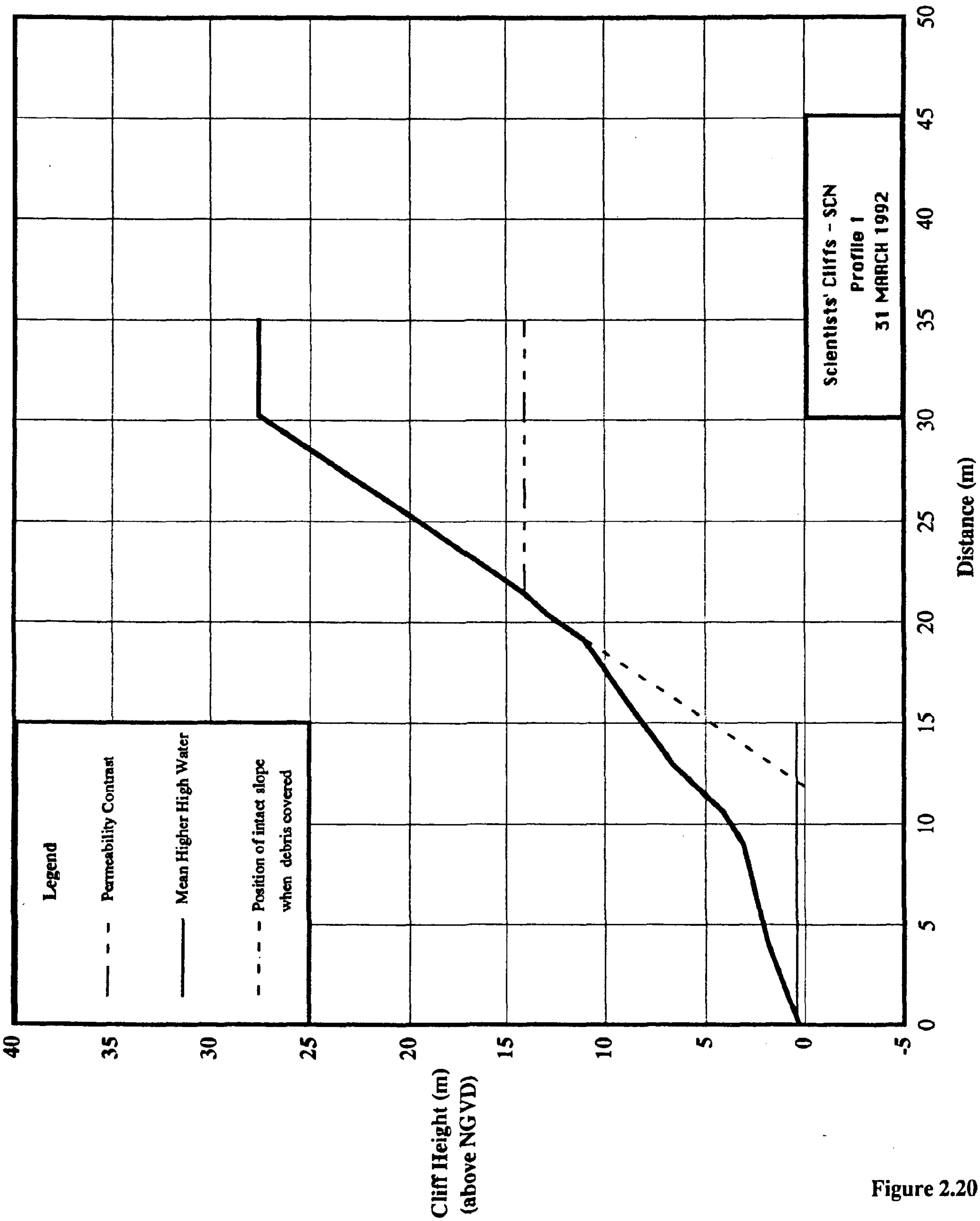

Scientists' Cliffs - SCN
Profile 1
31 MARCH 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Cliff Height (m) (above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.20

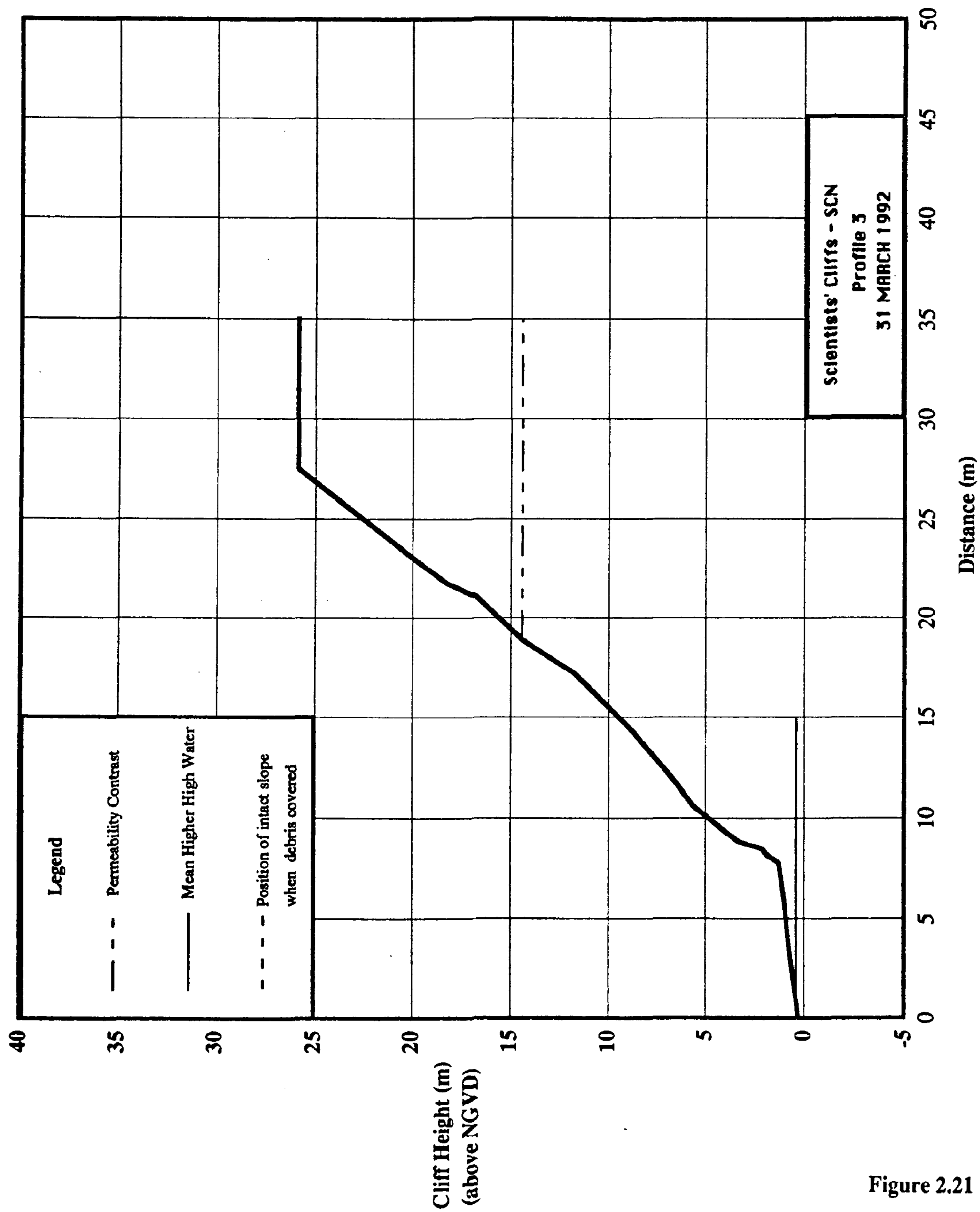

Scientists' Cliffs - SCN
Profile 3
31 MARCH 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Cliff Height (m) (above NGVD)
40
35
30
25
20
15
10
5
0
-5
Distance (m)
0
5
10
15
20
25
30
35
40
45
50

Figure 2.21

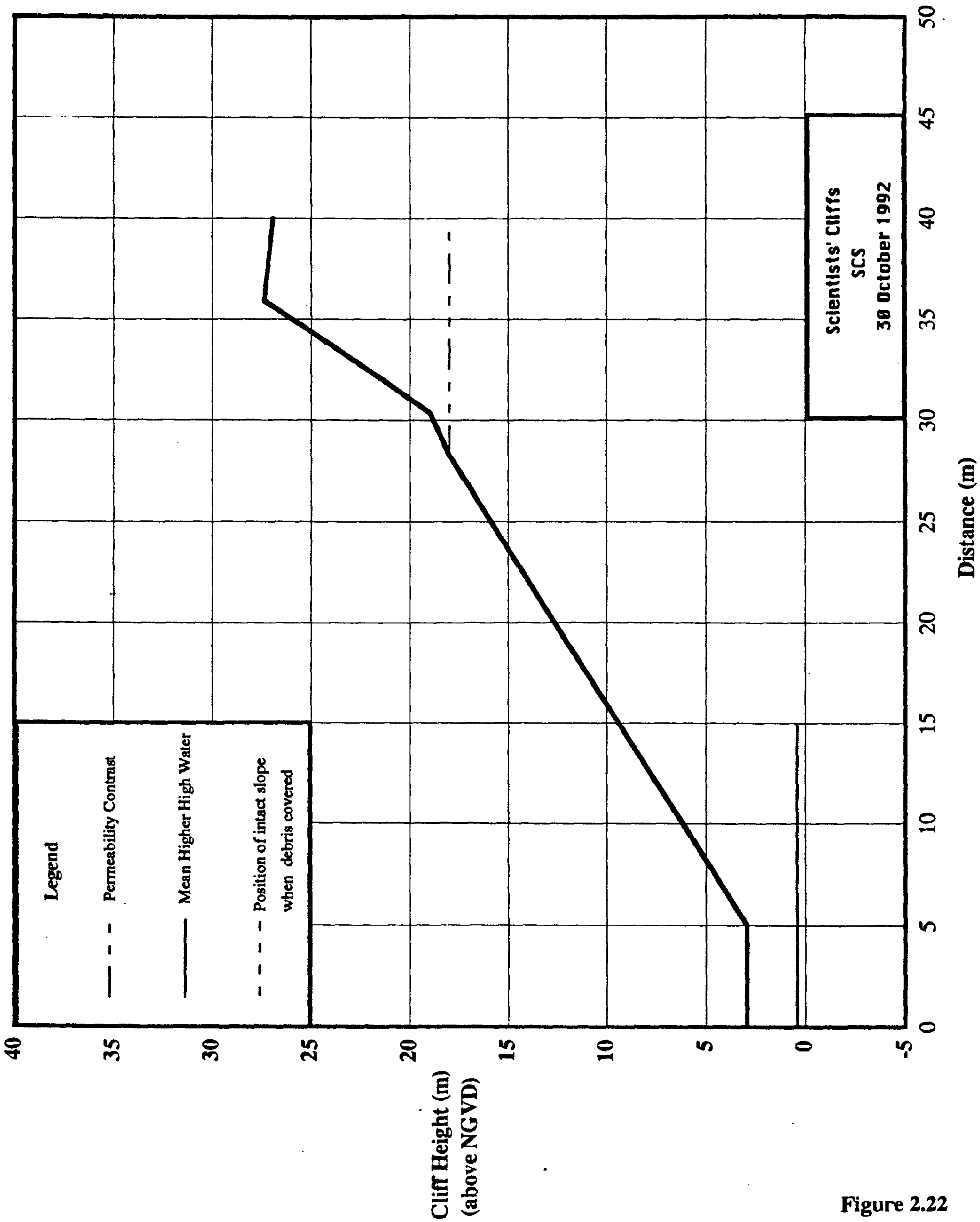

Scientists' Cliffs
SCS
30 October 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Distance (m)
Cliff Height (m)
(above NGVD)
0
5
10
15
20
25
30
35
40
45
50
-5

Figure 2.22

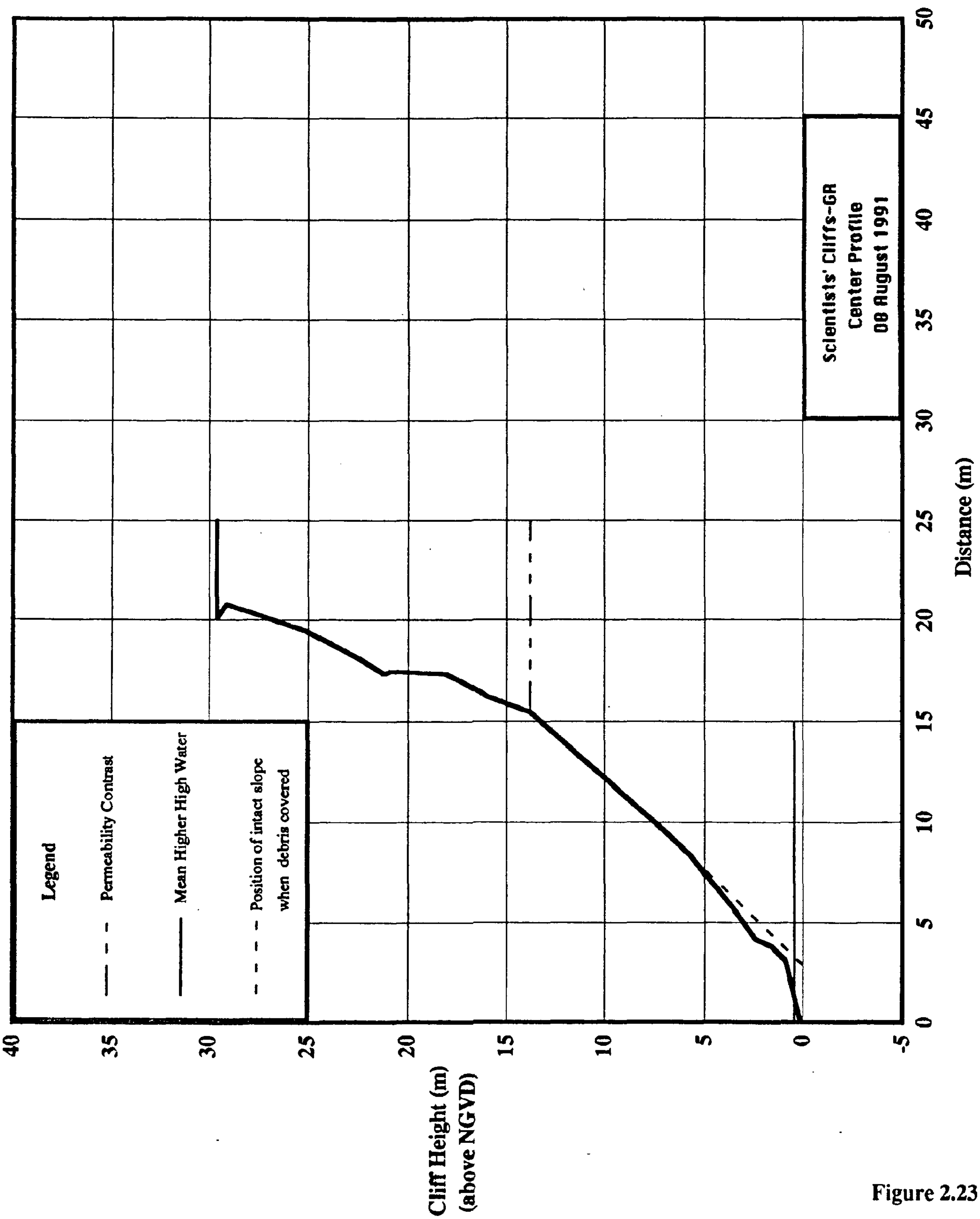
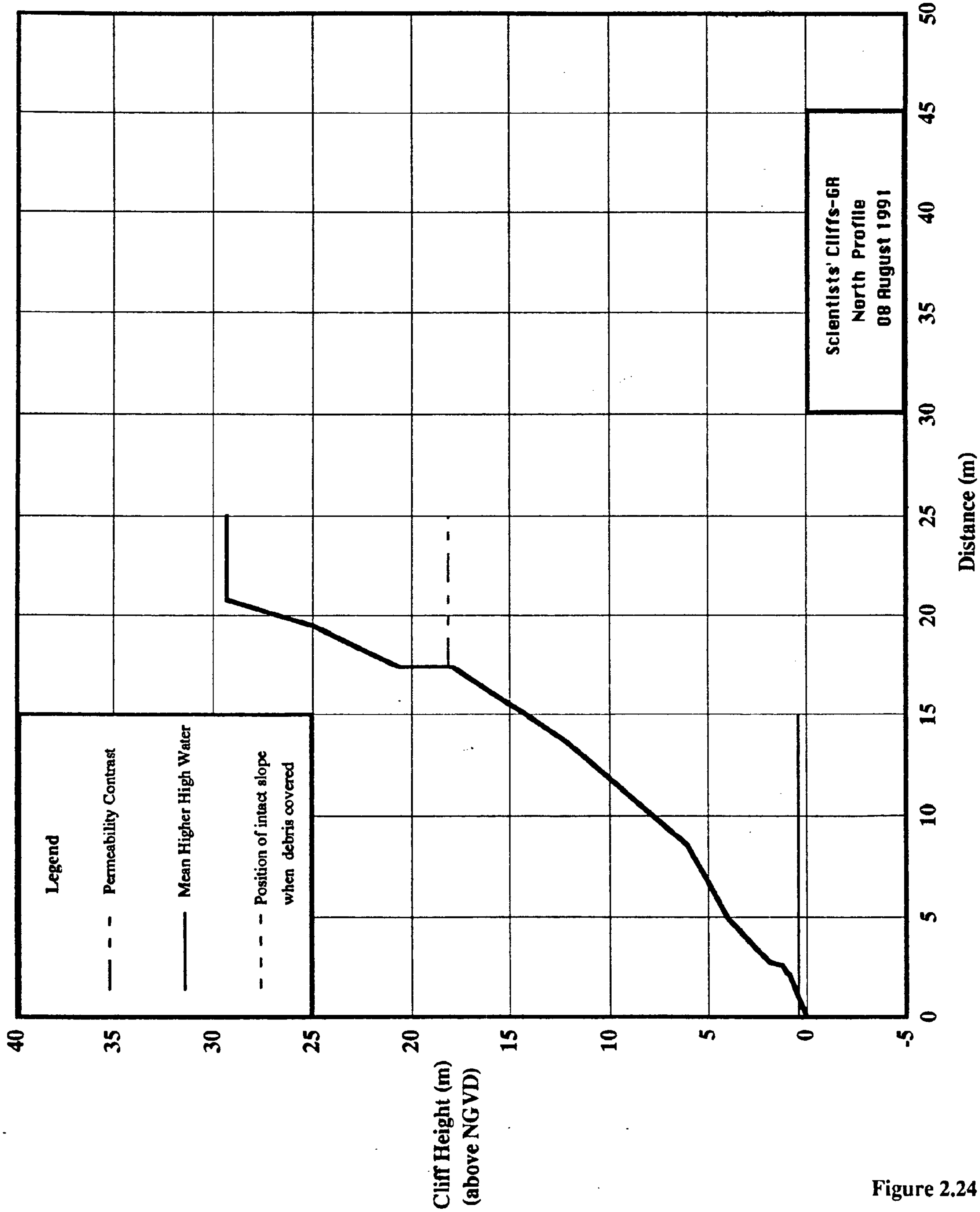

Scientists' Cliffs-GR
Center Profile
08 August 1991
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Cliff Height (m) (above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.23



Scientists' Cliffs-GR
North Profile
08 August 1991
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Distance (m)
Cliff Height (m) (above NGVD)
0
5
10
15
20
25
30
35
40
45
50
-5

Figure 2.24

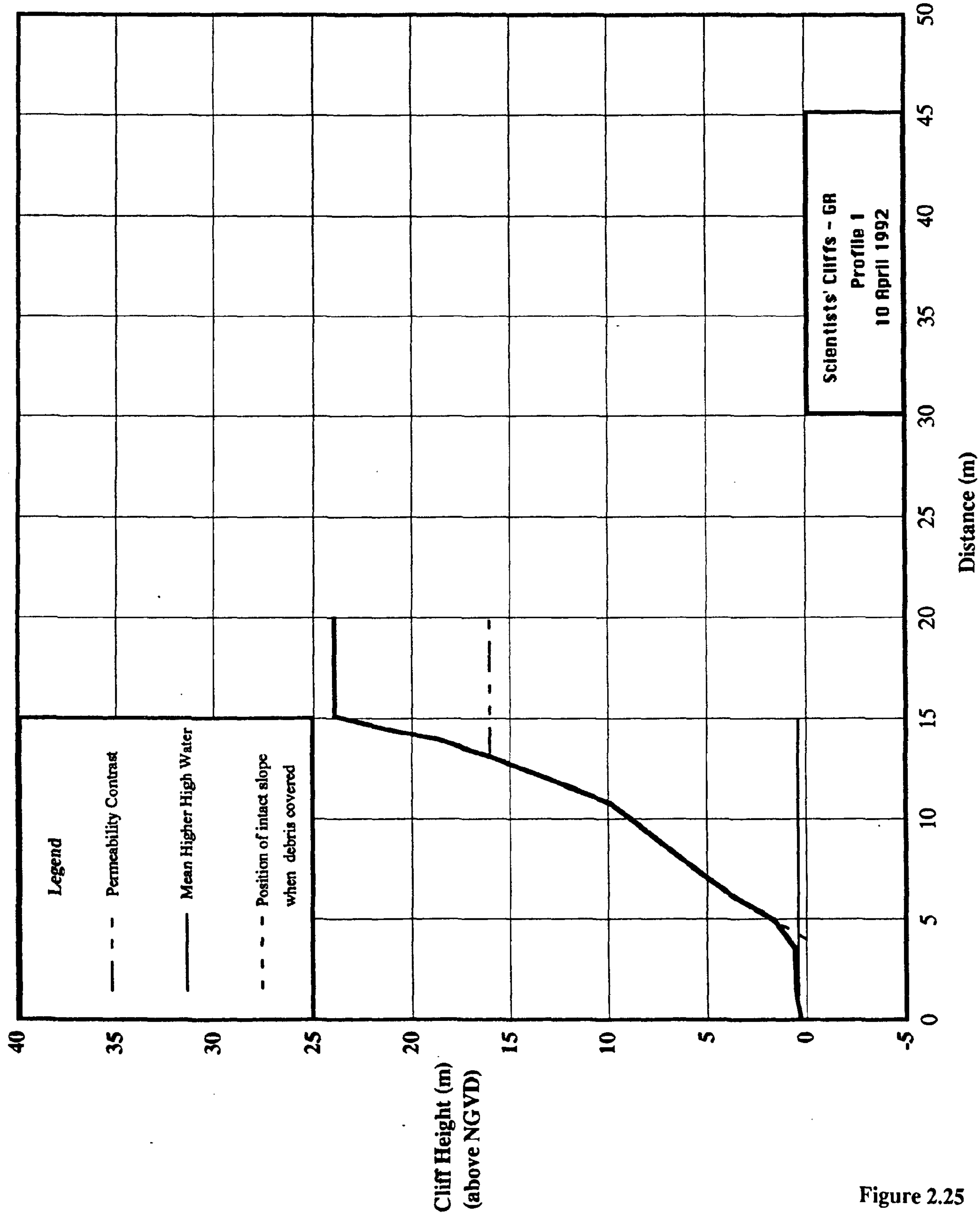

Scientists' Cliffs - GR
Profile 1
10 April 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Cliff Height (m) (above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.25

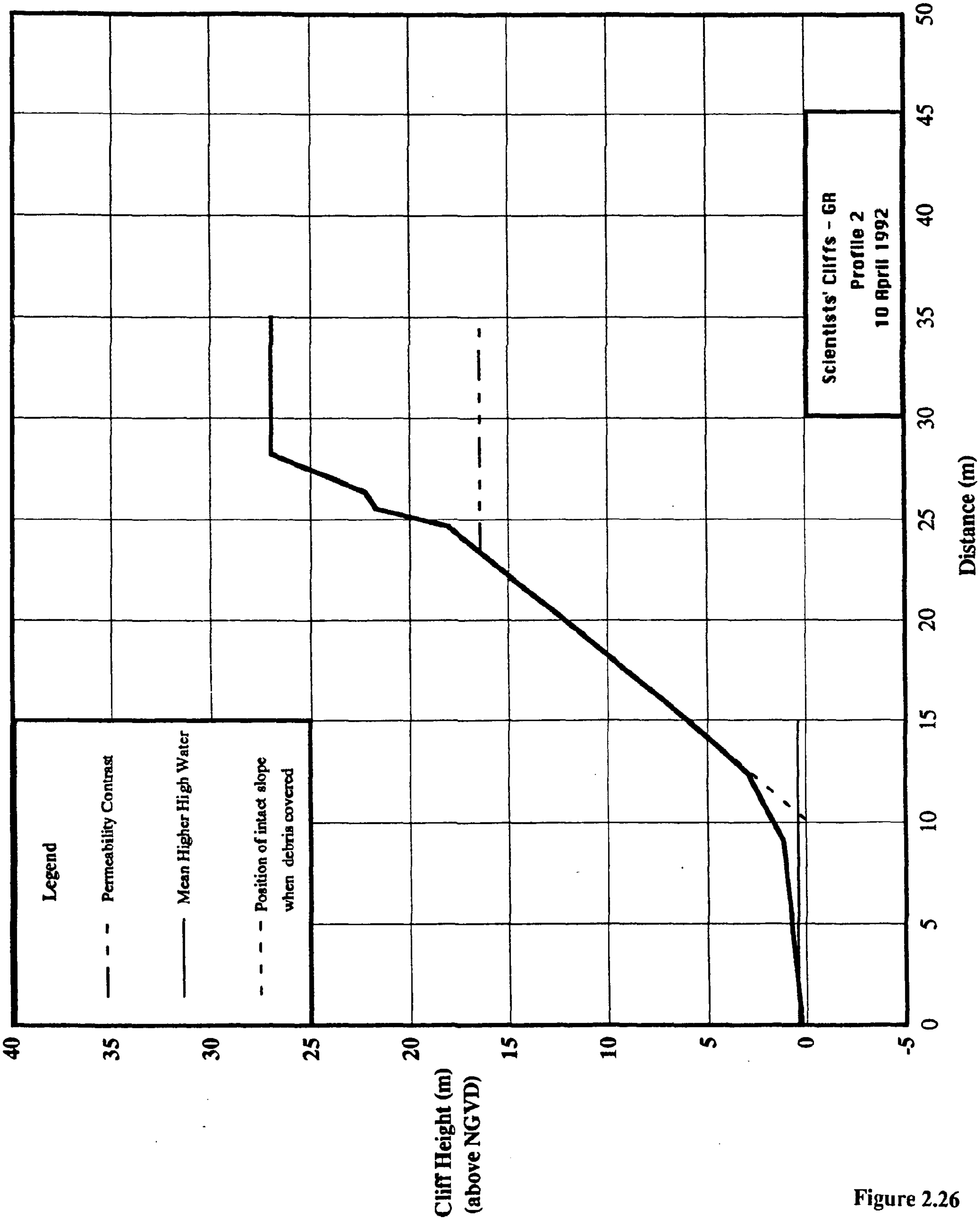

Scientists' Cliffs - GR
Profile 2
10 April 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Cliff Height (m)
(above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.26

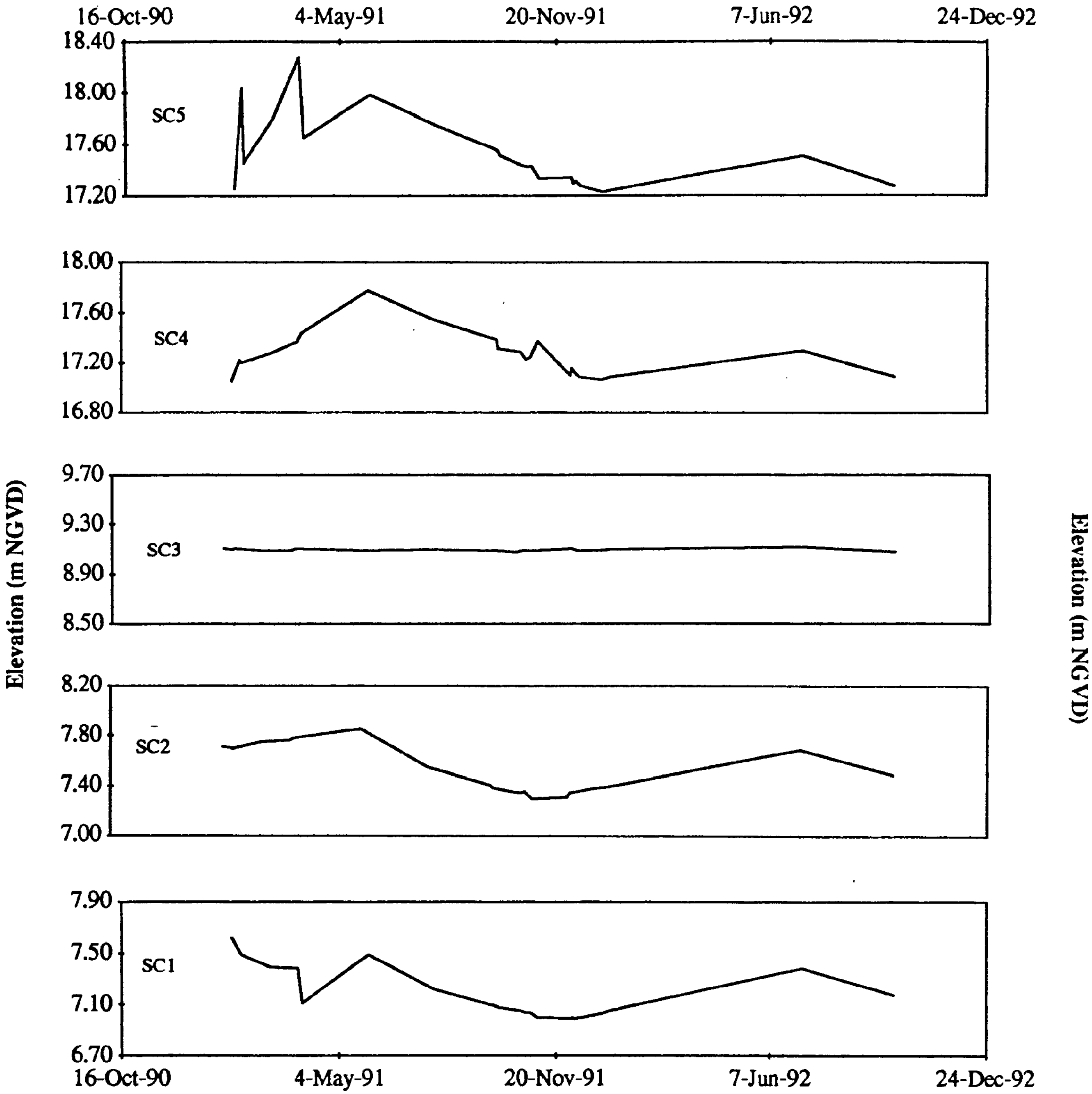
Groundwater levels (Figures 2.16 and 2.27)

Piezometers were installed at six elevations (Figure 2.16). Figure 2.27 is a plot of the elevation of the water surface in each piezometer versus time. The plot of water surface positions over time shows that the regional groundwater regime does not fluctuate rapidly. Instead, its slow and gradual changes with time reflect the long-term hydrologic conditions of the SC region.

Two relatively independent groundwater systems exist at this site. Groundwater seepage is evident along exposed cliff faces and tends to occur near the base of the two coarse-grained stratigraphic intervals (see Figure 2.16). A shallow, permanent water table exists above 10.0 m (stratigraphic elevations correspond to those measured at the piezometer site at SC). On slopes taller than 23 m, water infiltrating toward this groundwater zone is impeded by the presence of silts and clays near the surface. Based on the grain-size of this unit the hydraulic conductivity of the silts and clays in estimated to be 10^{-7} m/s to 10^{-8} m/s (see Figure 2.16). In the sandy units above 14.6 m the average grain size distribution is 85 percent sand, 7 percent silt, and 8 percent clay. The hydraulic conductivity of the sands is estimated to be 10^{-5} m/s. Between 10.0 and 14.6 m the average grain size distribution is 45 percent sand, 30 percent silt, and 25 percent clay. The hydraulic conductivity, based on the grain size of the material is estimated to range between 10^{-8} m/s near 14.6 m and decrease to 10^{-10} m/s at 10.0 m.. Piezometers SC5 (bottom elevation 16.8 m) and SC4 (bottom elevation 14.1 m) measure the piezometric levels in this groundwater body. Highly localized hilltop surface drainage contributes a large fraction of water to this horizon. Residential septic systems are frequently located above the permeability contrast which creates this groundwater body and are a source of its water. Water in piezometer SC4 is noted to have a septic smell. Seepage from this zone is responsible for undercutting the upper slopes along the SC site. The SC site topography consists of numerous hilltops separated by stream drainages. Therefore, this upper groundwater body is not continuous across the SC site, but exists as numerous isolated groundwater bodies above 13.4 m.

As discussed in geotechnical summary, a 3.4 m thickness of clays and silts occurs between 13.4 m and 10.0 m. This relatively impermeable sequence of materials effectively isolates the upper groundwater bodies occurring in the near surface materials from the deeper, permanent, regional groundwater regime. The groundwater regime below 10.0 m receives recharge from surface waters up to a kilometer away from the slope face. Piezometers SC1 (bottom elevation -0.5 m), SC2 (bottom elevation 4.8 m), and SC3 (bottom elevation 9.0 m) are located within the permanent groundwater flow system (see Figure 2.16).

Below 10.0 m the Drumcliff formation contains a large fraction of sand (83 percent). During the geotechnical investigation of the Calvert Cliffs Nuclear Power Plant site (FSAR, 1967), a laboratory hydraulic conductivity test was performed on material from the Drumcliff formation. Grain-size analyses from both sites indicate that the materials are very similar, both being fine sands with shells. The test results indicate that the hydraulic conductivity in this unit is 10^{-5} m/s. This figure also agrees well with those for similar materials published in groundwater literature (Freeze and Cherry, 1979). The hydraulic conductivity is inferred to increase to approximately 10^{-4} m/s in



Time Series of Water Levels at SC Piezometers

Figure 2.27

the Governor Run sand-clay interbeds which, at the well site, extend from 8.5 m to 4.4 m and are predominantly sand, with an average grain-size distribution of 93 percent sand, 4.5 percent silt, and 2.4 percent clay.

