LARGE-SCALE CYCLES OF HOLOCENE DEPOSITION AND EROSION AT THE ENTRANCE TO WILLAPA BAY, WASHINGTON IMPLICATIONS FOR FUTURE LAND LOSS AND COASTAL CHANGE

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SUMMARY

The severe beach erosion and frequent flooding at Washaway Beach, Empire Spit, and Tokeland Peninsula at the entrance to Willapa Bay, Washington are directly related to the location of the entrance channel and its historical northerly migration that destroyed the subaerial sand spits of Cape Shoalwater. Accurate prediction of future morphological changes and shoreline positions at the entrance to Willapa Bay depends partly on understanding the Holocene geologic history of the area and the physical conditions that were responsible for prior episodes of channel migration and spit construction.

Morphologic and stratigraphic evidence from north Willapa Bay indicates that the main entrance channel has occupied several positions within a zone approximately 4.5 km wide extending between its present northerly position and a more southerly position aligned with the east-west axis of the Willapa River. Northerly migration of the entrance channel is consistent with the inferred long-term net sediment transport to the north, and northward lateral accretion of Long Beach Peninsula. What requires explanation is the southerly relocation of the entrance channel and attendant construction of sand spits such as Kindred Island, Tokeland Peninsula, and Cape Shoalwater. Earthquake-related subsidence events or climatic-related changes in storm tracks and storm intensity are possible mechanisms for altering wave climate and sediment supply that would favor southerly transport and deposition of sand at the entrance to Willapa Bay. Unless sand supply and predominant sediment transport directions change dramatically in the future, the relative rise in sea level recorded at the tide gauge at Toke Point, frequent winter storms with high waves and strong currents, and deficit in the sand budget assure that beach erosion will continue on Empire Spit and those segments of Tokeland Peninsula that are exposed to high wave energy.

INTRODUCTION

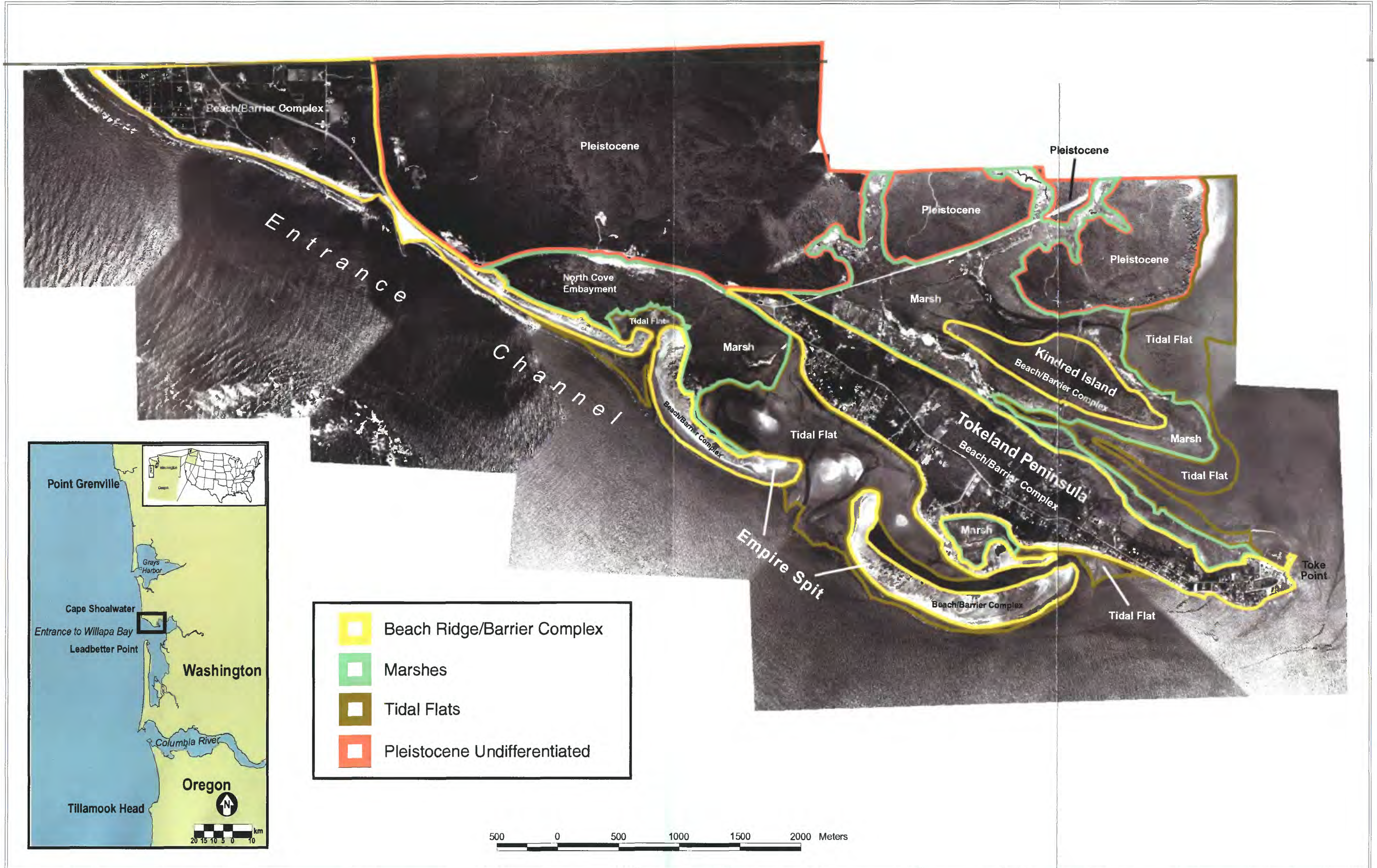
Coastal residents living at North Cove and Tokeland, Washington have witnessed extremely rapid beach recession associated with northward migration of the entrance channel to Willapa Bay (Fig. 1) and destruction of Cape Shoalwater (Andrews, 1965; Terich and Levensellar, 1986; Dingler and Clifton, 1994; Kaminsky et al., 1999). The rapid retreat of Cape Shoalwater since the late 1800s destroyed lighthouses and continues to demolish homes, threaten other coastal properties, and reduce the tribal lands and shellfish resources at the Shoalwater Bay Indian Reservation. The recent breaching of Empire Spit and partial loss of barrier protection from storm-surge flooding and direct attack from Pacific Ocean storm waves remains a constant concern of the local residents and property owners.

The following report examines the historical coastal changes at the entrance to Willapa Bay in the context of large-scale and long-term geological processes that were responsible for shaping the coast near North Cove and Tokeland Peninsula before human activities altered coastal processes and sand supply in the Columbia River littoral cell. The present beach retreat near the entrance channel and lack of sufficient sand supply to stabilize the beaches can be better understood by establishing the regional geologic framework and identifying cycles of coastal change and conditions that caused those changes.

Objectives

The primary purposes of this study were: (1) to determine the periods of optimum beach sand transport and storage in north Willapa Bay, (2) to differentiate the sediment contributions from local upland (Pleistocene) sea-cliff erosion and alongshore or offshore sources, and (3) to reconstruct the late Holocene geologic history of north Willapa Bay. Key issues relate to the timing and conditions that cause large-scale lateral migration of the entrance channel, sediment redistribution at the mouth of the bay, and transfer of sand to tidal flats within the bay. Some unanswered questions are: (1) What are the conditions that favor net southerly transport and deposition of large volumes of sand at the entrance to Willapa Bay, and (2) have threshold conditions been surpassed so that the previous northerly limit of erosion at North Cove will be exceeded? A secondary scientific question addressed the composition of the sediments beneath Tokeland, and whether or not there had been local sinking of the Toke Point tide gauge that would bias the recent sea-level record for Willapa Bay.

Figure 1. Distribution of Holocene and modern depositional environments of north Willapa Bay interpreted from field observations, topographic maps, and the 1999 aerial photograph.



Coastal Features

The north shore of Willapa Bay near its entrance is characterized by three prominent sand ridges that protrude obliquely into the bay (Fig. 1). Marshes and tidal flats form fringing wetlands that occupy the low elevations between the sand ridges. The oldest exposed sand ridge, Kindred Island, is low (< 4 m MLLW), uninhabited, and serves as an anchor point for dikes that transform the adjacent marshes into grazing pasture. A dense forest that originally covered the island was cleared for the cattle ranching operation. Tokeland Peninsula, the relatively large middle ridge, is also about 4 m above MLLW, densely forested, and supports a small community of residences and businesses. Both Tokeland Peninsula and Kindred Island are stable landforms that are experiencing wave-generated erosion of their southeastern margins.

In general, Empire Spit is a low (< 4 m MLLW), relatively young, segmented and unstable beach-washover deposit that is covered with grasses and low shrubs. Its recent formation is related to the rapid northward migration of the entrance channel and attendant 3.8 km historical beach retreat at Cape Shoalwater (Terich and Levensellar, 1986; Dingler and Clifton, 1994; Kaminsky et al., 1999). Two relatively shallow tidal inlets divide Empire Spit into three segments (Fig. 1). The northwestern segment, which is attached to the Pleistocene upland, is a transgressive beach that is migrating landward as the beach retreats and overwash sand is deposited into the adjacent North Cove marsh. At low tide, muddy marsh sediments are exposed along most of the beach of the northwestern spit segment.

The central segment of Empire Spit is also a transgressive feature that is migrating landward as a result of beach erosion and storm washover. The convex-seaward shape of the central spit segment is caused by rapid retreat along the margins of the two tidal inlets that form the lateral boundaries of the island. Rates of retreat along the central part of the island are slower than those on either end.

The southeastern spit segment is also arc shaped, but it has a different depositional history than the other segments of Empire Spit. The southeastern spit segment is simultaneously retreating along its western section while it is extending eastward and northward as a result of wave refraction and sand supplied by updrift erosion. Sand recently eroded from around the North Cove channel-diversion structure is transported to the southeast and is deposited on the southeastern end of the spit, causing it to build and re-curve northward toward Tokeland Peninsula (Fig.1).

Coastal Processes

The southwestern coast of Washington is a wave-dominated, meso-tidal range region that receives sediments primarily by northward longshore transport from the Columbia River (Ballard, 1964; White, 1970; Luepke and Clifton, 1983; Li and Komar, 1992). The high tide range ($\approx$ 4 m) and diurnal cycle create strong tidal currents and the exchange of large volumes of water into and out of Willapa Bay. Tidal current velocities of 3 m/s have been reported at the entrance to the bay (Andrews, 1965; Clifton and Phillips, 1980). At Toke Point (Fig. 1), daily tide gauge measurements show that still-water elevations during winter storms can be more than 4 m above MLLW. Runup of storm waves superimposed on the high water levels would significantly increase flood elevations near the shore along Empire Spit and along exposed southwesterly-facing segments of Tokeland Peninsula.

Summer waves in the Pacific Northwest have periods of 5-10 s, whereas winter waves have periods of 10-20 s (Tillotson and Komar, 1997). Seasonal changes in the angle of wave approach to the coast cause a reversal in longshore transport directions from predominantly southerly in the summer to predominantly northerly in the winter. Because wave energy and water levels tend to be higher in the winter, long-term net longshore transport is to the north (Ballard, 1964).

Recent analyses of deep-water waves off the west coast of the United States by Allen and Komar (2000) show that average significant wave heights range from 3.6 to 3.8 m, and the maximum significant wave heights are 14 to 15 m. Their analyses of annual wave heights also indicate that between 1975 and 1999, the largest storm-generated waves off the Washington coast increased in height from 8 to 12 m.

DATA ACQUISITION

Coastal Morphology

Maps and Aerial Photographs

Historical changes in and the spatial distribution of coastal environments at the entrance to Willapa Bay were documented by inspecting available charts, maps, and aerial photographs spanning the 128-year period from 1871 to 1999 (Table 1). All of the images show the outer entrance channel and the North Cove embayment, and most of the images also show the positions and shapes of Tokeland Peninsula and Kindred Island. The coastal charts prepared by the U.S. Coast Survey represent the oldest and most accurate depictions of landforms and water bodies near the turn of the 20th century. Comparison of those historical documents with subse-

Table 1. List of topographic maps, hydrographic charts, and aerial photographs used to interpret morphological changes near North Cove and Tokeland. Many of the historical charts and maps were presented either in Hands (2000) or Terich and Levensellar (1986).

Date and Description	Scale	Source or Reference
1871 topographic chart	1:10,000	U.S. Coast Survey
1911 topographic chart	1:20,000	U.S. Coast and Geodetic Survey
1912 topographic chart	1:20,000	U.S. Coast and Geodetic Survey
1926 topographic chart	1:20,000	U.S. Coast and Geodetic Survey
1928-1978 annual hydrographic surveys	1:60,000	U.S. Army Corps of Engineers
1938 topographic map	1:62,500	U.S. Army Corps of Engineers
1942 black and white aerial photographs	1:24,000	U.S. Army Air Corps
1950 topographic chart	1:10,000	U.S. Coast and Geodetic Survey
1963 black and white aerial photographs	1:12,000	Washington Department of Natural Resources
1974 black and white aerial photographs	1:24,000	Washington Department of Natural Resources
1993 black and white aerial photographs	1:12,000	Washington Department of Natural Resources
1995 color IR aerial photographs	1:24,000	U.S. Army Corps of Engineers
1999 color aerial photographs	1:12,000	Washington Department of Natural Resources

quent and recent aerial photographs provides a basis for evaluating the morphological stability of each area and explaining some of the stratigraphic successions recorded in the vibracores.

The oldest map of the area is a preliminary survey conducted in 1852 by the U.S. Coast Survey. The 1852 map was not included in the morphological analysis because it appears to be a generalized illustration of the area with limited horizontal control. In contrast, the 1871 map (Fig. 2) provides accurate details that can be judged of exceptionally high quality by its agreement with modern geographically controlled depictions of stable land features. The 1999 aerial photographs, representing the most recent geographically controlled depiction of the area, also served as a base for mapping depositional environments (Fig. 1), locating field observation sites (Figs. 3-5), and locating topographic transects (Fig. 6).

Topography and Bathymetry

The general topography and bathymetry of the study area are available from USGS 7.5 minute topographic quadrangles Bay Center, Washington and North Cove, Washington. Even though those quadrangles were revised on the basis of 1990 aerial photographs, additional detailed topographic and bathymetric surveys conducted in 2000 were necessary for two reasons. First, because topographic relief in the area is high, the lowest contour on the standard 1:24,000 maps is 6 m. Consequently all of the surface features of interest for this study are below the resolution of the first contour. Additional high-resolution surveys were also needed because the beach and nearshore zone of Empire Spit continues to undergo rapid change. As a result of these dynamic conditions, the topographic map is inaccurate and does not represent conditions of Empire Spit observed in the field.

Real-time kinematic GPS surveys conducted by the Washington Department of Ecology were used to construct 33 topographic profiles across and along Kindred Island, Tokeland Peninsula, and Empire Spit (Fig. 6 and Appendix A). Measurements obtained from the GPS topographic surveys were used to determine the ground elevation at each field observation site (Table 2). Profile 11 consisted of only a few data points on the crest of Empire Spit. Because it did not represent a profile of the barrier, it was deleted from the data set (Fig. 6 and Appendix A).

Subsurface Data

The stratigraphy of shallow late Quaternary sediments beneath north Willapa Bay and surrounding environs was investigated using data from a variety of sources including field observations, publications, and unpublished agency or consulting reports. Stratigraphic cross sections were prepared primarily from lithologic descriptions of short cores (Appendix B) and moderately deep boreholes. These interpretive tools were supplemented with other stratigraphic information presented in Golder Associates Inc. (1997) and unpublished water-well records made available by the Washington Department of Ecology.

Exposures, Auger Cores, and Vibracores

The most detailed stratigraphic information for the north Willapa Bay region comes from 28 observation sites that represent shallow trenches, auger cores, and vibracores (Fig. 3 and Appendix B). The geographic position of each of the sites (Table 2) was determined with a hand-held GPS receiver. These sites were selected during two-week field expeditions in 1999 and 2000. Sites were selected to examine one or more of the following conditions that pertain to the geologic history of the study area and the recent erosion of Tokeland Peninsula and Empire Spit: (1) the depth and nature of the contact between the Holocene bay fill and the Pleistocene upland deposits; (2) the lateral extent of sand around Kindred Island, Tokeland Peninsula, and Empire Spit; (3) the thickness of marsh mud in the North Cove embayment; (4) the composition of sediments beneath the North Cove marsh; and (5) the southern extent of marsh mud beneath Empire Spit.

Surface exposures, such as wave-cut scarps, and shallow trenches were excavated with a long-handle shovel where the feature of interest was above the water table and vibracoring would not have been an effective method to collect samples. Each of the surface exposures and trenches was cleaned, described, and photographed. At some locations, either a vibracore or an auger core was taken at the bottom of the trench. Core lengths (Table 2) may differ from the total depths shown on the core descriptions (Appendix B) if the core descriptions include

Figure 2. Oldest accurate map showing coastal features at the entrance to Willapa Bay. Prepared by the US Coast Survey based on field surveys in 1871.

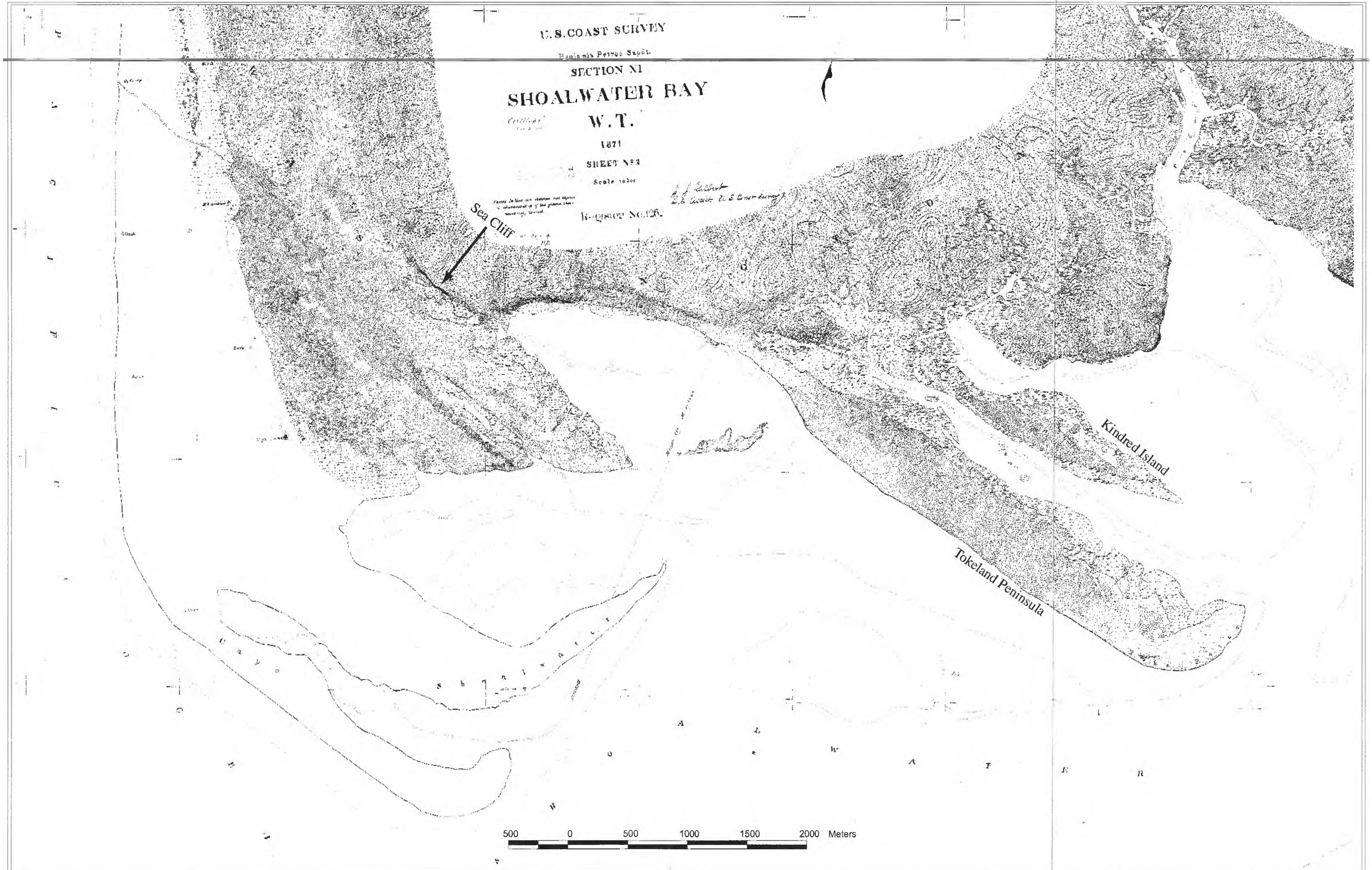


Figure 3. Locations of observation sites superimposed on the 1999 aerial photograph. Also shown are the locations of stratigraphic cross sections presented in Figs. 8-10.

Figure 4. Locations of observation sites superimposed on the 1942 aerial photograph.

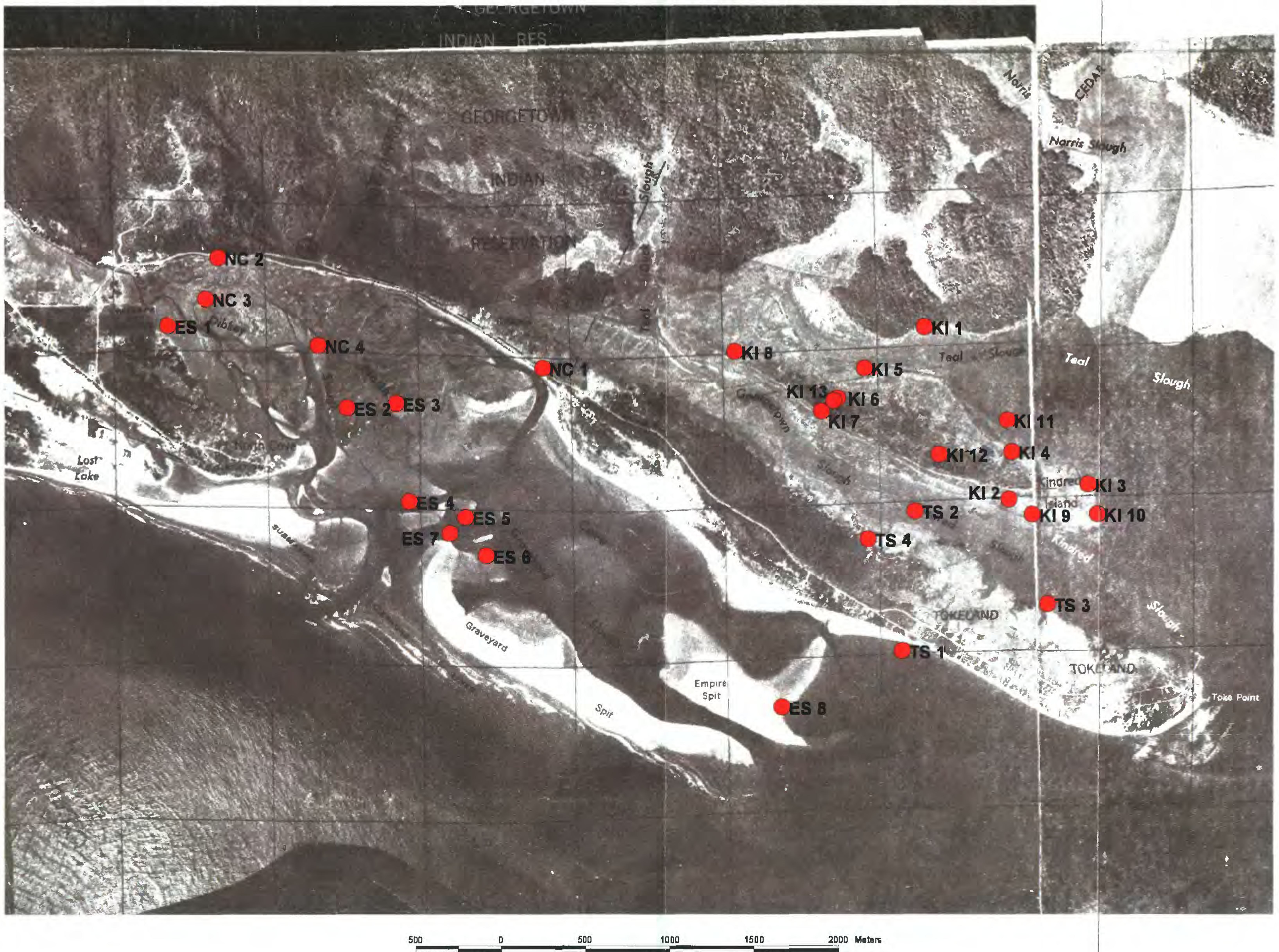


Figure 5. Locations of observation sites superimposed on the 1963 aerial photograph.

Figure 6. Locations of GPS topographic survey transects superimposed on the 1999 aerial photograph. Individual profiles are presented in Appendix A.

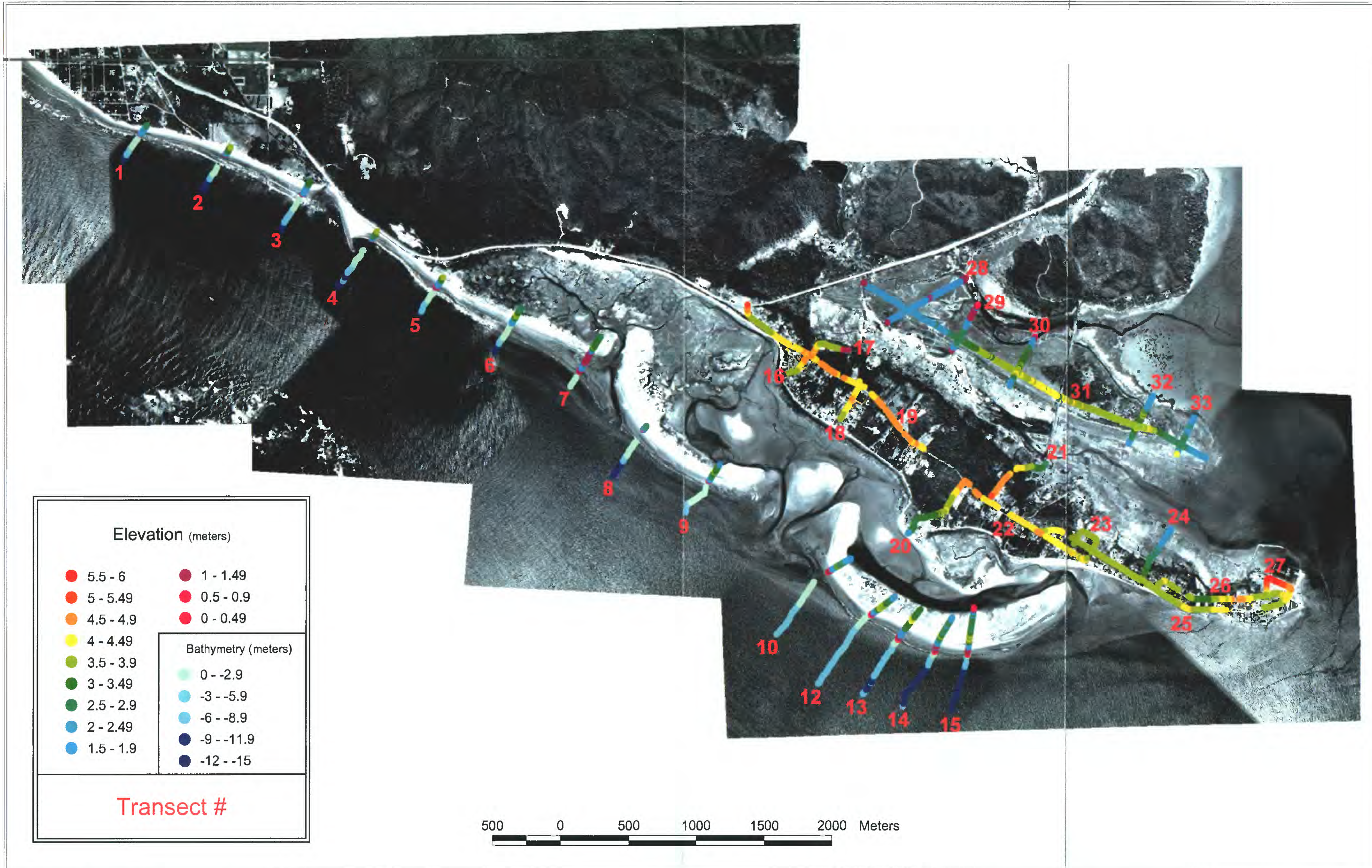


Table 2. Summary of geographic locations and sediment recovery depths at sample sites, north Willipa Bay. Elevations are heights above MLLW. T=trench, V=vibracore, A=auger core, G=gouge core.

Site Designation	Elev. (m)	Length (m)	Easting GPS UTM	Northing GPS UTM	Sample Type	Surface Environment
Kindred Is.						
KI - 1	1.8	1.50	0424477	5175053	T & V	High marsh
KI - 2	1.8	2.45	0424977	5174034	T & A	High marsh
KI - 3	2.3	2.10	0425446	5174123	A	High marsh
KI - 4	2.0	1.85	0424992	5174314	G	High marsh
KI - 5	1.2	1.43	0424124	5174809	G	Marsh
KI - 6	4.1	2.85	0423966	5174632	A	Ridge crest
KI - 7	2.0	1.60	0423868	5174555	T & A	Ridge flank
KI - 8	2.0	1.95	0423356	5174907	T & V	Ridge flank
KI - 9	1.2	1.97	0425117	5173943	V	Tidal flat-marsh
KI - 10	1.3	3.19	0425502	5173947	V	Tidal flat-marsh
KI - 11	1.3	5.04	0424965	5174501	V	Tidal flat marsh
KI - 12	3.9	0.80	0424564	5174300	T	Ridge crest
KI - 13	3.6	0.90	0423940	5174616	T	Ridge crest
Tokeland Pen.						
TS - 1	1.3	4.58	0424349	5173138	V	Channel margin
TS - 2	1.3	3.51	0424425	5173964	V	Marsh
TS - 3	1.2	3.99	0425207	5173415	V	Tidal flat
TS - 4	3.8	0.70	0424145	5173798	T	Ridge crest
North Cove						
NC - 1	1.3	2.36	0422219	5174809	V	Tidal flat-marsh
NC - 2	1.6	3.82	0420301	5175463	T & V	Marsh
NC - 3	1.6	4.31	0420228	5175221	V	Marsh
NC - 4	1.6	5.16	0420891	5174946	V	Marsh
Empire Spit						
ES - 1	1.0	1.61	0420002	5175063	V	Beach
ES - 2	1.4	1.27	0421063	5174575	G	Channel margin
ES - 3	2.5	2.60	0421356	5174602	A	High marsh
ES - 4	2.5	1.35	0421436	5174021	T	Beach
ES - 5	1.8	1.50	0421766	5173927	T	Marsh
ES - 6	1.5	0.30	0421886	5173700	T	Beach
ES - 7	1.5	3.00	0421672	5173831	V	Beach

(1) sediments trenched above the core, (2) sediments in channel banks and wave-cut scarps that are exposed above the core, or (3) sediments vibrated out of the bottom of the core during retrieval.

