Historical Shoreline Changes at Rincón, Puerto Rico, 1936-2006

By E. Robert Thieler, Rafael W. Rodríguez, and Emily A. Himmelstoss

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Conversion Factors and Abbreviations

SI to Inch/Pound

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
Rate		
meter per year (m/yr)	3.281	foot per year ft/yr)

Sea level, as used in this report, refers to the global mean sea level.

ACRONYMS	DEFINITIONS
CRIM	Centro de Recaudación de Ingresos Municipales of the Puerto Rico Office of Management and Budget
DSAS	Digital Shoreline Analysis System
ESRI	Environmental Systems Research Institute
GIS	Geographic Information System
GPS	Global Positioning System
IPCC	Intergovernmental Panel on Climate Change

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Abstract

The coast from Punta Higüero to Punta Cadena in Rincón, Puerto Rico is experiencing long-term erosion. This study documents historical shoreline changes at Rincón for the period 1936-2006 and constitutes a significant expansion and revision of previous work. The study area extends approximately 8 km from Punta Higüero to Punta Cadena. Fourteen historical shoreline positions were compiled from existing data, new orthophotography, and Global Positioning System (GPS) field surveys.

The study area can be divided into four distinct reaches on the basis of observed erosion rates, consistent with previous work. The coast of Reach A, from Punta Higüero to the north end of the Balneario de Rincón, is fairly stable and has a long-term (70 years) average erosion rate of -0.2 ± 0.1 m/yr. The coast of Reach B, from the Balneario de Rincón to 500 m south of the mouth of Quebrada los Ramos, has an average long-term erosion rate of -1.1 ± 0.3 m/yr. The coast of Reach C, from 500 m south of the mouth of Quebrada los Ramos to Córcega has an average long-term erosion rate of -0.4 ± 0.2 m/yr. The coast of Reach D, from Córcega to Punta Cadena, has an average long-term change rate of -0.2 ± 0.2 m/yr.

Previous work (Thieler and others, 1995) identified an apparent increase in erosion rate in Reach B that probably began between 1977 and 1987. New data and statistical analysis suggest that long-term and short-term rates of shoreline change are statistically similar. Nevertheless, the coast in Reach B is eroding at a rapid and statistically significant rate that is 2 to 10 times greater than in the other three reaches. Comparison of the 1994 and 2006 GPS shoreline positions indicates the following erosion rates occurred over the past 12 years: Reach A, -0.3 ± 0.4 m/yr; Reach B, -1.0 ± 0.4 m/yr; Reach C, -0.7 ± 0.4 m/yr; and Reach D, -0.3 ± 0.4 m/yr.

Thieler and others (1995) speculated that the increased erosion rate in Reach B could be attributed to the effects of marina construction in 1983 on the local sediment budget. New data and analysis suggest, however, that other factors may be equally or perhaps more important. For example, high-resolution lidar bathymetric data collected in 2001 show a complex nearshore bathymetry that may substantially affect wave refraction, diffraction, and reflection in Reach B where erosion rates are the highest. In addition, several historical photographs dating from 1951 to 2006 show a wide array of complex wave patterns that suggest the bathymetric influence on nearshore processes to be a long-term, rather than recent, phenomenon. In addition, removal of sand from the beach system may be contributing further to the elevated erosion rates in Reach B.

Development of potential options for addressing coastal erosion in Rincón was beyond the scope of this study, but the data and interpretations presented here provide a sound scientific foundation for further work to identify the causes of the increased erosion and to develop strategies to mitigate its effect.

Introduction

Coastal erosion is a widespread and ongoing process in Puerto Rico (Bush and others, 1995). As discussed by Thieler and others (1995), coastal erosion in Rincón is well documented. A previous assessment of shoreline change in Rincón (fig. 1) by Thieler and others (1995) computed long-term (44 years from 1950-1994) erosion rates and identified four distinct coastal reaches between Punta Higüero and Punta Cadena (fig. 2). Reach A, from Punta Higüero to just south of Punta Ensenada, was characterized as a relatively stable to slowly-eroding coast comprised of a thin sandy beach overlying various indurated (rocky) substrates. Reach B, from south of Punta Ensenada to south of Quebrada los Ramos, was characterized as a rapidly eroding sandy coast backed by unconsolidated alluvial deposits. There appeared to be a change in trend toward increasing erosion in Reach B between 1977 and 1987. Reach C, from south of Quebrada los Ramos to Córcega, was characterized as a slowly eroding sandy coast backed by unconsolidated alluvial deposits. Reach D, from Córcega to Punta Cadena, was characterized as a stable to slowly eroding sandy coast backed primarily by unconsolidated alluvial deposits.

Beaches within the study area are composed primarily of biogenic shelf carbonates and river-derived terrigenous material (Morelock, 1987). The primary sources of new sediment to the beach system are biological production and bioerosion of nearshore reefs, as well as erosion of both modern and relict alluvial deposits along the coast. The direction of net alongshore drift is to the south (Morelock, 1987).

Morelock (1987) describes the west coast of Puerto Rico as compartmentalized, with little to no sediment exchange between adjacent littoral cells. The insular shelf between Punta Higüero and Punta Cadena (the Rincón - Córcega littoral cell) is generally less than a few hundred meters wide. This situation further limits sediment transport between littoral cells; some sand is probably lost off the shelf into deeper water.

Thieler and others (1995) attribute an apparent increase in erosion rate in Reach B between 1977 and 1987 largely to the 1983 construction of a marina facility and its associated breakwater/jetty system, as well as sand-management practices that allowed dredged material to be removed from the coastal system instead of being bypassed to the downdrift coast. They predicted that the prevailing human response to erosion – building of seawalls and revetments – would lead to destruction of the beaches. Over the past 13 years, that has been the case: erosion has continued and there is little to no beach fronting most of the seawalled portions of the coast, particularly within Reach B. Since 1994, the length of shoreline fronted by seawalls and revetments also has increased.

This report documents shoreline changes that have occurred since the 1994 field survey and shoreline change-rate estimates reported by Thieler and others (1995), and constitutes a substantial expansion and revision of the previous work. The shoreline-change data and analysis presented in this report is expanded to include additional historical shorelines, as well as new GPS-based shoreline positions obtained in December 2005 and December 2006. The new shoreline data, as well as new ancillary data for the area, allow for a more refined picture of shoreline change trends and the potential underlying causes.

Methods

Historical shoreline positions spanning the period 1936-2006 were compiled using data from previous work (Thieler and Carlo, 1995), new shoreline positions digitized from georeferenced aerial photographs, and December 2005 and December 2006 GPS field surveys. A total of 14 shoreline positions were used for analysis (table 1). The 1950, 1963, 1971, 1974, 1977, 1987, and 1989 shorelines were produced by Thieler and Carlo (1995) using the Digital Shoreline Mapping System (Thieler and Danforth, 1994). The 1994, 2005, and 2006 shorelines were obtained by GPS field survey following methods described by Thieler and Carlo (1995). The 2004 shoreline was digitized from an orthophotograph supplied by the U.S. Army Corps of Engineers using ESRI ArcGIS software. The 1936 and 1983 shoreline positions were digitized using ESRI ArcGIS software from digital rectified aerial photograph mosaics produced by the U.S. Geological Survey Coastal Field Station at the University of Rhode Island.

The Digital Shoreline Analysis System (DSAS) version 3.2 (Thieler and others, 2005) was used to construct shore-perpendicular transects along the shoreline from Punta Higüero to Punta Cadena (fig. 3). A nominal spacing of 50 m between transects was used. The DSAS computes shoreline change using several different methods: (1) simple linear regression (2) weighted least squares regression, (3) least median of squares regression, and (4) endpoint rate. These and other methods of estimating shoreline change are described by Genz and others (2007). The standard error, correlation coefficient, and confidence interval also were computed for the simple and weighted least squares methods. A 95-percent confidence interval was selected to express the uncertainty associated with the rate of change statistics.

A SHOALS lidar bathymetry survey (see *http://shoals.sam.usace.army.mil* for information) was conducted in the study area during 2001. These data were obtained from the USGS lidar data repository in St. Petersburg, Florida. The lidar data were supplied as binned data with a horizontal resolution of 7.6 m. The nominal vertical accuracy of the data is 30 cm. The SHOALS data were gridded and visualized using IVS 3D Fledermaus software.

Historical Shoreline Changes, 1936-2006

The study area (fig. 1) can be divided into four distinct reaches (fig. 2) based on erosion rate, which is consistent with previous work. The simple and weighted least squares regression techniques yield generally similar shoreline rates of change. The weighted least squares regression results are used here. Average rates of change are shown in table 2. The coast in Reach A, from Punta Higüero to the north end of the Balneario de Rincón, is stable to slowly eroding and characterized by a long-term (70 years) average erosion rate of -0.2 ± 0.1 m/yr (fig. 4). In Reach B, from the Balneario de Rincón to 500 m south of the mouth of Quebrada los Ramos (approximately where the Rincón of the Seas resort fronts the ocean), the coast has a long-term average erosion rate of -1.1 ± 0.3 m/yr (fig. 5). Reach C extends from 500 m south of the mouth of Quebrada los Ramos to Córcega (a point on the beach seaward of where Carretera 429 joins Carretera 115). Here, the long-term erosion rate averages -0.4 ± 0.2 m/yr (fig. 6). Reach D, from Córcega to Punta Cadena, is characterized by long-term average shoreline change rates of -0.2 ± 0.2 m/yr (fig. 7).

End-point shoreline change rates were calculated for the two GPS field surveys done in 1994 and 2006 (table 2). These surveys are the most accurate available and are based on data obtained while actually walking the shoreline rather than interpretation of remotely sensed data. The average rates of change over the past 12 years are: Reach A -0.3 ± 0.4 m/yr (fig. 8), Reach B -1.0 ± 0.4 m/yr (fig. 9), Reach C -0.7 ± 0.4 m/yr (fig. 10), and Reach D -0.3 ± 0.4 m/yr (fig. 11).

Regional Bathymetry

The SHOALS lidar bathymetry is shown in figure 12. The insular shelf off the study area shows a complex and variable bathymetry. From Punta Higüero to Punta Ensenada, the shelf is dominated by rocky outcrops and coral reefs. There are two shore-parallel troughs that begin about 1 km north of Punta Ensenada and extend to the southeast. These troughs terminate just south of Punta Ensenada. Figure 13 shows an apparent shoal feature located offshore of the small embayment formed between Punta Ensenada and a small point just south of Quebrada los Ramos. The lobate morphology at the southeastern tip, and the possible presence of surficial bedforms (fig. 13), suggest the feature may be at least partially composed of unconsolidated sediment. A 1997 orthophotograph of the study area obtained from the Centro de Recaudación de Ingresos Municipales (CRIM) of the Puerto Rico Office of Management and Budget has sufficient water clarity to permit identification of what appears to be sandy deposits on the shoal (fig. 14). The possible bedforms, however, also could be structurally controlled. That is, the morphology and internal structure of the shoal may be influenced substantially by the underlying geologic framework. It is unknown whether or how much of the shoal is comprised of unconsolidated sediment.

The insular shelf between Quebrada los Ramos and Córcega is generally smooth and narrow, averaging about 500 m in width (fig. 12). Seaward of Punta Cadena, the shelf is about 1 km wide; a shelf-edge reef is present on the seaward margin. Data coverage in the nearshore zone is sparse; what data exist suggest that the rocky outcrops present on the beach in this area extend into the nearshore zone.

Discussion

The shoreline change data are discussed here in the context of the long- and short-term trends within the reaches identified in the study area. These analyses are limited by the lack of historical bathymetric data, detailed knowledge of the local geologic framework and sediment thickness, and physical oceanographic information. The shoreline changes are interpreted to reflect a multitude of potential underlying causes, including but not limited to

- the influence of underlying geology in the nearshore;
- interactions between the bathymetry of the insular shelf and physical oceanographic processes, such as waves and currents;
- long-term rise in relative sea level;
- hard stabilization along the coast, including both the jetty/breakwater at the Punta Ensenada marina as well as the ongoing installation of seawalls and revetments; and
- sand-management practices that allow removal of sand from the coastal system.

Reaches A and D

The long-term (1936-2006) and short-term (1994-2006) shoreline changes in Reaches A and D suggest a generally stable to slowly eroding coast in these areas. The average rate of change in Reach A indicates very slow long-term erosion. The average rate of change in Reach D is centered around zero and is not statistically significant within the resolution of the data and methods used in this study. In Reach A, the beach is a prism of sand overlying a rocky substrate that appears to erode and accrete in response to storms and seasonal variations in wave energy. The temporal spacing of the data, however, does not resolve such events. A 200 m stretch of coast near the “Steps” surfing beach (transects 27-31) shows a short-term trend of statistically significant erosion, but this could be due to a seasonal difference between the August 1994 survey and the December 2006 survey, recent storm history, or other factors.

The coast in Reach D has a similar geological setting. South of Córcega, the seaward extension of the Cerros de San Francisco appears to provide an underlying rocky substrate on which the beach is perched. The northern half of this reach (transects 119-139) may be backed by alluvial sediments and receive sediment input from Quebrada Grande de Calvache. Statistically significant long-term and short-term rates of shoreline change also are present in this area. As discussed below, it is possible that coastal erosion in updrift reaches (Reaches B and C) could be contributing sediment to this downdrift segment of the coastal system. If so, this could result in the "masking" of a real underlying trend of erosion due to a greater than normal supply of sediment.

Reach B

Historical shoreline changes in Reach B are quite complex. The long-term average erosion rate for the entire reach is -1.1 m/yr, but there is substantial alongshore variability (fig. 5). Reach B can be considered to have four subdivisions (fig. 15), based on examination of shoreline positions through time.

