GREAT LAKES FISHERY COMMISSION

Research Completion Report*

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LAKE TROUT SPAWNING HABITAT

IN THE SIX FATHOM BANK-YANKEE REEF

LAKE TROUT SANCTUARY, LAKE HURON

by

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INTRODUCTION

Attempts begun in the 1950s to reestablish fishable, self-sustaining stocks of lake trout (Salvelinus namaycush) throughout the Great Lakes met with the greatest success in Lake Superior, where remnant native stocks still spawned on ancestral spawning grounds. Success was limited elsewhere in the Great Lakes, where native stocks were completely or virtually extinguished and where rehabilitation depended solely on natural reproduction by hatchery-reared lake trout that were stocked as juveniles. Fishable stocks were created, and spawning occurred widely, but the production of viable offspring was demonstrated at only a few, widely spaced locations and recruitment of these progeny into the adult population was not conclusively demonstrated, except in one small area along the Michigan shoreline in northwest Lake Huron.

To avoid many of the problems believed to be contributing to the reproductive failure of stocked lake trout in the lower four Great Lakes (Eshenroder et al. 1984), the fishery management community adopted a strategy that called for the establishment of sanctuaries, where the reestablishment of self-sustaining stocks of lake trout would be the primary management objectives (Stanley et al. 1987). Two such sanctuaries were established in Lake Huron, one covering 65,000 ha in the northern end of the lake near Drummond Island and a second one covering 168,000 ha on Six Fathom Bank and Yankee Reef in the south-central portion lake (Fig. 1).

This paper describes the substrates and bathymetry of selected portions of the Six Fathom Bank-Yankee Reef sanctuary and evaluates the suitability of those portions of the sanctuary as spawning and fry production habitat for the shallow-water strains of lake trout that are currently being stocked in the lake.

METHODS

We used an EG&G[2] side-scan sonar system, including a Model 260 image correcting microprocessor, Model 360 digital tape recorder, and Model 272-T 100 kHz towfish with time-varied gain, to survey and map the lakebed on Six Fathom Bank and Yankee Reef. Survey and mapping methods were essentially those used in a similar study of lake trout spawning grounds in northern Lake Michigan in 1984-1985 (Edsall et al. 1989). We deployed the towfish from a cable and davit over the side of the survey vessel and adjusted the length of the cable so that the towfish ran 2-4 m beneath the surface of the lake and 5-40 m above the lakebed when the vessel cruised at 7.4 km/h (4 knots). The towfish directed a beam of acoustical energy to the lakebed, received the signal returning from the lakebed, amplified the signal, and transmitted it to the microprocessor and the tape recorder. The microprocessor converted the signal into a continuous strip chart record showing, in plan view, the physical features of the surface of a 200-m wide strip of lakebed beneath the towfish. We pulled the towfish along a series of parallel transects that covered the area to be surveyed and mapped; these transects followed Loran-C isograms with a bearing of about 350 degrees. Transect spacing was about 120 m and was designed to ensure overlapping representation of the lakebed on side-scan sonar strip chart records for adjacent transects. In the laboratory

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[2] Mention of brand names does not imply endorsement by U.S. Government.

we assembled the strip charts to form a 1:1000 scale mosaic map (Fig. 2) of each of the three areas that we surveyed.

Substrate components were classified according to a modified Wentworth scale: sand (< 2 mm), gravel (2-64 mm), rubble (65-256 mm), cobble (257-999 mm), and boulder (> 999 mm). Where these components occurred in mixtures, we identified the primary and secondary components, according to the amount of lakebed covered by each component, and described the mixture on that basis.

Water depth information displayed graphically on the margin or profile section of each strip chart composing the mosaic allowed us to construct a bathymetric overlay for each mosaic map. A contractor digitized the mosaic maps and bathymetric overlays, entered them into a geographic information system, and produced computer-drawn maps (Brown et al. 1988) at 1:4000 scale showing the distribution of major surficial substrates and the bathymetry of each surveyed area (Figs. 3-5).

Ground truthing to assist in the interpretation of the side-scan records and to permit an evaluation of the general condition of the lakebed was conducted with three different underwater video systems. Initially we used a towed, black and white format video camera (Video Sciences, Inc., Model 40095), but found it could not be readily positioned or maneuvered from the vessel deck to provide controlled viewing of the lakebed. We replaced the towed video camera with a Benthos, Inc. Mini-Rover MK II remotely operated vehicle that was equipped with a high resolution color video camera. The MK II was deployed on a tether by an operator who guided the movements of the vehicle with joystick controls, while monitoring the MK II video camera images displayed on a shipboard closed-circuit video monitor. A graphic display of the depth at which the MK II was operating and the compass heading it was following appeared on the shipboard video monitor and the entire screen display was videotaped to provide a permanent record of the lakebed features. We also conducted ground truthing from a small research submarine, the Johnson Sea Link II (Askew 1985), by direct observation and also using the color video camera aboard that vessel. We also recorded on the color videotapes, our real-time commentary on the condition and features of the lakebed.

We judged the size of rocks and distances between objects recorded on the color videotapes in two ways. The skids on which the MK II rested when it was on bottom extended forward into the field of view of the video camera and we used the distance between them (18 cm) as a measuring scale. The video camera aboard the Johnson Sea Link II carried two laser beam generators that projected parallel beams of light along the viewing plane of the camera. These beams registered as two red dots 10 cm apart on the lakebed in the center of the field of view and provided an accurate scale for estimating the size of lakebed objects recorded on the videotapes from that vessel. The substrate interstitial depth (the vertical distance into loose rock substrate to which lake trout eggs and fry could gravitate) was estimated from the size composition and amount of piling of the loose rock present, and the degree to which the loose rock assemblage appeared to be infilled with sand or other fine sediments.

Illustrations of the substrate in this paper were obtained in the laboratory by photographing videotape images of the lakebed that were displayed on a television monitor. Although the videotapes clearly documented the substrates present in the Six Fathom Bank-Yankee Reef sanctuary, the videotapes did not provide a sharply focused, still image for every substrate type that could be photographed successfully for reproduction.

RESULTS AND DISCUSSION

Substrate and Bathymetry

We mapped the lakebed at three sites in the Six Fathom Bank-Yankee Reef sanctuary in south-central Lake Huron (Fig. 1). These sites were near the crests of Six Fathom and Ipperwash scarps that transected the southern half of the lake along an approximately northwest to southeast axis. The sites were about 40 to 60 km from the nearest mainland shore and were surrounded by water 50 m or more deep. One site, Six Fathom Bank-North, was on the northern crest of the Six Fathom Scarp and included the scarp face; the second, Six Fathom Bank-Central, was near the center of the Six Fathom Scarp where the lakebed contours were more gently sloping; and the third, Yankee Reef, was on the crest of the Ipperwash Scarp and included the southeast face of the scarp.

Six Fathom Bank-North

The substrate and bathymetric map for the Six Fathom Bank-North site (Fig. 3) was an irregular polygon that covered 266.6 ha of lakebed at water depths of 20 m near the center of the mapped area to more than 50 m at the base of the scarp. We identified eight major substrate types ranging from sand to bedrock in the mapped area. Bedrock ridges (59.4 ha) dominated the substrate on the crest of the scarp at 20-25 m, northwest of the crest at 25-35 m, and east of the crest to about 30 m. A narrow band of bedrock ridges with scattered cobble covering 4.6 ha (of a total of 19.2 ha of this substrate; see Fig. 3 legend) intruded from the west into the bedrock ridges substrate along the 25 m depth contour. South of the bedrock ridges that formed the crest of the scarp, the substrate was rubble layers with cobble patches (100.8 ha) at 20 m to about 40 m, cobble layers with boulder patches (6.5 ha) at about 25 m, and sand (4.2 ha of a total of 33.8 ha of this substrate) at about 35 m. The substrates forming the northeast face of the scarp to depths of about 50-55 m were bedrock ridges with scattered cobble (14.6 ha) and cobble piles with rubble piles (17.9 ha); these substrates were easily distinguished on the side-scan sonar mosaic for this portion of the scarp (Fig. 2). Sand (15.2 ha) bordered the base of the scarp to the northeast at depths greater than 50 m. The substrate on the southeast face of the scarp to depths of about 45-50 m was cobble layers with rubble patches (16.2 ha). Sand (14.4 ha) and rubble evenly distributed on sand (12.8 ha) were the substrates on the southeast edge of the mapped area at depths greater than about 40 m.

Observations made from the submarine and the videotapes from the three underwater camera systems confirmed the large scale features shown for the Six Fathom Bank-North site in Figs. 2 and 3 and provided additional detailed information on the physical condition of the substrate, except within the 20 m depth contour, where a dense mat of periphyton covered the lake bed and obscured most of the bedrock surface. These observations and videotapes revealed that the scarp face had an irregular, stepped profile with individual steps or ridges rising vertically about 1-2 m. The face of each ridge was bedrock, or bedrock with broken boulder and cobble blocks that were lying in place or displaced downslope. Where several ridges occurred in close proximity, there was usually a narrow band of boulder and cobble blocks at the base of the deepest ridge. Interstitial depth along these ridge faces in cracks between loose rock and the bedrock scarp face, or in accumulations of loose rock, often exceeded 30 cm.

Most of the bedrock and loose rock at the Six Fathom Bank-North site was pitted and grooved, or showed other forms of surface erosion. On inclined bedrock pavements--the large, relatively flat expanses of bedrock without overburden that formed a portion of the top of the scarp--the pits were about 2-5 cm in diameter and 5-10 cm deep (Fig. 6). There were fewer than about 500 pits/m^2 and the surface of the bedrock pavement between the mouths of adjacent pits--was flat and smooth. The pits appeared to be distributed randomly across the bedrock surface, except where they occurred in series along grooves in the bedrock. The grooves showed no particular orientation and were usually less than 2 cm wide and up to several meters long. Some of the grooves were straight and others curved; some were isolated, others intersected, and yet others exhibited dendritic branching (Fig. 7). A second type of pitted bedrock surface was also observed at some locations, usually on the stepped pavements that composed the face of the scarp. There, pit density exceeded 500/m^2, the pits were less than 2 cm deep, they intersected or coalesced, and usually displayed sharp-crested interfluves that gave the bedrock surface an uneven, sawtoothed appearance.

Pitting was also common on rubble, cobble, and boulders throughout the area. Pitting on the angular cobble and boulders that had separated from the bedrock mass on the stepped pavements of the scarp face was usually of the high density type (> 500 pits/m^2) that produced a sawtoothed surface. On the inclined pavements on top of the scarp, pitted, angular rubble was produced by fracture of the pit interfluves. This rubble either remained in place (Fig. 8), or was transported to accretion areas on the inclined pavements. Pitting also occurred on much of the rounded rock that we observed in accretion areas on inclined pavements. All of the rocks that we collected typically showed deep pitting. One of these rocks, which was partly buried in sand, was rounded on the exposed surface, sharply sculptured on the buried surface, and showed complex pitting (Fig. 9). The remains of large, smooth pits up to 4 cm wide and 10 cm deep were present on the rounded side of the rock. Several pits about 1 cm or smaller in diameter and up to 15 cm long penetrated the rock parallel to the bedding plane and coalesced to form larger, complex chambers within the rock and a concave surface on the buried side of the rock.

Six Fathom Bank-Central

The substrate and bathymetric map for the Six Fathom Bank-Central site (Fig. 4) was nearly rectangular in shape and covered 154.5 ha. Depth contours were most closely spaced in the northern one-third of the mapped area. Water depth exceeded 35 m at the north end of the area, decreased to slightly less than 20 m about 0.5 km to the south, and then increased gradually to slightly more than 30 m at the south end of the mapped area. Five major substrate types were identified. Cobble piles with sand patches (18.8 ha) occupied a narrow band across the shallowest portion of the mapped area at about 20-25 m. This substrate was bounded immediately to the north at about 20-30 m by bedrock ridges (8.5 ha) and farther north at about 30 m and deeper by flat bedrock (19.9 ha). The central one-third of the mapped area at 20-30 m was broken bedrock on flat bedrock (55.8 ha). Substrate in the southern one-fourth of the area was rubble with sand patches (51.5 ha).