At other sites where obtaining a vibracore was not feasible, a hand auger with 1.5-m rods was used to drill shallow reconnaissance holes and to collect sediment samples. Sediments retained in the auger head were retrieved every 25 cm, and reassembled on the ground in their proper stratigraphic position until the hole was completed at the depth of refusal. Then the entire stratigraphic section was measured, described, and photographed. This field technique preserves sediment composition, color, and general contacts, but it destroys sedimentological characteristics such as burrowing or primary sedimentary structures. One auger core (CR-1, Table 2) was taken in a pasture on the north side of SR 105 and on the east side of Cedar River (location not shown on base maps). This coring site was selected because a scarp separates the floodplain from marshes lining the riverbank, and the floodplain is well above the elevations of the marshes. At a depth of 70 cm the auger recovered an organic-rich layer of clay containing wood fragments (Appendix B) that was not dated.

The vibracores were collected in 7.6-cm diameter aluminum pipes with standard portable coring equipment that included a cable-driven cement shaker powered by a gasoline engine. The vibracores were shipped to St. Petersburg, FL where they were split, photographed, described, and archived. Each of the lithologic records presented in Appendix B represents the entire stratigraphic section from the ground surface to the depth of recovery. This means that some lithologic records (KI-1, KI-2, KI-7, KI-8, TS-3, NC-2, NC-3, NC-4, ES-1) are composites of surface exposures or trenches and the underlying sediments recovered in the auger core or vibracore.

Water-Well Records

More than 50 water wells have been drilled on Tokeland Peninsula for residential, municipal, and commercial purposes. Reports prepared by various water-well drillers, which include general descriptions of sediments encountered while drilling, were obtained from the Washington Department of Ecology. A study conducted by Ron Lane of the USGS Water Resources Division, Tacoma office (personal communication) incorporates geographic positions and surface elevations of about 30 of the water wells. Most of the wells are about 50 to 100 m deep and they penetrate both Holocene and Pleistocene sediments.

The lithologic descriptions logged by the drillers typically include depths beneath the surface of stratigraphic contacts (lithologic changes), the predominant sediment type of each stratigraphic unit, sediment color, and possibly some modifiers such as the presence of shells or wood. Although lithologic descriptions of the drillers logs are less accurate and detailed than those that would be reported by a trained geologist, they are adequate for gross stratigraphic interpretation and facies analysis for the following reasons. The well spacing is sufficiently close and the lithologic differences are sufficiently distinct that general stratigraphic trends can be established. For example, repeated vertical successions of gravel, sand, and clay in many wells document clear upward-fining patterns. The upward-fining patterns are typical of channel-fill deposits that are common throughout the Holocene and Pleistocene tidal sediments of Willapa Bay (Clifton and Gingras, 1999). Also there are enough wells (sufficient sample size) that contact depths can be estimated and the Holocene sediments can be differentiated from Pleistocene sediments, despite the variability in the descriptions and reporting styles of the different drillers (lumpers versus splitters). More important, the lithologic descriptions represent the only subsurface stratigraphic control for analyzing the sedimentary fill beneath the barriers, tidal flats, and marshes of north Willapa Bay.

Pleistocene terrace deposits are well exposed in sea cliffs and quarries around Willapa Bay. Some of the quarries and sea-cliff exposures near Tokeland were photographed and described during the two field expeditions. Clifton and Gingras (1999) provided detailed descriptions of the Pleistocene terrace deposits. At least one of the water wells drilled on Tribal land west of Tokeland Peninsula is entirely within the Pleistocene terrace deposits. The lithologic observations in the quarries and sea cliffs, and descriptions of this well were used to establish criteria for recognizing Pleistocene sediments in other well records.

Borehole Records

In 1997, the Washington Department of Transportation (WSDOT) drilled 4 boreholes ranging in depth from 24 to 36 m as part of the Willapa Bay Channel Restoration Project. In addition to gross lithologies, the borehole summary sheets provide standard blow counts, sampling intervals, and other geotechnical information. The boreholes, which were located near the intersection of SR-105 and Smith Anderson Road, penetrated unconsolidated sand and gravel that were interpreted as Holocene beach and dune deposits and Pleistocene terrace deposits. Depths of the Holocene-Pleistocene unconformity were penetrated at – 11 m and – 16 m in boreholes 3 and 4, respectively.

Golder Associates Inc. (1997) conducted limited offshore geophysical surveys (bathymetry, side-scan sonar, seismic reflection and refraction) of the entrance channel to Willapa Bay in the vicinity of the groin at SR-105. Their report integrated depth plots of interpreted prominent seismic reflections corrected for two-way travel time and plots of the nearest WSDOT borehole logs. Unfortunately, illustrations presented in the report are only line drawings and do not include the original high-resolution seismic profiles. The offshore acoustical reflection plots indicate that near the groin, the Holocene section is composed of dune and beach sand to a depth of about 12 m. Strata below 12 m exhibit relatively steep-walled incised channels, and are interpreted as Pleistocene terrace deposits on the basis of projected depths of lithologies in the nearby WSDOT boreholes. The contact at 12 m between the Holocene and Pleistocene strata is relatively flat or low dipping seaward, which is the morphological expression that would be expected for the wave-cut ravinement surface constructed during the last rise in sea level. The offshore bathymetry and interpreted seismic reflections indicate that the steep north wall of the entrance channel at North Cove is excavated into the fine-grained slightly indurated Pleistocene terrace deposits. A seismic reflection at 24 m, and slightly below the present thalweg of the entrance channel is interpreted as possibly the erosional unconformity at the top of the Tertiary strata. The Golder Associates Inc. report (1997) gives no evidence for this stratigraphic interpretation, which appears to be too shallow, and it is contradicted by (1) descriptions of sediments in the WSDOT boreholes that penetrate below the interpreted Quaternary-Tertiary contact but apparently did not encounter Tertiary strata, and (2) lithologic records of a deep petroleum exploration well drilled in the community of North Cove by Union Oil Company of California. According to published reports, the Unocal well encountered the Quaternary-Tertiary contact at a depth of about 300 m (Rau and McFarland, 1982).

MORPHOLOGICAL ANALYSIS

Names and Locations

In dynamic coastal regions, the names of specific features commonly change locations as the features migrate or are obliterated by erosion. Cape Shoalwater is a good example of a complex feature that retained its name as the shoreline receded. Examining the various maps listed in Table 1 reveals some other changes in names and locations that are pertinent to the discussion of morphodynamics of Willapa Bay. The 1852 map shows the survey marker Toke and Toke Point as being on the southern tip of Cape Shoalwater. Subsequent maps show the survey marker (if present) is in the same location, but the name Toke Point was changed to identify the southern tip of Tokeland Peninsula, where it remains today. Similarly, North Cove is labeled on the 1911 map as the former entrance channel position preserved just south of the oldest (most landward) spit of Cape Shoalwater. As the Cape retreated, the name North Cove was shifted to the former entrance channel position preserved between Tokeland Peninsula and the oldest spit of Cape Shoalwater. For the purposes of this report, Empire Spit refers to the three beach segments that form the most seaward barrier complex in the North Cove area (Fig. 1). On the 1938 topographic map, the central segment is labeled Graveyard Spit, whereas the emergent sand flats attached to Tokeland Peninsula are labeled Empire Spit.

Entrance Channel

The cyclical realignment of the entrance channel to Willapa Bay occurs at two distinctly different temporal and spatial scales. The well-documented cycles of channel relocation are the high-frequency events (10 to 20 year periods) that involve only the outer shoals and entrance channel of the ebb-tidal delta. During a typical high-frequency cycle, sand accumulates on a submerged spit at Cape Shoalwater, the entrance channel migrates to the south, and eventually the spit is breached and the channel mouth is realigned to the northwest (Andrews, 1965; Hands and Shepsis, 1999; Hands, 2000). This repetitive channel realignment occurs across a relatively narrow zone that is located several kilometers seaward of the general shoreline trend between Cape Shoalwater and Leadbetter Point. In that position the channel-mouth is strongly influenced by alongshore currents and sand transport. It is free to oscillate to the north and the south, and is unconstrained by upland topography. Apparently the channel shifting at the mouth has to do with the balance between sand transport by longshore currents and the ability of the channel to eventually construct a more efficient course by breaching the submerged spit deposited concurrent with channel migration. Each of the documented channel realignments coincided with elevated water levels of an El Niño event (Hands and Shepsis, 1999), but each El Niño did not result in channel realignment.

Of greater interest for this study are the low-frequency, large-scale cycles of channel relocations that involve the entire entrance channel, not just the segment through outer bars of the ebb-tidal delta. The large-scale relocations occur landward of the general shoreline trend, not seaward of the shoreline, as do the high-frequency realignments. The large-scale relocations include meanders through the ebb-tidal delta with large radii-of-curvature, and the main channel segment that connects with the principal channels that drain the southern and eastern arms of Willapa Bay. The curvature of extant banks eroded by the entrance channel along the north shore of Willapa Bay is similar to the arc carved into the upland shore of the North Cove embayment (Fig. 1). Clifton and Phillips (1980) also recognized these similarities and attributed the North Cove embayment morphology to a former position of the entrance channel. At least two former positions of the entrance channel interpreted from the 1871 map (Fig. 2) indicate that the entrance channel migrated to the southwest as sand accumulated on Cape Shoalwater and the associated beach ridges and spits accreted laterally. Figure 2 also shows that Empire Spit did not exist in 1871.

North Cove Embayment

The oldest maps (1871, 1911) show North Cove embayment as the northward extension of a barren, shallow platform that was deposited between Tokeland Peninsula and Cape Shoalwater. A narrow fringing marsh formed the shore along the contact between the embayment and the upland sea cliff (Fig. 2). Subsequent maps (1926 and 1938) indicate shoaling around the northern margin of the embayment, aggradation and expansion of the intertidal mud flats, and eventual organization of tidal creeks on the flats. Pacific County Drainage Ditch No. 1 was constructed some time between 1926 and 1938, and some of the shoaling in the North Cove embayment can be attributed to sediment transported by the runoff from the cranberry bogs north of North Cove.

Surficial patterns exhibited on the 1942 air photo (Fig. 4) indicate a transitional period when the mud flats were being colonized by plants and converted to dense marsh. By 1950, marsh was prevalent in the North Cove embayment near Dibkey Slough (also labeled Cannery Slough). Predominant deposition of mud in the marshes is implied by the map labels compared to deposition of mud and sand on the barren flats. Subsequent images (1950 and 1963) illustrate the infilling of marshes and organization of tidal creeks so that the northern half of the North Cove embayment consisted of marsh and associated narrow tidal creeks (Fig. 5). As remnants of the oldest spit of Cape Shoalwater eroded and the northern two segments of Empire Spit migrated landward, the tidal creeks in the North Cove embayment were forced to reorganize in order to accommodate the tidal flow in and out of the marshes and tidal flats.

Beach Ridges and Adjacent Marshes

The 1871 map (Fig. 2) shows that both Kindred Island and Tokeland Peninsula have relatively straight shores facing the entrance to Willapa Bay, but their landward shores are irregular and lobate in form. Elevations decrease away from the axes of Kindred Island and Tokeland Peninsula and elevations both parallel to and perpendicular to the axes of both features are relatively uniform; most changes in elevation are gradual. The relatively smooth surface morphologies suggest that eolian dunes are not a significant component of these land features and the maximum surface elevations correspond to heights of wave runup and overwash on the beach rather than corresponding to the crests of sand dunes. The northwest-southeast upstream alignments of Kindred Island and Tokeland Peninsula with respect to the general east-west orientation of the Willapa River indicate that discharge of the river was minor when the beach ridges were deposited. The beach ridge orientations indicate that wave refraction and tidal flow into Willapa Bay was the most important process determining the alignment of the beach ridges.

Topographic transect 30 (Fig. 6 and Appendix A) illustrates the shore-normal morphology of Kindred Island near the crest of the feature. The relatively steep slope of the seaward-facing (southwestern) flank, the relatively narrow crest, and the more gently sloping landward flank display morphologies that are similar to the beach, crest, and washover apron of Empire Spit (see transect 12 Appendix A). Together the sediment textures (sand with some gravel) and morphology of Kindred Island are compelling evidence that it is a beach-ridge deposit with little dune ornamentation. A field reconnaissance of Kindred Island shows that the surface near KI-12 (Fig. 3) is characterized by low (< 1m) hummocky sand mounds that could be mistaken as eolian deposits. Shallow trenches at two sites near KI-12 reveal that the modern soil and associated sediments overlie a buried soil at depths ranging from 30 to 70 cm below the irregular surface. However, conversations with the landowner indicate that the buried soils are a result of recent human activities associated with ranching and disposal of sand excavated from construction sites.

The general morphology, size, and orientation of Tokeland Peninsula also indicate that it is a beach-ridge feature deposited primarily by wave runup, washover, and longshore currents. The beach face is not as well preserved as the one on Kindred Island; nevertheless, the elevations, slopes, and sediment textures are consistent with a beach-barrier origin. Maximum elevations on Tokeland Peninsula are about 4.5-5 m (profiles 18, 19, 20, 21), which is slightly higher than maximum elevations on Kindred Island or Empire Spit. Elevations at Tokeland generally decrease to the southeast, which would be consistent with lower elevations associated with younger deposits formed by lateral accretion and spit elongation. Elevations greater than 4 m at the southeastern end of the peninsula are anomalies, and may be associated with the disposal of sediments dredged from the adjacent marina.

The marshes and tidal flats around Kindred Island and Tokeland Peninsula are both natural features and products of human activities. The 1871 topographic map (Fig. 2) shows the distribution of natural fringing marshes that formed in the topographic lows separating the beach-ridge features and the mainland where the bay shores are sheltered from high wave energy. In their natural state, the marshes were tidally influenced by bay water flowing into and out of Teal Duck Slough and Kindred Slough. Between 1942 and 1950, a rubble dike composed of rock was constructed from the mainland, across Kindred Island, and onto Tokeland Peninsula (see Fig. 3). The dike, which has an elevation of about 5 m above MLLW, was constructed with tide gates to block tidal flow, while allowing upland runoff from the minor streams to continue draining through Teal Duck Slough and Kindred Slough. The altered hydrology associated with the dike and constructed drainage ditches changed the wetlands at higher elevations into uplands (grazing pasture), and the wetlands at lower elevations were converted to freshwater marshes. Tidal flats were converted to marshes on both sides of the dike where flow was restricted and sediment was trapped by the structure.

Maps and aerial photographs (Table 1) clearly show that Empire Spit is a recent beach-ridge feature that formed as Cape Shoalwater retreated and the sandy tidal flats adjacent to the Cape were exposed to strong wave energy. Segments of Empire Spit were constructed or became emergent in the late 1920s. Since then the spit has undergone substantial change including landward migration and lateral elongation (compare Figs. 2-5). The hydrographic chart of 1928 (Hands, 2000) shows a narrow, east-west trending spit attached to Cape Shoalwater and extending toward the North Cove embayment. At the same time, a narrow L-shaped island is shown on the platform between the entrance channel and Tokeland Peninsula, with the long end of the L nearly attached to the central part of the peninsula. By 1932 the east-west trending spit was detached and separated from Cape Shoalwater by a shallow subtidal flat. In subsequent years, the detached island migrated landward while growing to the southeast, and an L-shaped island continued to persist off the central part of Tokeland Peninsula.

Through the mid-1950s, open water and barren tidal flats comprised more of the area between the entrance channel and the shore of North Cove embayment than emergent islands and confined marsh. However, beginning in the early 1960s, the island segments of Empire Spit became connected to form a more continuous barrier, and the adjacent tidal flats converted to dense marsh in the northern end of North Cove embayment. Judging from the 1960-1975 hydrographic charts (Hands, 2000) and the 1963 aerial photograph (Fig. 5), the spit configuration consisted of two primary segments separated by a narrow inlet. The northwestern segment was attached to the Cape Shoalwater headland, the inlet was located near the center of the North Cove embayment, the southeastern tip of the isolated island coincided with the shoal attached to Tokeland Peninsula, and a deep narrow channel separated the island segment from the attached shoal (Fig. 5). Between 1963 and 1974, the narrow tidal inlet migrated rapidly to the southeast until the lagoon-side channels connected and the tidal inlet closed. The resulting single continuous barrier of Empire Spit was breached by an inlet opened sometime between 1974 and 1993 at the narrowest part of the barrier. That breach in the barrier has remained in the same position (see inlet at ES-2, Fig. 3). In 1995 another inlet breached the remaining barrier-island segment, resulting in the three segments of Empire Spit. Since 1993, lateral accretion of the southeastern recurved tip of Empire Spit has been rapid, and that accretion has forced the tidal channel landward of Empire Spit to locally impinge on and erode Tokeland Peninsula (Fig. 3).

SEDIMENTARY FACIES AND DEPOSITIONAL ENVIRONMENTS

The tidal-channel and tidal-flat environments of Willapa Bay are characterized by interlaminated and interbedded sand and mud deposits. Clifton and Phillips (1980) summarized the sedimentological characteristics of these environments and described how textural patterns of the Willapa Bay sediments change systematically from the entrance to upper estuary depending on energy available from waves and tidal currents. Hill (1981) conducted a detailed sedimentological and paleontological study of some mid-estuary intertidal flats on the east side of the bay. His study included sediment textures, sediment composition (light fraction, heavy minerals, clay minerals), sedimentary structures, micro fauna (foraminifers), and macro fauna (mollusks). Later Clifton (1983) presented sedimentological criteria for distinguishing between subtidal and intertidal deposits of the bay. The only unequivocal evidence for subtidal deposition is the presence of oyster shells in growth position. Other criteria that are diagnostic of subtidal conditions are large-scale cross stratification, widespread lag deposits, thin laterally extensive mud layers, and predominately concave-up orientations of shells. The only unequivocal evidence for intertidal deposition is the presence of plant roots. Other evidence of intertidal deposition is runoff channels, bluff breccias, and regular sand and mud laminations. Most of these criteria were established on the basis of outcrops, surface exposures, or boxcores with lateral continuity; consequently they are not all recognizable in narrow vibracores.

Facies Descriptions and Depositional Environments

Sediment textures, sediment colors, and accessory components such as roots, shells, and gravel are the most useful megascopic criteria for visually distinguishing among the different sedimentary facies in Willapa Bay deposits. Sand and mud represent the textural end members of predominant sediment types, whereas brown and gray represent the most common end member colors. Following are descriptions of the principal facies that constitute the largest volume of sediment recovered in the vibracores. Similar sedimentary facies are either described or inferred from the water-well records. Together the independent evidence provided by the lithologic descriptions generally is adequate to differentiate Pleistocene sediments from Holocene sediments, and to identify sedimentary facies within the Holocene deposits.

Brown Mud

In addition to its muddy composition and brown color, the brown mud facies is characterized by root mats or abundant fibrous roots near the top of the succession. At depth, the otherwise homogeneous mud is altered with sand-filled burrows and root traces with iron staining. Where present, this organic-rich facies also occupies the uppermost stratigraphic position. Its exclusive association with the intertidal and supratidal marsh depositional environment explains the composition, color, and stratigraphic position of the brown mud facies. Marshes consist of wetland plants that derive their nutrients and oxygen from the tidal circulation of surface water. The marsh plants trap fine-grained sediments (mud), and preferentially fix iron along their roots, giving the mud its brown color.

Gray Mud

Although gray mud and olive gray mud are common facies of Willapa Bay they make up less sediment volume than the other facies. The sediments composed predominantly of gray mud typically contain root traces and detrital organic material; shells and sand-filled burrows are also common constituents. The gray mud facies normally is in gradational contact with the mixed sand and mud facies.

The gray mud facies typically represents relatively low-energy subtidal subenvironments such as the bay center sink of fine-grained deposits. Other common sites of mud deposition are tidal flats, accretion banks, and abandoned tidal channels. The three protected areas between the Pleistocene upland and beach-ridge features are natural settings for mud deposition. These mud traps are analogous to mini lagoons of barrier islands where mud and mixed sand and mud with marine shells are common deposits.

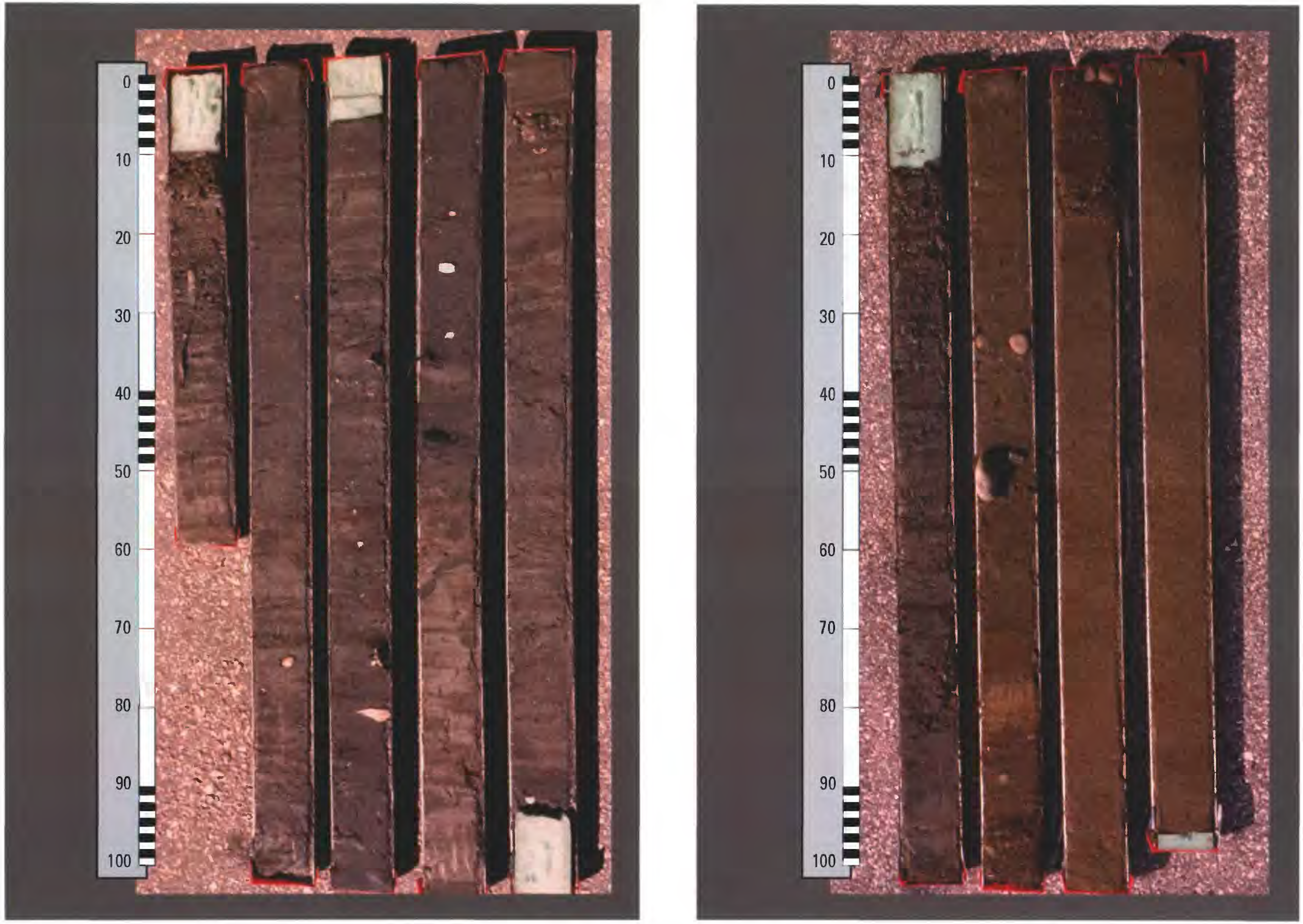
Gray Mixed Mud and Sand

Some of the mixed mud and sand sediments are interlaminated, whereas others are homogeneous, mottled, or bioturbated with sand-filled burrows. In some water-well records, the mixed mud and sand and organic-rich mud facies are described as being soft and mucky. These supplementary descriptions indicate high water contents that are characteristic of Holocene estuarine valley-fill deposits.

The relatively high physical energy of north Willapa Bay is reflected in the distribution of sedimentary facies. Thick sections of mud without any significant amounts of sand are rare because the tidal currents and wave-driven currents are capable frequently of suspending and transporting sand. Despite the high wave and tidal energy, the most common sediment type recovered in vibracores for this study is sandy mud. The common presence of mixed sand and mud is partly biased by the locations of cores, which were collected primarily from the marshes and fetch-limited tidal flats on the flanks of the sandy beach ridges. These subenvironments are protected from the strong waves and tidal currents that would winnow out the mud.

Figure 7. Photographs of vibracores (A) NC-3 and (B) NC-2.

NC-3 **NC-2**



Gray Sand

The gray sand facies (Fig. 7) consists of well-sorted fine to medium sand that is subrounded to subangular. The sand is composed of 40-50% quartz with the remaining grains being rock fragments and heavy minerals. In a few sediment layers, the dark gray color is clearly related to the abundance of heavy and accessory minerals, especially magnetite. Other components contributing to the gray color are organic material and interstitial mud. In general, the gray color is associated with a reduced geochemical environment. The gray sand occurs below the water table where anaerobic conditions persist.

Brown Sand

The brown sand facies (Fig. 7) also consists of well-sorted fine to medium sand that is subrounded to subangular. It is similar to the gray sand facies in texture and composition except the quartz and other minerals coated with iron staining are generally more abundant (Table 3). The brown color can also be related to the geochemical setting. At or near the surface the sandy sediments are always brown (NC-1, TS-1) because geochemically the sediments are exposed to air or oxygenated water and they are oxidized. However the association of brown sand and an oxidation state does not easily explain the presence of brown sand at depth beneath gray (presumably reduced) sediments. The brown-beneath-gray stratigraphic succession is present in vibracores ES-1, NC-2, TS-3, KI-8, KI-9, and KI-10 (Appendix B).

Depositional environments where the brown sand is present are beach/barrier complexes including washover and dune deposits, and tidal flats. Where gravel is concentrated in a layer rather than being disseminated, for example as in NC-2, the gravely sand and overlying well-sorted sand typically represent an upward-fining tidal creek deposit with the gravel representing the coarse lag at the bottom of the channel.

Undifferentiated Pre-Holocene Sediments

Pre-Holocene sediments around and beneath Willapa Bay consist of sand, mud, and mixtures of sand and mud containing common accessories such as gravel and shell. The marine terrace deposits that crop out around the bay have been dated as Pleistocene in age (Clifton and Phillips, 1980), and these same deposits should be present beneath the Pleistocene-Holocene unconformity (Figs. 8-10). Although the Pleistocene sediments represent the same facies present in overlying Holocene sediments, the Pleistocene sediments can be identified using several criteria. One criterion is the change in color at depth from gray or black to brown or yellow. The latter light colors register the former oxidized and weathered state of the Pleistocene sediments when they were subaerially exposed during the oxygen isotope stage 2 lowstand in sea level. Another criterion is the consolidation state of the sediments. Some muddy Pleistocene sediments are hard, rather than being soft or mucky like the water-saturated Holocene muds. Also there appears to be more gravel and shells in the Pleistocene sediments than in the Holocene sediments.

Stratigraphic Interpretations

The vertical and lateral arrangement of sedimentary facies combined with the historical maps and aerial photographs provide a basis for interpreting the depositional environments encountered in each of the vibracores and auger holes, or water-well records. The stratigraphic interpretations are presented in cross sections constructed parallel and perpendicular to depositional strike (Fig. 3).

The vertical successions of sediments recovered in the vibracores were reasonably predictable except for the deepest sediments penetrated in vibracores ES-1 and TS-1. Although ES-1 was located on the beach of Empire Spit (Fig. 3), it was expected that the deepest sediments penetrated would be either muddy sand or sandy mud because the 1942 aerial photographs show that ES-1 was within the arc that formed the fill of the abandoned entrance channel (Fig. 4). The brown sand in the bottom of ES-1 likely represents sand eroded from the nearby Pleistocene outcrops and deposited as barren tidal flats or subaqueous shoals associated with the oldest preserved spit of Cape Shoalwater. Because Tokeland Peninsula formed by longshore sand transport and lateral accretion, and TS-1 was obtained on its seaward (progradational) edge, the entire core was expected to be composed of well-sorted sand. Instead, sediments in the middle and bottom of the core are sandy muds containing some shells. The sand in the top of TS-1 represents reworked beach deposits, whereas the underlying sandy muds likely represent either muddy tidal-flat deposits or abandoned-channel fill similar to that found in the bottoms of vibracores NC-3 and NC-4.

PETROGRAPHIC ANALYSIS

Most of the sediments of north Willapa Bay exposed in outcrops and trenches, or recovered in cores, exhibit distinctly different colors at different depths. Typically the sediments are olive, gray, or brown although some sediment colors are mixtures of these end members. The color differences raise two important questions regarding the depositional history of Kindred Island, Tokeland Peninsula, and Empire Spit; (1) What is the source of the brown color, and (2) Are the sediment colors potential indicators of sediment sources. On the basis of sedimentological studies elsewhere (Dorn, 1998; Stanley et al., 2000) and the chemical composition of sediments from coastal southwest Washington, it was hypothesized that: (1) the brown color

Figure 8. Stratigraphic cross section A-A' along the axis of Tokeland Peninsula.