Reach B-1 (transects 55-61; fig. 16) comprises the Balneario de Rincón. This sub-reach appears to have had a generally fluctuating shoreline position since 1936. A large erosional event is recorded by the 1971 shoreline, with substantial recovery by 1974. The data indicate erosion occurred from 1974 to 1983. The shoreline was stable from 1983 through 1994. Since 1994, erosion has predominated at the north end of this sub-reach. Hard stabilization at transect 61 has pinned the shoreline in place since 1989.

Reach B-2 (transects 62 through 68/69; fig. 17) shows a fluctuating shoreline through 1977. By 1983, the shoreline had retreated about 50 m from the average position of the 1936-1977 shorelines. Between 1994 and 2006, over 30 m of shoreline retreat occurred at transects 68 and 69, leaving some infrastructure exposed in the surf zone (fig. 18).

Historical shorelines in Reach B-3 (transects 68/69 through 77; fig. 19) indicate a steadily eroding coast from 1936 to 1983. The shoreline position was stable from 1983 to 1989, and subsequently began eroding at about -1.5 m/yr. This coastal sub-reach was stabilized with a rock revetment sometime between 1994 and 2005. Vegetation obscures the shoreline in the 2004 orthophotograph of this area, so it is unclear whether the structure was present at that time.

Reach B-4 (transects 78-85; fig. 20) marks a transition from the complex shoreline behavior of Reaches B-1 to B-3 to the more consistent trend of Reach C. Long-term rates of erosion average just over -0.5 m/yr and decrease to the south.

The varied shoreline changes in Reach B and its subdivisions can be interpreted in the context of the nearshore and offshore geology of the area, as well as the history of human modification of the shoreline and impacts on the local sediment budget. In the southern end of Reach A, from Punta Ensenada to transect 54, clear-water aerial photography [for example, the 1997 CRIM photography (see fig. 14) or the imagery currently available in Google Earth (see *http://earth.google.com*)] shows the presence of nearshore rocky/reefal outcrops. The relatively stable coast in this area may be due to the influence of this shallow, underlying geologic framework, which is similar to the coastal stability observed north of Punta Ensenada. Such framework is not apparent between transects 55-75. Nearshore rock/reef also is present south of the mouth of Quebrada los Ramos, where the magnitude of the shoreline changes decreases.

There is not an obvious explanation for the fluctuating shoreline position in Reach B-1. It is possible that this area is impacted preferentially by storms or wave events coming from the south or west that move sand from the upper beach to the shallow nearshore. Over time, the sand is likely to be returned to the upper beach by fair-weather wave processes. This location also may receive episodic influxes of sediment from alongshore or offshore.

As shown in figure 13, the large offshore shoal feature appears to attach to the beach in Reach B-2. It may be that the historical shoreline stability here is due to onshore or obliquely alongshore sediment transport from the shoal. It is possible that the substantial erosion, indicated by the 1983 and later shorelines, is due to the impacts of the jetty/breakwater system at Punta Ensenada, which is consistent with that proposed by Thieler and others (1995). In this scenario, sediment flux along the beach could have been impounded by the marina and the volume of longshore transport reduced by the associated dredged material removal. It is also possible that the construction of the seaward jetty/breakwater on the rocky platform seaward of the historical “ambient” shoreline position of Punta Ensenada (fig. 21) is causing sediment to be deposited into deeper water where it is not able to return in substantial quantity to the beach. Accurate historical bathymetry and other data such as offshore sediment distribution and thickness would be required to test this speculation. Unfortunately, the requisite data apparently do not exist.

The offshore shoal body appears to exert a substantial influence on the nearshore wave energy in Reach B-2. As shown in figure 22, historical aerial photography shows a very complex pattern of reflected, refracted, and diffracted waves in this area that is not present in the other coastal reaches. This pattern was present at least periodically during large wave events since at least 1951, and could be a long-term feature of the nearshore oceanography of this region. It is unclear what impact on shoreline change such complex wave patterns and associated sediment transport may have. The spatial and temporal association of the wave patterns and shoreline change history, however, suggests a possible, albeit unknown, linkage. It is possible that physical oceanographic measurements (waves, currents, sediment transport) and modeling studies could provide insight into what linkages may exist here.

The consistent erosional trend in Reach B-3 from 1936 to 1983 could represent normal background erosion in this area. The period of shoreline stability from 1983 to 1989 could be due to a temporary increase in sediment supply from erosion of the updrift coast. As described above, much of this shoreline has been stabilized recently with a rock revetment. As described above, Reach B-4 appears to mark a transition from the complex shoreline behavior of Reaches B-1 to B-3 to the more consistent trend of Reach C.

Reach C

The long-term (1936-2006) erosion trend in Reach C averages -0.4 m/yr (fig. 5). The trend is very consistent over time, and consequently the error estimates of the regression used to compute the rates are small. Short-term (1994-2006) erosion rates average -0.7 m/yr, which is nearly double the long-term average. It is possible that the short-term rates are biased by seasonal or storm-related influences; at least four named tropical systems (Dennis, Emily, Alpha, and Gamma) passed to the south of Puerto Rico during the late summer and fall of 2005. Local observers reported substantial erosion in Reach C from these storms, although by the time of field surveys in December 2005, a great deal of beach recovery (seaward progradation and volume gain) had taken place. The long-term trend of erosion can be expected to continue; it probably reflects the ongoing “background” erosion rate in this reach due to variations in sediment supply, sea-level change, and other factors.

Future Outlook

Historical shoreline changes in Rincón provide a basis for a general interpretation of this small but complicated coastal system. Past changes alone are an insufficient source of information to guide future planning; therefore, further studies of regional geology and sediment transport are needed to provide information on the major processes that govern shoreline change. Ideally, management decisions about Rincón's coast will be based on long-term and multidisciplinary considerations such as principal uses of the shoreline and the potential effects of various structures (for example, continued construction of seawalls will over time eliminate the fronting beaches), as well as the potential effects of future sea-level rise and climate change.

Model simulations reported by the Intergovernmental Panel on Climate Change (IPCC) indicated that sea level may rise by as much as 0.6 m over the remainder of this century (Bindoff and others, 2007). Some scientists have argued that this estimate is conservative and have suggested that a rise of 1 to 2 m by 2100 may be more realistic, given the exclusion of contributions of ice-melt from land-based ice from the IPCC projections (Overpeck and others, 2006; Hansen and others, 2007; Rahmstorf, 2007; Rahmstorf and others, 2007). A sea-level rise of 0.6 m by 2100 would represent more than a threefold increase in the rate of relative sea-level rise over that observed in San Juan from 1962 to 1999 (National Oceanographic and Atmospheric Administration, 2006). The historical trend of erosion along much of the Rincón coast indicates that future sea-level rise will likely result in a continuation of, or perhaps increase in, the rate of coastal erosion.

The coastal sedimentary system in Rincón contains a substantial carbonate component, presumably derived from the adjacent coral reefs. Future climate change that results in damage to the reefs (for example, Winter and others, 1998; Waddell, 2005), such that reef-sediment production is decreased, could cause a regional decrease in sediment supply and, in turn, increase coastal erosion.

Conclusions

The coast of Rincón is most likely eroding as a result of natural and human-induced causes. The coast in Reach A appears to be relatively stable, probably because a rocky substrate underlies the thin, sandy beach, and because human intervention in coastal processes has not occurred. The history of shoreline changes in Reach B is highly complex as a result of the varied geologic setting, in addition to physical processes such as waves and currents, and human modification of the shoreline. Together, these factors preclude definitive identification of causality. Continued hard stabilization over time most likely will ultimately result in the disappearance of the beaches in Rincón. The long-term trend of erosion in Reach C can be expected to continue. It is also possible that continued hard stabilization in Reach B will reduce the sediment supply to Reach C, resulting in increased erosion rates. The same is true in presently-stable Reach D; ongoing hard stabilization in Reaches B and C may lead to reduced sediment supply and an increase in erosion rates. Future management plans for the Rincón shoreline will ideally include consideration of the potential impacts of various management strategies, as well as future sea-level rise and climate change.

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References Cited

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley, L.D., and Unnikrishnan, A., 2007, Observations: Oceanic climate change and sea level, *in* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L., eds., Climate change 2007: The physical science basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York Cambridge University Press, p. 385-432.

Bush, D.M., Liboy, J.G., Hyman, L., Webb., R.M.T., and Neal, W.J., 1995, Living with the Puerto Rico shore: Durham, N.C., Duke University Press, 193 p.

Genz, A.S., Fletcher, C.H., Dunn, R.A., Frazer, L.N., and Rooney, J.J., 2007, The predictive accuracy of shoreline change rate methods and alongshore beach variation on Maui, Hawaii: Journal of Coastal Research, v. 23, no. 1, p. 87-105.

Hansen, J., Sato, M., Kharecha, P., Russell, G., Lea, D.W., and Siddall, M., 2007, Climate change and trace gases: Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, v. 365, no. 1856, p. 1925-1954.

Morelock, J., 1987, Beach sand budget for western Puerto Rico: Coastal Sediments '87, p. 1333-1345.

National Oceanic and Atmospheric Administration, 2006, Sea Levels Online, accessed November 23, 2006, at *http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=9755371*.

Overpeck, J.T., Otto-Bliesner, B.L., Miller, G.H., Muhs, D.R., Alley, R.B., and Kiehl, J.T., 2006, Paleoclimatic Evidence for future ice-sheet instability and rapid sea-level rise: Science, v. 311, no. 5768, p. 1747-1750.

Rahmstorf, S., 2007, A semi-empirical approach to projecting future sea-level rise: Science, v. 315, p. 368-370.

Rahmstorf, S., Cazenave, A., Church, J.A., Hansen, J.E., Keeling, R.F., Parker, D.E., and Somerville, R.C.J., 2007, Recent climate observations compared to projections: Science, v. 316, no. 5825, p. 709.

Thieler, E.R., and Carlo, M., 1995. Historical shoreline changes at Rincón, Puerto Rico: U.S. Geological Survey Open-File Report 95-72, 27 p.

Thieler, E.R., and Danforth, W.W., 1994, Historical shoreline mapping (II): Application of the Digital Shoreline Mapping and Analysis Systems (DSMS/DSAS) to shoreline change mapping in Puerto Rico: Journal of Coastal Research, v. 10, no. 3, p. 600-620.

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L. and Miller, T.L., 2005, Digital Shoreline Analysis System (DSAS) version 3.0; An ArcGIS extension for calculating shoreline change: U.S. Geological Survey Open-File Report 2005-1304. (Available online at http://woodshole.er.usgs.gov/project-pages/dsas/).

Thieler, E.R., Rodriguez, R.W., and Carlo, M., 1995, Beach erosion and coastal development at Rincón, Puerto Rico: Shore and Beach, v. 63, no. 4, p. 18-28.

Waddell, J.E., ed., 2005, The state of coral reef ecosystems of the United States and Pacific Freely Associated States, 2005: NOAA Technical Memorandum NOS NCCOS 11. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team, Silver Spring, Md., 522 p.
Winter, A., Appeldoorn, R.S., Bruckner, A., Williams, Jr., E.H., and Goenaga, C., 1998, Sea surface temperatures and coral reef bleaching off La Parguera, Puerto Rico (northeastern Caribbean Sea): Coral Reefs, v. 17, no. 4, p. 377-382.
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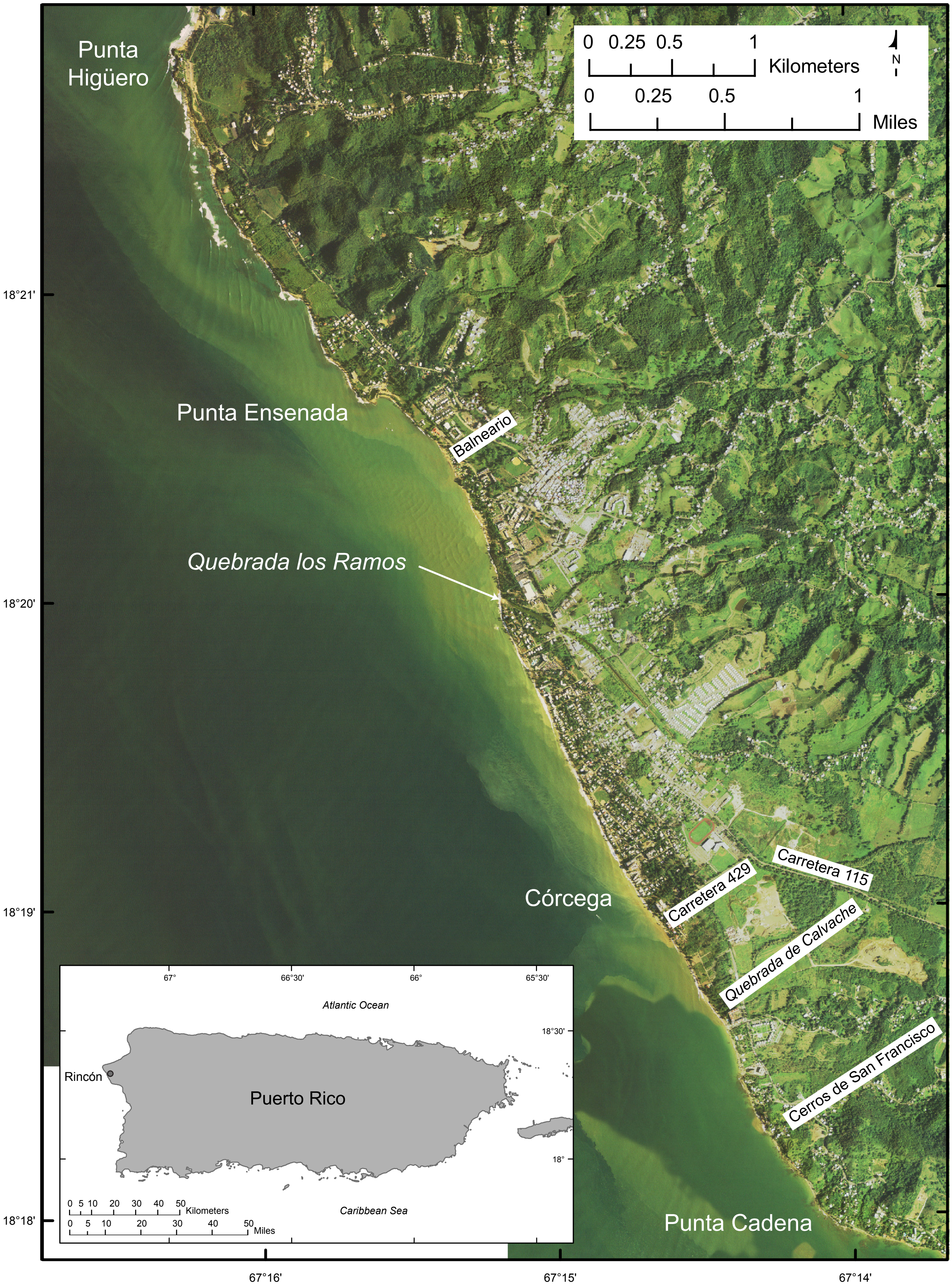

Figure 1. Map showing location of the study area in Rincón, Puerto Rico. (Image is a 2004 orthophotograph.)