The contact between the Choptank and Calvert formations occurs at 4.4 m. The contact is marked by the presence of the gray-green to olive-green, medium to fine sands (the Governor Run sand-clay interbeds) overlying a dry greenish-gray, clayey, silty, very fine sand (see Figure 2.16). It is the horizon along which the relative permeability changes and seepage occurs. Based on the grain-size of the upper Calvert formation, the maximum hydraulic conductivity of that material is two to three orders of magnitude smaller than the units above, ranging from approximately 10^{-7} m/s to 10^{-8} m/s. It is within the Governor Run sand-clay interbeds that a distinct darkening of the slope face sediments is noted along the majority of exposed slopes at the SC site. An exception exists at the PCS subsite where this darkening occurs within the upper Calvert formation. The darkening results from constant saturation of the materials below the regional groundwater surface and seepage from the slope face at stratigraphic permeability contrasts. The rate of seepage depends on the magnitude of the difference in permeability at the stratigraphic contacts.

Erosion Mechanisms

Site/Subsite: Scientists' Cliffs/ Parker Creek South (PCS)

Lower Slope. The toe zone is composed of a silty, sandy, clay. The elevation of the toe zone is near mean low water and the toe zone is subjected to nearly continuous wave undercutting which results in spalling of large blocks from the nearly vertical lower slope. Removal of the slope debris is generally quite rapid; only debris from the largest slope failures remains on the beach for periods longer than several weeks to a month.

A partial, ephemeral beach is present along portions of the PCS subsite. Active deposition and erosion of beach sand has been observed. Near the northern end of this subsite, excavation of the beach uncovered spalled blocks were noted to have been buried by beach depositional processes. Also, at this site, runoff from a heavy thunderstorm (1.5 inches in one hour) was observed to erode the top 15 to 20 cm of beach surface along the only portion of this subsite observed to have even a small beach.

Midslope. The active wave undercutting and retreat of the lower slope tends to steepen the midslope sections, which initiates further spalling and shallow sliding in the midslope zone. Typically, spalls work their way up the steep slope face to the perennial seepage zone where the lower sandy shell bed is located. Some spalls are sufficiently large that they extend from beach level to the perennial seep approximately 12 m above the beach. Undercutting and spalling tend to keep the slope face straight and nearly vertical. Above the seep, columnar slope sections separate from the face along tensional fractures and topple or fall to the beach.

Upper Slope. Weathered and leached materials near the bluff top tend to fail in undercut slumps that bury earlier spalled material. Undercut root zones eventually collapse in cantilever type failures.

Site/Subsite: Scientists' Cliffs/Scientists' Cliffs North and South (SCN and SCS)

Lower Slope. The entire length of the shoreline along the community of Scientists' Cliffs is partially protected by a beach built up behind evenly spaced groins. Along the southern portion of the shoreline, the slope toe is completely protected by a wide beach and parking lot. To the north, the slope toe is closer to the shoreline, but everywhere along the shore, the slope toe is above all but the highest of water levels. The result is that at most locations toe debris has accumulated and become vegetated with shrubs and trees. In a very few places along the groin-protected shoreline, the waves have removed all of the debris at the slope toe and eroded some intact material. At most places, however, the intact toe material still maintains a relatively gentle slope. During Tropical Storm Danielle (25 September 1992) the beach at the northern end of SCN was degraded approximately 10 to 15 cm vertically. At the same time, sand was deposited along the beach at SCS.

Midslope. Typically, the middle portion of cliffs along the Scientists' Cliffs Community is vegetated. Where exposures are present, a perennial seepage zone is evident where a gray-green, medium to fine sand overlies a gray, clayey, silty, very fine sand. Further upslope is an ephemeral seepage zone where a brown medium sand overlies a gray, clayey, sandy silt. Field inspection of this seepage zone indicates that it is subject to both piping and sapping erosion when the seepage is active. (Piping erosion is similar to sapping erosion in that it is caused by groundwater flow. However, the flow tends to be confined to narrow regions in the cliff face where the erosion creates holes that often resemble pipes). Flow from this seepage zone produces seepage erosion of lower units. Field strength tests indicate the shear strength of the materials comprising the cliffs to be at a minimum at the seepage interface. Sapping and piping erosion undercuts the material above, causing it to slump or fall. In this way, bluff top recession continues despite significant toe protection.

Mid-slope recession below the seepage zone occurs by physical and chemical weathering products being removed by surface wash. Vegetative cover serves to reduce raindrop impact and dry the upper slope surface by interception and evapotranspiration. However, roots of all plants contribute to the degradation of soil fiber by producing acidic conditions around them. Offsetting this effect is the binding action of the roots which forms mats. It is common at Calvert Cliffs for failure to occur along the base of the root mat, causing the mat to slide downslope.

Upper Slope. The bluff top recedes by both seepage undercutting and surface wash of weathered material. Most property owners have removed the tall trees from the cliff edge to prevent loss of root mass and associated soil when trees fall during strong winds.

Site/Subsite: Scientists' Cliffs/Governor Run (GR)

Lower Slope. Prior to late 1991, a small beach was present along the toe zone at the southern end of GR. The beach protected the toe zone from erosion except during extremely high tides. Since late 1991, it has been removed by waves. Currently, the toe zone is free of debris and the intact slope is constantly exposed to wave activity. Along the same part of the shoreline, the cliffs are tall (> 30 m) and seepage erosion has formed a substantial bench along the upper seepage zone (ephemeral seep). The bench is approximately 5 m wide and heavily vegetated. The result is that very little upper slope material is delivered from above the seepage zone to the toe zone. The lack of debris fans along this stretch of cliffs can be attributed to a lack of supply of debris from the upper slope to the slope toe, rather than to greater or more focused wave energy at this location. This is suggested by traces of isolated vegetation in triangular patches that may have become established on debris fans that had accumulated along the toe during bench formation. Once the bench was well-formed, the supply of upper slope debris diminished and the debris fans have been removed except for traces of their uppermost portions. Similar vegetated debris fans are currently present just north and south of the bench cut cliff, where upper slope material is still transported from cliffs of similar height to the toe zone.

Physical and chemical weathering result in disintegration of the clayey, very fine sand which comprises the intact slope material along the stretch where it is exposed. Also, the slope toe is slightly undercut here. This is the only section of the cliffs at this subsite that show evidence of spalling just above the toe.

Most of the toe zone, both to the north and south of this section is covered with either a light mantle of debris forming a laterally continuous wedge shaped deposit or a larger triangular debris fan. Light vegetation has become established on the unconsolidated debris along most of the slope toe.

Midslope. A nearly uniform, fairly gentle incline occurs from the base of the debris fans at the toe to the base of the root zone. A perennial seepage zone occurs at approximately 5 m above the beach where a gray-green medium to fine sand overlies a gray-green clayey, silty, very fine sand. The seepage tends to keep the slope face below moist. Below the seepage zone, the face is covered with a thin veneer of weathered debris which presents a generally uniform planar surface with small rills on its surface. Above the seepage zone is a drier face composed of a gray, clayey, sandy silt which coarsens upward to become a clayey, silty, very fine sand and is prone to fragmental disintegration due to desiccation and other weathering mechanisms. Continuing upslope a seepage zone is encountered where the clayey, silty, very fine sand meets a brown medium sand. Where the topographic surface behind the cliffs is low, this interface is a perennial seep. Where the surface is high, it is an ephemeral seepage zone. Overlying the medium sand is a thick shell bed with a brown medium sand matrix. At this subsite the shell bed is overlain by a one meter thick zone of medium to coarse, orange-brown sand which also exhibits a saturated face where the topographic surface is low.

Upper Slope. The upper slope at GR tends to be nearly vertical. As of October 1990, there were no slope-top trees on the beach along the entire subsite. However, by summer 1991, an upper slope slump in the upper sand bed had undercut a large tree, which subsequently toppled to the beach carrying a large root ball with it.

Erosion of the upper slope appears to be driven primarily by sapping erosion in a medium sand bed located at an elevation of 18 m. The sand is very loosely consolidated and prone to sapping erosion at its interface with an underlying shell bed. Sapping undercuts the materials lying above, causing them to fail. Material from these failures form fan-type debris piles along the toe zone.

The upper slope bench is located along the 150 m long section of GR with little beach and toe debris. The bench is formed within the upper medium sand that is prone to sapping erosion. The floor of the bench is formed by the less pervious shell bed which underlies the sand sapping zone. The location of the bench at this elevation suggests that the bench was formed by accelerated sapping erosion.

2.4 Calvert Cliffs State Park

General Site Description

The site encompasses the shoreline and cliffs from Rocky Point to 500 m south of Grays Creek (see Figure 2.28). The subsites are Rocky Point (RP), Grovers Creek South (GVCS), and Grays Creek South (GYCS).

The cliffs generally face northeast to east-northeast except at RP where the cliffs face northeast to east. There is no shore protection at this study site. A small beach is present during low tides, but waves frequently reach the cliff base. Offshore sand bars were not evident during an aerial inspection of the CCSP site in October, 1990 nor have any been observed for the duration of the project.

The cliff height at the RP subsite varies between 15 and 35 m and slope angles range between 65 and 85 degrees. The cliffs at the southern end of the RP subsite are substantially lower, ranging between 12 and 18 m. Here, the slope angle is approximately 60 degrees. Both the GVCS and GYCS subsites have slope angles of 60 degrees with the slope height varying between 15 to 30 m at GVCS and 15 to 25 m at GYCS.

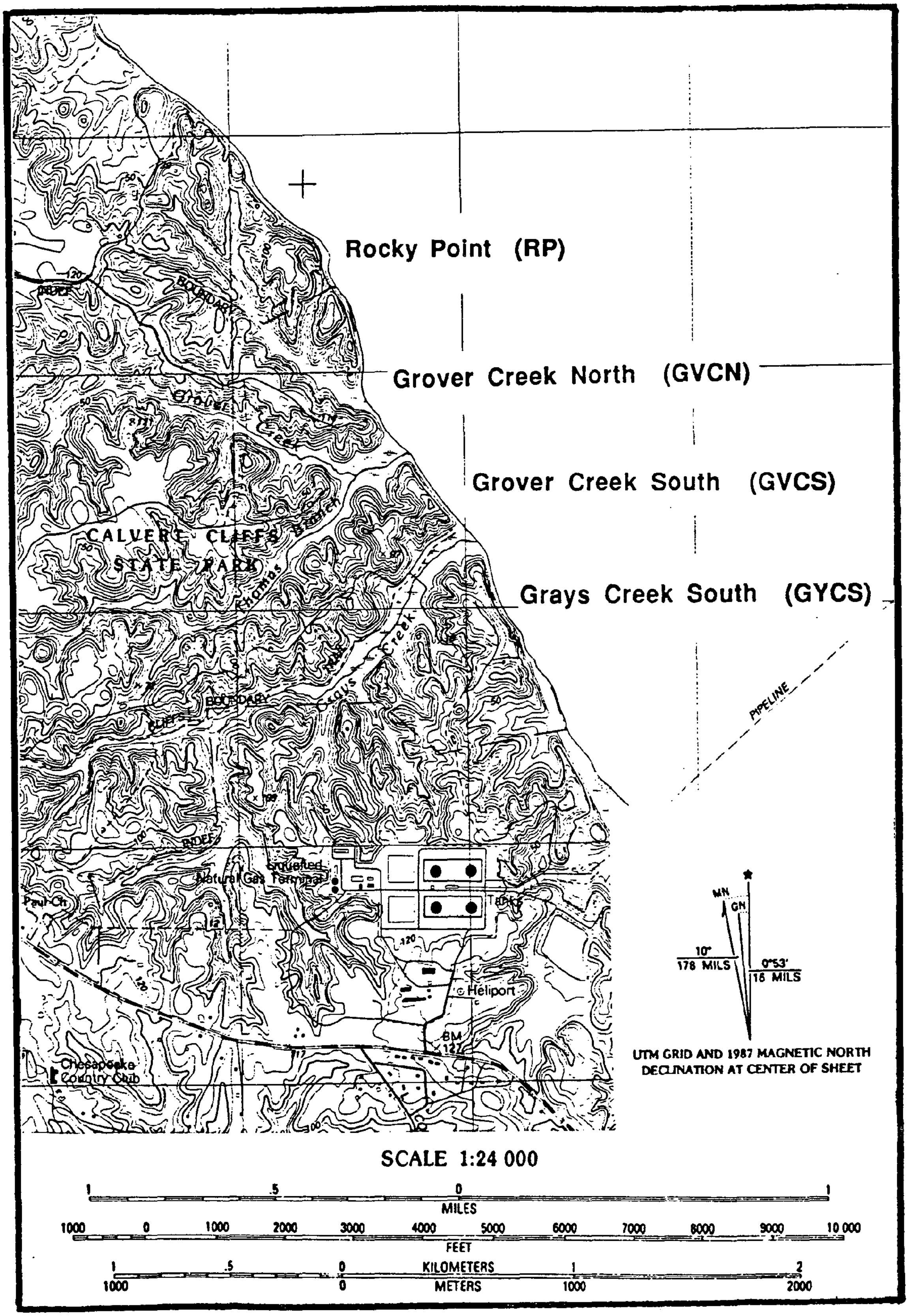
The surface drainage is quite homogeneous across the CCSP site. Surface water at the site drains toward the cliffs from an area extending approximately 250 m back from the cliff face. The cliff face is interrupted in three places by perennial streams. One or two groundwater seepage horizons are evident on the cliff face. A major seep occurs between 10 and 15 m from the cliff top at the contact between a coarse grain sandy unit overlying a gray clay. A smaller volume of seepage is discharged from a thin sandy unit approximately 4 m below the upper seep.

Geotechnical Properties

Six piezometers were installed at the GYCS subsite. They are designated CCSP1, CCSP2, CCSP3, CCSP4, CCSP5, and CCSP6 (see Figure 2.30). During the drilling, CCSP1 was sampled and SPTs were performed. Sampling was performed to an elevation of -2.3 m.

The site lies predominantly within the Miocene St. Marys formation. A small wedge of the highly fossiliferous uppermost Choptank Formation, the Boston Cliffs member (Kidwell, 1984) , occurs just above beach level at RP, but disappears below beach level within the GYCS subsite. A stratigraphic column was constructed for the piezometer site at the southern end of GYCS (Figure 2.30). A strong grain-size contrast occurs at approximately 8.4 m NGVD where a silty, dark gray sand overlies a 0.5m thick series of thinly interbedded sands and clays. The standard penetration test performed during the drilling of the piezometers indicated that the weakest portion of the materials comprising the CCSP slopes occur at and just above this contact (Figure 2.30).

The elevation at the well-head is 20.0 m. The root zone and soils are developed in a moist, orange-brown, silty, medium sand which is 1.6 m thick. A slightly moist, tan, medium sand containing traces of pea gravel and lenses of stiff white clay occurs at 18.4 m and extends to 16.8 m. A 3.1 m thick, slightly moist, light gray, silty clay with lenses of coarse sand is encountered next followed by a light gray to tan, mottled, fine sand with small amounts of silt and clay, the latter being saturated at about 12.3 m in elevation. The materials continue to be saturated as



Study Site CCSP:
Calvert Cliffs State Park

Figure 2.28

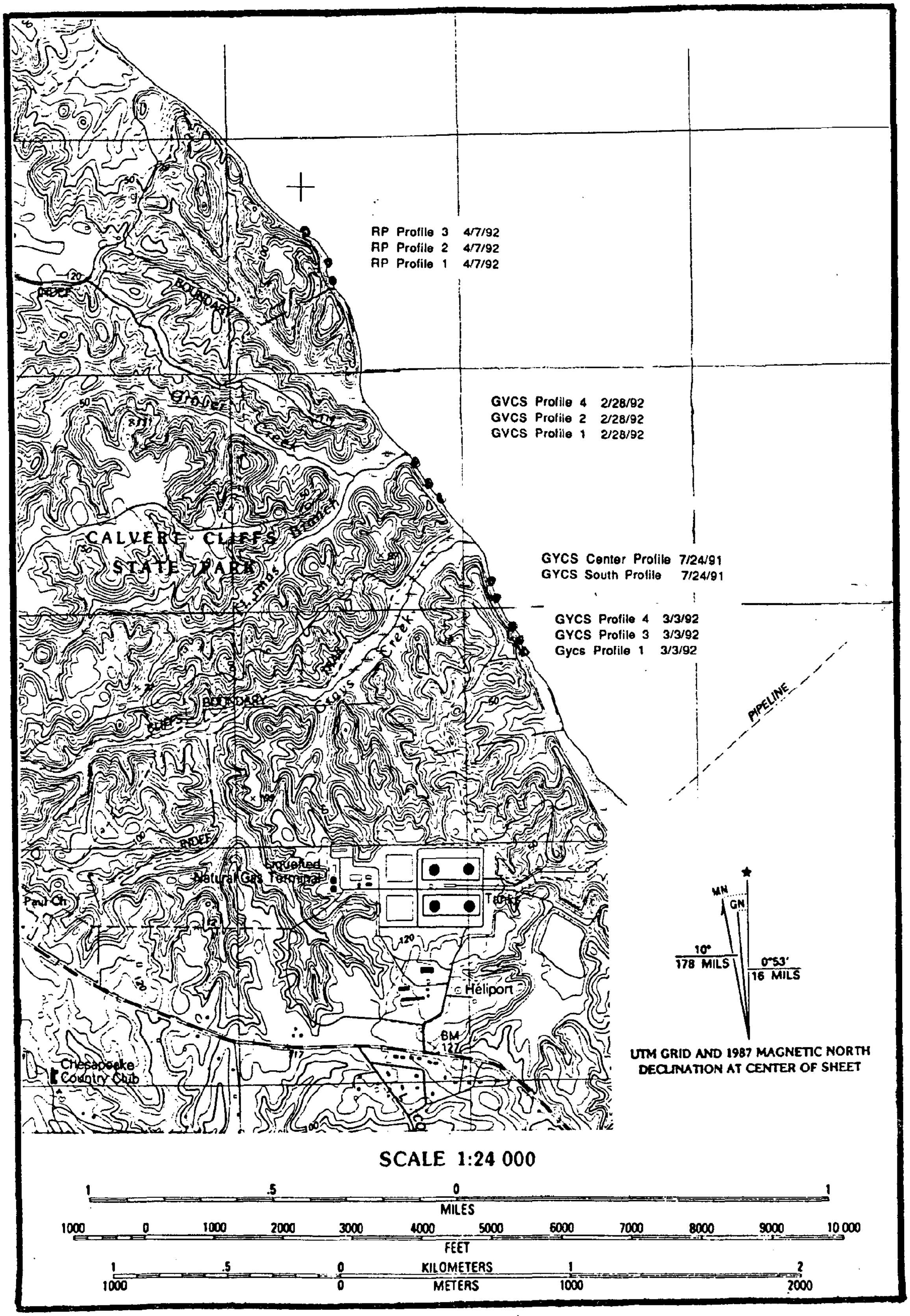


Figure 2.29

Study Site CCSP:
Locations of Slope Surveys

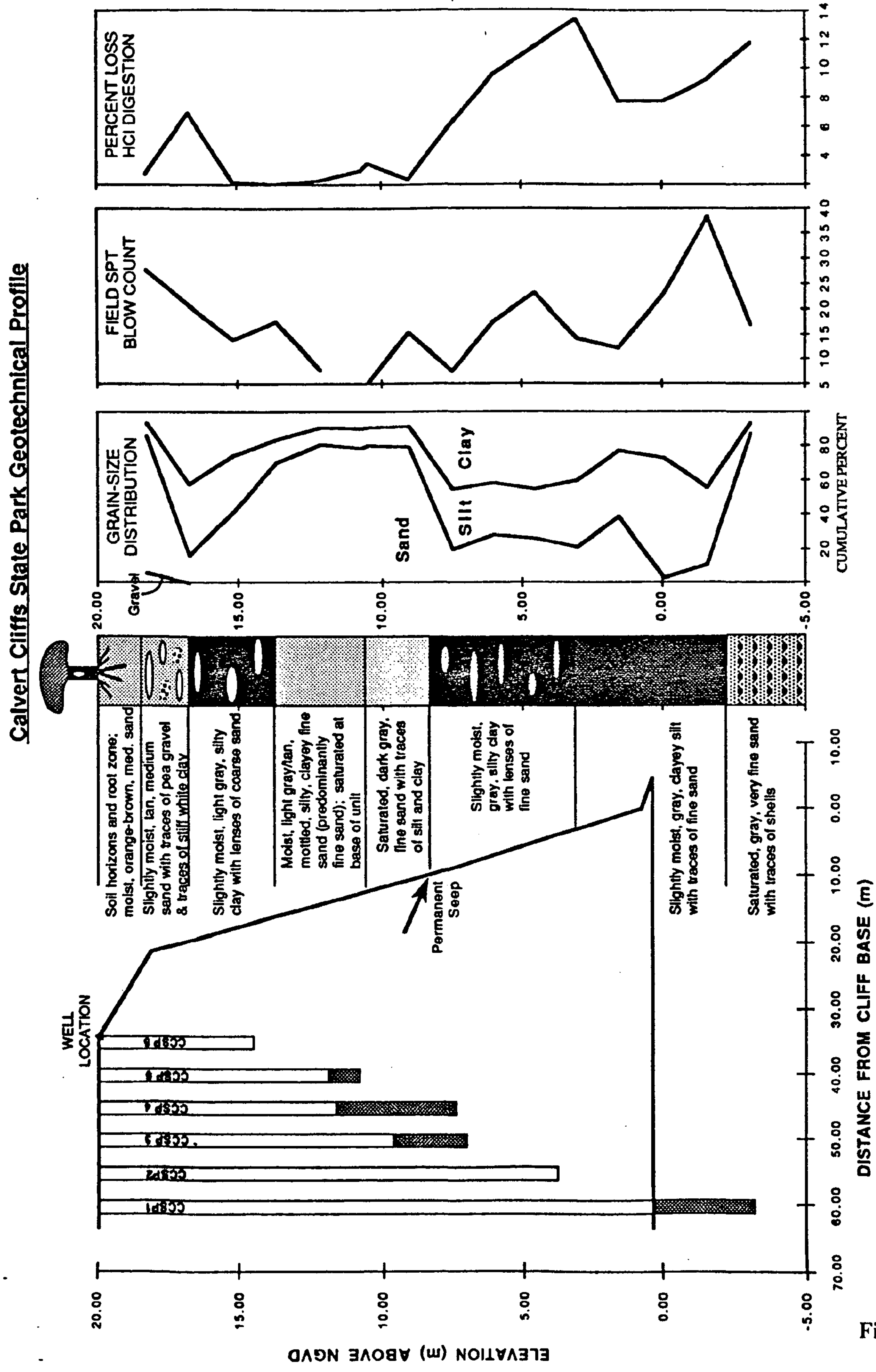

Calvert Cliffs State Park Geotechnical Profile
PERCENT LOSS
HCl DIGESTION
FIELD SPT
BLOW COUNT
GRAIN-SIZE
DISTRIBUTION
Gravel
Sand
Silt
Clay
CUMULATIVE PERCENT
Soil horizons and root zone; moist, orange-brown, med. sand
Slightly moist, tan, medium sand with traces of pea gravel & traces of stiff white clay
Slightly moist, light gray, silty clay with lenses of coarse sand
Moist, light gray/tan, mottled, silty, clayey fine sand (predominantly fine sand); saturated at base of unit
Saturated, dark gray, fine sand with traces of silt and clay
Slightly moist, gray, silty clay with lenses of fine sand
Slightly moist, gray, clayey silt with traces of fine sand
Saturated, gray, very fine sand with traces of shells
Permanent Seep
WELL LOCATION
CCSP1
CCSP2
CCSP3
CCSP4
CCSP5
CCSP6
ELEVATION (m) ABOVE NGVD
DISTANCE FROM CLIFF BASE (m)

Figure 2.30

they change to a dark gray color at 10.6 m. The grain size distribution remains remarkably similar across the color change; however, the material strength declines steadily from the surface down reaching a minimum at the color change.

At 8.4 m in elevation the units change from a dark gray, fine sand to a gray, silty clay with lenses of fine sand. The permeability contrast and saturation of the sand unit create a seepage zone at the base of the dark gray, fine sand. In several places along the cliffs at the Calvert Cliffs State Park site, this seepage zone is responsible for undercutting the weak sand above, resulting in small debris flows and slumps which create benches formed on the more cohesive layer below.

Below the base of the interbedded sands and clays which is located at approximately 8 m NGVD and extending to MLLW is a massively bedded sequence within which the grain-size of the sediments becomes finer in an upward direction. The base of the unit is composed of 39 percent sand, 39 percent silt and 22 percent clay. The material gradually fines until, near its top, at the base of the interbedded sands and clays, the material composition is 20 percent sand, 35 percent silt, and 45 percent clay. At 4.0 m NGVD, two thin, fine sand beds interrupt the sequence. They are each approximately 10 cm thick and separated by 0.5m of the parent unit. The sands are easily eroded and form lateral notches along the length of the GYCS site.

Below the thin beds of fine sands, the massive structure of the sand and silt unit is uninterrupted for 5.3 m. It exhibits the highest strength of all of the units in the Calvert Cliffs State Park profile; however, it is strongly jointed and tends to spall in large blocks along joint planes. Below the fining upwards sequence and extending to -2.3 m NGVD is a silty clay unit with very little sand. The upper most surface of the silty clay is found at MSL just north of the piezometer site and its upper surface forms a slippery erosional bench at beach level.

The Boston Cliffs member is found below the silty clay unit at approximately -2.3 m in elevation. The top of this bed is the top of the Choptank formation. The shell bed is a indurated, saturated layer with a gray sand matrix. The shell bed tends to be more resistant to wave erosion than the underlying strata, and less resistant than the overlying strata. Where the Boston Cliffs member is exposed near beach level, an undercut develops, forming a nose in the silt above. Eventually, the undercut nose fails along exfoliation planes and drops to the beach as large spalled blocks.

Slope Profiles (Figures 2.31to 2.41)

(Note: A dashed line representing the position of the intact slope is provided only on the profile figures where the slope toe is buried by debris).

Eleven slope profiles were surveyed at this site; three at RP, three at GVCS, and five at GYCS. The slopes just north of Rocky Point are steeper than the slopes further north or on the southern side (Figure 2.31). The lower slope stands at a steeper angle than the upper slope. The southern RP slopes display straight profiles with overall slope angles of 55 to 60 degrees(Figure 2.32). The steeper slopes just north of the point have steep lower slopes and somewhat gentler upper slopes with overall slope angles ranging between 60 and 65 degrees. The tallest slope surveyed is approximately 150 m north of Rocky Point, is 35 m high, and has an anomalous profile (Figure 2.33). It is quite steep in the lower slope and very gentle over the remainder of the slope. The slope angle is 47 degrees. All of the intact slope toes at RP are below MHHW. A narrow beach is present during low tide, but the slope toes are generally exposed to wave activity on a daily basis.

At the GVCS subsite, the slope angles range from 52 to 65 degrees. The intact slope toes are below MHHW. Although, in many places along the shoreline eroded debris provides temporary protection from the erosion of intact material by daily wave action. Near the southern end of the subsite the slopes are straight and steep (>74 degrees, Figure 2.34). In the central portion of this subsite, the lower slopes are steeper than the upper slopes displaying a two or three part profile depending on whether or not the roots maintain a vertical profile near the bluff top (Figure 2.35). The slope angles in this portion of the subsite range between 54 and 60 degrees. In the northern end of the subsite, the slopes have a straight, somewhat gentler profile, with slope angles ranging between 52 and 55 degrees (Figure 2.36)

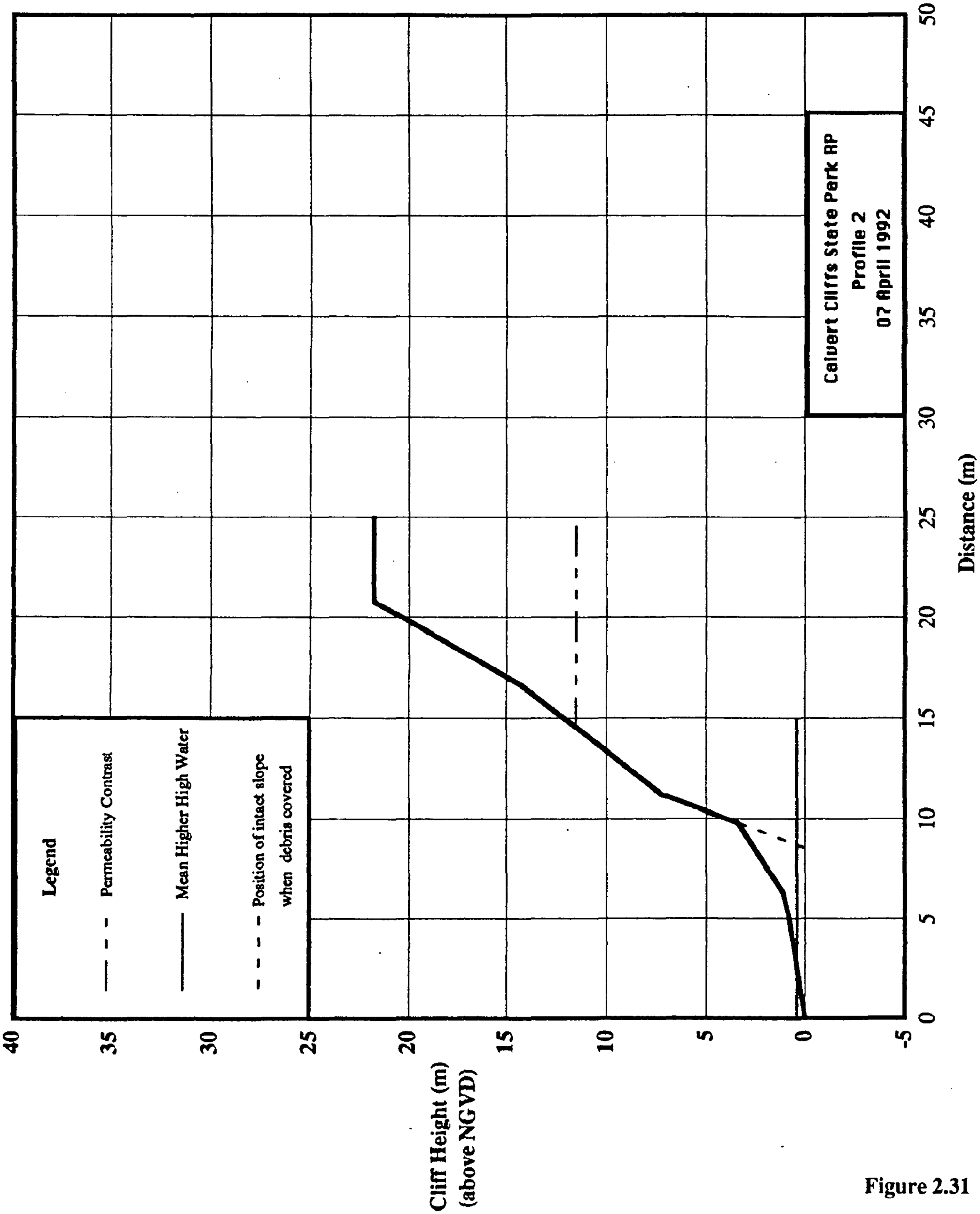

Calvert Cliffs State Park RP
Profile 2
07 April 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Distance (m)
0
5
10
15
20
25
30
35
40
45
50
Cliff Height (m)
(above NGVD)
40
35
30
25
20
15
10
5
0
-5

Figure 2.31

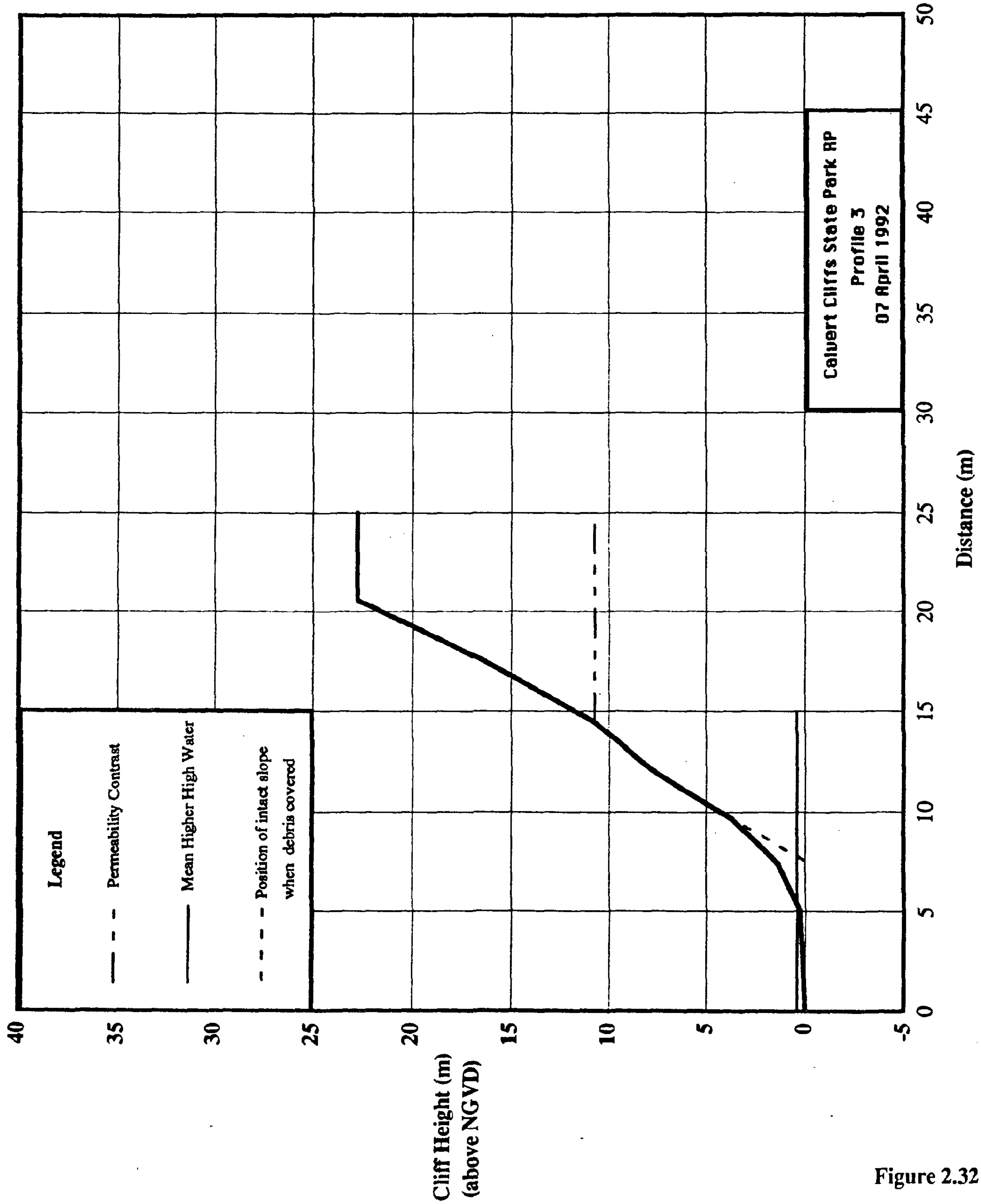

Calvert Cliffs State Park RP
Profile 3
07 April 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Cliff Height (m) (above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.32