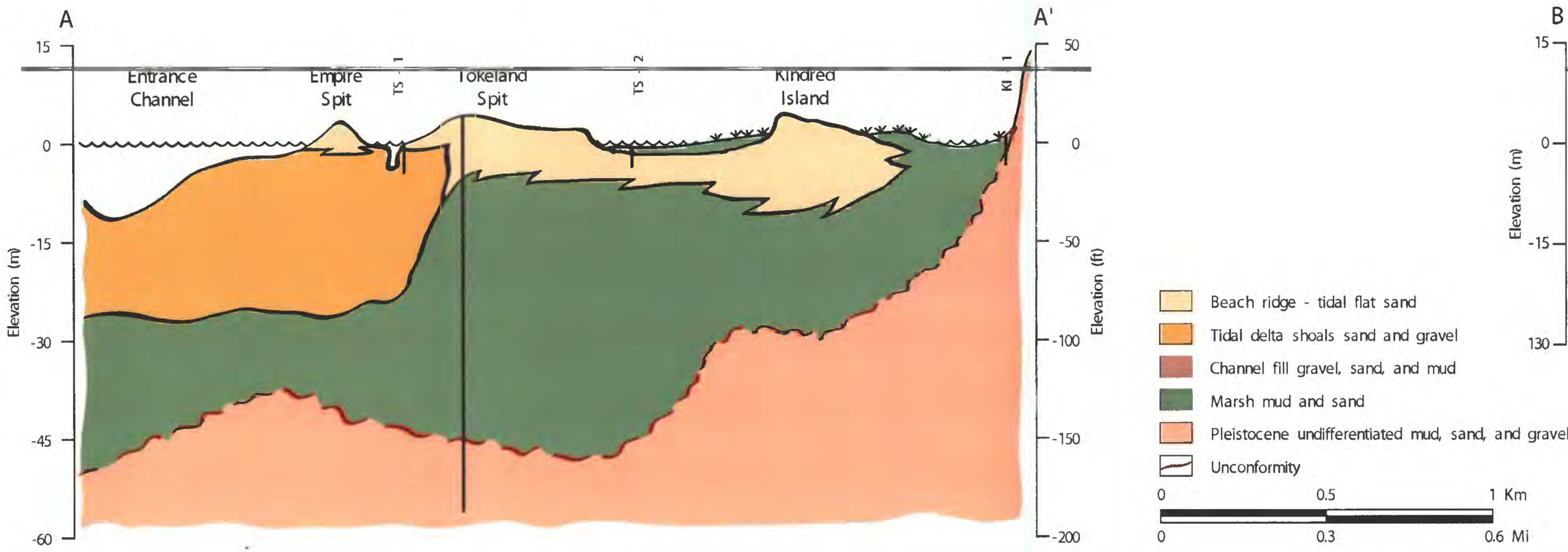
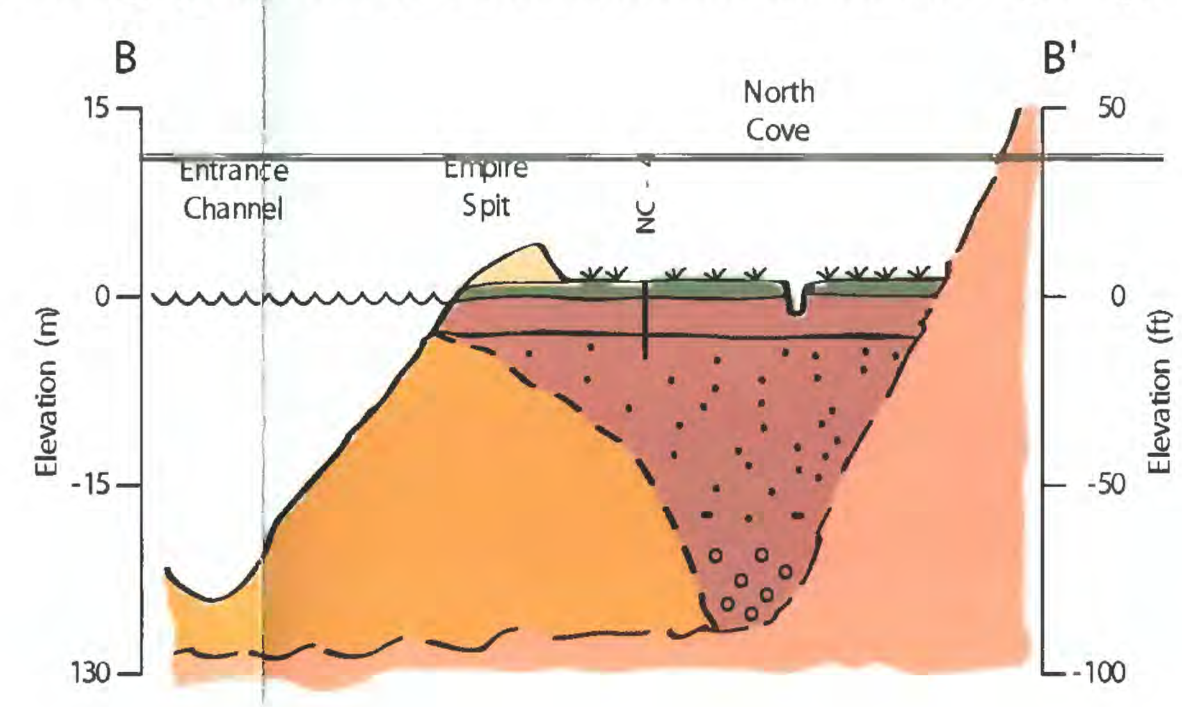


Figure 9. Stratigraphic cross section B-B' across North Cove and Empire Spit.



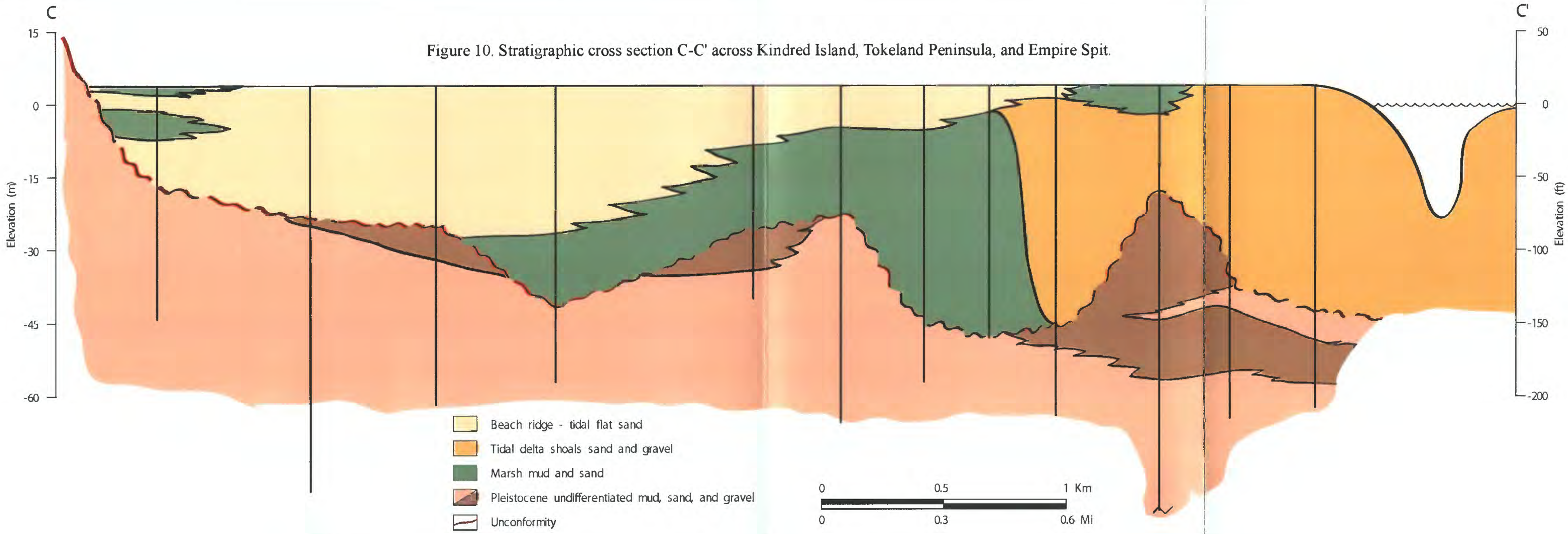


Figure 10. Stratigraphic cross section C-C' across Kindred Island, Tokeland Peninsula, and Empire Spit.

Table 3. Textures, colors, and percent iron coating of quartz grains in sediments from Willapa Bay vibracores.

Core	Depth (cm)	Grain Size	Color	% Iron Coating		
				none	partial	complete
NC 1	120	s	lo	51	42	7
NC 2	115-132	s	o	53	46	1
	154	gs	br	23	72	5
	191-196	gs	br	14	77	9
	213-227	gs	br	33	55	12
	243-247	s	br	35	55	10
	264	s	br	28	59	13
	325-327	s	br	38	52	10
	415	s	br	34	55	11
NC 3	159-178	sm	gr	78	20	2
	178-196	ms	gr	73	25	2
	196-211	sm	gr	69	30	1
	267	sm	gr	82	18	0
	313	ms	gr	84	15	1
	359	s	dgr	80	19	1
	530-535	s	gr	84	13	3
NC 4	97-109	sm	o	61	35	4
	159	s	o	53	42	5
	186-195	ms	o	56	39	5
	198-219	s	gr	66	28	6
	580	ms	gr	68	30	2
ES 1	90-112	s	dgr	70	24	6
	136	s	lbr	54	39	7
ES 8	50	s	lbr	59	36	5
	141	s	lbr	55	38	7
TS 1	90	s	lbr	59	35	6
	177	sm	o	81	19	0
TS 3	425	ms	gr	61	36	3
	447	s	lbr	56	40	4
KI 1	98	s	ggr	82	18	0
KI 8	180	s	o	50	47	3
	235	s	o	59	39	2
	317	s	br	55	43	2
KI 9	42	s	gr	71	29	0
	152	s	lbr	54	39	7
KI 10	107	s	lgr	75	23	2
	162	s	lbr	52	40	8

o = olive, lo = light olive, br = brown, lbr = light brown, ggr = greenish gray, gr = gray
lgr = light gray, dgr = dark gray, s = sand, m = mud, ms = muddy sand, sm = sandy mud, gs = gravely sand

is attributable to iron coating of the grains, and (2) the source of iron-coated sand in Holocene deposits is the Pleistocene terraces that are exposed on the north side of Willapa Bay.

The macroscopic examination and description of cores also showed that there were substantial differences in the abundance and composition of heavy minerals in the cored sediments. As a result of this observation, heavy minerals were also examined as possible tracers of sediment sources.

Methods

Thirty-seven samples were selected from the vibracores to examine the quartz coatings. The purpose of the grain counts was to determine the percentages of partly and completely iron-coated quartz grains as well as the percentages of the non-coated grains (Table 3). Samples for grain counts were selected from those stratigraphic intervals that were representative of common sedimentary facies and that had the potential to aid in the understanding of the depositional history. Because the cores from North Cove 2 and North Cove 3 were predominantly brown and gray, respectively, they were sampled more extensively in an attempt to obtain a more comprehensive identification of the percentages to be expected of gray and brown sediments at other coring locations.

Samples were removed from the core with a spatula, placed in labeled petri dishes, wet sieved using a 63 micron screen, and dried. The grain count was performed using a reflected-light microscope with a fiber optic light source. To make the grain counts random, a template was placed over each petri dish exposing only a narrow portion of the sample at one time. From each sample, 300 quartz grains were counted. The identification of quartz relied primarily on the colorless to cloudy characteristic of quartz and its nearly equant form. Grains that showed even slight cleavage, or were orange to red and perfectly transparent, were not counted. The latter grains could be another mineral, such as garnet.

The amount of iron coating for each grain was recorded following the classification of Stanley et al. (2000). The quartz grains that are clear to white represent uncoated grains because they do not have any iron staining. The grains that ranged from barely coated (either internally or externally) to almost fully coated with iron staining are designated partly coated (Table 3). The completely coated grains are typically a dark orange color due to extensive iron staining.

Several sources of error could influence the point-count results. The grain sampling and operator error probably represent only a few percent considering the similarity of results for samples within the same sediment type (Table 3, NC-3 below 163 cm for example). The greatest potential source of error comes from the changes in sediment color in the laboratory with time. Cores taken from sediments saturated with iron-enriched water will eventually change color and become tan, brown, or orange as the sediments are exposed to air and dry. As the iron-bearing water evaporates, coatings of iron oxide can form on the sediment grains, causing gray sediments to become olive gray or brown. The initial core descriptions and sampling for point counting was done shortly after the cores were opened, while the sediments were still wet, and before any substantive drying or oxidation occurred. Any subsequent sampling was designed to avoid the surface oxidation and associated alteration of the point count results. Thus care was taken to assure that the results presented in Table 3 are as accurate as possible.

Iron-coated Quartz Comparisons

The sediments of Willapa Bay contain abundant concentrations of magnetite, mica, and other iron-rich minerals that have been weathered. As a result, typically the ground waters are also iron bearing. Under these conditions, sediment grains exposed to the movement of iron-bearing ground water for prolonged periods would be expected to have iron coatings. The precipitation of iron can occur rapidly and is commonly aided by biogenic processes; either the extraction and subsequent precipitation of iron by plants around their roots, or as a result of bacterial processes. Dorn (1998) summarized the chemical characteristics of the depositional environment and biotic and abiotic processes that produce iron coatings of rocks and sediment grains.

In general there is a reasonably good correlation between brown sand color and relatively high percentages of iron-coated quartz in sediment from north Willapa Bay. The greatest concentration of partly or entirely iron-coated grains (77% and 12%, respectively) are found in the brown sandy sediments of core NC-2. Initially it was assumed that the brown sand color would represent at least 50% iron-coated grains and no more than about 50% clear grains. However, the data do not support those absolute values. All the sand samples described as being brown contain at least 5% totally iron-coated grains and 41% combined partly and totally iron-coated grains (Table 3), but not all samples exceeding these absolute values are brown. For example, individual samples in NC-4 contain as much as 47% combined partly and totally iron-coated grains and the sediment color is still gray (Table 3). The brown color of samples containing less than about 50% combined partly and totally iron-coated grains may be related to the presence of brown clay or dark heavy minerals in the sediments.

Although the ages and origins of the iron-coatings are uncertain, there are distinct systematic trends in the abundance of iron-coatings at depth (Table 3). These trends could be the result of sediment mixing by physical processes, or related to residence times of iron-bearing ground water. The three cores (NC-2, NC-3, NC-4) that have multiple grain counts from a range of depths all display systematic vertical trends, although each trend is different. In NC-2, which penetrated mostly brown sand (Fig. 7), the number of partly and totally iron-coated grains increases to a depth of about 150 cm (Table 3). Below that depth, the absolute percentage of totally iron-coated grains increases slightly, but the abundance of partly iron-coated grains decreases and the sample compositions are relatively uniform in distribution at greater depth. In NC-3, which contains no brown sand (Fig. 7), the abundance of clear or uncoated grains systematically decreases down core and there is a concomitant increase in partly coated grains; the abundance of totally coated grains remains essentially unchanged at depth (Table 3). The samples from 163 cm and below are clearly different from any of the overlying samples in that they have considerably more uncoated grains and less partly coated grains. The fact that NC-4 does not contain any brown sand is reflected in the high relative percentages of uncoated grains that increase in abundance with depth.

Interpretation of Results

Brown sand is present in all of the vibracores except NC-3, NC-4, TS-2, and KI-1. KI-11 did not recover any brown sand, but firm brown mud at a depth of 501 cm prevented deeper penetration. Most of the brown sandy sediments are in the bottoms of the cores. Exceptions to this statement are cores TS-1, where the brown sand is at the top of the core, and ES-8, where the entire core contains brown sand (Appendix B). The presence of brown sand in the bottoms of the cores can be explained by two different mechanisms. One explanation is that the iron coatings are a function of exposure to the iron-enriched ground water, and therefore the deeper sediments have been exposed longer and exhibit more grains with partial or complete iron-coatings. The vertical petrographic trends in NC-2, NC-3, and NC-4 tend to contradict that explanation because in all three of these cores the abundance of iron-coated grains decreases with depth and no brown sand is present in two of the cores. Another explanation is that the brown sand represents slightly older sediments derived from a source of brown sandy sediments such as the Pleistocene terrace deposits. The younger gray marsh-estuarine sediments overly and onlap the brown sandy sediments that represent slightly older beach deposits (Fig. 8, section A-A'). Although the petrographic data are not entirely diagnostic, the latter interpretation is supported by the preponderance of the evidence, and that interpretation is presented in the stratigraphic cross sections.

SAND VOLUME ANALYSIS

Knowing the sources and volumes of sand that are stored in Kindred Island, Tokeland Peninsula, and Empire Spit provides a basis for evaluating the different coastal processes operating during the late Holocene evolution of Willapa Bay. To estimate the volumes of sand associated with each beach feature, the surface topography and subsurface lateral limits of sand were integrated to depict the three-dimensional distribution of sand (Fig. 10).

Of the three sand-volume estimates, the one for Empire Spit is probably the most accurate because Empire Spit formed during the historical period of greatest control from maps and aerial photographs. The sand-volume estimates for Kindred Island and Tokeland Peninsula, in contrast, have a high error because the subsurface limits of sand are not well defined. In fact there probably are no definitive sand boundaries because at the time of deposition, the beach sand would have merged laterally with contemporaneous sand-rich, tidal-flat and tidal-channel deposits, just as the southeastern segment of Empire Spit merges with sand flats today (Fig. 1).

Volumetric Estimates

The GPS-controlled topographic profiles surveyed by the Department of Ecology (Appendix A) were integrated to construct three-dimensional surfaces of the landform elevations above the mean-high-water tidal datum, which was the datum used for the surveys. The sand-volume estimates assume that Kindred Island, Tokeland Peninsula, and Empire Spit are wave-sorted beach or submerged spit features composed almost entirely of sand. Longshore processes similar to those that have deposited the submerged bar and spit at Cape Shoalwater deposited the sand. Trenches and cores from Kindred Island and Empire Spit show that they are composed of well-sorted sand with some gravel, but very little mud. Near-surface lithologic control for Tokeland Peninsula is sparse, and comes primarily from water-well records, which also show that the feature is composed primarily of sand (Figs. 10 section C-C').

Using a horizontal datum, such as mean high water, to constrain the lower limit of sand distribution will underestimate the sand volume by some unknown amount. The minimum volume of sand excluded by that technique is equivalent, theoretically, to the shoreface depth of wave scour and sand deposition. To obtain a more realistic measure of sand volume stored in the beach-ridge features, the combined topographic-bathymetric profiles of Empire Spit (Appendix A) were examined for a break in slope that is seaward of the beach but above the steep wall of the entrance channel. Most of the Empire Spit profiles where the beach is retreating show a flattening of the profile at a depth between – 1 and – 2 m. On the basis of this observation, -1.5 m was used as the subtidal datum (lower limit) to estimate sand volumes. The results of this analysis indicate that minimum sand volumes are as follows: Kindred Island 3.3 million m^3, Tokeland 12.7 million m^3, and Empire Spit Island 4.5 million m^3.

Discussion of Results

The rapid northward migration of the entrance channel and Cape Shoalwater suggests that large volumes of sand have been released to the littoral system as the shoreline retreated. Closer examination of the conditions, however, indicates that only the subaerial sand volume is presently unaccounted for in the sand budget. The sand volume of Cape Shoalwater below approximately mean low water is still stored in the shoals that flank the entrance channel. Additional sand is liberated from erosion of the beach ridges at Washaway Beach and erosion of any sandy Pleistocene terrace deposits between Washaway Beach and the North Cove embayment. The lack of accurate topographic control from repeated surveys prevented estimating the sand volume associated with entrance channel erosion since the late 1800s.

The recent increased availability of sand at the entrance to Willapa Bay released by northward channel migration and the erosion of Cape Shoalwater may explain the field observation by Peterson et al. (in preparation) that sand is a recent surficial deposit in Willapa Bay. The surficial sand probably was transported landward by the entrance channel and swept onto the tidal flats near the entrance to Willapa Bay by flood-tidal currents and by storm waves. The recent deposition of sand along the bay margins also infers a shoaling trend, unless the rate of tidal-flat aggradation is less than the rate of relative sea-level rise.

GEOCHRONOLOGY INVESTIGATION

Deciphering the late Quaternary geologic history and evolution of north Willapa Bay depends largely on obtaining accurate dates of events that produced the coastal features and associated sedimentary deposits. Both radiocarbon and luminescence techniques were used to constrain the time when sand was deposited along the bay margin to form Kindred Island and Tokeland Peninsula, and when mud was deposited as fill of the abandoned entrance channel to form the North Cove embayment.

Radiocarbon Dating

Radiocarbon (C^{14}) dating is a widely applied technique for determining the age of organic material that is less than about 40,000 yrs old. The C^{14} age reported by the laboratory normally represents the elapsed time since the organic material (wood, peat, shell) was living. Care must be taken when attempting to use C^{14} to date geological events because the reported date may be in error due to contamination with more recent material (date is too young) or sediment reworking (date is too old). For reconstructing the late Quaternary geological history of an area, it is assumed that the radiocarbon dates are accurate and the organic material was living essentially at the same time it was incorporated into the sediments.

Six samples from north Willapa Bay were selected for radiocarbon analysis (Table 4) to provide general ages for specific geological events. For example, the sample from KI-7 is from a peat layer that correlates with an organic-rich mud in KI-8. That organic layer represents cessation of sand deposition and at least local prolonged inundation of the margin of the beach ridge. The sample from KI-11 should constrain the timing of tidal-flat aggradation associated with beach-ridge deposition, whereas charcoal collected from the central part of Kindred Island was intended to provide a general date for beach-ridge construction. The

Table 4. Results of radiocarbon dating of sediments from north Willapa Bay. Standard radiometric techniques are used when there is ample organic material, accelerator mass spectrometry (AMS) is used when the sample is small. Elevations are relative to NAVD 1988. Reported ages are calibrated to calendar years.

Location	Sample (Core) Depth cm	Sample Elevation meters	Type of Material	Analytical Method	Calibrated Age yrs BP
KI-7	62	1.38	peat	AMS	910 ± 40
KI-11	500	-3.70	shell	AMS	1590± 40
KI-12	52	3.38	wood	Standard	560 ± 30
TS-3	391	-2.32	shell	AMS	< 50
NC-3	352	-2.96	shell	AMS	610± 40
NC-4	455	-3.92	shell	AMS	620± 40

Table 5. Reported luminescence ages of sand deposits from north Willapa Bay. IRSL is infrared stimulated luminescence, TL is thermal luminescence, and NA is not analyzed. Elevations are relative to NAVD 1988. Reported ages are in calendar years.

Location	Sample (Trench) Depth cm	Sample Elevation meters	IRSL Age yrs BP	TL Age yrs BP
KI-12	90	3.00	NA	17800 ± 4500
KI-13	65	2.95	1160±140	7060±740
KI-13	70	2.90	1030±160	5760±670
TS-4	55	3.25	440±210	5680±950
TS-4	60	3.20	3460±280	15960±1540

sample from TS-3 was designed to date the time when the margin of Tokeland Peninsula was deposited. Shell samples from NC-3 and NC-4 were expected to provide a general date for the late filling of the abandoned entrance channel.

Luminescence Dating

Thermally stimulated luminescence or thermoluminescence (TL) and optically stimulated luminescence (OSL) are combined geochemical and geophysical dating techniques that can be used to obtain ages of Quaternary sedimentary deposits (Aitken, 1998). TL involves heating the sample and measuring the response, whereas OSL involves shining light on the sample and measuring the response. IRSL (Table 5) stands for infrared stimulated luminescence, which indicates the type of light that was used to stimulate the sample. Luminescence techniques are especially important when organic material for radiocarbon dating is either absent or the organic material is suspected of being much older (reworked) or younger (introduced) than the sand deposits of interest. Both Kindred Island and Tokeland Peninsula consist of well-sorted sand deposits that lack datable organic material that is not detrital. Consequently both TL and OSL techniques were used to try and obtain reliable dates for the timing of beach-ridge deposition on the north margin of Willapa Bay.

Sediment samples from beach ridges and other sand bodies deposited by subaqueous processes are subject to incomplete bleaching in sunlight because the water column reduces light penetration. As a general rule, TL techniques tend to give older ages than OSL (Table 5) because the TL residual in samples requires longer periods of exposure to sunlight in order to reset to zero. Consequently, TL ages represent maximum ages, not minimum ages. Although it is relatively common to obtain a TL age that is apparently older than the time of deposition, it is rare to get an age that is consistently younger than the other ages obtained from complementary dating techniques, unless the sample was inadvertently exposed to sunlight during sampling. Considering these principles, the youngest reported ages (Table 5) were used in conjunction with the C^{14} ages to establish the general geologic history of deposition for Kindred Island and Tokeland Peninsula.

Discussion of Results

Radiocarbon Ages

The oldest radiocarbon age reported for samples from north Willapa Bay is for shell fragments taken from KI-11 (Table 4, Appendix B), which was cored on the landward side of Kindred Island (Fig. 1). The age of the marine shells (1590 ±40 yrs BP) represents the onset of subaqueous sandy shoal deposition at the site. The depositional environment of the underlying firm brown mud is uncertain, but the color and firmness indicate prior subaerial exposure (paleosol). Submergence of a former ground surface could be caused either by a rise in water level or subsidence of the land surface. The change from mud to sand deposition at the bottom of KI-11 may have been related to the initial deposition of Kindred Island, which also is composed of sand.

Probably the youngest reliable radiocarbon age for Kindred Island deposition is for organic sediments taken from KI-7 (Table 4). The stratigraphic succession at KI-7 consists of well-sorted sand and pea gravel overlain by organic-rich mud (Appendix B). The vertical change in sedimentary facies is interpreted as a change from the relatively high-energy sandy nearshore environment of the beach (Kindred Island) to a low-energy marsh environment. The elevation of the peat-like layer in KI-7, about 1.4 m, is similar to that of the present-day marshes. The change from an exposed to a sheltered setting indicates that a barrier was present seaward of Kindred Island when the onlapping marsh sediments were deposited about 900 years ago. The age of the peat (910 ±40 yrs BP) helps constrain the maximum age of Tokeland Peninsula. The nearly identical radiocarbon ages from NC-3 and NC-4 (Table 4) also help constrain the age of Tokeland Peninsula. The morphology, stratigraphy, and C^{14} ages indicate that the entrance channel was seaward of Tokeland Peninsula about 600 years ago when sediments were being deposited in the channel as it moved to the south.

Charcoal collected from the trench at KI-12 was dated at 560 ±30 yrs BP (Table 4). Considering the inland geographic position of the beach-ridge feature and the date from KI-11, this date seems exceptionally young. The radiocarbon age is probably accurate, but it may represent the timing of plant growth on an older surface that post-dates beach-ridge deposition.

The shell sample from TS-3 was intended to help constrain the age of Tokeland Peninsula. It was assumed that the brown sand at the bottom of TS-3 was equivalent to some of the sand in Tokeland Peninsula and the overlying gray sand was probably storm washover sediments deposited during or after the deposition of Tokeland Peninsula. However, the very young radiocarbon age obtained from TS-3 (Table 4) suggests that either the shell material was contaminated with recent carbon, or the most recent rates of tidal-flat deposition along the landward margins of Tokeland are extremely high. Comparing shoreline features on the 1871 topographic map with those on the 1999 aerial photograph shows that the marsh shore of Tokeland Peninsula accreted from 40 to 55 m near site TS-3. The post-1871 marsh accretion filled in the creek embayments and made the shoreline less irregular. It is unclear what caused the shoreline to advance, whether it was natural or related to human activities such as development of Tokeland Peninsula and construction of the dike between Tokeland and Kindred

Island. It seems improbable that nearly 4 m of sediment have aggraded along the landward margin of Tokeland Peninsula during the past 150 yrs, but the scientific evidence suggesting that event is strong. Regardless of the explanation of the young radiocarbon age from TS-3, it does not help date the deposition of Tokeland Peninsula.

Luminescence Ages

The oldest luminescence age for Kindred Island is for a sand sample from the trench at KI-12 that yielded a TL date of 17800±4500 yrs (Table 5). This date is probably too old for a beach deposit near present-day sea level considering that global sea level was at a maximum lowstand (>-100 m) at that time. It is possible that sediment composing the core of Kindred Island was derived from the nearby outcropping Pleistocene sediments, and the short subaqueous transport distance and limited exposure time to sunlight may have prevented the sediments from being bleached, or reset to zero exposure time. Also the quartz content in the sample was diluted by the high concentrations of heavy minerals, mica, feldspar, and lithic fragments, which could also yield questionable TL results and make the date unreliable.

Sand samples from 60 and 68 cm in the trench at KI-13 yielded IRSL ages of 1160 yrs BP and 1030 yrs BP respectively (Table 5). Despite the reverse stratigraphic order of absolute values, ages of about 1000 yrs BP for samples from KI-13 are consistent with the C^{14} age of 910 yrs in KI-7 (Table 4). When these ages for relatively shallow samples are compared to the age of a deeper sample in KI-11 (1590 yrs BP), a range of about 900 to 1600 yrs can be established for the general period of deposition of the sandy core of Kindred Island.

The morphological setting of Tokeland Peninsula and the 440 yr IRSL age from TS-4 (Table 5) both indicate that the upper part of the sand body is composed of relatively young sediments. The large difference in ages reported for samples from TS-4 at 55 cm and 60 cm is difficult to explain considering that sediments throughout the sampled interval are homogeneous, and there is no physical evidence of an unconformity between the samples. The oldest luminescence age for Tokeland Peninsula (3460 ±280 yrs BP in TS-4) is probably anomalous considering that IRSL ages for sediments from Kindred Island are much younger (Table 5).

LATE HOLOCENE GEOLOGIC HISTORY OF NORTH WILLAPA BAY

The former spits of Cape Shoalwater and three parallel spits surrounded by tidal flats and marshes on the north shore of Willapa Bay (Kindred Island, Tokeland Peninsula, and Empire Spit, Fig. 1) reflect at least three episodes of large-scale entrance-channel migration, sediment influx and redistribution, and sand storage during the late Holocene. These events document the pre-historic and historical evolution of the estuary and subsequent reorganization at both millennial and decadal time scales. Swales separating the three spits are partly controlled by topographic lows and discharge associated with the network of local streams draining the nearby Pleistocene uplands.

Modern wrack lines of large trees and other debris demonstrate that all three spits and the intervening tidal flats and marshes are flooded periodically by winter storms and spring high tides during El Niño events. A residential development constructed in the swale between Empire Spit and Tokeland Peninsula was flooded during winter storms in 1999.

Kindred Island

The interior bay-margin location, abundant cobble composition, and southeasterly alignment of Kindred Island suggest that it was constructed as a headland-attached shoal and spit complex locally supplied by sediment eroded from the Pleistocene terrace deposits and transported to the southeast by longshore currents (Fig. 2). The inferred depositional age of Kindred Island (<900-1600 BP, Tables 4 and 5) correlates reasonably well with the period when processes changed from sea-cliff erosion to beach-ridge deposition within the Grayland plains north of Willapa Bay. Peterson et al. (1999) reported that the backedge date for the Grayland plains was about 2000 BP, whereas Phipps et al. (2001) dated a backedge buried scarp in the Grayland plains at 1100 BP. Theses ages are geologically consistent considering that the timing of sea-cliff erosion and initial beach-ridge progradation are not precisely constrained.

