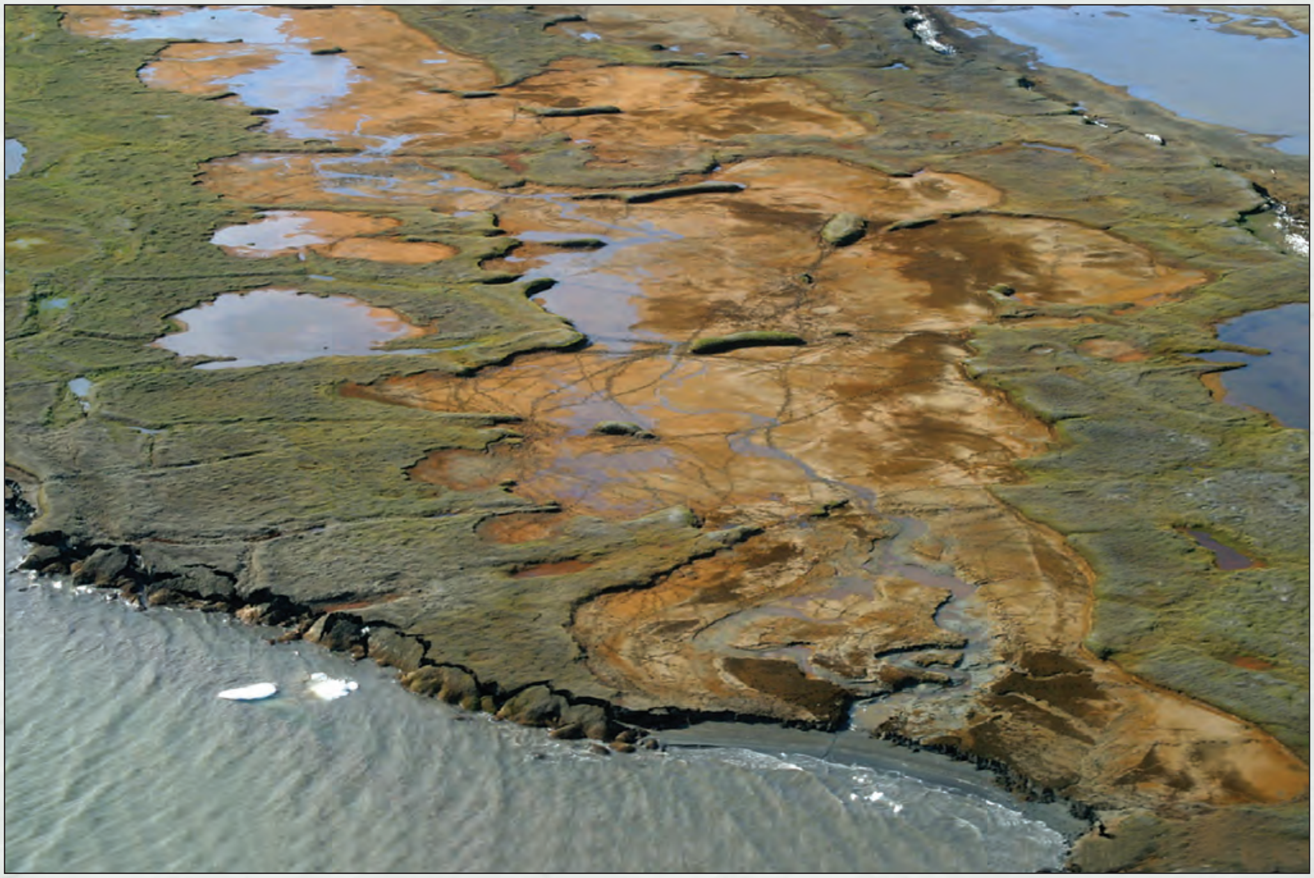
National Assessment of Shoreline Change—Historical Shoreline Change Along the North Coast of Alaska, U.S.-Canadian Border to Icy Cape



Open-File Report 2015–1048

U.S. Department of the Interior
U.S. Geological Survey

Cover: Oblique aerial photograph at Flaxman Island showing tapped and untapped thermokarst lakes, caribou tracks, narrow beaches, and bluff failures along the coast. Image taken August 9, 2006.

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By Ann E. Gibbs and Bruce M. Richmond

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U.S. Department of the Interior
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SALLY JEWELL, Secretary

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Conversion Factors

[International System of Units to Inch/Pounds]

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Erosion and accretion rate	
meter per year (m/yr)	3.281	foot per year (ft/yr)
	Coastal land loss rate	
square kilometer per year (km^2/yr)	0.3861	square mile per year (mi^2/yr)

Datums

All positional measurements were made in the Universal Transverse Mercator (UTM) coordinate system on the North American Datum of 1983 (NAD 83). Data provided with this report were reprojected to the Geographic Coordinate System (GCS, latitude and longitude) on the WGS 84 datum using the WGS_1984_(ITRF00)_To_NAD_1983 transformation in ESRI ArcGIS™ v. 10.1.

Elevation, as used in this report, refers to distance above sea level.

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By Ann E. Gibbs and Bruce M. Richmond

Executive Summary

Beach erosion is a persistent problem along most open-ocean shores of the United States. Along the Arctic coast of Alaska, coastal erosion is widespread, may be accelerating, and is threatening defense and energy-related infrastructure, coastal habitats, and Native communities. As coastal populations continue to expand and infrastructure and habitat are increasingly threatened by erosion, there is increased demand for accurate information regarding past and present trends and rates of shoreline movement. There also is a need for a comprehensive analysis of shoreline change with metrics that are consistent from one coastal region to another. To meet these national needs, the U.S. Geological Survey is conducting an analysis of historical shoreline changes along the open-ocean sandy shores of the conterminous United States and parts of Hawaii, Alaska, and the Great Lakes. One purpose of this work is to develop standard, repeatable methods for mapping and analyzing shoreline change so that periodic, systematic, and internally consistent updates regarding coastal erosion and land loss can be made nationally.

This report on shoreline change along the north coast of Alaska, between the U.S.-Canadian border and Icy Cape, is one in a series of regionally focused reports on historical shoreline change. Previous investigations include analyses and descriptive reports for the coasts of the U.S. Gulf of Mexico, the Southeast Atlantic, California, the New England and Mid-Atlantic, portions of Hawaii, and the Pacific Northwest coasts of Oregon and Washington.

Similar to the earlier reports in this series, this report summarizes the methods of analysis, documents and describes the results of the analysis, and explains historical trends and rates of shoreline change. This Alaska shoreline change assessment differs from previously published shoreline change assessments in that: (1) only two historical shorelines (from the 1940s and 2000s eras) were available for the Alaska study area whereas four or more shorelines (from 1850 to 2002) were available for the other assessments and, thus, only end-point rates for one long-term analysis period are reported here, compared to a combination of long-term and short-term rates as reported in other studies; (2) modern (2000s era) shorelines in this study represent a visually derived land-water interface position versus an elevation based, tidally referenced shoreline position; and (3) both exposed open-ocean and sheltered mainland-lagoon shorelines and rates of change are included in this study compared to other locations where only exposed open-ocean sandy shorelines or bluff edges were evaluated. No distinction was made between sand or gravel beaches, and the base of the unconsolidated coastal bluff was considered the shoreline where no fronting beach existed.

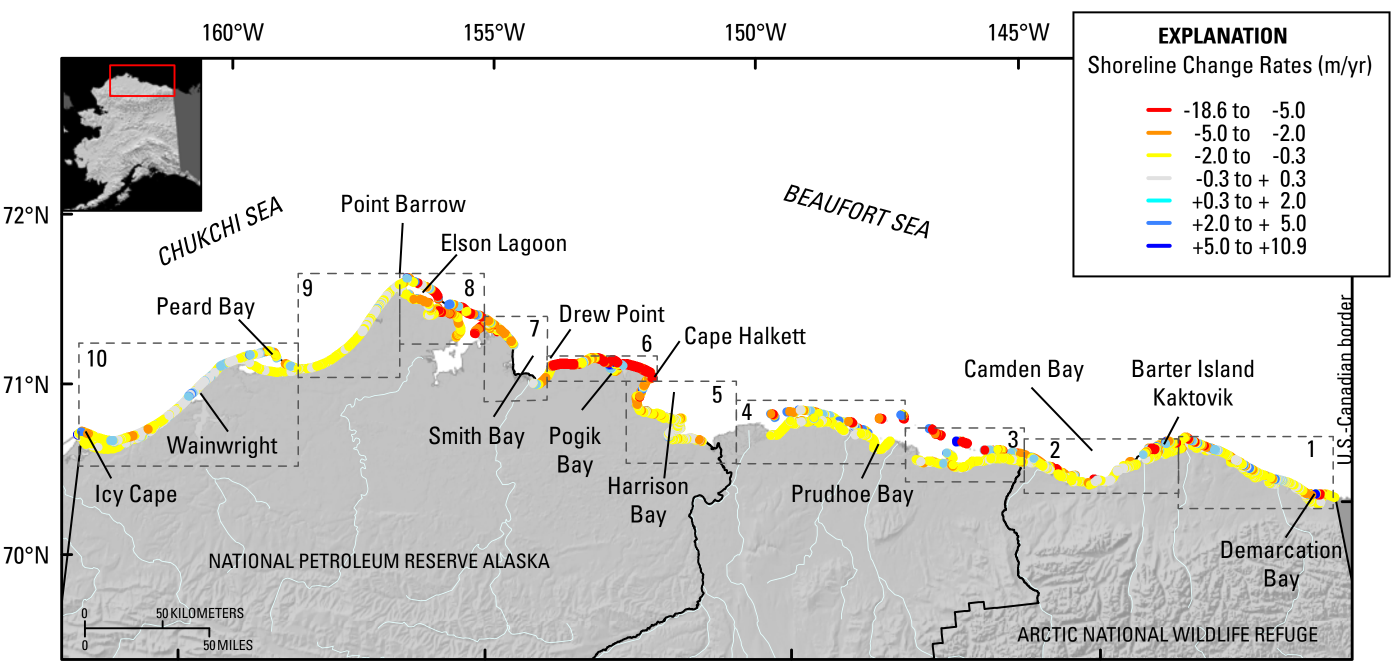
Shoreline change was evaluated by comparing historical shorelines derived from circa-1940s (1947 and 1949) topographic surveys and circa-2000s (1997–2012) vertical aerial photography, satellite imagery, and digital elevation models derived from lidar (light detection and ranging) surveys, thus producing an assessment for a 50- to 64-year time period. Shoreline change rates were calculated using the end-point method at transects spaced approximately every 50 m along both the mainland and barrier island coasts. Shorelines were not delineated nor change rates calculated for river deltas because of the high natural variability and complexity of these shoreline reaches. The rates of change presented in this report represent conditions up to the date of the most recent shoreline data and, therefore, are not intended for predicting future shoreline positions or rates of change. Future updates to this assessment will include shorelines derived from circa-1979 Alaska High Altitude Photography and 2009–2012 high-resolution coastal lidar elevation datasets.

The study area was subdivided into a total of 10 regions for the purposes of reporting regional trends in shoreline change rates. Shoreline change rates were derived from 26,567 individual transects, of which 84 percent were erosional. In order to maintain consistency with other National Assessment of Shoreline Change reports, the term "erosion" is used in this study to indicate the measured landward movement or retreat of the shoreline. No distinction is made between physical erosion and land loss or shoreline retreat as a result of breaching of coastal lake shorelines or flooding of the coast due to sea-level rise or land subsidence; in this context erosion and retreat are interchangeable. Accretion is the measured seaward

progradation of the shoreline and, particularly in case of barrier island and spits, also may represent the migration alongshore of a landscape feature. The average rate of shoreline change for the entire study area was -1.4 meters per year (m/yr) (range -18.6 to +10.9 m/yr) with an individual transect uncertainty of ±0.3 m/yr. Maximum erosion rates (18.6 m/yr) are some of the highest in the world, but are restricted to small sections of the north coast of Alaska . Average shoreline change rates along Beaufort Sea coast are nearly six times higher (-1.7 m/yr) than along the Chukchi Sea coast (-0.3 m/yr). The highest rates of both erosion and accretion in the study area were measured within Region 6 (Cape Halkett to Drew Point), with rates of erosion greater than 18 m/yr between Cape Halkett and Pogik Bay, and rates of accretion greater than +10.5 m/yr on the western side of Pogik Bay. The highest average rates of shoreline change (-5.8 m/yr) were measured within Region 6, and the lowest (-0.3 m/yr) along the Chukchi coast in Regions 9 and 10 (Barrow to Icy Cape).

Sheltered mainland-lagoon shorelines comprise 42 percent of all transects in the study area and are 88 percent erosional. Open-ocean exposed shorelines comprise 58 percent of all transects and are 81 percent erosional. Average shoreline change rates along exposed shorelines are twice as high (-1.8 m/yr) compared to sheltered shorelines (-0.9 m/yr). Barrier shoreline transects (includes barrier islands, spits, and beaches) comprise 29 percent of the total transects and 50 percent of all exposed shoreline transects. Average shoreline change rates on barrier shorelines are not significantly different than exposed mainland shorelines (-1.7 and -1.8 m/yr, respectively); however, the barrier transects have the lowest percent of erosional transects (75 percent) and highest accretional (25 percent) of all shoreline types. Considerable migration and translation in the position of the barrier islands and spits during the analysis period resulted in substantial erosion and accretion; however, because of the lack of overlapping shoreline positions, some of these changes could not be measured using the Digital Shoreline Analysis System method of analysis, particularly in Regions 3, 4, and 8. An analysis of changes in the surface area of those barrier islands in those regions, however, indicates a net gain in barrier island surface area of nearly 1.7 million square meters, or about 10 percent, during the study period. A volumetric change analysis could not be completed because of the lack of elevation values for the historical datasets.

In contrast to the majority of the Nation's shorelines, for all but 3 months of the year (July–September), the north coast of Alaska is protected by landfast sea ice from processes such as waves, winds, and currents that typically drive coastal change on beaches in more temperate regions of the world. Projected and observed increases in periods of sea-ice free conditions, as sea-ice melts earlier and forms later in the year, particularly in the autumn, when large storms are more common in the Arctic, suggest that Arctic coasts will be more vulnerable to storm surge and wave energy, potentially resulting in accelerated shoreline erosion and terrestrial habitat loss in the future.



Map of the north coast of Alaska study area showing color-coded shoreline change rates, the boundaries of the ten analysis regions (dashed boxes and numbers), and key geographic locations discussed in the report.

Introduction

U.S. Geological Survey National Assessment of Shoreline Change

Sandy beaches are some of the most popular tourist and recreational destinations in the United States, and coastal property constitutes some of the most valuable real estate in the country. Beaches are a dynamic interface between water and land with unique and complex natural ecosystems that are highly vulnerable to multiple natural hazards that can include flooding and drainage problems, effects of storms, sea-level rise, coastal erosion, and tsunami inundation. Partly in response to increasing coastal hazards, the U.S. Geological Survey (USGS) is conducting a nationwide assessment of coastal change. One component of this effort, the National Assessment of Shoreline Change (NASC) Project, documents changes in shoreline position as a proxy for coastal change. Shoreline position is one of the most commonly monitored indicators of environmental change (for example, Dolan and others, 1991; Fletcher, 1992; Morton, 1996; Douglas and others, 1998; Galgano and others, 1998), and it is an easily understood feature representing the historical movement of beaches.

A principal component of the USGS shoreline change research is to develop a common methodology so that shoreline change analyses can be updated periodically in a consistent and systematic manner. The primary objectives of the national assessment are to conduct research on improved methods of assessing and monitoring shoreline movement and develop a better understanding of the processes controlling shoreline change. Achieving these ongoing long-term objectives requires research that (1) examines the original sources of shoreline data (maps, aerial photographs, global positioning system [GPS], and light detection and ranging [lidar]); (2) evaluates the use of different shoreline proxies (geomorphic feature, water mark, tidal datum, and elevation), including the errors associated with each data source; (3) investigates bias and potential errors associated with integrating different shoreline proxies from different sources; (4) develops standard, uniform methods of shoreline change analysis; (5) examines the effects of localized human activities on shoreline movement and rates of change; and (6) integrates shoreline change observations with other information, such as geologic framework and sediment transport data.

Results of the NASC Project are organized by coastal regions. Previous investigations include analyses and descriptive reports, as well as the Geographic Information System (GIS) data used in the analyses for the Pacific Northwest (Kratzmann and others, 2013; Ruggiero and others, 2013), the Hawaiian Islands (Fletcher and others, 2012; Romine and others, 2012), the New England and Mid-Atlantic coasts (Hapke and others, 2010; Himmelstoss and others, 2010), California (Hapke and others, 2006, 2008; Hapke and Reid, 2006, 2007), the Southeast U.S. coast (Miller and others, 2004, 2005; Morton and Miller, 2005), and the U.S. Gulf of Mexico (Morton and others, 2004).

This report summarizes historical changes to shorelines along the north coast of Alaska between the U.S.-Canadian border and Icy Cape (fig. 1). Results are subdivided into 10 regions based on geomorphology for the purpose of presenting regional trends for the shoreline change rate data. GIS data used in the analyses are available from Gibbs and others (2015). The north coast of Alaska is a permafrost-bound microtidal coast with seasonal sea-ice conditions and is very different than the other U.S. coastlines studied by the NASC Project. Other differences between this study area and previous NASC study sites are the relative lack of tourist beaches and coastal tourism infrastructure, limited historical datasets, poor geodetic control and lack of a precise geoid model (a model of global mean sea level that is used to measure precise surface elevations), and very limited information on water levels or tidal datums. This report documents the coastal change hazard at regional scales and strives to relate this hazard to the body of knowledge regarding coastal geology of the northern Alaska region. Coastal change can have substantial impacts on local inhabitants, natural and cultural resources, habitat of U.S.-protected Trust species (many of which are threatened or endangered), Department of Defense and oil and gas industry related infrastructure, and organic carbon input into the marine environment.

This report is part of a series of reports summarizing methods, results, and implications of the results in addition to maps illustrating rates of shoreline change. The format, style, and methods used in this report closely follow that developed by Hapke and others (2006, 2011). Rates of shoreline change are published in this report for the purpose of regional characterization to identify coastal change hazard areas. The shoreline change results and products prepared by the USGS are not intended for detailed site-specific analysis of shoreline movement, nor are they intended to replace any official sources of shoreline change information identified by local or State government agencies, or other Federal entities that are used for regulatory purposes. Rates of shoreline change presented herein may differ from other published rates, and differences do not necessarily indicate that the other rates are inaccurate. Some discrepancies are expected, considering the many possible ways of determining shoreline positions and rates of change, and the inherent uncertainty in calculating these rates. Rates of shoreline change presented in this report represent shoreline movement under past conditions. The results are not intended for predicting future shoreline positions or future rates of shoreline change.

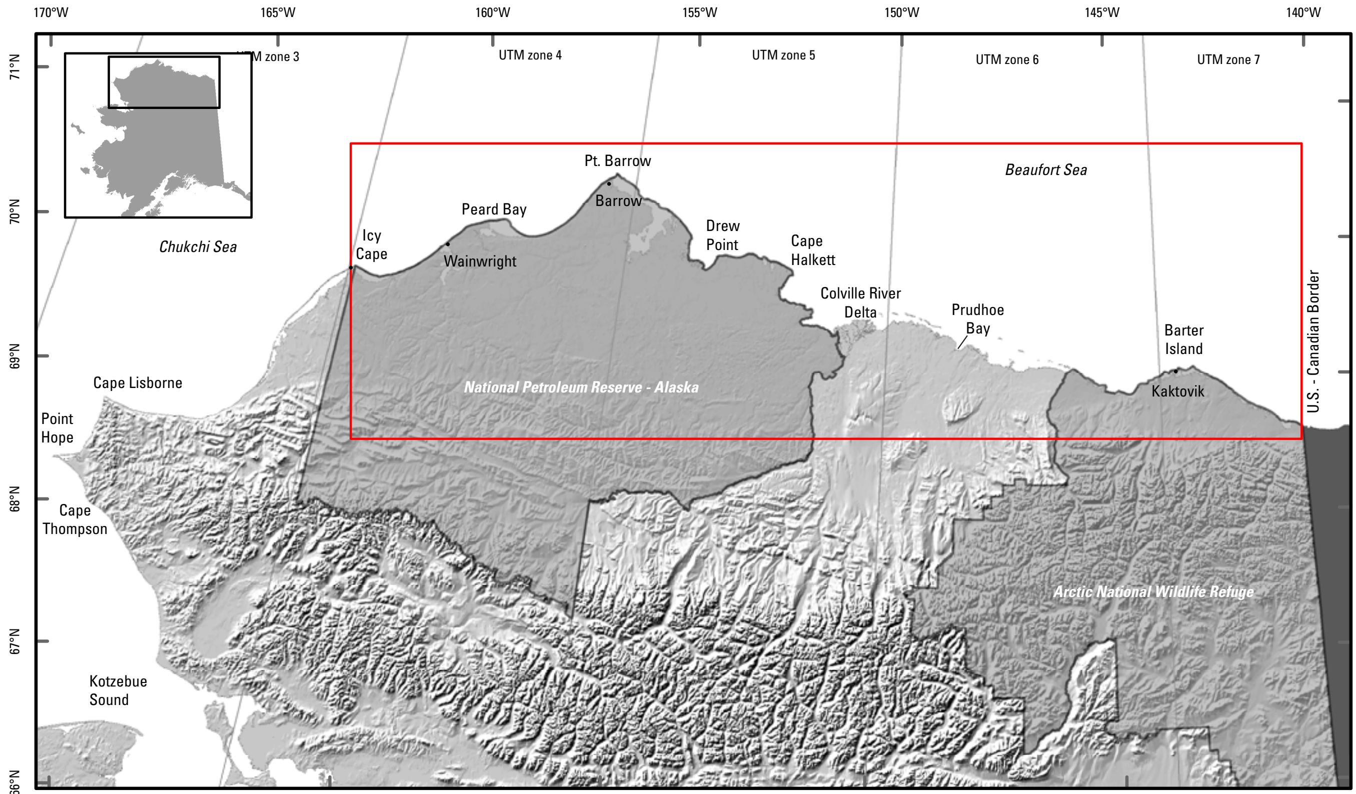


Figure 1. Shaded relief index map of the north coast of Alaska showing study area (U.S.-Canadian Border to Icy Cape; rectangular box) and key geographic locations.

The Role of State and Federal Governments

One reason for conducting this national assessment of shoreline change is that there is no widely accepted, standardized method of analyzing shoreline change. Each State or region has its own data needs and coastal-zone management responsibilities (for example, construction set-back lines, dune protection zones, and public access) and, therefore, each State uses a different technique and standard to compile shorelines and calculate rates of shoreline movement. Consequently, calculated rates of shoreline change and projected erosion hazard zones are inconsistent from State to State and often cannot be compared directly. These inconsistencies were clearly demonstrated by the Federal Emergency Management Agency (FEMA)-sponsored erosion studies (Crowell and Leatherman, 1999) that were used as the basis for evaluating erosion hazards (The H. John Heinz III Center for Science, Economics, and the Environment, 2000). The USGS national assessment of shoreline change represents the first effort to compile shorelines from original data sources and calculate rates of shoreline change on a national scale using internally consistent methods. The results of the analyses allow direct comparison of rates of change from one coastal segment to another and form the basis for future comparison of shoreline position.

Several Federal agencies (U.S. Geological Survey [USGS], Federal Emergency Management Agency [FEMA], National Oceanic and Atmospheric Administration [NOAA], and U.S. Army Corps of Engineers [USACE]) have regulatory or administrative responsibilities pertaining to shorelines. These responsibilities are different, however, and require different approaches. They also offer substantial opportunities for cooperation. For example, the USACE is authorized and funded by Congress to report on the economic and environmental implications of shoreline change and the costs of erosion mitigation. Its National Shoreline Management Study (Stauble and Brumbaugh, 2003) is being conducted using existing shoreline data. The USGS shares data and information, such as the lidar-derived shoreline and rates of change, in support of that effort. NOAA has a mandate to establish the official shoreline boundary for the Nation using tidal datums. The emphasis of NOAA's mandate is on safe navigation and using the shoreline to generate nautical charts. NOAA also conducts the VDatum program, which assists agencies in delineating shorelines for various purposes. Congress authorized and funded FEMA to report on the economic effect of erosion hazards on coastal communities, and on claims to the National Flood Insurance Fund. To accomplish this goal, FEMA contracted with State agencies and academic researchers to conduct a pilot study of erosion hazards that included shoreline change data for limited geographic areas. The USGS is responsible for conducting research pertaining to coastal change hazards, understanding the processes that cause coastal change, and developing models to predict future change. The USGS is the only government agency that has a dedicated program to monitor coastal change into the future using consistent methods nationwide. This program is critically important for the assessment of national issues such as the coastal effects of sea-level rise and climate change.

Previous National and Northern Alaska Shoreline Assessments

The U.S. Army Corps of Engineers (1971) conducted the first national assessment of coastal erosion. That study identified areas of critical and non-critical erosion on the basis of economic development and potential for property loss, but rates of shoreline movement were not evaluated. Dolan and others (1985) conducted a comprehensive analysis of shoreline change for most of the United States Their analysis was based on compilation of rates of shoreline change contributed by other investigators and derived from their own studies. Rates of change were presented and long-term trends of erosion and accretion were summarized. They mapped most of the north coast of Alaska as either severely or moderately eroding.

Early shoreline studies of the north coast of Alaska relied on geomorphic evidence to determine relative coastal stability. Erosion of the coast was first reported by Leffingwell (1919), who used fresh erosional bluff and bank scarps as evidence of recent erosion. He also noted that retreat rates probably varied with proximity of sea ice to the shore and suggested retreat rates may be more than 30 m/yr (100 ft/yr) at Drew Point (fig. 1). MacCarthy (1953) observed that, although protected from wave action by sea ice for much of the year, rapid coastal erosion is evident for much of the coast around the Barrow Peninsula.

Quantitative studies of regional shoreline change along parts of the coast of Alaska were conducted by Harper (1978), Reimnitz and others (1985, 1988), Barnes and Rollyson (1991), Barnes and others (1992), Jorgenson and Brown (2005), Mars and Houseknecht (2007), Jones and others (2008, 2009a), and, more recently, by Lantuit and others (2011). The results of these studies are briefly summarized:

- Harper (1978) measured cliff and waterline retreat rates along the Chukchi Sea coast for a 27-year period (1948/49–1976) by comparing coastal aerial photographs from Barrow to Peard Bay. Mean retreat rates for the waterline were -0.41 m/yr and coastal cliffs were -0.37 (cliff top) and -0.26 (cliff base) m/yr. Average cliff retreat rates over 5-km segments ranged from -0.06 to -1.50 m/yr.

- Reimnitz and others (1985, 1988) compared two sets of nautical charts showing shorelines for 1950 (U.S. Coast and Geodetic Survey, C&GS) and 1980 (National Ocean Survey, NOS) for the Beaufort Sea coast from the Colville River Delta to Drew Point (approximately 344 km). They determined an average erosion rate of -2.5 m/yr with rates as high as -18 m/yr, and large sections of coast ranging from -5 to -10 m/yr. In contrast to widespread erosion, they found that the Colville River Delta was accreting at an average rate of +0.4 m/yr, with localized accretion as much as +20 m/yr. In the western third of their study area, where the coastal plain deposits are mostly fine-grained, average retreat rates were -5.4 m/yr, whereas towards the east, where deposits are composed of mostly sand and gravel, the coast retreats at a slower rate of -1.4 m/yr.

- Barnes and Rollyson (1991) and Barnes and others (1992) used a similar methodology to Reimnitz and others (1985, 1988) using 1951 and 1981 charts to examine approximately 300 km of the Beaufort Sea coast from Flaxman Island to the Canadian Border. They measured a total average coastal change rate of 0.36 m/yr (accretion), but with a net coastal-volume loss of 400 (m^3/km)/yr. They found extensive bluff erosion to be nearly offset by delta accretion, and coastal change was nearly an order of magnitude less than the Reimnitz and others (1985, 1988) study area to the west.

- Jorgenson and Brown (2005) summarized most of the regional and local erosion data for the Beaufort Sea coast from previous studies in an effort to estimate carbon and sediment inputs to the Beaufort Sea from eroding shorelines. They found mean annual erosion rates varied by coastline type, with -0.7 m/yr for lagoon shorelines (maximum -10.4 m/yr) and -2.4 m/yr for exposed bluff shorelines (maximum -16.7 m/yr). Additionally, they reported higher rates for shorelines composed mostly of silt material (-3.2 m/yr) than for predominantly sand- (-1.2 m/yr) to gravel-dominated (-0.3 m/yr) coasts.

- Mars and Houseknecht (2007) examined 50 years of coastal change along approximately 130 km of coastline in the northeastern National Petroleum Reserve in Alaska (NPR-A) using 1955 USGS 1:250,000 topographic maps and 1985 and 2005 Landsat 5 imagery. They measured an approximate doubling in the average rate of coastal land loss for the two time periods examined: 1955–1985 (-0.5 km^2/yr) and 1985–2005 (-1.1 km^2/yr). As much as -0.9 km of erosion occurred in some areas, and they reported erosion responsible for breaching coastal freshwater thermokarst lakes resulting in marine inundation.

- Jones and others (2008, 2009a) focused on a 100-km stretch of coast of known high erosion rates between Drew Point, Cape Halkett, and Harrison Bay. They examined three time periods and documented an apparent acceleration in mean annual erosion rates between Drew Point and Cape Halkett: 1955–1979 (-6.8 m/yr), 1979–2002 (-8.7 m/yr), and, 2002–2007 (-13.6 m/yr). Additionally, they noted an increase in the uniformity of erosion and a complex relationship between the rate of erosion and ice content, thermokarst lake processes, and soil and vegetation characteristics of the coast. They also noted a decrease in erosion rates near Cape Halkett where erosion shifted the coast from an unvegetated thaw lake basin material landward to polygonal tundra with higher ice content and vegetative cover, which is more resistant to erosion.

- Lantuit and others (2011) recently summarized erosion rates for the entire Arctic coast where 101,447 km of coastline was subdivided into 1,315 segments with a resulting average retreat rate of -0.5 m/yr. The U.S. Beaufort Sea coast showed both the highest average erosion rate (-1.15 m/yr) and the greatest range in shoreline change rates. Lantuit and others (2011) also found that erosion rates were larger along unlithified shorelines and were positively correlated (weakly) to ice content.

Manley (2004) documented shoreline change near Barrow using orthorectified 1955 black-and-white aerial photographs and orthorectified 2002 radar imagery. The measured shoreline retreat rates were as much as 8 m/yr for the mainland coast and as much as 16 m/yr for the barrier islands.

To summarize:

- All these studies have documented localized high rates of shoreline retreat, especially when compared with the rest of the Nation.
- Shoreline retreat is widespread, chronic, and in settings where extremely high rates occur, as much as -18.1 m/yr.
- Accreting coastlines are mostly limited to deltas and sandy barrier extensions.
- Ice content and lithology of material composing the bluffs affect their erodibility, and hence, erosion rates. Coastlines with low ice- and mud-rich bluffs erode faster than higher bluffs composed of coarser sediment such as sand and gravel. Additionally, warmer air and water temperatures melt the ice, resulting in loss of mechanical strength and increased erosion.
- Several studies suggest that erosion rates have been accelerating (Mars and Houseknecht, 2007; Jones and others, 2008, 2009a; Arp and others, 2010; Overeem and others, 2011).

Geology and Geomorphology of the North Coast of Alaska

Lands of Unique Importance

The north coast of Alaska comprises large tracts of Federal, State, and Native Alaskan managed land, which includes the National Petroleum Reserve–Alaska (NPR-A), the Arctic National Wildlife Refuge (ANWR), the Teshekpuk Lake Special Area (TLSA), and the North Slope Borough.

The NPR-A is managed by the U.S. Department of the Interior, Bureau of Land Management (BLM). It encompasses nearly 9,551,000 hectares (23,600,000 acres) and is the largest tract of undisturbed public land in the United States. Several Inupiaq villages are located around its perimeter; the largest of which is Barrow (seat of the North Slope Borough). Part of the NPR-A, the Teshekpuk Lake Special Area (TLSA) provides important habitat to a wide variety of wildlife, including the Teshekpuk Caribou (*Rangifer tarandus*) Herd, muskox (*Ovibos moschatus*), brown bear (*Ursus arctos*), polar bear (*Ursus maritimus*), wolverine (*Gulo gulo*), wolves (*Canis lupus*), Arctic fox (*Alopex lagopus*), red fox (*Vulpes vulpes*), shrews (*Sorex ugyunak*), lemmings (*Lemmus trimucronatus*), more than a dozen fish species, shorebirds in unusually high densities, snowy owls (*Nyctea scandiaca*), jaegers (*Stercorarius pomarinus*), falcons (*Falconidae*), ravens (*Corvus corax*), and migratory waterfowl. Teshekpuk Lake is the largest lake in Arctic Alaska, the third largest lake in the State, and possibly the largest thermokarst lake on Earth (http://alaska.usgs.gov/science/geography/studies/Teshekpuk_Lake.php; accessed November 22, 2014). Teshekpuk Lake is only a few meters above sea level and has a surface area of about 850 km^2.

The Arctic National Wildlife Refuge (ANWR) is the largest (78,000 km^2) National Wildlife Refuge in the country and is administered by the U.S. Department of the Interior, U.S. Fish and Wildlife Service (USFWS) offices in Fairbanks. The refuge supports a greater variety of plant and animal life than any other protected area in the Arctic Circle, and spans about 300 km (200 mi) north to south extending, from interior Alaska north across the Brooks Range to the Arctic Ocean. The Refuge's wildlife includes 42 fish species, 37 land mammals, 8 marine mammals, and more than 200 migratory and resident bird species (http://www.fws.gov/alaska/nwr/arctic/; accessed November 22, 2014). Along the northern coast of the refuge, the barrier islands, coastal lagoons, salt marshes, and river deltas provide habitat for migratory water birds, fish, caribou, polar bears, and seals. Situated between NPR-A and ANWR is the Prudhoe Bay oil field, the largest oil field in North America. The land is owned by the State of Alaska, which leases sites to commercial firms.

The North Slope Borough is the governing body for the North Slope, and works with the Tribes, villages, corporations, schools, businesses, State and Federal agencies, and industry to sustain the economy and balance competing subsistence and development interests (http://www.north-slope.org/, accessed November 22, 2014). The Borough has a population of 9,430 (2010 census) and a total area of 245,440 km^2 (94,763 mi^2, larger than 39 States) of which, 229,700 km^2 (88,700 mi^2) is land and 15,700 km^2 (6,000 mi^2; 6.4 percent) is water.

Geologic and Tectonic Setting

Northern Alaska can be characterized by three physiographic regions: the mountainous Brooks Range, the Arctic foothills, and the low-relief Arctic coastal plain (fig. 2). The region has a complex plate tectonic history that includes Cretaceous rifting and opening of the oceanic Canada basin of the Arctic Ocean accompanied by rotational motion whereby northern Alaska moved counterclockwise (Bird, 1999). Northern Alaska is part of a continental fragment (Arctic Alaska microplate; Hubbard and others, 1987) that includes the coast and adjacent continental shelves, most of the Brooks Range, and part of northeastern Siberia. The major Alaskan oil accumulations owe their origin to the geologic structures created through the rift process; however, most of the bedrock geology along the North Slope is covered by younger surficial deposits. The younger deposits create the modern surficial landscape of northern Alaska.

The Late Quaternary

Dinter and others (1990) described the late Cenozoic geologic history of northern Alaska and adjacent continental shelves. Repeated glacioeustatic marine transgressions and regressions during the late Cenozoic abraded the Arctic coastal plain and shelf and deposited a veneer of unconsolidated marine and non-marine deposits over the gently seaward-dipping bedrock surface that extends from the foothills of the Brooks Range to the continental shelf break. These deposits comprise the Gubik Formation and range in thickness from about 60 m onshore to a few hundred meters on the shelf. Rawlinson (1993) described in detail the surficial marine, fluvial, deltaic, outwash, glacial, eolian, and lacustrine sediments of the Gubik Formation, including the timing and deposits of late Cenozoic marine transgressions on the coastal plain. In general, the marine facies record episodes of interglacial higher sea levels for the onshore deposits. The intervening nonmarine deposits represent a wide range of climate conditions and sea-level positions. The coastal

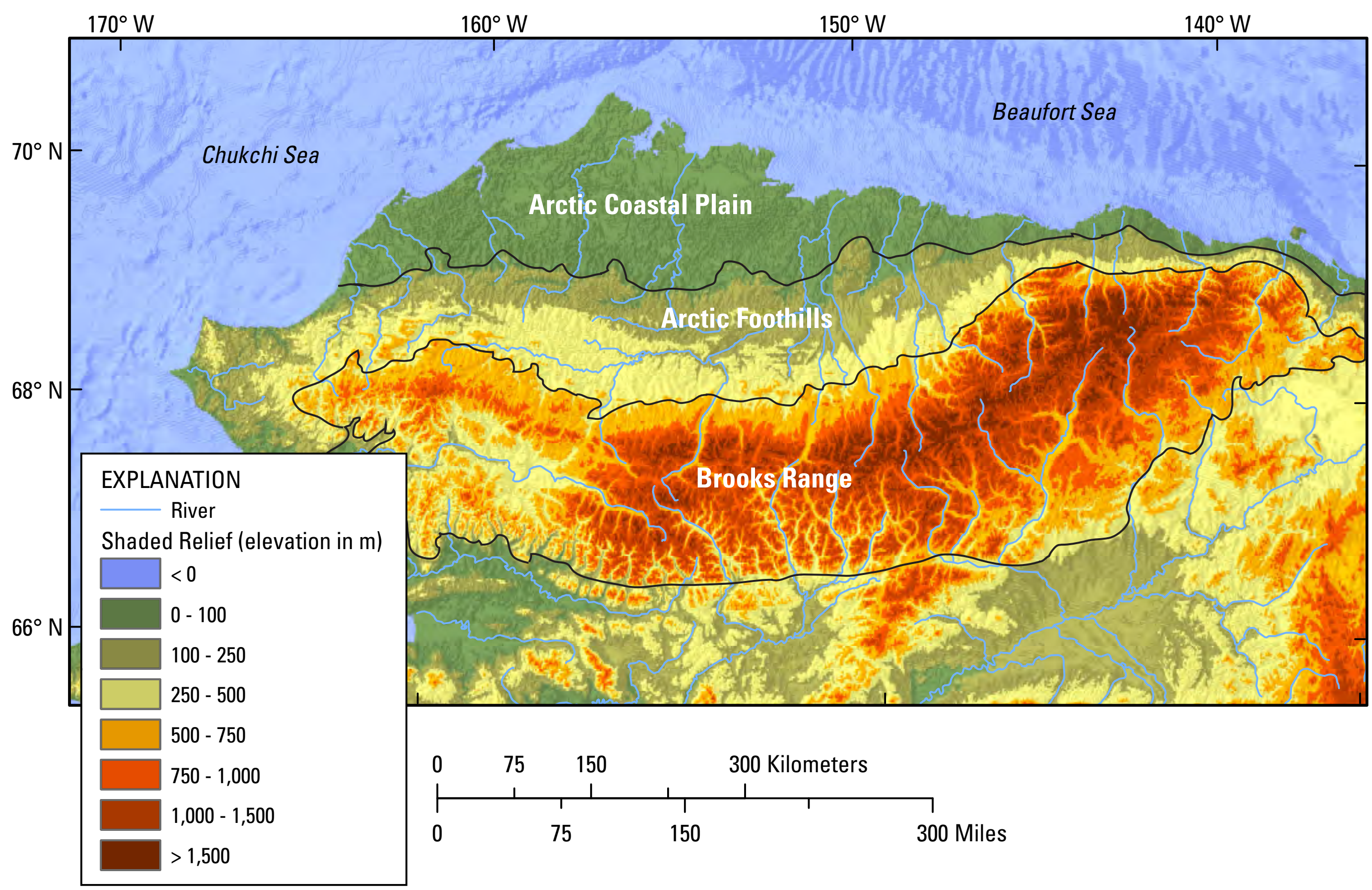


Figure 2. Relief map showing three major physiographic provinces of northern Alaska (from Amante and Eakins, 2009).

plain is underlain by numerous coalescing alluvial and glacial outwash fans extending south from the Brooks Range (Hopkins and Hartz, 1978). In addition to the fans, parts of the coastal plain are underlain by the Pleistocene Flaxman Member of the Gubik Formation (Brigham-Grette and Carter, 1992), a marine sandy mud with abundant glaciated gravel (mostly pebble to cobble size) derived from a source other than the Brooks Range, presumably from the east. Hopkins and Hartz (1978) noted that the Flaxman underlies most of Tigvariak Island, Flaxman Island, large mainland areas between and to the east of the distributaries of the Canning River, as well as smaller areas near Point McIntyre, Heald Point, and Point Brower.

Surficial Geology and Geomorphology

The generalized distribution of coastline type and surficial geology is shown in figure 3. Coastline type includes barrier island systems, bays and inlets, deltas, exposed coasts and bluffs (that is, not protected by offshore barrier islands), lagoons, remnant islands (islands with tundra characteristics similar to the adjacent mainland), and tapped basins (breached or drained thermokarst lakes). The generalized surficial geology includes marine silt and sand (glaciomarine origin with scattered pebbles and often associated with higher bluffs, 4–7 m high), alluvial silt, sand, and gravel (stream and delta deposits), eolian silt and sand, sandy diamicton (poorly sorted, mostly terrigenous mixture of mud, sand, and gravel), and glacial moraine and bedrock uplands well inland from the coast.

Coastal Environments

The Alaska Arctic coastal plain, stretching from Cape Thompson on the west to the Canadian border on the east, can be characterized as a low-relief (<20 m high), tundra-covered surface underlain by permafrost and marked by thousands of shallow thermokarst lakes. The shallow subsurface consists mostly of unconsolidated marine (near coast) and non-marine silt- to gravel-sized sediment (Bird, 1999).

The coastal morphology is a mixture of low-lying soft-sediment bluffs with varying amounts of ice content, sand and gravel beaches, barrier spits, offshore barrier islands, coastal lagoons, wetlands, and river deltas. Coastal relief, based on elevation at the shore, was classified by Hartwell (1973). Low relief coasts (<2 m high) comprise about 26 percent of the total coast and include barrier islands and spits, deltas, and low tundra coasts. Moderate relief coasts (2–5 m high) are the most common (44 percent) and are usually associated with coastal bluffs along eroding coasts. High (5–8 m high; 16 percent) and very high (>8 m high; 10 percent) relief coasts also are associated with coastal bluffs where bedrock type exerts some control on cliff height and retreat rates.

Coastal Bluffs

Coastal bluffs are common features of the north coast of Alaska. The bluff elevation and composition varies across the region, where heights range from low scarps a few meters high to cliffs nearly 25 m high in the Skull Cliff area southwest of

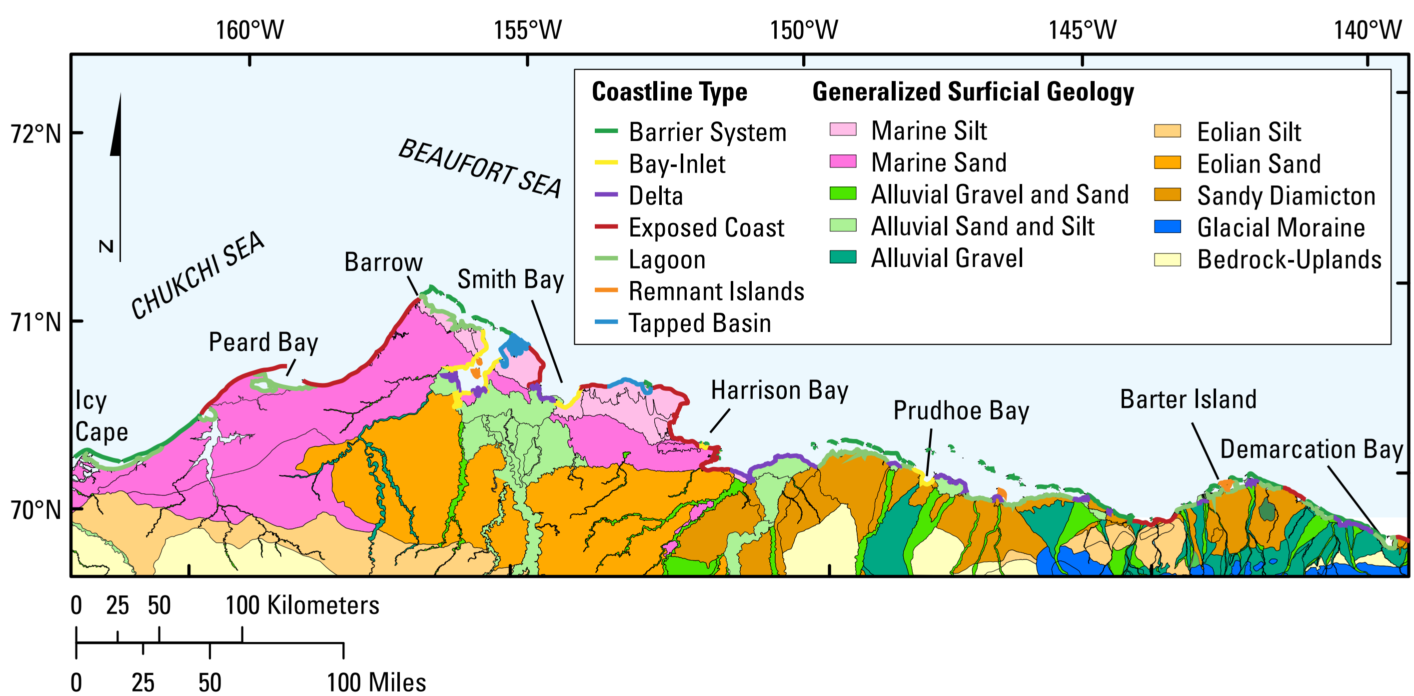


Figure 3. Map showing coastline type and generalized surficial geology of study area, north coast of Alaska (modified from Ping and others, 2011).