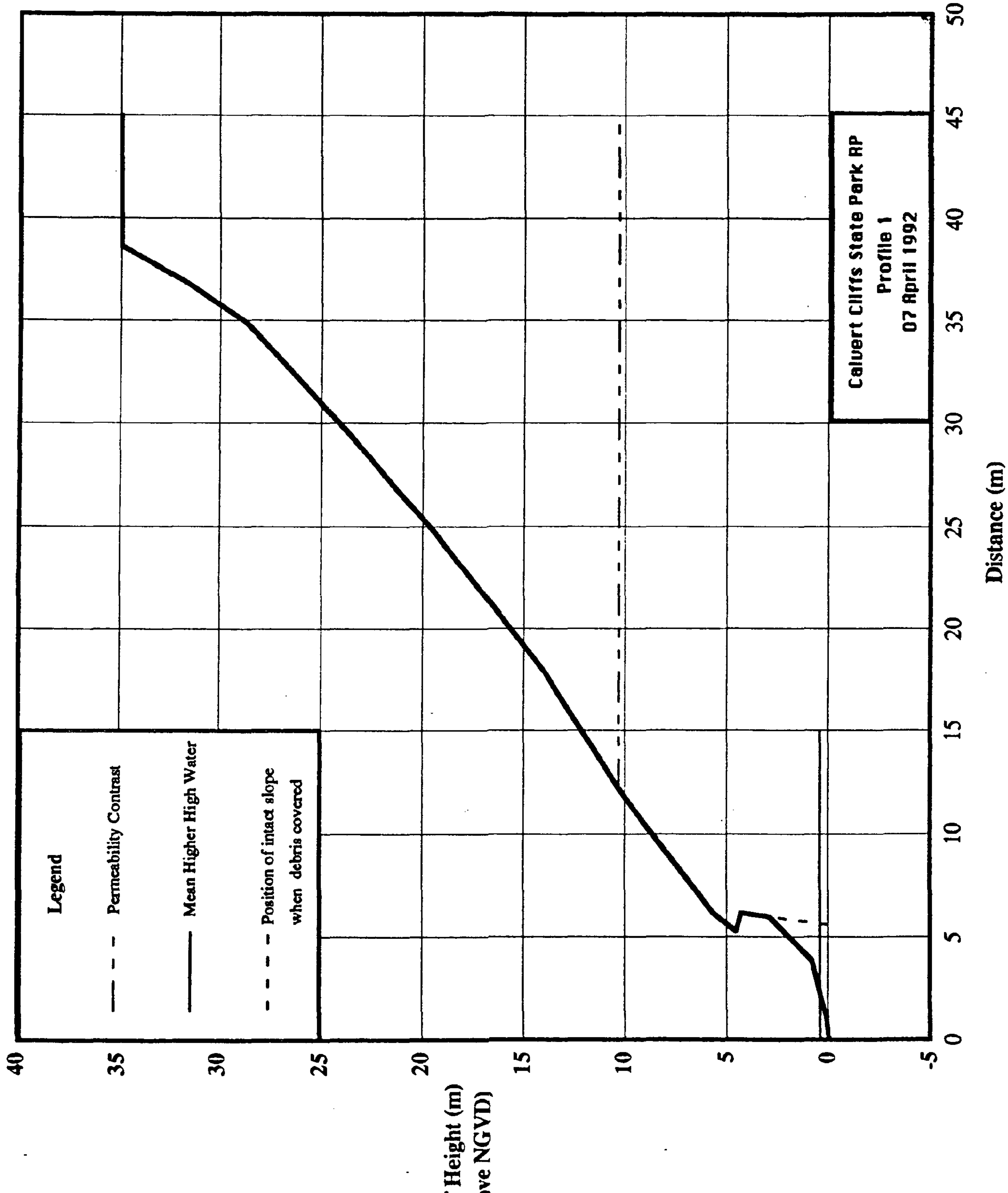

Calvert Cliffs State Park RP
Profile 1
07 April 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Cliff Height (m)
(above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.33

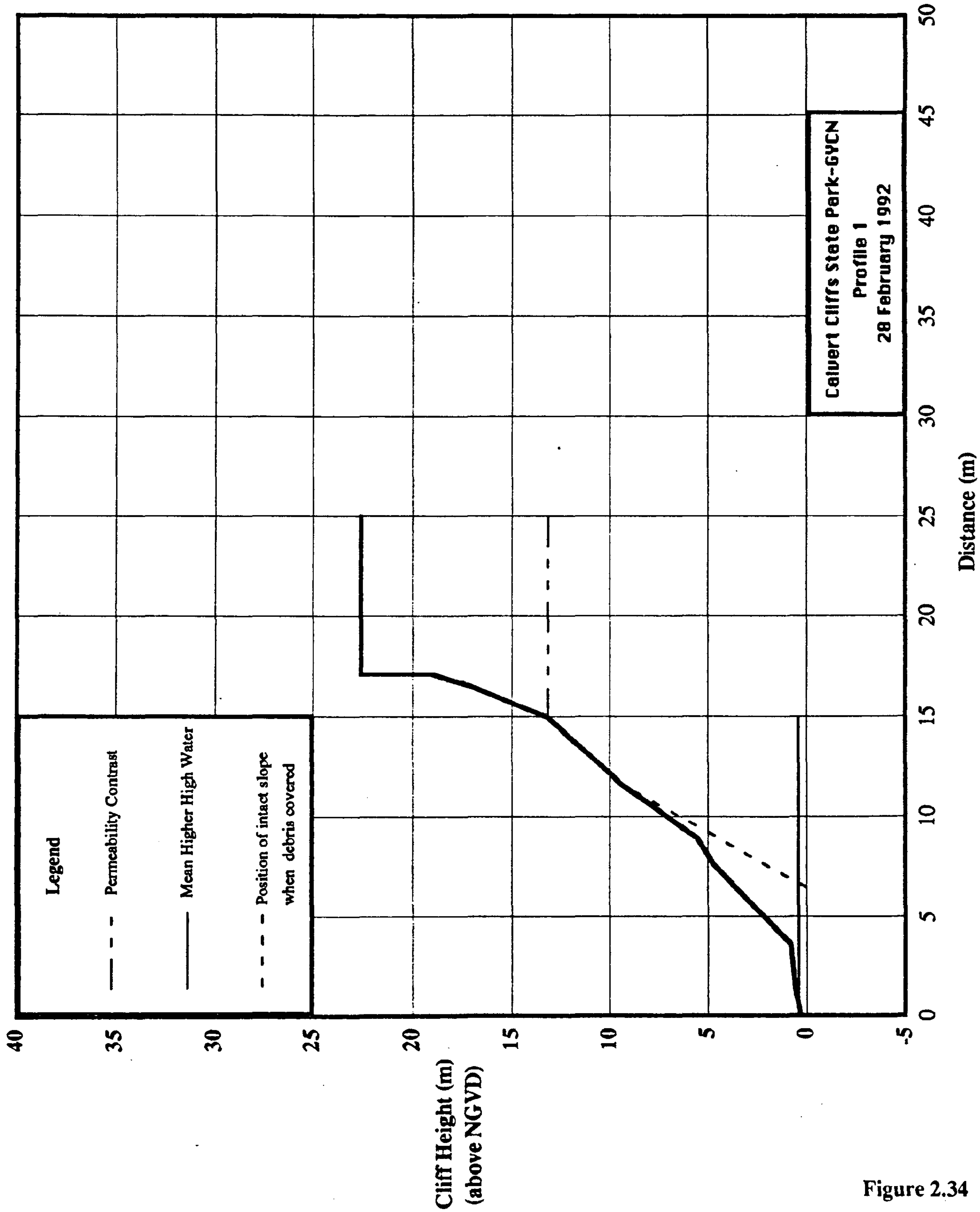

Calvert Cliffs State Park-GYCN
Profile 1
28 February 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Distance (m)
0
5
10
15
20
25
30
35
40
45
50
Cliff Height (m)
(above NGVD)
40
35
30
25
20
15
10
5
0
-5

Figure 2.34

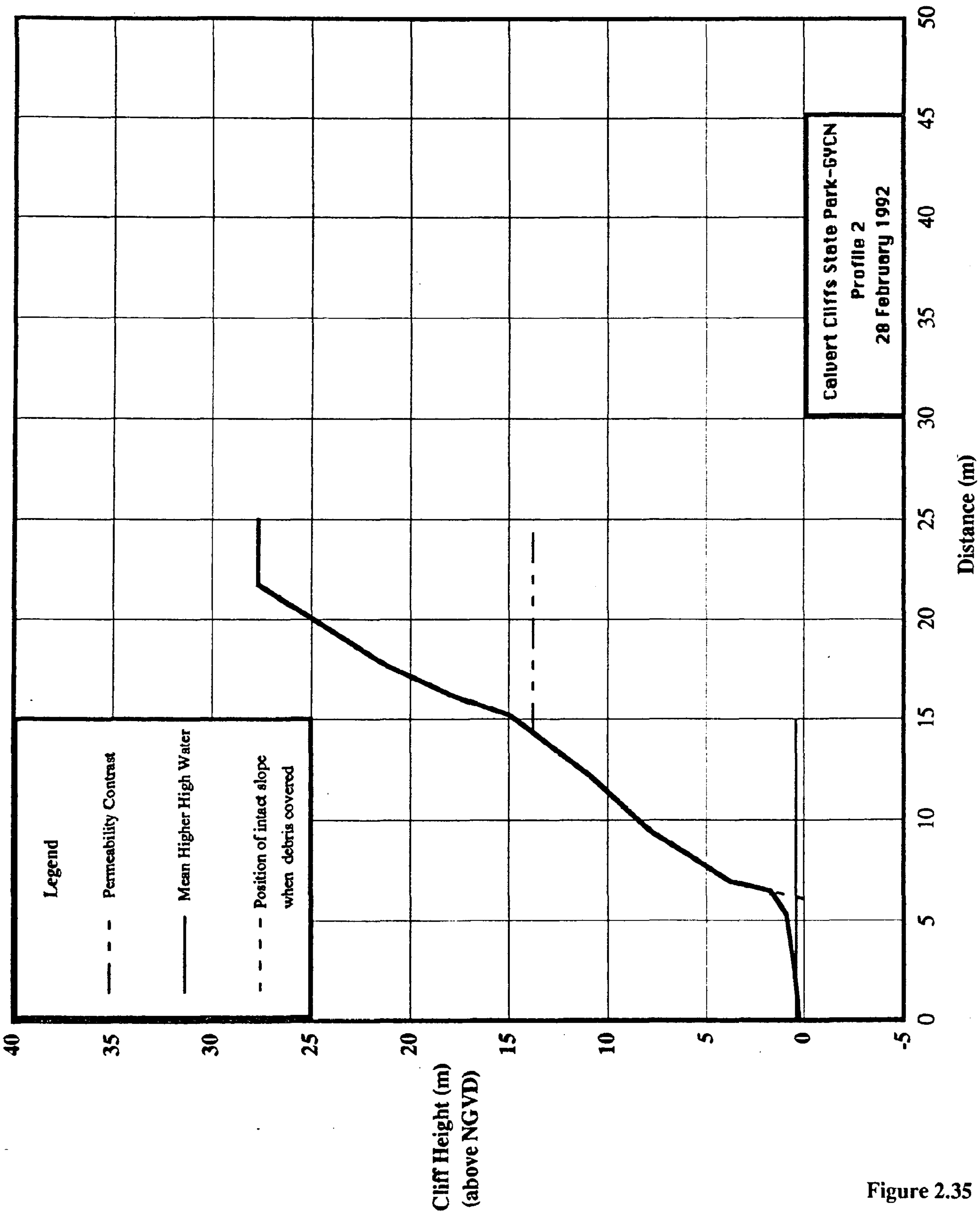

Calvert Cliffs State Park-GYCN
Profile 2
28 February 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Cliff Height (m) (above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.35

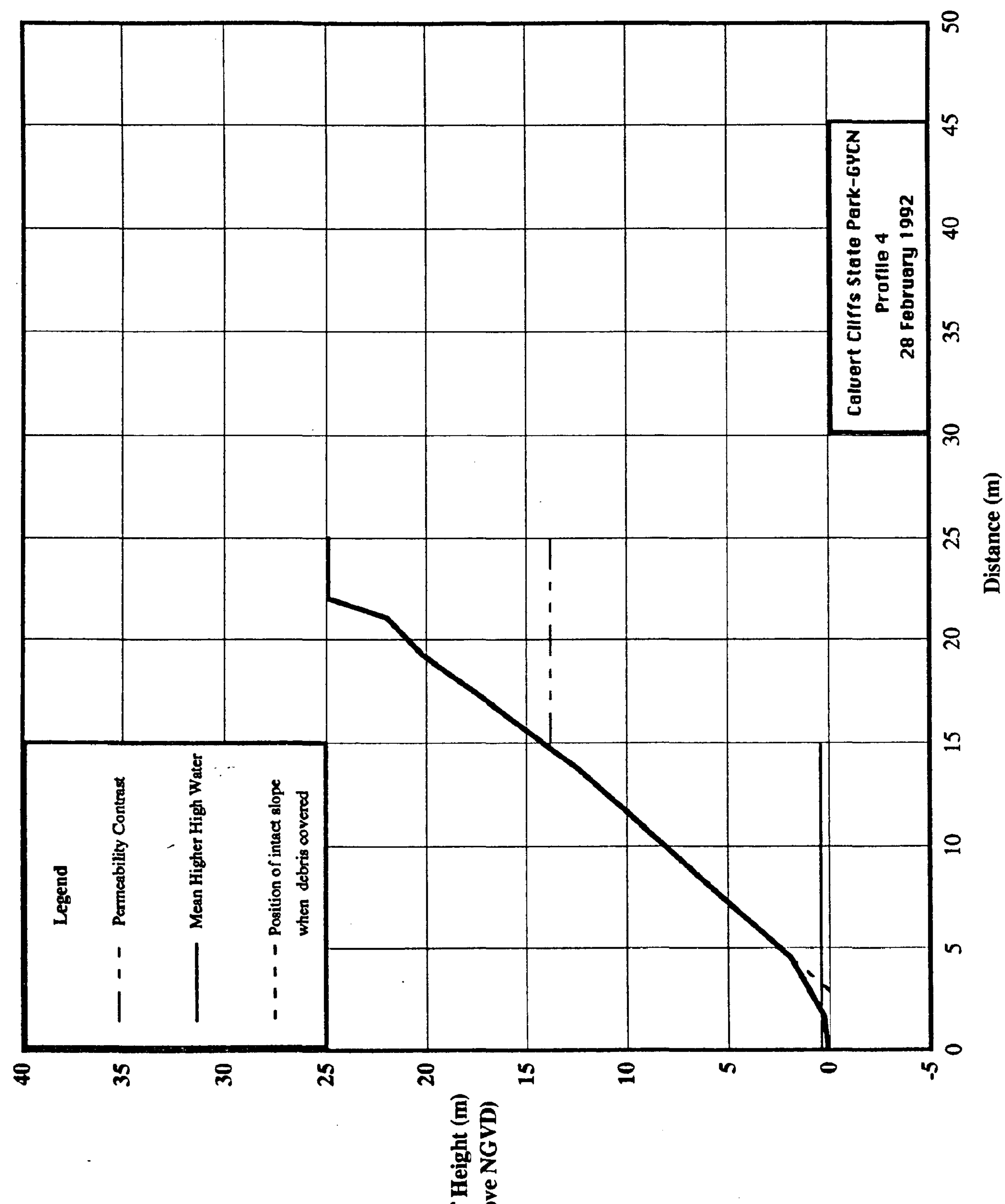

Calvert Cliffs State Park-GYCN
Profile 4
28 February 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Distance (m)
0
5
10
15
20
25
30
35
40
45
50
Cliff Height (m)
(above NGVD)
-5
0
5
10
15
20
25
30
35
40

Figure 2.36

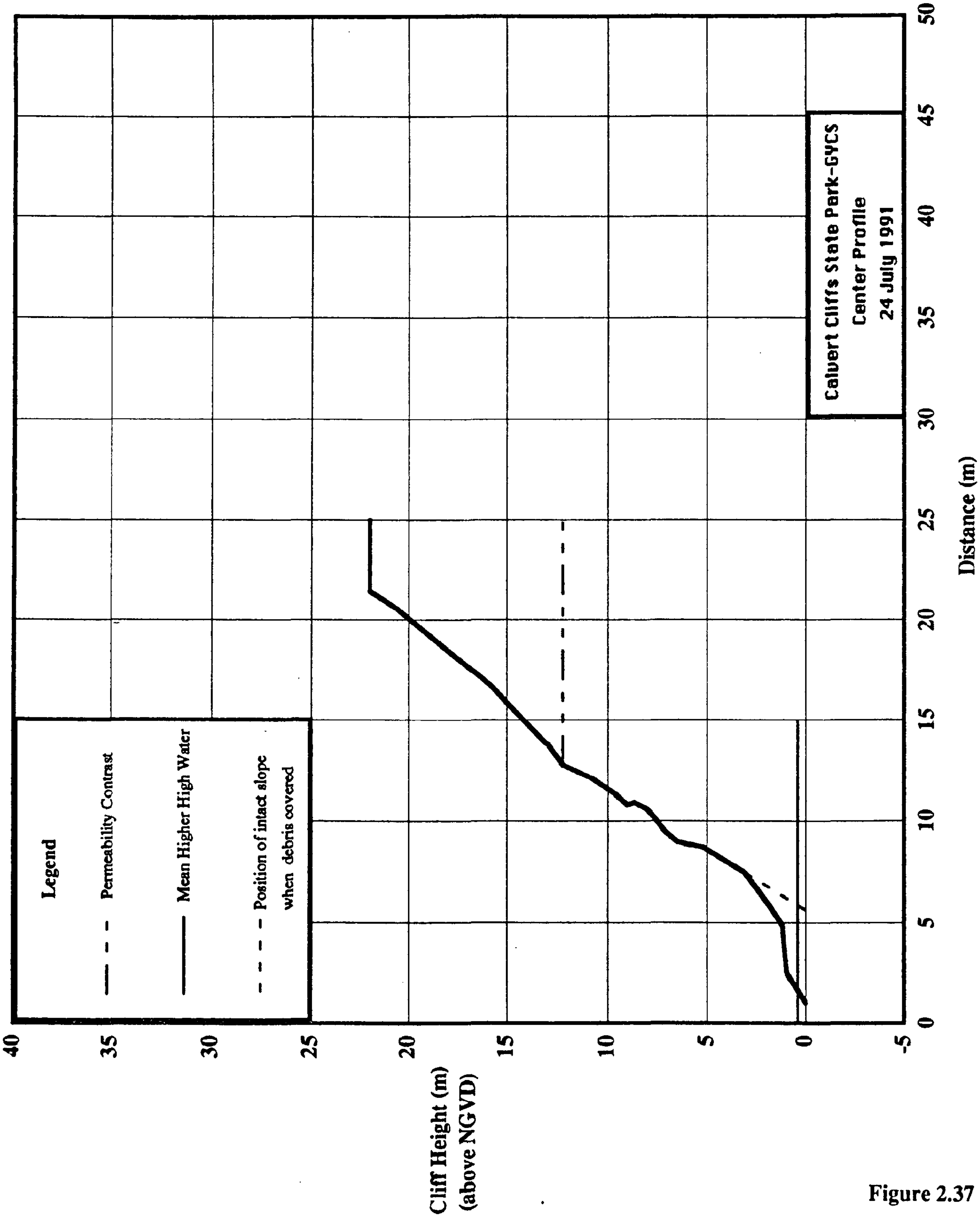

Calvert Cliffs State Park-GYCS
Center Profile
24 July 1991
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Cliff Height (m) (above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.37

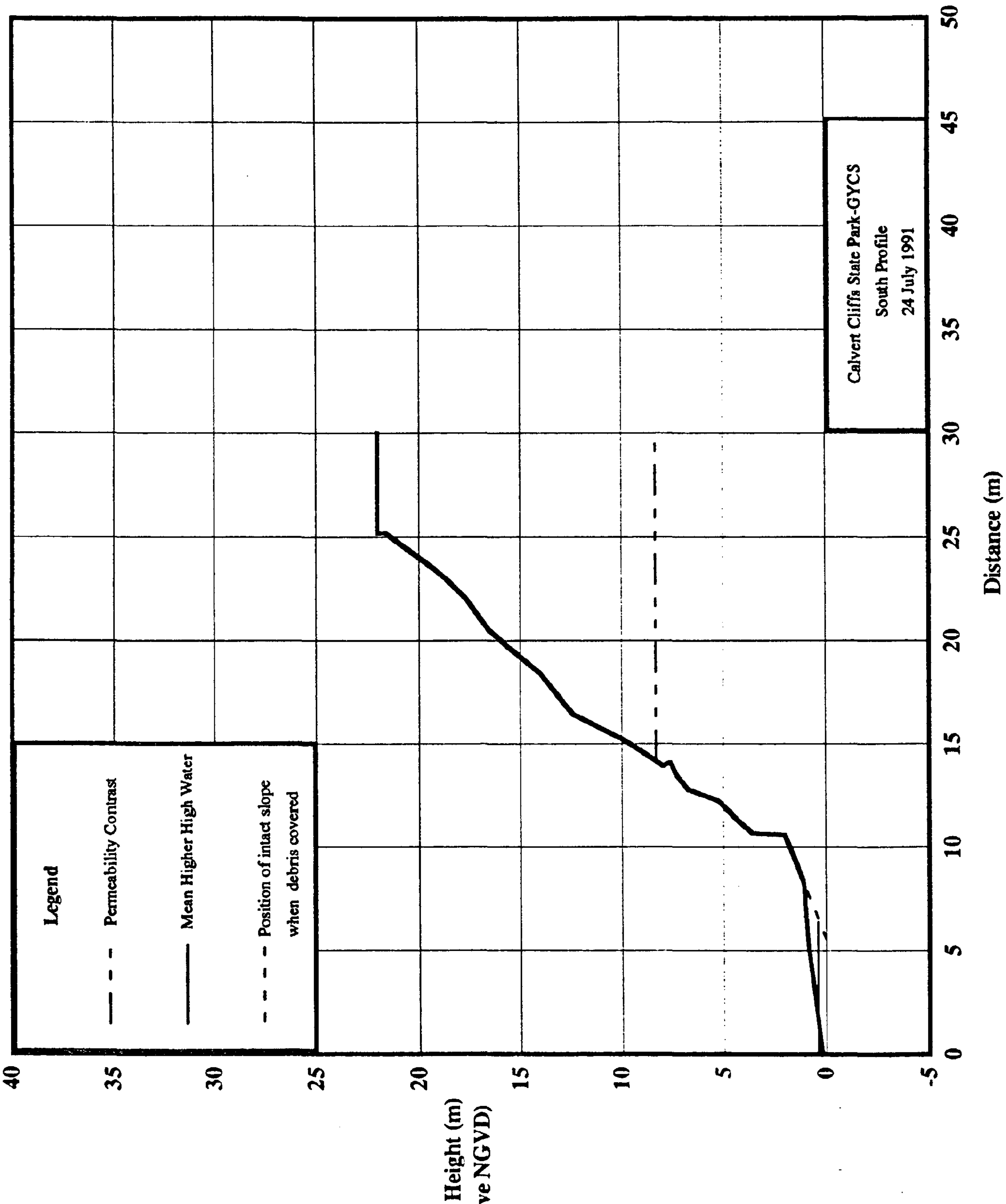

Calvert Cliffs State Park-GYCS
South Profile
24 July 1991
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Cliff Height (m)
(above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.38

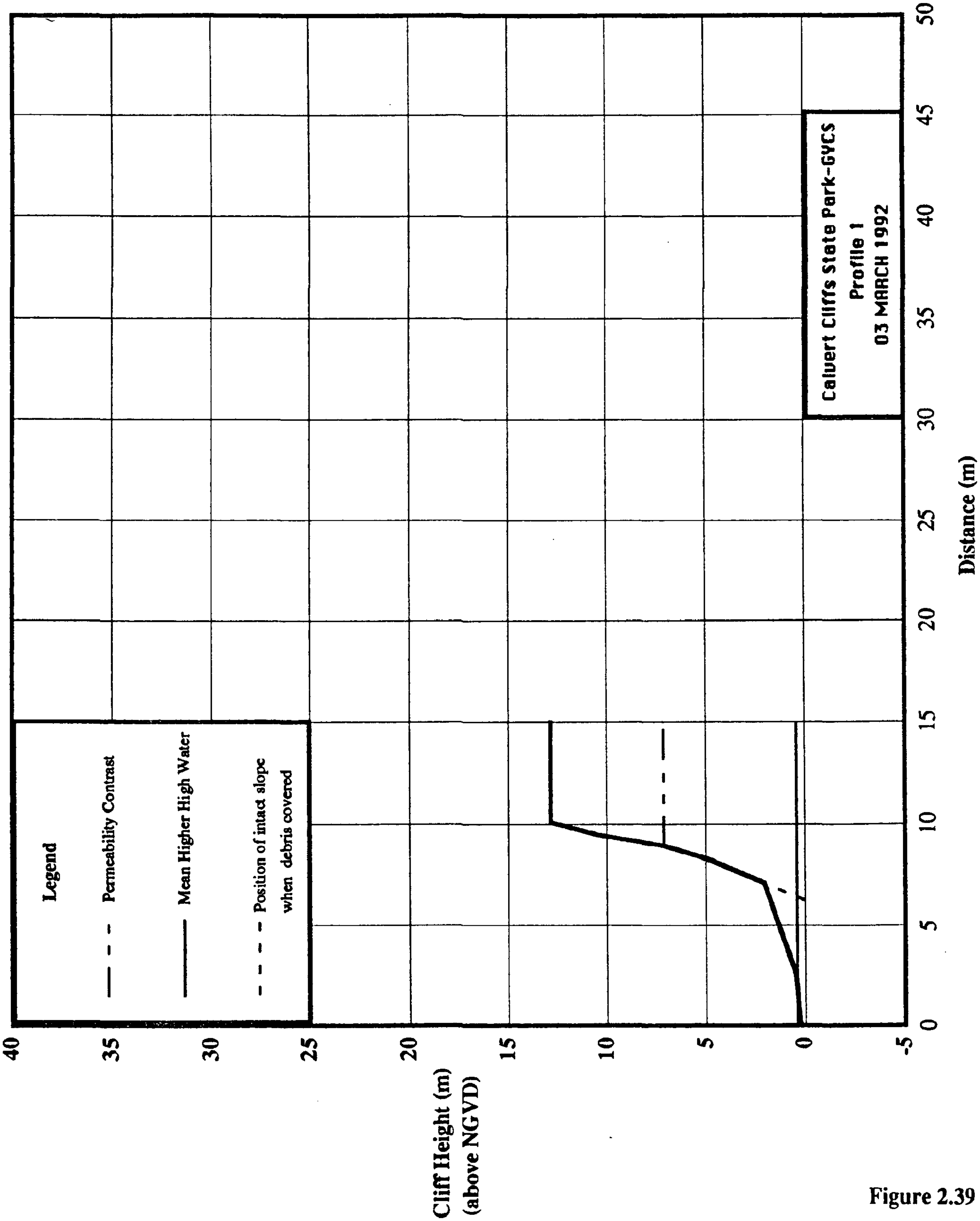

Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Calvert Cliffs State Park-GYCS
Profile 1
03 MARCH 1992
Distance (m)
Cliff Height (m)
(above NGVD)

Figure 2.39

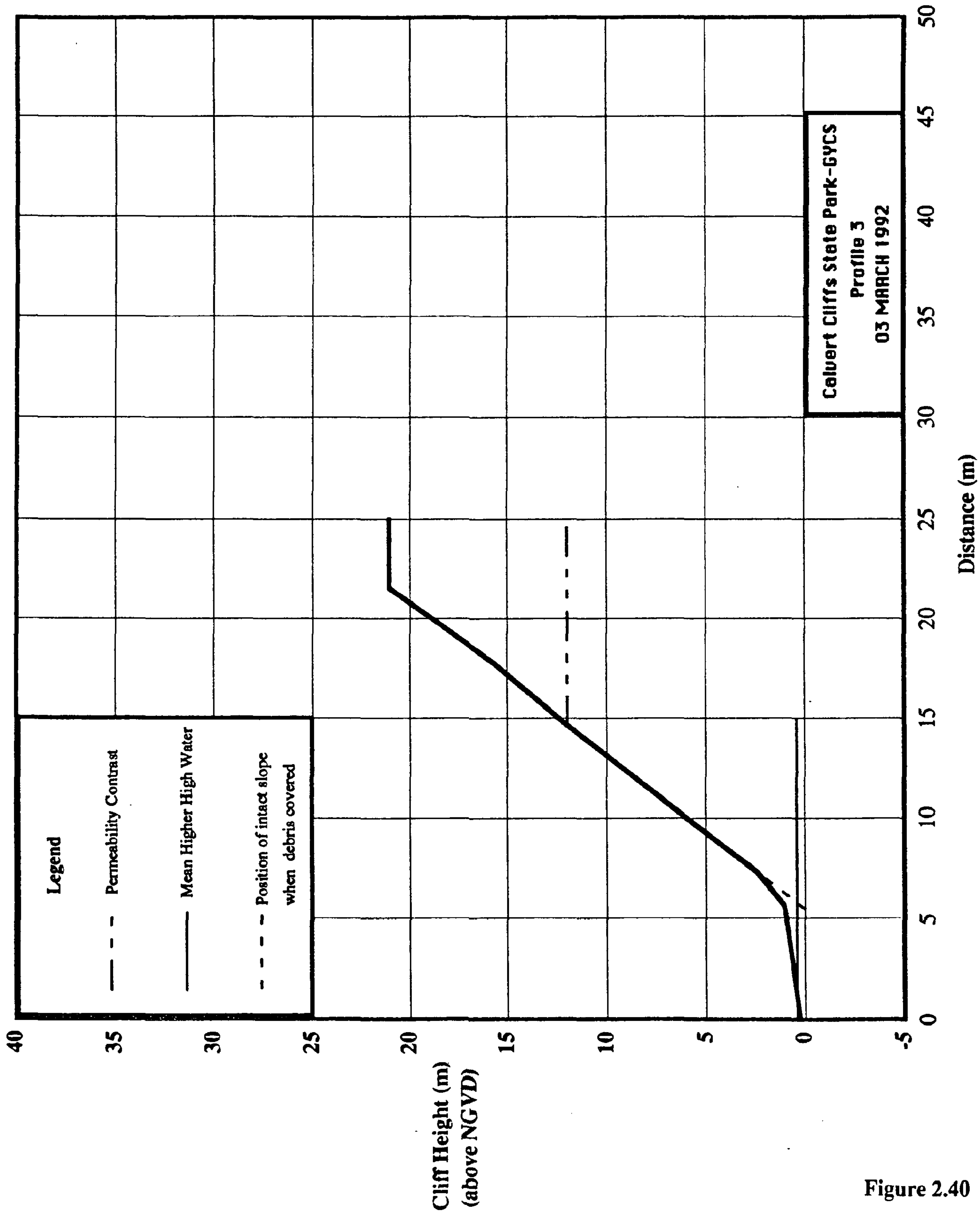

Calvert Cliffs State Park-GYCS
Profile 3
03 MARCH 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Cliff Height (m)
(above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.40