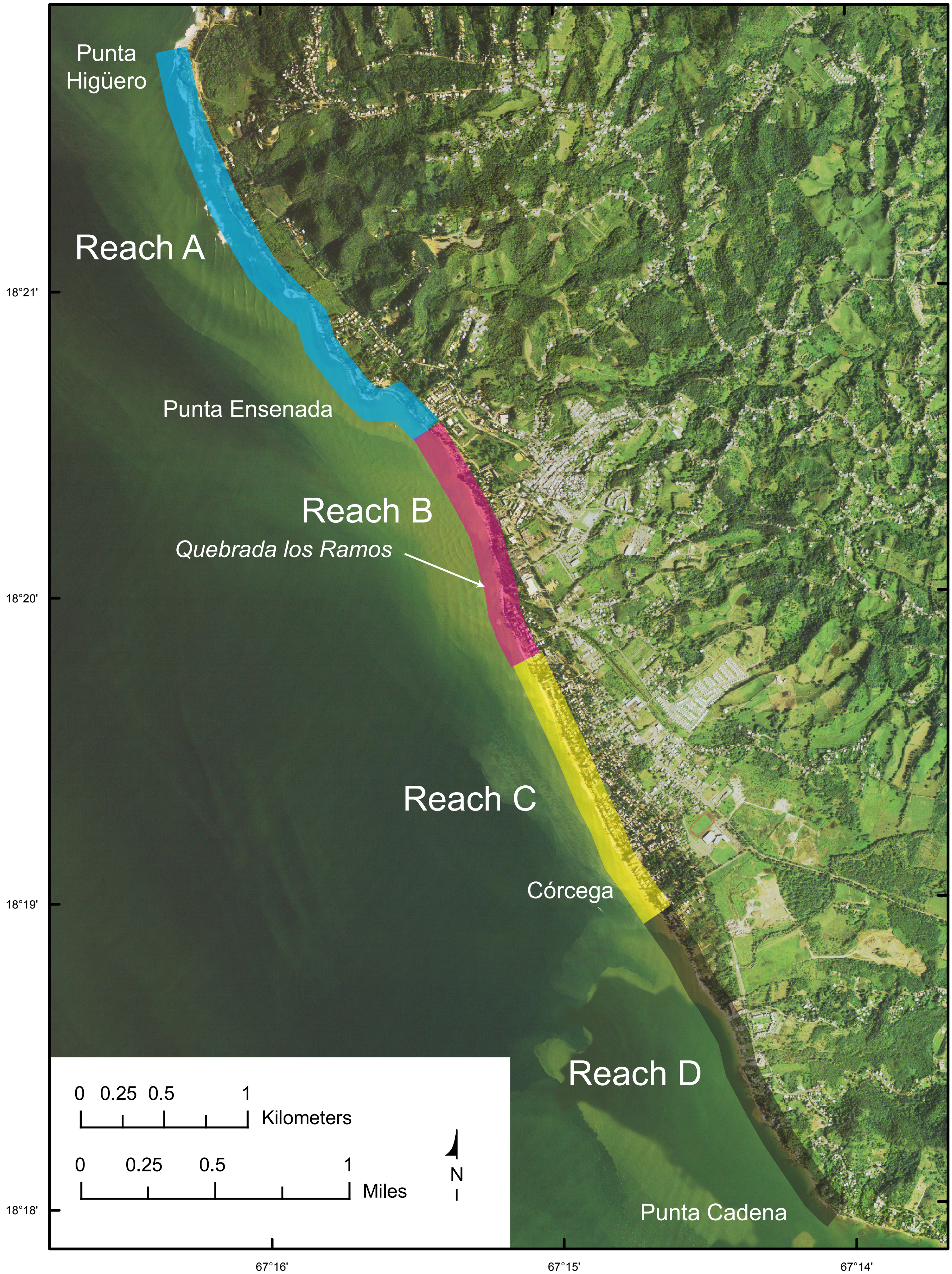

Figure 2. Map showing locations of four distinct shoreline reaches in the Rincon, Puerto Rico study area.

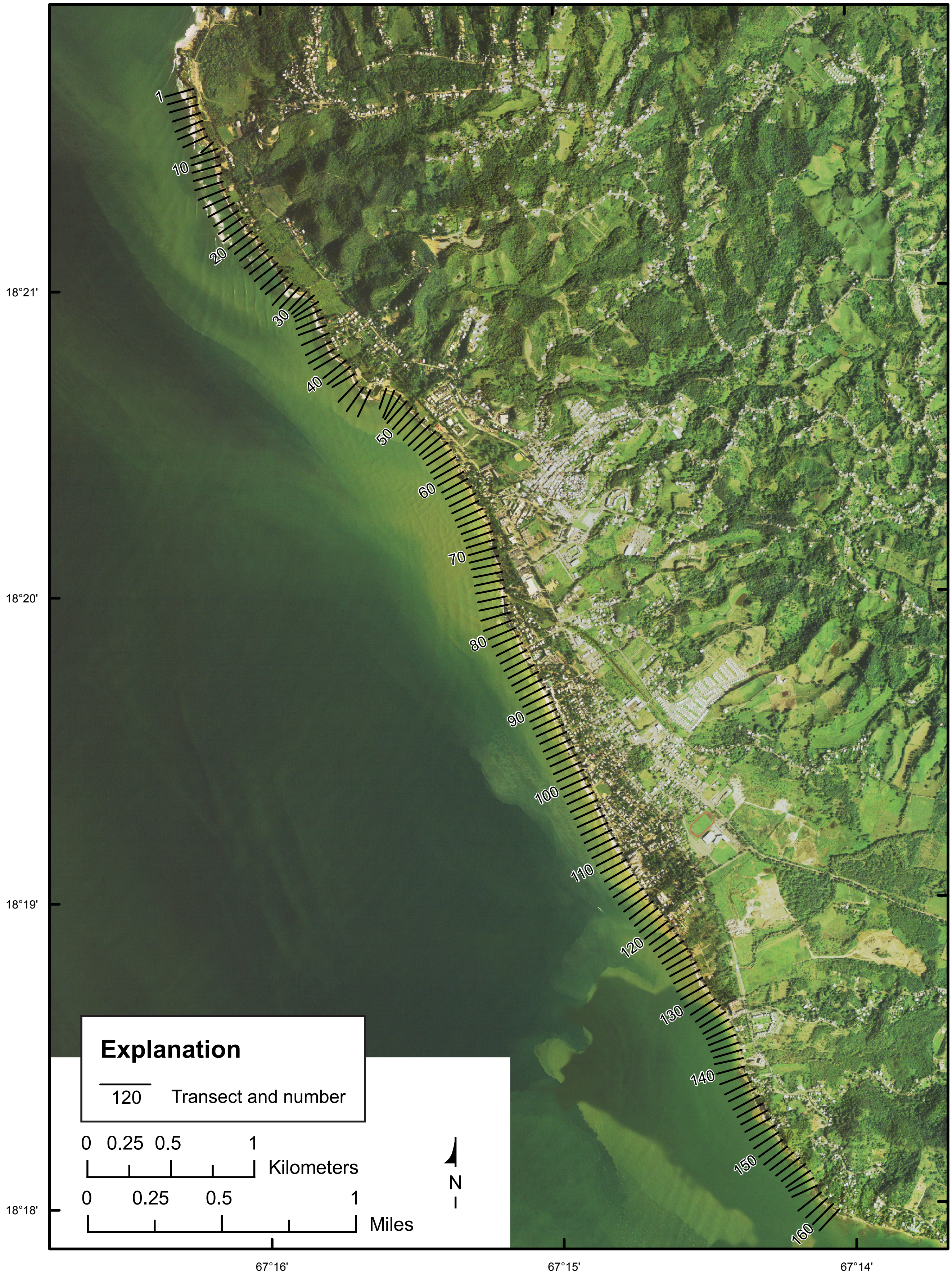

Figure 3. Map showing the location of transects used to calculate shoreline rates of change, Rincón, Puerto Rico study area.

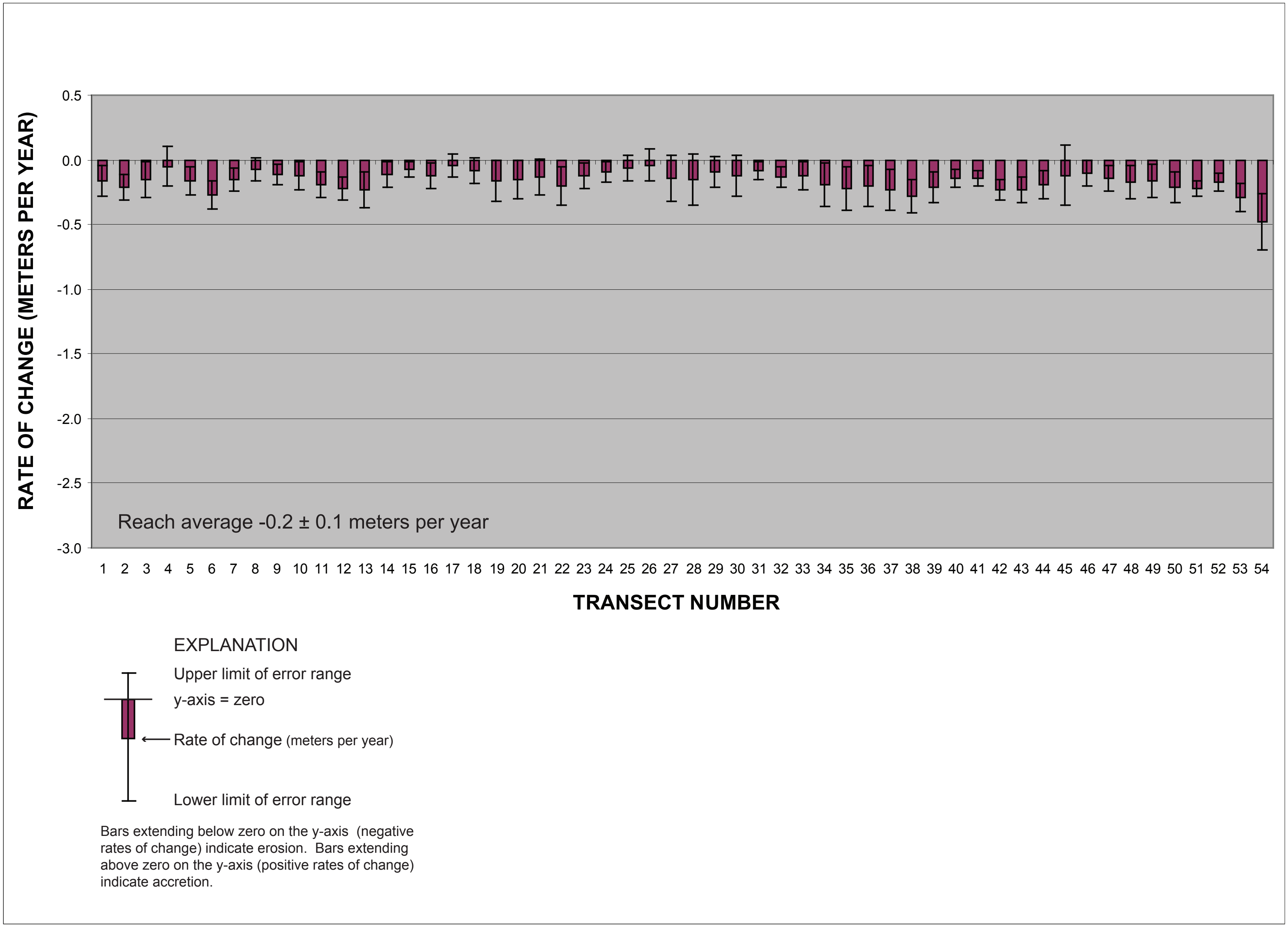

Figure 4. Graph showing alongshore spatial distribution of long-term (70 years from 1936-2006) rates of shoreline change (with error bars) for Reach A, Rincón, Puerto Rico, study area.

