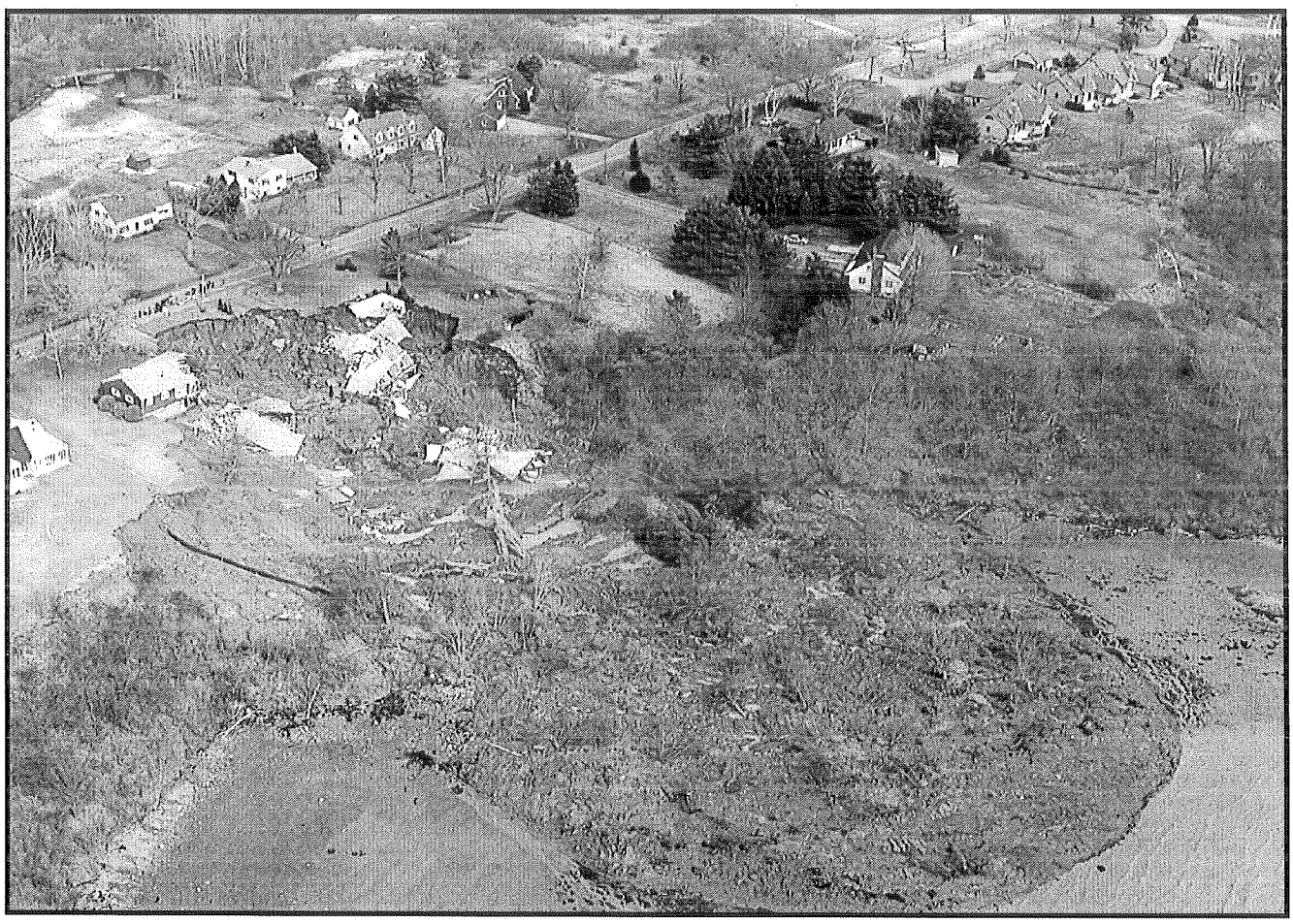
The April 1996 Rockland Landslide



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Cover photo: *Oblique airphoto of the April 1996 catastrophic landslide on the north shore of Rockland harbor. The high, steep bluff of clay gave way under its own weight and flowed out onto the mud flat below. Two houses were destroyed. Onlookers view the devastation from behind police barricades. (PDQ photography.)*

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PLATE 1: PANORAMAS OF THE 1973 AND 1996 LANDSLIDES, ROCKLAND, MAINE .. (separate from report)

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INTRODUCTION

This report describes the results of geological, geophysical, and geotechnical investigations made at the site of the April 1996 Rockland landslide. A team of geologists from the Maine Geological Survey of the Natural Resources Information and Mapping Center (NRIMC), the University of Maine Department of Geological Sciences, and the geological consulting firm Robert G. Gerber, Inc., made repeated visits to the site in order to determine the following:

(a) the potential for further slope failures at the immediate site,
(b) the need to evacuate additional homes,
(c) the relationship of this event to previous landslides nearby,
(d) the importance of more gradual bluff erosion caused by the sea, and
(e) the cause(s) of the landslide

so that the public and government officials would have better information to make decisions about public safety, infrastructure, and remedial actions.

OVERVIEW OF THE LANDSLIDE EVENT

Early in the morning of April 16, 1996, there was a landslide along the north shore of Rockland Harbor (Figure 1). The slide occurred along a steep bluff adjacent to Samoset Road. The bluff top was about 50 feet (15 m) above sea level and the base of the bluff slope ended at the high water mark. Slumping of the bluff occurred progressively in a series of discrete landslide events. This style of landslide is called a retrogressive landslide because it works gradually backward from the slope into the bluff. Most of the initial motion occurred between 1:15 AM and about 4:00 AM during a falling tide immediately preceding a new moon the following day, and prior to heavy rains in the afternoon of April 16. NRIMC geologists surveyed the site for signs of additional imminent failure at 1:00 PM on April 16 and consulted with city officials and emergency personnel.

The initial slide motion on April 16 awoke Douglas and Susan Gerrish, residents of 23 Samoset Road. They notified local authorities and removed two vehicles from their garage. The Rockland Fire Department evacuated Dorothy Smalley from the house next door and alerted the neighboring residents. Portions of the Gerrish home and the Smalley residence and garage fell into the main body of the landslide. These structures were

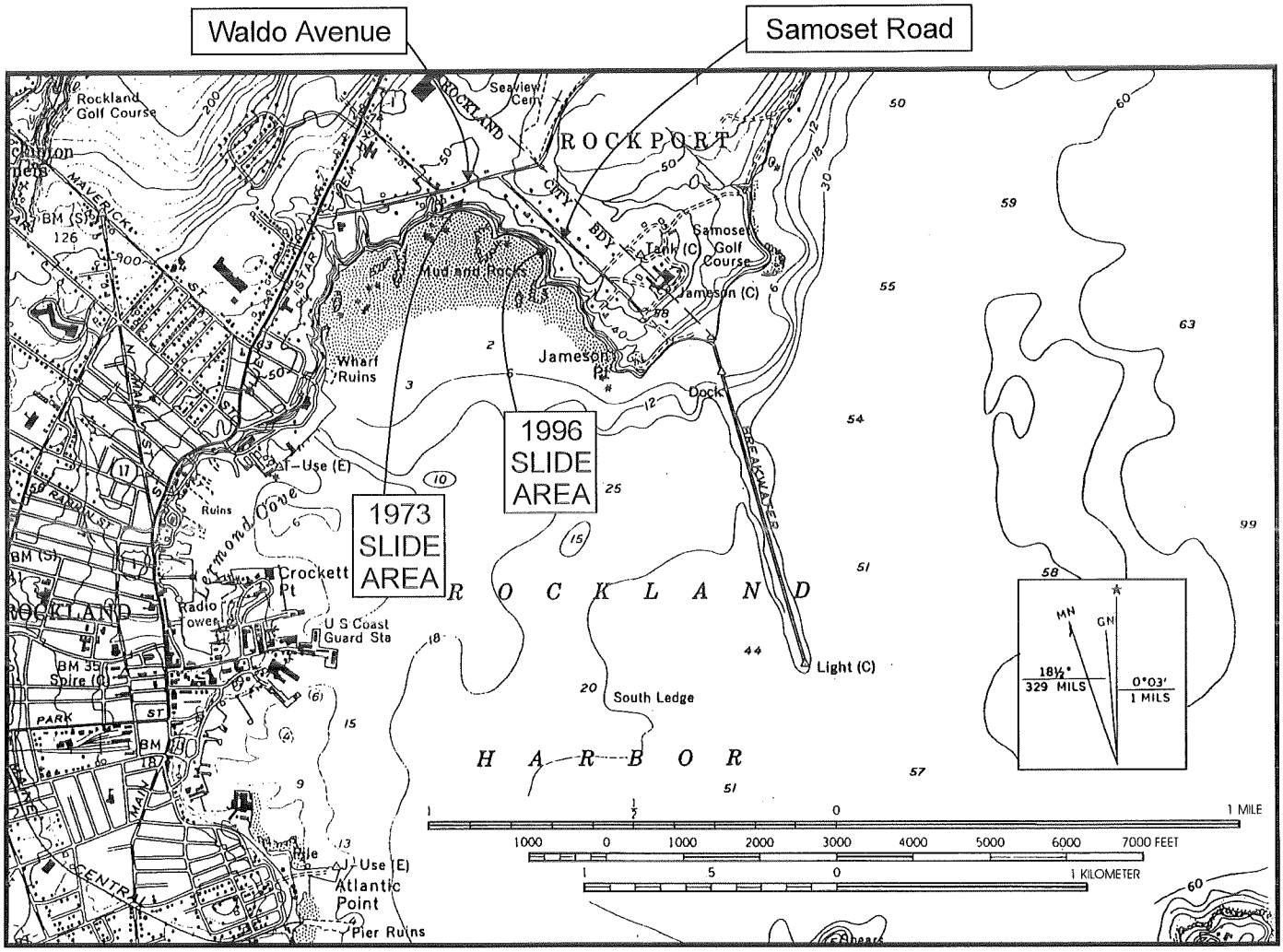


Figure 1. Location map showing 1973 and 1996 Rockland landslides (note that the most recent U. S. Geological Survey topographic map used as a figure base in this report was last revised in 1973. Therefore, the new Samoset Resort buildings and access road, and the Jameson Point condominiums are not shown. The buildings can be seen in the recent photos of Figure 2 and Figure 9, and in Appendix A, Figure A1.). Contour elevations in feet above and below mean sea level,

about 75 feet (23 m) landward of the top edge of the bluff prior to the landslide (Figure 2A). A topographic survey by geologists from the NRIMC and University of Maine determined that the slide displaced more than half an acre of backyard from the Smalley and Gerrish lots (Figures 2B, 2C, and 2D). When it was over, the slide had moved horizontally over 400 feet (120 m) onto the mudflats of the intertidal zone and had disturbed a total area of 3.5 acres (1.4 hectares). Nonetheless, even a month after the slide, some of the Gerrish home remained in place with a portion overhanging the main scarp.

For a month following the major slide event, smaller blocks continued to fall from the steep landward slopes. These continued slope failures resulted in enlargement of the affected area by landward progression of the vertical scarp. By landward retreat, the main scarp moved to within 15 feet (5 m) of a sewer main on the seaward side of Samoset Road. Possible disruption of a city water main buried beneath the landward shoulder of Samoset Road was also of public concern. In order to measure continued movement and to assess the potential for additional failures, the City of Rockland hired a geotechnical consulting firm, R.G. Gerber, Inc., that installed three inclinometers at the head of the slide near Samoset Road. The inclinometers were installed after drilling through the surficial deposits down to solid bedrock, and gave direct information about the subsurface geology at the landslide site. R. G. Gerber, Inc., also engineered the stabilization of the area during the Fall of 1996. As of the writing of this report, the total cost in terms of lost property value and cost to the city for emergency activities, evaluation of the two homes

Figure 2A. Airphoto before the 1996 slide; 10/4/92 (J. W. Sewall Company). Houses referred to in the text: Eaton (E), Gerrish (G), and Smalley (S).

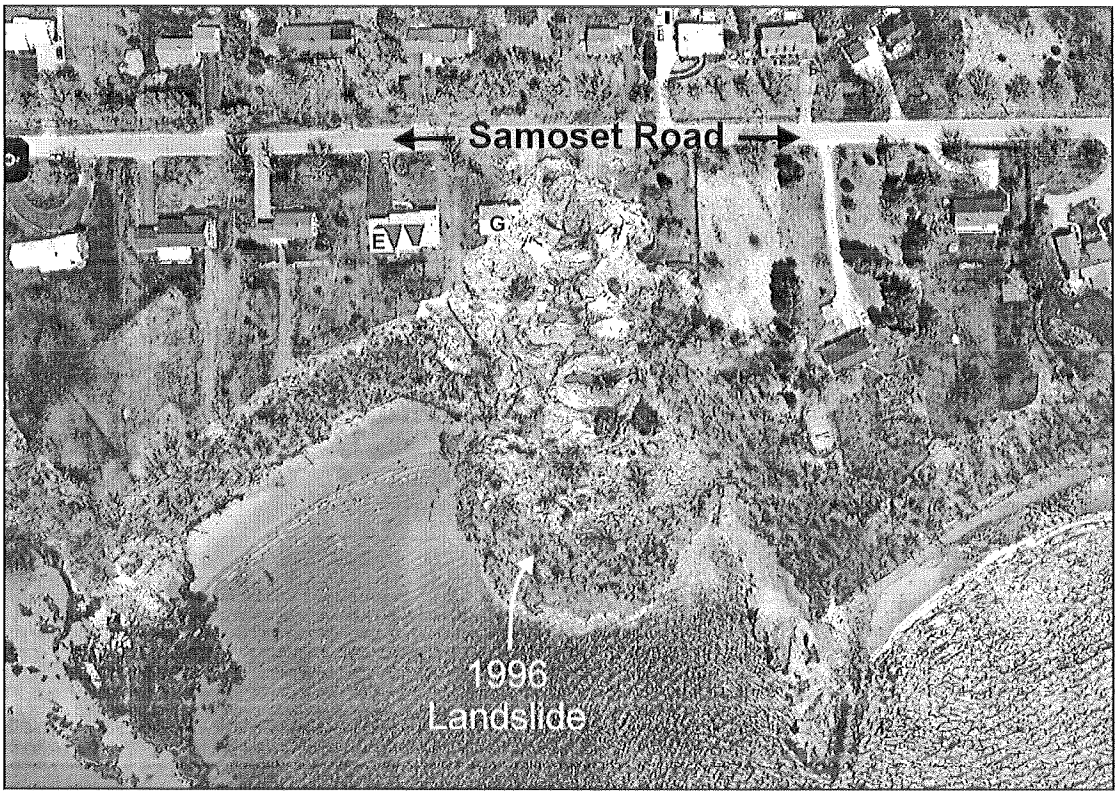
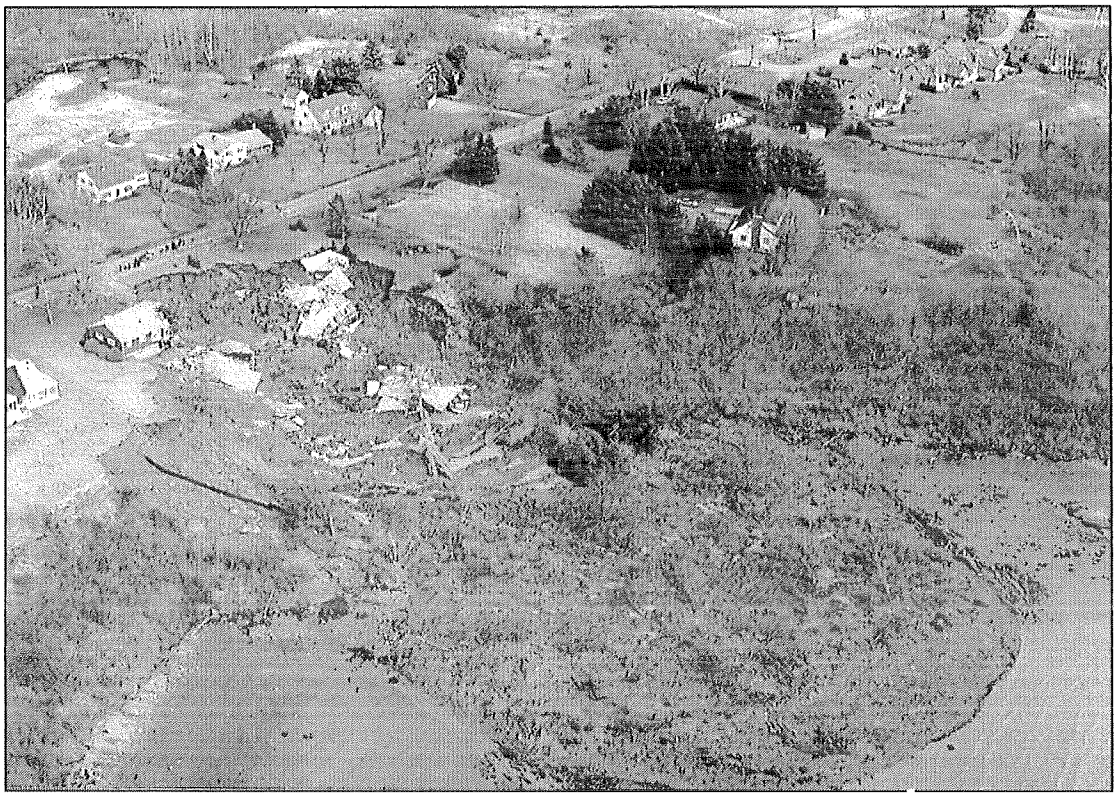


Figure 2B. Airphoto after the 1996 slide; 5/8/96 (J. W. Sewall Company). A portion of the Gerrish home (G) overhangs on the left wall of the landslide scarp. The Smalley home shown in Figure 2A was completely destroyed by the landslide.



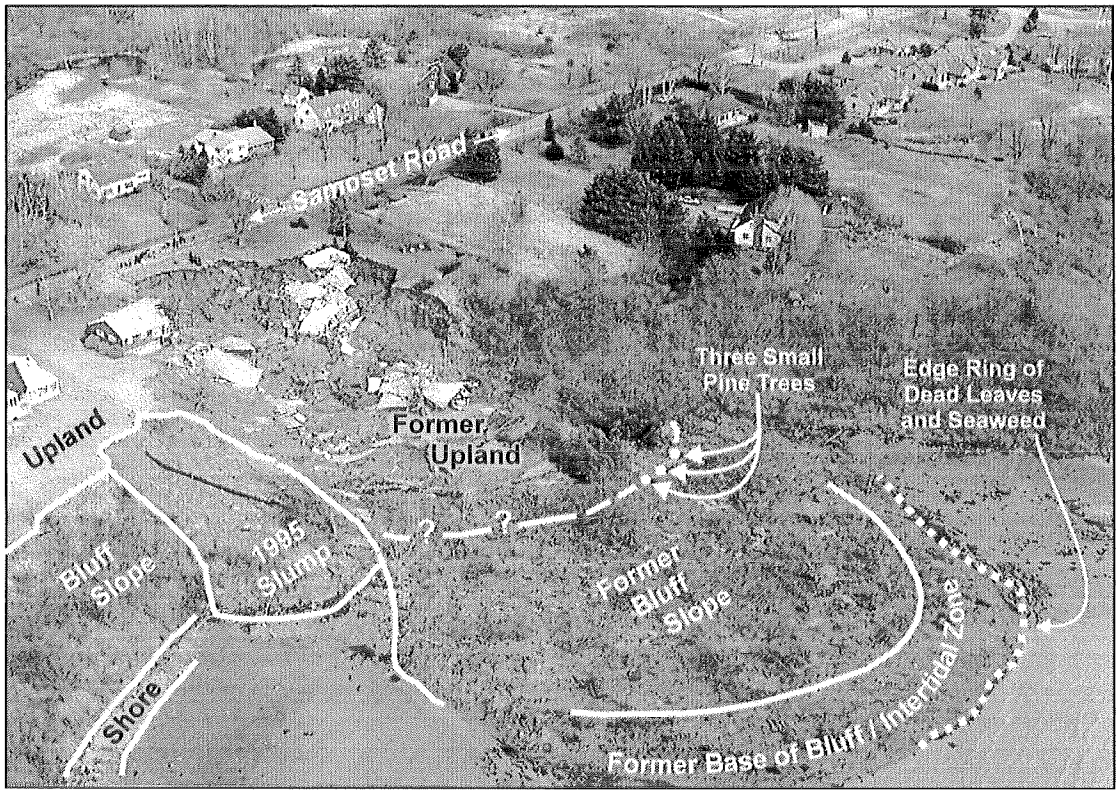
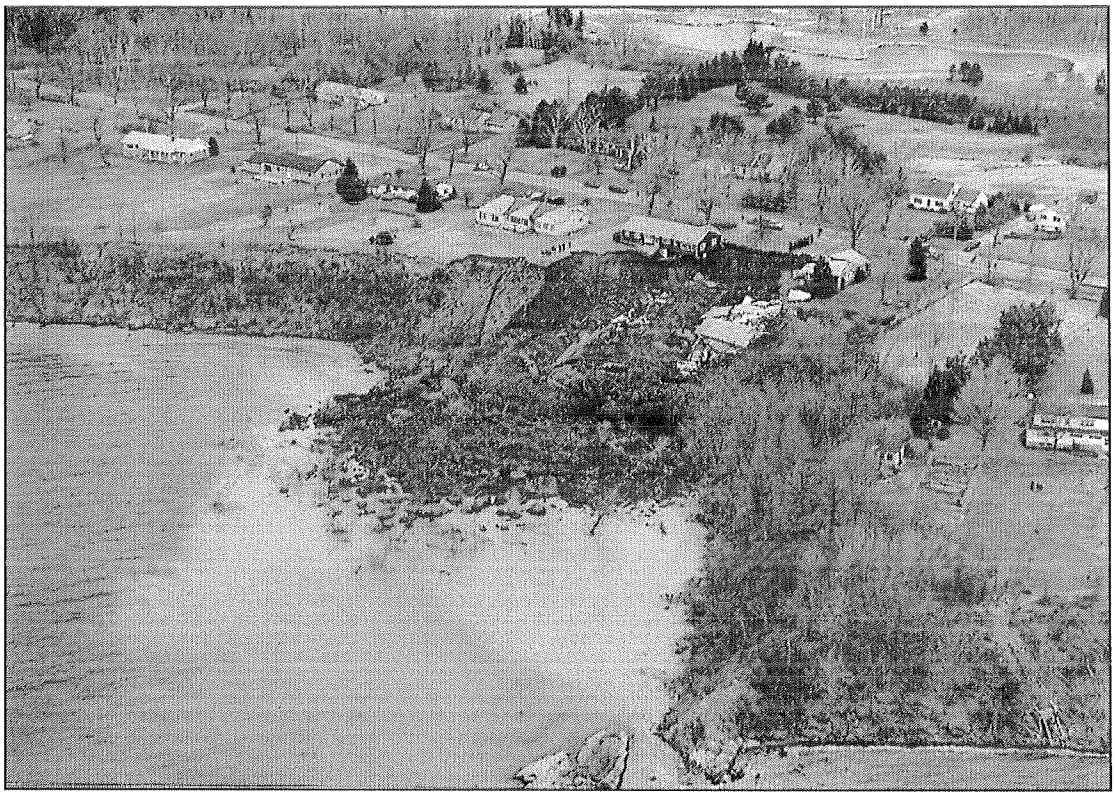


Figure 2C. Oblique airphoto of the landslide; view toward east, 4/17/96 or 4/18/96 (PDQ Photography). A small landslide scar (in area of exposed black drain pipe) from 2/95 is visible to left of 4/96 slide blocks. Lower photo shows interpretation of the landslide. The three small pine trees marked by dots were at the top edge of the bluff. To the left of these trees is lawn, turf, and landscaped plants. Toward the toe of the slide are grass clippings and yard waste followed by trees and shrubs that were on the bluff slope. At the toe of the slide (former base of bluff), deposit includes rounded stones with barnacles and seaweed growing on them. This debris was transported from the shoreline to the slide toe.