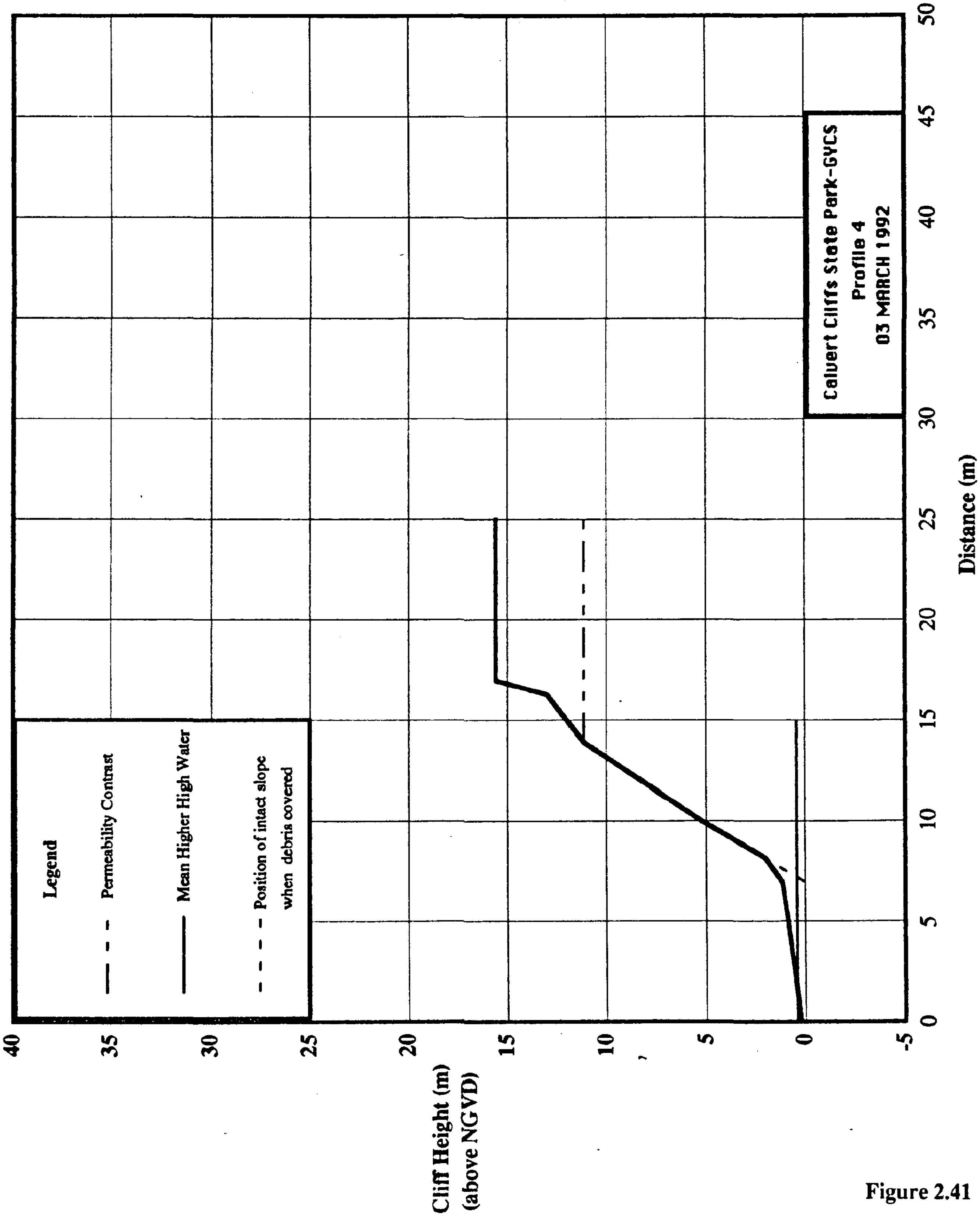
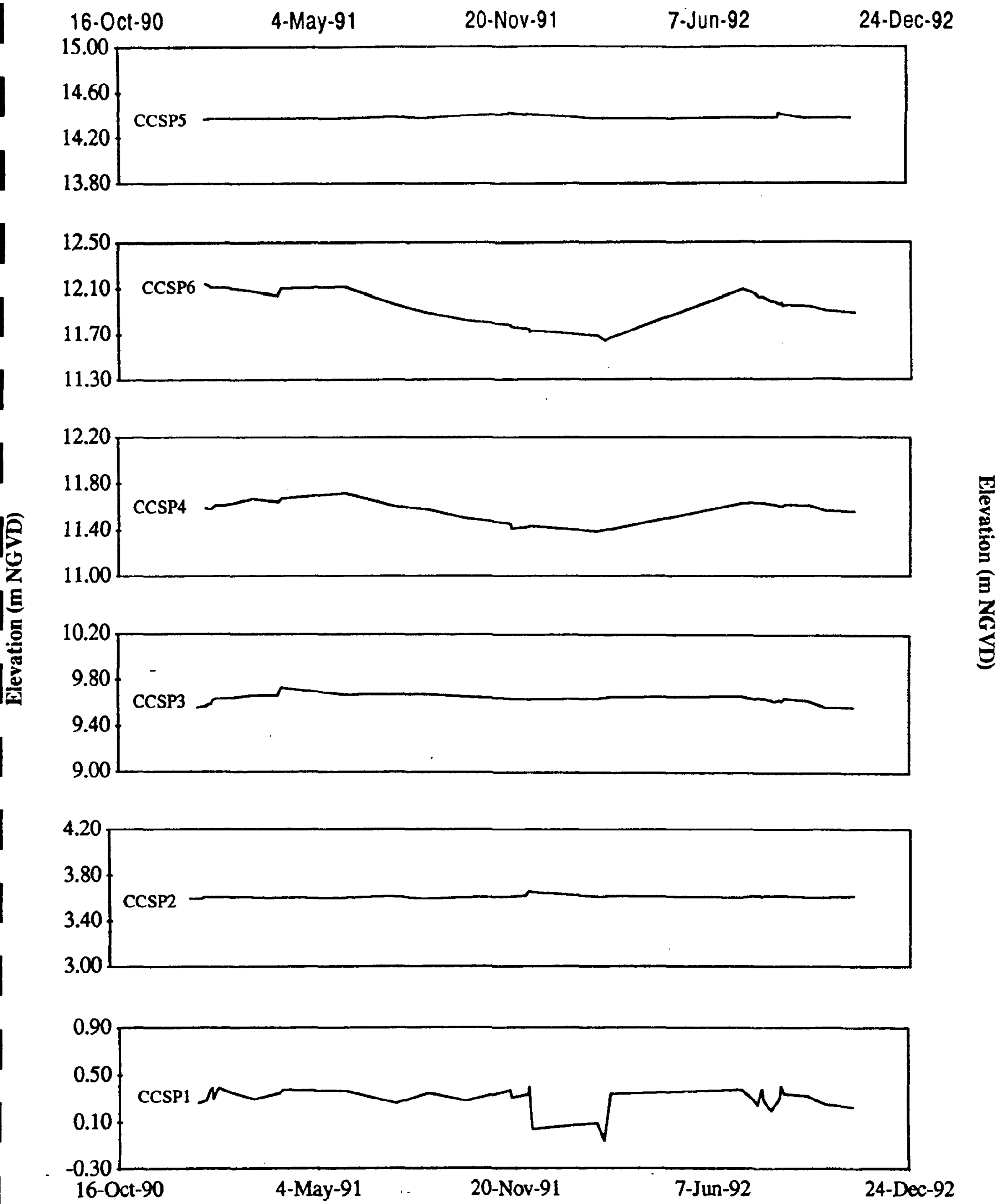

Calvert Cliffs State Park-GVCS
Profile 4
03 MARCH 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Cliff Height (m)
(above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.41

Groundwater levels (Figures 2.30 and 2.42)

A permanent groundwater table exists above 8.4 m NGVD. Surface water infiltrates over an area extending up to 200 m away from the bluff top and contributes to this groundwater zone. In tall slopes, a gravely, sandy, clay impedes the infiltration of water to the permanent groundwater table. Due to dissection by stream drainage, the clay is not laterally continuous and has not been observed to support a perched water table on its upper surface. The hydraulic conductivity of the relatively permeable zone between 8.4 and 17.2 m NGVD has been measured in-situ at 10^{-7} m/s (piezometer CCSP3). Piezometers CCSP3, CCSP5, and CCSP6 measure the piezometric surface at various intervals within this unit (Figure 2.42). The plot of water surface positions over time shows that this regional groundwater regime does not fluctuate rapidly, but varies gradually in response to the long-term hydrologic conditions of the Calvert Cliffs State Park. In the fine-grained material below 8.4 m NGVD, the hydraulic conductivity has been measured in-situ at 10^{-10} m/s (piezometer CCSP4).

Piezometer CCSP2 was installed at 4.0 m, the elevation at which the thin fine sand units occur. Although water is constantly present in the bottom of this well, the piezometric surface has not risen since observation began. This implies that the pressure in the sand is near atmospheric pressure. Piezometer CCSP1 extends into Boston Cliffs shell bed which is below sea-level at the well site. The water level in the well varies between MLLW and MHHW (Figure 2.42).



Time Series of Water Levels at CCSP Piezometers

Figure 2.42

Erosion Mechanisms

Site/Subsite: Calvert Cliffs State Park/Rocky Point

A few lenses of particularly durable, rock-like sediments are found along the Calvert Cliffs. The physical and chemical changes that occur in the sediments to create this rock-like material is known as induration. Induration is the key difference between the slopes at RP and the other slopes of the Calvert Cliffs State Park Site. Induration is apparent in all seepage zones. Laterally continuous, horizontally bedded ironstone formations form sheets of high shear strength which increase in thickness and number moving north from Grover Creek to Rocky Point. These sheets reinforce the slope and prevent major slumps or rotational events. However, surface runoff and sapping erosion carry sizable quantities of unconsolidated material to debris fans at the base of the slopes.

<u>Lower Slope</u>. Stratigraphically, the toe zone is entirely occupied by the shell bed described in the toe zone of the north end of the GYCS subsite. However, debris from slope activity above has largely covered the slope toe. Between the narrow triangular tops of the debris fans the face of the shell bed is evident and it exhibits a nearly vertical or, in some locations, a slightly concave profile.

<u>Midslope</u>. Immediately overlying the shell bed is an indurated sheet of ironstone nearly one meter thick and laterally very extensive. The shell bed below is eroded to the degree that the ironstone is cantilevered in many places and large rectangular fragments of ironstone litter the beach. From the bases of the debris fans on the beach to the base of the root zone near the bluff top, the slopes exhibit a regular inclined profile which is less steep that the profile at the GVCS subsite and nearly equivalent to the incline of the profile at the GYCS subsite.

Spalling is not as frequent along these slopes as at GVCS and tends to occur in thin sheets. In addition to spalling, physical and chemical weathering reduce the outer few centimeters of the slope face to a loose veneer which is removed by surface wash during rain storms. During rainfall, the weathered surficial material may become a viscous slurry and flow slowly down the slope. Material which doesn't reach the toe dries on the slope face until the next rain.

Seepage occurs above the ironstone horizons and produces sapping erosion, particularly near the top of the silt-clay unit. Within the overlying sand horizons, the thickness and induration of the ironstone decreases with increasing elevation. These ironstone layers do lend some stability to the upper unsaturated zone, which is very tall in places. Virtually no slumping of the unsaturated zone is evident, in contrast with the slumped unsaturated horizons at GVCS and at the Chesapeake Ranch Estate's Laramie Lane subsite.

Physical and chemical weathering of the slope surface combine with seepage and storm runoff to erode material from the slope and deliver it to the debris fans below. Large gullies extending the entire length of the slope are common at this subsite. The gullies tend to terminate on ironstone sheets especially where the sheets are cantilevered over the slope below.

Upper Slope. The bluff top is nearly vertical where bound together by tree roots. Virtually no trees are found on the beach along this section. indicating a relatively stable bluff top.

Site/Subsite: Calvert Cliffs State Park/Grover Creek South (GVCS)

Stratigraphically GVCS and GYCS are similar. However, the two sites are different hydrologically. GVCS has much smaller groundwater recharge area than GYCS. A comparison of these two subsites highlights the difference that the presence of groundwater seepage makes in coastal erosion process.

Lower Slope. Stratigraphically, the slope toe is entirely occupied by Boston Cliffs member of the upper Choptank. This is a sandy, fossiliferrous material easily eroded by waves. However, debris from slope activity above has covered much of the slope toe along the shoreline. Above the beach level debris fans, the intact silt-clay formations are exposed and their faces stand at steeper angles than the faces at GYCS. The silt-clay exposures show evidence of numerous spalling events and less freeze-thaw fracturing. It is likely that the tide level shell bed was eroded from beneath the silt-clay formations causing the silt-clay faces to be undercut and spall. Such a process is actively occurring at the north end of the GYCS subsite and is described below.

Midslope. Where the intact face is exposed, the slopes here tend to be steeper that those of the GYCS site. Spalling is more common and the individual events larger. This is principally due to the oversteepening of the slope below translating up slope - the steeper the slope, the greater the tensile stress on spalling faces, and the more frequent and larger the spalls. In addition, the lower rate of groundwater discharge from the perennial seep produces less surficial erosion than at GYCS. Surficial erosion by water tends to reduce the slope angle.

In addition to spalling, physical and chemical weathering reduce the outer few centimeters of the slope face to a loose veneer which is removed by surface wash during rain storms. During rainfall, the weathered surficial material may become a viscous slurry and flow slowly down the slope. Material which doesn't reach the toe dries on the slope face until the next rain.

Seepage and sapping erosion occurs at the same stratigraphic locations as at the GYCS subsite, but all seeps seem to be slightly less active than those at GYCS.

Upper Slope. As the oversteepening proceeds upslope it undercuts the leached and less coherent materials of the unsaturated zone. These materials slump when undercut, building a fan-like pile at the toe on top of the blocky debris previously spalled from the slope. The top two meters of the slope tend to stand in vertical faces or form overhangs due to the binding effect of tree roots. It is evident that the undermining of the bluff top has occurred rather rapidly. Trees and vegetative mats that have fallen from the bluff top are still alive indicating that their roots have not been exposed long enough to kill the plants. It should be noted here that there are many more downed trees on the beach along this section of slope than at the GYCS subsite.

During Tropical Storm Danielle, the GVCS subsite experienced the removal of large quantities of toe debris and active undercutting of the Boston Cliffs shell bed. This indicates that the toe debris offers no long term protection from wave attack.

Site/Subsite: Calvert Cliffs State Park/Grays Creek South (GYCS)

Lower Slope. Daily waves and tides are capable of removing all of the unconsolidated debris reaching the toe from the upper portions of the slope. The Boston Cliffs shell bed in the toe zone is actively being undercut by normal daily wave activity along the northern end of the subsite. The bed is densely fossiliferrous and the matrix surrounding the shells is a medium sand cemented with calcium carbonate. The shell bed dips below mean high tide at the Grays Creek site and is exposed above water level along approximately 200 m of shoreline. Above the shell zone, the lower slope fails by surficial erosion of weathered material by groundwater seepage and direct precipitation.

Midslope. Above the shell bed and above the beach where the shell bed is below tide, the slope maintains a relatively smooth, straight profile to the base of the root zone near the bluff top despite the existence of two sapping zones and two major changes in material composition. An 11 m thick sequence of clayey silts and silty clays extends from beach level to a contact with a unit of fine sand at which a permanent seep occurs. The mid-slope units are eroded in nearly equal proportions by two processes, surficial removal of weathered material and sheet spalling.

Physical and chemical weathering reduce the outer few centimeters of the slope face to a loose veneer which is removed by surface wash during rain storms. During rainfall, the weathered surficial material may become a viscous slurry and flow slowly down the slope. Material which doesn't reach the toe dries on the slope face until the next rain.

In addition to surface wash, the exposed surface material spalls in thin sheets along planes sub-parallel to the slope face. Spalling surfaces are ubiquitous in materials with high proportions of silt. Large spalls are uncommon at this subsite with the single exception of a large, blocky spalling event just south of the mouth of Grays Creek. Here, the toe zone shell bed was sufficiently undercut to cause a 5 m tall X 5 m wide X 1-2 m thick block to fail along a slope-parallel tension crack in Spring, 1991. Observers noted the widening of the tensional crack over a period of several weeks prior to the collapse. Since the collapse, the less consolidated material above the spalling cavity has slumped onto and buried the spalled blocks creating a fan like structure in the toe zone. Currently, such large block spalling is an anomalous condition along this slope. It is worth noting, however, that the large spall occurred along the section of slope undergoing the most severe undercutting.

Midway up the silt-clay sequence are two thin layers of fine sand separated by a massive silt layer. The sand layers are each 15 to 30 cm thick and the separating massive silt ranges between 20 and 40 cm in thickness. The sands are saturated and experience sapping erosion at the cliff face. The sapping zones are expressed on the cliff face as two horizontal gaps and are laterally continuous along the entire extent of this subsite. While their undercutting effects are minimal, they are capable of supplying a nearly continuous supply of water to the lower slope face. The moisture tends to accelerate physical and chemical weathering and may promote the weakening of near surface spalling faces.

Upper Slope. Overlying the 11 m thick silt-clay strata is a 6 m thick sequence of predominantly fine sand overlain by a 4 m thick sequence of silts and clays which become progressively more fine-grained until the root zone is encountered approximately 2 m below the bluff top. The fine-grained units near the surface are dissected in places by drainage channels and do not form a continuous horizontal barrier to infiltrating water. However, they tend to retard the rate at which the groundwater can move into the sandy units below. Hence, intense piping of groundwater at the sand/silt-clay interface tends to be less common than sapping. A permanent seep exists at the base of the sand unit at an elevation of 8-11 m.

A rare deep-seated rotational slump is apparent at the south end of GYCS slopes. The rotational failure surface originated in the saturated zone at the sand/silt-clay interface. The failure is intimately associated with a 0.5 - 1 m thick lens of ironstone formed within the saturated lower portion of the fine sand unit. The majority of the ironstone now rests as a debris pile resulting from a collapse of the layer. No witnesses have described the actual failure, but the configuration of a small remaining block of ironstone on the current slope indicates that the silts below were eroded by sapping and surficial erosion of weathered material, leaving the ironstone to form a cantilever support for the relatively independent slope above. The ironstone overhang eventually collapsed, truncating the toe of the upper slope and reducing its ability to maintain rotational equilibrium.

2.5 Chesapeake Ranch Estates

General Site Description

The site encompasses the shoreline and cliffs from Cove Point Hollow to Seahorse Beach (Figure 2.43). The subsites are Cove Point Hollow (CPH), Little Cove Point (LCP), Laramie Lane (LL), and Seahorse Beach North (SBN).

The cliff orientation ranges from east-northeast at CPH to southeast at SBN. The shoreline along the cliffs is unprotected except for a few groins at Driftwood Beach and Seahorse Beach, where no cliffs are present. During the summer of 1992, the groins at Driftwood Beach were extended and a revetment was constructed along the shoreline. A small beach is present during most tidal conditions along the entire site, except at the locations where slide debris extends to the low tide line. One notable exception is at the LCP subsite, where the cliff face extends into the water. One or two shore-parallel sand bars are found along most of the site.

The slope heights vary between 12 and 35 m across the CRE site. Slope angles also have a wide range at this site. Several of the short slopes are nearly vertical. The tallest slopes range between 55 and 65 degrees and the angles of slopes of moderate height may vary between 50 and 75 degrees.

At the CPH subsite, slope angles range between 55 and 75 degrees. The slope height varies between 18 and 30 m. The slopes at LCP have the shallowest angles of the CRE slopes, ranging between 50 and 60 degrees. Slope heights at LCP vary between 16 and 25 m. The slopes at the LL subsite are distinctly different from those at LCP, but similar to those at SBN. They range in height from 15 to 35 meters and are characterized by steep, nearly vertical bases, more gentle mid-slopes (40-60 degrees), and a nearly vertical bluff top. Three large recent slides have occurred in the upper materials at the Chesapeake Ranch Estates. The slide debris has accumulated at the slope toe giving the entire slope a moderate, nearly uniform profile at an inclination of approximately 50 degrees. The debris is being gradually removed by wave action over a period of one to three years. At the SBN subsite the slopes are 12 to 30 meters high and are inclined at angles of 55 to 80 degrees.

The site lies entirely within the Miocene St. Marys Formation. There is some question as to the age of the top 15 meters of coarse grained sediments. For our purpose, it is important to note that the geotechnical properties of the upper 15 meters is distinctly different from the lower 15 meters of cliff (Figure 2.45). The lower portion of cliff is comprised of interbedded fossiliferous sands, silts, and clays. The upper 15 meters is composed of coarse grained sands with some pebbles and gravels. Ironstone is present in laterally discontinuous patches up to one meter thick.

From the northern end of the LCP subsite to the LL subsite, surface drainage originates from as far as 700 meters from the cliff face. Along the northern portion of the SBN subsite, drainage toward the cliffs extends 350 meters from the cliff face. Surface drainage at along the southern portion of the SBN subsite is essentially that of a hilltop. Groundwater seepage is generally very active at the base of the coarse grained sands of the upper cliff sections. It is particularly strong where topographic lows intersect the cliff face.

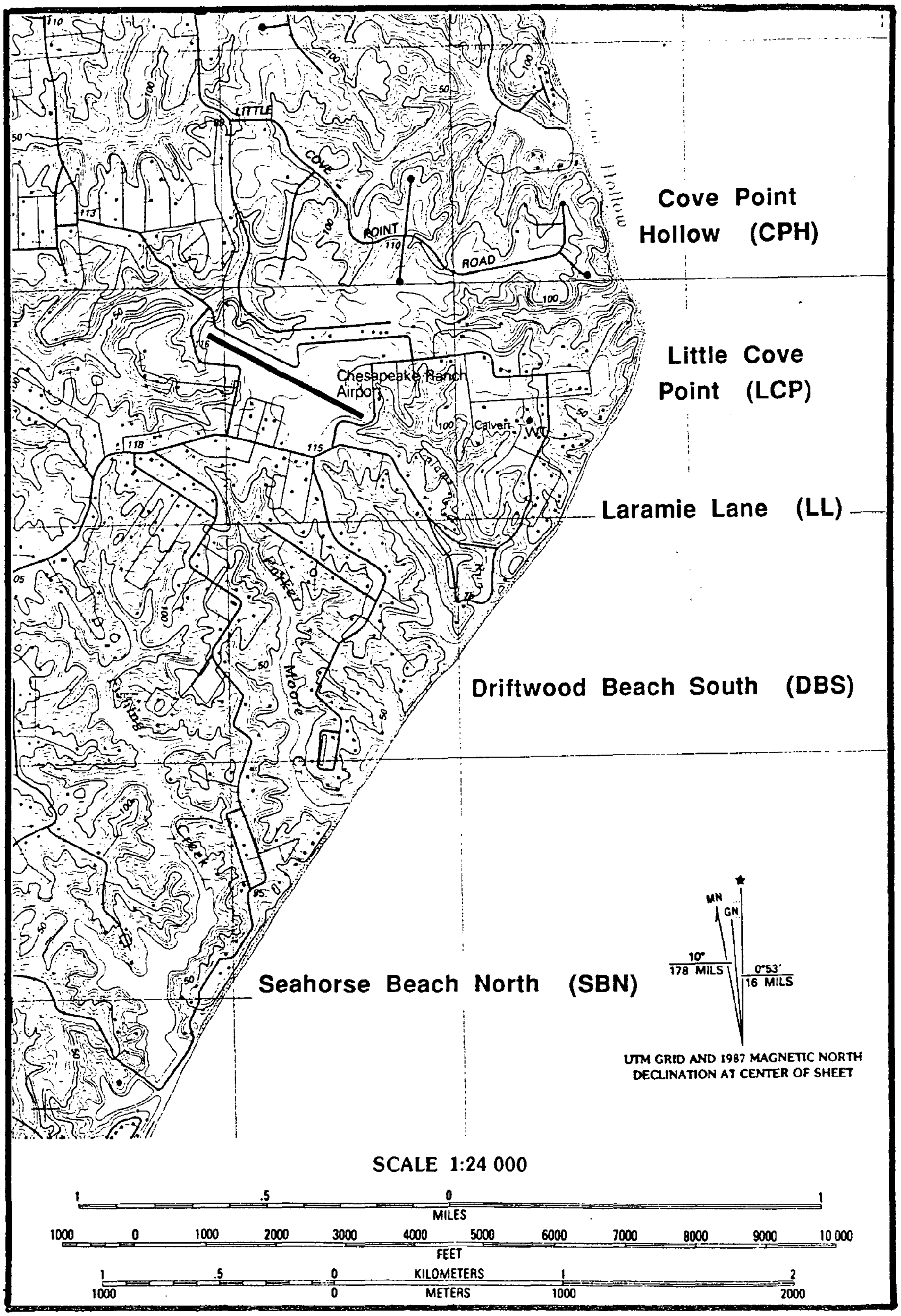


Figure 2.43

Study Site CRE:
Chesapeake Ranch Estates

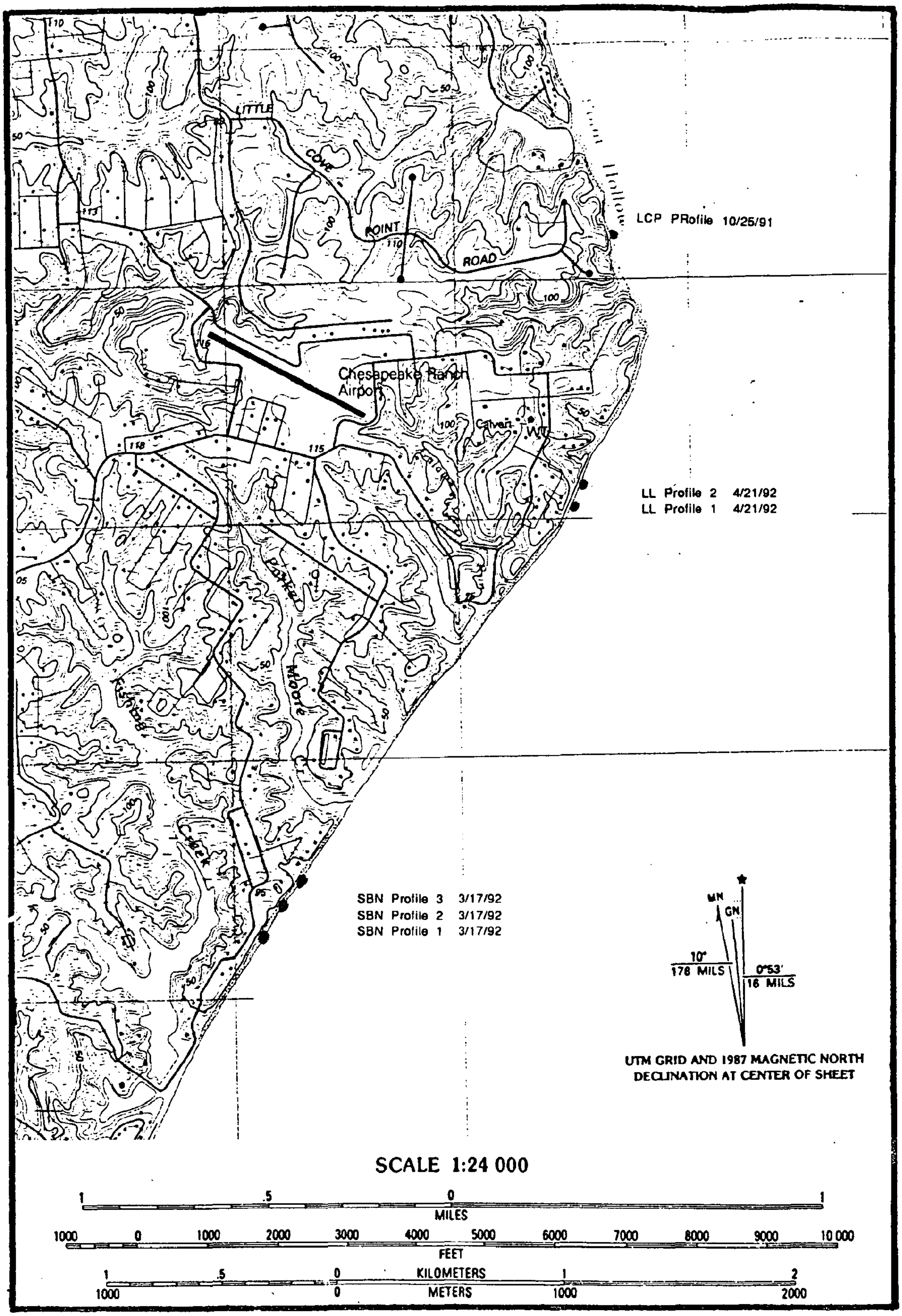
Geotechnical Properties

The cliffs at Chesapeake Ranch Estates range in height from 10 m to 35 m. The slope materials can be divided into five major groups. The soil horizons and root zone are developed in a sandy material. Below the soil and root zone is a thick, highly weathered, medium to coarse sand with traces of pea gravels and thin clay laminations. This unit is moist throughout and is saturated at its base. A seepage zone occurs where the sand unit overlies a series of interbedded sands and clays. About half way down the slope, the interbedded sands and clays give way to a distinct massively bedded fine sand with a significant silt fraction. This bed is nearly 6 meters thick and grades into a gray, clayey silt which extends below beach level.

Five piezometers were installed at the LL subsite. They are designated CRE1, CRE2, CRE3, CRE4, and CRE5 (see Figure 2.45). During the drilling, CRE1 was sampled and SPTs were performed. Sampling was performed to an elevation of 4.0 m. However, the bottom elevation of the piezometer CRE1 was completed at 6.6 m because of the collapse of the hole below that elevation after sampling and before the well was installed.

The ground surface at the well site is at an elevation of 30.2 m. The stratigraphic unit containing the soil horizons and root zone is approximately two meters thick and is composed of a moist, brown, silty, clayey sand. Immediately below, at an elevation of 28.1 m, lies an extensive sand zone which is highly weathered and is subject to iron staining; the color varying from tan to yellow to orange. A strength minimum occurs near the top of this unit and a maximum near the base. Thin lenses of pea gravel and clay laminations are present but discontinuous in this unit. The sands are nearly 12 meters thick and are highly porous and permeable resulting in a perennial seepage zone where they meet a series of interbedded clays and sands at an elevation of 16.3 m. The clay units range in thickness from centimeters to nearly a meter. The interbedded sands are of similar thicknesses and tend to be thin seepage zones. The saturated sands and clays of this unit are very weak and form the failure surface for the large slides observed in this section of the cliffs.

The top of the gray, fine sand unit just beneath the interbedded sands and clays occurs at an elevation of 14.8 m. About 30 percent of the material in this unit is finer than very fine sand resulting in a dense, massive texture. The SPT indicates that it is moderately strong. A series of thin shell beds occur near the base of this unit and exhibit a slight increase in the strength of the unit. Two permanent seeps occur in shell beds, each with a matrix of medium sized sand. Below the shell beds, at an elevation of 6.9 m is a bed of moist, gray, clayey silt which also appears to be massive and dense. However, the SPT indicates that the unit has a low to moderate strength.



Study Site CRE:
Locations of Slope Surveys

Figure 2.44

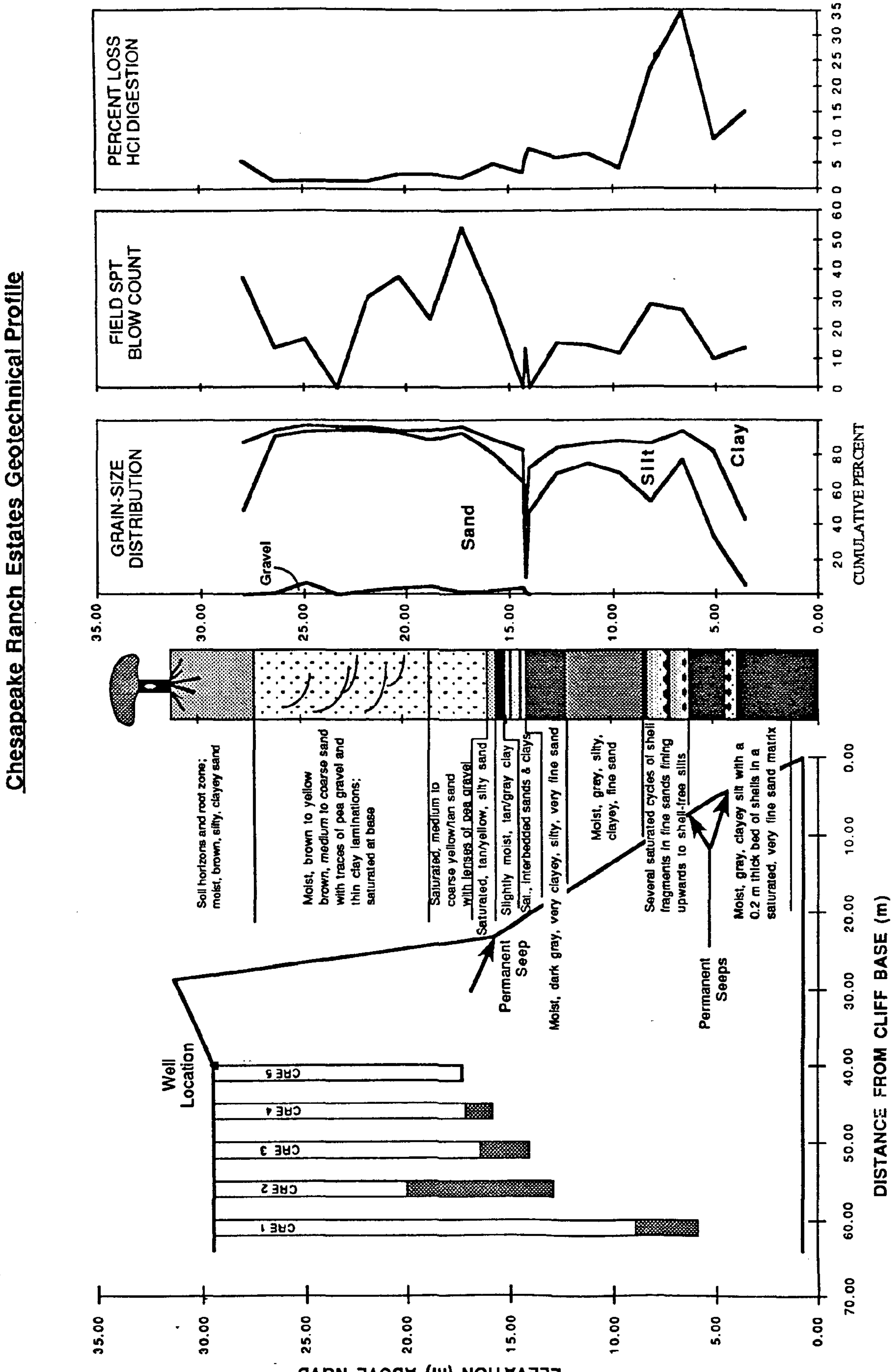

Chesapeake Ranch Estates Geotechnical Profile
PERCENT LOSS HCl DIGESTION
FIELD SPT BLOW COUNT
GRAIN-SIZE DISTRIBUTION
Gravel
Sand
Silt
Clay
CUMULATIVE PERCENT
Soil horizons and root zone; moist, brown, silty, clayey sand
Moist, brown to yellow brown, medium to coarse sand with traces of pea gravel and thin clay laminations; saturated at base
Saturated, medium to coarse yellow/tan sand with lenses of pea gravel
Saturated, tan/yellow, silty sand
Slightly moist, tan/gray clay
Sat., interbedded sands & clays
Moist, dark gray, very clayey, silty, very fine sand
Moist, gray, silty, clayey, fine sand
Several saturated cycles of shell fragments in fine sands fining upwards to shell-free silts
Moist, gray, clayey silt with a 0.2 m thick bed of shells in a saturated, very fine sand matrix
Permanent Seep
Permanent Seeps
Well Location
CRE 1
CRE 2
CRE 3
CRE 4
CRE 5
ELEVATION (m) ABOVE NGVD
DISTANCE FROM CLIFF BASE (m)

Figure 2.45

Slope Profiles (Figures 2.46 to 2.51)

(Note: A dashed line representing the position of the intact slope is provided only on the profile figures where the slope toe is buried by debris).

Six slope surveys were performed at the CRE site. At the LCP subsite (Figure 2.46) the slopes have an overall straight profile, with slight changes in slope angle at boundaries between different materials. Slope angles vary between 50 and 60 degrees. Cliff heights at the LCP subsite range between 16 and 25 meters. The majority of slope toes are at or just above MHHW. The intact slope extends below MSL along a small section of the shoreline just north of Little Cove Point. Wave erosion regularly removes debris deposits and sometimes erodes intact material at the slope toe. Slopes at LCP are generally straight slopes of moderate height and slope angle.

LL slopes are tall (25 m to 35 m) and somewhat steeper (55 degrees to 75 degrees, Figures 2.47 and 2.48). Figures 2.49, 2.50, and 2.51 are slope profiles at SBN. The stratigraphy, erosional processes, and slope profiles are similar at LL and SBN. The intact lower slopes are steep relative to the mid and upper slopes. Along the tallest slopes, large volumes of debris delivered from upslope are deposited at the slope toe. Viewed from above, the debris mounds at the slope toes extend into the bay, past the average position of the shoreline. The bayward edges of the debris mounds are at MSL and are constantly being eroded by waves. Where the debris mounds have been completely removed or do not exist, the intact slope toe is steep (>70 degrees) and extends to MSL. Small, ephemeral beaches occur along LL and SBN.

Groundwater Levels (Figure 2.45 and Figure 2.52)

A permanent, regional water table is present in the sand units above the top of the tan/gray clay. The top of the clay is at an elevation of 16.3 m (Figure 2.45). Wells CRE3, CRE4, and CRE5 are located within this groundwater regime. CRE2 is located within the interbedded sands and clays responsible for impeding the downward movement of the groundwater. The clays within the horizon monitored by CRE2 are the location of the principal failure surface for deep-seated rotational landslides typical of this site. CRE1 measures the water pressure in the silt units of the lower slope.