Much of the bedrock and loose rock in the mapped area exhibited some degree of pitting of the types found at the Six Fathom Bank-North site. The bedrock ridges substrate near the north end of the mapped area was densely pitted and had a sawtoothed surface, whereas the inclined pavements in the southern two-thirds of the mapped area displayed deeper, lower density pitting and extensive grooving. Much of the loose rock was also pitted. Rounded, unpitted rock that was probably brought into the area by glacial action was also present in accretion areas in the southern two-thirds of the mapped area.

Yankee Reef

On Yankee Reef we mapped an area that was nearly trapezoidal in shape and covered 273.4 ha (Fig. 5). Water depth was 20 m near the crest of the scarp that paralleled the southeastern border of the mapped area and increased sharply to about 60-70 m across the face of the scarp. The lakebed dipped gradually to the northwest from the crest of the scarp and water depth exceeded 30 m at the northwest boundary of the mapped area. Bedrock with sand patches (112.0 ha) occupied the northern end of the mapped area. Bedrock ridges with cobble piles (88.6 ha) was the dominant substrate along the crest of the scarp, over a large, irregularly shaped area north of the crest, and to a depth of about 40 m on a small area on the scarp face (Figs. 10 and 11). The bedrock ridges were conspicuous features on the mosaic (Fig. 12). They were oblong with rounded or tapered ends and their acoustic shadows (Mazel 1988) indicated they had a rounded or dome-shaped, cross-sectional profile. The largest were about 8 m wide and 25 m long and all had roughly a north-south orientation, with the stepped bedrock face to the east. If a cobble pile abutted a particular ridge it usually was on the east side of the ridge. Rubble piles with scattered cobble (20.5 ha) was the substrate on the remainder of the mapped area north of the scarp crest (Fig. 13). The scarp face at about 20-70 m was composed of rubble with cobble piles (14.9 ha; Figs. 14 and 15) and bedrock with cobble piles (Figs. 15 and 16; 12.4 ha). Sand (25.0 ha) composed the lake bed along the base of the scarp at depths greater than 50-70 m.

Most of the bedrock in the mapped area exhibited dense, shallow pitting and a sawtoothed surface (Fig. 17). However, in some areas north of the scarp crest the pitting was of lower density and deeper and the pit interfluves were smoother and flatter. In these areas an upper layer of bedrock 5-10 cm thick was sometimes separated from the underlying bedrock mass, producing flat, pitted rubble and cobble and exposing underlying patches of smooth, unpitted bedrock (Fig. 18). Flat cobble (Fig. 19) and rounded cobble with deep pitting (Fig. 15) occurred at slope changes near the base of the scarp.

Suitability

An evaluation of the habitats available to stocked lake trout for spawning and fry production in the Six Fathom Bank-Yankee Reef sanctuary is problematic because too few studies have been performed to demonstrate the full potential of these fish to occupy and use Great Lakes habitats. However, the strains that were selected for stocking were believed to have niche requirements resembling those of the extinct native strains that they were to supplant and so it seems reasonable to base an evaluation of the habitats in the sanctuary on what is known about the spawning and early life history requirements not only of the stocked fish, but also of the extinct native fish.

Historical accounts reviewed by Goodyear et al. (1982) described Six Fathom Bank as the most important lake trout spawning ground in the lake. These accounts also indicated that spawning occurred over unknown substrate on the shallowest portions of the bank in late October-early November, but provided no other information about the habitats used for spawning and fry production on the bank or on Yankee Reef. Elsewhere in Lake Huron, the native fish spawned historically on a variety of substrates that included honeycombed rock, honeycombed rock ridges, limestone, round rock, broken rock, gravel, and at a few locations, mud or sand. Spawning occurred in water 1-36 m deep, but at most locations it was restricted to the 4-25 m depth interval (Fig. 20). Spawning was also reported at depths of 55 m and 92 m near Presque Isle Light near Alpena, Michigan and at about 46-76 m on a mid-lake reef between Harbor Beach, Michigan and Port Sanilac, Ontario, but these deep-water spawners were probably Siscowets or "fat" trout, which had different reproductive requirements than the fish that are now being stocked into the lake.

Stocked lake trout spawned over a variety of substrates, including sand, in shallow water in the Great Lakes (Goodyear et al. 1982), but produced substantial numbers of fry only on reefs that had been used by the native trout, or on artificial reefs that resembled those used successfully by the native fish. Recent studies (Wagner 1982, Nester and Poe 1987, Peck 1986, Marsden et al. 1988, Marsden and Krueger 1990) suggest that angular or round rock about 5-50 cm in diameter with interstitial spaces 30 or more cm deep is the most suitable substrate for spawning and fry production by the strains of lake trout that are now being stocked into the Great Lakes.

Stocked fish tended to spawn in relatively shallow water in nearshore areas: 5-10 m in Lake Superior (Peck 1986), 2-9 m in Lake Michigan (Goodyear et al. 1982; Wagner 1982) 5-9 m in Lake Huron (Goodyear et al. 1982, Nester and Poe 1984), and 1-6 m in Lake Ontario (Sly and Schneider 1984, Marsden et al. 1988). However, stocked fish also spawned to depths of 15 m at several locations in Lake Michigan and a few fish in spawning condition were captured on the shallowest (42 m) portion of the mid-lake Milwaukee-Sheboygan Reef complex in southern Lake Michigan, suggesting that the stocked fish can spawn over most of the depth range (and thus most of the substrates) formerly used by native lake trout in the Six Fathom Bank-Yankee Reef sanctuary.

In the present study at the Six Fathom Bank-North site, we found that the bedrock ridges substrate that covered the crest of the scarp, at 20 m to about 35 m, had no interstitial depth and was unsuitable habitat for lake trout eggs and fry. The narrow band of bedrock ridges with scattered cobble substrate that intruded into the crest area along the 25 m depth contour included patches of broken boulder- and cobble-sized rock; interstitial depth exceeded 30 cm in this substrate at points where the slope decreased abruptly at the base of two or more closely spaced steps or ridges. Although the interstitial depth at these points more than met the interstitial depth criterion for good egg and fry habitat, the absence of rubble-sized rock increased the width of the interstitial spaces so that predators, including sculpins (Cottus sp.), and burbot (Lota lota), that were seen in the videotapes of these areas could penetrate much of this substrate. Thus, this substrate probably provided only marginal habitat for lake trout eggs and fry. South of the crest, the substrate on top of the scarp was good habitat in patches. The interstitial depths were about 10-30 cm in the cobble layers with boulder piles and in the rubble layers with cobble piles. Water depths at the north end of the area covered by these two substrates were within the range used most commonly for spawning by the extinct native fish, but at the south end of the area they exceeded the maximum depth used for spawning by native fish (36 m). On the scarp face, in the northeast corner of the mapped area, bedrock ridges with scattered cobble provided interstitial depths of more than 30 cm, but many of the interstitial spaces were wide enough to permit burbot and smaller predators to penetrate the substrate. A relatively small portion of the substrate was in water shallower than 25 m, but nearly all was shallower than 36 m. The cobble piles with rubble piles had interstitial depths of more than 30 cm, and spaces that would exclude most burbot and other larger predators, but almost all of this substrate occurred at depths greater than 36 m. The cobble layers with rubble patches that formed the scarp face in the southeast portion of the mapped area had interstitial depths to 30 cm in patches, but water depths over most of the area exceeded 36 m. Thus, it appears that the best spawning and fry production habitat for lake trout on the mapped portion of the Six Fathom Bank-North site was the rubble layers with cobble patches and the cobble layers with boulder patches, covering about 70 ha immediately south of the scarp crest.

At the Six Fathom Bank-Central site, the flat bedrock and the bedrock ridges substrates that composed the northern part of the mapped area had no interstitial depth and were unsuitable habitat for spawning and fry production. In contrast, the substrates composing the other 126.1 ha at this location appeared to be mostly good habitat for the egg and fry life stages. Interstitial depth was 10 cm to more than 30 cm on the cobble piles with sand patches substrate. The broken bedrock on flat bedrock substrate included patches of angular, pitted rubble with depths of 10 cm or more in the many narrow crevices and spaces among the loose rock. The flat bedrock component of this substrate included smooth, unbroken pavement that was unsuitable habitat; it also included smooth pavement that had pits and grooves 5-10 cm deep that provided <u>intra</u>stitial spaces that were potentially good habitat. The use of <u>intra</u>stitial space in carbonaceous pavements for reproduction by lake trout has not been previously proposed, but it appears that this space could offer eggs and fry adequate protection from dislocation and buffeting by water currents, and from predation by all but the smallest predators. The angular rubble and the rounded rubble and cobble that was mixed with it in accretion areas on the flat bedrock pavements at this location was often deeply pitted; these rocks, like the pitted bedrock pavement, offered intrastitial space that could provide suitable habitat for the egg and fry life stages. The rubble with sand patches at the south end of the mapped area had interstitial depths of about 10 cm in angular and rounded rubble and was moderately good habitat. Some of this rubble was deeply pitted and also provided intrastitial space.

On Yankee Reef the bedrock and sand substrate combinations on the northern part of the mapped area were not suitable habitat for lake trout eggs and fry because they lacked the mantle of loose rock with deep interstitial spaces and the pitted pavements that would protect eggs and fry. Farther south, the 109.1 ha of lakebed that spanned the mapped area and extended to the crest of the scarp, contained the best spawning substrate that we observed on Yankee Reef. The rubble piles with scattered cobble substrate on the western 20.5 ha of this area had interstitial depths to 30 cm and was uniformly good habitat. The rubble and cobble were deeply pitted and provided intrastitial spaces that could also protect eggs and fry. This substrate was bordered to the south and east by bedrock ridges with cobble piles. Some cobble piles were associated with the isolated, mound-like ridges that were conspicuous features on the mosaic. The cobble piles, which provided the only suitable habitat for spawning and fry production on this substrate, decreased in abundance from west to east. On the face of the scarp, the bedrock with cobble piles and the rubble with cobble piles substrates provided interstitial depths of 30 cm or more among piled, angular blocks of cobble. However, most of those piles occurred at depths (40-60 m) that exceeded those at which the shallow-water stocks of native lake trout spawned in Lake Huron. Burbot, which are predators of young lake trout (Stauffer and Wagner 1979), were common around these cobble piles and the interstitial spaces within the piles were large enough to permit them access to lake trout eggs and fry residing in this substrate. The bedrock and rubble components of the scarp face substrates had insufficient interstitial depth to protect eggs and fry; the bedrock was unbroken and much of the rubble was only slightly larger than gravel and was infiltrated with gravel and coarse sand. The sand substrate at the base of the scarp was unsuitable egg and fry habitat.

SUMMARY AND CONCLUSIONS

The 168,000 ha Six Fathom Bank-Yankee Reef sanctuary in southern Lake Huron includes the shallower portions of the Six Fathom and Ipperwash scarps that historically were important spawning areas for the now extinct native lake trout that once were abundant on the scarps.

