FINAL REPORT
ON
THE EFFECTS OF OFF-ROAD VEHICLES ON BEACH AND DUNE SYSTEMS FIRE ISLAND NATIONAL SEASHORE

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ABSTRACT

A three-year investigation was undertaken to examine the effects of off-road vehicles (ORVs) on the beach and dunes of Fire Island National Seashore, New York. Over 45,000 vehicle trips per year are concentrated in the zone seaward of the dune crest along this shoreline. The experimental approach was adopted in order to assess the environmental effects of ORVs. Specially developed instrumentation was used to measure the direct displacement of sand by vehicles on a daily basis. Adjacent impacted and unimpacted beaches were surveyed to examine differential profile changes. Swash and tracer tests were conducted to determine if swash interaction with vehicle tracks on the beach face contributed to additional erosion. Two experimental sites were monitored to evaluate the impacts of vehicles on the foredune vegetation and topography.

The results of the direct displacement studies showed that slope, sand compaction, and number of passes in the same track, were the principal factors controlling the measured net downslope displacement of sand. ORV tracks can lead to some increased mobility of beach sand as shown by the swash and tracer tests. This increased mobility could lead to accelerated erosion. However, there are no substantial yearly differences between natural and impacted beaches, except on and just in front of the dunes. Foredune vegetation was rapidly destroyed by low level ORV impacts, which resulted in a marked alteration in the cross-sectional profile of the dune zone. These changes signal increased dune instability during storm attack.

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SUMMARY AND MANAGEMENT RECOMMENDATIONS

Extensive research concerning the effects of off-road vehicles on barrier island ecology and morphology has previously been conducted at Cape Cod, Cape Hatteras, Padre Island, Assateague Island, and other National Seashores. In general, this research has concentrated on the vegetated environments rather than the beach zone. However, at Fire Island National Seashore, N.Y., ORV use is concentrated along the shoreline, between the dune crest and mean low water. Therefore, an investigation into the effects of off-road vehicles on the beach at Fire Island was conducted between 1977 and 1980. In particular, the National Seashore managers were concerned about the effects of ORVs in influencing natural geological processes and overall stability of the island. Both short- and long-term experiments were conducted on the beach and dune face to investigate the relationship between ORV use and barrier recession by shoreface erosion.

Direct displacement of sand as a result of ORV traffic was experimentally investigated using a specially-developed microtopography profiler. These experiments, conducted in four zones on the beach, showed that net downslope movement of sand along the beach as a result of ORV traffic does occur. Sediment displacement is directly related to beach slope and number of passes in the same vehicle track, and inversely correlated with sand compaction. The dune zone, with its steep slope and low compaction, displays the greatest net downslope movement of sand. The steep summer foreshore zone was second in net downslope displacement, followed by the backshore zones. In all cases, with the exception of the backshore-near-the-berm zone, net downslope displacement is equivalent to net seaward displacement. The north sloping backshore-berm-zone, which is generally present only during the summer-fall months, had a net duneward displacement of sand.

Although the cumulative amount of displacement increases, the net movement of sand decreases with each additional pass of a vehicle in the same track. On a pass-per-pass basis, the first several passes along the beach through a track displace the most sand, and each succeeding pass results in less sediment movement. The size of the vehicle track and overall environmental disruption of the beach followed the same trend as net downslope displacement.

The direct displacement experiments also showed that ORV traffic resulted in compaction of the beach sand at depth, but a net loosening of the surface of the beach occurred. The loosened surface material is more susceptible to aeolian and/or swash activity. Sand moisture was found to correlate highly with compaction and thus is inversely related to displacement.

The direct displacement experiments showed that ORV disruption to the beach environment could be substantially reduced by driving on the gently-sloped, highly compacted, foreshore during the winter months and on the duneward-sloping backshore-near-the-berm zone during the summer months. A substantial reduction in sediment movement by ORVs must also include a minimum number of individual ORV tracks. Ideally, one eastbound and one westbound track would reduce the environmental impact to a minimum. Speeds should be restricted to less than 30 mph since a greater rate of speed makes it impossible to stay in pre-existing tracks. With careful consideration of the above

recommendations, the present estimated maximum level of ORV sand contribution to the yearly net littoral drift (450,000 yds^3) could be reduced to only 7 per cent (29,760 yds^3) of the net amount.

The interaction between swash processes and an ORV-disturbed beach were examined using swash sampling, tracer, and swash profiling experiments. These experiments compared sediment mobility in adjacent foreshore impact and control sites. It is generally assumed that the littoral drift along the south shore of Long Island is undersupplied with sediment so that additional sand resulting form ORV activity could be easily entrained.

The results of the individual swash sampling experiments showed that in two-thirds of the tests there was more sand in the backflow of the swash on the impact side than on the unimpacted control. However, in the majority of cases, the additional sediment in suspension on the impact side was not significantly more than on the control. The remaining one-third of the tests had more sediment in the return flow of the swash on the control side, but not significantly more than on the impact side. These swash sampling results indicate that under certain conditions ORV tracks can accelerate beach erosion. An overall analysis indicates that ORVs lead to roughly twice as much suspended sediment in the backwash of impacted sites as compared to adjacent unimpacted sites.

A relative increase in sediment mobility in the swash zone and littoral drift system of adjacent impact and control sites was measured in 80 per cent of the individual tracer tests. Of these tests, 61 per cent showed the sediment on the impacted portion of the beach to be more mobile. In an overall analysis there was approximately 25 per cent greater sediment mobility for impact sites compared to the control sites during the period of experimentation.

The swash profile tests showed no difference between the foreshore profile of control and adjacent impact sites after only one tidal cycle. This finding is probably due to the insensitivity of the surveying instruments to detect very small vertical differences in elevation. There was, however, an observed reduction in sand compaction on the impact sites, which could lead to additional interaction of swash and sediment.

The three sets of swash experiments were conducted during the period of May through October, when the beach generally displays a summer profile. During this period, movement of sediment in an offshore and alongshore direction within the ORV impacted sites predominated over sediment movement in adjacent unimpacted sites. This indicates the potential for additional ORV associated erosion during the summer months. With more vigorous environmental conditions during the winter, the potential for additional ORV erosion could be expected to accelerate.

Frequent monitoring of the beach profile in adjacent control and impact sites near Kismet was designed to give longer-term data on beach changes resulting from ORV traffic. Profiles were surveyed on a periodic basis between June 1977 and October 1979. Despite the varying levels of ORV impact between sites, no major differences were noticeable in the beach profile during the period of measurement except along the dune toe. Limited measurements and observations during storms indicated that there was accelerated erosion on the impacted beach site. However, swash processes and littoral drift quickly repaired the impact beach during post-storm recovery, effectively masking the

storm erosion except near the dune. Accelerated dune erosion on the impact site did not recover during this time period.

Comparison of adjacent control and impact profiles showed that over the duration of the study the impact berm crest maintained a slightly, but significantly, more landward position than the berm crest on the unimpacted beach. Also, the backshore zone was slightly, but significantly, higher in elevation behind the berm on the impacted beach. This indicates that the impact beach profile is unnatural, but the exact effect of this small variation in profile on the stability of the beach is unknown. A similar survey site at Smith Point did not provide further insight.

During the measurement period the beach profile on the impact site was more variable than the profile on the unimpacted beach. Variability of the impact site increased during the winter months. These results also showed that a berm was present approximately half of the year, from about mid-May through mid-November.

ORV effects in the vicinity of the dune were examined at two sites: one near Whalehouse Point between July 1977 and October 1979, and one near Watch Hill between July and October 1979. In each case control and impact sites were established by closing off a section of the dune toe with posts and cable. Experimental impacts were applied at the rate of one pass per week for each one-half meter wide strip of impact site (½ m. is the maximum width directly affected by 1 pass of a tire). Vegetation and topographic profiles were monitored periodically to determine the effect of impacting.

Experiments showed that even low-level ORV impacting will severely damage dune vegetation. Within a few months the vegetation front within the impact zone was pushed landward, and density and cover were severely reduced. During the same period the vegetation cover and density increased, and the vegetation front grew seaward in the unimpacted control zone.

Elimination of low-level impacting for a five-month period resulted in modest advances in the vegetation front in the impact sites at Whalehouse Point. However, resumption of impacting at half the former level quickly destroyed the new growth. These results suggest rapid vegetation recovery is possible after impacting ceases, provided impacting has not been so severe as to destroy the dune grass rhizomes.

Dramatic changes in vegetation due to impacting were manifested in the dune topography. Periodic profiles at Whalehouse Point indicated that the impact sites showed slight erosion over the period of measurement, while the unimpacted sites showed an accumulation of sand. The result was a steepening of the foredune profile in the impacted zones. This unnatural steepening could lead to scarp formation during storm events and hence accelerated dune erosion.

The study sites at Whalehouse Point and Watch Hill confirm that even low-level driving in the vicinity of the dune toe can affect the vegetation and hence the dune topography. Therefore, even occasional driving near the dune toe during spring or storm high tides can cause significant damage. Vegetation within the exclosure advanced rapidly seaward during the period of experimentation indicating that the driving level prior to June 1977

was sufficient to retard the vegetation front in its seaward extension. Also, in selection of a second experimental site it was found that no area existed west of Watch Hill where there was substantial vegetation seaward of the dune crest. The lack of vegetation coincides with the increase in driving intensity. Furthermore, evidence from the survey site at Kismet shows that after two years of no impacting, vegetation on the control site extended an average of 15 m from the dune crest seaward, while the normally impacted site had almost no vegetation seaward of the dune crest. These measurements and observations point out that the current level of ORV use in the vicinity of the dune is beyond the carrying capacity of the vegetation. This suggests that the present topographic form of the primary dune along Fire Island has probably been altered from its natural condition by ORV use.

Measurement of scarps along Fire Island indicates that their occurrence corresponds to times when the waves approach the beach at a large angle. Scarps can cause rapid erosion of the beach and thus force drivers to impact the dune toe involuntarily. Environmental conditions which would result in the development of scarps or exceptionally high tides should be carefully monitored so that the beach can be closed to ORV use to prevent possible damage to the dune zone.

Recent wind data were collected from Kennedy Airport, which is approximately 30 miles west of Fire Island. Aeolian transport of sand is initiated by winds in excess of 12 mph. The three most recent years available (1974, 1975, 1976) indicate that winds capable of sand transport occur on an average of 47 per cent of the year. Most of the stronger winds occur during the winter and early spring months. For winds in this category, 62 per cent of the time the winds are blowing offshore (predominantly during winter), and 28 per cent of the time they blow onshore (predominantly during the summer). The dominance of offshore winds capable of sand transport, combined with a lessening of the sand compaction at the surface of the beach and destruction of the salt crust by ORVs, should lead to accelerated erosion, especially during the winter months.

Considering the entire body of data collected during this study (but not other factors such as recreational use or safety), it would be least detrimental to allow ORV use only during the summer months. During this time the beach is wide and a substantial berm is present. ORV users could ride just landward of the berm crest which would result in net sand displacement in a duneward direction. This would also help to minimize impacts to the dune zone, and interaction of the swash with ORV tracks. During the summer months, the winds capable of transporting sand are generally blowing onshore, which would nourish the dune. Scarp formation is less likely during the summer because of the generally calmer conditions, and thus drivers would not be forced near the dune toe. If driving near the toe must occur, the vegetation is quite evident during the growing season and therefore more easily avoided by the conscientious driver.

During the winter months the berm is usually not present so that net displacement of sand is seaward. The beach is generally quite narrow, and storms are more frequent, thus increasing the likelihood of impact on the dune. Also, during the winter, dune vegetation appears to be dead, and many new tillers are invisible, existing just below the sand surface. In this condition, most drivers would not hesitate to drive over the vegetation,

even if it is apparent. Furthermore, offshore winter winds generally dominate the wind regime. The zone of minimum slope and maximum compaction is the foreshore. If winter driving must occur, this beach zone is preferred since net downslope displacement is minimized, and the moist sand is less susceptible to aeolian transport. Swash interaction with loose sand could be minimized if only two ORV trails were allowed.

In the final analysis, the exact amount of erosion that occurs each year along Fire Island as a result of ORVs cannot be specifically determined, but only inferred from the data collected. Our best estimates indicate that increased sand mobility by ORV activity amounts to a maximum of 35 per cent (156,060 yds^3) of the net littoral drift. Applying a rule of thumb that 1 ft^2 of change in beach surface area is equal to 1 yd^3 of beach material gained or lost (U.S. Army Corps of Engineers, 1974) to this estimate yeilds a maximum of 0.9 ft/yr of erosion along the 33 mile length of Fire Island due to vehicle traffic. The actual contribution of ORV-mobilized sand to the longshore transport system is something less than this value. By minimizing the number of individual vehicle tracks on the beach, by driving only on the backshore-berm in summer and foreshore in winter, and by closing the beach to ORVs anytime the swash zone approaches the dune line, disruption to the beach caused by ORVs could be reduced to 7 per cent (29,760 yds^3) of the net littoral drift or less. This would amount to less than 0.2 ft/yr of erosion due to ORV use along the length of Fire Island.

INTRODUCTION

Fire Island is a dynamic barrier island along the South Shore of Long Island, N.Y. (Fig. 1). It is approximately 33 miles in length, extending from Fire Island Inlet to Moriches Inlet, and is separated from the mainland by Great South and Moriches Bays. The net westward movement of littoral drift along the South Shore supplies Fire Island with sediment derived from the eroding glacial cliffs at Montauk Point. It has been suggested that additional sand is supplied to Fire Island from an offshore source (Taney, 196la; Williams, 1976). However, the total sediment supply has been inadequate, and thus Fire Island has been undergoing seaside erosion estimated at 1.7 ft per yr (Shepard and Wanless, 1971). This erosion, coupled with rapid development in the past several decades, has led to problems approaching critical proportions (U.S. Corps of Engineers, 1976, 1977).

The effects of off-road vehicles on federal lands was the subject of much research and two Executive Orders (11644 and 11989) during the 1970's. The Executive Orders gave managers the power to control ORV use if environmental damage or safety hazards were evident. Research on various inland parks indicated that ORV use led to a reduction in environmental quality (Baldwin and Stoddard, 1973; Wilshire et al., 1976; Bury, 1976; Wilshire et al., 1978). The reader is directed to Steiner and Leatherman (1979b) for a complete annotated bibliography on ORV effects. Estensive research on the effects of ORVs in the coastal environments of Cape Cod indicated severe damage to vegetation and invertebrates (Leatherman and Godfrey, 1979). Other studies within National Seashores (Behrens et al., 1975; McAtee, 1975; Steiner and Leatherman, 1979a) and abroad (i.e., Liddle and Greig-Smith, 1975) further documented the detrimental effects of ORVs on coastal vegetation and associated soils.

Despite extensive studies of ORV impacts on coastal ecosystems, a thorough geomorphic analysis of the effects on beach environments has not been undertaken. Niedoroda (1975) found that the beach zone was not as sensitive to ORV damage as the back-dunes and thus confined most of his research to the latter. Leatherman and Long (1978) investigated ORV use and changes in beach profiles. Their results indicated increased variability in the profiles of impacted zones which could lead to accelerated erosion.

Off-road vehicles were in use on Fire Island prior to the establishment of the National Seashore in 1964 (U.S. Dept. of Interior, 1976). During the period 1977 to 1979, the western end of the Seashore alone averaged 44,175 vehicle trips per year with the average distance traveled estimated at 3 miles (NPS-FIIS records). ORV use on Fire Island is concentrated on the beach between the dune toe and mean-low-water. The effects of concentrated ORV use in this zone were unknown to Seashore managers who were charged with the responsibility of protecting the environmental quality of Fire Island. The potential for accelerated erosion over the long term as a result of ORV use was only intuitively evident. Two studies (Visco, 1977; Tauman, 1977)

indicated potentially damaging effects by ORVs. However, neither study yielded definitive answers since both suffered from lack of funding and short duration. The present study was initiated in 1977 to investigate if and how ORVs influence sand mobility and natural beach and dune erosion rates along Fire Island.

Experiments in the field were begun in June, 1977. At that time two study sites were established. The first site was located at the Kismet cross-over (Fig. 1), where the natural traffic pattern allowed us to compare the beach profile of a normally trafficated site with an adjacent unimpacted site over a three-year period. A second study site was established near Whale-house Point (Fig. 1) on the dune face to experimentally monitor the effect of ORVs on dune vegetation and topography. Direct impact studies to examine the specific displacement of beach sand by vehicles were initiated in 1977 along with swash tests, which were designed to measure possible accelerated erosion of ORV-displaced sand. These sand experiments were conducted through 1978 and 1979. Two additional study sites were established in 1979, one at Smith Point and another at Watch Hill. Experiments here duplicated those at Kismet and Whalehouse Point, respectively; this additional work was undertaken to insure that previous results were not of a site-specific nature. During 1978 greater emphasis was placed on the swash tests, and tracer tests were begun to further examine the littoral drift-ORV displaced sand question. These tests were also conducted during 1979 and 1980.

In addition to these major experiments, other measurements and observations were taken in the field. Portions of the Burma Road, which runs along the interior of Fire Island, were monitored through time. The rate of scarp retreat was also measured on two occasions. Wind data were collected from a nearby source (Kennedy Airport, 1949-1976), and the effects of ORVs on salt crusts and sand compaction were noted.

Test procedures, methods of analysis, and results are presented in this final report along with important observations and recommendations. While it is clear that this study could have been carried further through additional field tests, the authors feel confident that it represents the best possible analysis of the effects of ORVs on the beach at Fire Island given the time and resources available.

DIRECT DISPLACEMENT TESTS

Evaluation of the effects of off-road vehicles began with measurements of direct sand displacement resulting from vehicles traveling along the beach. Several variables were determined to be important in sand displacement by moving vehicles: number of passes by a vehicle in the same track, slope angle of the beach, vehicle orientation to the slope, horizontal and vertical compaction of the sand, sand moisture content, tire size and pressure, vehicle speed, and vehicle weight. Over 90 separate tests were conducted during two field seasons to determine the relationships between these variables and sand displacement.

Procedure

For each direct displacement test, certain of the experimental variables were held constant to minimize the number of critical measurements. Vehicle weight and tire size were uniform for each test. A four-wheel drive Dodge Power Wagon, of average weight (3600 lbs) with moderately wide tires (LR78x15) at 15 to 20 psi was used. Orientation of the vehicle to the natural slope of the beach was held constant at 90° for every test, which corresponds to average driving conditions along the beach. Tire pressure and vehicle speed were held constant for a particular test, but varied between the separate tests. The number of passes in the same track was increased incrementally, generally with the following progression between measurements: 1,3,5,10,15,20,25,30,40, and 50 passes. The remaining variables are associated with environmental conditions present at the time of testing, and thus were measured in the field. Upon selection of the test site, slope angle was measured using a Brunton compass. Several (at least four) measurements of slope were made perpendicular to the trend of the beach and averaged (Fig. 2). Surface sand samples were taken prior to each test and analyzed in the laboratory for moisture content by weighing each sample before and after laboratory drying. Vertical compaction was measured using a Soiltest Pocket Penetrometer with a special foot attachment for sand (Fig. 3). A specially adapted Soiltest Torvane Shear Device was used to measure horizontal compaction (Fig. 4). Both vertical and horizontal compaction were routinely measured prior to and during testing.

Test sites were selected in relatively undisturbed areas in one of four different regions (Fig. 5): (1) dune (south facing slope greater than 6 degrees), (2) backshore-near-the-dune (south facing slope between 0 and 6 degrees), (3) backshore-near-the-berm (north facing slope); and (4) foreshore (south facing slope, seaward of the berm crest). A nearly equal number of tests were conducted in each of these four zones at various locations along the length of Fire Island.

In order to accurately determine the amount of sand displaced by each pass of a vehicle, a microtopography profiler (MTP) was designed (Fig. 6). This instrument consists of a wooden frame with four adjustable legs. Suspended within the frame is a 48 inch long row of 1/4" diameter lightweight plastic rods of equal length. Loosening a clamp allows the rods to gradually descend to the surface while maintaining their single line posture. The lower ends of the rods rest on the surface, and the upper ends exactly duplicate the surface profile.

After the site was selected and the environmental variables were initialized, testing began by driving the vehicle through the test site one time at the designated speed. To determine the amount of sand displacement, the MTP was set up perpendicular to the track, and the rods were lowered to the surface. The profile of the upper end of the rods (duplicating the actual surface profile) was then traced onto a long sheet of paper (Figs. 7 and 8). The MTP was then removed, and sand compaction was remeasured in and adjacent to the tire track. The vehicle was then driven through the same track twice for a total of three passes. The MTP was set up again, at the same relative location, to determine the exact surface profile, and compaction was remeasured. This procedure was repeated after 5,10,15,20,25,30,40, and 50 passes through the same track. On several occasions 75 passes were completed to provide additional data for analysis and plotting.

Data and Analysis

The MTP data for each test were returned to the laboratory for analysis of surface profile changes resulting from vehicle impacting. Each impact profile had the original beach slope as determined from the slope gradient tied to the profile limits superimposed on it, and measurements of departure from this datum were made with a Dietzgen Polar Planimeter (Model D-1804-AM); (Fig. 9). Three primary measurements were taken for each profile: area of the track (area below the original surface, in which the tire passed), area of the downslope mound (ridge of sand downslope of the track resulting from tire displacement), and area of the upslope mound (ridge of sand upslope of the track resulting from tire displacement). From these three measurements, net downslope movement (downslope-upslope) and net disruption (track-(downslope + upslope)) were calculated.

Data from the track profiles were compared with test parameters and environmental data collected in the field. Graphical techniques allowed quantitative evaluations of the relationship between each of the test variables and the measured results.

In order to thoroughly analyze the interrelationship among all of the environmental variables and the measured results, the entire body of data was analyzed by computer with a stepwise linear regression program. The data were entered in two basic groups: (1) independent variables, which were generally the variables measured in the field during each test and (2) dependent variables, which were measured from the MTP profiles in the laboratory. The regression analysis generates an empirical equation, which defines the best combination of independent variables to explain each dependent variable. Significant in this equation is the order in which the independent variables appear. That selected first for the regression equation with F values large enough to be significant ($P<0.05$) is the most important in explaining the variance in the measured results. Each successive variable entered in the equation plays a diminished role in affecting the results.

Results

Evaluation of the displacement data produced some fundamental and important results. The average net downslope displacement, calculated from the MTP profiles, was compared to the number of passes by a vehicle in the same track for each of the four beach environments. The trend of the plots confirms that there is a net downslope movement of sand along the beach as a result of ORV

activity (Fig. 10). The shape of the curves indicate that as the number of passes increases, incremental displacement by each pass decreases in all environments. The steepest segment of the curves is near the origin, indicating that intitial passes were the most significant in displacing sand downslope. For example, the amount of additional net downslope displacement between the 2nd and 3rd passes of a vehicle in a track is much greater (33% to 200%, depending on the area) than that between the 43rd and 44th passes.

Impacts on the dune clearly resulted in the largest net downslope displacement, followed by the foreshore (Fig. 10). Area under the dune curve is twice that under the foreshore curve, and almost five times greater than the area of the back-dune and back-berm curves. However, the total amount of displacement on the foreshore was actually quite minimal. Comparison of the average volume of sand in the combined downslope and upslope mounds shows that the foreshore experienced disturbance equivalent to the backshore zones (Fig. 11).

To further investigate the reduction in net downslope displacement with vehicle passage, several tests were carried out beyond 50 passes (Fig. 12A). In these cases it can be seen that as the number of passes increases, the increment of additional displacement decreases. The noticeable deflection point of the curves begins between 5 and 10 passes (Fig. 11). Three additional tests were conducted in tracks with an unknown but substantial number of impacts (Fig. 12B). Additional impacts in these tracks resulted in some movement of sand, but the net result was little change in the downslope mound size. Deflections downward in the slope of these graphs reflect small-scale slumping, where material has moved from the mounds back into the track between impacts, resulting in a reduction in mound size.

Track data from the MTP indicated that the size of the tire impression was generally largest in the dune environment and smallest on the foreshore. This observation was confirmed by comparing the volume of the track with the number of vehicle passes for each environment (Fig. 13). Note that the vertical scale in Figure 13 is twice that in Figure 10, which means that the volume of the tire track is greater than the sediment displaced to the adjoining mounds. The shape of the curves indicates that the size of the tire track increases at an exponential rate with the first 5 passes in a track (Fig. 13). However, after 10 passes, the slope flattens considerably, which indicates less displacement in the track with each successive pass. Approximately 50% of the volume change in the track is due to compaction of the sediment at depth rather than displacement into the mounds (Fig. 14). The end result was a net elevation loss of the profile in the immediate vicinity of the track. The dependent variable, total disruption, is equal to the sum of the track volume (T) and volume of sediment in the adjacent mounds (D+U). Based on the data collected with the MTP, the dune environment sustained the greatest change with ORV impact, followed by the backshore zones, and finally the foreshore (Fig. 15). This analysis identifies the foreshore as the most resistant to change with ORV impact.

Displacement data were graphically evaluated in relation to the variables measured in the field. Horizontal and vertical compaction measurements taken in the tire track were plotted against the number of vehicle passes in the same track for each of the four zones. Foreshore sediments were well compacted, whereas dune sands exhibited the least compaction (Fig. 16). This differential amount of compaction was directly related to the higher moisture

content on the foreshore. In the backshore zones the horizontal compaction in the track decreased initially with vehicle passage, but then fluctuated near the original value with increased impact. The foreshore zones showed initial increases in horizontal compaction within the track, and compaction generally remained at a level that was higher than the pre-impact level. Vertical compaction in the track generally decreased with initial vehicle passage in all four zones due to loosening of the surficial sand (Fig. 17). Additional passes resulted in little change in the amount of compaction in the track. The net result on the beach was a loss of compaction in the ORV track.

These compaction measurements are in apparent conflict with the results obtained from the MTP profiles. Profiles showed that track volume was greater than the sum of the downslope and upslope mound volume, and hence compaction must have occurred. To resolve this apparent conflict several tests were conducted in the field in which alternating layers of dark and light sand were emplaced in the beach below the surface. These layers were impacted by a vehicle and then excavated and cross-sectioned to observe compaction with depth (Fig. 18). Calculations indicate that our test vehicle applied approximately 11 lb/in^2 of vertical pressure per tire to the sand surface (an average adult man applies about 2 lb/in^2 with each foot). These tests indicated that compaction could be measured up to depths of 35 cm. However, the uppermost surface of the track was loosened because of the shearing effect of the tires. This upper layer (approximately 2 cm thick) greatly influenced the vertical compaction readings. Thus, the net result of a vehicle passing along the beach is compaction of the sand at depth and loosening of the immediate surface layer.

Vertical compaction in the displaced mounds on either side of the track was compared to the number of passes (Fig. 19). The results in every area showed that the sand in the mounds was very loose, often below the sensitivity of the instrument (0.03 $tons/in^2/16$).

Moisture content of the surface sediment was compared to displacement after 10 passes (Fig. 20). A rough separation of points by area is apparent. The foreshore was characterized by high moisture (>2%) and low displacement, while the dune had low moisture (<2%) and high displacement. The two backshore cases lie between these extremes. There is generally a negative correlation between displacement and moisture content; greater moisture content, less displacement of sand by ORVs.

In order to determine the relationship between beach slope and vehicle disruption, initial slopes were compared to the cumulative net volume of sand displaced downslope after 50 passes (Fig. 21). These data indicated that steeper slopes generally resulted in larger downslope movement of sediment. An increasing rate of displacement vs. higher slope angles is suggested by the data. This means that as the slope steepens, the net downslope displacement grows at an increasing rate. For example, displacement on a 12^o slope will be more than double that occurring on a 6^o slope. It is apparent that the steeply-sloping face of the dunes will exhibit the greatest downslope displacements.

The effect of speed on downslope displacement appears to be quite complex (Fig. 22). Within the dune environment speed was inversely related to downslope displacement. That is, slower speeds produced more downslope movement

of sand since the vehicle tended to slide downslope on the steep dunes at low speeds. In the backshore-near-the-dune there was little correlation. In the backshore-near-the-berm and in the foreshore areas there was a positive correlation between displacement and slower speeds, but at high speeds there was no apparent relationship.

A stepwise linear regression analysis was used to examine the relationship between the independent and dependent variables measured from the MTP profiles (Table 1). Data from a total of 89 tests were used in this analysis. In every case examined, the dependent variables were largely explained by the first three independent variables (i.e. slope, number of passes, and vertical compaction) entered into the regression equation. The coefficient of determination (R^2) for these results was low (total less than 50%) because of the complex interactions between ORVs and the dynamic beach system. However, the F values associated with each equation were quite high, indicating that the results were very significant ($P < 0.01$). A total of 852 cases was used in this analysis.

The dependent variables, downslope mound size, upslope mound size, and net downslope displacement (D-U), all had a similar relationship to the independent variables (Table 2). Using the net downslope displacement to illustrate the pattern, slope was the first variable selected by the regression equation (R^2 = 29%, F = 328.2). Slope is directly related to net displacement as previously indicated (Fig. 21). The steeper the slope of the beach, the greater the component of gravity will be affecting each grain of sand. Therefore, once set in motion by an ORV pass, the number of sand grains moved in the downslope direction must increase with steepness of slope. The size of the downslope mound is strongly positively correlated with slope. The size of the upslope mound is inversely proportional to slope. Therefore, we can expect the largest upslope mounds on the backshore zones and hence the smallest net downslope displacement. The second most important independent variable was number of passes (R^2 = 10%, F = 129.9). More passes placed more grains into motion. Third was vertical compaction (R^2 = 4%, F = 52.0), and fourth was horizontal compaction (R^2 = 1%, F = 15.0). Both vertical and horizontal compaction are inversely related to downslope movement of sand. Increased compaction results in increased sand grain contact and hence increased friction between grains. Friction between grains is the primary force keeping grains from moving downslope under the influence of gravity. Therefore, the greater the compaction of the sediment, the smaller the displaced mounds.

Track size (size of the depression created by the tire) was another dependent variable examined (Table 2). The regression analysis showed that number of passes, resulting in compaction of sand at depth and motion at the surface, was the most important variable in explaining the track size (R^2 = 23%, F = 234.6). These two variables are positively correlated. The second most important variable was vertical compaction, which was found to be inversely correlated with track size (R^2 = 15%, F = 183.9). Increased compaction means increased friction and reduced motion of sand grains out of the vehicle track. Along the beach profile vertical sand compaction increases with distance from the dune, and ORV track size decreases. This explains why the foreshore had the smallest average track size, and the loosely compacted dunes resulted in the largest track size (Fig. 13). The third variable to enter the regression equation was tire pressure (R^2 = 7.5%, F = 107.8). Tire pressure is directly correlated to track size. Lower tire pressures will

help reduce ORV impact by distributing the weight of the vehicle over a broader surface. Hence there is less downward force over each square inch of track to result in compaction at depth. Slope was the fourth most important variable (R = 2%, F = 31.3), and speed was fifth (R = 1%, F = 9.8); these variables are directly related to track size.

The final dependent variable (net disruption) is equal to track size minus the sum of the downslope and upslope mounds. This variable is a measure of net elevation reduction within the area affected by an ORV pass. Variables were entered into the regression equation in the following order: number of passes, tire pressure, vertical compaction, speed, and horizontal compaction (Table 2). Vertical and horizontal compaction are negatively correlated with net disruption, while the other variables show a positive correlation.

As summarized in Table 2, slope, number of passes, vertical compaction, and tire pressure are the factors which most influence the disruption of the natural beach by vehicles. However, several important caveats must be made for this data summary. It was suggested by this statistical analysis that number of passes in the same track was an important variable in controlling displacement after any level of impacting (see Table 2). The graphic (MTP) results showed that number of passes was primarily important in the initial impacts, after which its role diminished (see Fig. 10). To resolve this nonlinear effect, the regression analysis was again computed, arbitrarily using only the data collected after 25 passes. Results of the second analysis showed that number of passes became much less important in the regression equation (Table 3). The relationship of independent variables to net downslope displacement changed significantly. Slope, which previously had an R^2 value of 29%, now had an R^2 value of 43%. Slope was a primary variable in each case, but after 25 passes its relative importance increased resulting from local slope adjustments. Number of passes became relatively unimportant (R^2 = 1%) after 25 passes as the local slope decreased and thus reduced the influence of gravity. These results confirm the general shape of the displacement curves (Figs. 10-14), indicating that less sand movement occurs with each additional vehicle pass. Number of passes was critical in the early stages of impacting when the local slopes were steep, but quickly diminished in importance.

Tire pressure was another variable that entered into the regression analysis whose importance was overestimated. A very limited range of tire pressures were evaluated in the experiments (Table 1), and thus the results may not adequately reflect the range of tire pressures normally encountered on the beach. The limited range resulted in the coefficient of variation for tire pressure being the lowest of all the variables. Therefore, once the major variables were used in the regression equation, tire pressure was selected preferentially over the remainder. Its correlation with displacement is still a positive one. Deflated tires decrease the amount of shear stress exerted on the sand surface by increasing the area of contact and decreasing the amount of pressure applied per square inch. Therefore, more pressure results in more displacement, but its importance in comparison to variables such as horizontal compaction and speed, cannot be properly assessed by the regression program. Thus, its relative importance in each of the displacement equations may be somewhat exaggerated.

Moisture was an independent variable that did not contribute to the regression equations. Horizontal compaction contributed only marginally in terms of measured displacement. Field observations during testing suggest that these variables were important in controlling ORV displacement of sand. Disparity between observation and results from the regression program can be explained by the high correlation between these two variables and vertical compaction (Table 4). The effect of the high correlation was that once vertical compaction entered into the regression equation, the remaining contribution that moisture and horizontal compaction could make to the regression equation was small, and hence they were not selected.

The case of track displacement can be used to clearly demonstrate the effect of this strong correlation. The first independent variable selected to explain track displacement was number of passes. The remaining independent variables had partial correlation coefficients as indicated in the left hand column of Table 4. Vertical compaction was the second independent variable to be selected since it had the highest partial correlation coefficient. Once it entered the equation the partial correlation coefficients of the remaining variables changed as indicated in the right hand column of Table 4. The coefficients for horizontal compaction and moisture dropped dramatically, such that they followed after slope and speed. Therefore, horizontal compaction and moisture were not used in the regression equation. In field terms the high correlation between moisture and compaction means these variables could be tested as a single factor. High moisture occurs closest to the swash zone, where continuous wave action results in a high degree of sediment compaction. Moisture content at the surface is reduced with increasing elevation toward the dunes and away from the swash. In the dunes, aeolian processes are responsible for only loosely deposited surface sediments. Moisture, horizontal compaction, and vertical compaction increase with distance from the dune, and hence displacement decreases.

Examination of correlation coefficients among speed, downslope mound, and net downslope displacement indicated a negative relationship. Upslope mound and track size were positively correlated with speed. In the field this means that as speed increased, the upslope mound increased in size while the downslope mound decreased. Track size also increased, thus resulting in a further net lowering of the local profile. Despite the very small contribution of speed to the amount of displacement, one important observation should be noted: speeds in excess of 30 mph make it difficult to stay in a pre-existing track and thus cause additional displacement by creating new tracks.

An explanation for the trend of net downslope displacement with number of passes as shown in Figure 10 was clearly needed. A local slope reduction in the track area would explain the decrease in the amount of net displacement with incremental impacting. When zero slope was approached in the track, the downslope and upslope mounds would receive sediment equally. Net displacement after each pass would therefore be minor, holding all other factors constant. In order to verify the reduction in local slope and shape of the displacement curves, measurements of slope were taken within the track after impacting (Fig. 23). Results of these post-test slope measurements are summarized in Table 5. It is obvious that the majority of slopes did decrease in angle after impacting, especially when the original slope was greater than 2°. Therefore, local slope reduction in the track was occurring after impacting, which would result in less net downslope displacement with each pass.

Discussion

The direct displacement tests point out several important considerations regarding the effects of ORVs on the beach. Vehicles move sand downslope, which generally is seaward along the beach. A constant flow of traffic would result in a net seaward migration of sand. This movement was most pronounced where slopes are the steepest, as near the dune. Downslope movement of sediment on the dune face was between 3 to 5 times the average of other beach zones. The exception to the seaward movement was the backshore-berm area, which slopes landward when present. Net migration, which is minimal in this zone, would be toward the dunes. Therefore, the backshore-berm area would be the optimim zone for driving if net seaward movement of sediment is to be minimized. If no other natural processes operated, the effect of driving on the backshore-berm zone would be to reduce the natural slope angle towards zero.

The dune zone was the most sensitive to overall environmental disruption. Size of the tire track and of displaced mounds were at a maximum in this environment, which emphasizes the fact that driving in the vicinity of the dune should be eliminated. The foreshore, with its high degree of compaction and moisture content, was the least susceptible zone to physical disturbance by ORVs.

During much of the winter at Fire Island a berm was not present. During these times the optimal place to drive is in the area where slope is at a minimum and compaction (vertical and horizontal compaction and moisture) is at a maximum. The general winter profile is a concave beach, with a fairly broad, flat foreshore with wave-compacted sand. The foreshore thus is the preferred environment for driving for minimization of ORV effects in all cases during winter.

ORV traffic changes the compaction of beach sand in the vicinity of the track. While compacting the sand at depth, which may lead to less percolation of swash, the immediate surface layer becomes less densely compacted. Loosened sediment could be more susceptible to swash processes, especially if velocities are not reduced by percolation and turbulence is increased. This loosened sediment could also be more susceptible to aeolian activity. Depending on wind direction, increased aeolian sediment transport could be viewed as beneficial or detrimental to the beach (Leatherman and Long, 1978). Vehicle tracks can act as traps for aeolian sand when blown perpendicular to track orientation, but wind directions vary considerably. Therefore, net aeolian transport of sand is enhanced by ORV tracks on the beach. The foreshore is the preferred environment for driving since direct sand displacement by the tire is minimized and moisture is high, hence the potential for aeolian transport is insignificant.

One of the major factors controlling environmental disturbance of the beach and net downslope movement of sand was the number of passes in the same track. Displacement can be greatly reduced by having drivers use pre-existing tracks rather than making new ones. For example, if 100 drivers travelled 3 miles on the beach backshore-dune area along a different path, they would displace approximately 1220 yd^3 of sand seaward. If those same 100 drivers travelled in just two tracks (i.e., one for eastbound traffic and one for westbound), only 74 yd^3 of sand would be displaced seaward. Restricting the number of new tracks on the beach will greatly minimize the amount of sand displacement by ORVs.

A few other practices will also aid in minimizing ORV disturbance to the natural beach. Speeds should be kept well below 30 mph or less to insure that vehicles stay in the same track. Tire pressures should be as low as conveniently possible (approximately 15 psi, depending on tire characteristics). In all tests conducted on the beach, the vehicle was orientated perpendicular to the natural slope. Turns were not specifically measured to determine the amount of displacement, but observations indicated that large volumes of sand were moved to the outside of the track in these cases. Also, tracks at turns appeared to be quite deep. The result is a greater disruption when sharp turns are made on the beach face. Vehicle weight and tire size were also constant for the test. Changing these factors would affect the magnitude of the results, but not the general trends. Light vehicles with wide tires will obviously result in less damage.

Gross estimates of the amount of sediment moving seaward as a result of ORV activity can be made using Fig. 10. These are only estimates because specific data on driving habits are unknown. Also, environmental factors such as wind velocity, tidal height, etc., vary on a daily basis and would affect the final result. Most of the direct displacement tests were conducted during the summer months when a berm was present. The steeper foreshore during the summer was not typically present during the winter. It should also be noted that these figures only indicate the net amount of sediment pushed seaward by vehicles and not the amount lost by erosion. Beach position, aeolian processes, and hydraulic processes determine how much of this displaced sand is actually removed from the beach profile. Between 45,000 and 65,000 vehicle trips were recorded for each year from 1977 through 1979 at Fire Island. At the western end, between 30,000 and 50,000 one-way trips, an average of 3 miles per trip were recorded. The eastern end varied between 14,000 and 17,000 one-way trips of approximately 8 miles each. (Data provided by Fire Island National Seashore). Each vehicle makes two tracks as it proceeds along the beach.

In Case 1 we assume the worst possible situation: all drivers are concentrated in one zone of the beach and each is following a separate trail. A conservative total of 36,000 drivers/yr for the west end, and 14,500 drivers/yr for the east end would mean a maximum of 224,000 miles of trail would be created. This amount of impact would result in a large range of net downslope displacement according to the four zones (Table 6). Over 4 million yd^3 of sand would be displaced in the dune zone alone if driving took place there.

In Case 2 we assume the best possible case: all drivers are concentrated in one zone of the beach and each is following one of two trails already established. Each track is 3 miles long on the west end and 8 miles long on the east end and 2 tracks are used. The net downslope displacement for one year in each of the four zones would be several orders of magnitude less than in Case 1 (Table 6).

Comparing these figures to estimates of net yearly longshore transport along Fire Island yields results ranging from 0.07% to 230% of the net drift. Estimates of net transport at Fire Island Inlet, based on the rate of growth of Democrat Point, vary between 400,000 and 600,000 yds^3 per year, with the most recent estimates at 450,000 yds^3 per year (Craig Everts, pers. comm. 1981). Comparison of ORV displaced sand with net drift rates do not take into account daily fluctuations in the littoral drift and thus results in higher estimates of the potential ORV sand contribution to beach erosion. A more appropriate comparison might be made between the potential ORV sand contribution and the gross littoral drift along Fire Island; however, no accurate estimates exist for the yearly gross transport.

Cases 1 and 2 represent extremes which bracket the real driving situations. Case 3 is a more realistic scenario for Fire Island. One hundred passes per day occur on the west end, and 40 passes per day occur on the east end, distributed as follows: 36% in two trails on the back-berm, 36% in two trails on the back-dune, 24% in two trails on the foreshore, and 4% in one trail on the dune toe. Old tracks are destroyed once every 3 days by natural processes. Displacement for a 3-day period would total 1413 yd^3 (Table 6). After one year, sand displacement would total 169,560 yds^3, which is about 38% of the total net littoral drift. However, the net seaward movement of material on the beach would be only 156,060 yds^3, since the back-berm measurements must be taken as a negative value (assumes a berm is present half of the year). The resulting amount of sand movement by vehicles in a down-beach direction is 35% of the volume of sediment moved by the net littoral drift.

A fourth case to consider is one in which every attempt was made to minimize impacts without reducing the current level of driving. In this case all impacts would occur on the foreshore in just two tracks during the winter "bermless" months, and traffic would be concentrated in two tracks on the back-berm area during the remainder of the year. Then for a 3-day period the displacement would be 670 yds^3 on the foreshore and 174 yds^3 on the back-berm (Table 6). On a yearly basis this level of impact would result in 40,200 yds^3 of displacement on the foreshore and 10,440 yds^3 on the backshore-berm. The net seaward movement of sand would be 29,760 yds^3 per year, which represents only 7% of the volume of sediment in the littoral drift system at Fire Island.

These figures only indicate the amounts of sand moved downslope by vehicles. As previously indicated, the actual potential for ORV-induced erosion would have to be something less than these values depending on the interactions between displaced sediment and vehicle tracks with swash processes and wind.

SWASH AND TRACER STUDIES

Results of the direct sand displacement tests showed a net seaward movement of beach sand due to downslope gravitational movement of sediment following vehicular impact. It is important to understand the interactions between a vehicle-disturbed beach and swash processes because additional mobility of sediment in the swash as a result of vehicle impacts could lead to accelerated erosion. Three different tests--swash sampling, tracer, and swash profile--were designed and carried out to investigate the potential for increased sediment mobility in the swash as a result of vehicular traffic. A generally accepted assumption (see McCormick, 1975) is that the littoral drift along the South Shore of Long Island is undersupplied with sediment over the long term and hence erosion is occurring along the beaches. Therefore, additional sand delivered to the swash zone by vehicular impact could incrementally be lost from the Fire Island beach system.

Procedure

Each of the three tests required the same initial conditions. A relatively unimpacted, uniform section of the foreshore was selected. This area was blocked from further vehicle traffic by constructing a temporary fence with posts and rope (Fig. 24). This exclosure extended the length of the test site along the berm crest (limit of swash penetration) and then seaward to the beach step. After one tidal cycle passed and removed all visible traces of vehicular traffic, the area was divided into a control site and a downdrift impact site. At the appropriate tidal position vehicular impacts were experimentally applied with our vehicle to the impact site of the exclosure (Fig. 25). Specification of the existing field conditions was required due to wide variations between tests. Therefore, measurements were taken of the following environmental parameters immediately prior to each test: wave height (average of eleven or more breaking wave heights using a hand-held wave staff), wave period (timed passage of eleven wave crests using a fixed point, and at least 3 period measurements averaged per test), wave direction (direction of predominant wave approach, determined with Brunton Compass), swash period (timed passage of eleven swashes passed a fixed object on the mid-point of the foreshore, at least 3 period measurements averaged per test), current direction (determined by movement of fluorescene dye released in the nearshore zone), current velocity (average of at least 3 measurements of the rate at which a floating object traveled a fixed distance), foreshore slope (average of at least 5 measurements of the maximum slope angle, variously distributed across the foreshore).

Swash sampling tests required two specially built sampling devices. Each sampler consisted of a length of PVC tube with two spongy rubber balls held firmly in each end as stoppers by a connecting length of surgical tubing (after Leatherman, 1978; Fig. 26). For the tests the balls were pulled out of the line of the tube, allowing water to pass freely through it. The tube was aligned parallel to the return flow of the swash. The balls, attached to a manual trigger, were released when activated, trapping a sample of water and suspended sediment in the tube (Fig. 27). A long handle with spacers attached to the bottom of the tube insured that scouring effects around the sampler were minimal.

For swash sampling tests, impacts were applied at low tide. On the rising tide a sampling device was positioned at each site (control and impact), approximately midway between the upper limit of swash penetration and the step (Fig. 28). Both sampling devices were located at the same elevation on the foreshore and fairly close together to minimize any natural longshore variations. As a swash impinged upon both the impact and control sites, the cocked samplers were readied. With initiation of the return flow, the samplers were simultaneously lowered to the foreshore surface and the triggers were released, trapping a suspended sediment sample from each site. The volume of water trapped in the sample was measured in a graduated cylinder in the field (Fig. 29). The suspended sediment was carefully cleaned out of the sampler and bagged for further analysis. The samplers were then re-cocked and positioned for the next swash. Between 10 and 34 paired samples were collected during each test. A total of 18 separate tests were conducted under various conditions. Tests 1 through 8 were conducted in the vicinity of Whalehouse Point, tests 9 and 10 at Kismet, and tests 11 through 18 in the vicinity of Watch Hill.