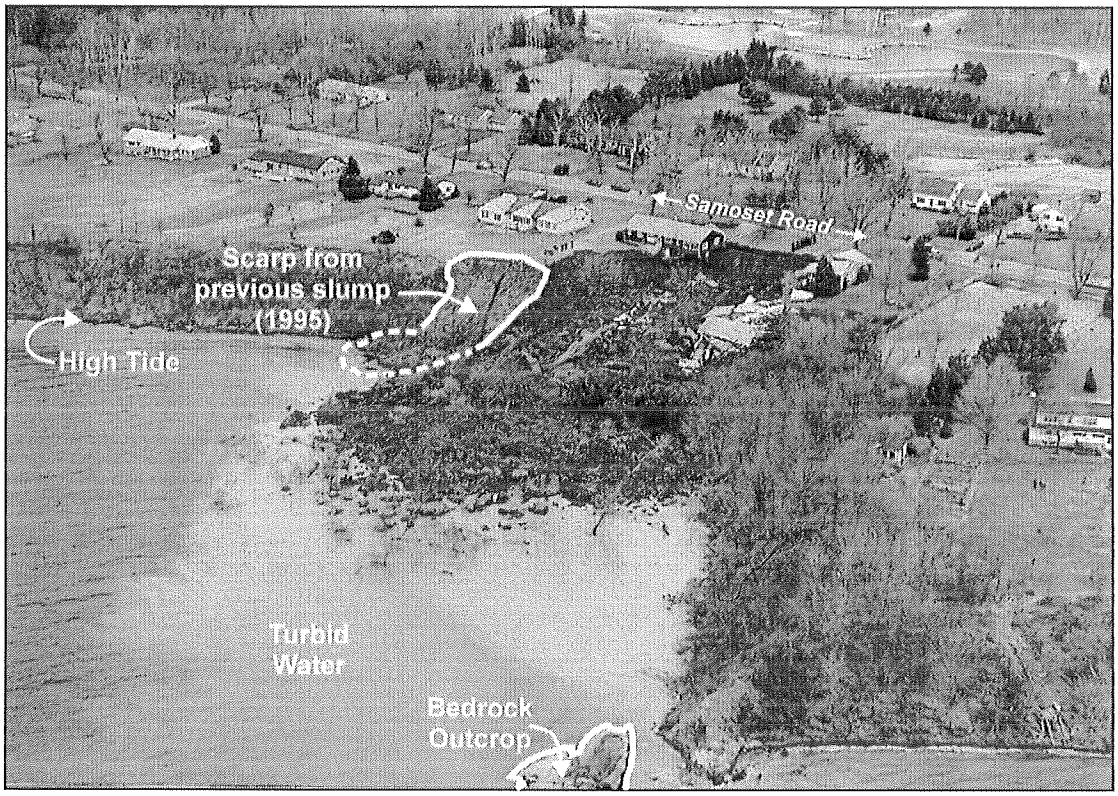


Figure 2D. Oblique airphoto of the landslide; view toward north, 4/16/96 (PDQ Photography). Note the turbid water where mud of the new landslide deposit is being quickly eroded to be redeposited on mud flats in deeper water. Photo taken prior to Figure 2C. Note Gerrish and Smalley houses and head scarp location as compared to previous figure.

destroyed and loss of land, clean up, and engineered stabilization was approximately $710,000 and is expected to exceed that when work is completed.

This field geology study and the analysis of other events for similar areas in coastal Maine led the authors to conclude that several factors in combination contributed to the April 1996 Rockland landslide. The necessary preconditions in this case appear to be the following:

(a) a thick section of poorly-drained, fine-grained sediment,
(b) a high water table (thick saturated zone) near the land surface , and
(c) a high and steep-sloped (unconfined) bluff toward open water.

DESCRIPTION AND GEOLOGY OF THE APRIL 16, 1996 LANDSLIDE

The pre-landslide bluff profile was relatively steep, dropping more than 40 feet (13 m) vertically over a horizontal distance of 80 feet (25 m) (Figure 3). Note that the pre-landslide bluff profile was never measured at the actual landslide site. The description here and in Figure 3 is for a nearby bluff about 165 ft (50 m) northwest of the landslide area. Prior to the April 16 event, a small landslide involving approximately 2,000 cu yds (1,530 cu m) had occurred on the upper part of the bluff on February 16, 1995 (reported to Stephen Dickson by William Eaton, next-door neighbor to the Gerrishes), remnants of which can be seen in Figure 2C. The remainder of the bluff was covered with oak and poplar trees and shrubs. The land surface above the bluff was relatively flat and covered by a lawn with houses (Figure 2A).

Following the event, the landslide site was surveyed with a total survey station (EDM) on April 24, 1996 (Figure 4), and a log of the stratigraphy of the exposed bluff was recorded (Figure 5). Numerous ground photographs were taken from around the landslide and on its surface on April 24 (Appendix A). Three test borings were drilled by Northeast Diamond Drilling and R. G. Gerber, Inc., around the landward edge of the slip face between April 26 and May 1, 1996 (Appendix B).

The landslide affected about 0.6 acres (0.25 hectares) of the upland, completely removing one house and largely destroying the second. The resulting headscarp was nearly semicircular, with the remnants of one house protruding from the northwest side (Figures 2D and 4). The erosional scarp resulting from the landslide was about 210 feet (65 m) across and involved upland more than 130 feet (40 m) from the former edge of the bluff. The headscarp dropped almost vertically for 26 feet (8 m) near the road and on the east side, and for about 13 feet (4 m) on the northwest side.

The landslide deposit occupied 3.5 acres (1.42 hectares) and projected 590 feet (180 m) seaward onto the tidal flat, or about 450 feet (140 m) seaward of the former top of the bluff. The surface of the landslide consisted of a series of intact blocks 3 - 10 feet (1-3 m) across, which near the head of the scarp were tilted landward. Trees and shrubs were still sitting in the blocks, even though they were tilted both landward and seaward as much as 45 degrees by the event. Many of the blocks were striated on their undersides. In the central part of the slide, the blocks were not arranged coherently across the slide deposit, but were disturbed in many places, so that no block was more than about 16 feet (5 m) long. Depressions, often filled with water, separated many of the blocks for the first 330 feet (100 m) from the headscarp.

The outer area of the slide deposit was more disturbed than the inner area. No large blocks were found here, and the surface of the slide consisted of a rubble of small blocks of mud 1.5 feet (0.5 m) long or less. The outer edge of the deposit formed a scarp up to 6 feet (2 m) high along the sides, but formed a more gradual, tapered shape at the toe (Figure 2C). Boulders were common around the periphery of the toe of the slide, as well as displaced blocks of salt marsh peat.

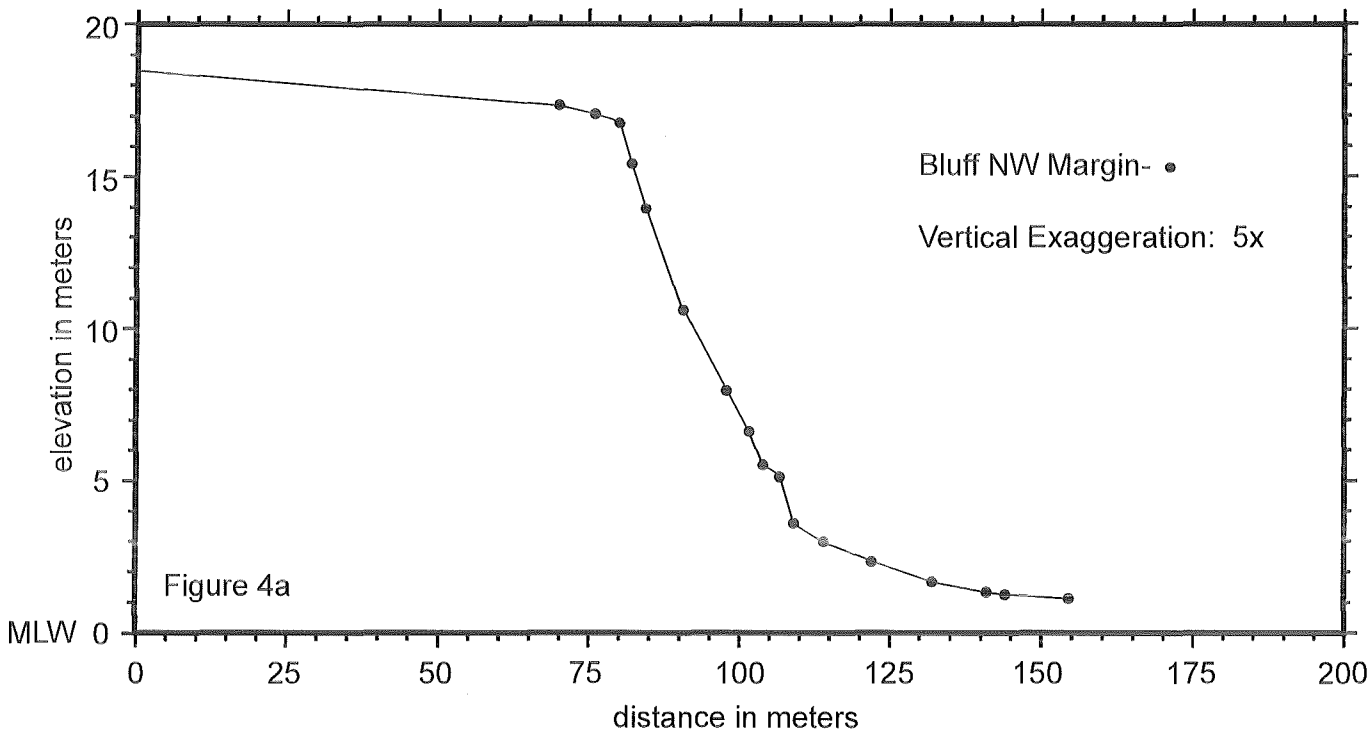
A description of the sedimentary section exposed in the northwest headscarp is shown in Figure 5. There is 1 foot (30 cm) of soil at the surface. Near the surface, the sediment displays obvious horizontal layering of interbedded clayey silt and 1 - 3 inch (2 - 5 cm) thick layers of coarse sand. Vertical fractures coated with purple-black (manganese oxide?) stains are found in the upper 6 feet (2 m). Below the upper 6 feet, the section is comprised of massive to faintly-bedded fine-grained sediment (predominantly clayey silt). Large stones are scattered throughout the material to the base of the section.

Bedrock Geology in the Area of the April 1996 Rockland Landslide

Rock Types. The bedrock, or ledge, which forms the natural, solid foundation of the northern side of Rockland Harbor consists of very old metamorphic rock. The bedrock has been divided according to rock type into two formations, the Ojier Point Formation and the North Haven Formation (Osberg and others, 1985). The Ojier Point Formation consists of andalusite-garnet-quartz-mica schist thinly interlayered with light gray biotitic quartzite. Both the schist and the quartzite contain a strong metamorphic foliation that was folded and contorted during formation of the Appalachians.

The North Haven Formation consists of layered greenstones and feldspar-rich gneisses. These rocks probably originated as mafic and felsic volcanic rocks or tuffs, but were recrystallized and deformed into metamorphic rocks at the same time as the Ojier Point Formation. The original rocks may be as old as Precambrian (Precambrian Z; 570 - 800 million years ago). They were metamorphosed and deformed along with other rocks of the Penobscot Bay region due to heat and pressure in the earth during a geologically active time, probably in the Silurian Period (about 430 million years ago).

Internal Bedrock Structure. The combination of ancient small folds and faults has produced a complex bedrock structure



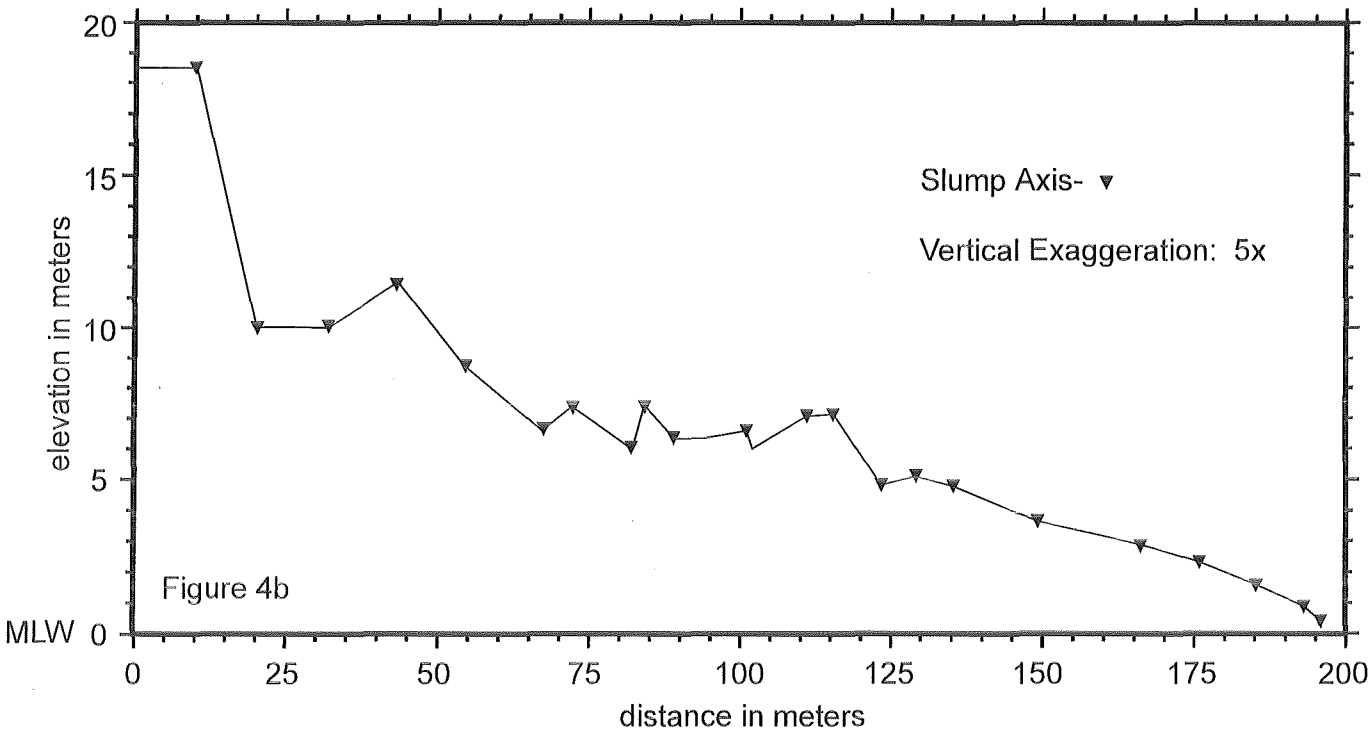


Figure 3. Rockland landslide survey, 4/24/96. Upper: profile of an adjacent undisturbed bluff slope northwest of the slide zone. Lower: profile of Rockland landslide (by D. F. Belknap).

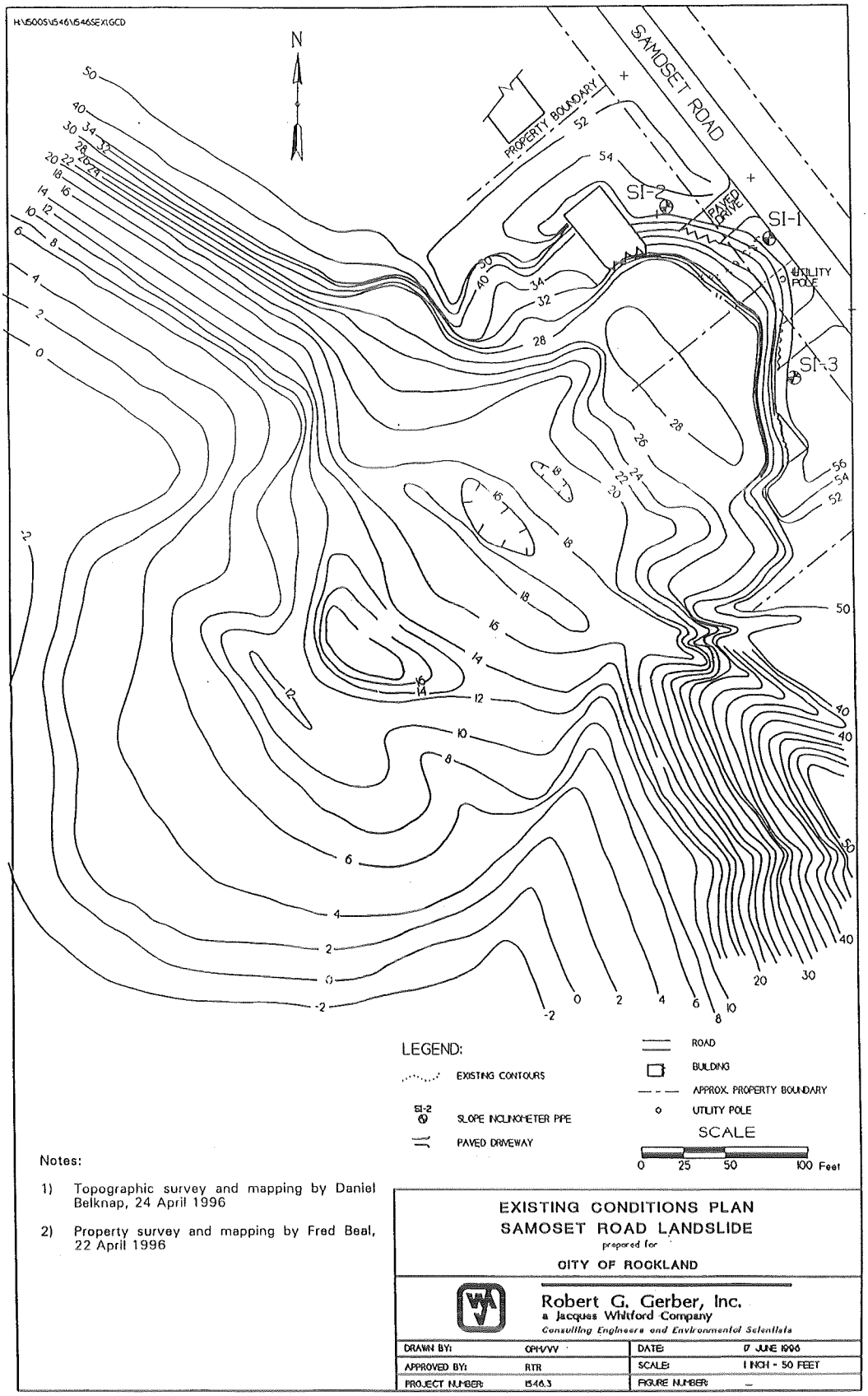


Figure 4. Rockland landslide survey 4/24/96. Map of landslide surface (by D. F. Belknap) made using a total survey station, and longitudinal and axial traverses through the slide and along its relief.

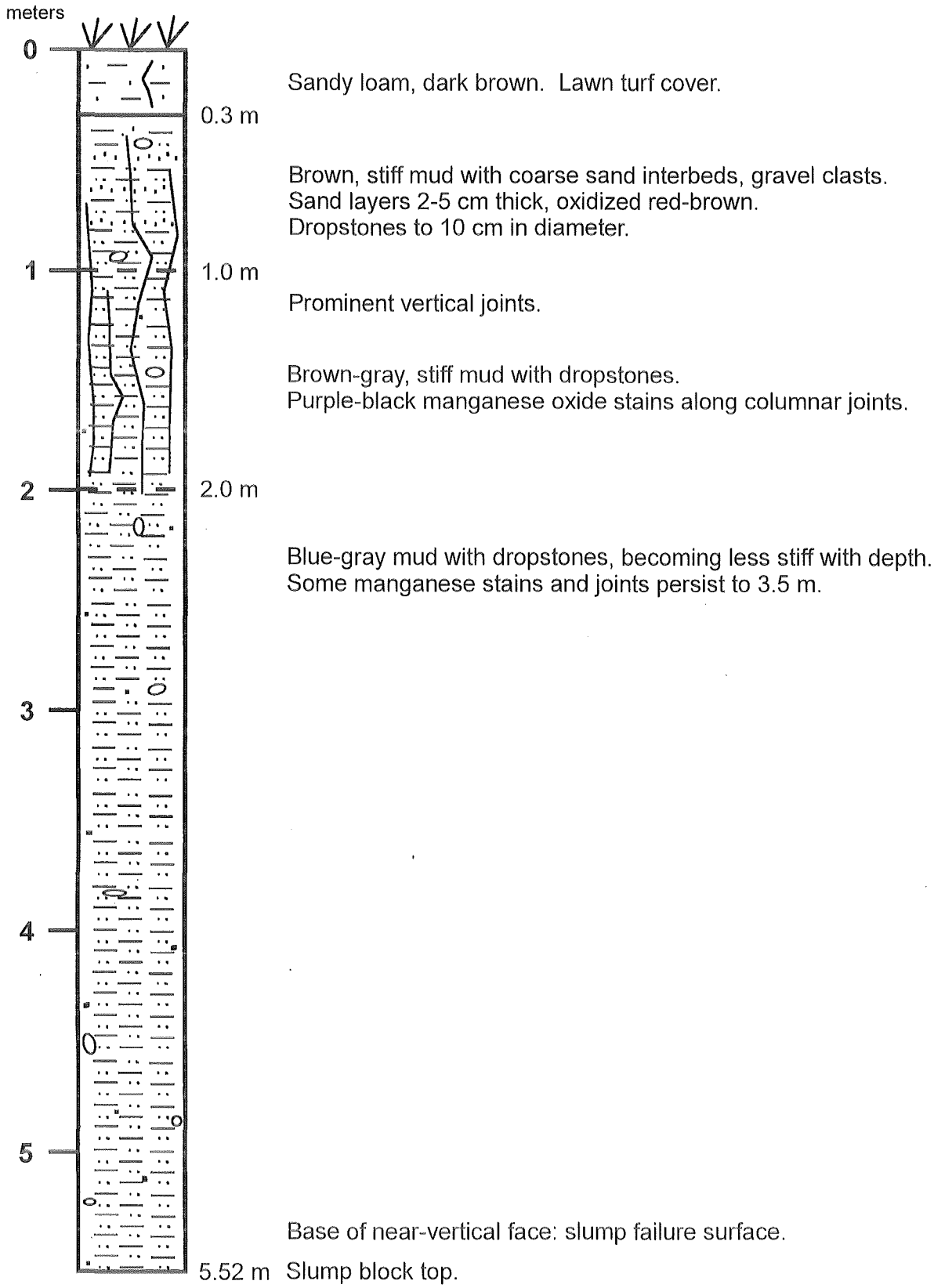


Figure 5. Rockland landslide survey 4/24/96. Measured vertical section, west scarp face (by D. F. Belknap).

in which the rock foliation has different orientations in different places. The foliation strikes between northwest and northeast, and dips moderately steeply toward the east. Minor fold hinges trend toward the north-northeast (N20°E to N30°E) with shallow plunges. Predominant fracture sets in the bedrock of northern Rockland Harbor are oriented west-northwest (N70°W) and north-northeast (N35°E). Such fractures are common in the bedrock of New England, presumably related to the opening of the Atlantic Ocean during the Mesozoic Era. It should be emphasized that no active faults have been identified in Maine. Weston Geophysical Observatory, Massachusetts, which monitors seismic activity in New England, reported to the NRIMC that there was no earthquake or seismic activity in coastal Maine at the time of the Rockland landslide.

Shape of the Bedrock Surface. The depth to bedrock, commonly referred to as ledge, depends on the thickness of any overlying sediment and the shape of the bedrock surface. The bedrock surface has an irregular shape because it has been eroded unevenly through geologic time. Even where the earth's surface is fairly flat such as along Samoset Road, the depth to bedrock is not everywhere the same due to the irregular shape of the bedrock surface beneath the overlying sediment. There are places along the shore where the bedrock is exposed in outcrops at the earth's surface. These places are indicated on the map in Figure 6. Bedrock of the North Haven Formation is well exposed in the ledges toward the end of Jameson Point and along the shore near the breakwater. Farther to the northwest, where the bedrock belongs to the Ojier Point Formation, there are gaps where bedrock is not exposed, especially in the coves. In these coves, the bedrock surface was more deeply eroded at some time before the end of the last ice age. That surface is now at an elevation below sea level, and the eroded depressions on the bedrock surface in those areas are infilled by glacial and postglacial sediments.

