**ARCTIC**
VOL. 48, NO. 4 (DECEMBER 1995) P. 342–353

# Erosion of the Geodetic Hills Fossil Forest, Axel Heiberg Island, Northwest Territories

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*(Received 23 February 1994; accepted in revised form 12 June 1995)*

ABSTRACT. Studies on the erosion of the Geodetic Hills Fossil Forest on the east side of Axel Heiberg Island, Northwest Territories have indicated that erosion by wind averaged a depth of 1.3 cm for the period 1988 to 1992. The fossil wood and leaf litter tend to dry on exposure, resulting in shrinkage and fragmention—sometimes in less than a year. Frost, especially at the boundaries of polygons, repeatedly compresses and disrupts the fossil-bearing strata. Erosion by water takes place as rills on the sides of hills. Solifluction displaces surface sediment on the sides of the hills in the range of 6 to 45 cm per year. In the last few years the physical disruption of stumps, tree trunks and forest mat has been caused mainly by people: by walking on the site, by excavating it, and by flying over and landing helicopters on it. Natural processes—including wind, freezing and thawing, rainfall, and wandering animals—also cause damage.

In 1992, 62 stumps recorded in the 1988 survey (ca. 10% of the total) could not be relocated. There are problems in accounting for this discrepancy, because only a few stumps are known to have been removed by investigators for study, and it seems unlikely (although it is possible) that others may have been removed by unknown visitors. Some of the "missing" stumps may still be present, but disturbance in the surface sediment caused by scientific excavation or wind-driven accretion have made them untraceable. Vestigial stumps may simply have weathered away in the period between surveys, and finally some of the losses may be accounted for by errors in the initial surveying.

Since preservation is important both for long-term scientific interpretation and for public access, the site should be better managed. The authors advocate that the site be managed by the Canadian Parks Service as an annex to Ellesmere Island National Park Reserve.

Key words: fossil forest, Axel Heiberg Island, wood, leaf litter, erosion, preservation

RÉSUMÉ. Des études sur l'érosion de la forêt fossile des collines géodésiques du côté est de l'île Axel Heiberg dans les Territoires du Nord-Ouest ont révélé que l'érosion éolienne était d'en moyenne 1,3 cm au cours de la période allant de 1988 à 1992. Le bois et la couche de feuilles mortes fossiles ont tendance à sécher s'ils sont exposés aux éléments, ce qui aboutit au retrait et à la fragmentation — parfois en moins d'un an. Le gel, en particulier aux limites des polygones, comprime et disloque les strates fossilifères de façon répétée. L'érosion hydrique se produit sous forme de rigoles sur les pentes des collines. La solifluxion déloge les sédiments de surface sur les pentes des collines à une vitesse de 6 à 45 cm par an. Au cours des dernières années, la perturbation physique des souches, des troncs d'arbre et du tapis forestier a été causée principalement par les humains: piétinement et excavation du site, survols et atterrissages des hélicoptères. Les processus naturels — y compris le vent, le gel et dégel, les précipitations et le déplacement des animaux — causent également des dommages.

En 1992, 62 souches consignées dans le relevé de 1988 (environ 10 p. cent du total) n'ont pu être retrouvées. On a de la difficulté à expliquer cet écart, car on sait que quelques souches seulement ont été enlevées par les chercheurs pour effectuer leurs travaux, et il semble peu probable (bien que ce soit possible) que d'autres souches aient été enlevées par des visiteurs inconnus. Il se peut que certaines des souches «absentes» soient toujours présentes, mais la perturbation des sédiments de surface causée par des excavations scientifiques ou l'accrétion éolienne fait qu'elles sont impossibles à retracer. Des souches résiduelles ont peut-être tout simplement été détruites par les éléments durant les périodes entre les relevés, et finalement, certaines des pertes peuvent être expliquées par des erreurs dans le relevé initial.

Vu que la conservation est importante à la fois pour l'interprétation scientifique à long terme et pour l'accès du public, le site devrait être mieux géré. Les auteurs recommandent que la gestion en soit remise au Service canadien des parcs, en tant qu'annexe à la réserve de parc national de l'île-d'Ellesmere.

Mots clés: forêt fossile, île Axel Heiberg, bois, couche de feuilles mortes, érosion, conservation

Traduit pour la revue *Arctic* par Nésida Loyer.

## INTRODUCTION

The discovery in August 1985 of the fossil forest at Geodetic Hills on Axel Heiberg Island, 79°55′N, 89°02′W, (Fig. 1) sparked much academic and popular interest not only because of its large size, but also because of the remarkable nature of the fossils preserved there. Fossil forests have been defined as "groups of preserved tree stumps found generally in growth

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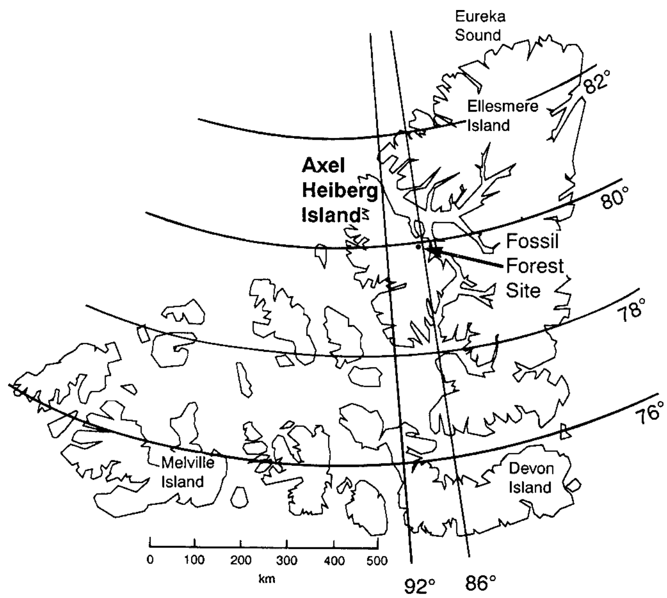


FIG. 1. Map showing Fossil Forest location.

position" (Christie and McMillan, 1991:xiii). However, the fossil forest in question has more than stumps in growth position: the forest mat in which they are still rooted is preserved, so that all the constituents are distinct and recognizable. In some locations, the forest mat has the appearance of relatively fresh material. Since 1985 when James Basinger, a palaeobotanist from the University of Saskatchewan, identified mummified wood and forest mat, researchers have observed a wide range of species and plant specimen types, including leaves, seeds, cones, tree stumps, tree trunks and branches as well as pollen and fungi. The results of multidisciplinary investigations begun in 1987 and coordinated by R.L. Christie of the Geological Survey of Canada (GSC) have been published in a special volume (Christie and McMillan, 1991). Since 1987, work has continued on the identification and analysis of fossil specimens (Basinger, 1991; Lepage, 1993).

The site, which is the only one of its type in Canada, can be regarded in many ways. It is an assemblage of specimens, a preserved environment, a time capsule, or a gigantic refrigerated repository for specimens. It can also be seen simply as a source of data. Each of the circa 27 strata containing leaf litter or wood represents a period of forest growth. Each preserves a particular group of botanical specimens and a particular spatial arrangement of the preserved plants. The site is of great value for its variety and number of plant species, for the disposition of fossils within specific periods of time, and for its record of how the vegetation changed with time. The variation in species distribution between leaf mat layers may also give information about climatic change. From the species distribution, it is possible to reconstruct the forests which grew on this site (Francis and McMillan, 1987; Basinger, 1991; Francis, 1991; McIntyre, 1991; Lepage, 1993).