For the tracer tests two equal volumes of sand (1 gallon) were collected from the foreshore and ovendried, and then painted with fluorescent orange (impact) and fluorescent green (control) spray paint (Fig. 30). All clumped sand gains were disaggregated after drying. Impacting was conducted at low tide in preparation for the advance of the high tide swash. A point within the impacted zone at approximately the mid-swash position of the previous high tide was selected as the injection point for the tracer sand. Twenty meters downdrift of this point the impact sampling line was established (Fig. 31). This line was set perpendicular to the trend of the beach and extended from the high tide swash penetration to 10 meters seaward. It was divided into two 5 meter long sampling lines. A similar injection point and sampling line was established in the adjacent control site.

At exactly 32 minutes before high tide the tracer sand was injected simultaneously at the control and impact sites (Williams et al. 1976). At one-half hour before high tide the first samples were taken from all four 5-meter long sampling lines. A sample from each line was taken every two minutes thereafter until one-half hour after high tide. The strategy for sampling around high tide was to minimize tidal influences between individual tests.

A total of four channel samples (a surficial scraping) were collected every two minutes: an upper and lower impact and an upper and lower control. Each channel sample was taken for a length of 5 m and to a depth of 3 cm, corresponding to the active sediment layer. Channel width was about 10 cm; this was governed strictly by the sampling device (Fig. 32). A piece of rectangular downspout pipe was used to take the sample. A pre-marked sample bag was held over one end, and the other end was pushed forward along the surface of the sampling line at the proper depth (Fig. 33). The sample was pushed through the pipe into the attached bag. After each sample was collected, the sampler was rinsed and a new bag was attached. A total of 120 samples was collected for each test, and 10 individual tests on different occasions were conducted at various locations along the length of Fire Island.

The swash profile tests started with establishment of a control and impact survey line perpendicular to the trend of the beach on the foreshore. A profile of each line was carefully surveyed at 0.5 m intervals at low tide, using standard rod-and-transit techniques. Vehicle impacting was then applied to the appropriate line. At the following low tide, the beach was resurveyed

along the same lines to determine if any profile changes were evident in the impact or control areas. After this survey, the impact area was again impacted and both areas were resurveyed at the next low tide. Penetrometer readings were also taken in conjunction with each survey to determine if impacting affected sand compaction after a complete tidal cycle. This test was conducted on only 4 occasions due to time limitations.

Data and Analysis

Samples from the swash tests were returned to the laboratory where they were dried and weighed. Weight per unit volume of water (g/ml) was then calculated using the volume data collected in the field. Data from the 18 swash tests were first treated as a whole for analysis purposes. Non-parametric Sign Tests and Wilcoxon Signed-Rank Tests were used to compare the 361 paired samples. Each test was then treated individually to determine if the difference in suspended sediment for impact and control sites was significant. An analysis of variance was calculated, using BMDP statistical computer programs. This analysis included the Levene Test and the Brown-Forsythe Test which calculate F statistics assuming an inequality in the group variances. Further analysis was necessary using the Non-parametric Sign Tests and Wilcoxon Signed-Rank Tests. Results of each test were also graphically compared to field-measured environmental variables.

Laboratory procedure for the tracer test first required thorough mixing of the samples. Once mixed, a uniform volume (240 ml) was extracted from each sample and spread out to form a very thin layer of sediment. A black light was used to count the number of fluorescent grains per unit volume of sample. Graphs of number of grains vs. elapsed time were constructed. Results of these graphs were compared to the various environmental variables measured in the field. Data on the number of grains counted in impact and control areas were also treated as paired samples, and Non-parametric Sign Tests and Wilcoxon Signed-Rank Tests were run on the entire data set. A total of 450 paired samples was used in the analysis.

Elevational profiles and compaction graphs were constructed from the swash transect data. These were evaluated to determine if the impact profile varied differently from the control profile.

Results

All 361 paired impact and control swash samples were compared using a BMDP non-parametric statistical package. This analysis indicated that, in 59% (216) of the paired samples, there was more sediment carried in the backwash per unit volume on the impact as compared to the control area. The mean weight/unit volume for the 361 impact samples was 4.3×10^{-2} g/ml vs. 2.3×10^{-2} g/ml for the mean weight/unit volume of the 361 control samples. Results from this over-all comparison indicated that the difference in weights per unit volume is highly significant ($P<0.01$). This suggests that over the range of conditions measured, impacting led, by a very narrow margin, to more sediment in the return flow of the swash.

Results of the 18 individual swash sampling tests are summarized in Table 7. The non-parametric statistical analysis showed that in only 4 of the 18 swash sampling tests was the amount of sediment in the impact samples sig-

nificantly larger ($P < 0.05$) than in the control samples. An additional eight tests showed more sand in the impact swash than the control, but not significantly more. One test showed equal amounts in the control and impact. The remaining five tests showed more suspended sediment in the control samples, but not significantly more. This indicates that impacting can lead to more sediment in suspension in the return flow of the swash, but not in all cases.

The environmental variables measured in the field were compared to the results of the 18 individual tests to determine if a certain variable or group of variables were responsible for the measured relationship between impact and control sediment weights (Table 8). No clear relationships were evident, however. In a few cases it was observed that control volume exceeded impact volume when wave heights (H_b) were small (<2.8 ft). It was also determined that in every case where the control site exhibited increased sediment transport, the longshore current was moving in an east-to-west direction and vice versa (Table 8). Angle of wave approach, wave height, and nearshore topography influence the direction and nature of the longshore current. It is not clear why the current would differentially affect two adjacent areas, especially since the other measured environmental variables provided no further discrimination.

Results of the tracer tests are summarized in Table 9. These data were also graphically portrayed (Figures 34-37). The plots indicate that in five of ten tracer cases, the impact side had more tracer sediment arriving sooner and in larger quantities than the control samples. This indicates a greater sediment mobility in ORV impacted sites for these tests. However, three tests showed more mobility in the control area, and the remaining two showed no real difference between impact and control. The plots exhibit two general forms: one of exponential decay of tracer grains with time (i.e., Fig. 34) and one of increased tracer grains until high tide and then a subsequent decrease (i.e., Fig. 35). No relationship was apparent between the form of the plot and dominance of impact or control.

The environmental variables measured in the field prior to each test were compared to the graphic results (Table 8). Of the seven variables measured, only current direction seemed to vary in a linear fashion with the tests. The three tests in which the control site sediment was more mobile than the impact site sediment all had a west-to-east longshore current. Four of the five tests in which the impact site was more mobile had an east-to-west current. The reason for this division based on current is not clear at this time.

Data on the number of grains counted in the impact and the control were also treated as paired samples using non-parametric statistics. A total of 450 paired samples was used in the analysis (Data from tests 1 and 2 were not used in this analysis because the sampling procedure was slightly different in these cases). The mean number of tracer grains counted per sample for the impact sites was 40.3 compared to 30.4 grains for the control. Sign Tests and Wilcoxon Signed-Rank Tests indicated that the difference between impact and control is significant ($P < 0.01$). This suggests that ORV impact increases the overall mobility of the beach sediment, within the range of conditions tested. However, the results of the individual tests showed that on a daily basis impacting does not always lead to increased sediment mobility.

There appeared to be no major differences between impact and control foreshore profiles. Examples of the results of the swash profile tests are given

in Figures 38, 39, and 40. Small profile variations may exist on the beach as a result of impacting, but these differences are not detectable, using this method of surveying and graphic illustration.

Penetrometer readings (to determine differential compaction on the foreshore) were taken concurrent with the swash profiles. The magnitude of change measured as a result of impaction was small relative to the changes occurring on the undisturbed beach. Observations in the field after conducting swash sampling and tracer tests indicated a net loosening of the foreshore surface sediment (Fig. 41).

Caution should be exercised in interpreting and applying these results, since there were a limited number of each type of test, and a limited range of environmental conditions. The nature of the tests and the large manpower requirements prevented further testing, which would have been beneficial. Despite this shortcoming, the results do have significant value in evaluating the effects of ORVs on the foreshore at Fire Island.

Discussion

In both the swash sampling tests and the tracer tests, the results showed that on an individual, day-to-day test basis, there are cases when impacting did not lead to more suspension and mobility of beach sediment. Observations indicated that at certain times (i.e., post-storm beach depositional conditions) vehicle tracks may even enhance the deposition of sediment on the beach. However, in well over half of the swash and tracer tests, impacting did lead to additional sand in suspension in the swash/surf zone, which could lead to accelerated erosion depending on environmental conditions. On an individual test basis, the extra amount of sand on the impact side was not always significantly larger than on the control, but grouping all the test data together, the overall difference between impact and control was significant. The impact side had almost double the amount of sediment in suspension as the control side, and mobility of sediment alongshore was 25% greater on the impact side.

The swash profile tests indicated that while sediment may be more mobile in impacted areas, no apparent difference in profile was evident after one tidal cycle. As stated earlier, the lack of apparent difference between impact and control profiles could be due to the inability of the measurement technique to detect small changes. Over time, these small undetectable differences between impact and control could be important. For example, a layer of sediment only 1 mm thick would not be detectable by this surveying method and would certainly not be graphable. However, if a 1 mm thick layer were eroded from a foreshore 9 m wide of an impacted beach 1.6 km long, it would result in the removal of roughly $13m^3$ of sand. This is equivalent to 3 to 4 dump trucks full. Observations indicated that a vehicle track could withstand approximately 10 swashes before its form was destroyed.

The swash profile tests also indicated a loosening of the foreshore beach sand as a result of impacting. This loosened material may in fact be related to the additional sediment mobility on the impact sites. Vehicle tracks and associated loose, displaced mounds of sand increase the roughness of the beach. The result of increased surface roughness is a decrease in swash uprush and an

increase in the turbulence of the return flow. The increased turbulence allows for more sediment to be entrained in the return flow. As the swash moves up the beach with increasing tidal stage, the zone of increased turbulence moves with it. The end result after one tidal cycle is the increased entrainment of foreshore sediment where loosened by ORV activity.

Additional turbulence in the swash zone is indicated by several observations. Figure 42 shows the turbulence of the swash around an impacted area and a reflected wave. Reflected waves from seawalls have been known to greatly accelerate beach erosion (Herbish and Ko, 1968). Figures 43 and 44 show heavy mineral concentrations at the surface of the foreshore associated with pedestrian and vehicular traffic. Heavy minerals, having a higher specific gravity, are stable on the foreshore under more turbulent conditions. Their presence, therefore, suggests that increased turbulence resulted in erosion of the lighter quartz sand grains, leaving the heavy minerals as a lag concentrate. Additional turbulence was produced by disruption of the smooth surface profile.

The specific environmental conditions associated with each test did not help decipher the critical variables prerequisite for accelerated erosion or deposition on the impact sites. In fact, the one factor which did vary consistently--current direction--yielded opposite results for the swash sampling and tracer tests. The role of current direction in determining erosion or deposition at one site on the beach is unclear at this time.

One other point to consider is the effect of ORVs on the natural mobility of the beach sand. Under a no-impact condition the amount of sediment moving along a beach varies with the environmental conditions. The effect of impacting increases the mobility at times and decreases it other times and therefore bounds of the normal range of sediment mobility are expanded. This could lead to changes in beach erosion rates such that it would be difficult or impossible to predict the long-term consequences of such cultural manipulations of the system.

BEACH PROFILES

At the inception of the study, a field site was selected near Kismet to investigate the effects of vehicle traffic on the beach face and its configuration. Form is a response to the interaction of wave-swash processes and sediment on the beach. A similar site was established during the third year of the study in the vicinity of Smith Point (Fig. 1).

All traffic traveling along the western end of Fire Island must enter or exit the beach at the Kismet dune cut (Fig. 45). Therefore, the beach immediately east of the cut receives heavy vehicle use while just west of the cut there is little vehicle traffic. Likewise, the point on the eastern end of Fire Island for traffic entering or exiting in the National Seashore is the Smith Point dune cut. In both cases we compared the heavily traveled (impact) beach to the lightly traveled (control) beach. The close proximity of the control and impact is assumed to minimize natural longshore variations. Observable differences in the beach form can therefore be attributed to vehicle impacts.

Procedure

At each field site a base line was established at the toe of the dunes, parallel to the trend of the beach (Figs. 46 and 47). Six stakes driven into the beach, spaced 50 m apart, were used to mark the line. Three stakes each were used to mark the control and impact lines. A stable benchmark was established behind the dunes for both sites. In the case of the Kismet site the benchmark was tied into known elevational benchmarks. At Smith Point only relative elevations are known.

Periodically, a profile line was surveyed from each of the six stakes, perpendicular to the trend of the baseline (Fig. 48). Standard rod-and-transit techniques were used to determine the profile elevations at a 2 m interval. The deeply rutted impact profile was smoothed prior to surveying to obtain an "average" profile (Leatherman and Long, 1978). At Kismet bi-weekly surveys were conducted during June to August and at least bi-monthly from September to May for 3 successive years (1976-1979). The period of record at Smith Point covers only one field season (1979) of surveys.

Data and Analysis

A computer was utilized to reduce and machine-plot the beach profile survey data. Areas under the curve were calculated for comparative purposes. These profiles were examined to identify any differences between impact and control. Average profiles and profile variations were also constructed for each location. Selected profiles will be discussed in this section. Berm height and beach width were compared for control and impact sites, using BMDP statistical programs.

Results

At Kismet a three-year profile record was obtained. From June 1977 until mid-September 1977 the beach in both the control and impact areas exhibited a summer profile with a definite berm (Figs. 49 and 50). During this time period the berm constantly shifted position and fluctuated in height.

In mid-September a small coastal storm partially removed the berm along the entire beach (Fig. 51), resulting in a uniform seaward slope (concave upward profile). The amount of sediment removed from the control and impact sites was not significantly different. Some recovery of the berm occurred (Fig. 52), but this was short-lived since a second small storm later in October 1977 completely removed any traces of the berm (Figs. 53 and 54). The narrow beach prevented accurate surveying beyond 20 meters in a seaward direction along certain profiles. The profiles indicate that within the 20-meter band uniformly surveyed along all lines, the control site lost an average volume of 6.3 m^3/m (standard deviation(s) = 2.6), while the impact site lost only 2.5 m^3/m (s = 6.3). However, by mid-January 1978 (Figs. 55 and 56) the control had increased in volume by an average of 6.1 m^3/m (s = .8), while during the same period the impact lost an average of 0.2 m^3/m (s = 19.3). This analysis indicates that the impact area exhibited greater variability in its erosion and deposition patterns.

The storm of February 6-8, 1978 was responsible for large scale erosion along Fire Island. Within the 30 meters of uniformly measurable beach at our experimental site, the impact area lost an average volume of 31.1 m^3/m (s = 0.9) of sand from the mid-January position (Figs. 55 and 56). A T-test determined that the control lost significantly ($P<0.025$) less: 19.1 m^3/m (s = 21.9). Recovery of the beach following the storm was slow (Figs. 57 and 58). By mid-May 1978 the impact increased its volume by an average of 23.3 m^3/m, while the control only increased by 12.5 m^3/m. A berm had formed by this date on both sites. Variation between survey lines during this time interval was greater in the control site. Comparison of profiles between June 1977 and June 1978 (Figs. 59 and 60) indicated incomplete beach recovery resulting from the February storm. The impact volume averaged 29.9 m^3/m (s = 18.1) less than the previous year, while the control volume was reduced only 16 m^3/m (s = 0.9). By late August the beach in both the impact and control sites had recovered sufficiently to effectively mask any traces of the February storm erosion. There was no significant difference in the beach profiles from the previous August (Figs. 61 and 62).

An important observation should be presented at this point. During the establishment of the field site in 1977 the baseline was located at the toe of the dune. During the February storm, the dune line was severely eroded, leaving our baseline exposed on the impact backshore. The baseline was resurveyed and moved back 6 m to the toe of the dune on the impact side. The control side required no immediate movement of baseline stakes since the dune had retreated only 1 or 2 meters during the February storm. Almost no recovery of the dune is visually evident since that date on either the control or impact sites.

From October 1978 until June 1979 the beach displayed a winter profile. No major storms occurred during the '78-'79 winter season. Intensive surveying was conducted from April 30 to May 2, 1979, corresponding to a major reduction (43%) in driving levels during this time period. The upper section

of the profile (0-40 m) in both impact and control showed a slight loss of sediment. In the lower portions of the profile (40-72 m) both sites accumulated sand, but a T-test showed the impact accumulated significantly ($P < 0.05$) more (75%) than the control (3.3 m^3/m vs. 0.3 m^3/m). The sediment deficit present on the impact side of the beach may be attributed to ORVs or natural causes, but it is interesting to note that the profile was restored after impacting ceased. A definite berm developed on both sites by mid-June 1979, and remained intact through August. Minor variations in berm position and height are evident during that time. Over the two-year period of July 1977 to July 1979, no major changes in the beach profiles are evident within or between the impact and control sites. Despite the evident short-term differences from June 1977 through August 1979, the impact and control sites exhibited long-term equality (Figs. 63 and 64).

Profile elevations were examined to compute the average winter and summer profiles (Figs. 65-68). Also, standard deviation in elevation around each point was computed and graphed. Deviation about the mean shows the normal range of the beach profile which represents the day-to-day conditions under which ORVs travel. From these graphs it is evident that the profile range for the impact case was increased over the normal range as indicated by the control profiles. This is especially evident in the vicinity of the dunes and backshore where the normal profile range was less than 0.4 m. On the impact site the profile range was increased to approximately 0.5 m during the summer months. During the winter, when no berm is present and the beach is narrow, driving occurs closer to the dune. At this time the elevation of the impact profile near the dune varied approximately 1.0 m.

In the two control cases (summer and winter) variability in the beach profile increased progressively seaward until a certain point was reached where the variability was reduced and remained fairly constant thereafter (Figs. 65 and 67). The point at which the increased profile variability tapers off appears to coincide with the limit of swash action on the beach (40-50 m from the dune toe without a berm, and 60 m with a berm). The variability on the impact sites (summer and winter) increased very rapidly and to a higher level near the dunes than the control sites (Figs. 66 and 68). This high variability was maintained seaward until the same point was reached on the foreshore. This point approximately coincided with the upper limit of wave runup and hence regular ORV track removal. Variability of the profile was reduced seaward of this point.

During the period of measurement (June 1977 through August 1979) the profiles indicated that a berm was present on the impact site approximately 60% of the time vs. 55% for the control site. Thus, there was no significant difference in berm presence, only in its configuration.

Measurements of the height of the berm crest (when present) and the elevation of the lowest point on the backshore were compared in control and impact areas. The distance between those points was also compared over the duration of the study. The data for all three survey lines on the control yielded an average distance of 14.7 m ($s = 5.8$) between the berm crest and the lowest point on the backshore. The impact profiles had an average distance of 12.3 m ($s = 5.5$). A one-way ANOVA test indicated that the 2.4 m difference between control and impact was significant ($P < 0.05$).

Elevations of the berm on the impact lines averaged 1.85 m (s = 0.7) and 1.82 m (s = 0.8) on the control; this difference is not significant. The elevation of the backshore low point was measured relative to the height of the berm crest. Elevation of the low point on the impact site averaged 0.28 m (s = 0.20) below the berm crest. On the control site the low point averaged 0.39 m (s = 0.22) below the berm crest. An analysis of the variance indicated that the difference in backshore elevations (impact 0.11 m higher) is significant ($P < 0.05$), despite the small difference.

Periodic surveys and berm measurements were also made at the Smith Point site. However, the short period of record (June 1979 to October 1979) prevented extensive analysis. The five surveys conducted during this time period did not reveal any major variations in the control and impact profiles (Figs. 69 and 70). In general, the profiles showed that the berm grew in height from late June to early August. From August through October the berm retreated landward. Analysis of these five data sets did not indicate any significant difference in berm position or height between the impact and control sites.

Discussion

Short-term differences were evident between the impact and control sites. For example, the February 1978 storm resulted in much more erosion on the impact than the control site. Assuming that close proximity of the two sites prevented natural variations of this magnitude, differences can be attributed to ORV impacts. Based on this one case only, one would conclude that impacting does lead to accelerated erosion during major coastal storms, which agrees with the findings of Tauman (1977). However, additional evidence from a much smaller storm in October 1977 provided opposite results to invalidate this conclusion.

In both cases, it is important to note beach response after the storm event. Natural forces (i.e., longshore drift) acted to equalize the beach such that the deficit in any one area was no longer noticeable. Recovery after the February storm was most rapid on the impact site. After the small October 1977 storm, recovery occurred on the control site, while erosion continued on the impact site. In each case the final result was an equalization of the beach over the entire study area.

It is important to recognize that severe dune erosion occurred along the impact lines while almost no dune erosion occurred on the control lines during the February 1978 storm. The results from one storm cannot be considered conclusive; however, these data do suggest that ORV impact can result in some additional permanent loss of sand if erosion progresses to the dunes.

Small variations in the berm position at Kismet were evident over the short term, and were significant during the entire study period. The difference in backshore heights between control and impact was due to ORV traffic directly moving sand downhill and thereby increasing the elevation of the backshore. The specific effect of these slight changes in profile are not known, but they could influence a beach's overall response to storm attack.

Despite the greater variability in the impact profile, no major difference occurred in the average control and impact profiles. The wider range of variation on the impact site is due to ORV traffic. The result of this increased sediment transport on the impact site appeared to be minor since

the long-term profiles appear similar. It is apparent that any major short-term differences between the control and impact sites, with the exception of those already discussed, would be masked over the longer term by the natural forces acting on the beach. The very nature of wave attack is to establish a straight, uniform coastline by filling indentations and eroding protruding points. If the indentations have resulted due to erosion of ORV impacted sites then each equilibration involves infilling at the expense of adjacent unimpacted sites. The result is a small net erosion. It should be remembered that on any beach on which there is both impacted and non-impacted areas there are spatial and temporal lags in the natural system so that uniformity of the beach can only be considered over the long term.

A commonly held viewpoint is that the effects of ORVs are small compared to those of coastal storms. Most geologists would agree with this statement, and these data support this contention. However, the question arises as to the incremental effects of ORVs on a beach. Given two identical beaches, one with ORVs and one without, would they behave similarly during a storm? The February storm profiles and the greater variability along the impact profiles suggest that they behave differently, but the longshore drift and natural beach dynamics mask any long-term evidence.

Thompson (1978) showed that even continuous dredging of beach sediment by conveyor belt produced only a very short-term deficit in the locally impacted shoreline because of the equilibration of natural forces. Over the long term, the only way major beach profile differences could be measured adequately would be to have two identical but totally independent field areas, one with impacting and the other without or else revert to extensive controlled laboratory experiments with their inherent scale problems.

FOREDUNE STUDIES

The effects of ORVs on dune vegetation have been evaluated at Whalehouse Point (Fig. 1) since the inception of the study in 1977. This site consisted of one control and two adjacent experimental impact areas. A similar site with only one impact area was established during 1979 at Watch Hill (Fig. 1). Both sites were selected because they are among only a few areas on Fire Island where there is still extensive vegetation seaward of the primary dune. Uniformity of vegetation within each site, in terms of seaward extent, density, and species present, was also a primary consideration in selection. Beach grass (Ammophila breviligulata) and Dusty Miller (Artemisia stellariana) are the most abundant species present on the foredunes. Growth and development of the foredune is closely linked to the health and abundance of these species. Beach grass is especially noted for its ability to trap blowing sand. Therefore, in addition to monitoring ORV effects on dune vegetation, the foredune profile was periodically examined to determine if vegetative changes were accompanied by topographic changes.

Procedure

An area of total ORV exclosure was located at Whalehouse Point using posts and cable (Fig. 71). The enclosed area extended from the base of the primary dune seaward to the toe of the foredune (25 m), and 45 m parallel to the trend of the beach (Fig. 72). To each side of the exclosure an 8x20 m experimental impact site was established. A baseline and benchmarks were installed at the base of the primary dunes. The baseline consisted of 12 stakes: 6 control and 6 impact. The benchmark was useful for calculation of relative elevation only. Experimental impacts were applied to each impact site at the equivalent rate of 8 passes per week through the 8 m wide site (Fig 73) at approximately 10 mph. Therefore, every 0.5 m wide strip of impact area (0.5 m is the maximum width affected by an individual tire pass) received the equivalent of only 1 pass per week. Impacts were applied every two weeks during the summer field season, and monthly during the remainder of the year. In June 1979, after 6 months of no impacts, impacting was resumed at half the former rate. Each 0.5 m wide strip in the impact site received one pass every two weeks.

The Watch Hill field site consisted of an exclosure area 15 m wide and 24 m long with only one impact site (Fig. 74). The 8x15 m impact site was located immediately east of the exclosure. Four stakes, two control and two impact, determined the baseline. A benchmark for computing relative elevations was also established. Experimental impacting proceeded at the equivalent rate of 1 pass per week over each 0.5 m wide strip of impact site.

At both sites vegetation was monitored in the control and impact areas prior to impacting, using the standard quadrat technique (Fig. 75). A tape measure was stretched 24 m seaward from each of the baseline stakes. At a 1 meter interval along this line, a 0.5 m x 0.5 m quadrat was used to gather data for determination of relative vegetation cover, density, and frequency.

Cover is a measure of the percentage of ground space within each quadrat plot covered by the leaves and stems of a particular species. Density is the percentage of aboveground stems per species per quadrat plot. Frequency is the percentage of quadrat plots in which a species occurs. This procedure was repeated twice during each field season.

Vegetation was also monitored at each site prior to impacting by constructing vegetative front maps through time (Fig. 76). A tape measure was stretched from west to east parallel to the baseline, but 18 m seaward of it. A second tape was used to measure the distance from the 18 m line to the seawardmost plant for every meter interval. The result is a map showing the approximate seaward limit of the vegetation in the control and in the impact sites. This procedure was repeated biweekly during the summer field seasons and at least every two months during the remainder of the year.

The topographic expression of the vegetative changes was monitored by surveying profiles of the foredune from each of the baseline stakes (Fig. 77). The survey lines extended perpendicular from the baseline 24 m seaward, at a 2 m interval which allowed for a good representation of the natural dune profile, while permitting the collection of data within a reasonable amount of time. Standard rod-and-transit techniques were used to determine the profile elevations.

Data and Analysis

Cover, density, and frequency data was calculated as a percentage for each species for every quadrat plot. These data were examined spatially along each survey line (dune crest to dune toe) and at equal distances from the baseline perpendicular to the survey lines. Once spatially defined, the data were examined to note changes along and across the exclosure site with time as a result of the experimental impacting. T-tests were used to define the statistical significance of these changes.

Data collected on the position of the vegetative front through time were analyzed using a BMDP computer program which calculated a standard analysis of variance between control and impact sites. In addition, a Levene Test and a Brown-Forsythe Test, in which the variances are not assumed to be equal, were also preformed on the control and impact data. The results of these tests were used to determine the significance of the results. The vegetative front data were plotted and overlays of various dates were constructed for visual comparison.

Survey data was reduced and profiles were plotted using a Calcomp plotter. Specific overlays were constructed to examine the temporal changes in the dune profile with changing vegetation and impacting.

Results

A graphic and statistical comparison of the first vegetation front map of July 26, 1977 with that of September 29, 1977 shows that after 9 weeks of impacting, no significant difference was detectable between the control and impact sites. During this period the protected control vegetation advanced seaward an average of 0.13 m while the impact sites showed an average retreat (landward) in the vegetation front of 0.10 m for a net difference of 0.23 m. An additional 3 weeks of impacting resulted in the further retreat of the

eastern impact site by an average of 0.45 m from the original position. During the same interval the control area experienced an average advance of 0.52 m (Fig. 78) for a net difference of 0.97 m. The change which occurred in the control and east impact sites is significantly ($P < 0.05$) different.

From October 1977 through January 1978, the data show that the vegetation in the control area had retreated naturally such that the average net advance since July 1977 was only 0.20 m (Fig 79). At the same time, the eastern impact site showed a very slight advance in the vegetation so that the net change between the east impact site and the control site was no longer significantly different. However, the vegetation front in the west impact site retreated rapidly after October so that by January it showed a net retreat of 1.66 m. This change was significant ($P < 0.05$) when compared to the control vegetation front.

As a result of the February 6-8, 1978 coastal storm, there was general landward retreat of the vegetation front in the entire field site by swash erosion. The east impact vegetation front showed the largest average retreat (1.70 m) as a direct result of the storm (Fig. 80). This may be attributable to prior impacting which weakened the vegetation and its resistance to storm attack. The vegetation in the control area was vigorously attacked because of its seaward position, but its hardiness prevented major retreat (average 0.81 m). The vegetation front on the west impact site had been pushed far enough duneward as a result of experimental impacting that the storm swash barely reached the vegetation and thus only minor retreat occurred (average retreat 0.18 m). Comparing the front map of March 21, 1978 with the original map of July 1977, there was 1.83 m of retreat in the west impact area, 2.02 m in the east impact area, and 0.61 m in the control area. The variable retreat occurring in the control vs. the impact vegetation fronts between July and March was significantly ($P < 0.05$) different.

The mid-May 1978 vegetation front map compared to the post-storm front map (March 1978) shows that experimental impacting continued to cause a retreat along the vegetation fronts in both impact sites (average retreat of 1.81 m for east impact). During the same time interval, the control area showed signs of rapid recovery (average advance of 1.33 m) from its storm position.

One full year after experimental impacting of the vegetation front began, the two impact sites showed a similar average net retreat of 4.09 m (Fig. 81). The net advance in the control area averaged 1.12 m over the same period. The changes which were measured between impact and control over this one year period were significantly different ($P<0.01$). The disparity between the control and impact vegetation fronts continued throughout the 1978 field season (Fig. 82).

In January 1979 experimental impacting was greatly reduced (less than 2 passes/month) on both impact sites, and was discontinued in March 1979. No impacting was conducted until June 18, 1979. A comparison of the January 1979 and June 1979 vegetation fronts shows an average advance in the vegetation in all areas (Fig. 83). This suggests that recovery is possible after low levels of impacting have ceased (Figs. 84 and 85), which agrees with the results of Brodhead and Godfrey (1978).

Experimental impacts were resumed in June 1979, but at the reduced level of 1 pass per 2 weeks per 0.5 m wide strip. The results of the renewed impacting are made evident by comparing the June 18 and August 20, 1979 vegetation front maps (Fig. 86). Retreat began again in the impact areas, pushing the vegetation fronts back to their pre-January 1979 positions (Fig. 87). At the same time the control vegetation continued to advance so that by August it was 2.70 m seaward of its January position.

A comparison of the first vegetation front map of July 26, 1977 to the last one of October 20, 1979 shows a very significant ($P < 0.01$) difference in the movement of the vegetation front as a result of low level impacting (Fig. 88). During this time period the control vegetation showed a net seaward advance averaging 3.37 m while the vegetation fronts in the west (Fig. 89) and east (Fig. 90) impact sites retreated landward an average net distance of 4.40 m and 6.04 m, respectively, with a net difference between control and impact of over 7.77 m. The additional retreat in the east impact vegetation front reflects a 2-meter duneward shift in applying impacts on the east site as of September 9, 1978. By October 1979 the vegetation front in each impact site had been pushed outside the site boundaries, despite the reduced level of impacting.

Cover, density, and frequency measurements support the conclusions reached in the vegetation front analysis. During the two-year period 8/1/77 to 8/23/79, Ammophila cover fluctuated greatly, but no significant change occurred in the first twelve meters of each survey line (Table 10). After one year of impacting (8/1/77 to 8/15/77), Ammophila cover for the first twelve meters of each survey line increased, but then decreased again during the following year. In contrast to the small changes in the first 12 meters of each line was the 15-21 meter area, which received direct experimental impact. After one year of impacting in this zone, the western impact area dropped from an average cover of 1.2% to 0, and the eastern impact area dropped from 3.2% to 0.6%. During the same one-year period, the control area increased in cover from an average of 2.8% to 3.6%. The reduction in cover in the two impact areas within this zone is significant ($P < 0.05$).

The period of no impact from January to June 1979 is evident in the cover measurements taken in July. The control area continued to increase its cover, as did the impact areas. Without impacts for approximately 6 months, the western impact increased from 0 to 1.6% cover, and the eastern impact went from 0.6% to 2.2% cover. However, the gains in vegetation cover were short-lived once impacting was resumed (at a lower level). By the end of August the cover in the west site had dropped to 0.4% and to 0% in the east site.

Ammophila in the 15 to 20 meter range of the control area, showed a significant ($P < 0.05$) increase in cover over the two-year period of measurement. During the same interval the east impact site showed a significant ($P < 0.05$) decrease in cover. The west impact site showed a significant ($P < 0.05$) decrease in cover after 1 year, but after the period of no impact in 1979 the cover loss was no longer significant. Changes in Ammophila cover were surprising at the 13 and 14 meter survey points (Table 11). Overall, average cover in the control area changed from 3.4% to 14.0% over the two-year period. However, in the western impact area there was even a greater increase in vegetation cover in this zone, just duneward of the impact zone. The average cover increased by 21.6%. The east impact site showed an increase in cover after one year in the 13 and 14 meter range also, but the site boundary was

shifted 2 m duneward during the second year to compensate for the initially landward vegetation front in that area.

Artemisia generally increased in cover along the first 12 meters of both the control and impact areas. The distribution of Artemisia is more sporadic than Ammophila, but average cover in the control increased from 8.0% to 12.8% and from 4.3% to 9.9% in the non-impacted part of the impact zone over the 2 year period. Within the experimentally impacted zone (15 m+), very little Artemisia was initially present, and it was completely eliminated within one full year of impacting.

While other species were present within the field site, in no case did they ever exceed 7% cover, and generally comprised from 0 to 2% of the cover. As a result, the relative density of Ammophila and Artemisia within the first 13 meters of every site was not affected by the presence of other species and therefore showed very little change over the two-year period.

Ammophila density data in the 15+ m zone did show the effects of ORV impacts (Table 12). Initially, the relative density of Ammophila was quite high in the impacted zones, but after two years the density dropped to zero. It should be noted that relative density is a measure of particular species density relative to that of other species. Therefore, if only one Ammophila plant is present with no other species, the density within the control area of the 15+ m zone remained constant or increased.

It is well known that Ammophila acts as an excellent sediment trap by effectively stilling the wind near the surface (Huiskes, 1979). Therefore, changes in vegetation cover and density could result in alterations of dune topography. Figures 91 to 102 show the foredune profile in late July 1977, prior to experimental impacting, and 2 years later after impacting had affected the vegetation. Impacting occurred between 15 and 23 m on the west impact site (lines 30,25,20 west). On the east impact site (lines 50,55,60 east), impacting for the first full year occurred between 15 and 23 m, but was later (9/78) shifted to between 13 and 21 m.

The control profiles (Figs. 94-99) show that the natural foredune accumulated sand in the 8 to 24 m range during the period of measurement. The upper portions (near the dune crest) have accumulated little sand since the Ammophila effectively trapped most of the sediment close to its source (the beach backshore). Thus, the amount of sand accumulated generally increases in a seaward direction. The result has been an increase in elevation of the central portions of the dune profile by 0.5 m. Over the lower portion of each profile the amount of sand accumulated is nearly equally distributed. The most seaward extent of each line has accumulated the least sand because vegetation was not growing there prior to the establishment of the exclosure.

The impact profiles (Figs. 91-93; 100-102) show a slight reduction in the elevation of the foredune profile in the zone of actual impact (15-23 m). This lowering could be due to vehicle transport of sand downslope or to the removal of vegetation with subsequent aeolian erosion. The profiles also show an accumulation of sand just duneward of the experimental impact boundary; this deposition amounts to a maximum of 0.75 m near the 12 m line on the west impact side. Accumulation of sand in the upper portions of the impact profiles and the loss in the lower portions has resulted in a

marked steepening of the foredune slope in the 12-16 m range of each survey line. This trend was not present within the control survey area since sand was more uniformly deposited along the profile.

Results from the vegetation front maps and quadrat studies at Watch Hill were similar to that obtained for Whalehouse Point (Fig. 103). Comparison of the initial vegetation front map (7/31/79) with one completed only a month later shows that the control area experienced no net change (Fig. 104). The impact vegetation front, however, retreated an average of 0.70 m duneward as a result of experimental impacting. Two non-parametric analyses of variance (Sign Test and Wilcoxon Signed-Rank Test) indicated that the differential change between control and impact was significant ($P < 0.05$). Comparison of the first vegetation front map with one completed in October 1979, shows that the impact vegetation retreated duneward an average of 3.64 m (Fig. 105). The control also showed a net duneward movement, but it averaged only 0.15 m. The difference between impact and control at this site after only 3 full months of impacting was very significant ($P < 0.01$; Fig. 106).

Only two quadrat surveys, taken at less than a one-month interval, were available for the Watch Hill field site; however, the results were significant. Within the first 13 meters of both the control and impact zone, there was no significant reduction in Ammophila cover between 8/2/79 and 8/27/79; this area received no vehicle impact. In the 14 to 18 m zone, the control area showed a slight increase in cover, while there was a dramatic decline in vegetation on the impact site (Table 13). The change from 9.6% to 0.4% in less than one month as a result of low level ORV traffic was significant ($P < 0.05$). Changes in relative density of Ammophila indicate that reduction in cover is a result of differential loss of plant species: some plants (i.e., Artemisia, Cakile edentula, Euphorbia polygonifolia) are more susceptible to ORV impact than Ammophila.

Despite the significant change in the vegetation front and Ammophila cover of the impact side, no noticeable change in topography occurred. Profiles constructed in late July 1979 and October 1979 have not changed despite the vegetational changes over the short term. Over the longer term deflation of the artificially devegetated dune face areas would be anticipated, as occurred at the Whalehouse Point site.

Discussion

Vegetation front maps and quadrat studies at both Whalehouse Point and Watch Hill showed that even low-level ORV impacting (one pass per week) is severely damaging to natural foredune vegetation. The two primary colonizing species, beach grass (Ammophila breviligulata) and Dusty Miller (Artemisia stellariana) have evolved to accommodate the stressful conditions present on the seaward dune face and toe, but mechanized stresses quickly exceed their natural tolerances. Figures 107 and 108 document that even one pass by an ORV can affect the dune vegetation dramatically. Figure 107 was taken in July 1979, 4 months after an unknown driver went across the dune near Whalehouse Point. Figure 108 is the same set of tracks one year later. The tracks are still visible despite the long intervening time.

Regrowth of vegetation in the impacted sites during the spring of 1979 and the marked seaward advance of the vegetation front within the control zone indicated that rapid recovery is possible after termination of impacting. Pre-

vious experiments have shown that a few passes in the same track are sufficient to disturb the sand to a depth well below that of Ammophila rhizomes (Brodhead and Godfrey, 1978). However, rapid regrowth suggests that the rhizomes must be bending with the sediment rather than shearing off at this low level of impacting. Most rhizome growth occurs in late summer and early fall. Therefore, rapid regrowth in the spring means that the rhizomes must have already been in place since the previous fall, and they were not broken by the level of driving which took place prior to January 1979. Most regrowth took place within several meters of the vegetation front, indicating that rhizome growth was the principal means of propagation. Therefore, it appears that ORVs are responsible for killing only the surface portion of the plant. Provided some above-ground portion of the plant is not destroyed so that chlorophyll can still be manufactured, the rhizomes can survive and generate new leaves once impacting stops. This may not be the case for higher levels of impact.

The fact that impacting disturbs the surface vegetation so severely is quite important. After rhizome growth in the early fall, tillers develop off the nodes of the rhizome and work their way upward to just below the sand surface where they remain dormant until the following spring. At that time they emerge and develop into a new plant. The vegetation is brown-colored during the winter, and thus most drivers would not hesitate to run over a plant since it appears to be dead. Also the winter beach is very narrow, forcing drivers closer to the dune and increasing the potential for severe damage to the vegetation front (Fig. 109). Even a driver who carefully avoids the present vegetation could be inadvertently impacting the tillers and thus preventing the seaward advance of the front the following spring. Seaward growth of vegetation within the exclosure suggests that this sort of unintentional impact was occurring along large segments of the open beach.

Alterations of foredune topography, resulting from ORV impacting, could have serious long-term effects on the dune line. It is apparent that the resulting difference in vegetation in the impact and control areas was responsible for topographic changes. Beach grass was shown to be an effective sediment trap in the control area, promoting sand deposition on the foredune. Also, the quadrat data suggested that healthy vegetation acted as a sand stabilizer and thus helped to prevent aeolian and storm swash erosion. The broad foredune profile within the control area is a good form for dissipation of storm wave energy.

Vegetation was eliminated from the lower portions of the impact profiles. The loss of vegetation stimulated growth of those plants close to the impact boundary at the expense of the area undergoing artificial ORV impact. The end result was a steepening of the seaward face of the foredune profile. The steeper, vehicle-influenced dune profile would appear to have a greater potential for scarp development. The highly oblique wave attack along Fire Island, locally generated by meteorological events, often results in the development of scarps (McCormick, 1975). Thus artificial steepening of the profile by ORVs could be contributing to the demise of the foredune.

ADDITIONAL TESTS

Scarps

The opportunity to collect data on the formation and retreat of scarps (Fig. 110) along Fire Island occurred twice during the study (Table 14). During each occasion environmental variables, such as breaker wave height, longshore current velocity, etc., were measured in order to determine the conditions responsible for scarp development. In each case fixed reference points were located along the beach from which scarp retreat could be measured through time.

The first scarp formed on September 13, 1977, under conditions of an eastward-moving longshore current. Nine reference points were established parallel to the trend of the beach, after scarp formation had already begun. During the period of measurement the average rate of landward retreat of the scarp in front of the nine reference points was 0.7 m/hr; the maximum rate measured was 2.34 m/hr. Since the scarp maintained an average height of 0.51 m, the average volume of sand lost was 0.36 m^3/m/hr.

Twenty reference points equally spaced over a distance of 330 meters along the beach were used to monitor retreat of a second scarp on August 24, 1978. The average rate of retreat of this scarp was 1.8 m/hr, resulting in more than 9 meters of landward erosion over a single tidal cycle. The average scarp height was 0.9 m during the period of measurement, which amounted to an average volume lost of approximately 1.4 m^3/m/hr. Over the entire test area roughly 460 m^3/m/hr of sand was removed from the beach by scarping. Assuming a dump truck holds 3 yds^3 of sand, the loss experienced over the 330-meter test distance would total approximately 200 full dump trucks in one hour.

In both cases, scarp retreat within the test areas subsided with the occurrence of low tide. Scarping continued with the next high tide but the rate of retreat was greatly reduced in each case with moderating environmental conditions. During each test period we smoothed out portions of the scarp repeatedly using a shovel and rake. Our purpose was to see if the scarp would reform once obliterated, which it did in every case within 20 minutes.

During the second event the scarp obtained its maximum height when the position of the scarp coincided with the position of the berm crest (Fig. 111). Measurements of scarp retreat showed a declining rate of retreat one hour before high tide. The maximum volumetric retreat did not occur when the scarp reached the berm crest. This finding suggests that the volume of sand lost by scarp formation and retreat is primarily controlled by the wave and current processes and to a lesser extent by beach form.

There was no apparent relationship between scarp retreat and ORV impacts; however, a similar set of mild storm conditions occurring when the beach is narrower, or more intense conditions at the same time of year, could have important

effects on ORV usage (Fig. 112). A reduction in beach width of 1.8 m/hr during the winter, when the beach is naturally narrow, would force drivers to ride on the toe of the dunes along much of the beach. The small-scale storm, which produced the second scarp, had a maximum rate of scarp retreat of 4.2 m/hr. More intense climatic conditions are frequently encountered in this area throughout the year, and scarp formation could reduce the width of the backshore, resulting in driving problems in the spring and fall, and possibly even during the summer.

Burma Road

Five sites along the Burma Road were monitored for topographic and vegetational changes occurring as a result of vehicle traffic (Fig. 113). Standard surveying techniques were used to monitor these changes (Fig. 114). The first three sites were established east of Long Cove Cut, an area which receives very little vehicle traffic (this area is generally closed to ORVs except for emergency vehicle use when the beach is too narrow for driving). The last two sites were located between Long Cove and Watch Hill, a section which receives relatively heavy usage (at least 4 impacts per day; Table 15). Each site consisted of several survey lines. Figures 115 to 121 are overlays of representative profiles for each area surveyed at different times.

Profiles in areas 1,2, and 3 showed that the road and its surroundings were rather stable, with only slight mean changes in elevation. Over the two years of measurement (1977-1979), profile fluctuation was within such narrow bounds that net profile change was minor. Within the track the maximum variation in elevation of the level areas (1 and 3) did not exceed more than 0.1 m, and in area 2, which is on the side of a dune, the variation did not exceed 0.3 m.

Areas 4 and 5 are similar topographically and vegetationally to areas 1 and 2, respectively; the major difference being increased traffic (Table 14). Profile alterations in these two cases did not appear to be very different from those monitored in the low impact sites. Profiles in sites 4 and 5 fluctuated through a narrow range with time; with a maximum of 0.1 m at site 4 and 0.3 m at site 5. The width of the road at all 5 sites has also remained constant through time (Figs. 115-121).

Vegetation position along the border of the road exhibited no net change. At different times of the year, the vegetation is closer or farther from the road, but it fluctuates within narrow (0.5 m) bounds.

The results of these surveys indicate that the Burma Road, which has been in use for many years, has reached a point of dynamic stability. It has eroded to the point where current levels of impact have little to no effect on the road. No additional environmental damage appears to be resulting from present levels of impacting.

Some caution should be exercised in applying these results, since along a 30-mile long road, only 5 sites were surveyed. It is certain that not every combination of topography and vegetation was accounted for in these 5 sites. The effect of driving up and over back dunes is just one situation not assessed. Two years of surveys show no trends in the road surface, but it is possible that over a longer term there could be a net change in the elevation of the road. A significant increase in traffic could result in a

net lowering of the road profile, and surely would result in a widening of the road (and hence vegetation loss) due to head-on confrontations of two vehicles.

Wind

Aeolian transport of sand on the beach at Fire Island is an important consideration (Fig. 122). As previously discussed, ORV passage produces a mound of sand to either side of the track. Penetrometer readings showed this mounded sand is very loose and hence susceptible to wind transport. In addition, ORVs are responsible for the disruption of any salt crust and vegetation present on the backshore, which act as natural inhibitors to aeolian movement. The depressed portion of vehicle tracks can act as a sediment trap under favorable wind conditions.

Several important points should be noted regarding aeolian transport in this locality. Fire Island is oriented generally WSW to ENE. Therefore, any winds blowing from the W, NW, N, or NE can be considered offshore winds. These winds would generally blow sand from the beach to the water and thus contribute to erosion of transportable (fine) grains. Winds from the SW, S, SE, and E would be onshore and generally would move sand from the beach to the dunes. Moisture has a dampening effect on aeolian transport so that higher wind velocities are necessary to set wet sand grains in motion. Given any velocity of wind, only sand grains of a certain size or smaller will be moved.