Barrow on the Chukchi Sea coast. Hartwell (1973) determined that approximately 74 percent of the north coast of Alaska is fronted by bluffs of 5 m in height or less. Bluff lithology along the Beaufort Sea coast ranges from ice-rich predominantly reworked marine silt to the west (Elson Lagoon to Cape Halkett), to ice-poor sand in eolian deposits in the central region (Fish Creek), to moderately ice-rich pebbly silty sand towards the east (Oliktok to Demarcation Bay; Jorgenson, 2011). Much of the northern Chukchi Sea coast is bordered by high cliffs exposing Quaternary marine and coastal deposits of the Gubik Formation.

Bluff erosion can occur by a number of process, or combinations thereof, including block failure, slumping, and flow of water-saturated sediment (Reimnitz and others, 1988). Jones and others (2009b) described erosion of ice-rich bluffs occurring by a thermo-mechanical erosion process that includes creation of an erosional niche at the base of the bluff by thermal (relatively warm seawater) and mechanical (wave action) processes. When the niche incision exceeds the bluff strength, collapse occurs and the block is further degraded by thermal and mechanical processes in the littoral zone. This process is a function of sea-surface temperature, duration of ice-free conditions, storm wave frequency and intensity, and local sea level (Reimnitz and others, 1988; Jones and others, 2009b). Ice-wedges within the bluff further impose a change in along-bluff strength characteristics, creating zones of weakness (Hoque and Pollard, 2009). Thawing of ice-rich permafrost slopes can create sediment-rich mud-flows, producing retrogressive thaw slump deposits at the base.

Beaches and Barrier Spits

Sand and gravel beaches are common features throughout the study area, typically fronting coastal bluffs or forming barrier spit extensions from the mainland. The beaches are typically narrow (<10 m wide) and composed of fine-to-coarse sand and fine gravel. Beach sediment generally coarsens from west to east across the Beaufort Sea coast, presumably in response to an eastward coarsening of fluvial and bluff sediment (Reimnitz and others, 1988). The beaches are frozen most of the year, thawing during the summer months but maintaining permafrost underneath the thawed active layer. Active beaches have deep active layers (as deep as 2 m), whereas inland ridges typically have permafrost within 0.5 m of the surface (Jorgenson, 2011). Coastal currents generated by the predominant northeasterly winds drive sediment westward while occasional northwesterly autumn storms drive sediment in the opposite direction, although westerly sediment transport prevails (Reimnitz and Kempema, 1983; Barnes and others, 1988).

Barrier Islands

Barrier islands are widespread across the north coast of Alaska fronting approximately 20 percent of the mainland coast and 13 percent of the world's barrier islands—a total of 272—surround the Arctic Ocean (Stutz and Pilkey, 2011). Two general types of barrier islands occur in the study area: (1) low-lying, unconsolidated sand and gravel islands with a wide range of vegetation coverage from non-vegetated to sparsely vegetated to an extensively vegetated; (2) elevated tundra islands of similar composition to the mainland tundra coast. A combination of the two types is common. Tundra islands can be relic features formed during Pleistocene interglacial episodes of higher sea level, or, as erosional remnants of the coastal plain that have become isolated from the mainland by thermokarst subsidence and erosion.

There are a number of hypotheses that describe the origin and construction of barrier islands in the Arctic (for example, Hopkins and Hartz, 1978; Ruz and others, 1992). Low-lying non-vegetated to vegetated barrier island can form as emergent depositional shoals linked to the outer fringes of river deltas, or by recent (<1,000 years) deposition of longshore or cross-shore transported sediment including the breaching of spits connected to the mainland or other islands. Reimnitz and others (1990) describe an ice-shove process where sand and gravel is excavated by ice from the seabed in nearshore water depths and reformed into ridges along the shoreline.

Ruz and others (1992) put forth a model for barrier island construction in the southern Canadian Beaufort Sea, which could apply to the north coast of Alaska as well. In that conceptual model, sea-level rise over a landscape of thermokarst basins and low-relief coasts composed of ice and unconsolidated sediment leads to the formation of embayments and rapidly eroding headlands from which spits develop. Subsequently, spits erode and evolve into barrier islands primarily through the process of overwash and eventual breaching. Once formed, stability of the island depends on equilibrium between sediment supply for deposition and energy available to transport the sediment.

Stutz and Pilkey (2011) found that island lengths in the Arctic are on average (5 km) only one-half the global average (10 km) because of the effect of sea ice on fetch and thus wave energy. Storm frequency in the high and middle latitudes is suggested to result in shorter and narrower islands relative to those on swell-dominated low-latitude coasts and the ratio of storm wave height to annual mean wave height is a good indicator of the degree of storm influence on island evolution. They also noted the potential for significant climate and sea-level change this century underscores the need to improve understanding of the fundamental roles that these two factors have played historically in island evolution in order to predict their future effects on the islands.

Coastal Lagoons

Lagoons are present along large sections of the north coast of Alaska and are typically bordered by offshore barrier island chains and/or barrier spits and the mainland, or, they can be drowned fluvial drainage systems enclosed by tundra uplands such as Wainwright Lagoon. The lagoons extend alongshore for up to 70 km, have varying widths with maximum depths around

3–4 m (Jorgenson, 2011). They provide essential waterfowl habitat for significant numbers of breeding and post-breeding migratory birds (Lysne and others, 2004). During the summer months, the coastal lagoons water temperature is typically warmer than the adjacent seas because of heating in the shallow lagoons and limited ocean mixing through narrow passages.

Wetlands

Arctic wetlands occur near peatlands, shallow lakes, ponds, topographic lows such as low-center polygons, and abandoned stream channels. Coastal salt marshes, which occur in sheltered bays and inlets, are typically extensive and can accumulate (near-) continuous vegetation cover, however, because of the low tidal range the development of strong vegetation zones is limited. During summer conditions, the nearshore waters tend to be more brackish because of freshwater input increases (Jefferies, 1977). The coastal lakes and deltas during the summer months are associated with sedge and grass marshes creating an ideal habitat for migratory birds and foraging mammals.

Deltas

There are numerous rivers draining the northern Alaska coastal plain, with the Colville River being the largest and draining about 29 percent of the North Slope (Jorgenson, 2011). Fluvial sediment delivered to the coast is mostly mud to sand size, and more rarely gravel. Because of their closer proximity to the Brooks Range, the eastern rivers typically terminate in sand and gravel outwash fans, whereas the western river deltas are generally characterized by numerous shallow shoals and mud flats interrupted by shallow broad channels. Delta sediment is typically composed of mixtures of silt, fine sand, and finely disseminated peat in channels and flats (Rawlinson, 1993). Reimnitz and others (1988) estimated that sediment yield from coastal erosion yields seven times more sediment to the continental shelf than that derived from streams in their study area along the central Beaufort Sea coast.

Permafrost

Permafrost is perennially frozen ground characteristic of polar regions and is an important component to landscape and ecological development in high latitudes. Jorgenson (2011) provides a summary of northern Alaska permafrost including permafrost development and associated coastal and lacustrine landforms. The Arctic coastal plain is underlain by continuous permafrost that extends underneath the inner continental shelf to about 20 m isobath (Brothers and others, 2012). Seasonal thawing of the upper permafrost during summer months produces an active layer of water and sediment/soil. Permafrost thickness is generally greater than several hundred meters on the coastal plain. The northern Alaska coastal plain tundra surface is characterized by a wide variety of permafrost related small-scale surface features creating a patterned ground including polygons (low-relief low-centered, high-relief low-centered, low-relief high centered, and high-relief high-centered), talik (unfrozen zones) associated with shallow lakes and gullies. The intersection of complex polygon boundaries with coastal bluffs can exert control on bluff failure mechanisms (Jones and others, 2009b)

Thermokarst

Thermokarst topography is widespread on the Arctic coastal plain and is characterized by an irregular pitted landscape often with small hummocks and shallow pools that somewhat resembles karst topography in tropical limestone terrains. Thermokarst lakes, also called thaw lakes, are freshwater bodies formed in shallow depressions. Thermokarst lakes and associated drained lake basins are widespread in permafrost lowlands with ice-rich sediments. Thermokarst lake formation occurs during permafrost degradation and is linked to surface disturbance, subsequent melting of ground ice, surface subsidence, water impoundment, and positive feedbacks between lake growth and permafrost thaw, whereas lake drainage generally results in local permafrost aggradation (Grosse and others, 2013). The lakes characteristically have unique limnological, morphological, and biogeochemical characteristics that are closely tied to cold-climate conditions and permafrost properties. They also have a tendency toward drainage through permafrost degradation and erosion. Thermokarst lake dynamics strongly affect the development of landscape geomorphology, hydrology, and the habitat characteristic of permafrost lowlands.

Dunes

Holocene dunes are present or downwind of nearly all active river and delta systems and along the seaward edge of tundra-covered barrier islands that have a beach (Rawlinson, 1993). Black (1951) studied the eolian deposits of Alaska and described the Arctic coastal plain suitable for eolian transport because of high winds, lack of topographic obstacle, low precipitation, and an abundance of silt and sand sediment. He also noted that permafrost and tundra vegetation limit modern dune formation. Eolian deposits of the coastal plain consist of dunes, sand sheets, and loess blankets, although the most widespread deposits are pre-Holocene in age with active dunes generally limited to river systems (Jorgenson, 2011).

Methods of Analyzing Shoreline Change

Compilation of Historical Shorelines

Coastal researchers in universities and government agencies in the United States have been quantifying rates of shoreline movement and studying coastal change for decades. Time series of shoreline positions can be used to document coastal change and are interpreted to improve our understanding of shoreline stability. Before global positioning system (GPS) and lidar technologies were developed, the most commonly used sources of historical shoreline position were NOAA topographic sheets (T-sheets) (Shalowitz, 1964) and aerial photographs. Extraction of shoreline position from these data sources involves georeferencing maps or aerial photographs, and subsequently interpreting and digitizing a shoreline position. Depending on location, data source, and scientific preference, different proxies for shoreline position (shoreline reference feature) are used to document coastal change, including high water line (HWL), wet-dry line, vegetation line, dune toe or crest, toe or berm of the beach, cliff base or top, the line of mean high water (MHW), or a tide-coordinated or instantaneous land-water interface.

This study incorporates shoreline positions for two time periods, circa-1940s and circa-2000s derived from a variety of dates and data sources (table 1, fig. 4). Datasets were selected based on having regional coverage over a relatively consistent time period and that were also available in digital format and previously georeferenced or readily done so (for example, T-sheets with geographic coordinate information).

The shoreline reference features, or shoreline proxy, mapped in this study were the "approximate mean high water line" (aHWL) as defined and mapped on the 1940s era T-sheets and the instantaneous land-water interface on the 2000s era photography, satellite imagery, vector shorelines, and lidar DEM.

Common proxies for high-water lines (for example, beach wrack, wet/dry line, toe or berm of the beach) were difficult to determine in the 2000s era data sources used in this study due to narrow beaches, low contrast of beach sediment, low sun angles, and/or lack of debris material. The intersection of the water line and the beachface was identified as an appropriate proxy and was digitized where a beach was present. Where no beach was present, the bluff edge was digitized. The land-water interface proxy for the 2000s era shoreline was generally well defined in all the imagery, except where obscured by clouds, shadows, waves, or ice. Shorelines were not digitized for highly variable deltaic regions and for intertidal mudflats because of uncertainties identifying waterline intersections on gently sloping shorelines. The land-water interface is not an ideal feature to use as a shoreline proxy because of the potentially wide variations in the horizontal position of the shoreline due to fluctuating water levels, which is especially pronounced in gently-sloping environments. However, because of the difficulties identifying other shoreline proxies outlined above,

Table 1. Providers and original sources of historical shoreline data for the north coast of Alaska.

[ANWR, Alaska National Wildlife Refuge; NPR-A, National Petroleum Reserve, Alaska; DEM, Digital Elevation Model; lidar, light detection and ranging]

Organization	Original data source	Spatial coverage
National Oceanic and Atmospheric Administration (NOAA), Coastal Services Center	Scanned NOAA T-sheets (1947, 1949)	All regions
U.S. Fish and Wildlife Service	Pan-sharpened multispectral QuickBird™ satellite imagery (2003)	ANWR coast; Staines River to the U.S.-Canadian border
U.S. Geological Survey	Color-infrared Digital orthophotographs Quarter Quadrangles (2002, 2005)	NPR-A; Kikolik Creek to Colville River Delta
ConocoPhillips	Color-infrared digital orthophotographs (2004, 2006)	Fish Creek/Colville River Delta to about 9 km east of Oliktok Point, including Thetis, Spy, Leavitt, and Cross Islands
BP Exploration (Alaska), Inc.	Color-infrared digital orthophotographs (2006, 2007)	About 9 km east of Oliktok Point to about 9 km east of Point Thomson, including offshore barrier islands between Pingok and Stump Islands
BP Exploration (Alaska), Inc.	Digitized vector shorelines from planimetric maps (1997, 2001)	Offshore barrier islands from Reindeer Island to Brownlow Point
Geographic Information Network of Alaska	Alaska Statewide Orthoimagery Mosaic, SPOT5 satellite imagery (2010, 2011)	Eastern Peard Bay and Wainwright Inlet
U.S. Geological Survey	Airborne lidar DEM (2010, 2011, 2012)	Icy Cape to Kikolik Creek

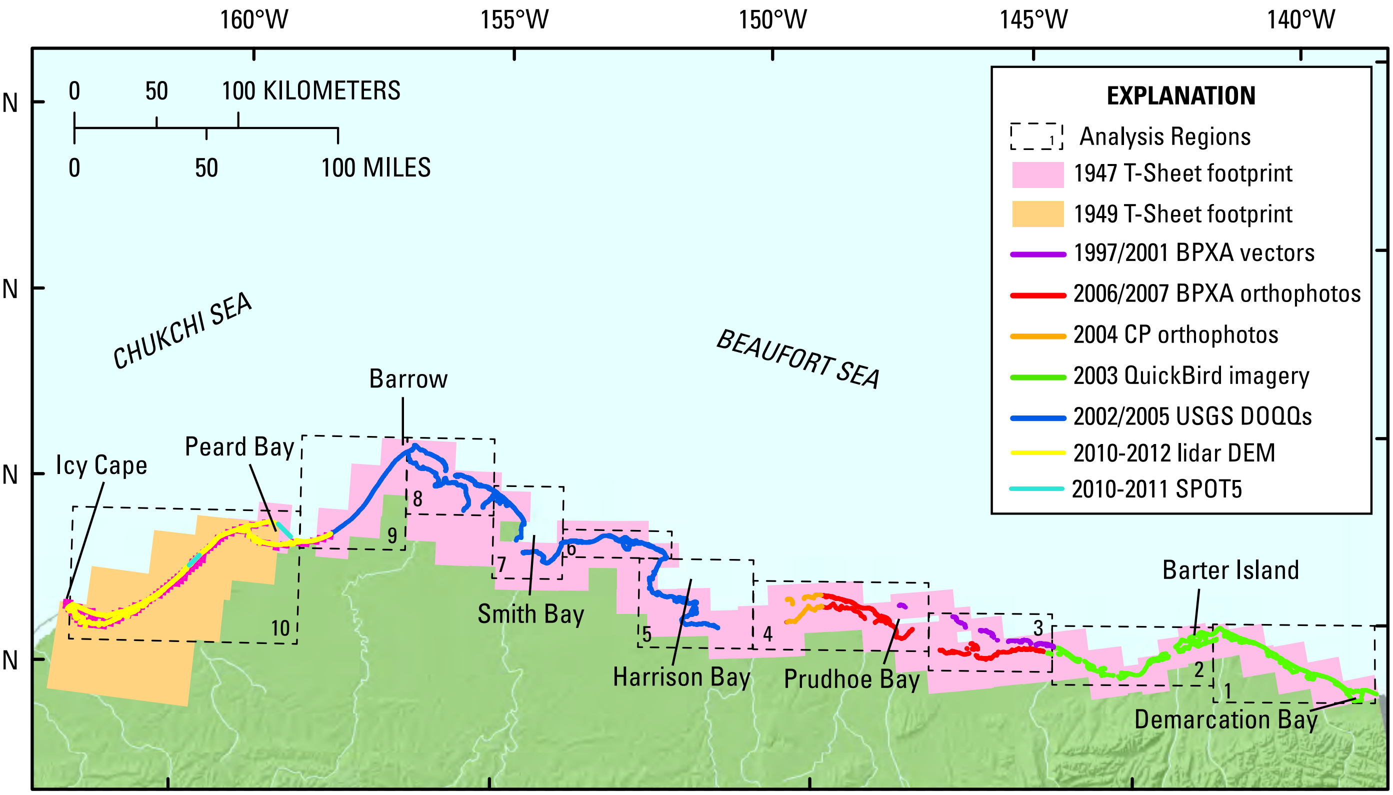


Figure 4. Index map of the north coast of Alaska showing shoreline data sources used in this study and their approximate extents.

and because of the low diurnal tidal range along the Arctic coast (< 0.21 m; National Oceanic and Atmospheric Administration, 2014), this method was deemed acceptable for this study. Uncertainties regarding the position of the digitized shorelines is discussed in section, "Estimation of Shoreline Position Uncertainty."

To generate shorelines from the various imagery and maps, the shoreline reference features for each dataset were digitized in ArcGIS™ at a scale of 1:1,500-7,000, depending on the source resolution. All shoreline vectors were converted to Universal Transverse Mercator (UTM) projection for their specific zone (zones 4-7) on the North American Datum of 1983 (NAD 83).

1940s-Era Shorelines

Circa-1940s shorelines were delineated from 1947 or 1949 National Ocean Service (NOS; formerly U.S. Coast and Geodetic Survey) T-sheets (table 2; fig. 4). Previous workers (Shalowitz, 1964; Crowell and others, 1991; Daniels and Huxford, 2001) who addressed the accuracy of T-sheets found that they meet national map accuracy standards (Ellis, 1978) and recommended them for use in shoreline change studies as a valuable source of data needed to extend the time series of historical shoreline positions (National Research Council, 1990). The 1940s T-sheets are highly detailed and include survey reference points, many of which are included in the National Geodetic Survey (NGS) benchmark database. Roads, buildings, lakes and drainage patterns, muddy and marsh areas, hills and ridges, cliffs, bluffs, mud deposits and shoal areas are consistently delineated on the maps. The original source of the T-sheets, as discussed in the *Descriptive Reports* associated with each sheet, is primarily from a combination of vertical and oblique aerial photography collected in June and July 1947 and 1949. Questionable areas were addressed using information acquired during corresponding hydrographic surveys and/or supplemental ground surveys and field checking completed between 1949 and 1952.

T-sheets were requested from NOAA Coastal Services Center (Adam Bode, written. commun., 2007) and received as digital (1,200 dpi), unregistered, TIFF images. T-sheets were georeferenced in-house using ESRI ArcMap™ 9.3 software. A minimum of eight ground control points (GCPs), distributed throughout the image on the T-sheet graticule, were used to apply a third order polynomial transformation. For the 1940s T-sheets, it was necessary to shift the graticule coordinates from the original mapped local datum coordinates to the North American Datum of 1983 (NAD 83) coordinates using datum transformation information provided by the National Geodetic Survey (NGS; Dave Doyle, written commun., 2008). The datum transformation was applied to T-sheet graticule coordinates prior to rectification.

Table 2. Shorelines used to calculate change rates for the north coast of Alaska by coastal segment.

[aHWL, approximate mean high water line; LWI, land-water interface; Lidar DEM, light detection and ranging Digital Elevation Model. **Date:** For details about dates of shoreline data used at specific locations within a region, refer to the shoreline data files available for download in the companion online data report (Gibbs and others, 2015). **Source:** C, ConocoPhillips; B, BP Alaska; U, USGS]

Region	Date	Source	Type
(1) U.S.-Canadian Border to Jago River	1947	T-sheet	aHWL
	2003	QuickBird™	LWI
(2) Jago River to Staines River	1947	T-sheet	aHWL
	2003	QuickBird™	LWI
(3) Staines River to Sagavanirktok River	1947	T-sheet	aHWL
	2003	QuickBird™	LWI
	2006	C-B Aerial photograph	LWI
	1997	B Aerial photograph	LWI
	2001	B Aerial photograph	LWI
(4) Sagavanirktok River to Colville River	1947	T-sheet	aHWL
	1997	B Aerial photograph	LWI
	2004	C-B Aerial photograph	LWI
	2006	C-B Aerial photograph	LWI
	2007	C-B Aerial photograph	LWI
(5) Colville River to Cape Halkett	1947	T-sheet	aHWL
	2002	U Aerial photograph	LWI
(6) Cape Halkett to Drew Point	1947	T-sheet	aHWL
	2002	U Aerial photograph	LWI
(7) Drew Point to Dease Inlet	1947	T-sheet	aHWL
	2002	U Aerial photograph	LWI
(8) Dease Inlet to Barrow	1947	T-sheet	aHWL
	2002	U Aerial photograph	LWI
	2005	U Aerial photograph	LWI
(9) Barrow to Peard Bay	1947	T-sheet	aHWL
	2005	U Aerial photograph	LWI
	2010	Lidar DEM	LWI
(10) Peard Bay to Icy Cape	1947	T-sheet	aHWL
	1949	T-sheet	aHWL
	2010–12	Lidar DEM	LWI
	2010–11	SPOT5	LWI

To verify T-sheets and datum transformations, a comparison was made between the georeferenced T-sheets, georeferenced 2000s era imagery, and published locations of the NGS benchmark locations, which were mapped on and used as survey control for the T-sheets. A problem unique to the north coast of Alaska, compared to the conterminous U.S. coast, is the relative paucity of temporally consistent, region-wide shoreline datasets and limited horizontal and vertical control with which to reference the geographic data. A poor geoid model and existing digital elevation model (DEM), and lack of extensive infrastructure of roads, buildings, etc. away from villages and oil and gas related development also makes it difficult to control imagery, accurately assess position errors, and/or compare datasets from one time period to the next. For this study, lake shorelines, other geomorphic features, benchmark locations, and limited roads, building, or infrastructure were used to evaluate the relative consistency or accuracy of the T-sheets with the assumption that most of these features have not changed significantly through time. Although there was some disagreement with lake edges near the corner of the sheets and with increasing distance from the coast, for the most part features in the datasets corresponded well and were within the uncertainty tolerance of the original scale, registration and digitization process.

2000s-Era Shorelines

Circa-2000s shorelines were developed using a combination of data sources including vector shorelines, vertical aerial photographs, satellite imagery, and a DEM derived from airborne lidar elevation data (table 2; fig. 4). 1997 and 2001 vector shoreline data (provided by BP-Alaska, BPXA) were digitized from 1:6000 scale planimetric maps derived from 1:2000 CIR photography and have an estimated horizontal accuracy of 3.7 m (12 ft ; Ken Ambrosius, written commun., 2007). 2004–2007, 1-foot pixel resolution color orthophotograph mosaics were provided by ConocoPhillips (CP) and BPXA and have an estimated horizontal accuracy of 3.0 m (10 ft ; Ken Ambrosius, written commun., 2007). 2002 and 2005, 2.5 m pixel resolution CIR Digital Orthophoto Quarter Quads (DOQQs) (acquired from USGS and available on the EarthExplorer web site; http://earthexplorer.usgs.gov/) have a specified horizontal accuracy of 3.0 m RMSE (Tom Sturm, U.S. Geological Survey, written commun., 2011). 2003, 0.6 m pixel resolution pan-sharpened QuickBird™ image mosaics (provided by USFWS) have a stated accuracy of 6.2 m RMSE, according to the QuickBird™ Imagery Products Product Guide.

No historical images were available for the portion of the Chukchi Sea coast between Kikolik Creek and Icy Cape. For this section, a 3-m pixel resolution digital elevation model (DEM) was generated from coastal lidar elevation data collected between 2010 and 2012. The land-water interface (shoreline) was interpreted and then digitized from a 30x vertical exaggeration hillshade derived from the DEM. Shorelines for the barrier islands on the eastern side of Peard Bay and at the mouth of Wainwright Inlet were derived from 2.5 m SPOT5 satellite orthoimagery for 2010 and 2011, respectively (Alaska Statewide Orthoimagery Mosaic, accessed November 22, 2014, at http://www.alaskamapped.org/).

Estimation of Shoreline Position Uncertainty

Several sources of error affect the accuracy of historical shoreline positions and the uncertainties associated with the shoreline change rates calculated from them. Measurement uncertainties, including errors related to shoreline digitization, image resolution, image rectification, and T-sheet plotting, are related to analyst manipulation of the map and photograph products. For T-sheets, National Map Accuracy Standards (U.S. Bureau of the Budget, 1947) were adopted that provide a measure of both position and measurement uncertainties. For photographs, measurement uncertainty is related to the orthorectification process and onscreen delineation of the shoreline.

Anders and Byrnes (1991), Crowell and others (1991), Thieler and Danforth (1994), and Moore (2000) provided general estimates of the typical High Water Line (HWL) measurement uncertainties associated with (1) mapping methods and materials for historical shorelines, (2) the registration of shoreline position relative to geographic coordinates, and (3) shoreline digitizing. Using methods by Crowell and others (1993) and further developed and applied by Hapke and others (2006, 2010), we identify five uncertainty terms for HWL-type shorelines: georeferencing uncertainty (U_g), digitizing uncertainty (U_d), T-sheet survey uncertainty (U_t), and aerial/satellite image uncertainty (U_a). The georeferencing uncertainty (U_g) represents the maximum acceptable root mean square error (RMSE) for T-sheets at a scale of 1:20,000 and is applied to historical shorelines derived from T-sheets only. In this study, the total RMSE was maintained below 0.0001 degrees, which is approximately 11 m at this latitude. Typically, the resulting RMSE was much lower than 0.0001 degree. The digitizing uncertainty (U_d) is the uncertainty associated with digitizing the shoreline and was assumed to be equal to one-half the line width (typically about 10 m) on the scanned T-sheets and two times the pixel resolution of the imagery. The maximum T-sheet survey uncertainty (U_t), determined by Shalowitz (1964), incorporates all errors associated with the mapping process, including distance to rodded points, plane-table position, and identification of the HWL. The aerial/satellite image uncertainty (U_a) is the horizontal accuracy or RMSE of the orthorectification process of the image data. Values were provided by the data originators and are different for the individual datasets (table 3).

An additional uncertainty term in our shoreline change analysis is the uncertainty in the position of the water line at the time of the survey (U_{pd}). Because ocean water levels fluctuate due to daily tides and in response to changing winds, waves, and air pressure, a photograph can capture the shoreline at a range of water levels. The tidal range along north coast of Alaska is only about 0.21 m (National Oceanic and Atmospheric Administration, 2014), however, water levels can become elevated or depressed up to several meters due to winds and low-pressure systems; westerly winds tend to elevate water levels at the coast, whereas easterly wind events tend to lower water levels (Reimnitz and Maurer, 1979; Sultan and others, 2011; Li Erikson, U.S. Geological Survey, written commun., 2014). We assume these water level offsets were accounted for during the T-sheet mapping efforts, as noted in the Descriptive Reports accompanying the surveys, by conducting concurrent water level surveys during image acquisition and mapping and per standard mapping practices described in Shalowitz (1964). However, elevated or reduced absolute water levels during acquisition of the 2000s era datasets, have the potential to significantly modify the horizontal position of the shoreline as determined from the land-water interface, especially in low-lying areas. In order to estimate the positional uncertainties associated with the land-water interface shoreline, we evaluated water levels at the Prudhoe Bay tide gauge, the only continuously recording tide gauge on the north coast of Alaska, for the dates of acquisition of the aerial photographs, satellite images, and lidar data. The minimum and maximum value of water levels below and above the MHW datum for the time period during survey acquisition ranged between -0.19 and +0.56 m (table 4). No comprehensive information on regional beach slopes exists for the study area, however, based on limited field validation and the generally narrow width of beaches (< 50 m) which are comprised primarily of gravel and coarse sand, a slope of 1:20, (5 percent or approximately 3 degrees), was chosen as a conservative estimate of beach slope for the entire study area. The average water level deviation from MHW for each dataset was multiplied by 20 to determine the estimated uncertainty of the land-water interface digitized water line position relative to MHW at the time of the survey(U_{pd}). This average horizontal position uncertainty ranges between -1.5 and +6.0 m (table 4).

Water levels at locations elsewhere along the North Slope can deviate significantly from those measured at Prudhoe Bay, near the center of the study area. To support the results

Table 3. Measurement uncertainties associated with all datasets.

[BPXA, BP-Alaska; DEM, Digital Elevation Model; lidar DEM; light detection and ranging Digital Elevation Model; DOQQs, Digital Orthophoto Quarter Quads; -, not applicable]

Measurement uncertainty (meters)	1947 T-sheets	1997 vector shoreline	2001 vector shoreline	2003 QuickBird™	2004 CPhillips photographs	2006 BPXA photographs	2007 BPXA photographs	2002 DOQQs	2005 DOQQs	2010 lidar DEM	2011 lidar DEM
Georeferencing (U_g)	11	-		-	-				-		-
Digitizing (U_d)	5	1		1	1				5		6
T-sheet survey (U_t)	10	-		-	-				-		-
Air/satellite photograph (U_a)	-	4		6	3				3		-
High water line (U_{pd})	-	4.2	-0.1	-1.2	4.3	2.3	1.4	1.3	-1.5	4.3	4.9
Total shoreline position uncertainty (U_p)	15.7	5.7	3.8	6.2	5.3	4.2	3.4	6.0	6.0	7.4	7.8

Table 4. Water level deviation from Mean High Water (MHW) and associated change in shoreline position.

[BPXA, BP-Alaska; DOQQ, Digital Orthophoto Quarter Quad; lidar; light detection and ranging]

Data source	Acquisition	Water level deviation from MHW (meters)			Horizontal change (meters)		
		Maximum	Minimum	Average	Maximum	Minimum	Average
1997 vector	07-24-97	0.33	0.09	0.21	6.6	1.8	4.2
2001 vector	08-30-01	0.13	-0.14	0.00	2.6	-2.8	-0.1
2002 DOQQ	07-16-02	0.15	-0.03	0.06	3.0	-0.7	1.2
2002 DOQQ	07-17-02	0.26	-0.06	0.10	5.1	-1.2	2.0
2002 DOQQ	07-18-02	0.15	-0.06	0.05	2.9	-1.1	0.9
2003 QuickBird™	08-29-03	0.07	-0.19	-0.06	1.4	-3.8	-1.2
2004 CPhillips	07-26-04	0.23	0.20	0.22	4.6	4.0	4.3
2005 DOQQs	07-25-05	0.05	**-0.19**	-0.07	0.9	-3.8	-1.5
2006 BPXA	07-12-06	0.02	0.01	0.01	0.3	0.2	0.3
2006 BPXA	07-24-06	0.11	0.09	0.10	2.2	1.7	1.9
2006 BPXA	07-25-06	0.24	0.22	0.23	4.8	4.5	4.6
2007 BPXA	07-04-07	0.13	0.01	0.07	2.5	0.2	1.4
2010 lidar	07-28-10	0.26	0.00	0.13	5.2	-0.1	2.6
2010 lidar	08-02-10	**0.56**	0.05	0.30	11.1	0.9	6.0
2011 lidar	09-13-11	0.38	0.12	0.25	7.5	2.3	4.9

described above, we compared our results to a similar study (Li Erikson, U.S. Geological Survey, written commun., 2014) where shoreline position uncertainty estimates related to wind-setup were obtained from numerical model runs in the vicinity of Barter Island, Alaska, about 185 km east of Prudhoe Bay. In this study, sustained winds up to 15 m/s oriented from the west were used as boundary conditions to simulate storm surge levels; a wind speed of 15 m/s was assumed to be the upper limit conditions that small aircraft obtaining aerial photography were able to fly (R. Wyland, U.S. Geological Survey, oral. commun., 2010). Shoreline position uncertainties were estimated to be ± 0.4 m in the vertical (±2 to ±8 m in the horizontal for a slope of 1:5 and 1:20, respectively) due to wind set-up, and ± 0.2 cm in the vertical (±1 to ±4 m in the horizontal for a slope of 1:5 and 1:20, respectively) due to astronomic tides (National Oceanic and Atmospheric Administration, 2014), which agree well with our observed and calculated values observed at Prudhoe Bay during image data acquisition.

For each shoreline position, the total uncertainty is found as the square root of the sum of squares (Taylor, 1997) of the relevant uncertainty terms, based on an assumption that each term is random and independent of the others. For shorelines derived for this study, the total shoreline position uncertainty at each transect *i*, is calculated following the method developed by Hapke and others (2006, 2010):

$$Up_i = \sqrt{Ug_i^2 + Ud_i^2 + Ut_i^2 + Ua_i^2 + Upd_i^2} \qquad (1)$$

Calculation of Shoreline Change Rates

Rates of shoreline change were generated in ArcGIS™ with the Digital Shoreline Analysis System (DSAS) version 4.3, an ArcGIS™ extension developed by the USGS in cooperation with TPMC Environmental Services (Thieler and others, 2009). This tool allows the user to generate transects relative to a baseline that intersect the shorelines at a user-defined separation along the coast and calculate rates of change based on spatial and temporal differences between successive shorelines. For this analysis, baselines were constructed seaward of, and roughly parallel to, the general trend of the oldest shoreline. Using DSAS, transects were spaced at 50-m intervals and manually edited to assure they were as orthogonal to the most recent shorelines as possible and non-overlapping. DSAS employs the single-transect method (ST) to calculate change rates and rate uncertainties at regularly spaced transects (measurement locations) alongshore. ST uses various methods (for example, end point rate, linear regression rates, least squares, weighted least squares) to fit a trend line to the time series of historical shoreline positions at a transect. ST is the most commonly utilized method for calculating shoreline change (for example, see Fletcher and others, 2003; Morton and others, 2004; Morton and Miller, 2005; Hapke and others, 2006; Hapke and Reid, 2007).

Because shorelines from only two time periods were evaluated in this study, shoreline change rates were calculated at each transect using the end-point rate method. The end-point rate is found as the difference in shoreline position between 2 shoreline years, divided by the time between surveys. For an end-point rate, there is no assumption that the rate was linear between the 2 survey years; the rate represents the net change between the surveys. Thus, rates of change represent averages over an approximately 60-year time period and do not reflect the episodic nature of the coastal change, particularly with regards to bluff retreat, which can cause substantial changes to the coastline in a short amount of time due to the collapse of meters-wide blocks of unconsolidated sediment from the bluffs.

Estimation of Shoreline Change Rate Uncertainty at Individual Transects

The uncertainty of a single transect's end-point shoreline change rate (U_R) is found as the quadrature addition of the uncertainties for each year's shoreline position, divided by the number of years between the shoreline surveys:

$$U_{R_i} = \frac{\sqrt{U_{p1_i}^2 + U_{p2_i}^2}}{year_2 - year_1} \qquad (2)$$

where U_{p1_i} and U_{p2_i} are the shoreline position uncertainties of the first ($year_1$) and second ($year_2$) shorelines, respectively, at transect *i*, found through equation (2) (after Hapke and others, 2006). For this study, all transects have a (U_R) value of 0.3 m/yr.

Estimation of Regionally Averaged Shoreline Change Rate Uncertainty

Regionally averaged shoreline change rates are the average of rates from all transects in a coastal region. The uncertainty at each transect is assumed to be random and independent. Therefore, the uncertainty of an average rate (U_{avg}) can be calculated as the root sum of squares of rate uncertainties (U_R) at all transects divided by n:

$$U_{avg} = \frac{\sqrt{\sum_{i=1}^{n} U_R^2}}{n} \qquad (3)$$

The resulting average rate and uncertainty are often small relative to rates from individual transects. The greater the number of transects over which the uncertainty is averaged, the smaller the uncertainty of the average rate. To avoid reporting statistically significant average rates as indicating no change or having zero uncertainty, average rates were reported at higher precision (centimeters per year, 0.00 m/yr) than rates from individual transects (decimeters per year, 0.0 m/yr) (after Fletcher and others, 2012).

Historical Shoreline Change Analysis

For the presentation of shoreline change rates, the north coast of Alaska was subdivided into 10 regions (fig. 5), which are based broadly on coastal geomorphology and orientation of the coast. Barter and Tigvariak Islands were analyzed separately and only their exposed open-ocean shorelines are included in the regional averages. Index maps showing geographic locations described in the text are shown in figures 6–9.

In contrast to other NASC studies which evaluated only open-ocean sandy shorelines and coastal cliffs, this report presents rates for exposed open-ocean and sheltered mainland shorelines. We define exposed open-ocean shorelines to include mainland coast, barrier beaches, islands, or spits that are exposed directly to open-ocean wave, wind, and sea-ice conditions. Sheltered shorelines, typically mainland lagoon coasts, are sheltered from open-ocean conditions by an offshore barrier spit or island. No distinction was made between a sand or gravel beach versus a coastal bluff with no fronting beach – the shoreline mapped was the land-water interface whether it was a beach or the base of a bluff.

Each section below describes the geographical extent of the region, including any special features, population centers, or oil and gas or U.S. Department of Defense Distant Early Warning site (DEW) related infrastructure, followed by a summary of coastal geomorphology, including relative coastal elevations derived from airborne lidar surveys collected over the study area between 2009 and 2012 (Gibbs and others, 2013) and Interferometric Synthetic Aperture Radar (InSAR) elevation data collected in 2002, and finally a summary of shoreline change rates for the region as a whole and for subregions within. Table 5 summarizes total shoreline change rates and ranges for each of the regions and subregions as well as for the exposed and sheltered segments of the shorelines.

Along a continuous mainland coast, shorelines can accrete or erode through time, but are largely present from one year to the next. An exception to this situation along a mainland coast might arise near river mouth bars or spits that may form, erode, or migrate intermittently from year to year. For the most part, shoreline change rates calculated using the DSAS method along mainland coasts provide a relatively complete assessment of the shoreline change history and the amount of land gained or lost through time.

On barrier coasts, however, where islands and spits can form, erode, and migrate through space and time, single transect DSAS rates may provide an incomplete or even misleading record of the shoreline change history because a piece of land may have completely eroded, formed, or migrated into a location where no previous landform existed during one or more of the analytical time periods and change rates could not be measured. Although we present in this report DSAS rates for all barrier shorelines where rates could be determined, caution should be used when evaluating the rates, as discussed in the text. For selected barrier islands and island chains in Regions 3, 4, and 8, information on the change in total surface area of the barriers are reported in addition to the DSAS results. The surface area is the total, two-dimensional, polygonal surface areas (square meters) of each barrier island, digitized from the data sources describe above.

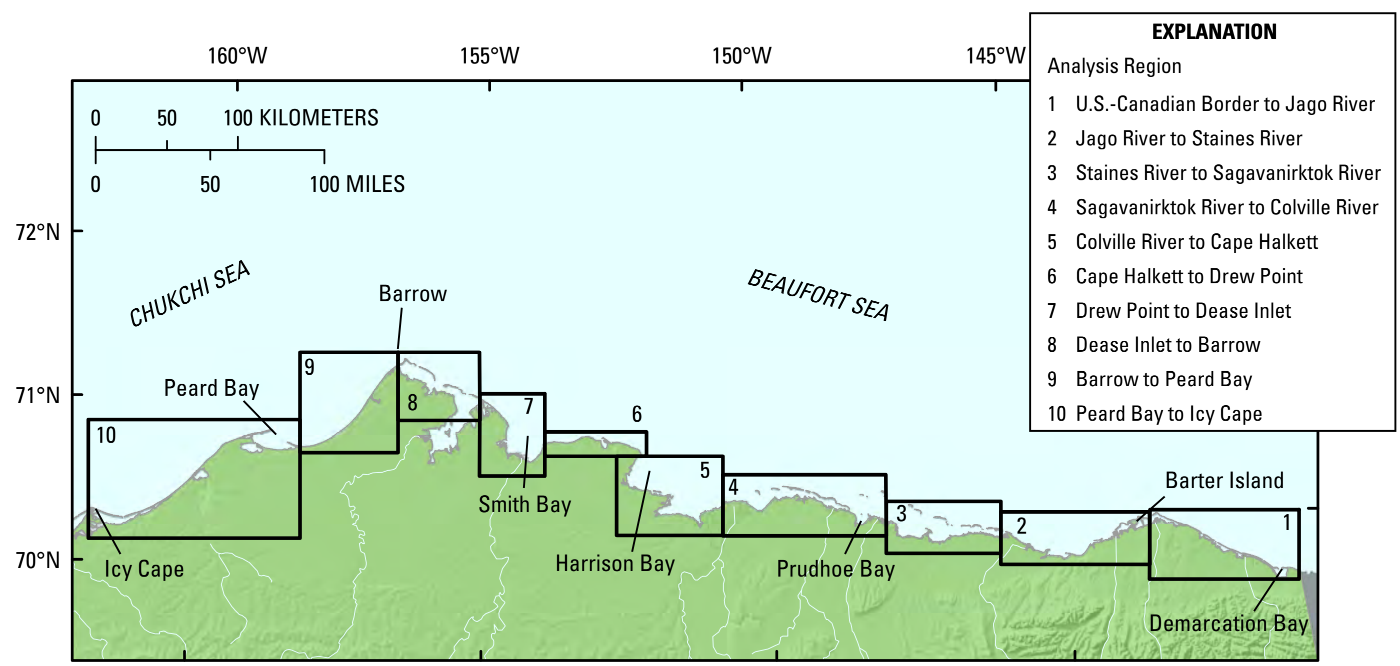


Figure 5. Index map of the north coast of Alaska showing the 10 analysis regions used in this study.

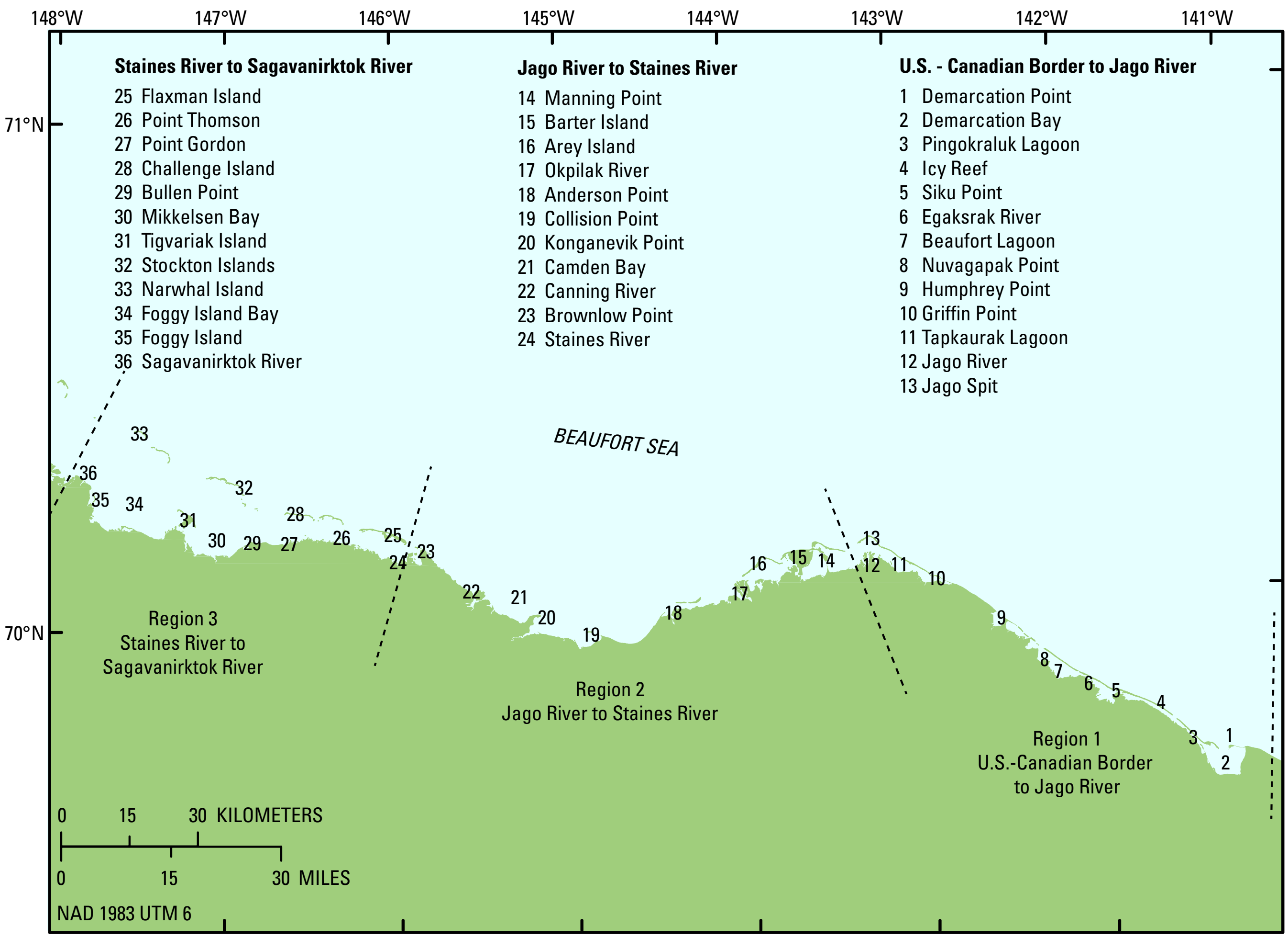


Figure 6. Index map of Regions 1, 2, and 3 showing geographic names discussed in the report.