In 1986 the National Museum of Natural Sciences (now the Canadian Museum of Nature) became interested in assembling collections and interpreting the site for the public. Many of the initial specimens recovered for the museum—which included a tree stump, cones, and sections of leaf mat—were very fragile, and some tended to disintegrate after removal from their arctic environment to the laboratory. While some collectors have found fossil specimens from this site have sufficient physical integrity for scientific study, their fragile condition is unsuitable for the stringent requirements of very long-term preservation in museums, where even under the most carefully controlled conditions it is impossible to prevent some physical or environmental disturbances from occurring. For these reasons, the Canadian Conservation Institute, (CCI) was invited to become involved in the project. The museum was also concerned with minimizing damage to the fossil forest site. In response to this request, CCI has attempted to monitor some of the changes that are taking place. For six years, we have studied the effect of the natural environment, as well as the impact of people. This article reports and comments upon the initial results of our work. Questions about the stability and integrity of the site are being answered through an on-site monitoring programme. This includes photography and mapping of stumps and logs, aerial photography, and monitoring of erosion markers placed in sensitive locations.

Scientists from CCI visited the site regularly from 1987 to 1992. In addition, several programmes of laboratory work have been undertaken to analyze the specimens collected and to develop new conservation procedures for their stabilization.

## THE FOSSIL FOREST SITE

Although the site has been extensively described in other publications (Christie and McMillan, 1991), a brief description is useful here. The site contains the remains of ancient Tertiary forests (ca. 45 million years old), and several layers of forest "floor" have been exposed in a state that is remarkably undisturbed despite the passage of time. The forest remains are abundant. Many large tree stumps project from the ground, and several periods of forest growth are evident in forest litter containing strata interspersed with sands and silt deposits (Francis and McMillan, 1987; Francis, 1991; Ricketts, 1991). Tree stumps and forest litter, including cones, seeds and leaves, have remained undisturbed for millions of years. The trees include several species which likely would have grown in warm and wet conditions. Examples are *Glyptostrobus* sp. and Dawn Redwood (*Metasequoia glyptostroboides*).

The site is remarkable for the unusual condition of the specimens that are commonly described as "mummified": the majority of the fossil leaves, trees, cones, etc. are not mineralized (i.e., there has been negligible mineral replacement of the vegetable tissue) and coalification has occurred only to a limited extent. The ash content of a sample of mummified wood, a useful indicator of the degree of mineralization, is reported as being about 1% by weight by Grattan (1991) and up to 5% by Obst et al. (1991). This compares with approximately 0.2% to 0.5% for fresh wood. Petrified wood can have

FIG. 2. A “sandstorm” in the Fossil Forest, 1988.

mineral content up to 100% (i.e., complete replacement of organic material with minerals) with correspondingly high ash content, depending on the minerals present. Although these fossils represent some of the best-preserved Eocene specimens known, it is incorrect to consider them undeteriorated or like “fresh wood.” Much of the cellulose fraction (the main component of fresh wood) is missing, and the molecular weight of what remains is less than one-tenth that of fresh wood (Grattan, 1991). Furthermore, the wood is typically crushed (Grattan and Drouin, 1987) and the cell structure distorted (Young, 1991). The mummified condition also presents some challenging conservation problems.

Specimens remain wet while buried; when they dry after removal from their wet environment, they become exceedingly vulnerable to rapid deterioration. The wood shrinks in the low arctic humidity and may crack apart. Even the merest touch of a soft brush on a dry cone or leaf is enough to dislodge fragments or cause crumbling. At the beginning of the project, in 1986, there were no conservation procedures available for preservation. New preservation techniques (such as parylene deposition) have since been developed or adapted to preserve these specimens (Grattan, 1991). These new techniques allowed an entire collection to be treated for the Canadian Museum of Nature. The work reported here, however, is not concerned with individual specimens, but with the whole site.

The site consists mainly of exposures in a hill referred to as “Fossil Forest Hill” or “The Hill” in the following text. Related sites, considered part of the fossil forest, occur in the surrounding hills where strata from the same levels are exposed. Major exposures occur in a hill to the east of Fossil Forest Hill, referred to as “The East Hill.”

## EROSION

The sedimentary deposits in which the forest is found are very poorly consolidated when unfrozen, a situation that favours rapid erosion in the harsh northern environment, “a terrain in which disintegration is at a maximum and decomposition at a minimum” (Ray, 1951:200). Initial examination identified the following causes of erosion or disruption of the site and of loss or damage to specimens: 1) wind; 2) frost action; 3) water, leading to solifluction and mud flow; and 4) disruption by people, wandering animals, and aircraft wind-blast.

Wind causes direct erosion or ablation of the site as is seen in Fig. 2, which shows dust being lifted hundreds of meters into the air (and also the scalloped shape of the west end of the Hill) during a severe windstorm in 1988. Wind speeds of up to 90 km/h were measured at valley floor level, and speeds were substantially greater on the hilltops. During the storm, the wind rapidly removed surface leaf litter and sand. Permafrost prevents dune formation in the poorly consolidated hills of the fossil forest region and keeps the active zone (i.e., the portion of the ground above the permafrost) cold and wet, which helps minimize wind ablation.

The most obvious effect of frost is the formation of patterned ground (tundra polygons). In areas where consolidation of the ground is very poor, polygon formation is not observed. However, at the west end of the site where there is a large area of exposed leaf mat, rectangular frost polygons are present. This much-studied phenomenon is caused by the formation of cracks, which are evident at the edges of polygons. These cracks fill up with water during thaw and refreeze to form ice wedges. Wedges prevent the reexpansion of enclosed units in the active zone and thus continually enlarge by as much as 1.5 mm per year (Drew and Tedrow, 1962). The result of this repeated compression is the disruption of deposits along the boundaries of tundra polygons. In the west region of Fossil Forest Hill, where a thick (ca. 30 cm) layer of leaf mat is exposed, the polygons are very regular squares, approximately 7 $m^2$, and the cracks were measured at about 1 m across. In a younger deposit of leaf litter nearby, the polygons are slightly less uniform in size and form smaller units (sides typically 1 m, cracks ca. 6 cm in width).

Water, as rain or snowmelt, is not a major source of direct erosion. The surface of Fossil Forest Hill is quite porous, so that water in light rainfall is absorbed. Interestingly, heavier rain has been reported as only wetting the surface (Basinger, pers. comm. 1993). It is argued that wet, clay-like surfaces seal the active zone, which remains comparatively dry, while surface water is lost as runoff. However, rills are observed only in certain regions—usually at maximum slope. As seen in the upper portion of Figure 3, a rill may originate at the top of a hill, disappear as a more porous layer is encountered, and then reappear. The movement of moisture through or over the active zone as rainfall or as melt is clearly variable. Water cannot penetrate the hill deeply, because the permafrost table is ca. 20 cm below the surface. Annual precipitation in this region is reported to be less than 100 mm, of which 30% to 40% falls as liquid precipitation (Maxwell, 1981). During the spring thaw the erosion channels, which occur all around the hill, become active. On the north-facing slopes of the hill, some erosion channels have enlarged into collapse basins up to 30 m in diameter (Fig. 4) with mud flows at the base. These collapse basins are clearly increasing in size, but not at a steady rate. Sudden collapse of the upper edges has been observed after heavy rain. Solifluction is most noticeable at the lower angles of slope at the base of the hill, where there has been mass movement of water-saturated ground over the permafrost table.

FIG. 4. Collapse basins on north side of Fossil Forest Hill.