The amount of sand transported is related to the velocity of the wind (ignoring moisture) and the size of the material to be moved. Winds of less than 12 mph, which account for approximately 50% of those on Fire Island, are ineffective in sand transport. Using an empirical method developed by Hsu (1974), we have constructed a graph of instantaneous wind velocity measured at a height between 2 and 10 m versus the rate of sand transport (gm/cm-sec) for Fire Island (Fig. 123). Two curves are presented representing the dunes (mean grain size = 0.32mm) and the foreshore (mean grain size = 0.40mm). The rate of sand transport on the backshore would be between the foreshore and dune (mean grain size = 0.35mm). From this graph it is clear that as wind velocity increases, the rate of sediment transport increases exponentially and finer grain sizes are easier to move. This means higher velocity winds are much more effective in transporting sediment; i.e., a wind of 50 mph has a transport rate of nearly 10 times that of a wind of 25 mph.

Wind data for the Long Island region between 1951 and 1960 were summarized by McCormick (1975) based on information collected at Kennedy Airport (Fig. 124). Winds along the Long Island coast are predominantly from the northwest during the winter and from the south and west during the summer. Mean wind velocity for the region during this period was calculated as 12.9 mph (Panuzio, 1968). This analysis considered all winds, irregardless of their ability to transport sand.

Additional wind data were also obtained directly from Kennedy Airport in order to evaluate the potential for sand transport. The three most recent years available (1974-1976) were analyzed in more detail (Figs. 125-127). While Kennedy Airport is over 30 miles to the WSW of Fire Island, the regional wind patterns should be similar. Over these three years, winds of 12 mph or

more occurred approximately 47% of the time. The NW quadrant predominated, with winds in excess of 12 mph occurring approximately 13.7% of the time, followed by the southern direction with 13.5%, and finally the west direction with 12.8%. The average for the onshore winds totaled 28%, while the offshore totaled 62%, the remainder was alongshore.

Analysis of the 1974-1976 wind data show that in the six winter-spring months, winds capable of transporting sand occurred more than 50% of the time, with those from the NW sector dominant. During the summer-fall months winds were generally less than 12 mph, but when they exceeded that velocity, it generally was from the southern quadrant. Winds in excess of 24 mph follow a similar pattern: from May through November they occur less than 3% of the time. From December through April they occur more than 3% of the time. The NW quadrant was the primary direction for winds in excess of 24 mph.

In terms of potential aeolian transport, it would appear that the summer and fall months are the best times for ORV driving on the beach since winds capable of transporting fine grained sand during that time are at a minimum, and generally blow onshore. High velocity winds are infrequent, minimizing sediment transport. Any fine grained ORV-disturbed sand would be moved duneward by the onshore winds. However, the winter and spring, when most driving generally occurs, are the windiest months, with offshore winds predominating. Driving during this time would be more likely to lead to erosion by aeolian processes.

It is unknown how much additional beach sand is lost along Fire Island as a result of ORV traffic and aeolian processes. Wind velocity, wind direction, wind duration, moisture, and driving habits and number of vehicle trips all combine to determine the amount of aeolian erosion.

Kismet Vegetation

During the last two summer field seasons in which beach profile measurements were taken at Kismet, a driving lane was established through the control area to minimize impact by those few vehicles having to travel the entire beach. It was noted in 1979 that the vegetation on the control side (Fig. 128) was farther seaward than it was on the impact site (Fig. 129). This apparently resulted from the elimination of all vehicles in the vicinity of the control area dunes, while the impact dunes sustained a normal level of ORV traffic.

A map showing the relative position of the dune crest and the vegetation front was constructed for the control and impact sites (Figs. 130 and 131). The technique used was similar to that employed in the foredune studies (see p. 29). These vegetation front maps show that in the control area the average distance between the vegetation front and dune crest was 15.5 m. Conversely, the average dune crest to vegetation front distance was only 2.8 m for the impact area. These data indicate that the normal level of driving along Fire Island is sufficient to adversely affect beachfront vegetation. Furthermore, with the elimination of driving, vegetation will recover, but it may take several years for that recovery to be noticeable. These results support the conclusions reached in the foredune studies, where topography and vegetation were shown to be closely related. Thus we can conclude that the beach profiles at Kismet, especially in the vicinity of the dune, have been detrimentally influenced by ORV traffic.

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Table 1. Variables used in the calculation of the regression equation, with their range of measured values. N = 788.

Variable	Mean	Smallest Value	Largest Value
1. Place (I)	---	1	4
2. Slope Angle (I)	4.11	0.00	20.00
3. Horiz. Comp. (I)	1.08	0.00	3.80
4. Vertical Comp. (I)	2.06	0.05	9.99
5. Moisture (I)	1.77	0.02	12.08
6. Speed (I)	15.88	5.00	40.00
7. Num. of Passes (I)	19.23	1.00	75.00
8. Tire Pressure (I)	19.10	15.00	25.00
9. Track Displacement (D)	27.81	0.00	116.00
10. Down Slope Displace (D)	10.60	0.00	57.80
11. Up Slope Displace (D)	2.96	0.00	15.60
12. Down-Up (Net Down) (D)	7.65	-11.80	57.80
13. Track - (Down + Up) (D)	14.25	-32.40	91.10

I = Independent variable
D = Dependent variable
Slope angle = degrees
Horiz. Comp. = tons/sq. in./1440
Vertical Comp. = tons/sq. in./16
Moisture = % weight
Speed = mph
Tire Pressure = lbs./sq. in.
Displacement (9-13) = sq. in./in.

Table 2. Summary of regression analyses.
N = 788.

ORDER OF USE IN REGRESSION EQUATION

DEPENDENT VARIABLES — INDEPENDENT VARIABLES

1) DOWNSLOPE DISPLACEMENT = -8.12+1.39(S)+0.29(#P)-2.11(VC)+0.54(TP)+1.35(HC)

	1	2	3	4	5
	SLOPE	#PASSES	VERT. COMP.	TIRE PRES.	HORIZ. COMP.
R^2(%)	19.3	20.6	7.7	1.7	0.5
Cum. R^2(%)	19.3	39.9	47.6	49.3	49.8
F value	187.7	269.3	115.0	26.0	7.8
P<	0.01	0.01	0.01	0.01	0.01
Correlation	+	+	-	+	-

2) UPSLOPE DISPLACEMENT = -0.83-0.24(S)+0.07(#P)-0.36(VC)+0.19(TP)+0.03(SP)

	1	2	3	4	5
	SLOPE	#PASSES	VERT. COMP.	TIRE PRES.	SPEED
R^2(%)	13.7	9.5	3.3	2.0	0.4
Cum. R^2(%)	13.7	23.2	26.5	28.5	28.9
F value	125.1	96.6	35.4	22.2	4.4
P<	0.01	0.01	0.01	0.01	0.01
Correlation	-	+	-	+	+

3) NET DOWNSLOPE DISPLACEMENT = 2.75+1.25(S)+0.21(#P)-2.01(VC)+2.29(HC)-0.09(SP)
(Down - Up)

	1	2	3	4	5
	SLOPE	#PASSES	VERT. COMP.	HORIZ. COMP.	SPEED
R^2(%)	29.5	10.0	3.8	1.1	0.5
Cum. R^2(%)	29.5	39.5	43.2	44.3	44.8
F value	328.2	129.9	52.0	15.0	6.4
P<	0.01	0.01	0.01	0.01	0.01
Correlation	+	+	-	-	+

4) TRACK DISPLACEMENT = -25.18+0.62(#P)-4.20(VC)+2.33(TP)+0.68(S)+0.20(SP)

	1	2	3	4	5
	#PASSES	VERT. COMP.	TIRE PRES.	SLOPE	SPEED
R^2(%)	23.0	14.6	7.5	2.1	0.6
Cum. R^2(%)	23.0	37.6	45.1	47.3	47.9
F value	234.6	183.9	107.8	31.3	9.8
P<	0.01	0.01	0.01	0.01	0.01
Correlation	+	-	+	+	+

5) NET DISRUPTION = -20.26+0.28(#P)+1.60(TP)-1.44(VC)+0.27(SP)-2.55(HC)
(Track-(Down+Up))

	1	2	3	4	5
	#PASSES	TIRE PRES.	VERT. COMP.	SPEED	HORIZ. COMP.
R^2(%)	7.7	7.7	4.8	1.6	0.8
Cum. R^2(%)	7.7	15.4	20.2	21.8	22.6
F value	65.5	71.9	46.9	16.3	7.7
P<	0.01	0.01	0.01	0.01	0.01
Correlation	+	+	-	+	-

S = Slope
#P = Number of Passes
TP = Tire Pressure
VC = Vertical Compaction
HC = Horizontal Compaction
SP = Speed

Table 3. Summary of regression analysis results using only data from 25 or more passes. N = 298.

DEPENDENT VARIABLES	ORDER OF USE IN REGRESSION EQUATION 1	2	3	4
	INDEPENDENT VARIABLES			
1) NET DOWNSLOPE DISPLACEMENT (Down - Up) = -12.78+2.14(S)+0.77(TP)-1.02(VC)+0.14(#P)	SLOPE	TIRE PRES.	VERT. COMP.	#PASSES
R^2 (%)	43.4	2.3	1.6	1.5
Cum. R^2 (%)	43.4	45.7	47.2	48.7
F value	226.7	12.4	8.6	8.5
P<	0.01	0.01	0.01	0.01
Correlation	+	+	-	+
2) TRACK DISPLACEMENT = -30.88-4.19(VC)+3.32(TP)+1.03(S)+0.31(#P)	VERT. COMP.	TIRE PRES.	SLOPE	#PASSES
R^2 (%)	16.1	11.3	3.5	3.0
Cum. R^2 (%)	16.1	27.4	30.9	33.9
F value	56.6	45.9	15.1	13.2
P<	0.01	0.01	0.01	0.01
Correlation	-	+	+	+

S = Slope
VC = Vertical Compaction
TP = Tire Pressure
#P = Number of Passes

Table 4. Use of the independent variables vertical compaction, horizontal compaction, and moisture, in the regression analysis.

Correlation coefficents: (From regression analysis)	Vert. Comp.	Moisture	Horiz. Comp.
Vertical Compaction	1.0	0.75	0.71
Moisture		1.0	0.66
Horizontal Compaction			1.0

Partial correlation coefficents during the regression analysis of the dependent variable TRACK, before and after Vertical Compaction was used in the equation:

Remaining Variables	BEFORE	AFTER
Slope	= .17	= .15
Horiz. Comp.	= -.27	= -.06
Moisture	= -.28	= -.07
Speed	= .08	= .16
Tire Pres.	= .35	= .35
Vert. Comp.	= -.44	- - - - -

Table 5. The number of slopes which showed a net change (% of total) after impacting within the same test track. N = 65.

	All Tests	Original Slope >1.5°	Original Slope >2.0°	Original Slope >2.5°
Slope Changes				
Slope increased	20.0	4.9	0.0	0.0
Slope decreased	49.2	73.2	80.0	82.4
Slope decreased to zero and then increased in the opposite direction (i.e. 7° N. to 2° S)	10.7	7.3	8.6	8.8
No net slope change	20.0	14.6	11.4	8.8

Table 6. New downslope displacement of sand by ORVs assuming current level of use.

CASE 1. All drivers make their own trail, all driving concentrated in one area.

Beach environment	Displacement/inch after 1 pass	Miles of trail	Tracks/trail	Net downslope displacement per year
Foreshore	1.7 in^3	224,000	2	1,034,000 yds^3
Back-Berm	1.5 in^3	224,000	2	912,600 yds^3
Back-Dune	1.3 in^3	224,000	2	790,900 yds^3

CASE 2. All drivers follow existing trails, all driving concentrated in one area.

Beach environment		Displacement/inch after 1 pass	Miles of trail	Tracks/trail	Total net downslope displacement per year
Foreshore	West	25.0 in^3	6	2	1,015 yds^3
	East	14.0 in^3	16	2	
Back-Berm	West	10.0 in^3	6	2	293 yds^3
	East	3.0 in^3	16	2	
Back-Dune	West	10.0 in^3	6	2	380 yds^3
	East	5.0 in^3	16	2	

Table 6. (Continued)

CASE 3. Approximation of current level of displacement.

Beach environment		# passes/day	Net displacement per inch of track after 3 days	Miles of trail	Net displacement after 3 days
Foreshore	West	24	1.3 in^3	3	212 yds^3
	East	10	7.0 in^3	8	304 yds^3
Back-Berm	West	36	4.5 in^3	3	73 yds^3
	East	14	3.5 in^3	8	152 yds^3
Back-Dune	West	36	5.0 in^3	3	81 yds^3
	East	14	4.5 in^3	8	196 yds^3
Dune	West	4	16.5 in^3	3	134 yds^3
	East	2	12.0 in^3	8	261 yds^3
				Total net displacement after 3 days =	1413 yds^3
				Total net displacement after 1 year =	169,560 yds^3

CASE 4. All driving restricted to Foreshore (winter) and Back-Berm (summer).

Beach environment		# passes/day	Net displacement per inch of track after 3 days	Miles of trail	Net displacement after 3 days
Foreshore	West	100	14.5 in^3	3	236 yds^3
	East	40	10.0 in^3	8	435 yds^3
				Total net displacement after 3 days =	670 yds^3
Back-Berm	West	100	4.0 in^3	3	65 yds^3
	East	40	2.5 in^3	8	109 yds^3
				Total net displacement after 3 days =	174 yds^3
				Total net displacement after 1 year =	50,640 yds^3
				Total net seaward displacement after 1 year =	29,760 yds^3

Table 7. Summary of swash test results.
Sample weight calculated in gm/ml.
Tests 1-8 conducted at Whalehouse Point,
9 and 10 at Kismet, and 11-18 at Watch Hill.

Test #	# Paired Samples Collected	IMPACT		CONTROL	
		Average Weight	Std. Dev.	Average Weight	Std. Dev.
1	10	.0219	.0325	.0140	.0303
2	15	.0292	.0604	.0337	.0866
3[a]	31	.1212	.1211	.0329	.0435
4[a]	26	.0713	.1035	.0253	.0364
5	34	.0969	.1643	.0542	.0777
6	23	.0590	.1766	.0255	.0350
7[a]	30	.1100	.1573	.0484	.0457
8[a]	26	.0541	.1053	.0067	.0127
9	17	.0038	.0020	.0035	.0021
10	16	.0023	.0029	.0127	.0247
11	15	.0306	.0372	.0300	.0616
12	15	.0255	.0718	.0131	.0167
13	17	.0085	.0092	.0085	.0135
14	18	.0291	.0587	.0255	.0359
15	15	.0061	.0072	.0027	.0019
16	20	.0047	.0063	.0061	.0085
17	18	.0056	.0055	.0059	.0088
18	15	.0013	.0034	.0054	.0129

a = Significant difference ($P \leq .10$) $I > C$ (using nonparametric Sign Test and Wilcoxon-Signed Rank Test)

Table 8. Field variables measured during swash and tracer tests. Test locations indicated on tables 7 and 9.

Swash Test#	Wave Height (ft.)	Wave Period (sec.)	Wave Direction	Current Velocity (m/sec)	Current Direction	Swash Period (sec.)	Beach Slope (deg.)
1	2.6	9.1	---	---	---	---	---
2	1.6	---	---	---	---	---	---
3	1.5	8.6	SSW	.04	W to E	---	---
4	3.0	10.0	SE	.013	E to W	---	---
5	2.7	7.5	SSW	---	W to E	---	---
6	2.9	6.2	SSW		W to E	---	---
7	1.4	8.3	SSW	---	W to E	---	---
8	2.0	6.0	---	---	---	6.0	---
9	2.8	6.7	SSE	.78	E to W	9.1	8.2
10	2.5	5.6	SE	1.6	E to W	8.7	---
11	2.9	7.9	S	.25	W to E	6.6	11.0
12	2.4	4.4	SSW	.25	W to E	5.7	6.0
13	4.8	4.2	S	.68	W to E	11.1	9.6
14	4.7	7.9	S	.24	W to E	8.4	11.0
15	3.8	7.9	S	.57	W to E	10.0	12.0
16	2.7	9.2	SSE	.18	E to W	7.8	9.7
17	1.4	7.8	SE	.22	E to W	8.9	4.0
18	1.3	7.8	SSE	.22	E to W	8.9	4.0
Tracer Test #							
1	1.9	7.7	SSE	.19	W to E	8.4	4.0
2	2.8	7.3	SSE	1.08	E to W	6.9	7.5
3	3.0	6.2	SE	1.67	E to W	7.4	---
4	2.6	7.1	S	.25	W to E	6.5	9.0
5	4.2	5.8	SSW	.15	W to E	5.9	6.3
6	3.6	7.2	S	.42	W to E	6.4	12.7
7	4.7	7.9	S	.24	W to E	10.4	11.0
8	2.7	9.2	SSE	.18	E to W	7.8	9.7
9	1.4	7.8	SE	.22	E to W	8.9	4.0
10	0.4	6.2	SSE	.08	E to W	6.4	7.4

Table 9. Summary of tracer test results.
All tests were conducted between Watch Hill and Whalehouse Point.

Test #	Site	Average number of tracer grains/volume of sample	Std. Dev.
1	Impact	1.8	0.9
	Control	18.3	7.3
2	Impact	43.5	81.6
	Control	18.9	59.8
3	Impact	14.5	18.5
	Control	9.5	9.6
4	Impact	2.7	1.0
	Control	11.1	5.2
5	Impact	5.7	4.1
	Control	20.2	11.6
6	Impact	25.4	14.0
	Control	19.6	14.8
7	Impact	59.8	21.0
	Control	62.7	27.5
8	Impact	14.7	14.3
	Control	5.4	5.0
9	Impact	176.7	93.3
	Control	97.0	87.5
10	Impact	7.8	5.2
	Control	5.4	3.6

Table 10. Whalehouse Point, average cover (Std. Dev.) for Ammophila breviligulata expressed as a percent of the total area.

	Site	8/1/77	8/15/78	7/3/79	8/23/79	Significance between 1st. and last dates.
1 to 11m. range.	West Impact	23.5(10.2)	35.7(7.8)	24.7(19.5)	24.5(8.3)	Insignificant
	West Control	20.8(6.7)	26.5(8.4)	14.1(6.1)	16.6(5.7)	Insignificant
	East Control	4.5(3.9)	10.8(5.8)	7.6(3.8)	7.7(4.1)	Insignificant
	East Impact	13.2(9.9)	27.4(10.1)	20.3(10.6)	16.2(7.2)	Insignificant
15 to 21m. range (zone of experimental impact)	West Impact	1.2(1.5)	0.0(0)	1.6(3.1)	0.4(1.0)	Insignificant*
	West Control	3.6(5.0)	8.7(9.2)	14.5(10.3)	13.7(8.4)	$P < .01$
	East Control	2.0(2.3)	2.6(4.8)	5.8(5.3)	6.3(5.2)	$P < .05$
	East Impact	3.2(3.8)	0.6(1.6)	2.2(5.8)	0.0(0)	$P < .05$

* The west impact side between 8/1/77 and 8/23/79 in the 15 to 21m. range showed no significant loss of Ammophila cover due to the period of no impacting (1/3/79). However, the loss between 8/1/77 and 8/15/78 was significant ($P < .05$)

Table 11. Whalehouse Point, average cover for Ammophila breviligulata, expressed as a percent of the total area.

	Site	8/1/77	8.15.78	7/3/79	8/23/79
12 meters from the baseline	West Impact	26.4	36.1	19.4	22.7
	West Control	13.9	26.4	0.0	12.0
	East Control	0.0	4.2	19.4	6.7
	East Impact	2.8	33.3	25.0	14.7
13 meters from the baseline	West Impact	8.3	29.2	19.4	34.7
	West Control	1.4	18.1	12.5	9.3
	East Control	0.0	15.3	27.8	22.7
	East Impact	0.0	1.4	12.5	5.3
14 meters from the baseline	West Impact	4.2	9.7	25.0	20.0
	West Control	6.9	19.4	8.3	6.7
	East Control	5.6	16.7	18.1	17.3
	East Impact	1.4	8.3	2.8	0.0

Table 12. Whalehouse Point, average density for Ammophila breviligulata expressed as a percent of the density of all species combined.

	Site	Quadrat Survey Date			
		8/1/77	8/15/78	7/3/79	8/23/79
15 meters from the baseline	West Impact	20.0	0.0	100.0	100.0
	West Control	100.0	100.0	100.0	100.0
	East Control	100.0	95.0	96.7	96.4
	East Impact	0.0	100.0	100.0	0.0
16 meters from the baseline	West Impact	2.12	0.0	100.0	0.0
	West Control	100.0	100.0	100.0	100.0
	East Control	0.0	100.0	100.0	100.0
	East Impact	2.0	0.0	0.0	0.0
17 meters from the baseline	West Impact	100.0	0.0	0.0	0.0
	West Control	55.0	63.6	88.2	100.0
	East Control	41.7	0.0	0.0	100.0
	East Impact	100.0	0.0	0.0	0.0
18 meters from the baseline	West Impact	100.0	0.0	0.0	0.0
	West Control	0.0	100.0	78.6	92.0
	East Control	100.0	0.0	100.0	100.0
	East Impact	100.0	0.0	0.0	0.0
19 meters from the baseline	West Impact	100.0	0.0	0.0	0.0
	West Control	100.0	100.0	100.0	100.0
	East Control	0.0	0.0	100.0	100.0
	East Impact	43.5	0.0	0.0	0.0
20 meters from the baseline	West Impact	0.0	0.0	0.0	0.0
	West Control	0.0	0.0	100.0	100.0
	East Control	0.0	0.0	0.0	0.0
	East Impact	0.0	0.0	0.0	0.0
21 meters from the baseline	West Impact	0.0	0.0	0.0	0.0
	West Control	0.0	0.0	100.0	100.0
	East Control	0.0	0.0	0.0	0.0
	East Impact	0.0	0.0	0.0	0.0

Table 13. Watch Hill, average cover (Std. Dev.) for Ammophila breviligulata expressed as a percent of the total area.

		8/2/79	8/27/79	Significant Difference Between Dates
1-13m Range	Impact	21.0(11.3)	19.6(10.1)	not significant
	Control	18.0(12.1)	15.7(10.8)	not significant
14-18m Range	Impact	9.6(9.5)	0.4(0.9)	$P < .05$
	Control	9.6(3.6)	10.8(5.4)	not significant

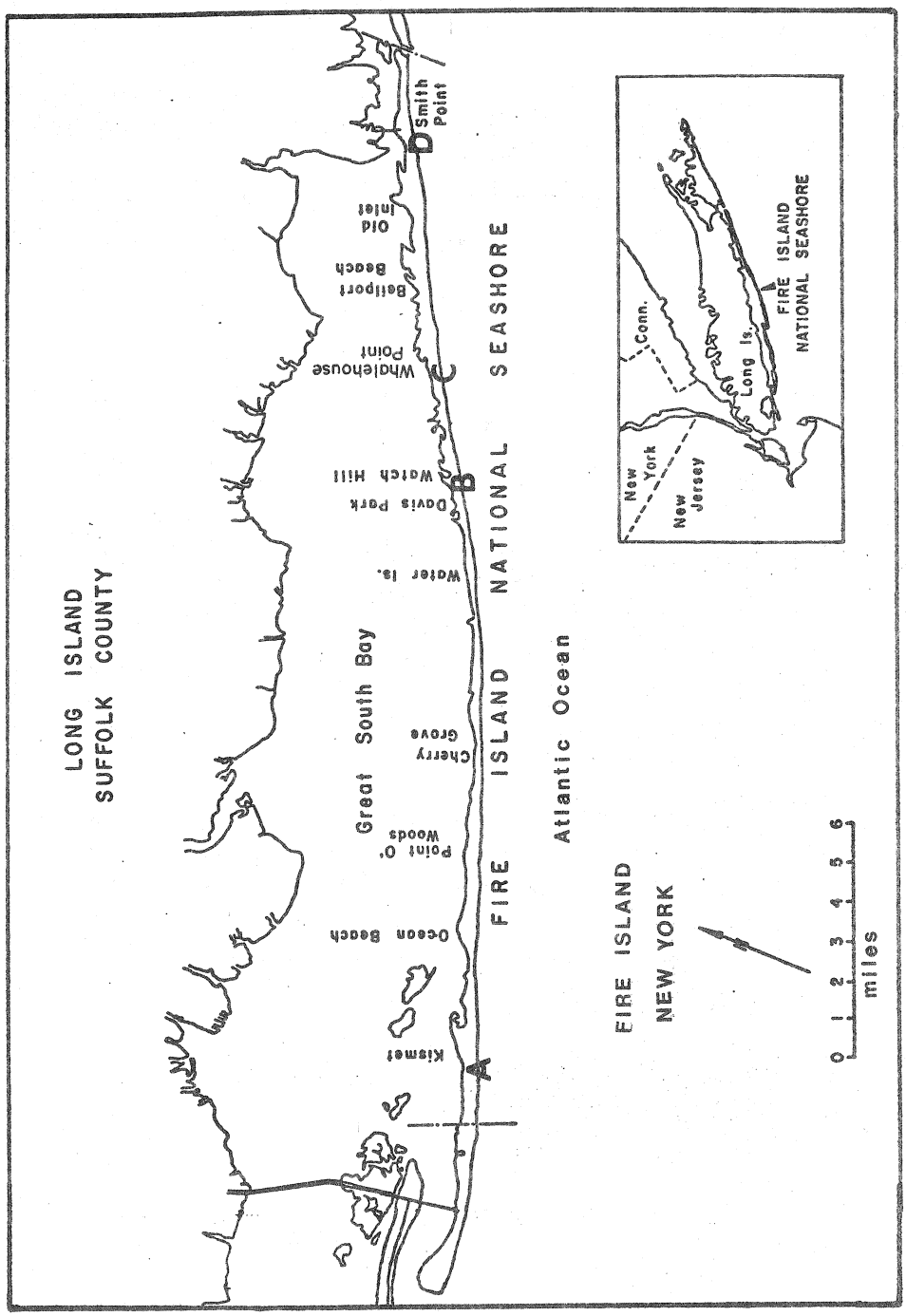
Table 14. Summary of environmental data collected during periods of scarp formation.

Measurements	Sept. 13, 1977	August 24, 1978
Wave Direction	Southwest	Southeast
Wave Height	3 to 4 feet	3 to 4 feet
Wave Period	5.5 sec.	4.5 sec.
Current Velocity	1.7 m/sec.	1.5 m/sec.
Current Direction	East	West
Length of test area	63m	329m
Average scarp height	.5m	.9m
Average linear erosional rate	.7 m/hr	1.8 m/hr
Average volume loss	.4 m^3/m/hr	1.4 m^3/m/hr
Max. Linear erosional rate	2.3 m/hr	4.2 m/hr
Average rate of scarp reformation	less than 20 min.	less than 20 min.

Table 15. Summary of Burma Road field sites.

	Location	# of survey lines	volume of traffic since study began	summary of vegetation types present*
Area 1	East of Long Cove Cut	8	Light (occasional pass per month)	Beach Grass Beach Plum
Area 2	East of Long Cove	3	Light (occasional pass per month)	Poison Ivy Beach Plum Beach Grass Chocke Cherry
Area 3	East of Long Cove Cut	2	Light (occasional pass per month)	Poison Ivy Greenbriar Bayberry Beach Grass
Area 4	West of Long Cove	8	Heavy (at least 4 passes per day)	Beach Brass Beach Plum Bearberry Beach Heather
Area 5	West of Long Cove	2	Heavy (at least 4 passes per day)	Poison Ivy Greenbriar Beach Grass Beach Plum

*vegetation adjacent to sand road



A = Kismet Field Site: Profiles, Direct Displacement Tests, Swash Tests, Scarps.
B = Watch Hill Field Site: Foredune Vegetation, Swash Tests, Tracer Tests.
C = Whalehouse Point Field Site: Foredune Vegetation, Direct Displacement Tests, Swash Tests.
D = Smith Point Field Site: Beach Profiles.

Figure 1. Location map: Fire Island National Seashore.



Figure 2. Measuring beach slope.

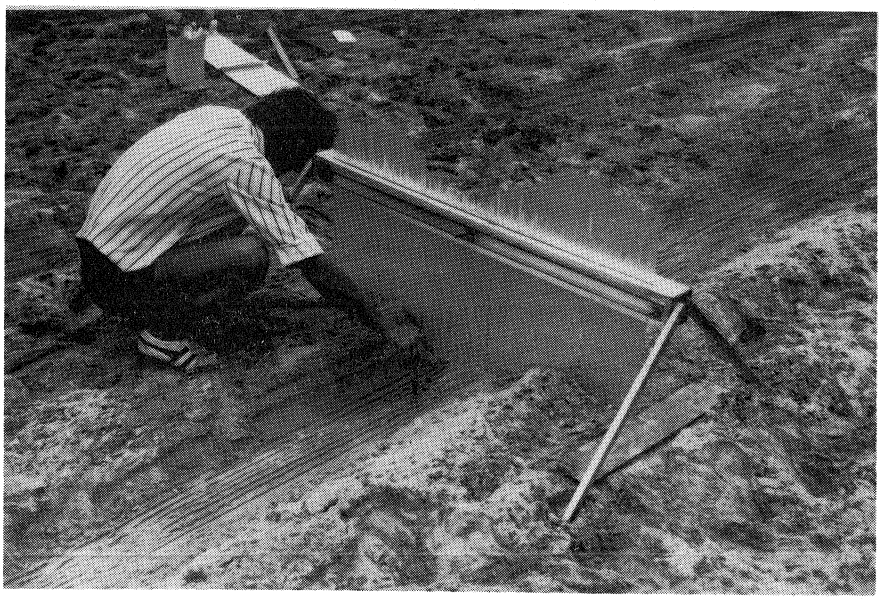


Figure 3. Measuring vertical compaction with penetrometer, MTP in background.

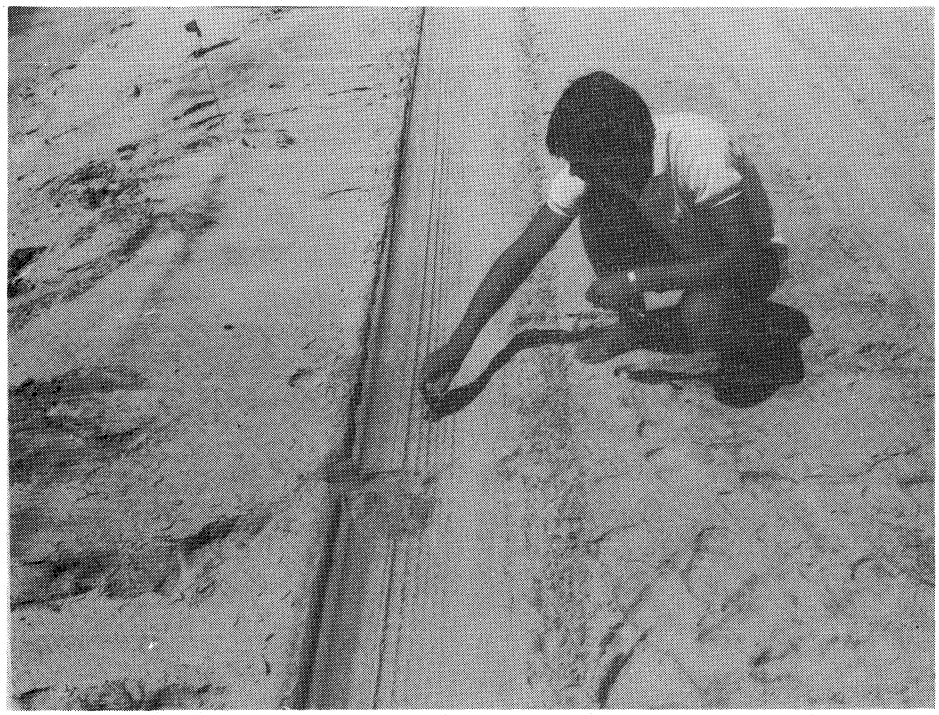


Figure 4. Measuring horizontal compaction with a Torvane.

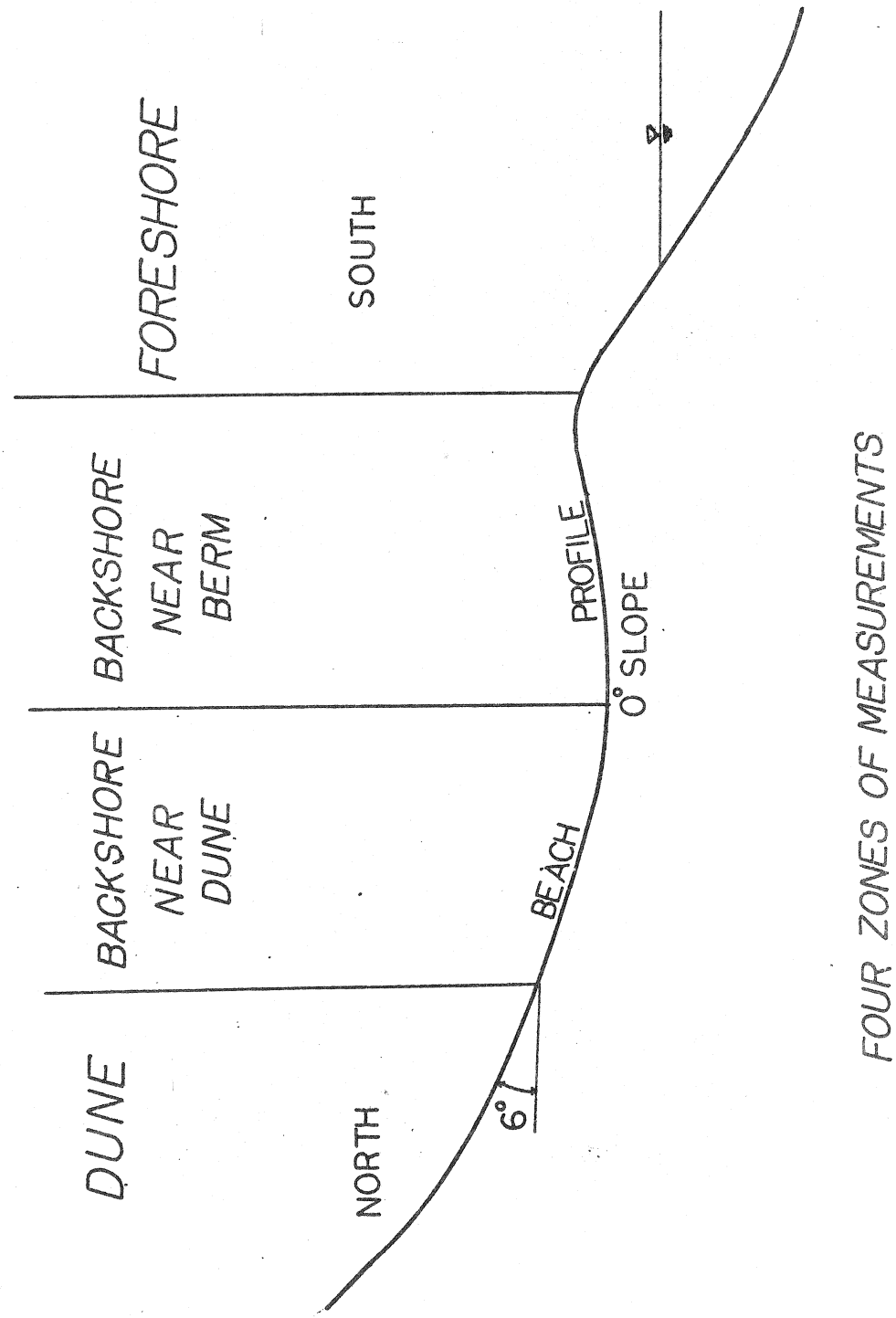


Figure 5. Typical beach profile with environments.

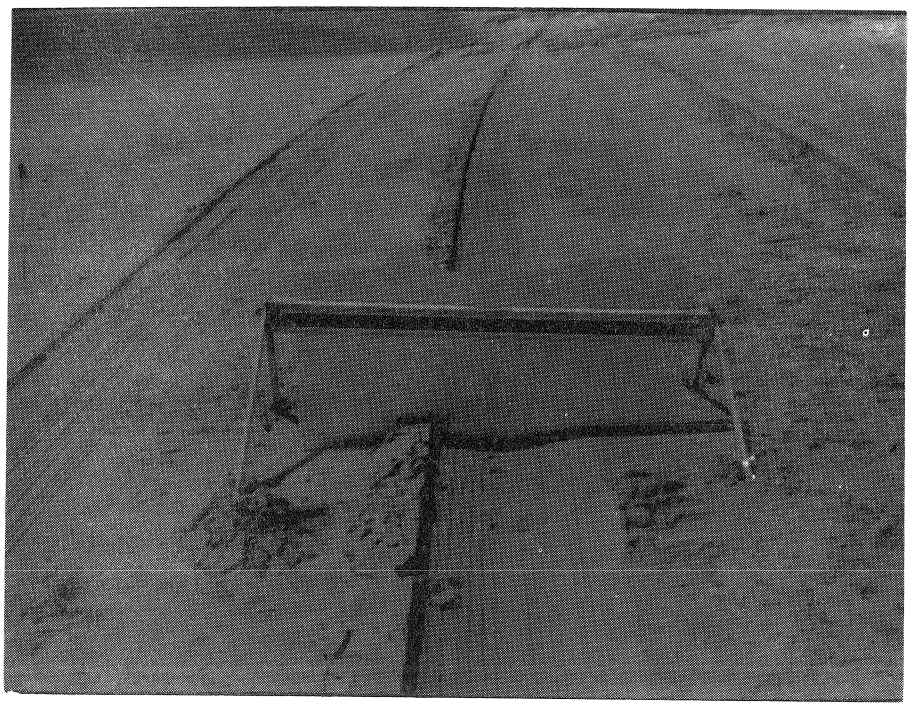


Figure 6. Microtopography Profiler.

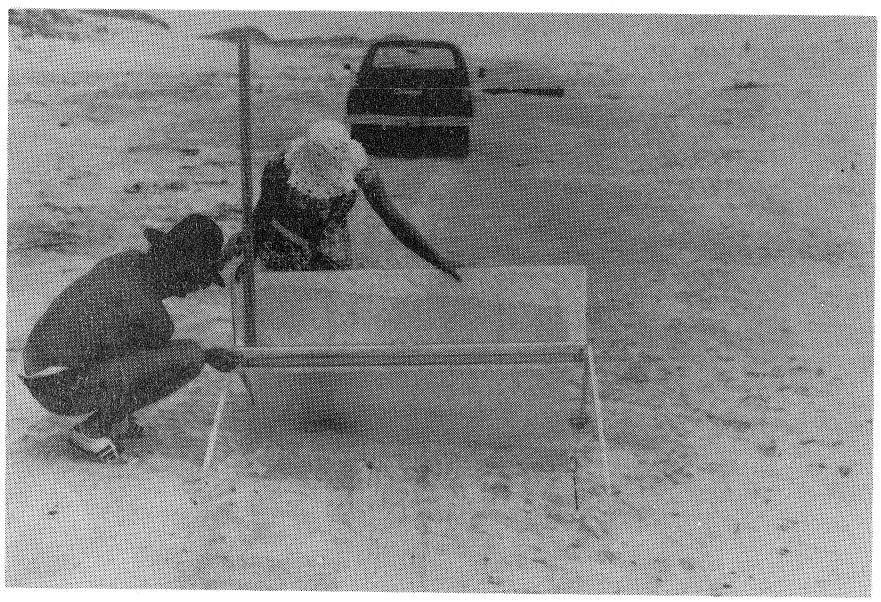


Figure 7. Microtopography Profiler with tracing board.

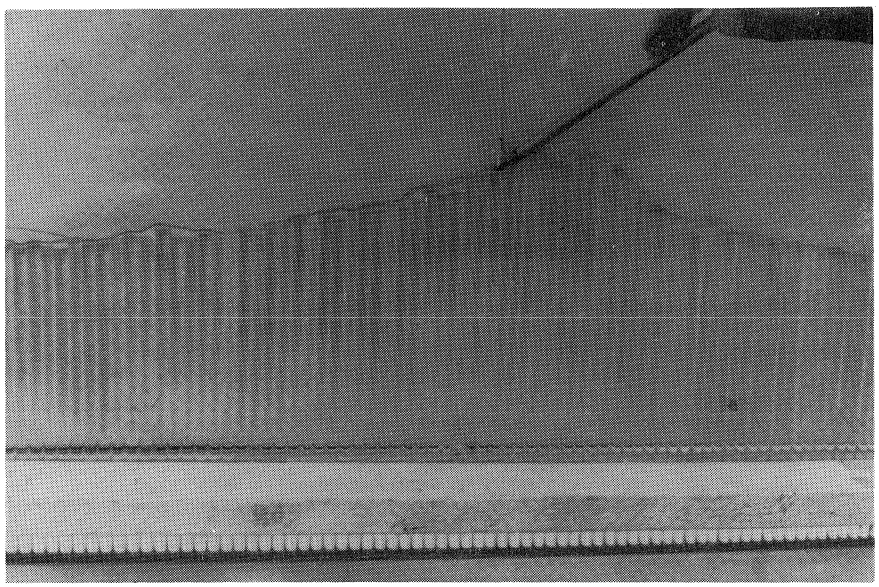


Figure 8. Close-up of MTP with tracing board.

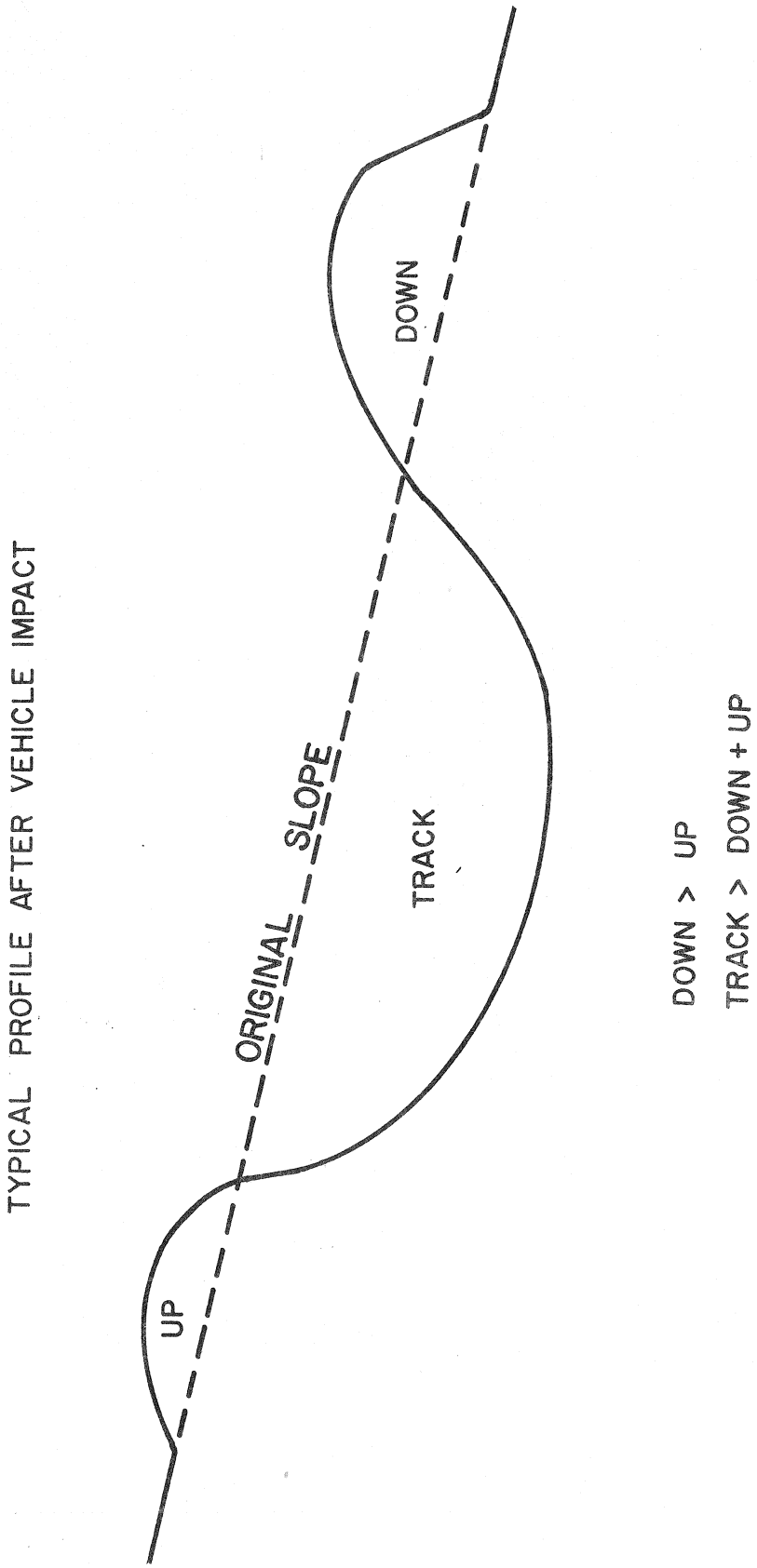


Figure 9. Typical ORV track profile.