The sandy materials in the upper 15 m of slope at CRE are the most permeable materials found anywhere in the CCSEP study region. The average grain size distribution of the materials above an elevation of 15m and below the soil horizon is 89 percent sand, 5 percent silt, and 6 percent clay. The hydraulic conductivity of the sands and gravels in this zone is estimated to be 10^{-3} m/s. The average grain size distribution for the layered clays just below the sandy materials is 10 percent sand, 30 percent silt, and 60 percent clay. This material has the highest clay content of all of the sampled materials in the CCSEP study region. The contrast in hydraulic conductivity between the sandy materials and the clays below is five orders of magnitude. The estimated hydraulic conductivity for the clay beds is 10^{-8} m/s.

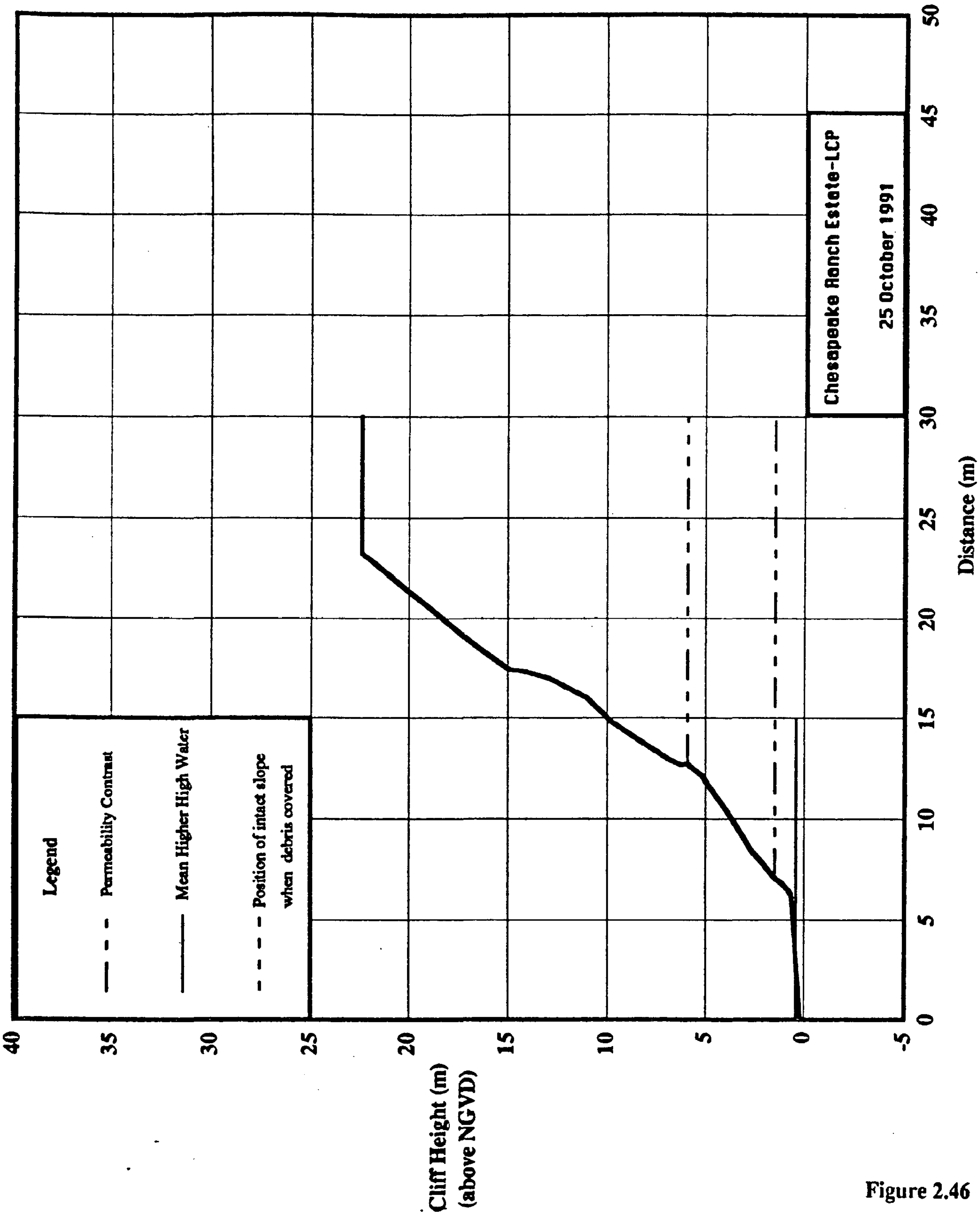

Chesapeake Ranch Estate-LCP
25 October 1991
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Distance (m)
0
5
10
15
20
25
30
35
40
45
50
Cliff Height (m)
(above NGVD)
-5
0
5
10
15
20
25
30
35
40

Figure 2.46

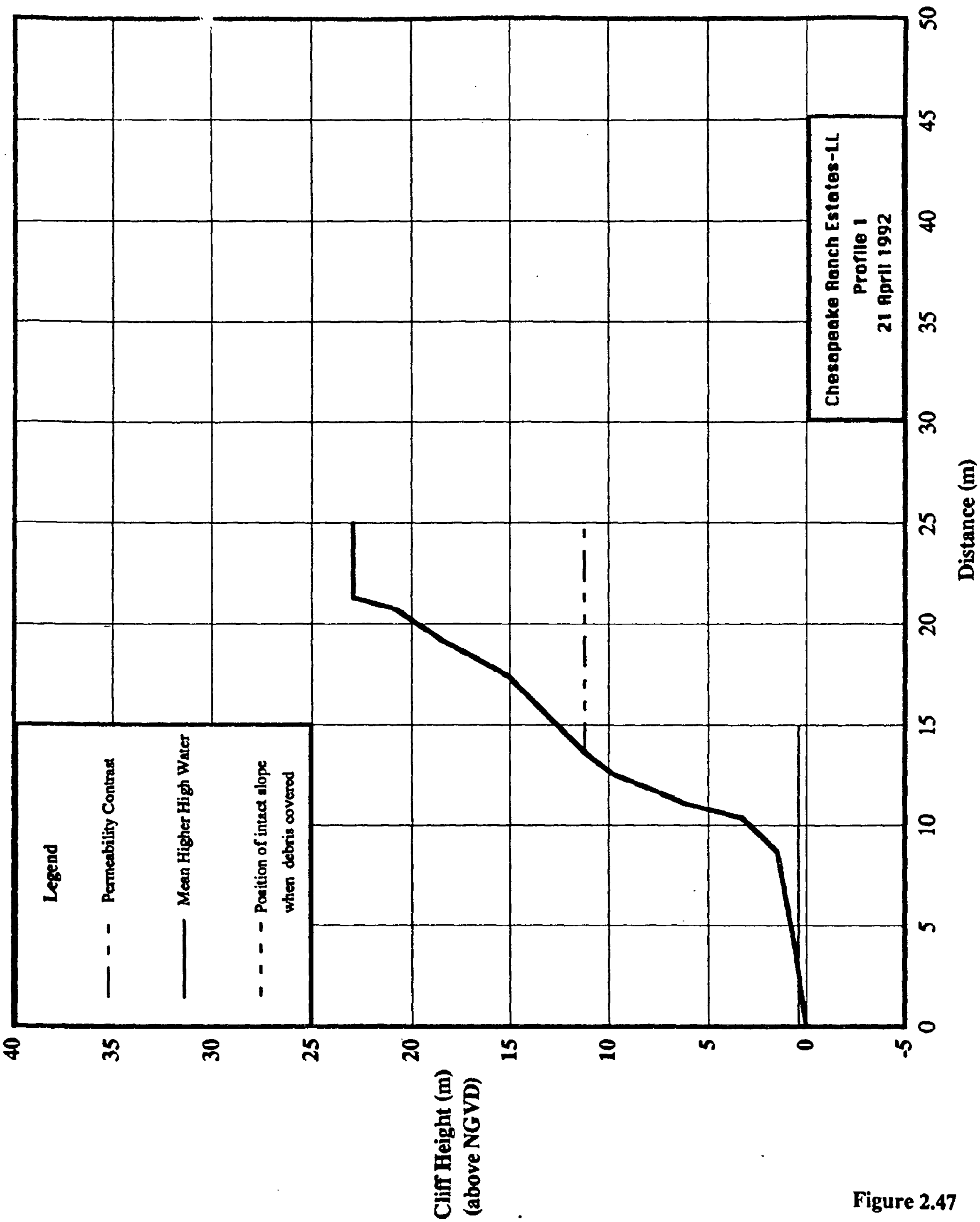

Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Chesapeake Ranch Estates-LL
Profile 1
21 April 1992
Cliff Height (m)
(above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.47

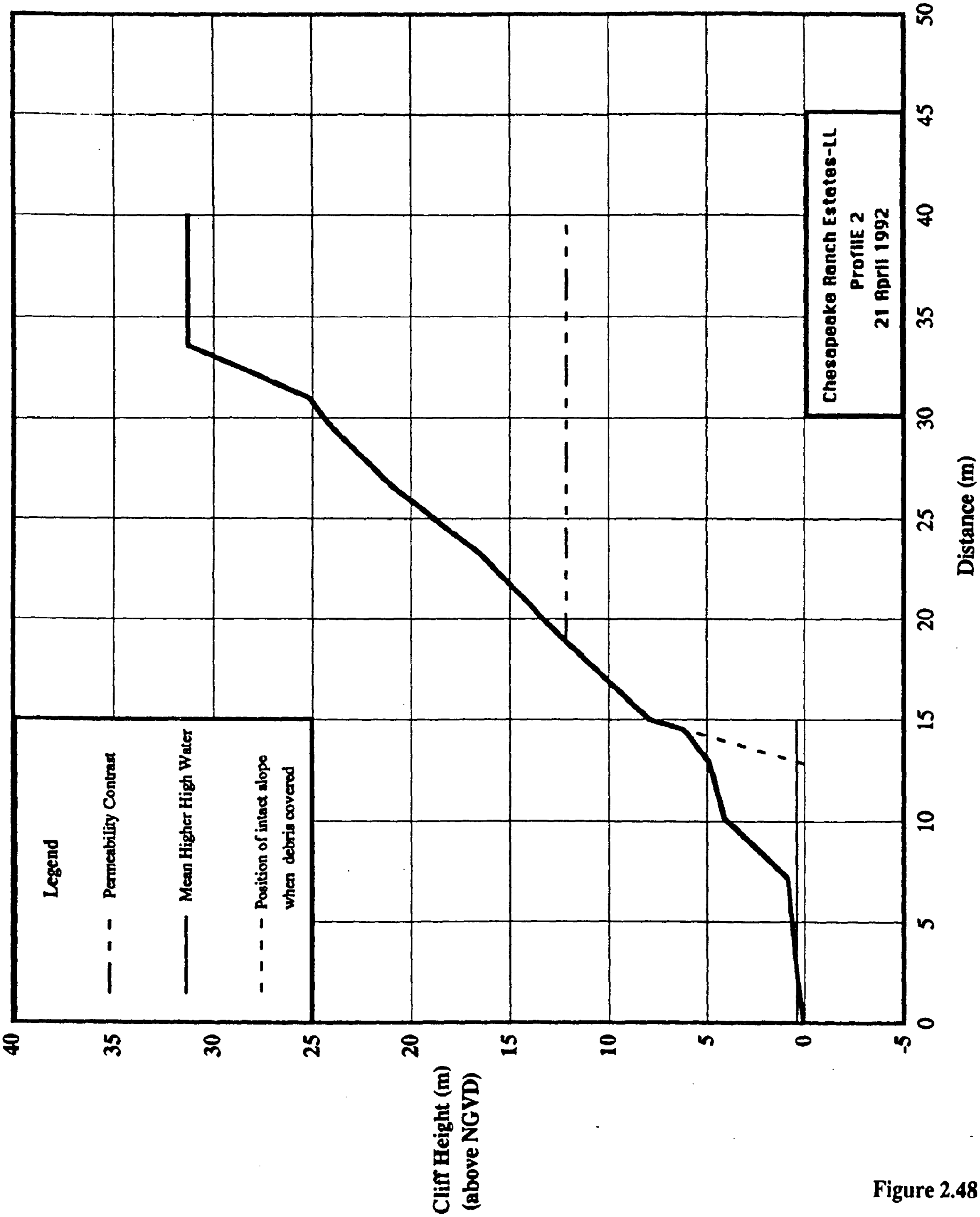

Chesapeake Ranch Estates-LL
Profile 2
21 April 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope when debris covered
Cliff Height (m) (above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.48

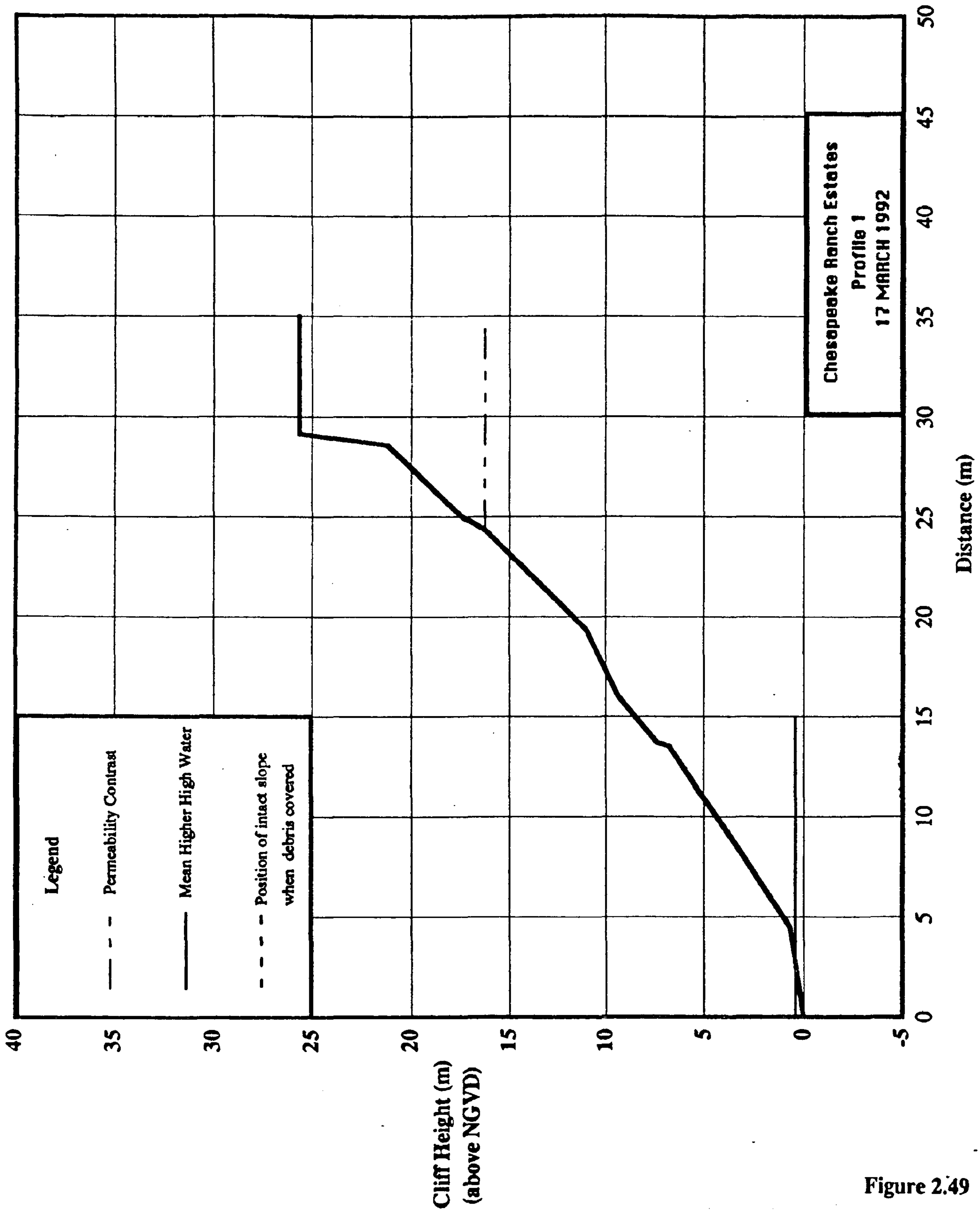

Chesapeake Ranch Estates
Profile 1
17 MARCH 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Distance (m)
0
5
10
15
20
25
30
35
40
45
50
Cliff Height (m)
(above NGVD)
40
35
30
25
20
15
10
5
0
-5

Figure 2.49

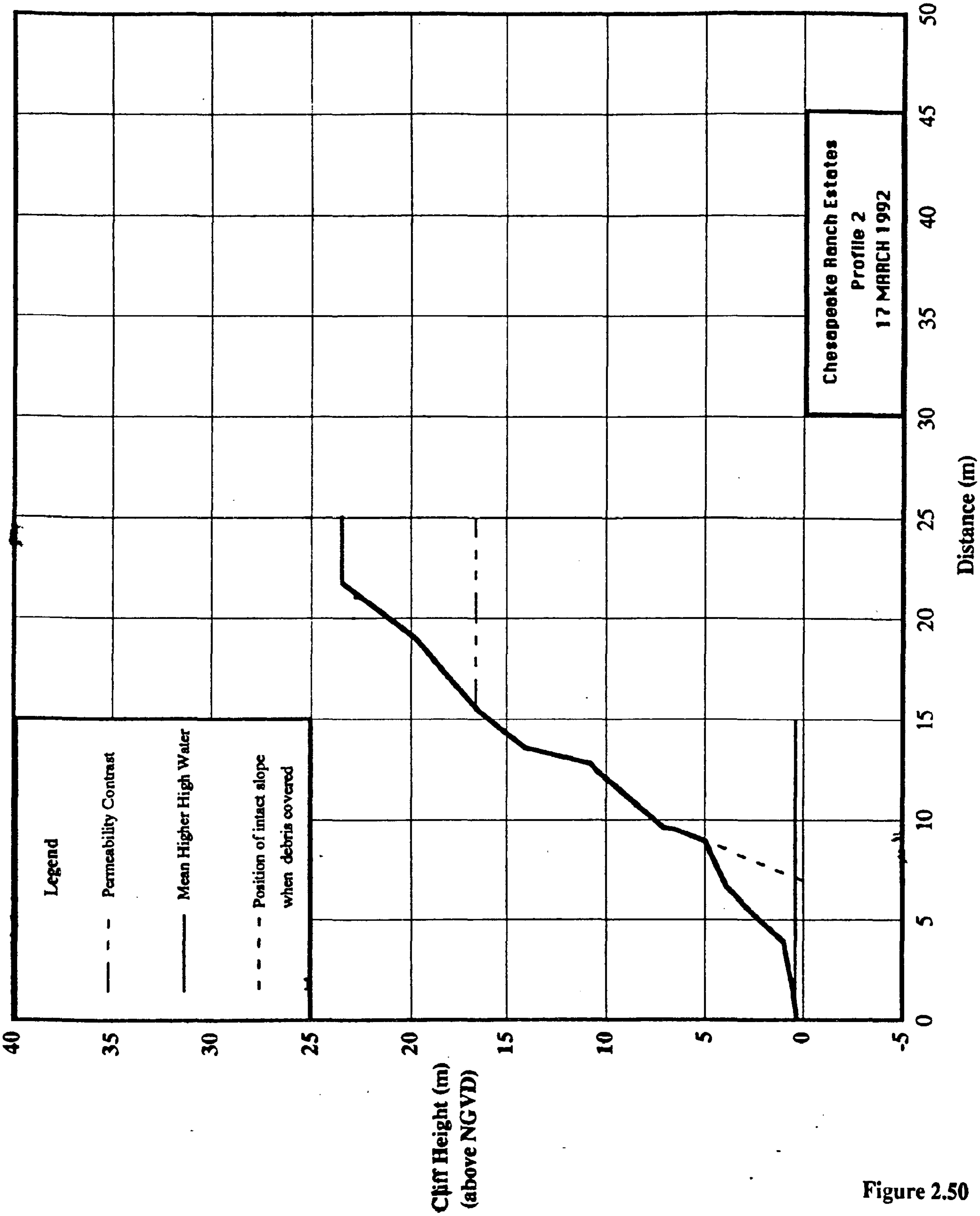

Chesapeake Ranch Estates
Profile 2
17 MARCH 1992
Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Cliff Height (m)
(above NGVD)
Distance (m)
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40
45
50

Figure 2.50

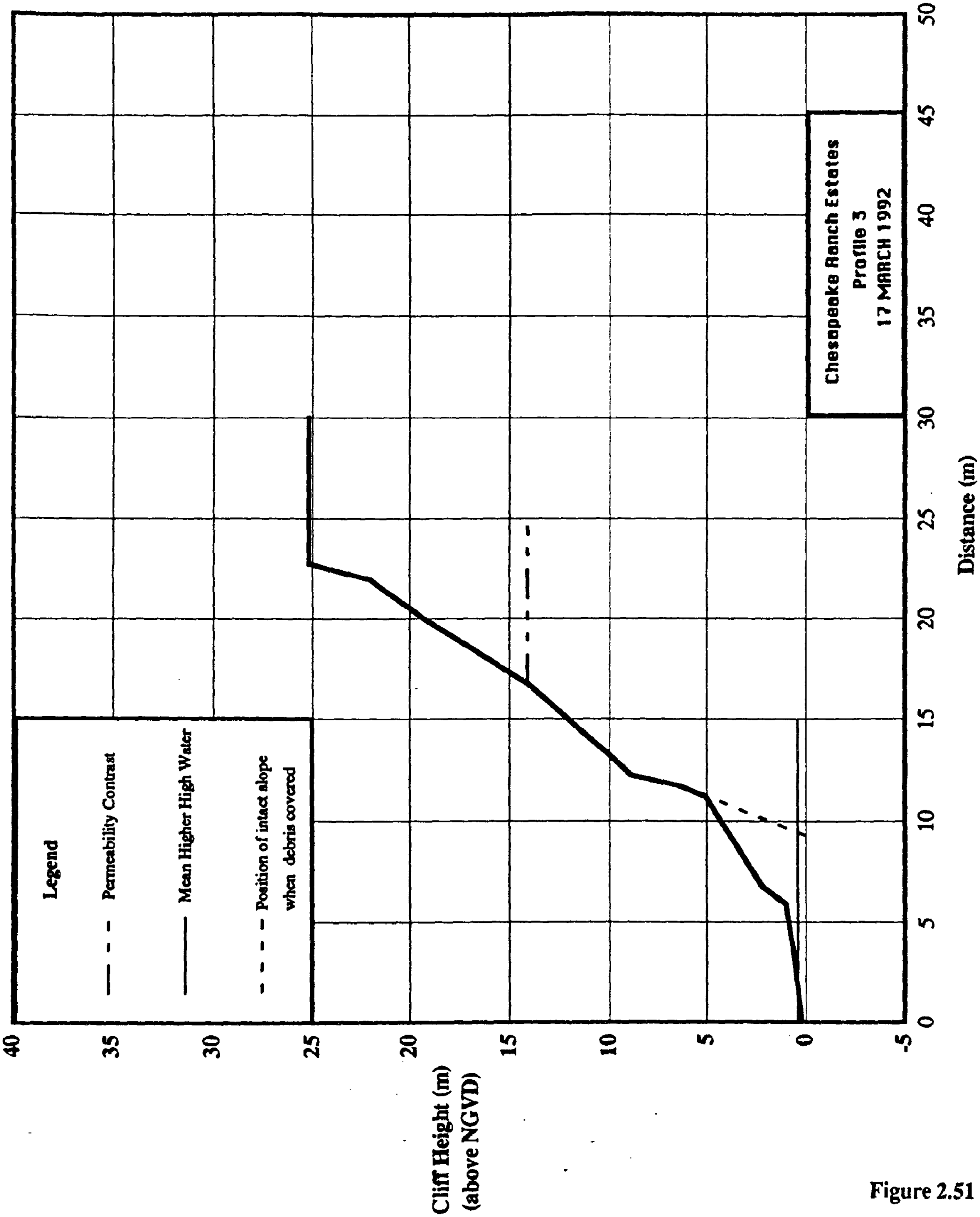
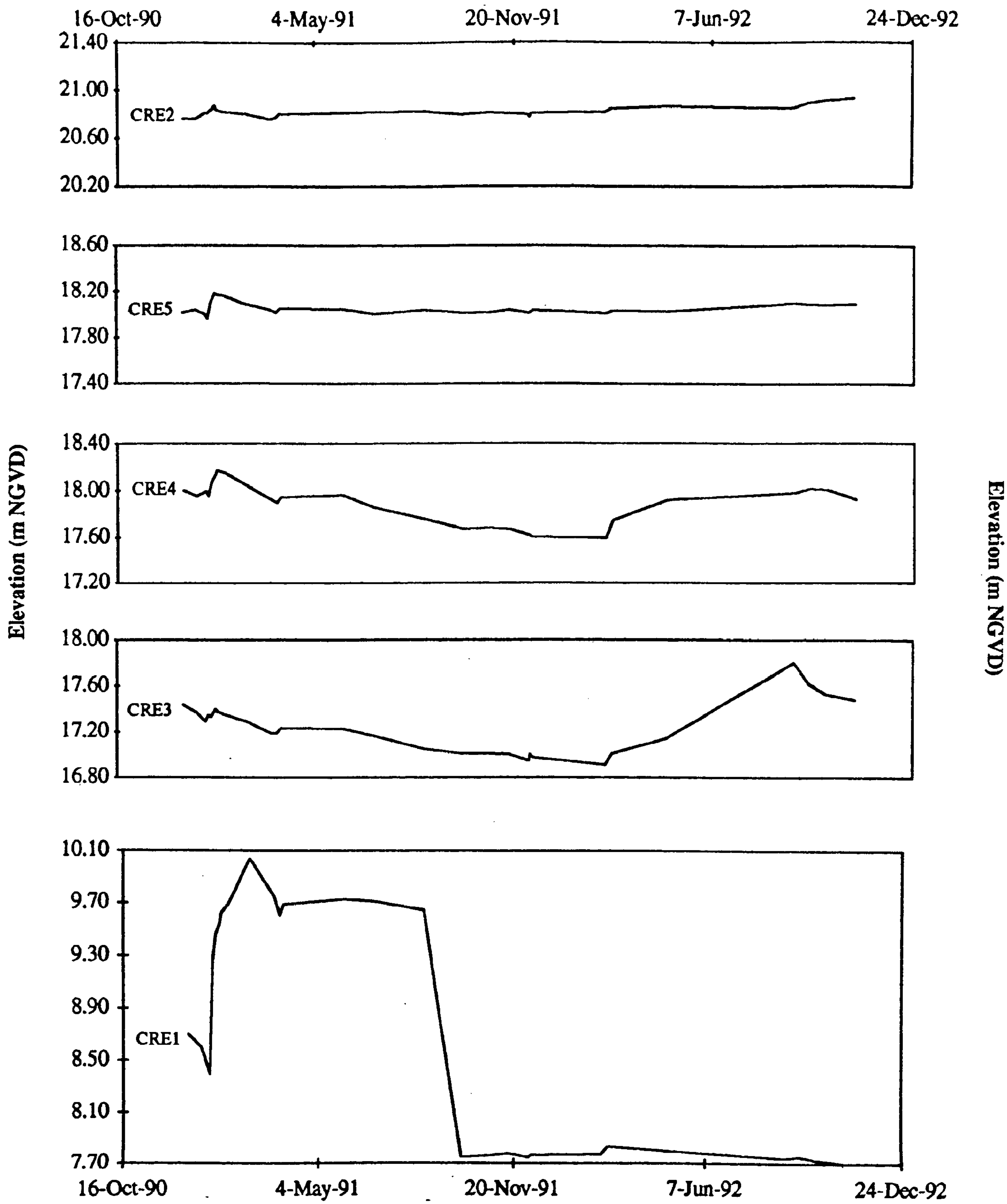

Legend
Permeability Contrast
Mean Higher High Water
Position of intact slope
when debris covered
Chesapeake Ranch Estates
Profile 3
17 MARCH 1992
Distance (m)
0
5
10
15
20
25
30
35
40
45
50
Cliff Height (m)
(above NGVD)
40
35
30
25
20
15
10
5
0
-5

Figure 2.51



Time Series of Water Levels at CRE Piezometers

Figure 2.52

Water levels in the middle three wells (CRE2, CRE3, and CRE4) remained nearly constant during the study period (Figure 2.52). CRE5 is located just above the permanent water table. It was designed to capture the transient response of the groundwater surface to short-term periods of high precipitation. However, precipitation has been well below normal since the installation of the wells. Wells CRE3 and CRE4 show a gradual variation to changes in the regional groundwater regime. Groundwater moves very slowly through the clays at CRE2. However, this material experiences the highest pore water pressure of all the materials in the slope which decreases the available strength, making the clays susceptible to shear failure.

Piezometer CRE1 is located in the lower slope silts. The water surface record for this well is anomalous. It shows a dramatic drop of over 2 m in early September, 1991. Except for that change, the water levels have been fairly static since installation of the well. No external change in the groundwater recharge conditions has been documented and no other wells have recorded such a dramatic drop in the water surface. We have tentatively concluded that this anomaly is due to a change internal to the well, such as the clearing of a blockage or settling of the material which collapsed into the hole during drilling.

Erosion Mechanisms

Site/Subsite: Chesapeake Ranch Estates/Cove Point Hollow (CPH)

Lower Slope. The intact material of the lower slope is eroded by waves. Large block failures occur and involve the entire silt bed below the coarse-grained materials of the upper slope. Block separation occurs along vertical exfoliation planes and translational sliding occurs on an inferred weak surface parallel to bedding near MLLW. Groundwater seepage is strong at the permeability contrast and flows along the slope surface and along exfoliation joints. The large blocks fall or topple in front of the slope toe. Debris deposited at the slope toe provides temporary protection from wave attack until it is eventually removed. The intact toe is once again exposed to active wave erosion. Thus, a cyclic erosional process occurs within the toe zone of the CPH slopes. A large block failure like the one described above occurred below the Bannister property at CPH in early September, 1991.

Midslope. After a large failure in the lower zone silts, the unsaturated material near the surface of the upper slope is no longer supported by the silt below and soon fails under its own weight. The sandy material comprising the midslope is highly susceptible to erosion by groundwater seepage and overland flow. Piping and sapping are common at the sand/silt interface. Subsequent to shallow translational slides, groundwater seepage and overland flow degrade the midslope so that the midslope angle becomes shallow compared to the lower slope.

Upper Slope. The upper slope is steep due to clay deposition in the soil profile and binding by roots. Failure occurs by a combination of trees toppling from the blufftop due wind from strong storms and undercutting by retreat of the midslope.

Site/Subsite: Chesapeake Ranch Estates/Little Cove Point (LCP)

Lower Slope. Physical and chemical weathering of exposed surface material reduces cohesion and causes disintegration. Gravity and storm runoff transports the loosened material downslope creating a thin, patchy mantle of surficial debris on the slope toe. The geometry of the toe zone at LCP and north stands in striking contrast to the steep intact toe zones of the slopes at the LL subsite. At LCP the toe is gently inclined at a shallow angle. Where small beaches are present, is apparent that waves are able to remove the veneer of surface debris from the toe just above beach level. But, undercutting and spalling due to wave action in the toe zone are rare. The material comprising the toe zone from the northern portion of the LL subsite to north of Little Cove Point is a clayey silt. The composition varies little along this length of cliff. Apparently, the wave energy striking the northeast facing slopes of Little Cove Point is substantially less than that striking the southeast facing slopes at LL.

A seepage zone exists approximately 5 m above the beach and at this interface sapping erosion truncates the gently inclined profile of the more permeable unit above by removing intact slope material and undermining the gullied slope above.

Midslope. Slumping and spalling are minimal north of Little Cove Point. The material comprising the upper slopes north of Little Cove Point is stronger and partially cemented in places. Ironstone formations are common. Slope erosion occurs principally through chemical and physical weathering and erosion by seepage and surface runoff. Field inspection indicates that the seepage discharge in the mid-slope north of Little Cove Point is significantly smaller than that observed along the slopes from Driftwood Beach to Little Cove Point. Large gullies are present on most of the slopes. An upper intermittent seepage zone also exhibits evidence of sapping erosion and is responsible for creating significant overhangs above.

Upper Slope. The roots of trees and shrubs tend to bind the upper 1-2 m into a mass that frequently either over hangs the upper slope or results in a vertical face at the bluff top. Retreat of the bluff top occurs when undercut trees and portions of root mass eventually fall, along with spherical masses of soil.

Site/Subsite: Chesapeake Ranch Estates/Laramie Lane (LL)

Lower Slope. Physical and chemical weathering of exposed surface material reduces cohesion and causes fragmental disintegration. Gravity and surface runoff transports the loosened material downslope creating wedge shaped debris fans that thickens toward the toe.

Daily waves and tides and non-catastrophic storm runoff are capable of removing most of the unconsolidated debris generated by slopes 20 m or less in height. Taller slopes have accumulations of upper slope debris at the toe. Intense wave action due to strong onshore winds and/or high tides removes large volumes of toe debris and undercuts intact slope material. Here, in contrast to SBN, the toe debris seems to be more vigorously removed by daily waves, tides, and storm run-off. Spalling of blocks of the clayey silt in the toe zone is common and continuous. The spalling process is accelerated by groundwater leaching along nearly vertical tension planes which are weakened and act as fracture surfaces for spalling events. Here, spalling at the base of the permanently saturated clayey silt of the toe zone actively undercuts the remainder of the lower slope, forming nose-like profiles at the interface with the sandier unit above and vertical to concave faces in the clayey silt below. The permeability contrast at this interface creates a perennial seep along which sapping erosion occurs forming thin, concave gaps where the sands have been removed.

Spalling and midslope failures contribute large volumes of debris to the slope toe. Toe erosion is cyclic in nature as described in the discussion of the lower slope processes at CPH. A difference in the materials composing the toe zone is postulated to be the reason that spalling is more active at LL than at SBN. Field observations indicate that the toe zone strata are finer grained north of Driftwood Beach than the equivalent material north of Seahorse Beach. It should be noted, however, that a greater magnitude of wave undercutting could also be responsible for more active spalling at that site.

Midslope. A strong perennial seep occurs at about 5 to 6 m elevation along the cliffs from Driftwood Beach to the area of shoreline lying just east of LL. The seepage zone marks the boundary between a gray clayey silt and an overlying unit containing several fining upwards cycles of shell fragments in a matrix composed of fine sand at the base of each cycle and fining to a silt at the top of each cycle. At the seepage interface, thin horizontal trenches are formed by sapping erosion. The cyclic shell sequence is lightly cemented and is relatively strong, as indicated by field shear strength tests. The strength and cementation of this unit causes it to form nose like projections in profile.