The predominant causes of physical disruption are the effects of wandering people and animals, excavation, and hovering and landing helicopters. Footprints in the loosely consolidated surface can easily survive twelve months and may initiate erosion channels. Excavation, though necessary for scientific studies, may disrupt spatial relationships among specimens and certainly limits future interpretation of the site. Unfilled excavation around stumps, as shown in Figure 5, leads to premature disintegration—although a contrary argument (Basinger, pers. comm. 1993) has been advanced that stumps exposed do not disintegrate, and that leaving

FIG. 3. Erosion channels on north side of Fossil Forest Hill.

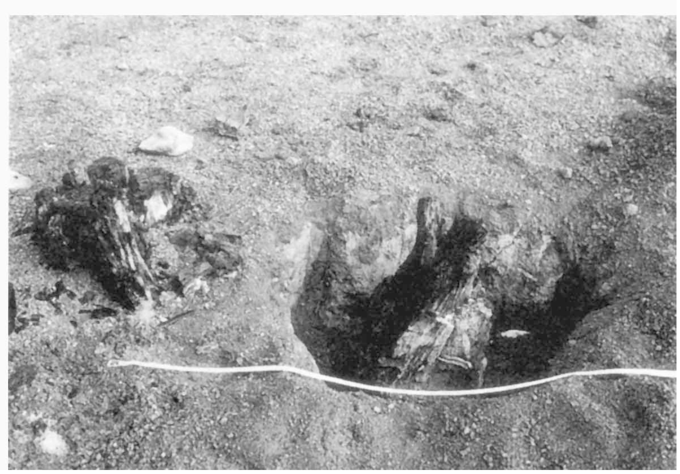

FIG. 5. This stump has been left exposed and vulnerable to drying out and cracking.

holes unfilled at least shows clearly where excavations have been made. Helicopters cause tremendous downdraughts which can blow leaf mat or loose sand and silt around. This may accelerate degradation of stumps and logs as well as scattering pieces of them away from their original location.

The above agents, by eroding or disrupting the hill, have a severe effect on the exposed fossils. There is an abrupt change in water content at the boundary between buried and exposed mummified wood in the summer (Grattan, 1991). Field measurements with a resistance moisture meter were carried out on a partially buried trunk section (1.8 m length, 13 cm × 20 cm cross-section) in a typical Fossil Forest Hill litter deposit (Fig. 2). The upper 40 cm of the litter layer was exposed and the remainder buried to a maximum depth of 33 cm in the active zone. At ground level, moisture content changed very abruptly from ca. 37% to 8% in partially buried wood. The buried wood therefore had a moisture content in excess of the fibre saturation point, previously estimated as 18.9% (Grattan and Drouin, 1987), and the exposed wood was surprisingly dry. In seasons other than the summer, the exposed wood would certainly be much wetter, and in the intermediate seasons it would undergo frequent cycles of freezing and thawing.

It was also demonstrated (Grattan and Drouin, 1987) that the mummified wood shrinks and expands in response to absorption or desorption of moisture. Going from complete dryness to the fibre saturation point, the wood expanded by 4% in each of the principal dimensions of wood (tangential, radial and longitudinal), which is 11% volumetrically.

These observations explain why buried fossil wood remains intact and does not fragment, but exposed wood fragments, delaminates and warps. The mummified wood is so degraded (by degradation of the polymeric structure of the cellulose which gives wood its strength) that the wood has lost its elastic properties. If it shrinks, it breaks. Continual shrinkage and expansion caused by moisture absorption and desorption cause the wood to fracture until it disintegrates and is blown or washed away. These phenomena, to some extent, also apply to leaf litter and other plant remains. However, it is noteworthy that blocks of leaf mat tend to mesh together and survive as intact units better than the surrounding silts and sands.

## MEASUREMENTS AND MAPPING METHODS

### *Erosion Markers*

Two types of markers were placed in July 1988: these were termed “floating” and “permanent” (Fig. 6). Their purpose was to measure wind erosion as loss of surface area and movement of the active zone by frost or solifluction. Permanent markers consist of 1.2 m sections of 12 mm diameter steel rod (standard 1/2" concrete reinforcing rod) driven into the permafrost with at least 0.3 m penetration. Usually this left about 0.3 m projecting above ground. The intention was to provide semipermanent reference points to which changes

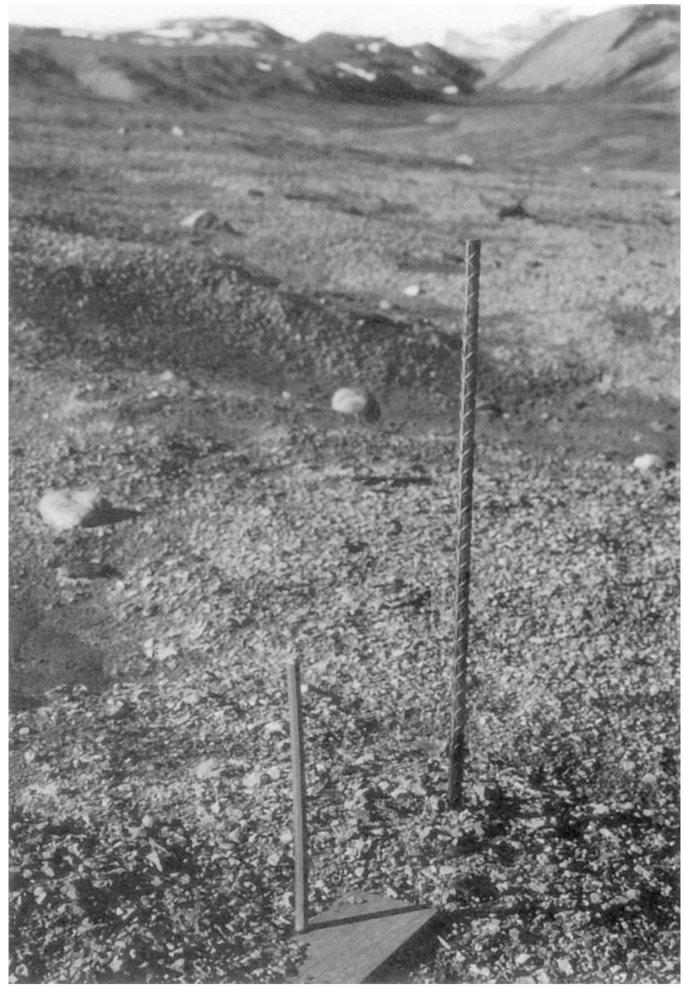

FIG. 6. A floating and a permanent marker. The partially covered floating marker is direct evidence of accretion.

in surface level, encroachment of erosion channels and movement of the floating markers could be related. We assume that the permafrost remains stable, as reported by Ray (1951). A larger number of floating markers were also installed. Placed at known distances from the fixed markers, these floating markers consist of 15 $cm^2$ marine plywood sections with 0.3 m × 10 mm dowels driven through the centre at right angles. The floating markers were intended to move with the active zone if slippage or solifluction took place. The steel rod markers were placed in rows, usually at 10 m intervals in the flatter regions (i.e., within exposures) of the Hill. Wooden floating markers (also at intervals of 10 m) were placed so as to continue these arrays down the sides of the hill through regions of maximum slope. A floating marker was placed at ca. 30 cm from each steel marker. Four sets of markers in arrays were placed in different areas of the hill (Fig. 7). Three arrays (A, C and D) cross areas of exposed leaf litter and the side of the hill. In one instance (C) the floating markers were taken almost to valley floor level, and over both north and south sides of the hill. One array of markers (B) was placed in three parallel lines in the vicinity of the largest erosion channel on the north side of Fossil Forest Hill. In all, 24 steel rod markers and 60 floating markers were installed. All