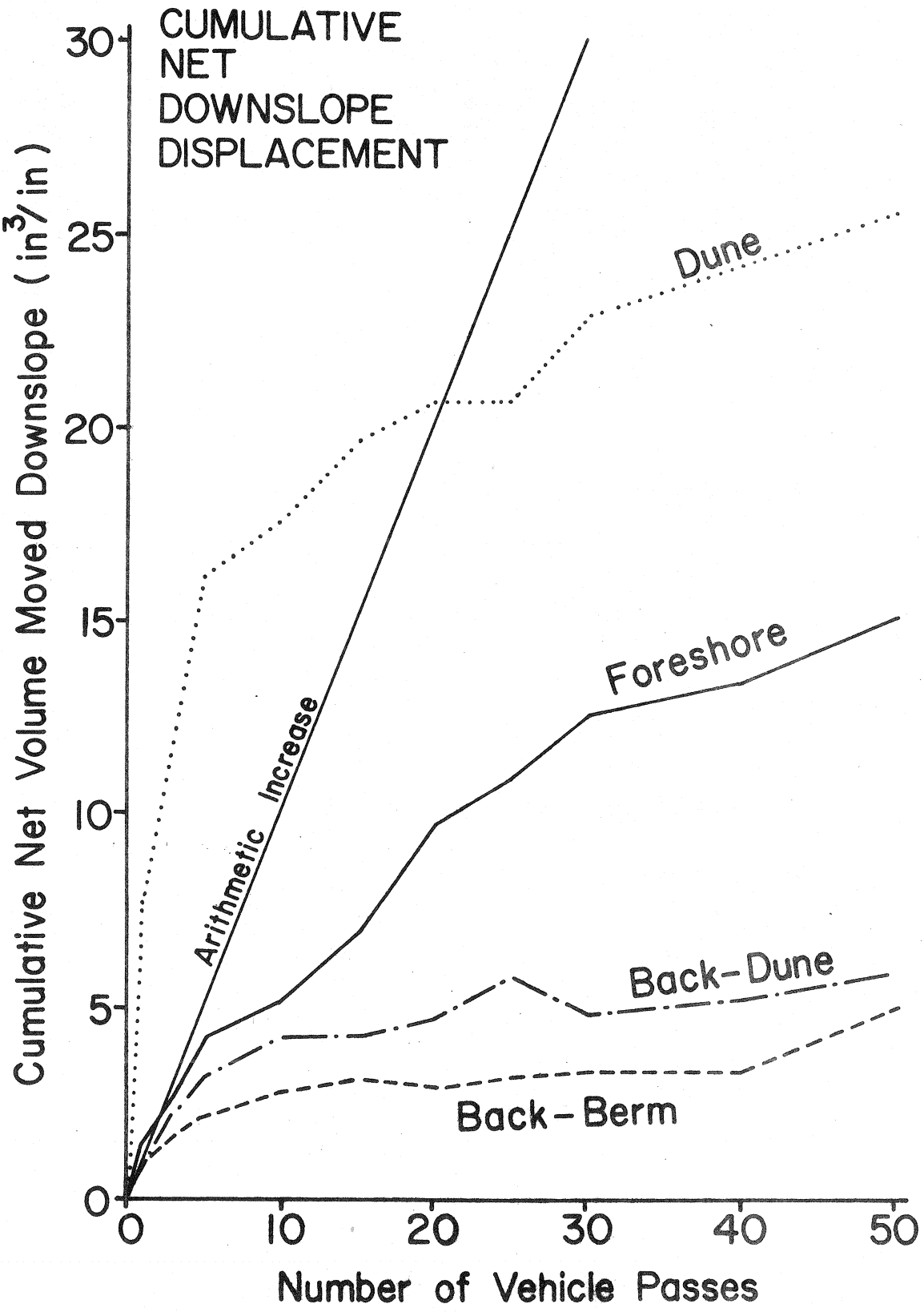


Figure 10. Cumulative net downslope displacement vs. number of passes. (Arithmetic line shown for comparative purposes only)

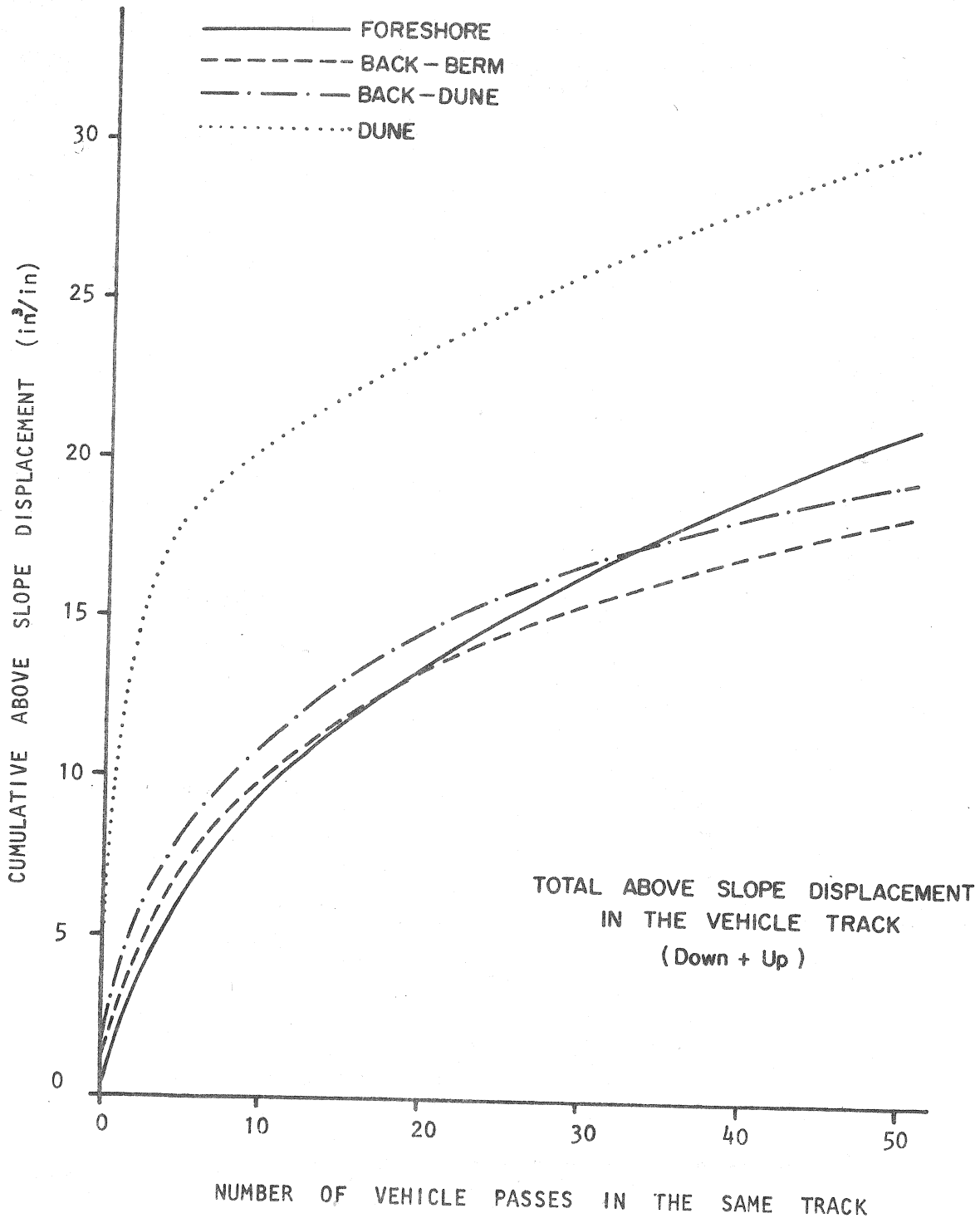


Figure 11. Total above slope displacement vs. number of passes.

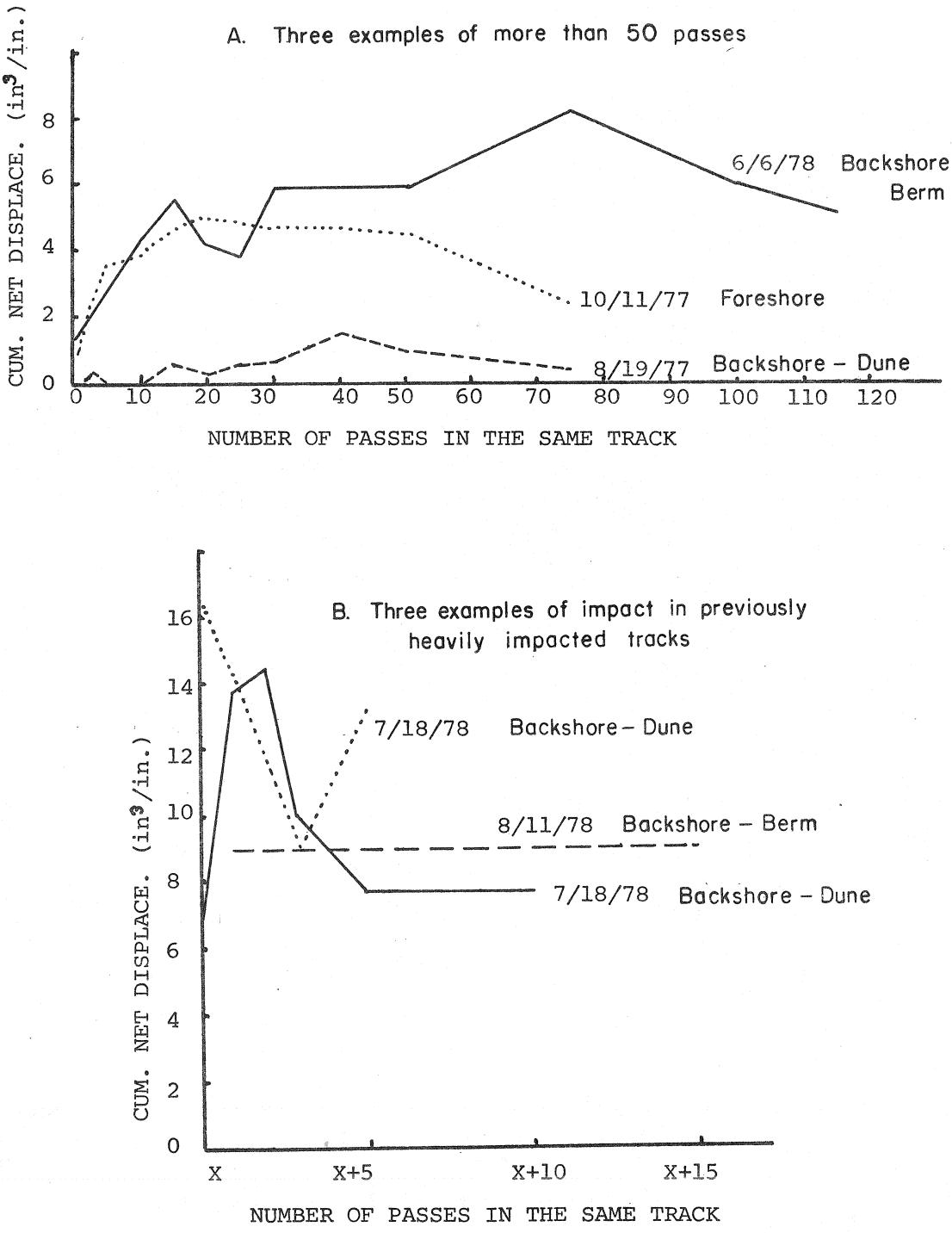


Figure 12, A&B. Cumulative net displacement vs. number of passes for more than 50 passes in the same track.

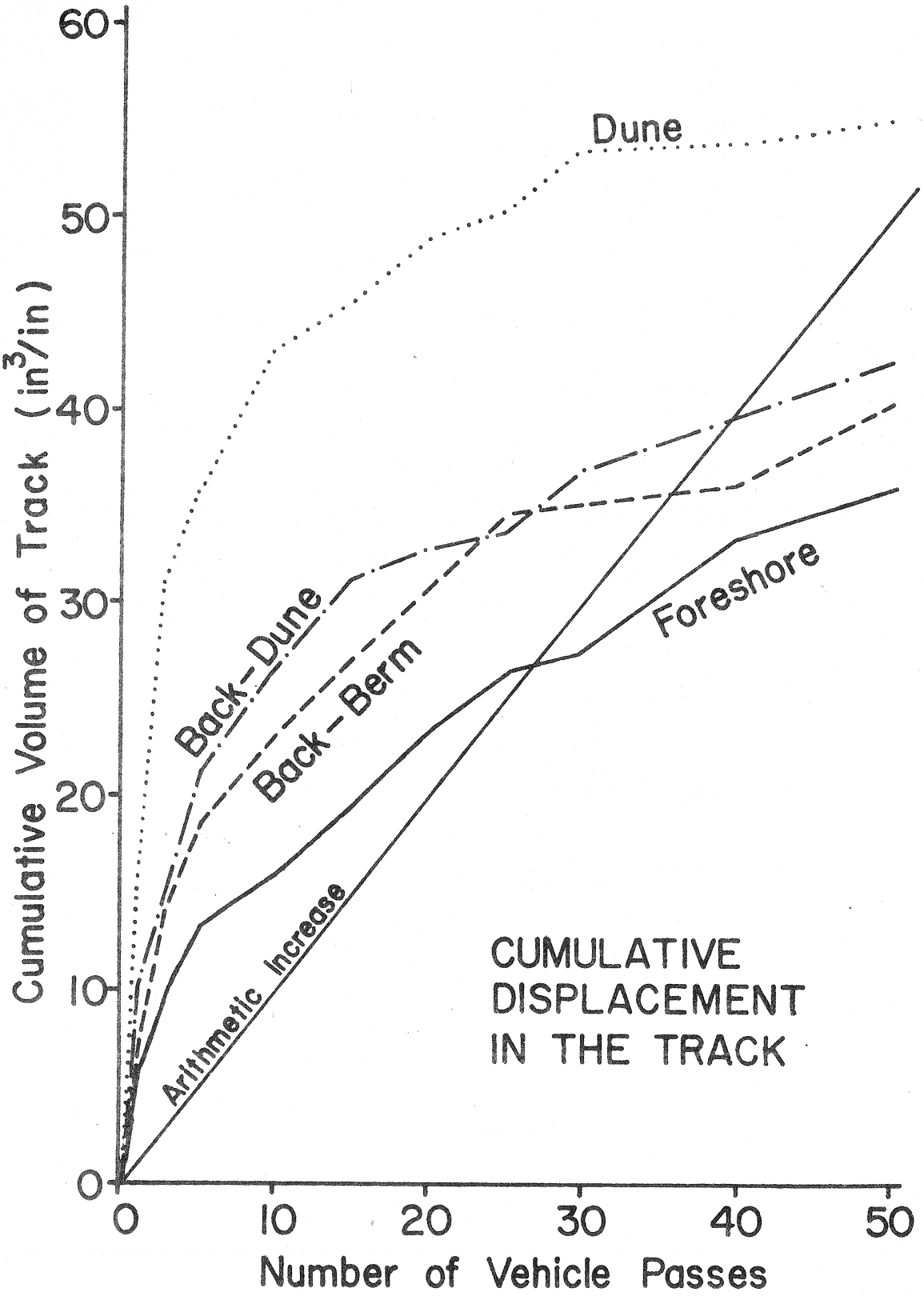


Figure 13. Cumulative track volume vs. number of passes. (Arithmetic line shown for comparative purposes only)

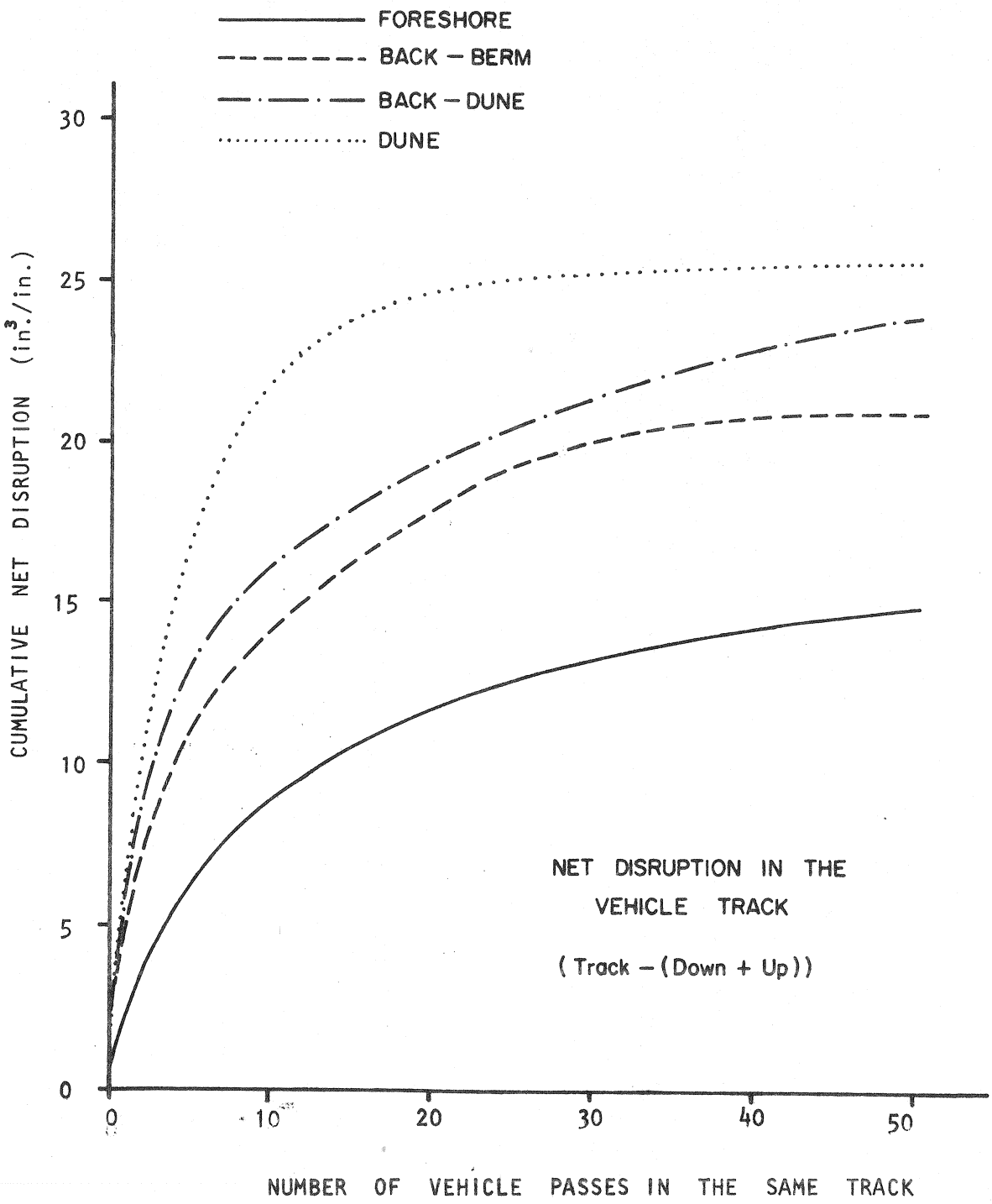


Figure 14. Net Disruption (T-(D+U)) vs. number of passes.

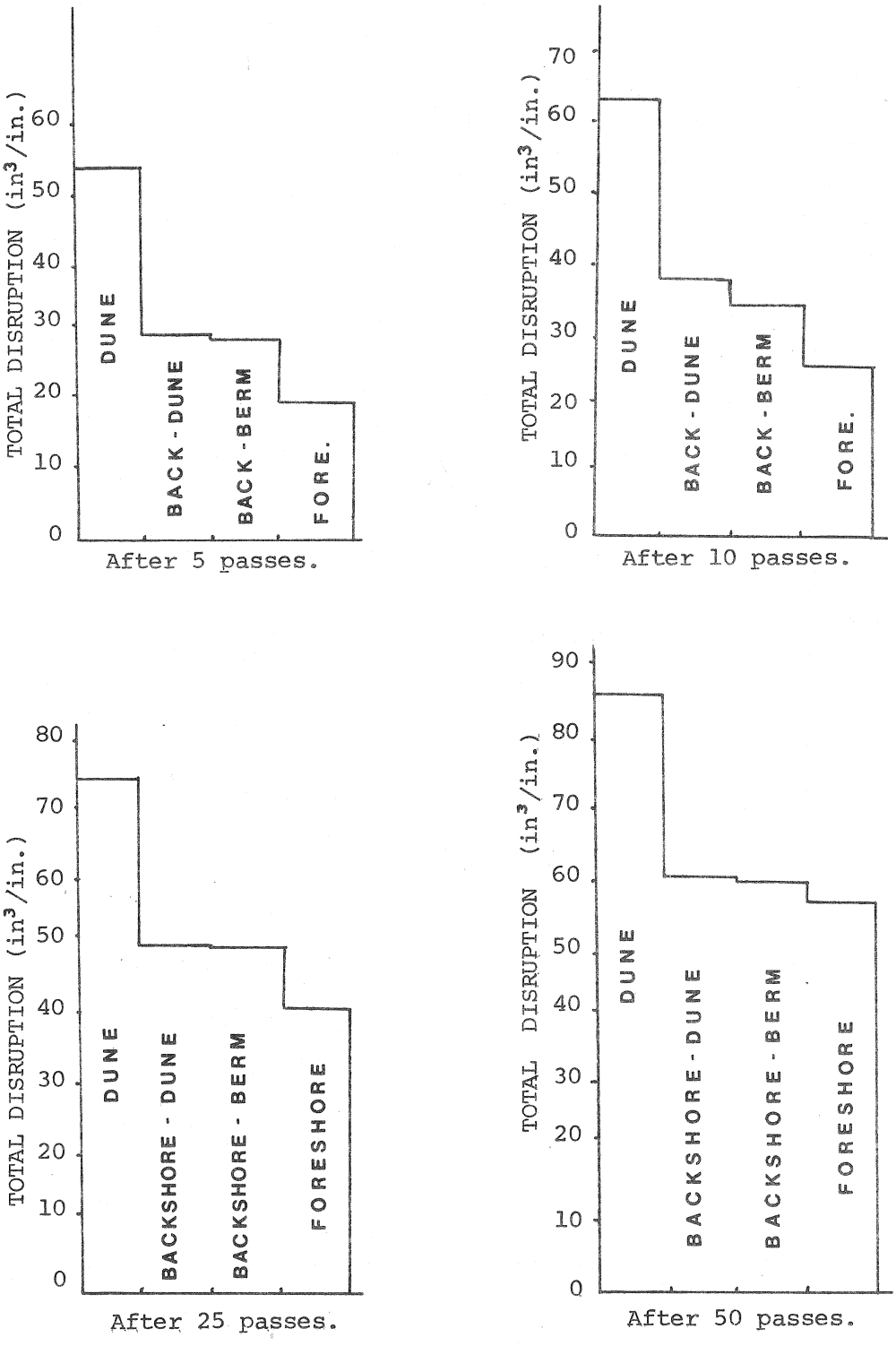


Figure 15. Total Disruption (T+D+U) resulting from ORV travel along the beach.

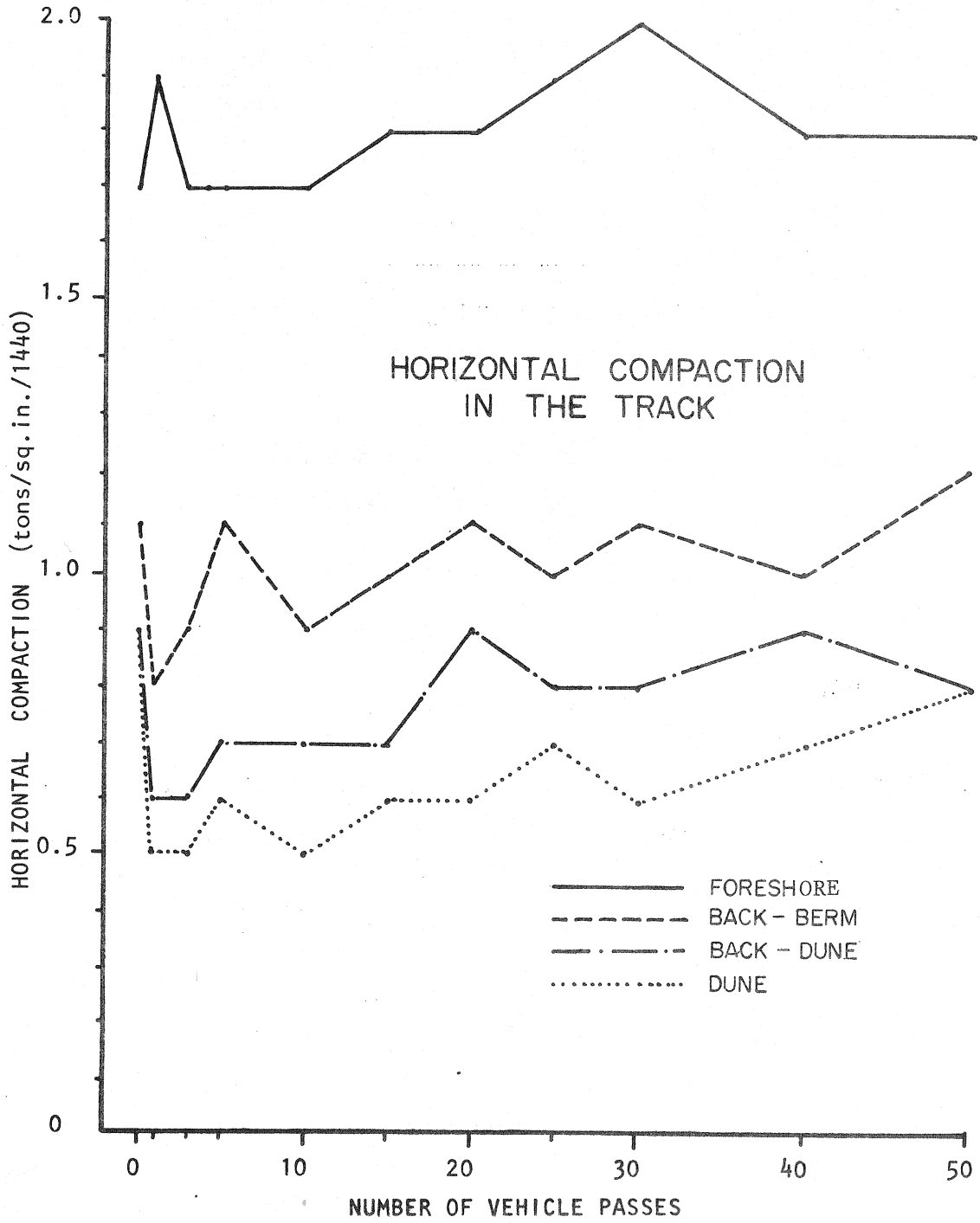


Figure 16. Horizontal Compaction vs. number of passes. Division by 1440 is to compensate for the special foot attachment to the Torvane.

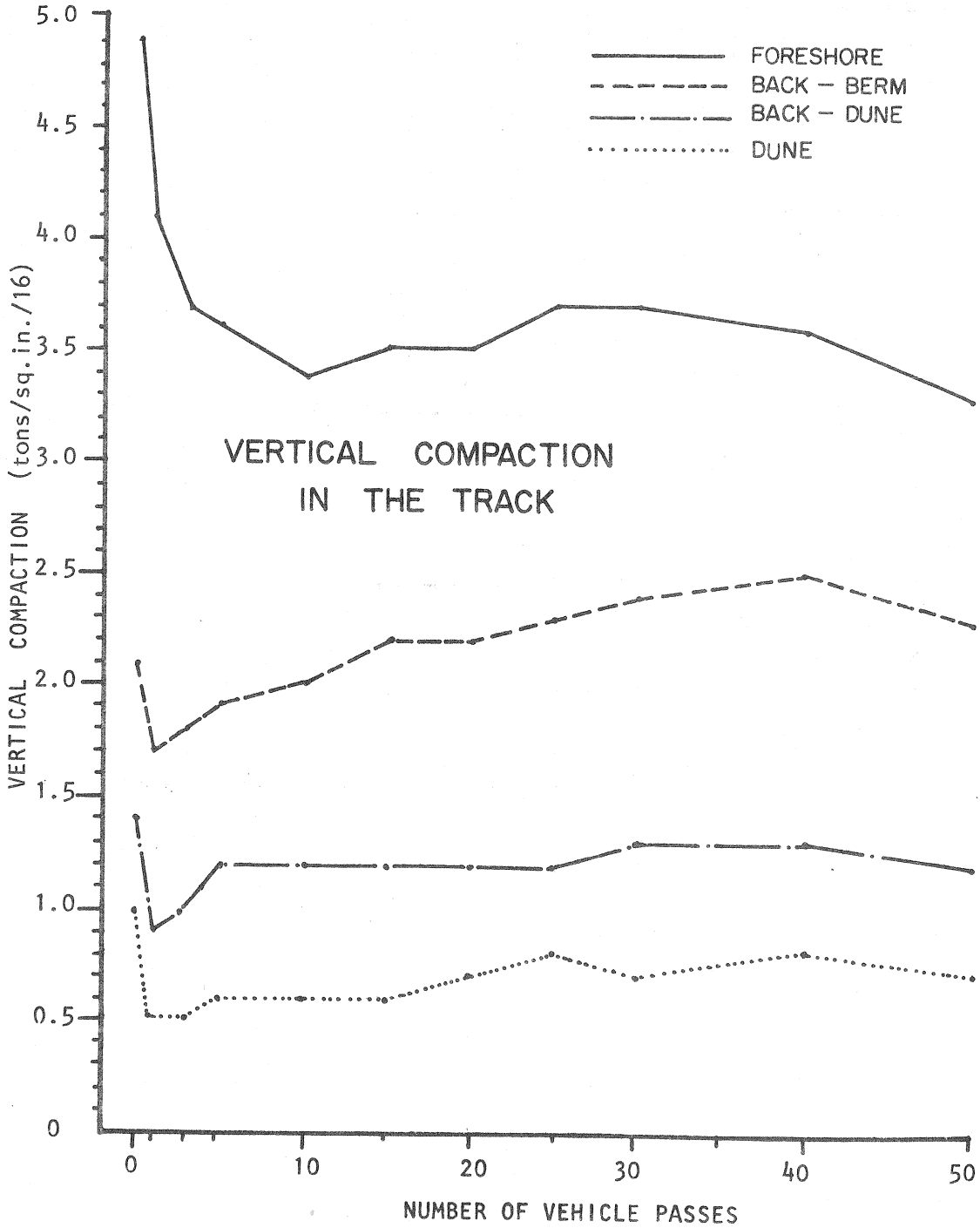


Figure 17. Vertical Compaction vs. number of passes. Division by 16 is to compensate for the special foot attachment to the penetrometer.

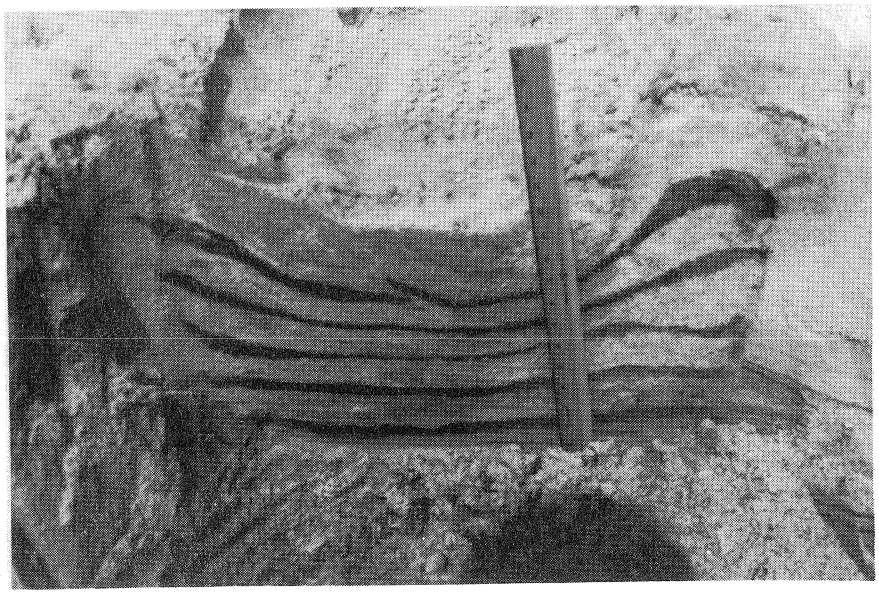


Figure 18. Sand compaction with depth after impacting. Artificial bands of quartz alternating with heavy minerals were horizontally layered on the beach prior to impacting.

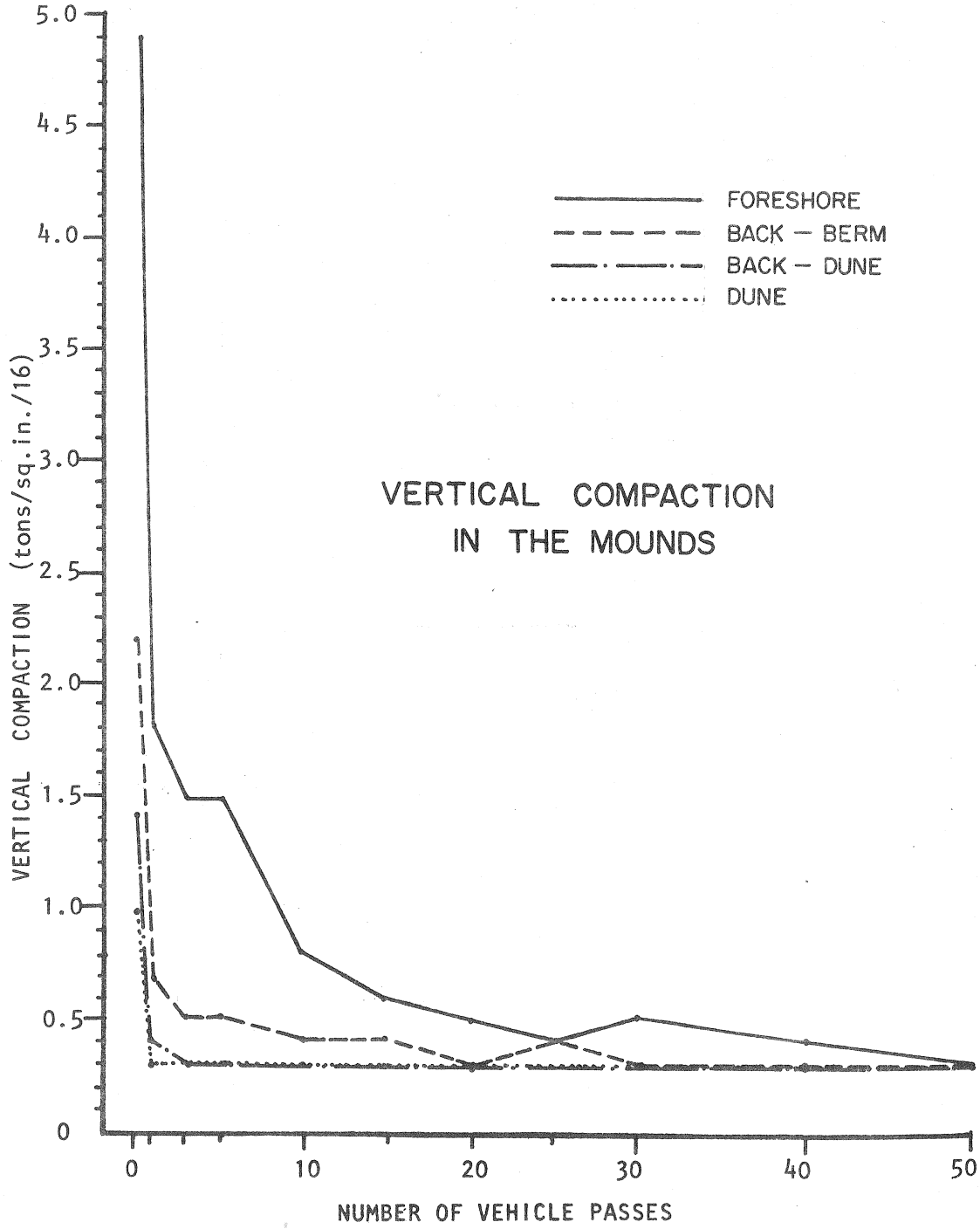


Figure 19. Vertical compaction in the mounds vs. number of passes. Minimum level of sensitivity of penetrometer is 0.3. Division by 16 is to compensate for the special foot attachment to the penetrometer.

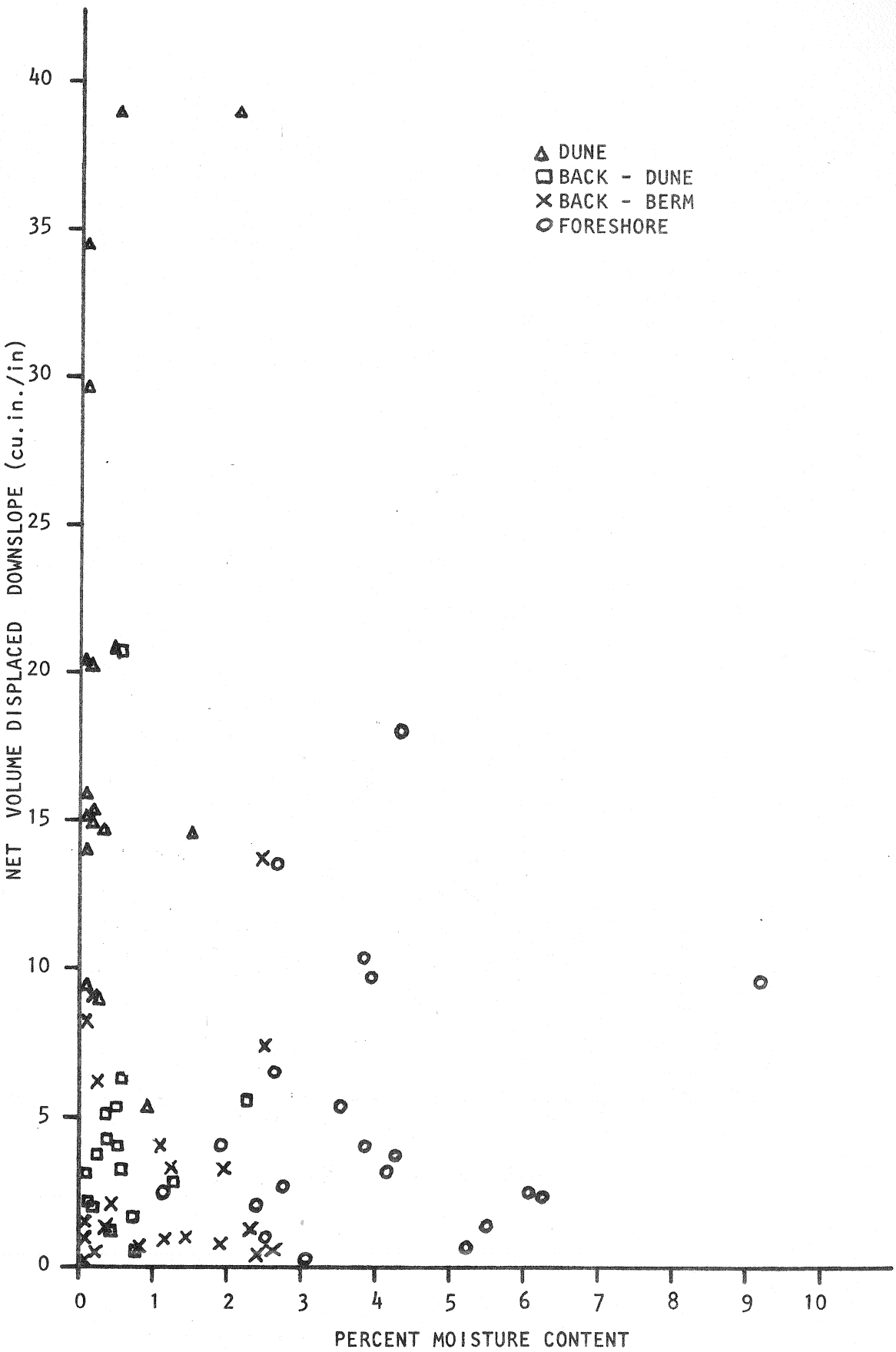


Figure 20. Mositure content vs. Net downslope displacement after 10 passes.

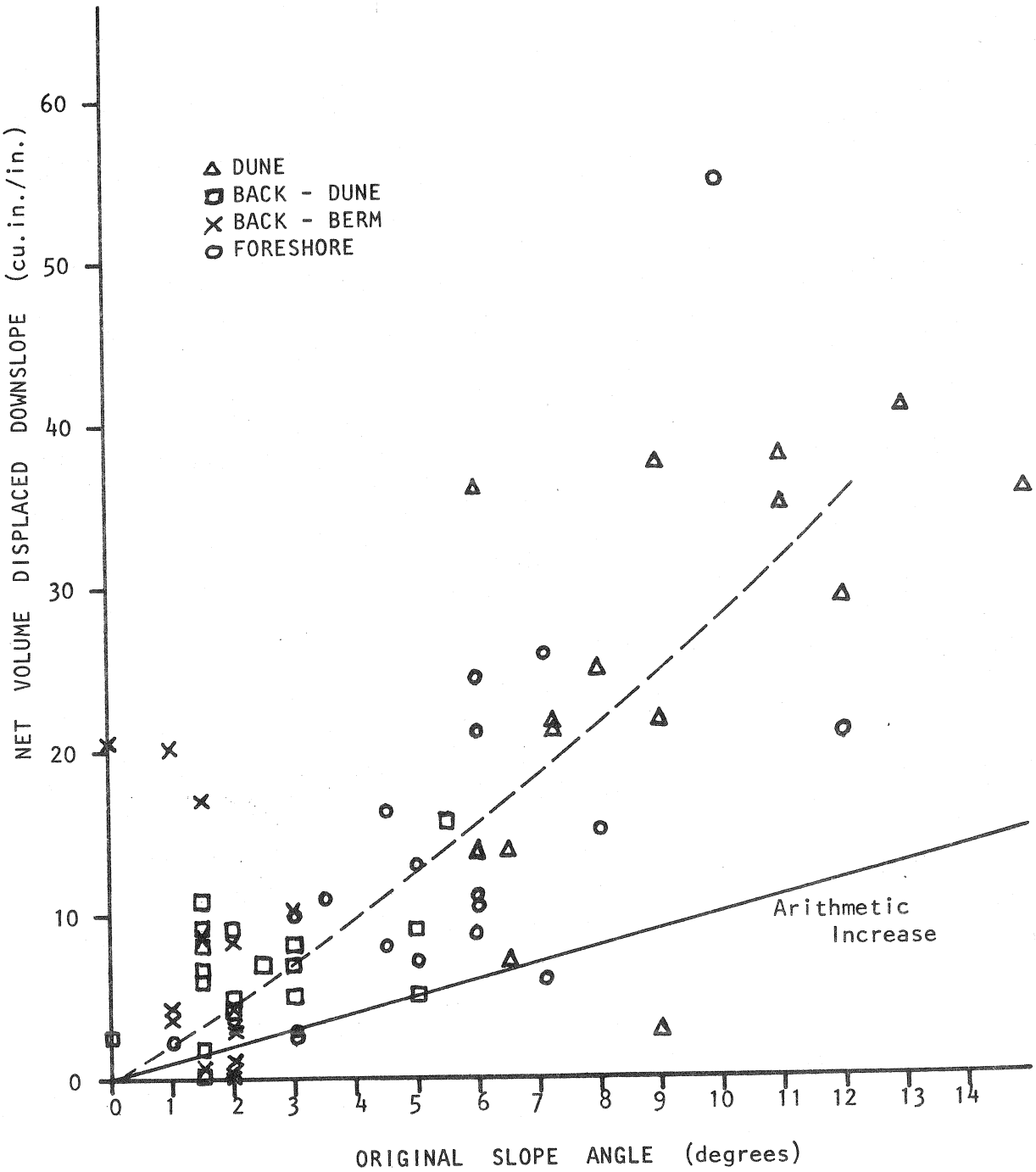


Figure 21. Slope vs. net downslope displacement after 50 passes. Dashed line represents visually approximated slope of the points. Arithmetic line shown for comparative purposes only.

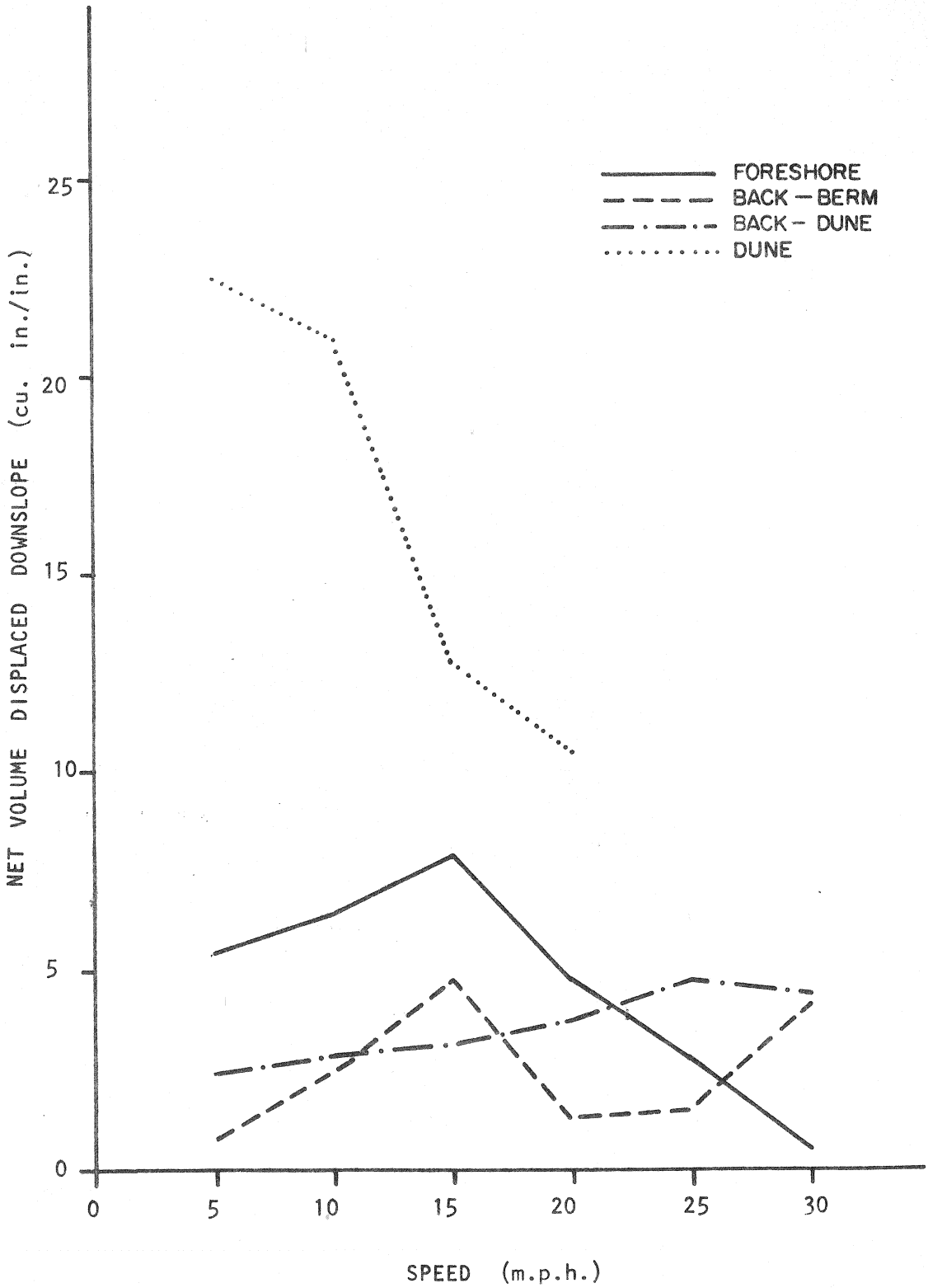


Figure 22. Speed vs. net downslope displacement after 10 passes.