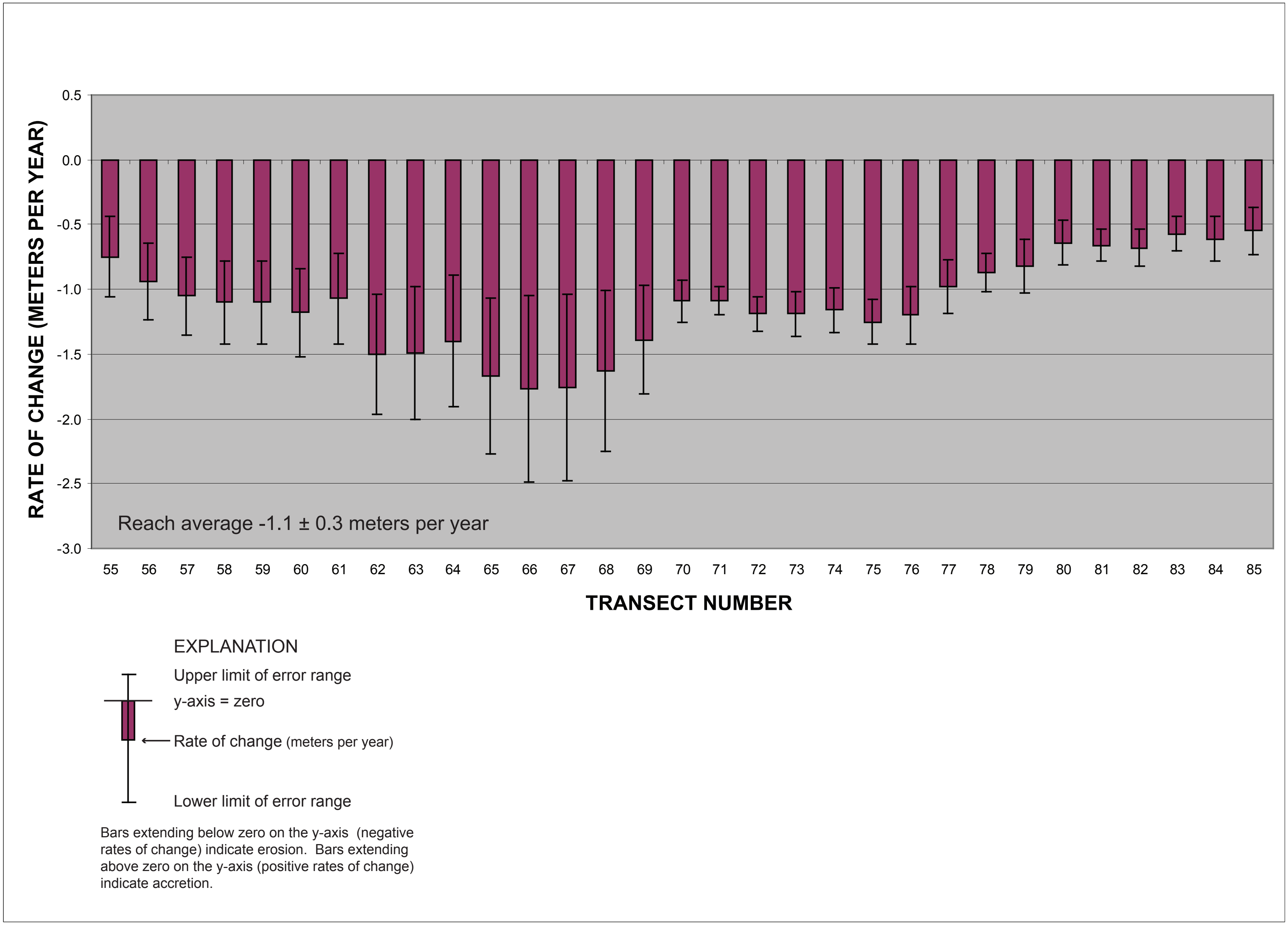

Figure 5. Graph showing alongshore spatial distribution of long-term (70 years from 1936-2006) rates of shoreline change (with error bars) for Reach B, Rincón, Puerto Rico, study area.

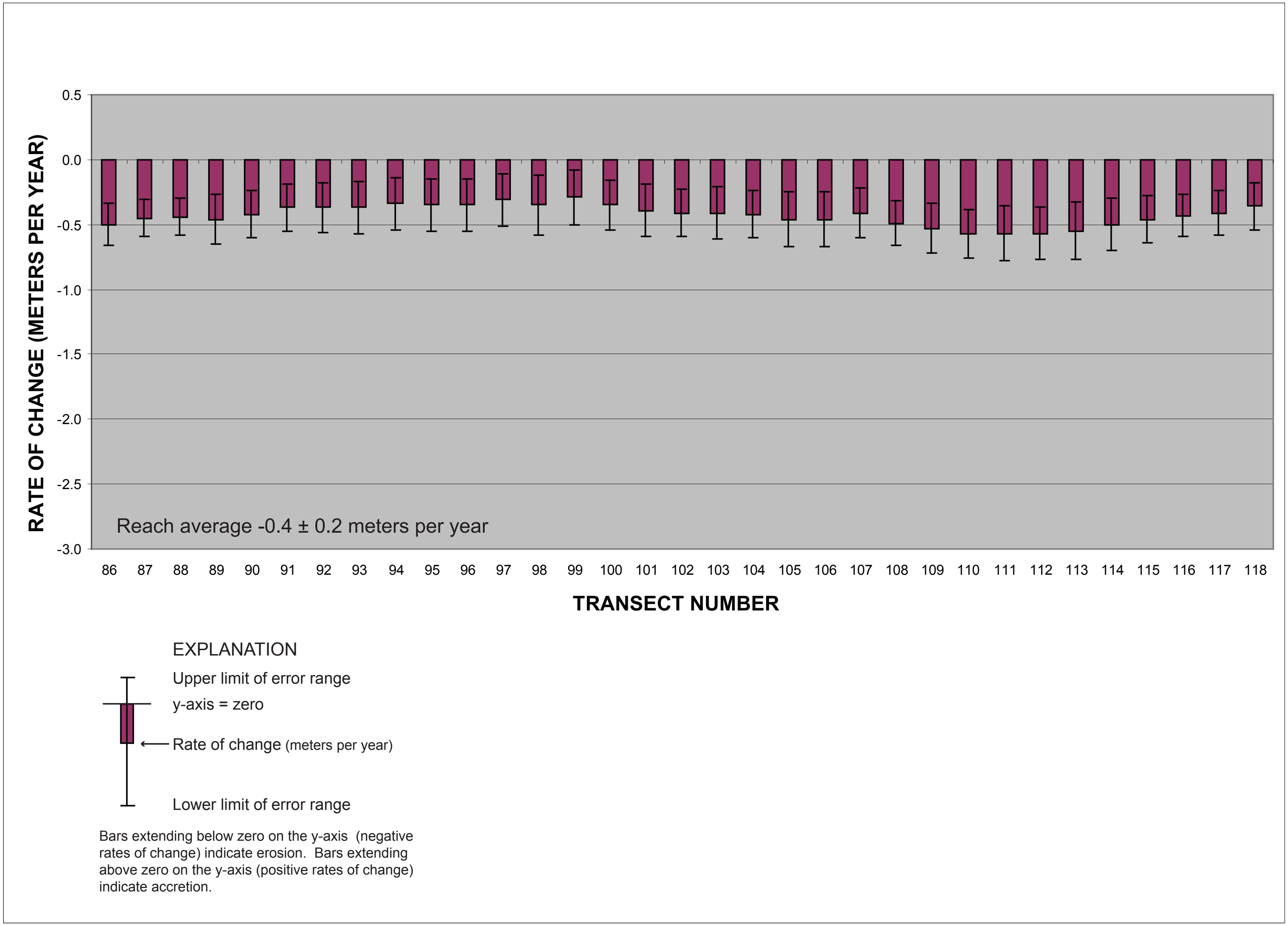

Figure 6. Graph showing alongshore spatial distribution of long-term (70 years from 1936-2006) rates of shoreline change (with error bars) for Reach C, Rincón, Puerto Rico, study area.

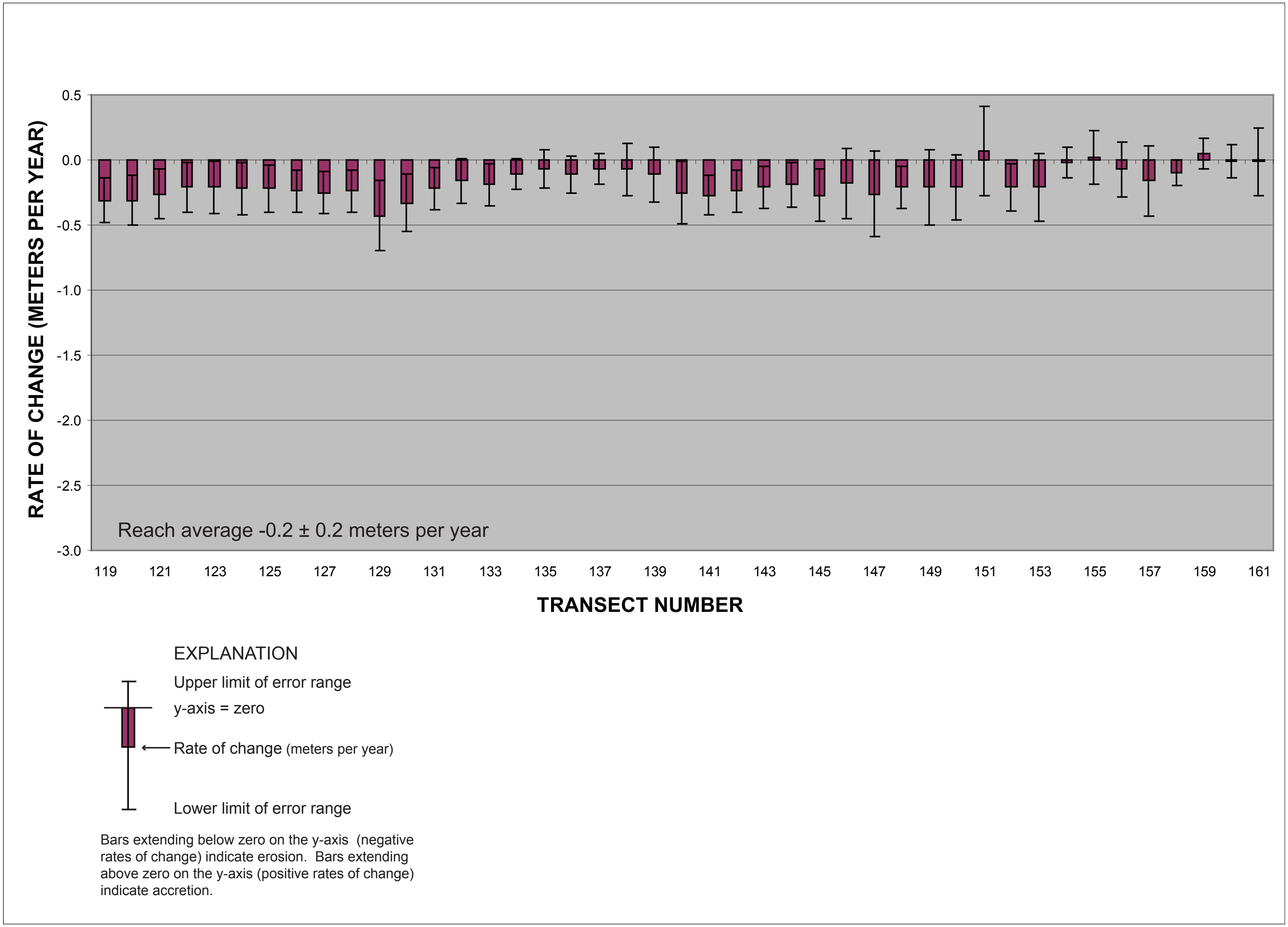

Figure 7. Graph showing alongshore spatial distribution of long-term (70 years from 1936-2006) rates of shoreline change (with error bars) for Reach D, Rincón, Puerto Rico, study area.