The thickness of surficial deposits in northern Rockland Harbor and along Samoset Road varies in part due to the depth to bedrock. From the shoreline bedrock outcrops alone it is difficult to judge precisely the depth to bedrock inland from the shore. In general, bedrock is inferred to be close to the ground surface at the south end of Jameson Point because of the abundance of shoreline outcrops, the presence of a bedrock outcrop on the Samoset Golf Course (beside the 5th fairway), and a report by the Jameson Point groundskeeper that ledge was encountered during excavation for the two condominiums farthest toward the southeast end of Samoset Road. There are no bedrock outcrops farther to the northwest along Samoset Road or along Waldo Avenue to the west.

Seismic reflection profiles 1500 feet (460 m) offshore of the coast reveal a prominent sub-bottom acoustic reflector ranging from less than 16 feet (5 m) to greater than 65 feet (20 m) beneath the seafloor (Figure 7). This reflector is the acoustic basement and its high relief and strong, coherent return appears like a reflector recognized in previous work as bedrock (Belknap and others, 1989). The bedrock reflector is shallowest seaward of bedrock outcrops along the coast at Jameson Point, and descends to greater than 65 feet (20 m) beneath the seafloor seaward of the 1996 landslide. Bedrock consistently remains shallow seaward of coastal bedrock outcrops and is more deeply buried seaward of coastal embayments with eroding bluffs and past landslides.

In detail, the bedrock surface in this area is irregular due to the combination of a north-northeast trending bedrock foliation, northeasterly and northwesterly-trending fractures, and a southerly ice flow direction during the last glaciation. Any of these factors may affect the shape of the bedrock surface. In order to determine the depth to the bedrock surface inland from the shore, especially in the areas of the 1973 and 1996 landslides, NRIMC conducted a seismic refraction survey in May, 1996. The results of this survey are found in Appendix C of this report. These data and the depth to bedrock from the boring logs (Appendix B), and records reported to NRIMC from water well drillers provided information to prepare a bedrock surface contour map (Figure 8).

Figure 8 represents the elevation and shape of the bedrock surface in the landslide area along Waldo Avenue and Samoset Road. The areas of higher bedrock elevations generally correspond to the areas where bedrock outcrops occur along the coast (Figure 6). These areas have a shallow depth to bedrock, and hence a relatively thin cover of overlying sediment. Those areas where no outcrop is present along the coast correspond to low areas on the bedrock surface, and at the coast are where eroding embayments of thick sediment overlying the bedrock are found.

Surficial Geology of the Area Surrounding the April 1996 Rockland Landslide

Surficial Sediments in the Vicinity of the Landslide. Surfical geologic materials (such as sand, gravel, silt, and clay) are the unconsolidated sediments that lie on top of the bedrock over much of New England. In Maine, these sediments form deposits left by glacial ice, water, wind, and organic processes. Most of them were deposited within the past 25,000 years, during and after the most recent glacial episode.

The Maine Geological Survey has mapped the surficial geology for much of Maine. Current information is available at different levels of detail for different parts of the state. New maps and information become available as they are produced. The surficial geology of the Rockland quadrangle was mapped at a reconnaissance level by Smith (1974). Two principal types of glacial deposits are found at or near the landslide site: till and glacial-marine clayey silt.

Till is a heterogeneous mixture of rock debris that was deposited directly from glacial ice. It may contain sediment ranging from silt and clay-size particles to large boulders. Till is often the lowest and oldest surficial stratigraphic unit in any particular area, and commonly rests on top of the bedrock. It has been mapped at the ground surface on the higher terrain west of U.S. Route 1 in Rockland, usually at elevations above 100 feet (30) m; but closer to the coast, the till is largely concealed beneath

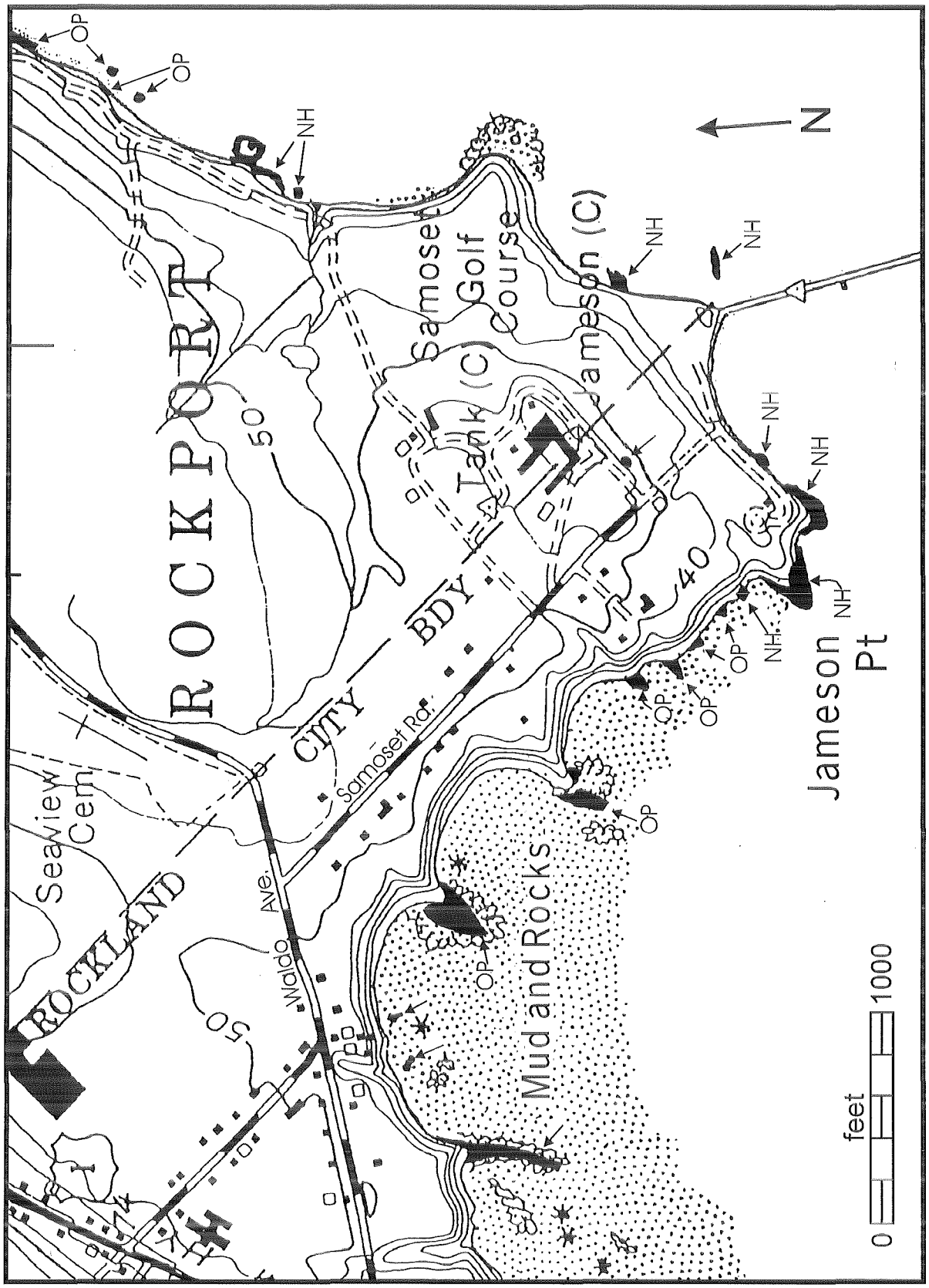


Figure 6. Location and geology of bedrock outcrops, north shore of Rockland Harbor. Outcrops are shaded black, indicated by arrows, and labeled where formation name is known (OP indicates Ojier Point Formation; NH indicates North Haven Formation).

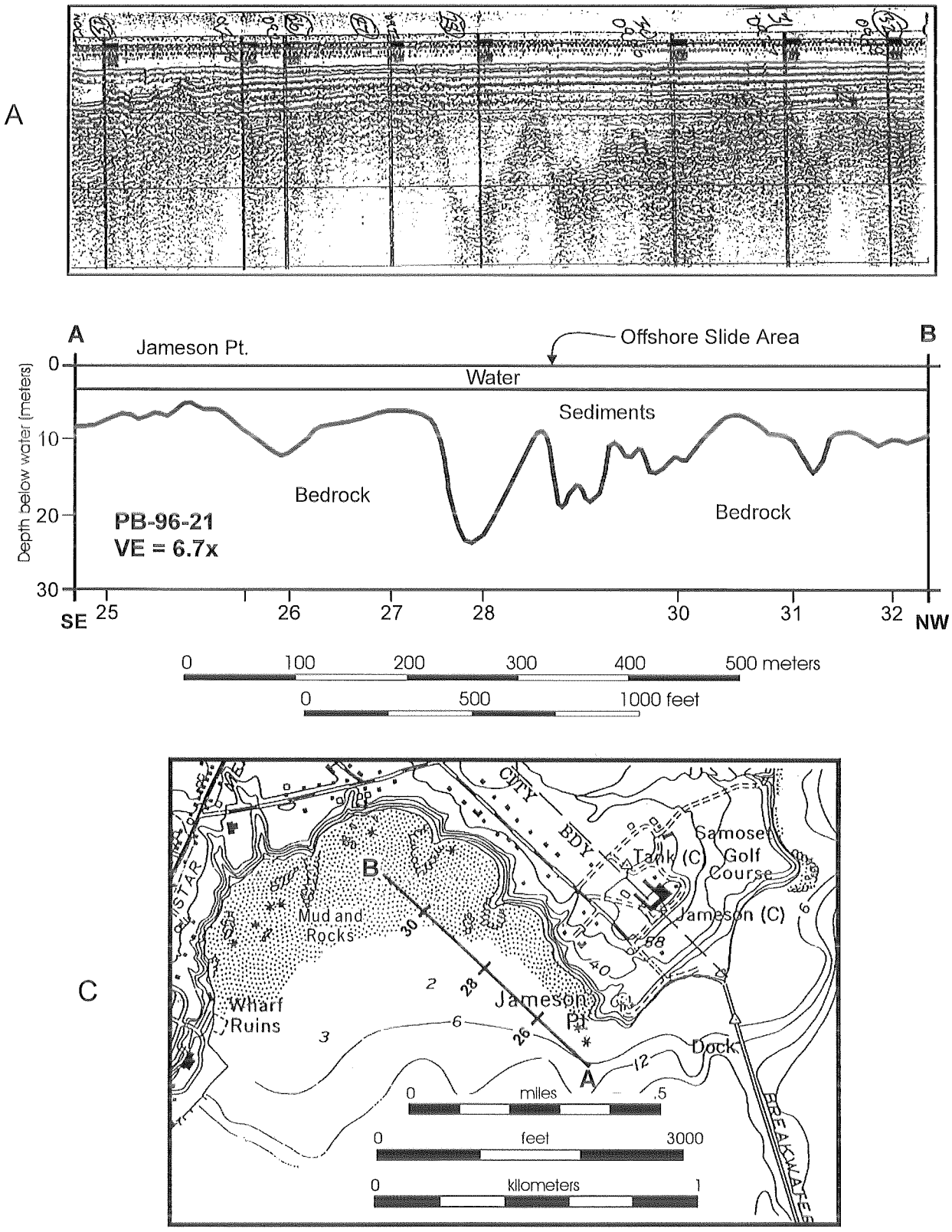


Figure 7. Seismic reflection profile and interpretation, line PB-96-21, Rockland Harbor made with an ORE Geopulse. Survey made around 9:25 AM 6/26/96 from the Research Vessel Lee. Time event/marks on the original data and interpretation correspond to numbers along the A - B line on the map. (A) Seismic reflection profile shows a strong reflector below sea floor. (B) Interpretation of profile in (A). Sub-bottom bedrock surface is irregular, thus sediment above bedrock is a different thickness from place to place. The thickest sediment is near points 28 and 30. (C) Map showing location of the offshore seismic reflection profile. Notice that points 28 and 30 are offshore from coastal embayments.

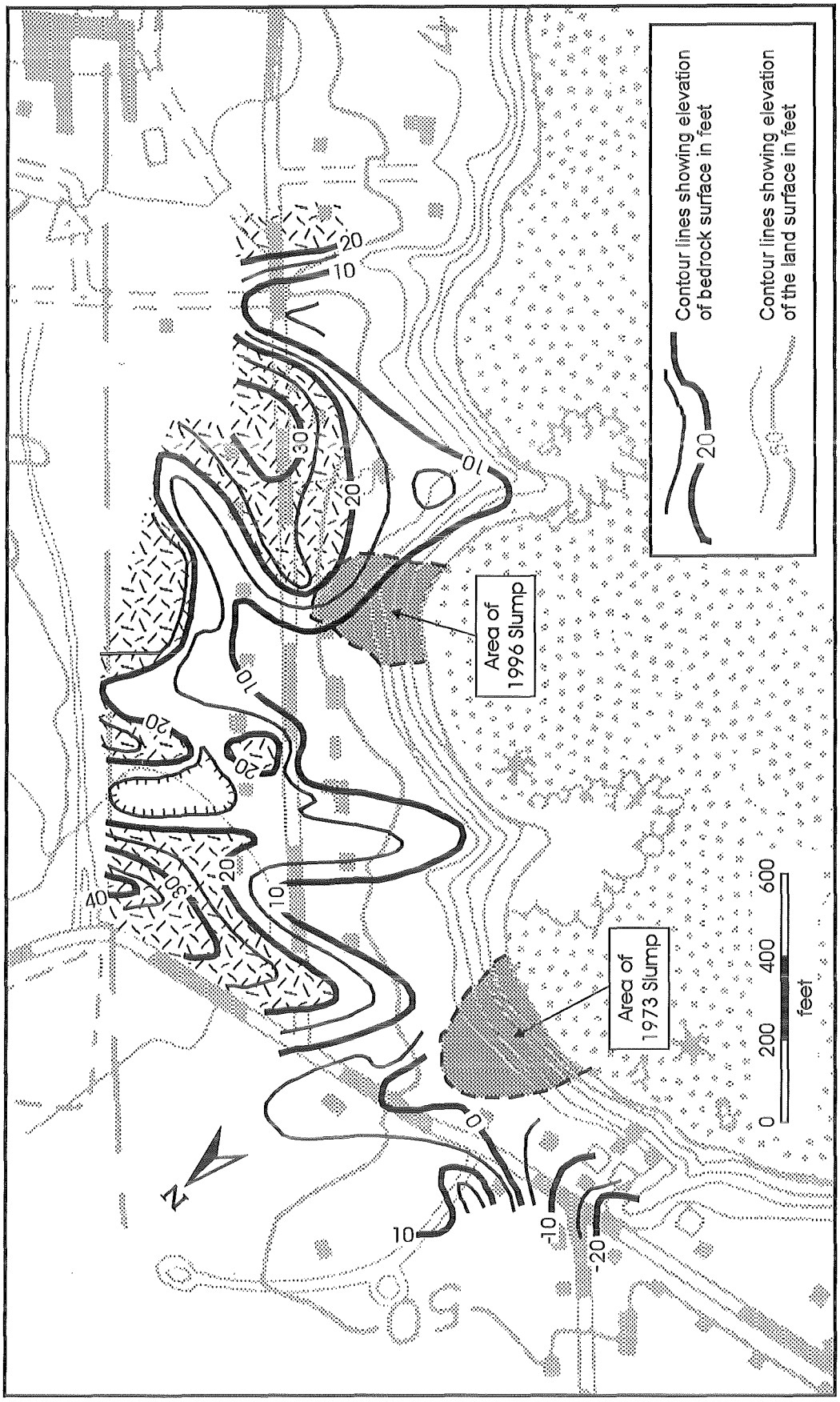


Figure 8. Elevation of bedrock surface in the areas of the 1973 and 1996 Rockland landslides, as interpreted from seismic refraction survey by the Maine Geological Survey, May 1996. Areas of higher bedrock elevations (more than 20 feet above sea level) are indicated by hachured pattern.

the younger mud deposits. Shoreline exposures on the point just southeast of the slide show the clayey silt directly overlying bedrock, so till deposits are not present over the entire area. However, the three boring records (Appendix B) drilled near the head of the landslide showed variable thicknesses of till resting on bedrock, ranging from less than a foot (30 cm) to about 10 feet (3 m) thick. Based on field observations, the landslide itself appears to have occurred entirely within the glacial-marine clayey silt.

The glacial-marine clayey silt is part of a widespread geologic unit called the "Presumpscot Formation" (Bloom, 1960, 1963), which is very common in lowland areas and river valleys of coastal Maine and is named after exposures along the Presumpscot River in Portland. It is commonly called "clay" or "blue clay" by well drillers and the general public. Actually, this generally massive-appearing formation contains a mixture of clay, silt, and sand particles in varying proportions, and often in alternating layers of differing thickness and particle size range. Clay and silt size particles are typically dominant, being mixed together to texturally form a clayey silt or silty clay, or what might simply be called "mud." However, in geotechnical engineering, the term mud implies an extremely soft consistency (Sowers and Sowers, 1970). Hence, in keeping with popular and familiar usage of this term, the Presumpscot Formation will be called clay here.

The Presumpscot clay is made of finely pulverized rock material that settled to the sea floor from muddy plumes of glacial meltwater that flowed into the ocean (which flooded large areas of southern Maine during the recession of the last ice sheet). Thus, the mineral composition of most of this glacial sediment consists of common minerals such as quartz, feldspar, and mica (Kelley, 1989).

The Presumpscot Formation is limited to low-lying areas that experienced marine submergence in late-glacial time (described below), so the glacial-marine clay generally occurs only at elevations below 200 to 300 feet (60 - 90 m) in southern Maine (and at even lower elevations near the landslide, as noted above). Clay thickness is usually measured in tens of feet, but may exceed 100 feet (30 m) in some valleys and coastal areas. The clay deposits extend out under the ocean, where they are buried by younger marine sediments (Kelley and Belknap, 1991).

Where the landslide occurred , the clay thickness was 35 to 45 feet (10 - 14 m) thick. The upper part of the clay shows a typical brownish-gray color resulting from weathering near the original ground surface, while deeper parts of the deposit have the gray or blue-gray color of fresh, non-oxidized Presumpscot Formation. The transition from brownish-gray to blue-gray color occurred at a depth of 6 feet (2 m) in the exposed headscarp (Figure 5) and at depths of 8 to 10 feet (2.5 - 3 m) in the three borings near the head of the slide (Appendix B). Blocks of clay exposed in the lower part of the slide deposit contain many stones that originally were probably dropped from icebergs when the ice sheet was retreating from the area. These same blocks also contain fossil shells of a marine mollusk species called *Portlandia arctica*, which lived in cold muddy waters close to the ice margin.

Glacial-marine clays whose age and origin are similar to the Presumpscot Formation occur in the St. Lawrence Lowland of eastern Canada (Elson, 1988) and other recently glaciated parts of the world. These clays commonly are vulnerable to landslide hazards, particularly where local conditions of slope, relief, drainage, toe erosion, and other factors conspire to reduce the stability of the deposits (Amos and Sandford, 1987).

Glacial and Postglacial Geologic History of the Landslide Area. It is not certain how many glacial episodes occurred in Maine during the Pleistocene "Ice Age," because the last glaciation removed much of the evidence of earlier glacial action. The most recent ice sheet covered southern Maine between about 25,000 and 14,000 years ago. Rock debris that was eroded and dragged beneath the slowly flowing ice caused the bedrock surface to be ground smooth in many places. Glacial scratches and grooves are seen on the ledge surfaces along the shoreline near the landslide, with especially good examples on the point just south of the slide. In this area, the grooved rock surface records a complex history of ice-flow directions, resulting from shifting flow patterns over time and local deflections of ice flow by the knobby rock surface. Overall in the landslide area, the dominant flow direction in late-glacial time was apparently slightly west of south, averaging S5^{o}W (azimuth 185°).

The weight of the ice sheet caused a depression of the earth's crust by hundreds of feet, and the land did not immediately rise back to its original elevation when the glacier margin withdrew from the coast. Therefore, the ocean flooded the coastal lowland (including the landslide site), and marine sediments were deposited in large areas where there is now dry land. Meltwater streams issuing from the ice deposited sand, gravel, and clay into the ocean in these areas. The water-laid sediments blanketed much of the layer of till that had been previously deposited beneath the ice. Periodically the edge of the glacier stood still or advanced slightly, and ridges of sediment (called "moraines") accumulated along the ice margin.

Soon after the Presumpscot clay was deposited, the rising land forced the sea to recede far offshore. As the world's glaciers continued to melt, sea level gradually rose over several thousand years, first more rapidly and later more slowly. Sea level is still rising to this day. During this period of ongoing sea-level rise, erosion of glacial sediments has been occurring, causing shoreline retreat and landslides along the Maine coast.

Seismic Refraction Data and Interpretation

Seismic Refraction Methods. During the period from May 6 - 16, 1996, the NRIMC conducted seismic refraction surveys in order to gather subsurface geologic and hydrogeologic information in the area of the Rockland landslides of 1996 and 1973 (Figure 9). Site survey lines were located roughly perpendicular as well as parallel to the directions of the slides. Actual locations selected were made on the basis of access and surface suitability.

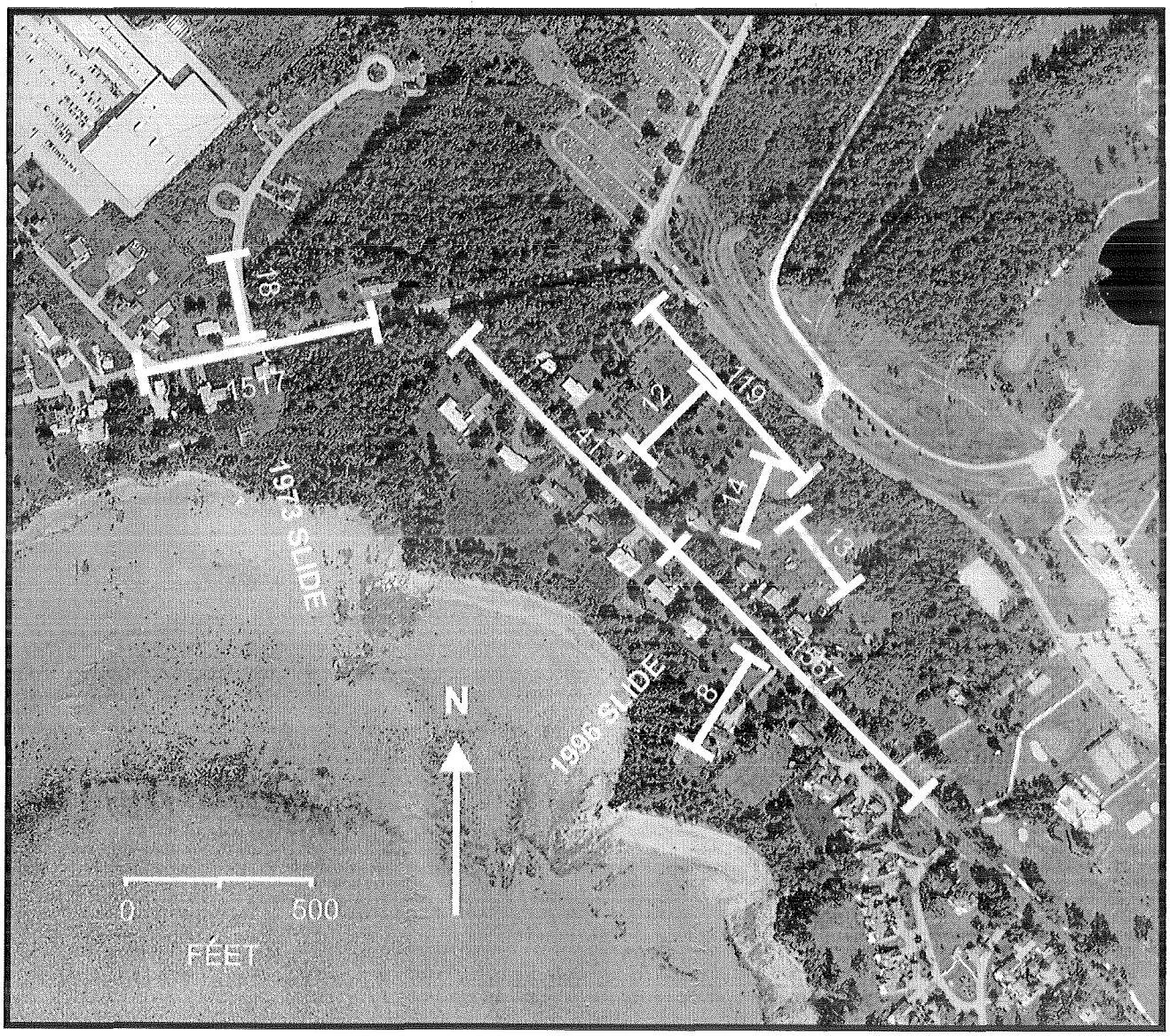


Figure 9. Site map of 12-channel seismic refraction lines, Rockland landslide area.