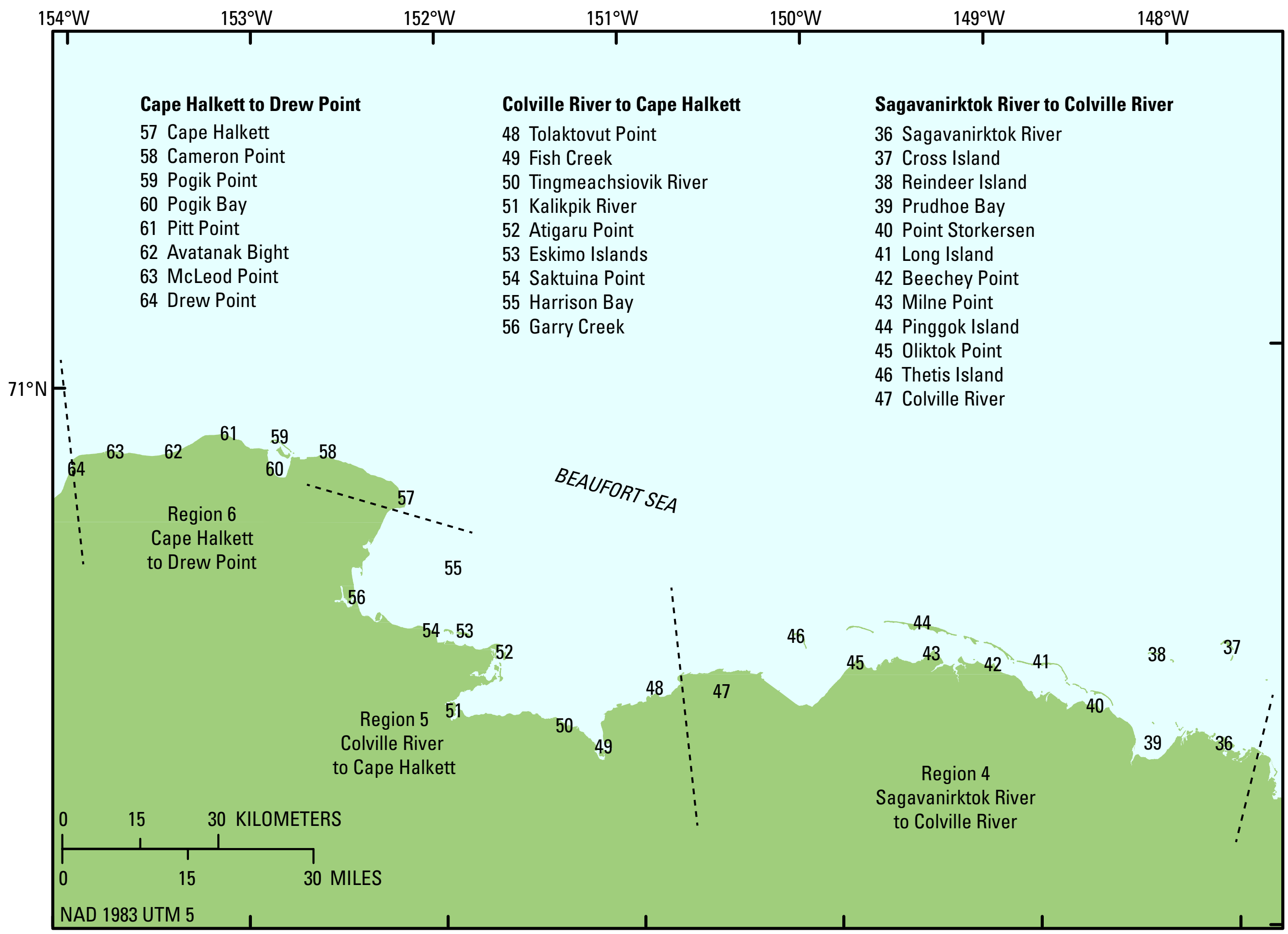


Figure 7. Index map of Regions 4, 5 and 6 showing geographic names discussed in the report.

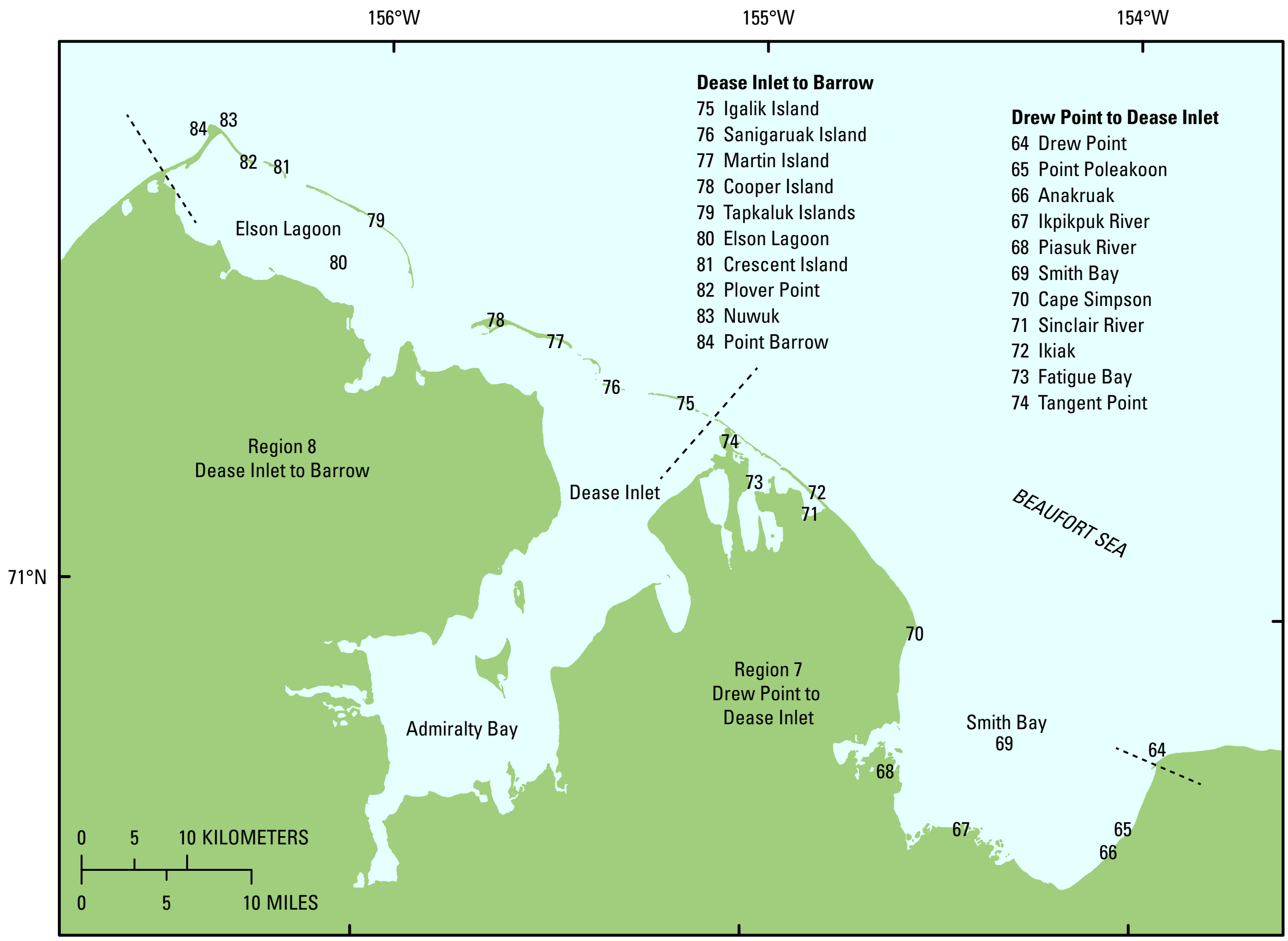


Figure 8. Index map of Regions 7 and 8 showing geographic names discussed in the report.

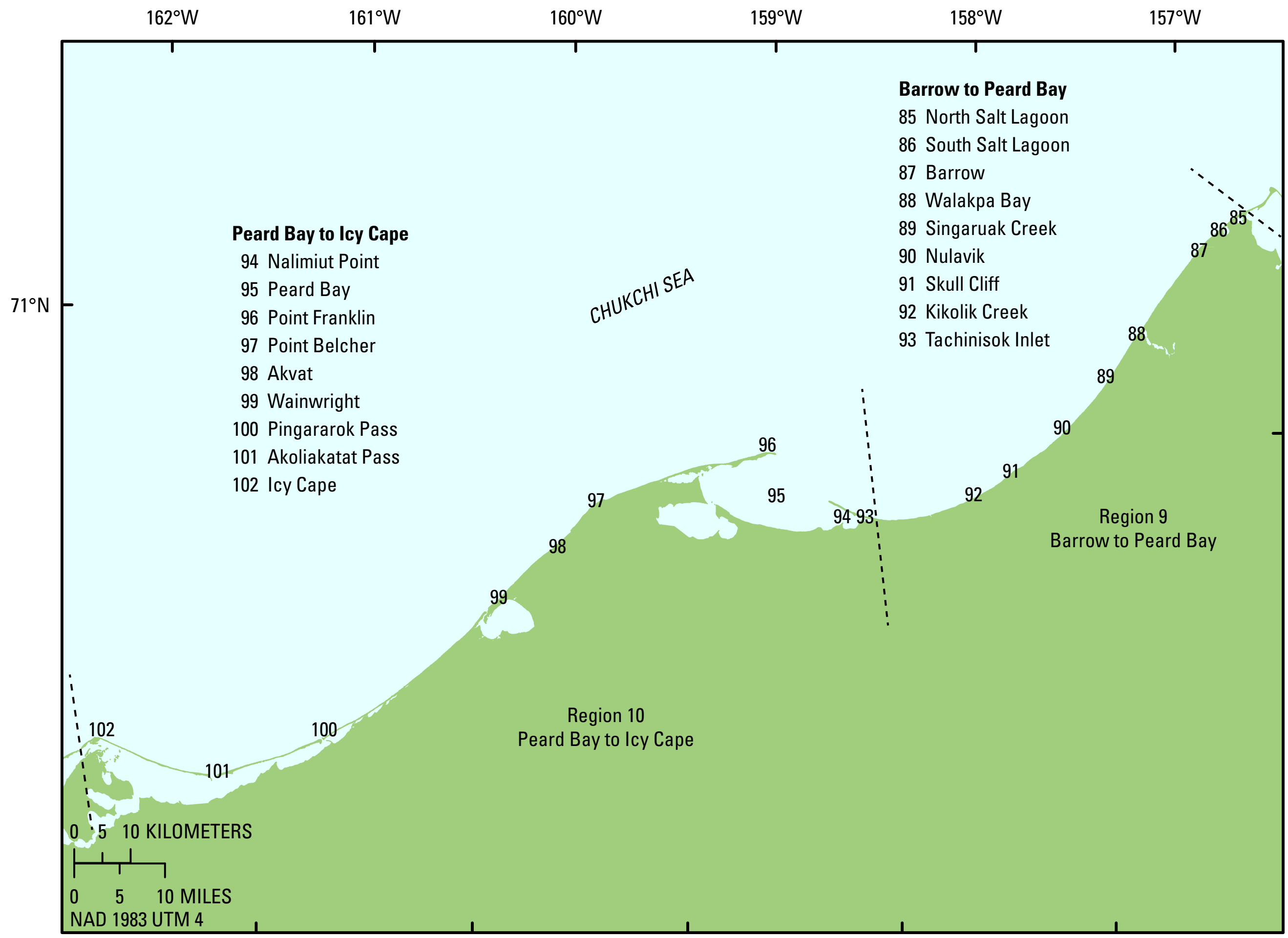


Figure 9. Index map of Regions 9 and 10 showing geographic names discussed in the report.

Table 5. Shoreline change rates for north coast of Alaska regions and subregions.

[m/y, meters per year]

Shoreline type	Subregion	Number of transects	Average of rates (m/yr)	Maximum rate (m/yr)		Percent of transects		
				Erosion	Accretion	Eroding	Accreting	Not changing
All transects	**U.S.-Canadian border to Icy Cape**	**26,567**	**-1.4**	**-18.6**	**10.9**	**84**	**16**	**0**
	REGION 1: U.S.-Canadian Border to Jago River (see fig. 10 for locations of subregions)							
	All transects	**3,673**	**-1.0**	**-13.5**	**5.5**	**86**	**14**	**0**
Sheltered	**All transects**	**1,705**	**-0.5**	**-3.0**	**1.7**	**90**	**9**	**1**
	Demarcation Bay	273	-0.5	-1.6	1.7	93	7	0
	Demarcation Bay to Kongakut River Delta	218	-0.2	-1.0	0.4	78	22	0
	Egaksrak Lagoon	162	-0.3	-1.5	0.3	86	12	2
	Aichilik-Egaksrak River Delta to Pokok Bay	632	-0.6	-2.6	0.8	96	3	1
	Pokok Lagoon to Jago River Delta	420	-0.5	-3.0	1.6	87	12	0
Exposed	**All transects**	**1,968**	**-1.4**	**-13.5**	**5.5**	**82**	**18**	**0**
Mainland coast	All transects	386	-1.4	-3.6	0.5	99	1	0
	Border to Demarcation Bay	184	-1.4	-2.4	-0.4	100	0	0
	Angun Lagoon to Pokok Bay	22	-0.7	-3.5	0.5	77	23	0
	Pokok Bay to Pokok Lagoon	180	-1.4	-3.6	-0.2	100	0	0
Barrier coast	All transects	1,582	-1.4	-13.5	5.5	77	23	0
	Demarcation Bay Spits	138	-4.8	13.5	5.3	86	14	0
	Demarcation Bay to Siku Entrance (Icy Reef)	462	-0.5	-2.8	2.5	82	18	0
	Siku Entrance to Pokok Bay	510	-1.0	-8.7	5	21	79	0
	Pokok Lagoon to Jago Entrance	494	-1.6	-7.8	5.5	68	32	0
	REGION 2: Jago River to Staines River (see fig. 16 for locations of subregions)							
	All transects	**3,464**	**-1.1**	**-16.4**	**9.6**	**84**	**15**	**0**
Sheltered	**All transects**	**1,749**	**-0.5**	**-4.5**	**1.9**	**85**	**14**	**1**
	Jago River Delta to Okpilak-Hulahula River Delta	901	-0.6	-4.5	1.5	84	16	0
	Okpilak-Hulahula River Delta to Sadlerochit River	216	-0.5	-1.6	0.3	92	8	0
	Sadlerochit River to Konganevik Point	188	-0.3	-2.3	0.5	72	27	2
	Konganevik Point to Staines River	444	-0.5	-1.5	1.9	92	8	0
Exposed	**All transects**	**1,715**	**-1.6**	**-16.4**	**9.6**	**83**	**17**	**0**
	Jago River Delta to Okpilak-Hulahula River Delta	488	-1.9	-16.4	9.6	68	32	0
	Okpilak-Hulahula River Delta to Sadlerochit River	54	-2.5	-4.3	-0.5	100	0	0
	Sadlerochit River to Konganevik Point	647	-1.0	-13.2	2.0	88	12	0
	Sadlerochit River to Konganevik Point – without spit at Collinson Point	550	-0.5	-3.1	2.0	87	13	0
	Konganevik Point to Staines River	526	-2.1	-7.3	1.9	89	11	0
Mainland/Island	All transects	849	-0.9	-5.4	1.0	91	9	0
	Jago River Delta to Okpilak-Hulahula River Delta (Barter Island)	93	-1.3	-2.6	0.9	5	95	0
	Sadlerochit River to Konganevik Point	545	-0.6	-2.7	1.0	11	89	0
	Konganevik Point to Staines River	190	-1.4	-5.4	0.7	95	5	0
Barrier/Spit	All transects	866	-2.4	-16.4	9.6	75	25	0
	Jago River Delta to Okpilak-Hulahula River Delta	395	-2.0	-16.4	9.6	61	39	0
	Okpilak-Hulahula Delta to Konganevik Point	91	-1.5	-4.3	2.0	82	18	0
	Okpilak-Hulahula River Delta to Konganevik Point - without spit at Collinson Point	135	-3.0	-13.2	2.0	88	12	0
	Konganevik Point to Staines River	336	-2.6	-7.3	1.9	85	15	0

Table 5. Shoreline change rates for north coast of Alaska regions and subregions.—Continued

[m/y, meters per year]

Shoreline type	Subregion	Number of transcts	Average of rates (m/yr)	Maximum rate (m/yr)		Percent of transects		
				Erosion	Accretion	Eroding	Accreting	Not changing
All transects	**U.S.-Canadian border to Icy Cape**	**26,567**	**-1.4**	**-18.6**	**10.9**	**84**	**16**	**0**
	REGION 2: Jago River to Staines River (see fig. 16 for locations of subregions)—Continued							
Barter Island	**All transects**	**512**	**-0.5**	**-3.0**	**4.0**	**80**	**20**	**0**
	Exposed tundra-bluff coast	93	-1.3	-2.6	0.9	95	5	0
	Exposed spits	62	-0.1	-2.8	3.2	48	52	0
	Sheltered coast	357	-0.3	-3.0	3.4	81	18	0
	REGION 3: Staines River to Sagavanirktok River (see fig. 23 for locations of subregions)							
	All transects	**2,162**	**-1.5**	**-16.8**	**6.7**	**89**	**11**	**0**
Sheltered	**All transects**	**1,439**	**-0.8**	**-4.4**	**2.7**	**93**	**6**	**0**
	Staines River to Point Gordon	560	-0.8	-4.4	1.4	93	7	0
	Point Gordon to Sagavanirktok River	879	-0.8	-3.6	2.7	94	6	0
Exposed	**All transects**	**723**	**-3.0**	**-16.8**	**6.7**	**81**	**19**	**0**
	Flaxman Island	210	-2.3	-10.4	1.9	83	17	0
	Maguire Islands	169	-1.8	-13.7	6.7	66	34	0
	Stockton Islands	143	-4.6	-11.2	6.0	85	15	0
	McClure Islands	93	-6.5	-16.8	3.5	92	8	0
	Tigvariak Island and adjacent barrier island	108	-1.1	-7.0	2.8	86	14	0
Tigvariak Islands	**All Transects**	**236**	**-0.7**	**-7.0**	**2.8**	**88**	**12**	**0**
	Exposed tundra-bluff coast	48	-0.5	-1.5	0.9	83	17	0
	Exposed spits	60	-1.5	-7.0	2.8	88	12	0
	Sheltered coast	128	-0.4	-2.2	0.2	89	10	0
	REGION 4: Sagavanirktok River to Colville River (see fig. 31 for locations of subregions)							
	All transects	**2,973**	**-1.1**	**-14.7**	**7.0**	**85**	**15**	**0**
Sheltered	**All transects**	**1,918**	**-0.8**	**-4.2**	**1.2**	**95**	**5**	**0**
	Heald Point to Point McIntyre	484	-0.8	-2.5	1.1	97	3	0
	Point McIntyre to Kuparuk River Delta	180	-0.6	-3.7	0.9	96	4	0
	Kuparuk River Delta to Milne Point	529	-0.7	-2.8	1.2	94	6	0
	Milne Point to Oliktok Point	389	-1.1	-4.2	1.2	90	9	1
	Oliktok Point to Colville River Delta	336	-0.8	-1.9	0.7	98	2	0
Exposed	**All transects**	**1,055**	**-1.6**	**-14.7**	**7.0**	**66**	**34**	**0**
	Cross Island	70	-4.7	-14.4	4.0	81	19	0
	Midway Islands (Reindeer only)	44	-6.6	-10.0	-2.4	100	0	0
	Stump Island to Thetis Island	941	-1.1	-14.7	7.0	63	37	0
	Stump, Egg, and East Long Islands	213	-1.8	-9.2	7.0	72	28	0
	West Long Island to Leavitt Island	536	-0.7	-14.7	4.1	56	44	0
	Spy Islands	101	-1.4	-4.0	4.3	82	18	0
	Thetis Island	93	-1.8	-6.6	4.1	65	35	0
	REGION 5: Colville River to Cape Halkett (see fig. 38 for locations of subregions)							
Exposed	**All transects**	**1,989**	**-1.1**	**-9.6**	**5.0**	**92**	**8**	**0**
	Tingmeachsoivik River to Kalikpik River	454	-0.7	-4.7	1.1	93	6	1
	Tingmeachsoivik River to Kogru River	1,136	-0.5	-4.7	3.8	90	9	1
	Kalikpik River to Atigaru Point	419	-0.2	-1.6	3.8	81	17	1
	Atigaru Point to Kogru River	260	-0.8	-3.1	0.1	98	2	0
	Kogru River to Cape Halkett	856	-1.7	-9.6	5.0	94	6	0
	Kogru River to Garry Creek	413	-1.2	-5.6	1.9	97	3	0
	Garry Creek to embayment	248	-2.7	-9.6	-0.3	100	0	0
	Embayment to Cape Halkett	195	-1.7	-3.7	5.0	82	18	0

Table 5. Shoreline change rates for north coast of Alaska regions and subregions.—Continued
[m/y, meters per year]

Shoreline type	Subregion	Number of transects	Average of rates (m/yr)	Maximum rate (m/yr)		Percent of transects		
				Erosion	Accretion	Eroding	Accreting	Not changing
All transects	**U.S.-Canadian border to Icy Cape**	**26,567**	**-1.4**	**-18.6**	**10.9**	**84**	**16**	**0**
REGION 6: Cape Halkett to Drew Point (see fig. 43 for locations of subregions)								
	All transects	**1,545**	**-6.3**	**-18.6**	**10.9**	**90**	**10**	**0**
Sheltered	**Pogik Bay**	**202**	**-0.5**	**-5.7**	**10.9**	**62**	**38**	**0**
	Pogik Island	124	-0.3	-4.3	6.9	72	28	0
Exposed	**All transects**	**1,343**	**-7.1**	**-18.6**	**7.3**	**94**	**6**	**0**
	Mainland coast	1,264	-7.0	-18.6	7.3	94	6	0
	Barrier island	79	-8.8	-12.9	-5.6	100	0	0
REGION 7: Drew Point to Dease Inlet (see fig. 48 for locations of subregions)								
	All transects	**1,315**	**-2.4**	**-16.4**	**3.4**	**92**	**8**	**0**
Sheltered	**All transects**	**457**	**-3.2**	**-16.4**	**0.6**	**96**	**4**	**0**
	Sinclair River to Tangent Point	244	-1.3	-10.3	0.6	93	7	0
	Tangent Point to Black Head	213	-5.5	-16.4	-0.4	100	0	0
Exposed	**All transects**	**858**	**-1.9**	**-6.8**	**3.4**	**89**	**11**	**0**
	Drew Point to Ikpikpuk River Delta	349	-1.5	-4.1	1.7	93	7	0
	Cape Simpson to Kulgurak Island	509	-2.1	-6.8	3.4	89	11	0
	Mainland coast	603	-1.9	-4.6	3.4	91	9	0
	Barrier coast	255	-1.9	-6.8	3.4	89	11	0
REGION 8: Dease Inlet to Barrow (see fig. 53 for locations of subregions)								
	All transects	**2,228**	**-2.5**	**-17.9**	**7.0**	**90**	**10**	**0**
Sheltered	**All transects**	**1,406**	**-2.1**	**-9.9**	**4.9**	**95**	**5**	**0**
Exposed	**All transects**	**822**	**-3.2**	**-17.9**	**7.0**	**82**	**18**	**0**
Barrier island	All transects	588	-3.9	-17.9	4.1	80	20	0
	Igalik Island to Sanigaruak Pass	82	-5.6	-17.9	2.7	80	20	0
	Sanigaruak Pass to Ekilukruak Entrance	228	-3.3	-13.2	4.1	76	23	0
	Ekilukruak Entrance to Eluitkak Pass	278	-3.9	-10.5	3.6	82	18	0
Barrier spit	All transects	234	-1.3	-3.1	7.0	89	11	0
	Plover Point to Point Barrow	107	-2.2	-3.0	-0.3	100	0	0
	Point Barrow to Barrow Peninsula	126	-0.6	-3.0	7.0	79	21	0
REGION 9: Barrow to Peard Bay (see fig. 60 for locations of subregions)								
Exposed	**All Transects**	**1,779**	**-0.3**	**-1.2**	**0.7**	**86**	**14**	**1**
	Barrow to Nulavik	840	-0.2	-1.1	0.7	71	28	1
	Nulavik to Peard Bay	939	-0.4	-1.2	0.3	99	1	0
REGION 10: Peard Bay to Icy Cape (see fig. 64 for locations of subregions)								
	All transects	**5,439**	**-0.3**	**-8.5**	**8.0**	**71**	**29**	**1**
Sheltered	**All transects**	**2,323**	**-0.3**	**-2.2**	**2.0**	**77**	**23**	**0**
	Peard Bay	856	-0.3	-2.2	1.7	87	13	0
	Kilmantavi to Icy Cape	1,467	-0.3	-2.1	2.0	71	28	0
	6 kilometers west of Nivat Point to Icy Cape	715	-0.6	-2.1	1.7	94	6	0
Exposed	**All transects**	**3,116**	**-0.4**	**-8.5**	**8.0**	**66**	**33**	**1**
	Tachinosok Inlet to Atanik	717	-0.4	-5.2	2.9	62	37	0
	Point Franklin to Atanik	445	0.0	-2.7	2.9	49	51	1
	Atanik to Wainwright Inlet	774	0.0	-3.9	4.1	50	49	1
	Wainwright Inlet to Kilmantavi	372	0.1	-0.9	5.3	50	49	1
	Kilmantavi to Icy Cape Pass	1,253	-0.8	-8.5	8.0	83	17	0
	Mainland coast	716	0.0	-3.9	4.1	53	46	1
	Barrier islands and spits	2,079	-0.5	-8.5	8.0	74	26	0
	Barrier beaches	321	0.0	0.9	1.0	43	56	1

(1) U.S.-Canadian Border to Jago River

Introduction

The coast of Region 1 extends approximately 105 km between the U.S.-Canadian border and the Jago River Delta along the northern coast of ANWR (figs. 5 and 10). In contrast to the rest of the U.S. Beaufort Sea coast, which largely trends west to east and faces north, the coastline of Region 1 generally faces northeast and trends northwest to southeast. The only development along this stretch of coast is the former Demarcation Bay Intermediate DEW Line Site at Nuvagapak Point. The site was closed in 1963, buildings were removed in 2000, and only the gravel pad and runway of the former airstrip remain. There are no permanent villages in this region.

This coastal reach is dominated by an extended chain of low-lying (<3 m high), unvegetated to poorly vegetated barrier islands that front narrow (<3 km wide) lagoons, embayments, and three large river deltas (Kongakut, Aichilik-Egaksrak, and Jago) (figs. 10 and 11). The sheltered mainland-lagoon coast is characterized by low bluffs (<3 m high, except in Demarcation Bay where they reach as high as 8 m), low-lying tundra, and numerous rivers, creeks, drainages, and deltas. Narrow (<20 m wide) beaches are common, although not pervasive, at the base of the bluffs. The mainland coast is exposed directly to the open ocean at only three locations: (1) east of Demarcation Bay, where low-lying tundra, tapped thermokarst lakes, and moderately high (<5 m) coastal bluffs continue to the U.S.-Canadian border; (2) a relatively short (<900 m) section of low-lying (<2 m) tundra on a narrow peninsula between Angun Lagoon and Pokok Bay; and (3) an approximately 9 km long stretch between Pokok Bay and Pokok Lagoon, where coastal bluffs reach as high as 15 m. Sand and gravel beaches front the mainland coast at all three locations.

The coastal plain between Demarcation Bay and the U.S.-Canadian border and between Pokok Bay and the Jago River is dominated by large thermokarst lakes. On the intervening coastal plain between Pokok Bay and Demarcation Bay, however, thermokarst lakes are rare and the coastal plain comprises alluvial fan, floodplain, and delta deposits associated with the numerous rivers draining the interior Brooks Range.

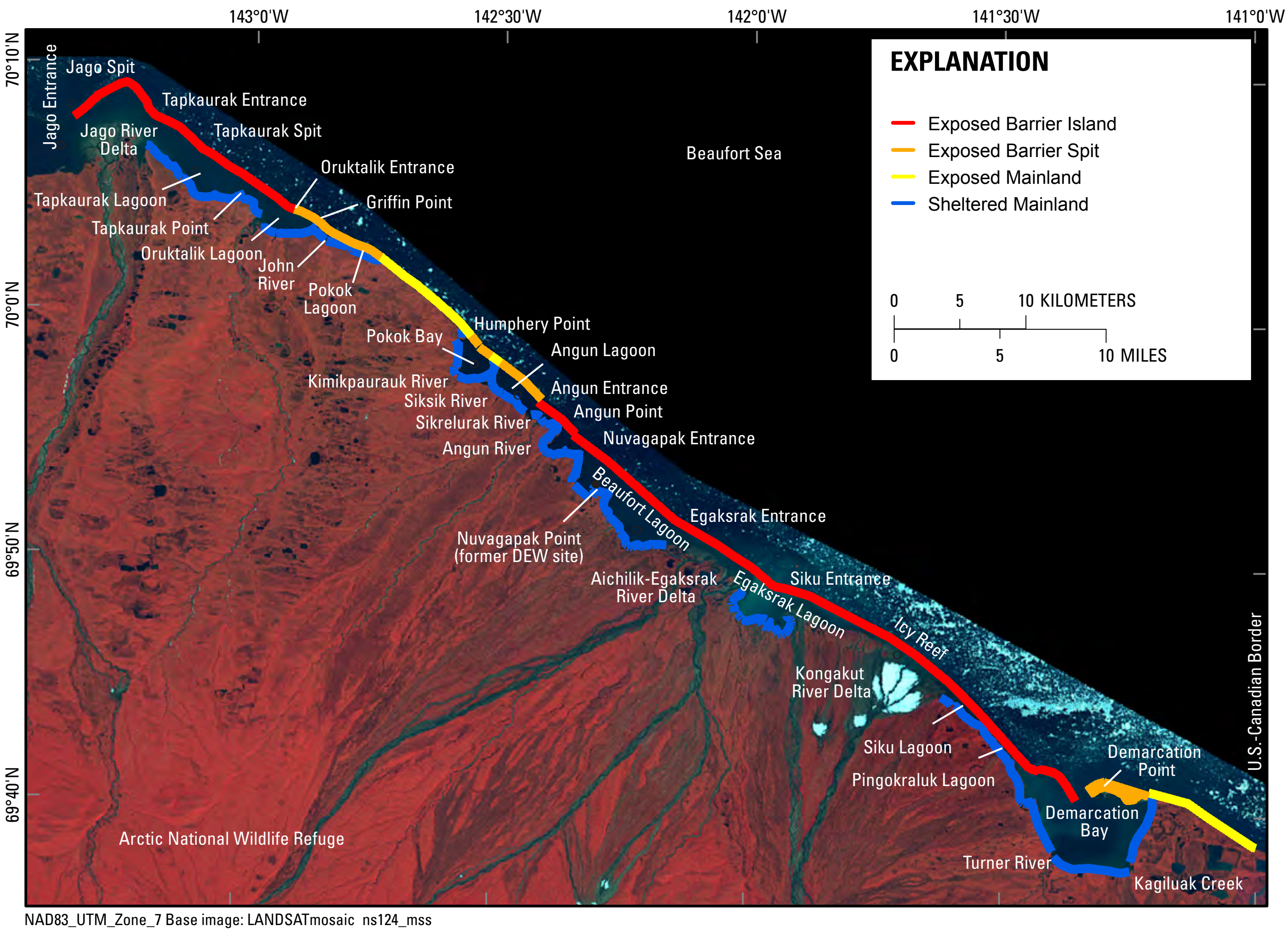


Figure 10. Map showing color-coded shoreline types within Region 1, U.S.-Canadian border to Jago River, north coast of Alaska.

Figure 11. Aerial photograph characteristic of Region 1, U.S.-Canadian border to Jago River, north coast of Alaska, near Siku Entrance and Egaksrak Lagoon where a narrow lagoon separates a low-lying, unvegetated barrier island along the open coast from the low-lying, tundra coast on the landward side of the lagoon. Brooks Range is visible in the background. View looking south. (Photograph from 2006; Gibbs and Richmond, 2009.)

Shoreline change rates for Region 1 were determined using 1947 T-sheets and 2003 QuickBird™ satellite imagery (table 2; fig. 4). The region is predominantly erosional (86 percent of transects) with combined shoreline change rates for both the exposed open-ocean and sheltered mainland-lagoon shorelines averaging -1.0 m/yr and ranging between -13.5 and +5.5 m/yr (fig. 12; table 5). The average shoreline change rate for exposed open-ocean shorelines (barrier island, spit, and mainland coasts) is almost 50 percent higher (-1.4 m/yr) as the regional average, whereas the average rate for sheltered mainland-lagoon shorelines is nearly one-half (-0.5 m/yr) the regional average (table 5).

Sheltered Mainland-Lagoon Shoreline Change

The sheltered mainland coast of Region 1 is predominantly erosional (90 percent of transects) with shoreline change rates averaging -0.5 m/yr and ranging between -3.0 and +1.7 m/yr (figs. 12 and 13). Average rates are some of the lowest in the study area and near the limit of our uncertainty estimates on individual transects (±0.3 m/yr). The highest rates of erosion are associated with the erosion of the headland at Nuvagapak Point and the loss of a pond west of Pokok Lagoon. The highest rates of accretion are associated with extension of a spit near Kagiluak Creek in Demarcation Bay and near the Jago River Delta.

Exposed Open-Ocean Shoreline Change

The exposed open-ocean coast of Region 1, which includes barrier islands, spits and mainland coast, is predominantly erosional (82 percent of transects) with shoreline change rates averaging -1.4 m/yr and ranging between -13.5 and +5.5 m/yr (figs. 12 and 14). The DSAS rate calculations do not account for the considerable accretion and extension of spits and barrier islands—for example, near Demarcation Point, Pokok Bay, Tapkaurak Point, and Jago Spit—because of non-overlapping shorelines. The highest rates of erosion in the region were measured on the barrier spits fronting Demarcation Bay that migrated landward up to 700 m between 1947 and 2003. Accretion rates were highest near Oruktalik Lagoon, where a barrier spit migrated west from Griffin Point to close the Oruktalik Entrance channel (fig. 15).

No significant differences in average erosion rates by shoreline type were observed (for example, barrier islands, spits, and mainland coastal types all average -1.4 m/yr); however, considerable differences were observed spatially, with higher rates of erosion and accretion associated with the formation and closure of inlets and the migration and rotation of the ends of barrier islands and spits, particularly fronting Demarcation Bay (table 5). The remainder of the open-coast shoreline experienced little net change during the study period. For example, most of the 30 km long Icy Reef barrier island fronting the Kongakut River Delta between Siku Entrance and Demarcation Bay changed by less than 40 m in 56 years, although there was considerable change at both ends (fig. 12). Shoreline change rates were also generally higher west of Pokok Lagoon, which may reflect the formation of numerous breaches, landward migration of the barrier islands, and/or inlet filling.

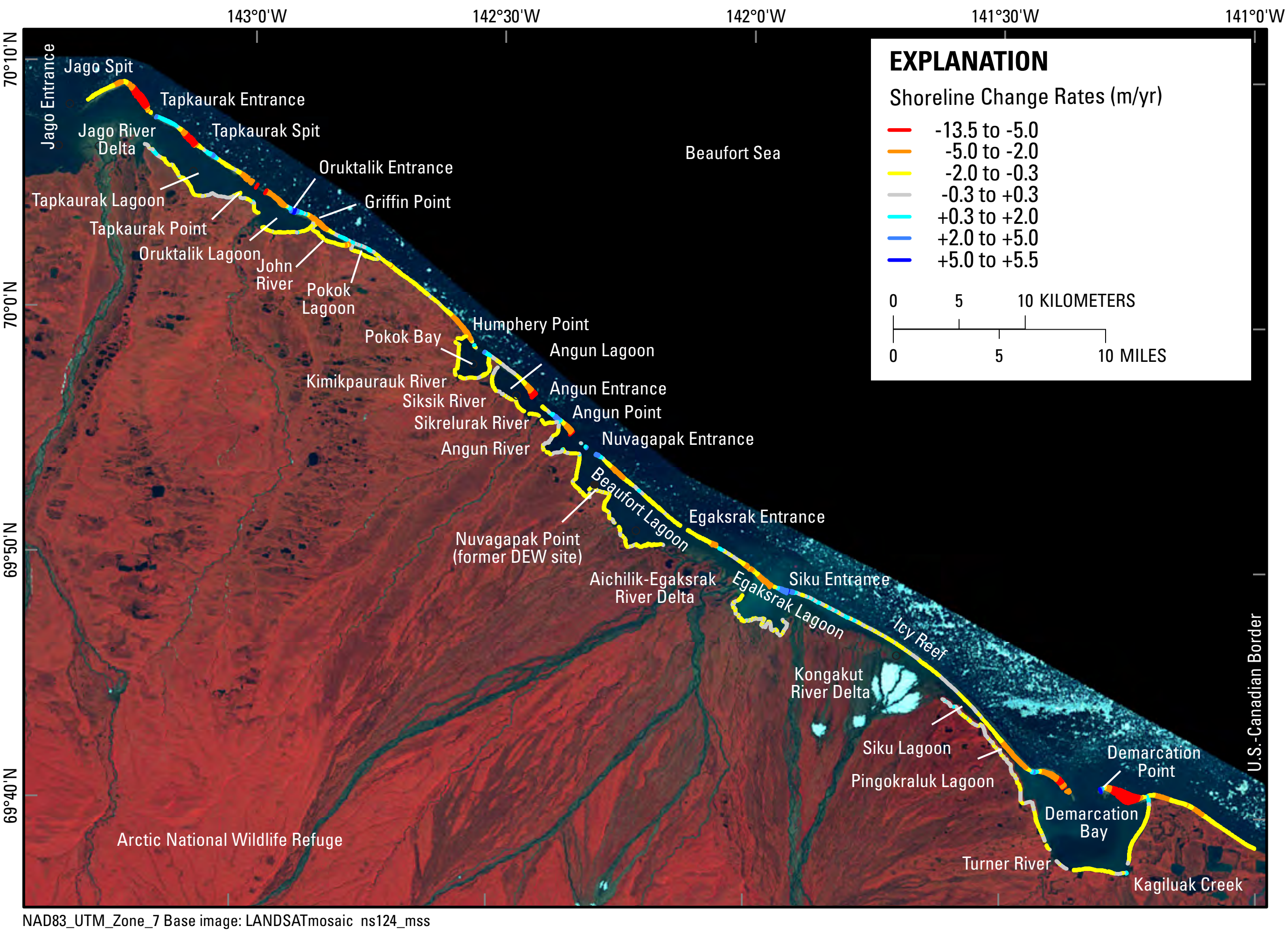
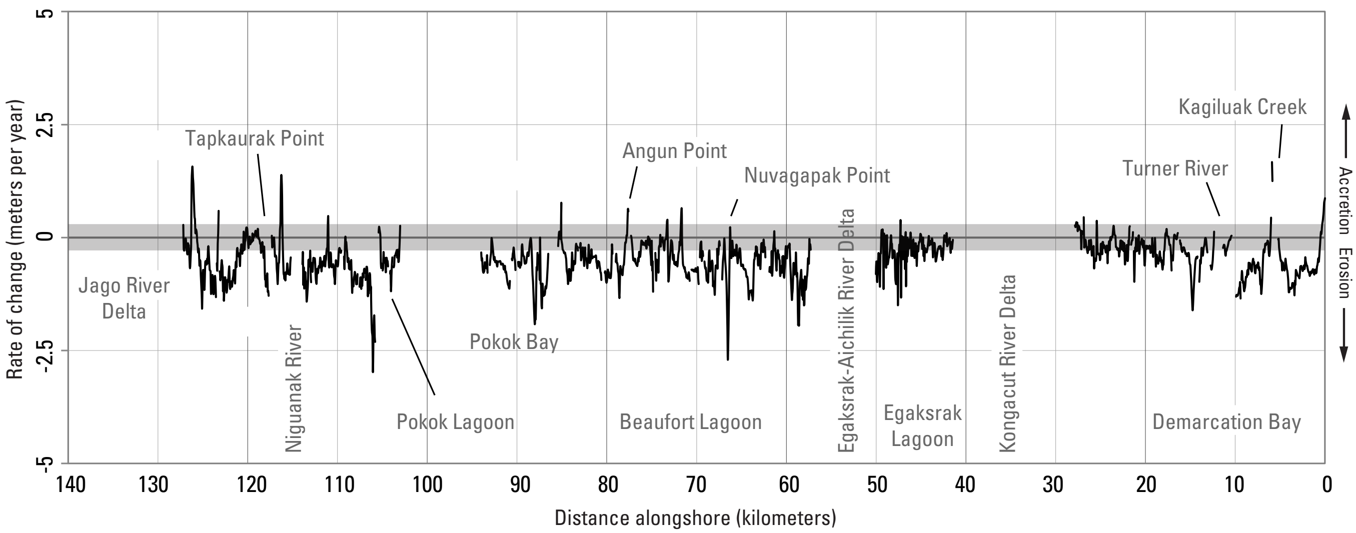
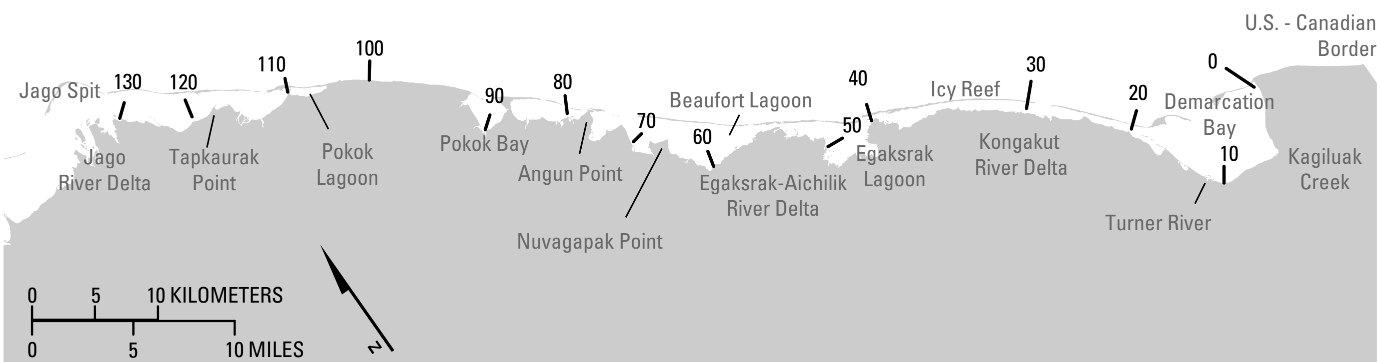


Figure 12. Map showing color-coded shoreline change rates in Region 1, U.S.-Canadian border to Jago River, north coast of Alaska. Width of line represents shoreline change envelope, or total shoreline change over analysis period, and distance between historical shorelines.





NAD 1983 UTM 7

Figure 13. Top: Graph of shoreline change rates for sheltered mainland-lagoon coast of Region 1, U.S.-Canadian border to Jago River, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 1 indicating distances measured alongshore.

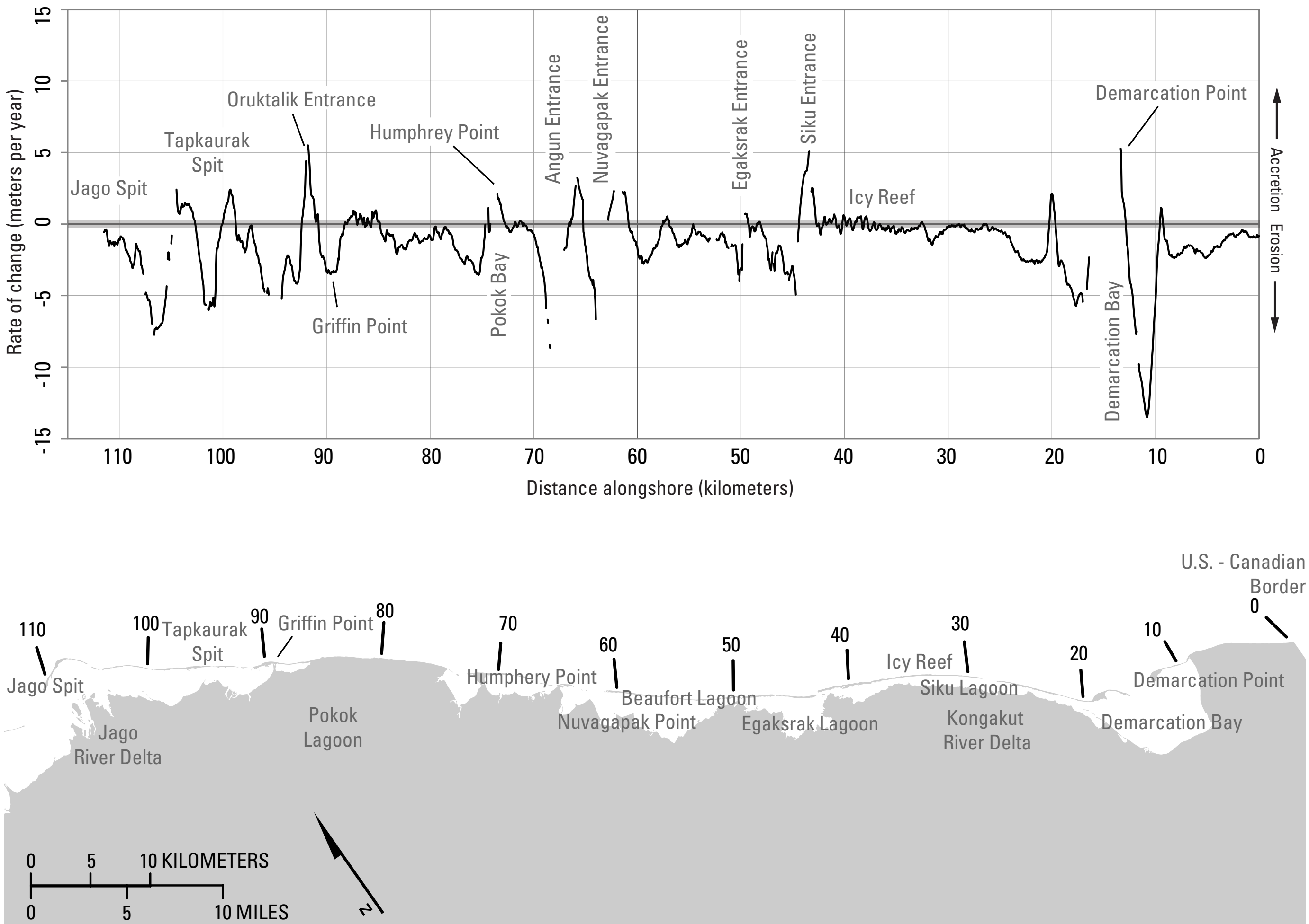


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Figure 14. Top: Graph of shoreline change rates for exposed open-ocean coast of Region 1, U.S.-Canadian border to Jago River, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 1 indicating distances alongshore.