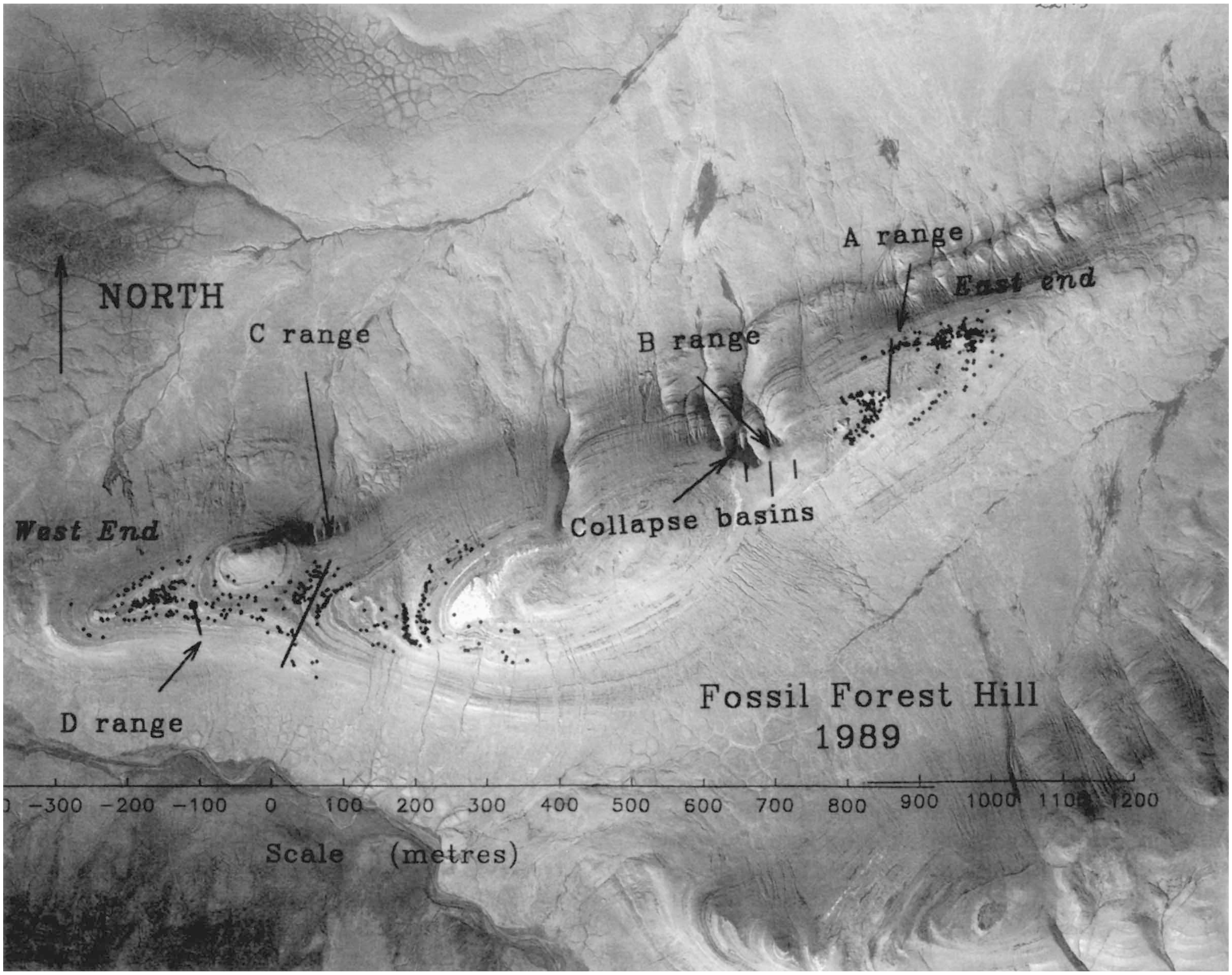


FIG. 7. Aerial photograph of Fossil Forest Hill at 1067 m altitude. (N.B. At this altitude, it is calculated that the aircraft was 795 m above the valley floor, or 713 m above the highest point of Fossil Forest Hill). Note that the East Hill is at the right side of the lower edge of the photograph (Photograph by H.P. Roy, PCSP survey, 1989). The overlay shows all mapped stumps. Also noted are the collapse basins, and the A, B, C and D ranges of erosion markers. The lines show the approximate position of the permanent marker ranges. The floating markers extend considerably farther.

distances between markers were measured by steel tape held parallel to the ground surface. Permanent marker heights were measured by placing two pieces of 15 cm × 15 cm × 1 cm marine plywood near each marker, one on the up-slope and the other on the down-slope. A tape measure was placed on each piece of wood and read at the top of the marker. The height above ground was taken as the average of the two values.

*Ground Survey*

Several reference points (also known as "trig. points") were established on the high spots overlooking stump exposures on Fossil Forest Hill and on the hills to the south and east. Steel marker pins (made of the same steel rod used for the permanent markers) were driven into the permafrost to mark each location. In addition, two more markers were placed in the valley to the south of the hill to form a baseline. A theodolite was employed to take bearings from each marker to all other unobscured markers. The length of the baseline was measured at 613 m by stadia interval, and this enabled us to prepare a scale drawing of the reference points.

For charting stumps and logs, a theodolite (1989, 1992 surveys) or alidade and plane table (1988 survey) was established at each reference point overlooking exposures. Each stump and each of the larger logs was surveyed for location and for height. Comments relating to the size and condition were recorded, and an identification number was assigned to each feature. This allowed plans of various regions of Fossil Forest Hill to be drawn up. All data have been digitized, enabling maps to be drawn by computer using Sigmaplot. The fossil stump maps from each exposure were integrated into one map (Fig. 8). The software allows maps of any scale to be drawn, and also permits the selection of any specific area for enlargement. This is a convenient method for tracking changes such as disintegration or exposure of stumps.