Subsurface Profiles from Seismic Data. In total, eighteen 12-channel lines were seismically surveyed, yielding 5 single-line profiles and three multiple-line composite profiles. Interpreted hydrogeologic profiles resulting from the seismic-refraction surveys are presented in Appendix C. Distances shown on the x-axes are measured from geophone number 1 for each profile. The y-axes show the elevation or altitude above sea level. Note that the vertical scale of the diagrams has been expanded to 6 times the horizontal scale to better illustrate changes in elevation. The geologic materials at depth have been inferred from their measured seismic velocities. Since there is a greater concentration of redundant bedrock data in the middle of the lines than at the ends, the bedrock surfaces depicted in the central portions of the lines reflect subsurface conditions with a greater amount of certainty than do the ends of the lines. Abrupt changes in the interpreted bedrock surface at the extreme ends of the lines might not reflect actual bedrock topography. In most cases, overlapping and intersecting lines gave profiles in close agreement with each other. The exception is where the southeast end of profile ROCK-18 approaches the middle of the multiple-line profile ROCK-1517 along Waldo Avenue. Although these lines did not actually intersect, they were only separated by about 30 feet (10 m), the width of the road, yet the elevation of the bedrock surface shown on the two profiles differs by about 18 feet (6 m). This apparent discrepancy remains unresolved, but suggests that the simple interpretation presented for the south end of profile ROCK-18 may be incorrect due to some subsurface complication in that area. Profile ROCK-1517 is based on three

lines that gave results in good agreement, so for purely statistical reasons the data near the middle of profile ROCK-1517 is more reliable than the data near the end of the single line ROCK-18.

Water Table. The water table is the underground surface that separates unsaturated material above, from water-saturated material below. Because seismic waves travel faster through saturated material, the water table depth was detected by the seismic survey. The water table is indicated on the profiles in Appendix C by a thin black line with a small black triangle pointing to it. Below the water table, the glacial deposits (mainly clay) are fully saturated with ground water.

The depth at which the change from saturated clay to unsaturated clay occurs is difficult to verify directly by sampling because water is transmitted so slowly through the clay. The seismic data is supported, however, by the observed features at the landslide site. Where the landslide occurred, the fresh exposure in the bluff face (Figure 3) and the observations from drilling (Appendix B) showed a distinct change between the upper oxidized clay with dessication cracks, and the underlying massive, blue-gray clay. This change is attributed to unsaturated versus saturated clay. The observed change from unsaturated to saturated clay occurred at 6 to 10 feet (2 - 3 m) depth, matching well the depth at which the measured seismic velocity changed. Therefore, the field observations confirm that the line depicted in the seismic profiles is the water table.

The depth to the water table shown in the seismic profiles is between 4 and 7 feet (1 - 2 m) below the ground surface. As is normally the case in New England, changes in the water table from place to place closely follow changes in the ground surface elevation. Over areas where the ground surface is flat, the water table is approximately horizontal. The seismic profile along Samoset Road that crossed the area of the 1996 landslide is shown in profiles ROCK-41 and ROCK-1567 (Appendix C). The head of the 1996 landslide is in the vicinity of the 100 foot distance mark on profile ROCK-1567. These profiles show nothing unusual in the water table where the landslide occurred.

No tests were done to assess movement of ground water. Even so, the seismic data alone provide important information about ground-water flow. For example, the ground-water table beneath Samoset Road (Appendix C; ROCK-41, ROCK-1567) is at higher elevation than the water table beneath Waldo Avenue (Appendix C; ROCK-1517). Hence, the ground-water flow will be along gradient, from higher to lower potential, or in this case from the higher elevation landward areas along the roads toward the lower elevation along the coast.

Marine Geology

Rockland Harbor occupies a curved embayment along the western shore of Penobscot Bay. This is within the Island-Bay coastal compartment (Kelley, 1987), an area defined by estuaries sheltered by numerous islands. Vinalhaven, North Haven, and Islesboro Islands protect Rockland Harbor from waves from the southeast, east, and northeast, respectively. Owls Head peninsula blocks waves approaching Rockland from due south. The mainland is rocky and steep on the southern side of the harbor, with up to 200 feet (60 m) of local relief. To the north and west the relief is subdued except on the shoreline itself where a 20 to 40 foot (6 - 12 m) scarp rims the harbor.

Tides in the area average 9.8 feet (3 m). The wind at the Rockland Coast Guard Station comes most often from the western quadrants; the strongest gusts are from the northwest and northeast. No studies have been made of wave heights in the harbor, but on the basis of the wind data, it appears that the largest waves would be derived from east-northeast directions. It was probably for that reason that the breakwater was built in 1904 along a generally north-south orientation from Jameson Point (Figure 1). The breakwater extends 4300 feet (1.3 km), almost halfway across the opening to Rockland Harbor, and may inhibit tidal exchange somewhat compared to conditions prior to its construction.

Sea level has risen in the outer Penobscot Bay area from around 10,500 years ago (Barnhardt and others, 1995). Early rates of rise were rapid, about an inch (2.5 cm) per year, but slowed appreciably in the middle to late Holocene. By 1,000 years ago, sea level had slowed its rate of rise in southern Maine to less than 1 mm/yr until this century (Kelley and others, 1995). The tide gauge in Bar Harbor has recorded a 2.6 mm/yr rate of sea-level rise there since 1947 (Lyles and others, 1988).

Coastal bluffs of glacial-marine sediment have retreated since sea level began to rise. The contemporary bluffs are all retreating through a variety of mechanisms, including landslides, in response to the long-term rise of the sea (Kelley and others, 1987). The rate of bluff retreat on the Maine coast varies due to local conditions such as wave exposure and the physical properties of the bluff, but probably ranges from about an inch to a foot (2 - 30 cm) per year. The northern shore of Rockland Harbor was identified as a hazard zone for bluff erosion by Kelley and others (1989) because of the high bluffs of glacial marine clay, scalloped shoreline shape, and past history of landslides there.

OTHER MAINE LANDSLIDES

Rockland, January 25, 1973

During the early morning of January 25, 1973, a landslide covering about three acres occurred within tens of feet of two homes on Waldo Avenue in Rockland (Figure 1). Reports of this event were published in local newspapers, and the Bangor Daily News and Portland Press Herald. There are no known technical reports describing the landslide at the time of the event. However, newspaper accounts and the general descriptions and photographs of the event by geologists who visited the site (including geologists from the Maine Geological Survey and Bowdoin College; one author of this report, Belknap, was a Bowdoin College student at the time) indicate the slide was similar in size and displacement to the 1996 slide. The Portland Press Herald (February 7, 1973) reported that weather conditions at the time

of the 1973 slide were warm temperatures (January "thaw"), and that drainage was "excessive," and that in the opinion of geologists who visited the site, the slide was due in part to these conditions.

Photographs of the 1973 slide (Plate 1) show that it had the classic features of a retrogressive (headward) landslide, with a steep headscarp and slumped blocks rotated toward the headscarp. Toward the slide toe, the surface of the slumped material appears to have flowed, as though it had bulldozed across the land surface. The slide is described in an inventory and bibliography of Maine landslides as a complex lateral spread / soil flow (Novak, 1987a; Figure 10). Some newspaper reports of the event incorrectly quote Arthur M. Hussey II, geology professor of Bowdoin College who visited the site, as saying that a smooth rock surface at the base of the clay provided the glide surface. Our seismic work in the area of the January 1973 slide shows bedrock to be at least 10 feet below sea level in this area. Professor Hussey (personal communication, 1996), who visited the 1973 landslide, states that he pointed out that while bedrock was exposed nearby along the coast, it was not exposed at the base of the slide and probably was not the slip surface upon which the slide moved.

Other than newspaper articles, the only published report on the 1973 landslide is by *Time and Tide Resource Conservation and Development*, entitled "Rockland Shore Erosion Critical Area Measure, Final Report, April 1978" (anonymous author). This report outlines the history of local, federal, and state involvement regarding potential remediation activities of the 1973 slide. Results of findings and conclusions in the report include an outline of potential causes of the 1973 slide as well as corrective measures. The potential causes included removal of lateral support or oversteepening of the bluffs, additional surface weight by placement of fill or increased moisture, blockage of already slow drainage, introduction of excess water through septic systems, and loosely backfilled water main, storm drain, and sewer main trenches. Recommendations for several corrective measures included appropriate city ordinances preventing excess water drainage into the ground from septic systems, storm drains, and gutters; upland water surface runoff control; bank shaping and slope reduction; protection from wave erosion by rip-rap; loading of the slide toe to provide weight and increased stability; blanketing the face of the bank with free draining material; establish suitable vegetative cover; and engineering deep internal drainage systems. The recommendations were underscored by the statement that an engineering consultant with proven expertise in landslide prevention and suitable design control be obtained by the City of Rockland.

Gorham, September 28, 1983

Novak (1987b) and Sanford and Amos (1987) provide an account of the 1983 Gorham landslide. This landslide occurred in a bluff of marine sediments at the confluence of the Stroudwater River and Indian Camp Brook. Seven acres (3 hectares) of land slid to the south and southwest into the river and the brook, taking with it a house and garage, several vehicles, a tank truck, and a well drilling rig. The total area affected by the slide was about 12 acres (5 hectares). This slide is classified as a complex type, having components of translational slide (blocks move out or down along a planar surface without rotation), a rotational slump (blocks which rotate about an axis parallel to the slope and along a concave-up slip surface), and an earth flow (a fluidized failure lacking distinct blocks). The slide failure plane was calculated to be at a depth of about 42 feet (13 m), within a thick section of Presumpscot clay.

Factors contributing to this slide include the following: geomorphology - the slope was unconfined on two sides; thickness of clay - bluffs of 20-25 feet (6 - 8 m) high in a section of marine sediments up to 70 feet (21 m) thick; load from fill - there is disagreement concerning the degree to which fill contributed to this slide. For the size of the slide, the estimated 480 tons of fill used for the driveway and building site are relatively small, but it is possible that this additional load could have contributed to the initiation of a small block of the slide. Also, vibrations from the construction traffic and drilling of a nearby bedrock water-well drilling operation may have contributed as a trigger, but only because the site was already unstable. The landslide occurred shortly after the drill rig had penetrated approximately 5 feet (1.5 m) into the bedrock.

Abnormal precipitation conditions are not considered to have been a significant factor in this slide. September is a relatively dry time of year and significant rains had not fallen at the site in a week. There was some evidence of water expulsion during or after the slide, but the importance of precipitation as a slide trigger is speculative. However, liquefaction by the well-drilling operation either by introduction of water to the subsurface, or by vibrations of the drilling or construction operations may have been a factor in the cause of the slide.

Norridgewock Landfill Slide, August 14, 1989

Although this slide occurred in an artificial mound of compacted trash and cover materials (R.G. Gerber, Inc., 1991; Reynolds, 1991), it is useful to illustrate some of the factors contributing to landslides. Underlying the landfill site is 50 to 60 feet (15 - 18 m) of marine clay and silt. On top of this clay, the landfill operator had added about 70 feet (21 m) of compacted trash and cover material (sand and gravel) covering over several acres.

When the landfill gave way in the early morning of August 14, it did so as a retrogressive failure with individual blocks moving to the southwest, west, and northwest as they slid on the underlying clay. A detailed investigation followed the slide and concluded that a series of interrelated events resulted in the failure.

(1) Excavation of stiff clay from the toe of the landfill slope. This removed some lateral support from the soft clay and silt beneath the landfill.

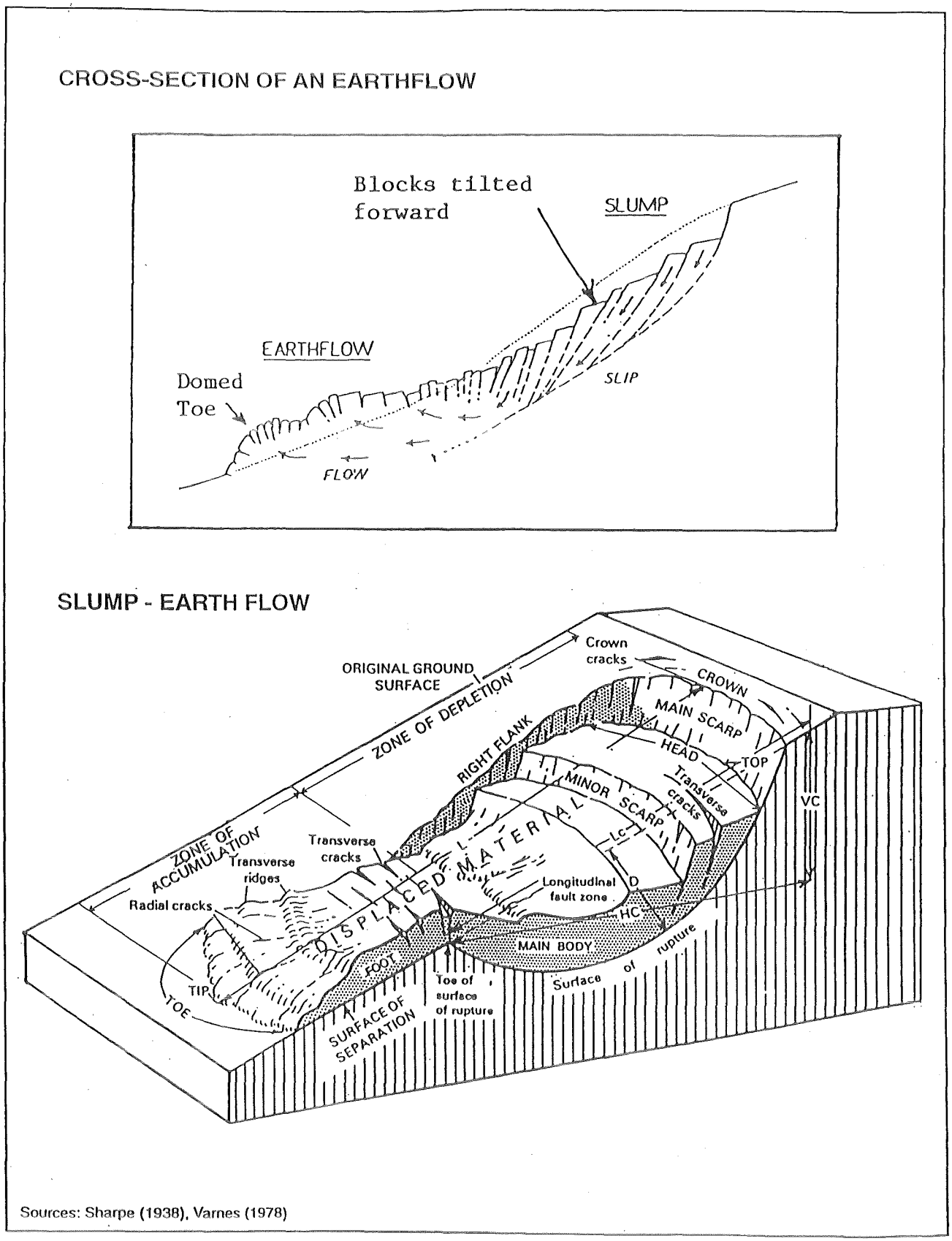


Figure 10. Cross-section and terminology of a slump-earthflow (from Macdonald, 1994).

(2) Storage of materials on top of the landfill. Excavated materials were stored on the crest of the landfill to await future use as capping material for an expanded portion of the landfill. This added weight to the load on the materials within and beneath the landfill.

(3) Addition of waste. In addition to the stockpile of cover material, waste continued to be added to the landfill, further increasing the load.

(4) Trench at toe of landfill. To intercept leachate from under the landfill, a trench was excavated at the toe of the landfill. This further reduced the lateral resistance that supported the soft clay and silt under the landfill.

(5) Heavy rain. The failure followed a 10-day period in which a total of 5 inches of rain fell. The rain saturated soil cover on the landfill and added further load to the system.

FACTORS CONTRIBUTING TO LANDSLIDE POTENTIAL

Factors which contribute to landslide potential of an area may be divided into natural factors and human factors. Natural factors most often cited in the literature are material type and thickness, geomorphology, precipitation, and undercutting of slopes. Human factors include modification of slopes, overloading slope tops, modification of drainage, and removal of vegetation. Much of the information in this section has been taken from Pomeroy (1982), Schuster and Krizek (1978), Keefer and Johnson (1983), and Sidle and others (1985). Engineering aspects and case studies of geotechnical problems associated with the Presumpscot Formation in Maine are presented in Andrews and others (1987).

Natural Factors

Material type and thickness. Landslides and mass movements of all types tend to occur in geological materials that are poorly consolidated (loosely packed) and fine grained in texture. Investigations of earth flows (Keefer and Johnson, 1978) show that they occur in a variety of grain sizes: sand, silt, and clay. Silt and clay predominate, and these materials tend to be of lower strength and more easily deformable than coarser materials. Sediment thickness or overburden thickness is a significant factor in determining slide potential. With increasing thickness of the unit or overlying units, there is an increase in load. Failure occurs when this load exceeds the internal strength of the material.

It should be noted that not all sediment materials within the Presumpscot Formation have the same strength. Furthermore, once sediment has been disturbed or deformed it becomes weaker than the original, undisturbed unit, a material property called sensitivity. A study of the 1983 Gorham landslide (Amos and Sandford, 1987) found that the Presumpscot Formation at that site has a lower strength and higher sensitivity than the Presumpscot Formation found at Bunganuc Point, Brunswick, another location in Maine where landslides are common. This small difference in strength properties may account for the fact that the bluffs at Gorham that were only 20 to 25 ft (6 - 8 m) high failed in a catastrophic retrogressive landslide, while the bluffs at Bunganuc Point that are almost 40 ft (12 m) high have not failed in such a catastrophic manner. Because of the variability of natural sediments, it is difficult to predict the strength of the Presumpscot Formation from place to place without careful measurements by a soils engineer.

Geomorphology. Slides occur where there is a steep slope on an unconfined face in material of low strength. Where there is a more gradual slope, more weight at the base of the slope helps to confine the pressure at depth. In the case of the Rockland slides, failure was at the base of a relatively steep slope where pressure was not constrained by weight of slope material. However, some of the more fluid types of slides can be initiated on remarkably gentle slopes of 7% (Sidle and others, 1985). Larger rotational slides typically require at least a 12% slope for initiation. More typically, slides require slopes of at least 15% to 25% for initiation of movement (e.g. Pomeroy, 1982; Schultz and Southworth, 1987).

Precipitation. Almost universal in the literature is the recognition that precipitation can play a significant role in initiation of landslides. Heavy winter precipitation, severe late winter and early spring rains, and rapid spring thaws resulting in loss of soil strength and additional water in the system all present landslide problems in North America (see, for example Pomeroy, 1982; Schultz and Southworth, 1987; Keefer and Johnson, 1983). Precipitation from extratropical storms can be factors, even when they occur during the period in which ground conditions are usually their driest (Pomeroy, 1982; Schultz and Southworth, 1987). Additional water in the system affects the stability in two ways. First, the weight of the water is an additional load on the materials in the system: second, the pore pressure increases with the additional water and reduces the strength of the material. Once strength is reduced, gravitational forces exceed friction and slope failure begins.

Undercutting of slopes. As stream and river courses meander, slopes are undercut on curves. In the marine setting, tides, waves, and currents undercut slopes of unconsolidated material. These are normally slow, but incessant, processes, and erosion undermines the stability of slopes. Bank erosion can be extremely rapid during storms, where water level of rivers, streams, or the ocean are elevated above normal and sediment is removed rapidly.

Human Factors

Modification of slopes. Oversteepening and undercutting of slopes are common in road and facilities engineering, or bank landscaping construction. Undercutting of slopes commonly occurs to provide more flat space for buildings or roadways. This practice removes lateral support and undermines the slope, leading to landslides in many areas (Pomeroy, 1982; Schuster and

Krizek, 1978). Oversteepening of slopes can occur as fill is used to extend flat areas near tops of slopes.

Overloading slope tops. The weight of fill and structures on top of a slope places additional load on the materials below. If this additional load causes the total load to exceed the strength of the material, then a slide can occur. Additional load of this nature has been identified as a contributing factor in the Gorham slide (Sanford and Amos, 1987) and in the Norridgewock landfill slide (R.G. Gerber, Inc., 1991).

Modification of drainage. Factors include leaking water and sewer lines, poorly drained roads, septic systems, landscape watering, seepage from reservoirs, and others (see Terzaghi, 1960; Pomeroy, 1982; Sidle and others, 1985). These modifications can result in additional load from water weight and reduction in material strength through increased pore pressure.

Removal of vegetation. Plant roots stabilize slopes by binding soil particles. Vegetation and roots also slow runoff, thereby reducing gullying and the removal of soil. Evapotranspiration by vegetation can also reduce pore pressure at some times of year by removing ground water. Thus, removal of vegetation can promote slope instabilty. However, it is only the upper part of the section of soil that is stabilized by vegetation. Moreover, in the case of large trees, there is both reinforcement of the slope by tree roots and extra loading on the slope by the force of wind on the branches. The net effect suggests that shrubs are superior to trees for slope stabilization, or that removing large trees will actually increase slope stability somewhat. Immediately after the 1996 April landslide, the City of Rockland cut down the large trees still standing above the headscarp in an attempt to stop further retrogression of the landslide.

LANDSLIDE POTENTIAL ALONG THE NORTH SHORE OF ROCKLAND HARBOR

While none of the north shore of Rockland Harbor is without risk of future landslides, our work suggests that some areas have more potential than others for a catastrophic slide of the type that occurred April 16, 1996. Although exact prediction of such landslides is not possible, the primary factors which bear on the potential for catastrophic landslides in the area are the following: (1) thick section of glacial marine clay (Presumpscot Formation), (2) high and steep bluffs lacking lateral support, and (3) water, especially ground-water conditions, but also precipitation and surface drainage. Other factors may only be minor contributors to increased potential for catastrophic landslides. However, the less dramatic but continual gradual erosion, small-scale slumping, and bluff recession that has occurred in the past, will continue over time just as it has been along the north shore of the harbor.

Thick Section of Clay

As the thickness of clay increases, the weight of this thickness, or overburden, may exceed the strength of the clay material itself. Technical staff from R. G. Gerber, Inc., made vane shear measurements in several boreholes around the April 1996 slide area. These tests used a Geonor 65 mm x 130 mm vane coupled with lightweight actuating rods and torqued with a calibrated torque wrench. The test is described in ASTM Special Technical Publication 1014 (Richards, 1988) and is a standard method for measuring the *in situ* undrained shear strength of silts and clays.

The results of the vane shear measurements show the strength of the clay at various depths (Figure 11). The line shown on the diagram shows the expected strength of normally consolidated clay of the Presumpscot Formation. At depths greater than 25 feet, the measured values are close to the expected values, indicating that the clay at depth is normally consolidated. At depths less than 25 feet, the measured shear strength is much greater than expected for normally consolidated clay, indicating the clay near the surface is "overconsolidated."

This might be explained by natural weathering of the clay surface over time, which can pull the clay structure together, giving it added strength. The brown color of the clay and the staining along vertical fractures in the clay which extend from the surface to about a 13 ft (4 m) depth are the result of normal weathering processes (oxidation and dessication). Hence, the apparent overconsolidation of the clay can be attributed to these weathering processes. Also, changes in depth of the water table in the clay may have occurred in the geologic past during dryer and wetter times thousands of years ago, and may, in part, have contributed to the overconsolidated nature of the upper part of the clay.