The locations where these native fish spawned are not precisely known, but our side-scan sonar, underwater video camera, and manned submersible surveys of three areas covering nearly 700 ha on the shallower portions of the scarps found more than 300 ha of substrate that appeared to be suitable for spawning and fry production by the shallow-water strains of lake trout that are now being stocked in the lake. These suitable substrates were located in water 20-36 m deep and generally had interstitial depths of 20 cm to more than 30 cm. These substrates provided good habitat that was distributed in a non-continuous or patchy manner in the rubble layers with cobble patches and in the cobble layers with boulder patches that covered about 107 ha on the Six Fathom Bank-North site. Patchy but good habitat was also provided by the cobble piles with sand patches and by the broken bedrock on flat bedrock that covered about 75 ha on the Six Fathom Bank-Central site. On Yankee Reef, the bedrock ridges with cobble piles substrate provided about 89 ha of good, but patchy habitat. The rubble piles with scattered cobble substrate that covered about 21 ha on Yankee Reef provided the most non-patchy, uniformly good spawning and fry production habitat that we found in the sanctuary.

In these areas of good substrate where the interstitial depth was 20-30 cm or more, deeply pitted and grooved inclined bedrock pavements and deeply pitted loose rock provided considerable amounts of intrastitial space that also appeared to be suitable habitat for eggs and fry.

On the basis of the foregoing evaluation, we conclude that the Six Fathom Bank-Yankee Reef sanctuary has potential to support the reestablishment of one or more self-sustaining stocks of lake trout, developed from spawnings by feral fish of the shallow-water strains that are being stocked into the lake.

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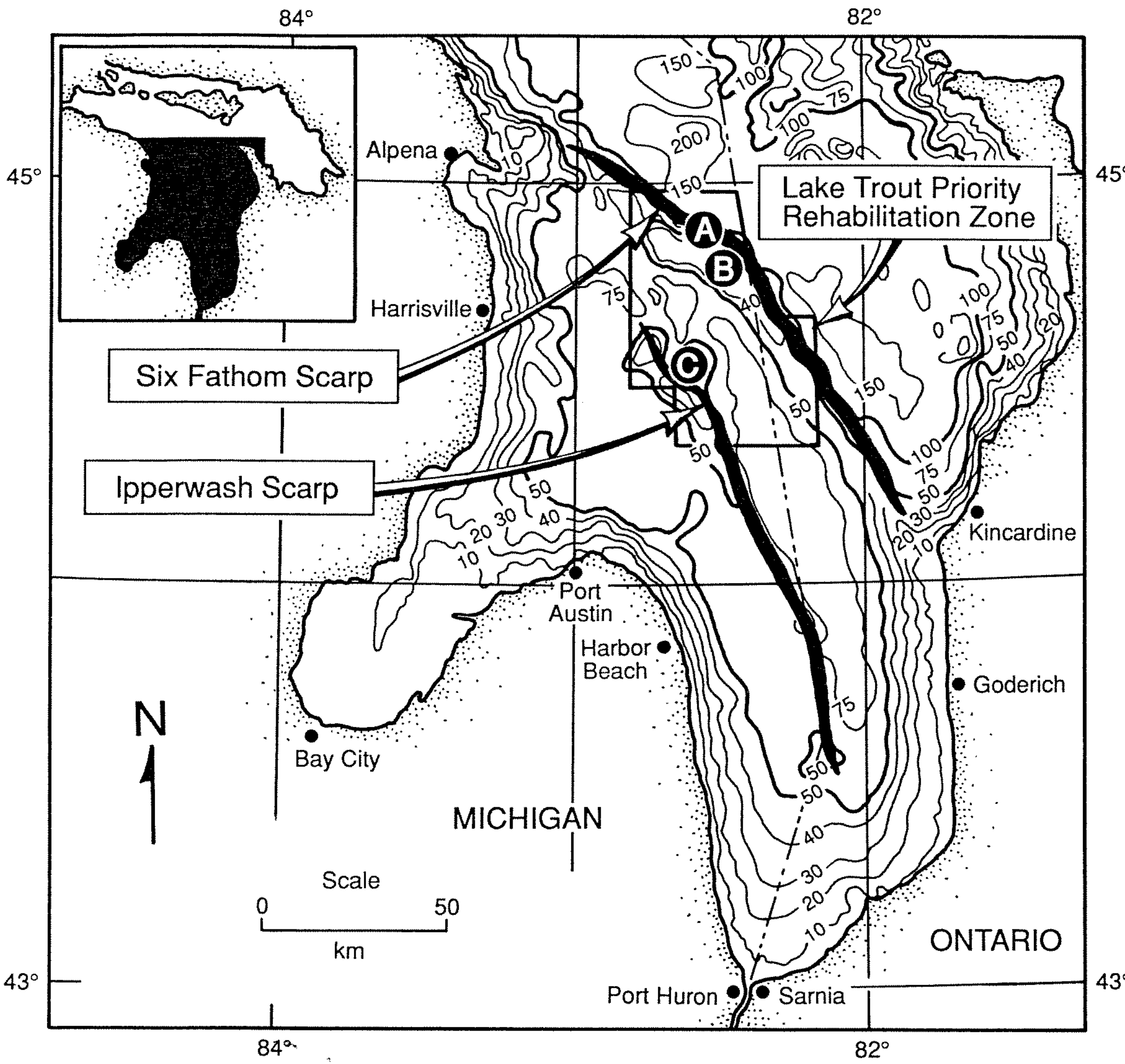

Figure 1. Lake trout priority rehabilitation zone in south-central Lake Huron. This sanctuary includes historically important lake trout spawning grounds on the mid-lake shallows along the Six Fathom and Ipperwash scarps. Side-scan sonar surveys were conducted at three sites: (A) Six Fathom Bank-North, (B) Six Fathom Bank-Central, and (C) Yankee Reef.

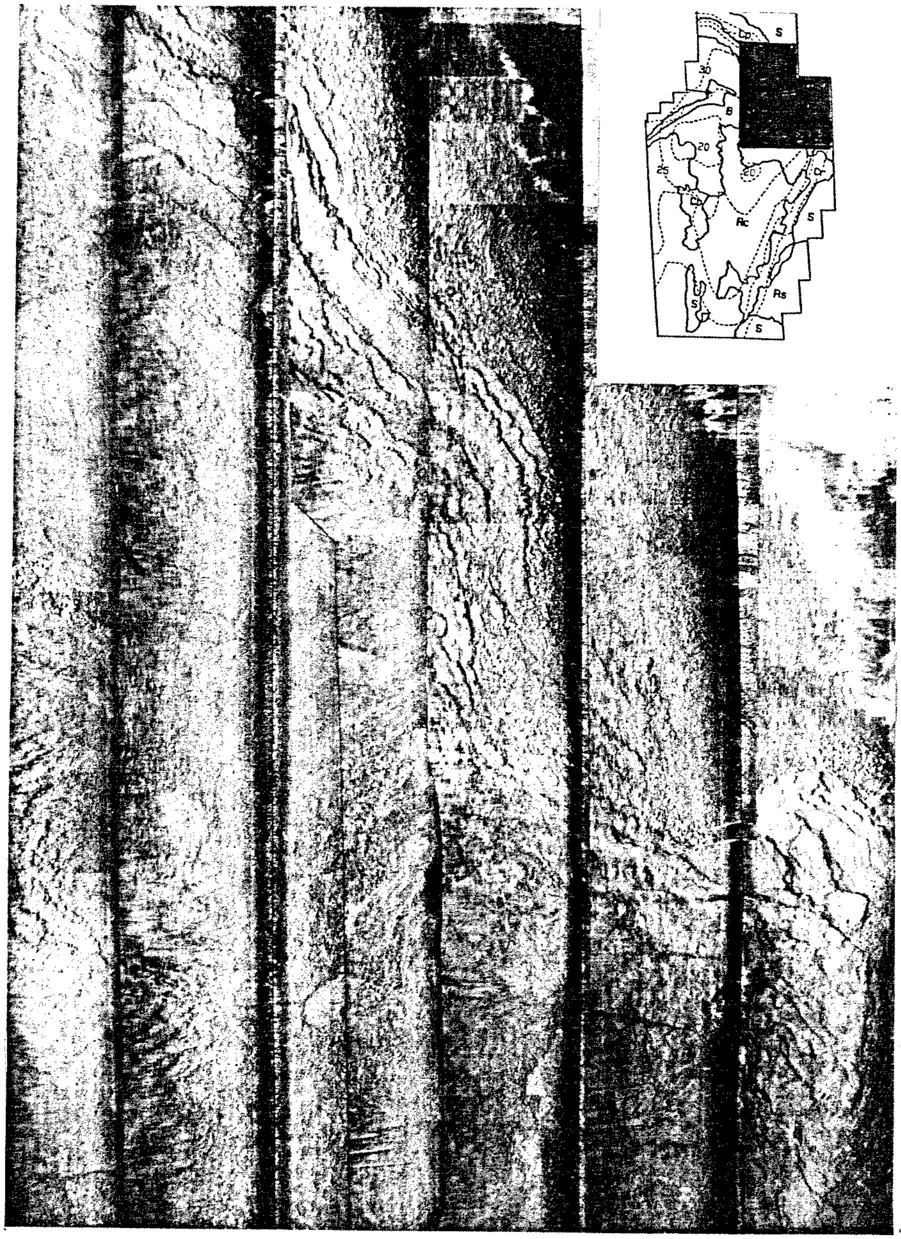

Figure 2. Side-scan sonar mosaic map of the northeast portion of the Six Fathom Bank-North site. The rugged features aligned generally in a northwest to southeast direction are bedrock ridges, the light areas to the northeast are sand, and the intervening grainy or textured areas are cobble piles and rubble piles. Inset is based on Figure 3.

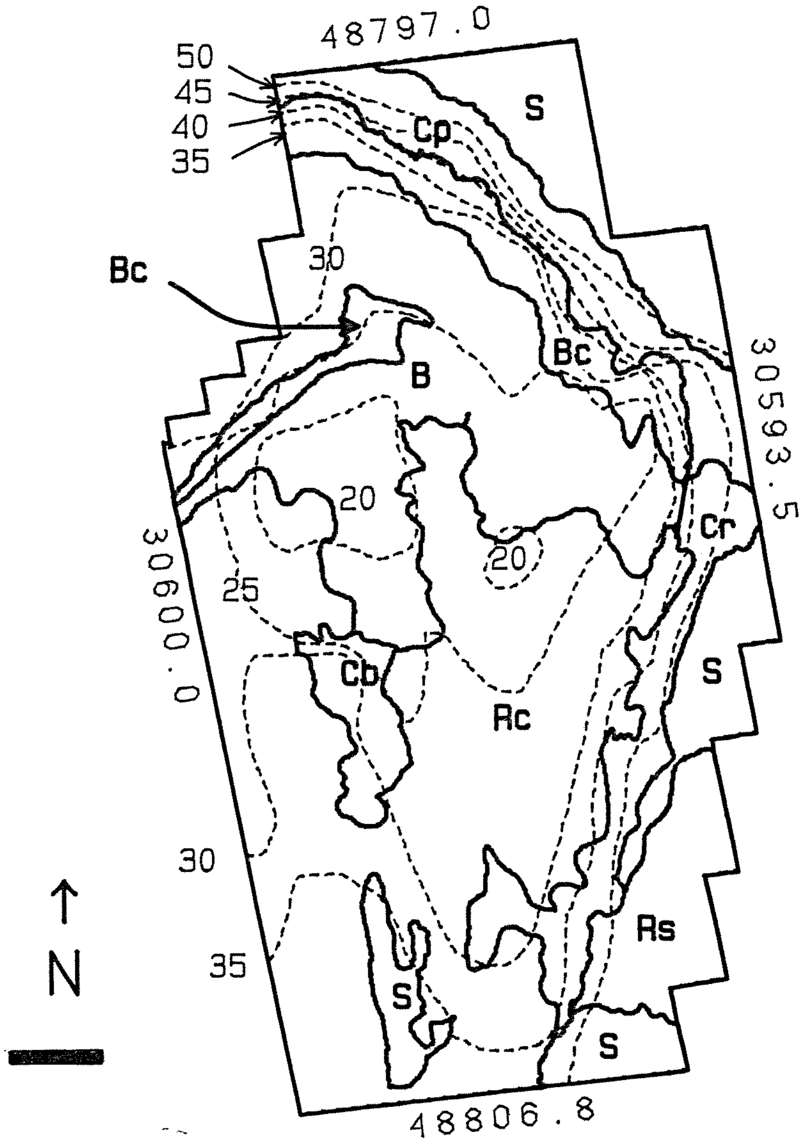

Figure 3. Substrate and bathymetric map produced from side-scan sonar records of the Six Fathom Bank-North site. Water depths (dashed lines) are in meters. Loran C isograms are given for the map borders. Bar represents 0.2 km.