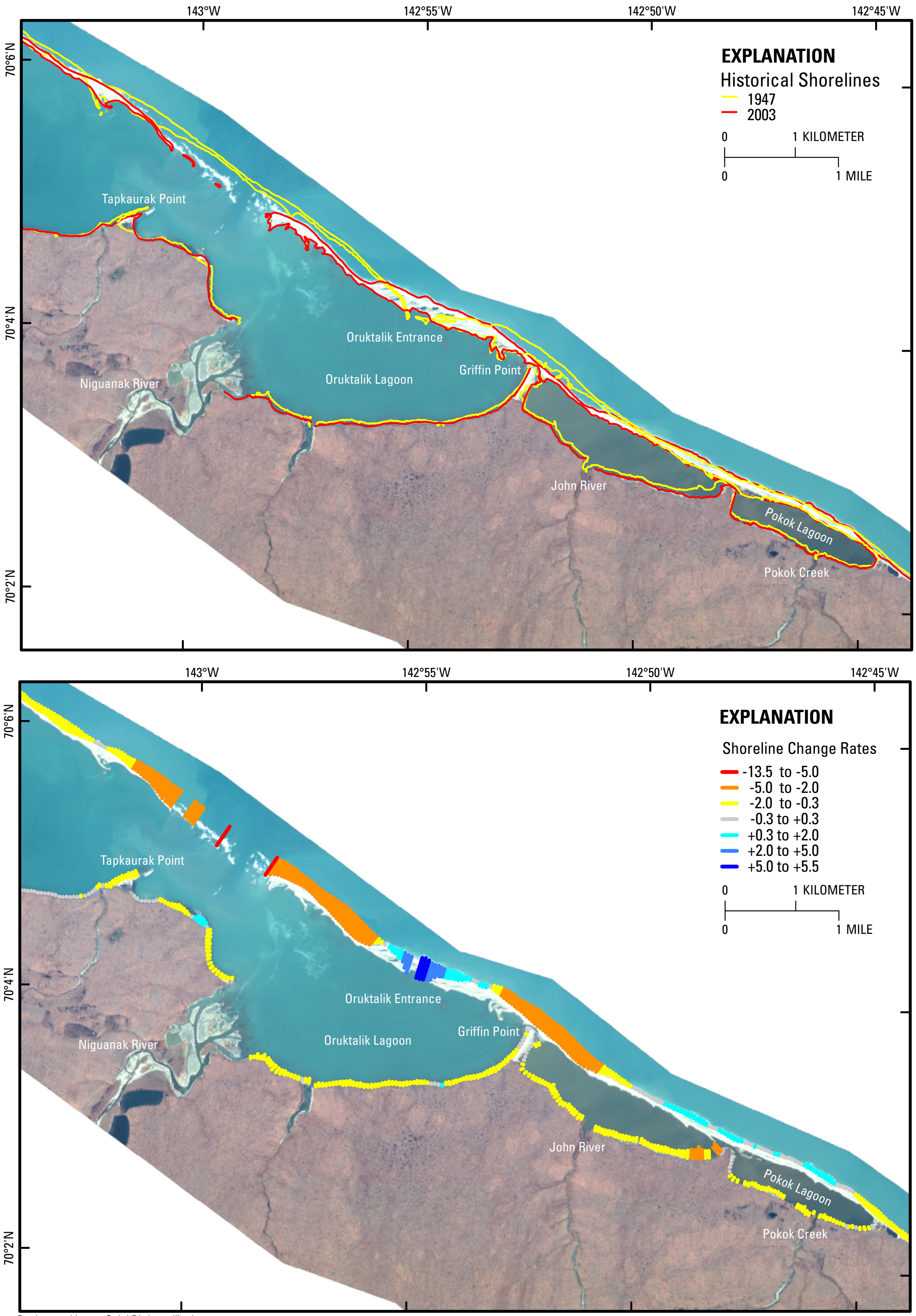


Figure 15. Maps showing examples of shoreline change at Oruktalik Lagoon, north coast of Alaska, where barrier migration resulted in the closure of Oruktalik Entrance between 1947 and 2003.

(2) Jago River to Staines River

Introduction

Region 2 extends approximately 110 km along the ANWR coast between the Jago and Staines Rivers (fig. 16). The reach most notably includes Barter Island, where the village of Kaktovik (with a 2010 census population of 239; State of Alaska, 2015), the Barter Island airport, the former DEW Line Main Site, and the currently (2014) active North Warning System Long Range Radar Site (NWS-LRRS) are located. The Barter Island DEW site was de-activated in 1989 and upgraded to a NWS-LRRS in 1990 (fig. 17A). The Brownlow Point DEW Line Intermediate site (also known as Collinson Point, Kangigivik Point, Agilguagruk, Camden Bay, and Nuvubaq in Inupiat) was also located in this region, about 50 km southwest of Kaktovik, on the eastern shore of Simpson Cove at Camden Bay. The site was closed and abandoned in 1963 and demolition of buildings and remediation occurred around 2000. A gravel runway and building pads remain.

The coast of Region 2 includes barrier islands, spits, and both exposed and sheltered mainland-lagoon coast (fig. 16). The mainland is segmented by five large river and delta complexes (Okpilak-Hulahula, Sadlerochit, Katakturuk, and Canning-Tamayariak and Staines) and many smaller creeks and drainages. The coastline generally trends E-W, includes the arcuate Camden Bay, and crosses two UTM zones (6 and 7).

The mainland coast is predominantly low-lying (<2 m high) except where higher coastal bluffs occur between Jago River and Barter Island, near Kajutakrok Creek, between the Sadlerochit River and Marsh Creek, in central Simpson Cove, and Konganevik and Brownlow Points. Numerous, large, tapped and untapped thermokarst lakes are common on both the coastal plain and shoreline near Arey Lagoon and west of Konganevik Point. In contrast, the coastal plain and shoreline near Jago Lagoon, most of Kaktovik Lagoon, and between the Okpilak-Hulahula River Delta and Konganevik Point is characterized by few thermokarst lakes, wide braided river channels and flood plains separated by low to high tundra plateaus and deeply incised gullies.

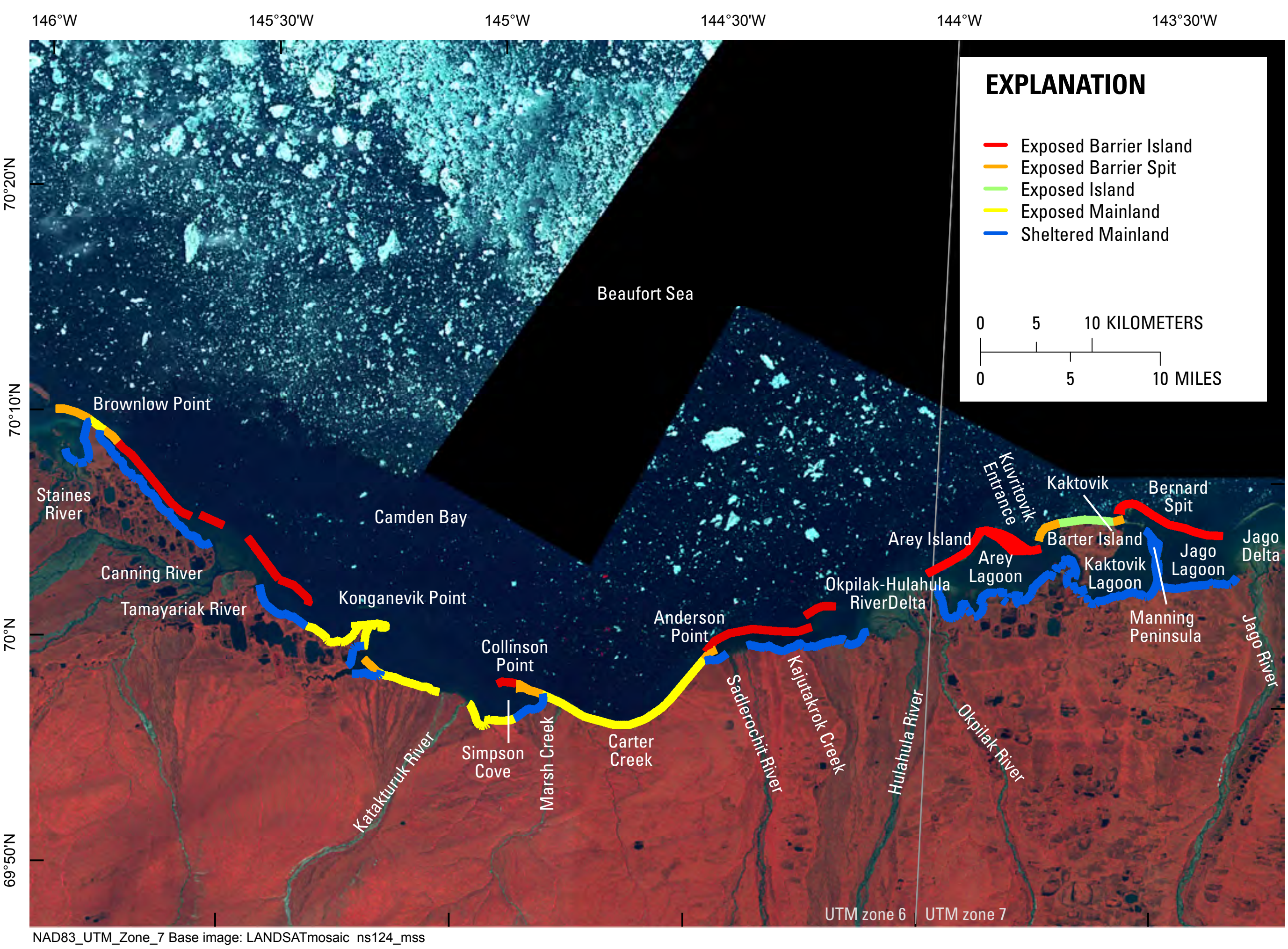


Figure 16. Map showing color-coded shoreline types within Region 2, Jago River to Staines River, north coast of Alaska.

Figure 17. Aerial photographs showing typical examples of the coast of Region 2, Jago River to Staines River, north coast of Alaska. A, View of the Barter Island airstrip to the west. Village of Kaktovik and white radar dome of the Barter Island Long Range Radar Station are visible in the upper left of the photograph. Low-lying Barter Island airstrip provides primary access to Native village of Kaktovik and to Radar Station. Airstrip is flooded almost annually when water levels are elevated during the passage of large storms. B, Coast between Anderson Point and Marsh Creek showing relatively wide beaches, ice-wedge polygons, and thaw slumps in the coastal tundra, and high bluffs in the background; view to the south. Note the beach material encroaching landward over the tundra surface and the lack of large thermokarst lakes along this coast. C, Low bluffs at the coast between Konganevik Point and Canning River. Note the large thermokarst lakes in the background; view to south. D, Low-lying barrier coast near Canning River. Note the narrow lagoon and mainland coast with numerous thermokarst lakes. (All photographs from 2006; Gibbs and Richmond, 2009.)

Barrier spits and islands discontinuously front much of the mainland coast of Region 2 except between the Sadlerochit River and Konganevik Point where the coastal plain is relatively steeper and higher than to the east or west. Extensive and well-formed barrier spits and islands front Jago, Kaktovik, and Arey Lagoons and also extend east and west on Barter Island and Brownlow Point. Narrow, discontinuous barrier spits and islands front the Okpilak-Hulahula River Delta and continue west to the Sadlerochit River and the spit at Anderson Point, west of Marsh Creek to Collinson Point, and between Konganevik Point and the Canning River Delta. The Okpilak-Hulahula delta complex is also fronted by numerous low-relief, likely intertidal, shoals. These shoals appear to be highly variable between datasets and are therefore probably active sites of erosion and deposition.

Shoreline change rates in Region 2 were determined using 1947 T-sheets and 2003 Quickbird™ satellite imagery (table 2; fig. 4). The coast is predominantly erosional (84 percent of transects) with combined shoreline change rates for both the exposed open-ocean and sheltered mainland-lagoon shorelines averaging -1.1 m/yr and ranging between -16.4 and +9.6 m/yr. Average shoreline change rates along exposed open-ocean coasts (-1.6 m/yr) high) are more than three times higher than along sheltered mainland-lagoon coasts (-0.5 m/yr). Shoreline change rates along the barrier coasts are more than twice as high compared to exposed mainland and island coasts (-2.4 and -0.9 m/yr, respectively) (fig. 18, table 5). Coastal geomorphology, shoreline change rates, and patterns of change within Region 2 vary considerably and are separated into several subregions in the sections that follow.

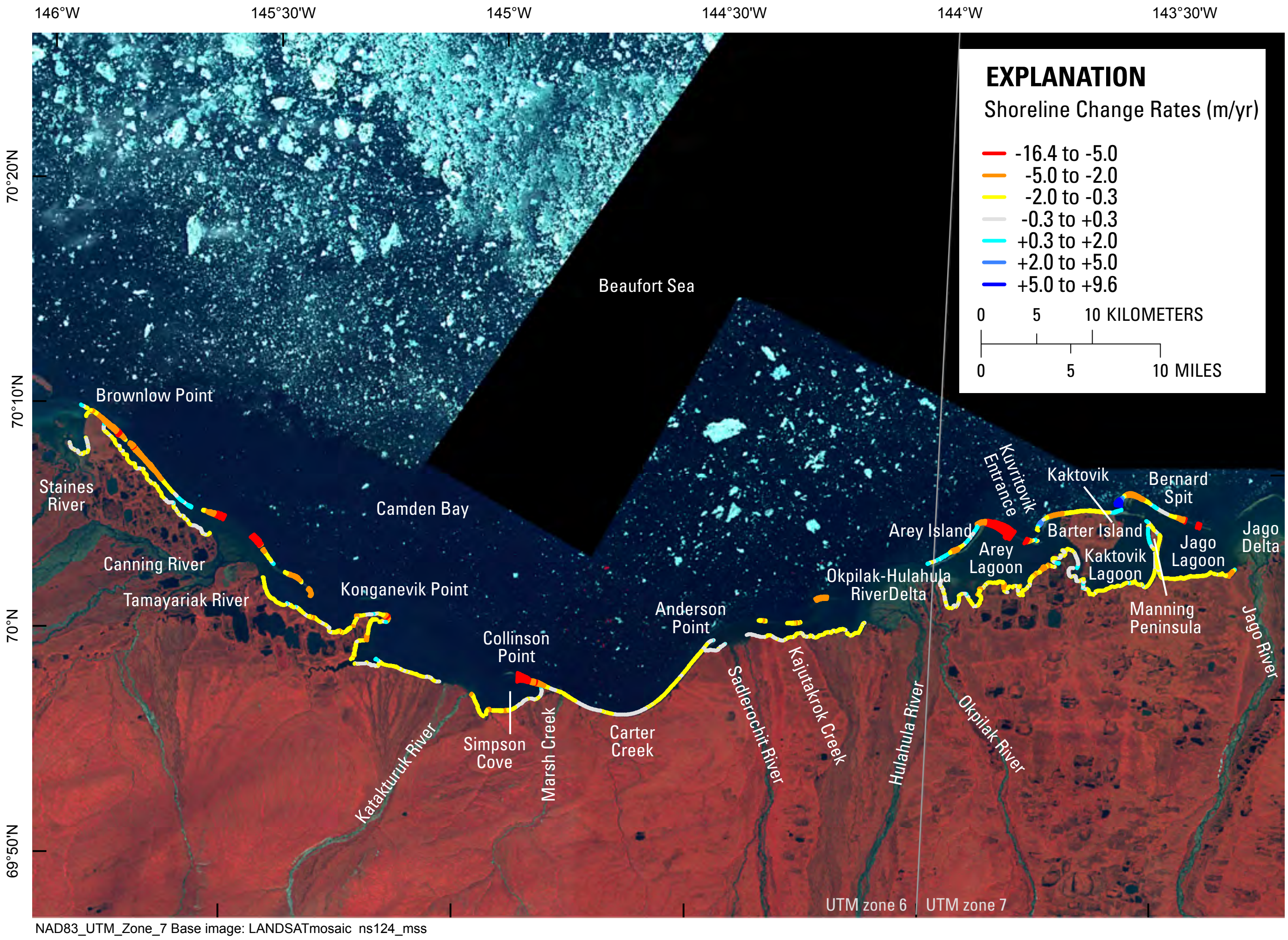


Figure 18. Map showing color-coded shoreline change rates in Region 2, U.S.-Canadian border to Jago River, north coast of Alaska. Width of line represents shoreline change envelope, or total shoreline change over analysis period, and distance between historical shorelines.

Sheltered Mainland-Lagoon Shoreline Change

Jago River Delta to Okpilak-Hulahula River Delta

The mainland coast between the Jago River Delta and the Okpilak-Hulahula River Delta is sheltered by Bernard Spit, Barter Island, and Arey Island, and is markedly different east and west of Barter Island. East of Barter Island the mainland coast of Jago Lagoon and the eastern two-thirds of Kaktovik Lagoon is characterized by moderately high tundra bluffs (about 2–4 m high) fronted by narrow (<25 m) beaches. In contrast, the coast of western Kaktovik and Arey Lagoons is predominantly low tundra bluffs (<2 m high) and lower-lying wet-sedge marsh and tapped thermokarst lake deposits fronted discontinuously by narrow beaches (<20 m wide). The Manning Peninsula, a narrow strip of land that extends northward from the coast and separates Jago and Kaktovik Lagoons, comprises narrow, unvegetated barrier spits and a high tundra island with ~3-m high coastal bluffs fronted by beaches except on the northeast side. The sheltered mainland-lagoon coast of Region 2 between the Jago River Delta and Okpilak-Hulahula River Deltas is predominantly erosional (84 percent of transects) with an average shoreline change rate of -0.6 m/yr and range of -4.5 to +1.5 m/yr. The only noteworthy accretion was measured on the west side of the Manning peninsula (figs. 18 and 19; table 5).

Okpilak-Hulahula River Delta to Sadlerochit River

The mainland coast between the Okpilak-Hulahula River Delta and the Sadlerochit River is sheltered by a discontinuous chain of low-lying barrier islands and shoals. The mainland-lagoon coast here is typically low-lying (<2 m) with discontinuous, moderately wide beaches (<50 m wide) except near Kajutakrok Creek, where coastal bluffs reach up to 5-m high and beaches are generally continuous but narrower (<20 m wide). The sheltered mainland-lagoon coast of Region 2 between the Okpilak-Hulahula River Delta and Sadlerochit River is predominantly erosional (92 percent of transects), averaging -0.5 m/yr and ranging between -1.6 and +0.3 m/yr (figs. 18 and 19; table 5).

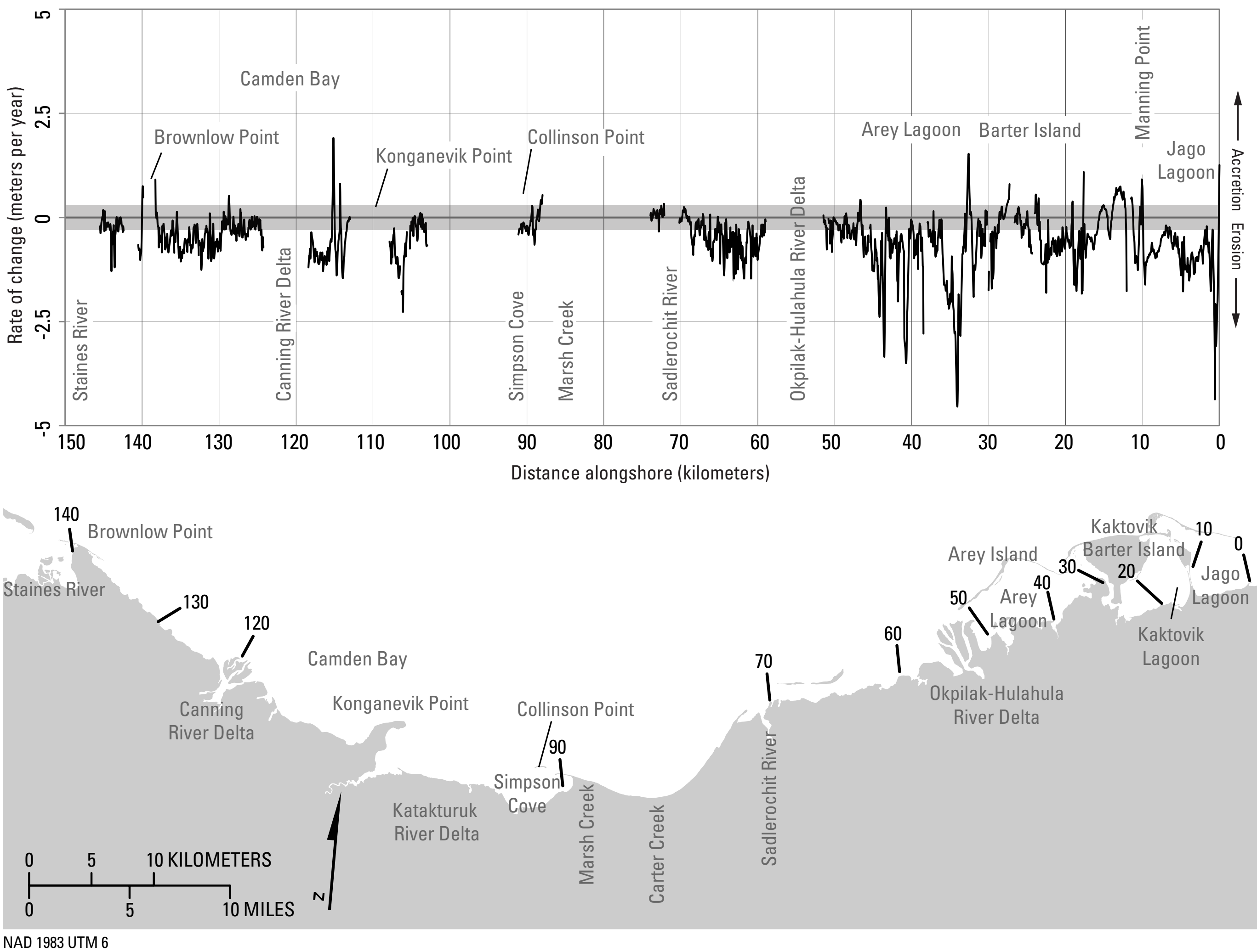


Figure 19. Top: Graph of shoreline change rates for sheltered mainland-lagoon coast of Region 2, Jago River to Staines River, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 2 indicating distances measured alongshore.

Sadlerochit River to Konganevik Point

Between the Sadlerochit River and Konganevik Point, the mainland coast is sheltered by discontinuous barrier spits and islands only near Anderson Point, fronting Simpson Cove, and the embayment east of Konganevik Point. The coast here is largely low lying (<2 m high), except between the Sadlerochit River and Marsh Creek, where bluffs reach up to 15 m high. Beaches are common west of Sadlerochit River, except near the Katakturuk River, and range in width between about 20 and 70 m. In some locations, sand and gravel, presumably derived from the numerous shallow stream channels and gullies in the area, appear to be encroaching on the low-lying tundra landscape (fig. 17B). The sheltered mainland-lagoon coast of Region 2 between the Sadlerochit River and Konganevik Point is predominantly erosional (72 percent of transects) and shoreline change rates are extremely low, averaging -0.3 m/yr and ranging between -2.3 and +0.5 m/yr. (figs. 18 and 19; table 5).

Konganevik Point to Staines River

Between Konganevik Point and the Staines River, the coast and coastal plain are quite different than to the east, primarily due to the predominance of numerous, large, tapped and untapped thermokarst lakes west of Konganevik Point (fig. 17C). The coast along this stretch is generally less than 2-m high except for isolated bluffs at Konganevik and Brownlow Points that reach 4-m high. The shoreline along this stretch of coast consists of low tundra bluffs and low-lying tapped thermokarst lakes. Fronting beaches are narrow (<15 m wide), when present. Low-lying, unvegetated barrier spits and islands extending east and west from Brownlow Point shelter much of the mainland along this stretch of coast (fig. 16). The sheltered mainland-lagoon coast of Region 2 between the Konganevik Point and Staines River is predominantly erosional (92 percent of transects) with shoreline change rates averaging -0.5 and ranging from -1.5 to +1.9 m/yr (figs. 18 and 19; table 5).

Exposed Open-Ocean Shoreline Change

Exposed open-ocean shoreline types in Region 2 include island (Barter Island), barrier island, barrier spit, and mainland coast (fig. 16).

Jago River Delta to Okpilak-Hulahula River Delta

The exposed open-ocean coast between the Jago and Okpilak-Hulahula River Deltas comprises Bernard Spit, Barter Island, and Arey Island. Bernard Spit is a chain of three, low-lying (<2 m high), barrier islands extending west from the entrance to Jago Lagoon. The islands are unvegetated except discontinuous mats of vegetation in topographic lows and isolated higher vegetation near the western end of the island.

Bernard Spit is mapped on the 1947 T-sheet as a single, continuous island over 7-km long. Between 1947 and 2003, the island segmented into three separate islands. The eastern part of the island extended eastward into Jago Entrance channel and migrated approximately 400 m landward, the western end extended approximately 500 m to the west and prograded about 275 m seaward, while the central portion of the island remained relatively stable. Barter Island is a high tundra island with large, recurved sand and gravel spits extending to the east and west on the Beaufort sea coast of the island. The eastern spit is partially sheltered from the open ocean by Bernard Spit. Coastal bluffs reach up to 10-m high near the center of the island and the fronting beaches are discontinuous and typically narrow. The exposed open-ocean coast of Barter Island where shoreline change rates were calculated stretches approximately 8 km from the Kaktovik Airport to the west end of the Barter Island spit. Between 1947 and 2003, the coast of Barter Island was predominantly erosional except for accretion and extension of the spits at both the eastern and western ends of the island. Arey Island extends about 11 km between Kuvritovik Entrance and the Okpilak-Hulahula River Delta. The Arey Island and Lagoon system has experienced a complex history of shoreline change with multiple segmentation and island migration episodes (Li Erikson, U.S. Geological Survey, written commun., 2014). The 1947 T-sheets show Arey Island as one continuous barrier island. By 2003, the relatively lower and narrower eastern portion of the island segmented into multiple islands and migrated to the southwest by as much as 900 m. The apex of island eroded and migrated to the southwest and the western portion of the island remained mostly stable to slightly accretional.

The exposed open-ocean coast of Region 2 between the Jago River Delta and the Okpilak-Hulahula River Delta is erosional (68 percent of transects) with an average rate of shoreline change of -1.9 m/yr and range of -16.5 to +9.6 m/yr. The highest rates of both erosion and accretion within Region 2 were measured within this subsection at Arey Island and Bernard Spit, respectively (figs. 18 and 20; table 5). Because of the loss of land and/or migration beyond a common footprint (i.e., where only one shoreline is present), some of the erosion and accretion of both Bernard Spit and Arey Island is not accounted for in the DSAS analysis.

In order to maintain consistency with other National Assessment of Shoreline Change products that evaluate rates of shoreline change only along exposed open-ocean coastlines, average rates of shoreline change for Region 2 include only rates calculated along the exposed open-ocean coast of Barter Island (fig. 16). Because Barter Island is one of the few population centers on the North Slope, however, shorelines, baselines, transects, and rates of change are included in the GIS database (Gibbs and others, 2015), and summarized in table 5 and fig. 21.

Okpilak-Hulahula River Delta to Sadlerochit River

Between the Okpilak-Hulahula River Delta and the Sadlerochit River, the exposed open-ocean coast is marked by a discontinuous chain of extremely low-lying (<1-m high), narrow (<100 m wide), and unvegetated barrier islands and shoals. Considerably more islands are apparent in the 2003 imagery than were mapped on the 1947 T-sheets, although extensive intertidal-subtidal shoals are outlined on the T-sheets (fig. 22). The emergent barrier islands appear to have eroded and migrated landward on average 143 m (range: 30-243 m) between 1947 and 2003. Shoreline change rates were calculated using only emergent island areas and not the intertidal shoals. Shoreline change rates calculated for this section of coast are 100 percent erosional, with shoreline change rates averaging -2.5 m/yr and ranging between -4.3 and -0.5 m/yr (figs. 18 and 20; table 5), however, the apparent accretion and extension of the barrier islands that occurred between 1947 and 2003 is not included in the DSAS calculated rates because the islands migrated beyond their 1947 footprint.

Sadlerochit River to Konganevik Point

Between the Sadlerochit River and Konganevik Point, the coast is exposed mainland except where spits and barrier islands exist near Anderson Point, fronting Simpson Cove, and fronting the embayment east of Konganevik Point. Little change to the spit at Anderson Point occurred between 1947 and 2003 aside from the formation of a narrow channel. In contrast, the spit fronting Simpson Cove, which in 1947 extended nearly 3 km west of Marsh Creek to Collinson Point, migrated on average 350 m onshore, eroding the former location of Collinson Point, and creating a new, detached island to the west. The barrier island fronting the embayment east of Konganevik Point as mapped in the 1947 T-sheets deteriorated to a narrow, low-lying bar, whereas the spit on the east side of the embayment accreted and extended further west across the embayment.

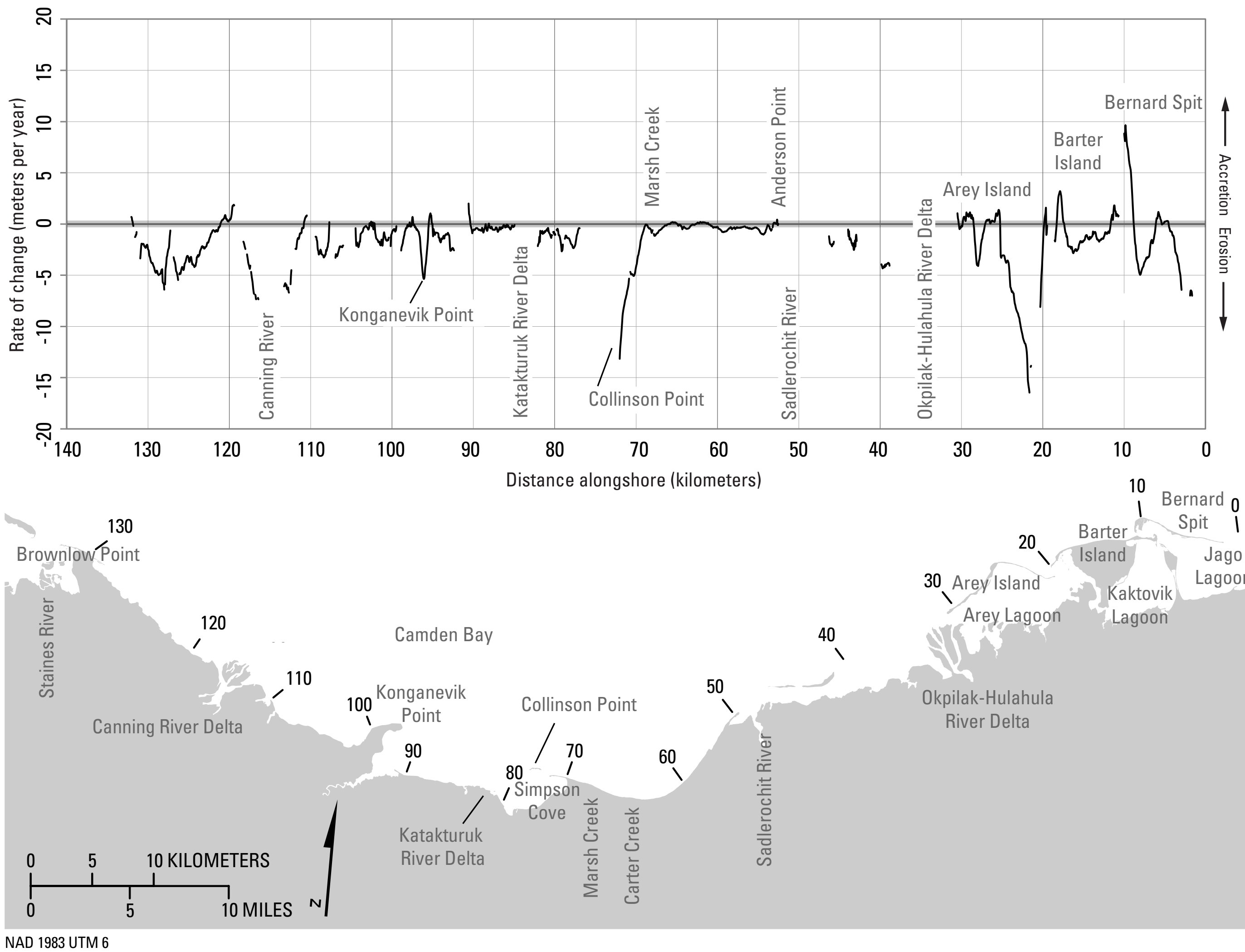


Figure 20. Graph of shoreline change rates for the exposed open-ocean coast of Region 2, Jago River to Staines River, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 2 indicating distances measured alongshore.

The exposed open-ocean coast of Region 2 between Sadlerochit River and Konganevik Point is predominantly erosional (88 percent of transects) and rates of shoreline change average -1.0 and range between -13.2 to +2.0 m/yr. The barrier spit fronting Simpson Cove near Collinson Point, however, is by far the most dynamic feature along this stretch of coast and dominates the calculated shoreline change rate averages. Average rates calculated for this stretch are reduced by one-half, to -0.5 m/yr, when the erosion of the spit is excluded (figs. 18 and 20, table 5).

Konganevik Point to the Staines River

The exposed open-ocean coast between Konganevik and the Staines River is predominantly low-lying, unvegetated barrier islands and spits and low-lying to moderately high exposed mainland coast near Konganevik and Brownlow Points (fig. 16). The barrier islands and spits along this reach are extremely low lying (<1.5-m high), narrow (<100-m wide), and unvegetated (fig. 17D). The exposed open-ocean coast of Region 2 between Konganevik Point and the Staines River is predominantly erosional (89 percent of transects) and shoreline change rates average -2.1 and range from -7.3 to +1.9 m/yr. The highest erosion rates are associated with the erosion and landward migration of the barrier spits and islands, particularly around the Tamayariak and Canning River Deltas (figs. 18 and 20). Average shoreline change rates are nearly twice as high on the barrier island-spit coasts compared to the exposed mainland coasts (-2.6 and -1.4 m/yr, respectively [table 5]).

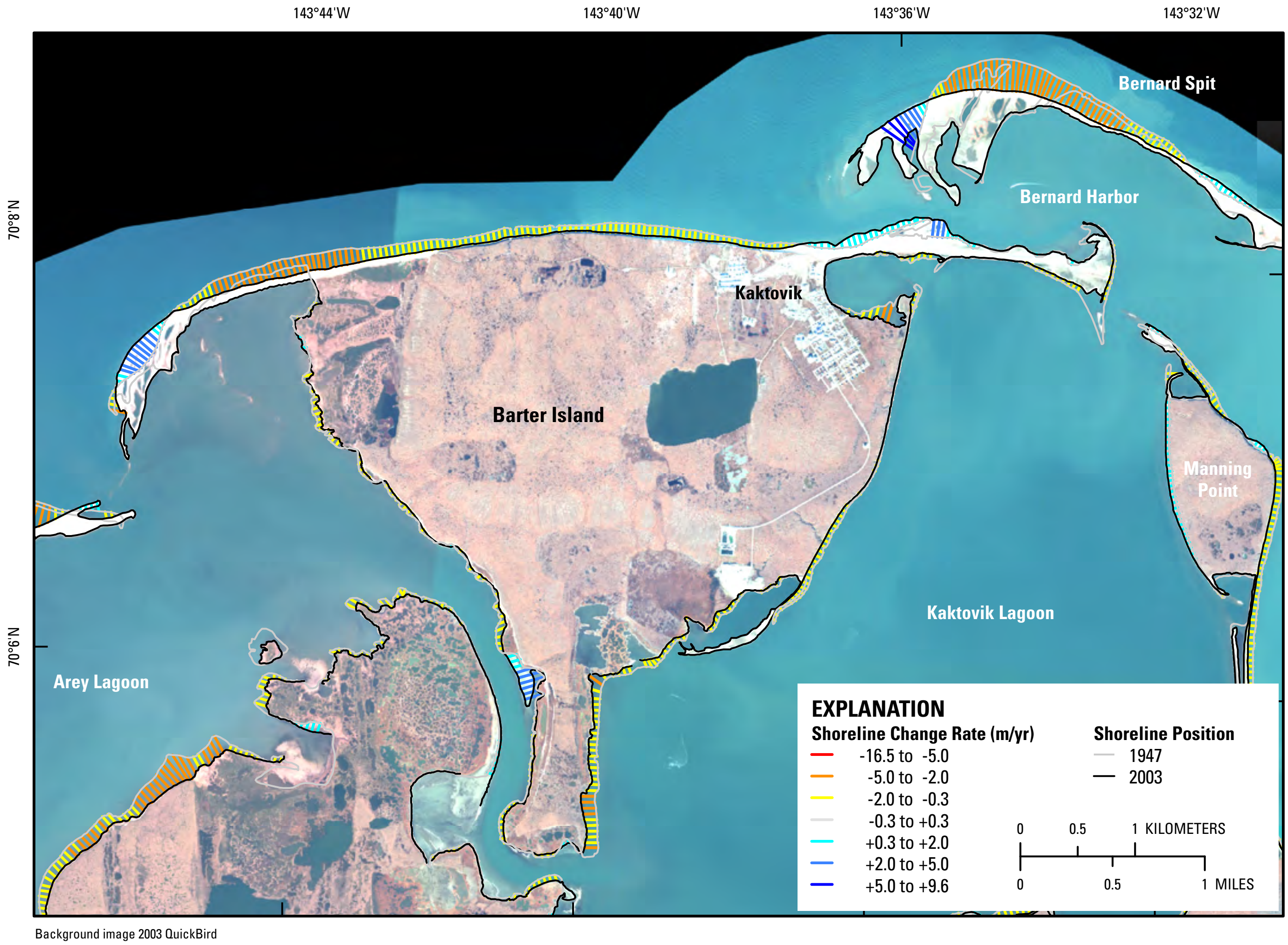


Figure 21. Map showing color-coded shoreline change rates for Barter Island and adjacent areas, Region 2, Jago River to Staines River, north coast of Alaska. Width of line represents shoreline change envelope, or total shoreline change over analysis period, and distance between historical shorelines.

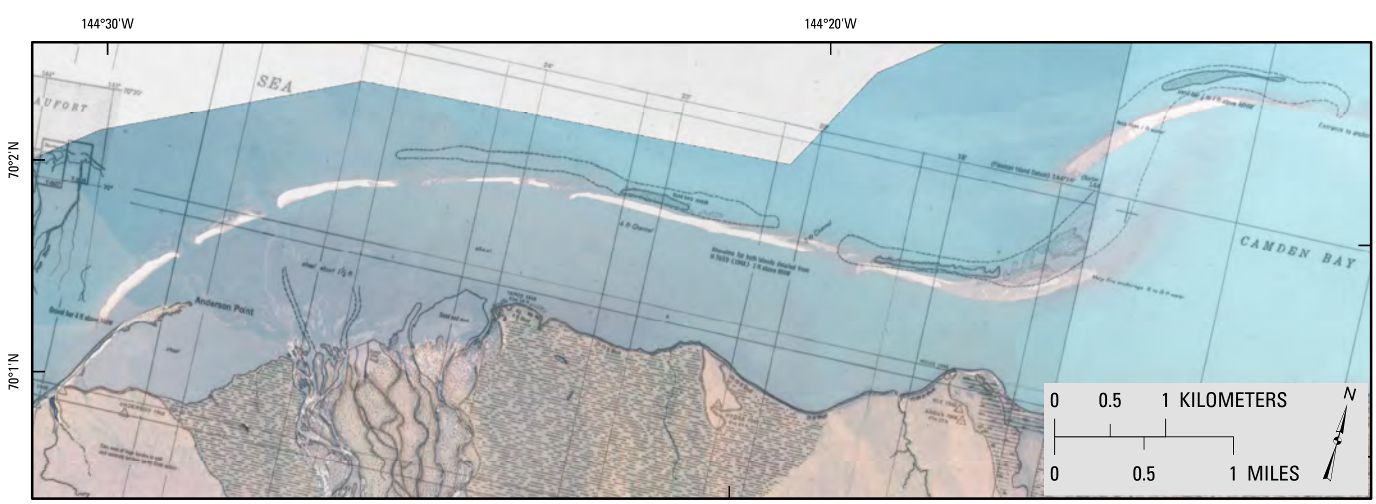


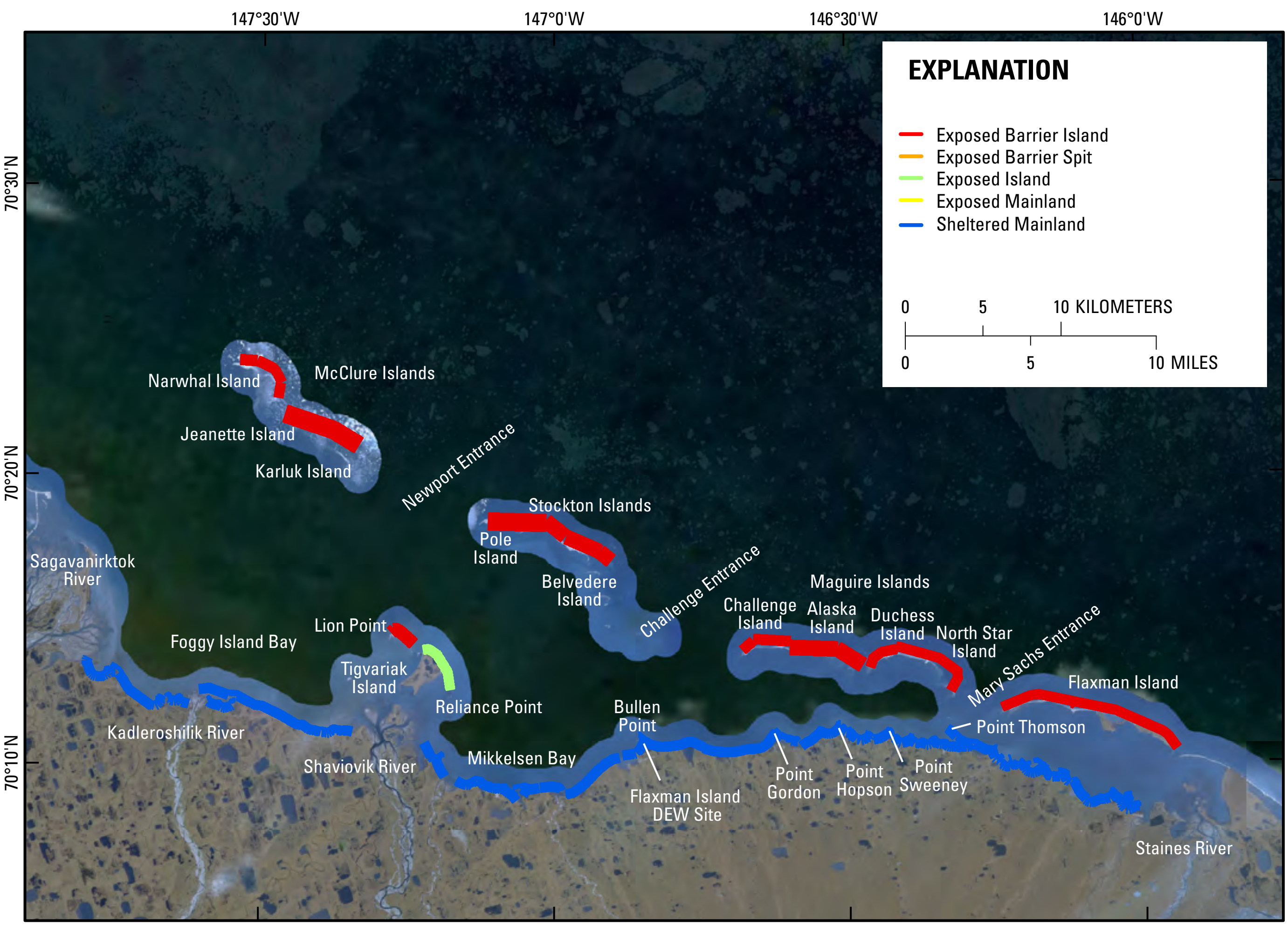
Figure 22. Map of 1947 T-sheet data overlain on 2003 QuickBird™ satellite image showing barrier islands offshore of Okpilak-Hulahula River Delta and Sadlerochit River in Region 2, Jago River to Staines River, north coast of Alaska. Note the much smaller extent of barrier islands (solid line) and intertidal shoals (dashed line) mapped in 1947 compared to the islands and shoals apparent in the 2003 imagery.

(3) Staines River to Sagavanirktok River

Introduction

The coast of Region 3 extends approximately 70 km between the Staines and the Sagavanirktok River Deltas (fig. 23) and generally trends E-W. Coastal development in the region includes oil and gas related infrastructure and remnants of the Flaxman Island (also known as Bullen Point) Auxiliary DEW site, deactivated in 1971, and the North Warning System Short Range Radar Station that operated from 1994 until 2007 when it was closed and site remediation occurred (fig. 24A). There are no permanent villages in this region.

The mainland coast of Region 3 is sheltered by a chain of barrier islands that increase in distance from the mainland coast from east to west. The mainland coast is segmented by the Shaviovik and Kadleroshilik Rivers and several small, unnamed rivers. Mikkelsen Bay and Foggy Island Bay are two large embayments separated by Tigvariak Island and the Shaviovik River Delta. Between the Staines River and Point Gordon, where the barrier islands are relatively close to shore, the coastline is irregular and more crenulated than to the west. The coastal plain in this region is generally low-lying (<3 m high; fig. 24B) although discontinuous bluffs up to 5 m high are present west of Point Gordon. Barrier spits, cuspate headlands, and baymouth bars and beaches fronting embayments are pervasive along the mainland coast. Narrow beaches, 10-50 m wide, are found throughout the area and are generally more common and wider east of the Shaviovik River. Thermokarst lakes are common on the coastal plain and are generally elongated in an E-W direction east of the Shaviovik River; west of the iver the thermokarst lakes are generally larger and elongated in a NW-SE orientation.



Background image courtesy UAF-GINA (http://alaskamapped.org/bdl); includes material © CNES 2011, Distribution Spot Image S.A., France, SICORP, USA, all rights reserved.