The expected strength has been calculated by multiplying the estimated overburden stress by a value of 0.2 (the undrained strength ratio). The estimated overburden stress, or pressure, is caused by the weight of the overlying material. This weight has been estimated by assuming an average density for the clay. Laboratory tests on Presumpscot clay in southern Maine typically give an undrained strength ratio of 0.2 (unpublished data, R. G. Gerber, Inc.).

From this, we conclude that those areas underlain by 25 or more feet (8 m) of clay, when coupled with a steep bluff slope, have a higher risk for landslides than those areas underlain by thinner clay sections. Yet, localized factors such as bluff slope inclination and drainage do, however, preclude the use of 25 feet of clay as a hard and fast rule for landslide prediction. Also, subtle variations in the clay moisture content, strength, and other factors will determine whether a single block of clay will fail during the landslide, or whether there will be several blocks failing in a retrogressive manner.

Nonetheless, our seismic work along Samoset Road and Waldo Avenue show several areas beneath which the clay is 25 feet (8 m) or more thick. There are several areas of particular concern (Figure 12). One is along Waldo Avenue from just west of its intersection with Samoset Road and extending westward. Along this section the ground surface is at about 45 feet (14 m) above mean sea level while the bedrock surface deepens to 20 feet (6 m) below mean sea level for a total thickness of 60 to 70

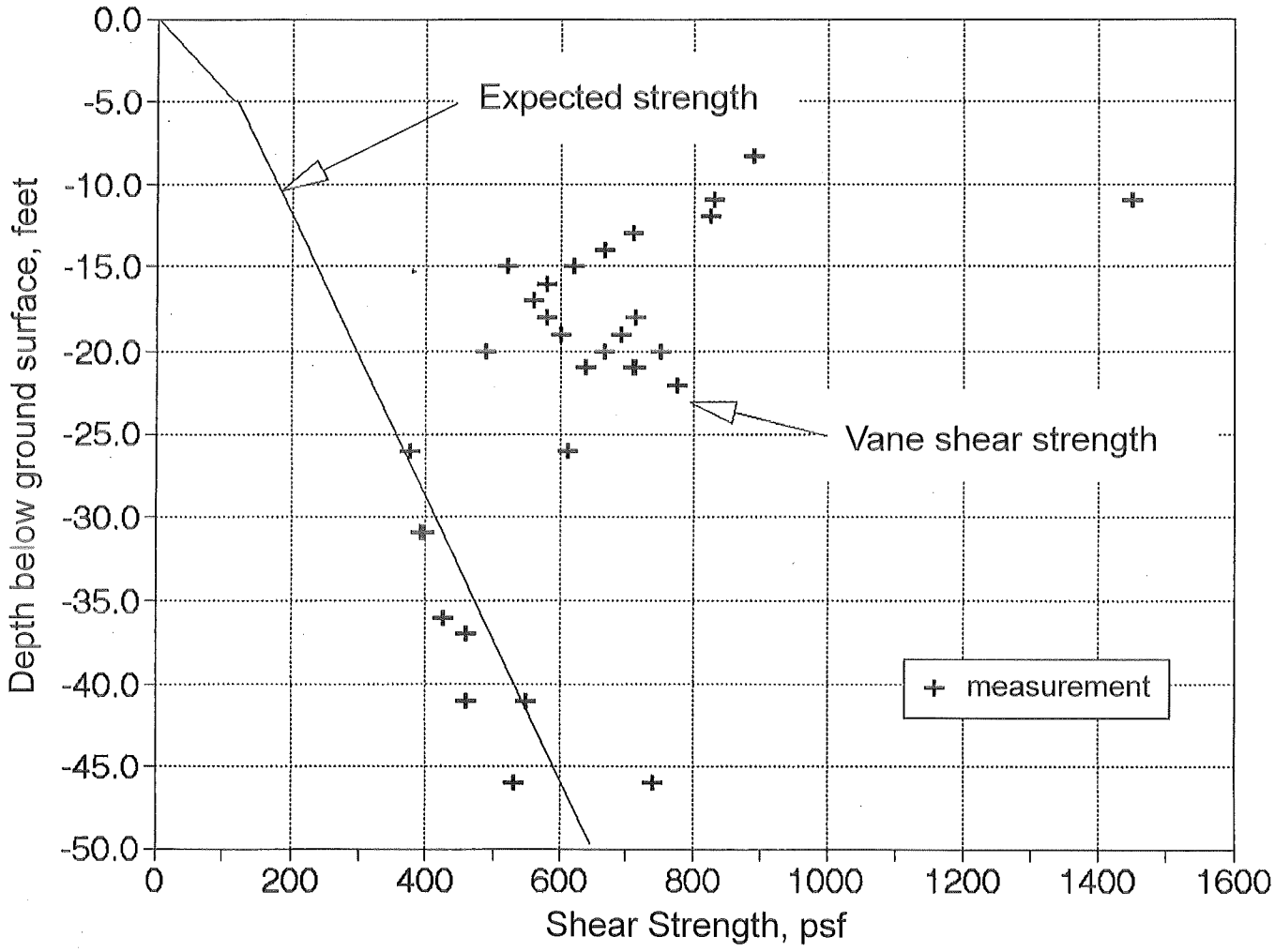


Figure 11. Diagram showing vane shear strength of the clay at various depths. Vane shear strength measurements of clay from boreholes at the 1996 Rockland landslide site are shown by "+" symbols. The line drawn on the diagram shows the expected strength of normally consolidated clay of the Presumpscot Formation.

feet (18 - 21 m) (also see Figure 8). Our seismic work does not extend westward beyond the intersection of Waldo Avenue with Glen Road, but at this intersection the thickness of the clay is greatest. It is likely that the thickness of the clay decreases westward from there to a place immediately north of the prominent rocky peninsula (Figure 12).

Other areas of concern are along Samoset Road (Figure 12). There are three embayments along the coast which correspond to troughs on the bedrock surface in which the thickness of the overlying clay is greater than 40 feet. The first is southwest of the intersection with Waldo Ave, the second is near the 1996 slide, and the third near the intersection with the old dirt access road to the Samoset resort. These embayments are indicated by arrows on Figure 12.

We can further generalize to say that areas landward of exposed ledge along the shore generally have thinner covers of clay than those areas which lack such exposures. Where detailed seismic data are lacking, such a generalization may be useful in assessing relative risk among neighboring areas.

High Bluffs Lacking Support

High and steep-sloped bluffs lacking lateral support at the base of the slope along the shore are a factor along the entire northern shore of Rockland Harbor. The bluff height and slope decrease approaching the southeastern end of Samoset Road near Jameson Point, so at present the relative risk of a catastrophic landslide decreases toward the breakwater. Slopes are more gradual there, and clay thickness and overall elevation of the land is less. However, small scale slumping, gradual erosion, and bluff recession will continue along the shore here. Potential for

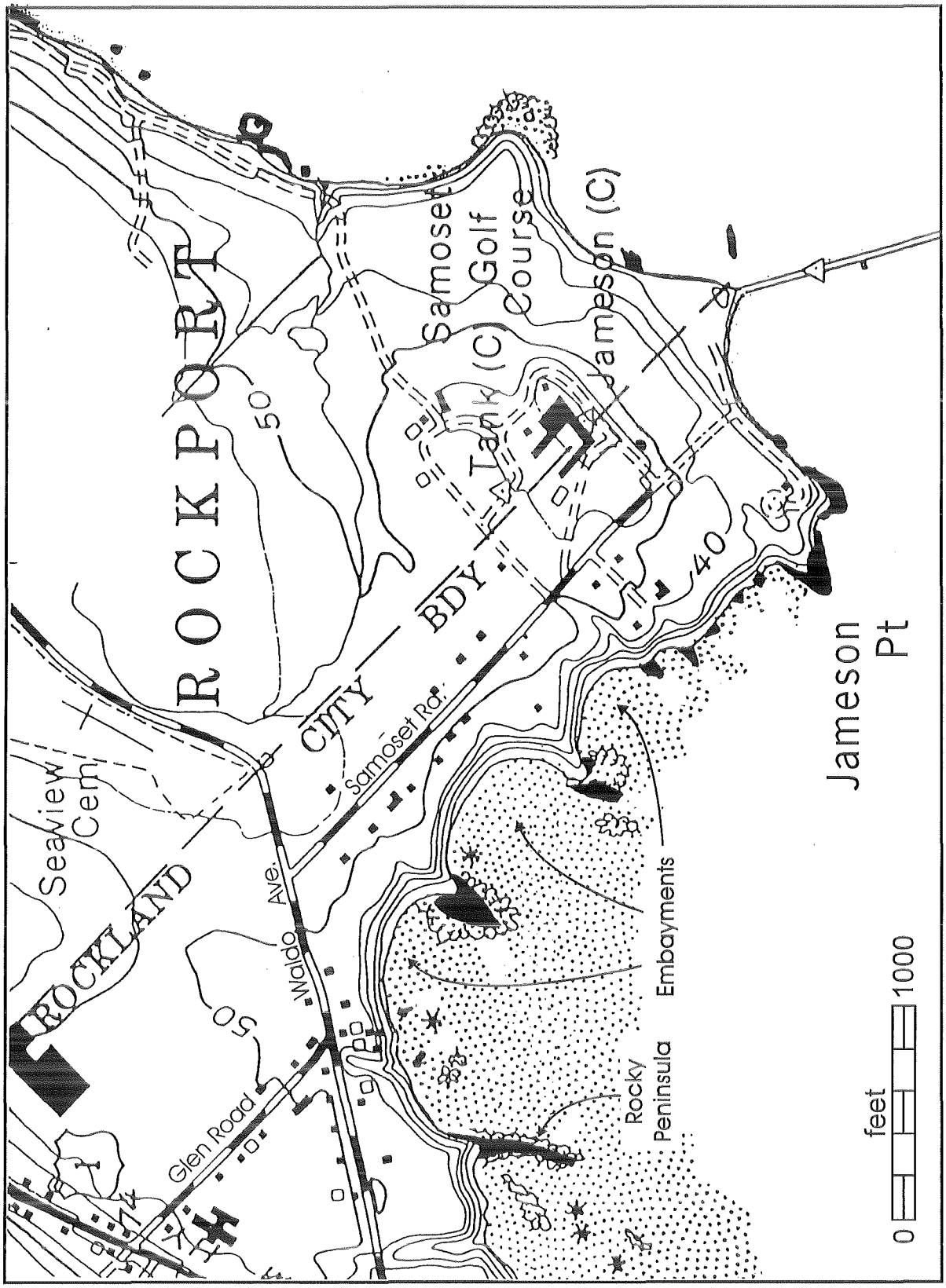


Figure 12. Location map of areas discussed in text where thick sections of clay are located along Waldo Avenue and Samoset Road. Exposed ledge (taken from Figure 5) is shown in black.

slides may increase over time, depending on erosion and slope steepness.

Water

The previous section cites several published references describing the role of water and precipitation in initiating ground failures. It is likely that the melting winter snowpack of 1996 followed by Spring precipitation may have resulted in high ground-water levels and may have contributed to the conditions leading to the April 1996 landslide. The weight of this water and its contribution to lowering the strength of the clay may be factors in the slide. A mid-winter thaw may have been a contributing factor to the 1973 slide along Waldo Avenue.

Also, it is suspected that an elevated ground-water head may have existed in glacial till or sandy deposits near the base of the slope at the time of the landslide. Whether such a sandy layer existed there is not known because the base of the bluff was disrupted and is now covered by debris. It was not found on the shore in the area of the slide, but sandy deposits were found about 20 feet below the surface of the landslide in some hand borings made where the old shore line would have been. This suggests that there may have been a sand layer several feet below the beach. Such a sand layer overlain by thick clay would be expected to develop a high pore pressure. An artesian condition in glacial till at the toe of the bluff slope would have reduced the lateral support for the bluff at the shoreline. This elevated head of water would have dissipated in the landslide area relatively soon after the slide occurred so it could not be measured after the fact. However, geologists from R. G. Gerber, Inc., did note slight upward pressures on the slope inclinometer casings at the top of the landslide during their installation, and slight artesian conditions in hand borings drilled in the 1996 landslide area. Of course, it is not known whether an excess head existed in the sand before the landslide, only that there was evidence for it after the slide.

From our seismic work, it is clear that modifications to drainage and ground water along Glen Road where major retail centers recently have been built were not factors in the 1996 landslide. The water table along Waldo Avenue at the time of our survey was lower than along Samoset Road in the area of the slide, and the water table gradient along Waldo Avenue (Appendix C; ROCK-41) is away from Samoset Road. These observations indicate that ground water in the Glen Road area moves down gradient toward the ocean and not toward the area of the 1996 landslide.

Modifications to drainage at the Samoset Resort are not likely to have contributed to the initiation of the 1996 landslide. This area was a stream and swamp prior to development into small ponds. The area lies on the north side of a minor drainage divide which generally directs water to the northern side of the resort property, away from Samoset Road. Furthermore, behind the houses on the northeast side of Samoset Road are several small intermittent wet areas which had standing water at the time of our investigations. These areas drain to the northeast. None of these water bodies showed sudden changes in water elevation in response to the landslide, as would be expected if there was a direct hydraulic link between them and the landslide failure surface. The water table does not change significantly in the vicinity of the slide, and there were only minor amounts of ground water seeping from the head scarp of the slide during our field surveys. In fact, in this area as in most areas of coastal Maine, the natural water table is within several feet of the ground surface for most of the year so that most of the clay deposits are saturated most of the time.

Apparently, the two houses involved in the 1996 slide were still using private septic systems. The addition of effluent from these systems may have increased the load on and reduced the strength of the underlying materials. Also, it should be noted that in the area of the February, 1995 landslide (adjacent to the April 1996 slide), ceramic drainage pipes protrude from the top of the bluff. One of these has a black plastic drainage pipe attached to it and is visible on the surface of the 1995 slide in Figures 2B, 2C, and 2D. Water was noted to be flowing at a very low rate from the black plastic pipe during a field visit to the slide the day of April 24, 1996. The landowner (William Eaton, personal communication to Stephen Dickson, April 1996) stated that his residence is currently on town sewer, but that with a dye test he determined that one of the ceramic pipes is from a basement drain in his home. The origin of the other drain is unknown. Drainage easements between the Eaton and Gerrish homes, and on the east side of the Smalley home are recorded on the City of Rockland sewer map for Samoset Road (Rockland Wastewater Treatment Facility). These septic and drainage systems provide potential pathways for increasing the amount of groundwater to the February 1995 and April 1996 landslide areas, and therefore may have been contributing factors.

Other Factors

Several residents indicated that fill had been used along some areas of Samoset Road and placed in the area of the 1996 landslide in order to eliminate wetlands and otherwise improve the land for building construction. Artificial fill can certainly be a contributing factor in some slides. However, the borehole lithologic logs for the April 1996 site (Appendix A) show about 3 feet (1 m) of fill material only in the driveway area of the Gerrish house. The other borings show natural soils grading down into natural geological materials. In our investigations of the site we reviewed the head scarp and sidewalls of the slide and found only natural geological materials, with the exception of a 3 - 4 foot (~1 m) wide section of fill immediately adjacent to the foundation of the Gerrish house. Similar fill was noted around what remained of the Smalley foundation, and neighbors stated that a small amount of fill had been added to her property for gardening purposes. In the toe sections of the slide investigated, no fill material was found. Based on this information, we con-

clude that artificial fill had no or only limited effect in causing the landslide.

DISCUSSION OF POSSIBLE COURSES OF ACTION

Many courses of action are possible for dealing with the landslide hazard of northern Rockland Harbor. Some of these possibilities are listed here with brief comments. A more extensive analysis of alternatives should be considered prior to taking any action. For example, some of these options may require further geologic or engineering study of specific sites to better characterize their landslide risk. In addition to geologic factors, these options must be considered in terms of cost of the action compared with the value of properties to be protected or remediated. And since the risk of catastrophic landslides depends on a combination of several contributing factors, a combination of options should be considered if engineering solutions are pursued to reduce risk.

(1) Do nothing. This option certainly costs the least up front, but may eventually have severe and costly consequences as properties are destroyed and lives are jeopardized. If Mrs. Smalley had not been evacuated from her home, she could have been killed. To take no action may seem a relatively safe gamble, since it has been more than 20 years since the last major landslide in the area. However, as with hurricanes, the recurrence time and location of such events in the area is unpredictable. Yet the similarity of the 1973 and 1996 events shows that the 1996 event was not a unique occurrence, and recurrence is to be expected (Plate 1).

(2) Move structures from the highest risk areas of the shore. This option would require finding new building sites and moving existing buildings, which may not be economically feasible in all cases. The benefits of this option are that properties and lives would be removed from the areas of highest risk.

(3) Reduce slope and rip-rap base of the bluff at high risk properties, with appropriate surface drainage. This is expensive but most likely less costly than option 2. A reduction in slope would reduce load and lateral stress on underlying materials, which is the fundamental cause of catastrophic landslides. Enough room would be required between the current slope top and existing buildings to adequately reduce the slope. Rip-rap, if properly installed and maintained, would reduce or eliminate wave erosion at the base of the bluff slope and maintain the shape of the slope. However, installation of it might actually lead to increased erosion at the toe of the rip-rap if placed in the intertidal zone, and also may be illegal under the Natural Resources Protection Act under some circumstances. Properties so remediated would still be subject to landslide risk, although probably reduced. Engineering studies would be necessary to determine the factor of safety for proposed designs.

If slope reduction is considered, various engineered designs may be available depending on the site. One simple example is the engineered waterfront slope behind the Littlefield Memorial Baptist Church, at the west end of Waldo Avenue, about 1500 feet west of the 1973 landslide site (Figure 13). Because there was enough space behind the buildings, it was possible to grade the bluff to a long, gradual slope. Rip-rap was placed at the base to reduce wave erosion, and vegetation on the slope reduces gullying and erosion by surface water runoff. The cost of this project in 1979 was about $25,000. Other, more sophisticated designs may be neccessary for structural stabilization of higher, steeper slopes with less upland behind existing buildings. Such construction has been done on the Pacific Coast and has resulted in esthetically pleasing, structurally sound slopes, but at significant cost.

(4) Ground-water management. A design of French drains and/or pumping wells could be developed to artificially lower the water table in the areas of highest risk. Such a system would be expensive and would require maintenance. Furthermore, if pursued as the sole option, its effectiveness in reducing risk is uncertain because the level of the water table is only one of the contributing factors to catastrophic landslides, and it may not be the most significant factor.

(5) Infrastructure improvements. Minor contributing factors to landslide risk could include improper road drainage and leakage of water supply and sewer lines. These systems could be improved, but their effectiveness at significantly reducing risk, while uncertain, is probably low. Also, it may be worthwhile to consider relocation of some of these critical services outside of the areas of highest risk.

(6) Discourage inappropriate development in high-risk areas. In this way the future cost of reparations or remediation could be avoided. The buildings destroyed by the 1996 landslide were well within current setback and zoning regulations. Better education or new policies could be considered to avert the construction of additional structures at risk.

(7) Prepare for the next catastrophic event. Local emergency personnel, including the city manager, police, fire, and public works personnel were available and responded well to the 1996 catastrophic landslide. However, when NRIMC geologists visited the site on April 16, few of the local people on the scene knew about the 1973 event that had occurred in just the next cove. It would seem prudent to develop emergency plans and response policies for destructive landslides in northern Rockland Harbor and in geologically similar areas. Most homeowner insurance policies do not cover landslide losses. And with a total pricetag approaching $1 million, the 1996 event has been expensive for the city of Rockland as well.

GENERAL SUMMARY

The April 16, 1996 landslide in Rockland, Maine, was a catastrophic event. Fortunately, there was no loss of life, but two homes were completely destroyed, and along with the total emergency operations, damage, and reparations, the cost had reached approximately $710,000 by the fall of 1996, and will most likely exceed that when all work is completed.

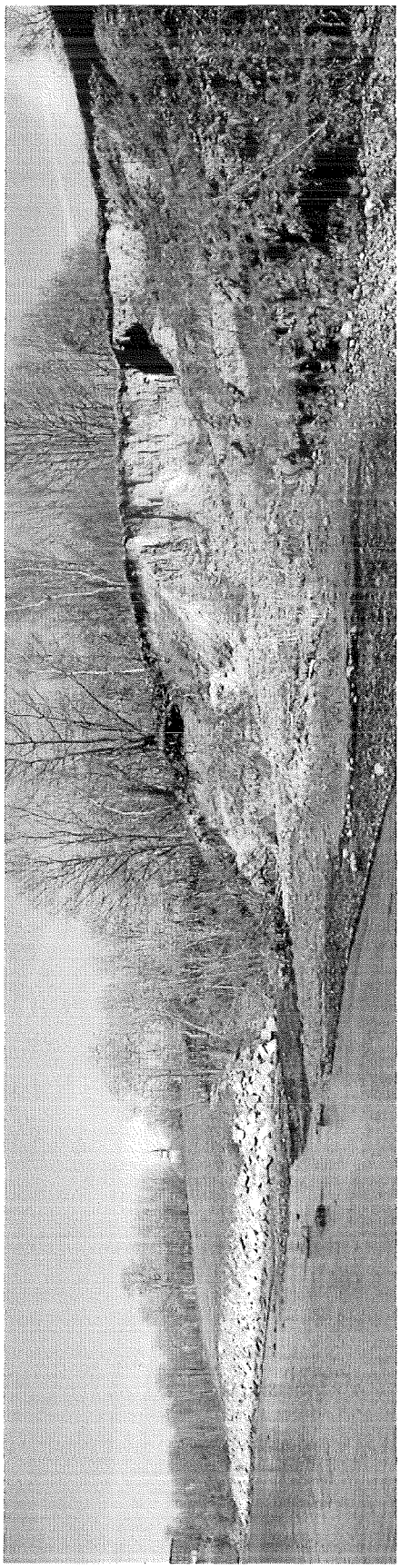


Figure 13. Panorama of engineered, stabilized slope contrasted with naturally eroding and slumping bluff along north shore of Rockland Harbor. View is to the northwest. Property of the Littlefield Memorial Baptist Church, at the west end of Waldo Avenue (Figure 1), was engineered in 1978-1979 to prevent slumping along the shore. The bluff face was modified to make a more gradual slope, and rip-rap was placed at the base of the slope to reduce wave erosion. Cost of this project was approximately $25,000 (personal communication, 11/1/96, Eliot Gamadge of Rockland). The adjacent area to the right is undergoing natural erosion and slumping at a smaller scale than the 1996 landslide along Samoset Road. Note person in front of steep bluff on right for scale. Photography by Daniel Locke (NRMC), May 1996.

- Similar events have occurred before, both in Rockland and elsewhere in Maine, but not very often. A number of factors contributed to the slide including but not necessarily limited to a high, steep-sloped bluff, a thick section of poorly-drained clay, and a high water table.

- The general geologic environment of the April 1996 landslide is present in places other than Rockland. Hence, at some time in the future, similar landslides will occur in Maine. Depending on the specific locality, the results could be as severe, more severe, or less severe than the April 1996 Rockland event. Exact prediction of these types of events is not possible.

- Common sense and knowledge of general geologic conditions are useful in evaluating the general suitability of a construction site, but it is strongly advised that an engineering firm assess a "factor of safety" with respect to landslides for existing or planned individual sites in Maine.

ACKNOWLEDGMENTS

The authors wish to express their thanks to the following individuals for their participation in the work of preparing this report: Robert Tucker and John Poisson of NRIMC for their assistance with preparing the text and figures (all photography in the report is by John Poisson except where otherwise noted); Mike Foley and Craig Neil of NRIMC provided seismic line data collection and reduction; Robert Estes of RGGI hand-augered borings and measured downhole vane shear strengths at the head of the landslide scarp. RGGI thanks Northeast Diamond Drilling for the test borings drilled at the site. Finally, the authors wish to thank the City of Rockland, in particular City Managers Cathy Sleeper and Richard Michaud and Wastewater Treatment Facility Plant Manager Steven MacDonald for supplying town data and information. We especially thank all private landowners for permitting access to their properties and talking with us during this unnerving episode.