Substrate Type	Hectares
S = Sand	33.8
Rs = Rubble evenly distributed on sand	12.8
Rc = Rubble layers with cobble patches	100.8
Cr = Cobble layers with rubble patches	16.2
Cb = Cobble layers with boulder patches	6.5
Cp = Cobble piles with rubble piles	17.9
B = Bedrock ridges	59.4
Bc = Bedrock ridges with scattered cobble	19.2
	266.6

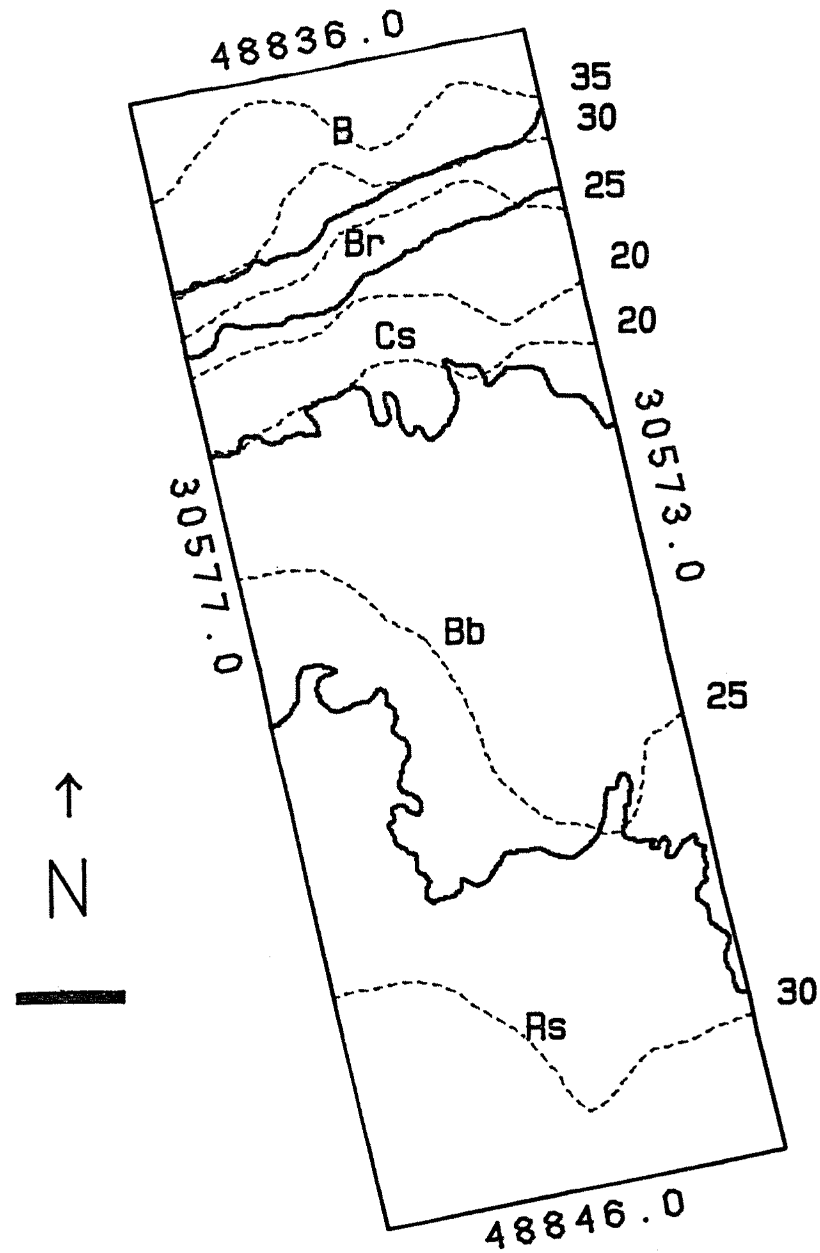

Figure 4. Substrate and bathymetric map produced from side-scan sonar records of the Six Fathom Bank-Central site. Water depths (dashed lines) are in meters. Loran C isograms are given for the map borders. Bar represents 0.2 km.

Substrate Type	Hectares
Rs = Rubble with sand patches	51.5
Cs = Cobble piles with sand patches	18.8
B = Flat bedrock	19.9
Br = Bedrock ridges	8.5
Bb = Broken bedrock on flat bedrock	55.5
	154.5

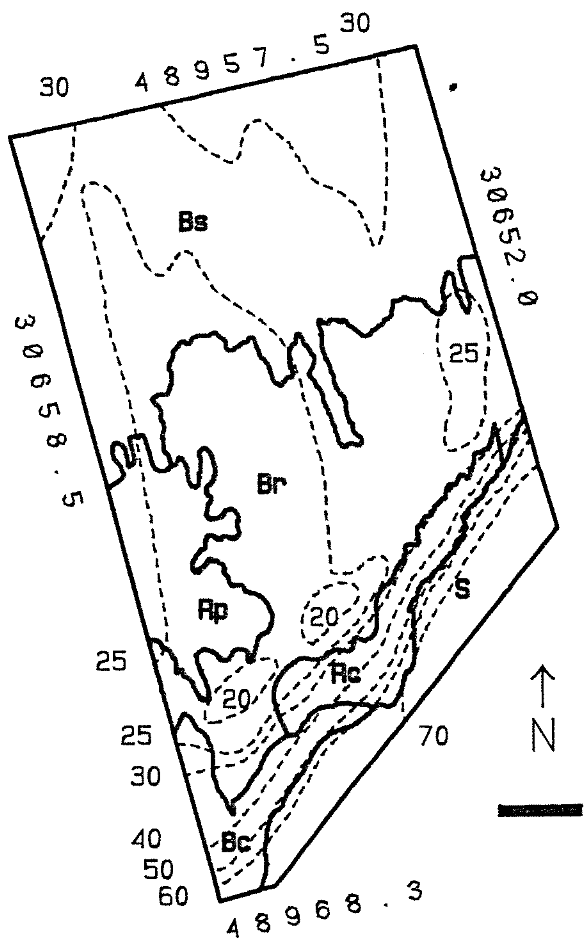

Figure 5. Substrate and bathymetric map produced from side-scan sonar records of the Yankee Reef site. Water depths (dashed lines) are in meters. Loran C isograms are given for the map borders. Bar represents 0.2 km.

Substrate Type	Hectares
S = Sand	25.0
Bc = Bedrock with cobble piles	12.4
Rc = Rubble with cobble piles	14.9
Rp = Rubble piles with scattered cobble	20.5
Br = Bedrock ridges with cobble piles	88.6
Bs = Bedrock with sand patches	112.0
	273.4

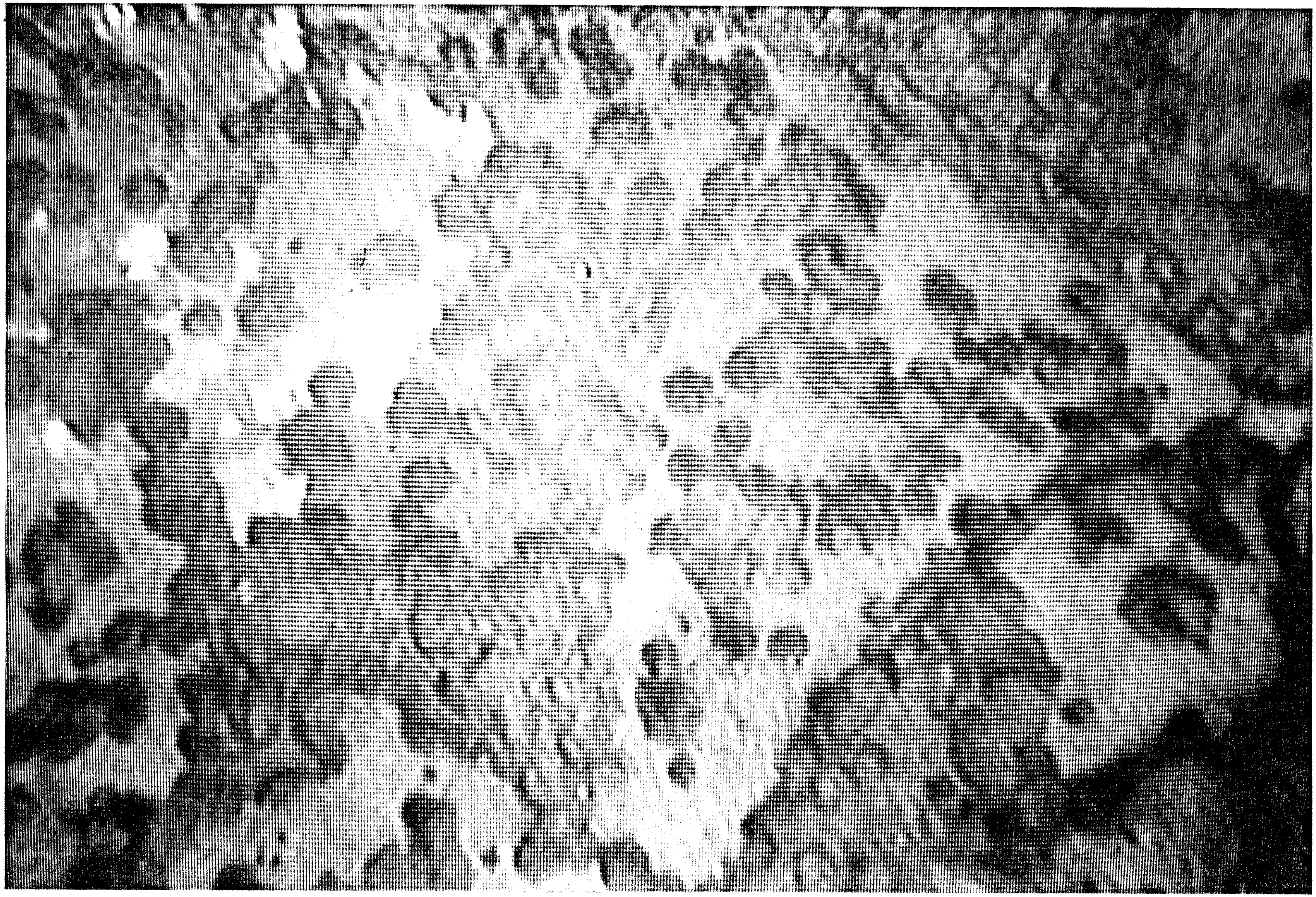

Figure 6. Inclined bedrock pavement at the Six Fathom Bank-North site showing pitting and grooving. Individual pits are 2-5 cm in diameter and 5-10 cm deep. The pavement surface (interfluves) between the pit mouths is flat and smooth.