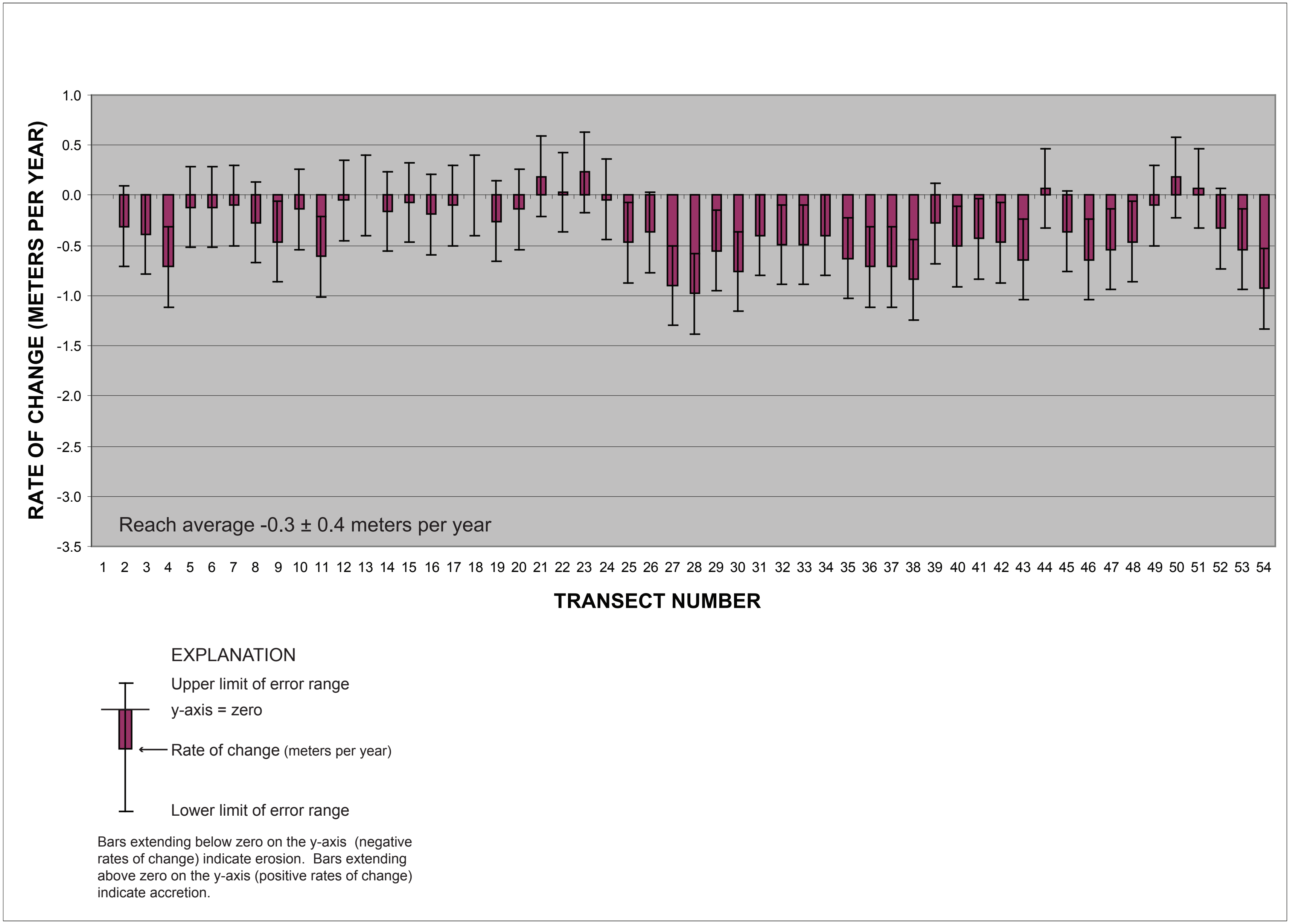

Figure 8. Graph showing alongshore spatial distribution of short-term (12 years from 1994-2006) rates of shoreline change (with error bars) for Reach A, Rincón, Puerto Rico, study area.

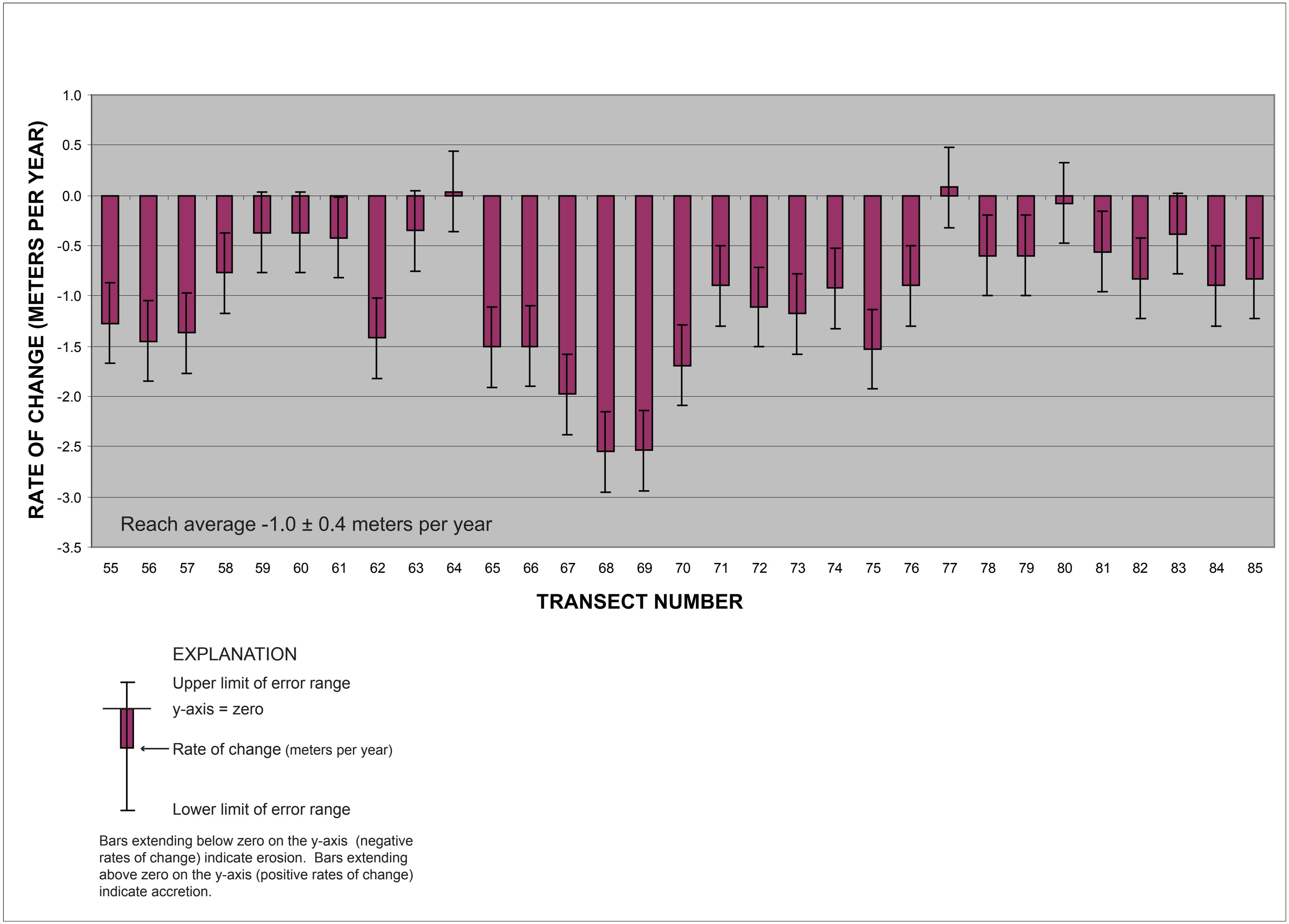

Figure 9. Graph showing alongshore spatial distribution of short-term (12 years from 1994-2006) rates of shoreline change (with error bars) for Reach B, Rincón, Puerto Rico, study area.

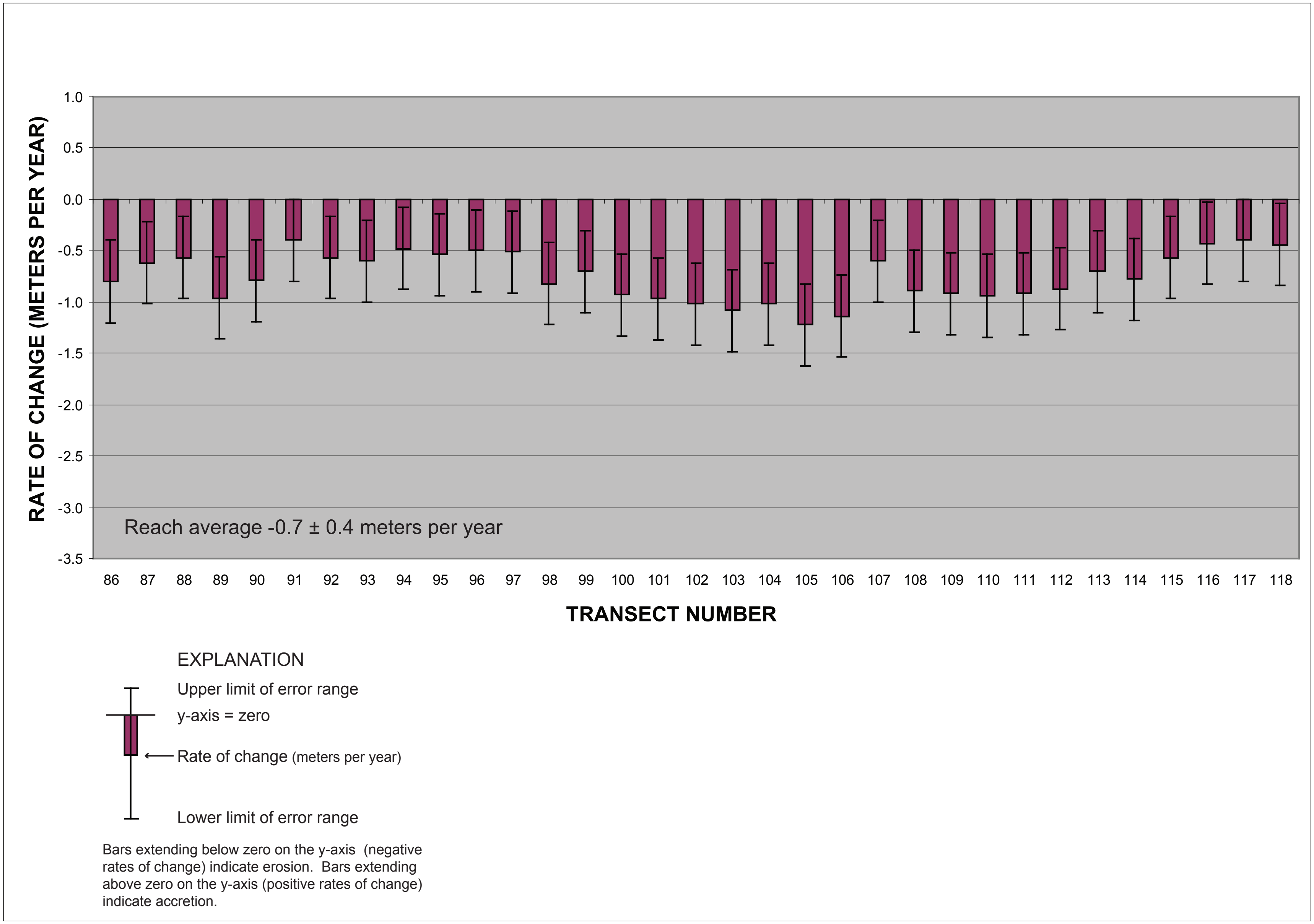

Figure 10. Graph showing alongshore spatial distribution of short-term (12 years from 1994-2006) rates of shoreline change (with error bars) for Reach C, Rincón, Puerto Rico, study area.

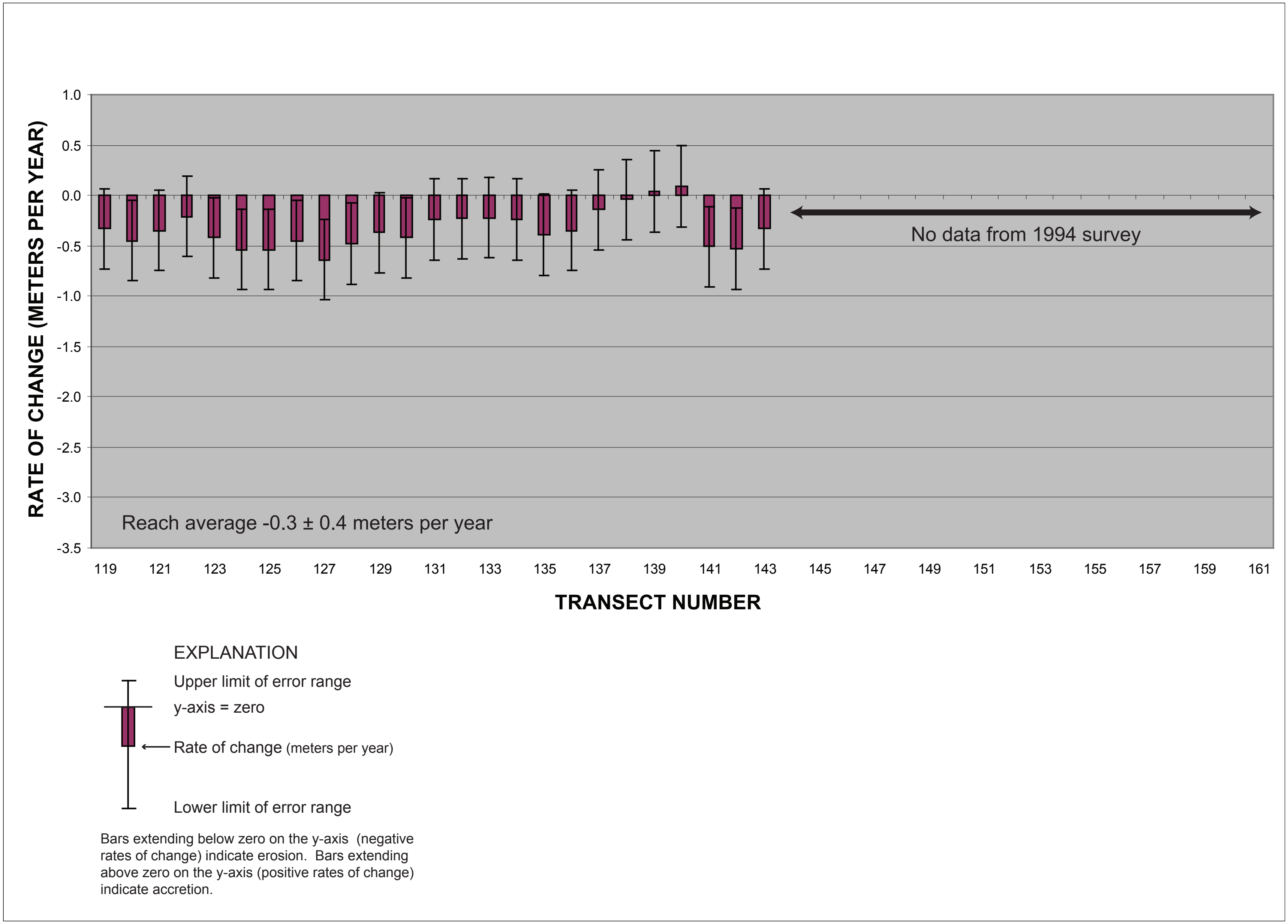

Figure 11. Graph showing alongshore spatial distribution of short-term (12 years from 1994-2006) rates of shoreline change (with error bars) for Reach D, Rincón, Puerto Rico, study area.