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Appendix A: Photographs of 1996 Landslide Site

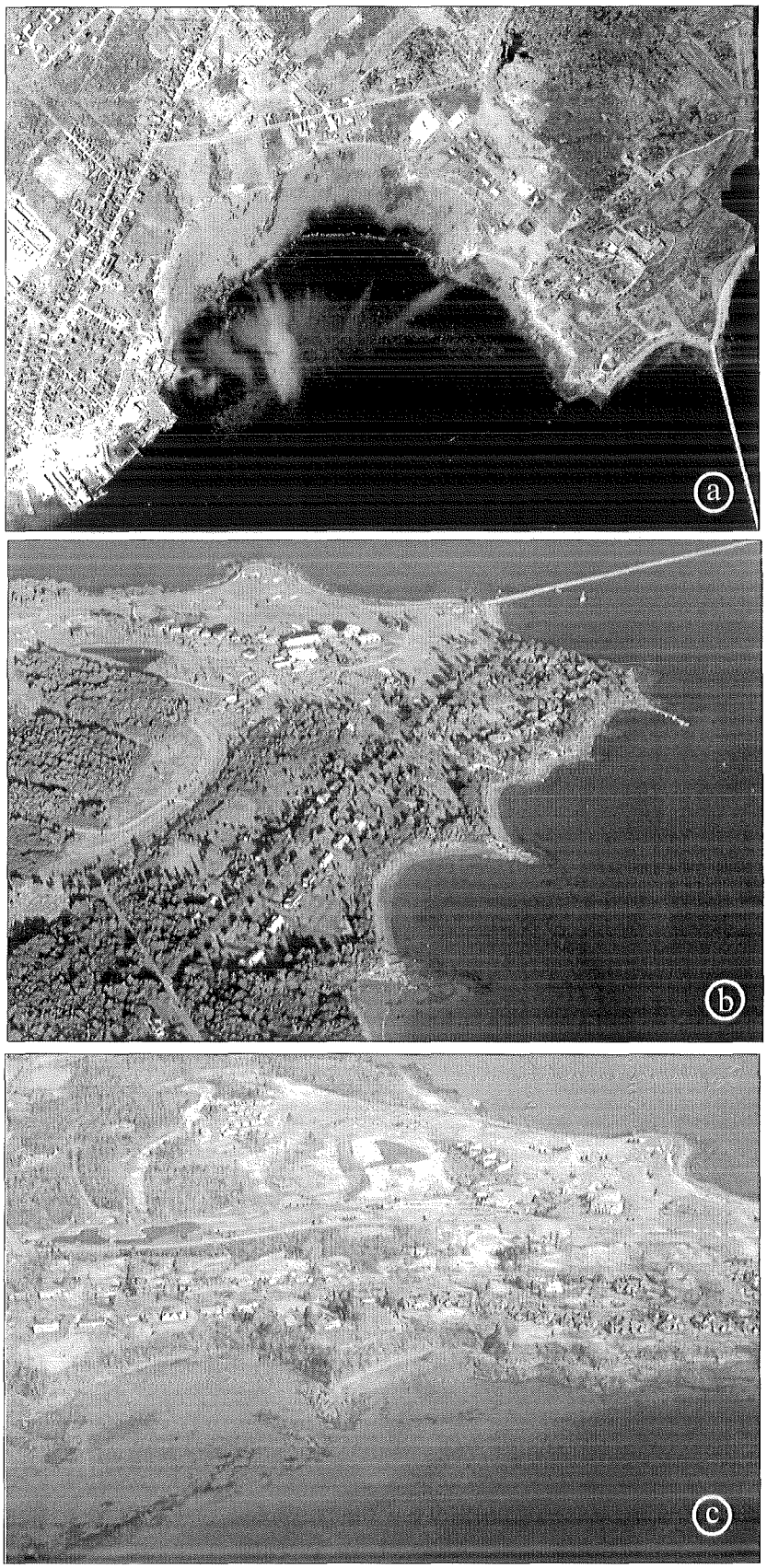


Figure A1. Airphotos of northern shore of Rockland Harbor prior to 16 April, 1996 landslide. (a) 5/3/66 (photo by J. W. Sewall Company) showing old Samoset Resort; (b) 9/4/87 (photo by J. T. Kelley); (c) 11/94 (photo by J. T. Kelley). Photos (b) and (c) show progress of work along access road to new Samoset Resort.

Figure A2. The Gerrish house several days after slide. Pavement of Samoset Street is visible in extreme lower right. Typical arcuate head scarp of the slide cuts across lawn and driveway of the Gerrish house. The first major failure involved land behind the house. The second major failure destroyed the Gerrishs' garage and portion of their house.

Figure A3. View to northwest across slide toward the Gerrish house showing the vertical head scarp. Natural horizontal layering of marine clay can be seen at left of house indicating that this area has very little fill over the marine clay. Roof of Smalley house in foreground.

Figure A4. View to the southeast across slide to the Smalley property showing rotational slide blocks mantled with a carpet of turf. Typical scarpward tilting of slide blocks is evident in the slab of driveway pavement just to left of and below lamp post.

Figure A5. View to southeast from behind the Gerrish house of the arcuate head scarp of slide. Behind trees in center of picture is the curved toe of the slide extending 450 feet (140 meters) onto adjacent mudflat.

Figure A6. In foreground are clay blocks which have spalled off the head scarp. Spalling is facilitated by vertical fractures in the upper part of the marine clay which form the offset vertical surfaces in the scarp behind the fallen blocks. Manganese staining of the fractures indicates that ground water had been flowing through the fractures for some time.

Figure A7. View across the widest section of slide showing destruction of buildings that collapsed into the slide. Before the landslide, most of this area was backyard lawn.

Figure A8. View to the northeast from the intertidal mud flat. This photograph shows clay blocks in the toe of the slide. The damaged Gerrish house is visible in upper left and the Smalley house site is visible in upper right. The extreme toe of the slide contains sediments which originally were at the wave-cut base of the bluff.

Figure A9. View from the Gerrish backyard of the toe of the slide showing several slide blocks with their tops rotated landward toward the head scarp. This is particularly apparent in the block topped with turf in left center and the group of poplar trees just above it. Rainwater has pooled in the depressions between blocks.

Figure A10. View toward the north showing the toe of the slide. Most trees in the slide show backward rotation toward the head scarp but several in this photo and elsewhere are vertical or at different orientations. This may be indicative of flow rather than simple block rotation as the mode of failure in some parts of the slide. Geologists in foreground survey the perimeter of the slide.

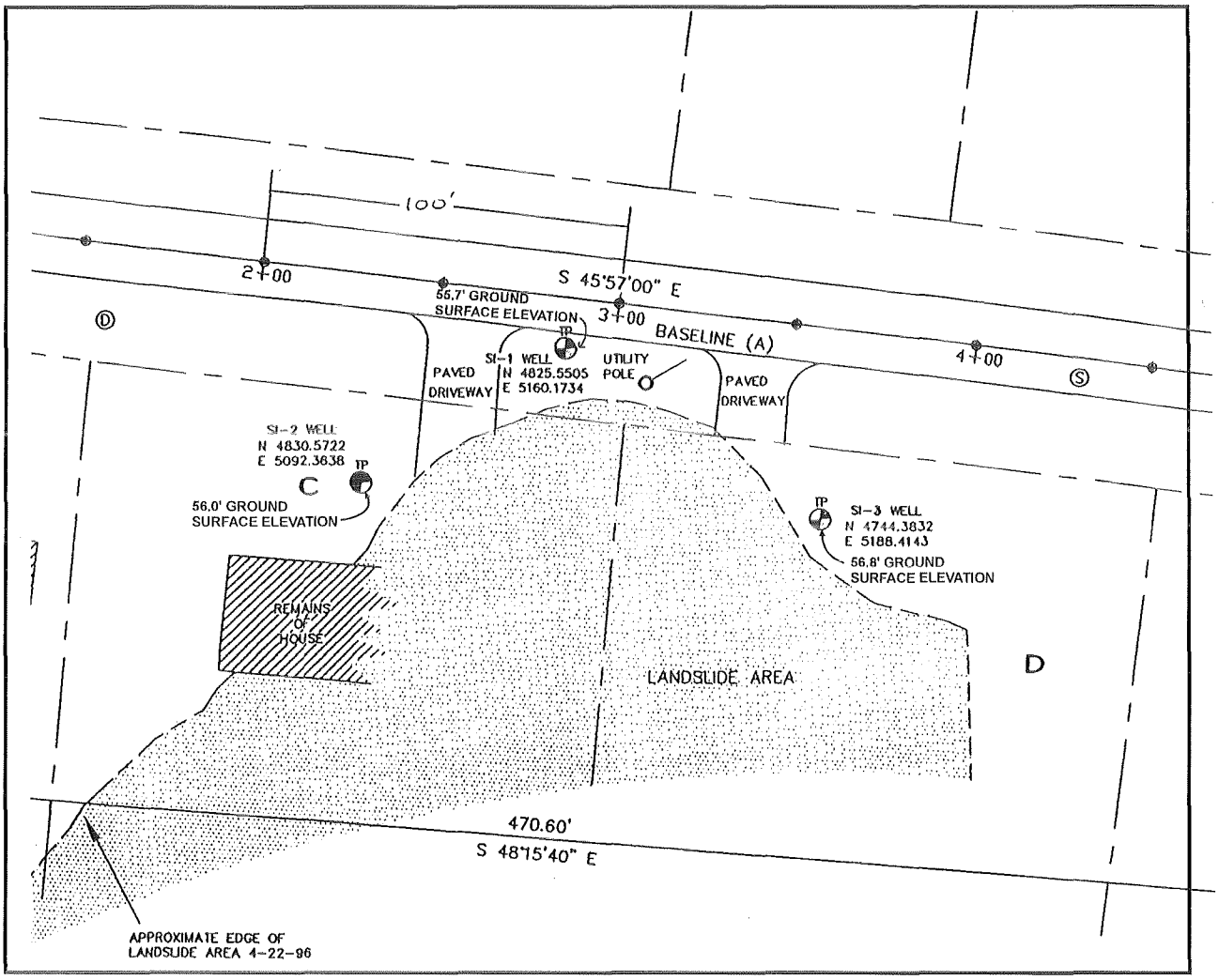
Figure A11. Close-up of a rotated block composed of fractured marine clay. Unlike the 1973 slide, few blocks remained intact in the 1996 slide. Notice grooves in the clay that formed as different blocks slid past each other and around the tree. Cracks formed as the clay dried and shrank.

Figure A12. View to southeast across the slide. Motion was from left to right. In this photograph, several curved ridges representing individual slide blocks extend from lower foreground across the slide to the far side. Each ridge is a single block of the same material along its length, either soil or turf, but neighboring ridges may be made of different materials. The retrogressive failure did vary the orientation of blocks and trees, but it did not result in the mixing of different layers. The whole area pictured used to be the flat area on top of the bluff that is missing from figure A7. The former slope at the front of the bluff has moved onto the mudflat, to the right of this picture.

Figure A13. Photograph of arcuate ridges showing their common, subparallel orientation and height of several feet.

Appendix B: Boring Log Records, R. G. Gerber, Inc.

The test drilling logs by Robert G. Gerber, Inc., provide verification for the depth to bedrock determined by seismic data in the area of the borings (Appendix C). Also, the stratigraphic logs from the borings are similar to the log of the exposed section (Figure 5). Note that vane shear strengths on the logs are presented to the right of the material description, under the column entitled Volatile Organic Compounds (ppm) in large type. These measurments are in units of pounds/sq ft. The vane shear measurements are summarized in Figure 11 of the report.



Location of wells SI-1, SI-2, and SI-3 from which boring logs were taken. The head of the 1996 landslide is shown.

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a Jacques Whitford Company
Consulting Engineers and Environmental Scientists

174 South Freeport Road
Freeport, Maine 04032-6115
207-865-6138

LOG OF BORING SI-1

Project:	Rockland Landslide	Surface Elev.:	55.7	Total Depth:	58.0
Job No.:	1546.1	Top of PVC Elev.:	58.96	Hole Diameter:	4"
Location:	Rockland	Equipment:	Mobile B-47		
Coordinates:	N 4,825.6 E 5,160.2	Drilling Method:	Cased		

Elevation, feet	Depth, feet	Graphic Log and Sample Types	Sample No.	% Recovery	MATERIAL DESCRIPTION	SPT, N value or RQD in %	Volatile Organic Compounds (ppm)	COMMENTS	WELL INSTALLATION DETAILS
55.7	0				Olive brown silt, some clay, trace gravel, mottled, damp.				Stick up = 3.3'. 6" x 7' Steel standpipe Grouted with 300 lbs cement and 5% bentonite.
53.8					Gray/brown fine sand, some silt, moist, wet.				
53.5					Light gray/brown fine sand, mottled, moist, uniform.				
51.9					Olive brown/gray clayey silt, moist, mottled.				
50	5								
47.4					Gray clayey silt with few fine sand seams, wet. GLACIOMARINE				
	10		V-1				1448 / 383		
40	15		V-2				521 / 188		
			V-3				596 / 210		
	20		V-4				488 / 154		
			V-5				514 / 218		
30	25		V-6				375 / 113		
			V-7				420 / 113		
	30		V-8				391 / 97		
			V-9				375 / 94		

Boring continues on next page

Date Started:	4/26/96	9:45	Symbols:	Remarks:
Date Completed:	4/29/96	13:00	Auger Cutting; Vane Shear; SPT; WL at time of boring; UD; Penetrometer; Rock Core	
Drilling Contractor:	NEDD			
Engineer/Geologist:	RAE			
Approved By:				

All depths in feet. Unless otherwise noted, water encountered but not recorded.

The stratification lines represent approximate boundaries. The transition may be gradual.

Sheet 1 of 2

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174 South Freeport Road
Freeport, Maine 04032-6115
207-865-6138

LOG OF BORING SI-1
(continued)

Project:	Rockland Landslide	Surface Elev.:	55.7
Job No.:	1546.1	Top of PVC Elev.:	58.96
Location:	Rockland	Equipment:	Mobile B-47
Coordinates:	N 4,825.6 E 5,160.2	Drilling Method:	Cased

Total Depth: 58.0
Hole Diameter: 4"

Elevation, feet	Depth, feet	Graphic Log and Sample Types	Sample No.	% Recovery	MATERIAL DESCRIPTION	SPT, N value or RQD in %	Volatile Organic Compounds (ppm)	COMMENTS	WELL INSTALLATION DETAILS
20	35		V-10		35'-36.5' Some gravel.		460 (101)		
			V-11				575 (156)		
	40		V-12				552 (133)		
			V-13				547 (150)		
10	45		V-14				741 (209)	Vane refusal at 46.8'.	
7.1					Gray sand and gravel, some silt, with cobbles, dense. TILL	60/.2'			
6.0	50		D-1	14	Gray phyllite/schist, some fractures. BEDROCK				
			R-1						
0	55		R-2						
-2.3					Boring terminated at 58.0'				Installed SI-1 at 58.0'.

Date Started:	4/26/96 9:45	Symbols:	WL at time of boring
Date Completed:	4/29/96 13:00	Auger Cutting	UD
Drilling Contractor:	NEDD	Vane Shear	Penetrometer
Engineer/Geologist:	RAE	SPT	Rock Core
Approved By:			

Remarks:

All depths in feet. Unless otherwise noted, water encountered but not recorded.

The stratification lines represent approximate boundaries. The transition may be gradual.

Sheet 2 of 2

Robert G. Gerber, Inc.
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Consulting Engineers and Environmental Scientists

174 South Freeport Road
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LOG OF BORING SI-2

Project:	Rockland Landslide	Surface Elev.:	56.0	Total Depth:	59.5
Job No.:	1546.1	Top of PVC Elev.:	59.53	Hole Diameter:	4"
Location:	Rockland	Equipment:	Mobile B-47		
Coordinates:	N 4,830.6 E 5,092.4	Drilling Method:	Cased		

Elevation, feet	Depth, feet	Graphic Log and Sample Types	Sample No.	% Recovery	MATERIAL DESCRIPTION	SPT, N value or RQD in %	Volatile Organic Compounds [ppm]	COMMENTS	WELL INSTALLATION DETAILS
56.0	0				Brown/reddish brown sand and gravel, widely graded. FILL				Stick up = 3.5'. 6" x 7' Steel standpipe Grouted with 300 lbs cement and 5% bentonite.
52.8									
52.5					Gray/dark brown silt, some sand and gravel, damp.				
51.0	5				Brownish gray fine sand, uniform, mottled, damp.				
50					Light gray fine sand, uniform, moist.				
49.4					Light gray and yellowish brown sand, moderately well graded, wet.				
48.2					Olive brown/gray clayey silt, trace sand, mottled, wet.				
45.5	10		V-1		Gray clayey silt with few fine sand seams. GLACIOMARINE		>1875		
40	15		V-2				>1875		
	20		V-3				713 (266)		
			V-4				675 (263)		
30	25		V-5				611 (208)		
			V-6				450 (146)		
	30		V-7				398 (115)		
			V-8				389 (129)		

Boring continues on next page

Date Started:	4/29/96	14:30	Symbols:	Remarks:
Date Completed:	4/30/96	17:00	Auger Cutting; Vane Shear; SPT; WL at time of boring; UD; Penetrometer; Rock Core	
Drilling Contractor:	NEDD			
Engineer/Geologist:	RAE			
Approved By:				

All depths in feet. Unless otherwise noted, water encountered but not recorded.

The stratification lines represent approximate boundaries. The transition may be gradual.

Sheet 1 of 2

Robert G. Gerber, Inc.
a Jacques Whitford Company
Consulting Engineers and Environmental Scientists

174 South Freeport Road
Freeport, Maine 04032-6115
207-865-6138

LOG OF BORING SI-2
(continued)

Project:	Rockland Landslide	Surface Elev.:	56.0	Total Depth:	59.5
Job No.:	1546.1	Top of PVC Elev.:	59.53	Hole Diameter:	4"
Location:	Rockland	Equipment:	Mobile B-47		
Coordinates:	N 4,830.6 E 5,092.4	Drilling Method:	Cased		

Elevation, feet	Depth, feet	Graphic Log and Sample Types	Sample No.	% Recovery	MATERIAL DESCRIPTION	SPT, N value or RQD in %	Volatile Organic Compounds [ppm]	COMMENTS	WELL INSTALLATION DETAILS
	35		V-9				426 127		
20			V-10				414 120		
	40		V-11				460 150		
			V-12				483 150		
	45		V-13				529 177		
10			V-14				495 184		
					48' Possibly some cobbles.				
6.5	50		D-1		Gray fine sand, trace gravel, trace silt, firm. TILL	18			
2.7					Gray phyllite/schist, few fractures. BEDROCK				
	55		R-1						
0									
-3.5					Boring terminated at 59.5'.				Installed SI-2 at 59.5'.

Date Started:	4/29/96 14:30	Symbols:	WL at time of boring
Date Completed:	4/30/96 17:00	Auger Cutting	UD
Drilling Contractor:	NEDD	Vane Shear	Penetrometer
Engineer/Geologist:	RAE	SPT	Rock Core
Approved By:			

Remarks:

All depths in feet. Unless otherwise noted, water encountered but not recorded.

The stratification lines represent approximate boundaries. The transition may be gradual.

Sheet 2 of 2

Robert G. Gerber, Inc.
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Consulting Engineers and Environmental Scientists

174 South Freeport Road
Freeport, Maine 04032-6116
207-865-6138

LOG OF BORING SI-3

Project:	Rockland Landslide	Surface Elev.:	56.8	Total Depth:	50.0
Job No.:	1546.1	Top of PVC Elev.:	60.25	Hole Diameter:	4"
Location:	Rockland	Equipment:	Mobile B-47		
Coordinates:	N 4,744.4 E 5,188.4	Drilling Method:	Cased		

Elevation, feet	Depth, feet	Graphic Log and Sample Types	Sample No.	% Recovery	MATERIAL DESCRIPTION	SPT, N value or RQD in %	Volatile Organic Compounds (ppm)	COMMENTS	WELL INSTALLATION DETAILS
56.8	0				See SI-1 for soil descriptions.			Auger to 5'. Push casing and wash out to 10'. No samples taken.	Stick up = 3.5'. 6" x 7' Steel standpipe Grouted with 300 lbs cement and 5% bentonite.
54.9									
54.6									
53.0									
	5								
50									
46.8	10		V-1		Gray clayey silt with few fine sand seams, wet. GLACIOMARINE		>1500		
	15		V-2				>1500		
40									
	20		V-3				2818		
	25		V-4				551 206		
			V-5				544 206		
30									
	30		V-6				544 206		
			V-7				638 199		

Boring continues on next page

Date Started:	5/1/96	7:45	Symbols:	WL at time of boring	Remarks:
Date Completed:	5/1/96	15:30	Auger Cutting	UD	
Drilling Contractor:	NEDD		Vane Shear	Penetrometer	
Engineer/Geologist:	RAE		SPT	Rock Core	
Approved By:					

All depths in feet. Unless otherwise noted, water encountered but not recorded.

The stratification lines represent approximate boundaries. The transition may be gradual.

Sheet 1 of 2

Robert G. Gerber, Inc.
a Jacques Whitford Company
Consulting Engineers and Environmental Scientists

174 South Freeport Road
Freeport, Maine 04032-6115
207-865-6138

LOG OF BORING SI-3
(continued)

Project:	Rockland Landslide	Surface Elev.:	56.8
Job No.:	1546.1	Top of PVC Elev.:	60.25
Location:	Rockland	Equipment:	Mobile B-47
Coordinates:	N 4,744.4 E 5,188.4	Drilling Method:	Cased

Total Depth: 50.0
Hole Diameter: 4"

Elevation, feet	Depth, feet	Graphic Log and Sample Types	Sample No.	% Recovery	MATERIAL DESCRIPTION	SPT, N value or RQD in %	Volatile Organic Compounds [ppm]	COMMENTS	WELL INSTALLATION DETAILS
21.5	35		V-8		Gray silty sand, trace clay, some gravel, loose. TILL			Vane refusal.	
20									
	40		D-1			6			
			R-1		42.2'-44.0' Boulder.			Core through boulder.	
	45								
10.9			D-2		Gray phyllite/schist. BEDROCK	25/.4'			
10								Drill with stabilizer bit to 50.0'. Caved to 47.0'.	Installed SI-3 at 47.0'.
6.8	50				Boring terminated at 50.0'.				

Date Started:	5/1/96	7:45
Date Completed:	5/1/96	15:30
Drilling Contractor:	NEDD	
Engineer/Geologist:	RAE	
Approved By:		

Symbols: Auger Cutting, Vane Shear, SPT, WL at time of boring, UD, Penetrometer, Rock Core

Remarks:

All depths in feet. Unless otherwise noted, water encountered but not recorded.

The stratification lines represent approximate boundaries. The transition may be gradual.