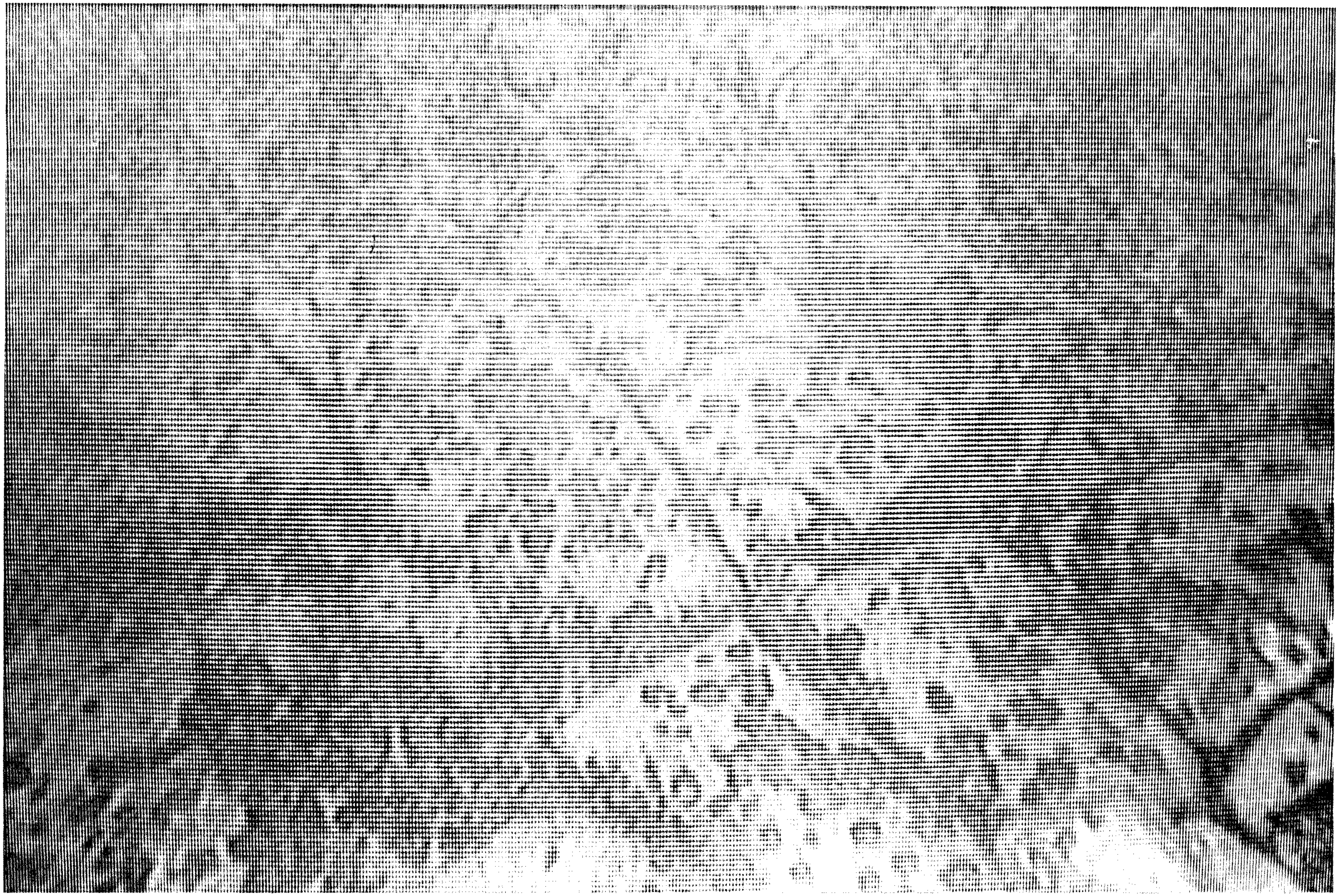

Figure 7. Inclined bedrock pavement at the Six Fathom Bank-North site showing straight, curved, intersecting, and dendritic groove forms.

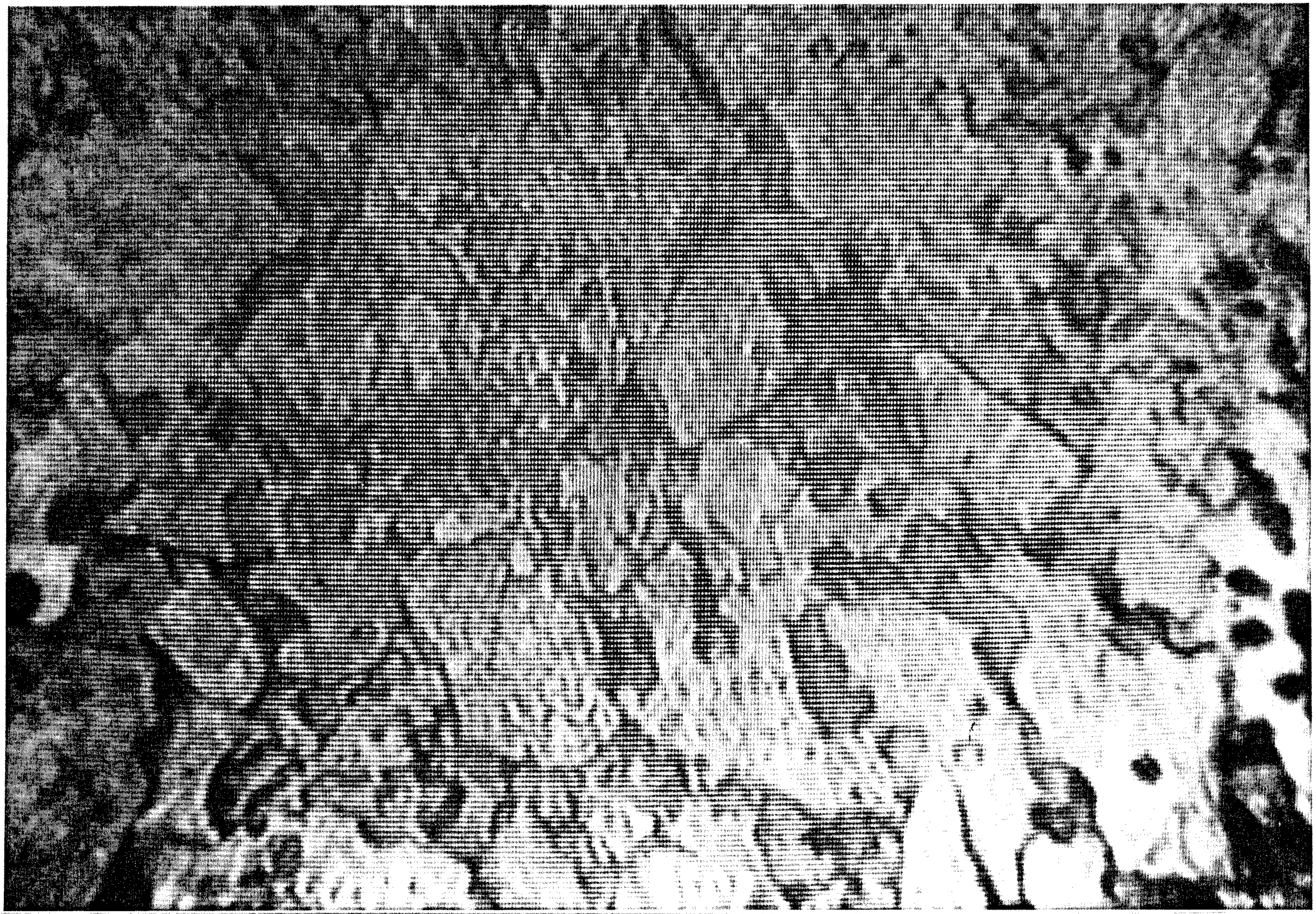

Figure 8. Angular rubble produced on inclined pavement by fracture of pit interfluves at the Six Fathom Bank-North site.

Figure 9. Deep, complex pitting of rubble-sized rock. More than 30 pits up to 4 cm in diameter and 15 cm deep penetrated the rock.

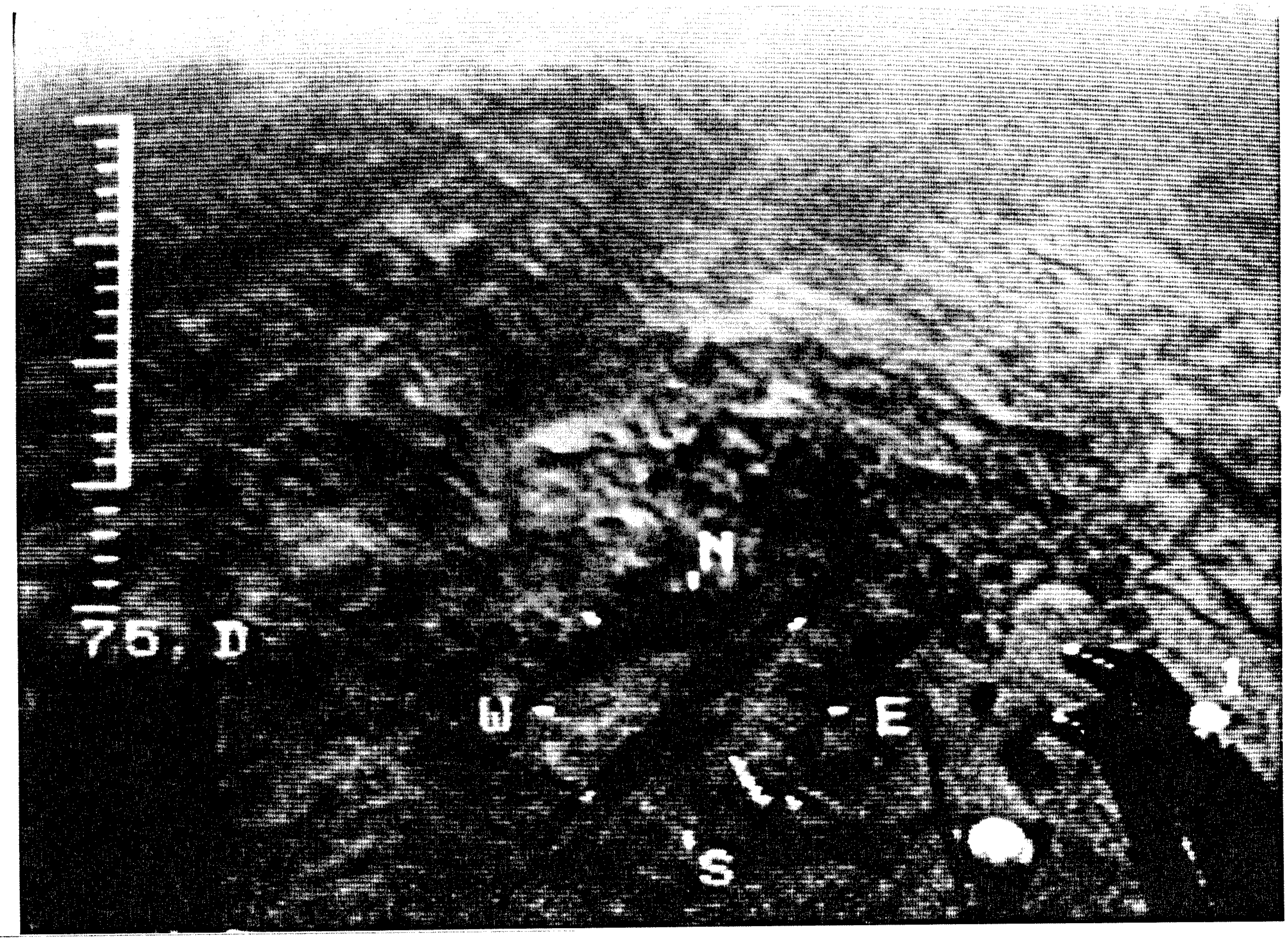

Figure 10. Bedrock ridges near the crest of Yankee Reef. Ridges were about 1-2 m high and oriented roughly northwest to southeast, with the stepped face on the north-east side. The video camera was pointed southeast, parallel to the ridge line. Water depth (75 D) was 75 ft (about 23 m).