Elevations and morphology of Kindred Island suggest that it was exposed to deep-water ocean waves and was submerged periodically at least during storms. While Kindred Island was being deposited, the entrance channel was south of the spit and centered on the east-west alignment of the Willapa River. It is likely that the mouth of Willapa Bay and associated shoals of the ebb tidal delta were near the shore at that time. Whether or not the entrance channel also flowed seaward of and parallel to Kindred Island, similar to its extant position relative to Empire Spit, is unknown and could only be determined with subsurface data.

Tokeland Peninsula

Morphological and sedimentological evidence indicates that Tokeland Peninsula formed as a headland attached spit either before or at the same time that the deep entrance channel was pinned on the north shore of Willapa Bay and occupied what is now the North Cove embayment (Fig. 1). Ages of the channel fill and ages of sediments from Tokeland Peninsula and Kindred Island indicate that Tokeland Peninsula sand was being deposited from at least 400 to about 900 yrs BP. How deposition of Tokeland Peninsula correlates with beach-ridge deposition in the Grayland plains is uncertain because the ages of the beach ridges are not well constrained. All the reported ages for Tokeland Peninsula indicate that deposition of the feature preceded the 1700 AD earthquake event by several hundred years.

Elevations and variable widths of the peninsula suggest that it was exposed to deep-water ocean waves and overwashed during winter storms and some spring high tides. As the entrance channel migrated to the south and recurved spits were deposited to form Cape Shoalwater, Tokeland Peninsula was protected from direct wave attack. During the subsequent erosion and northward retreat of Cape Shoalwater, both deposition and erosion occurred on the seaward side of Tokeland Peninsula, giving it a more irregular shape. Sand accumulated on the central part of the peninsula as the shoal and tidal flat protected by Empire Spit emerged and became attached to the western shore. Concurrently, the southeastern end of the peninsula was exposed to increased wave and current energy that caused substantial erosion and narrowing of the peninsula (compare Figs. 2 and 3).

Entrance Channel, Cape Shoalwater, and North Cove Embayment

After Tokeland Peninsula formed, seaward and southward migration of the entrance channel constructed Cape Shoalwater and a series of terminal spits recurved to the southeast (Fig. 2). Large volumes of sand were deposited along Cape Shoalwater when oceanographic conditions favored southerly sand transport, in a direction opposite to that of net longshore drift. This required changes in the physical processes (net longshore currents and wave directions), as well as an abundant sand supply. A thick wedge of sand would have been deposited if rapid abandonment of the northern channel position to the middle course was accompanied by sand deposition at Cape Shoalwater. The large-scale lateral channel migration and spit construction probably were concurrent with regional beach-ridge progradation on North Beach Peninsula and the Grayland Plains.

Pacific County Drainage Ditch No. 1 was constructed to remove overland runoff and excess irrigation water from the cranberry bogs (Lum, 1984). Although the ditch now crosses the beach and empties into the Willapa Bay entrance channel on the north side of the channel-deflection dike, the ditch originally emptied into the tidal flats of the North Cove embayment. The 1942 aerial photograph shows that the upland ditch transformed a channel across the tidal flats (Dibkey Slough) into a conveyor of fine-grained sediments that constructed a small delta-like deposit. The sediments transported through the ditch and deposited on the delta contributed to aggradation of the tidal flats and their subsequent conversion to vegetated marshes. Deposition of mud and expansion of the marsh in the North Cove embayment significantly reduced the barren intertidal flats seaward of Tokeland Peninsula that were productive sites for clams.

Empire Spit

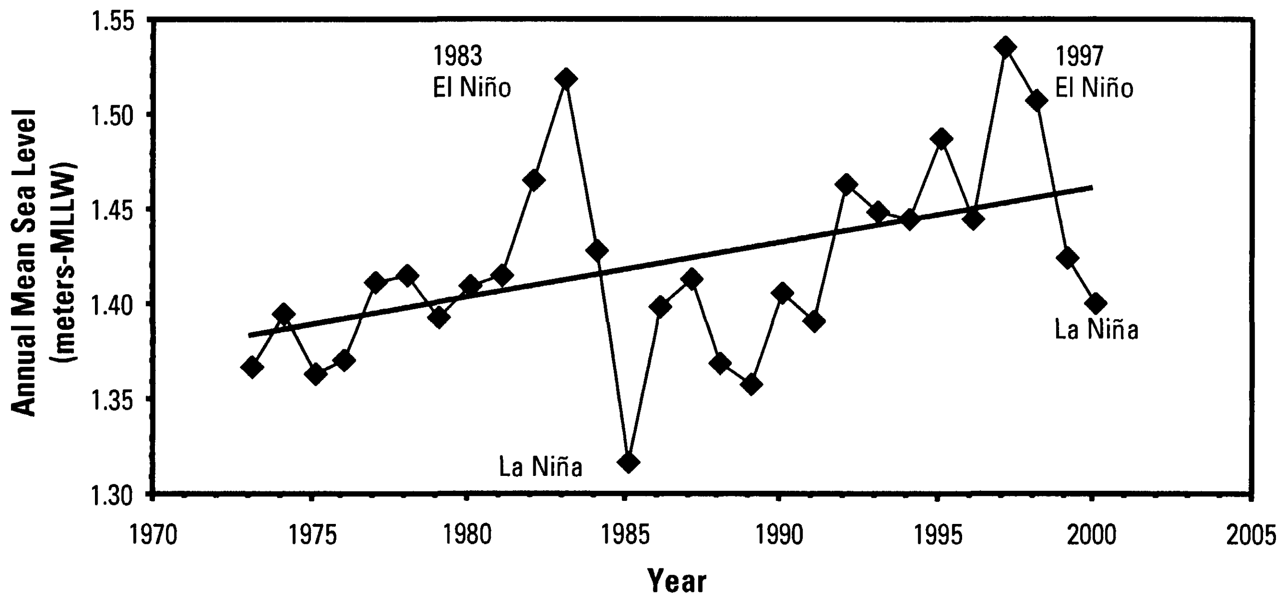
Beginning in the late 1920s, Empire Spit was constructed as a result of combined headland erosion (remnants of Cape Shoalwater), southeastward alongshore sediment transport, and terminal spit deposition that was initiated as the Cape Shoalwater spits were destroyed by northward migration of the entrance channel. In terms of erosional and depositional processes, the formation of Empire Spit serves as a geological model for the construction of Kindred Island and Tokeland Peninsula. Recent acceleration in the retreat rate of northern Empire Spit may be related to the retreat path and underlying mud (Fig. 9). It appears that the shallow shoreface of Empire Spit has intercepted and is excavating the marsh and channel-fill mud rather than the tidal-delta sand that it transgressed previously.

In 1998, the Washington Department of Transportation built a groin-like structure in an attempt to deflect the entrance channel to the south and to protect State Road 105 from further erosion. The groin is located at a geological contact between (1) the sand-rich Holocene beach-ridge complex of the Grayland Plains and (2) the muddy Pleistocene marine-terrace deposits (Fig. 1).

RECENT SEA LEVEL HISTORY OF WILLAPA BAY

Emery and Aubrey (1991) analyzed and interpreted tide-gauge records around the world including gauges from the Pacific coast of the United States. They reported that the record of approximately 60 years at Astoria, Washington shows a relative fall in sea level of about 0. 7 mm/yr, whereas the record of approximately 80 years at Seattle shows average submergence of about 2.4 mm/yr. Although the tide gauge at Toke Point at the entrance to Willapa Bay has operated for only 27 years, during that period it has recorded significant annual fluctuations in average water level associated with El Niño and La Niña events (Fig. 11). This decadal record also indicates a relative rise in sea level that averages about 2.8 mm/yr (Gibbs, 2000), which agrees closely with the historical average rate of sea level rise at the Seattle gauge. The tide gauge record at Toke Point contains important information regarding potential coastal flooding at two different time scales. Future high frequency flooding events will likely be related to winter storms superimposed on the elevated water levels associated with El Niño events, whereas progressively increased flooding will likely be associated with the long-term relative rise in sea level.

Figure 11. Historical water level fluctuations recorded at the Toke Point tide gauge. Location of tide gauge is shown on Fig. 1.



The increase in water level relative to the land surface could be caused by a eustatic rise in sea level or a loss in surface elevation due to land-surface subsidence or crustal subsidence. The global average rise in sea level is about 1.8 mm/yr (Douglas, 1997; Peltier and Jiang, 1997), which means that the rate of subsidence at Tokeland is about 0.6 mm/yr. The thick sand deposits and over-consolidated Pleistocene sediments beneath Tokeland Peninsula (Fig. 10 section C-C') are not susceptible to recent rapid compaction as an explanation for the relative rise in sea level. Furthermore, it is unlikely that there is any land-surface subsidence as a result of groundwater withdrawal from residential and commercial wells. Lum (1984) reported that the rates of groundwater production are low and water levels in monitoring wells fluctuated less than 30 cm within a year.

DISCUSSION AND CONCLUSIONS

The coastal residents of north Willapa Bay are concerned about potential frequent flooding and land loss associated with winter storms and beach erosion. For residents of Tokeland Peninsula, the threat of these coastal hazards will increase as (1) the protection provided by Empire Spit is nullified as the northern segments continue to erode, and (2) the inlet formed between the two southerly segments in 1995 is maintained by natural tidal flow. The challenge for coastal scientists and engineers is predicting what will happen in the future on the basis of what has happened in the past, taking into account the present conditions including any human alterations to the littoral system.

Of critical importance to prediction is knowing the prevailing wave and current conditions for those times in the past when surplus volumes of sand were transported into and deposited on the northern margin of Willapa Bay. Longshore currents flowing from the north and northwest would promote highest rates of sand transport and deposition along the Ocean Shores Peninsula and along the north Willapa Bay spits including Kindred Island, Tokeland Peninsula and Cape Shoalwater. In contrast, longshore currents flowing from the south and southwest would generate highest rates of sand transport to the north, such as along Long Beach Peninsula. The alongshore distribution of sand from the mouth of the Columbia River takes on some aspects of a delta, at least in the sense of the limit of sediment transport away from the source. Like other river-mouth systems, most of the sediment (sand) in the Columbia littoral cell is deposited near the source and progressively less sediment is deposited downdrift. At the present highstand in sea level, most of the sand from the Columbia deposited in beach and estuarine environments is in the Long Beach Peninsula-Willapa Bay complex. Progressively less sand from the Columbia is available for beach construction and estuarine fill northward to the mouth of the Copalis River, where the beach abuts against the upland sea cliffs, and the shoreline of maximum transgression still has not been established.

The large-scale long-term cycles of deposition and erosion at the entrance to Willapa Bay during the past few thousand years occurred prior to human activities such as damming the Columbia River, constructing jetties at the mouth of the Columbia or Grays Harbor, or constructing the channel diversion dike near North Cove. Consequently, there must be natural mechanisms that periodically altered sediment supply and the littoral sand transport system in southwest Washington. Preliminary results from this study suggest that southerly relocation of the entrance channel and attendant cessation of beach erosion along Empire Spit and Tokeland Peninsula are unlikely unless large sand volumes are introduced to the littoral system of north Willapa Bay.

There are at least two possible explanations for the conditions that promote sand-spit deposition in north Willapa Bay: (1) co-seismic subsidence, and (2) long-period cycles of shifting storm tracks in the northern Pacific Ocean. Co-seismic subsidence is an appealing mechanism to cause the necessary changes in sediment supply because it is already recognized as a recurring phenomenon that influences the region (Atwater, 1987; Meyers et al., 1996; Atwater and Hemphill-Haley, 1997), and the sudden changes in land elevations and water depths could relocate the entrance channel. Co-seismic subsidence also would lower sandy beach-ridge deposits of the Grayland Plains or Leadbetter Point into the surf zone where they would be out of equilibrium with waves of the Pacific. Subsequent establishment of an equilibrium beach and shoreface profile would rework the sand and make it available for southerly transport into north Willapa Bay. The general recurrence frequency of co-seismic subsidence events covers a broad range (300 to 1,000 yrs, Darienzo and Peterson, 1990; Meyers et al., 1996); consequently, the next earthquake-related subsidence event is essentially unpredictable.

The depositional fate of sand eroded from beach scarps formed as a result of earthquake-induced subsidence events is unknown. Relatively rapid beach/dune erosion is implied as a result of instantaneous subsidence of as much as 2 m and consequent sudden introduction of sand into the littoral system. Luminescence ages of shallow samples from Kindred Island essentially coincide with the 990 yr BP earthquake event documented by Meyers et al. (1996) and Atwater and Hemphill-Haley (1997). The apparent temporal correlation of earthquake-induced regional erosion, as indicated by beach-scarps along the Grayland Plains with large-scale downdrift spit deposition into north Willapa Bay has a certain logical appeal that satisfies principal sediment budget requirements of sediment sources and sinks. The IRSL and C^{14} ages provide the basis for correlating Kindred Island with the 990 yr BP scarp and Cape Shoalwater with the 300 yr BP scarp. Despite this reasonable temporal correlation, the geomorphic correlation between the dated scarps and beach ridges is poor for the following reasons. There are more discrete beach ridge features (3) than there are erosional scarps (2), and there is no regionally extensive intermediate scarp reported between the 300 yr BP and 990 yr BP earthquake events (Meyers et al, 1996; Atwater and Hemphill-Haley, 1997) that would match the reported age of Tokeland Peninsula. The best chronological and morphological correlation is erosion of the 300 yr BP scarp with deposition of Cape Shoalwater. However, the 990 yr BP scarp is located and aligned far seaward of the alignments of Kindred Island and Tokeland Peninsula.

The coincidence of ages of isolated beach-ridge deposition into north Willapa Bay and earthquake events may be more apparent than real given the range of possible dates reported for the same samples depending on technique and assumed ground-water saturation history. Furthermore, earthquakes are instantaneous events whereas beach-ridge deposition is a prolonged process that precludes precise dating. Massive erosion suggested by the presence of the co-seismic subsidence scarps and concomitant deposition of the beach ridges may be related, but the ages of the beach ridges would have to be revised in order to obtain a better match. Recent calibrations of luminescence ages with well-constrained C^{14} ages indicate that some IRSL ages may severely underestimate actual ages (Wallinga et al., 2002). If the ages of Kindred Island and Tokeland Peninsula are actually older than suggested by the IRSL ages, then these geological features may correlate as follows: deposition of Kindred Island with erosion of the sea cliff, deposition of Tokeland Peninsula following the 990 yr BP subsidence event, and deposition of Cape Shoalwater following the 300 yr BP subsidence event.

Pre-historic climatic changes and their influence on the positions of storm tracks and storm intensities in the northern Pacific are not well known. Graham and Diaz (2001) found that during the past 50 years wave heights had increased in the northern Pacific as a result of stronger winds and more frequent intense winter storms attendant with shifts in storm tracks. Allen and Komar (2000) also reported recent increases in wave heights in the eastern Pacific. These studies suggest that past climatic changes and resulting altered wave states at the coast might explain periods of preferred southerly sand transport into north Willapa Bay. During the past two thousand years, long-term shifts in storm characteristics, including El Niño and La Niña events, could have significantly altered water levels, wave approach of winter ocean swells, and directions of sediment movement so that the component of southerly sand transport was substantially increased compared to present conditions. Although realignment of the entrance channel through the outer bar has been correlated with El Niño events (Kaminsky et al, 1999; Hands, 2000), there is no evidence that extant storms are capable of large-scale channel relocation at the entrance to Willapa Bay. Apparently hydrodynamic processes operating over much longer periods are necessary for channel relocation and deposition of large volumes of sand comparable to Tokeland Peninsula or Cape Shoalwater.

Persistent erosion of the spits comprising Cape Shoalwater and subsequent retreat of Empire Spit demonstrate that the beach and shoreface at the entrance to Willapa Bay form a sand bypass system that terminates at the southeastern end of Empire Spit and the entrance channel. The surficial layer of sand reported in vibracores from Willapa Bay (Peterson et al, in preparation) may be a redistribution of the sand eroded from Cape Shoalwater and adjacent shores. Shoreface erosion along the northwestern half of Empire Spit probably does not contribute significantly to the sand supply of downdrift beaches or flats because the sediments eroded from either the Pleistocene outcrops or the North Cove embayment are composed mostly of mud. Furthermore the field data suggest that the northwestern segment of Empire Spit is losing sand volume, which will make it more vulnerable to erosion and tend to cause high rates of shoreline retreat. The geologic setting, ongoing relative rise in sea level, and frequent winter storms, which are all highly predictable, assure continued beach erosion on Empire Spit and segments of Tokeland Peninsula exposed to high wave energy. If existing conditions persist, as expected, then long-term projection of current trends indicate migration of Empire Spit across the marsh and tidal flats of the North Cove embayment and eventual merging with Tokeland Peninsula.

RECOMMENDATIONS FOR ADDITIONAL STUDIES

The following suggestions for additional studies are based on the need for data that would improve the understanding of erosion and land loss at the entrance to Willapa Bay. These are offered as short-term specialty investigations that would answer specific scientific questions.

Landform Chronology - The quantitative geologic history at the entrance to Willapa Bay is still uncertain because the luminescence techniques did not provide unequivocal ages for Kindred Island and Tokeland Peninsula. Without knowing the timing of deposition of these features, it is difficult to relate their formation to dated events in surrounding areas such as the construction of beach ridges in the Grayland Plains and on Long Beach. Additional radiocarbon analyses could help constrain the ages of Kindred Island and Tokeland Peninsula so that the timing of their deposition could be compared to global climate changes and sea level fluctuations.

Shoreline Change Analysis – Quantitative predictions of future coastal conditions at the entrance to Willapa Bay are hampered because accurate information regarding historical shoreline movement is not available. Shoreline changes and rates of shoreline movement have been quantified for the rapid retreat of Cape Shoalwater (Terich and Levenseller, 1986) and for changes along the ocean shore of Pacific County (Kaminsky et al., 1999), but comparable trends and rates of movement have not been established for Empire Spit and Tokeland Peninsula. The basic resources (T-sheets and aerial photographs) used for the morphological investigation are available for the shoreline comparison. What is needed is a systematic compilation of shoreline positions between Cape Shoalwater and Toke Point, measurement of shoreline movement, calculation of rates of movement, and interpretation of the trends and rates of change.

Physical Processes and Bathymetric Changes – The fate of sediment eroded from the beach, shoreface, and entrance channel to Willapa Bay is unknown, but knowing that information would improve the understanding of physical processes, sand transport, and local sediment budget. If the surficial sand layer observed on the tidal flats is related to historical retreat of Cape Shoalwater, then the bay response to changing oceanic shoreline position can be extremely rapid. An anaylsis of the hydrodynamics and sediment transport along Empire Spit and within the entrance channel could be accomplished by obtaining electronic data for currents and waves, and integrating those data with repeated surveys of topography and bathymetry. At some time this information will be necessary to evaluate the actions recommended to mitigate the coastal erosion. An opportunity to field monitor the movement of dredged material placed near the 1995 inlet, such as the year 2000 disposal event, would be useful.

Sand Supply Mechanisms - Co-seismic subsidence and paleoclimatic affects on storm tracks and storm intensity were identified as possible explanations for the southerly relocation of the entrance channel and attendant construction of Cape Shoalwater. Periods when southerly sand transport is optimized can be described conceptually; however, clear evidence of the oceanic conditions that promoted sand spit construction is still lacking. Brief literature reviews of the state of knowledge regarding past atmospheric conditions and inferred wave climates would help determine if the changing storm track hypothesis is feasible. Also, examining the predicted erosional and depositional shoreface responses to co-seismic subsidence events involving beach ridges of the Grayland Plains or Long Beach Peninsula (Cowell, 2000) would help determine if sufficient volumes of sand would be available to construct large spits along the north margin of Willapa Bay that would force the entrance channel to the south.

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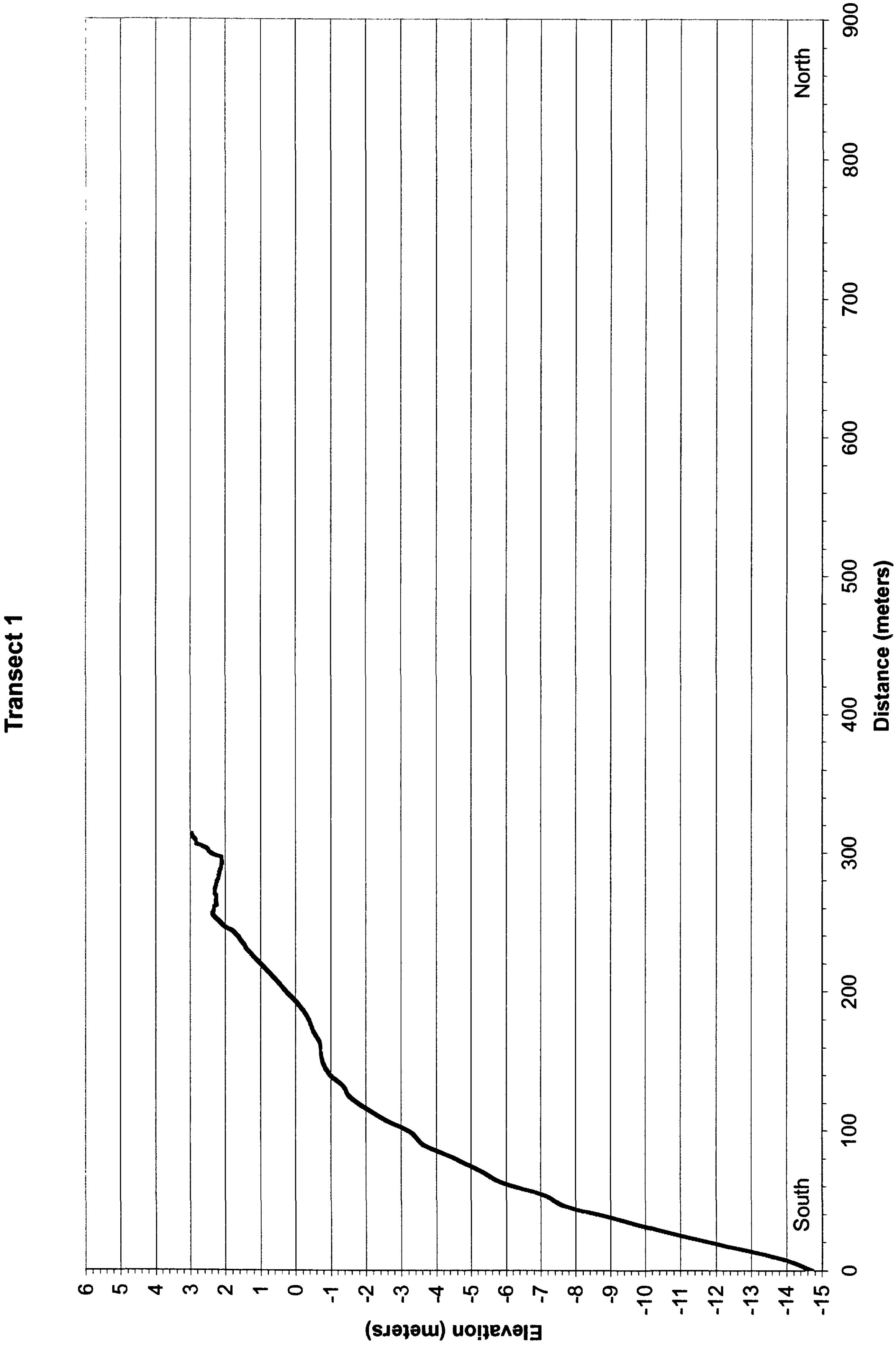
APPENDIX A
TOPOGRAPHIC PROFILES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3
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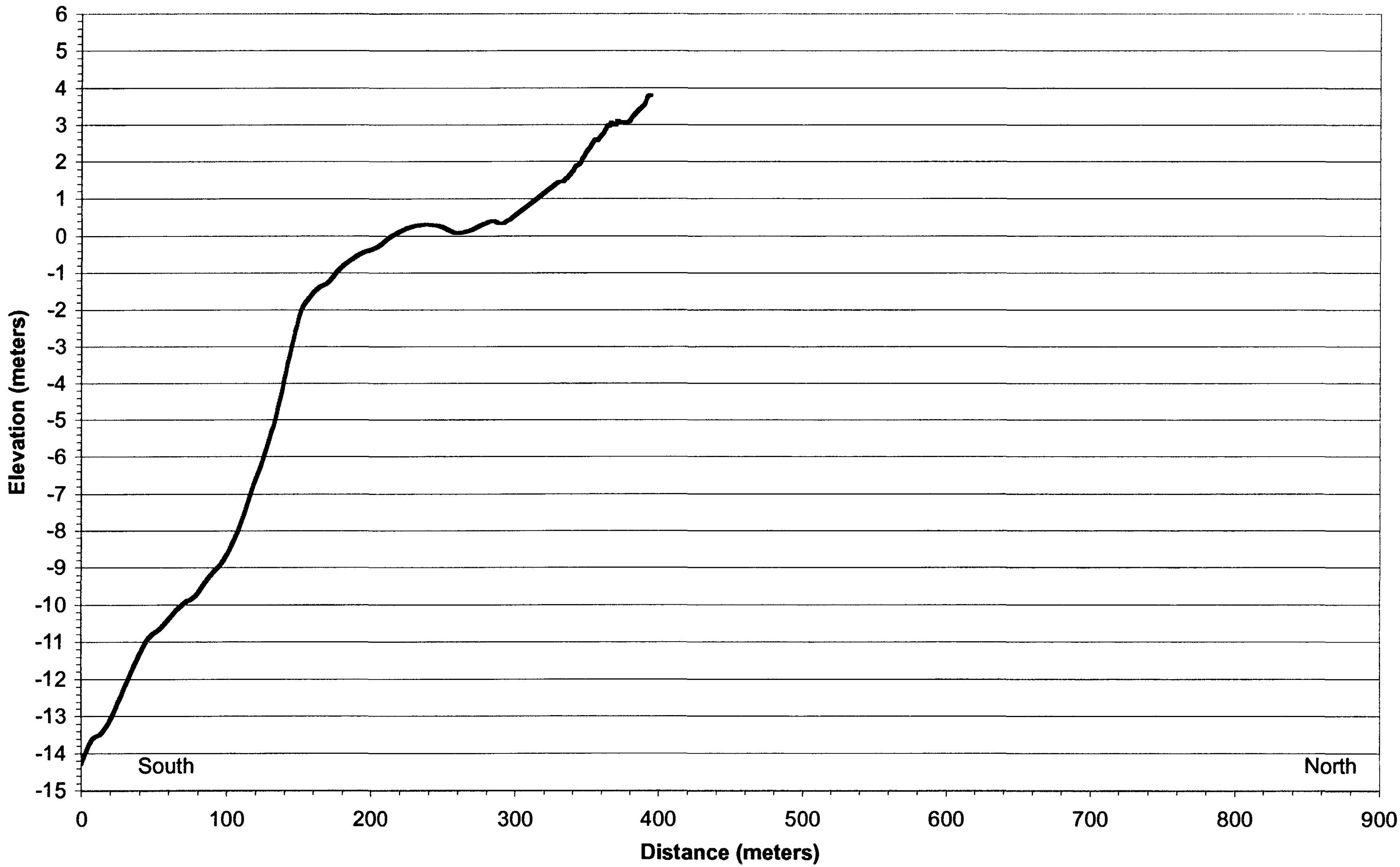
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
South
North
0
100
200
300
400
500
600
700
800
900
Distance (meters)

Transect 2



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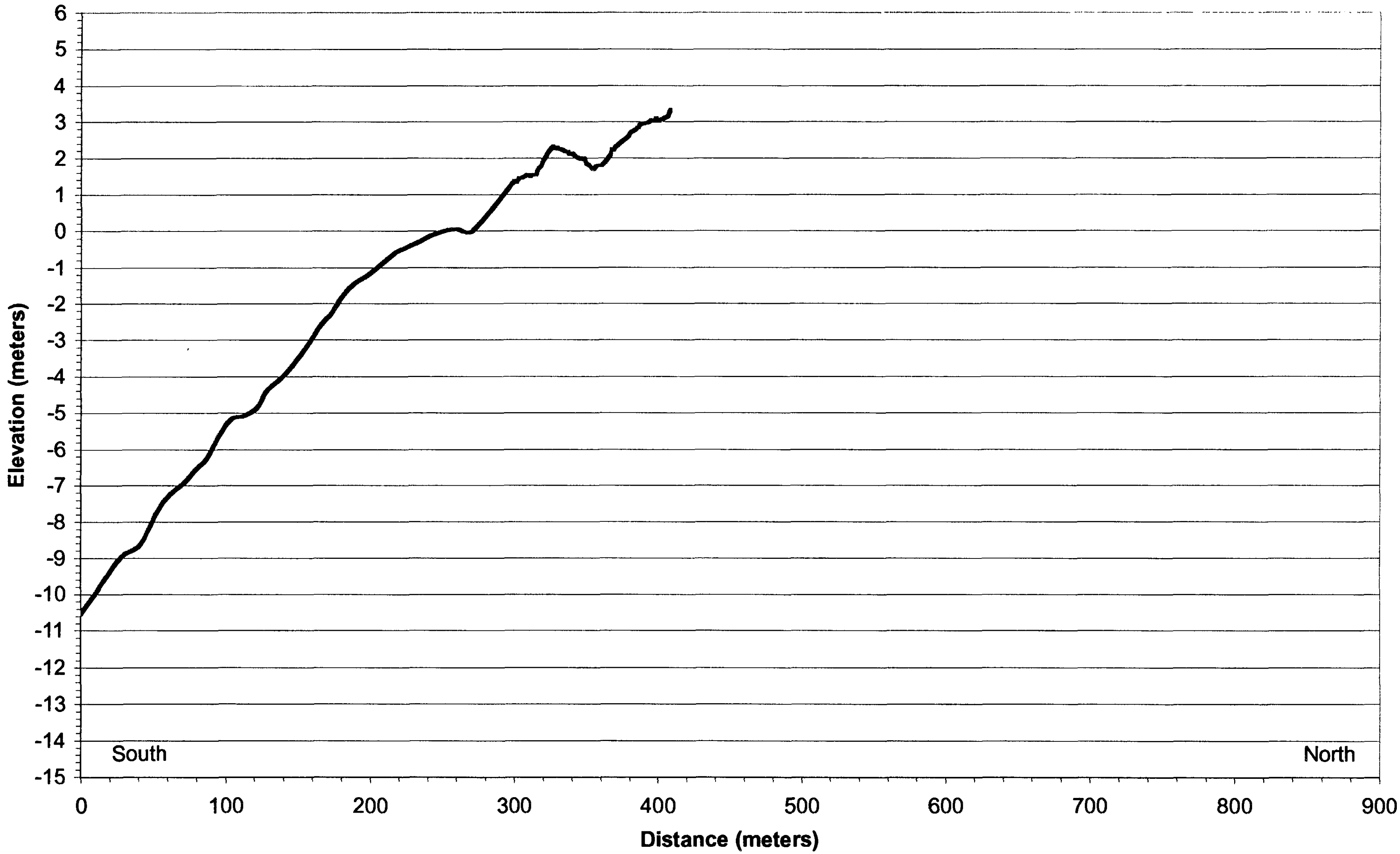
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
South
North
0
100
200
300
400
500
600
700
800
900
Distance (meters)