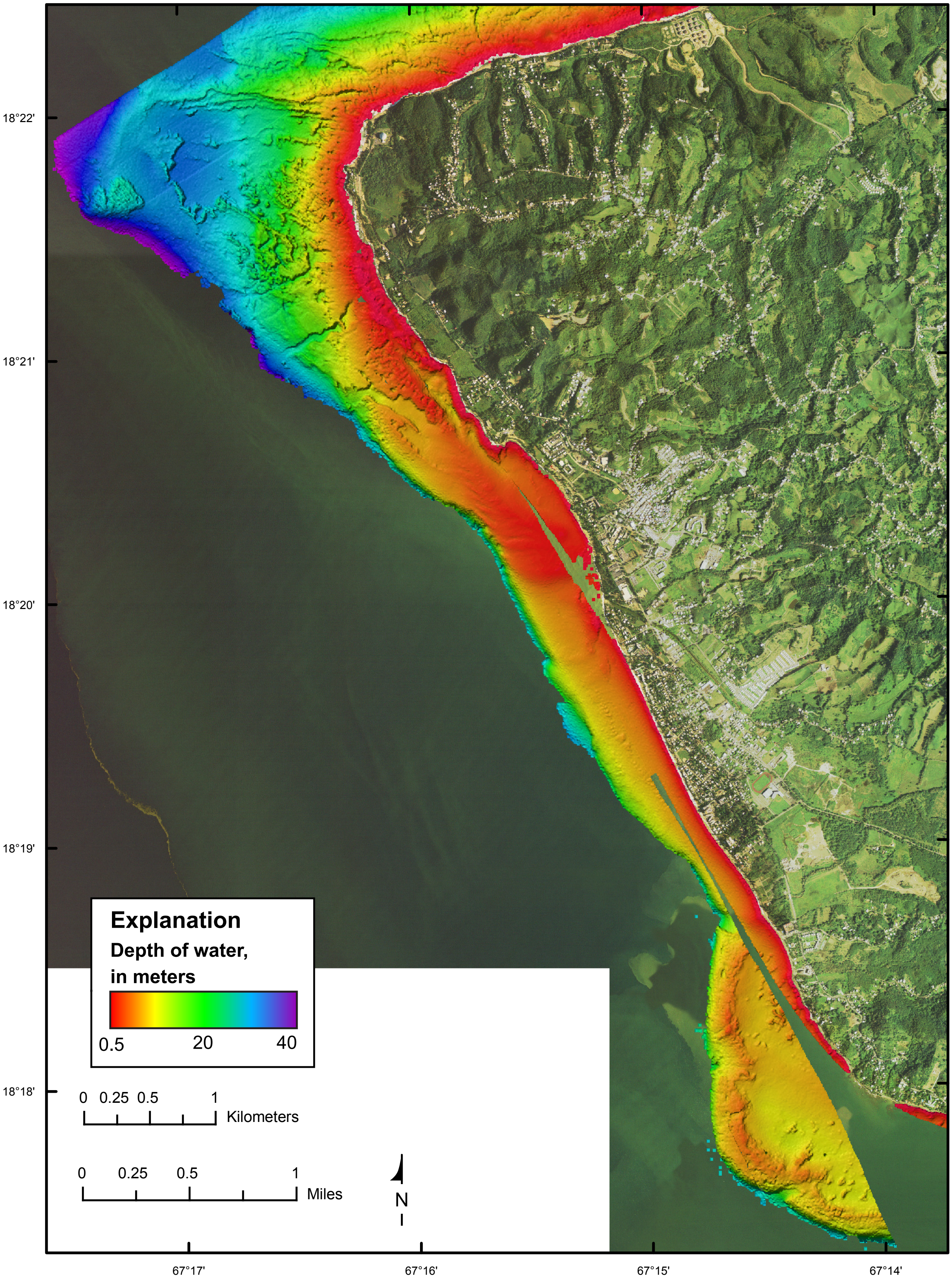

Figure 12. Bathymetry of the Rincón, Puerto Rico, study area based on a SHOALS lidar survey completed in 2001.

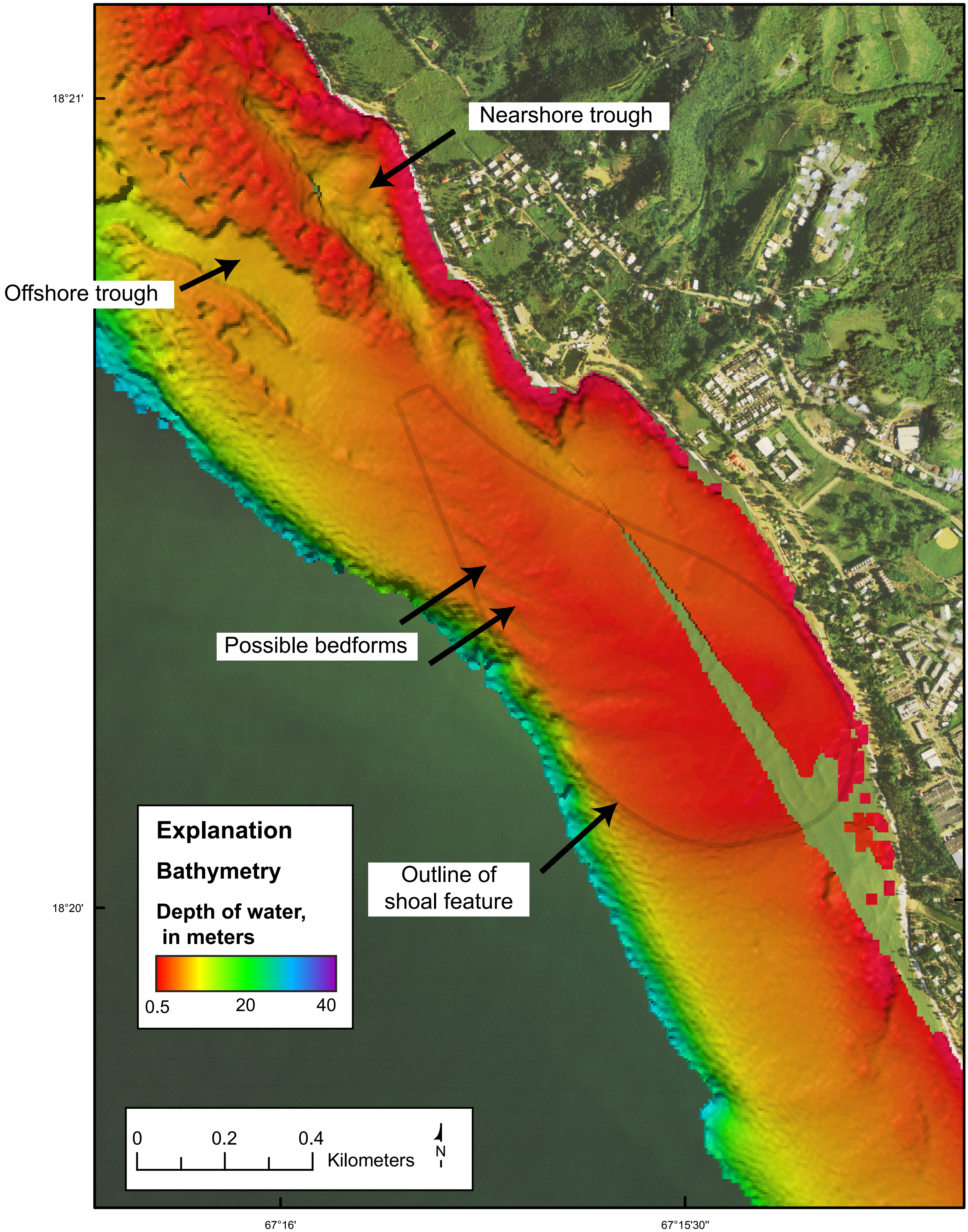

Figure 13. Seafloor features off Punta Ensenada, Rincón, Puerto Rico, study area.

Figure 14. A 1997 orthophotograph showing possible sandy deposits on the shoal feature southwest of Punta Ensenada, Rincón, Puerto Rico. (Photo from Centro de Recaudación de Ingresos Municipales (CRIM) of the Puerto Rico Office of Management and Budget.)

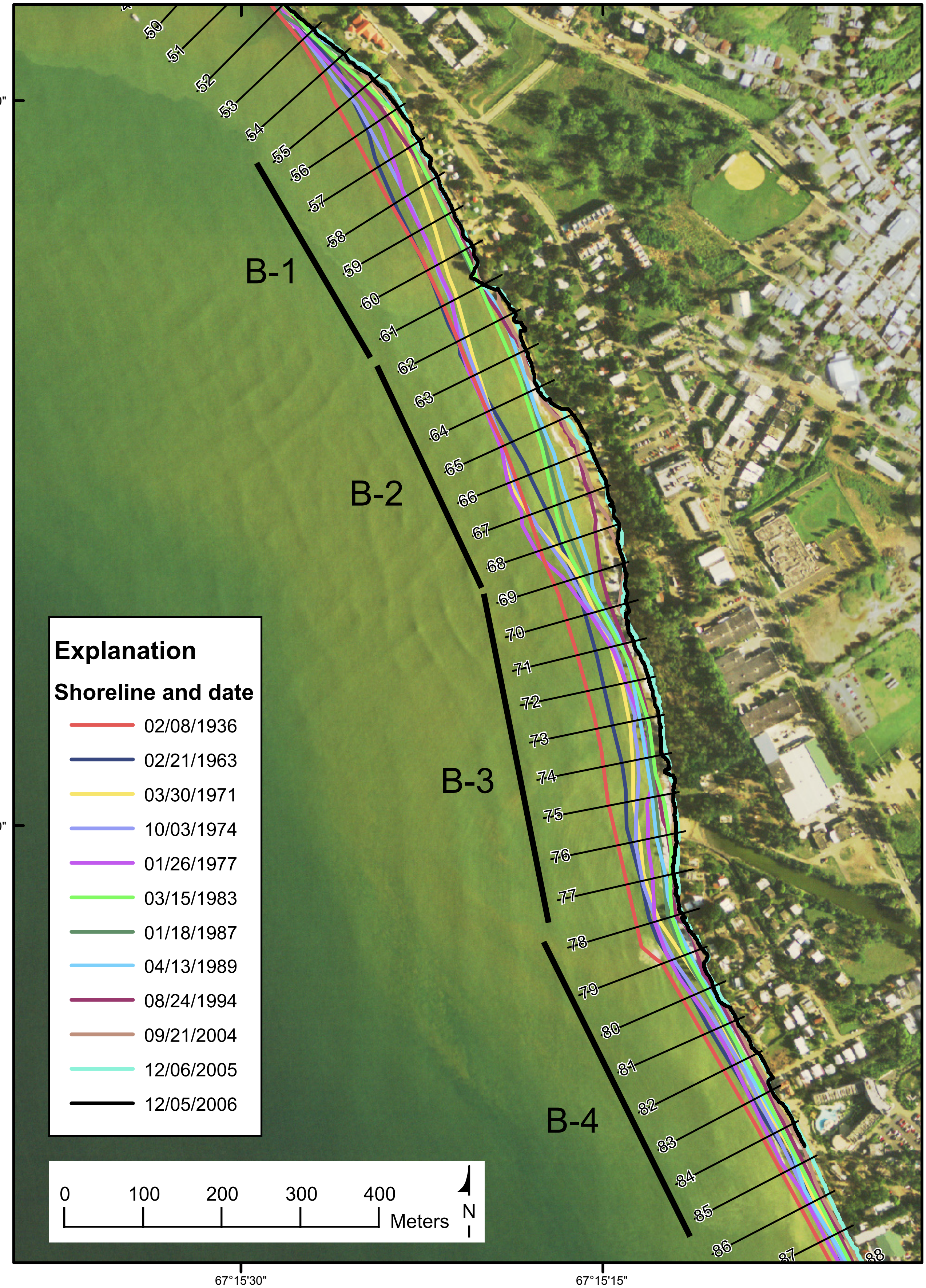

Figure 15. Map showing locations of the four subdivisions identified in Reach B, Rincón, Puerto Rico study area.