Figure 23. Map showing color-coded shoreline types within Region 3. Staines River to Sagavanirktok River, north coast of Alaska.

Figure 24. Aerial photographs showing typical examples of the coast of Region 3, Staines River to Sagavanirktok River, north coast of Alaska. A, Former site of Flaxman Island/Bullen Point Distant Early Warning (DEW) and Short Range Radar Station; view to south west. B, Low-lying mainland coast near Point Hopson. View to east. C, Bluffs and tapped thermokarst lake on Flaxman Island. D, Narwhal Island. Note ice push ridges on coast and wood wrack on the topographically higher, central part of the island. (All photographs from 2006; Gibbs and Richmond, 2009).

The barrier island coast of Region 3 is an approximately 65 km long barrier chain that includes Flaxman Island, the Maguire Islands (North Star, Duchess, Alaska, and Challenge Islands), the Stockton Islands (Belvedere and Pole Islands), Tigvariak Islands (Tigvariak Island and an adjacent unnamed barrier island), and McClure Islands (Karluk, Jeanette, and Narwhal Islands). With the exception of the Tigvariak Islands the barrier islands increase in distance from the mainland coast from about 2 km at Flaxman and Maguire Islands to more than 21 km at Narwhal Island. Portions of Flaxman Island and Tigvariak Island are slightly elevated tundra remnant islands, whereas the other barrier islands are low-lying, largely unvegetated sand and gravel islands with multiple ridges and well-developed recurved spits at their ends. Debris wrack lines are common on the higher portions of the unvegetated islands. Interior shallow water bodies, both connected and unconnected to the sea, are common.

Shoreline change rates were determined using 1947 T-sheets and a combination of 1997 and 2001 vector shorelines, 2003 QuickBird™ satellite imagery, and 2006 and 2007 orthorectified aerial photography (table 2; fig. 4). There is an approximately 2 km gap in the 2000 era imagery just west of the Staines River that includes part of the mainland coast and no rates were calculated for that area. Region 3 is predominantly erosional (89 percent of transects) with combined shoreline change rates for both the mainland and barrier island coasts averaging -1.5 m/yr and ranging between -16.8 to +6.7 m/yr (fig. 25; table 5). Average shoreline change rates along the exposed open-ocean coast are more than three times as high compare to the sheltered mainland-lagoon coast (-3.0 and -0.8 m/yr, respectively), although much of the change to the barrier islands is not accounted for in the DSAS results due to the lack of overlapping shorelines.

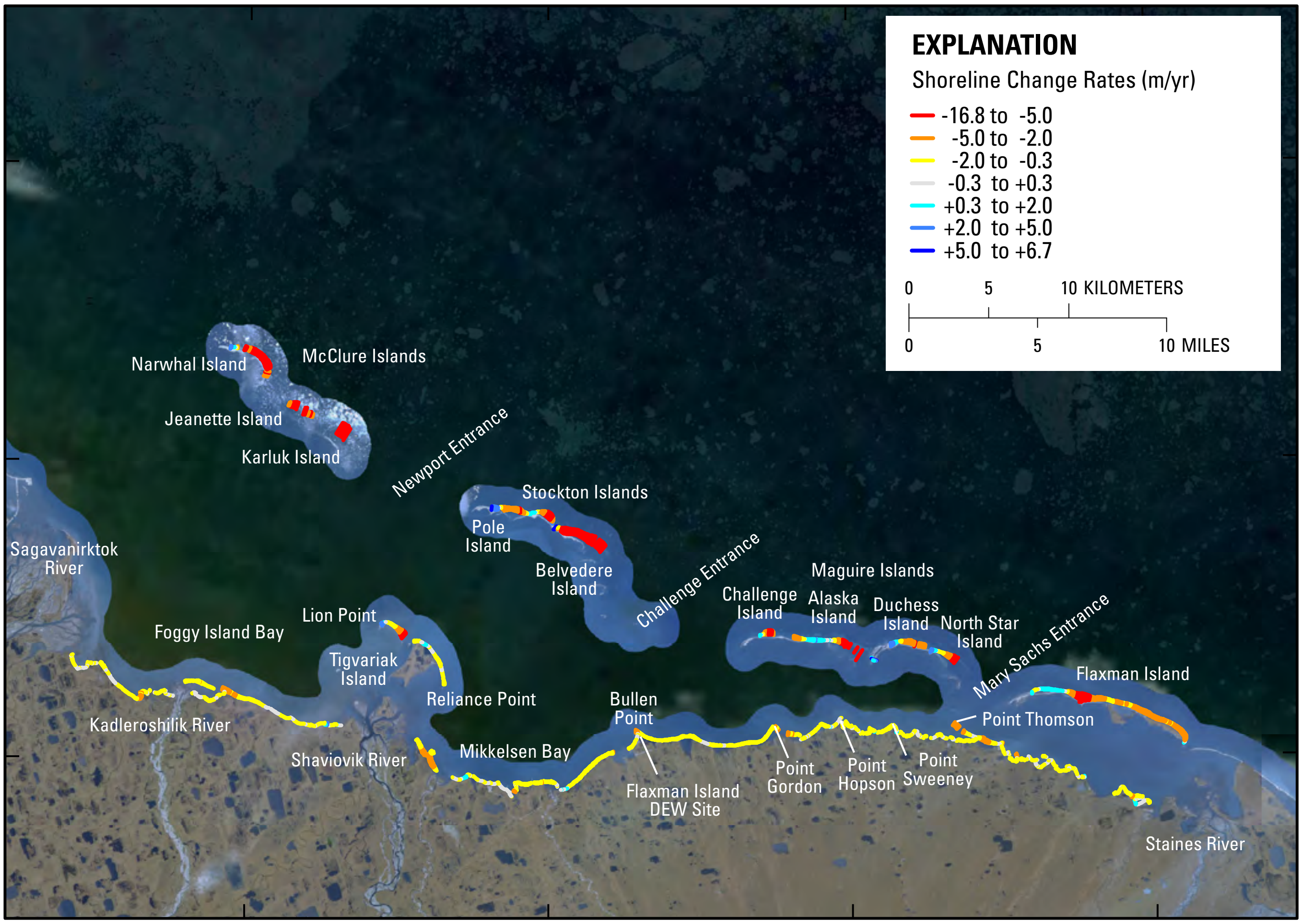


Figure 25. Map showing color-coded shoreline change rates in Region 3, Staines River to Sagavanirktok River, north coast of Alaska. Width of line represents shoreline change envelope, or total shoreline change over analysis period, and distance between historical shorelines.

Sheltered Mainland-Lagoon Shoreline Change

The sheltered mainland-lagoon coast of Region 3 is predominantly erosional (93 percent of transects) with shoreline change rates averaging -0.8 m/yr and ranging between -4.4 and +2.7 m/yr (figs. 25 and 26). The highest rates of erosion along the mainland coast are associated with the migration and degradation of barrier spits near Point Thomson. Similar loss of barrier spits elsewhere in the region (for example, at Bullen Point) is not accounted for in the DSAS analysis because of the complete loss of the spits during the study period. On the west side of Mikkelsen Bay, erosion has resulted in the near total loss of a prominent headland (fig. 27). Despite the increase shoreline complexity and crenulation between the Staines River and Point Gordon, there seems to be no significant change in shoreline change rates associated with distance from the offshore barrier islands or shoreline morphology along the mainland coast (table 5).

Exposed Open-Ocean Shoreline Change

The exposed open-ocean shorelines in Region 3 are dominantly erosional (81 percent of transects) with shoreline change rates averaging -3.0 m/yr and ranging between -16.8 and +6.7 m/yr (figs. 25 and 28). The barrier islands show a complex and dynamic pattern of change, with many islands showing a clockwise-rotational pattern of change, with the western ends of the islands remaining relatively stable, prograding northward and/or extending to the west/southwest and the eastern portions eroding and/or migrating considerably landward from their 1947 position (fig. 29). Much of this change is not accounted for in the DSAS analysis because of the lack of overlapping shorelines. Between 1947 and 1991/2006 the total barrier island area, not including the Tigvariak Islands, increased by 381,754 m^2 (table 6). A detailed description of changes in island morphology and rates of shoreline change for the barrier islands in Region 3 follows.

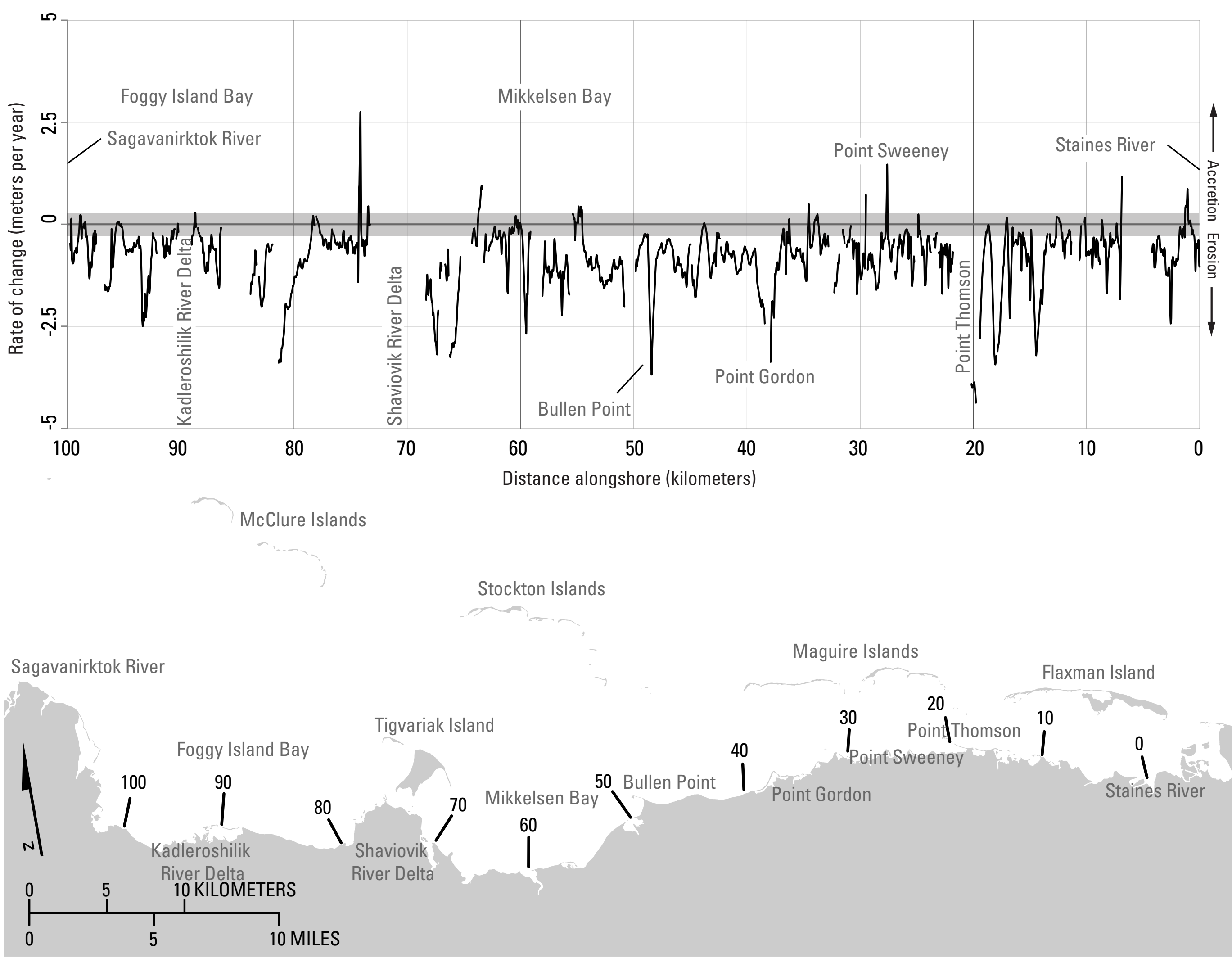
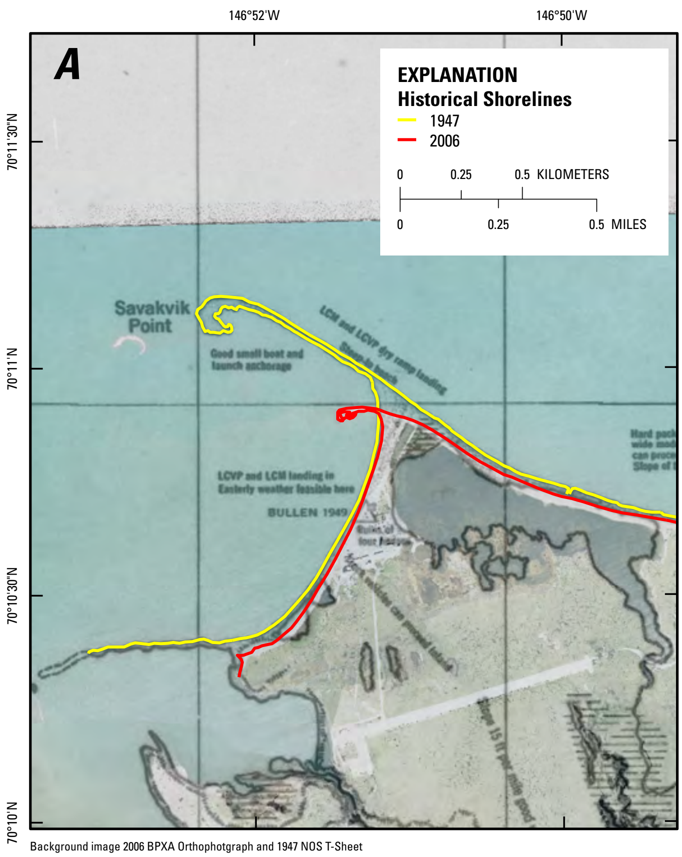


Figure 26. Top: Graph of shoreline change rates for the sheltered mainland-lagoon coast of Region 3, Staines River to Sagavanirktok River, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 3 indicating distances measured alongshore.



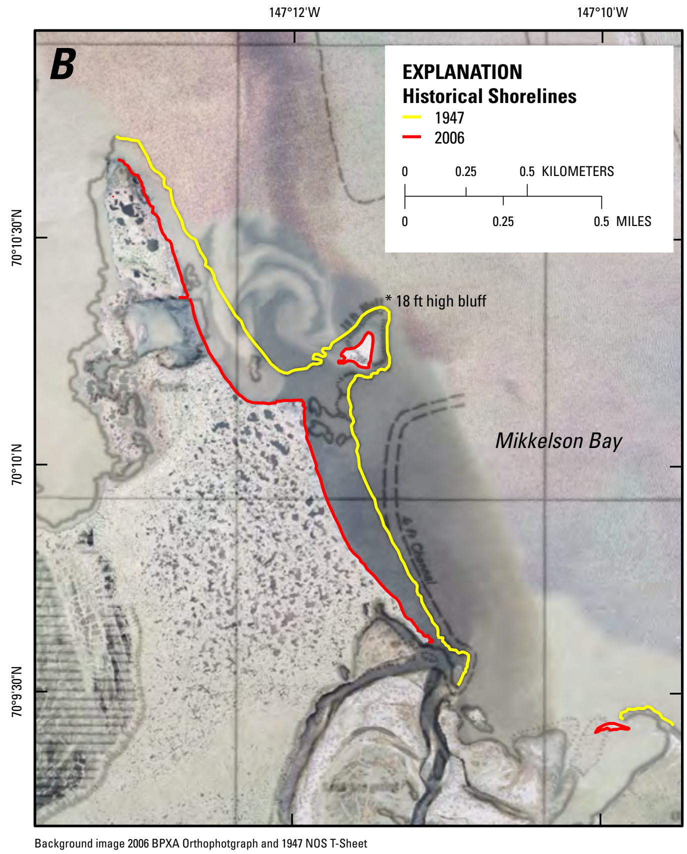


Figure 27. Maps showing examples of shoreline change along mainland coast of Region 3, Staines River to Sagavanirktok River, north coast of Alaska. A, Nearly complete loss of barrier spit between Bullen Point and Savakvik Point. B, Almost 0.25 kilometers of shoreline erosion and loss of a headland (and "18 ft high bluff") on the west side of Mikkelson Bay.

Table 6. Total barrier island area in Region 3, Staines River to Sagavanirktok River, north coast of Alaska, for each era and total change during analysis period, in square meters.

Island name	1940s	2000s	2000s–1940s
Flaxman Island	3,287,368	2,911,841	-375,526
Maguire Islands	632,727	1,203,616	570,890
Stockton Islands	779,673	1,014,997	235,324
McClure Islands	618,489	569,556	-48,933
Tigvariak Islands	3,834,609	3,645,970	-188,638
Total with Tigvariak Islands	**9,152,865**	**9,345,981**	**193,116**
Total without Tigvariak Islands	**5,318,256**	**5,700,010**	**381,754**

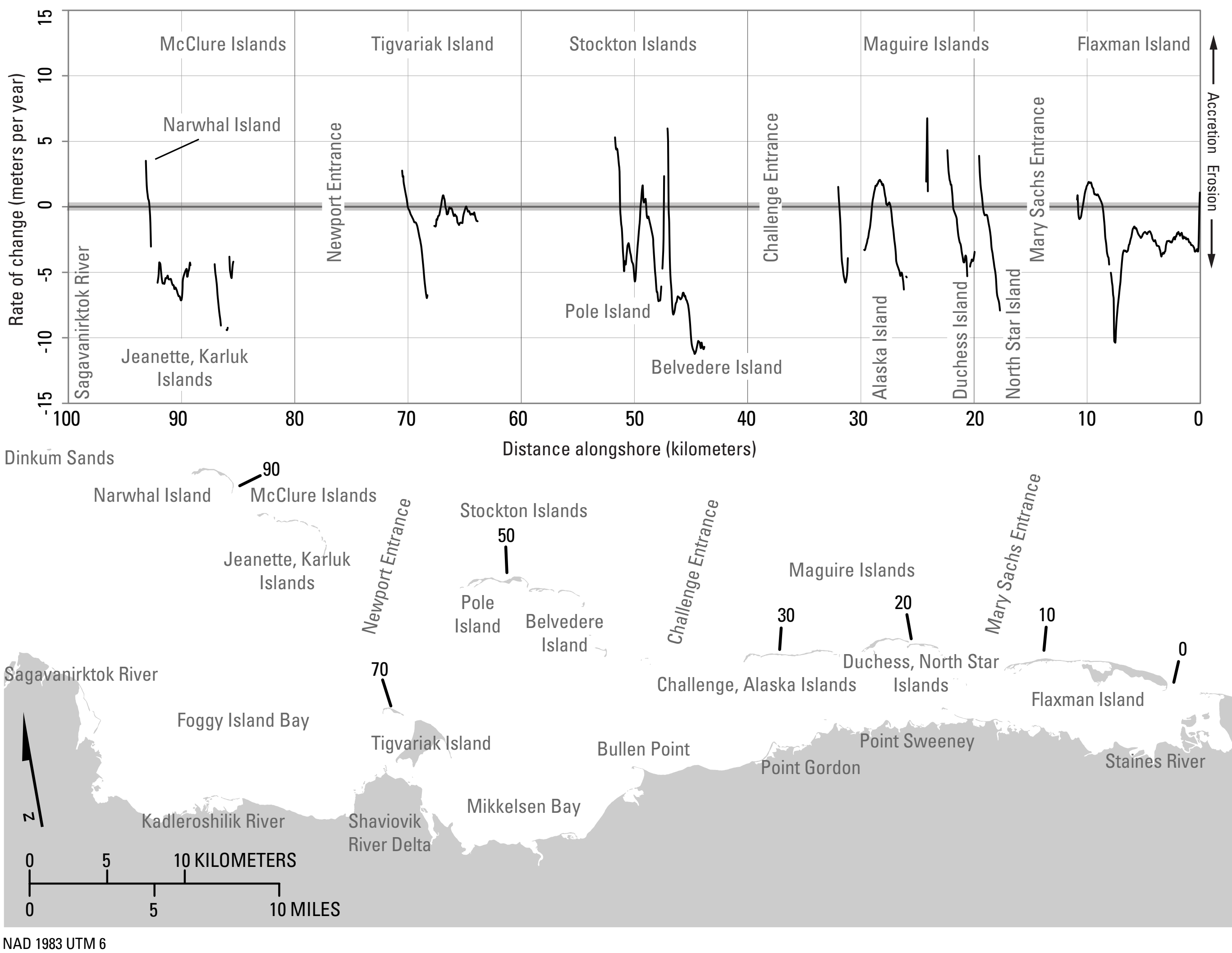
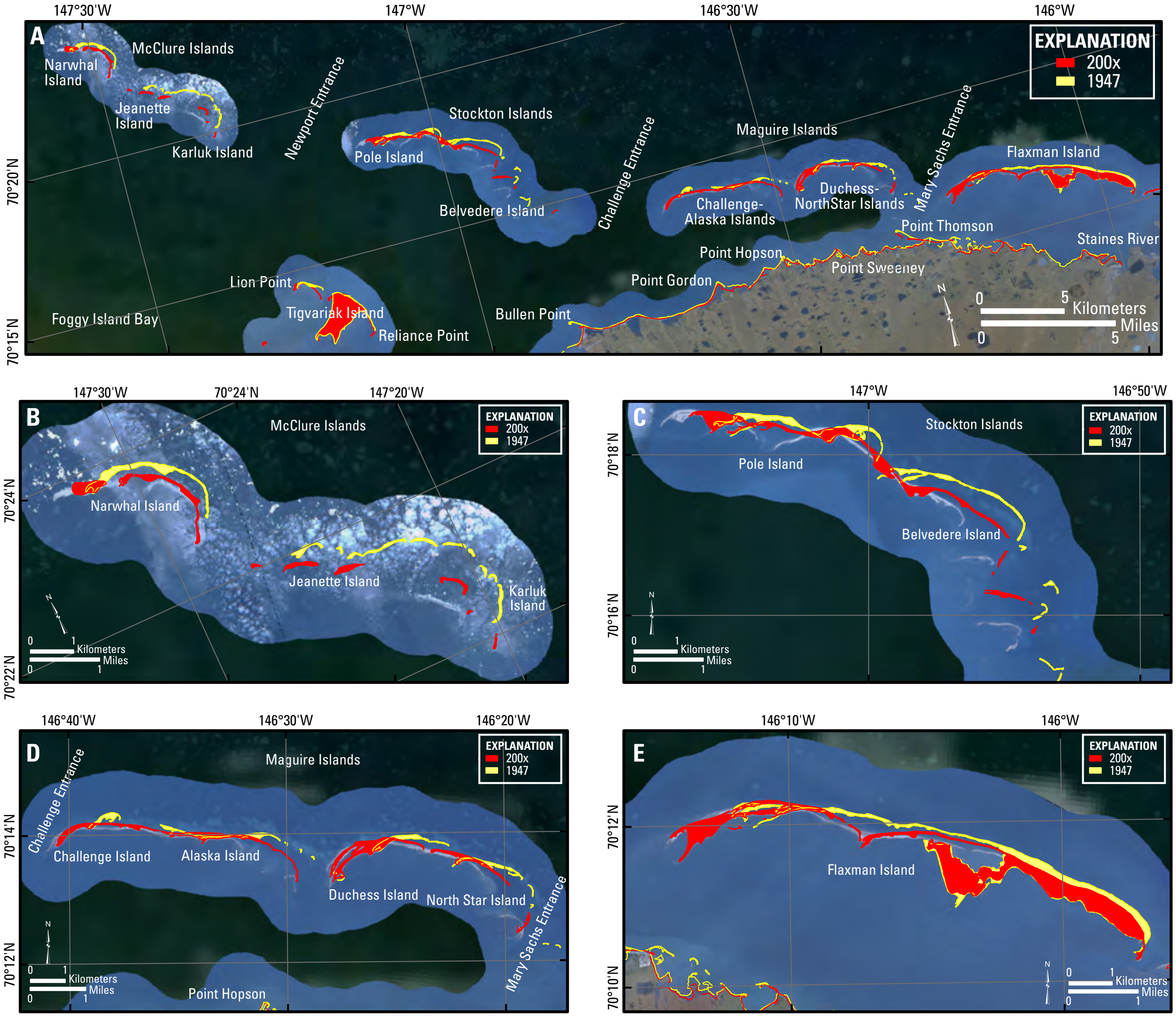


Figure 28. Top: Graph of shoreline change rates for exposed open-ocean coast of Region 3, Staines River to Sagavanirktok River, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 3 indicating distances measured alongshore.



Background images courtesy UAF-GINA (http://alaskamapped.org/bdl); includes material © CNES 2011, Distribution Spot Image S.A., France, SICORP, USA, all rights reserved.

Figure 29. Detailed maps of barrier islands in Region 3, Staines River to Sagavanirktok River, north coast of Alaska. Note rotation from north for figures A and B.

Flaxman Island

Flaxman Island, the easternmost island in the barrier chain, was mapped as a single, 11 km long island on 1947 T-sheets. By 2001, the island was apparently breached and segmented into multiple islands (fig. 29E). The eastern 3.5 km of Flaxman Island is a well-vegetated, remnant tundra island with a low-lying, recurved spit at the extreme eastern end. Bluffs along the tundra coast reach over 6 m high in the east and decrease in height to the west. Beaches fronting the bluffs are rare and narrow (<5 m wide) when present. Thermokarst lakes and high-center polygons are common (fig. 24C). At least two artificial ponds and a gravel airstrip are visible in the 2006 aerial photography (Gibbs and Richmond, 2009). The western 8.5 km of the island chain consists of several low-lying (<1.5 m high), unvegetated, narrow spits and barrier islands, generally less than 50 m wide. At the western end, multiple beach ridges are separated by shallow ponds and lagoons. Between 1947 and 2001, the island experienced considerable erosion, averaging 150 m retreat along the remnant tundra coastline and 180 m landward migration of the low-lying barriers. The western quarter of the island prograded on average 50 m seaward and extended about 1.5 km to the west. DSAS generated shoreline change rates indicate that the open-ocean coast of Flaxman Island is dominantly erosional (83 percent of transects) averaging -2.3 m/yr and ranging from -10.4 to +1.9 m/yr (table 5); however, the rate calculations do not account for much of the accretion and extension of the island beyond the 1947 footprint. The total island area decreased by 375,526 m^2 (table 6).

Maguire Islands

The Maguire Islands, bound by Mary Sachs Entrance on the east and Challenge Entrance on the west, is an approximately 15 km long barrier chain including North Star, Duchess, Alaska, and Challenge Islands and numerous small, unnamed islands. The islands are low-lying (<2 m high), unvegetated, and narrow. The Maguire Island chain shows a complex pattern of change between 1947 and 2001, including erosion, accretion, and extension of the islands to the east and west (fig. 29D). DSAS calculated shoreline change rates indicate that the open-ocean coast of the Maguire Islands is erosional (66 percent of transects) averaging -1.8 m/yr and ranging from -13.7 to +6.7 m/yr (table 5); however, the calculations do not account for much of the accretion and extension of the islands due to the lack of overlapping shorelines. The total island area increased by 570,890 m^2 (table 6).

Stockton Islands

The Stockton Islands, between Challenge Entrance on the east and Newport Entrance on the west, are an approximately 8 km long barrier chain including Belvedere and Pole Islands and numerous unnamed islands and shoals. The islands are low-lying (<2 m high) and mostly unvegetated except for low-lying vegetation in topographic lows, and sparse higher vegetation near the central, stable part of Pole Island. Between 1947 and 1997, the Stockton Islands nearly completely migrated landward of their 1947 position, with only the central/eastern end of Pole Island sharing a similar footprint (fig. 29C). Belvedere Island migrated on average 402 m landward, while Pole Island migrated landward on average 165 m, but also extended nearly 600 m to the east. By 1997, Belvedere and Pole Islands had merged into one nearly continuous, 8 km long island, separated by two narrow passes. The numerous small islands and shoals south of Belvedere Island and within Challenge Entrance share no overlapping footprints suggesting the islands migrated landward and/or eroded completely and reformed in a new location hundreds of meters landward of their 1947 location. Shoreline change rates were not calculated for these discontinuous small islands and shoals, however, their areas are included in the overall area calculation. DSAS calculated shoreline change rates indicate that the open-ocean coast of the Stockton Islands is dominantly erosional (85 percent of transects) averaging -4.6 m/yr and ranging from -11.2 to +6.0 m/yr (table 5); however, the calculations do not account for much of the accretion and extension of the islands beyond the 1947 footprint. The total island area increased by 235,324 m^2 (table 6).

McClure Islands

The McClure Islands, the westernmost islands in Region 3, include Karluk, Jeanette, and Narwhal Islands and several unnamed islands between Karluk and Jeanette. By 1997, the islands had migrated landward of their 1947 footprint to occupy an entirely new footprint, except the western end of Narwhal Island which remained generally stable and accreted to the west (fig. 29B). Narwhal Island, mapped as one island in 1947, segmented into 2 separate islands, and rotated counter-clockwise, with the eastern part of the island migrating landward on average 285 m and extending 675 m to the southwest, and the western part of the island remaining stable, prograding, or extending about 350 m to the northwest. Jeanette, Karluk, and the unnamed islands migrated on average 675 m to the southwest. DSAS calculated shoreline change rates indicate that the open-ocean coast of the McClure Islands is dominantly erosional (92 percent of transects) averaging -6.5 m/yr and ranging from -16.8 to +3.5 m/yr; however, the calculations do not account for much of the accretion and extension of the islands beyond their original footprint, nor the loss of many of the smaller islands between Jeanette and Karluk Islands. The total island area decreased by 48,933 m^2 (table 6) between 1947 and 1997.

Tigvariak Islands

The Tigvariak Islands, located just off the mouth of the Shaviovik River, include a large tundra remnant island with a recurved barrier spit extending about 1.5 km eastward to Reliance Point and a detached 2 km long barrier island extending west to Lion Point. The barrier spit and island are low-lying (<1.5 m high) and generally less than 50 m wide, although wider on the east and west ends, respectively. They are mostly unvegetated except for low-lying vegetation in topographic lows on the western side of the barrier island. The larger Tigvariak Island reaches up to 5 m high in the center of the island, but is generally less than 3 m high and fronted by narrow sand and gravel beaches. An abandoned gravel pad is present on the northeast side of the island. The barrier spit and open-ocean coast of the tundra island have experienced relatively little shoreline change between 1947 and 2006, however, the detached barrier island shows a shoreline change pattern similar to the barriers offshore, with considerable erosion on the east side of the island and deposition, progradation, and extension of the western shore (figs. 25 and 28). In order to maintain consistency with other National Assessment of Shoreline Change products that evaluate rates of shoreline change only along exposed open-ocean coastlines, average rates of shoreline change for Region 3 include only rates calculated along the exposed open-ocean coast of the Tigvariak Islands (figs. 23 and 25). Because Tigvariak Island is a major geomorphic feature along north coast of Alaska, however, shorelines, baselines, transects, and rates of change are included in the GIS data base (Gibbs and others, 2015, and historical changes are summarized in tables 5 and 6 and figure 30.

The exposed open-ocean coast of the Tigvariak Islands are dominantly erosional (86 percent of transects) with an average shoreline change rate of -1.1 m/yr and range of -7.0 to +2.8 m/yr (table 5). Similar to the other islands in this region, the calculations do not account for much of the accretion and extension of the islands beyond their original footprint (fig. 30; table 5). The total island area decreased by 188,638 m^2 between 1947 and 2006 (table 6).

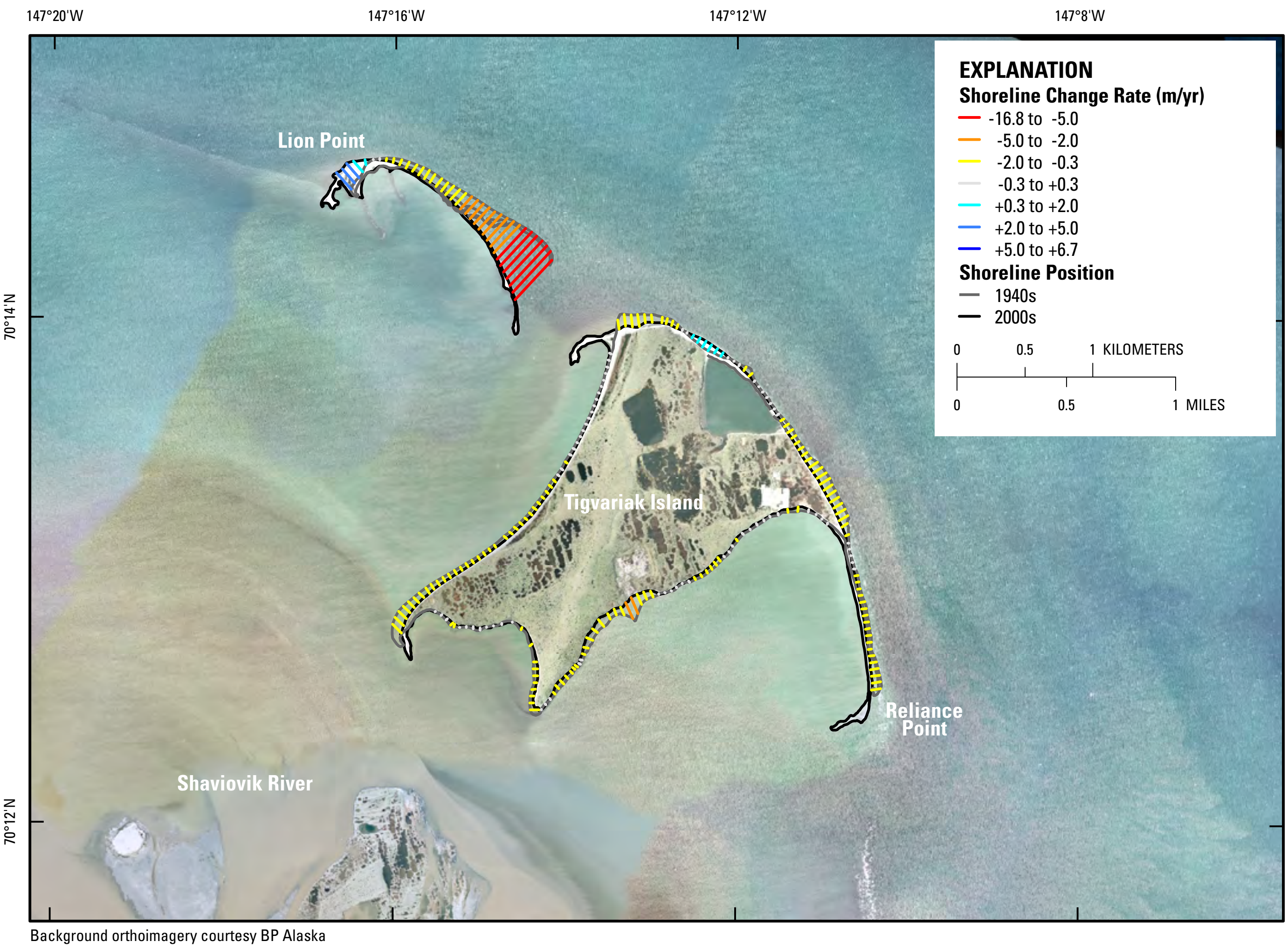


Figure 30. Map showing shoreline change rates for the Tigvariak Islands, Region 3, Staines River to Sagavanirktok River, north coast of Alaska. Length of line represents shoreline change envelope, or total shoreline change over analysis period, and distance between historical shorelines.

(4) Sagavanirktok River to Colville River

Introduction

Region 4 extends approximately 100 km between the Sagavanirktok and Colville River Deltas and includes both exposed open/barrier coast and sheltered mainland/lagoon coast (fig. 31). There is considerable oil and gas related development in the region, notably near Oliktok Point and Prudhoe Bay, the Prudhoe Dock, and the West Dock causeway which leads to the artificial Endicott Island. There are two DEW sites along this coast, the former Intermediate DEW site at Point McIntyre, which closed in 1963, and the former Auxiliary DEW site and current North Warning System Long Range Radar site at Oliktok Point. Local fish camps and/or non-oil and gas related structures exist near Beechey Point, Milne Point and Oliktok Point. The unincorporated community of Deadhorse is located about 12 km south of Prudhoe Bay at the end of the James W. Dalton Highway, a supply road built to support the Prudhoe Bay oilfields and Trans-Alaska Pipeline System and the only road connecting the North Slope to the rest of Alaska. Development in Deadhorse includes the Deadhorse/Prudhoe Bay Airport and numerous support facilities for the workers and companies that operate the nearby oil fields.

Region 4 is characterized by a chain of barrier islands fronting a low- to moderately-high tundra mainland coast. The mainland coast extends approximately 95 km from Heald Point, at the western side of the Sagavanirktok River Delta, to the eastern side of the Colville River Delta. It is segmented by the Kuparuk River and Delta, several rivers (Putuligayuk, Sakonowyak, Ugnuravik), creeks (Fawn Creek and Kalubik), three unnamed rivers between Beechey and Milne Points, Prudhoe Dock, and the West Dock causeway. The coast of Prudhoe Bay, between Heald Point and Point McIntyre, is somewhat exposed to open-ocean energy conditions, although Cross and Reindeer-Midway Islands, located about 15 km offshore, and the West Dock causeway, may dampen some incident wave energy. Between Point McIntyre and the Colville River, the mainland coast is separated from the barrier island chain by Gwydyr Bay and Simpson Lagoon. The mainland coast is predominantly low- to moderately-high bluffs (<3 m high) and low-lying landscape (<2 m high) associated

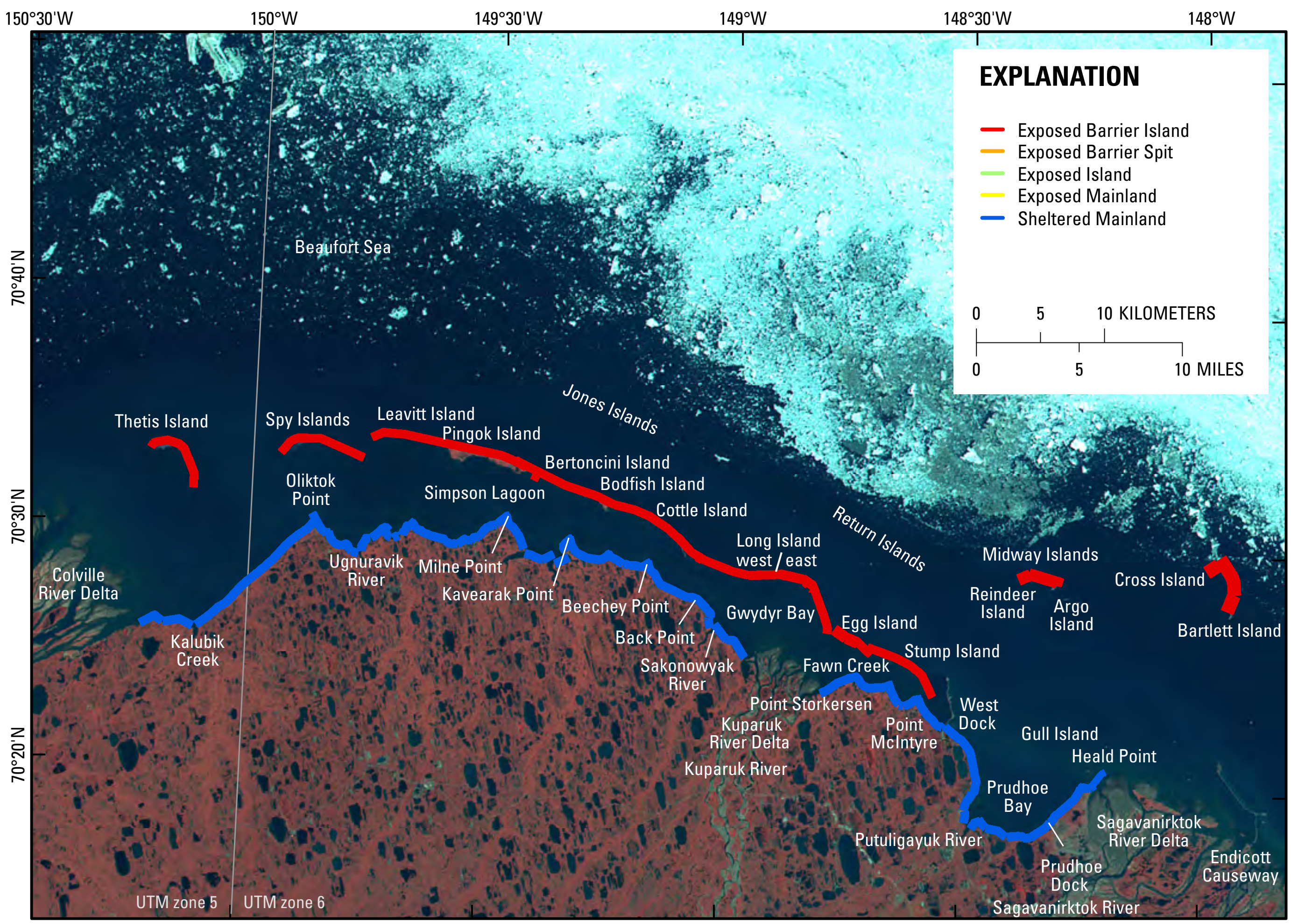


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Figure 31. Map showing color-coded shoreline types within Region 4, Sagavanirktok River to Colville River, north coast of Alaska.

with tapped thermokarst lakes and adjacent rivers, creeks, and drainages. Relatively higher bluffs (up to 5 m high) are found only near Heald Point on the eastern coast of Prudhoe Bay. Beaches are generally narrow, when present, but reach up to 30 m wide at several locations.

The barrier island coast of Region 4 includes Cross Island and the Midway Islands (Argo and Reindeer) located 15–20 km north of Prudhoe Bay and an approximately 65 km long, nearly continuous barrier island chain that stretches between Stump Island and Thetis Island. The island chain trends southeast-northwest and increases in distance from the mainland from east to west, from about 1 km near Stump Island to more than 9 km at Thetis Island. Most of the islands are low-lying and unvegetated to sparsely-vegetated, except for the remnant-tundra portions of the Jones Islands (Cottle, Bodfish, Bertoncini, and Pingok Islands) which are well-vegetated and up to 5 m high.

Shoreline change rates were determined using 1947 T-sheets and a combination of 1997 vector shorelines (Reindeer/Midway Islands) and 2004, 2006, or 2007 orthorectified aerial photography (table 2; fig. 4). The region crosses two UTM zones (5 and 6). Region 4 is predominantly erosional (85 percent of transects) with combined shoreline change rates for both the sheltered mainland and exposed open-ocean barrier island coasts averaging -1.1 m/yr and ranging between -14.7 to +7.0 m/yr (fig. 32; table 5). Average rates of shoreline change for the mainland coast are half of the barrier island coast (-0.8 and -1.6 m/yr, respectively). The highest erosion and accretion rates are associated with the migration of barrier islands and associated formation and infilling of inlets, although much of the change to the barrier island coast is not accounted for in the DSAS analysis because of island migration beyond the original island footprint. The total surface area of the barrier islands decreased by 113,245 m^2 between 1947 and 2007, largely due to the considerable loss of land at Pingok Island (table 7). A detailed discussion of the geomorphology and shoreline change history for the mainland and barrier coasts follows.

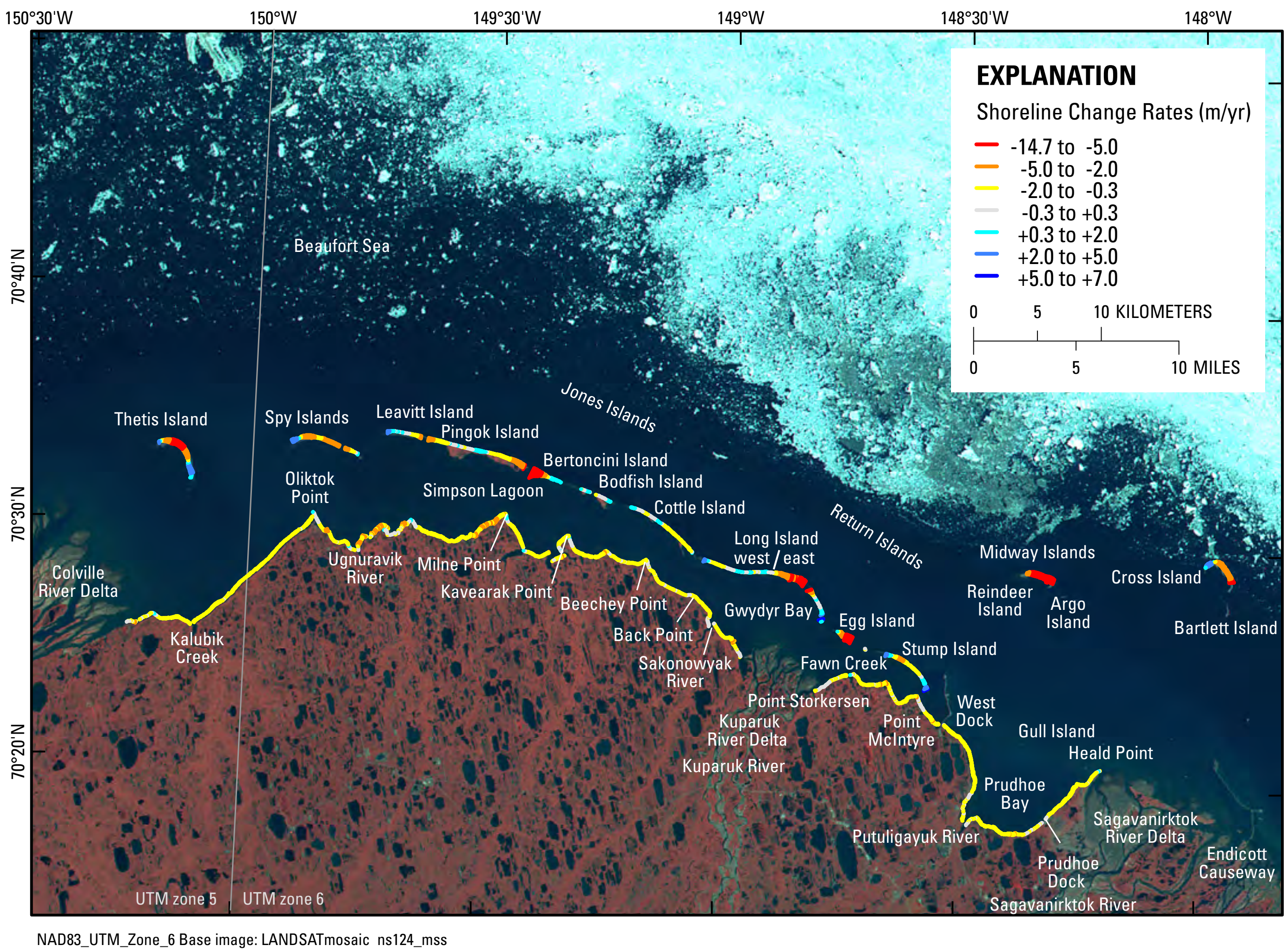


Figure 32. Map showing color-coded shoreline change rates in Region 4, Sagavanirktok River to Colville River, north coast of Alaska. Width of line represents shoreline change envelope, or total shoreline change over analysis period, and distance between historical shorelines.