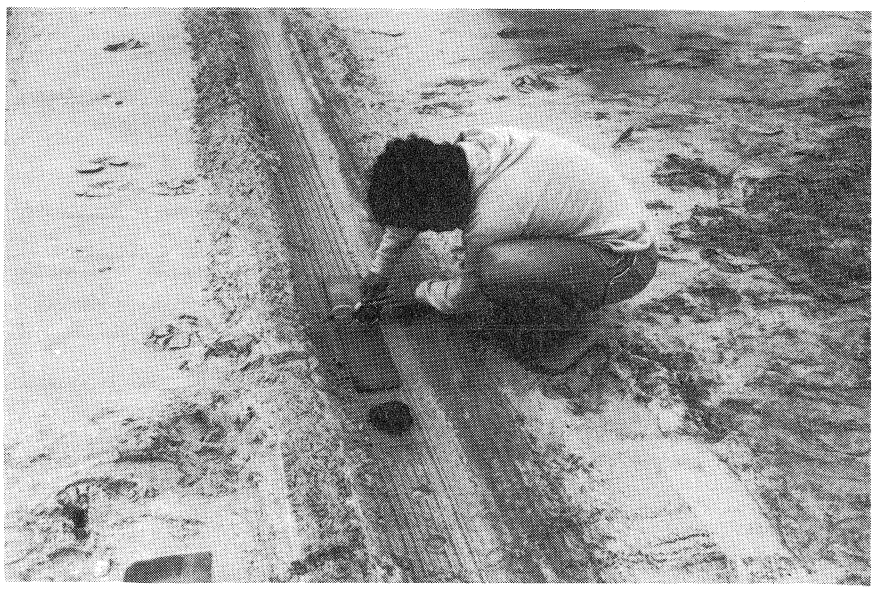


Figure 23. Measuring slope in the track, after testing.

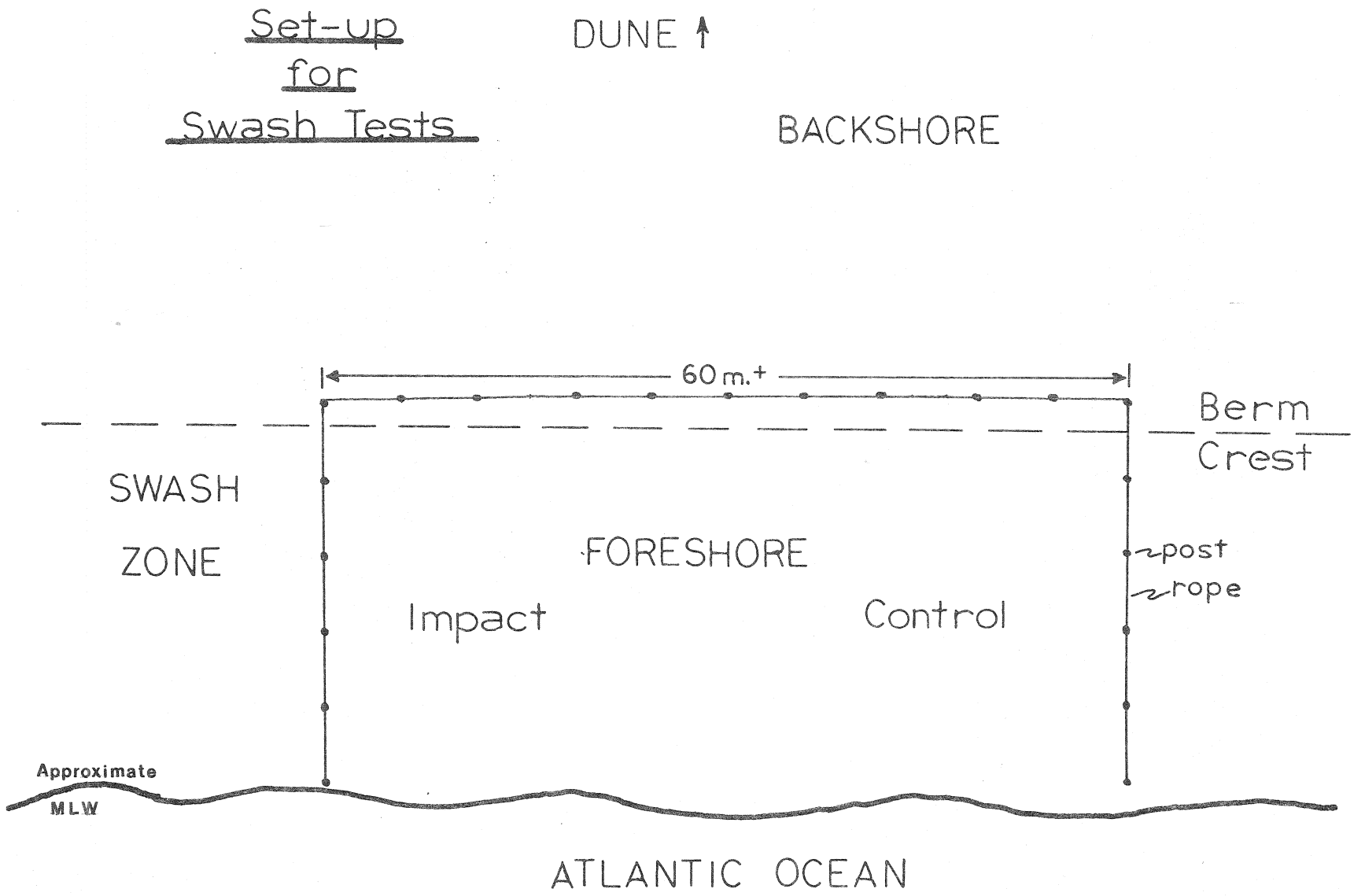


Figure 24. Typical exclosure site for swash tests.



Figure 25. Impacting the foreshore.

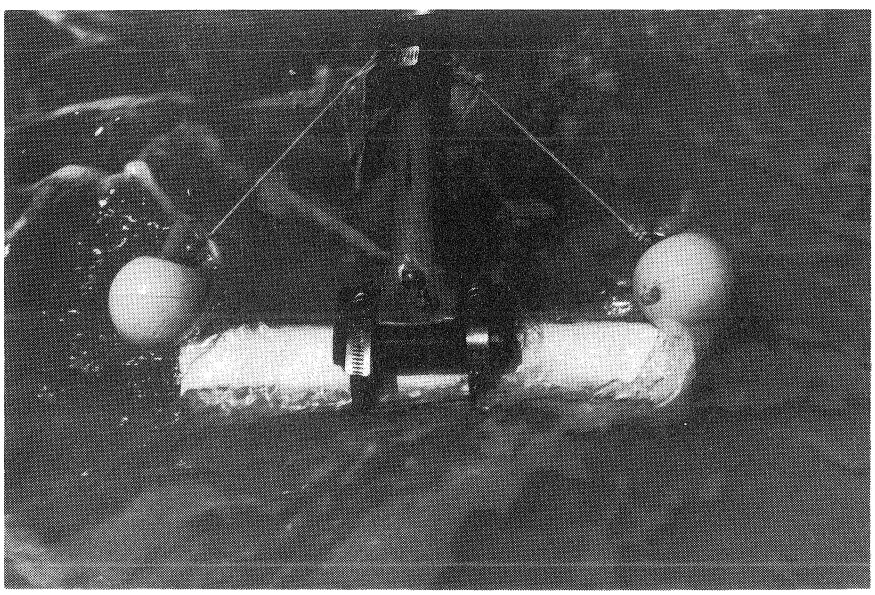


Figure 26. Swash Sampler, open

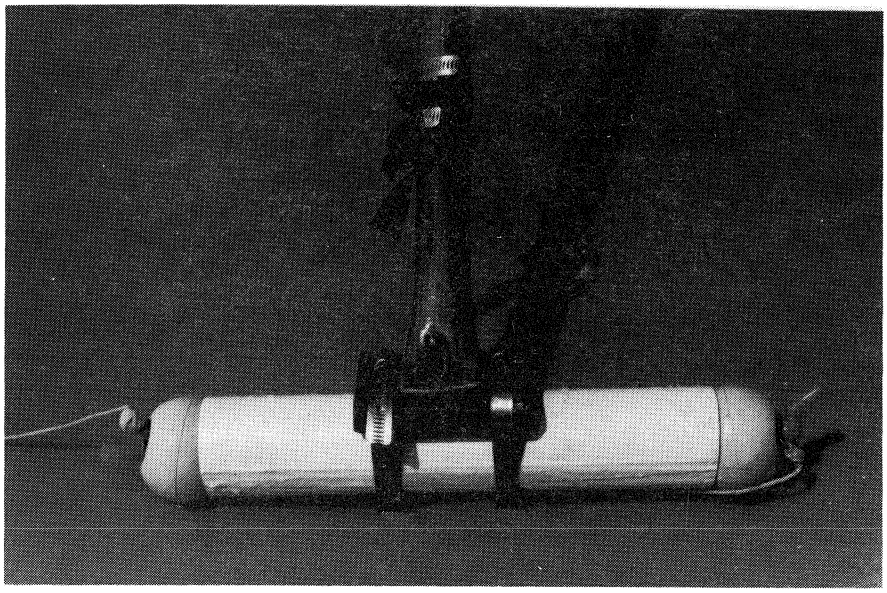


Figure 27. Swash Sampler, closed.



Figure 28. Swash Samplers in position on the beach.

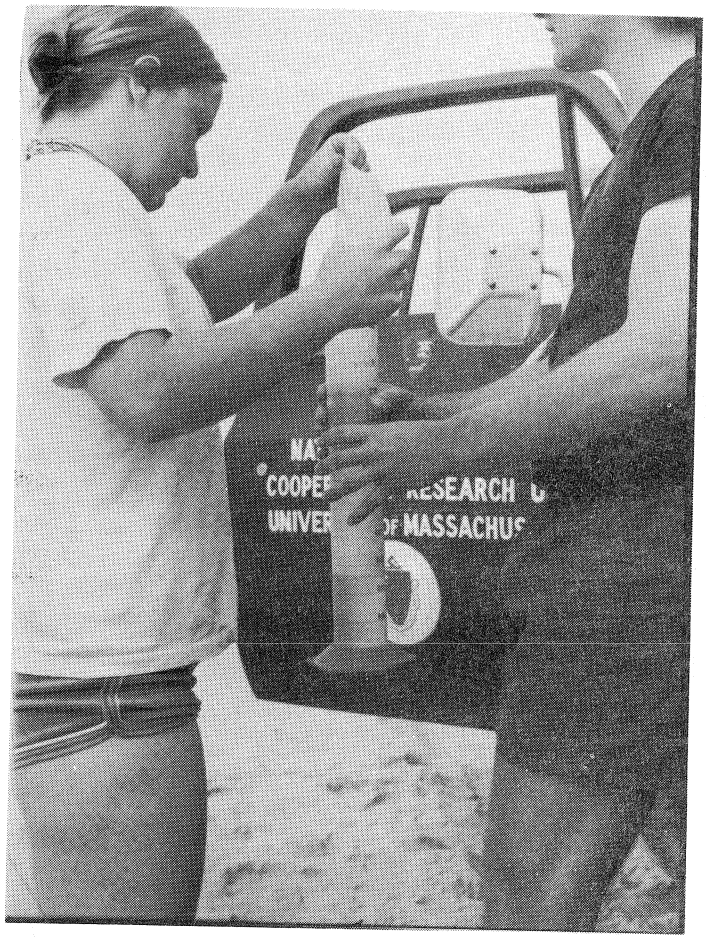


Figure 29. Measuring water volume from swash sample.

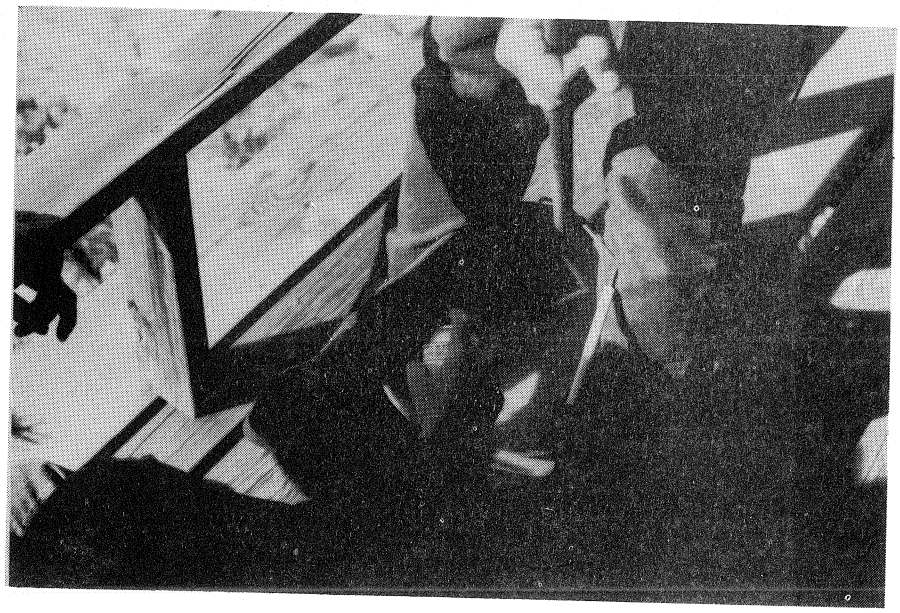


Figure 30. Painting tracer sand.



Figure 31. Impact and control sampling lines.



Figure 32. Tracer test sampler.



Figure 33. Samples being collected during tracer test.

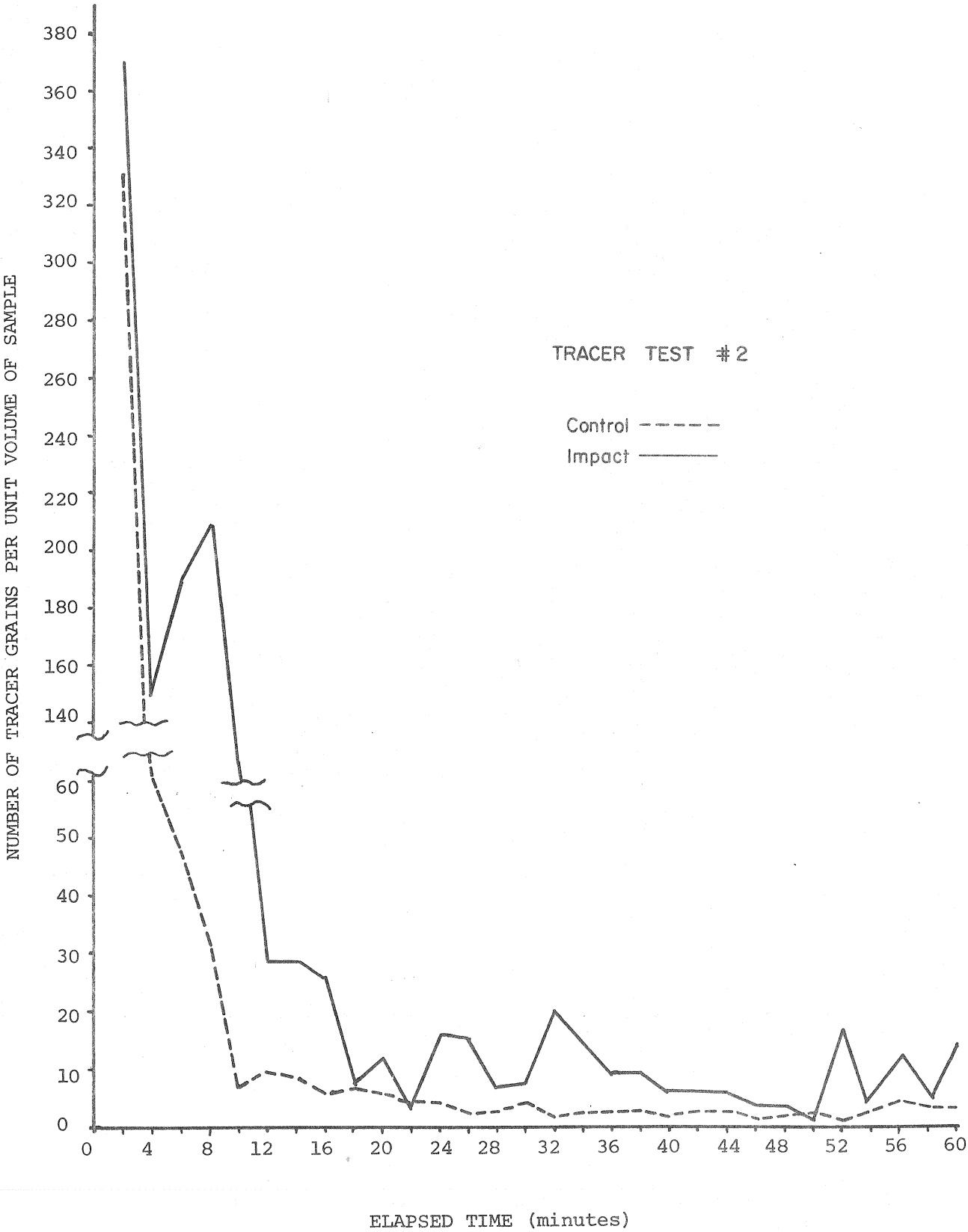


Figure 34. Tracer test results, impact greater.

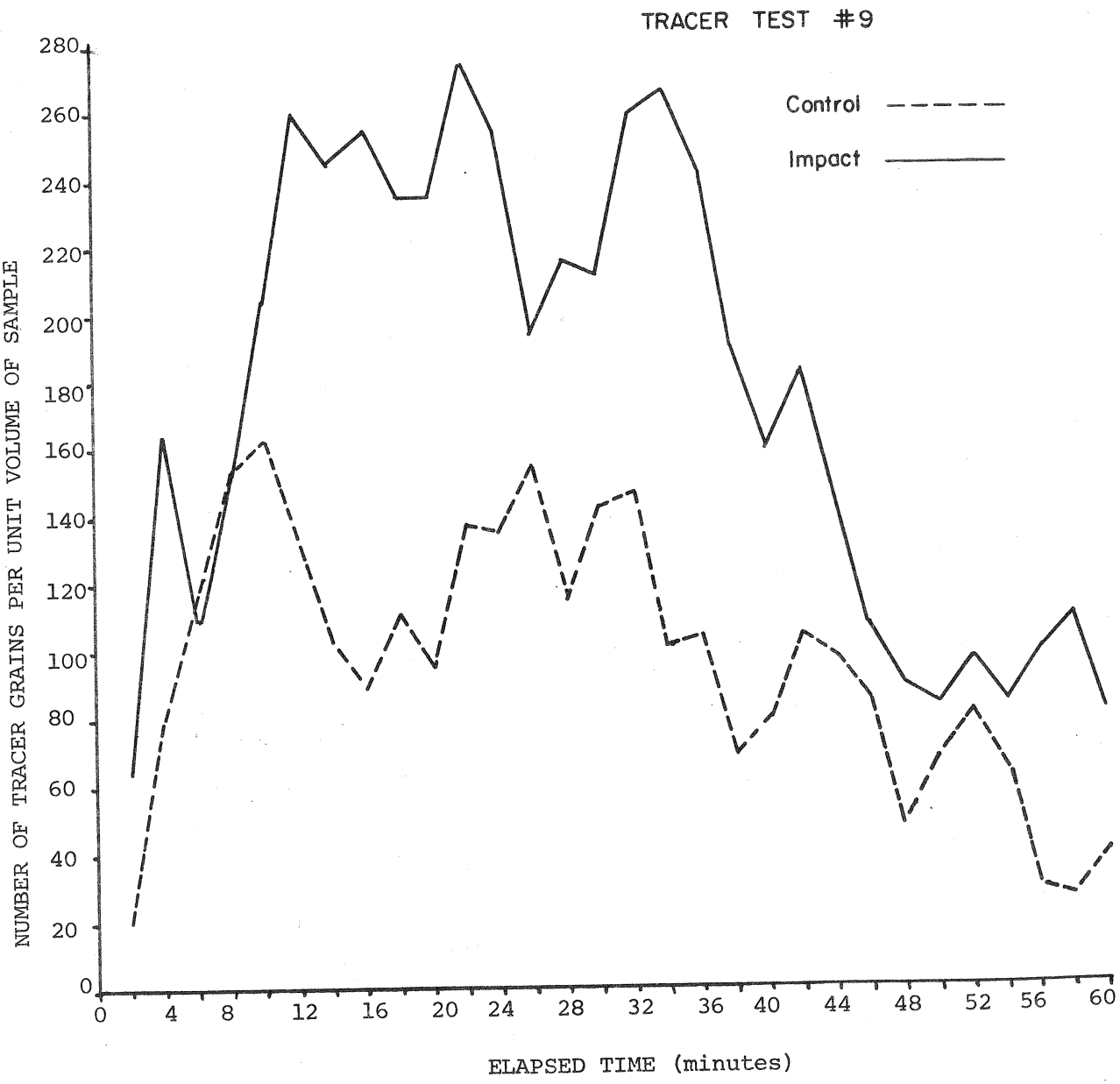


Figure 35. Tracer test results, impact greater.

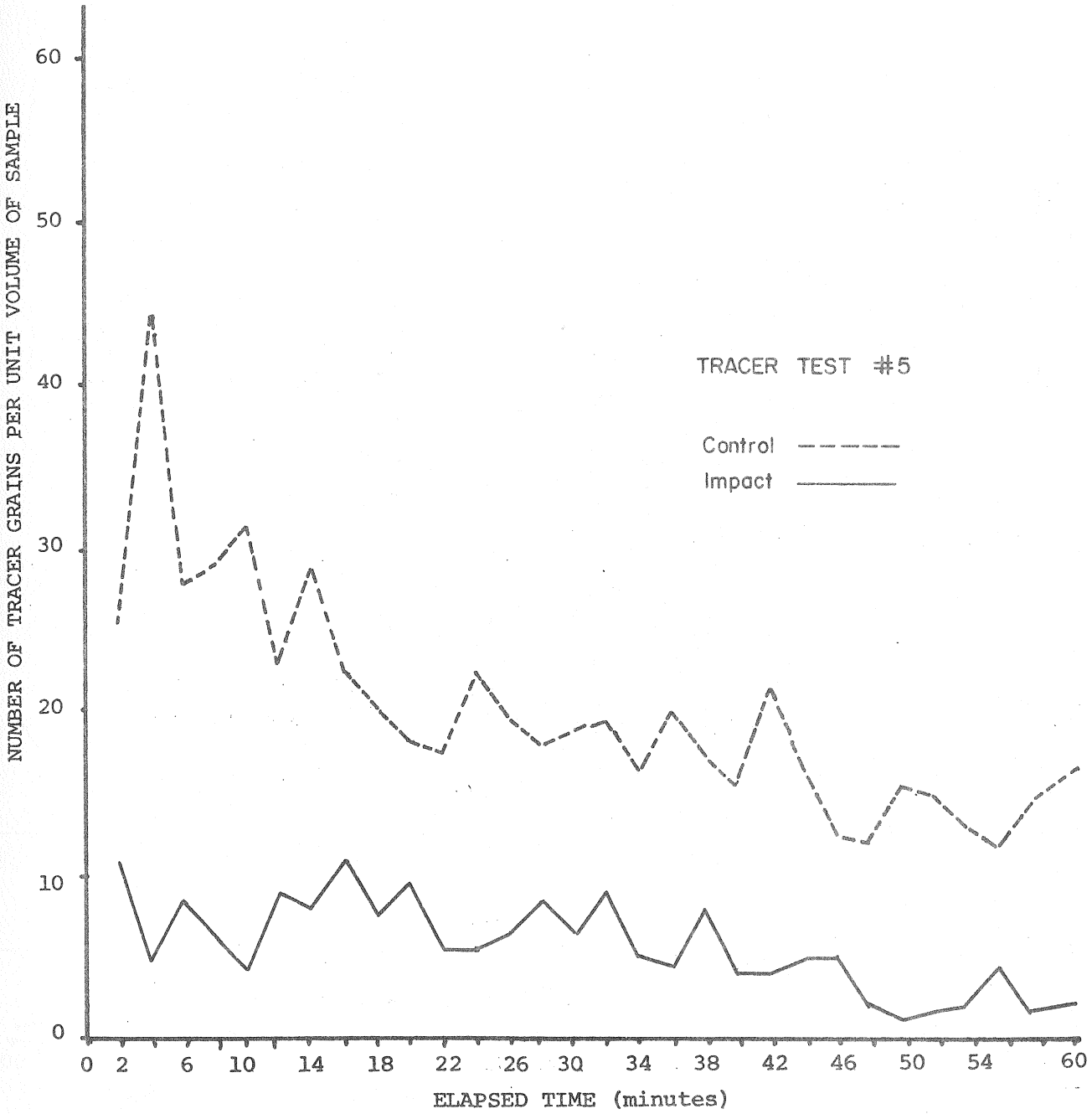


Figure 36. Tracer test results, control greater.

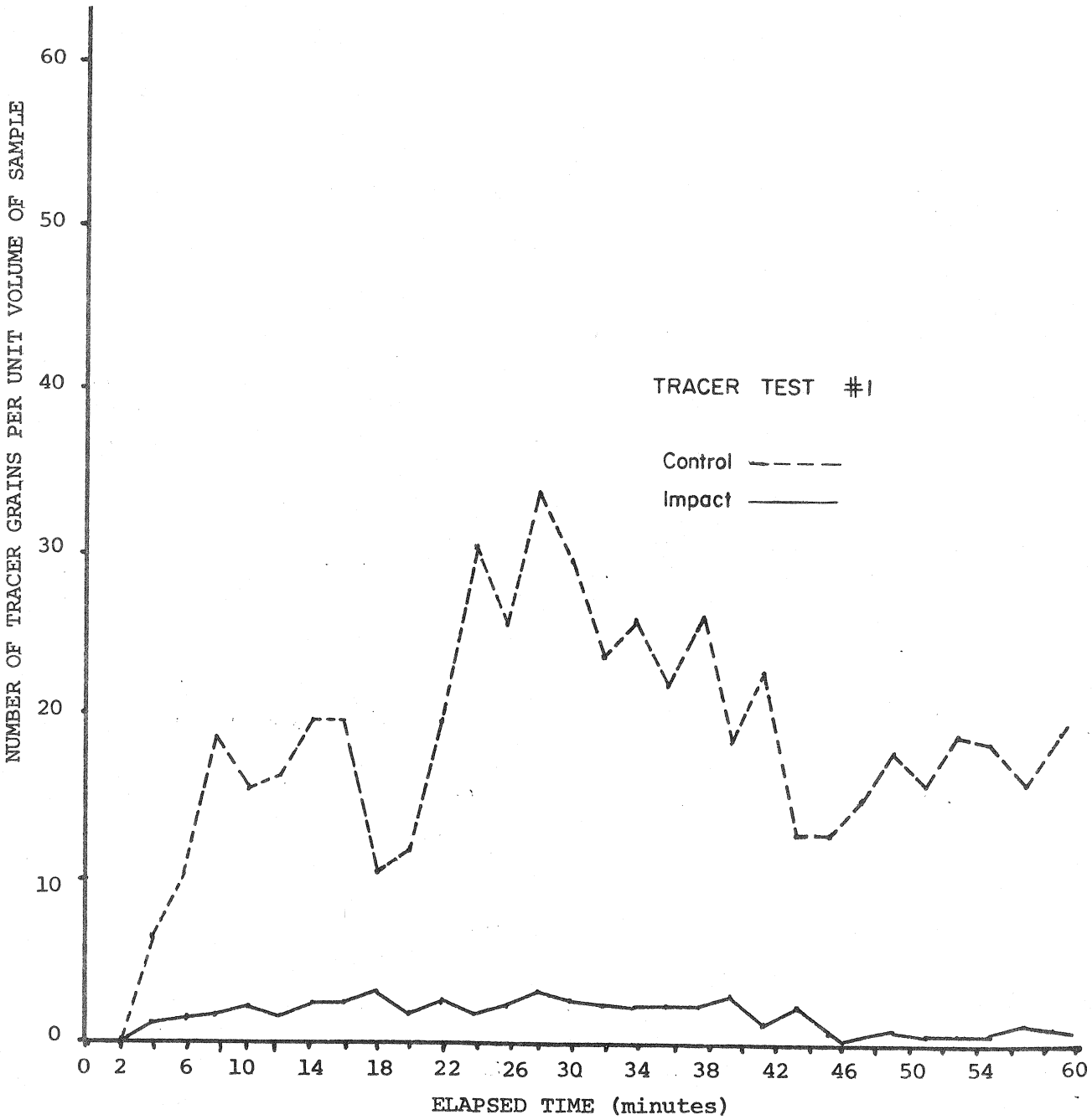


Figure 37. Tracer test results, control greater.

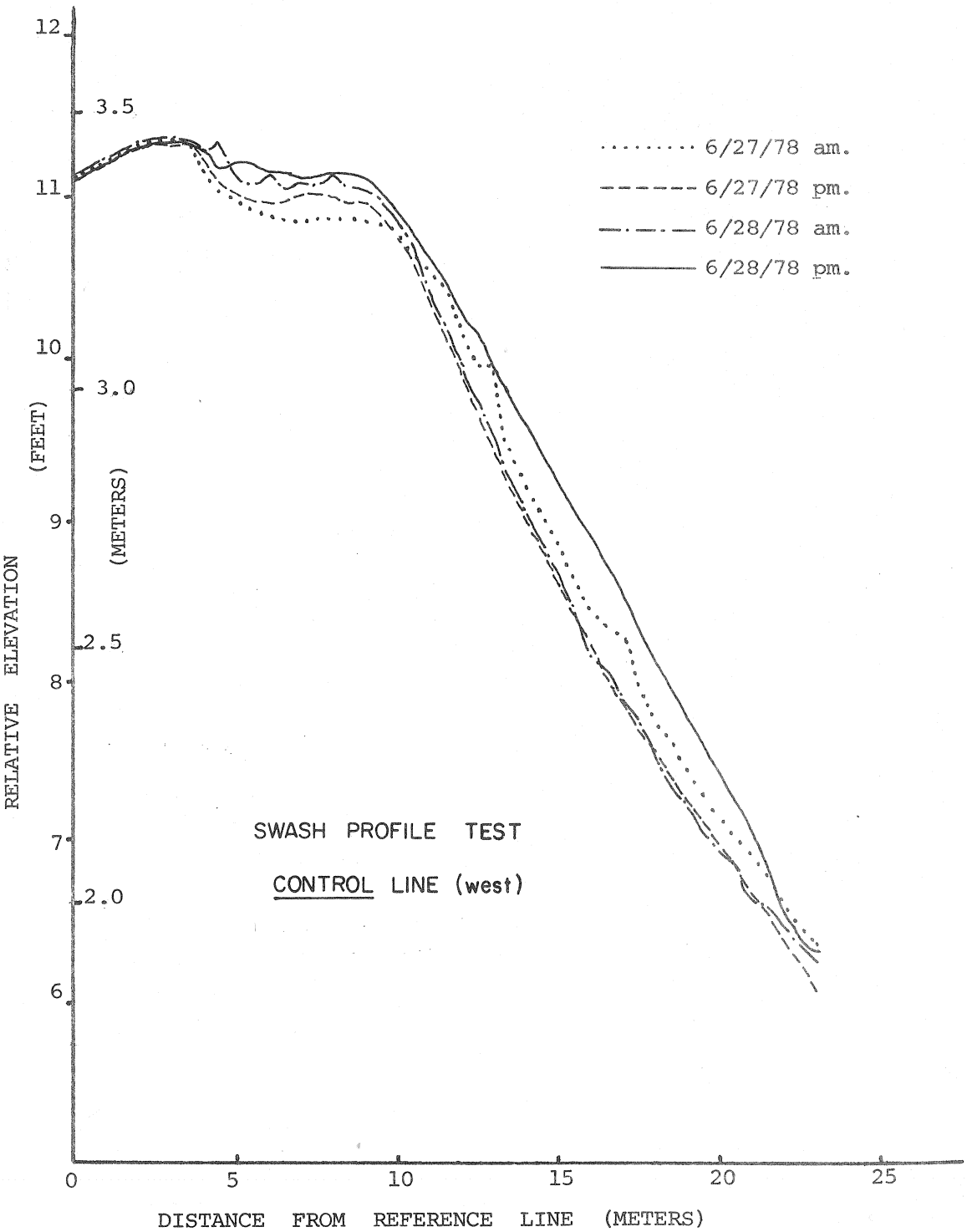


Figure 38. Swash test profile, control.

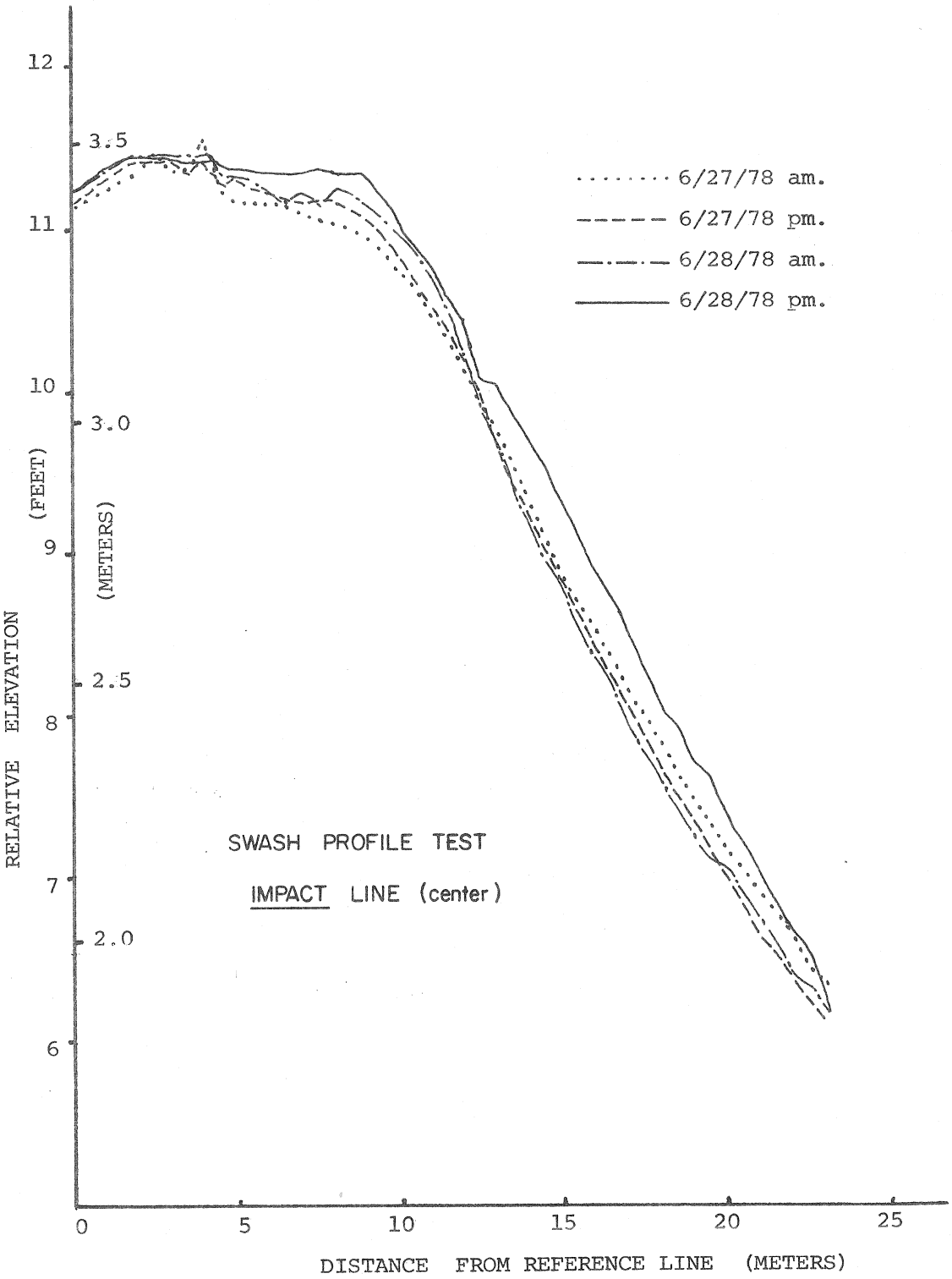


Figure 39. Swash Test Profile, Impact.

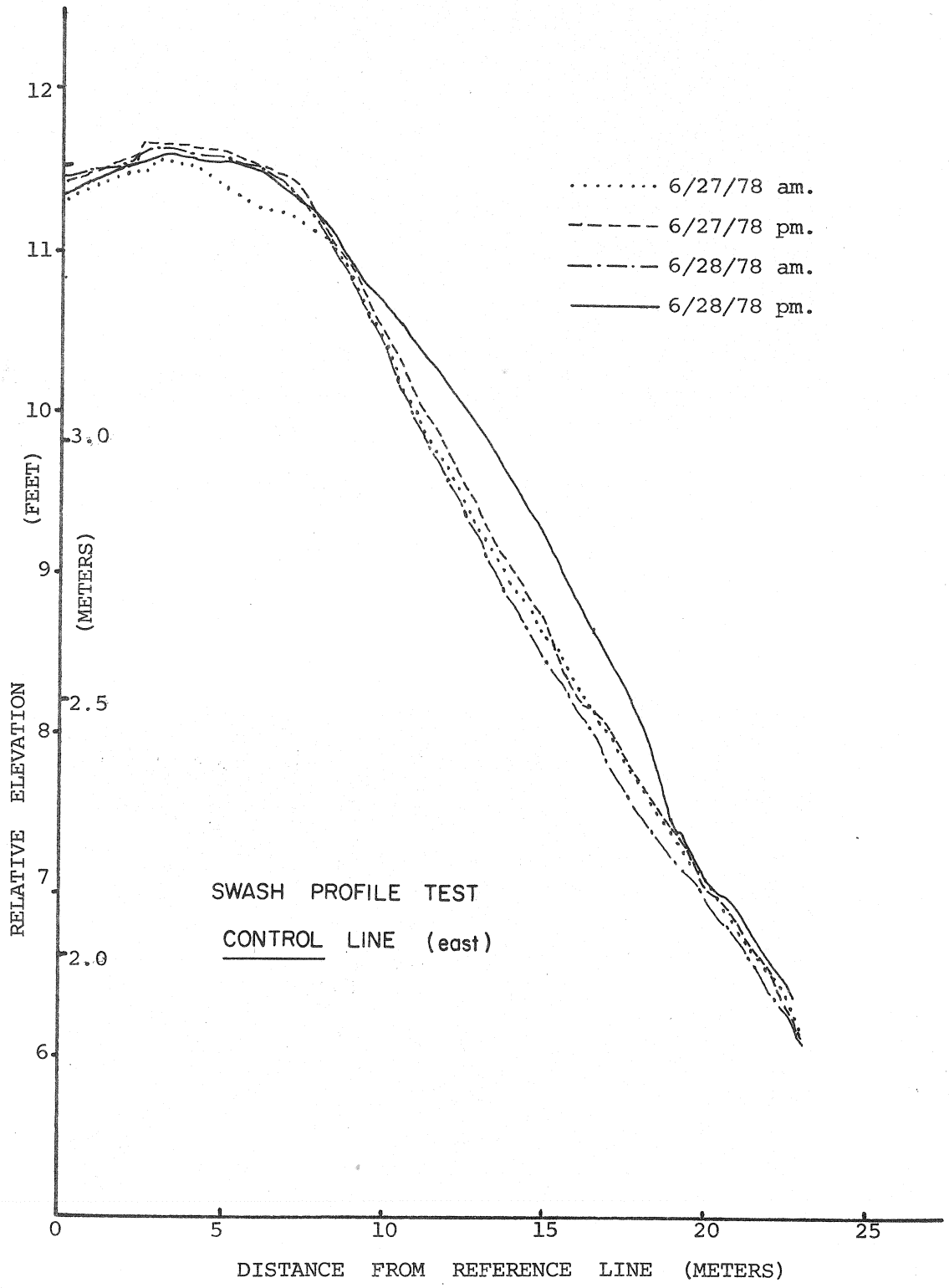


Figure 40. Swash test profile, control.

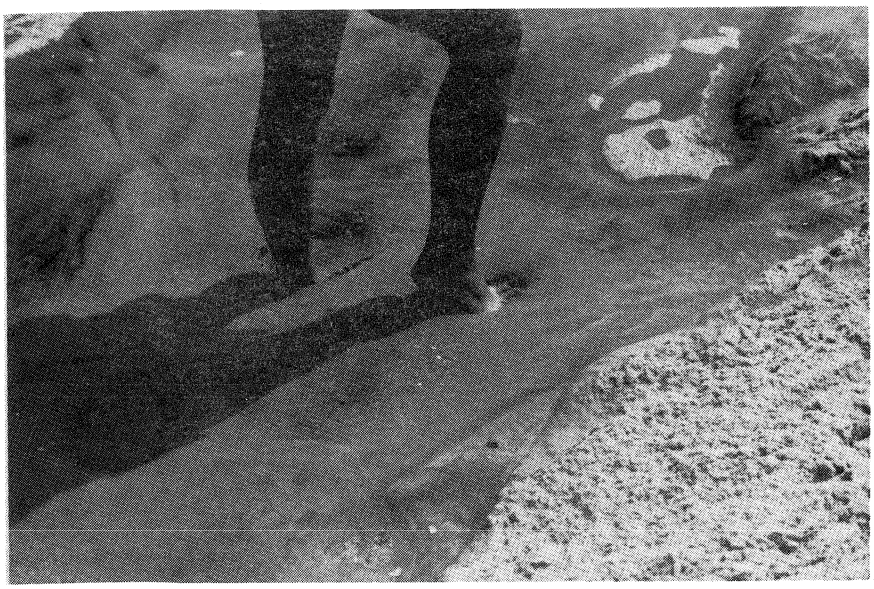


Figure 41. Soft sand on impacted foreshore.



Figure 42. Turbulence and reflected wave due to ORV tracks.

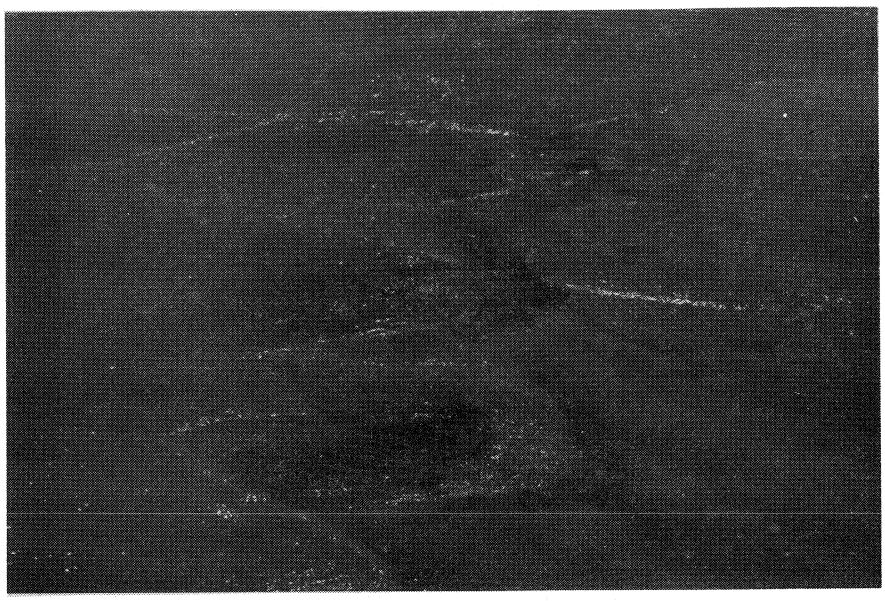


Figure 43. Turbulence around footprints and resultant heavy mineral lag deposit.

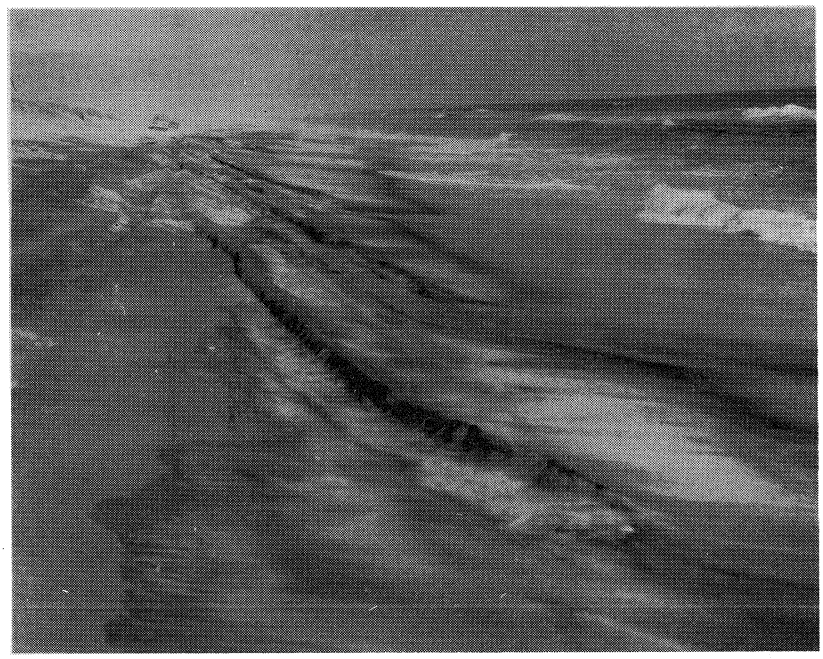


Figure 44. ORV tracks and heavy mineral lag deposit due to turbulent interaction with swash.



Figure 45. Aerial view of Kismet Dune Cut (center). All traffic moves along the beach east (right) of the dune cut.