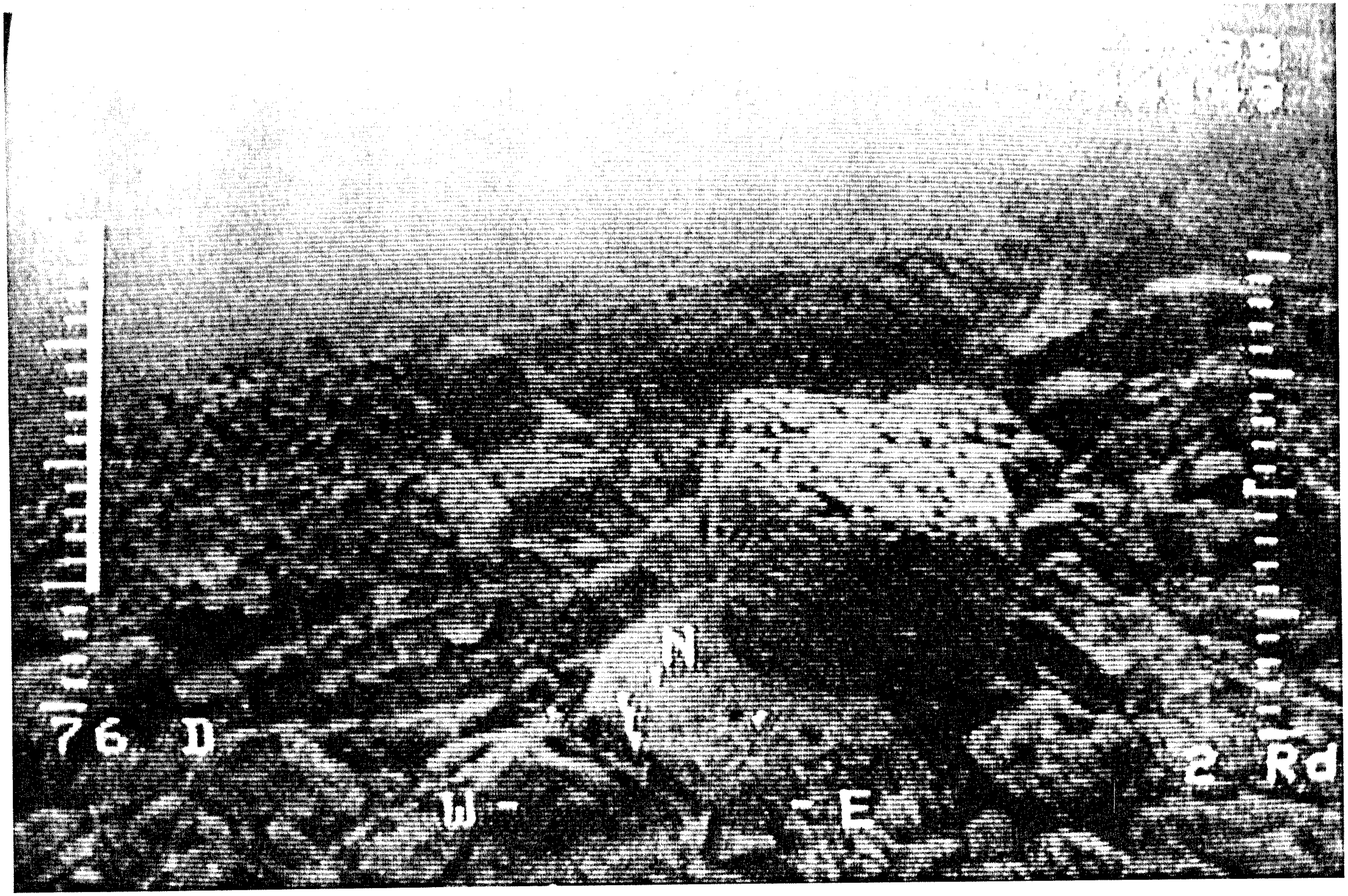

Figure 11. Cobble piles were often present near the bedrock ridges shown in Figure 10.

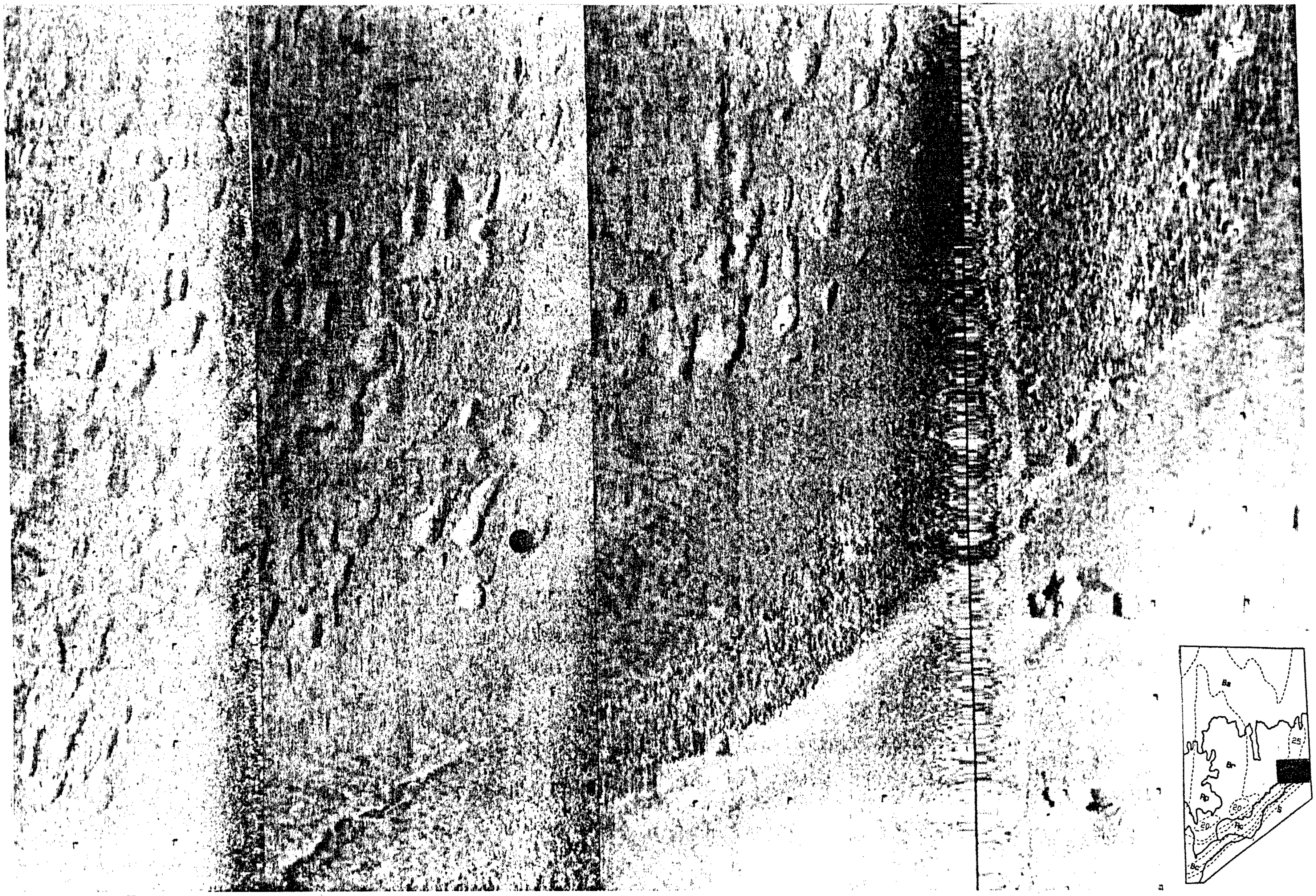

Figure 12. Side-scan sonar mosaic of the bedrock ridges and associated cobble piles shown in Figures 10 and 11. The ridges and piles appear as mound-like structures on the crest of the reef. The light area in the lower right along the base of the reef is sand. The darker grainy area along the reef face is small rubble; cobble piles and scattered cobble are visible at the base of the reef near the sand.

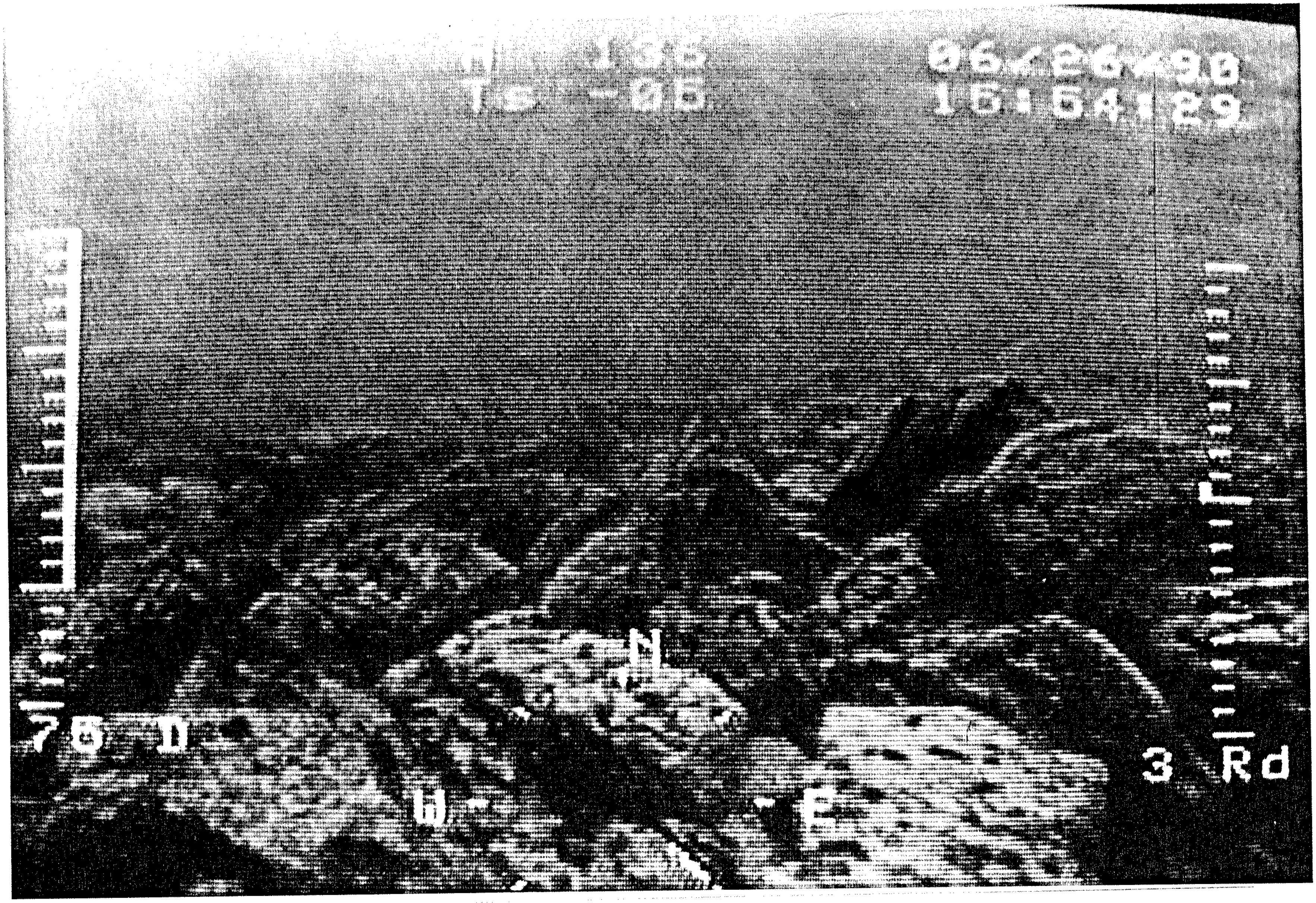

Figure 13. Rubble piles with scattered cobble was a dominant substrate along the western border of Yankee Reef.