Transect 3



Elevation (meters)
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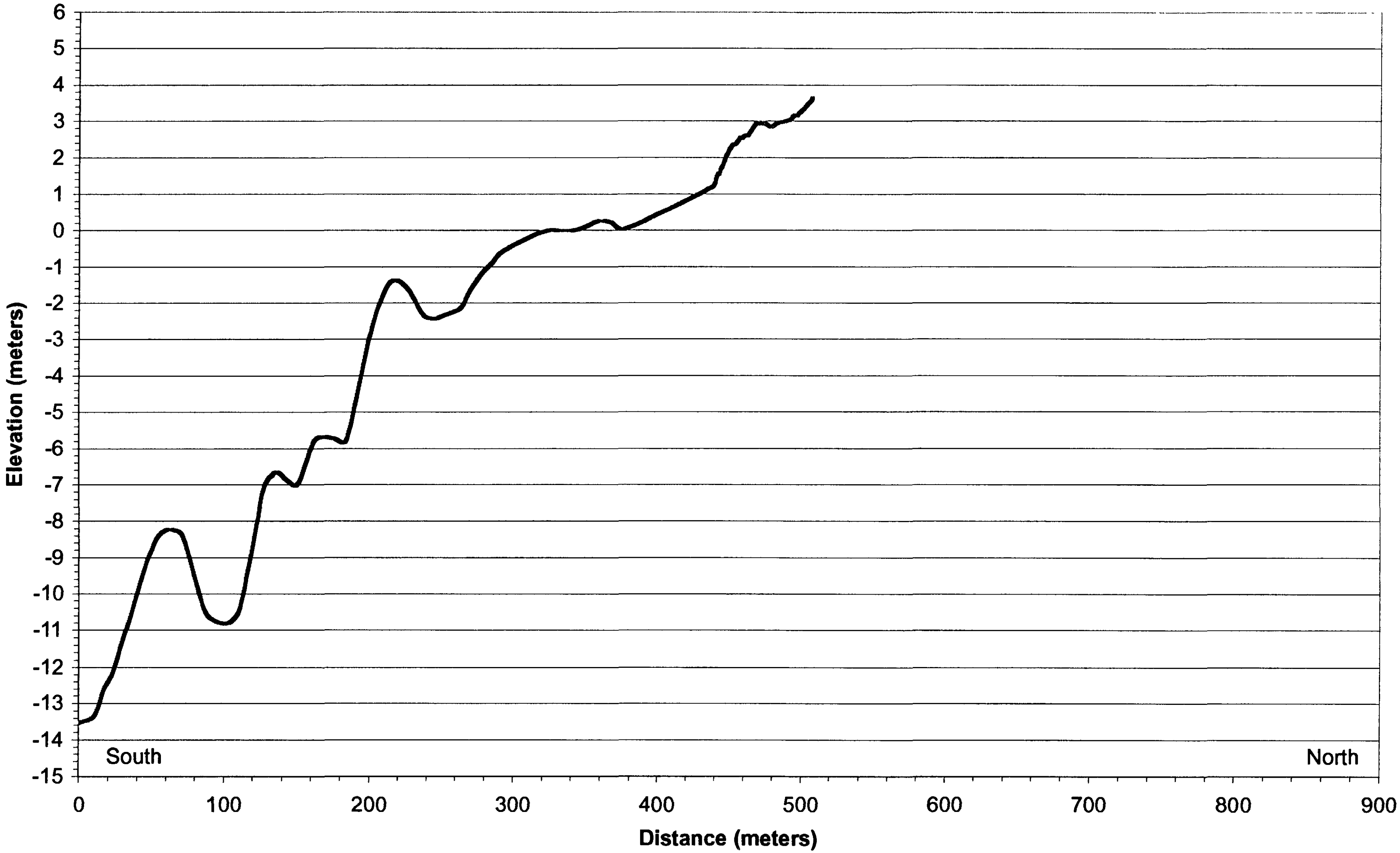
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
South
North
0
100
200
300
400
500
600
700
800
900
Distance (meters)

Transect 4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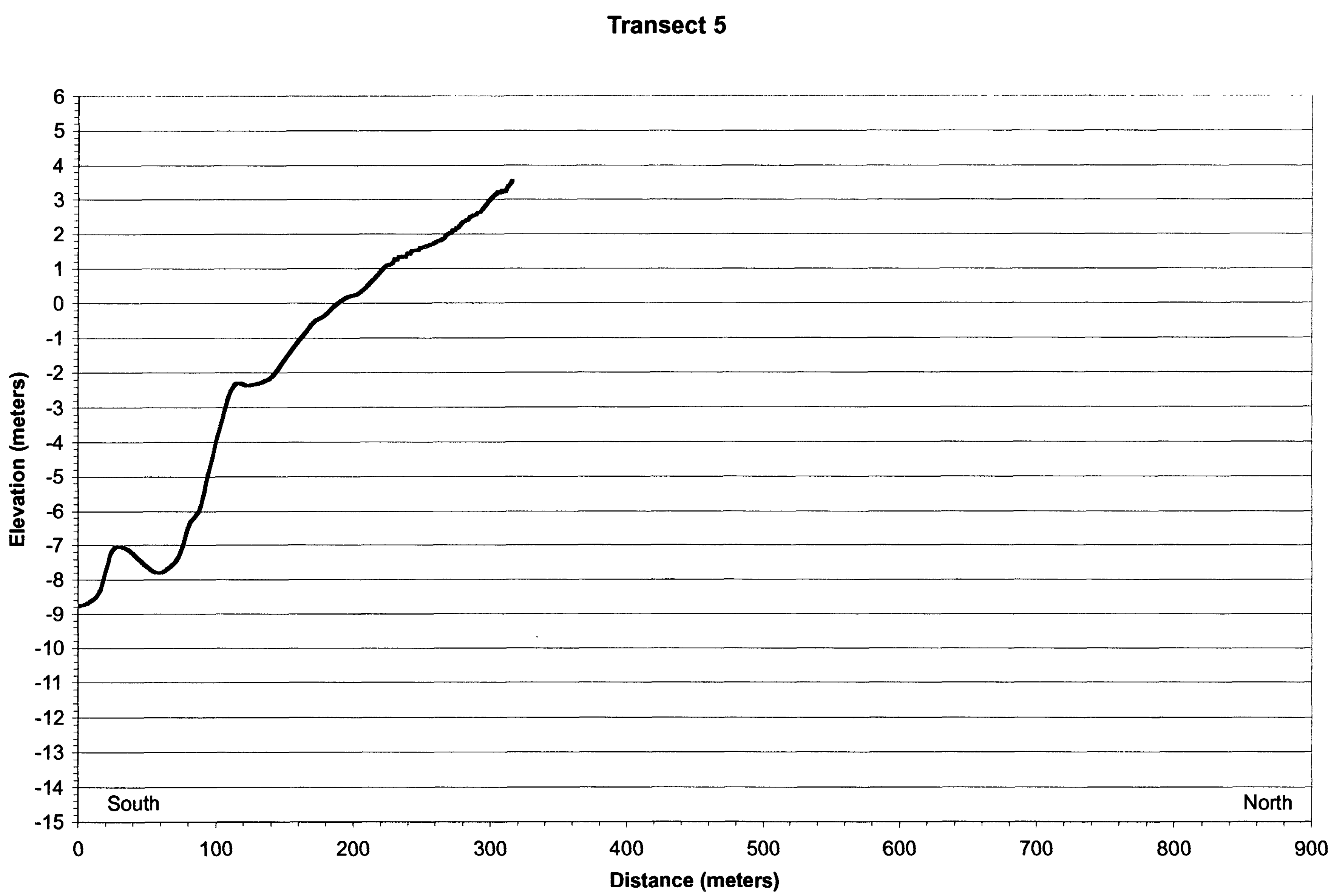
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
South
North
0
100
200
300
400
500
600
700
800
900
Distance (meters)


Transect 5
Elevation (meters)
Distance (meters)
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North
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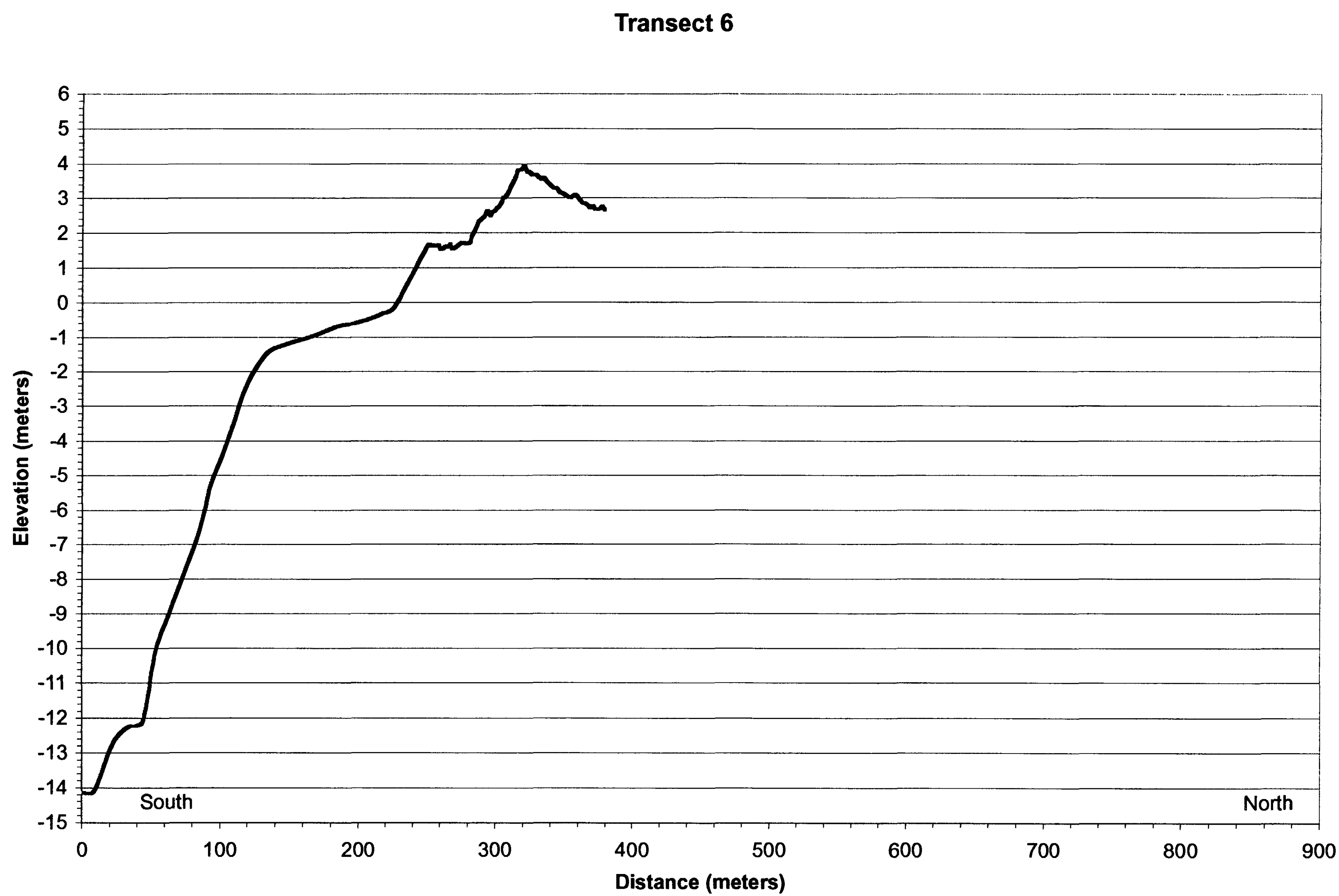
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
0
100
200
300
400
500
600
700
800
900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Elevation (meters)
Distance (meters)
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North
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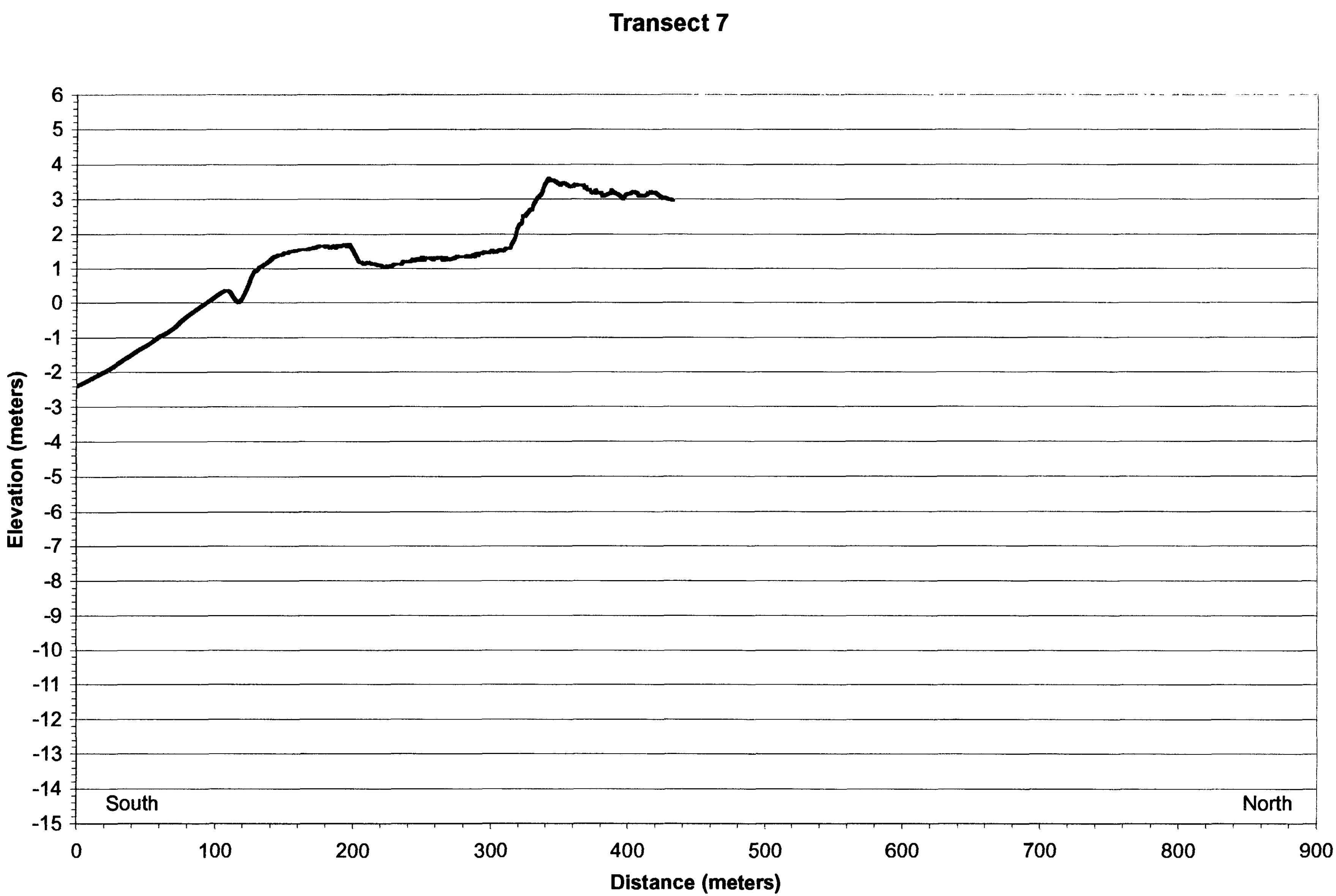
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
0
100
200
300
400
500
600
700
800
900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Elevation (meters)
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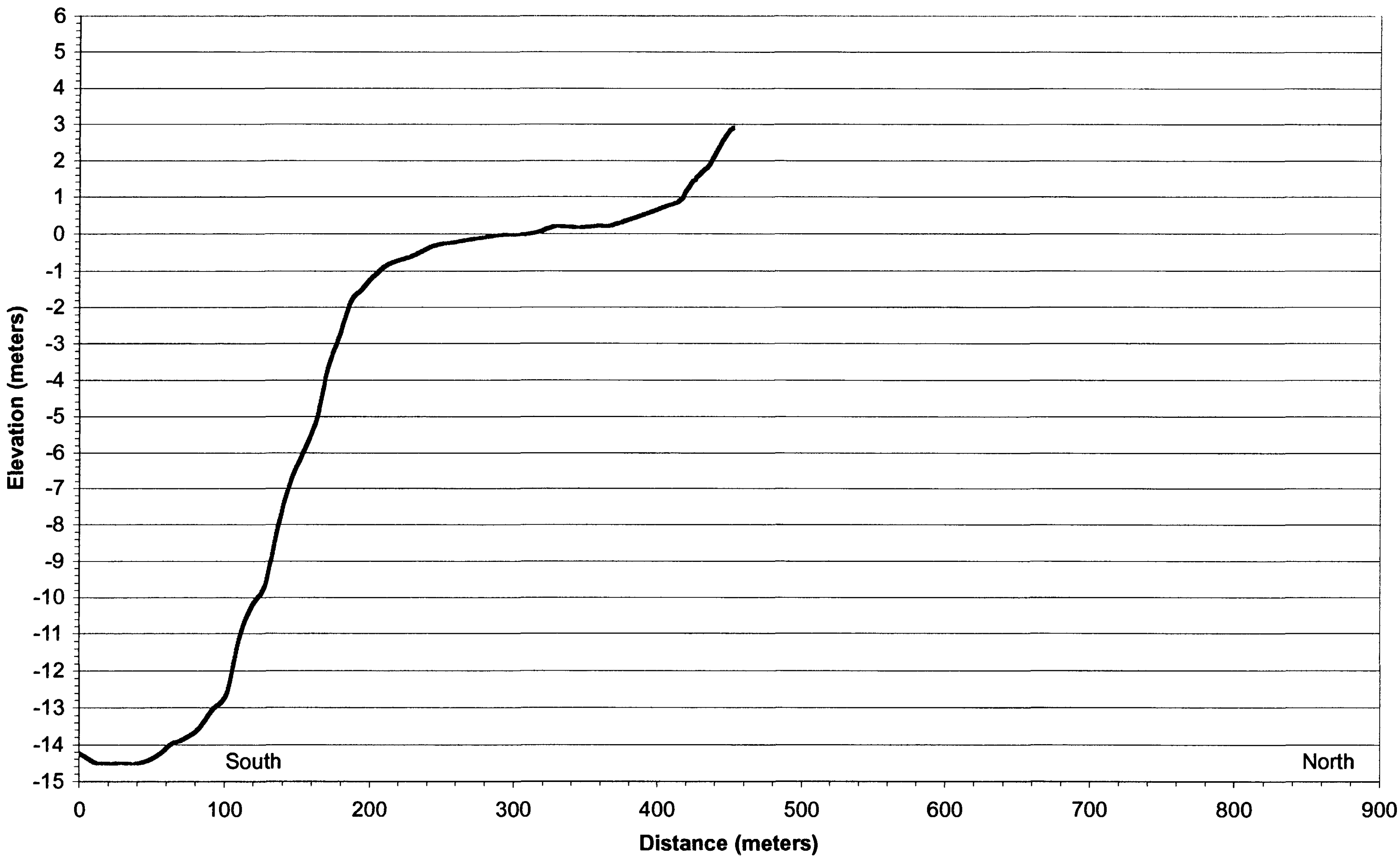
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
South
North
0
100
200
300
400
500
600
700
800
900
Distance (meters)

Transect 8



Elevation (meters)
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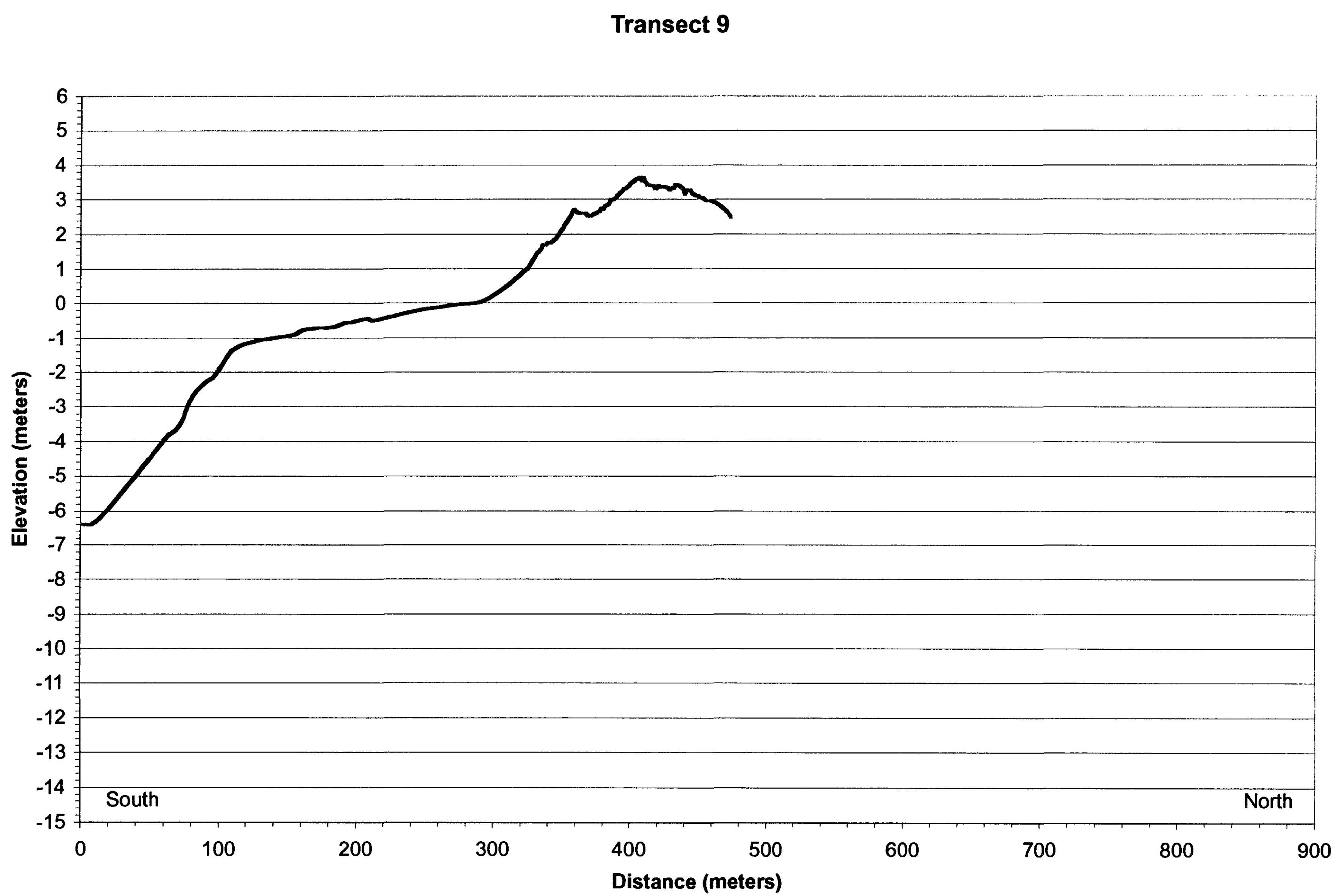
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
South
North
0
100
200
300
400
500
600
700
800
900
Distance (meters)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Elevation (meters)
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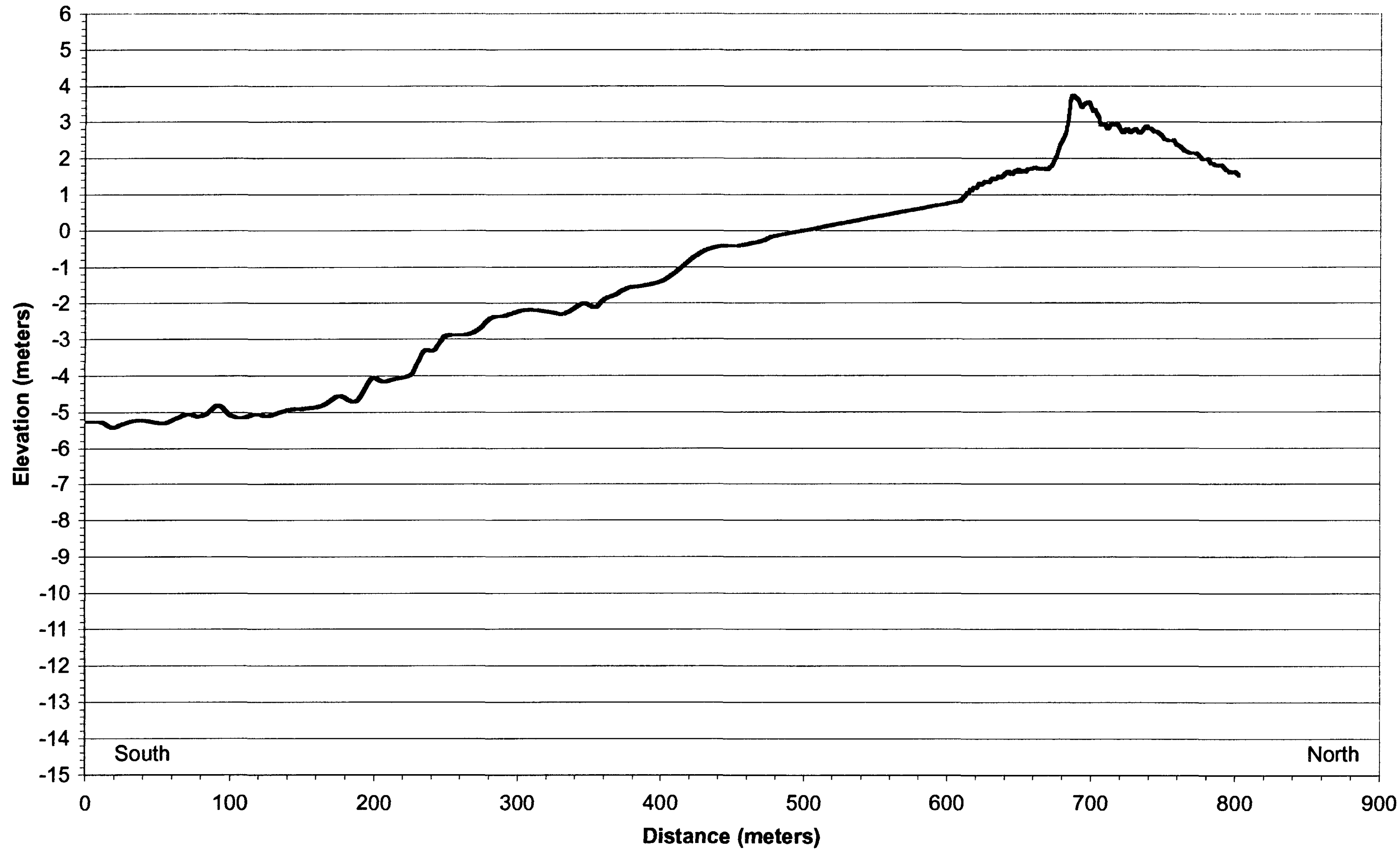
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
South
North
0
100
200
300
400
500
600
700
800
900
Distance (meters)

Transect 10



Elevation (meters)
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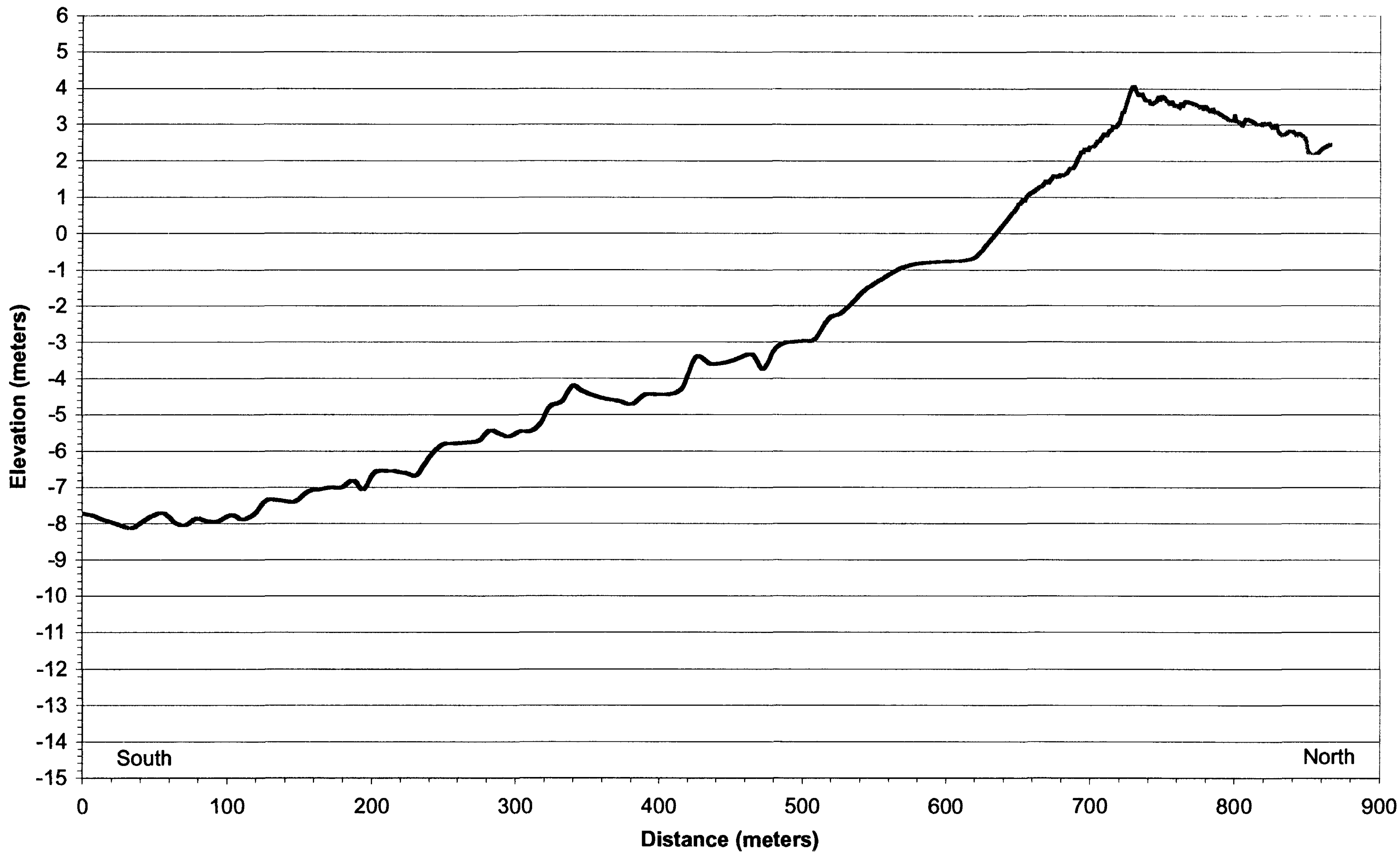
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
South
North
0
100
200
300
400
500
600
700
800
900
Distance (meters)