Above the cyclic shell beds is the same gray, silty, clayey, very fine sand found in the toe zone just north of Seahorse Beach. Like the Seahorse Beach location, this unit does not spall, but is covered by a thin veneer of weathered fragmental material. It is also prone to gullying by surface wash. At 16 m above the beach, the gray, silty, clayey, very fine sand grades into the layer of interbedded, saturated medium sands and clays previously discussed for Seahorse Beach location. As at SBN, a minimum shear strength is indicated in the SPT tests for the seepage zone perched on the interbedded sands and clays. Where the overburden above the interbedded sands and clays is sufficiently large (>25m), the saturated clays, weakened by sapping erosion, fail in rotational failures. Spherical scarps are evident with nearly vertical upper faces indicating that the failure is rotational in nature.

Several sandy zones of varying permeability can occur above the interbedded sand/clay zone. The exact number of zones on any slope face varies with the cliff height. Each of the permeability contrasts creates a perched water table. At locations without a recent deep-seated slide, the seepage flow exits the slope face at sapping or piping zones, undercuts portions of the slope above, and transports sediment and debris down the slope face to the slope toe via gullies. Gullies on faces subject to piping originate at the permeability contrast and widen downward. Stormwater runoff also washes over the entire slope face carrying weathered, loose debris to the slope toe.

Upper Slope. The upper strata are composed of medium to coarse sands with lenses of pebbles and cobbles and tend to be highly leached and weathered. The mid-slope rotational slides either simultaneously carry into the upper slope materials or undercut them to such an extent that subsequent bluff top failures are inevitable. The roots of trees and shrubs tend to bind the upper 1-2 m into a mass that frequently either over hangs the upper slope or results in a vertical face at the bluff top. Retreat of the bluff top occurs when undercut trees and portions of root mass eventually fall, along with spherical masses of soil.

Site/Subsite:Chesapeake Ranch Estates/Seahorse Beach North (SBN)

Lower Slope. Physical and chemical weathering of exposed surface material reduces cohesion and causes fragmental disintegration. Gravity and surface runoff transport the loosened material downslope creating a wedge-shaped mantle that thickens toward the toe.

Daily waves and tides and storm runoff are capable of removing most of the unconsolidated debris generated by slopes 20 m or less in height. Taller slopes may have accumulations of upper slope debris at the toe. Intense wave action due to strong onshore winds and/or high tides removes large volumes of toe debris and may undercut intact slope material; however, vertical slopes or overhangs indicative of intense undercutting are not observed at this site.

Midslope. A strong perennial seep occurs at about 5 m above the toe from Seahorse beach to Driftwood beach. The seepage zone marks the transition between a lower gray silty clayey very fine sand and an overlying thin interval of interbedded medium sands and clays. The sands of the interbedded unit are continuously saturated, which maintains the clays in a moist, plastic state. In addition, the sands are prone to piping and sapping which removes the sand from the between the clays creating gaps which, eventually collapse. In the taller cliffs (> 25 m), the weight of the overburden is sufficient to cause failure within the saturated clays and a sliding surface is produced along the clay/sand beds. It is likely that the saturated sands contribute additional water to the already weakened surface and the failure propagates along the clay/sand bed. Spherical scarps are evident with nearly vertical upper faces indicating that the failure is rotational in nature.

Along sections without a recent rotational failure, a break in the slope profile typically occurs at the perennial seep. The underlying saturated very fine sand offers more resistance to surficial erosion and stands at a steeper angle than the looser interbedded sands above. Water from overlying seepage zones exits the slope face at sapping or piping zones and undercuts the overlying material, transporting sediment and debris down the slope face to the slope toe via gullies. Gullies on faces subject to piping originate in the middle of the slope and widen downward. Stormwater runoff also washes over the entire slope face carrying weathered, loose debris to the slope toe.

Upper Slope. The upper strata tend to be highly leached and weathered. The mid-slope rotational slides either simultaneously carry into the upper slope materials or undercut them to such an extent that subsequent bluff top failures are inevitable. The roots of trees and shrubs tend to bind the upper 1-2 m into a mass that frequently either over hangs the upper slope or results in a vertical face at the bluff top. Retreat of the bluff top occurs when undercut trees and portions of root mass eventually fall, along with spherical masses of soil.

3. Frequency and Controlling Factors of Large Landslides

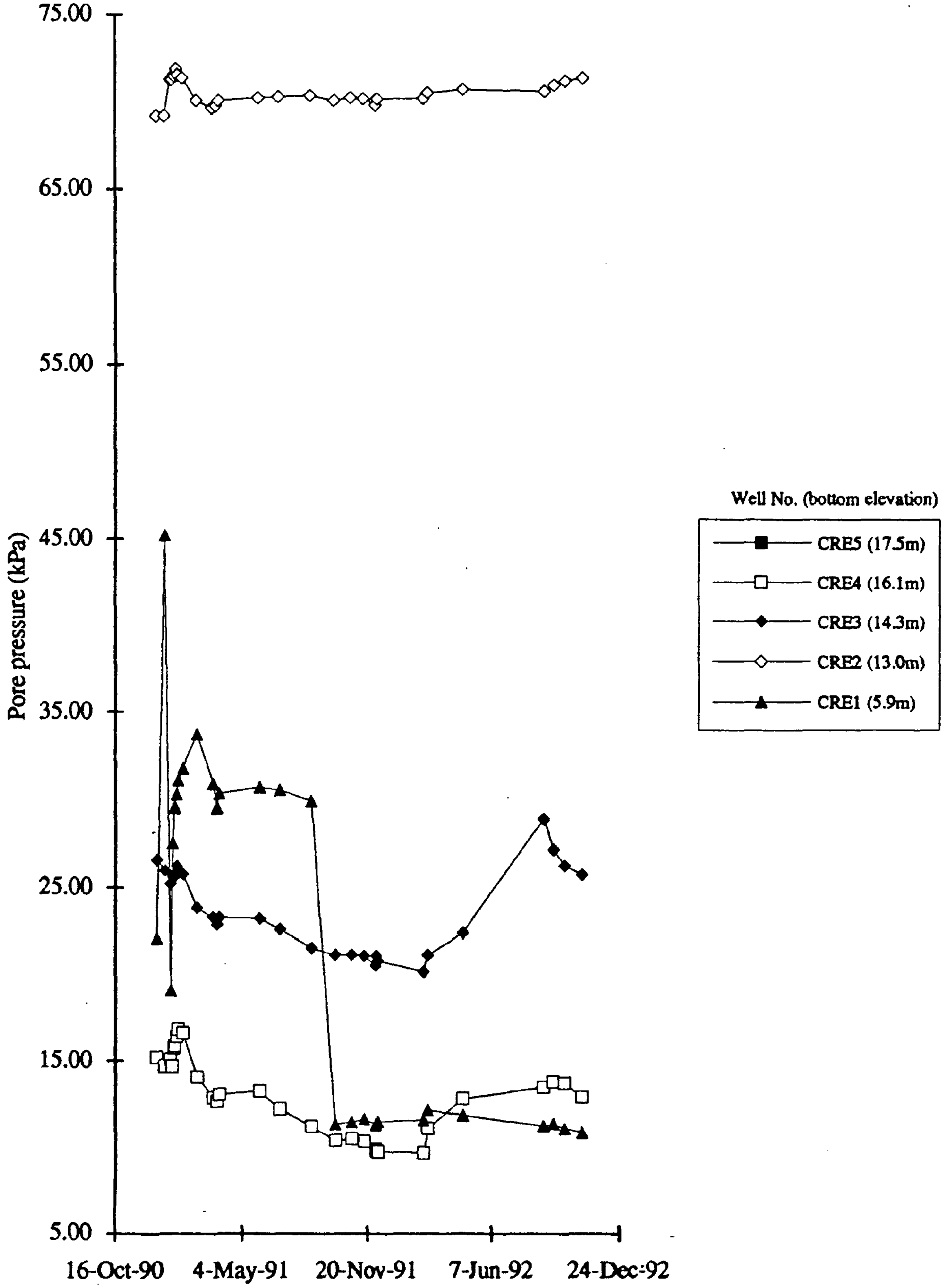
Several deep-seated landslides occurred in the late 1980s in the tall slopes at CRE. Field inspection of the slide scarps and landslide debris showed the slides to have common characteristics. Each slide initiated on a weak, saturated clay layer in the mid-slope. The top of the clay layer is located at 16.3 m (see Figure 2.41). In each case, this clay was stratigraphically intact at the base of the slide debris. The slide scarps are circular or elliptical in profile and the vertical portions intersect the bluff top. Only the tallest slopes experienced deep-seated sliding indicating that the slope height above the weak layer is a controlling factor in this type of deep-seated slide.

The potential for sliding in any slope can be viewed as a balance between forces within the slope. If the materials within the slope are capable of resisting the stresses imposed upon them, then the slope is stable. If the strength of the material is exceeded by the stress imposed on it, it will fail. Shearing stresses are controlled by the slope geometry. The important geometric controlling factors are the slope height and slope angle. The taller the slope above the weak zone, the more weight that is imposed on that layer. Steep slopes are less stable than shallow slopes.

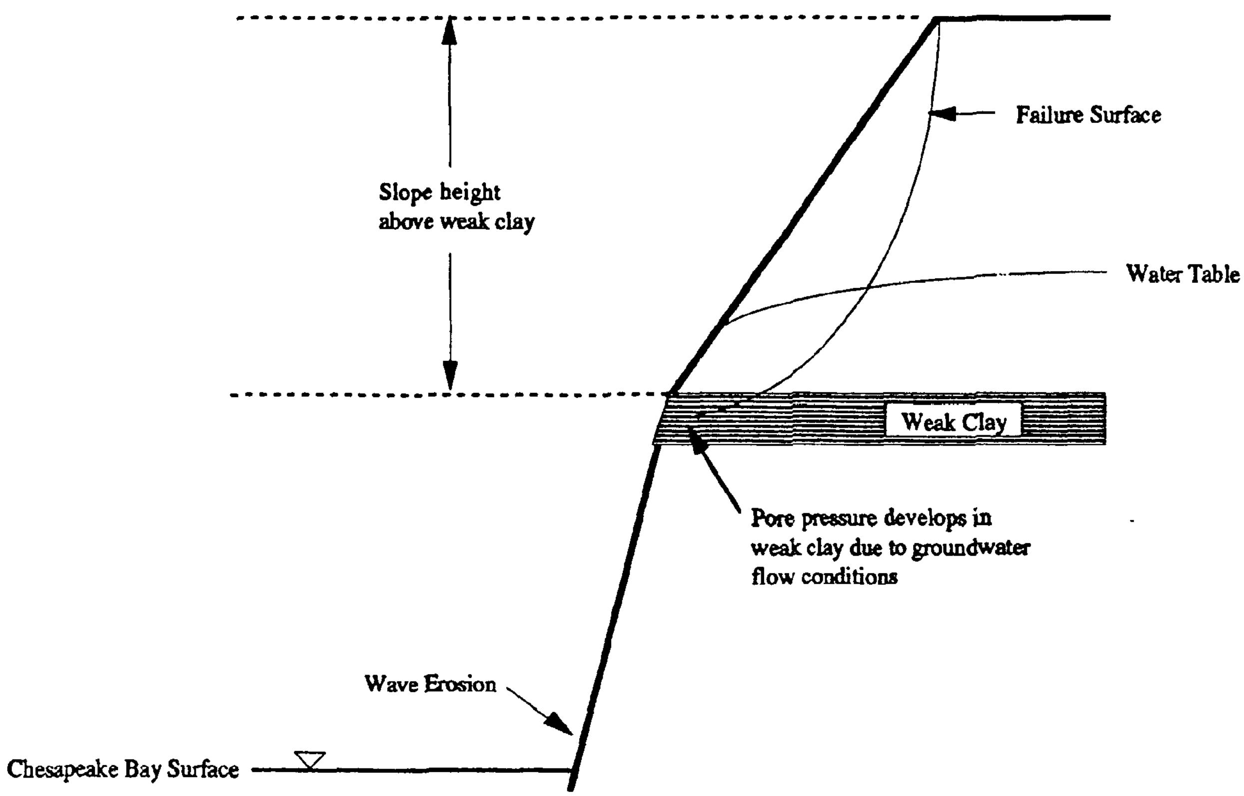
The build-up of water pressure between the soil grains in saturated materials affects the ability of a slope to resist stress. This pressure, known as pore pressure, acts against the frictional component of material strength. The effective normal stress promoting frictional strength is directly reduced by the pore pressure. The higher the pore water pressure, the less the material is able to resist stress. The magnitude of the pore pressure within the weak material is determined by the groundwater flow conditions.

Piezometers are designed to measure pore water pressure at specific elevations. Piezometer CRE2 measures the pore pressure in the weak clay at that site. Water surface elevations from this piezometer indicate that the pore pressure is relatively high in the clay when compared to the other materials in the CRE slopes (Figures 3.1 and 2.45). No deep-seated landslides have occurred since the inception of the CCSEP project. The probable reason is that 1991 and 1992 have been years of low precipitation. Hence, recharge to groundwater regimes has been below normal. Precipitation in 1991 was approximately 30 percent below the normal annual accumulation and precipitation through mid-November 1992 was 15 percent below normal.

Two environmental controlling factors of slope stability are likely to naturally change on eroding coastal slopes. The first is the slope angle. Surficial erosion and wave undercutting may steepen a slope, resulting in instability. The second environmental control with potential for change is the pore pressure. The groundwater conditions within a slope are rarely static. Deep-seated landslides, such as those found along the Calvert Cliffs, may be initiated by steepening of the slope surface, an increase in pore pressure due to groundwater changes, or a combination of changes in both controlling factors.



Chesapeake Ranch Estates Piezometer Pore Pressure Time Series **Figure 3.1**



Controls of Deep-seated Landslides at the Chesapeake Ranch Estates

Figure 3.2

Along the CRE site, the events leading to a landslide are described by the following model (see Figure 3.1). The lower slope is steepened by wave undercutting. Shallow sliding translates upslope, steepening the segment of slope in which the weak clays occur. Given enough time, the steepening alone would be sufficient to initiate a failure. The clay layer, weakened by an increase in pore pressure, slope steepening, or both, experiences a shear failure which propagates along a circular or elliptical surface extending to the bluff top. This is part of an erosion process described in section 4.3.

One other rotational failure at the southern end of CCSP-GYSC has occurred in the recent past. The sequence of events and the timing of the failure is not well documented. But, it is clear that this failure initiated within a saturated, weak clay in a slope with a steep lower zone. No similar weak stratigraphic horizons at critical elevations are known to exist at SC or NRL.

4. Analysis: Slope Classification Based on Erosion Mechanism and Slope Geometry

4.1. Overview

In an attempt to bring some order to a complex variety of erosion processes, we propose a system for classifying coastal cliffs according to their geometry and the relative rates of the dominant erosion processes. The goal of the classification is an identification of the dominant erosion processes from readily observable slope features. This provides a conceptual basis for identifying appropriate erosion control measures and a background for estimating the types and rates of erosion mechanisms that may occur in response to changes in sea level or other external variables.

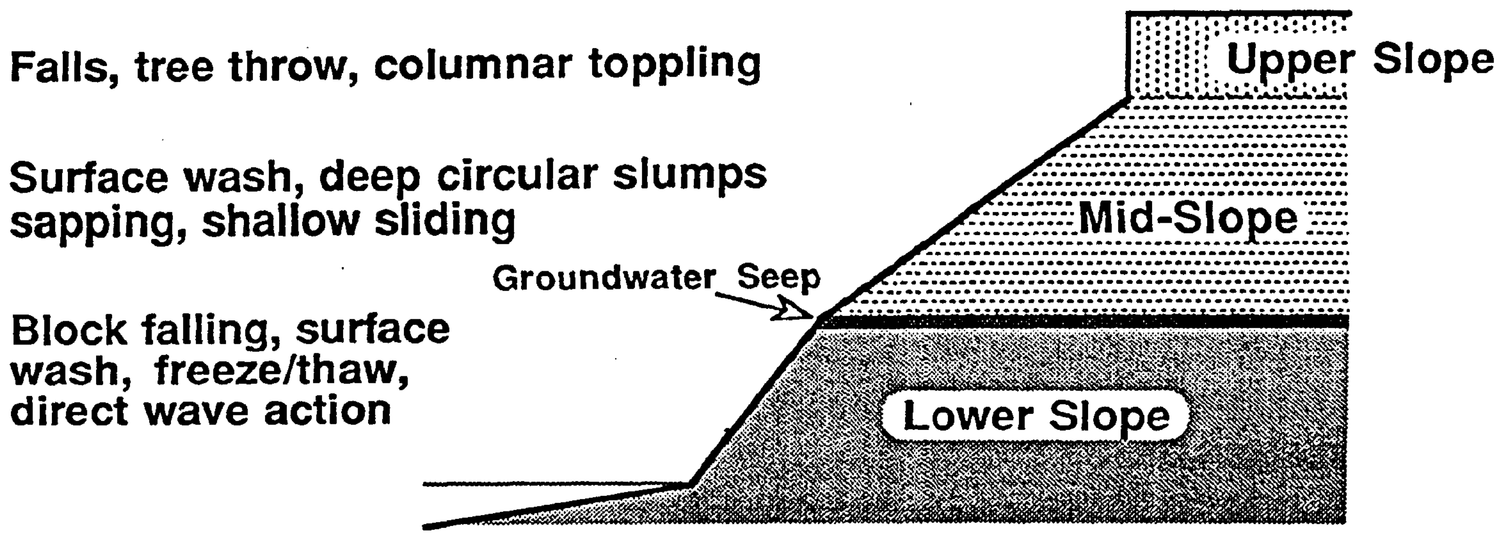
The classification is based on the observation that the slopes may be divided into lower, middle, and upper segments and that particular material properties and suites of erosion mechanisms are typically associated with each segment. A similar association between slope segment and characteristic erosion processes has been noted by Edil And Vallejo (1977) for the coastal slopes of Lake Michigan. We couple this observation with the slope geometry that necessarily develops when the different slope segments recede at different rates. Finally, we suggest that the resulting correlation between the composite slope geometry and the relative recession rates of different slope segments can then be used in the inverse to estimate the dominant erosion mechanisms from the slope geometry.

4.2. Characteristic Slope Segments and Associated Erosion Mechanisms

A fundamental component of our slope classification is a division of the slopes into three segments, based on common material properties and erosion mechanisms (Figure 4.1).

Lower Slope. A strong downward decrease in permeability is generally found 5 m to 15 m above the base of the cliffs. The permeability contrast is used to define the boundary between lower and middle slope segments. The lower slope materials are continuously saturated in most locations. Materials immediately overlying the permeability boundary are typically porous, granular in structure, and form a zone of groundwater seepage that is continuous or nearly so in most locations. The lower slope material is much less permeable, generally darker in color, and massive in structure. The lower slope materials tend to be more resistant to surficial erosion processes related to surface wash and wetting/drying cycles and are eroded primarily by direct wave action and block falling along vertical separation joints.

Mid-slope. The mid-slope materials overlying the permeability contrast may also fail by falling or shallow sliding (generally on slopes dominated by wave undercutting and rapid lower slope recession). More commonly, the mid-slopes segments are eroded by surficial erosion of weathered material by overland flow from direct precipitation or groundwater seepage, and occasionally by deep-seated failures along a weak strata experiencing high groundwater pore pressures. The dominant mid-slope erosion mechanism correlates well with the overall angle between slope toe and slope top. Slopes with lower angles are dominated by surface wash. Slopes with the highest overall angles are dominated by shallow translational sliding. Most of the mid-slope segments of the Calvert Cliffs have overall slope angles between these two extremes and the mid-slope segments undergo erosion through some combination of



Characteristic Slope Segments and the Associated Erosion Processes

Figure 4.1

surface wash, groundwater sapping, or deep-seated rotational slumps where a weak strata is found near a seepage layer and there is sufficient slope height above the weak zone to produce critical shear stresses in the weak zone.

Upper Slope. We define the upper boundary of the mid-slope as the base of the root zone of the slope-top vegetation. The upper slope material is generally unsaturated and the material strength is often increased by clay deposition, weak cementation, and root binding. These slopes often stand nearly vertical and fail as mid-slope recession undercuts the upper slope and produces falling of intact soil and toppling of separated soil columns. Root mats often overhang at the slope top and the ultimate recession of the slope top often occurs via tree throw. Because the extent to which an overhang may develop is limited, the recession rate of the slope top is completely dependent on recession rate of lower and mid-slope.

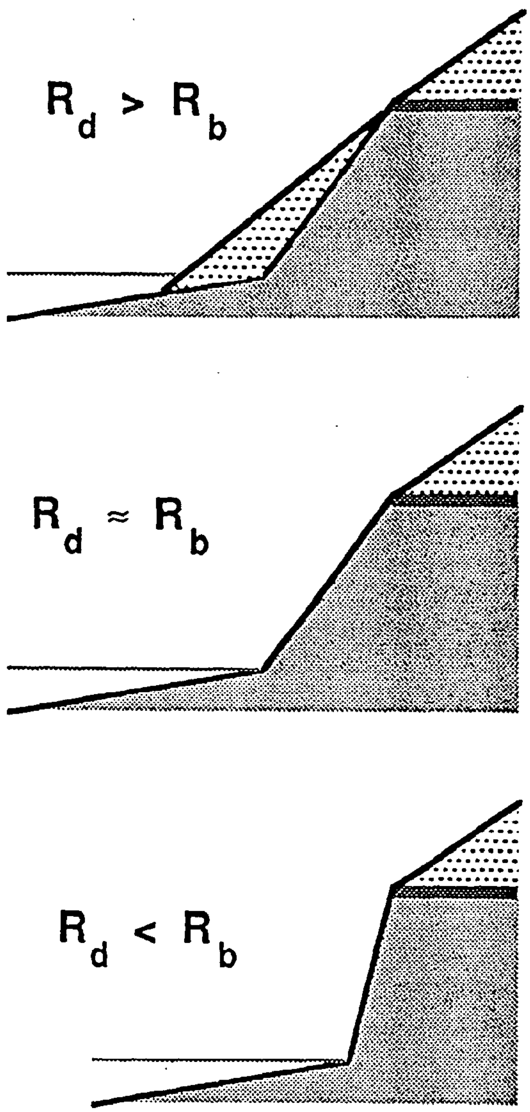
4.3. Combinations of Slope Segments: Characteristic Slope Profiles

The next step in organizing a classification system for coastal slopes is to define the slope geometry that results from different relative recession rates of the individual slope segments. Because the groups of erosion mechanisms acting on the various slope segments can be quite different, a geometric differentiation based on the relative recession rates of individual slope segments can also serve to identify the relative rates at which the different erosion mechanisms operate. At this point, it is necessary to distinguish only the relative rates at which the different segments erode, rather than their absolute erosion rates, because it is the relative difference that determines the resulting slope geometry. To define the recession rates of the three segments, it is necessary to define three individual rates:

- R_d: rate of delivery of debris to the slope toe
- R_b: rate of debris removal & slope undercutting at the slope base (generally wave-driven)
- R_m: erosion rate of the mid-slope (may be driven by surface and groundwater runoff, elevated pore pressures in weak, subsurface horizons, or wave erosion via the rapid recession of the lower slope)

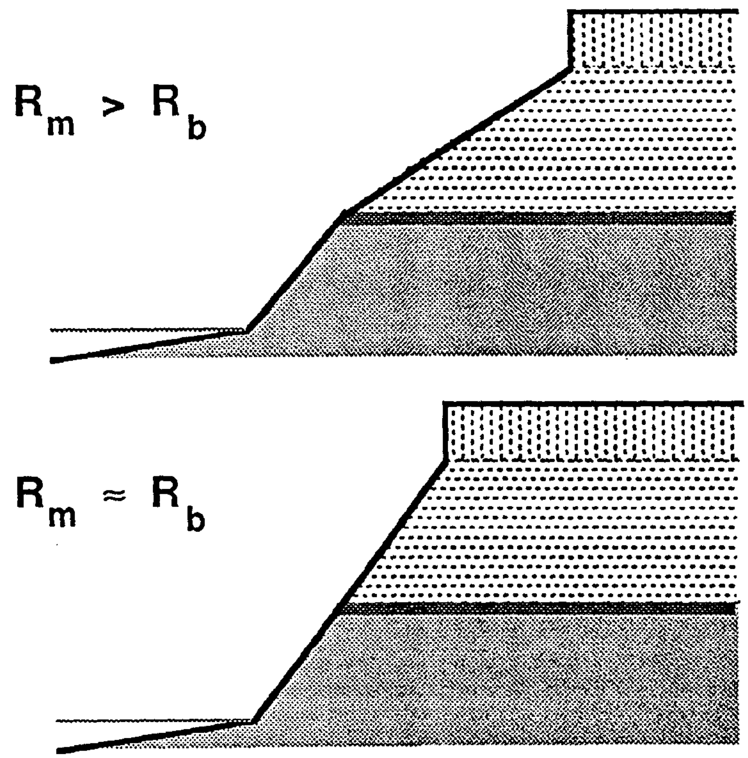
The balance between R_b and R_d determines the build up of debris at the slope toe and the amount of erosion of intact toe material (Figure 4.2). If $R_d > R_b$, slope debris builds up at the slope toe and protects the slope toe from further erosion. If $R_d < R_b$, the slope toe is generally free of debris and waves may directly erode and steepen the lower slope. The balance between these two rates also plays a role in the frequency and duration of the cyclic coastal erosion process previously defined by Hutchinson (1973) and Quigley and Gelinas (1976).

The balance between R_b and R_m determines the overall geometry of the slope (Figure 4.3). If $R_m > R_b$, as we often observe along the Calvert Cliffs, the mid-slope segment will tend to recede away from the lower slope, producing a lower mid-slope angle. Combined with the typically very steep upper slope, the resulting overall slope profile has three parts. If the two rates R_b and R_m are comparable, a relatively straight slope profile may result. In this case, we generally find that both lower and mid-slopes are eroded by the same mechanism, with wash-driven erosion dominating in cases with gentler slope angles, and shallow sliding and block falling dominating in cases with steeper slopes. Because the slope materials have little tensile strength, cases with $R_b > R_m$, which would



Relative recession rates: Various slope forms produced by varying R_d, the rate of debris delivery to the slope toe relative to R_b, the rate of debris removal and slope undercutting by waves.

Figure 4.2



Relative Recession Rates: Various Slope Forms Produced by Varying Rm, the Rate of Mid-Slope Recession Relative to Rb, the Rate of Debris Removal and Slope Undercutting by Waves

Figure 4.3

produce an overhang at the slope toe, cannot be maintained for any substantial period of time. Rather, the effect of a large value of R_b would be to produce a corresponding increase in R_m, often causing the mid-slope erosion mechanism to shift from one of wash-driven erosion to one of shallow sliding on a steeper slope.

Figure 4.4 illustrates the composite slopes that result from combining the different relative recession rates illustrated in Figures 4.2 and 4.3. We distinguish four types of slopes: each has distinctive geometry and is found to occur along the Calvert Cliffs.

Type I Slopes ($R_d > R_b$). Type I slopes no longer experience toe erosion. Slope debris accumulates and builds a gently inclined mantle up from the slope toe (a typical angle is on the order of 35°). The debris fan may terminate in the mid-slope section, in which case a three part slope is formed, with the slope angle increasing with elevation. After an extended period of time, the debris fan may entirely cover the mid-slope and a two-part slope (fan/upper slope) exists. Upper slopes tend to be quite steep, ranging from 55 degrees to vertical. Erosion of the intact slope above the debris fan occurs via undercutting by ephemeral seepage, surficial erosion by overland flow, and columnar toppling. Control of this erosion depends on the quantity and location of surface water and groundwater discharge. Anchoring by vegetation on the debris fan and mid-slope can be effective in decreasing erosion rates on these slopes.

A similar slope type has been observed Hutchinson (1973) and Quigley and Gelinas (1976). The presence of a three-part, concave profile (Figure 4.4) may be more common in the Calvert Cliffs than in the more fine-grained materials examined in other coastal cliffs.

Type II Slopes ($R_d \approx R_b$). On Type II slopes, waves can remove most debris from the slope toe and may occasionally erode some intact toe material. Typically, the wave erosion operates more slowly than the rate at which wash-driven erosion processes operate on the lower slope. As a result, wash-driven erosion dominates from the slope toe to the base of the root zone at the upper slope and relatively straight profiles occur in slopes formed in materials of uniform erodibility. Slopes with materials of contrasting geotechnical properties at different elevations will show slope breaks at material transitions, although the variation in slope angle is smaller than that found between the lower slope and mid-slope typical of the more common Type III slopes. The angle of individual slope segments of Type II slopes fall within a range of 35° to 65°.

Although wave action removes debris from the base of Type II slopes, hydrologic processes dominate their overall form. Two factors may control the response of the lower slopes. First, the wave climate over time may be sufficient to remove the debris delivered to the slope toe from above, but not capable of great amounts of additional erosion. Secondly, the material comprising the slope toe may be strong enough to resist significant erosion by the waves. An increase in toe erosion rate (e.g., driven by an increase in water level, an increase in wave height, or an increase in the frequency of wave events) would tend to change a Type II slope into a Type III slope.

Below the perennial seepage zone, the rate of erosion of Type II slopes is controlled primarily by the seepage discharge and the quantity of overland flow from upslope. Above the perennial seep, direct seepage erosion may also undercut the overlying strata causing oversteepening and collapse. Control of recession rates on Type II slopes depends primarily on the quantity and location of surface water and groundwater discharge. These slopes are often too steep and actively eroded to support substantial vegetation.

Type II slopes have a similar sediment balance to the type defined by Hutchinson (1973) as demonstrating a balance between the rate of toe erosion and the rate of delivery of slope debris to the slope toe. Type II slopes at the Calvert Cliffs are dominated by surface erosion and have a characteristically straight profile, whereas the corresponding slopes in the London Clay fail by mudflows and shallow sliding and have a characteristic concave shape.

Type III Slopes ($R_d < R_b$ and $R_m > R_b$). Type III slopes are common along the Calvert Cliffs. On these slopes, waves erode intact lower slope material at rates sufficiently fast to cause them to steepen and fail by block falls along stress-release joints. At the same time, however, hydrologically driven erosion proceeds even more rapidly and causes the mid-slope to recede back from the lower slope. The result is a slope that displays a decrease in slope angle at the permeability contrast separating the lower and mid-slopes. Most commonly, the mid-slope erosion is related to groundwater seepage. The prevalence of this type of slope along the Calvert Cliffs points to the importance of hydrologically driven erosion process in the general cliff retreat (Leatherman, 1984).

The lower portions of Type III slopes have angles between 70° and 90°, whereas the mid-slope angles generally fall between 35 and 65 degrees. A variety of different hydrologic conditions produce different mid-slope erosion mechanisms and different mid-slope profiles. Direct erosion of soil grains by surface wash is common to most Type III slopes. A concentrated groundwater discharge will cause localized erosion downslope, creating gullies with their heads at the pipe exit. The resulting slope has a distinctive ribbed appearance. A more laterally continuous groundwater seepage zone produces more uniform erosion of the slope below, resulting in a smooth, planar mid-slope. Erosion at a laterally continuous seepage zone can also undercut the overlying slope segment, producing further retreat of the slope top. The upper and mid-slope segments of a Type III slope can also experience deep-seated landslides. These occur where a soft clay layer is found within the saturated seepage zone at the lower/mid-slope boundary and a sufficient thickness of permeable slope exists above the seepage zone, producing elevated pore pressures and high shear stresses within the soft clay. The result is a rotational scarp extending upward through the unsaturated zone to near the bluff top. The debris resulting from the slide accumulates at the toe in wedges that are removed by subsequent wave action.

Mid-slope recession of Type III slopes is controlled by the configuration, location, and rate of groundwater discharge, the relative magnitude of seepage discharge and overland flow, and, in the presence of a weak subsurface zone, the occurrence of high groundwater pore pressures. Erosion control for a Type III slope should include, in addition to toe protection, groundwater control by, for example, diversion of surface stormwater and installation of subsurface drains. An increase in the toe erosion rate could cause a Type III slope to change to a Type IV slope. This would develop if the rate of lower slope recession exceeded the rate at which hydrologically driven erosion cause the mid-slope to recede. As a result, the mid-slope would steepen to the point where shallow sliding would be initiated.

Type III slopes correspond to similar slopes defined by Hutchinson (1973) and Quigley and Gelinas (1976) in which the rate of toe erosion exceeds the rate of delivery of slope debris to the slope toe. Type III slopes may undergo parallel retreat with an approximately constant slope geometry, as noted by Quigley and Gelinas (1976), or they may undergo cyclic variations in slope geometry and dominant erosion mechanism, as noted for both the London Clay and Lake Erie slopes. The occurrence of deep-seated failures and the associated cyclic slope evolution is not as common on the Calvert Cliffs, and the cycle time may often be shorter.

Type IV Slopes ($R_m \approx R_b$). In these slopes, wave undercutting is sufficiently rapid that the recession rate of the lower slope is greater than the rate at which hydrologically driven processes cause the mid-slope to erode. The mid-slope becomes oversteepened and both lower and mid-slope erosion is driven by block falling and shallow sliding at a rate determined directly by the rate of wave-driven undercutting. Where the geotechnical properties of the slope are relatively homogeneous throughout the slope, steep, straight slopes develop at angles in excess of 70°. Where vertical contrasts in geotechnical properties exist, each slope segment will fail at a different characteristic angle, resulting in a steep, relatively straight slope profile with distinct segments corresponding to the different stratigraphic units. Type IV slopes are characterized by an overall slope angle that is steeper than any of the other types. Even though both Type IV and Type II slopes may have relatively straight profiles, the two types may be distinguished by overall slope angle.

The base of Type IV slopes are typically found at elevations near or below the mean tide level, so that wave erosion occurs on a daily basis. The slope geometry and recession rate of Type IV slopes are determined by the rate of toe undercutting.

Type IV slopes are similar in some respects to slopes observed along the western shore of Lake Michigan (Edil and Vallejo, 1977) in that active toe erosion initiates shallow slides and accelerated surface erosion that may move upslope in a successive fashion. Type IV slopes along the Calvert Cliffs tend to be steeper and more continuously undercut than those observed along Lake Michigan. They also typically fail through a combination of shallow slides and block falls and undergo parallel retreat with only minor change in slope form

It is worth emphasizing that the classification system is based on *relative* erosion rates of the lower and mid-slope. Although all Type IV slopes experience significant toe undercutting, a Type IV slope may not necessarily experience greater wave energy, or even greater undercutting rates, than other slope types. For example, a Type III slope might experience large lower slope recession rates, but would be classified as a Type III slope if the mid-slope recession rate exceeds that of the lower slope. The purpose of the slope classification, then, is to identify the dominant erosion mechanisms occurring on a particular slope. This information can then be used to identify the controlling factors of slope erosion for the purpose of evaluating erosion control measures or estimating the slope response to changes in external variables.