Table 7. Total barrier island area in Region 4, Sagavanirktok River to Colville River, north coast of Alaska, for each era and total change during analysis period, in square meters.

Island	1940s	2000s	2000s–1940s
Cross Island	622,868	634,507	11,639
Midway (Argo) Islands	35,115	0	-35,115
Midway (Reindeer) Islands	156,010	352,294	196,284
Stump Island	310,055	526,115	216,060
Egg Islands	133,226	102,494	-30,732
East Long Island	323,676	364,676	41,000
West Long Island	659,793	2,742,875	2,083,082
Cottle Island	928,741	0	-928,741
Bodfish Island	521,437	0	-521,437
Bertoncini Island	155,788	0	-155,788
Pingok Island	4,531,796	2,922,684	-1,609,112
Leavitt Island	0	426,882	426,882
Spy Islands	479,330	664,580	185,250
Thetis Island	523,600	531,084	7,484
TOTAL	**9,381,435**	**9,268,190**	**-113,245**

Sheltered Mainland-Lagoon Shoreline Change

The mainland coast of Region 4 is predominantly erosional (95 percent of transects), with an average shoreline change rate of -0.8 and range between -4.2 and +1.2 m/yr (table 5). The highest erosion rates are associated with inundation and loss of low-lying land between Milne and Oliktok Points. Notable rates of accretion were measured at Heald Point, Prudhoe Dock, and between Milne and Oliktok Points, where hardened shorelines were constructed to protect or support oil and gas related infrastructure, and on the northeastern facing sides of the headlands at Milne and Kavearak Points. Lower accretion rates, less than 0.3 m/yr, were measured at McIntyre, Beechey and Oliktok Points. Overall, shoreline change rates along the mainland coast were relatively consistent throughout Region 4 and there is no apparent differences in shoreline change rates that can be related to the presence or absence of barrier islands, nor their distance offshore of the mainland (table 5, fig. 33).

Heald Point to Point McIntyre (Prudhoe Bay)

The coastline of eastern Prudhoe Bay, from Heald Point to the Putuligayuk River, is predominantly low-lying coast (<2m) with higher bluffs (<5m) near Heald Point. There are relatively continuous but narrow (<10 m) beaches between Heald Point to about 4 km east of Putuligayuk River, where the land is low-lying (<1.5 m high) and fronted discontinuously with very narrow (<5 m wide) beaches. Along this low-lying stretch, brown, salt-killed tundra indicative of marine inundation is common. From the Putuligayuk River to Point McIntyre, the western Prudhoe Bay coastline is predominantly low bluffs (<2 m high) fronted by discontinuous, narrow beaches (<5m wide). In some places, the gravel pads associated with oil and gas infrastructure is less than 10 m from the actively eroding shoreline (fig. 34A). Low-lying, relatively wide beaches and barrier spits (~30 m wide) comprise the coast between West Dock and Point McIntyre (fig. 34B). Shoreline change rates along the mainland coast of Prudhoe Bay, between Heald Point and Point McIntyre, are dominantly erosional (97 percent of transects) with rates averaging -0.8 m/yr and ranging from -2.5 to +1.1 m/yr (table 5). The only significant accretion (greater than +0.3 m/yr) was measured at Heald Point and is associated with the artificially hardened shoreline associated with the oil and gas development.

Point McIntyre to Kuparuk River Delta

Between Point McIntyre and the Kuparuk River Delta the coast is low-lying (<1.5 m high) with low bluffs fronted by narrow (<10 m wide) beaches east of Fawn Creek (fig. 34C) and low to moderately-high bluffs (2–3 m high) with relatively wide (10–30 m wide) beaches between Fawn Creek and the Kuparuk Delta. Shoreline change rates along the mainland coast between Point McIntyre and the Kuparuk River Delta are dominantly erosional (96 percent of transects) with rates averaging -0.6 m/yr and ranging from -3.7 to +0.9 m/yr (figs. 32 and 33; table 5).

Kuparuk River Delta to Milne Point

From the west side of the Kuparuk River Delta to Milne Point, the coast is characterized by low-lying bluffs (<3 m) fronted by narrow beaches (<10 m wide) and scattered pocket beaches. Shoreline change rates along the mainland coast between the

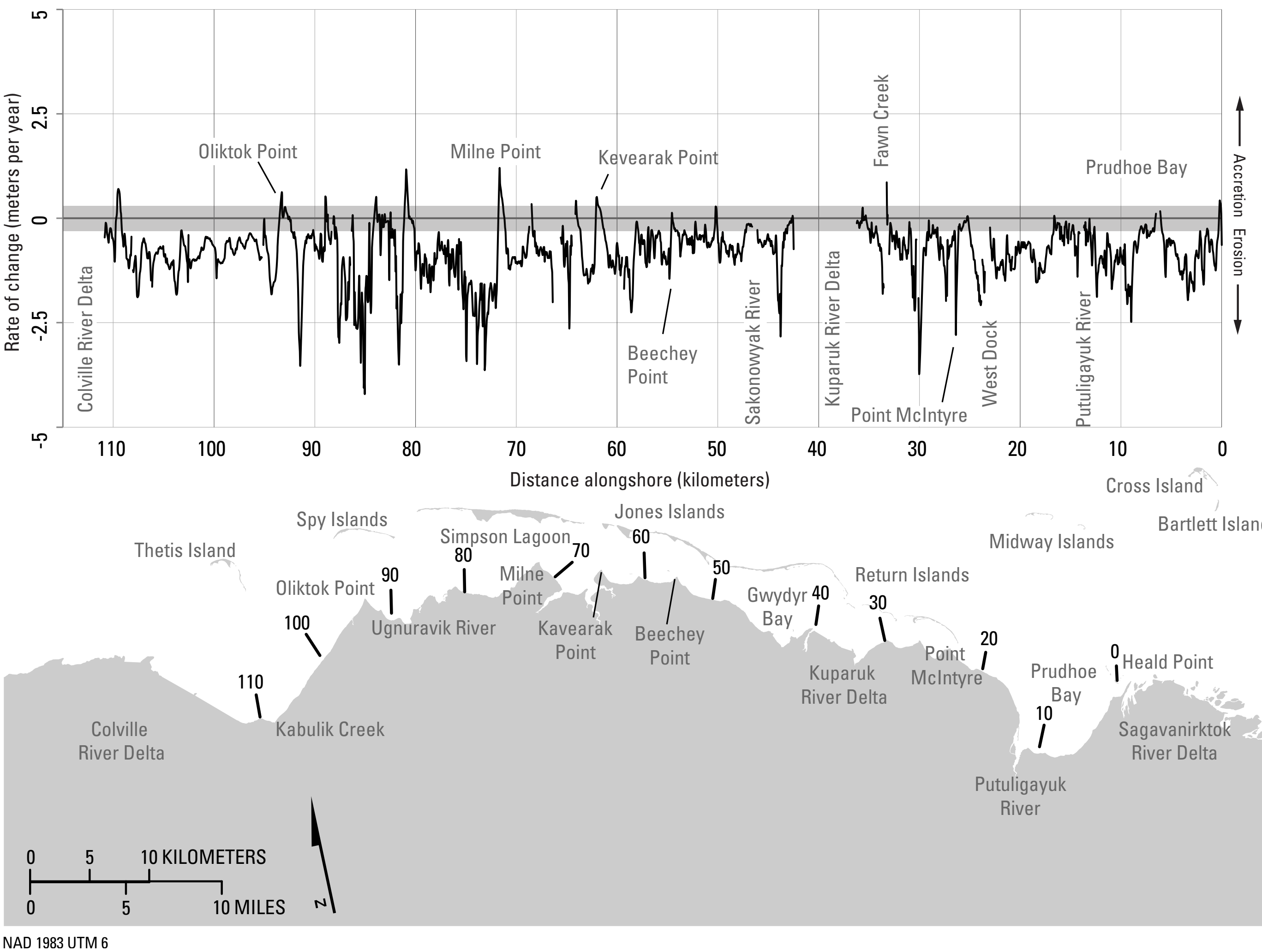


Figure 33. Top: Graph of shoreline change rates for sheltered mainland-lagoon coast of Region 4, Sagavanirktok River to the Colville River, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 4 indicating distances measured alongshore.

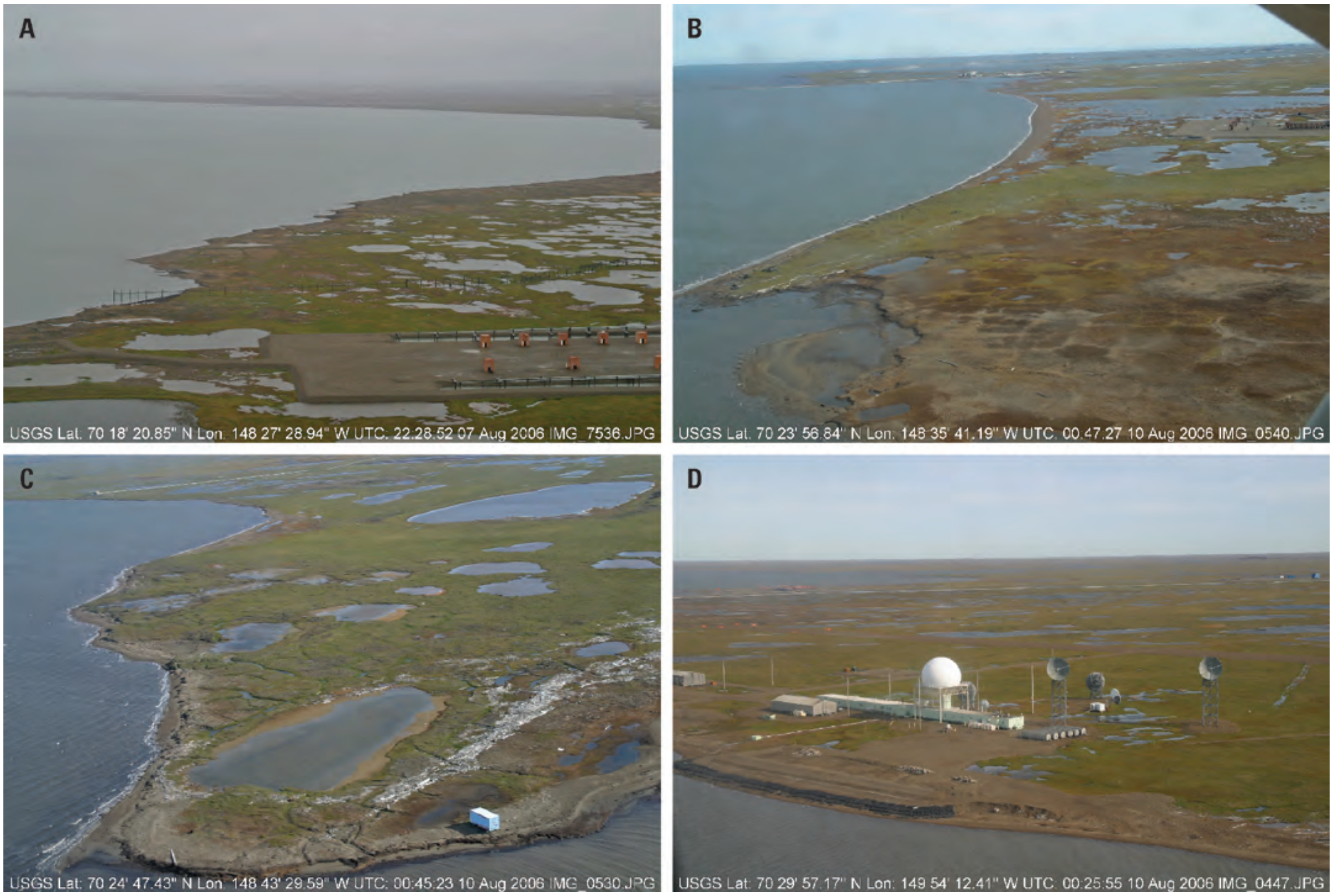


Figure 34. Aerial photographs showing typical examples of mainland coast of Region 4, Sagavanirktok River to Colville River, north coast of Alaska. *A*, Low-lying, Prudhoe Bay coastline; view to east. Note salt-killed (brown) tundra, thermokarst lakes, gravel pad, and oil and gas infrastructure located adjacent to shoreline. *B*, View from Point McIntyre east toward West Dock causeway. *C*, Low bluffs and perched beaches near Fawn Creek. Note large amount of wood debris on tundra surface indicating inundation or flooding extents. Large white container in foreground contains oil spill response supplies. *D*, The Oliktok Point Distant Early Warning (DEW) station. Note shore protection structures fronting the station. (All photographs from 2006; Gibbs and Richmond, 2009).

Kuparuk River Delta and Milne Point are dominantly erosional (94 percent of transects) with rates averaging -0.7 m/yr and ranging from -2.8 to +1.2 m/yr (table 5). The highest rates of shoreline change along this stretch of coast are associated with erosion of a deteriorating headland and former thermokarst lake near the Kuparuk River and erosion of the western side of the unnamed headland between Beechey and Kavearak Point. All four headlands along this section of coast show erosion on the northwest facing side and beach accretion on the northeastern facing sides (figs. 32 and 33).

Milne Point to Oliktok Point

The highest erosion rates along the mainland shoreline of Region 4 were measured between Milne Point and Oliktok Point. The coast is dominantly erosional (90 percent of transects) with shoreline change rates averaging -1.1 m/yr and ranging from -4.2 to +1.2 m/yr (table 5). This section of coast is characterized by low bluffs (<2 m high) with narrow (<10 m wide) beach and low-lying (<1.5 m), tapped thermokarst lake shorelines. Similar to the coastal reach between Kuparuk River Delta and Milne Point, erosion rates are relatively higher on the northwest-facing side of the headlands compared to the northeast-facing sides (figs. 32 and 33). Simpson Lagoon is relatively wider and the fronting barrier islands (Leavitt and Spy Islands) somewhat further offshore and less continuous than to the east. An oil and gas facility on the headland between Milne and Oliktok Points shows net accretion, although this may be the result of emplacement of a gravel pad and shore protection structures (fig. 34D).

Oliktok Point to Colville River Delta

The mainland coast between Oliktok Point and the Colville River Delta trends NE-SW and is characterized by low to moderately-high bluffs (<3 m high) segmented by drainages and fronted by relatively wide, continuous beaches (10–30 m wide).

Thetis Island is located about 9 km offshore to the northwest. Shoreline change rates along this section are dominantly erosional (98 percent of transects) with rates averaging -0.8 m/yr and ranging from -1.9 to +0.7 m/yr (table 5). Erosion rates are relatively uniform along this section of coast regardless of whether the back beach is relatively high tundra bluffs or low-lying land associated with thermokarst lakes and drainages.

Exposed Open-Ocean Shoreline Change

The exposed open-ocean coast of Region 4, comprised entirely of barrier islands, is predominantly erosional (66 percent of transects), averaging -1.6 m/yr and ranging between -14.7 and +7.0 m/yr (figs. 32 and 35; table 5). The highest rates of erosion are associated with the formation of inlets, particularly on the east and west ends of Pingok Island, and the southwesterly or landward migration of the islands, particularly Reindeer, Long, Stump, and Thetis Islands. The total barrier island area decreased by 113,245 m^2 during the study period, although individual islands show considerably different patterns of change (table 7). Differences in the geology and morphology of the barrier islands within Region 4 result in a complex pattern of shoreline changes that are discussed in detail below.

Cross Island

Cross Island, the easternmost island in the region, is low-lying (<2 m high) except for a 5-m high gravel pad built on the northwestern end of the island, and ranges in width between 50 and 300 m. The island is a popular location for whaling activities and there are also several cabins and structures located on the northwest end of the island. The island is mostly unvegetated except for some low-lying vegetation in the topographic lows on the northwest part of the island (figs. 36A and 36B). Between 1947 and 2006, Cross Island merged from two separate islands (Bartlett and Cross) into one continuous island, nearly 5 km in length, and increased in area by 11,639 m^2 (table 7). The

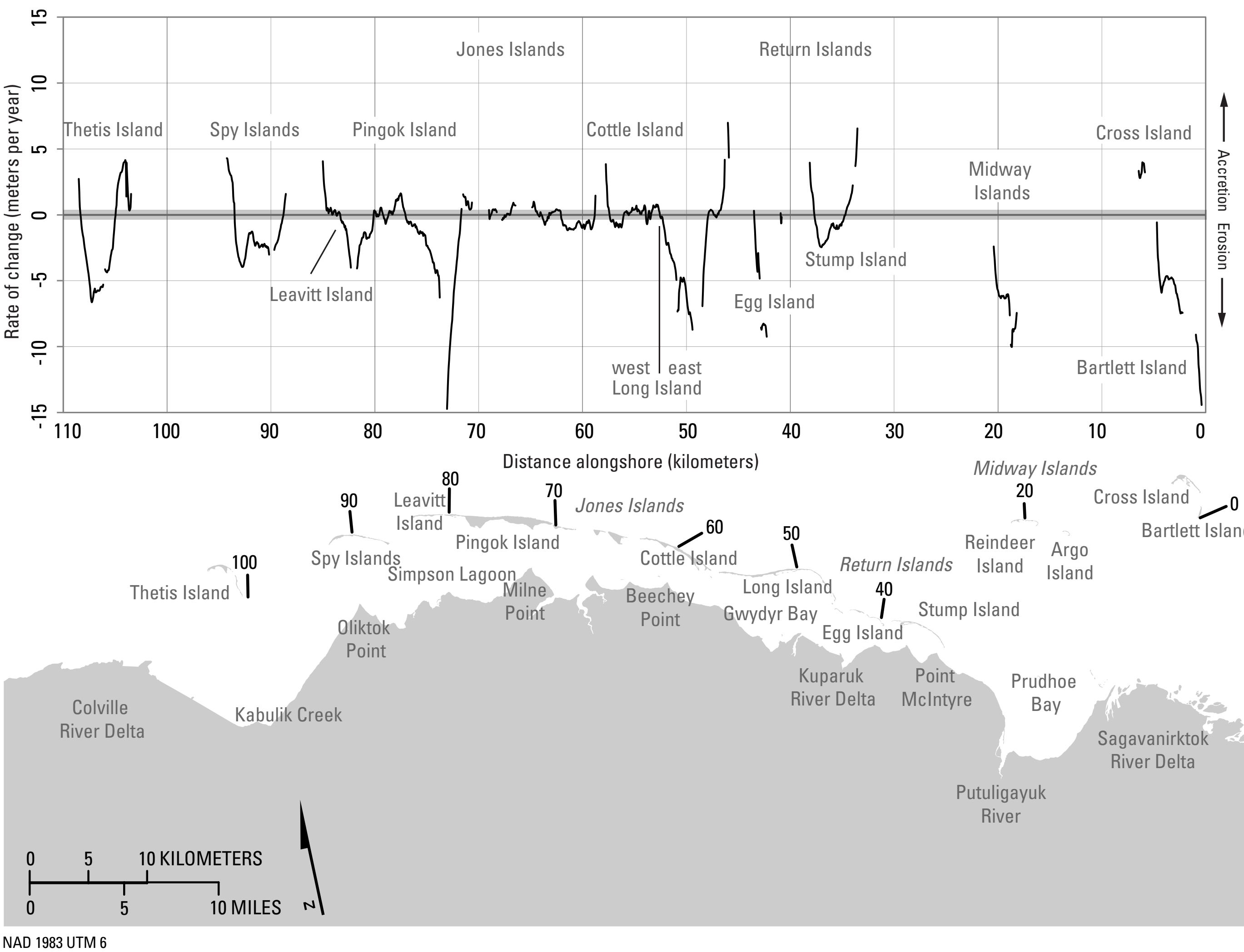


Figure 35. Top: Graph of shoreline change rates for exposed open-ocean coast of Region 4, Sagavanirktok River to Colville River, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 4 indicating distances measured alongshore.

Figure 36. Aerial photographs showing typical examples of the barrier island coast of Region 4, Sagavanirktok River to Colville River, north coast of Alaska. A, Bowhead whale bones at Cross Island. Note vegetation in low-lying areas, wood wrack, and steep scarp fronting open-ocean coastline. B, Cross Island, showing low-lying vegetation in back-barrier environment. C, Pingok Island, a remnant tundra island, with drained thermokarst lakes and thaw slump deposits on rapidly eroding eastern end of island. D, Spy Islands. Note well-defined scarp, wood debris on higher parts of island, and vegetation only in topographic lows. (All photographs from 2006; Gibbs and Richmond, 2009).

northwestern part of Cross Island prograded about 200 m to the north and extended about 250 m to the west while the southern end extended nearly 2 km to the south west and migrated landward approximately 400 m to the southwest. The open-ocean shorelines of Cross Island are erosional (81 percent of transects) with shoreline change rates between 1947 and 2006 averaging -4.7 m/yr and ranging from -14.4 to +4.0 m/yr (table 5), although the DSAS analysis does not account for the total accretion of land associated with the progradation and extension of the island.

Midway Islands

The Midway Islands, including Argo and Reindeer Islands, are low-lying (<1 m high), predominantly unvegetated islands with little wood wrack or debris deposits. A shoreline was not delineated for Argo Island in the 1997 dataset used in this area, and thus, shoreline change rates could not be determined for the island. An island was photographed in 2006 by Gibbs and Richmond (2009) about 700 m southwest Argo Island's 1947 footprint, suggesting the island does exist, but has migrated further than the extent of existing datasets. The Midway Islands, mapped as a single Reindeer Island in 1947, migrated up to up to 500 m (mean 329 m) to the southwest, extended about 1 km to the west, split into two islands (Reindeer and Argo), and increased in area by 161,168 m^2 (table 7). There is only a very small area of overlapping area of Reindeer Island in the 1947 and 2006 island footprints. The open-ocean shorelines of Reindeer Island are entirely erosional (100 percent of transects) with shoreline change rates averaging -6.6 m/yr and ranging from -10.0 to -2.4 m/yr (table 5), although the DSAS analysis does not account for the accretion of land associated with the westward extension of the island.

Stump, Egg, and Eastern Long Islands

Between Stump Island and the eastern part of Long Island where the orientation of the coast changes from northwest-southeast to east-west, the barrier islands are narrow (< 100 m wide), low lying (<2 m high), and unvegetated. Between 1947 and 2007, Stump Island extended nearly 2 km to the northwest, about 900 km to the southeast, and the central portion of the island migrated 150 m to the southwest. During the same time period, the Egg Islands segmented into numerous smaller islands, extended about 600 km to the west and migrated as much as 554 m to the southwest. The eastern part of Long Island segmented into at least four separate islands and portions migrated landward over 500 m. Some of the loss of the Egg Islands likely is responsible for a portion of the westward extension of Stump Island and eastward extension of Long Island. Shoreline change rates for this eastern part of the barrier chain average -1.8 m/yr and range between -9.2 and +7.0 m/yr (table 5), although DSAS rates do not include the extension of Stump nor eastern Long Island nor the loss of most of the Egg Islands (fig. 37B). The total area of Stump, Egg, and eastern Long Island increased by 226,328 m^2 between 1947 and 2007 (table 7).

West Long Island to Leavitt Island

From the eastern part of Long Island where the orientation of the coast changes from northwest-southeast to east-west to Leavitt Island, the barrier islands show a much more stable to accretionary shoreline change pattern during the study period compared to the islands to the east and west in Region 4 (fig. 37C). Long, Cottle, Bodfish, and Bertoncini Islands, mapped as four discrete islands on the 1947 T-sheets, merged into a single, 22 km long island connected by low-lying, narrow, barrier spits by 2004. Pingok Island, mapped as a 13 km long island in 1947, was breached at both ends, forming inlets resulting in considerable erosion and loss of land on the eastern end of Pingok Island and the formation of Leavitt Island in the west. The former Cottle, Bodfish, and Bertoncini Islands are recognizable as remnant tundra islands that are relatively wide (>100 m) and reach nearly 5 m high. These are well-vegetated and the shoreline is typified by low bluffs fronted by beaches. The barriers between the remnant tundra islands and west of Bertoncini Island are generally narrow (<100 m) and low-lying (<2 m), except along western Long Island where the seaward beach berms reach up to 3 m high and the maximum width of the island is about 300 m. These barrier islands are unvegetated, except along the historically stable areas of the island chain where some low-lying vegetation and wood debris deposits were observed. Pingok Island is a relatively large (8 km long in 2004), well-vegetated, tundra remnant island with a narrow, unvegetated, recurved western end. The eastern quarter of the island is characterized by high bluffs (up to 5 m high) fronted by narrow to no beach deposits, and tapped thermokarst lake shorelines (fig. 36C). The western three-quarters of the island includes low to high bluffs (generally less than 3 m) fronted by relatively wide beach deposits (up to 100 m wide). The eastern and western portions of Pingok Island experienced considerable erosion between 1947 and 2004 while the central portion remained stable or accreted. In contrast to many of the other barrier islands in the study area, Pingok Island also experienced extensive erosion along the lagoon coast. In the 2004 imagery, Leavitt Island is just over 4 km long and recurved at both ends. The island is low-lying (<2 m), narrow (<200 m), and mostly unvegetated. The position and width of the central portion of the island remained relatively stable during the study period, whereas the west end of the island extended westward about 1.5 km and the eastern end migrated over 200 m landward in response to the formation of the inlet between Leavitt and Pingok Island. Some low-lying vegetation and wood debris were observed in the stable, central portion of the island.

Aside from the accretion of new land between Long, Cottle, Bodfish and Bertoncini Islands, the westward extension of Bertoncini Island and Leavitt Islands, and the erosion associated with the formation of the inlets bounding Pingok Island, the barrier island chain from western Long Island to Leavitt Island experienced little change in shoreline position or barrier morphology between 1947 and 2004, with generally less than 100 m of change in shoreline position. Shoreline change rates along the exposed open-ocean coast of the barrier islands between western Long Island and Leavitt Island average -0.7 m/yr and range from -14.7 to +4.1 m/yr (table 5), although much of the accretion of land is not accounted for in the DSAS analysis due to the lack of overlapping shorelines. The total island area between western Long Island and Leavitt Island decreased by 705,114 m^2 between 1947 and 2007, primarily as a result of the considerable loss of Pingok Island land area (table 7).

Spy Islands

The Spy Islands (two islands in 2004) are approximately 7 km long and low-lying, less than 2 m high. The islands are unvegetated except for low-lying vegetation near the stable and accreting area at the eastern and western extents of the island, where wood debris is also present (fig. 36D). The island varies in width between 15 and 350 m, and is widest on the western end. Between 1947 and 2004, the Spy Islands (one island in 1947) segmented into two islands, extended about 1200 m to the southwest and 270 m to the southeast. The central portion of the island migrated 224 m landward (to the southwest) and the western end accreted approximately 245 m. Shoreline change rates for the open-ocean coast of the Spy Islands average -1.4 m/yr and range from -4.0 to +4.3 m/yr (table 5), although the DSAS rates do not account for the extension of the island to the west. The total island area increased by 185,250 m^2 between 1947 and 2007 table 7).

Thetis Island

Thetis Island is approximately 6 km long and low-lying, generally less than 2 m high, although a gravel pad at the western end increases the maximum island elevation to approximately 3 m high. The island is unvegetated and varies in width between 25 and 275 m and is widest on the western end. Between 1947 and 2004, the two Thetis Islands mapped in 1947 merged into a single island. The island extended 800 m to the west and 730 m to south. The northwest portion of the island migrated landward nearly 800 m and the southeastern portion of the island extended nearly 300 to the northeast. Shoreline change rates for the open-ocean coast of Thetis Island average -1.8 m/yr and range from -6.6 to +4.1 m/yr (table 5), although the DSAS rates do not account for the extension of the island to the west and south. The total island area increased by 7,484 m^2 between 1947 and 2007 (table 7).

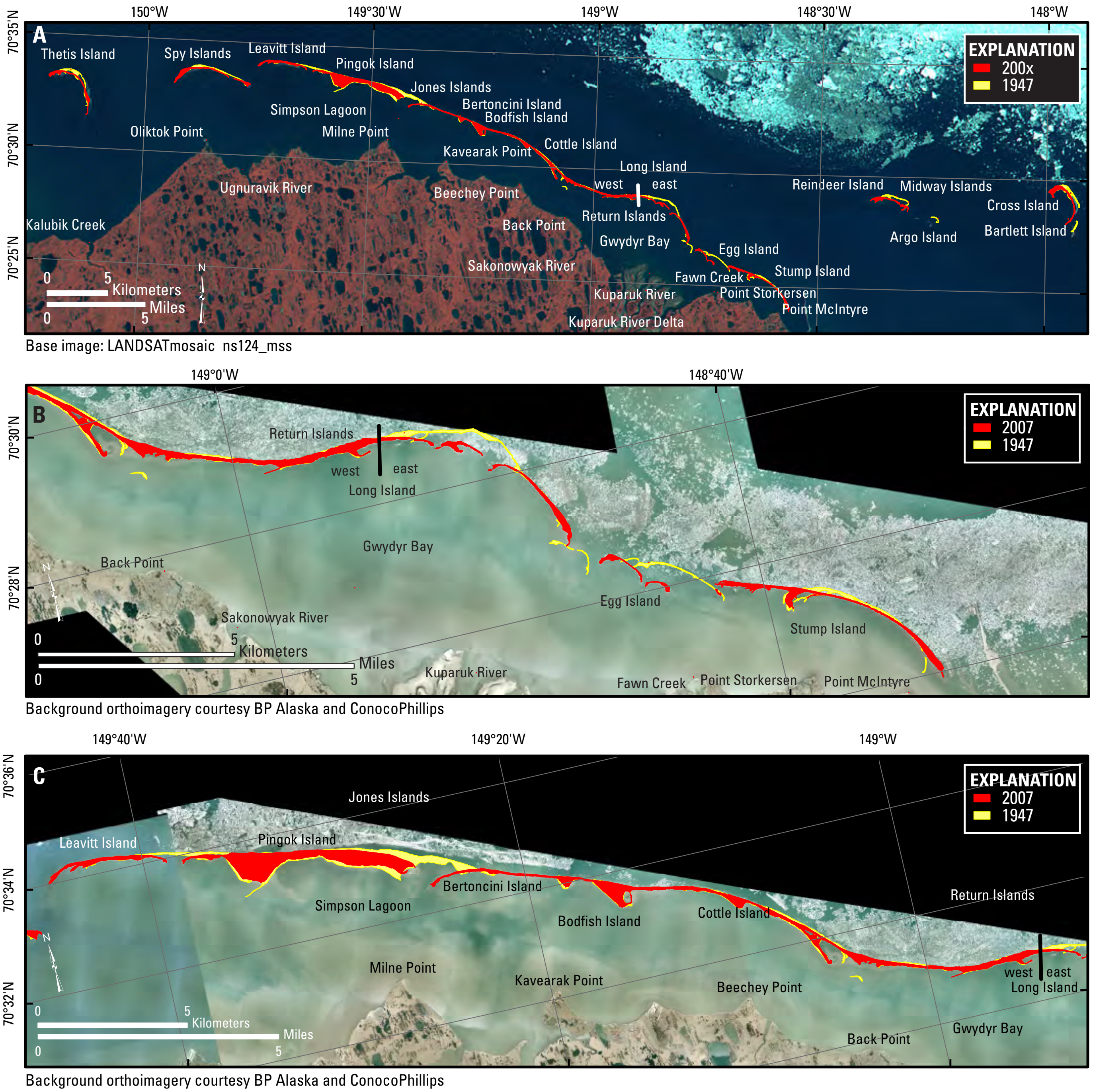


Figure 37. Detailed maps showing shoreline change to the barrier island chain in Region 4, Sagavanirktok River to Colville River, north coast of Alaska. A, All barrier islands in Region 4 showing the change in island footprint between 1947 and 2006/2007. B, Stump Island to west Long Island. C, West Long Island to Leavitt Island. Note deviation from north of the maps in figures B and C.

(5) Colville River to Cape Halkett

Introduction

Region 5 extends approximately 100 km along the west coast of Harrison Bay between the Tingmeachsiovik River on the western side of the Colville River Delta and Cape Halkett. The region is part of both the NPR-A and TLSA. The coast is undeveloped aside from the Kogru Intermediate DEW site, which closed in 1963 and was located on the Kogru River and about 2 km inland from the open coast. There are no permanent villages.

The coast of Region 5 faces northeast, trends northeast to southwest, and is relatively sheltered from dominant wave energy from the northwest. Several, small remnant tundra islands are present south of Atigaru Point, south of Garry Creek, and the larger Eskimo Islands near the mouth of the Kogru River. The remaining mainland coast is segmented by two large rivers (Kalikpik and Kogru), Garry Creek, and a large embayment about half-way between Garry Creek and Cape Halkett (fig. 38). The coastal plain is dominated by thermokarst lakes, but is markedly different north and south of the Kogru River, with relatively small thermokarst lakes south of the Kogru River and larger, elongated (northwest-southeast) lakes north of the Kogru River. InSAR elevation data shows a distinct change in the regional coastal slope around the Kogru River, where south of the river, elevations reach up to 15 m within 4 km of the coast compared to a distance greater than 8 km to the north (fig. 39). Beaches along this section of coast are primarily associated with tapped thermokarst lakes and more rarely fronting tundra bluffs, where they are typically narrow (<10 m wide), when present.

Shoreline change rates were calculated using 1947 T-sheets and 2002 DOQQ imagery (table 2; fig. 4). Shoreline change rates were not calculated for the remnant tundra islands. All rates presented are for the exposed, open-ocean, mainland coast. The coast of Region 5 is predominantly erosional (92 percent of transects) and has some of the lowest rates of shoreline change in the study area, with shoreline

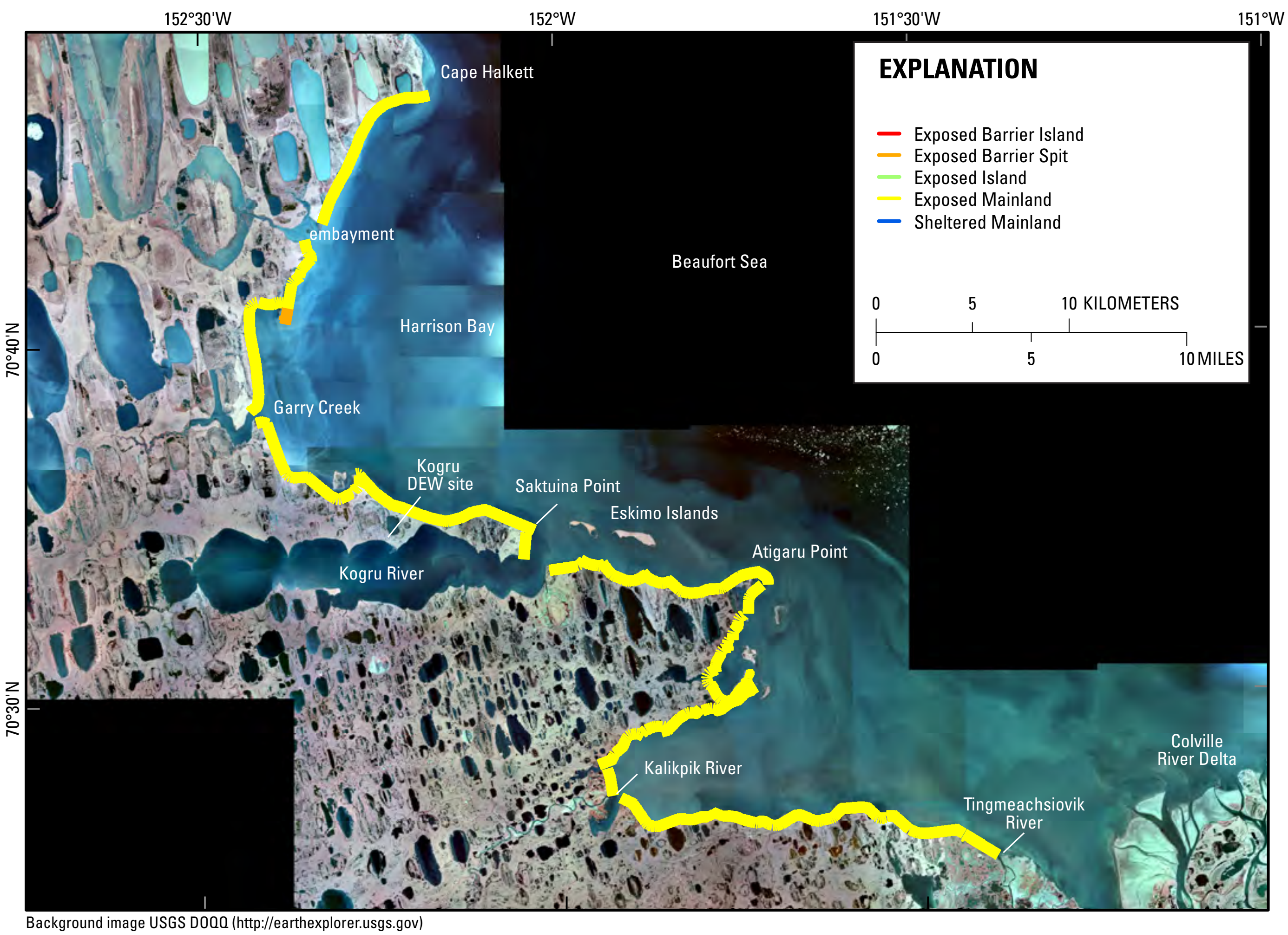


Figure 38. Map showing color-coded shoreline types within Region 5, Colville River to Cape Halkett, north coast of Alaska.

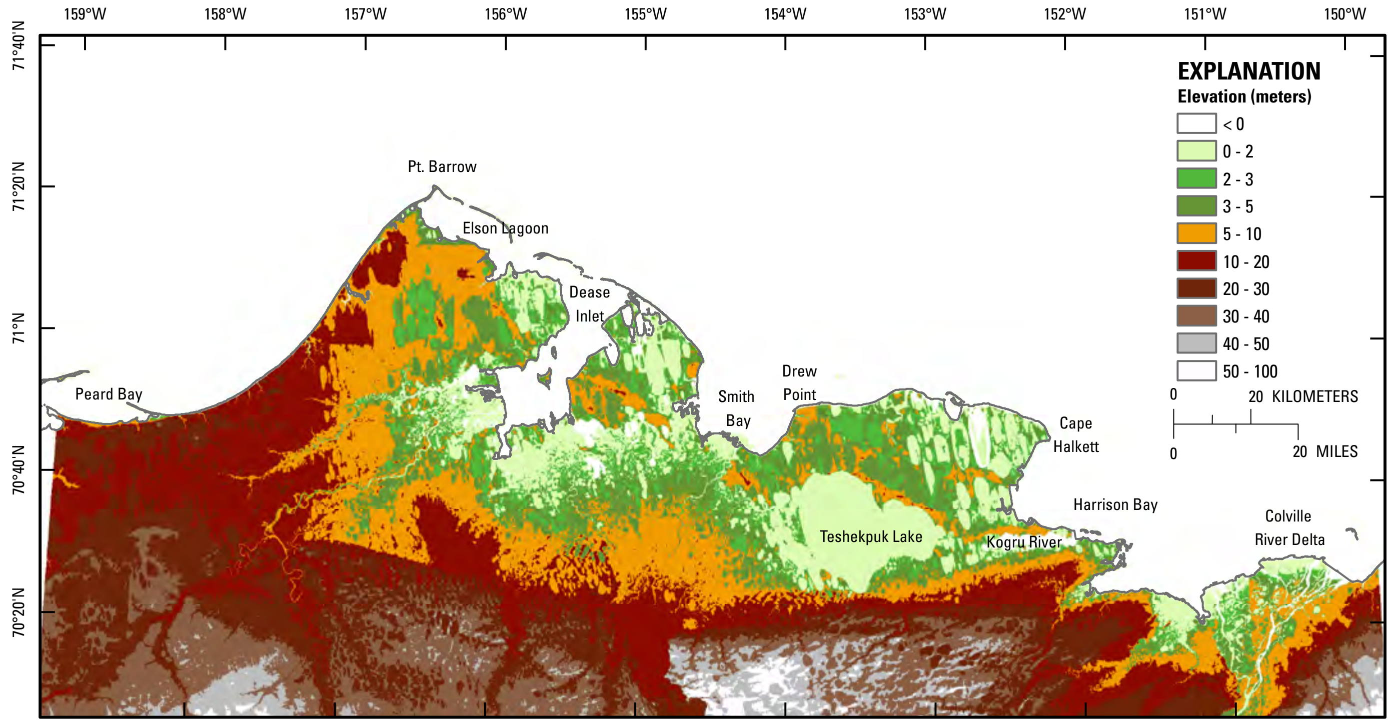


Figure 39. Coastal elevation map derived from Interferometric Synthetic Aperture Radar data for parts of Regions 5–9, Colville River to Icy Cape, north coast of Alaska. Note distinct differences in elevation of coastal plain north and south of Kogru River and along Chukchi Sea coast.

change rates averaging -1.1 m/yr and ranging from -9.6 to +5.0 m/yr (figs. 40 and 41; table 5). Erosion rates are generally higher west of Atigaru Point with highest erosion rates associated with an eroded spit about 5 km north of Garry Creek (figs. 40 and 41). There are only a few areas of significant accretion in the region, including the spit at the embayment between Garry Creek and Cape Halkett, just east of Garry Creek, at the Kalikpik River, and individual transects between the Tingmeachsiovik River and Atigaru Point.

Shoreline morphology, geology, and patterns of shoreline change are considerably different north and south of the Kogru River. Whereas both sections are predominantly erosional, average erosion rates are over 3 times higher north of the Kogru River compared to south (-1.7 and -0.5 m/yr, respectively; table 5). The bluffs between the Tingmeachsiovik River and the Kogru River appear in aerial photographs to be sandier (lighter color) and no visible ice was observed in the bluffs, suggesting a low ice content, which may be partly responsible for the observed lower erosion rates.

Exposed Open-Ocean Shoreline Change

Tingmeachsiovik River to Kalikpik River

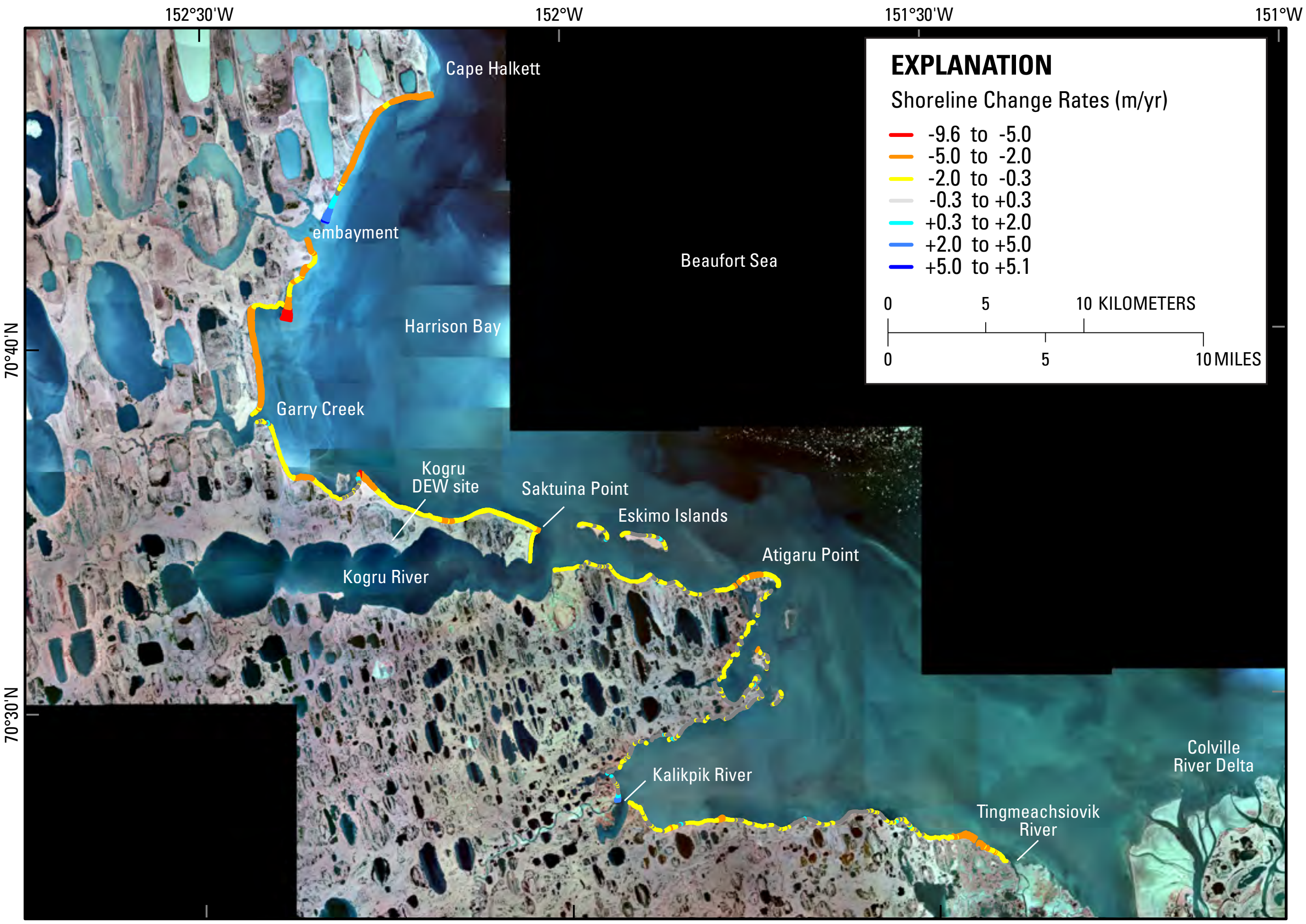
At the southeastern boundary of Region 5, between the Tingmeachsiovik and Kalikpik Rivers, the coast is dominated by low-lying, vegetated marsh with no beaches, that transitions to moderately-high to high bluffs (3–10 m high) fronted by narrow beaches (< 10 m wide) approaching the Kalikpik River (figs. 42A and 42B). Shoreline change rates for this stretch are predominantly erosional (93 percent of transects; average, -0.7 m/yr; range, -4.7 to +1.1 m/yr) (table 5), with the highest rates measured in the low-lying marsh areas adjacent to the Tingmeachsiovik River.