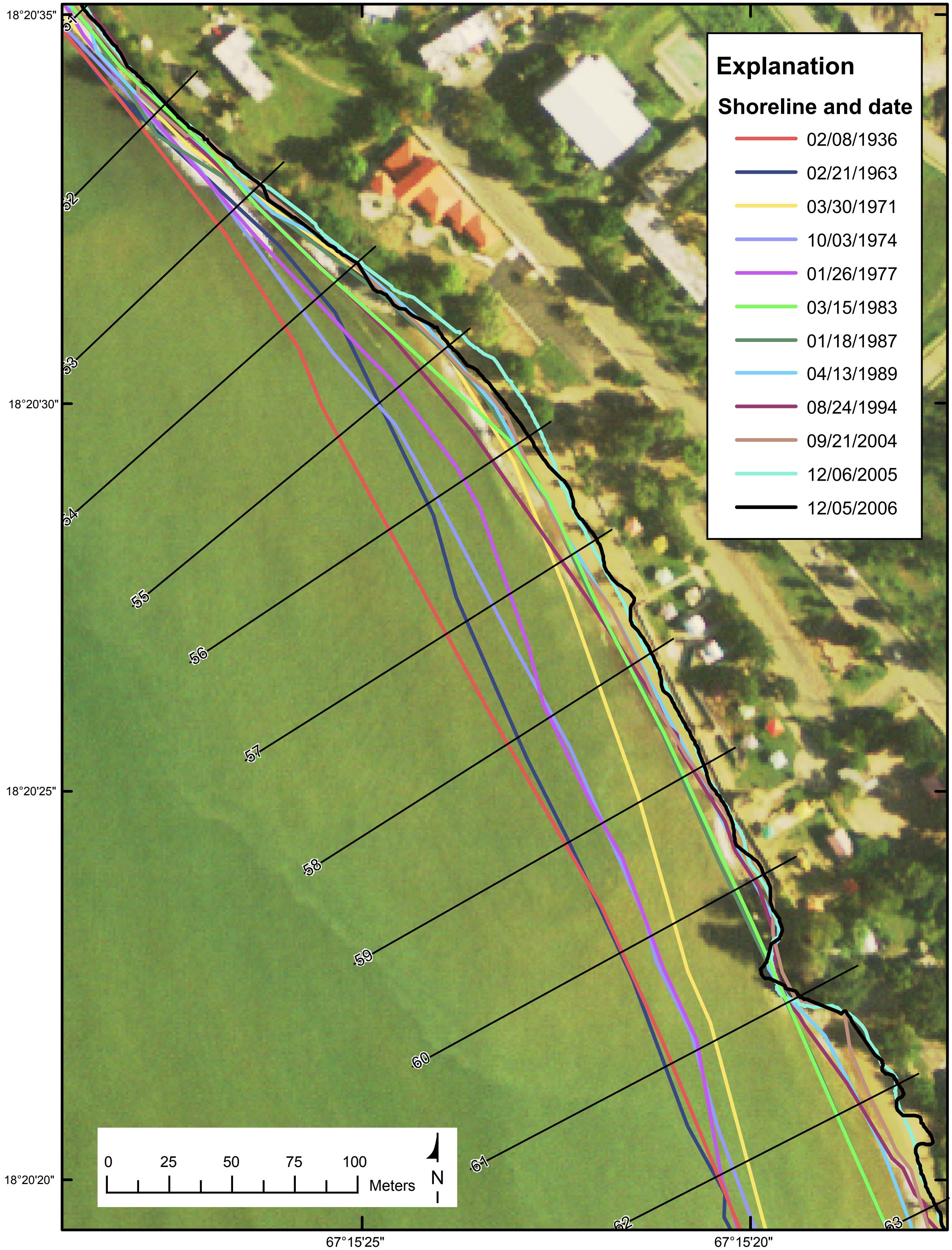

Figure 16. Map showing locations of the historical shorelines and transects in Reach B-1, Rincón, Puerto Rico study area, 1936-2006.

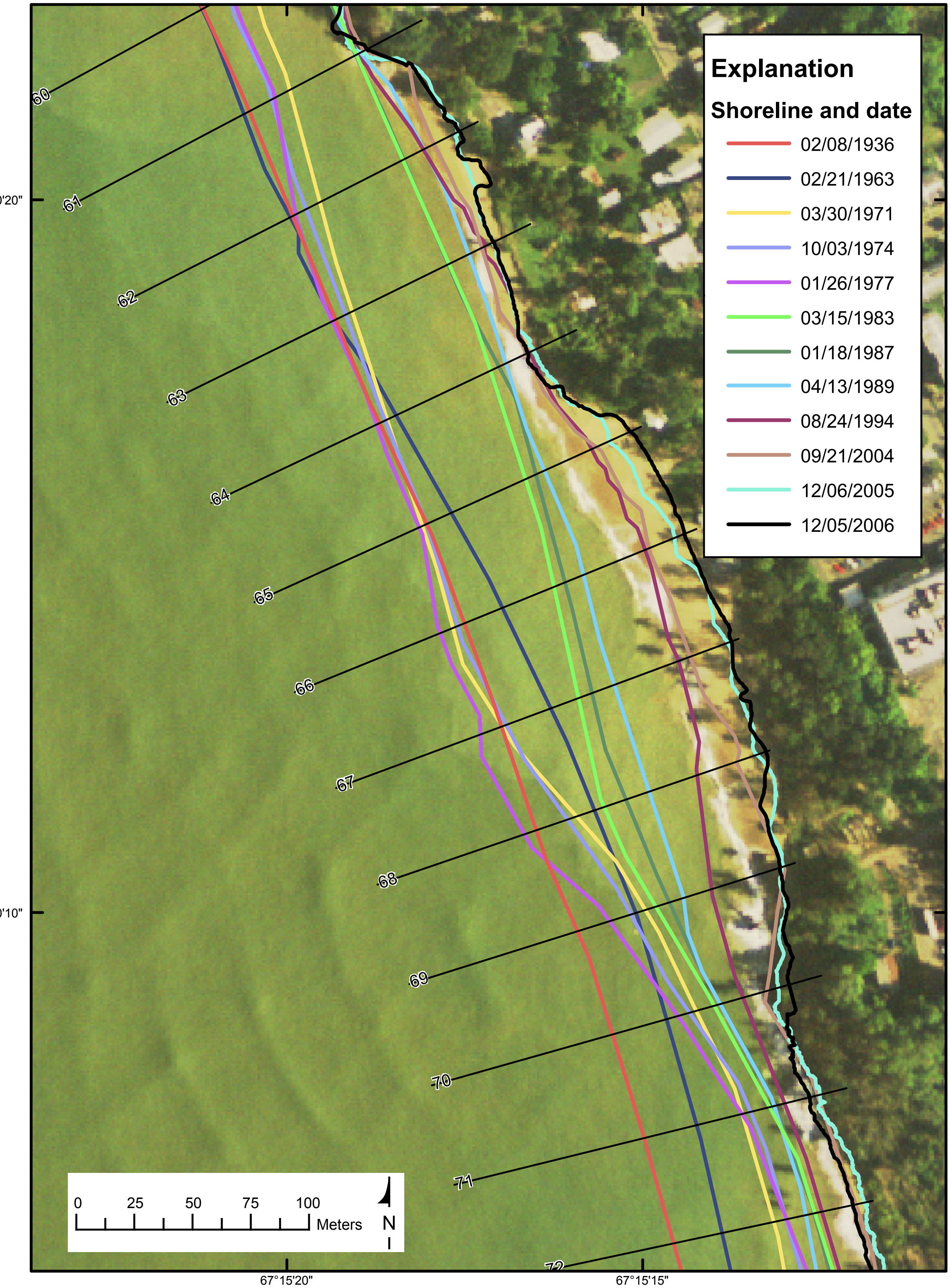

Figure 17. Map showing locations of the historical shorelines and transects in Reach B-2, Rincón, Puerto Rico study area, 1936-2006.

Figure 18. Photograph taken on 05 December 2005 showing infrastructure that is now on the beach and in the surf zone in Reach B-2, Rincón, Puerto Rico, study area.

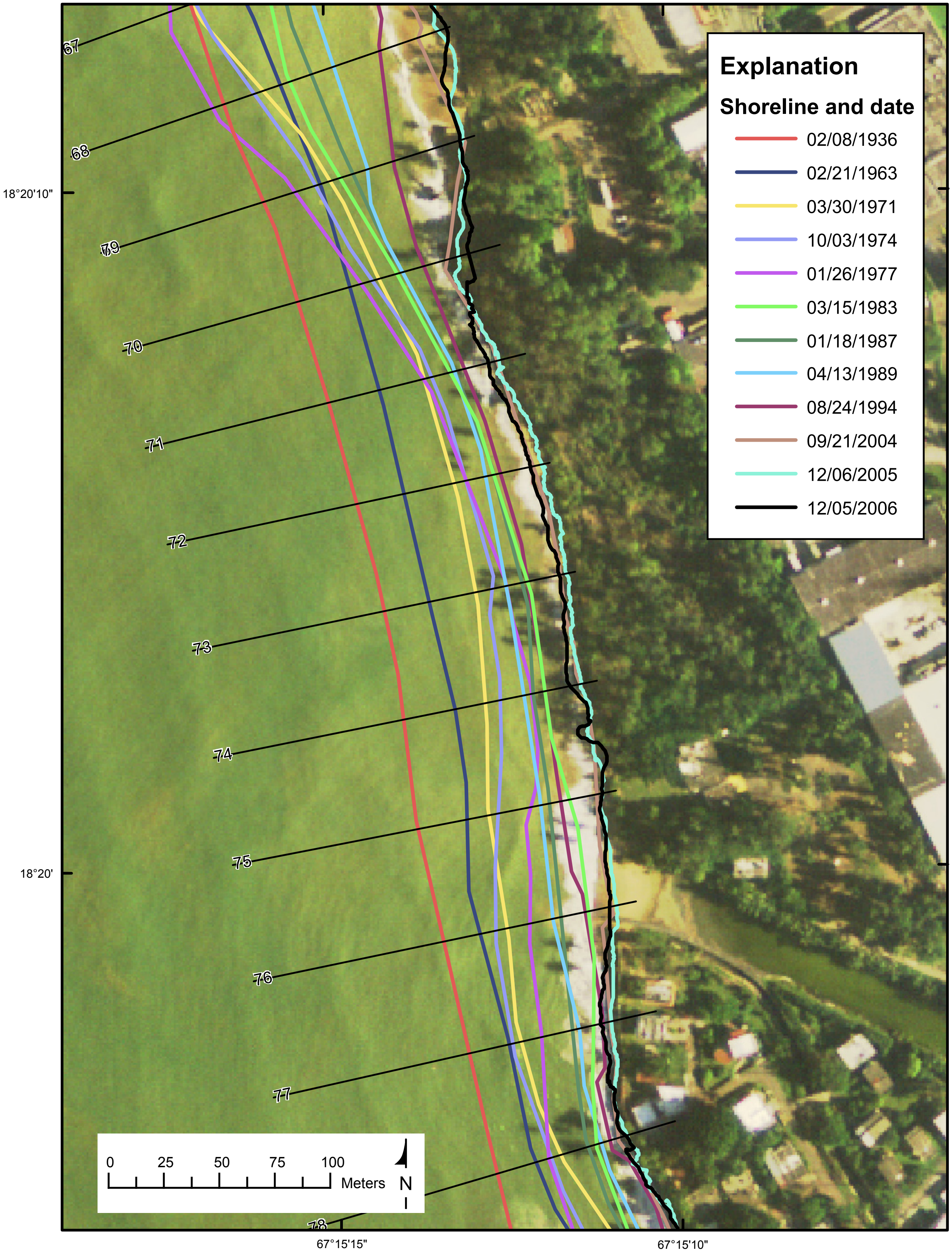

Figure 19. Map showing locations of the historical shorelines and transects in Reach B-3, Rincón, Puerto Rico study area, 1936-2006.

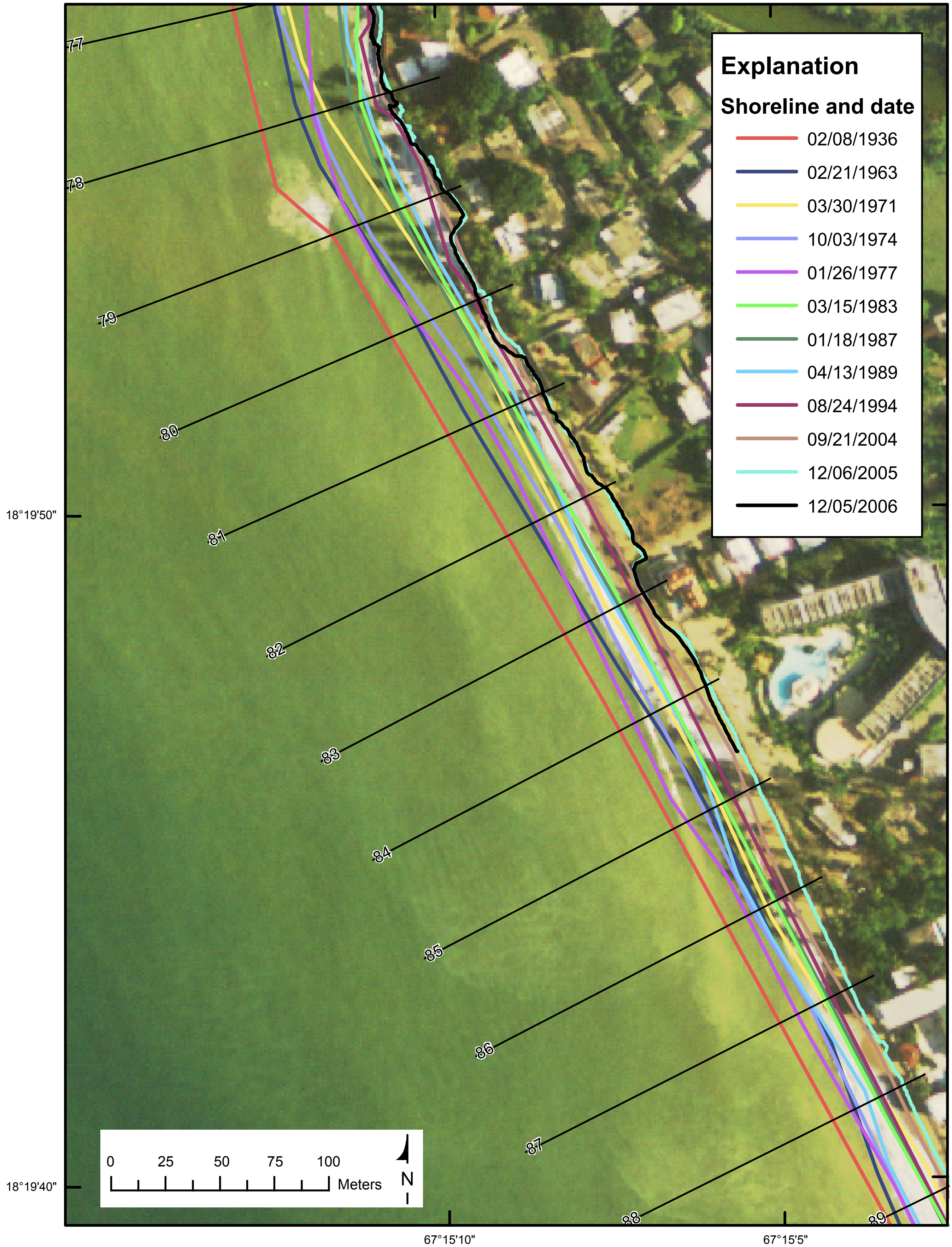

Figure 20. Map showing locations of the historical shorelines and transects in Reach B-4, Rincón, Puerto Rico study area, 1936-2006.