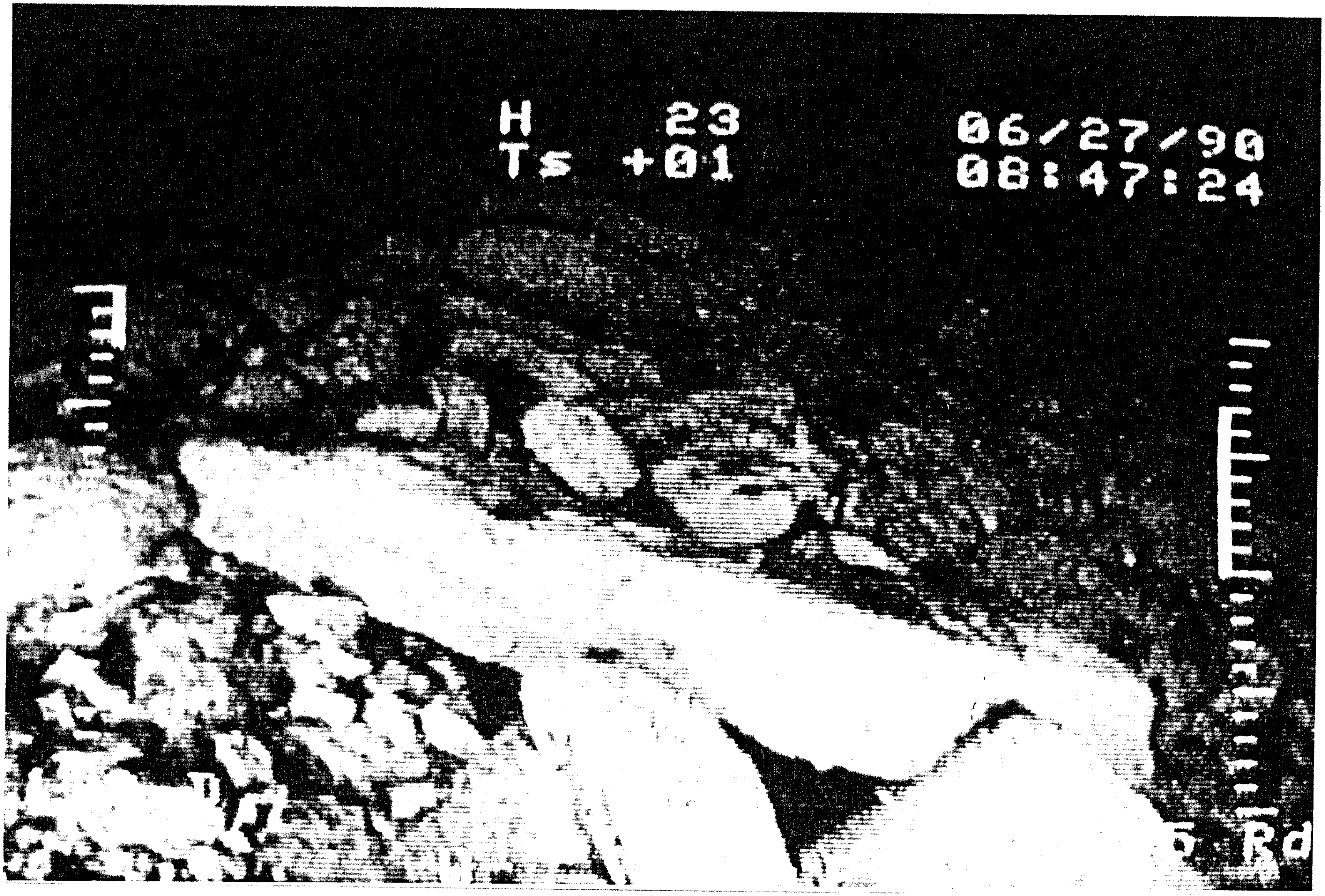

Figure 14. Small rubble mixed with gravel, coarse sand, and soft sediment occupied most of the face of the scarp within the mapped portion of Yankee Reef. In many places the scarp face substrate appeared unstable.

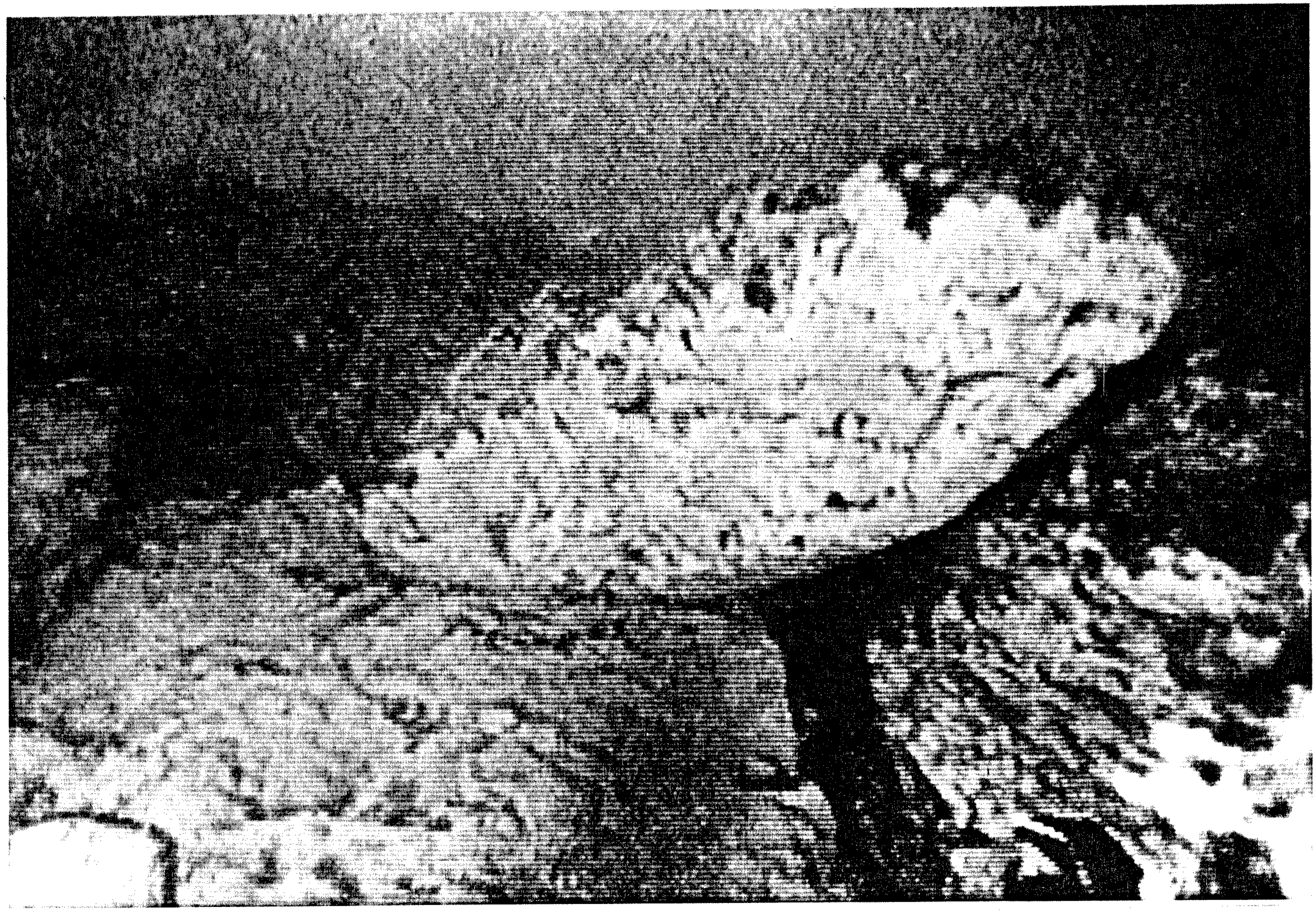

Figure 15. Piles of deeply pitted, rounded and angular cobble were present along the base of the scarp on Yankee Reef.

Figure 16. Bedrock on the face of Yankee Reef.

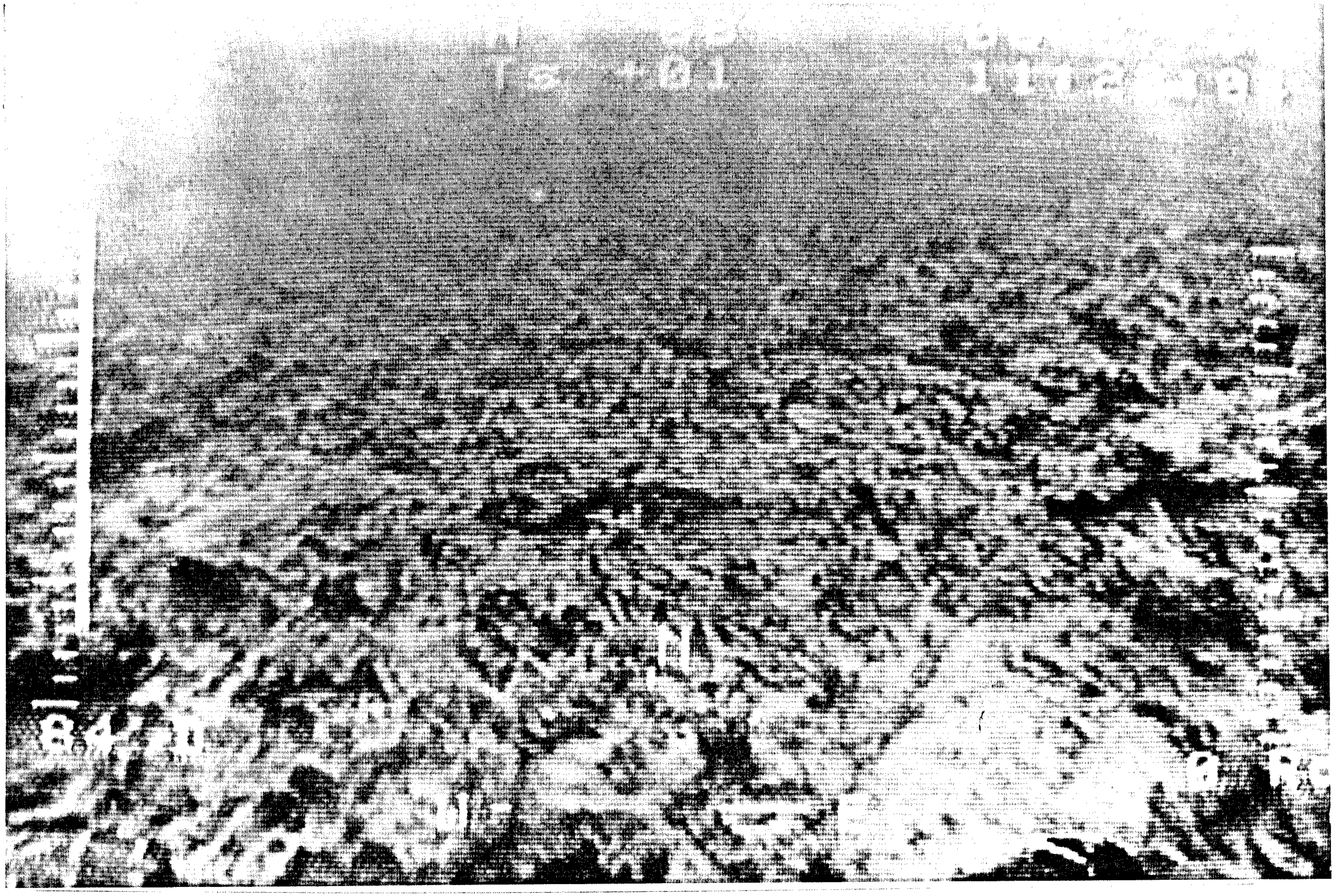

Figure 17. Extensively pitted bedrock with sharp pit interfluves created an uneven, sawtoothed surface that occurred over much of Yankee Reef.