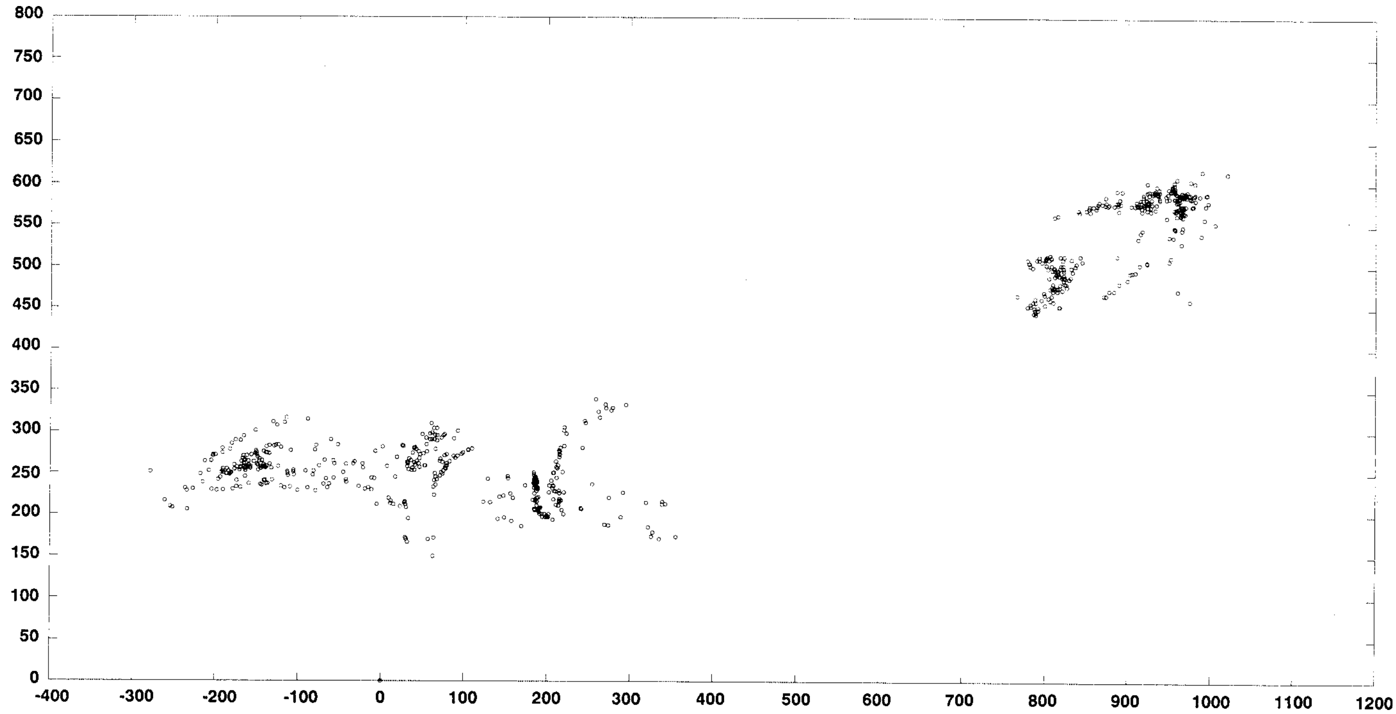


FIG. 8. Cumulative plot of stumps surveyed in 1988, 1989 and 1992. The horizontal axis follows the baseline joining trig points B (0,0) and A (613,0). All distances are in metres.

Mapping of the major features of the exposures has been carried out in three phases. In 1988 a plane table/alidade survey of the upper exposure at the east end of Fossil Forest Hill was completed. The lower (i.e., most easterly) exposure in this region was not evident at that date. In 1989 the mapping of the entire site was completed except for the small area at the east end which had been surveyed in 1988.

To determine what changes had occurred in the three years following the 1989 survey, the entire site was resurveyed in 1992. More stumps had appeared as a result of erosion and wind. Some stumps that had been noted earlier had disappeared either through erosion or by removal for scientific purposes or inclusion in museum collections.

Before aerial photography was conducted, white markers one metre square were placed next to reference points and at 30 m intervals along the various baselines used in different exposures of stumps and leaf litter. The ground survey data and arrays of erosion markers can be accurately located within aerial photographs.

In the 1988, 1989 and 1992 field seasons, low-level photography was conducted by helicopter at ca. 300 m altitude. This corresponds to 100 m above the valley floor at reference point B, or 18 m above the highest point of Fossil Forest Hill. Although the images produced are distorted because the camera could not point directly downwards, they are useful because of the detail recorded (e.g., Figs. 3, 4).

In 1989, a comprehensive aerial survey was conducted by the Polar Continental Shelf Project of Energy Mines and Resources Canada. Overlapping images were obtained at altitudes of 610, 1067 and 1829 m. One of the images taken at 1067 m altitude is shown in Figure 7.

## RESULTS AND DISCUSSION

### *Erosion*

*Movement of Permanent Markers Relative to One Another:* The location of the erosion markers is shown in Figure 7. None of the permanent markers, which are spaced at 10 m intervals, moved in relation to one another (within ca. 0.01 m). Thus it is evident that no major changes have occurred in the structure of the hill and that the permafrost has, indeed, remained stable over the period of the test (although as surface erosion occurs, the permafrost table gradually moves downwards, because the depth of the active zone remains roughly constant from summer to summer).

*Surface Losses from Wind Erosion*: Figures 9A, 9B, 9C and 9D show the change in surface height relative to the tops of the permanent markers. These markers, as noted above, are located in flatter areas, and these measurements show the effect of wind erosion (or accretion). Erosion is the main process in all regions where measurements were made. At certain locations, particularly in flatter regions, accretion (i.e., accumulation of wind-blown sand) also occurs. Profiles of the Hill in the region of each array are also shown in Figures 9A to D. It appears that wind erosion is a little greater in the region of the maximum slope (Figs. 9C and 9D). The "C" range of permanent markers (Fig. 9C) crosses a deposit of silt at its centre, then on each side of the central region it passes through areas of leaf mat. At the edges it again passes into silty regions. Figure 9C shows clearly that the silty region at centre is eroding much faster than the surrounding leaf-mat regions. In the period from 1988 to 1992, the average erosion