Kalikpik River to Atigaru Point

From the Kalikpik River to Atigaru Point the coast is dominantly low-lying tundra bluffs, generally less than 2 m high, but reaching up to 6 m high in places. Beaches are rare, except fronting the higher bluffs. The coastline here trends southwest to northeast, and is sheltered from nearly all incident wave energy, however, for this analysis it is still considered open-ocean mainland coast because there are no protective barrier islands. The reach is erosional (81 percent of transects) with an average shoreline change rate of -0.2 m/yr (range, -1.6 to +3.8 m/yr) (table 5), which is below the analytical uncertainty on individual transects. This reach has some of the lowest shoreline change rates measured in the study area.

Atigaru Point to Kogru River

Between Atigaru Point and the Kogru River, the coast is dominated by high bluffs (<5 m high) fronted by relatively wide beaches (10–20 m). In the 2002 imagery, the low-lying (2 m high) headland near Atigaru Point is separated



Background image USGS DOQQ (http://earthexplorer.usgs.gov)

Figure 40. Map showing the color-coded shoreline change rates in Region 5, Colville River to Cape Halkett, north coast of Alaska. Width of line represents shoreline change envelope, or total shoreline change over analysis period, and distance between historical shorelines.

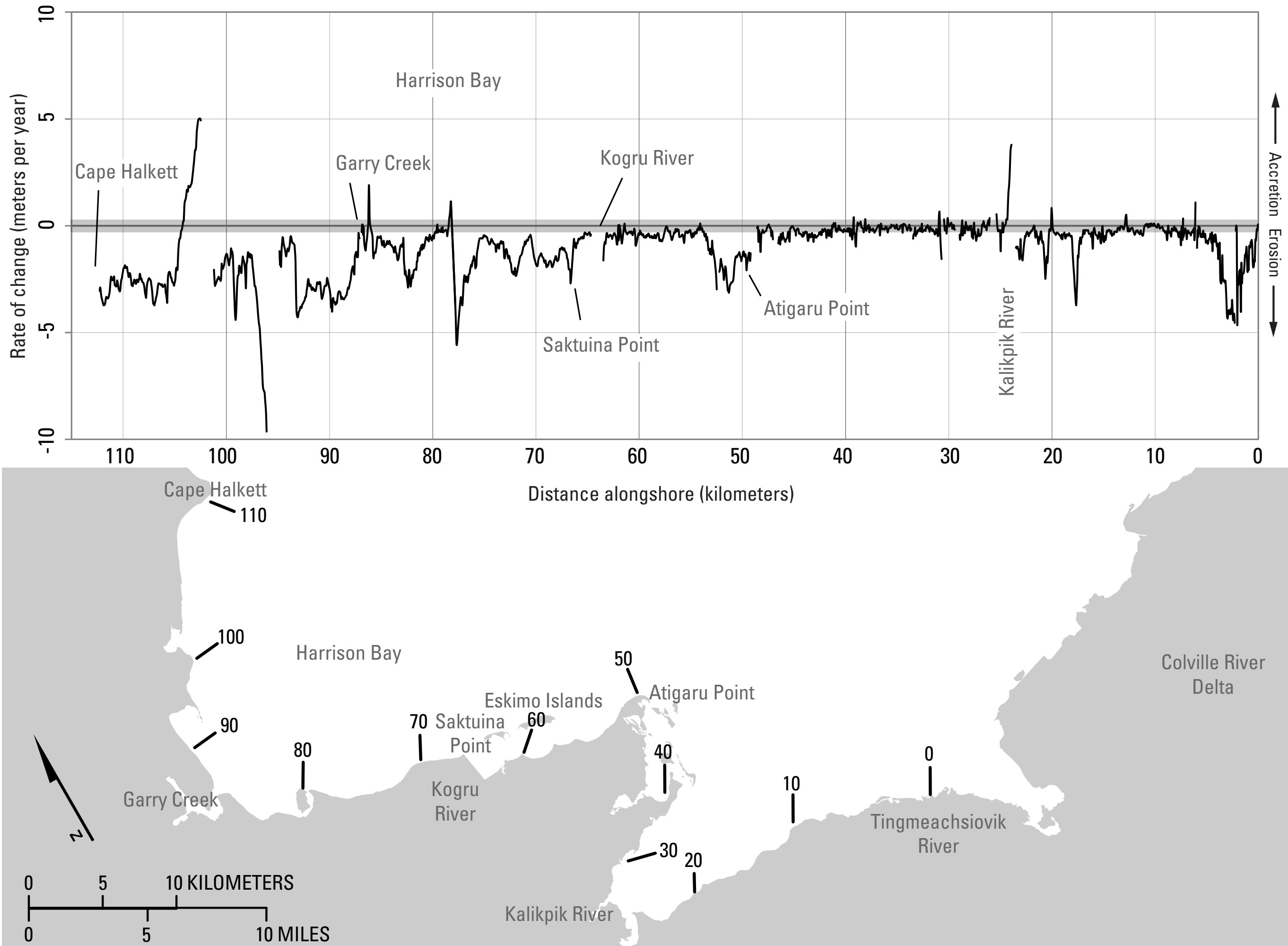


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Figure 41. Top: Graph of shoreline change rates for exposed open-ocean coast of Region 5, Colville River to Cape Halkett, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 5 indicating distances measured alongshore.

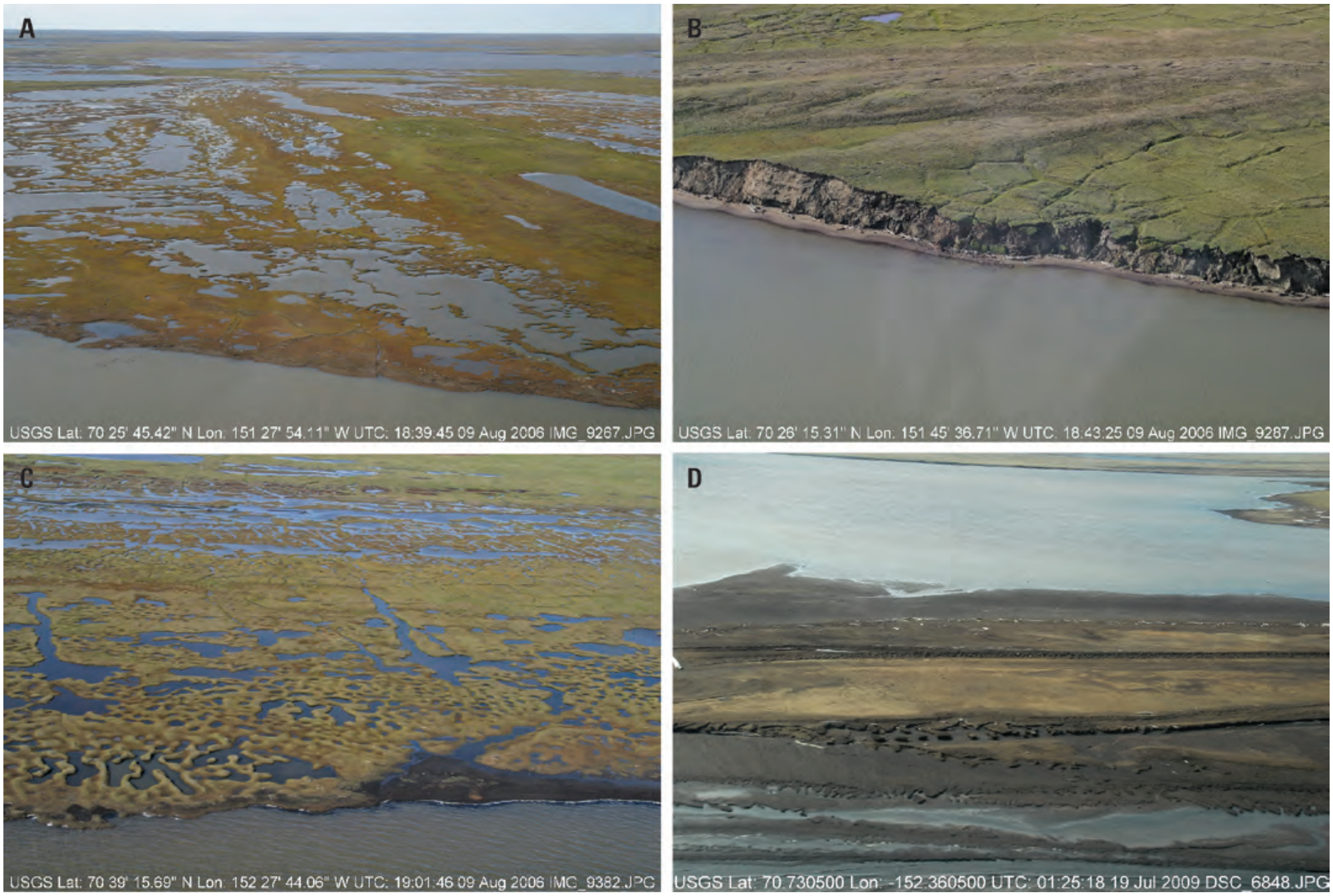


Figure 42. Aerial photographs showing typical examples of the coast of Region 5, Colville River to Cape Halkett, north coast of Alaska. A, Low lying marsh/tundra deposits near Tingmeachsiovik River. B, High bluffs (8 m high) near the Kalikpik River. C, Inundated tundra with an irregular pattern near Garry Creek. D, One of the few areas of deposition in Region 5, an accretional spit deposited on northern side of embayment between Garry Creek and Cape Halkett. This entire feature accreted since 1947. (Photographs A,B,C taken in 2006, and D taken in 2009; Gibbs and Richmond, 2009, 2010).

from the adjacent mainland by a narrow channel, but for this analysis it is still considered open-ocean mainland coast. The remnant tundra Eskimo Islands are just offshore the mouth of the Kogru River and provide some protection from incident wave energy to the adjacent mainland. This reach is dominantly erosional (98 percent of transects) with an average shoreline change rate of -0.8 m/yr and a range of -3.1 to +0.1 m/yr (table 5),with the highest erosion rates measured near Atigaru Point.

Kogru River to Cape Halkett

North of the Kogru River, from Saktuina Point to about 5 km southwest of Garry Creek, the coast is characterized by relatively high bluffs (<5 m high) and narrow beaches (<10 m wide). Segregated ice layers can be seen in the bluff faces, in contrast to the bluffs to the south and east (Gibbs and Richmond, 2009, 2010). From about 5 km southwest of Garry Creek and continuing north to Cape Halkett, the coast comprises numerous low-lying (< 1 m), tapped thermokarst lakes, fronted by narrow beaches, and few moderately-high bluffs (<3m high). Discontinuous beaches fronting the bluffs are typical. There are well-developed ice-wedge polygons in the tundra at several places along this section of coast. North of Garry Creek, there is an interesting form of patterned tundra observed only in this area, very low lying (< ~2 m) inundated and irregular tundra surface intermittently fronted by narrow fine-grained beaches (fig. 42C). The reach is dominantly erosional (94 percent of transects) with an average shoreline change rate of -1.7 m/yr and a range of -9.6 to +5.0 m/yr (table 5).

The highest average (and total) erosion rates (100 percent of transects) in this region were measured in the section between Garry Creek and the embayment one-half way between Garry Creek and Cape Halkett (average, -2.7; range, -9.6 to -0.3 m/yr) associated with an eroded spit. The highest accretion rates (up to +5.0 m/yr) were measured between the embayment and Cape Halkett, associated with an accreted spit (table 5; figs. 41 and 42D).

(6) Cape Halkett to Drew Point

Introduction

Region 6 extends approximately 70 km between Cape Halkett and Drew Point and includes some of the most rapidly eroding coastline in the world (Reimnitz and others, 1985, 1988; Mars and Houseknecht, 2007; Jones and others, 2008, 2009a and b). The coast is within the NPR-A and marks the seaward boundary of the Teshekpuk Lake Special Area. The region is undeveloped and uninhabited aside from the Lonely DEW site that was deactivated in 1990 and closed in 2007. Cleanup and site remediation is ongoing. There are also numerous oil and gas exploration wells along this coast that are threatened by coastal erosion.

This coastal stretch trends nearly east to west and includes primarily exposed mainland coast but also the sheltered mainland coast of Pogik Bay, an exposed barrier island fronting Pogik Bay, and a sheltered remnant tundra island between the two, hereafter referred to here as Pogik Island (fig. 43). The coastal plain along this stretch of coast is dominated by large, elongated thermokarst lakes, with much of the land surface affected by thermokarst lake processes (Hinkel and others, 2005). The coast is generally very low-lying (<3 m) except for several short segments of higher coastal bluffs between Cape Halkett and Pitt Point, and a relatively continuous stretch between McLeod and Drew Points, where coastal bluffs reach up to 6 m high (figs. 39, 44A and 44F). Coastline features also include unvegetated, recently tapped thermokarst lakes, vegetated former lake basins, and vegetated tundra uplands not affected by thermokarst lake activity (Jones and others, 2009a) (fig. 44). Much of the region is vulnerable to coastal inundation as evidenced by the presence of brown, salt-killed tundra and wood wrack deposited far inland (fig. 44D). Beach and barrier spit deposits are relatively common along this stretch of coast but tend to be low-lying and laterally discontinuous. There are many stretches of coast with actively eroding bluffs fronted by little or no beaches. Pogik Bay appears to be a remnant tapped thermokarst lake with both tundra and barrier islands at the entrance to the bay.

Shoreline change rates were calculated using 1947 T-sheets and 2002 DOQQ imagery (table 2; fig. 4). Numerous small shoals and barrier islands present between Pogik Bay and Cape Halkett were not considered part of the primary

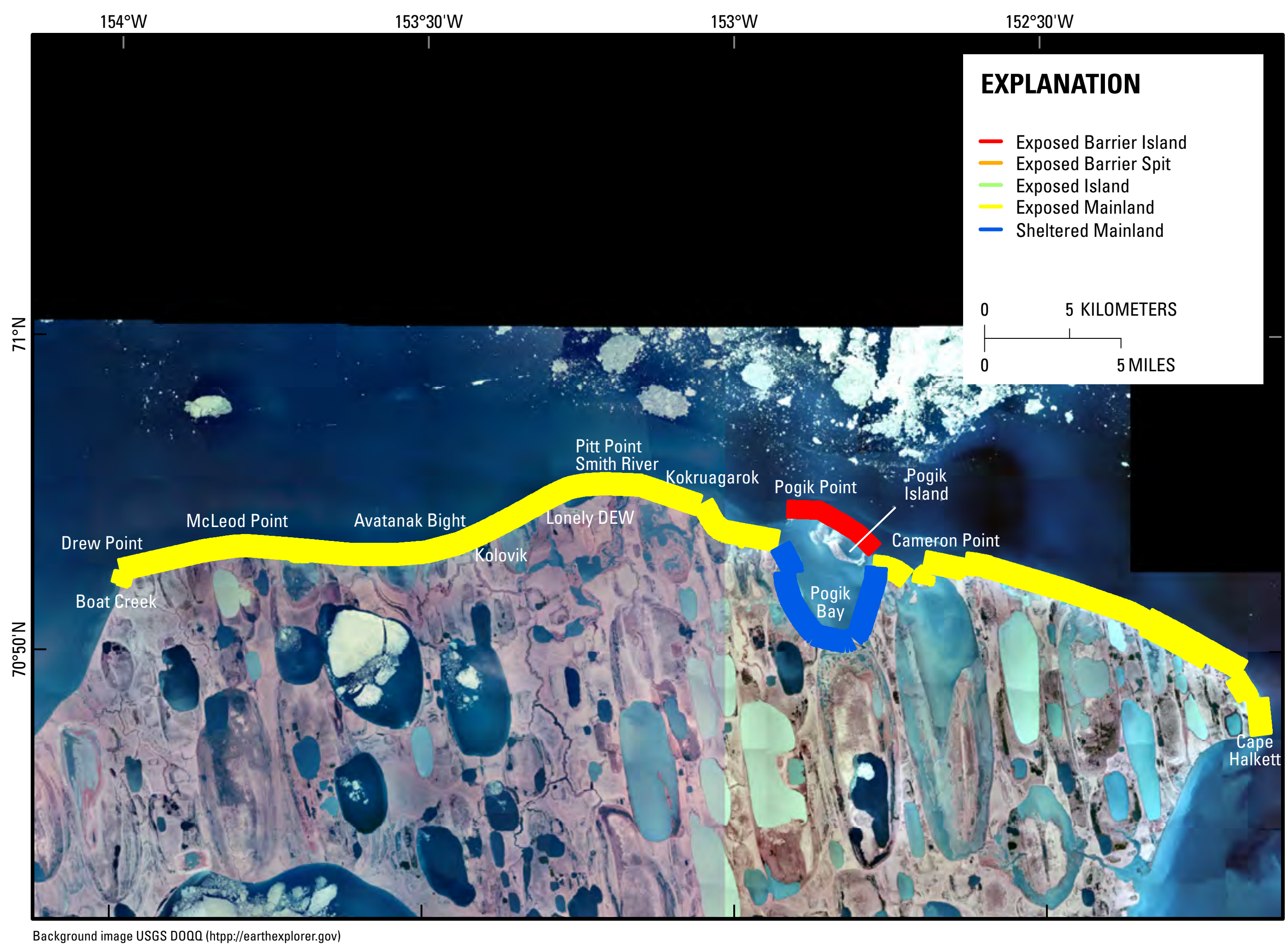


Figure 43. Map showing color-coded shoreline types within Region 6, Cape Halkett to Drew Point, north coast of Alaska.

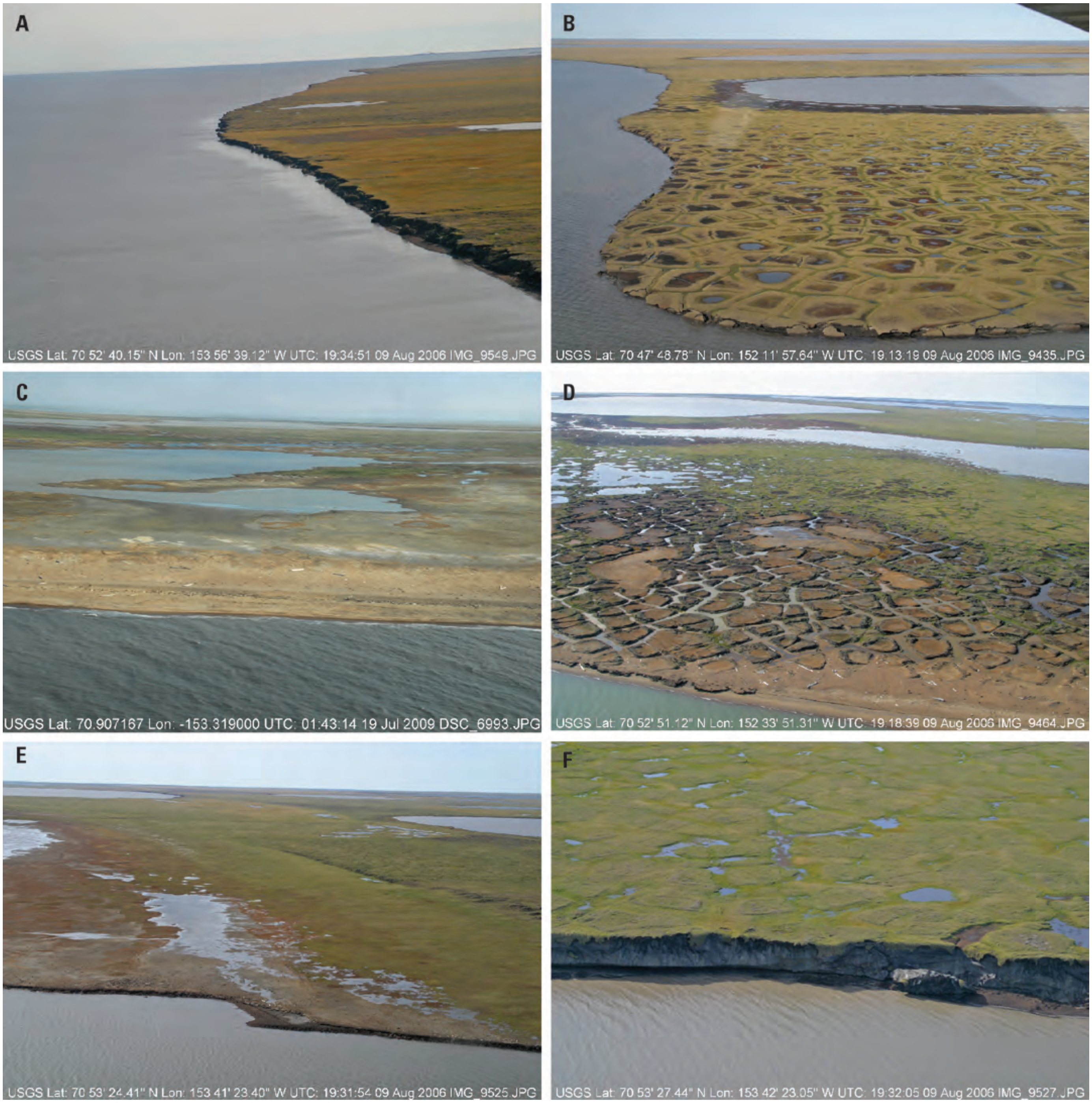


Figure 44. Aerial photographs showing typical examples of coast of Region 6, Cape Halkett to Drew Point, northern Alaska. A, Overview photograph of Drew Point showing about 6-m high bluffs, tundra upland and vegetated former lake basin, view to the east. B, Patterned ground near Cape Halkett, view to southwest. C, Recently tapped thermokarst lake west of Lonely, view to south. D, Degrading polygonal tundra showing evidence of inundation of low-lying ground including brown, salt-killed tundra and overwash of sediments, and wood debris just east of Cameron Point, view to south. E, Partially vegetated tapped lake, view to south. F, High bluffs near McLeod Point. Note high ice content in bluffs, themoerosional niche at base of bluffs, overhanging tundra, and lack of a fronting beach. (Photographs A,B,D,E,F taken in 2006, and C taken in 2009; from Gibbs and Richmond, 2009, 2010).

shoreline and were excluded from the analysis. In order to maintain consistency in this study and evaluating only exposed open-ocean and sheltered mainland-lagoon shorelines, Pogik Island was also not included in average shoreline change rate calculations presented here, however, shorelines, baselines, and transects are included in the accompanying GIS report (Gibbs and others, 2015) and historical changes are summarized in table 5.

The coast of Region 6 is predominantly erosional (90 percent of transects) with combined shoreline change rates for both the exposed open-ocean and sheltered shorelines averaging -6.3 m/yr. The maximum erosion (-18.6 m/yr) and accretion (+10.9 m/yr) rates within the entire study area were measured within Region 6 (fig. 45; table 5). The average shoreline change rate along exposed open-ocean shorelines (mainland coast and barrier island) is considerably higher (-7.1 m/yr) compared to the sheltered shorelines of Pogik Bay (-0.5 m/yr) or Pogik Island (-0.3 m/yr) (table 5).

Sheltered Coast Shoreline Change

The sheltered shorelines in Region 6 along the mainland coast of Pogik Bay are overall erosional (62 percent of transects) with shoreline change rates averaging -0.5 m/yr and ranging between -5.7 and +10.9 m/yr (table 5). The highest rates of accretion in the study area were measured on the northwest coast of Pogik Bay, where the shoreline prograded nearly 600 m between 1947 and 2002 (figs. 45 and 46).

Pogik Island eroded along both the north and south coasts of the central part of the island and the southeast tip remained relatively stable. The apparent accretion on the northeast side of the island may reflect true aggradation of the mudflats mapped in the 1947 T-sheets, but may also be a result of defining the boundary of intertidal to subtidal lands as supratidal deposits when digitizing the shoreline, which is certainly possible along this very low-lying coastal environment.

Figure 45. Map showing the color-coded shoreline change rates in Region 6, Cape Halkett to Drew Point, north coast of Alaska. Width of line represents shoreline change envelope, or total shoreline change over analysis period, and distance between historical shorelines.

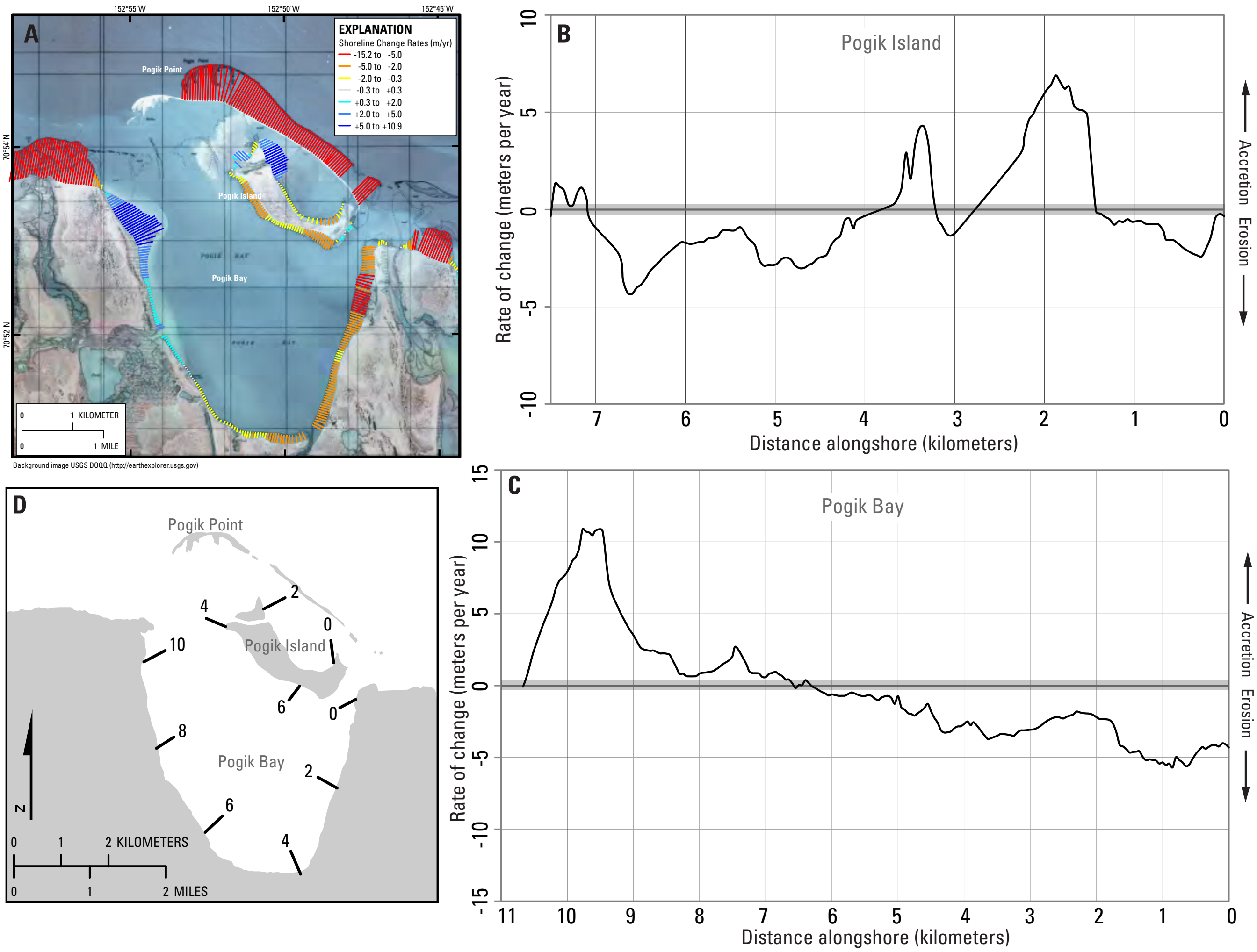


Figure 46. Maps and graphs showing shoreline change rates for Pogik Bay and neighboring coastline within Region 6, Cape Halkett to Drew Point, northern Alaska. A, Map showing the color-coded shoreline change rates and shoreline change envelope, or total shoreline change over analysis period for exposed and sheltered coastlines. Accretion measured at northwest part of Pogik Bay (>10.5 m/yr) is the highest measured in the study area. B, Plot of shoreline change rates on Pogik Island, and C, within Pogik Bay. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. D, Map of coast of Pogik Bay indicating distances measured alongshore in C and D.

Exposed Open-Ocean Shoreline Change

Open-ocean shorelines in Region 6 are predominantly erosional (94 percent of transects), with average shoreline change rates of -7.1 m/yr and a range of -18.6 to +7.3 m/yr (figs. 45 and 47; table 5). The highest erosion rates in the study area (>18 m/yr) were measured near Cameron Point, where over 1 km of land has eroded between 1947 and 2002. Much of the eroding land is low-lying and presumably composed mostly of ice-rich, fine-grained sediment so despite high erosion rates, little sediment is being added to the system to create a protective coastal buffer (beach). Only 6 percent of transects along the open-ocean coast are accretional and are limited to an area just north of Cape Halkett, where a spit has been accreting southeast into Harrison Bay, west of Cameron Point, near the abandoned site of Kolovik, and west of Drew Point, where a headland is accreting southeastward into Smith Bay. A remarkably stable section of coast between Lonely and Kolovik has only eroded on average about 65 m between 1947 and 2002 (figs. 45 and 47).

The barrier fronting Pogik Bay migrated 300–700 m to the southwest and extended about 1 km to the west (average rate of change, -8.8 m/yr) (table 5). Nearby shoals, islands, and mudflats present in 1947 mostly disappeared by 2002.

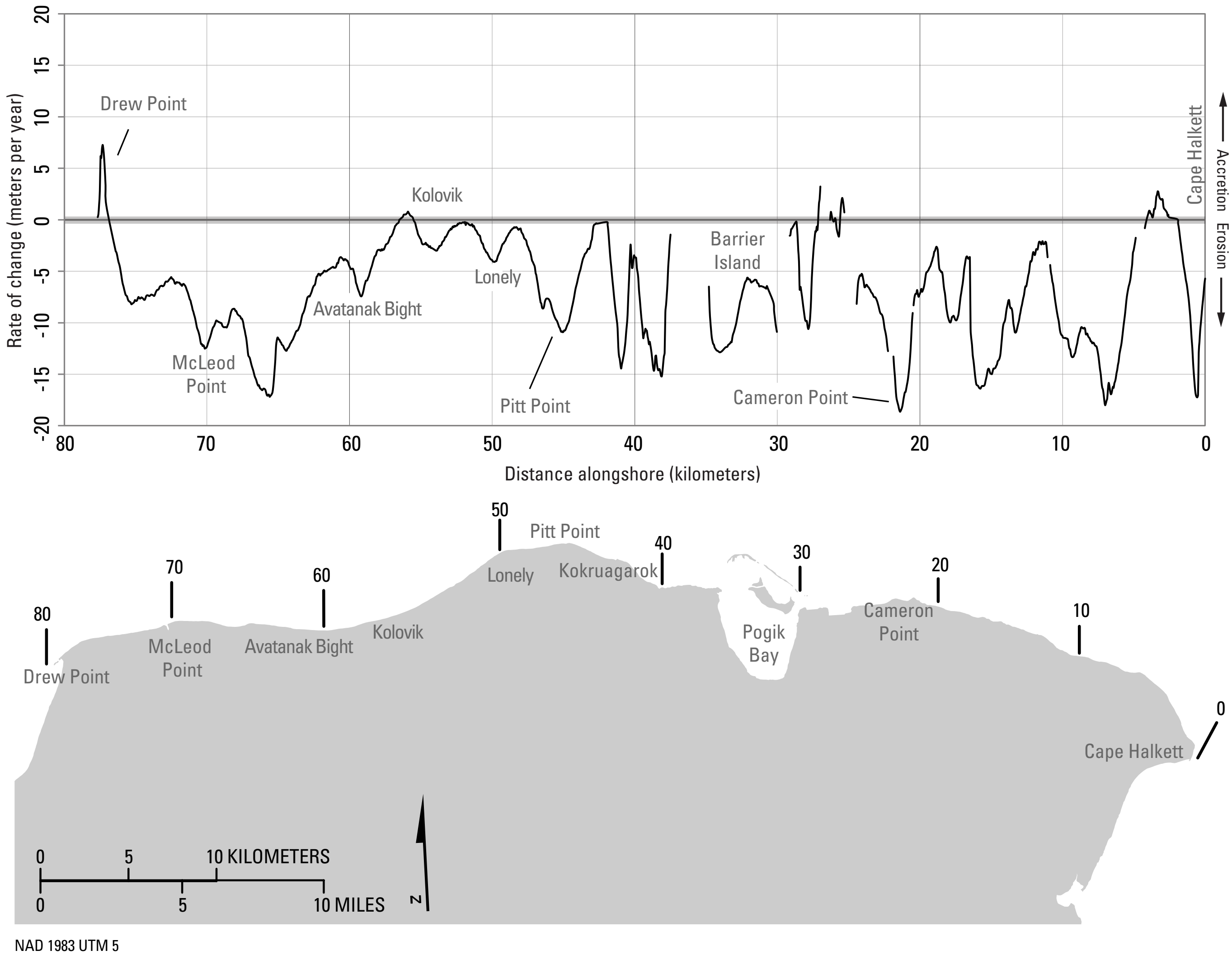


Figure 47. Top: Graph of shoreline change rates for exposed open-ocean coast of Region 6, Cape Halkett to Drew Point, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 6 indicating distances measured alongshore.

(7) Drew Point to Dease Inlet

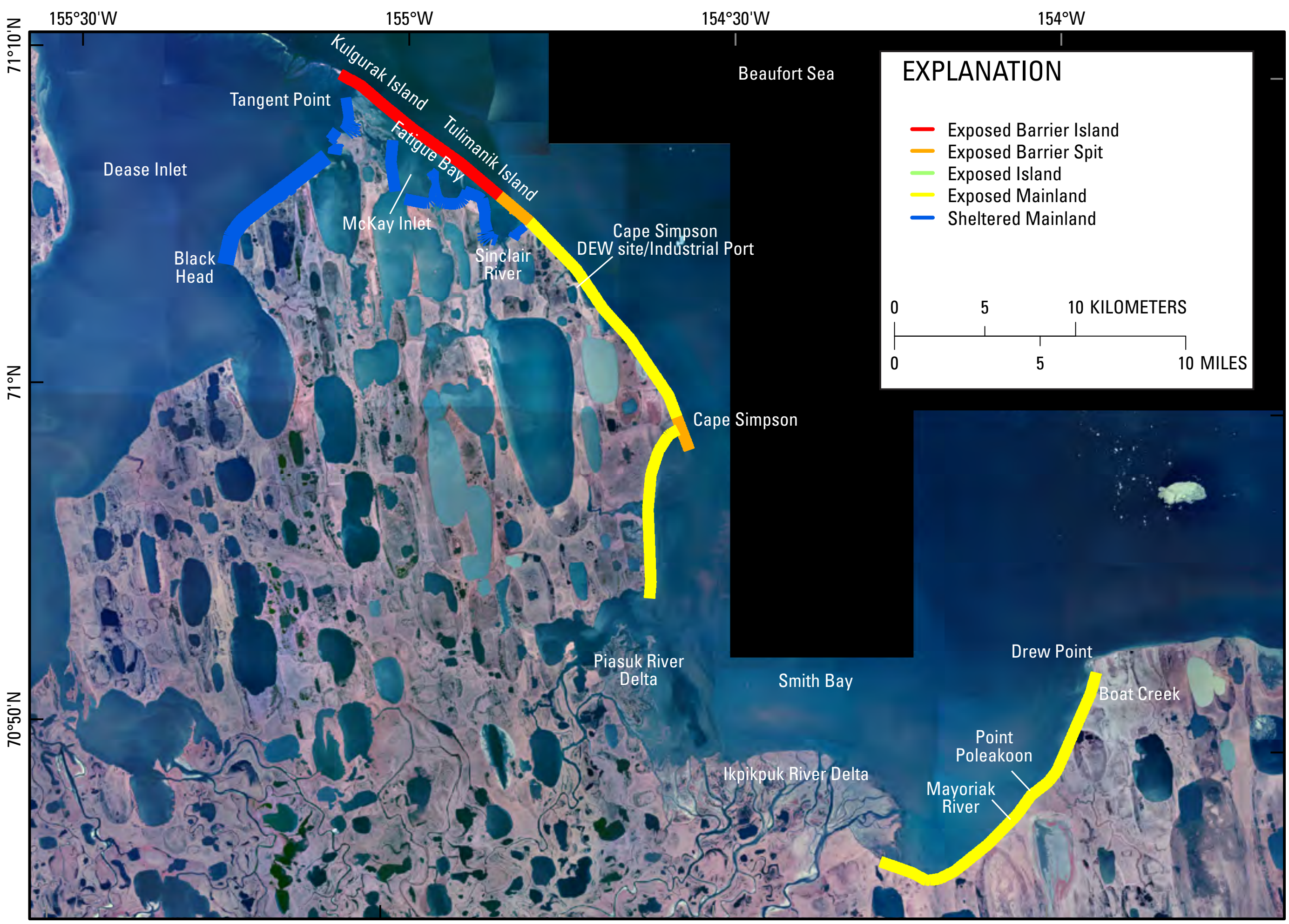
Introduction

Region 7 extends about 52 km between Drew Point and Dease Inlet and includes both exposed open-ocean mainland, barrier island and barrier spit shorelines and sheltered mainland-lagoon shorelines (fig. 48). It is included within the NPR-A and the Teshekpuk Lake Special Area. This stretch of coast is undeveloped and uninhabited aside from the Cape Simpson Industrial Port, an oilfield service camp owned and operated by Ukpeaġvik Iñupiat Corporation (UIC) at the former location of the Cape Simpson Intermediate DEW site, which was deactivated in 1963 (fig. 49A).

The exposed open-ocean coast of Region 7 includes an 18 km section along the east side of Smith Bay between Drew Point and the Ikpikpuk River Delta and a 29 km stretch from about 1.4 km northwest of Cape Simpson to the west end of Kulgurak Island, as it was mapped in 1947; Kulgurak Island subsequently segmented into several individual islands, portions of which are included in Region 8 analysis. The Ikpikpuk and Piasuk Rivers and Deltas separate these two analysis sections on opposite sides of Smith Bay. The coastal plain in this area is characterized by low- to high-tundra with numerous, large, tapped and untapped thermokarst lakes (figs. 39 and 48).

The mainland-lagoon coast of Region 7 extends about 16 km along the shore of Fatigue Bay from approximately 1 km east of Sinclair River west to Tangent Point, then southwest about 12 km to Black Head on the eastern shore of Dease Inlet. The coast along this stretch is extremely low-lying, with many tapped thermokarst lakes and inundated tundra surfaces.

Shoreline change rates were determined from two datasets, 1947 T-sheets and DOQQ imagery from 2002 (table 2; fig. 4). No historical T-sheets exist between the Piasuk River Delta and the section beginning 1.4 km north of Cape Simpson and thus no shoreline change rates were calculated for that section. Region 7 is dominantly erosional (92 percent of transects) with an average combined shoreline change rate for both exposed and sheltered shorelines of -2.4 m/yr and range of -16.4 to +3.4 m/yr (table 5). The highest accretion rates are associated with spit formation and infilling of inlets along the barrier island coast. Erosion rates are highest along the east coast of Dease Inlet, between Tangent Point and Black Head, likely a result of inundation and/or subsidence of this extremely



Background image USGS DOQQ (http://earthexplorer.usgs.gov)

Figure 48. Map showing color-coded shoreline change rates in Region 7, Drew Point to Dease Inlet, north coast of Alaska.

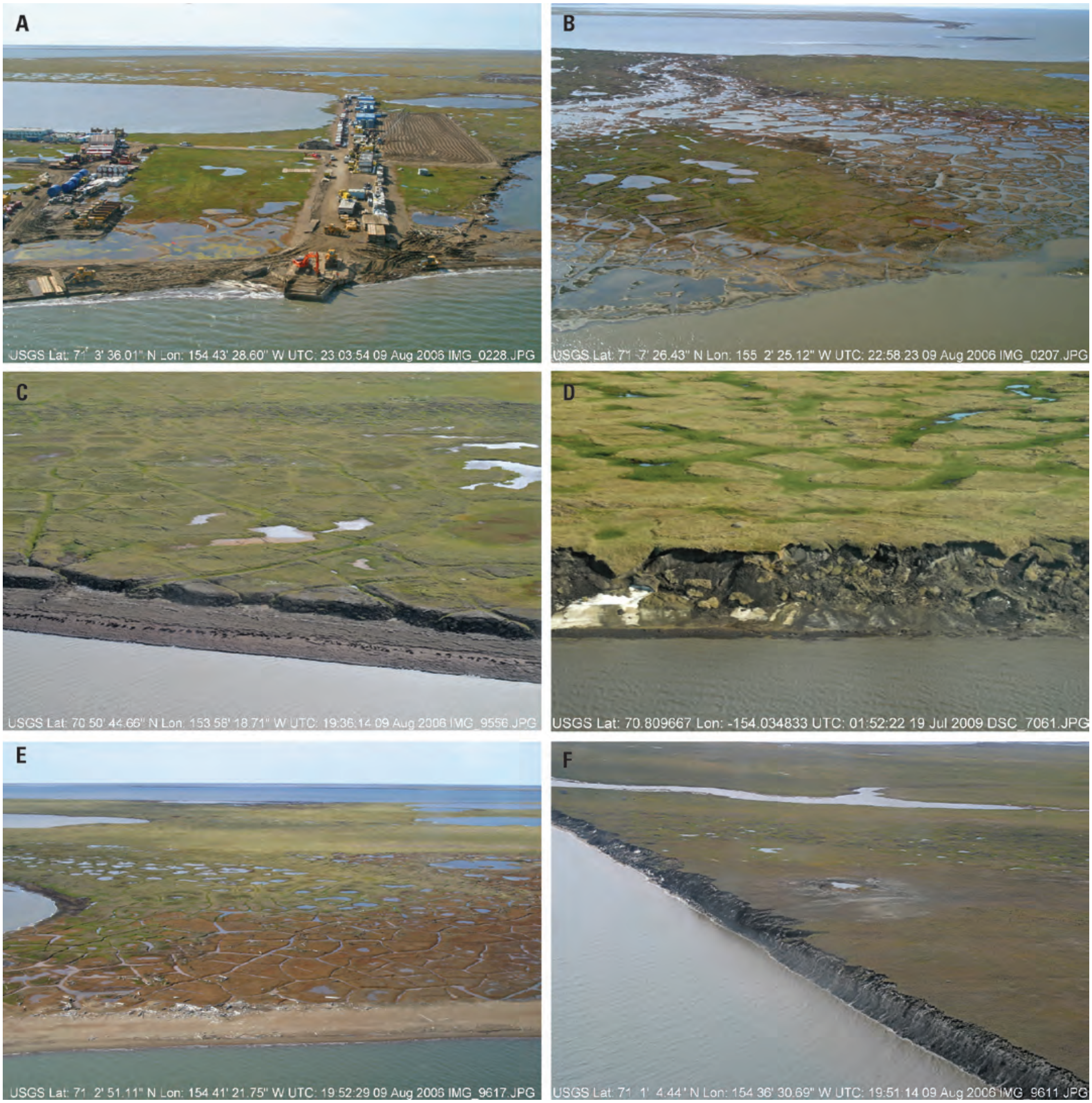


Figure 49. Aerial photographs showing typical examples of coast of Region 7, Drew Point to Dease Inlet, north coast of Alaska. A, The Cape Simpson Industrial Port, an oil field service camp, at location of former Cape Simpson Distant Early Warning (DEW) station. B, Inundated tundra near Tangent Point, view to southeast. C, Shoreline along east coast of Smith Bay with low bluffs fronted by fine-grained beach. D, Coastal bluffs with no fronting beach on east coast of Smith Bay. E, Low-lying tundra with relatively wide fronting beach between Cape Simpson and Kulgurak Island. Note wood debris and brown color of the tundra, which indicates salt-killed vegetation owing to inundation. F, high bluffs (about 10 m) with no fronting beach between Cape Simpson and Kulgurak Island. (Photographs A, B, C, E, and F taken in 2006, and D taken in 2009; Gibbs and Richmond, 2009, 2010.)

low-lying coast (fig. 50). In contrast to other regions in the study area, average shoreline change rates in Region 7 are nearly twice as high along the sheltered mainland lagoon shorelines compared to exposed open-ocean shorelines (-3.2 and -1.9 m/yr, respectively) (table 5).

Sheltered Mainland-Lagoon Shoreline Change

The sheltered mainland-lagoon coast of Region 7 is dominantly erosional (96 percent of transects) with average shoreline change rates of -3.2 m/yr and a range of -16.4 to +0.6 m/yr (fig. 51; table 5).

Sinclair River to Tangent Point

The lagoon coast of Fatigue Bay between the Sinclair River and Tangent Point is extremely low lying (<0.5 m), predominantly inundated tundra with well-developed polygonal structure (fig. 49B). Low bluffs (<2 m high) outcrop only near Sinclair River. This section of coast is dominantly erosional (93 percent of transects); shoreline change rates average -1.3 m/yr and range from -10.3 to +0.6 m/yr (table 5). The highest erosion rates are along the eastern shore of a pond just west of the Sinclair River (figs. 50 and 51).