Sheet 2 of 2

Appendix C: Hydrogeologic and Depth-to-Bedrock Seismic Refraction Profiles

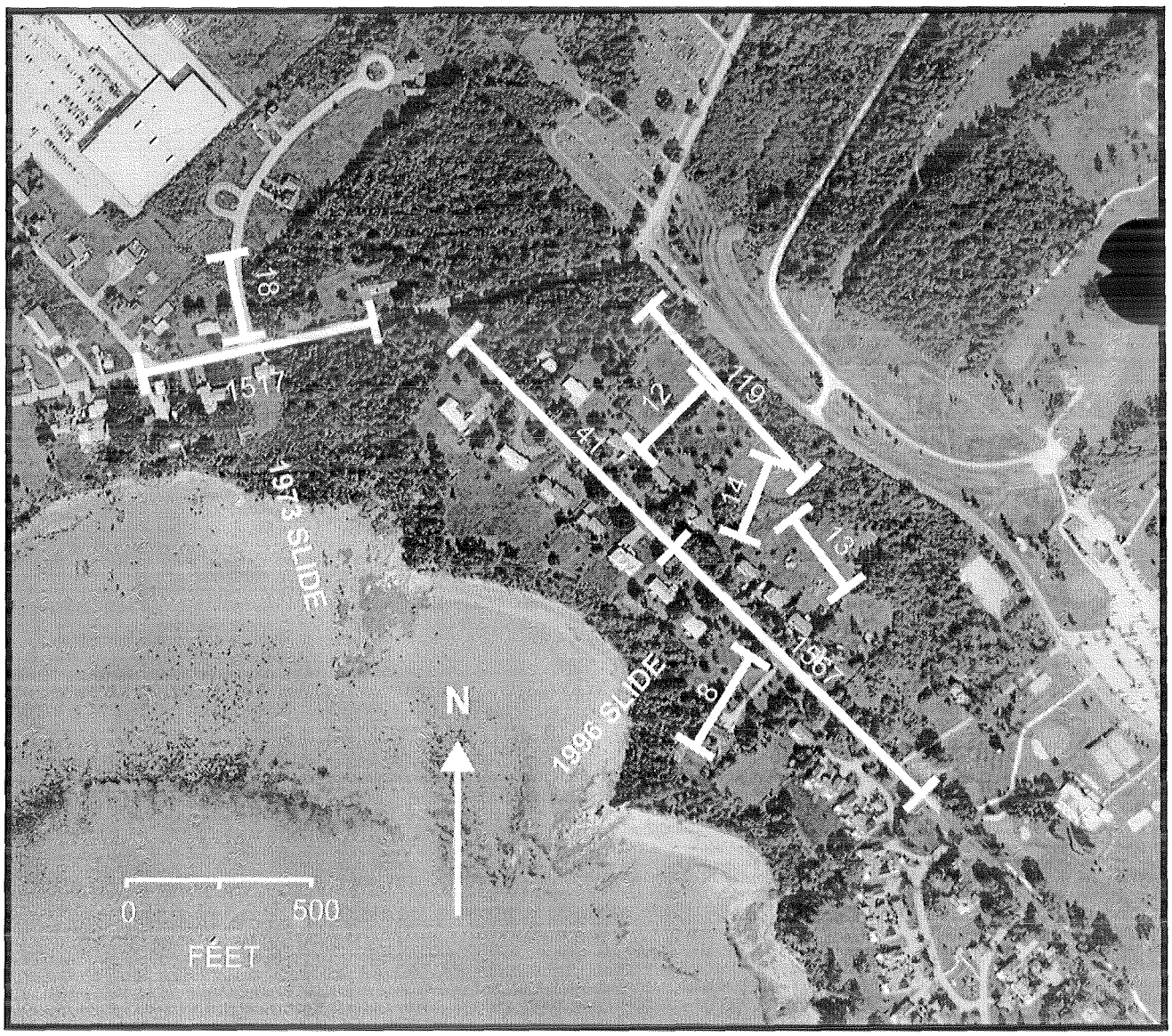
During the period from May 6 - 16, 1996, the NRIMC conducted 18 seismic refraction surveys in order to gather subsurface geologic and hydrogeologic information in the area of the Rockland landslides of 1996 and 1973. Total horizontal distance of all lines cumulatively is 4,305 feet (1.23 km). Site survey lines were located roughly perpendicular as well as parallel to the directions of the slides. Actual locations selected were made on the basis of access and surface suitability.

Seismic refraction techniques, following field procedures described by Haeni (1988), were used to obtain profiles showing the depth to water table, depth to bedrock, and topography of the bedrock surface. In seismic exploration, seismic waves are generated at the surface by an energy source such as a small explosion or a sledge hammer blow to a metal plate. These compressional waves travel through the ground at different velocities depending upon the material--the denser the material, the faster the wave velocity. The seismic waves are then detected by geophones positioned in a line along the ground. In order to detect different layers of underground material by refraction, the seismic velocity must increase with depth and there must be a significant velocity contrast between the layers.

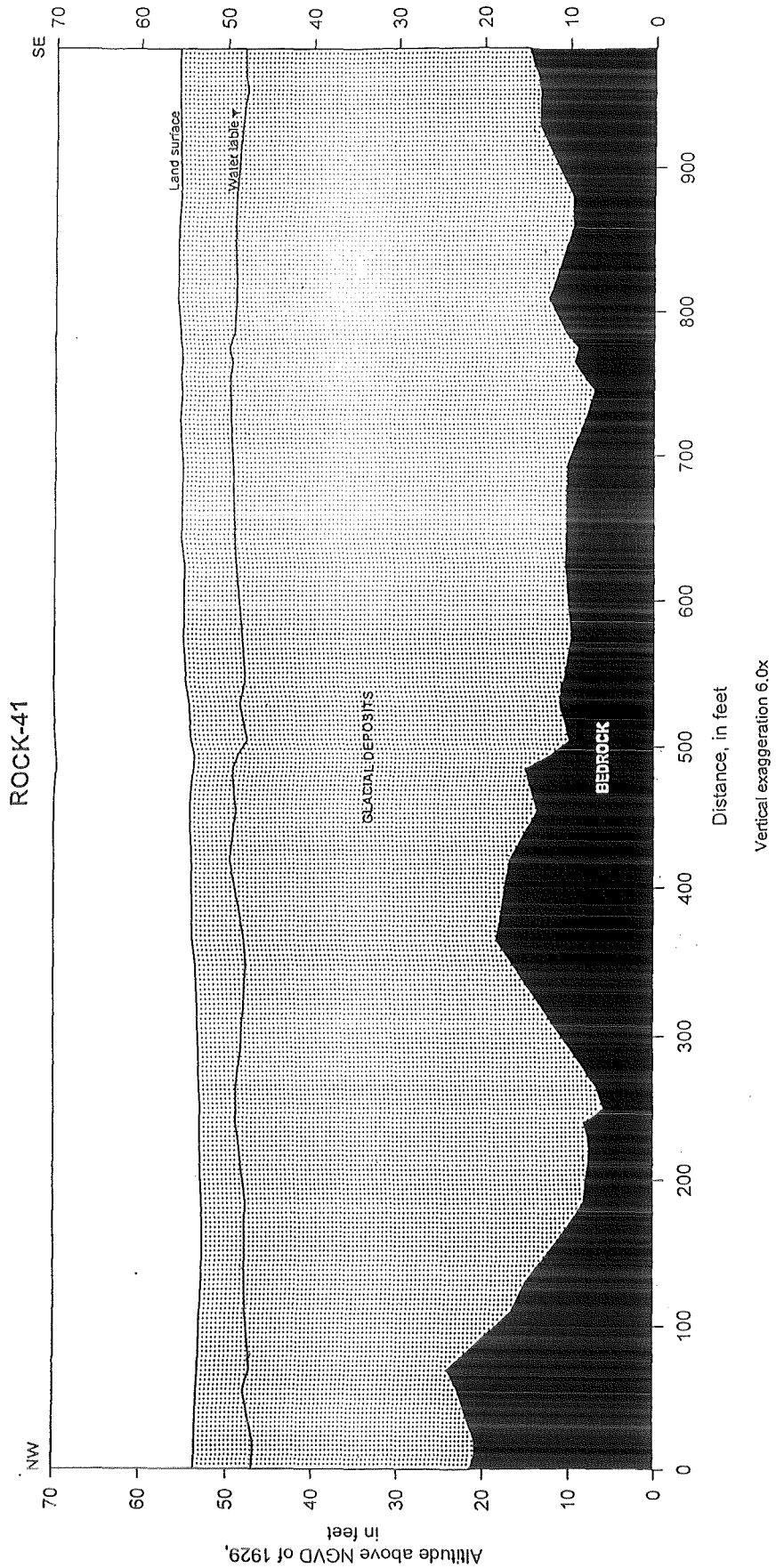
In this study, seismic refraction was used to distinguish between unsaturated glacial deposits (above the water table), saturated glacial deposits (below the water table), and bedrock, which were found to have seismic velocities appropriate for the method. A 12-channel, EG&G Geometrics ES-1225 seismograph was used in this study. The instrument is sensitive and delivers a relatively high degree of resolution. Individual seismic lines varied from 230 to 280 feet (70 - 85 m) in length. Three longer profiles, up to 1000 feet (300 m) total, were obtained by overlapping several lines end to end. Shot points and geophones for each line were surveyed to determine their elevations relative to mean sea level (NGVD). A computer program (described by Scott and others, 1972) was used to determine each layer's seismic velocity and to generate a profile of the water table and bedrock surface beneath each line.

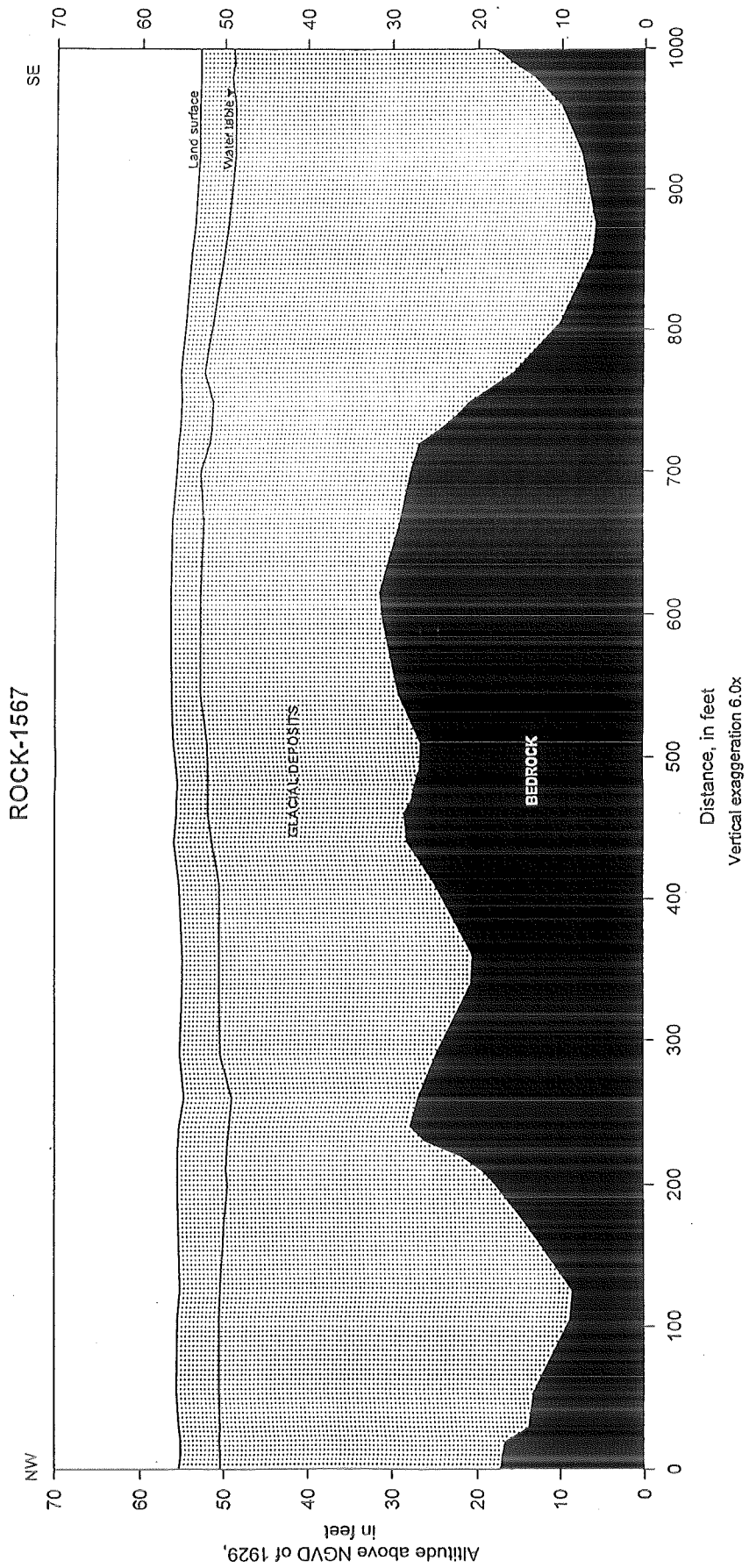
In the area studied, the average seismic velocity measured in unsaturated glacial deposits has a range from 582 to 1426 feet per second (ft/s) (177 - 435 m/s), with an average velocity for all lines of 903 ft/s (275 m/s). Saturated glacial deposits have average velocities of 4403 to 5225 ft/s (1342 - 1592 m/s) with an average velocity for all lines of 4717 ft/s (1438 m/s). Bedrock seismic velocities in the study area vary from 12,679 to 18,767 ft/s (3864 - 5720 m/s) with an average velocity for all lines of 14,895 ft/s (4540 m/s). Thickness of glacial deposits varies from 25 to 61 ft (8 - 18 m), with an average thickness of 40 ft (12 m). Bedrock surface elevation varies from -18 feet (-6 m) below sea level to 41 feet (12 m) above sea level, with an average elevation of 14 feet (4 m) above sea level.

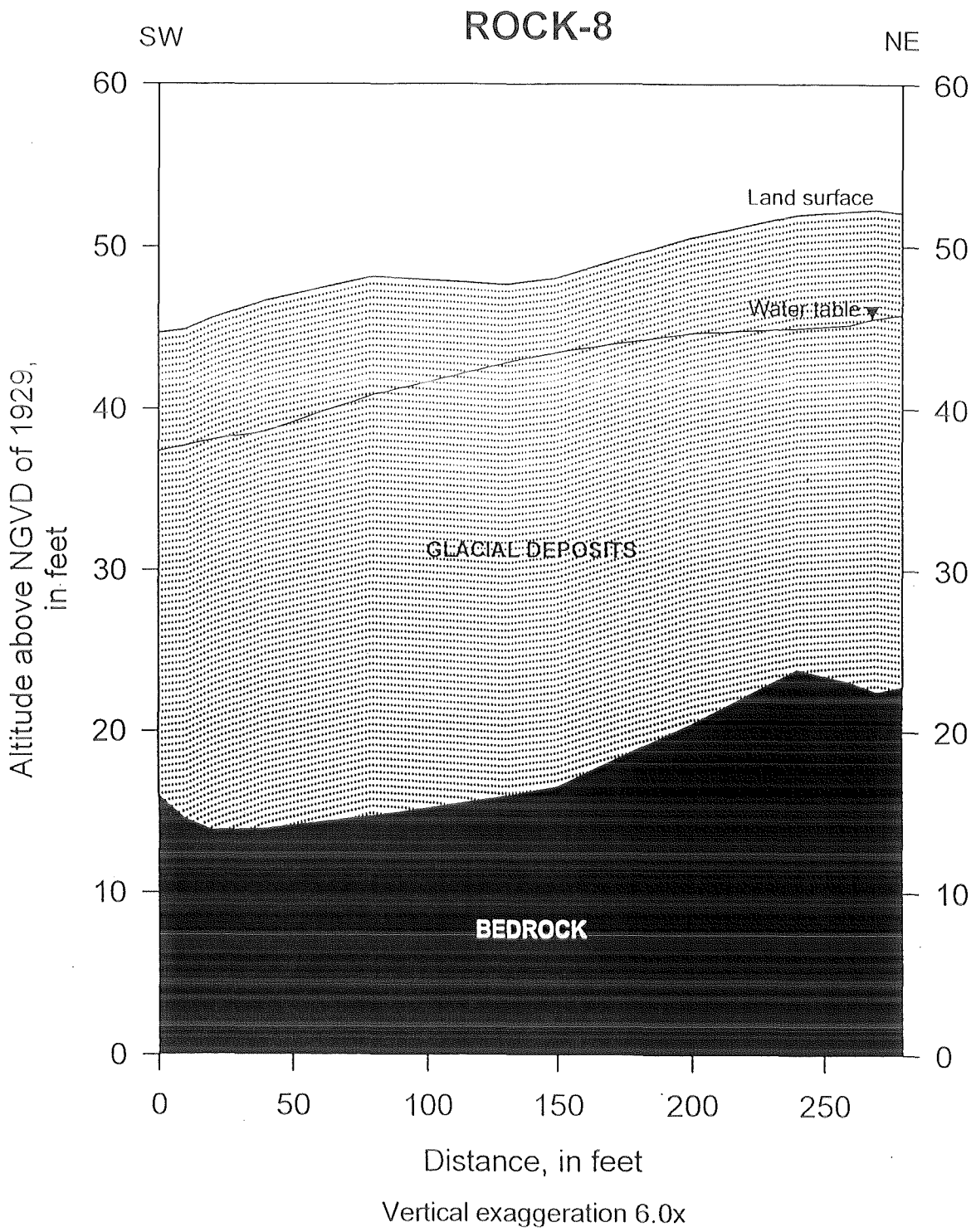
Test drilling information collected by Robert G. Gerber, Inc. (Appendix B), after the April landslide was used to verify and calibrate the lines. Such direct measurement of the depth to bedrock was available only for the holes drilled near the head of the 1996 landslide. The seismic information collected from the other areas has not been confirmed by drilling.

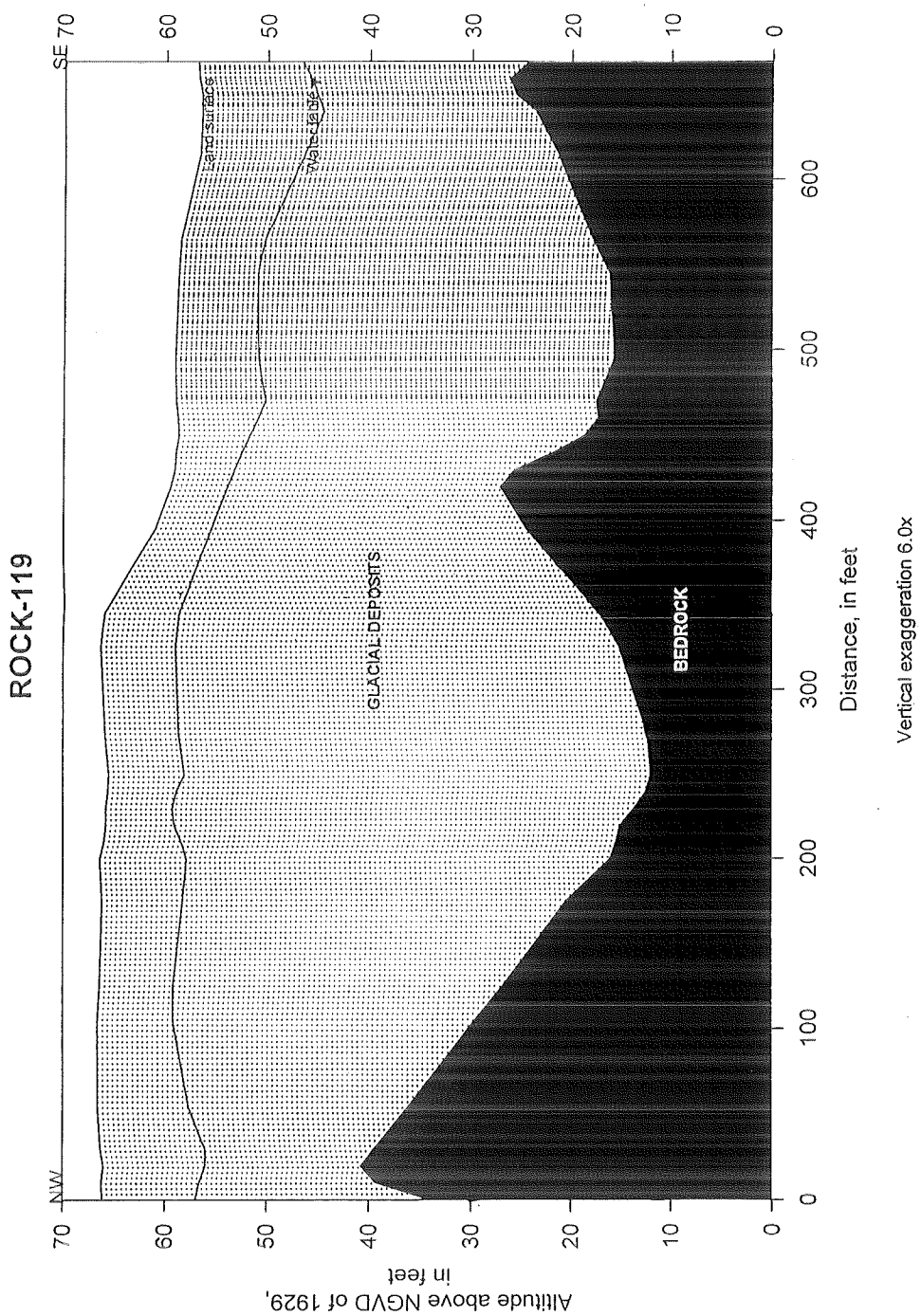


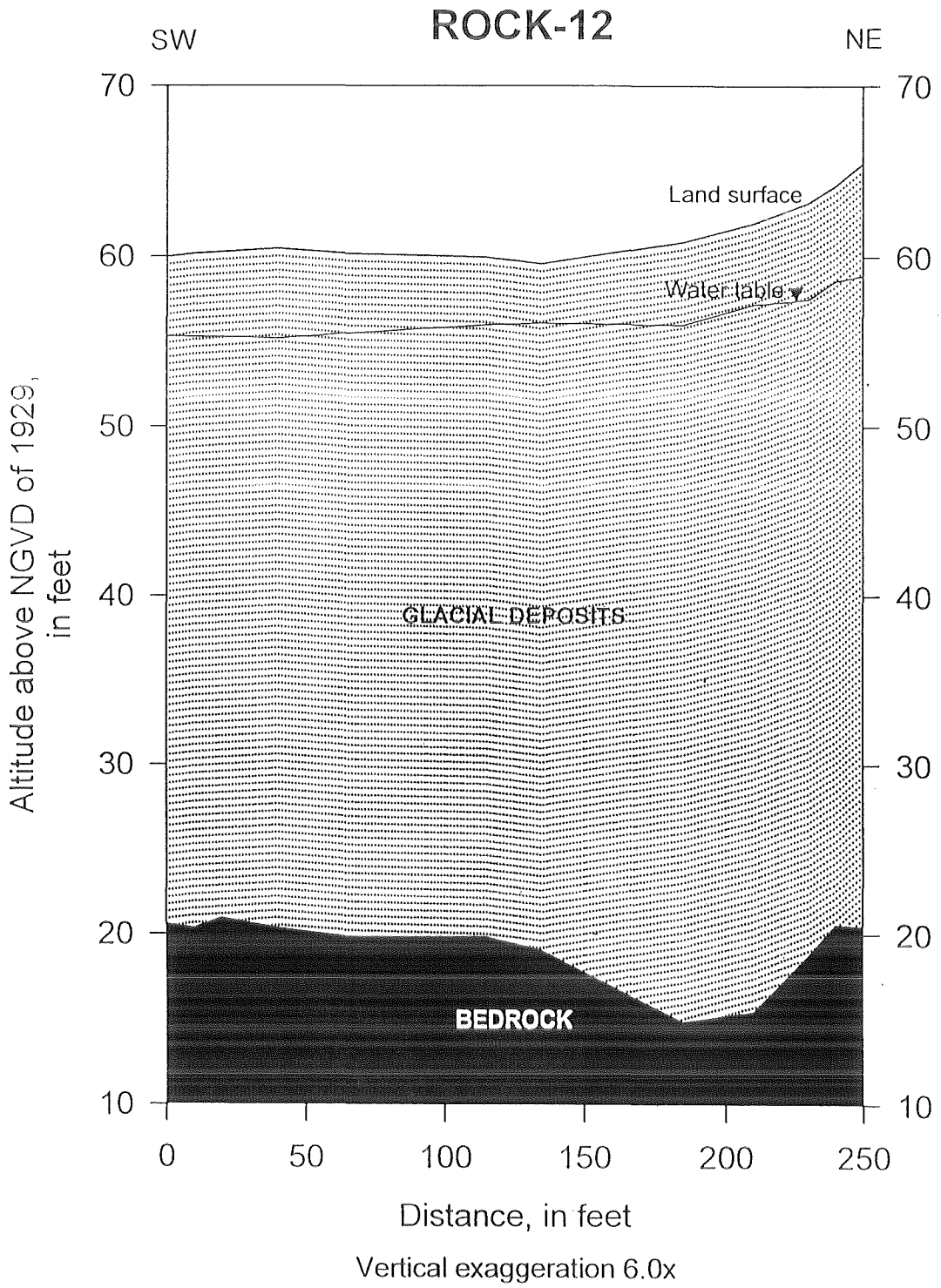
Site map of 12-channel seismic refraction lines, Rockland landslide area.