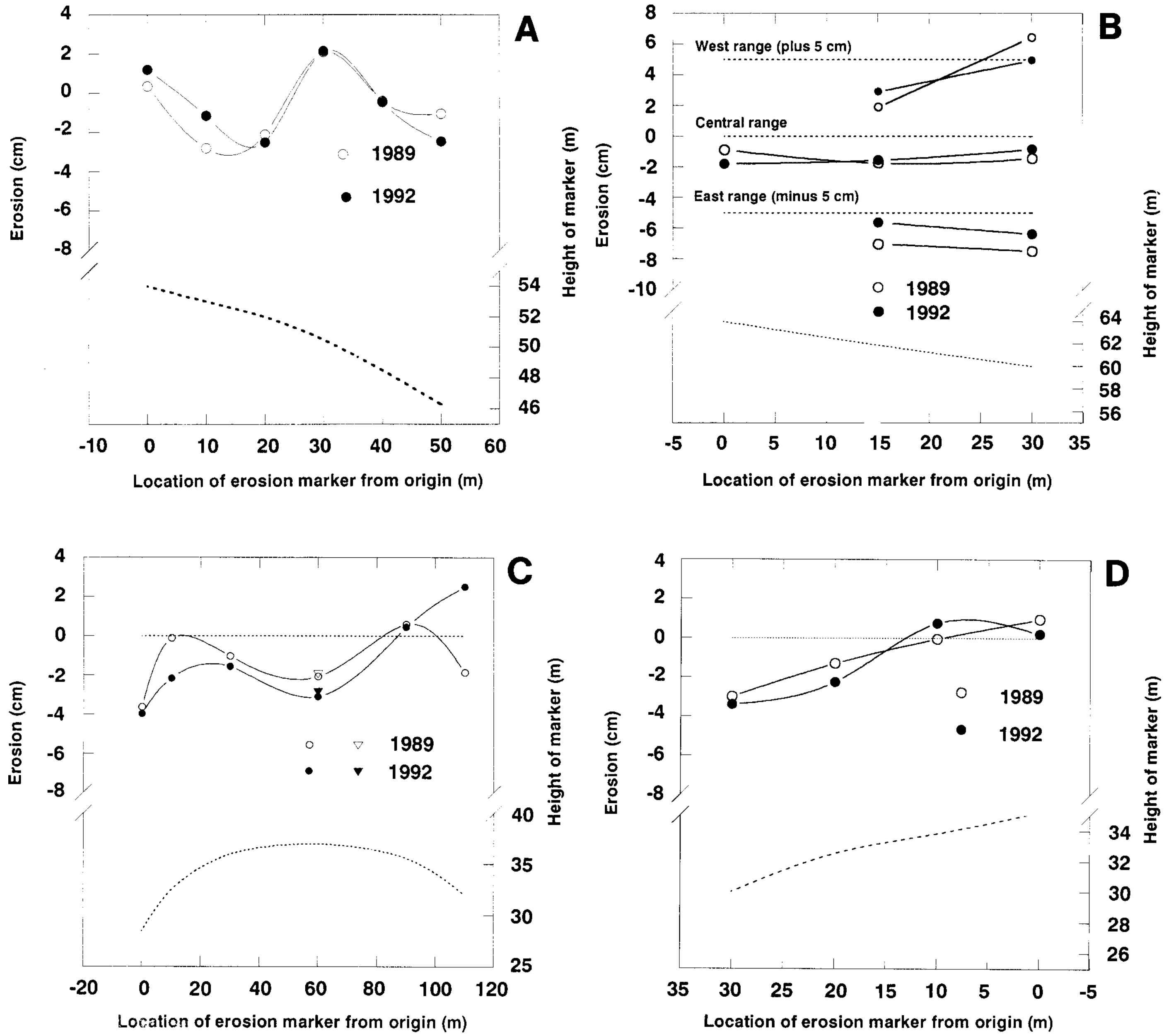


FIG. 9. Surface erosion as given by the alterations in the distance between the tops of permanent markers and the surface of the ground. These data are compared to hill profiles (lower curves) which are given by plots of the heights of markers, in metres, above reference point B. Graphs A, B, C and D display readings at ranges A, B, C and D respectively. Negative values indicate erosion. The triangular points in 9C are for a marker displaced 10 m at right angles to the line of the main C array.

rate for the 24 permanent markers was calculated to be 0.33 cm per year (Fig. 10). It appears that this rate is not constant, since there was less erosion between 1989 and 1992 than in the one-year period from 1988 to 1989.

*Active Zone Movement in the Vicinity of Permanent Markers:* In flatter regions, the average movement between floating and permanent markers is between 0.2 and 1.0 cm (Table 1). These relatively small changes indicate little or no movement of the active zone where there is no significant slope.

Floating markers in arrays down the sides of the Hill gave information about active zone slippage within the slopes as land slip, solifluction, mud slide, and collapse. Results shown in Table 2 indicate that some down-slope movement took place. The experimental error is large for various reasons. Markers were sometimes moved, as evidenced by broken shafts or by their being half pulled out. In 1989 a sonic device was used for distance measurement. This proved very unreliable, as the data had to be corrected because of errors in the readings from the device. Over the lengths of the arrays of up to 90 m, it is possible to obtain a cumulative error of ca. 15 cm using this device.

In the A range at the east end of the Hill, where an extended array of floating markers goes into a steeply declining and totally unconsolidated slope, average total movement was 33 cm by 1992. This rate is sufficiently in excess of the estimated error of measurement to indicate rapid slippage.

In the B range, in the region of the collapse basins on the north side of the Hill, the floating markers were too widely

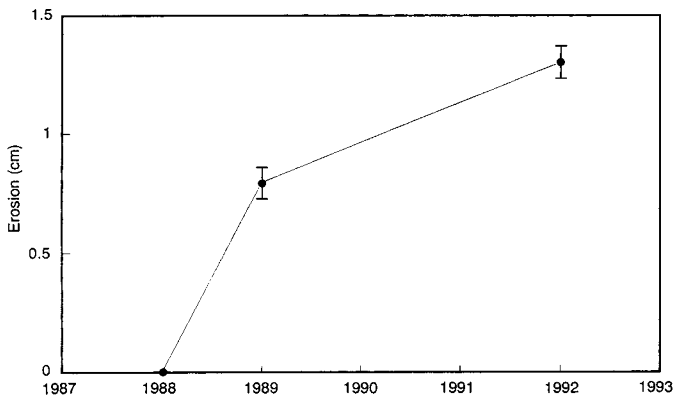


FIG. 10. Average of surface erosion measurements of all 24 permanent markers, with error bars showing the standard deviation.

TABLE 1. Average movement of floating markers relative to permanent markers from 1988 to 1989 and from 1988 to 1992.

| Range[1] | Year | Number of markers | | Average movement between permanent and floating markers (cm) |
|---|---|---|---|---|
| | from 1988 to: | Initially | At time of measurement | |
| A | 1989 | 6 | 6 | 0.20 |
| A | 1992 | 6 | 6 | 0.38 |
| B | 1989 | 7 | 6 | 0.57 |
| B | 1992 | 7 | 4 | 0.23 |
| C | 1989 | 7 | 7 | 0.94 |
| C | 1992 | 7 | 1 | 0.50 |
| D | 1989 | 4 | 4 | 0.90 |
| D | 1992 | 4 | 1 | 0.20 |

[1] The locations of ranges are shown in Figure 7 and are discussed in the text under *Erosion Markers*.

TABLE 2. Surface movement as indicated by movement in floating marker arrays.

| Range | Year | Number of markers | | Length of array | Marker interval | Average movement down-slope |
|---|---|---|---|---|---|---|
| | From 1988 to: | Initially | At time of measurement | (m) | (m) | (cm) |
| A | 1989 | 9 | 9 | 90 | 10 | 10 |
| A | 1992 | 9 | 6 | 90 | 10 | 33 |
| B[1] | 1989 | 5 | 4[2] | 5-30 | 5-10 | 18 |
| B[1] | 1992 | 5 | 2 | 5-30 | 5-10 | 4.5 |
| C south | 1989 | 8 | 8 | 100 | 10 | 6 |
| C south | 1992 | 8 | 1 | 100 | 10 | (16)[3] |
| C north | 1989 | 5 | 3 | 50 | 10 | 17 |
| C north | 1992 | 5 | 2 | 50 | 10 | 26 |
| D | 1989 | 2 | 1 | 20 | 10 | (163)[3] |
| D | 1992 | 2 | 0 | 20 | 10 | - |

[1] Average of readings taken from the three parallel arrays of floating markers which are directed towards the lip of the collapse basin (Fig. 7).

[2] One floating marker fell into the collapse basin in the summer of 1988.

[3] Unreliable data because of loss or suspected dislocation of floating marker(s).

spaced to give much idea of the progress of the collapsing front over the time scale of the experiment. It was noted that one erosion marker was carried away as subsidence took place in 1988. It does seem, however, that there is movement of the surface towards the lip of the basin, perhaps by solifluction. Up-slope solifluction lobes associated with collapse basin formation have been reported elsewhere (Price, 1969); however, here there is no visual evidence of such a lobe.

In the C range, which is located at the west end of the Hill, the floating marker arrays were laid over both northern and southern slopes. Little movement of these markers was documented from 1988 to 1989. However, by 1989 nearly all the floating markers in this array had disappeared. As noted below, this is the region of the fossil forest where there has been most human activity, and the loss of the markers could be an indication of site disturbance by "non-natural" processes.

Similarly, the D range floating markers have also been disrupted and all have now disappeared.

Interestingly, erosion markers illustrate another phenomenon for which they were not originally intended—wind-driven surface accretion, or more correctly, "aeolian sand" (Fig. 6).

### *Stump Survey*

The survey of stumps has confirmed that the site is in a state of rapid change (Figs. 8, 11, 12). By 1989, 497 stumps had been surveyed. In 1992, another 198 stumps were noted, but 62 of the previously identified stumps were untraceable. Accounting for these losses is difficult. Even allowing for errors in plotting or recording of data, these numbers are significant. Of the 62 missing stumps, only a few had been removed by investigators for scientific study. Up to ten were removed by J. Basinger and his colleagues for scientific study (Basinger, pers. comm. 1993). One of these, a very large stump, was transferred to the Canadian Museum of Nature and received conservation treatment at the Canadian Conservation Institute (Grattan, 1991). It is possible that other stumps may have been removed by unknown visitors to the site, but at present we have no system of accounting, although the present work now allows each stump to be located. Some untraceable stumps may well be still present, but concealed by disturbances in the surface sediment from scientific excavation or covered by aeolian sand. Some of the vestigial stumps (particularly those on the higher northeastern exposures) may have weathered away. Surface disturbance may account for our inability to trace stumps at the west end of the site (Fig. 7); of the 89 stumps observed in 1989, 27 could not be located in 1992. This was the largest concentration of missing stumps in the fossil forest. Here the surface sediments have been much excavated, and about 50% of the fossil-bearing exposures have been thoroughly disturbed.