Transect 12



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5
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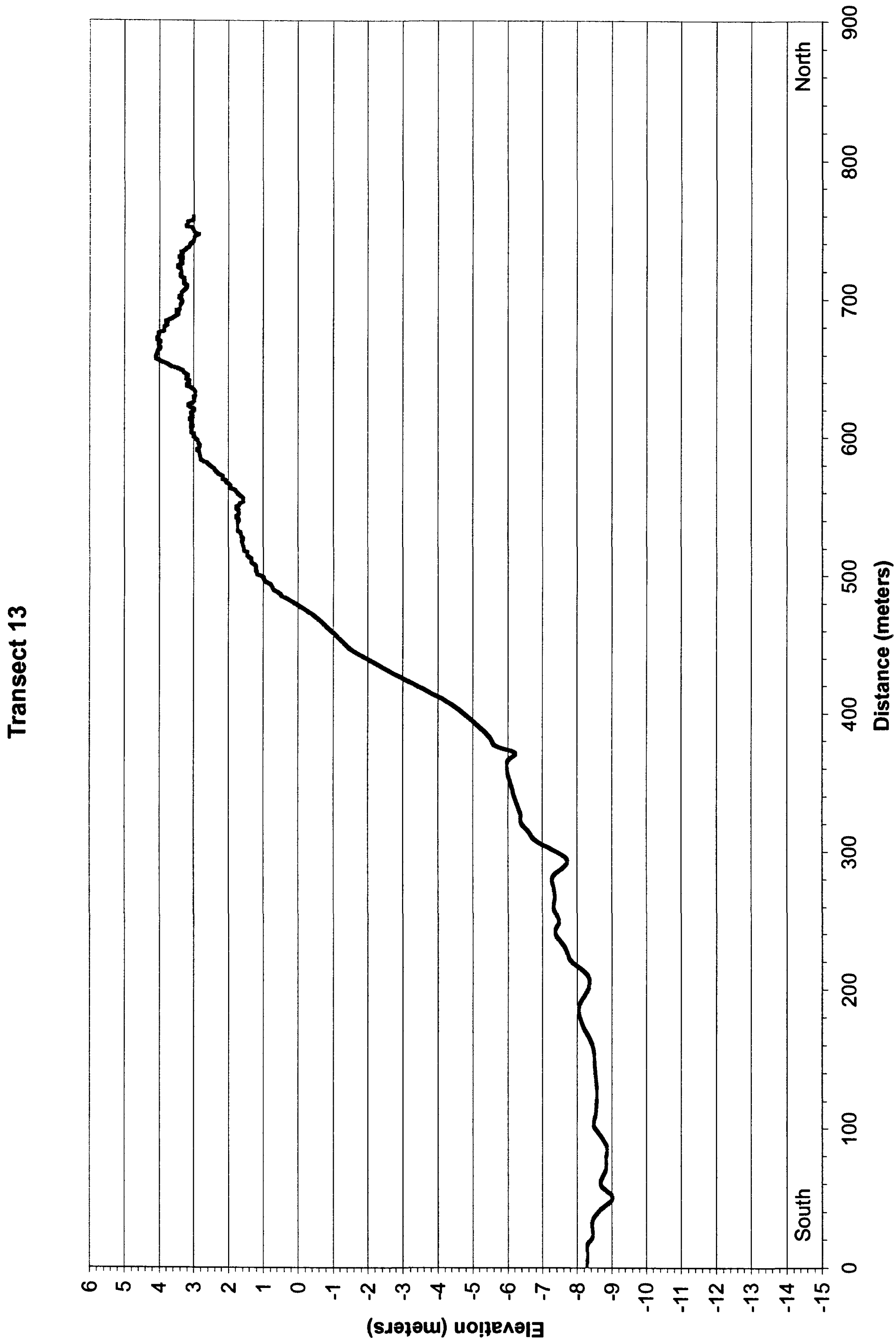
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
Elevation (meters)
South
North
0
100
200
300
400
500
600
700
800
900
Distance (meters)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Elevation (meters)
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4
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-2
-3
-4
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-6
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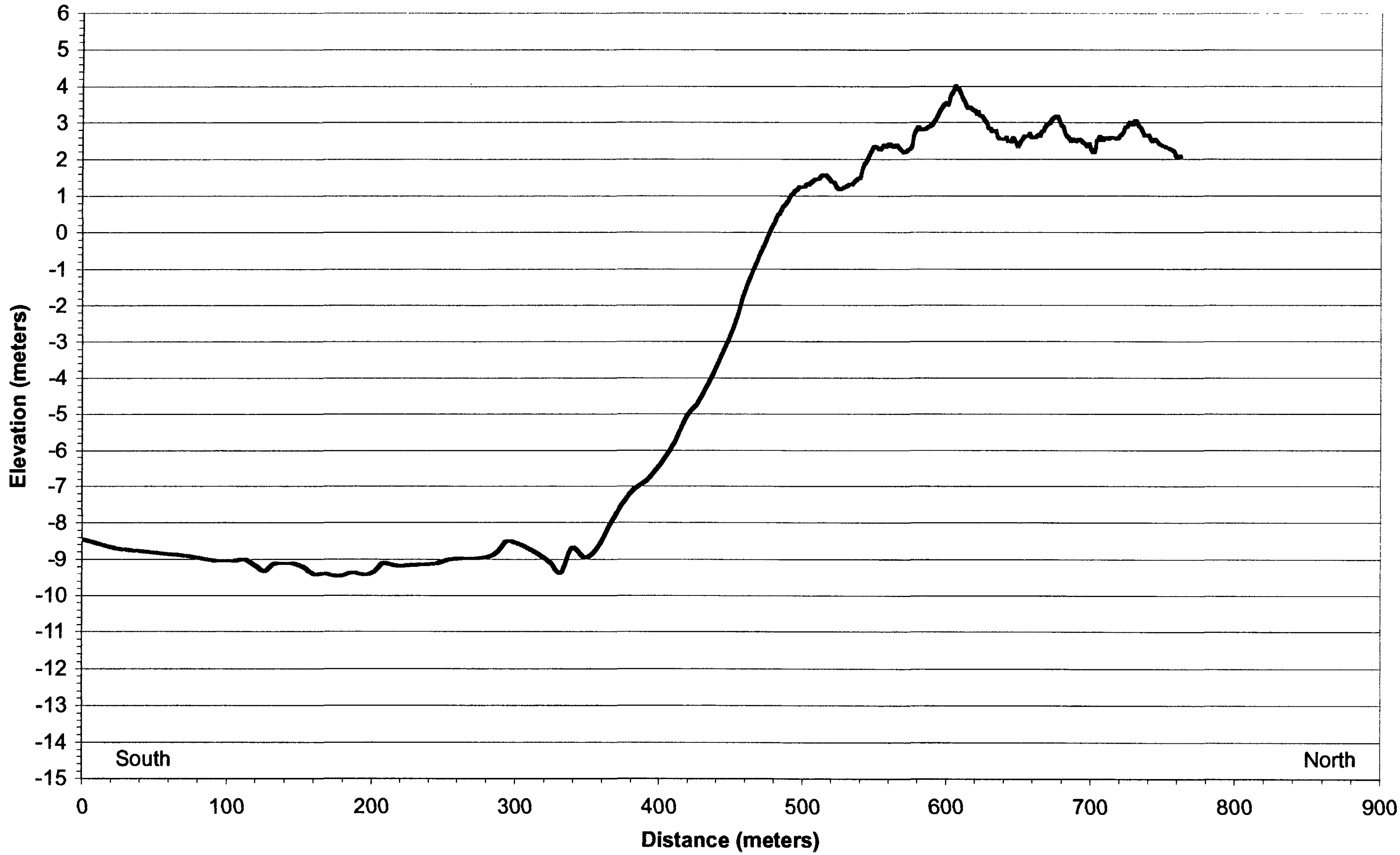
-10
-11
-12
-13
-14
-15
Distance (meters)
0
100
200
300
400
500
600
700
800
900
South
North

Transect 14



Elevation (meters)
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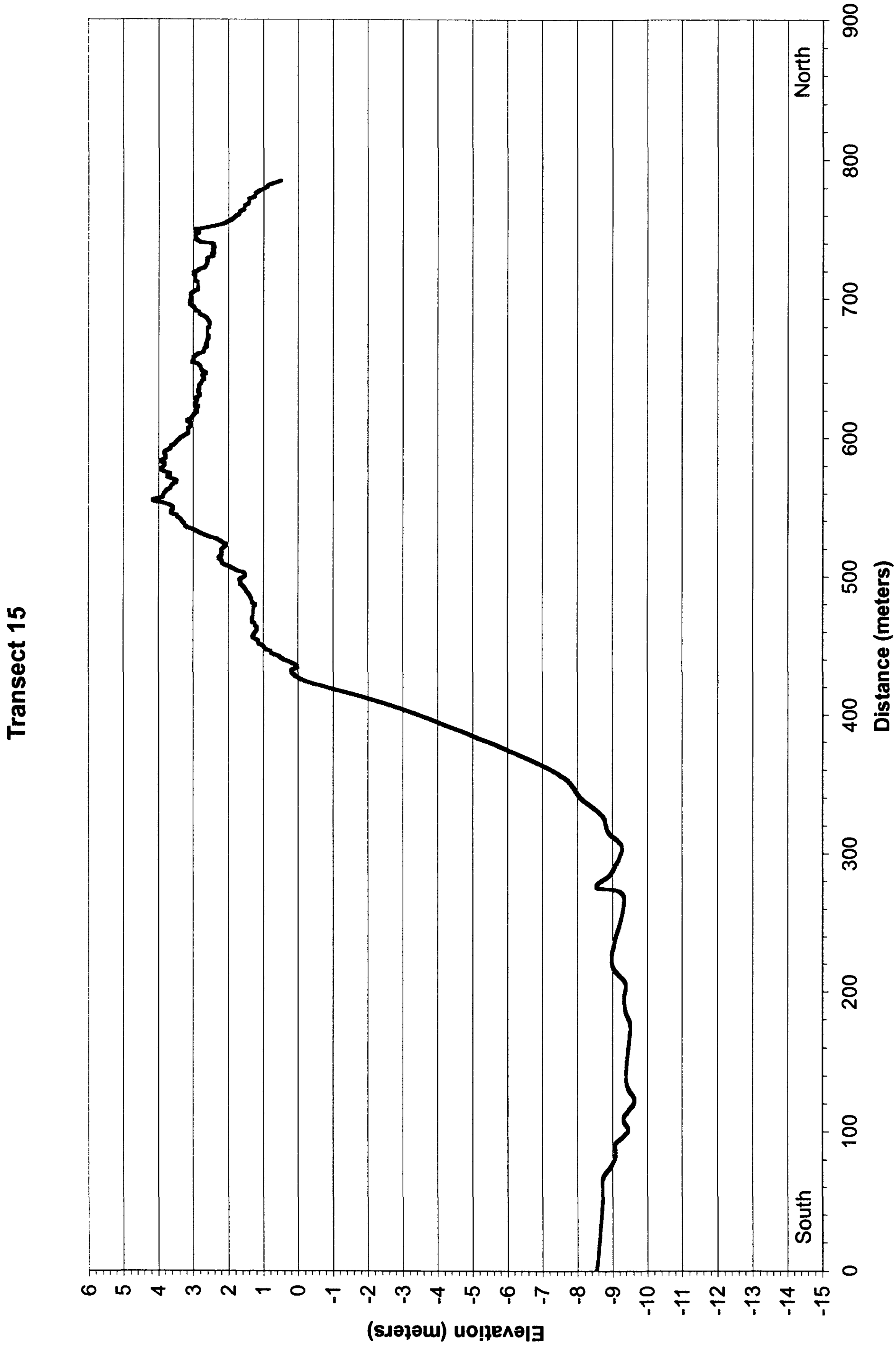
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
South
North
0
100
200
300
400
500
600
700
800
900
Distance (meters)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Elevation (meters)
Distance (meters)
South
North
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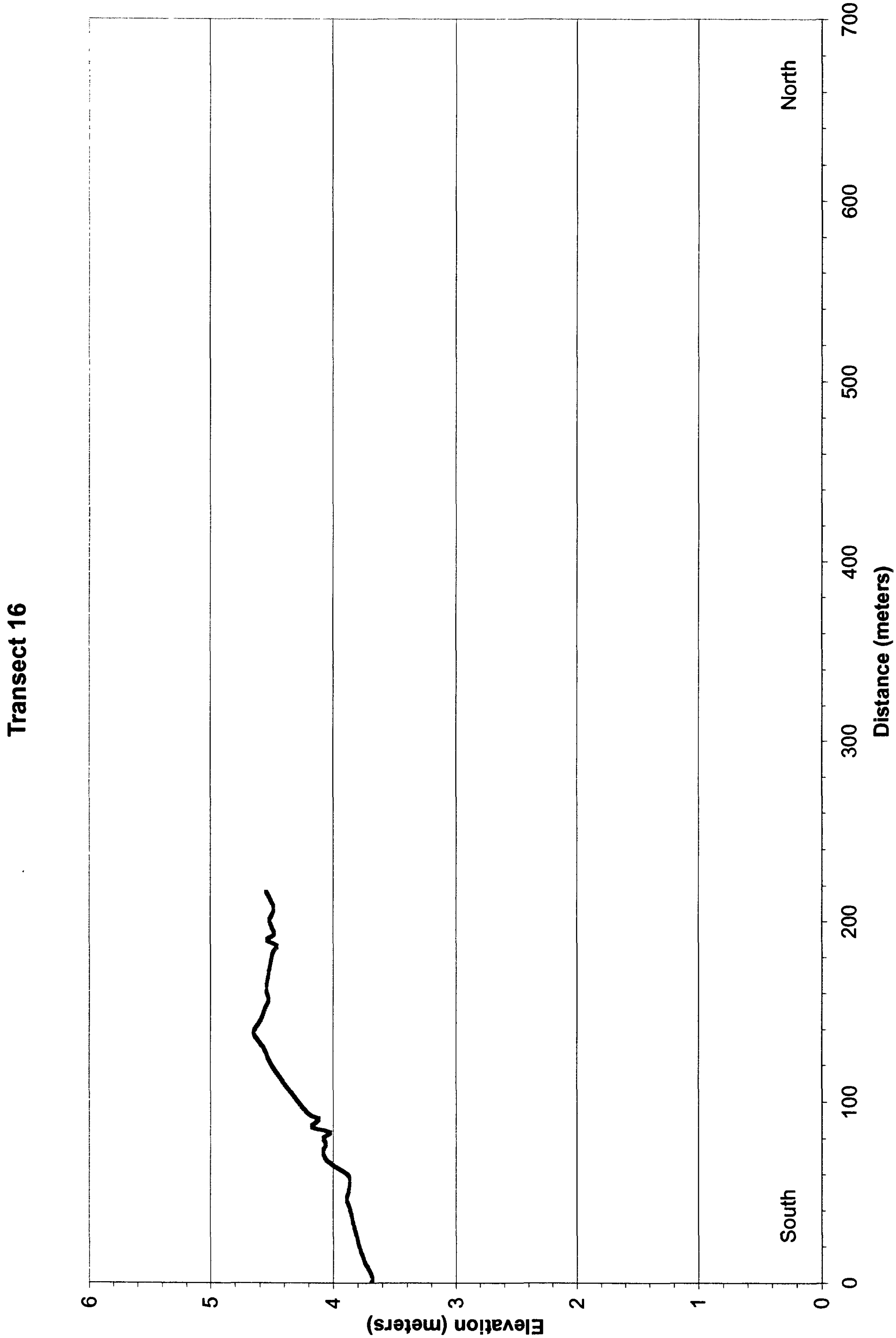
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
0
100
200
300
400
500
600
700
800
900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Elevation (meters)
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3
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5
6
Distance (meters)
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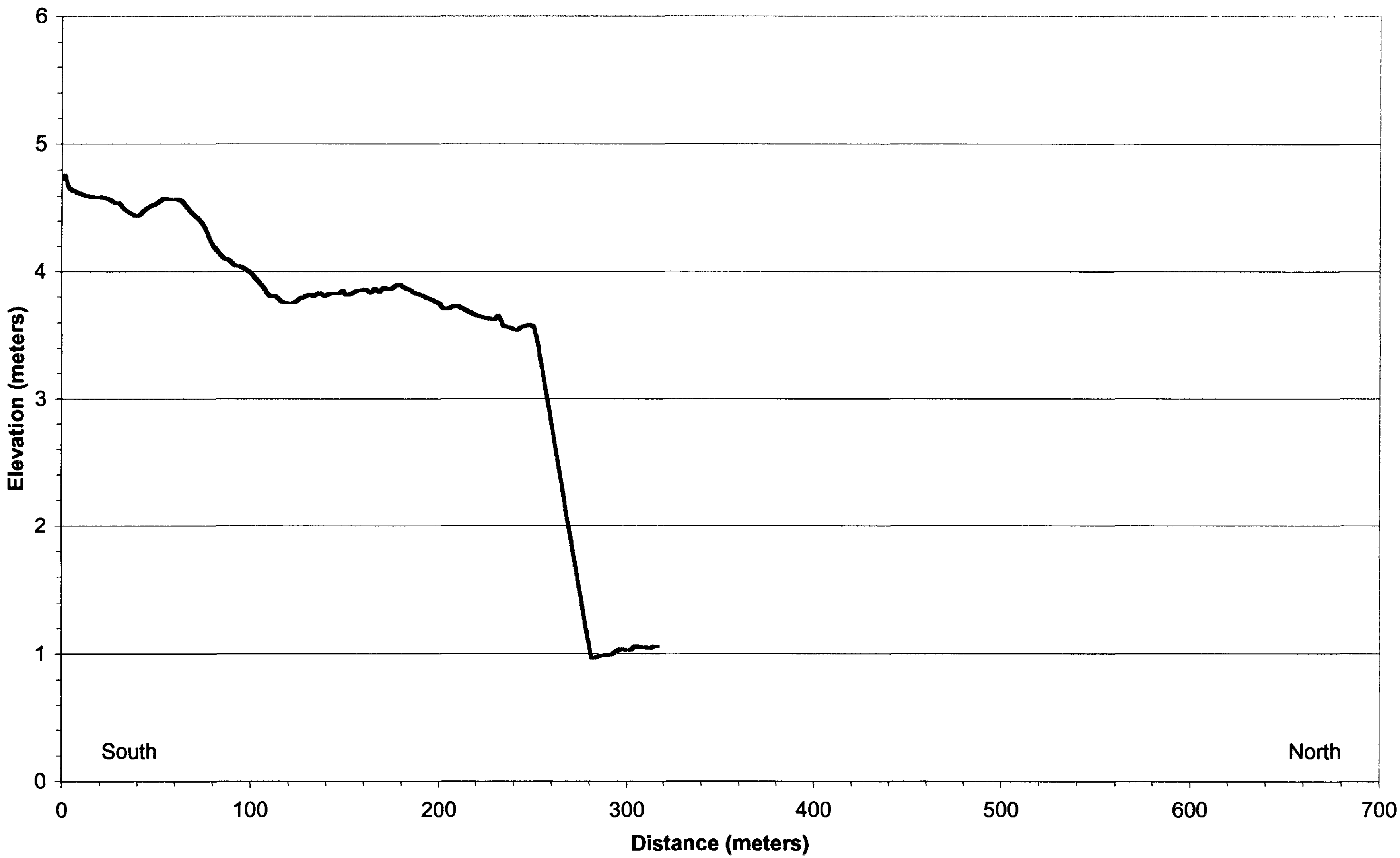
200
300
400
500
600
700
South
North

Transect 17



Elevation (meters)
Distance (meters)
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North
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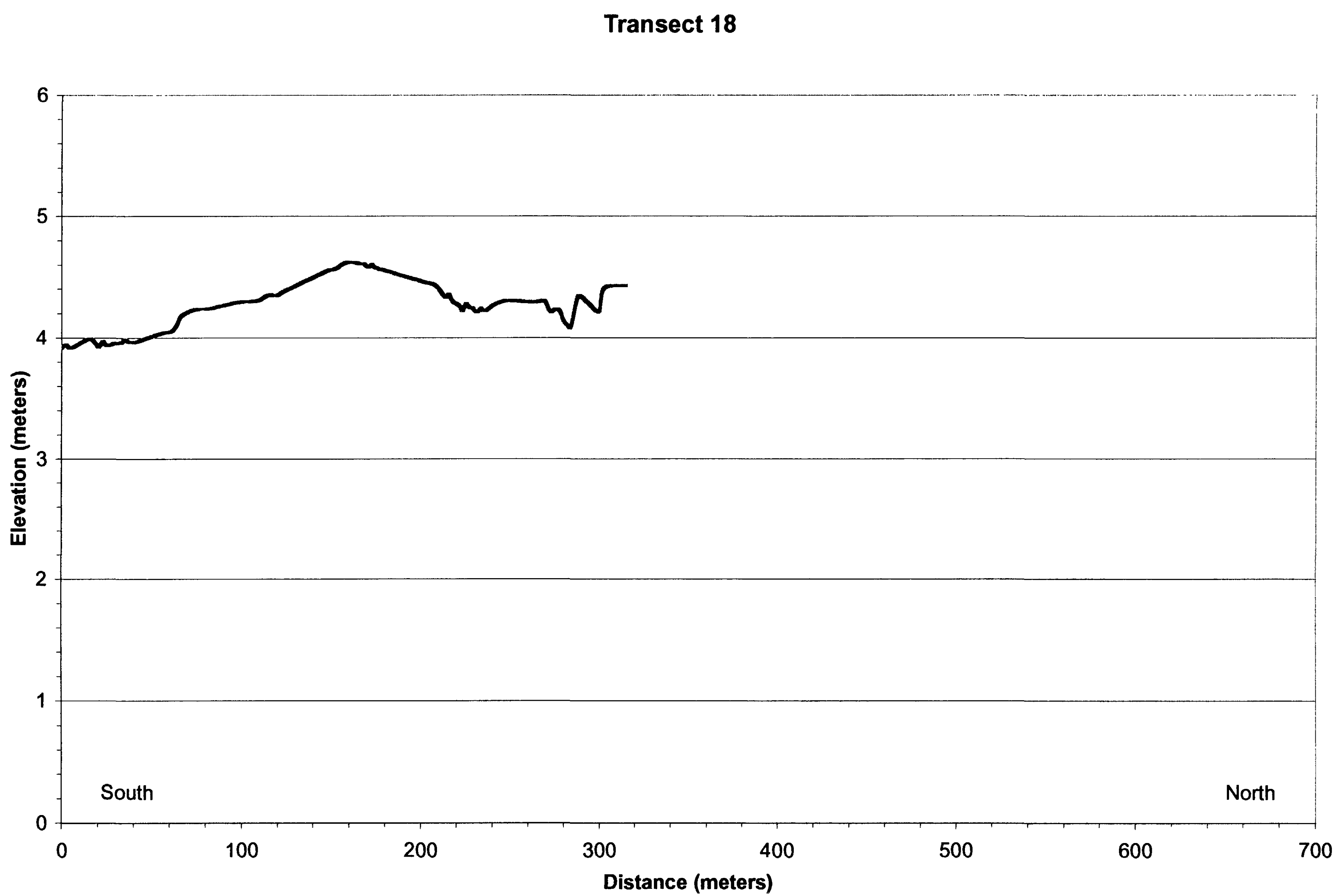
1
2
3
4
5
6
0
100
200
300
400
500
600
700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Elevation (meters)
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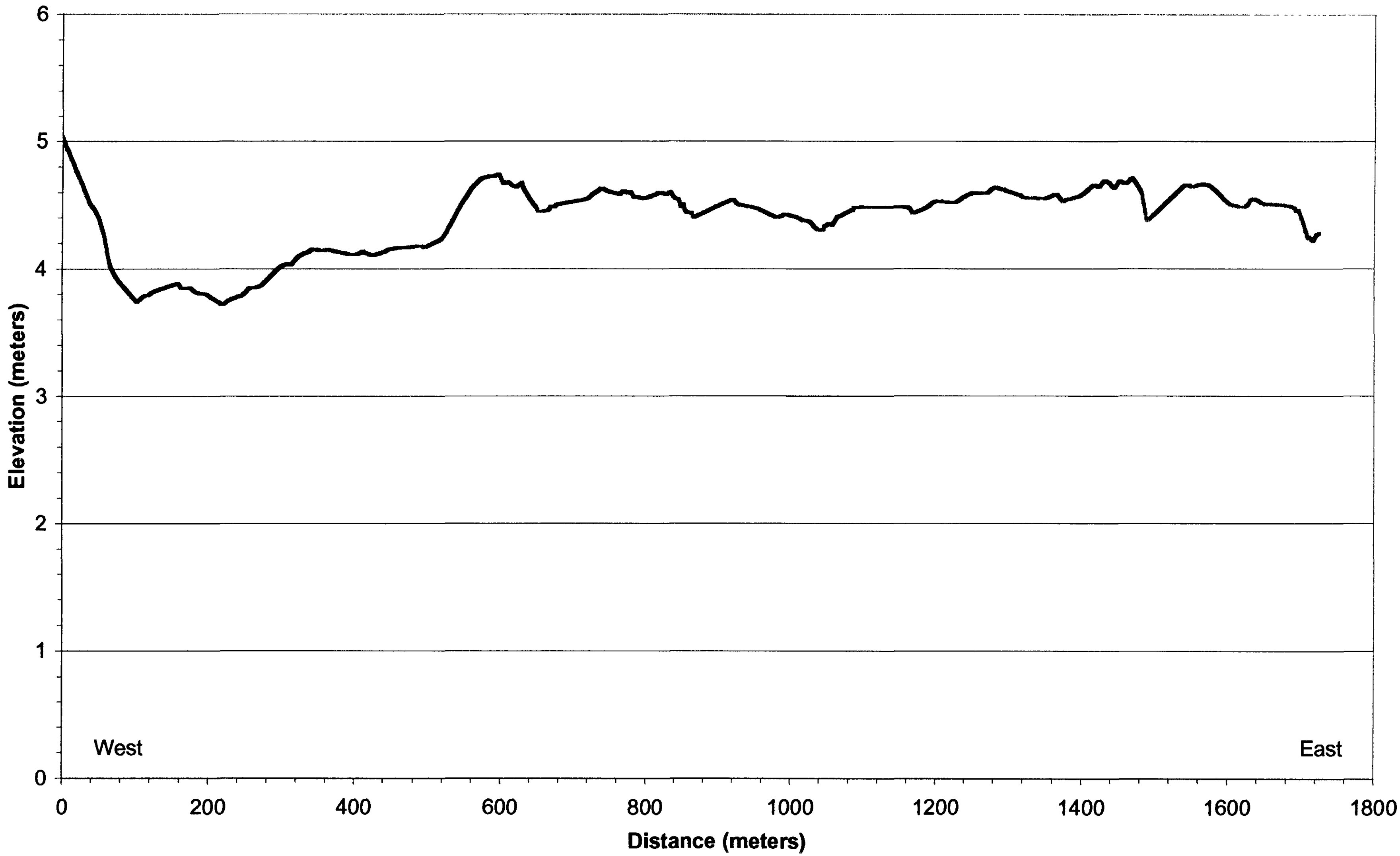
5
4
3
2
1
0
South
North
0
100
200
300
400
500
600
700
Distance (meters)