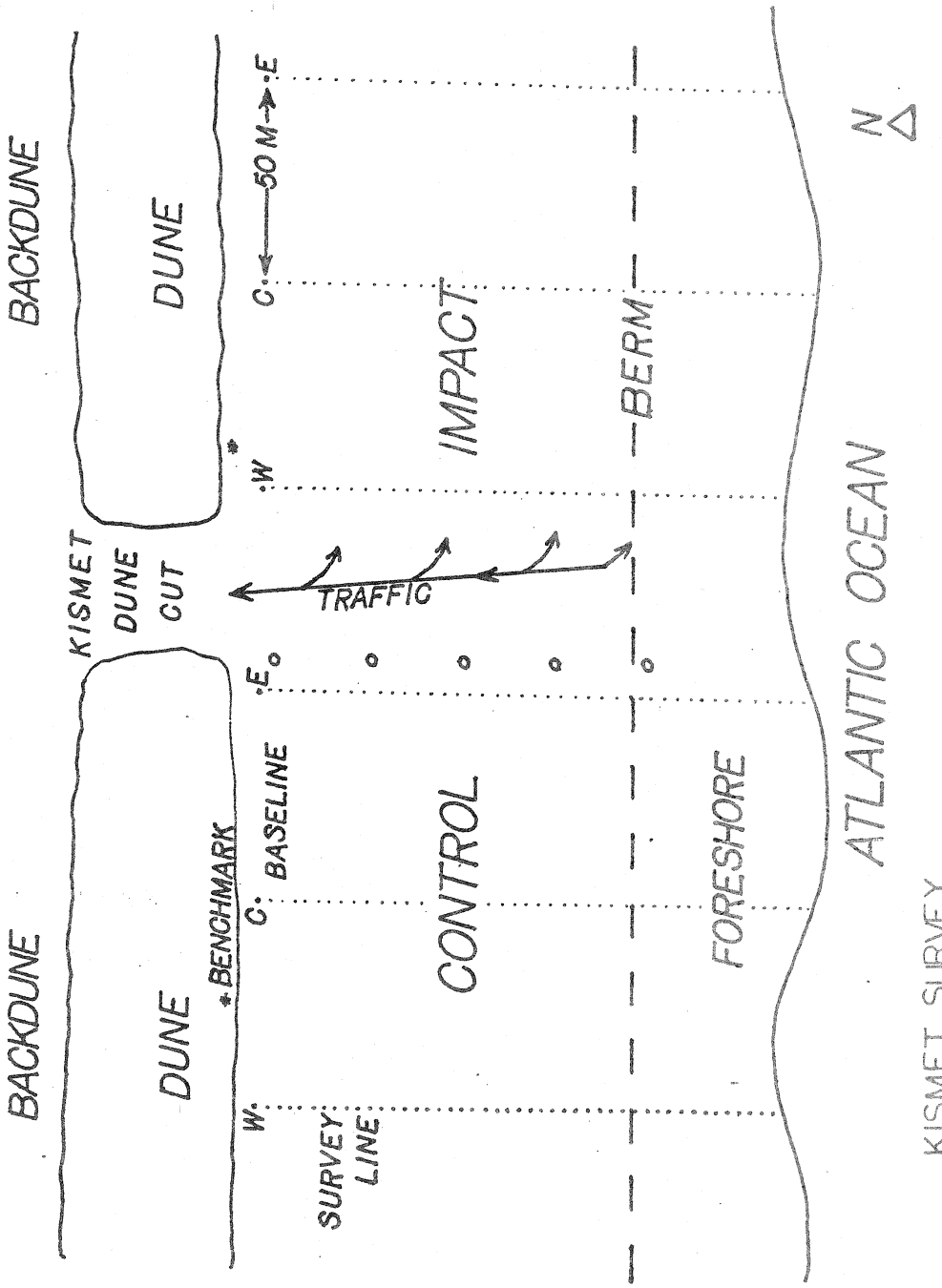
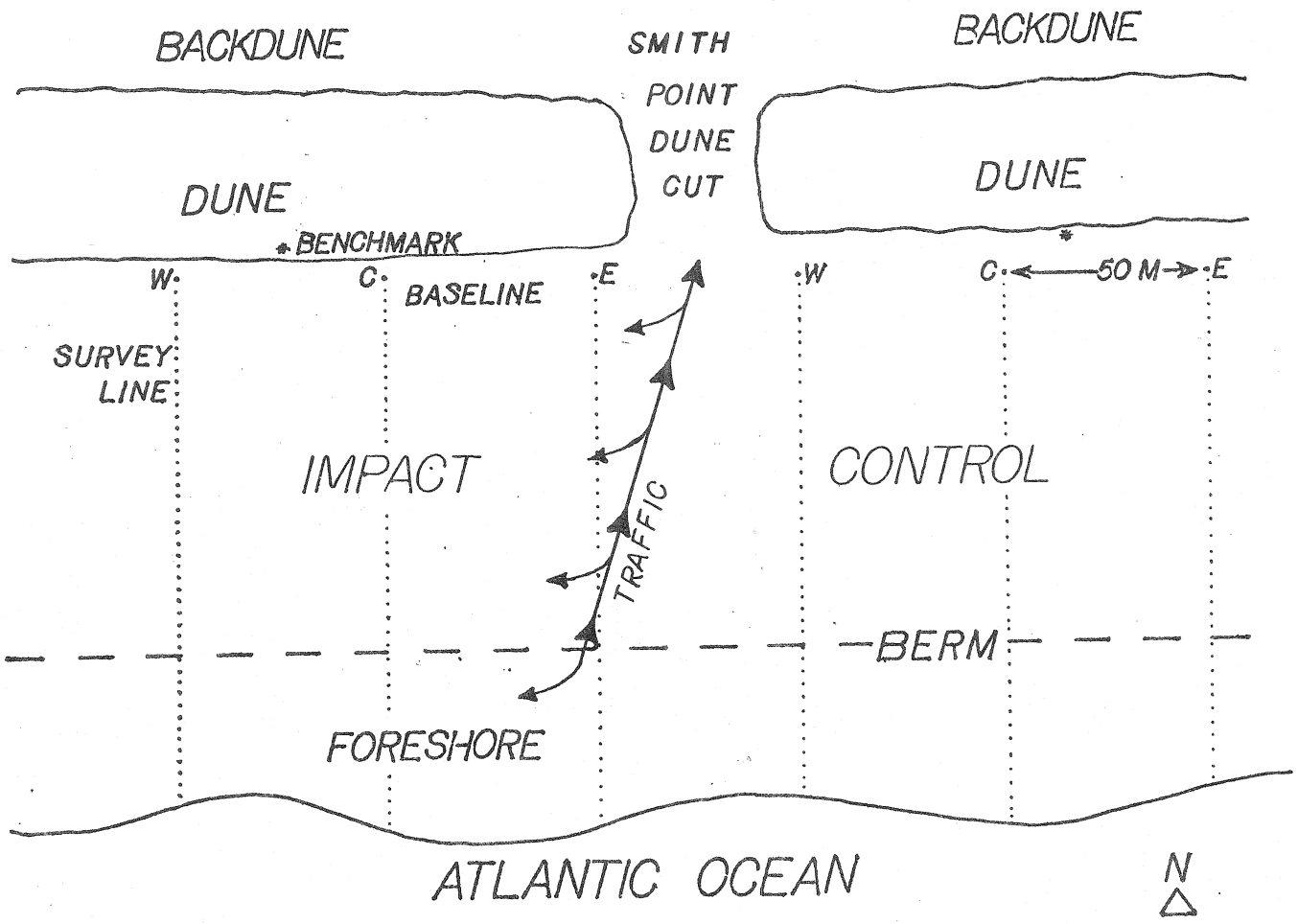


Figure 46. Map of Kismet field site.



SMITH POINT SURVEY SITE

Figure 47. Map of Smith Point field site.



Figure 48. Surveying the beach profile at Kismet

Figure 49. Kismet Profiles.

Figure 50. Kismet Profiles.

Figure 51. Kismet Profiles.

Figure 52. Kismet Profiles.

Figure 53. Kismet Profiles.

Figure 54. Kismet Profiles.

Figure 57. Kismet Profiles.

Figure 58. Kismet Profiles.

Figure 59. Kismet Profiles.

Figure 60. Kismet Profiles.

Figure 61. Kismet Profiles.

Figure 62. Kismet Profiles.

Figure 63. Kismet Profiles.

Figure 64. Kismet Profiles.

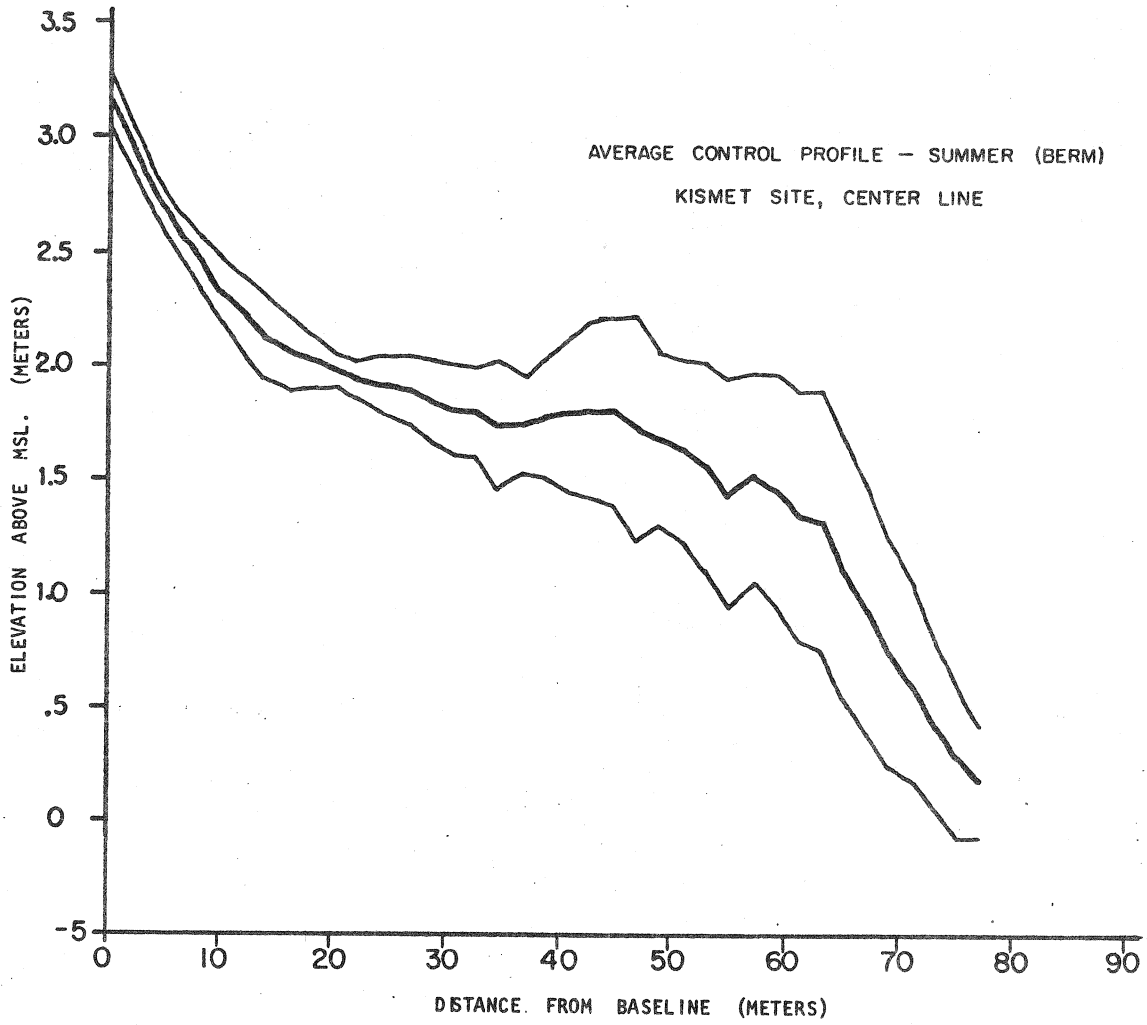


Figure 65. Kismet, average summer profile for control site, with normal range of variation (std. dev.).

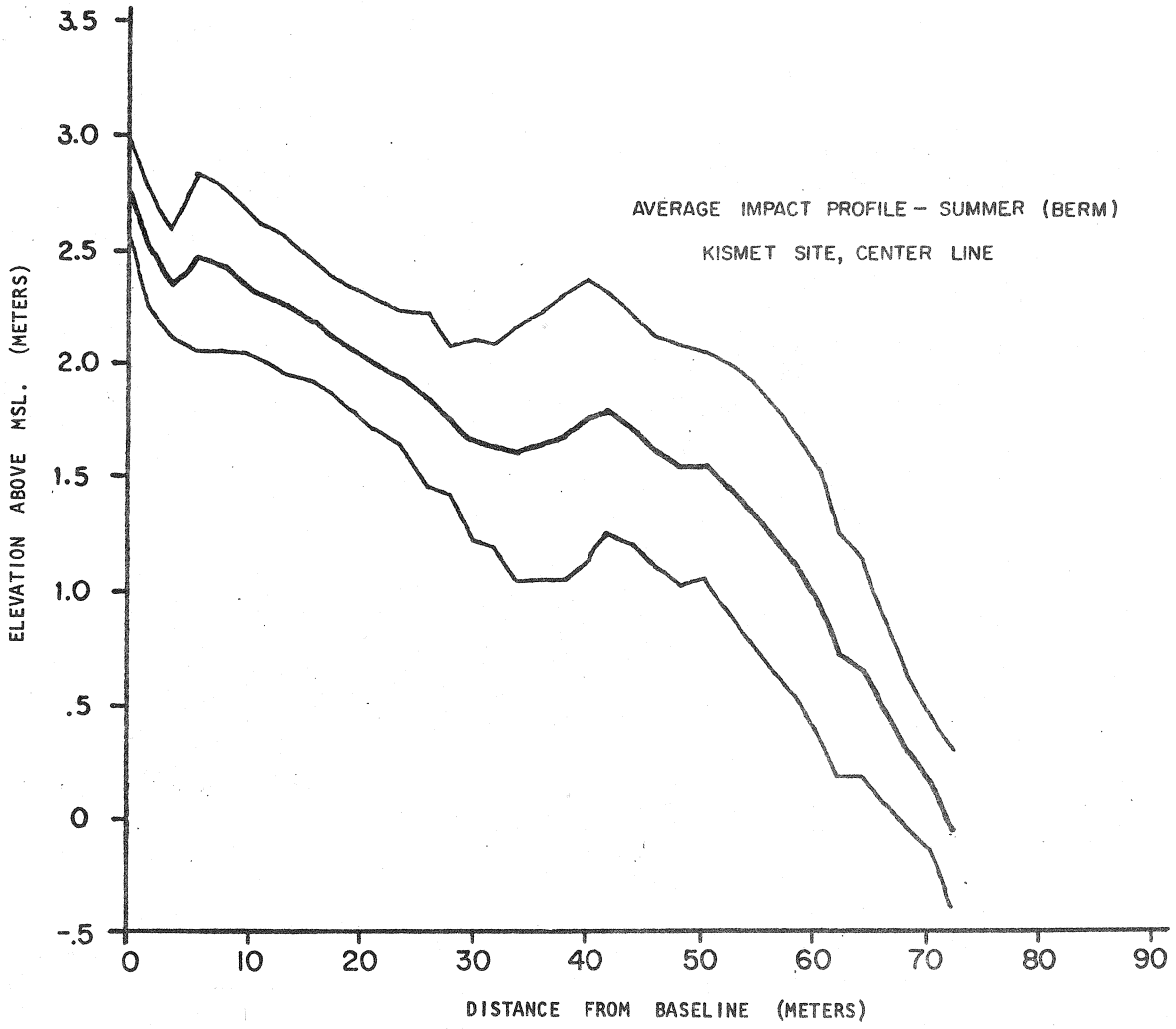


Figure 66. Kismet, average summer profile for impact site, with normal range of variation (std. dev.).

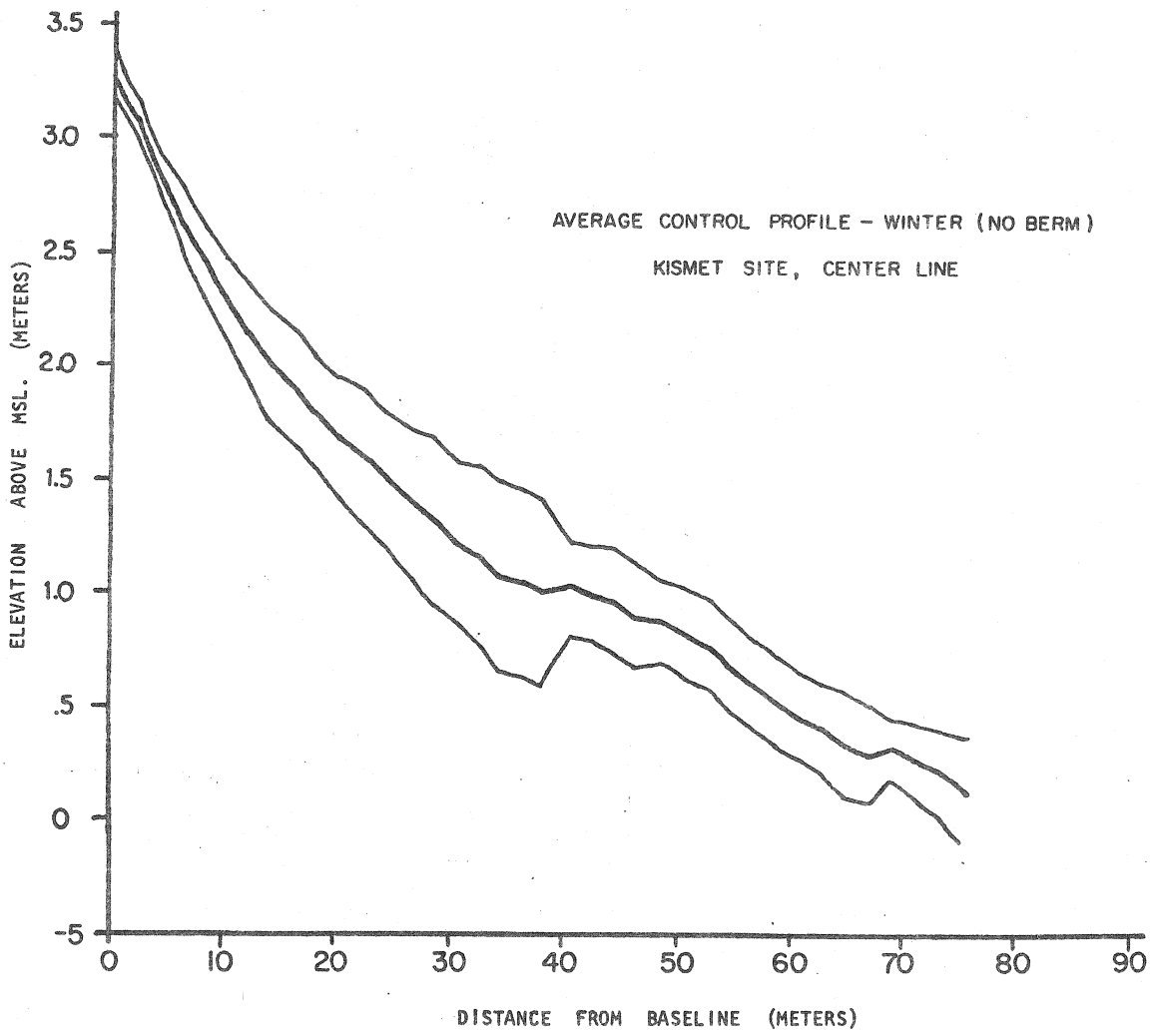


Figure 67. Kismet, average winter profile for control site, with normal range of variation (std. dev.).

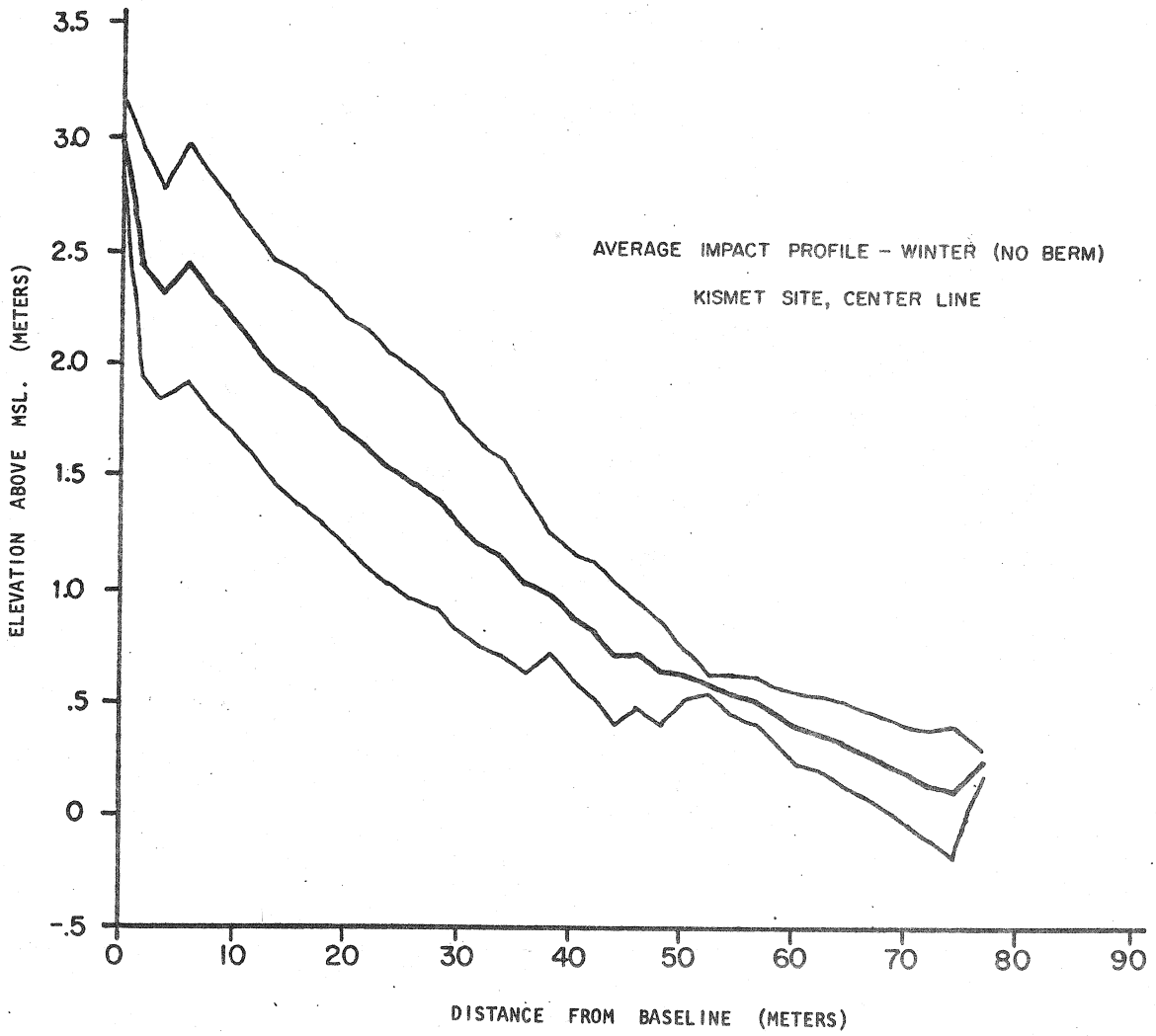


Figure 68. Kismet, average winter profile for impact site, with normal range of variation (std. dev.).

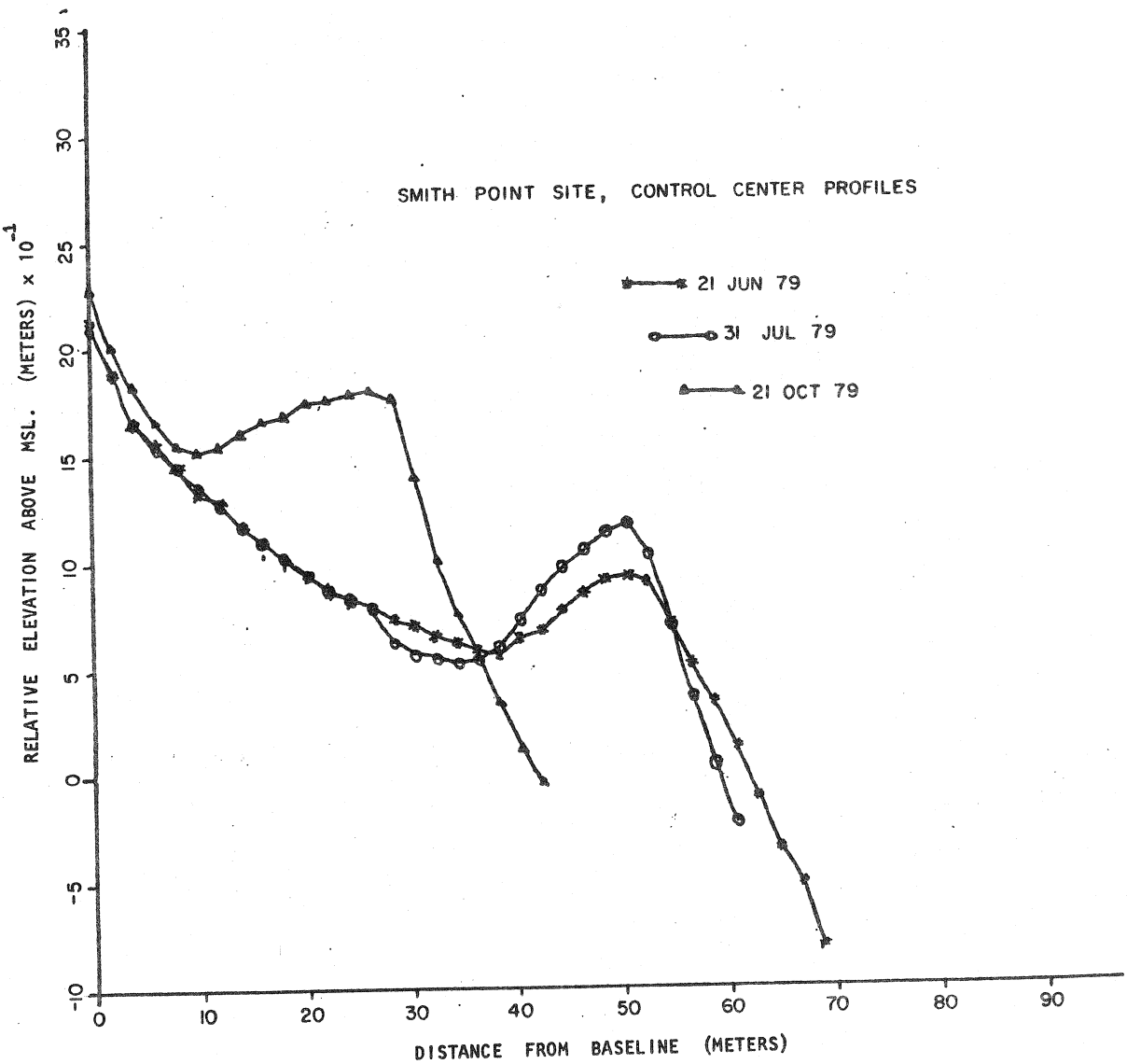


Figure 69. Smith Point Profiles.

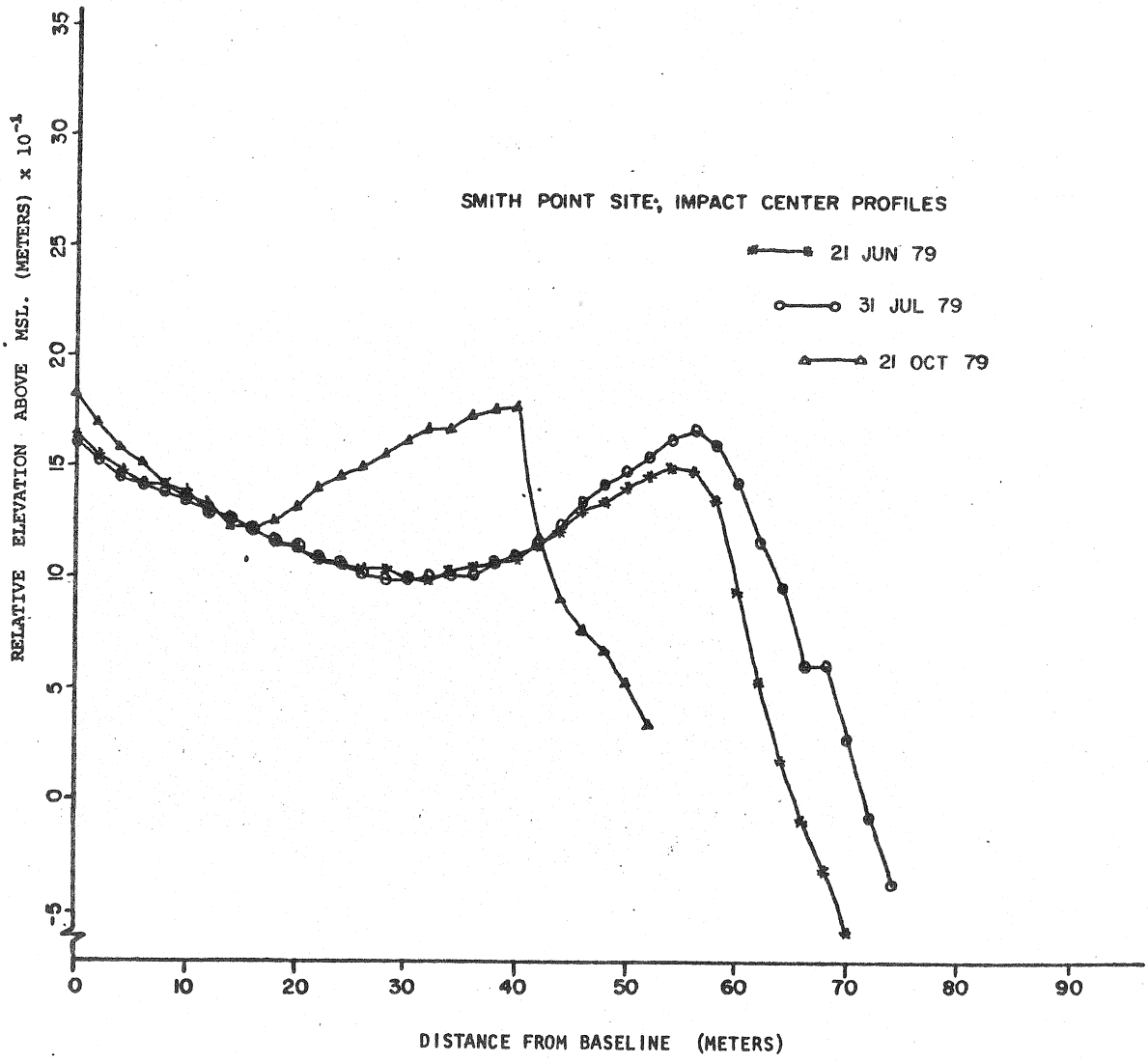


Figure 70. Smith Point Profiles.

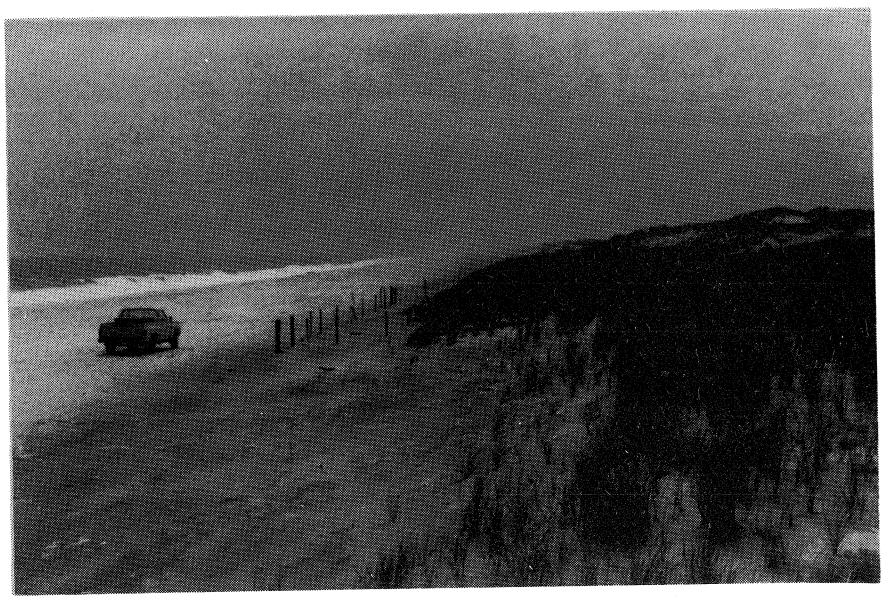


Figure 71. Whalehouse Point exclosure site.

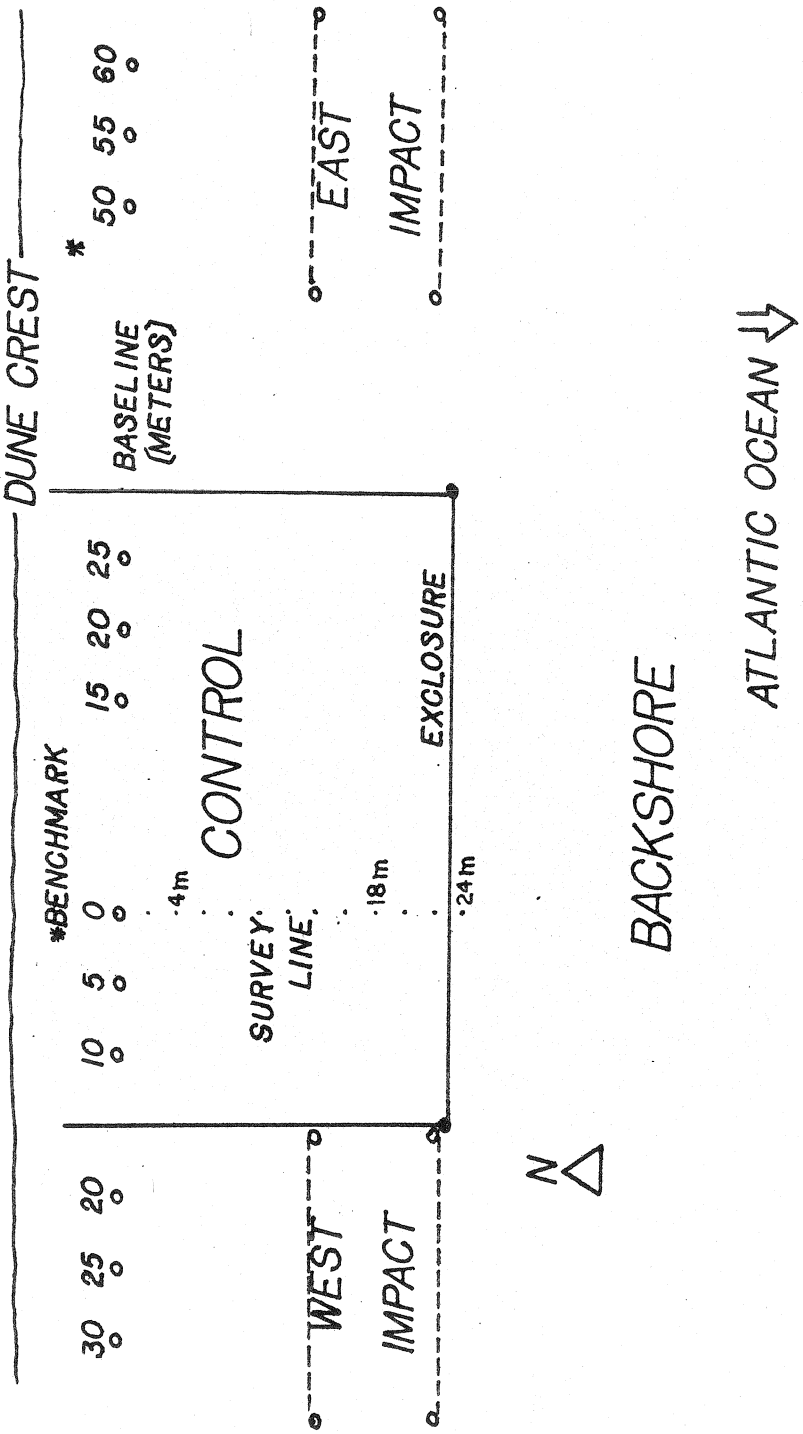


Figure 72. Map of Whalehouse Pt. field site.



Figure 73. Experimental impacting of the foredune.

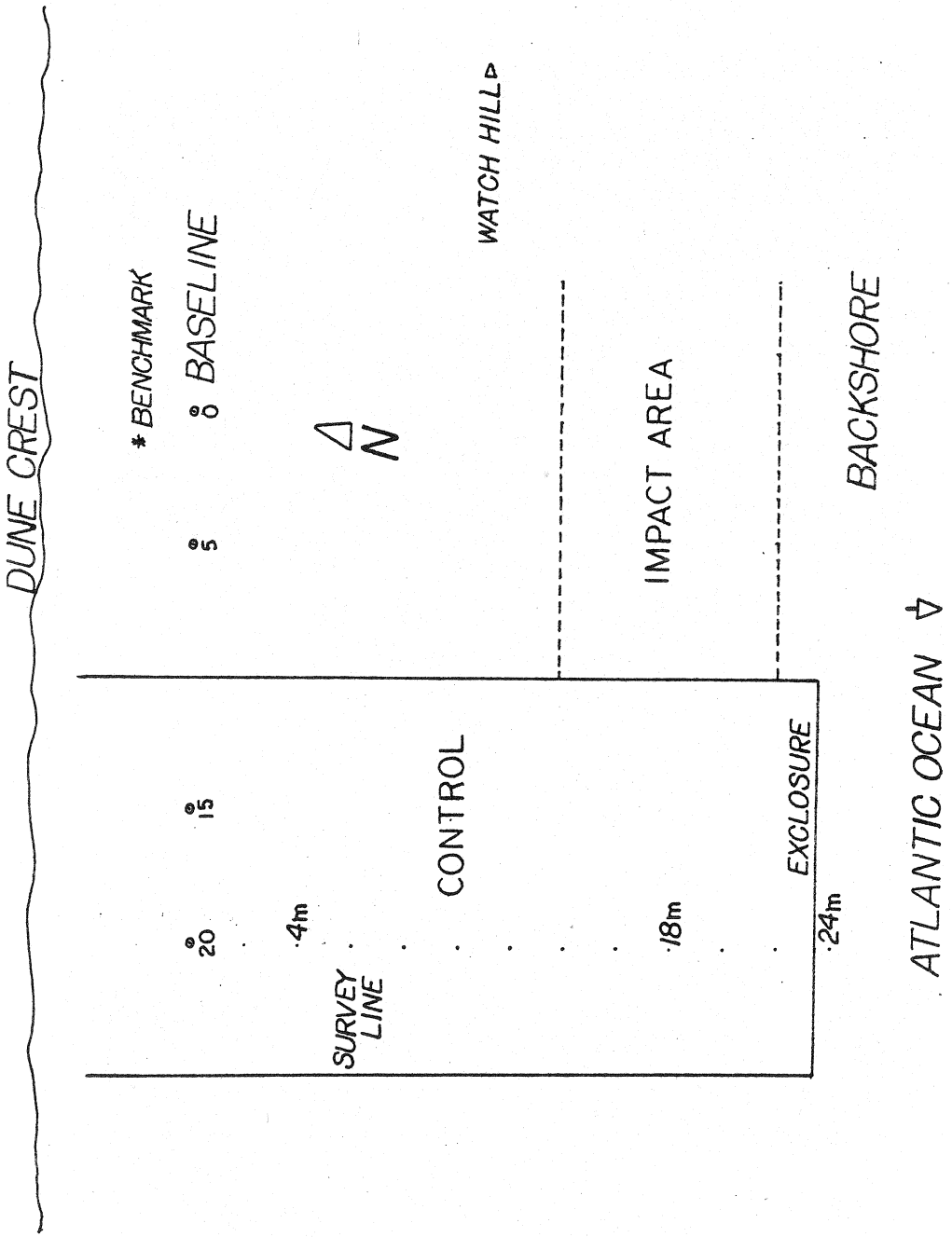


Figure 74. Map of Watch Hill field site.



Figure 75. Quadrat technique.



Figure 76. Front map construction.



Figure 77. Surveying the foredune profile.

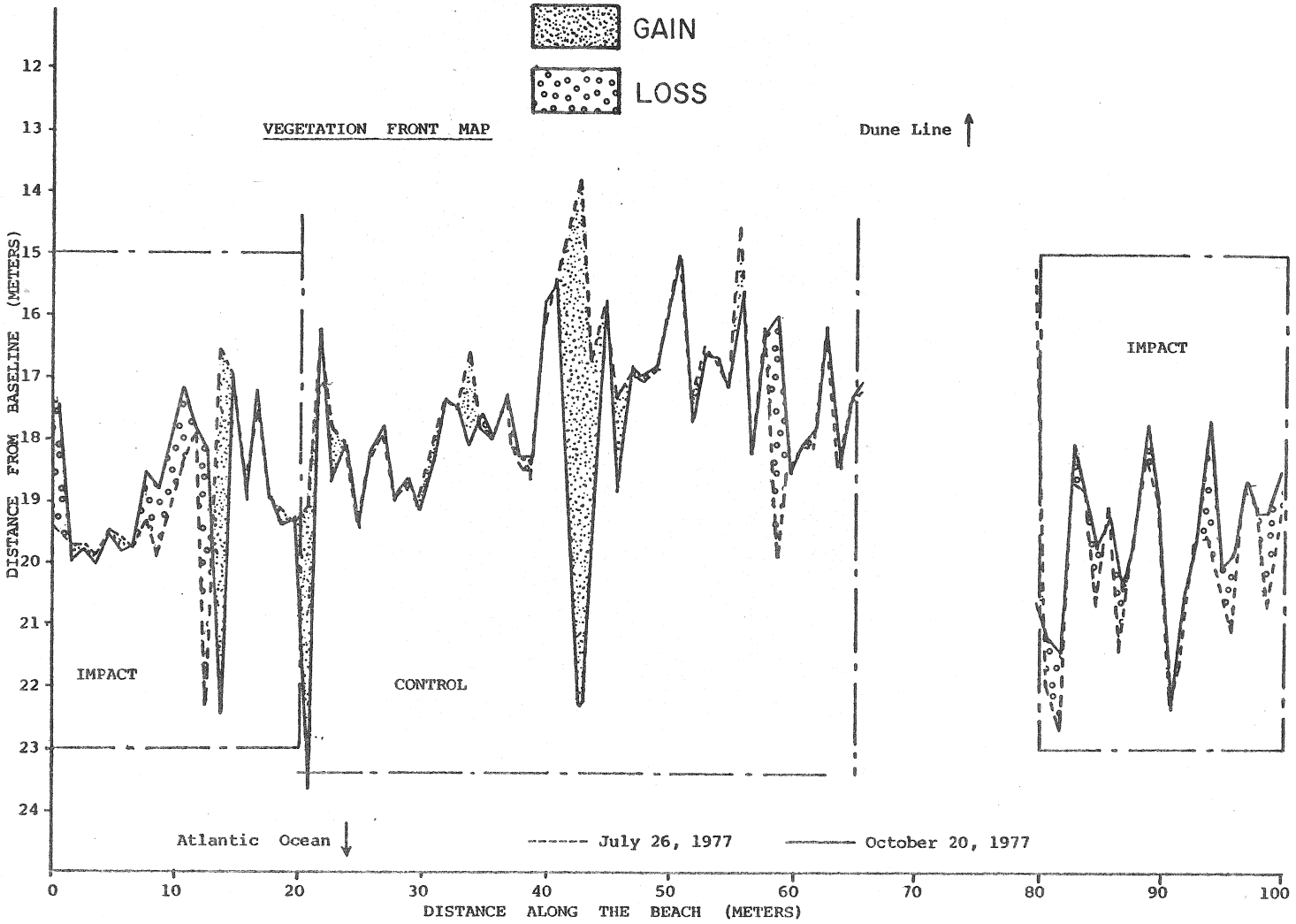


Figure 78. Whalehouse Point vegetation front map.

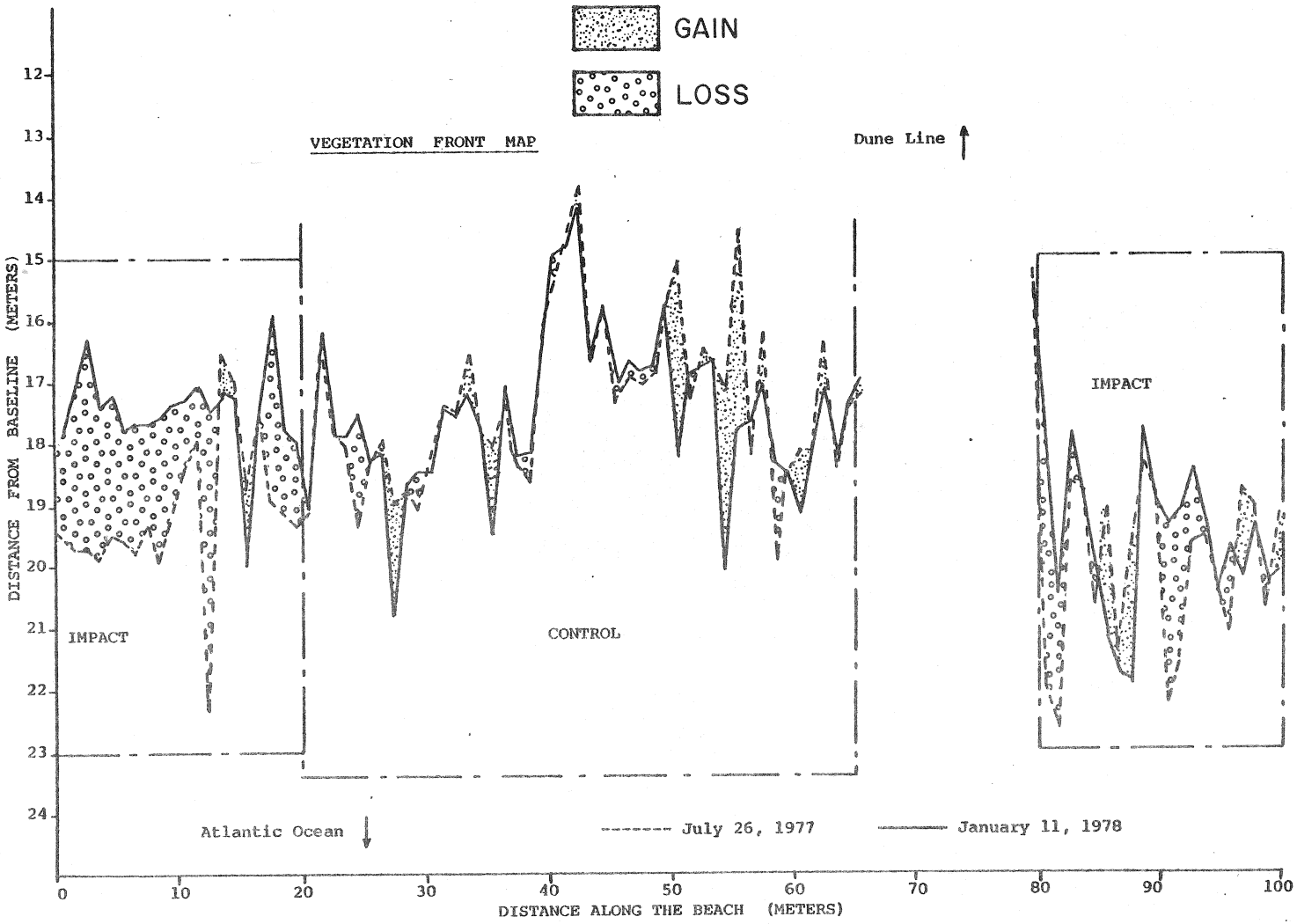


Figure 79. Whalehouse Point vegetation front map.