It is clear that the "mummified" fossils are ephemeral once they have been exposed by erosion. For this reason we have been observing some of the exposed stumps in the forest to monitor changes that take place. In Figures 13 and 14 the same stump is shown in 1989 and in 1992. In the three years

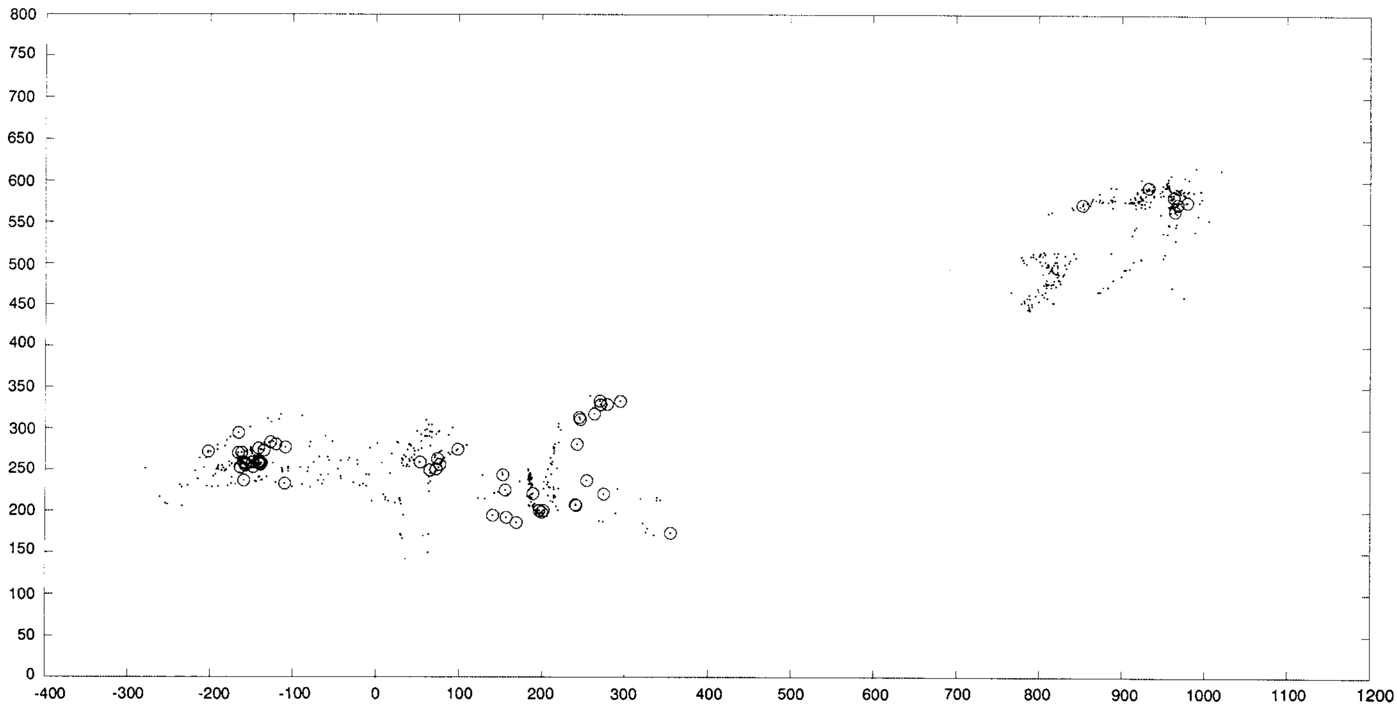


FIG. 11. Stumps surveyed in 1988, 1989 and 1992. Circled stumps were noted as missing in 1992.

that elapsed, significant changes took place. The earlier picture shows about 11 "flakes" on the upper part of the stump. These flakes are sections which have cleaved along growth rings, cracked radially, and peeled away from the trunk as they dried out. They probably peeled away because the outer surface dried more quickly and therefore shrank more than the inner surface. By 1992, these sections had broken off.

## CONCLUSIONS

The site is eroding, at least 3 mm per year on average, with erosion of slopes occurring more rapidly, particularly on the north side of the Hill, and much less erosion in the flatter regions. In future we expect to see more erosion of stumps and leaf mat. Scientifically this could be very useful—particularly if the various stages of erosion could be recorded.

Investigators and other visitors are hastening the rate of destruction by disturbing fossil deposits, by flying and walking over the site, and by removing stumps leaving unfilled excavations. We believe that scientists must continue to investigate the site, and that visitors ought to have access to see it. The question thus is how can this best be done without hastening erosion? Investigators and visitors to the site must be aware of the consequences of their actions so that damage can be minimized. Removal or excavation of stumps is a more controversial issue because another viewpoint which has been expressed (Basinger, pers. comm. 1993) is that stumps do not suffer once exposed—possibly because of natural freeze-drying—and it is better to indicate clearly disturbed regions of the site so that future investigators are not misled. While there may be some validity in these arguments, our observations show that exposed stumps deteriorate faster than those which are covered up. In an investigation of natural freeze-drying of wood several years ago, it was found that there was only a limited prevention of shrinkage for untreated wood (Grattan et. al, 1980). Degraded wood still cracked and suffered shrinkage. It is worth emphasising that wood shrinks regardless of the method of drying, and it is our observation that the fossil wood, having lost its elasticity, has very limited tolerance for dimensional change.

All exposed fossil logs, stumps and leaves are being destroyed by the environment. There is some evidence that leaf mat blocks erode at a slower rate than surrounding silts. Obviously it is futile to try to alter the natural course of events. This rate of change must be understood by those who are interested in recording or interpreting the site. It is important to record and investigate as much as possible to get a full picture as soon as possible. Further investigations could include: 1) more complete recording of the site using various media; 2) continued academic study; 3) creating a repository for samples removed that meets full current museological standards; 4) establishing a code of practice to be observed by all those investigating the site; and 5) continued monitoring of the site.

We have tried to record the site and changes in it by both ground survey and aerial photography. Ground survey only pinpoints features and is a very limited record. Aerial survey records the whole site, but not in enough detail to locate individual stumps or logs. It would be useful to have the site recorded photographically closer to the ground, using a bipod or a tethered balloon. Initial tests with a camera suspended from a kite have indicated that this might be a very useful approach.