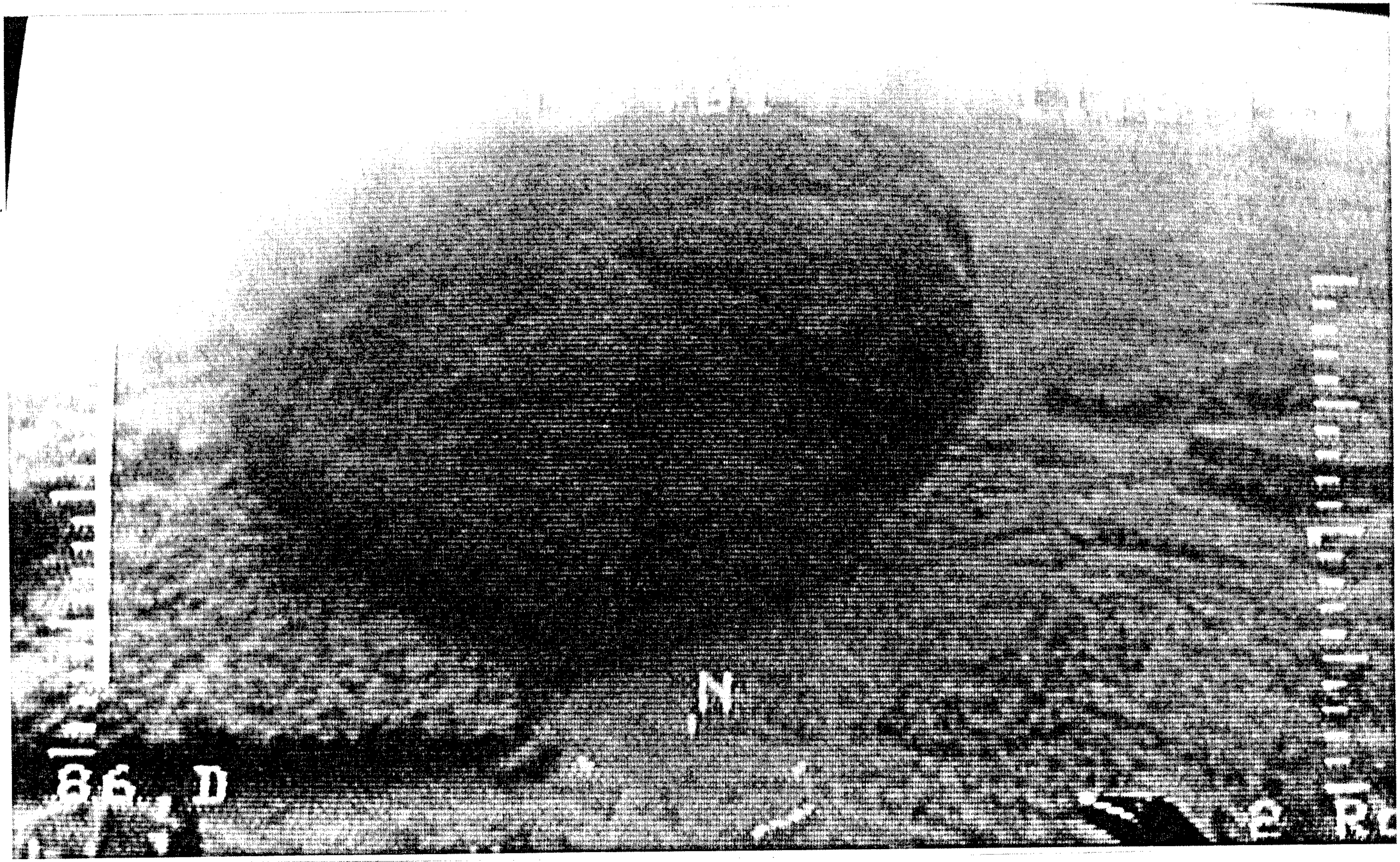

Figure 18. Smooth bedrock produced on pitted pavement by separation and displacement of the upper layers of bedrock. The large boulder was probably a glacial erratic from precambrian sources to the north or east.

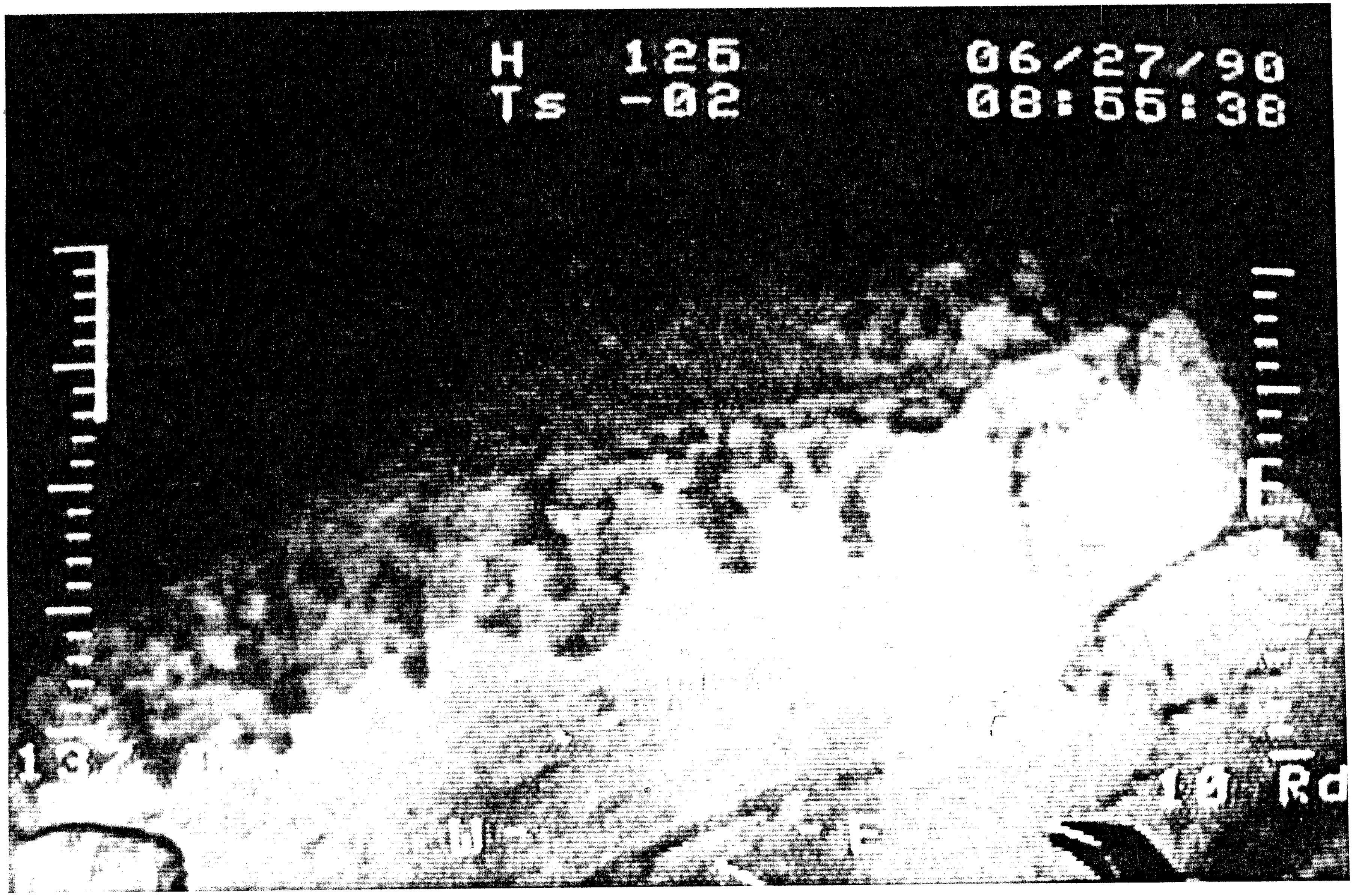

Figure 19. Large cobble blocks with deep pitting on one side were common along portions of the base of the scarp.

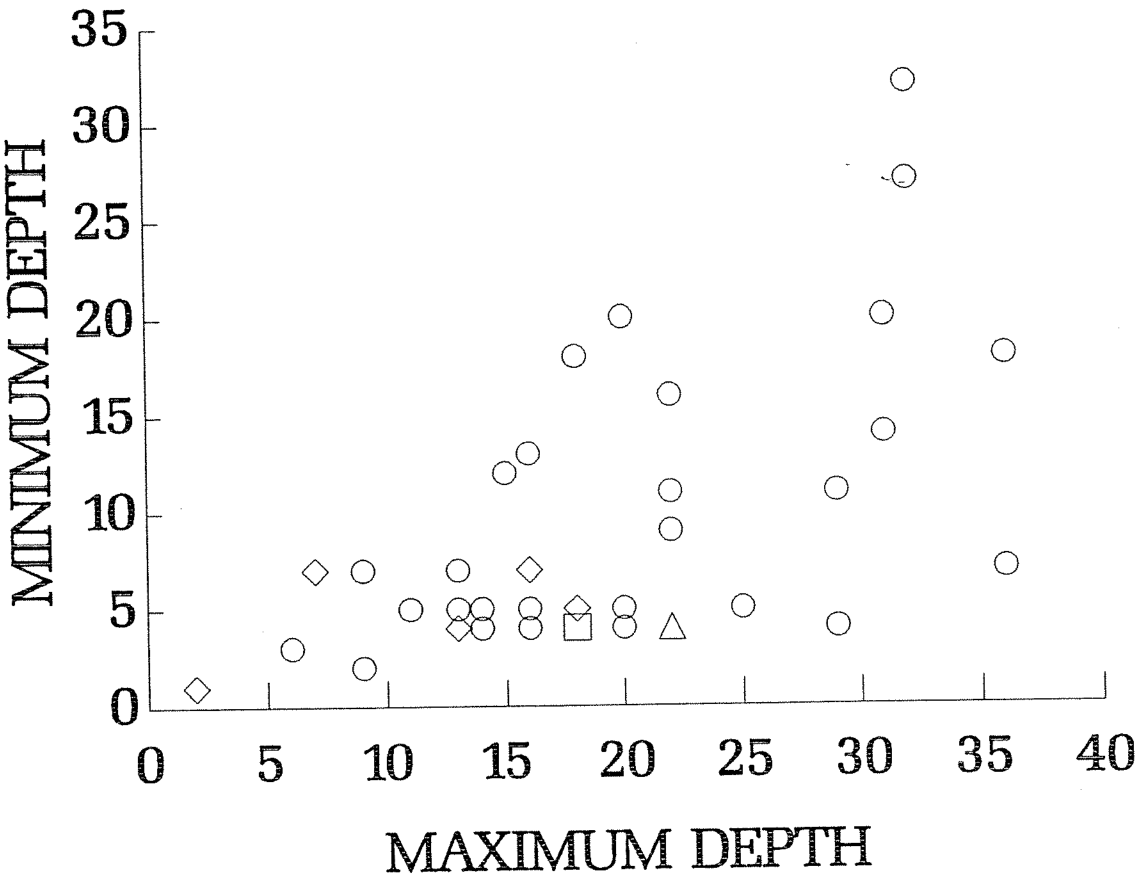

Figure 20. Minimum and maximum water depths (m) at 50 sites where lake trout spawned historically in Lake Huron, according to Goodyear et al. (1982). The number of sites represented is: circle, 1; diamond, 2; triangle, 4; and square, 8.