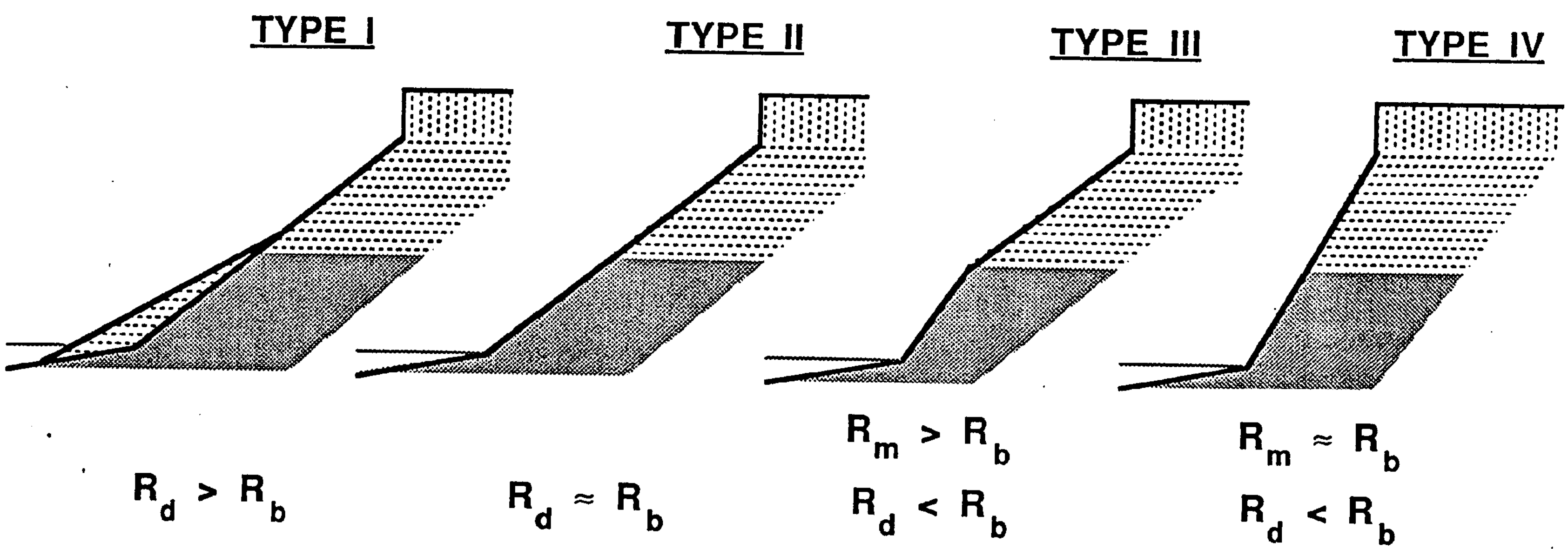
4.4. Observed Slope Geometry at the Calvert Cliffs

Figure 4.5 presents the profiles of 16 representative slopes along the Calvert Cliffs. The slopes have been selected to be representative of the range of coastal cliffs occurring within Calvert County, Maryland. The slope are organized according to the types presented in the classification system. The classification type assigned to each slope has been determined based on both the observed slope geometry and our observations of the dominant erosion process for each slope segment.

Figure 4.6 presents the range of slope angles observed for 33 different slope profiles arranged by slope type. The slope angle is measured from the slope base in intact material to the bluff top, except in the case of Type I slopes, for which the toe of the intact slope is difficult to accurately identify. Because Type I slopes have a characteristic debris fan and concave slope profile, the difference in measuring slope angle should not have a critical effect on application of the slope classification.

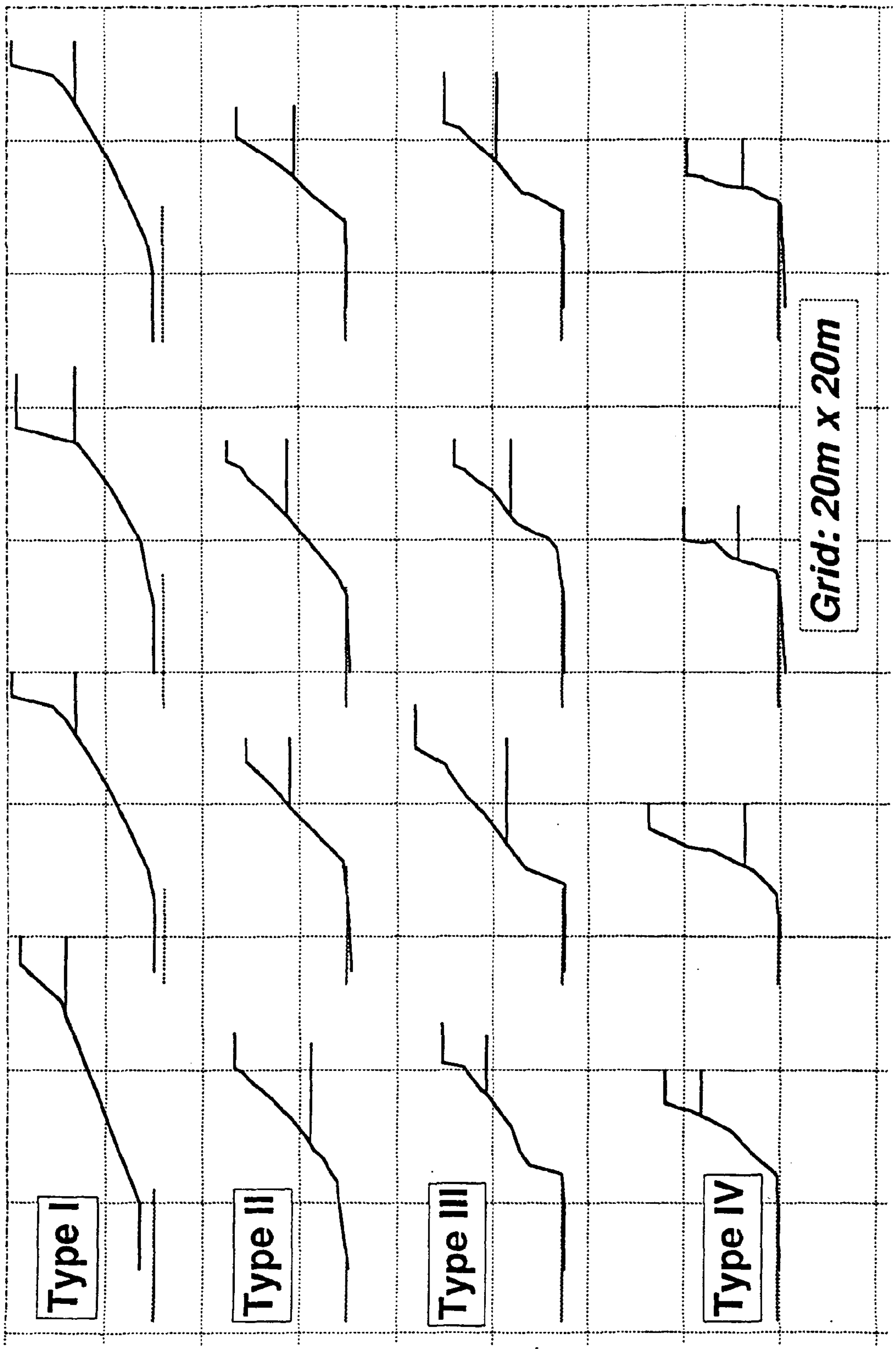
Type I slopes have angles less than 46° and have a characteristic concave, segmented slope form (Figures 4.4 and 4.5). Type II slopes have angles falling between 50° and 60° and have straight or somewhat concave profiles. Type III slopes have angles falling between 47° and 62° (all but one is steeper than 54°) and have characteristic composite (Figures 4.4 and 4.5) or convex slope profiles. Type IV slopes all have slope angles in excess of 63° and have straight or somewhat concave slope profiles.

The slope angles characteristic of the four basic slope types fall into distinct, non overlapping groups. Type I slopes are all less than 46°, Type IV slopes are all steeper than 63°, and Types II and III fall within 47° and 62°. Types II and III are distinguished from each other based on characteristic differences in slope shape. The distinction of slope type by overall slope angle is a potentially important and useful result. Our slope classification is based on observations of groups of erosion processes and rates that typically occur together, and on the slope geometry developed by these groups of processes If the type of slope and, therefore, the typical group of erosion processes, can be determined based on the overall slope angle, the classification of individual slopes can be done quite readily. For example, classification of past slope types can be made from measurements of slope width on aerial photographs and observations of present slope height in the field or from detailed topographic maps. Once classified into a particular type, the erosion mechanisms acting on that slope, and the environmental factors controlling that erosion, can be estimated.



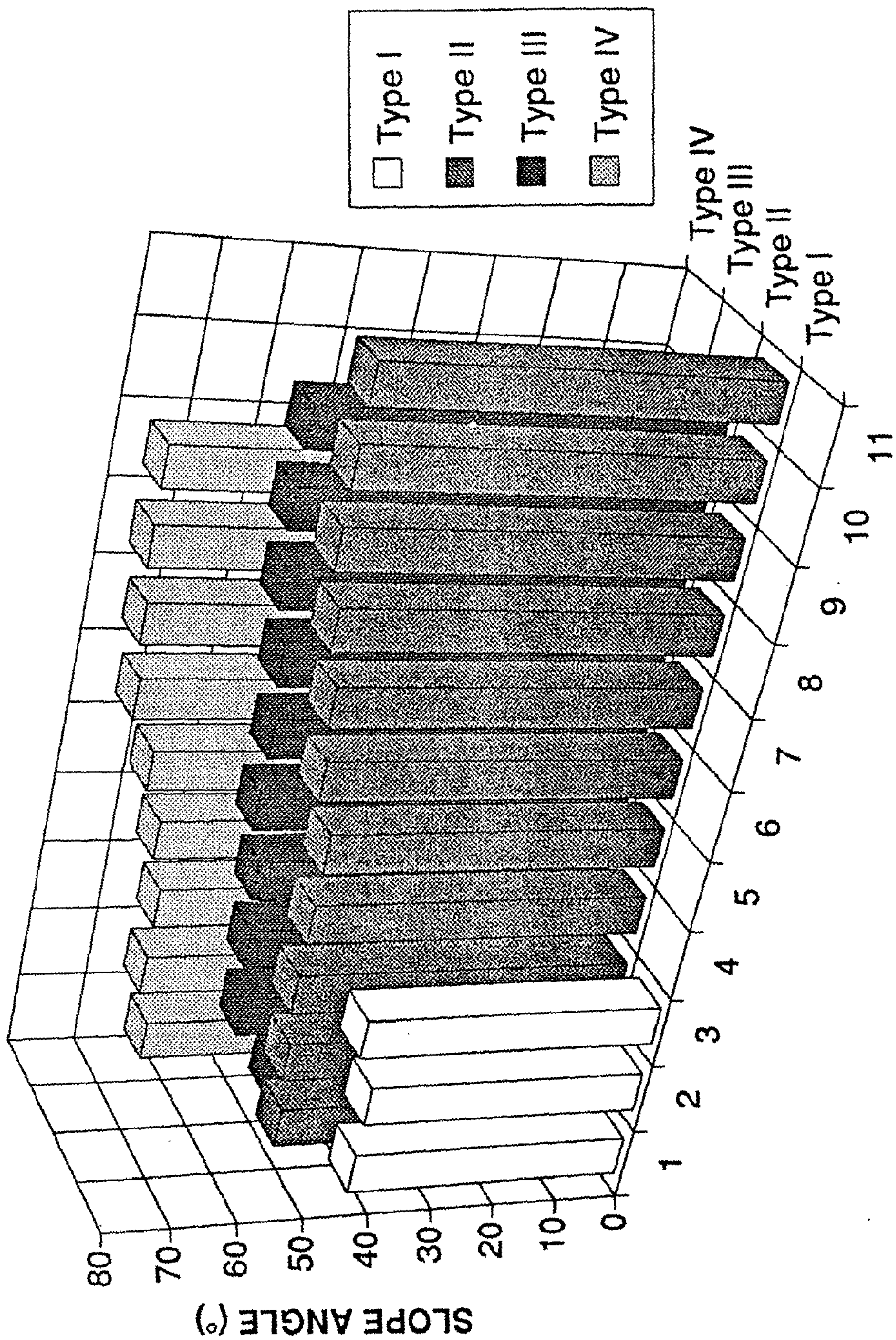
A Coastal Slope Classification: **Composite Slopes for Different Relative Recession Rates of Individual Slope Segments. Rd, Rb, and Rm are as Defined in Figure 4.2 and 4.3**

Figure 4.4



Typical Slope Profiles for the Calvert Cliffs. Horizontal Line Within Each Slope Profile Indicated the Boundary Between Upper and Lower Slope Units. Gray Line Outside of the Slope Toe Represents Mean High Water

Figure 4.5



Range of Overall Slope Angles Observed for Different Slope Types Along the Calvert Cliffs

Figure 4.6

4.5. Application of the Classification System

Figure 4.7 outlines the information needed to apply the coastal slope classification system presented here. The information required may be obtained from simple observations of the slope geometry and the location of any dominant seepage faces. Classification of any particular coastal slope requires the elevation of the slope toe and bluff top, and the average slope angle from the slope toe to the bluff top. The geometric data can be obtained from a detailed topographic map or from a simple field survey. Prediction of the probability and timing of individual large slope failures requires the identification of a seepage zone in close proximity to a weak subsurface layer.

Once the type of slope (Type I, II, III, or IV) is determined, the types and relative rates of erosion mechanisms can be estimated. This information can then be used to evaluate slope protection methods and guide policy on slope protection, setback distances, and public safety. Particular objectives, such as the design of erosion control works, or the evaluation of public safety hazards, depend directly on an identification of the dominant erosion mechanisms acting on a slope. Other objectives, such as estimating cliff response to changes in external variables, require a determination of the present erosion mechanisms in order estimate the potential changes in both the types and rates of erosion. Although prediction of the short term probability and timing of individual large slope failures in the short term requires a site investigation of the potential of high pore pressures in a weak subsurface zone, this detailed information is not as central to an evaluation of long-term recession rates, which are driven by the cumulative effect of many individual failures and are less dependent on the detailed geometry of the slope at any time.

An identification of the dominant erosion mechanisms occurring at each location permits the environmental factors controlling the erosion to be accurately identified. For instance, low wave energies might be capable of very little erosion, allowing a colluvial fan to develop along the lower slope. In this case, control of slope erosion would depend primarily on slope hydrology; remediation efforts must focus on control of surface water and groundwater. At a similar site, a much larger amount of wave energy would be capable of cutting into intact material, causing falling and, during wet periods, shallow sliding, that would proceed far more rapidly than any other erosion mechanism, thereby driving the recession of the entire slope. In this case, the slope would be relatively dry and hydrologically driven erosion processes, although still active, would not contribute significantly to the overall slope recession. The probability of deep-seated failures, even in the presence of an overall steepened slope geometry, may be reduced because negative pore pressures can develop at depth in response to the rapid unloading at the slope. As a consequence, attempts to address slope recession through surface water and groundwater controlling factors would have little effectiveness. Identification of erosion mechanisms and their controlling factors (in this example, the level of wave energy) is central to a quantitative approach to evaluating erosion control measures and predicting the slope response to changes in external variables, such as a sea level rise.

Essential Observations	Result	Example Applications
Slope Angle		Probability, location and timing of large slope failures
Slope Shape	Slope Type Dominant erosion mechanisms	Evaluation of appropriate erosion control methods Toe protection Stormwater management Slope drainage
Toe Elevation		
Seepage zone		
Cliff height above seepage zone		Estimation of slope response to changes in external variables Climate change Sea Level Change

Schematic Application of the Coastal Slope Classification

Figure 4.7

5. Cliff Response to Design Storms and Sea Level Rise

5.1 Observations During and After Tropical Storm Danielle

The center of Tropical Storm Danielle moved northeast along Maryland's Atlantic coast on 25 September 1992. The counterclockwise circulation around the storm's center caused sustained northeast winds of 30 km/hr to 40 km/hr along the Chesapeake Bay. The wind conditions occurred between the hours of 0100 and 2000 hours on that day. Precipitation was light during the course of the storm. Rainfall data collected at NRL and SC show approximately 1 inch of rain fell during the passage of the storm. During the morning and early afternoon intermittent light showers were occurred at the NRL site. During most of that time, no precipitation occurred. After approximately 1400 hours, steady precipitation occurred at the SC site and continued into the early evening. Although Tropical Storm Danielle is not considered an extreme meteorological event when compared to the history of storms in the Chesapeake Bay, it was the most extreme wind and wave event that occurred during the course of the CCSEP study.

The mean water surface and wave heights were measured at NRL during the storm. Measurements were performed at 1330 hours at NRLS on the pilings supporting a small fishing pier. The axis of the wave crests were oriented 50 degrees south of east or approximately SSE to NNW. The mean water surface was measured at an elevation 0.95 m. This is 0.55 m above MHHW and 0.78 m above MSL. The crests of the largest waves were recorded at an elevation of 1.41 m and the troughs at 0.49 m. The maximum trough to crest wave height was 0.92 m. The mean wave height was approximately 0.7 m. The maximum height wave occurred approximately 20 times during a 30 minute observation period. The crest heights of the maximum height waves were quite consistent.

Similar measurements were made at SCS on a small dock adjacent to the boat ramp. The dock is not referenced to the NGVD therefore, the wave height measurements are not tied to the NGVD. The wind speed and direction and orientation of the wave crests were similar to those at NRL. The mean storm water surface was measured to be approximately 0.7 m above the normal daily mean water surface. Maximum trough to crest heights were consistently 1 m and occurred regularly.

Additional observations were made of slope and beach conditions during the storm. Because precipitation was relatively light over the course of the storm, conditions were excellent for separating wave induced erosion from rainfall induced erosion.

Wave run-up at subsite NRL-RC reached nearly 1.5 m above MHHW. A recently constructed, lobate shaped revetment just north of the Randle Cliff pier was in danger of being overtopped with maximum waves breaking approximately 0.25 m below the top of the revetment. Waves were striking the lower slope with considerable force creating low frequency, popping sounds as they impacted the slope. Because of the constant wave attack, it was difficult to monitor erosion of the slope surface in the wave zone.

Maximum wave crests were striking within 0.5 m of the top of the bulkhead along NRLN and NRLS. The slope toe along this portion of shoreline is approximately 30 m to 40 m shoreward of the bulkhead and was in no danger of being affected by wave activity.

The slope toe at subsite NRL-HB was completely submerged. No beach was discernible and waves broke to a level of approximately 1.0 m above the normal water surface. Wedge shaped debris deposits that had accumulated in the toe zone prior to the storm were completely removed by the wave activity. No tree throw was observed along the bluff top, although a good deal of tree sway was evident.

Observations made along the SC site showed wave run-up occurring to approximately 1.5 m at subsite SC-PCS where the slope toes are steep and normally near or below MSL. Along SCN and SCS the beach was completely submerged to elevations of 0.8 m and waves regularly reached the slope toe everywhere, except at the southern end of SCS where a substantial beach has accumulated. In the wave affected toe zones, previously accumulated debris was removed. The slope toes were completely submerged south of the parking lot at SCS and along the entirety of subsite GR. All toe debris was removed along this portion of the slope and intact material was being attacked by waves. No tree throw was observed along SC although significant tree sway was occurring.

Site CRE was visited toward evening of 25 September 1992. The shoreline along this site faces southeast and is protected by Cove Point from storms from the northeast. It was not exposed to the direct force of the wind and waves generated by Tropical Storm Danielle. Water levels were observed to be within 10 cm of normal and wave heights approximately 0.3 m. Tropical Storm Danielle was not an extreme event for site CRE.

A field inspection was conducted on 11 September 1992 of NRL subsites RC and HB, all SC subsites, CCSP subsite GYCS, and CRE subsites CPH, LCP, and LL. A field inspection of the same subsites, except the CRE subsites, was conducted on 29 September 1992, four days after Tropical Storm Danielle.

Several small, fresh spall surfaces were visible just above the top surface of the Fairhaven diatomaceous silt at subsite NRL-RC. No debris was accumulated in the shallow water along the slope toe. Apparently, no trees had been dislodged from the bluff top during the storm. This was true for all CCSEP subsites inspected. The NRL-HB slope toe had been completely stripped of all debris and beach. Small waves were breaking on the intact slope.

A few small, fresh spalls were also visible at SC-PCS. The beach along SC-SCN had been stripped of the upper 20 cm of sand and debris along the slope base had been removed. The beach along the southern end of subsite SC-SCS had accumulated approximately 5 cm of sand. Approximately 5 cm of sand also accumulated south of the SC boat ramp as far south as southernmost groin at Scientists' Cliffs. However, the deposition must have occurred as the storm waned because most of the slope toe debris was removed prior to deposition of the sand. The intact slope toe south of the southernmost groin (subsite GR) is exposed and generally free of debris deposits, as it had been prior to the storm. If wave undercutting occurred at this site, it was distributed evenly across the surface of the toe and very difficult to distinguish.

Prior to Tropical Storm Danielle, a small beach and large debris deposit had accumulated just south of the mouth of Grays Creek (northern CCSP-GYCS). Spalling had been occurring in the lower 6 m of slope for over a year. Several spalled blocks measuring 5m tall by 4 m wide and 0.5 m thick had accumulated at the slope toe. The storm removed most of this material, leaving no beach and only a few remnants of spalled blocks. Further south, near the central portion of GYCS, it was apparent that, during the storm, the root mass of a large fallen tree had impacted the intact slope and caused a large portion of the lower slope to spall. The spalled block measured 4 m tall by 4 m wide by 0.7 m thick. This block must have spalled late into the storm because it was largely intact on 29 September 1992. The toe zone along the entire 500 m of subsite GYCS had been cleared of virtually all erosional debris, except the spalled block just mentioned and several large blocks of ironstone that have occupied the tidal zone at the extreme southern end of the subsite for the duration of CCSEP. A beach approximately 0.7 m thick had accumulated a southern GYCS during the storm but, has since been removed to expose intact material at tide level. The sandy, fossiliferous, slightly indurated Boston Cliffs member of the upper Choptank formation is exposed at beach level in the northern half of GYCS. This unit was undercut an average of 0.4 m laterally along this section of the subsite. The resultant toe zone morphology is an overhang of the silt unit immediately above the shell bed. Further large-scale spalling can be expected along this portion of shoreline as groundwater seepage and freeze-thaw activity weakens exfoliation planes and waves continue to undercut the shell bed below.

5.2 Design Storm Characteristics

Wang, et al., 1982 performed an analysis of storm conditions in the northern Chesapeake Bay which predicted the elevations of wave run-up for storms of one (annual), ten, and one hundred year "return periods". The concept of a wave run-up elevation associated with a particular "return period" is defined by statistics. It means that the probability is 100 percent that the given elevation will be matched or exceeded by the wave height at least once during a length of time equal to the return period. For instance, if an elevation of 2 m is given as the wave run-up elevation for a storm with a return period of ten years, it means that it is 100 percent probable that waves will reach or overtop a point of 2 m in elevation at least once in a ten year period.

The elevation of wave run-up was determined by (Wang, et al., 1982) for 0.5 km reaches of shoreline along the northern Chesapeake Bay. The predicted elevation of wave-run-up for a given return period at a particular site consisted of two parts. A prediction of the storm surge elevation above MSL, and a prediction of the estimated storm wave height superimposed on the surge elevation.

Two types of storms were identified as significant to the shoreline erosion in the northern Chesapeake Bay. They were, tropical hurricanes and extratropical "northeasters." Extratropical storms occurred frequently enough to allow prediction by statistical analysis of the likelihood of their future occurrence. Tidal and weather data records have been kept for sufficient lengths of time in this region to allow a meaningful statistical evaluation of storms and surges with return periods of five years or less. Tropical storms (mainly hurricanes) were arbitrarily defined as those storms with a return period of ten years or greater. More frequent, weaker storms generated in the tropics with return periods of less than ten years were, by default, assigned to the analysis of extratropical storms based on historical records. In fact, a literature review by Wang, et al. (1982) showed the historical frequency of all tropical storms affecting the bay to be one tropical storm every 1 to 1.5 years.

High Frequency (Annual) Wave Run-up

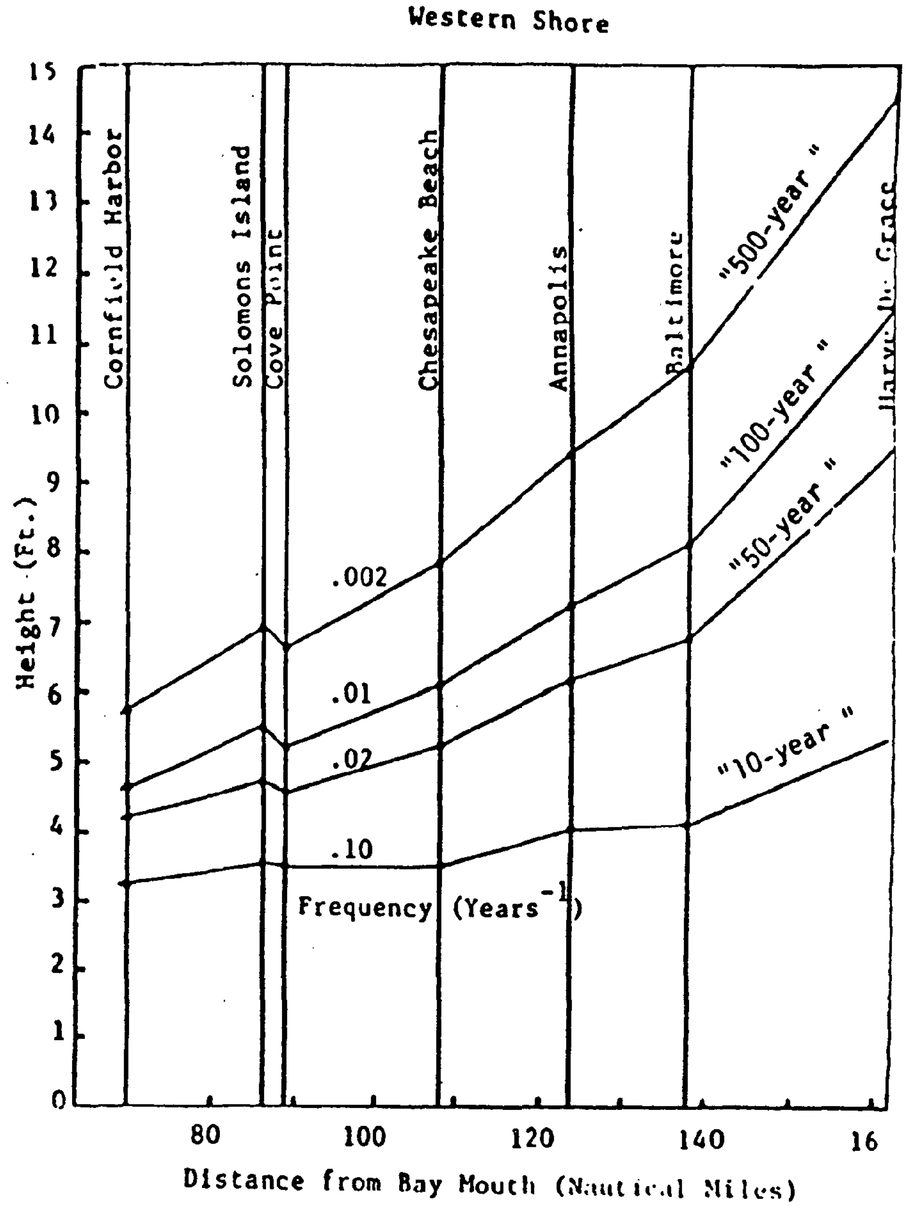
Storm surge elevations with annual return periods were statistically determined from tidal records. The annual wave climate for the northern Chesapeake bay was determined using a hindcast numerical computer model developed by COER, Inc. An empirical wave height and period formula developed by Wilson (1965) and a procedure described by St. Denis (1969) was used as the basis for the computer model. The model uses wind speed and direction as input. Annual storms, judged to be mainly extratropical storms, were assigned uniform wind speeds (determined from historical weather data) and wind directions of north, northeast, or east depending on the maximum wave fetch for the portion of shoreline in consideration. Annual storm wave heights generated by this model were added to the tidal surge elevations described above to determine annual wave run-up elevations for every 0.5 km of northern Chesapeake Bay shoreline.

Low Frequency (Return Period 10 Years or Greater) Wave Run-up

Historical records were not sufficient to allow statistical methods to be used to predict the elevation and frequency of storm surge events produced by hurricanes. Instead a computer simulation model developed by Chen (1978) was used to produce low frequency surge height curves (Figure 5.1). The input parameters were based on historical hurricanes that produced the greatest storm surge in the upper Chesapeake Bay. The historic path of the center of such storms is east of the Chesapeake Bay along a south to north line from the tip of Cape Hatteras, NC, along Maryland's Atlantic coast, and across Delaware Bay. It was assumed that this type of storm would also produce the greatest wave heights. Therefore, wave heights produced by low frequency storms were calculated using wind speed and direction data from a hurricane of this type. The same model used to generate annual wave heights was used for the low frequency events. The wave heights for 10 and 100 year storms were added to the respective storm surges obtained from the Chen simulation. A wave-run-up elevation was computed for 40 sites along the northern Chesapeake Bay shoreline for 10 and 100 year return periods.

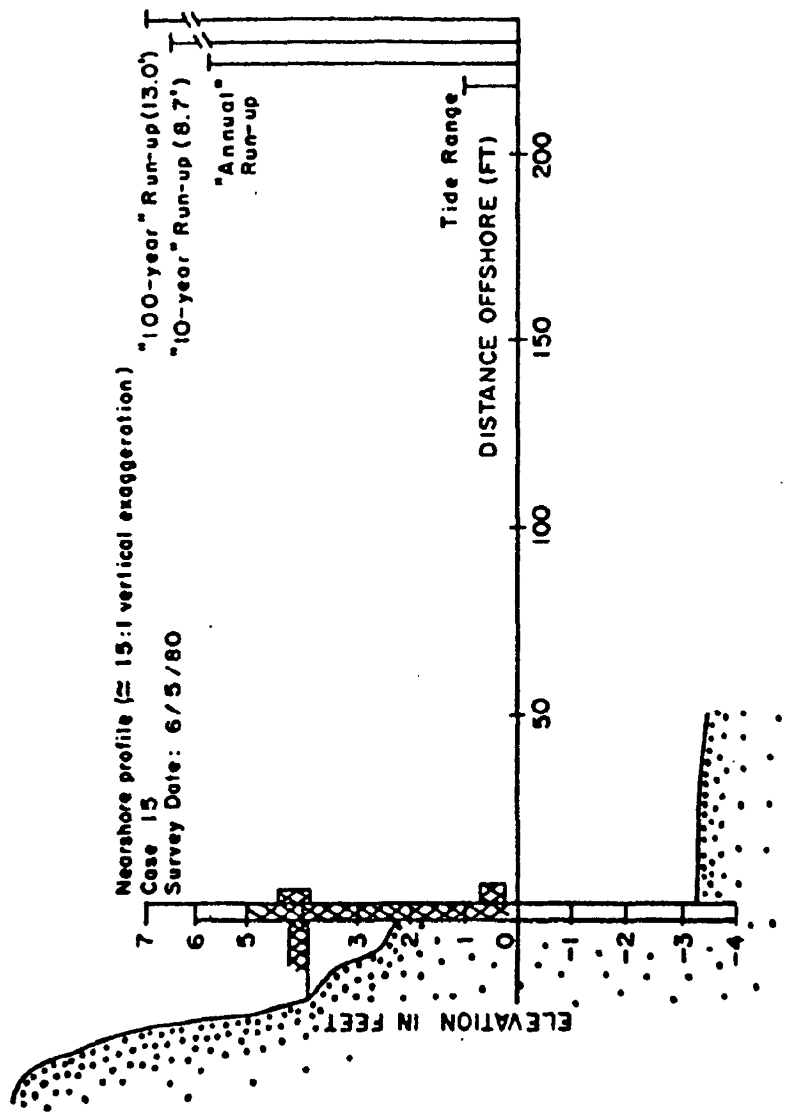
Based on the above wave run-up analysis, the entire Calvert County shoreline was determined to be within a zone along which the wave energy of an annual storm is "high". "The wave energy is considered 'high' if the maximum wave height during an 'annual' storm is over 4.0 feet" [1.22 m] (Wang, et al., 1982).

Two of the 40 study sites are also CCSEP sites. They are NRL and SC. Figure 5.2 shows a cross-section of the bulkhead along the NRLN and NRLS subsites. The elevations for the annual, 10 year, and 100 year wave run-up is shown. The elevations are referenced to MSL. Figure 5.3 shows similar data for a cross-section of the gabion groin protected beach along SCN and SCS.