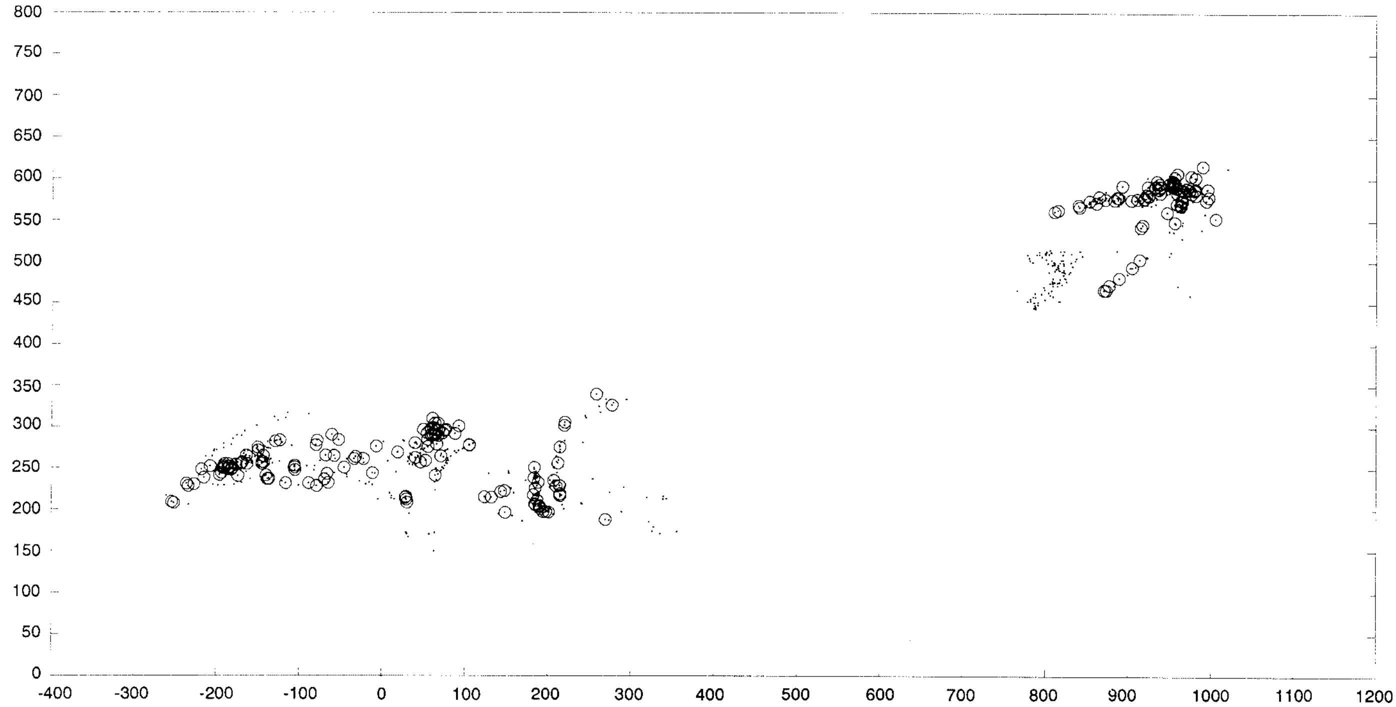


FIG. 12. Stumps surveyed in 1988, 1989 and 1992. Circled stumps were noted as newly exposed in 1992.

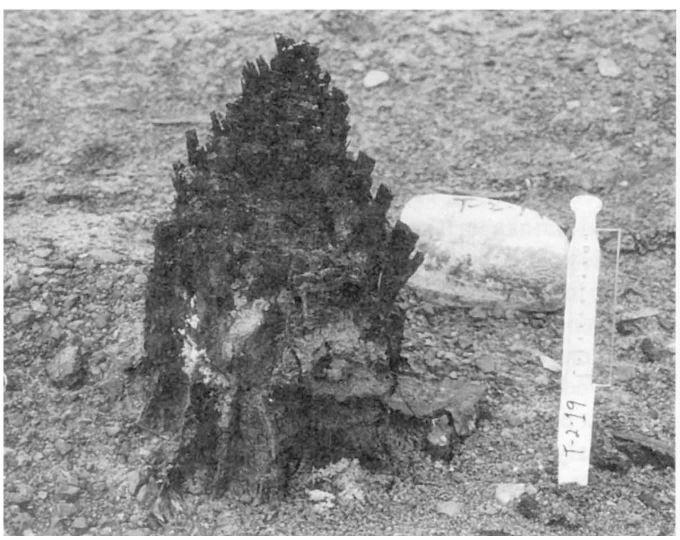


FIG. 13. Stump T2-19 when first surveyed in 1989.

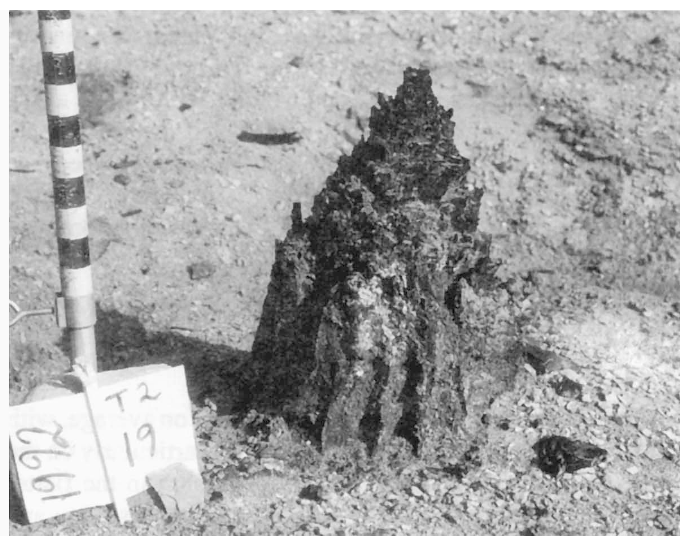


FIG. 14. Stump T2-19 in 1992. Note the losses in the surface where the wood has flaked away.

At present, small collections have been established in various institutions. In view of the fragility of the specimens and their significance, it is important to make sure that they receive the best care that current museological/conservation techniques can offer.

If the site is not monitored, we will not know what changes take place nor will we know whether this initial assessment, which is based on quite limited data, is accurate. If this site has long-term value for Canadians, then we have a responsibility to inform people about the integrity of the site.

In future, as data accumulates, it is expected that the site will become of more interest to tourists and of less interest to scientists. Perhaps the only body which can give the site the protection it needs is the Canadian Parks Service. These authors hope that in due course the Fossil Forest will be included as an annex to Ellesmere Island National Park Reserve.

## ACKNOWLEDGEMENTS

We thank the Polar Continental Shelf Project for field support, and for conducting the aerial survey; H.P. Roy for his work in the aerial survey; S. Cumbaa and R.G. Day of the Canadian Museum of Nature, for their considerable assistance on numerous occasions; and L.V. Hills for field assistance and advice. We would also like to thank

J.F. Basinger, N.J. McMillan, R.L. Christie, D.J. McIntyre, B. Ricketts, and R.G. Day for their constructive comments on this work.

## ADDENDUM

In August 1995 erosion measurements as well as down-slope slippage measurements were repeated in the Fossil Forest by David Grattan and Tom Strang of the Canadian Conservation Institute. The new information supports earlier conclusions about erosion. The overall rate now averages 0.39 cm loss of material per year (i.e., the average total loss per marker is 2.7 cm.). The maximum loss observed was 10.8 cm for a marker on a north-facing slope, where the cutting edge of a scallop-shaped wind gouge had recently passed by. Down-slope slippage in the vicinity of a major collapse basin increased towards the lip, and markers near the edge have moved as much as 20 cm down slope since 1992. On another site on the north side of the hill, markers have moved as much as 60 cm down slope since 1988. No down-slope slippage has been observed on a gentler south-facing slope. Photography of stumps has revealed that all exposed tree stumps are continuing to break up. Some which were intact in 1988 are now fragmentary; a number of "new" stumps are now visible because of surface erosion, and some stumps observed in 1992 have disappeared.

The new data suggest that, if anything, erosion rates are a little faster than measured earlier.

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