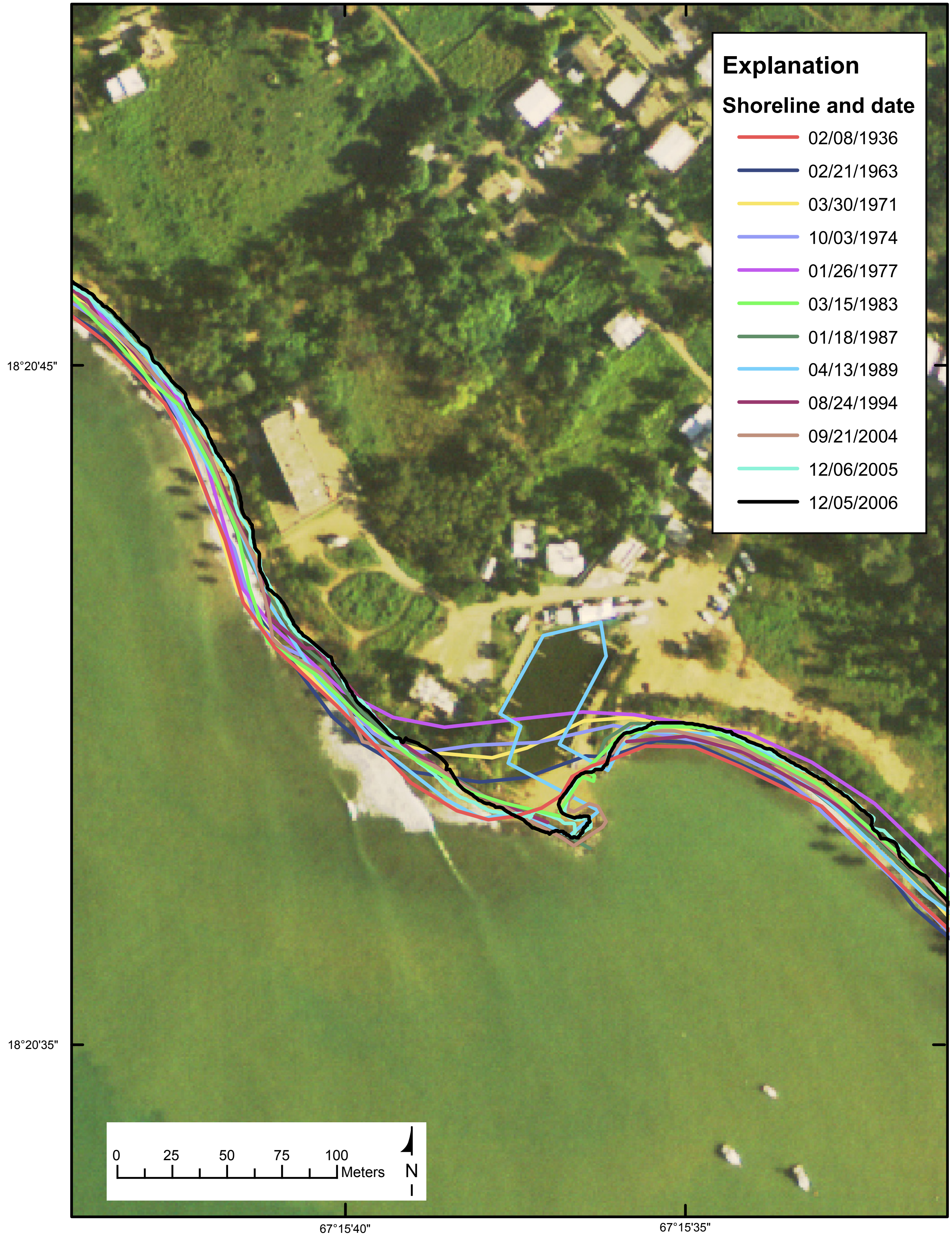

Figure 21. Map showing locations of the historical shoreline positions at Punta Ensenada, Rincón, Puerto Rico study area, 1936-2006.

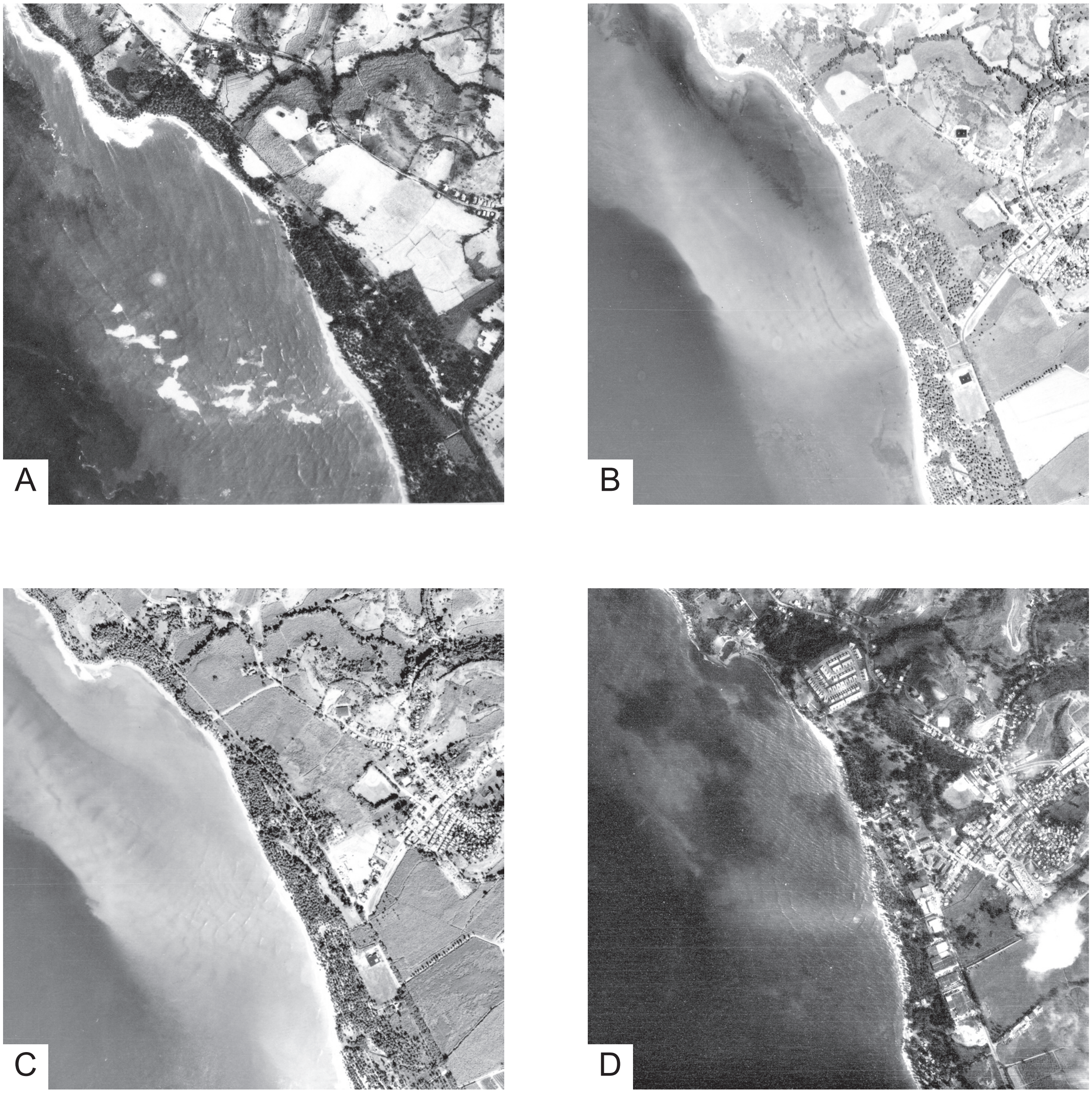

Figure 22. A seven-panel time series of aerial photographs showing complex wave patterns (refraction, reflection, diffraction) in Reach B of the Rincón, Puerto Rico, study area, (A) 14 March 1951, (B) 21 February 1963, (C) 24 December 1963, (D) March 1983, (E) April 1989, (F) 21 September 2004, and (G) undated recent imagery from Google^{TM} Earth (image © 2006 Digital Globe).

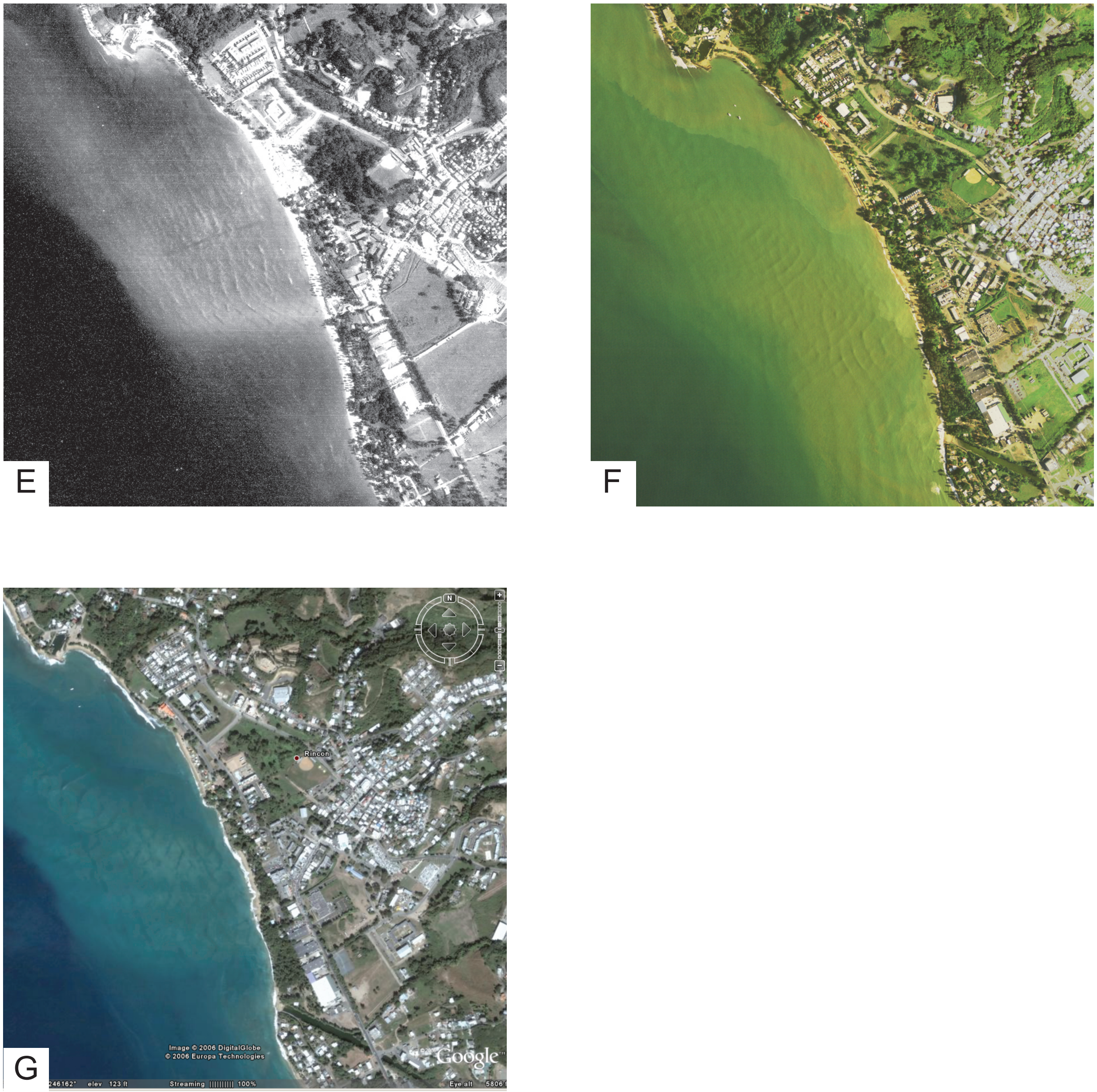

Figure 22. A seven-panel time series of aerial photographs showing complex wave patterns (refraction, reflection, diffraction) in Reach B of the Rincón, Puerto Rico, study area, (A) 14 March 1951, (B) 21 February 1963, (C) 24 December 1963, (D) March 1983, (E) April 1989, (F) 21 September 2004, and (G) undated recent imagery from Google™ Earth (image © 2006 Digital Globe). - - Continued