Transect 19



Elevation (meters)
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5
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0
West
East
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200
400
600
800
1000
1200
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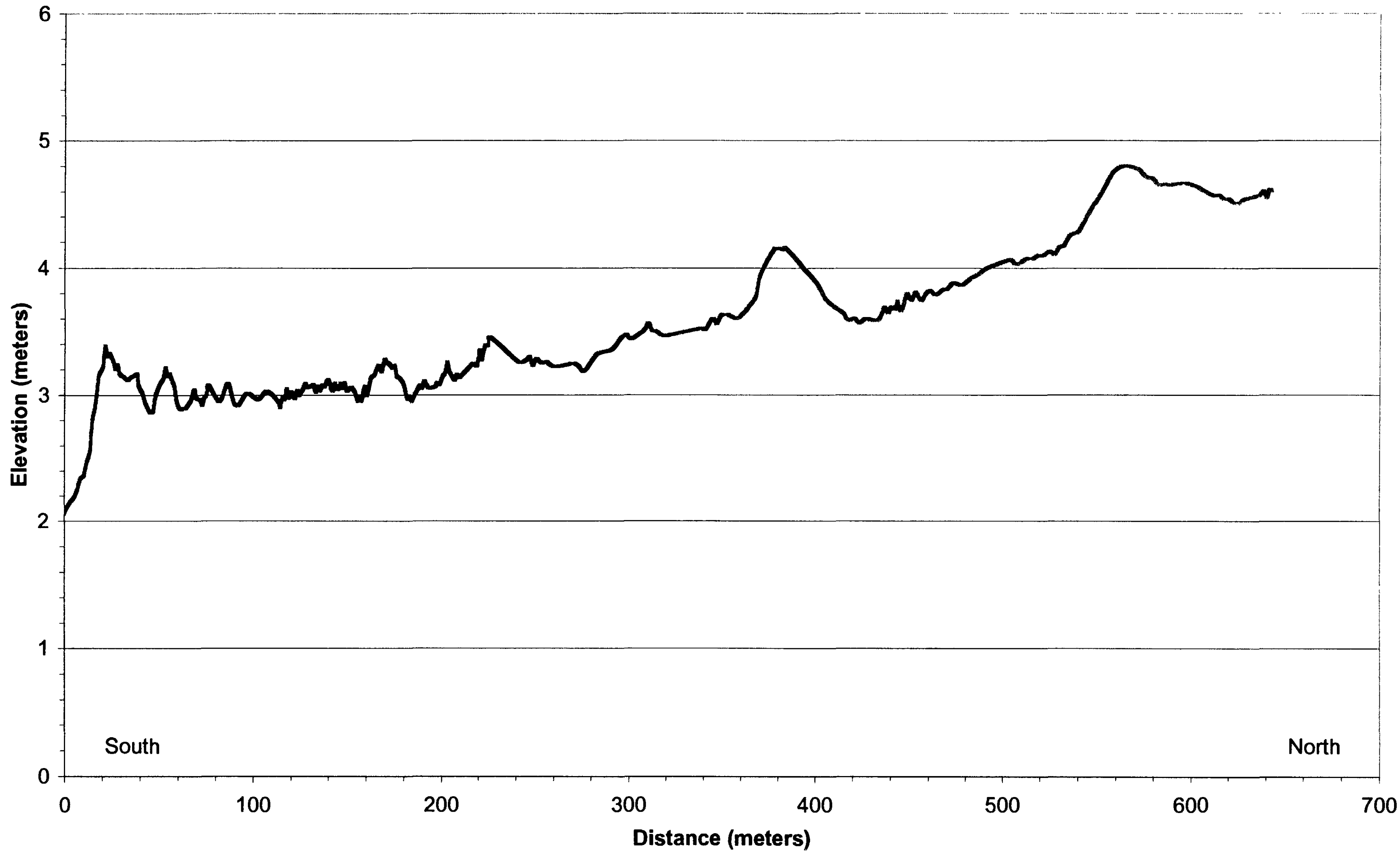
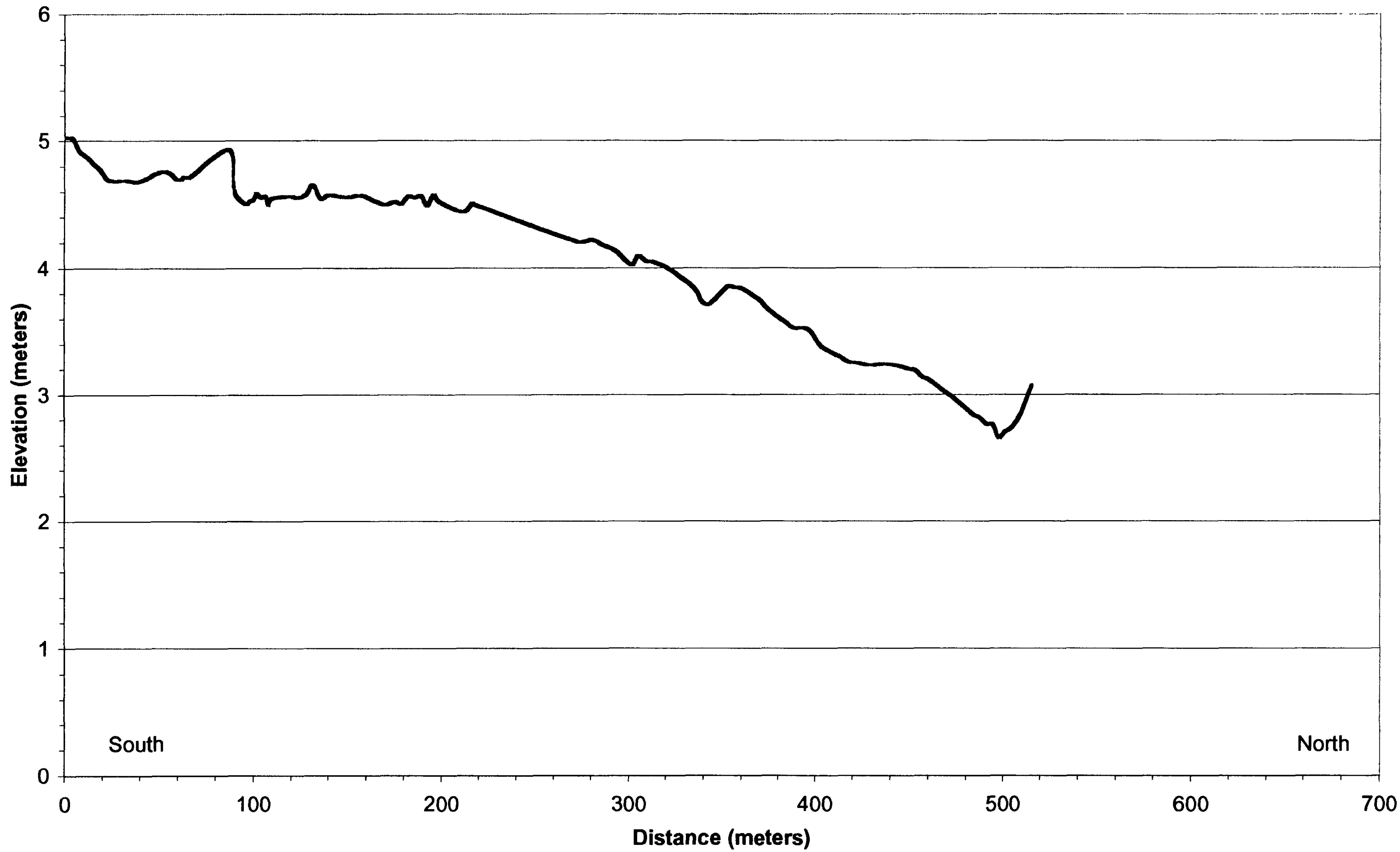
1800
Distance (meters)

Transect 20



Elevation (meters)
6
5
4
3
2
1
0
South
North
0
100
200
300
400
500
600
700
Distance (meters)

Transect 21



6
5
4
3
2
1
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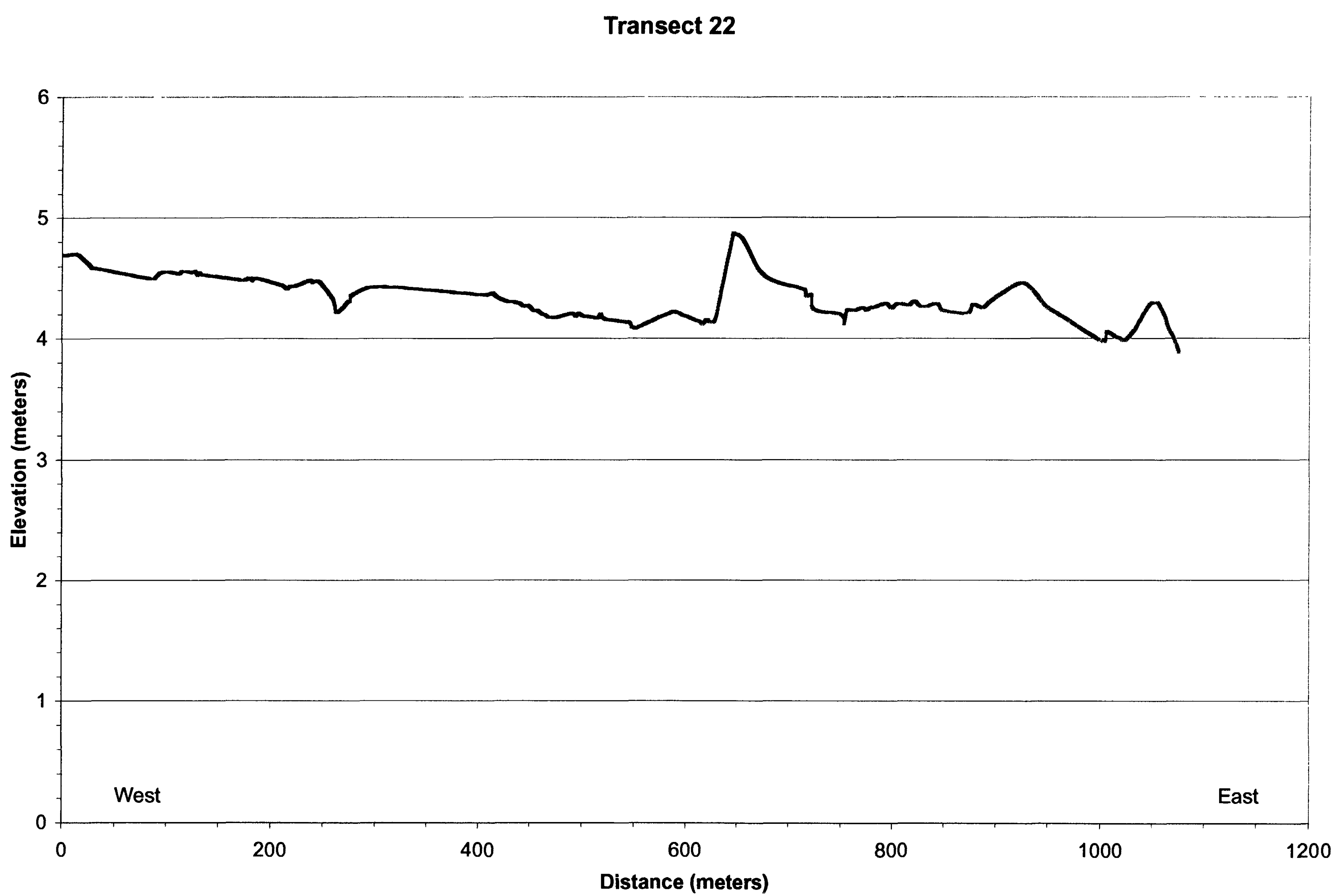
Elevation (meters)
South
North
0
100
200
300
400
500
600
700
Distance (meters)



Transect 22
Elevation (meters)
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3
2
1
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West
East
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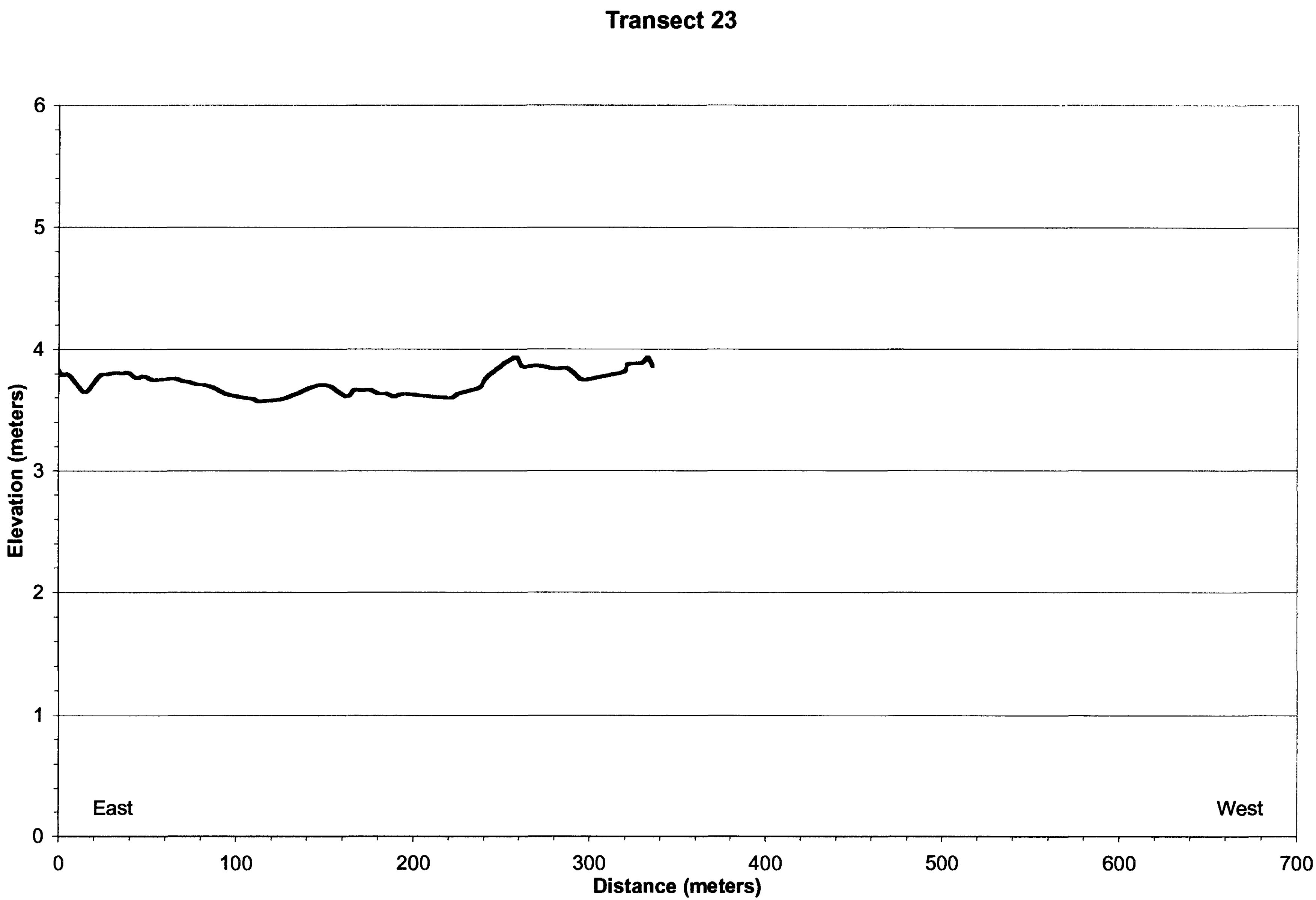
200
400
600
800
1000
1200
Distance (meters)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3
4
5
6
Distance (meters)
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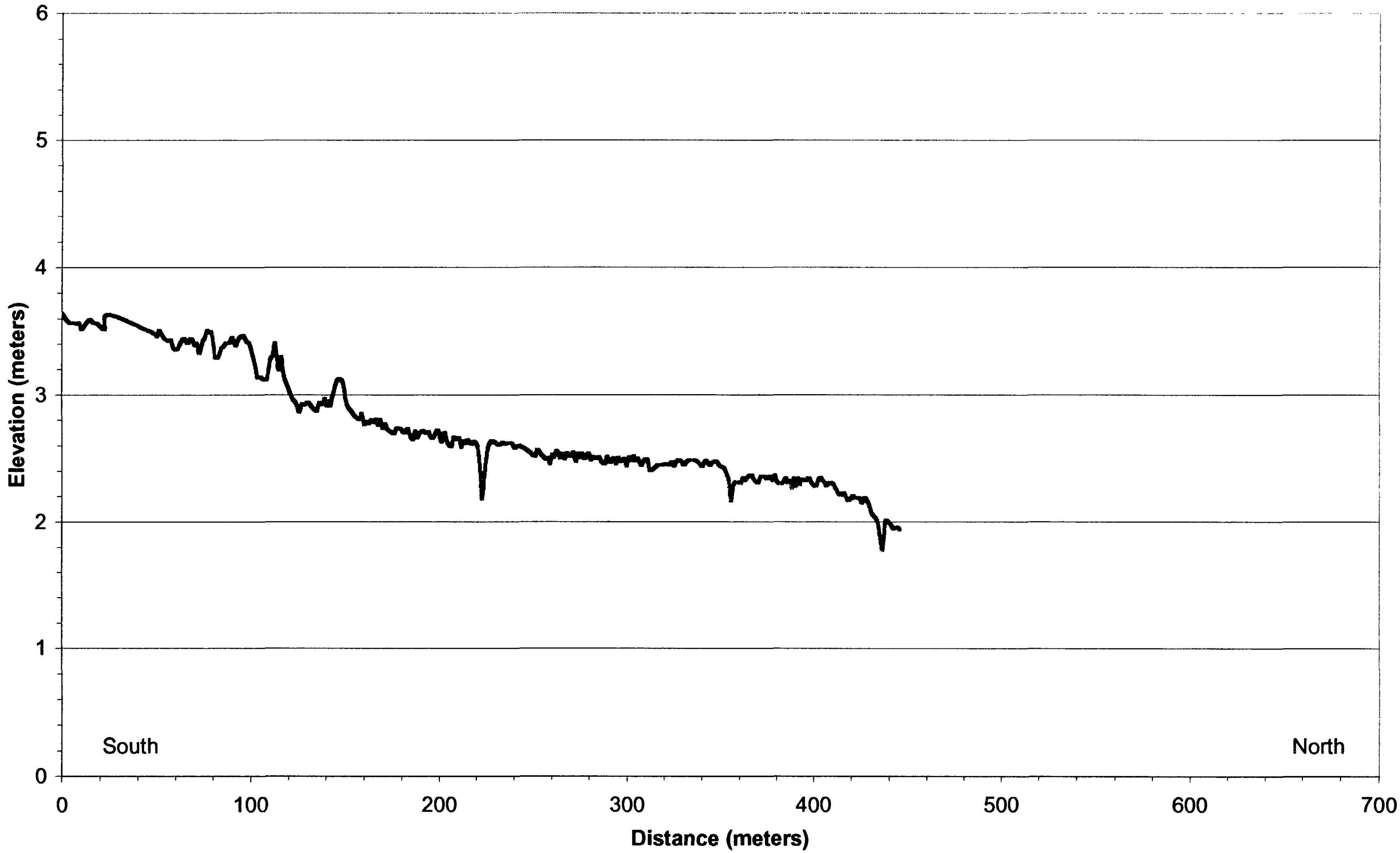
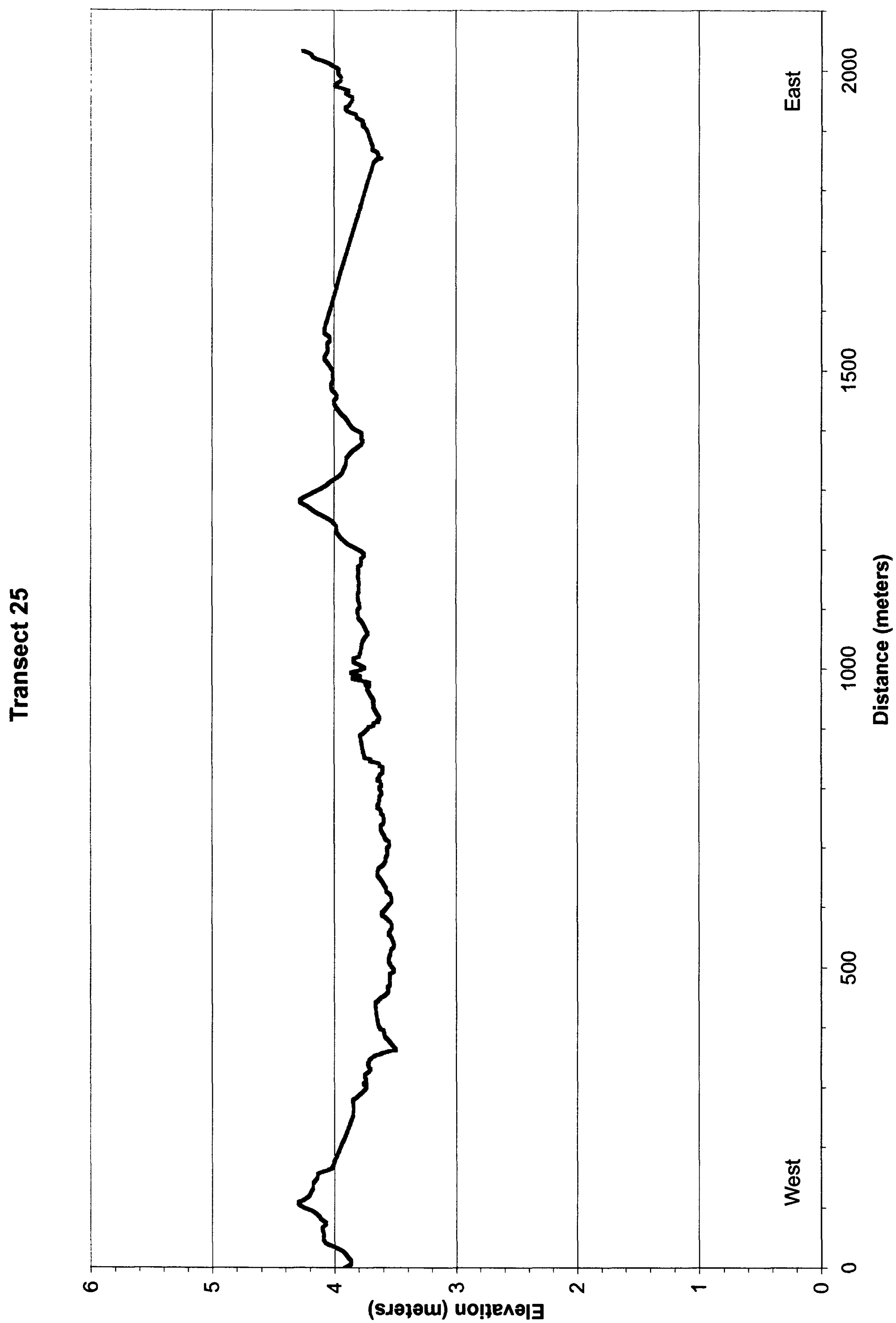
100
200
300
400
500
600
700
East
West

Transect 24



6
5
4
3
2
1
0
Elevation (meters)
0
100
200
300
400
500
600
700
Distance (meters)
South
North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1500
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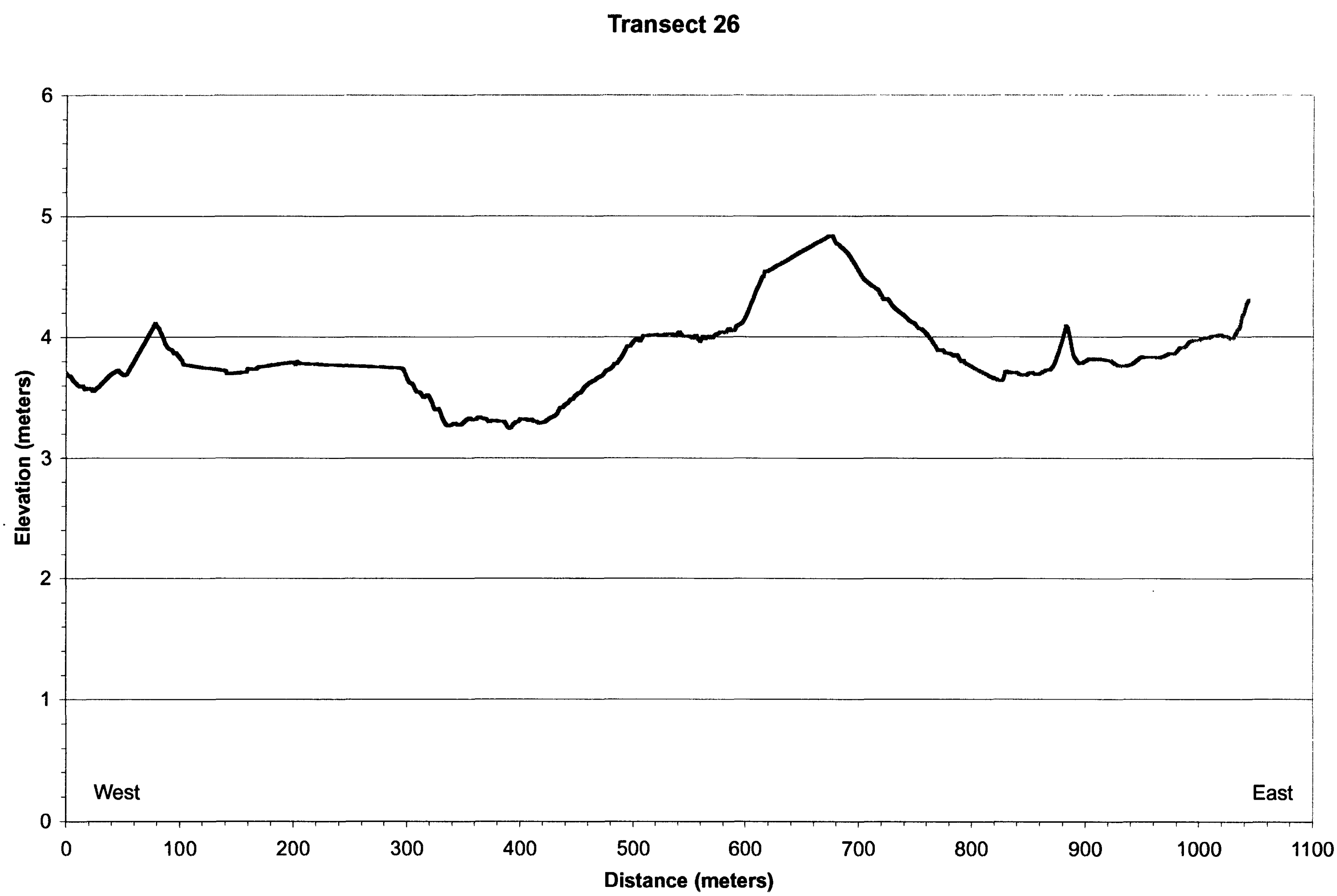
1
2
3
4
5
6



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4
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2
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300
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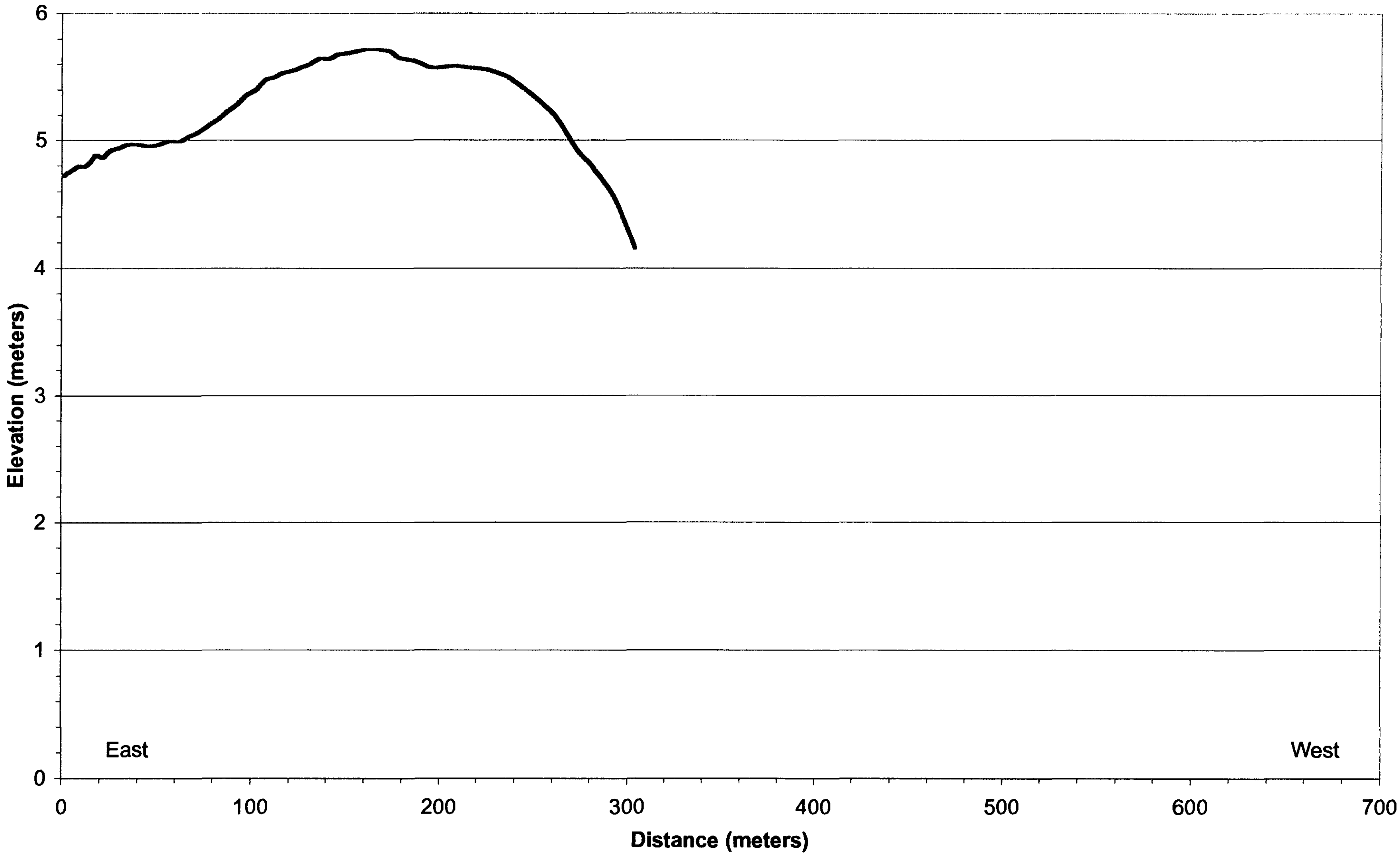
500
600
700
800
900
1000
1100
Distance (meters)
West
East

Transect 27



Elevation (meters)
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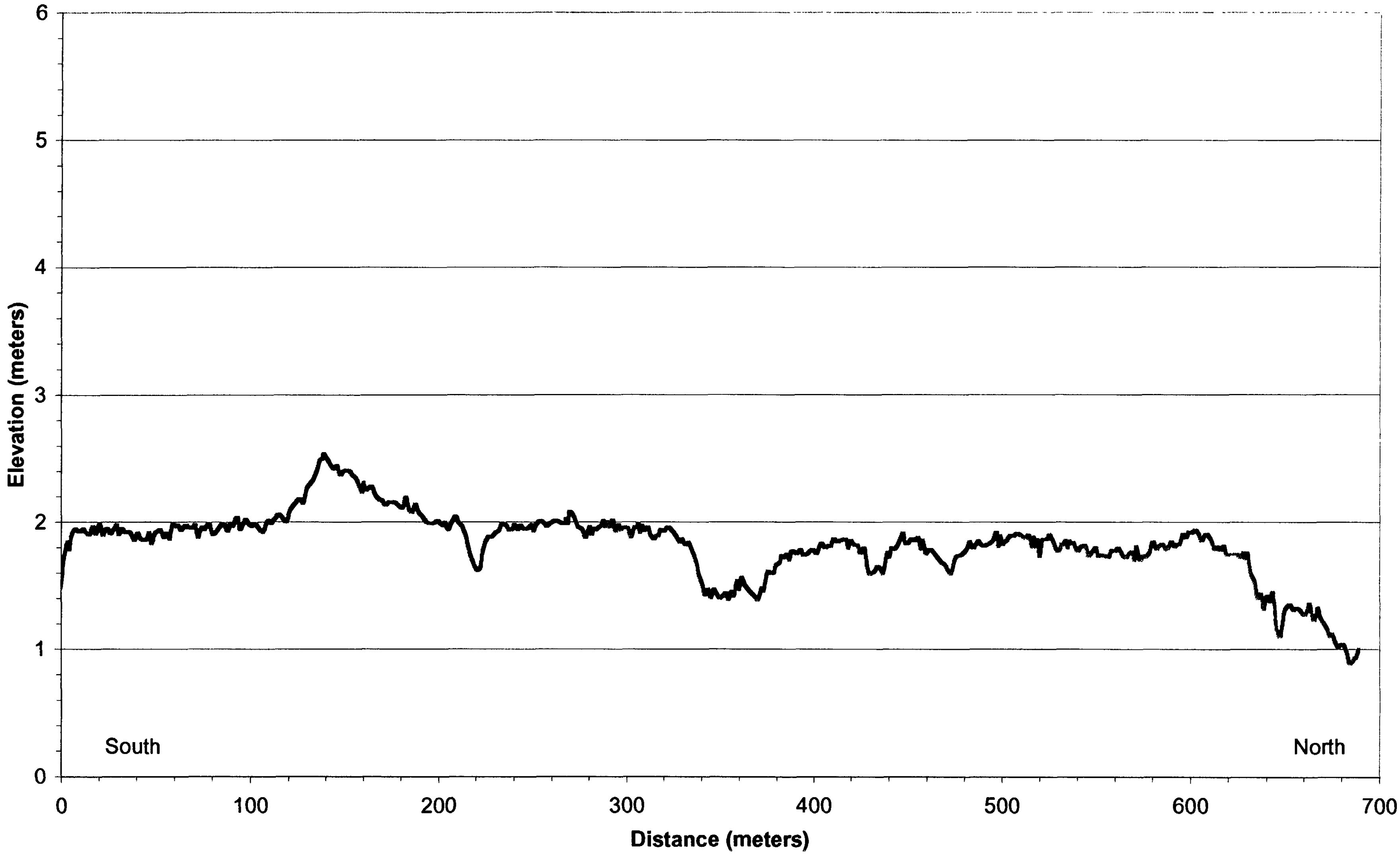
5
4
3
2
1
0
East
West
0
100
200
300
400
500
600
700
Distance (meters)