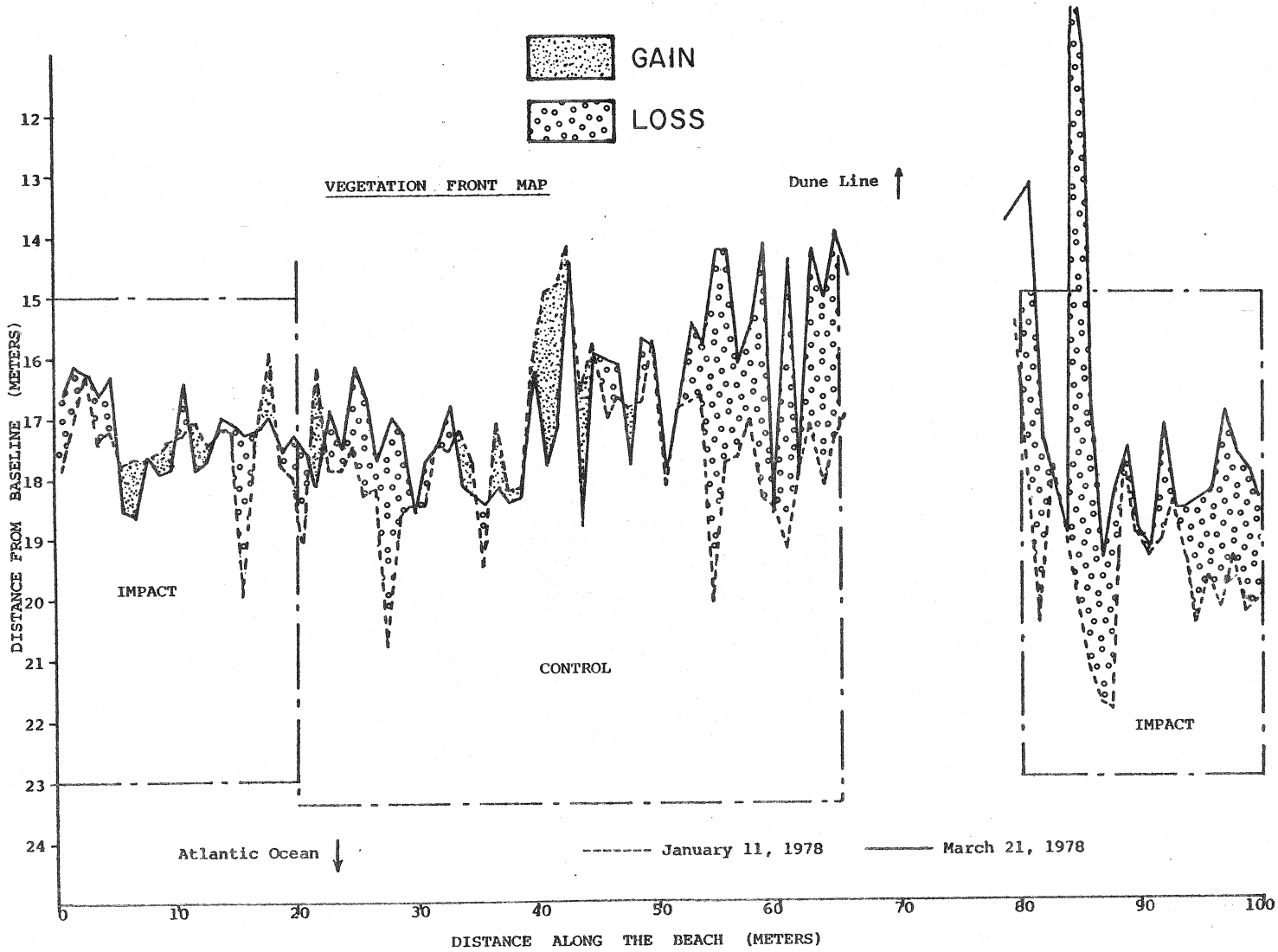


Figure 80. Whalehouse Point vegetation front map.

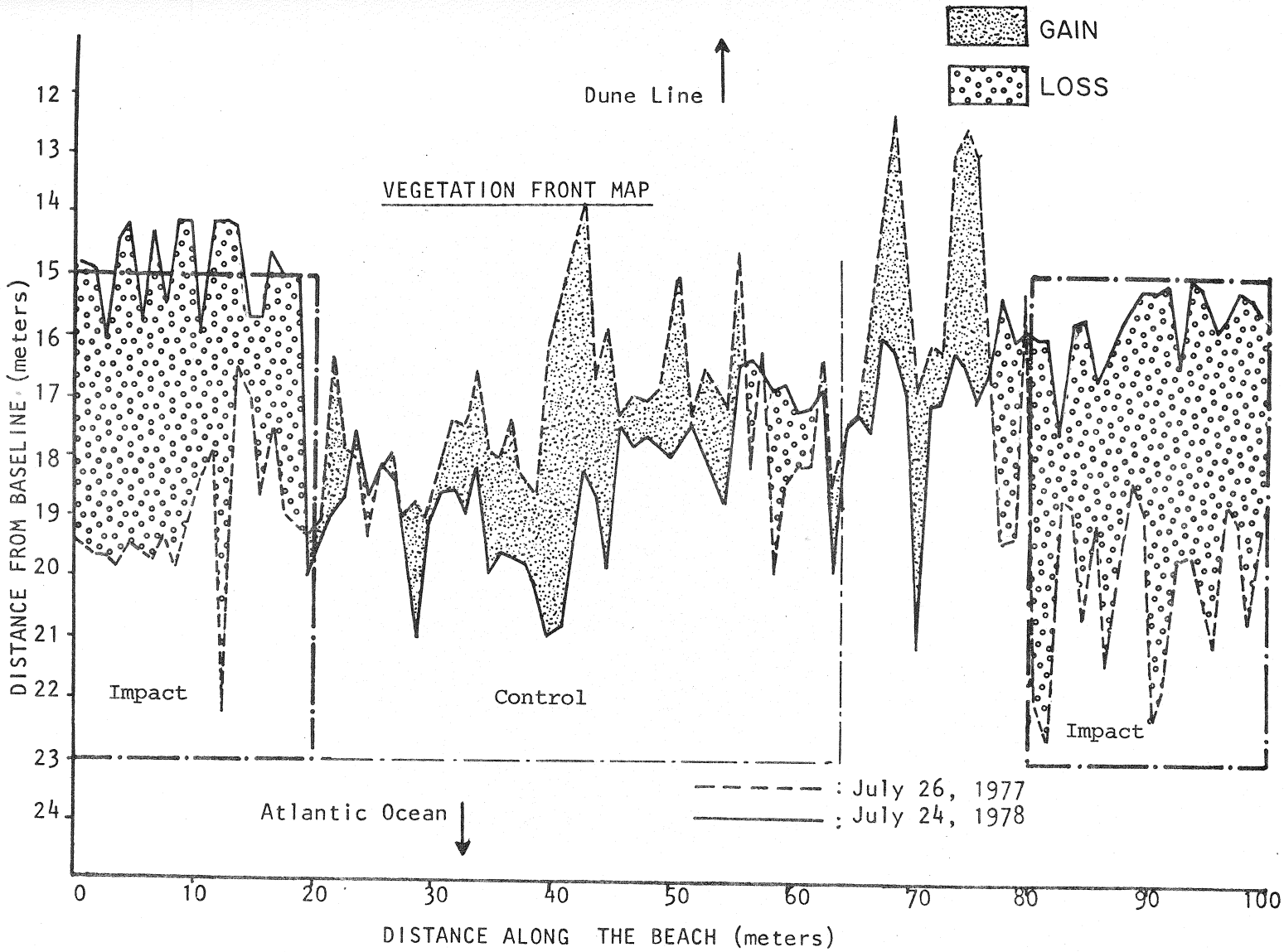


Figure 81. Whalehouse Point vegetation front map.



Figure 82. West impact site, summer 1978.

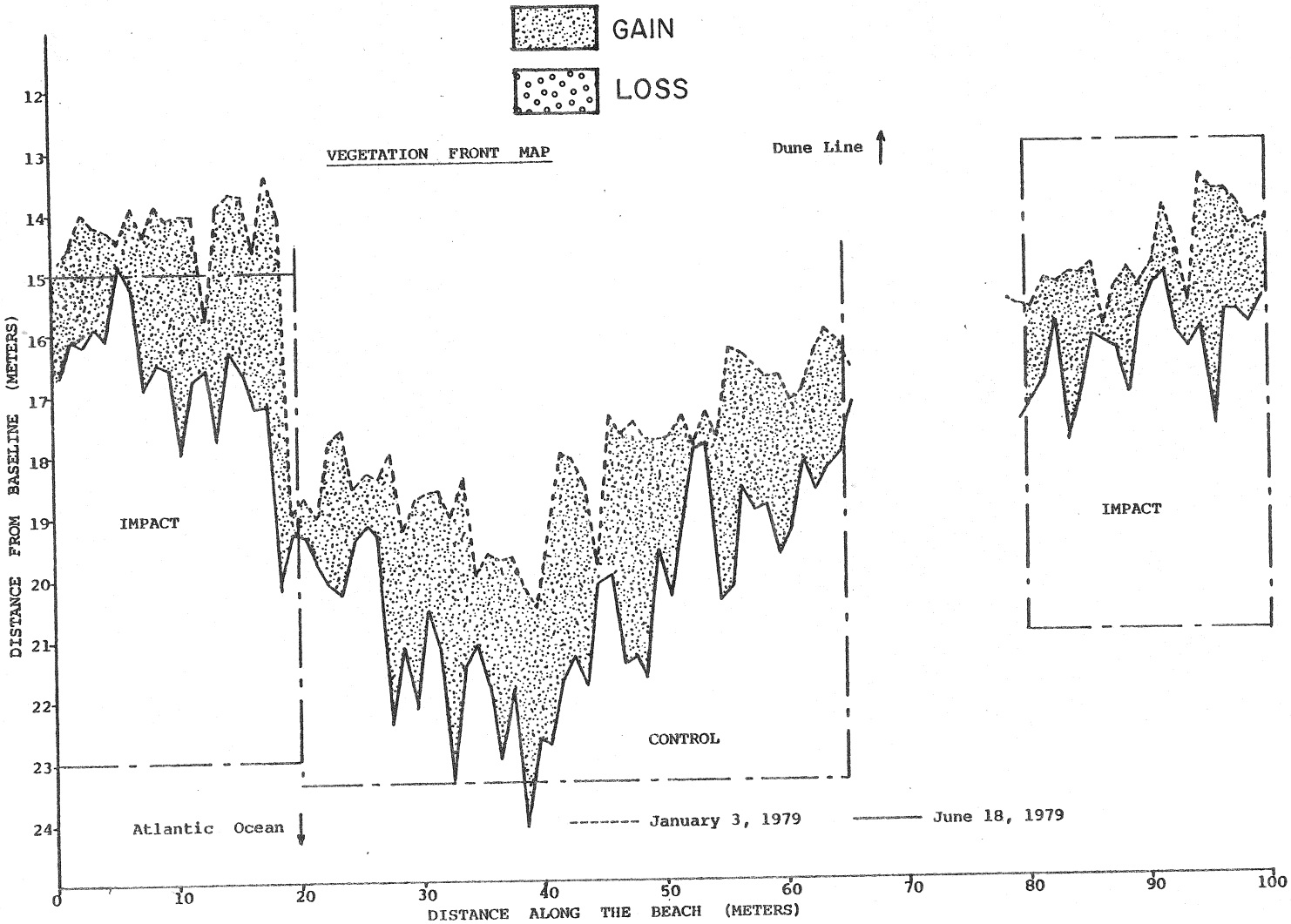


Figure 83. Whalehouse Point vegetation front map.



Figure 84. West impact site, spring 1979.
Note regrowth after period of no impact.



Figure 85. Exclosure site (control), summer 1979.

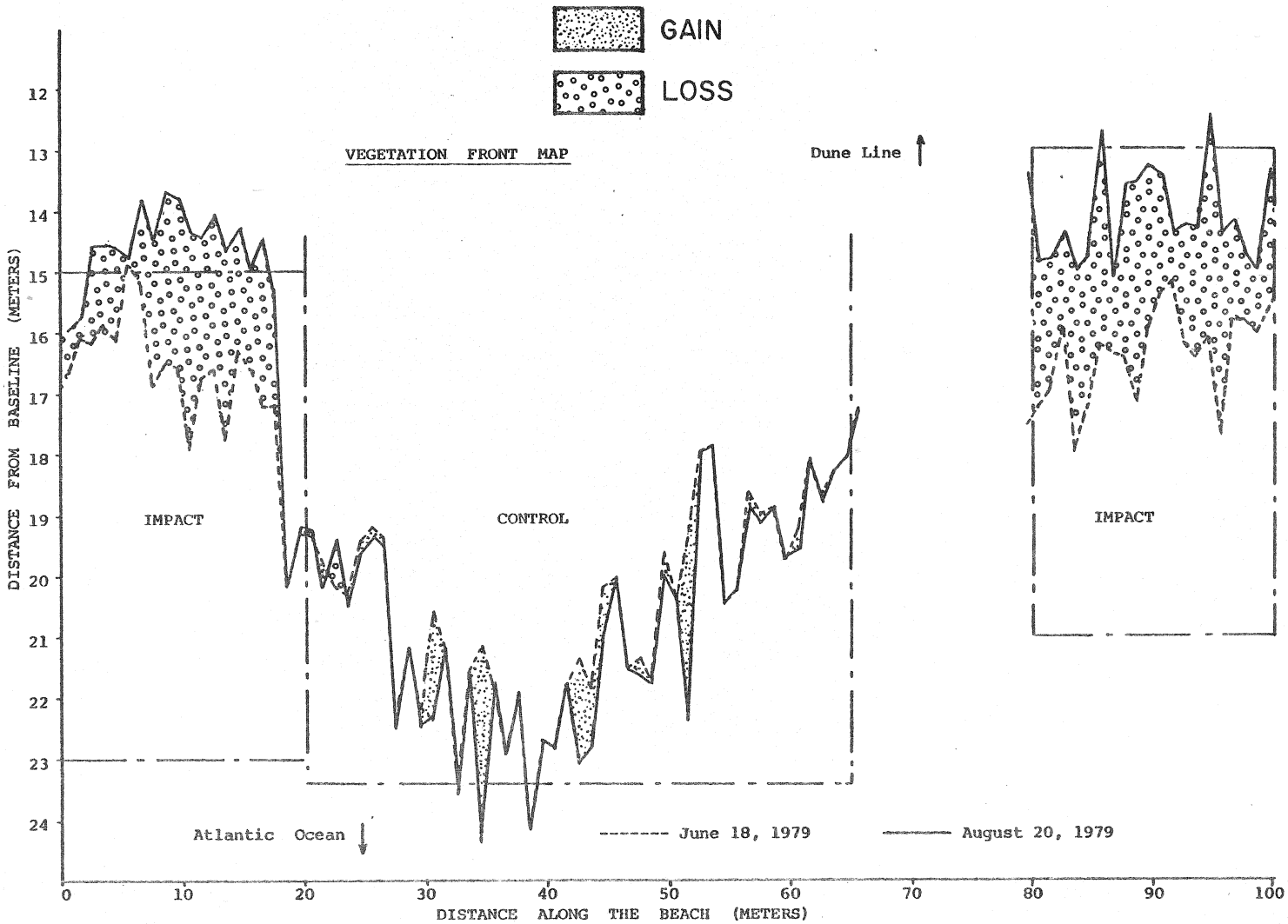


Figure 86. Whalehouse Point vegetation front map.



Figure 87. West impact site, fall 1978.

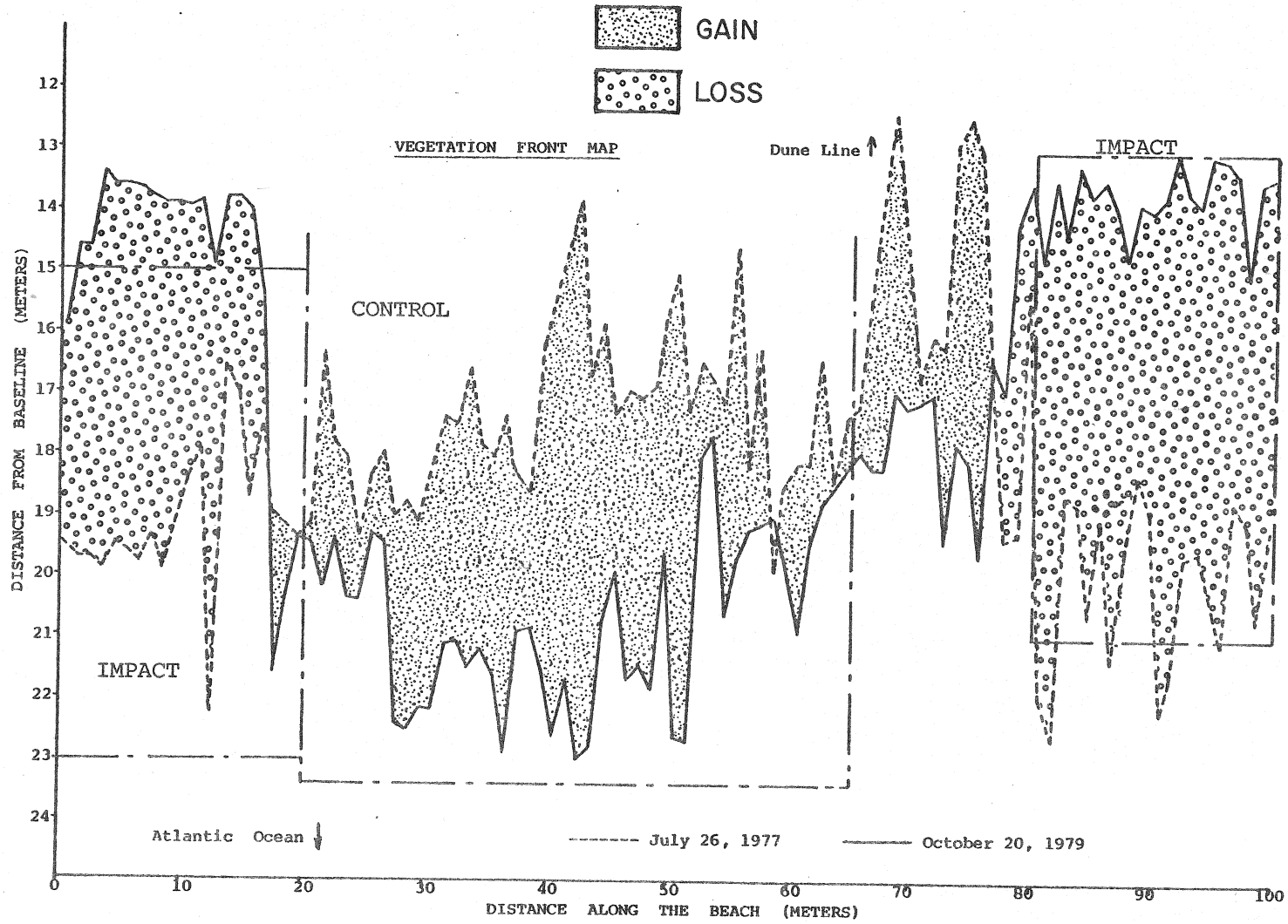


Figure 88. Whalehouse Point vegetation front map.



Figure 89. Whalehouse Point field site, looking east, Oct. 1979.



Figure 90. Whalehouse Point field site, looking west, Oct. 1979.

Figure 91. Whalehouse Pt. foredune profiles.

Figure 92. Whalehouse Pt. foredune profiles.

Figure 93. Whalehouse Pt. foredune profiles.

Figure 94. Whalehouse Pt. foredune profiles.

Figure 95. Whalehouse Pt. foredune profiles.

Figure 96. Whalehouse Pt. foredune profiles.

Figure 97. Whalehouse Pt. foredune profiles.

Figure 98. Whalehouse Pt. foredune profiles.

Figure 99. Whalehouse Pt. foredune profiles.

Figure 100. Whalehouse Pt. foredune profiles.

Figure 101. Whalehouse Pt. foredune profiles.

Figure 102. Whalehouse Pt. foredune profiles.

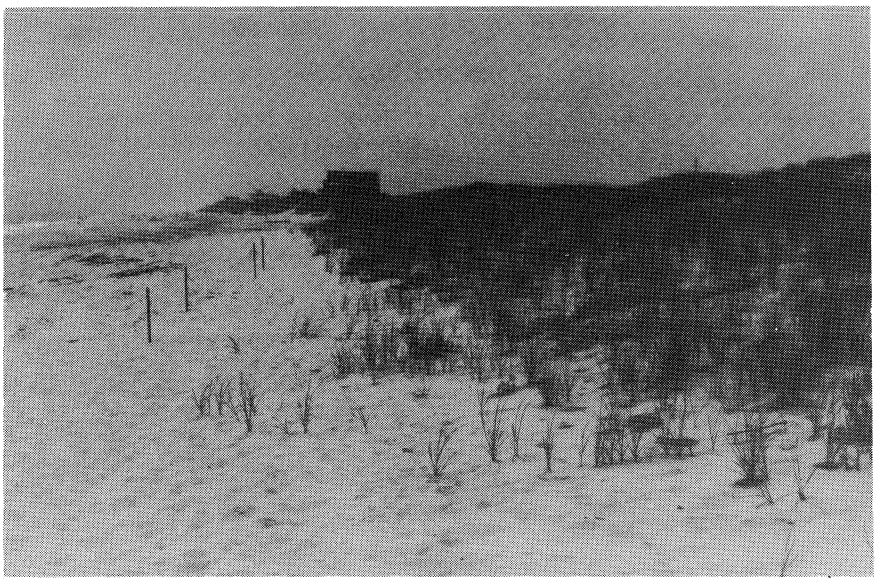


Figure 103. Watch Hill exclosure site prior to impacting.

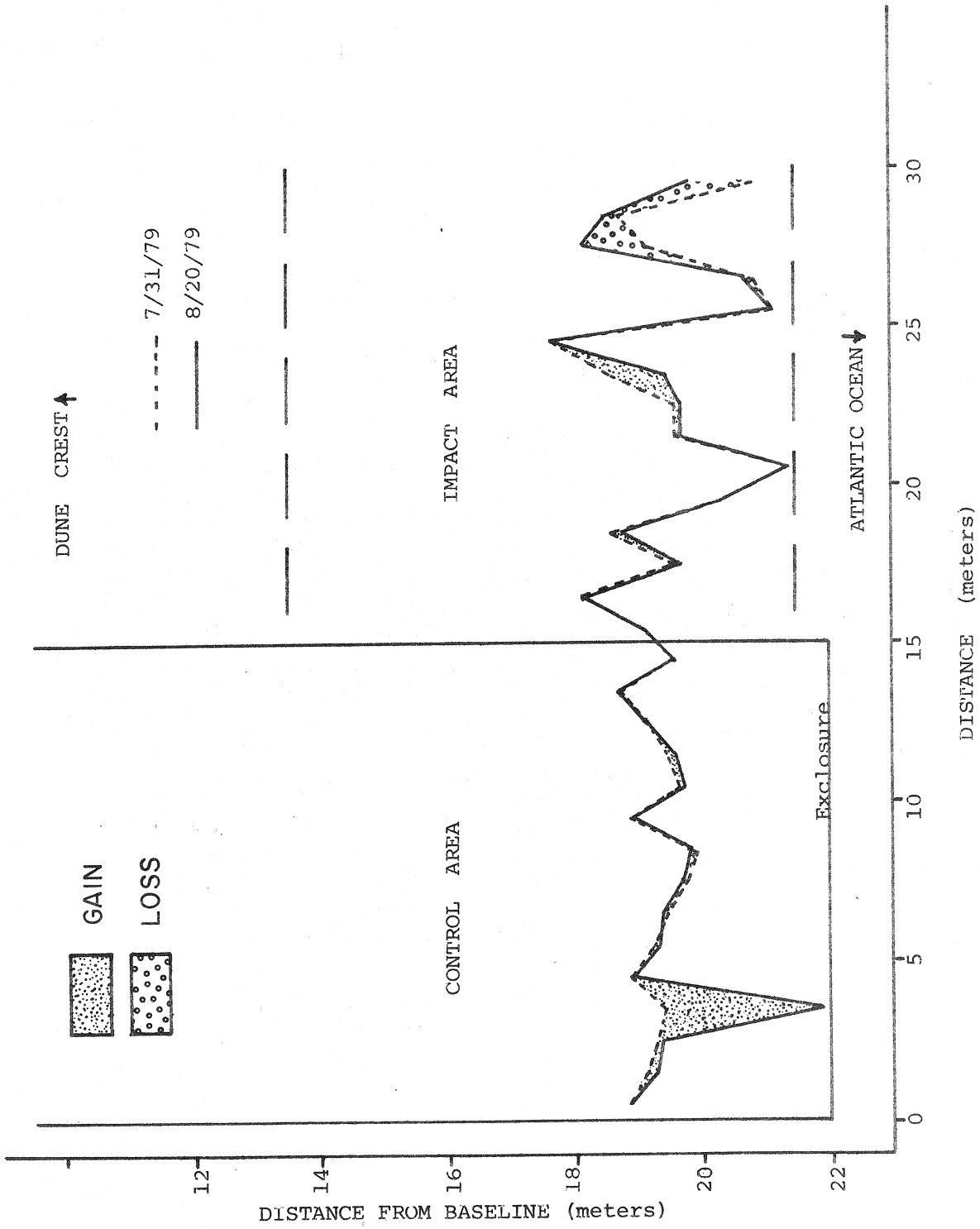


Figure 104. Vegetation Front Map, Watch Hill Site.

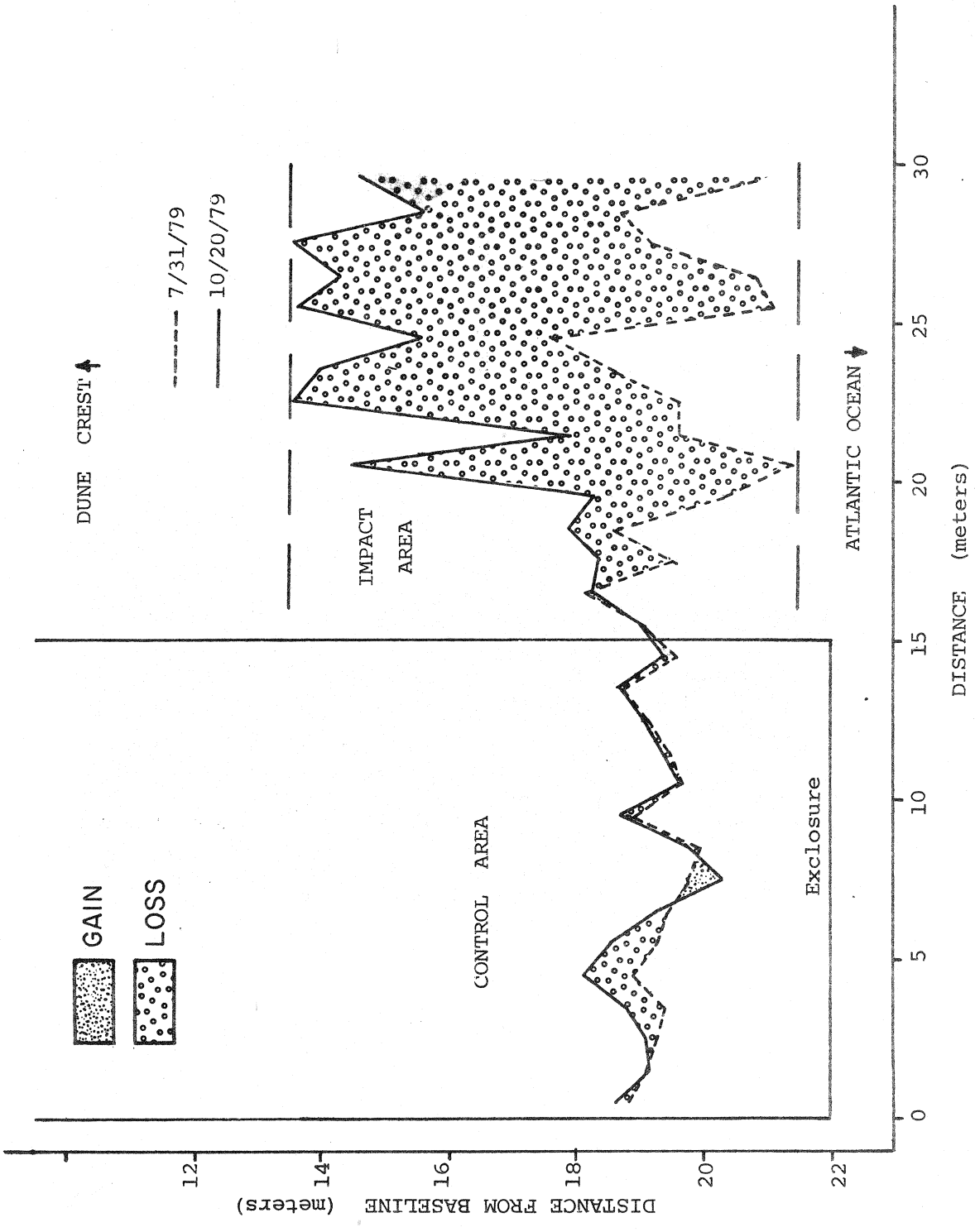


Figure 105. Vegetation Front Map, Watch Hill Site.



Figure 106. Watch Hill exclosure site, October 1979.

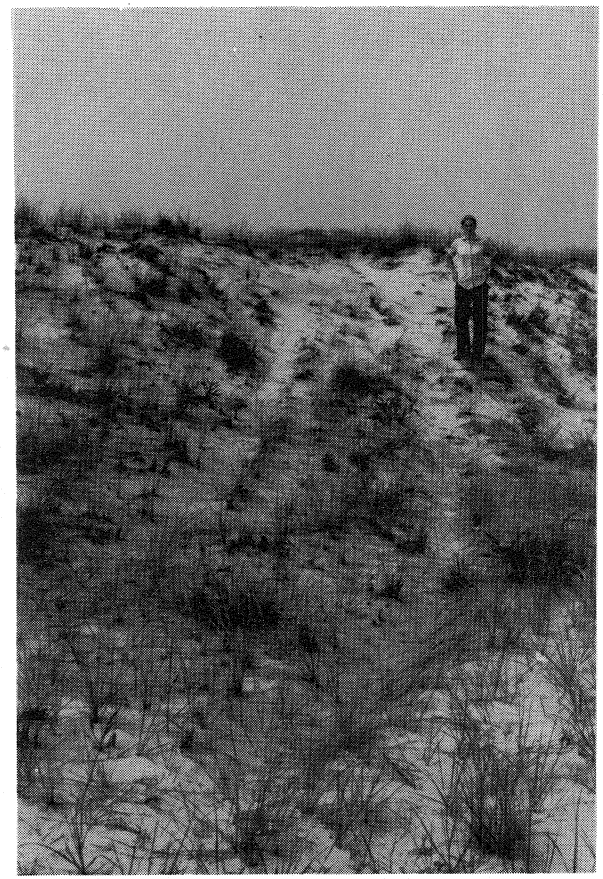


Figure 107. Four months after one vehicle pass over the dunes.

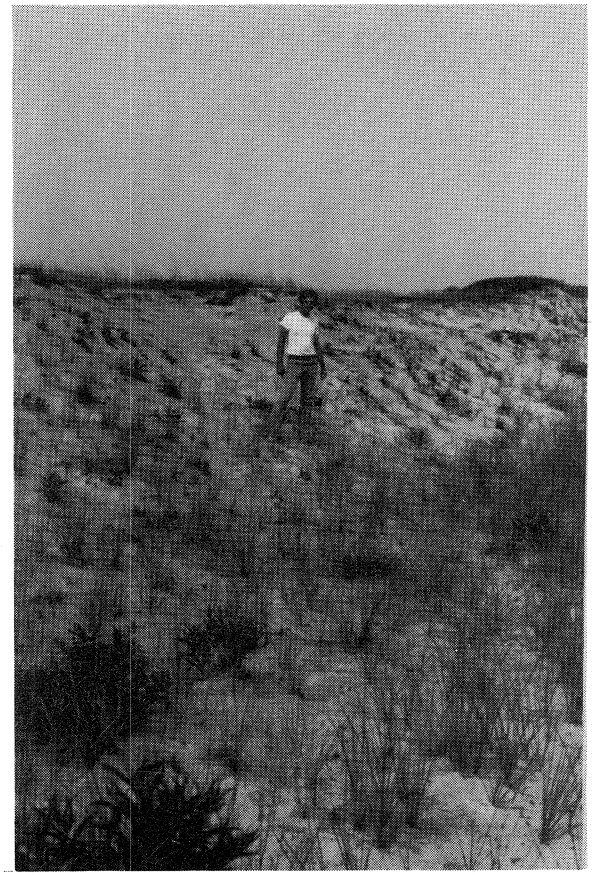


Figure 108. One year and four months after one vehicle pass over the dunes.



Figure 109. Vehicle on dune toe due to spring tides.



Figure 110. Developing beach scarp.

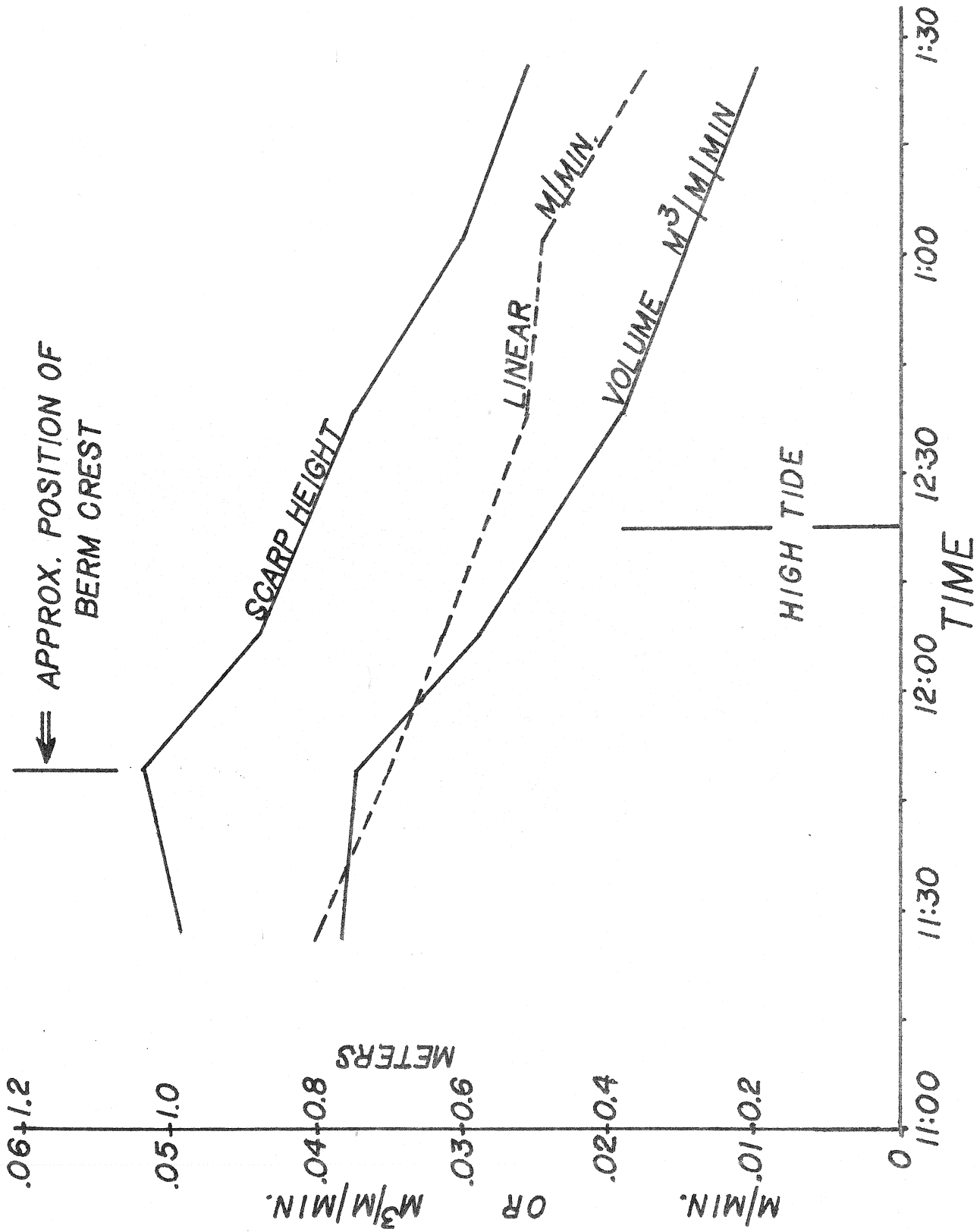


Figure 111. Rate of scarp retreat.



Figure 112. Narrow backshore from scarping.

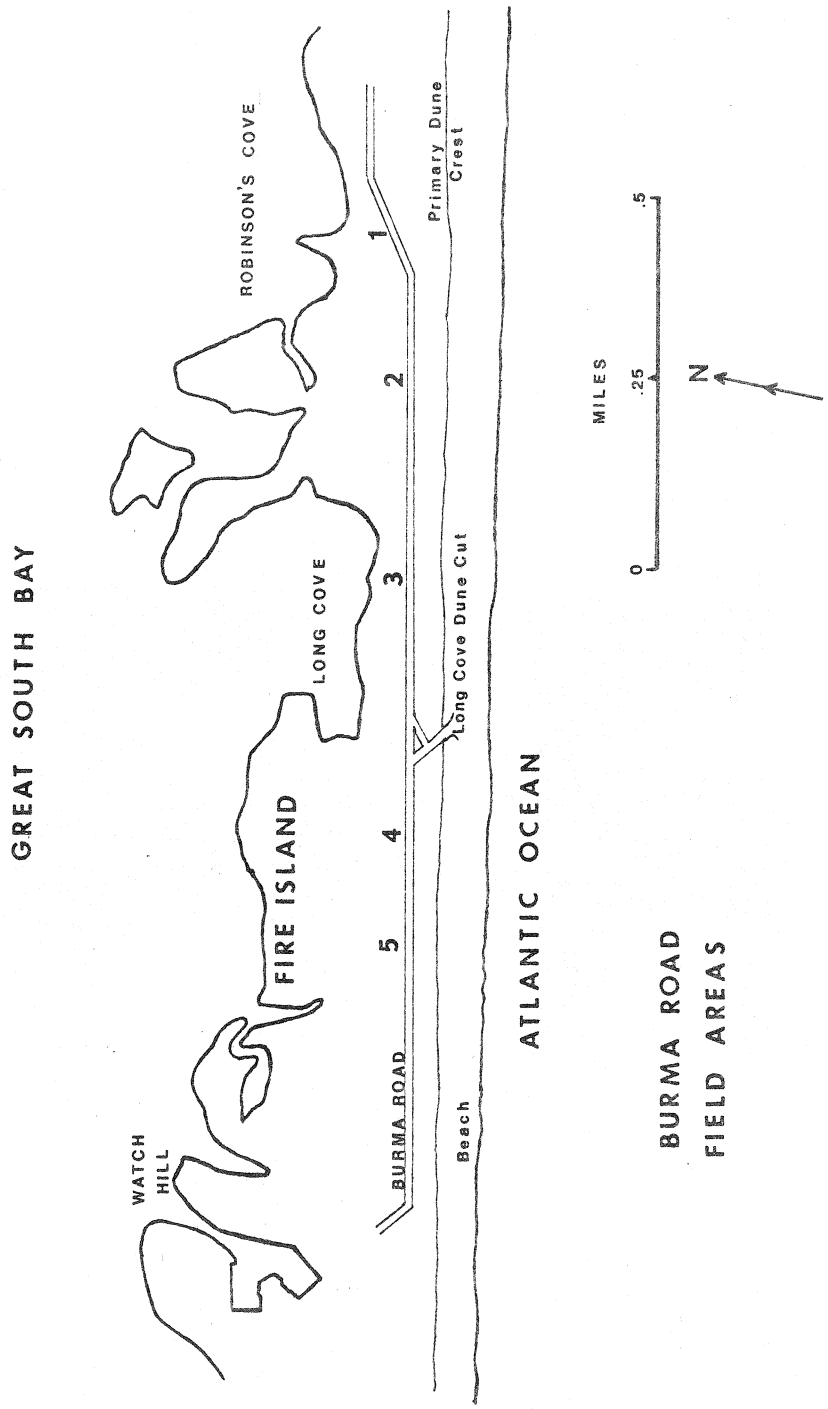


Figure 113. Location map: Burma Road field sites.



Figure 114. Surveying the Burma Road field sites.

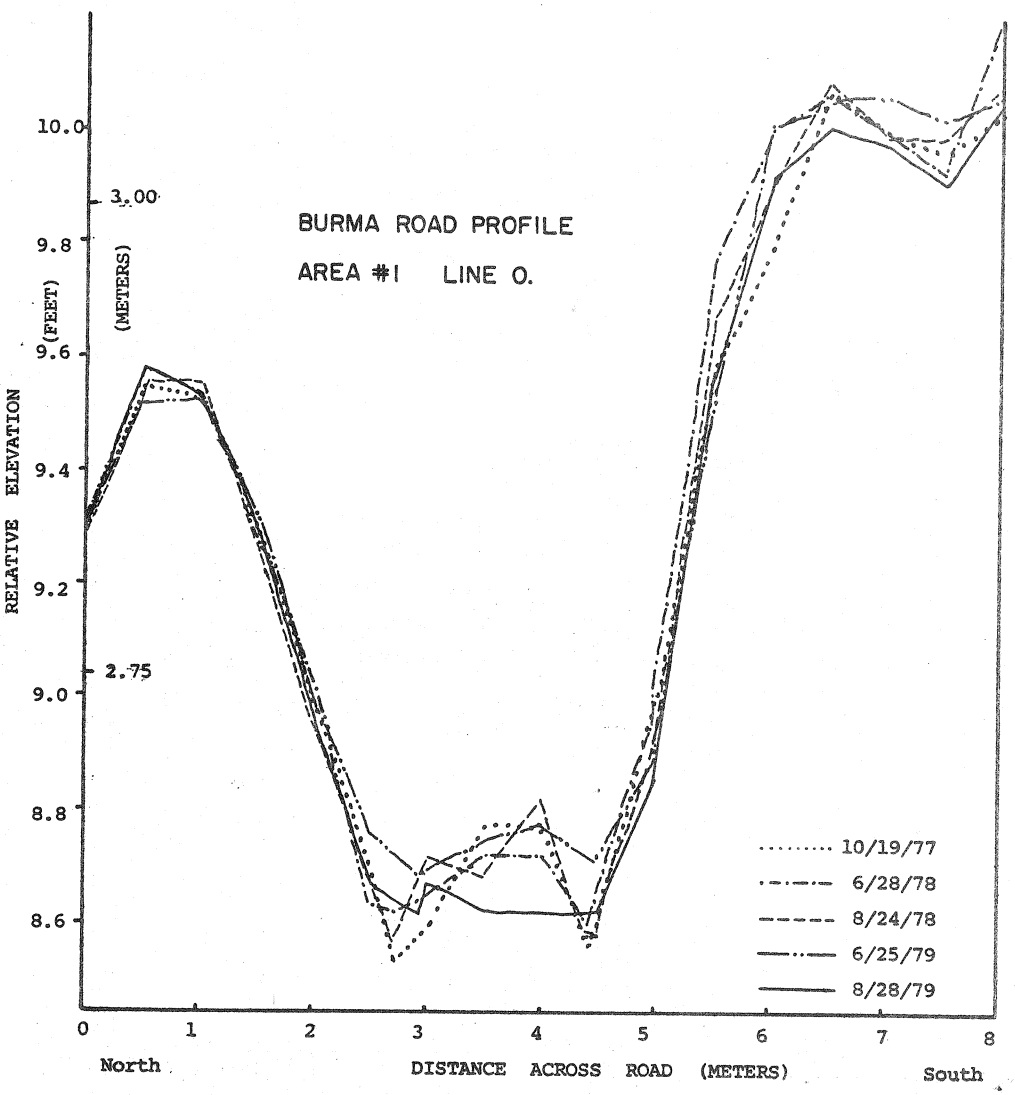


Figure 115. Profile of Burma Road through time.