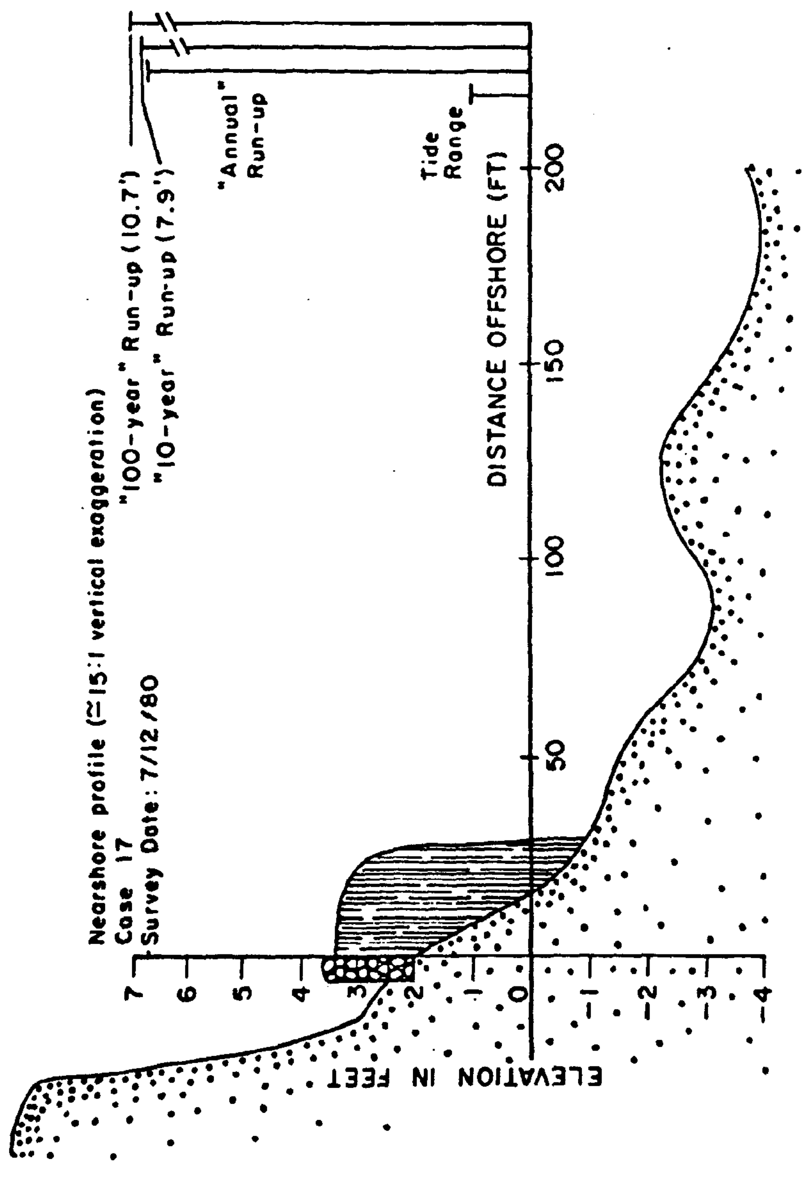
Height-Frequency Estimates of Storm Surge for Low Frequency Events (Wang et. al. 1982)

Figure 5.1



Naval Research Laboratory Wave Run-up Frequency and Elevation (Wang et. al. 1982)

Figure 5.2



Scientists' Cliffs Wave Run-up Frequency and Elevation (Wang et. al. 1982)

Figure 5.3

Comparison with Tropical Storm Danielle

Despite being a tropical storm, Danielle had the characteristics of an extratropical (annual) storm as described by Wang, et al. (1982). The winds were steady at 30 to 40 km/hr from the north east and the wave run-up as measured at NRL was 1.41 m. This is 0.5 m lower than the run-up for an annual storm at this site. Therefore, an occurrence like Tropical Storm Danielle can be expected on a frequent basis.

5.3 Sea Level Change on the Chesapeake Bay

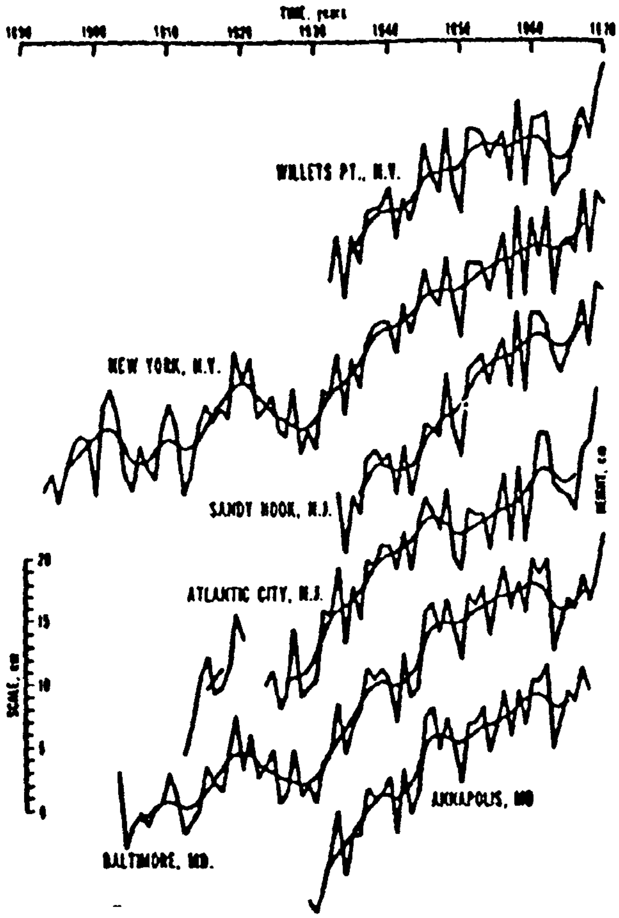
Sea-level has been measured at Baltimore since the early 1900s and at Annapolis, MD, Washington D.C., and Solomons, MD since the 1930s. The rate of observed sea-level rise at these four northern Chesapeake Bay tide gauges averaged over the duration of their operation is 2.8 mm per year (see Figure 5.4). Colman, et al., (1991) compiled Chesapeake Bay sea-level rise data from several sources and established a sea-level curve for the past 10,000 years (Figure 5.5). The average rise in sea-level determined from the linear portion of the curve over the last 2,500 years is approximately 1.3 mm/year. The current rate as measured at the four tide gauging stations is 2.8 mm/year.

Major contributions to apparent local sea-level rise may include isostatic adjustment to Pleistocene glaciation, crustal downwarping resulting from accumulating sediments, compaction of aquifers due to groundwater withdrawal, thermal expansion from rising ocean water temperatures, and melt water from ice caps, ice sheets, and glaciers. The relative proportion of each source to apparent sea-level rise is difficult to distinguish. For the purposes of this report, it is important to note that the current rate of sea-level rise is over twice that of the average rate during the past two millennia. At the current rate of local apparent sea-level rise, 2.8 mm per year, MSL would stand 0.30 m above current MSL at the end of the 21st century.

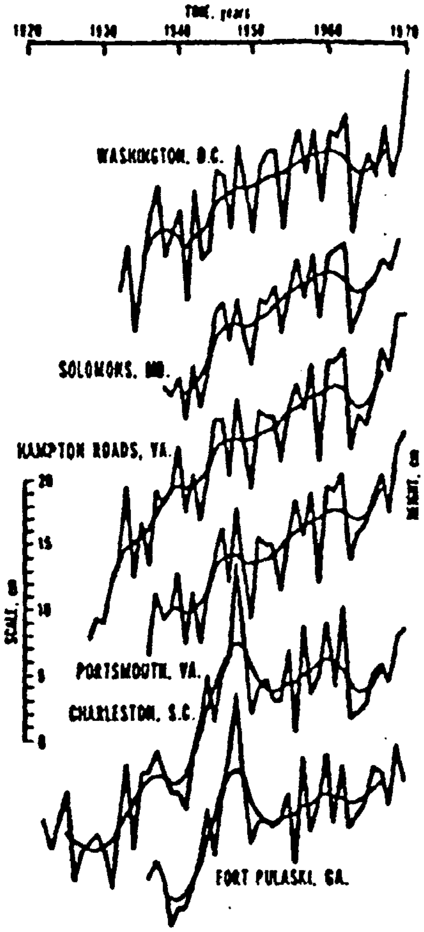
5.4 Comparison with Historical Erosion Rates

As discussed in section 1.1, estimates of slope recession over a period of 100 years have been prepared from an analysis of historical maps and modern aerial photographs (Slaughter, 1949). Historical, time-averaged erosion rates provide valuable comparisons for future estimates of slope erosion. However, since coastal slope erosion processes vary over relatively short periods of time, application of historical data to the prediction of erosion rates is restricted to defining the long-term magnitude of the cumulative erosion of a series of short-term erosion episodes.

The purpose of this section is to identify the historical erosion rate at each study site so that an estimate of the long-term rate of slope recession is available from the outset and to provide a measure of comparison for the erosion rates determined in this project.



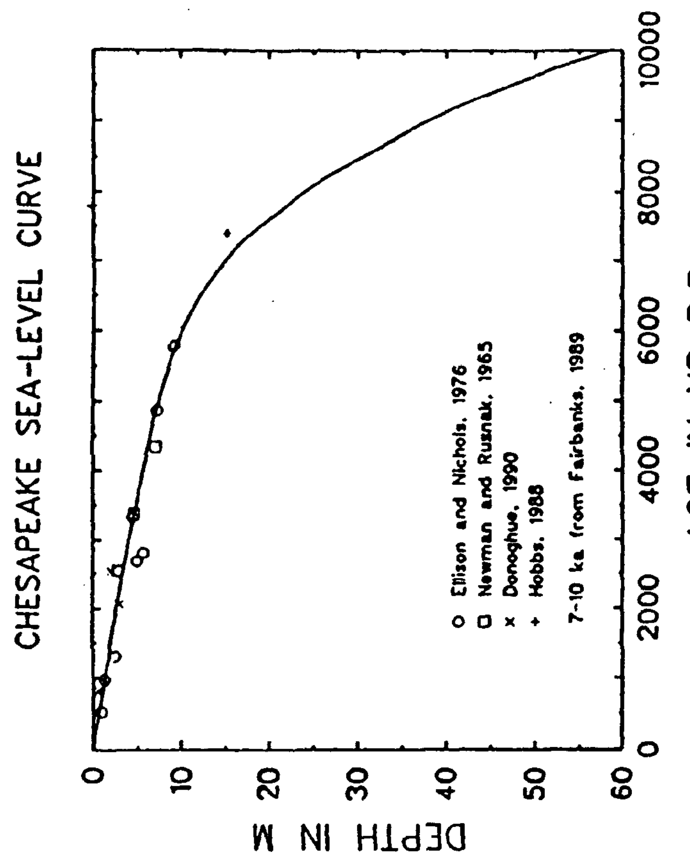
Change in sea level with respect to adjacent land for stations from New York to Maryland. Straight-line segments connect yearly mean sea level values. Curved lines connect yearly values smoothed by weighting array.



Change in sea level with respect to adjacent land for stations from the District of Columbia to Georgia. Straight-line segments connect yearly mean sea level values. Curved lines connect yearly values smoothed by weighting array.

Sea Level Rise at Northern Chesapeake Bay Tide Gauging Stations (Hicks, 1972)

Figure 5.4



(Coleman et. al. 1991)

Figure 5.5

The historical erosion maps prepared by the Maryland Geological Survey provide erosion rates for shoreline segments and are presented on 1:24,000 scale topographic base maps. An earlier study (Slaughter, 1949) produced shoreline recession rates over a 100 year period. An update of these rates to 1988 is currently underway. Therefore, the time span covered on each quadrangle varies from map to map. The erosion rates are presented as:

S (or s) = slight erosion rate; < 2 feet/year

L (or l) = low erosion rate; 2 - 4 feet/year

M (or m) = moderate erosion rate; 4 - 8 feet/year

H (or h) = high erosion rate; >8 feet/year

A (or a) = indicates accretion

The historical erosion maps do not distinguish between beach erosion or slope erosion. They base their estimate of shoreline erosion on the change in the position of the mean high tide line, or vegetation line where vegetation is present, from the beginning of the period to the end of the period.

Historical erosion rates for the Naval Research Lab site:

Two time periods are used to estimate erosion rates for the shoreline segments along the NRL site. The first is an 87 year period between 1847 and 1934, and the second is a 36 year period between 1934 and 1970.

The resolution of the map does not permit distinction between a beach and a submerged slope toe. However, the bluff top is estimated to have receded approximately 125 feet over the two periods combined (123 years). Hence, the average rate of bluff top recession for this site is 1 foot per year. The only exception to this erosion rate is in the southernmost portion of the site at Holiday Beach where the maximum shoreline recession over the 123 year period is approximately 275 feet or 2.2 feet per year. It should be noted that the slope toe along the Navy Research Lab proper has been protected since the 1930's and has experienced no erosion since then, but the bluff top continues to recede.

Historical erosion rates for the Scientists' Cliffs site:

A single 105 year period, from 1848 to 1953, was used to quantify the shoreline erosion at the Scientists' Cliffs site. During that period the Parker Creek South subsite shoreline eroded 300 feet for an average rate of approximately 2.8 feet per year. For a short segment of beach near the northern end of the Scientists' Cliffs community where an erosion rate of approximately 1 foot per year is recorded over the period, the Scientists' Cliffs shoreline has accreted or remained nearly stable, although bluff top retreat continues. The shoreline along the Governors Run subsite shows no net loss or gain over the 105 year period, while the upper portions of the slope have receded.

The shoreline along the Scientists' Cliffs community has been partially protected by gabion groins which have helped to establish a beach. Anecdotal information provided by Scientists' Cliffs residents indicates an average bluff top recession of approximately 0.33 feet per year.

Historical erosion rates for the Calvert Cliffs State Park site:

A single 94 year period, from 1849 to 1943, was used to quantify the shoreline erosion at the Calvert Cliffs State Park site. Once again, the maps do not distinguish between beach or slope erosion, making the estimates near the Cove Point or southern end of the site difficult to interpret. Cove Point is a marshy, low lying point of sand and silt which has slowly been migrating south over the past 150 years. It is postulated that a significant beach was present in the late 1800's and early 1900's on the northern portion of the current Columbia Liquid Natural Gas property immediately south of the Calvert Cliffs State Park. This assumption is supported by the offshore remnants of a salt marsh in this vicinity. The current salt marsh is well south of the state park and protected by a barrier beach.

The historical erosion map indicates that approximately 400 feet (4.5 feet/year) of shoreline have been eroded from the central portions of this site in the 94 year period. A lower rate of approximately 1 foot per year occurs just south of Rocky Point (at the northern end of the site) and a higher rate of 6.4 feet per year is indicated for the extreme southern portion of the site near the submerged salt marsh.

Two structures present on the state park property, one at the northern end just north of Grover Creek and one at the southern end south of Grays Creek, help to establish a rate of bluff top recession between 1943 and 1987 of approximately 4 feet per year (180 feet in 44 years).

Historical erosion rates for the Chesapeake Ranch Estates site:

A single 96 year period, from 1848 to 1944, was used to quantify the shoreline erosion at the Chesapeake Ranch Estates site. The rate of shoreline erosion during this period ranges from near zero at the mouth of Parker Moore Creek near the central portion of this site to approximately 2 feet per year both to the north and to the south of Parker Moore Creek.

At Little Cove Point the shoreline has remained nearly stable, but the shoreline several hundred feet to the north and south has receded an average of slightly over 2 feet per year. The maximum shoreline erosion over this 96 year period was approximately 2.4 feet per year and occurred at the northern end of the CRE site between Little Cove Point and Cove Point Hollow.

It should be noted that the Chesapeake Ranch Estate property has been substantially developed since 1944. Field observations indicate that the rate of slope erosion is accelerating north of Seahorse Beach and north of Driftwood Beach.

Summary and discussion of the historical erosion rates along the Calvert Cliffs

Table 5.1 summarizes the historical erosion rates at each site. Generally, the historical rate of recession of the mean high tide or vegetation line increases southward along the Calvert Cliffs. Notable exceptions occur where shoreline protection has been constructed, where local induration has occurred, and at the southernmost study site, the Chesapeake Ranch Estates, where the slopes are generally taller than those at the other study sites. The trend of higher slope toe erosion rates toward the south correlates well with the decreasing age (and decreasing consolidation) of the stratigraphic materials southward. Exceptions occur where factors other than the erodibility of the material in the toe zone exert an influence. For instance, bulkheads and groins reduce or eliminate the wave impact on the slope toe and reduce recession rates. Local induration provides increased material resistance to erosion and locally diminishes recession rates. Tall slopes contain greater volumes of material than shorter slopes; material which must be removed before shoreline recession can take place. For tall slopes, the rate of removal must be substantially greater than that for shorter slopes for equal amounts of shoreline recession to be observed.

Local and short-term variations in shoreline recession (i.e.. variations within individual study sites) tend to be obscured by long-term, time-averaged recession rates. However, such variations may be extremely significant because of their implications for property owners, land-planners, officials responsible for public safety, and bay sediment supply and transport evaluations. Both the Naval Research Laboratory and Scientists' Cliffs study sites offer opportunities to evaluate the effect of protective structures on slope stability. Where shore protection is in-place at both sites, the bluff tops continue to recede. However, recession is evident for the entirety of the unprotected slopes at both locations. Scientists' Cliffs offers a particularly good site for evaluating the impact of gradual increases in sea-level because the position of the slope toe relative to the water level gradually changes across the length of the site. Here, the conditions range from no protection to complete protection. The two southernmost sites (i.e.. Calvert Cliffs State Park and the Chesapeake Ranch Estates) have varying shoreline orientations and no toe protection. These conditions allow the effect of wave climate on short-term slope stability to be evaluated. Also, the differences in slope height between the two southern sites allows a comparison to be made regarding the effect of slope height on short-tern failure modes and patterns of sequential erosion processes.

Table 5.1. - Summary of Historical Erosion Rates

Site - subsite	Historical erosion rate (ft/yr) averaged over at least 96 years.	Comments
NRL - Randle Cliffs	1	
NRL - Naval Research Lab North	1	60 years of toe protection, bluff top continues to recede
NRL - Naval Research Lab South	1	60 years of toe protection, bluff top continues to recede
NRL - Holiday Beach	2.2	Highest recession where slope heights are lowest.
SC - Parker Creek	2.8	
SC - Scientists' Cliffs North	1	
SC - Scientists' Cliffs South	Stable shoreline	60 years of toe protection, bluff top continues to recede
SC - Governor Run	Stable	Field observations indicate active slope erosion, historical map accuracy is questionable.
CCSP - Rocky Point	1.0	Local induration present.
CCSP - Grover Creek North	4.5	
CCSP - Grover Creek South	4.5	
CCSP - Grays Creek South	4.5	A higher historical rate of 6.4 ft/yr occurs in the vicinity of salt marsh
CRE - Little Cove Point	Stable	Local induration present. Just north and south of LCP the average rate is approx. 2 ft/yr.
CRE - Laramie Lane	2	Relatively tall slopes.
CRE - Driftwood Beach South	2	Relatively tall slopes.
CRE - Seahorse Beach North	2	Relatively tall slopes.

5.5 Coastal Slope Response to Design Storms and Sea-Level Rise.

There is little doubt that property currently free of coastal erosion problems will be affected over the course of the next century due to rising sea-level. The question to be addressed here is: How will the timing, rate, and magnitude of coastal slope erosion along the Chesapeake Bay be affected by a constantly rising bay level? Historical rates of shoreline retreat provide broadly averaged estimates of long-term retreat. But, they are not as useful in terms of understanding the fundamental controlling factors on the rate of coastal slope erosion. Historical retreat rates are not suited for estimating the response of slopes to strong storms or changes in the slope hydrology.

The slope classification system presented in Section 4.0 addresses the issue of slope response to changes in the controlling environmental factors. Identifying the slope segments on which suites of dominant erosional processes act and associating the segments and processes with characteristic geometric slope forms allows changes in the values of controlling factors to be evaluated in terms of slope response.

Design Storms

The power of the slope classification scheme lies in its ability to anticipate the slope response to environmental changes. For instance, storms with annual return periods such as Tropical Storm Danielle are very effective at clearing debris from the lower slope. The mechanism of toe debris removal is important in maintaining the parallel retreat of relatively straight Type II slopes and is part of the cycle of the Type III slopes experiencing rotational landslides. It can be anticipated that stronger, low frequency storms may go beyond the removal of slope toe debris and actively undercut the intact material of the lower zone. Such activity could initiate lower zone falling and steepening in slopes not previously prone to this form of erosion. As the dominant erosional processes change, so does the rate of erosion of that slope segment.

Storms with heavy precipitation will be most destructive to slopes sensitive to hydrologic erosion. The slope classification scheme readily identifies existing slopes predominantly eroded by stormflow and groundwater erosion. It may also be used to assess the impacts that erosion control might have on the dominant suite of erosion processes. A slope that receives some form of toe modification may change from one dominated by shallow sliding driven by wave undercutting to one eroded by surficial erosion related to stormflow. Recognition of this possibility allows planners and engineers to anticipate significant changes in the erosional processes and implement proper management techniques.

Sea-level Rise

Continued sea-level rise will impact slopes not currently affected by wave erosion and may aggravate the erosion of currently eroding slopes. Significant changes will take place where once protected slope toes are exposed to wave erosion and on slopes where the lower slope is particularly sensitive to increases in wave energy. The results of the CCSEP may be applied to both cases.

Slopes with varying degrees of toe protection have been examined at both NRL and SC. In each case, the protection has significantly slowed the overall rate of erosion and has been instrumental in changing the dominant suite of erosional processes at each site. This has been established by applying the slope classification scheme in a comparison of adjacent protected vs. unprotected slopes. The slope changes resulting from sea-level rise that are identified by the slope classification scheme are useful in developing future erosion control schemes. For instance, unless the bulkhead at the NRL site is substantially heightened and strengthened, it will eventually be overtopped. Wave erosion at the base of the NRL slopes may be expected to produce Type IV slopes similar to those at the adjacent subsites RC and HB. The slope protection at SC is constantly maintained at a level relative to the water surface and it may be expected that continued regular maintenance of the gabion-groin structures will provide a level of erosion protection similar to the existing level of service.

Unprotected slopes may also undergo significant erosional process changes. Slopes especially susceptible to changes in the rate and type of erosion are those where an increase in sea-level will move the wave activity to an elevation where easily eroded materials exist. It is possible that this type of situation could change a slowly eroding Type II slope into a more rapidly eroding Type III or IV slope. The inverse of this situation is also possible. The rising water surface could move the bulk of the wave activity into a more resistant strata and result in the slowing of toe zone erosion. It is conceivable that such slopes may change from being wave-dominated to hydrologically dominated slopes.

6. Conclusions

This report provides a summary of the materials, hydrogeology, and slope geometry along four sections of the Calvert Cliffs. The primary goals of the work are to identify the dominant erosion mechanisms acting on each cliff and develop a general framework for simple observations of these rapidly eroding and evolving cliffs that focuses on the mechanisms by which the cliffs erode. The erosion mechanisms must be known before further analyses of stability and recession rate can be made, so it is the first information needed in developing engineering plans, zoning, or policy for the cliffs.

We propose a simple classification for rapidly eroding coastal slopes. The goal is to develop a correlation between slope geometry (angle and shape) and the types of erosion mechanism acting on the slope. After identifying lower, middle and upper slope segments, the classification separates slope types based on the characteristic slope geometry produced by relative recession rates of the various slope segments. Because characteristic suites of erosion mechanisms can be associated with each slope segment, the relative magnitude of the segment recession rates can be used to identify the dominant erosion processes acting on the slope. In this way, the slope geometry (which is what we can easily observe in a slope) can be used to deduce the dominant erosion mechanisms.

The classification of coastal slopes presented here builds on those previously given by Hutchinson (1973), Quigley and Gelinas (1976), and Edil and Vallejo (1977). We add an additional slope category (Type IV), in which rapid wave erosion dominates the mechanisms and form of the entire slope. We also make explicit use of the typical presence of distinct lower, middle, and upper slope segments the composite slope geometry that result from different recession rates of the individual slope segments. Because particular erosion mechanisms are often associated with these different segments, the relative recession rates that may be deduced from the slope geometry can then be used to estimate the dominant erosion mechanisms.

The particular values of slope angle associated with the various slope types depend, in part, on the geotechnical properties of the slope materials and may not be directly translated to other locations. The general organization of the classification system, however, is based only on the occurrence of a lower and mid-slope section separated by a seepage zone and elementary geometric requirements that follow from the relative recession rates of the different slope segments. When distinctive suites of erosion processes may be associated with each slope segment, the classification system suggested here may be used to identify erosion mechanism from the geometry of other tall, rapidly eroding cliffs.

The importance of identifying the mechanisms by which cliffs erode lies in the fact that each erosion mechanism responds differently to possible changes in the variables that control slope erosion. If only one factor changes (e.g. wave undercutting rate or local stormwater conditions behind the slope top), some erosion mechanisms will change more than others, so that a shift from one dominant erosion mechanism to another may occur. An increase in sea level can increase undercutting rates and increase the rates at which some erosion mechanisms, such as toppling and shallow sliding, proceed. An increase in undercutting rate may actually cause other mechanisms to operate less rapidly because steeper slopes tend to have less overland flow from both direct precipitation and groundwater seepage. A change in a different controlling variable, for example, groundwater recharge rate, can cause other erosion processes, such as deep sliding, to operate more rapidly or frequently. Thus, an estimate of future cliff behavior (e.g. in response to engineering works or a change in an external variable such as sea level) requires that the erosion mechanisms be identified.

7. Future Work

Purpose

A slope erosion model is needed to provide a basis for designing and evaluating erosion control projects and developing coastal zone policy for the tall, eroding cliffs of the Chesapeake Bay. The model can be initially developed and tested for the tall, eroding cliffs in Calvert County and then applied to other coastal areas of the Chesapeake Bay. Accurate model results are needed to analyze the technical and economic feasibility of erosion control projects at the local and bay-wide levels.

Tasks

Monitoring: It is important to continue to monitor groundwater pore pressures and seepage rates, and the slope erosion at each of the four study sites established in the Calvert Cliffs Slope Erosion Project. A large expense has been incurred in developing these monitoring sites; they provide, for the first time, a comprehensive set of base-line information on the controlling factors and erosion rates of tall slopes along the Chesapeake Bay. Because these cliffs erode through a variety of mechanisms which may vary in relative intensity over time, a longer time series of observations is needed to understand at a practical level the types, rates, and controlling factors of cliff recession. It is strongly recommended that automatic, electronic water level monitoring and data storage devices be installed at each well cluster.

Future work should focus on establishing erosion rates associated with specific suites of dominant processes and the threshold values of the environmental factors for which changes between dominant processes take place. The Calvert County sites established in CCSEP provide excellent conditions for quantifying erosion rates. A range of materials representative of the Chesapeake Bay region is exposed there, as well as prime conditions for varying the experimental controlling factors of slope height, angle, shoreline orientation, and groundwater conditions.

Slope erosion prediction tool: A slope erosion prediction tool is needed to estimate slope response to sea level change and to evaluate different strategies for erosion remediation. Such a model should be developed using models of slope stability and should incorporate observations of the geotechnical and hydrologic conditions producing erosion. An important goal is to identify the critical environmental conditions for different types, sizes, and timing of slope failures. These critical environmental conditions can then be combined with quantitative models of individual slope processes in a multi-component model to estimate future slope failures along the cliffs. Once this shore erosion prediction tool is developed for the Calvert Cliffs, it can then be tested along other areas of similar cliffs around the Bay. The basic input for the end-user is the location of the cliff section and the height and mean angle of the slope. With this information, a topographic map, and a stratigraphic section, the geotechnical properties, groundwater flow patterns, seepage rates, and wave and storm surge climate can be estimated. These data would then be combined with the input slope height and angle to predict the mechanisms and rates of slope erosion, including the probability, location, and timing of large slope failures.

Technical and economic feasibility of erosion control on tall cliffs. Erosion remediation along tall cliffs is very expensive. It will be necessary to simultaneously investigate the technical and economic feasibility of design alternatives for stabilizing the tall, eroding cliffs. Such projects present extraordinarily difficult engineering, economic, and policy problems. The slope and angle of many of these cliffs exceed those for which standard engineering methods are practical. Erosion control designs must include some combination of toe protection (for which a number of methods of widely different cost and effectiveness are possible), grading, vegetation, and stormwater control. Any individual type of erosion control is likely to be unsuccessful if not considered in the context of all erosion mechanisms acting on any individual cliff.

If engineering solutions to the erosion are found, decisions to protect such slopes require a balance of the protection cost against the value of preventing further slope recession. The latter quantity must take into account a wide variety of factors, including land value, economic opportunity, public perception of the importance of property and structures lost to erosion, public safety, sediment supply to the Chesapeake Bay, and the intrinsic value of the cliffs as a scenic, tourist, and paleontological resource.

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Appendix A

Table A1: Sedimentological parameters - split spoon samples collected January 23-31, 1991 - Navy Research Lab

Well number	Depth to top of sample (ft)	(m)	Water (%)	Sand (%)	Silt (%)	Clay (%)	Shepard's class	Weight loss (%)
NRL1	3.0	0.9	17.18	44.75	21.19	34.06	SaSiCl	9.53
NRL1	8.0	2.4	10.72	56.15	24.85	18.99	SiSa	8.41
NRL1	13.0	4.0	17.10	57.84	21.31	20.85	SaSiCl	9.12
NRL1	18.0	5.5	22.92	70.20	14.45	15.35	ClSa	0.79
NRL1	23.0	7.0	34.09	57.26	22.77	19.97	SiSa	8.00
NRL6	25.0	7.6	31.00	56.12	24.80	19.08	SiSa	6.75
NRL1	28.0	8.5	35.70	50.87	26.39	22.74	SaSiCl	9.12
NRL1	33.0	10.1	46.34	21.34	50.79	27.88	SaSiCl	9.30
NRL1	38.0	11.6	26.64	74.91	14.15	10.94	SiSa	11.93
NRL1	43.0	13.1	37.54	40.68	29.01	30.31	SaSiCl	15.56
NRL1	48.0	14.6	26.98	95.57	3.21	1.21	Sa	24.66
NRL1	53.0	16.2	26.02	87.86	8.63	3.51	Sa	10.31
NRL1	58.0	17.7	33.35	77.37	11.87	10.76	Sa	4.74
NRL1	63.0	19.2	37.32	59.85	22.13	18.02	SiSa	9.63
NRL1	68.0	20.7	36.21	62.58	20.28	17.14	SiSa	13.23
NRL1	73.0	22.3	32.28	77.42	11.71	10.87	Sa	5.16
NRL1	78.0	23.8	31.27	69.64	17.84	12.52	SiSa	12.69
NRL1	83.0	25.3	32.73	40.32	35.63	24.06	SaSiCl	13.12
NRL1	88.0	26.8	37.57	19.65	48.07	32.28	ClSi	13.54

Table A2: Sedimentological parameters - split spoon samples collected January 14-17, 1991 - Scientists' Cliffs

Well number	Depth to top of sample (ft)	(m)	Water (%)	Sand (%)	Silt (%)	Clay (%)	Shepard's class	Weight loss (%)
SC1	5.0	1.5	14.11	83.98	11.22	4.80	Sa	1.92
SC1	15.0	4.6	27.95	51.45	26.92	21.62	SaSiCl	----
SC1	20.0	6.1	13.90	88.02	4.77	7.21	Sa	47.81
SC1	25.0	7.6	13.90	91.00	4.65	4.35	Sa	35.49
SC1	30.0	9.1	23.43	83.56	7.64	8.80	Sa	3.73
SC1	35.0	10.7	25.06	77.46	12.26	10.28	Sa	12.18
SC1	40.0	12.2	29.22	64.04	17.82	18.14	ClSa	7.53
SC1	45.0	13.7	29.68	43.99	32.36	23.65	SaSiCl	9.83
SC1	50.0	15.2	28.44	25.66	40.08	34.26	SaSiCl	15.83
SC1	55.0	16.8	14.76	82.70	8.47	8.83	Sa	32.49
SC1	60.0	18.3	15.50	92.32	3.63	4.05	Sa	8.49
SC1	65.0	19.8	19.31	93.74	4.89	1.37	Sa	13.61
SC1	70.0	21.3	21.89	93.66	4.53	1.81	Sa	9.86
SC1	75.0	22.9	26.74	66.30	14.96	18.74	ClSa	13.96
SC1	80.0	24.4	24.13	75.71	10.92	13.37	Sa	7.94
SC1	85.0	25.9	25.04	79.70	12.34	7.96	Sa	8.59

Table A3: Sedimentological parameters - split spoon samples collected December 17-20, 1990 - Calvert Cliffs State Park

Well number	Depth to top of sample (ft)	(m)	Water (%)	Sand (%)	Silt (%)	Clay (%)	Shepard's class	Weight loss (%)
CCSP1	5.0	1.5	3.01	86.19	7.20	6.61	Sa	2.83
CCSP1	10.0	3.0	14.69	16.08	41.73	42.19	SiCl	6.95
CCSP1	15.0	4.6	16.09	41.52	33.52	24.97	SaSiCl	2.24
CCSP1	20.0	6.1	11.47	70.66	12.85	16.48	ClSa	2.06
CCSP1	25.0	7.6	18.87	81.15	9.61	9.24	Sa	2.36
CCSP1	30.0	9.1	18.48	78.76	11.16	10.08	Sa	3.02
CCSP1	30.8	9.4	20.16	79.99	11.06	8.94	Sa	3.53
CCSP1	35.0	10.7	22.18	79.58	12.18	8.24	Sa	2.41
CCSP1	40.0	12.2	22.58	19.59	35.28	45.13	SiCl	6.20
CCSP1	45.0	13.7	19.08	28.08	30.63	41.29	SaSiCl	9.49
CCSP1	50.0	15.2	18.78	25.91	29.05	45.04	SaSiCl	11.40
CCSP1	55.0	16.8	23.19	21.18	39.00	39.82	SaSiCl	13.39
CCSP1	60.0	18.3	21.82	38.65	39.14	22.20	SaSiCl	7.80
CCSP1	65.0	19.8	23.00	3.15	70.26	26.59	ClSi	7.77
CCSP1	70.0	21.3	26.42	10.97	44.70	44.33	ClSi	9.26
CCSP1	75.0	22.9	19.60	87.64	5.79	6.57	Sa	11.80

Table A4: Sedimentological parameters - split spoon samples collected December 6-10, 1990 - Chesapeake Ranch Estates

Well number	Depth to top of sample (ft)	(m)	Water (%)	Sand (%)	Silt (%)	Clay (%)	Shepard's class	Weight loss (%)
CRE1	4.5	1.4	10.58	48.62	38.69	12.70	SiSa	5.69
CRE1	9.5	2.9	5.46	90.62	3.95	5.43	Sa	1.68
CRE1	14.5	4.4	4.97	93.91	3.21	2.87	Sa	1.64
CRE1	19.5	5.9	5.95	94.36	2.49	3.16	Sa	1.64
CRE1	24.5	7.5	5.58	94.13	2.47	3.40	Sa	1.69
CRE1	29.5	9.0	10.89	92.80	1.70	5.50	Sa	3.13
CRE1	34.5	10.5	11.05	88.75	5.46	5.80	Sa	3.06
CRE1	39.5	12.0	12.07	92.78	3.64	3.59	Sa	2.52
CRE1	44.5	13.6	13.23	80.72	7.99	11.29	Sa	5.10
CRE1	49.5	15.1	14.58	65.09	17.84	17.07	SiSa	3.48
CRE1	50.0	15.2	26.57	10.27	30.10	59.62	SiCl	5.74
CRE1	50.5	15.4	19.28	47.42	25.23	27.35	SaSiCl	7.93
CRE1	54.5	16.6	13.31	69.99	14.89	15.12	ClSa	6.40
CRE1	59.5	18.1	17.83	75.63	10.94	13.43	Sa	7.09
CRE1	64.5	19.7	20.60	69.95	17.82	12.23	SiSa	4.18
CRE1	69.5	21.2	19.68	53.27	33.06	13.67	SiSa	23.07
CRE1	74.5	22.7	20.31	77.37	16.47	6.16	Sa	34.62
CRE1	79.5	24.2	20.65	32.89	49.67	17.43	SaSi	9.94
CRE1	84.5	25.8	22.73	5.00	38.02	56.98	SiCl	15.08