Transect 28



Elevation (meters)
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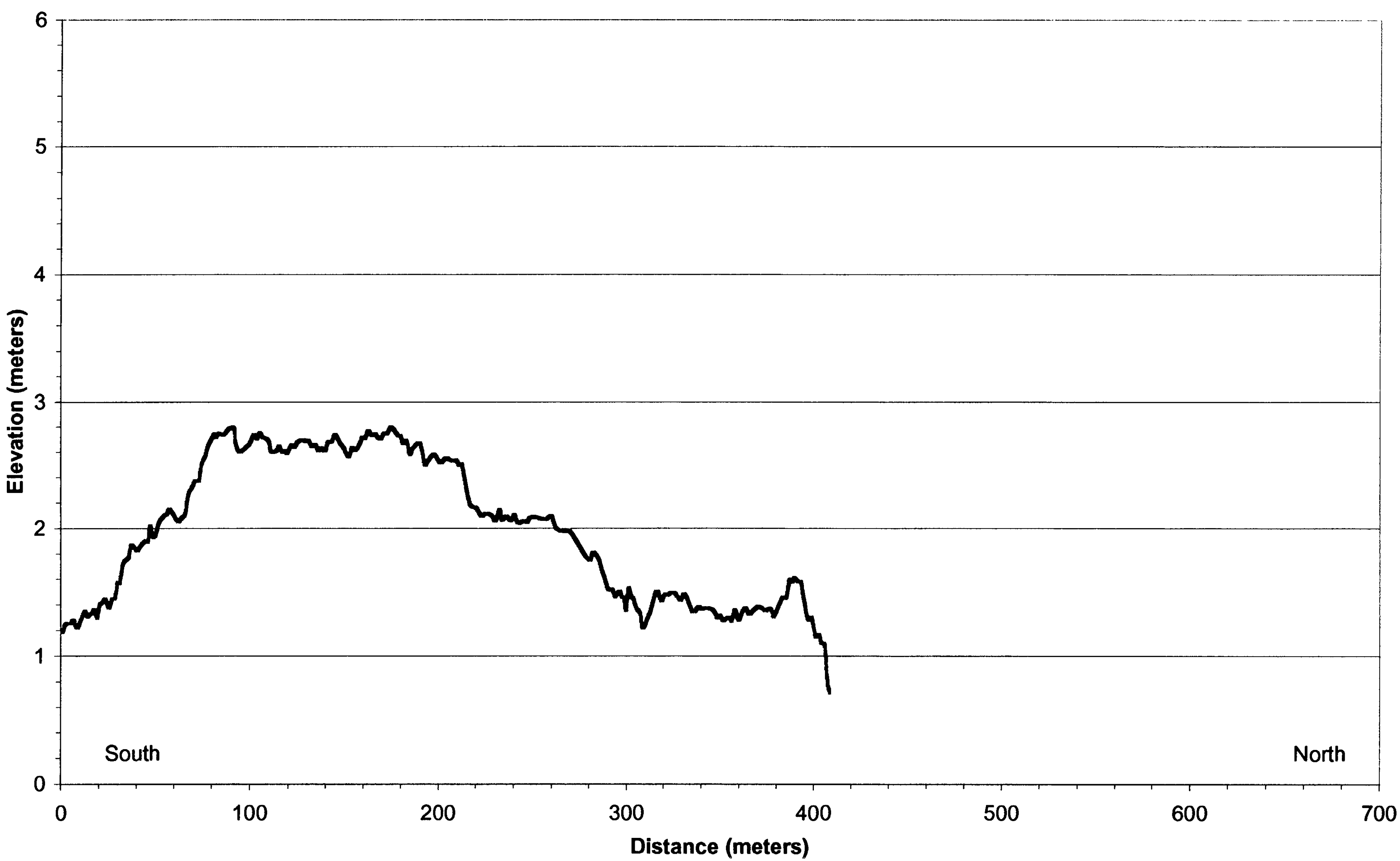
5
4
3
2
1
0
South
North
0
100
200
300
400
500
600
700
Distance (meters)

Transect 29



Elevation (meters)
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1
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South
North
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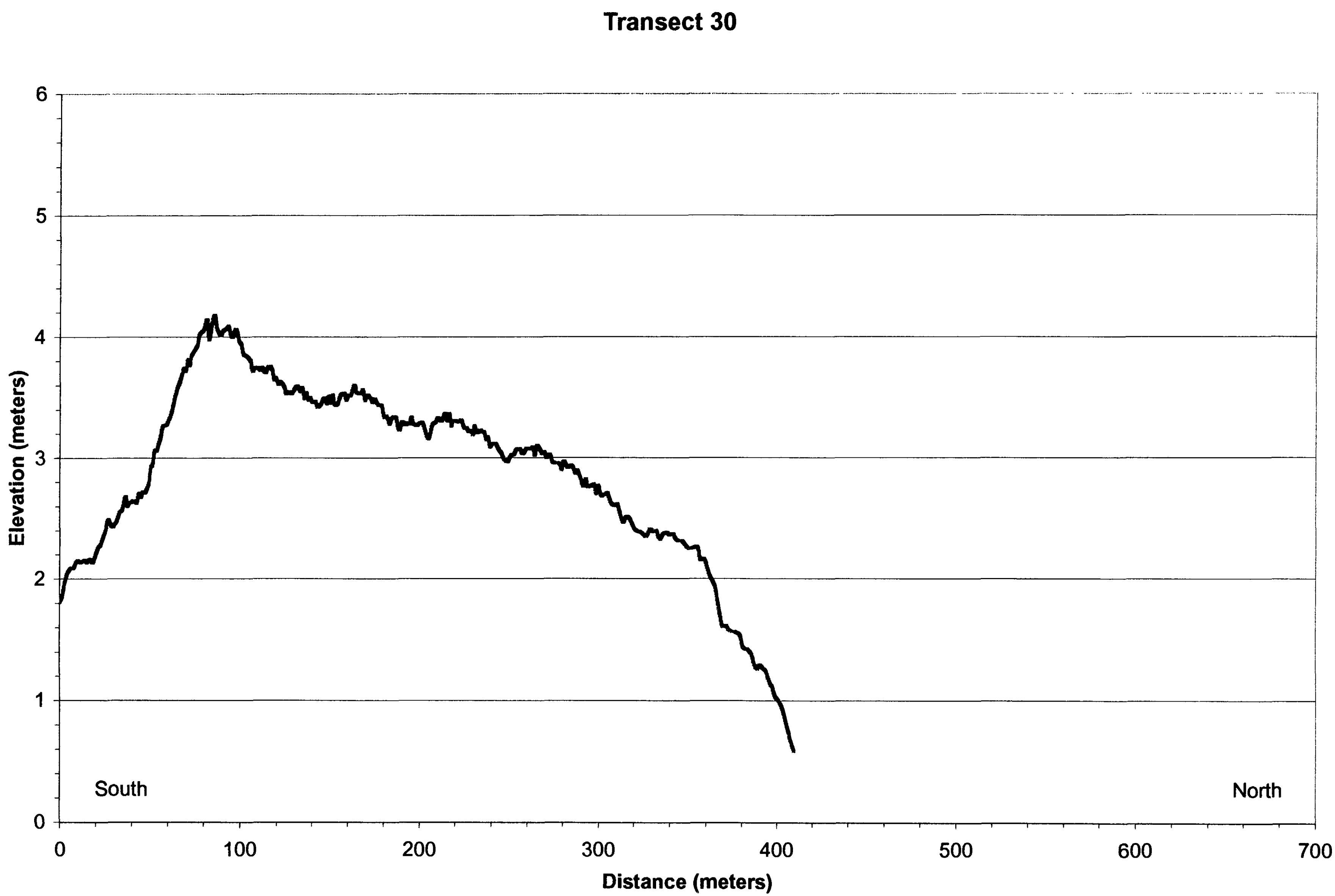
100
200
300
400
500
600
700
Distance (meters)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Elevation (meters)
Distance (meters)
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North
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1
2
3
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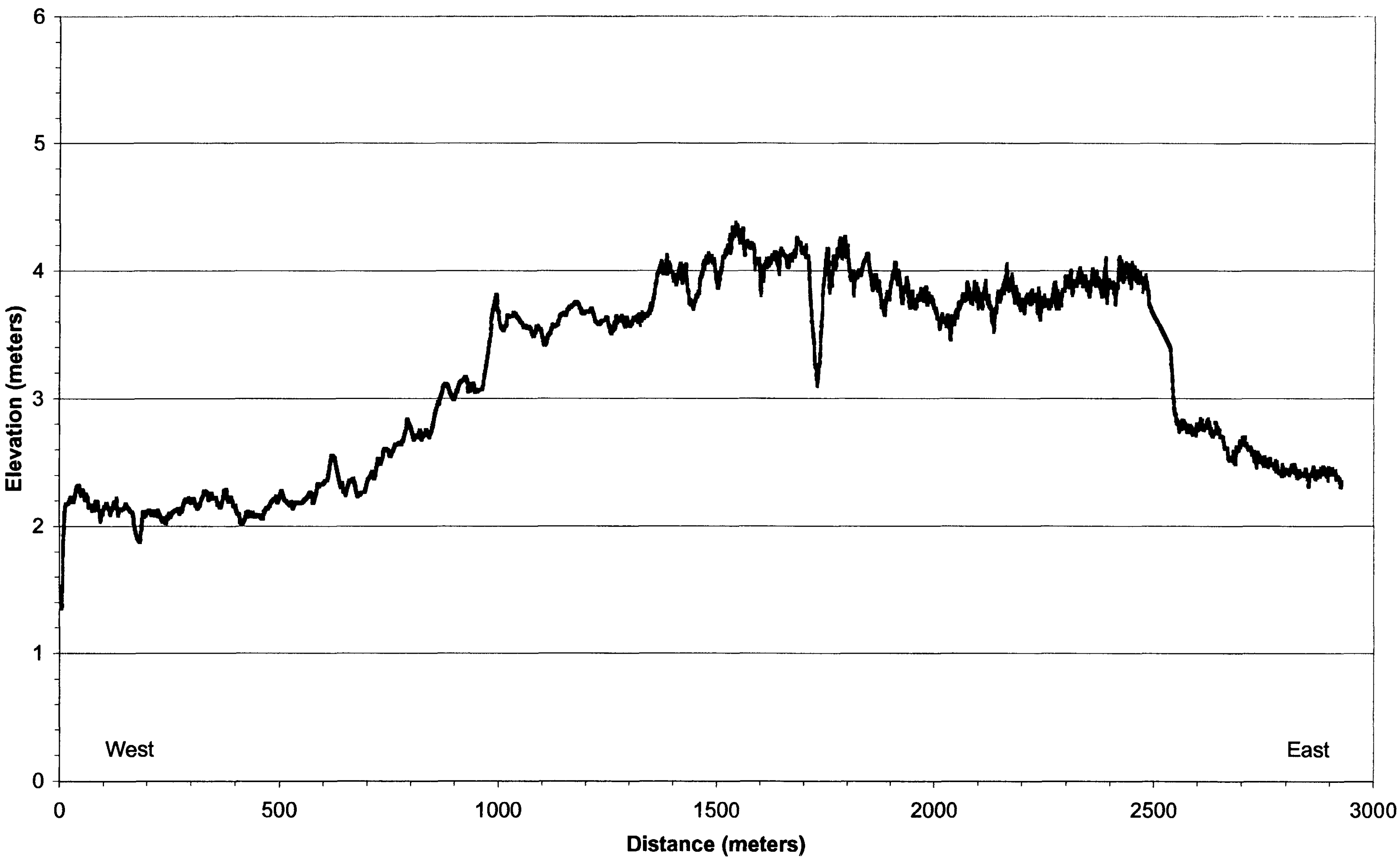
5
6
0
100
200
300
400
500
600
700

Transect 31


Elevation (meters)
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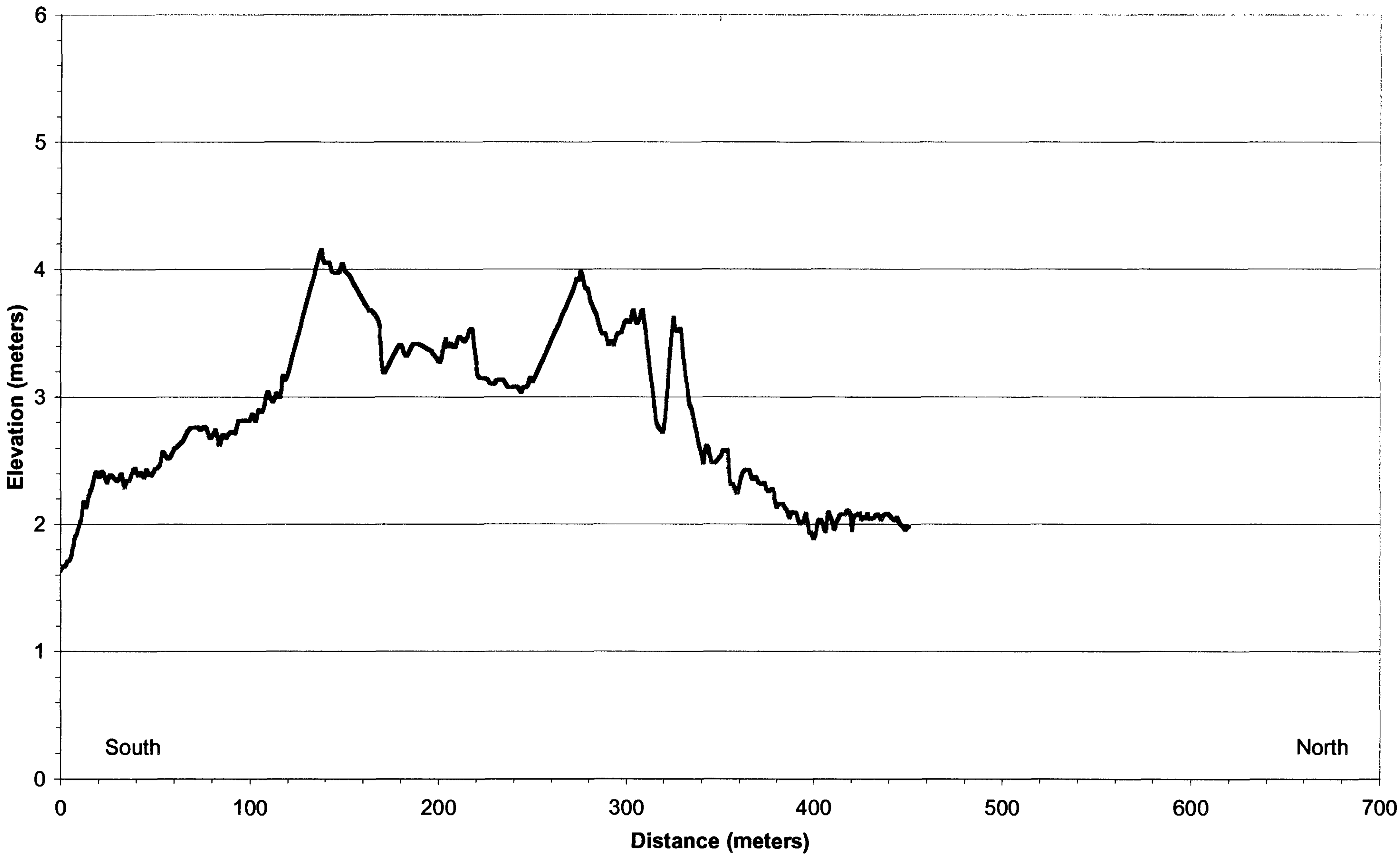
West
East
0
500
1000
1500
2000
2500
3000
Distance (meters)

Transect 32



Elevation (meters)
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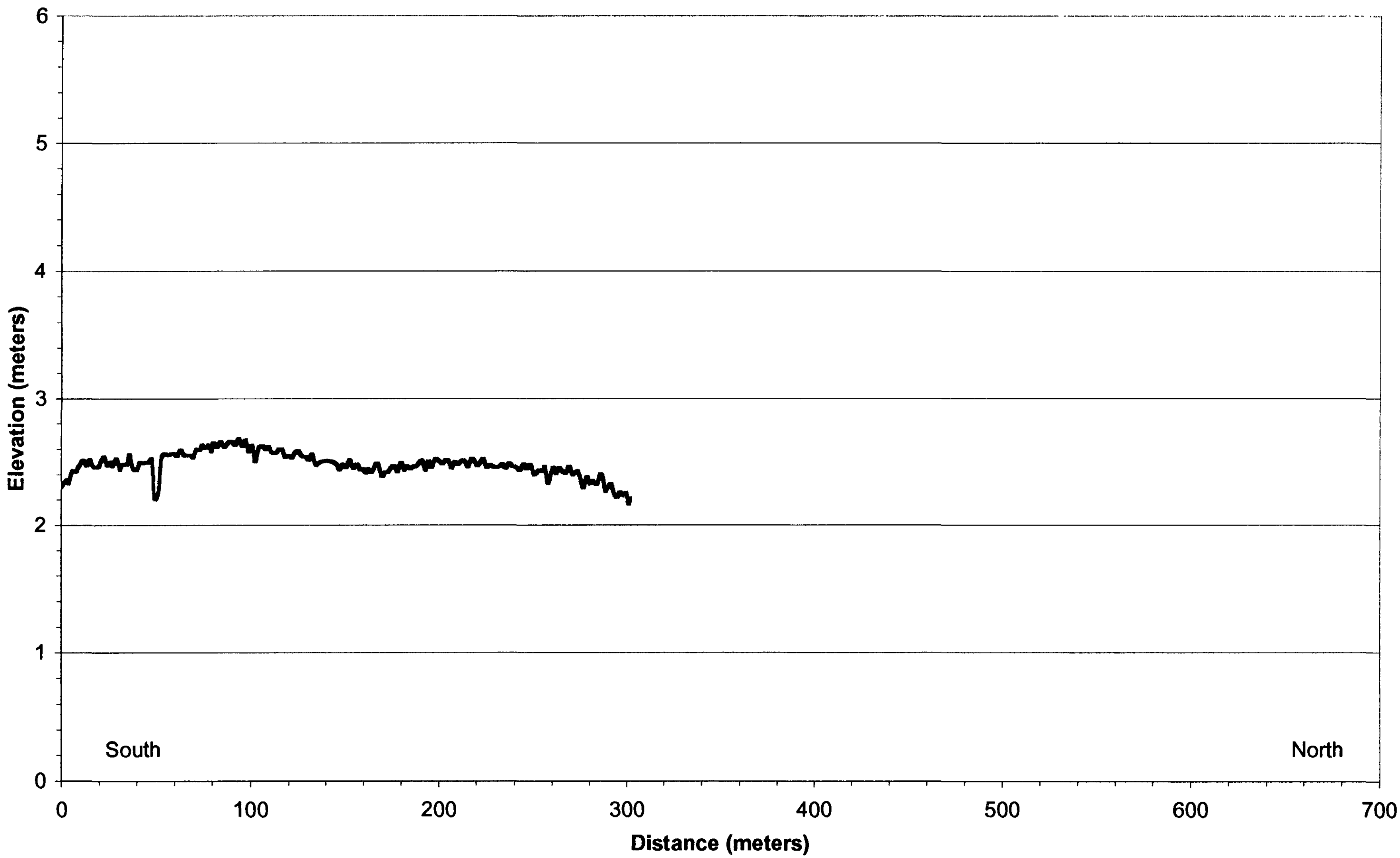
2
1
0
South
North
0
100
200
300
400
500
600
700
Distance (meters)

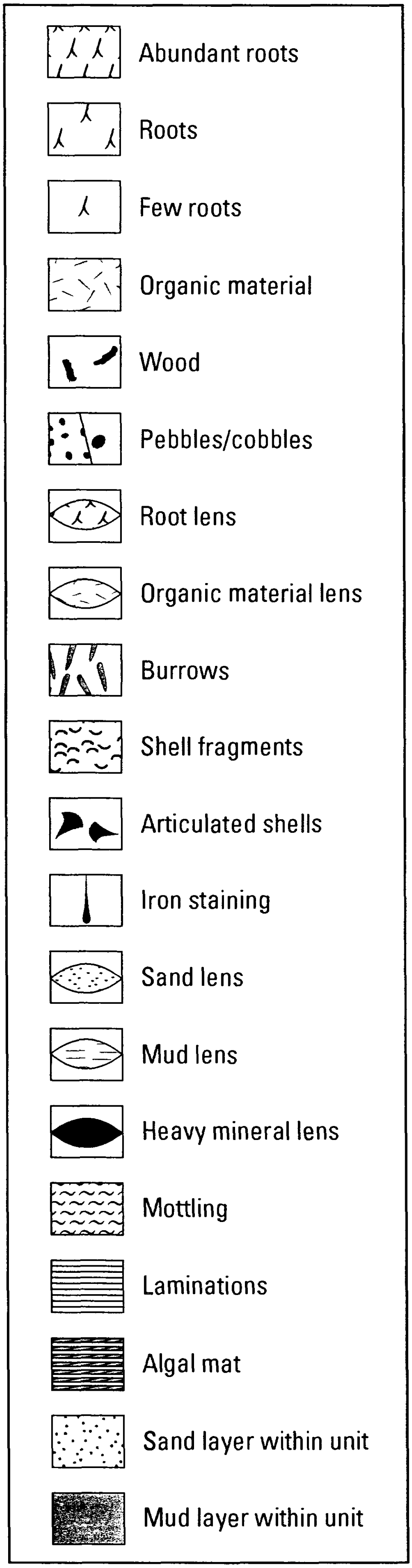
Transect 33

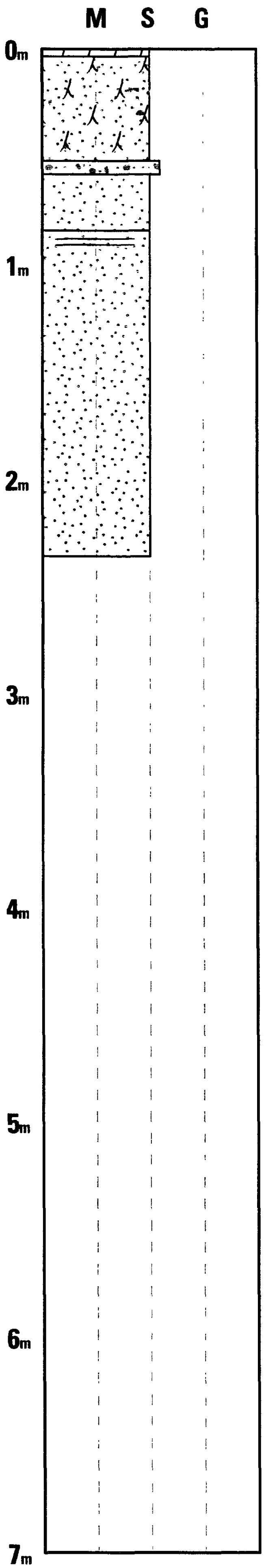


6
5
4
3
2
1
0
Elevation (meters)
South
North
0
100
200
300
400
500
600
700
Distance (meters)

APPENDIX B
CORE DESCRIPTIONS

Symbol Key


Abundant roots
Roots
Few roots
Organic material
Wood
Pebbles/cobbles
Root lens
Organic material lens
Burrows
Shell fragments
Articulated shells
Iron staining
Sand lens
Mud lens
Heavy mineral lens
Mottling
Laminations
Algal mat
Sand layer within unit
Mud layer within unit



Core # NC-092100-1

Location North Cove, Pacific Co. WA

GPSUTM 0422219 5174809 | Type vibracore

Length recovered 2.36 m | % Shortening 42

Date obtained 09/21/2000 | Date described 10/23/2000

0-2.5cm **Light Olive Gray Brown Rooted Sand** (5Y 5/4)

Root mat – roots: ~ 1cm diameter

Sand: fine-grained sand, subrounded-subangular, well sorted, 40% quartz, 60% rock fragments (yellow, green, gray, black)

* distinct contact

2.5-52cm **Light Olive Gray Brown Sand** (5Y 5/4)

Roots: very random, <1mm diameter

Sand: fine-grained sand, subrounded-subangular, well sorted, 40% quartz, 60% rock fragments (orange, green, black)

Gravel: very random (33cm, 42cm) pebble size (5-15mm), bladed/oblate

* distinct contact (but gravel is more like a lens)

52-58cm **Light Olive Gray Brown Gravely Sand** (5Y5/4)

~15% Gravel: pebbles, well rounded, bladed/oblate,

Rock fragments (gravel) – gray, green, purple (no obvious orientation within matrix)

Sand: same as 2.5-52cm (above)

* gradational contact

58-84cm **Moderate Olive Gray Sand** (5Y4/2)

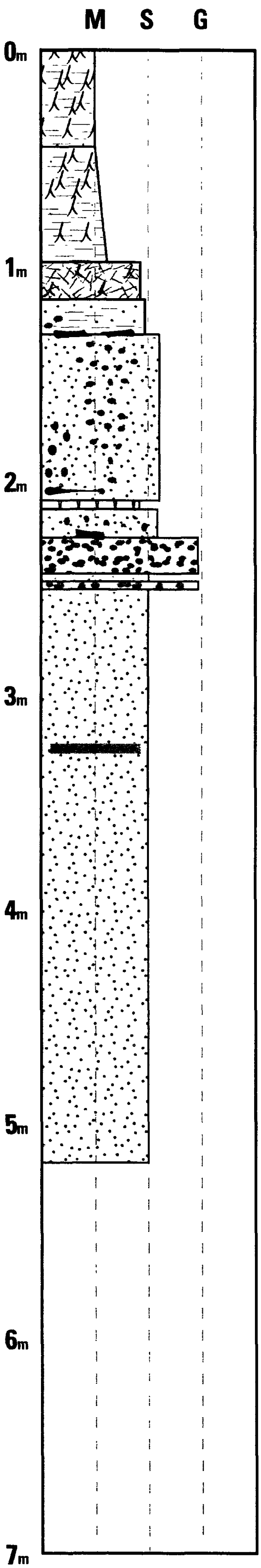
Sand: fine-grained sand, subrounded-subangular, well sorted, 20% quartz, 80% rock fragments (yellow, green, gray, black)

* gradational contact

84-236cm **Light Olive Gray Sand** (5Y 5/2)

Sand: fine-grained sand, subrounded-subangular, well sorted, 40% quartz, 60% rock fragments (green, black)

(-- vibracore section break at 108cm)



Core # NC-092100-2

Location North Cove, Pacific Co. WA

GPSUTM 0420301 5175463 — Type shovel & vibracore

Length recovered 5.18 m — % Shortening 10

Date obtained 09/21/2000 — Date described 10/26/2000

0-45cm **Red Brown Rooted Mud**
Root mat – dense at top, abundant thick roots
(-- shovel ends at 45cm, vibracore begins below)

45-98cm **Olive Gray Organic Mud** (5Y 3/2)
Roots: 20% .5-2mm, 80% ≤ 1 – fibrous, root density greatest 45-51cm, root density decreases downcore within section
Some very fine-grained sand beginning ~75cm (but difficult to determine) bottom of section: ~3% sand, 97% mud
* distinct contact

98-115cm **Olive Gray Organic Muddy Sand** (5Y 3/2)
Mud: 20%
Sand: fine-grained sand, subrounded-subangular, well sorted, 40% quartz, 60% rock fragments (green, black)
Roots: (1), 1-2mm diameter root with pieces of darker organic material disseminated
* gradational contact

115-132cm **Olive Gray Muddy Sand** (5Y 3/2)
Mud: 10%
Sand: fine-grained sand, subrounded-subangular, well sorted, 40% quartz, 60% rock fragments (green, black)
2 pebbles at 128cm and 130cm
* distinct contact (color change and wood remnants)

132-209cm **Moderate Olive Brown Gravely Sand** (5Y 4/4)
Sand: fine-medium-grained sand, subrounded-subangular, poorly sorted, 40% quartz, 60% rock fragments (orange, green, black)
~ 15% Gravel: rounded granules, pebbles, 1 cobble disseminated – with larger size gravel generally between 174-187cm
% gravel decreases downcore within section
Light Brown (5YR 5/6) iron stained area between 191-196cm (v-shaped, open to left)
(-- vibracore section break at 134cm)
* distinct contact (sand-filled burrows penetrating top of muddy sand)

209-213cm **Light Olive Brown Muddy Sand** (5Y 5/4)
Mud: 30% (mud gives this section a lighter color)
Sand: fine-grained sand, subrounded-subangular, well sorted, 40% quartz, 60% rock fragments (yellow, green, gray, black)
Some iron staining (orange) disseminated around/at contact (below) with 2 or more gravel clasts (saprolites)
* gradational contact

213-227cm **Moderate Olive Brown Gravely Sand**
Sand: see 132-209cm
* distinct contact (also: piece of driftwood)

227-243cm **Moderate Olive Brown Sandy Gravel** (5Y 4/4)
Sand: 10% - see sand 132-209cm
Gravel: 90% - coarse sand to pebble size clasts, rounded
(-- vibracore section break at 234cm)
* distinct contact

243-247cm **Moderate Olive Brown Sand**
Sand: fine-medium-grained sand, subrounded-subangular, poorly sorted, 40% quartz, 60% rock fragments (orange, green, black) (see 132-209cm and 213-227cm)
* distinct contact

247-251cm **Moderate Olive Brown Sandy Gravel**
Same as 227-243cm but smaller size gravel, 10% sand, 90% gravel
* distinct contact (with ~5 cm drag)

251-518cm **Moderate Olive Brown Sand** (5Y 4/4)
Sand: fine-medium-grained sand, subrounded-subangular, poorly sorted, 40% quartz, 60% rock fragments (orange, green, black) (see 132-209cm and 213-227cm)
More mica, very random coarse grained sand and fine pebbles
325-327cm increase in mica in a layer/lens
328.5cm - 1mm (thin) stiff layer
(-- vibracore section break at 334cm)