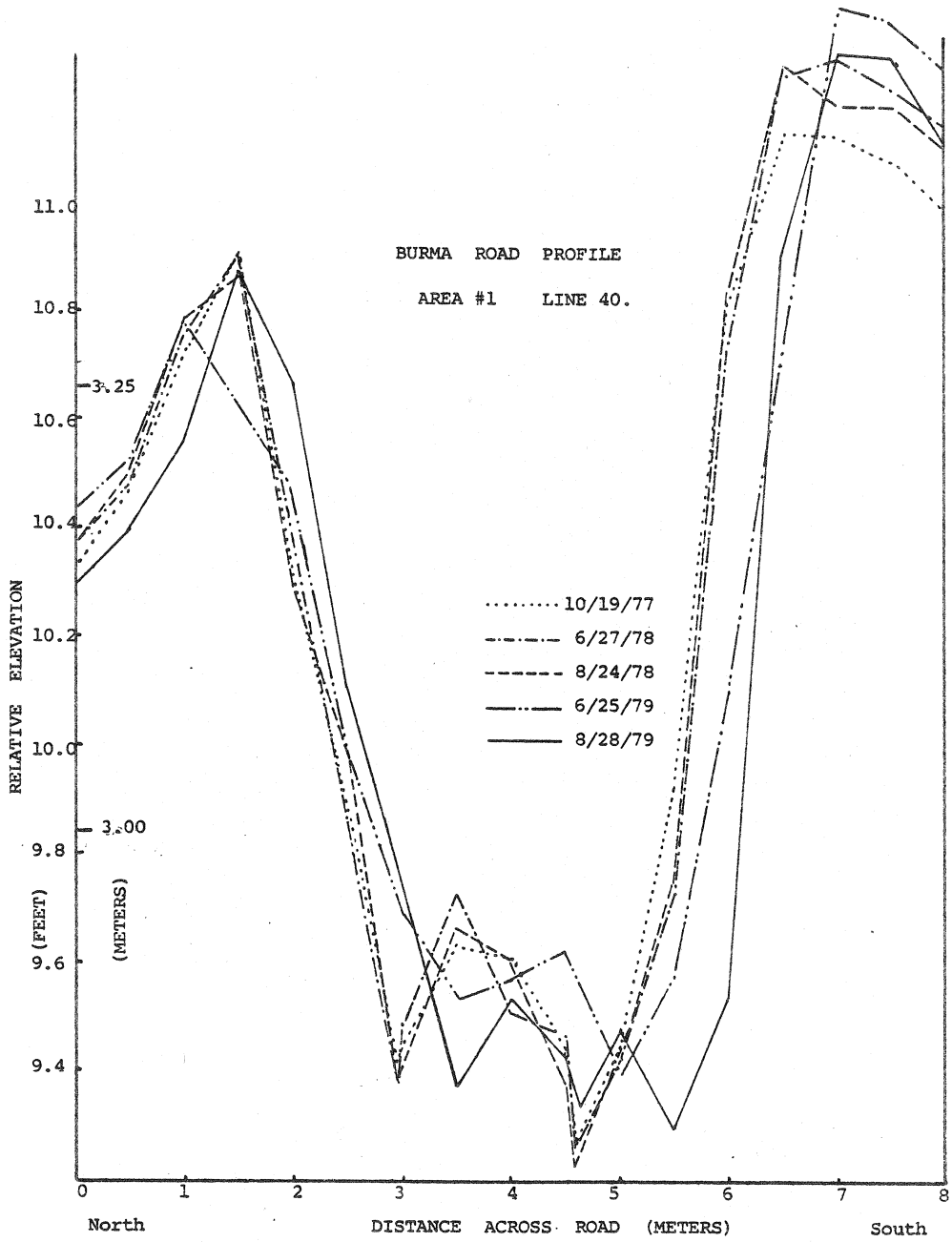


Figure 116. Profile of Burma Road through time.

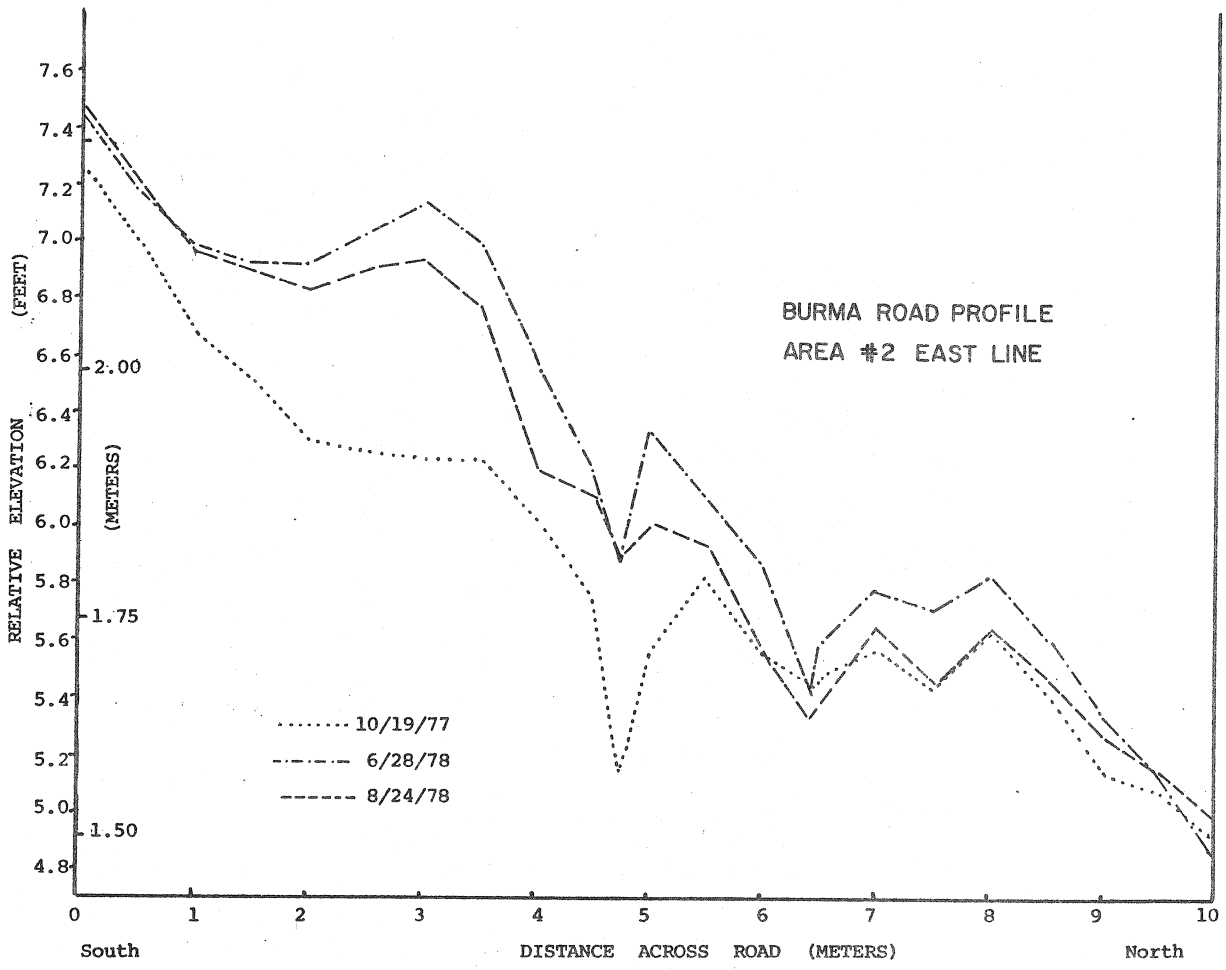


Figure 117. Profile of Burma Road through time.

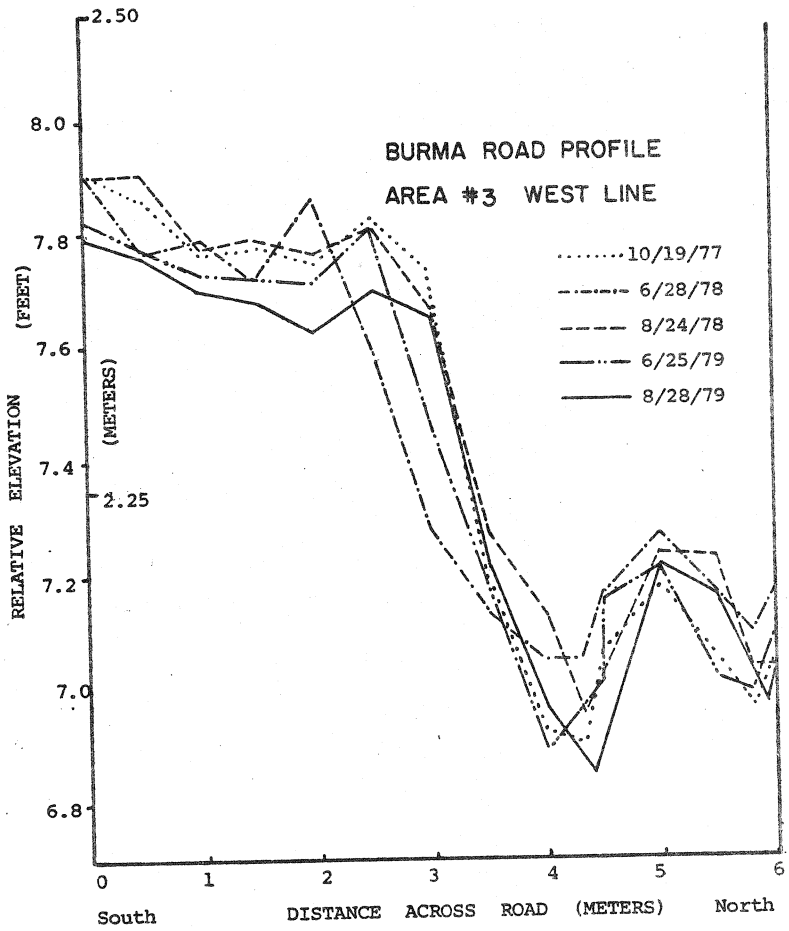


Figure 118. Profile of Burma Road through time.

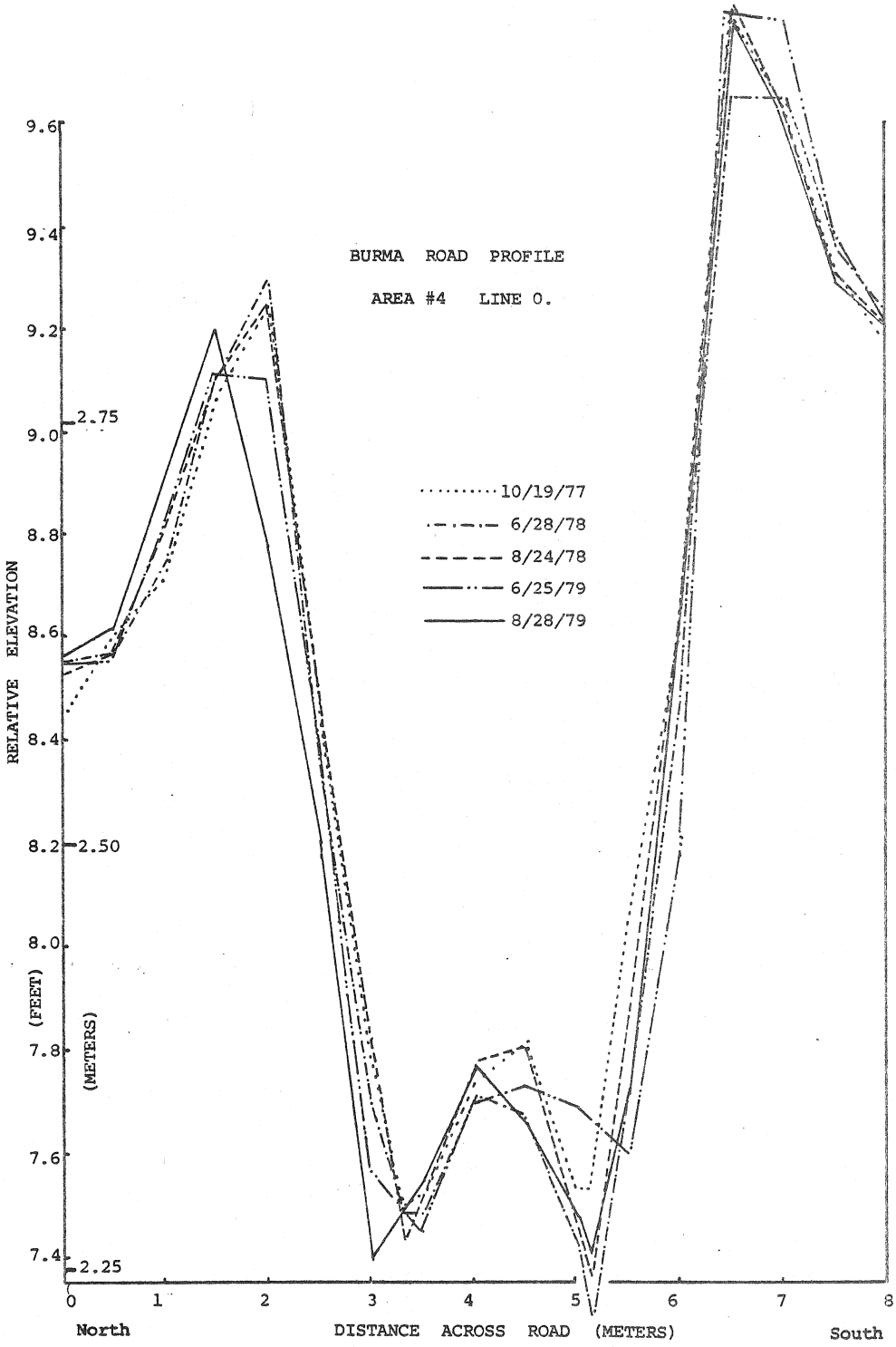


Figure 119. Profile of Burma Road through time.

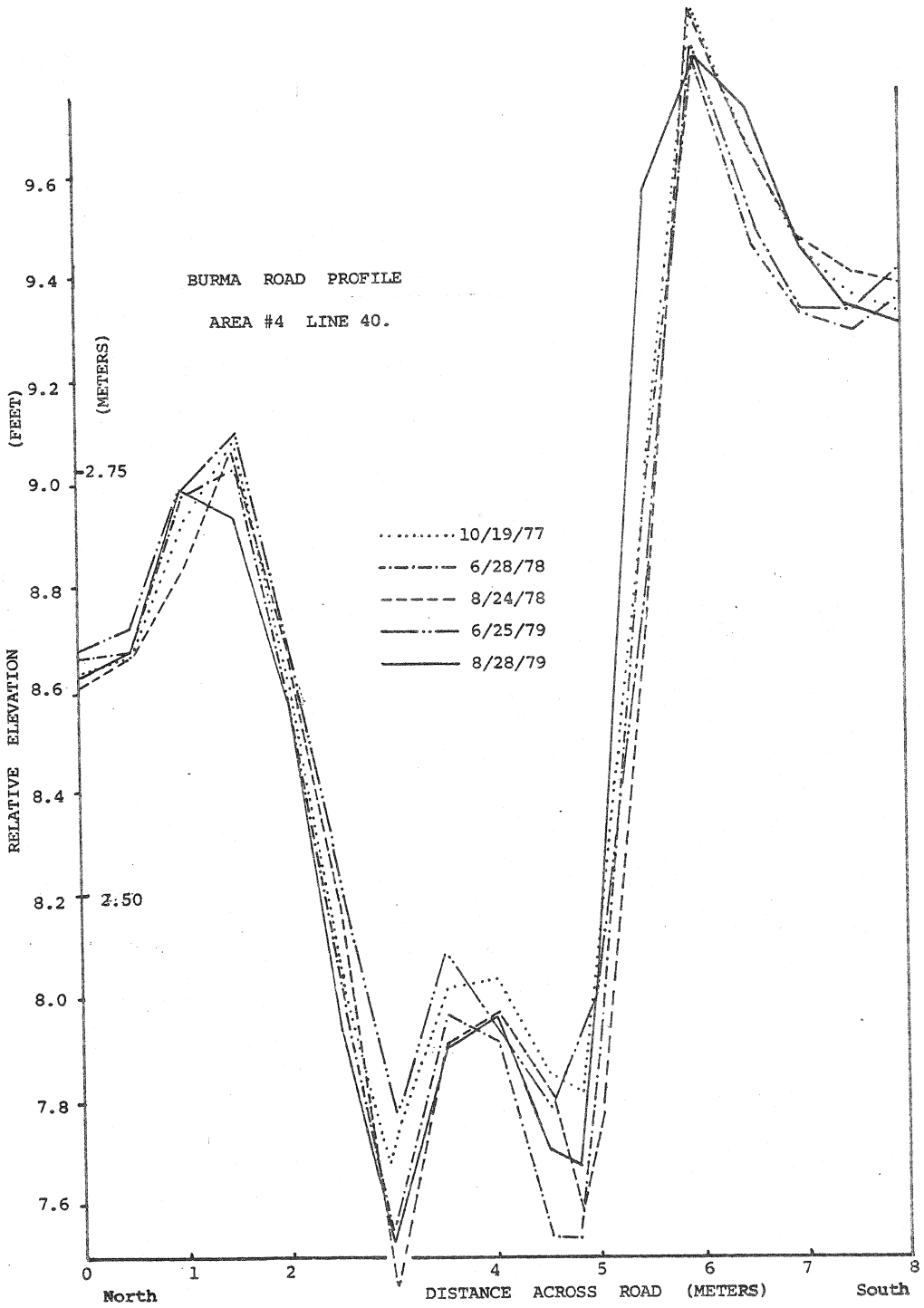


Figure 120. Profile of Burma Road through time.

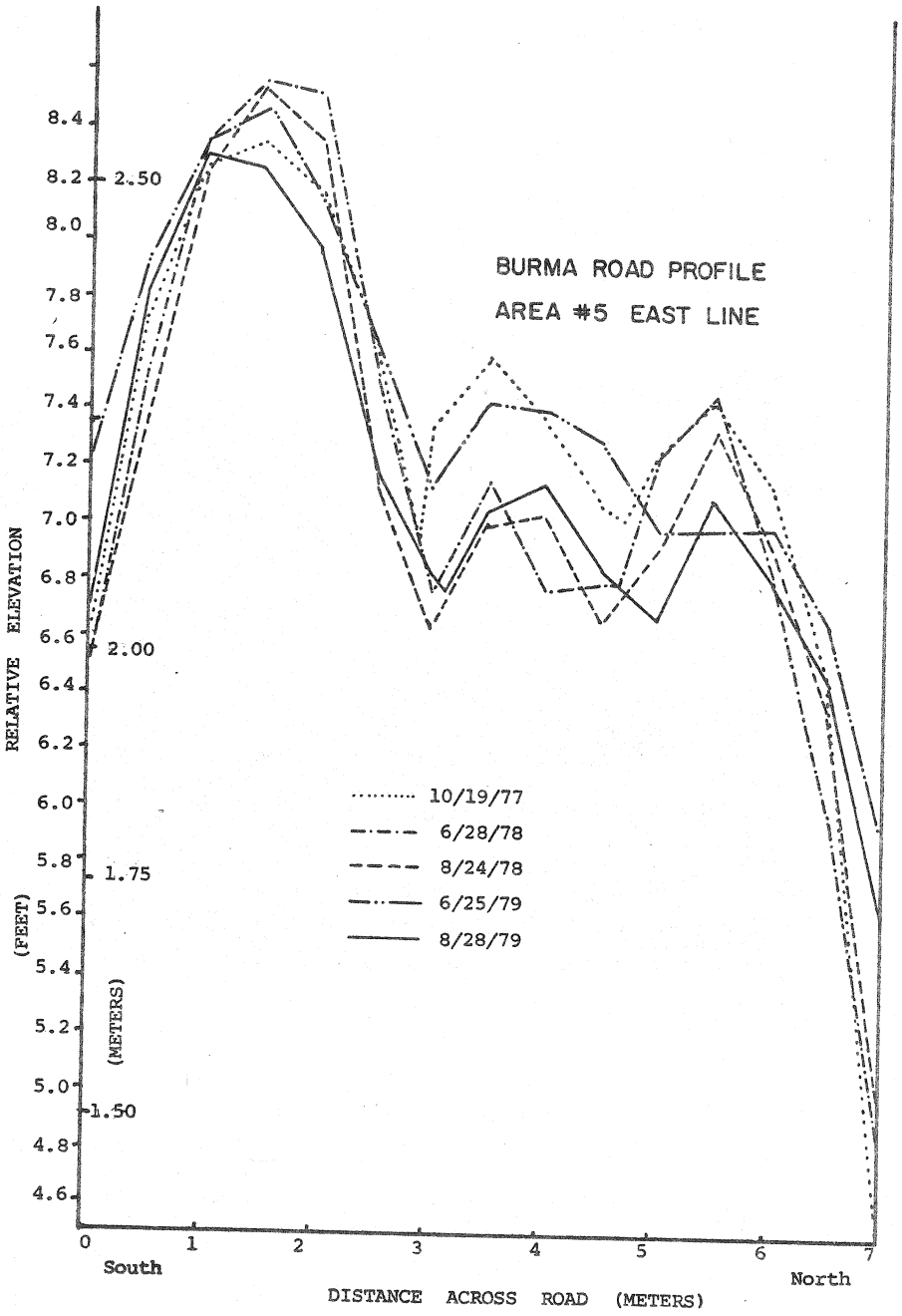


Figure 121. Profile of Burma Road through time.



Figure 122. Aeolian transport along the beach. (photo taken at Kismet)

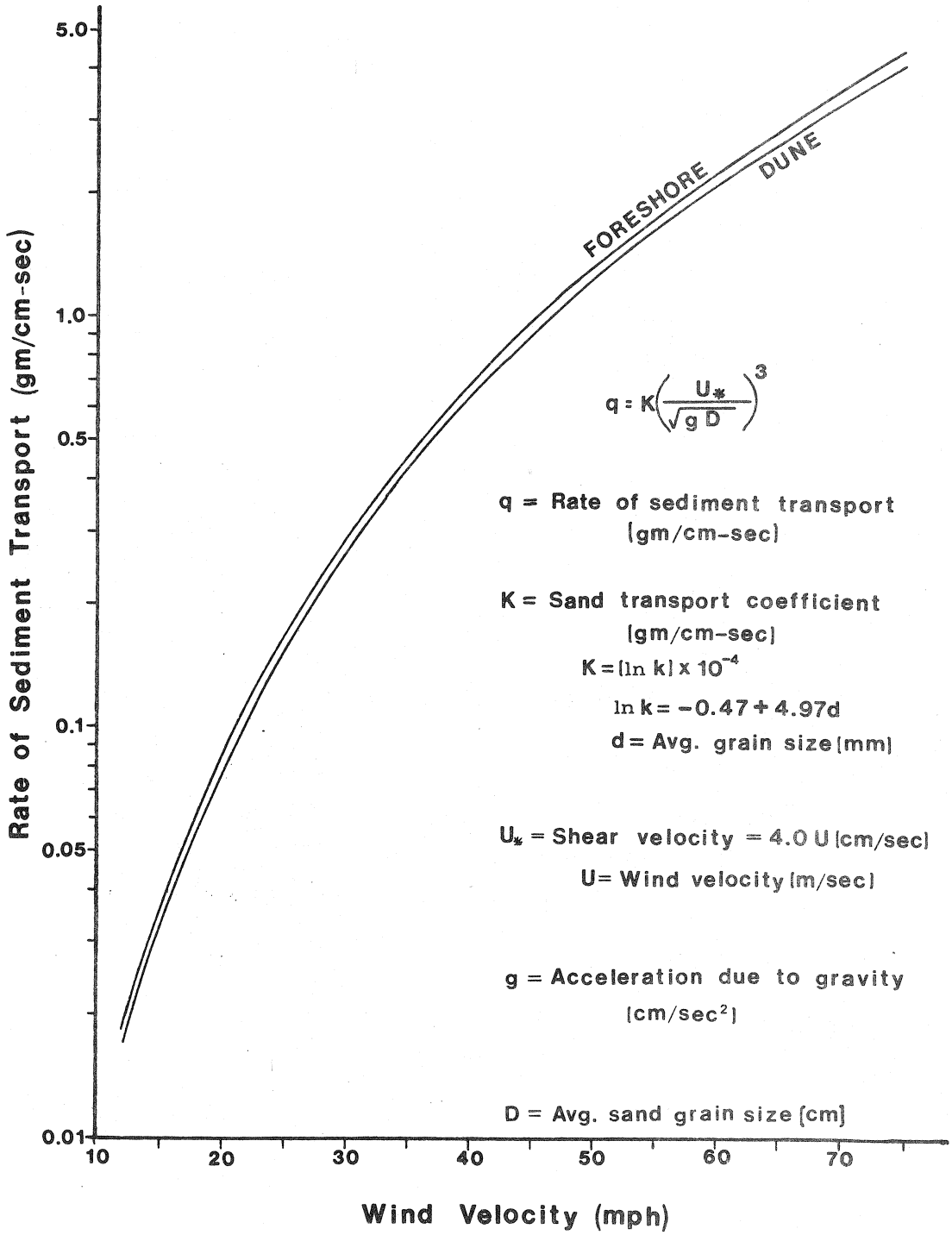


Figure 123. Calculated rate of sediment transport based on a rating curve derived from an empirical approximation (Hsu, 1974). Average dune grain size = 0.32mm. Average foreshore grain size = 0.40mm.

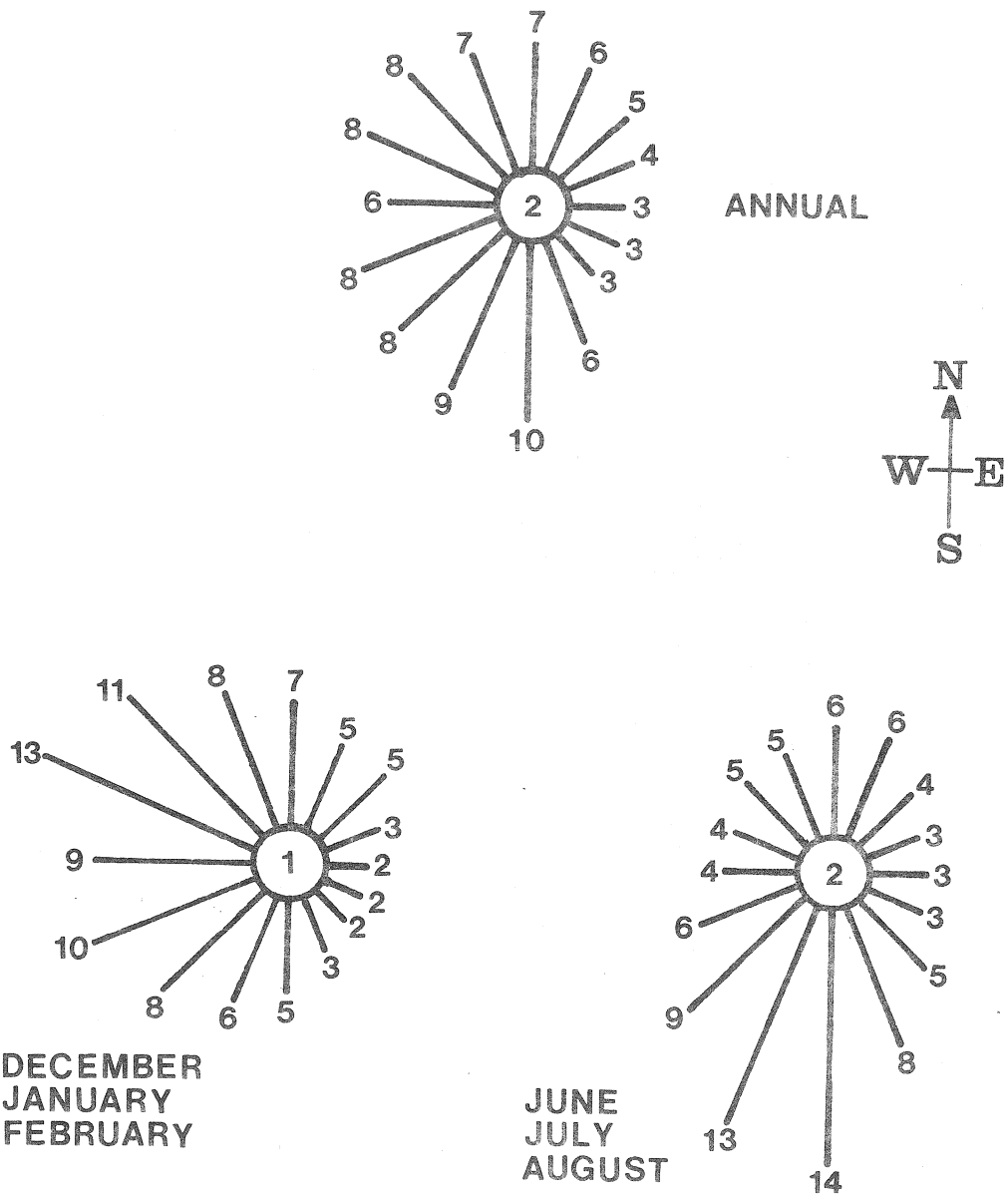


Figure 124. Annual, winter, and summer wind roses for the Long Island region, based on data collected at Kennedy International Airport between 1951 and 1960 (from McCormick, 1975). Percent from each direction shown at the end of each vector, percent calms shown in the center of the roses.

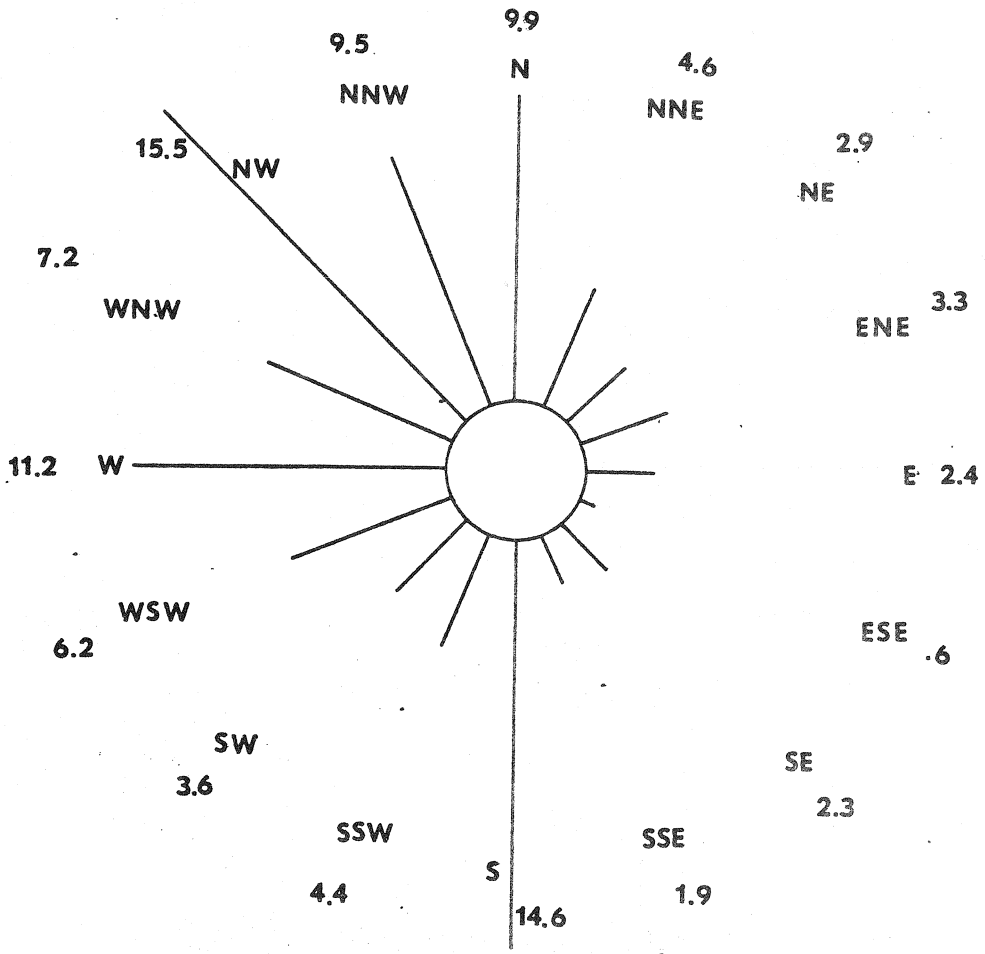


Figure 125. 1974, Winds over 12 mph.- % from each direction.

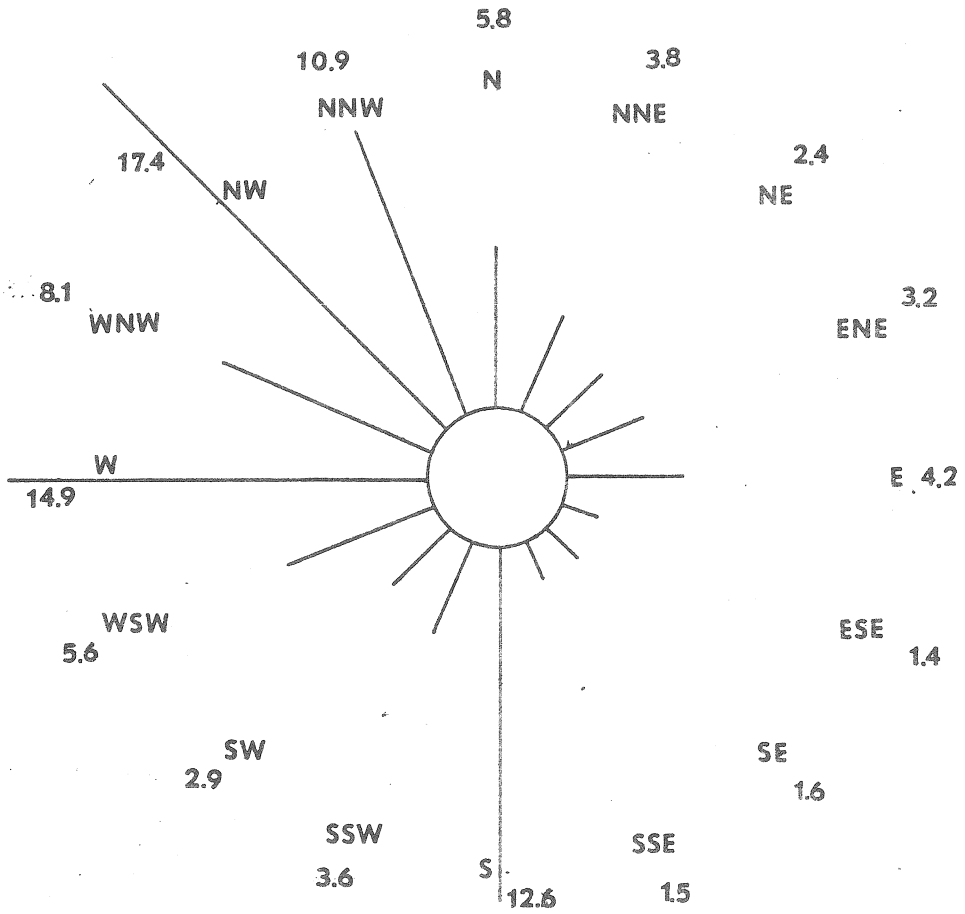


Figure 126. 1975, Winds over 12 mph.- % from each direction.

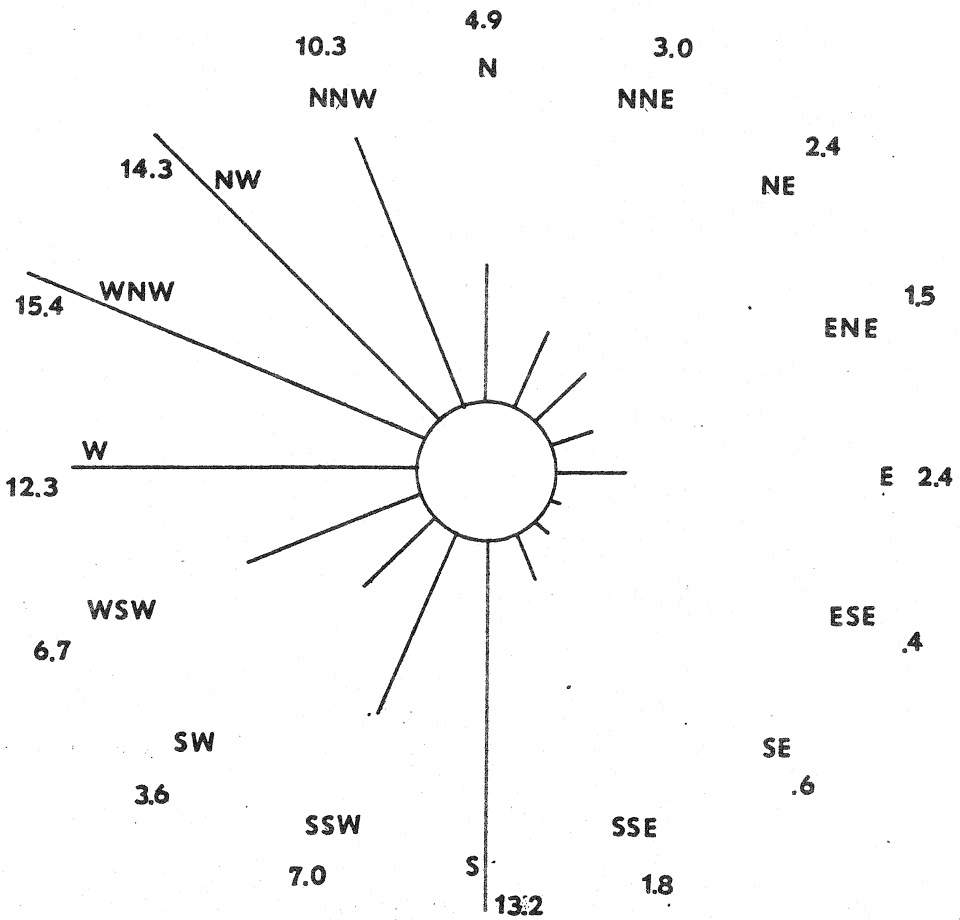


Figure 127. 1976, Winds over 12 mph.- % from each direction.



Figure 128. Vegetation front at Kismet, control.

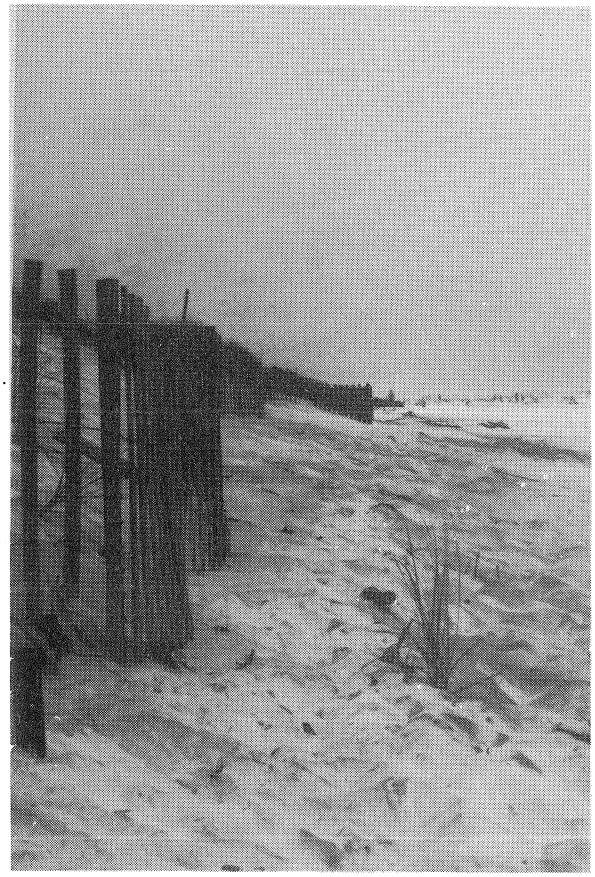


Figure 129. Vegetation front at Kismet, impact.

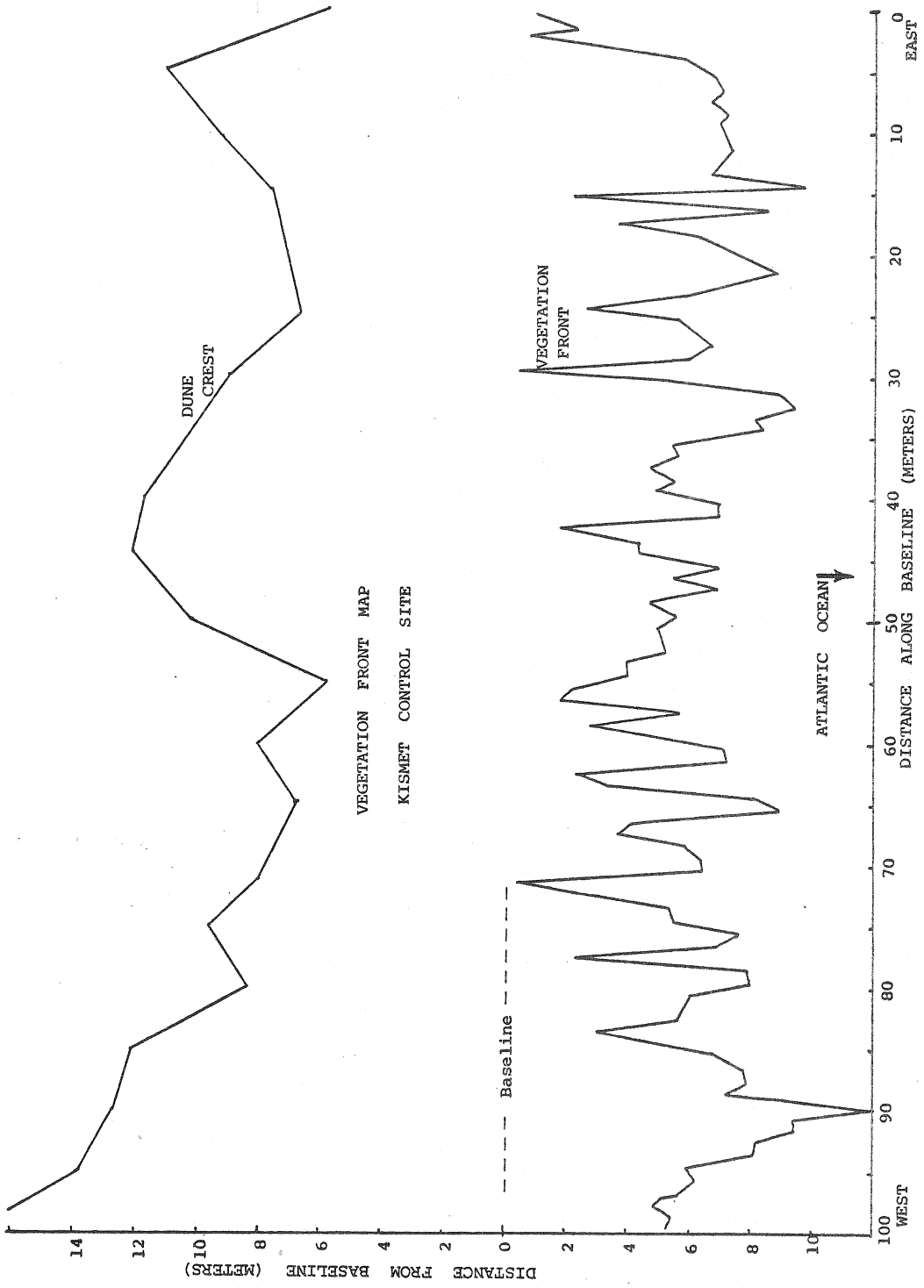


Figure 130. Vegetation front map at Kismet.

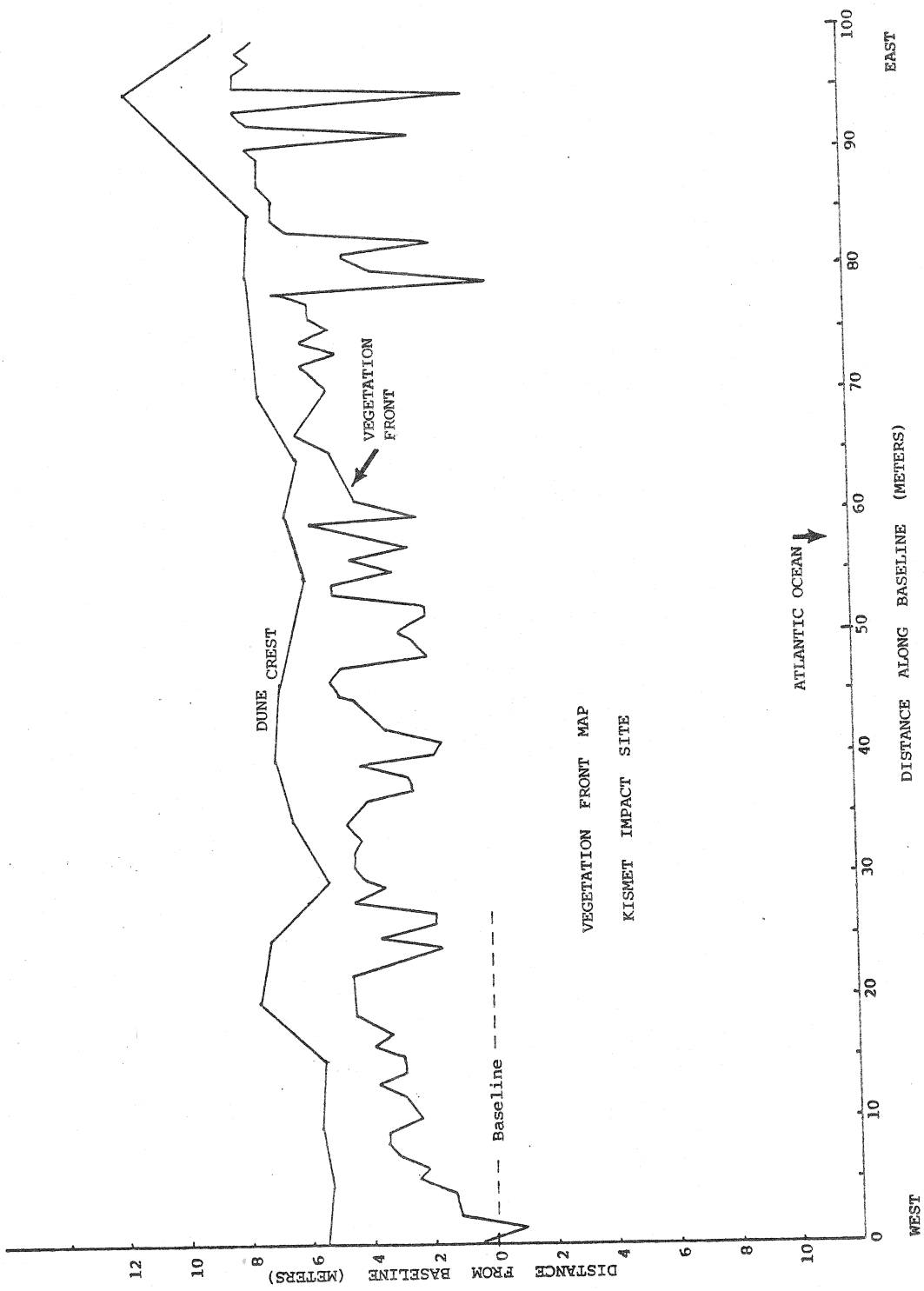


Figure 131. Vegetation front map at Kismet.