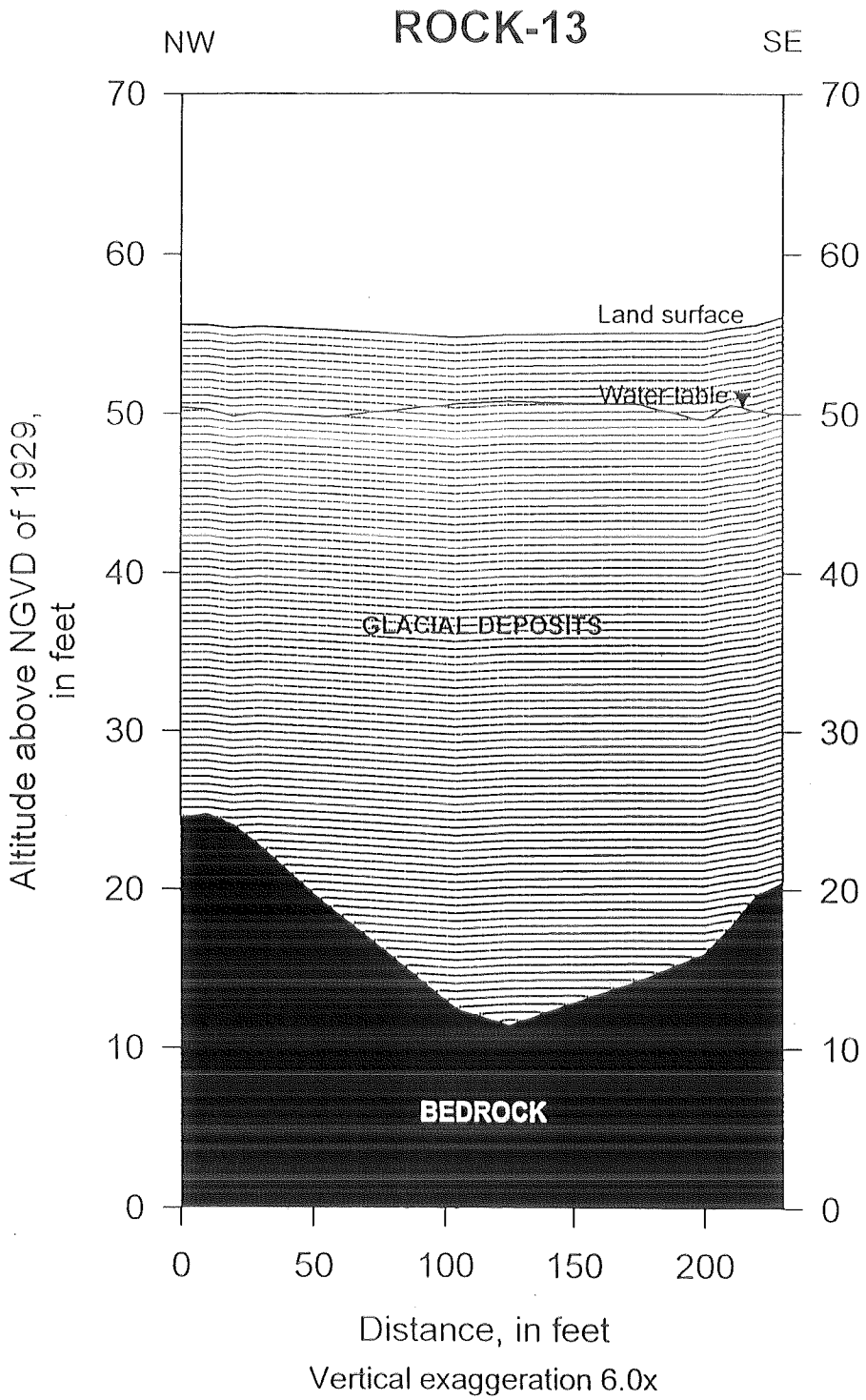

ROCK-41
NW
SE
Land surface
Water table
GLACIAL DEPOSITS
BEDROCK
Distance, in feet
Vertical exaggeration 6.0x
Altitude above NGVD of 1929, in feet
0
10
20
30
40
50
60
70
100
200
300
400
500
600
700
800
900

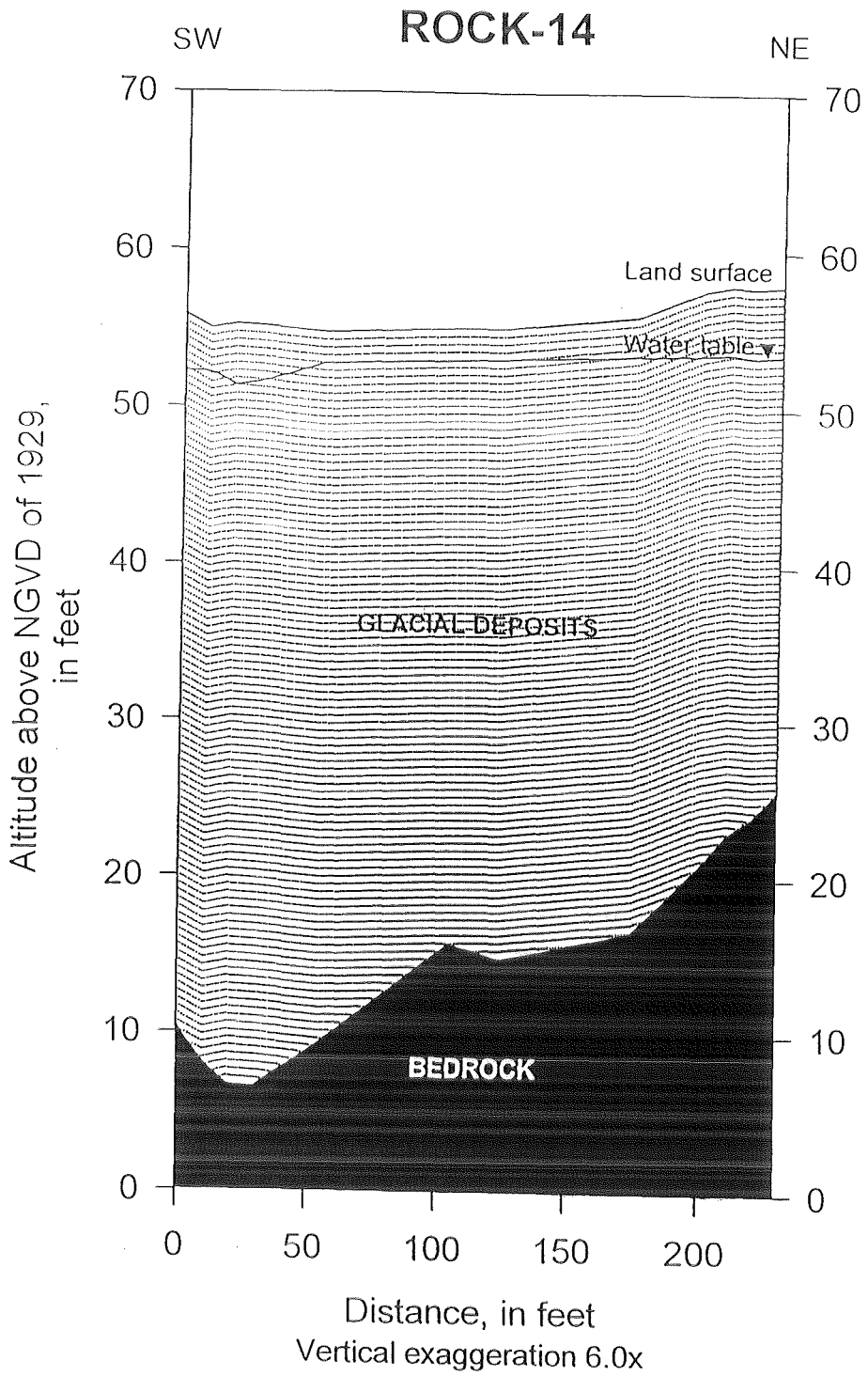

ROCK-1567
NW
SE
Land surface
Water table
GLACIAL DEPOSITS
BEDROCK
Distance, in feet
Vertical exaggeration 6.0x
Altitude above NGVD of 1929, in feet
0
10
20
30
40
50
60
70
100
200
300
400
500
600
700
800
900
1000

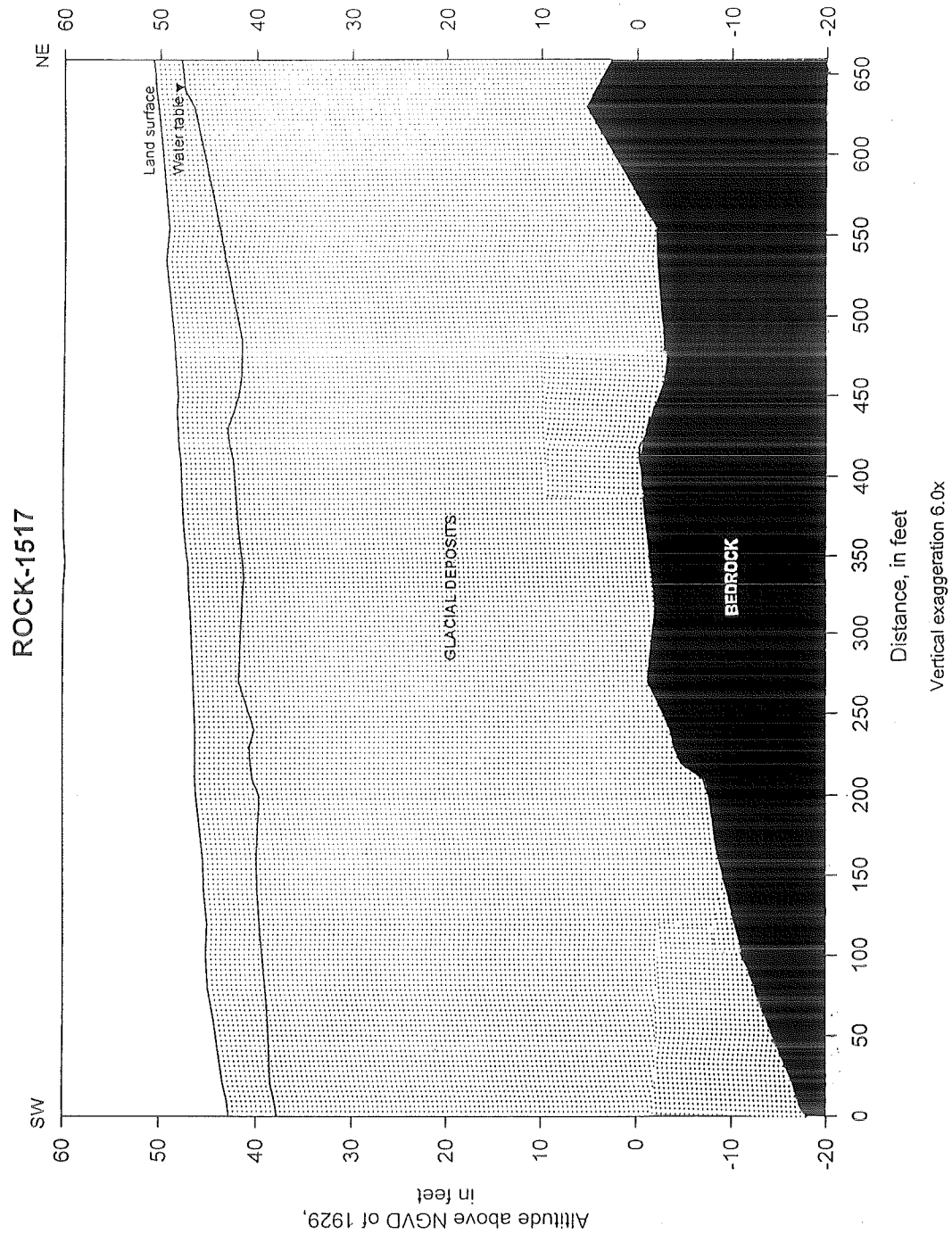

ROCK-8
SW
NE
Land surface
Water table
GLACIAL DEPOSITS
BEDROCK
Altitude above NGVD of 1929, in feet
60
50
40
30
20
10
0
0
50
100
150
200
250
Distance, in feet
Vertical exaggeration 6.0x

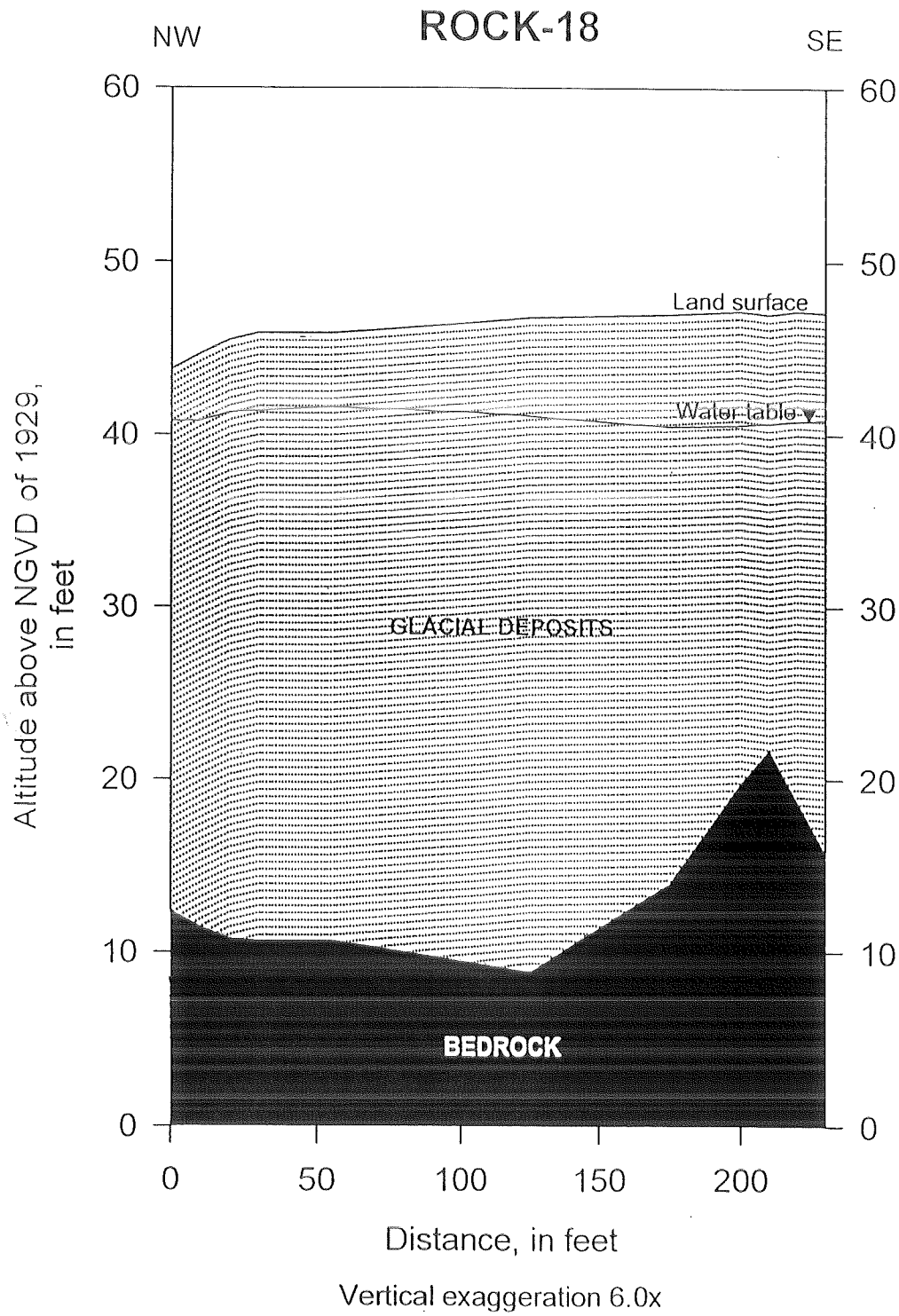

ROCK-119
NW
SE
land surface
water table
GLACIAL DEPOSITS
BEDROCK
Altitude above NGVD of 1929, in feet
Distance, in feet
Vertical exaggeration 6.0x
0
10
20
30
40
50
60
70
100
200
300
400
500
600


ROCK-12
SW
NE
70
60
50
40
30
20
10
Land surface
Water table
GLACIAL DEPOSITS
BEDROCK
Altitude above NGVD of 1929, in feet
0
50
100
150
200
250
Distance, in feet
Vertical exaggeration 6.0x


ROCK-13
NW
SE
70
60
50
40
30
20
10
0
Land surface
Water table
GLACIAL DEPOSITS
BEDROCK
Altitude above NGVD of 1929, in feet
0
50
100
150
200
Distance, in feet
Vertical exaggeration 6.0x


ROCK-14
SW
NE
Land surface
Water table
GLACIAL DEPOSITS
BEDROCK
Altitude above NGVD of 1929, in feet
70
60
50
40
30
20
10
0
0
50
100
150
200
Distance, in feet
Vertical exaggeration 6.0x


ROCK-1517
SW
NE
Land surface
Water table
GLACIAL DEPOSITS
BEDROCK
Altitude above NGVD of 1929, in feet
Distance, in feet
Vertical exaggeration 6.0x
60
50
40
30
20
10
0
-10
-20
0
50
100
150
200
250
300
350
400
450
500
550
600
650


ROCK-18
NW
SE
Land surface
Water table
GLACIAL DEPOSITS
BEDROCK
Altitude above NGVD of 1929, in feet
60
50
40
30
20
10
0
0
50
100
150
200
Distance, in feet
Vertical exaggeration 6.0x

Panoramas of the 1973 and 1996 Landslides, Rockland, Maine

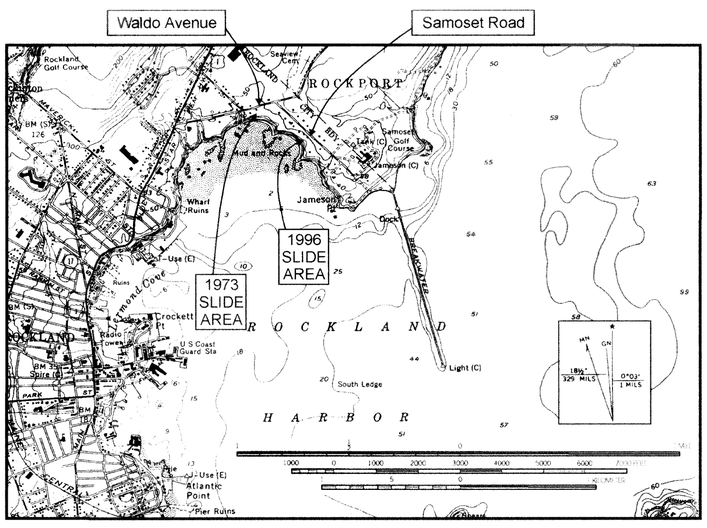


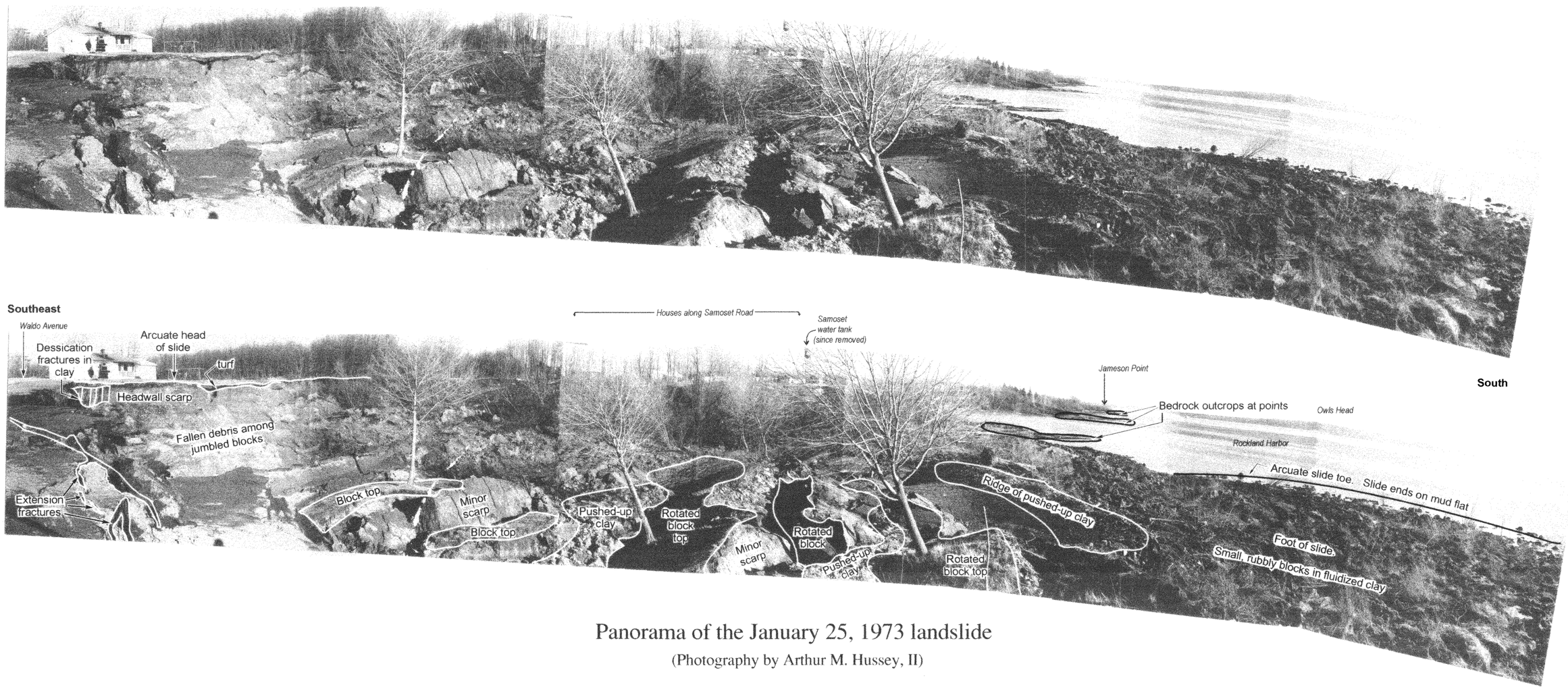
Plate 1 to accompany
"The April 1996 Rockland Landslide,"
Open-File Report 96-18

Robert G. Marvinney, State Geologist
Maine Geological Survey
Natural Resources Information and Mapping Center
DEPARTMENT OF CONSERVATION

1996

Catastrophic landslides occurred in adjacent coves of Rockland Harbor, Maine, in 1973 and in 1996. Despite the long time between the landslides, their marked similarity indicates that such catastrophic landslides are recurring events in this region, and not isolated ones. In both cases the landslides occurred in embayments on the north shore of Rockland Harbor, which has a scalloped shoreline (shown on the map at left). Bedrock outcrops are found only on the points of land between embayments. The shoreline has steep bluffs 30 to 40 feet high of Pleistocene glacial-marine clay. The combination of a steep slope and a high bluff seems to have been sufficient to cause the clay to fail under its own weight. Continual small slumps on the bluff face and gradual marine erosion at the base of the bluff may have set the stage for the catastrophic failures.

The panoramic views illustrate the immense scale of the landslides. The 1996 event destroyed two houses and came within a few feet of Samoset Road. The details indicated on the photos reveal how the events happened and demonstrate how closely the two landslides compare. In this type of landslide, known as a retrogressive slump, the main movement involves the weak clay at depth flowing out away from the bluff onto the mud flat. Under such circumstances the weak, saturated clay flows easily, like a fluid. This fluidized material with small chunks of broken clay can be seen in the outer lobe, or foot, of the landslide. As the lower part of the mass moves, the upper part breaks into large blocks that move down and out with the flow. These blocks can be seen in the middle area of the slides. Many of the blocks have moved hundreds of feet, with trees, shrubs, and grass intact. Blocks near the bluff face move first, followed in succession by blocks farther and farther inland. In this process, the individual blocks are commonly tipped backward toward the head of the slide. The 1973 slide shows examples of such rotated blocks. The sliding blocks may also push the fluidized clay ahead of them into ridges. By the time the movement reaches the head of the landslide, the pile of blocks in front inhibits the lateral movement, and the motion is more of a vertical dropping of blocks into a jumble of debris. Notice that the turf and other vegetation does not prevent this type of catastrophic landslide from occurring.



Panorama of the January 25, 1973 landslide

(Photography by Arthur M. Hussey, II)

Panorama of the April 16, 1996 landslide

(Photography by John Poisson)