Tangent Point to Black Head

The complex coast along the east coast of Dease Inlet is a mixture of low-lying (<2 m high) tundra and tapped thermokarst lake bluffs fronted by a mud apron or narrow (likely intertidal) beach deposits (<20 m), shoals and spits fronting a large embayment (likely a former thermokarst lake), and low-lying mud flats and low tundra (<0. 5 m) near Tangent Point. This section of coast is erosional (100 percent of transects), with an average shoreline change rate of -5.5 m/yr and a range of -16.4 to -0.4 m/yr (table 5). The highest erosion

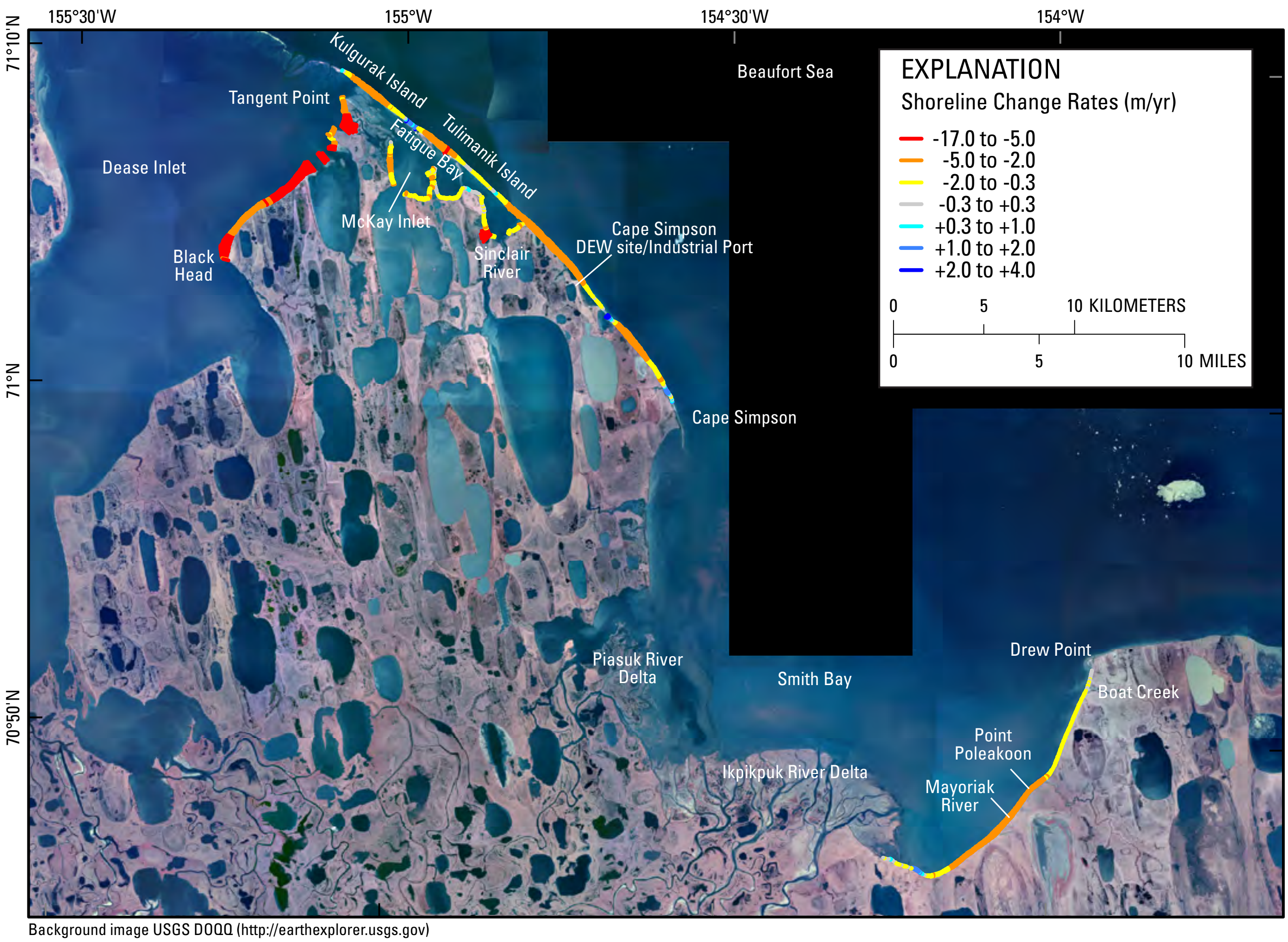


Figure 50. Map showing color-coded shoreline change rates in Region 7, Drew Point to Dease Inlet, north coast of Alaska. Width of line represents shoreline change envelope, or total shoreline change over analysis period, and distance between historical shorelines. Note change in scale from other figures.

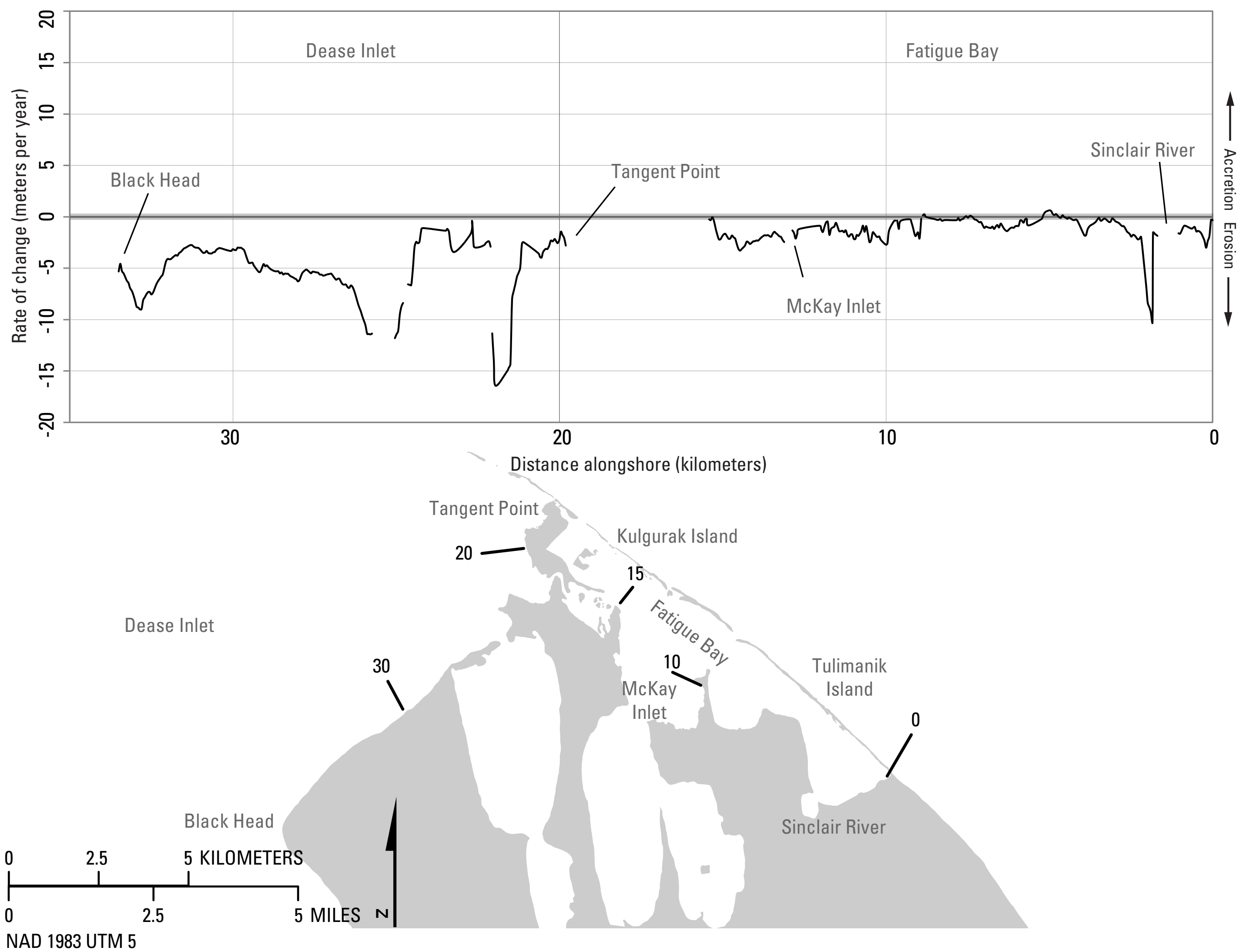


Figure 51. Top: Graph of shoreline change rates for sheltered mainland-lagoon coast of Region 7, Sinclair River to Black Head, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 7 indicating distances measured alongshore.

rates are associated with the inundation or erosion of the low-lying tundra just south of Tangent Point.

Exposed Open-Ocean Shoreline Change

The exposed open-ocean coast of Region 7 is dominantly erosional (89 percent of transects) with average shoreline change rates of -1.9 m/yr and a range of -6.8 to +3.4 m/yr (table 5). Average rates of shoreline change are somewhat lower on the northwest-facing, east side of Smith Bay compared to the northeast-facing section between Cape Simpson and Kulgurak Island (-1.5 compared to -2.1 m/yr, respectively), although there is no difference in average rates between mainland and barrier shorelines (each average -1.9 m/yr) (figs. 50 and 52; table 5).

Drew Point to Ikpikpuk River Delta

On the east side of Smith Bay, between Drew Point and the Ikpikpuk River Delta, tundra bluffs, typically 2–3 m high but reaching up to 7 m near Point Poleakoon, define the coastline. The bluffs are segmented by several small creeks, streams, and unnamed drainages. This section of coast trends NE-SW and faces northwest, from which occasional storm waves approach. This section of coast is dominantly erosional (93 percent of transects); shoreline change rates average -1.5 m/yr and range from -4.1 to +1.7 m/yr (table 5). Change rates are relatively lower between Drew Point and the large, unnamed drainage northeast of Point Poleakoon. Here the bluffs are fronted by relatively wide (<30 m) and continuous fine-grained beaches (fig. 49C). South of the drainage and along the relatively higher bluffs around Point

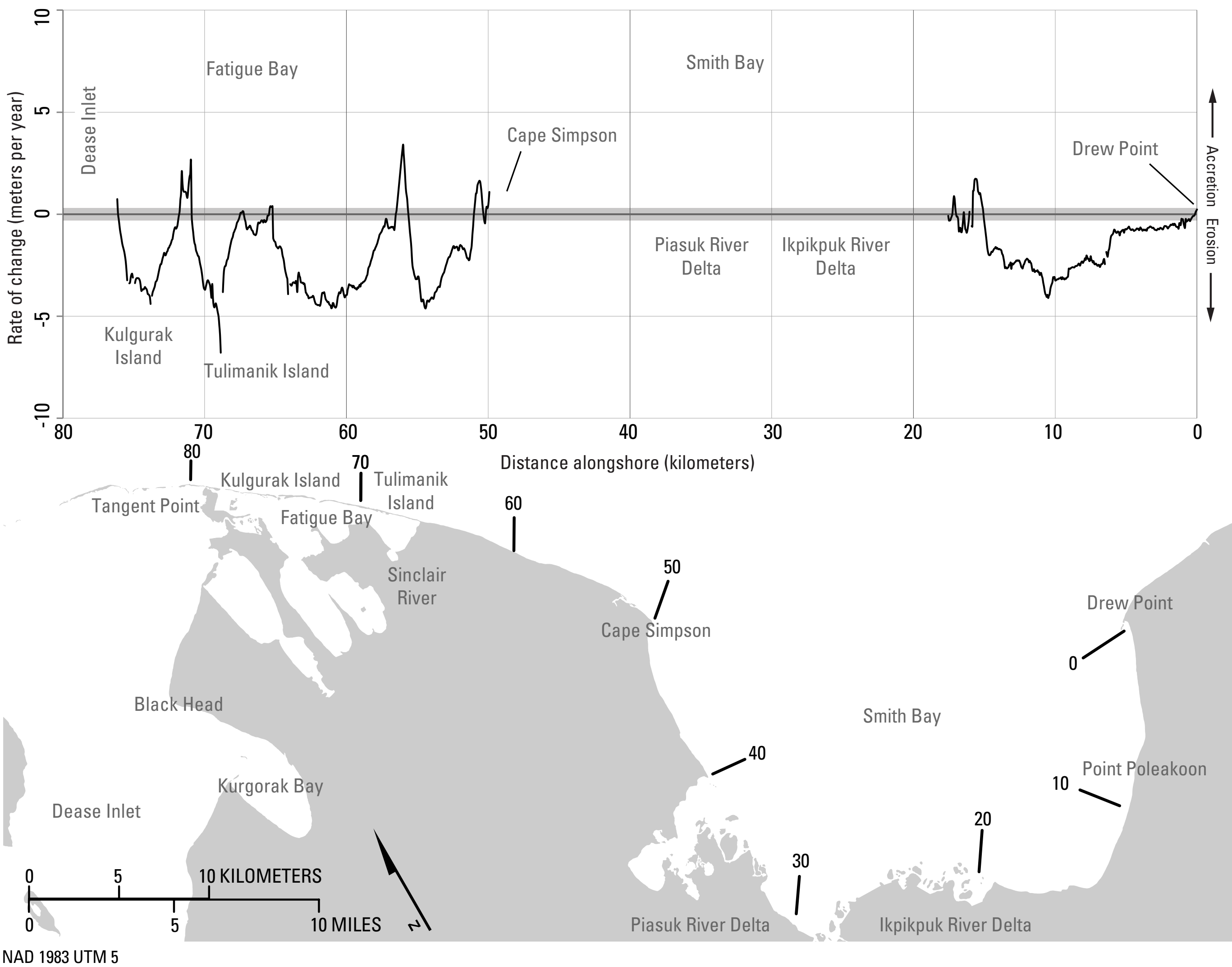


Figure 52. Top: Graph of shoreline change rates for exposed open-ocean coast of Region 7, Drew Point to Kulgurak Island, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 7 indicating distances measured alongshore.

Poleakoon, the beaches narrow (<5 m) and the bluffs appear in photographs to have a relatively higher ice content, and debris fans are common at their base (fig. 49D). Farther south, narrow beaches front lower bluffs and shoreline retreat change rates decrease toward Ikpikpuk River Delta.

Cape Simpson to Kulgurak Island

West of Smith Bay, between Cape Simpson and Kulgurak Island, the coast includes tundra bluffs 2–10 m high and very low-lying (~1 m high) tundra and unvegetated barrier spits, beaches and islands. Beaches occur along most of the coast, except fronting the highest bluffs in easternmost part of the region (figs. 49E and 49F). This section of coast is mostly erosional (89 percent of transects). Shoreline change rates average -2.1 m/yr and range from -6.8 to +3.4 m/yr (table 5). Accretion was measured at four locations: (1) at the eastern end of the section and associated with spit extension to the southeast; (2) associated with the formation of a barrier beach fronting a former embayment; (3) barrier migration and closure of McKay Inlet; and (4) the northwestern extension of Tulimanik Island and attachment with Kulgurak Island.

(8) Dease Inlet to Barrow

Introduction

Region 8 stretches nearly 60 km from Dease Inlet to the Barrow Peninsula and includes exposed barrier spits and islands and sheltered mainland-lagoon shorelines (fig. 53). The region straddles two UTM zones (4 and 5) and is included within the NPR-A. The portion of the coast between Dease Inlet and Iko Bay is part of the TLSA. There are no villages or coastal infrastructure along this section of coast although primitive access roads have been established by off-road vehicle use on the spit between Barrow and Point Barrow. Point Barrow is also known for its numerous archeological sites.

Region 8 is characteristically low-lying, with coastal elevations generally less than 3 m, but locally as high as 5 m, above sea level. The coastal reach is dominated by an extended chain of barrier islands, known as the Plover Islands, which are separated from the mainland coast by Elson Lagoon and Dease Inlet. The mainland coast includes tundra bluffs (3–5 m high), segmented by multiple sloughs, rivers, drainages, bays, and tapped (drained) thermokarst lakes (figs. 39 and 54). The tapped thermokarst lakes are more common along the shoreline east of the Mayoeak River. Beaches are rare along this coast and generally restricted to bay and rivermouth bars, pocket beaches between eroded bluff segments, and fronting tapped thermokarst lakes. Small, narrow beaches are also present adjacent to Barrow spit, near Tekegakrok Point, east of Mayoeak River, in Iko Bay, at Ross Point, at Tulageak Point, and fronting Kachiksuk Bluffs.

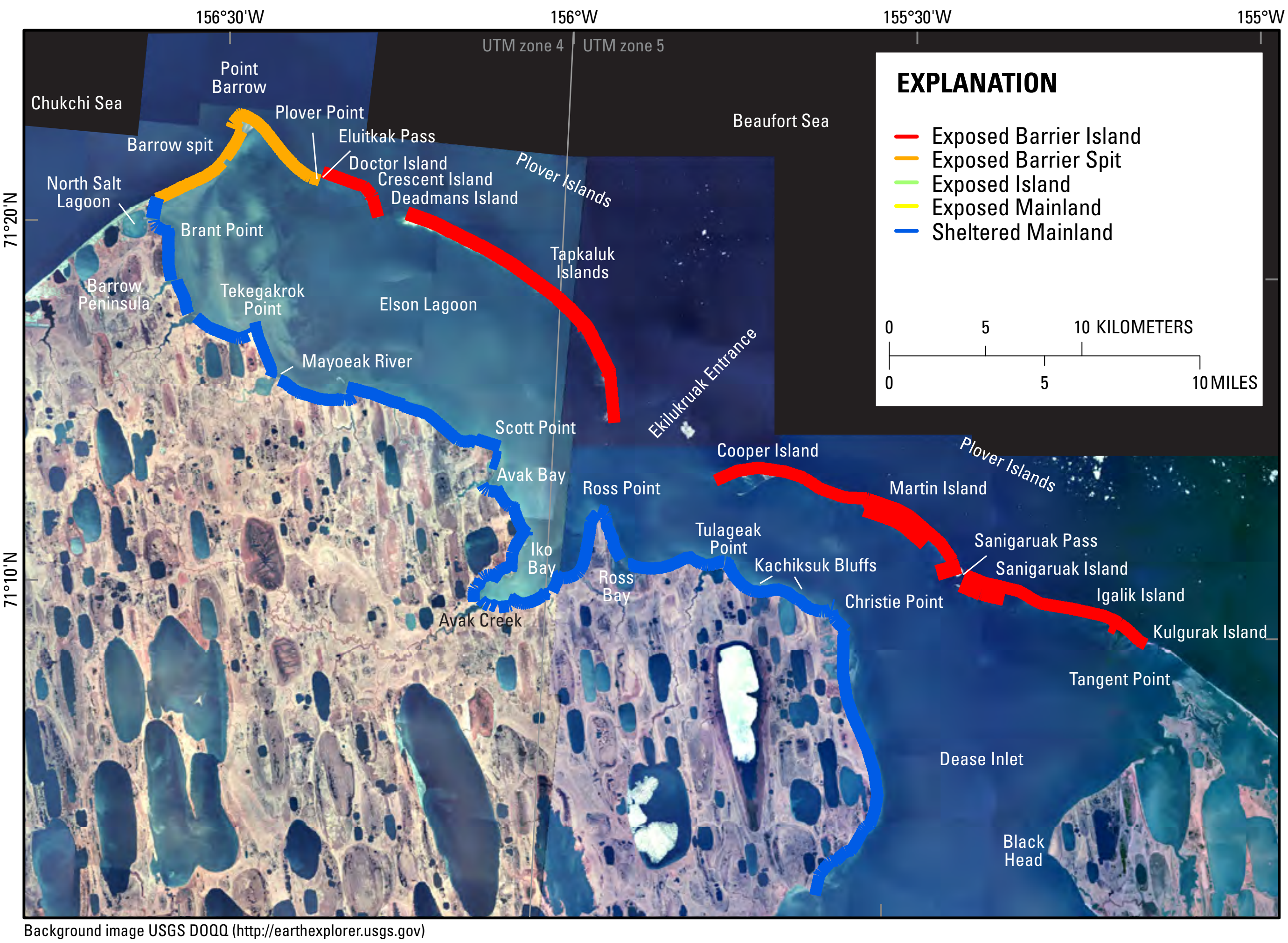


Figure 53. Map showing color-coded shoreline types within Region 8, Dease Inlet to Barrow, north coast of Alaska.

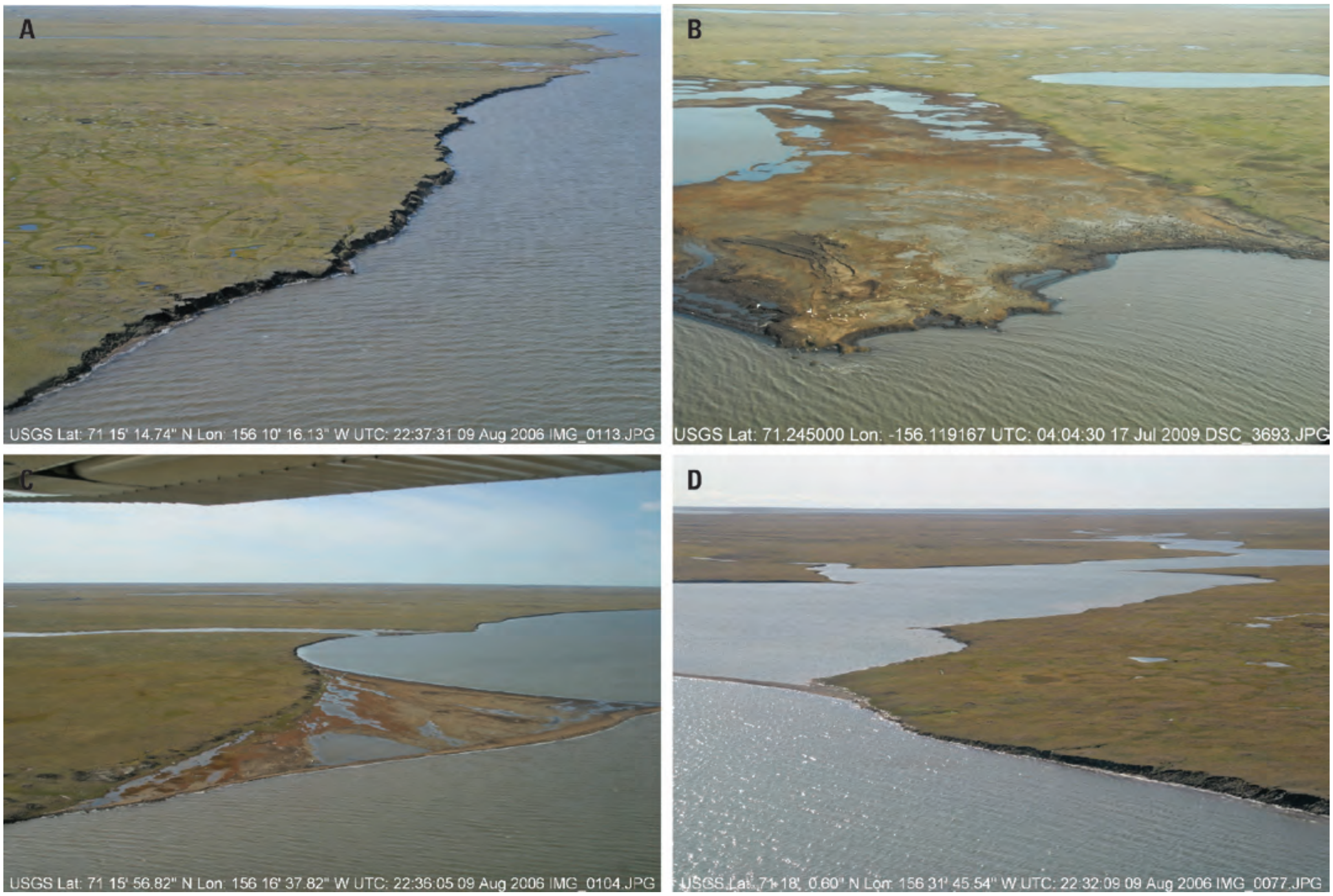


Figure 54. Aerial photographs showing typical examples of mainland coast of Region 8, Dease Inlet to Barrow, northern Alaska. A, Tundra bluff fronted by scattered, pocket beaches along the mainland-lagoon coast of Elson Lagoon, view to northwest. B, Tapped thermokarst lake shoreline near Scott Point, view to south. C, Cuspate headland east of the Mayoeak River, view to southwest. D, Baymouth bar and eroding bluffs near Ikpik Slough, view to southeast. (Photographs A, C, and D taken in 2006, and B taken in 2009; Gibbs and Richmond, 2009, 2010).

The barrier coast of Region 8 includes the Plover Islands, a chain of barrier islands which extend northwest about 48 km between Igalik Island and Eluitkak Pass, and a barrier spit that extends about 5 km northwest between Plover Point and Point Barrow, then about 6 km southwest from Point Barrow to near North Salt Lagoon where the Barrow Peninsula and tundra coastal plain begin. The barriers are generally low lying (<2 m high) and narrow (<300 m wide), except near Point Barrow where shore parallel ridges reach up to 5 m high and the spit is nearly 900 km wide. The barriers are mostly unvegetated although discontinuous, low-lying vegetation is present in topographic lows along Barrow spit, at Point Barrow, and on portions of the barrier islands where little shoreline change has occurred since 1947 (for example, the west end of Cooper Island and central Tapkaluk Island (fig. 55).

Shoreline change rates for Region 8 were determined from two of three datasets, 1947 T-sheets and DOQQ imagery from 2002 or 2005 (table 2; fig. 4). Region 8 is predominantly erosional (90 percent of transects) with combined shoreline change rates for both the exposed open-ocean and sheltered mainland-lagoon shorelines averaging -2.5 m/yr and ranging between -17.9 to +7.0 m/yr (table 5). Average shoreline change rates along exposed open-ocean coasts (-3.2 m/yr) are just over 1.5 times higher compared to sheltered mainland-lagoon coasts (-2.1 m/yr) (fig. 56; table 5); however, much of the change to the barrier islands is not accounted for in the DSAS results due to the lack of overlapping shorelines.

Sheltered Mainland-Lagoon Shoreline Change

Shoreline change rates along the sheltered mainland/lagoon shoreline of Region 8 are predominantly erosional (95 percent of transects), averaging -2.1 m/yr and ranging between -9.9 and

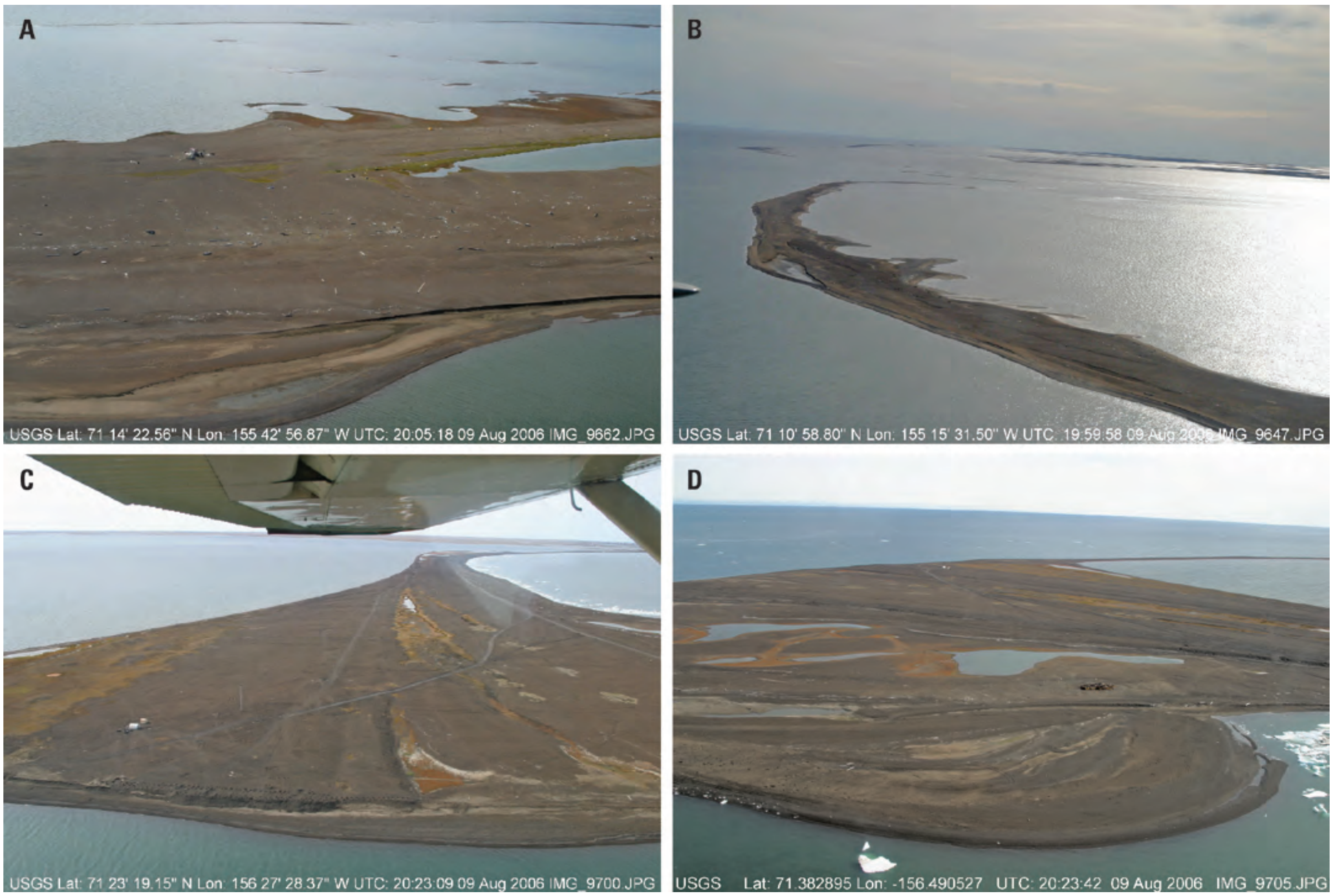
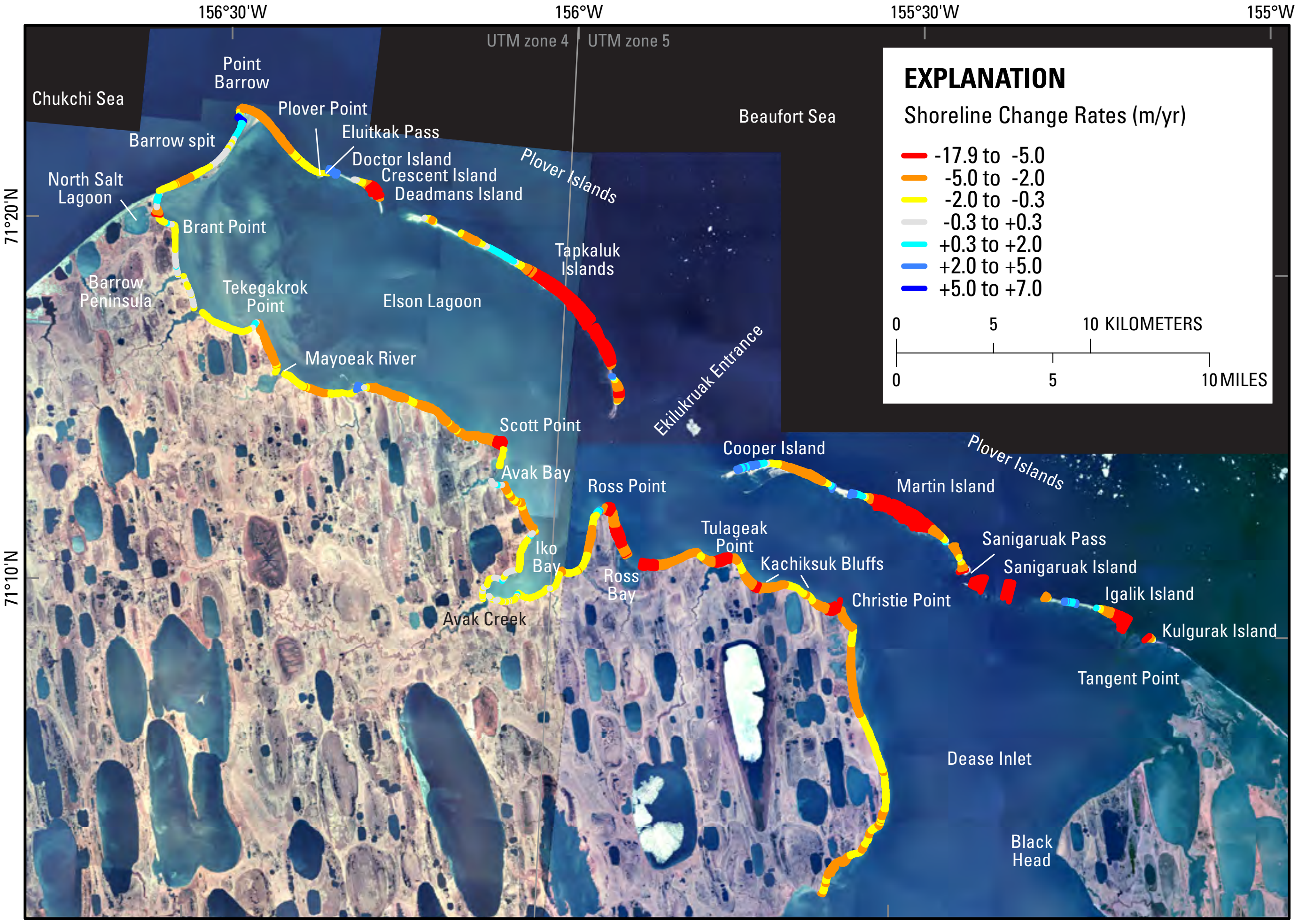


Figure 55. Aerial photographs showing typical examples of barrier coast of Region 8, Dease Inlet to Barrow, northern Alaska. A. Cooper Island, a typical, low-lying barrier island within Region 8 located just east of Ekilukruak Entrance; view to southeast. In contrast to other barrier islands along coast, which are narrow, unvegetated, and experience high rates of coastal erosion, this part of Cooper Island has been relatively stable since 1947; it is relatively wider here and sparse vegetation can be seen in foreground of photograph. B, Igalik Island, a characteristic low-lying, unvegetated barrier island. Dease Inlet is on right and Kulgurak Island and Tangent Point are visible in the background; view to east. The island reformed in this location between 1947 and 2002. C, Linear ridges and low-lying vegetation at Point Barrow; view to south down Barrow spit. D. Point Barrow, showing the lobe of sediment deposited on the south side of the point between 1947 and 2005, view to northeast. (All photographs taken in 2006; Gibbs and Richmond, 2009).



Background image USGS DOQQ (http://earthexplorer.usgs.gov)

Figure 56. Map showing color-coded shoreline change rates in Region 8, Dease Inlet to Barrow, north coast of Alaska. Width of line represents shoreline change envelope, or total shoreline change over analysis period, and distance between historical shorelines.

+4.9 m/yr (figs. 56, 57; table 5). The highest erosion rates occur between Christie Point and Ross Point along a section of coast adjacent to Ekilukruak Entrance, a ~6+ km wide gap in the barrier island chain. Rates are relatively low between the Barrow Peninsula and Tekegakrok Point, except at the mouth of North Salt Lagoon, where the entrance channel widened and an offshore bar or delta disappeared between 1947 and 2005. Erosion rates generally increase from west to east across the region, with the highest erosion rates associated with Scott Point, Ross Point, and Christie Point, and lowest rates in Iko Bay and east of Christie Point. Shoreline accretion is very low along this section of coast, with only three areas showing >0.5 m/yr of accretion during the study period: north of North Salt Lagoon, west of Tekegakrok Point, a cuspate headland between Mayoeak River and Scott Point, and a spit west of Ross Point. The variation in shoreline change rates along the mainland lagoon coast is likely driven by the presence or absence of the protection from wave exposure offered by the off shore barrier islands.

Exposed Open-Ocean Shoreline Change

The barrier islands and spits within Region 8 show a dynamic and complex pattern of erosion and accretion between 1947 and 2002/2005. Some islands were overwashed, breached, and/or segmented into multiple smaller islands (for example, eastern Tapkaluk Islands), while others extended in length and/or melded into single island (for example, western Tapkaluk Islands). Many migrated, rotated, and reformed landward of their 1947 position. Because of the dynamic nature of these islands, the DSAS results give a somewhat incomplete summary of the change in the area, especially where new islands have formed or migrated into a location where no previous landform existed and there are no overlapping shorelines.

Shoreline change rates along the exposed open-ocean coast of Region 8 are predominantly erosional (82 percent of transects), averaging -3.2 m/yr and ranging between -17.9 and

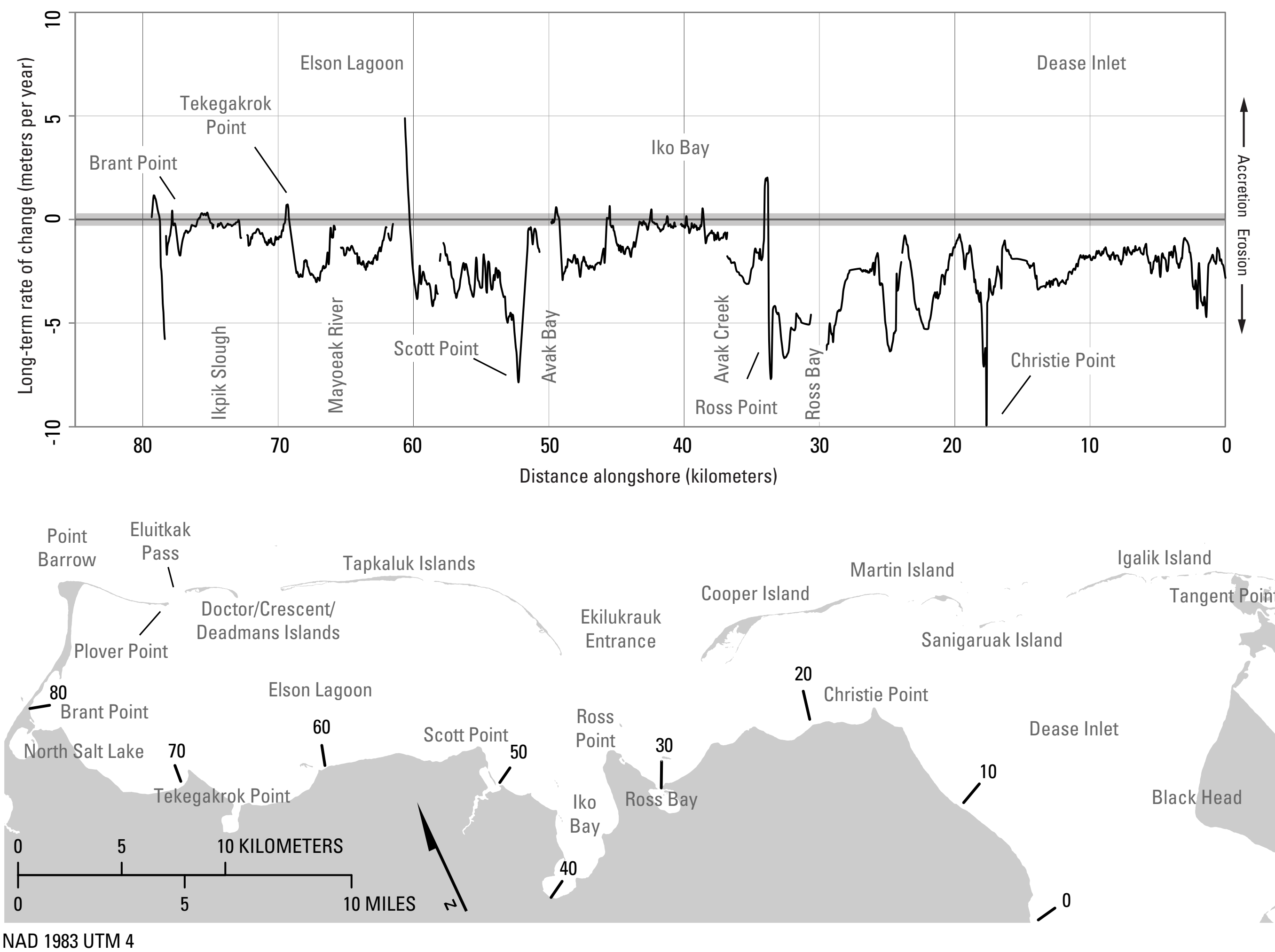


Figure 57. Top: Graph of shoreline change rates for sheltered mainland-lagoon coast of Region 8, Dease Inlet to Barrow, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 8, indicating distances measured alongshore.

+7.0 m/yr (figs. 56 and 58; table 5); however, because of the lack of overlapping shorelines, all changes to the barrier island shorelines are not accounted for in the DSAS analysis. Between 1947 and 2005 the total barrier island area, and not including the spit between Plover Point and Barrow Peninsula, increased by 1,022,534 m^2 (table 8). Average shoreline change for the barrier islands between Igalik Island and Eluitkak Pass is three times higher than for the barrier spit between Plover Point and the Barrow Peninsula (-3.9 and -1.3 m/yr, respectively; table 5).There is an overall decrease in erosion rates from east to west, with the highest rates of shoreline change measured between Igalik and Cooper Islands. This analysis, however, does not take into considerable amounts of accretion and erosion observed for much of the Plover Islands, as described below.

Igalik Island to Sanigaruak Pass

Marking the eastern extend of Region 8, the islands between Kulgurak Island and Sanigaruak Pass as mapped in 1947 included the ~3.5 km Igalik Island, the ~1 km long Sanigaruak Island, and five unnamed islands. By 2002, these islands had eroded and reformed as a continuous, nearly 4 km long island to the west of the former Igalik Island, along with numerous smaller islands and shoals located several hundred meters landward of the former island chain (fig. 59). The barrier islands are extremely low lying (<1.5 m high) and unvegetated. Average rates of shoreline change for the islands between Kulgurak Island and Sanigaruak Pass average -5.6 m/yr and range between -17.9 and +2.7 m/yr (table 5), although these rates do not include the considerable amounts of island accretion and erosion observed between 1947 and 2002. During the same time period, the total surface area of the Igalik and Sanigaruak Islands increased by 106,874 m^2 (table 8).

Sanigaruak Pass to Ekilukruak Entrance

The reach between Sanigaruak Pass and the Ekilukruak Entrance includes Martin Island, Cooper Island, and several

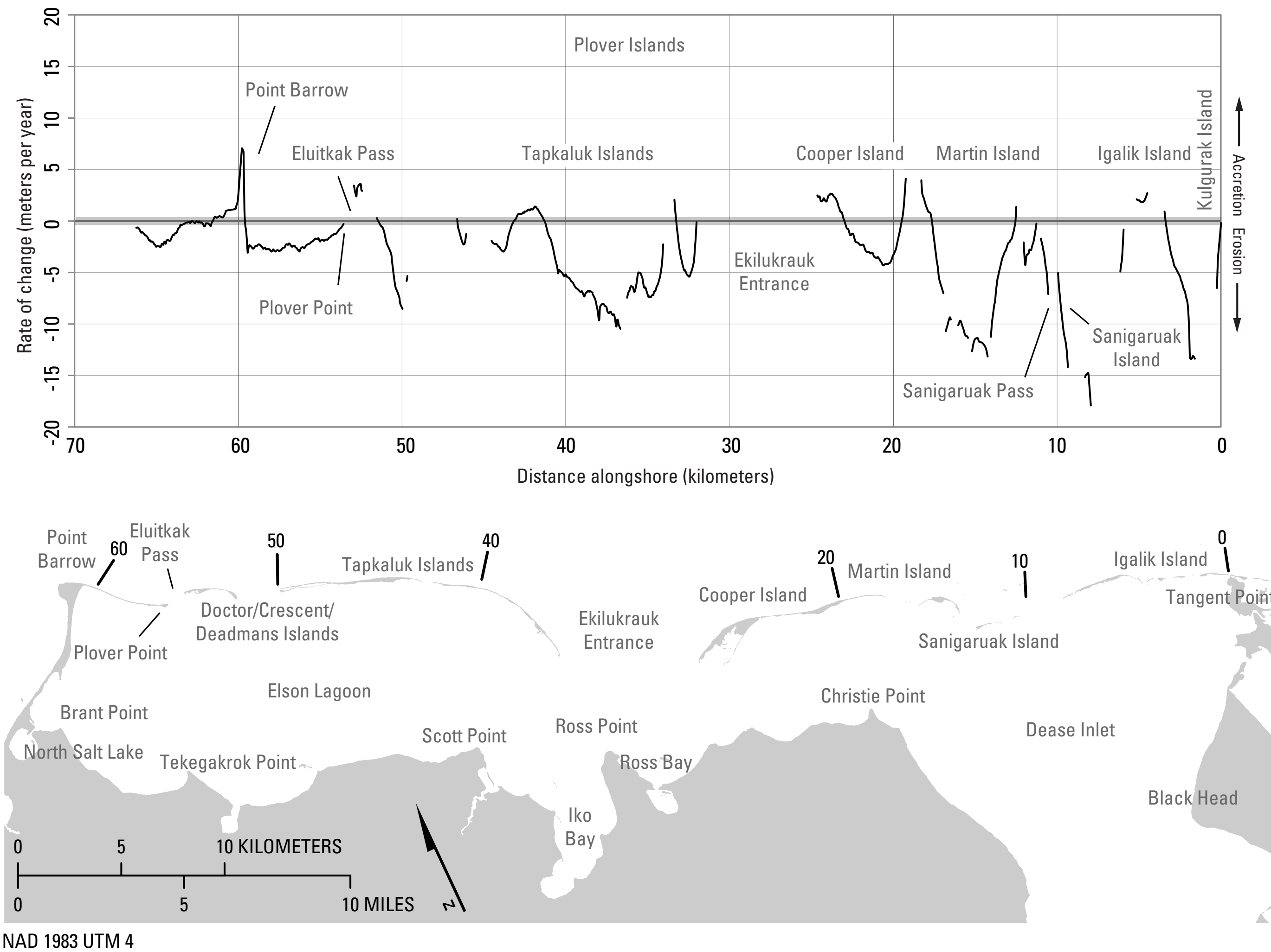
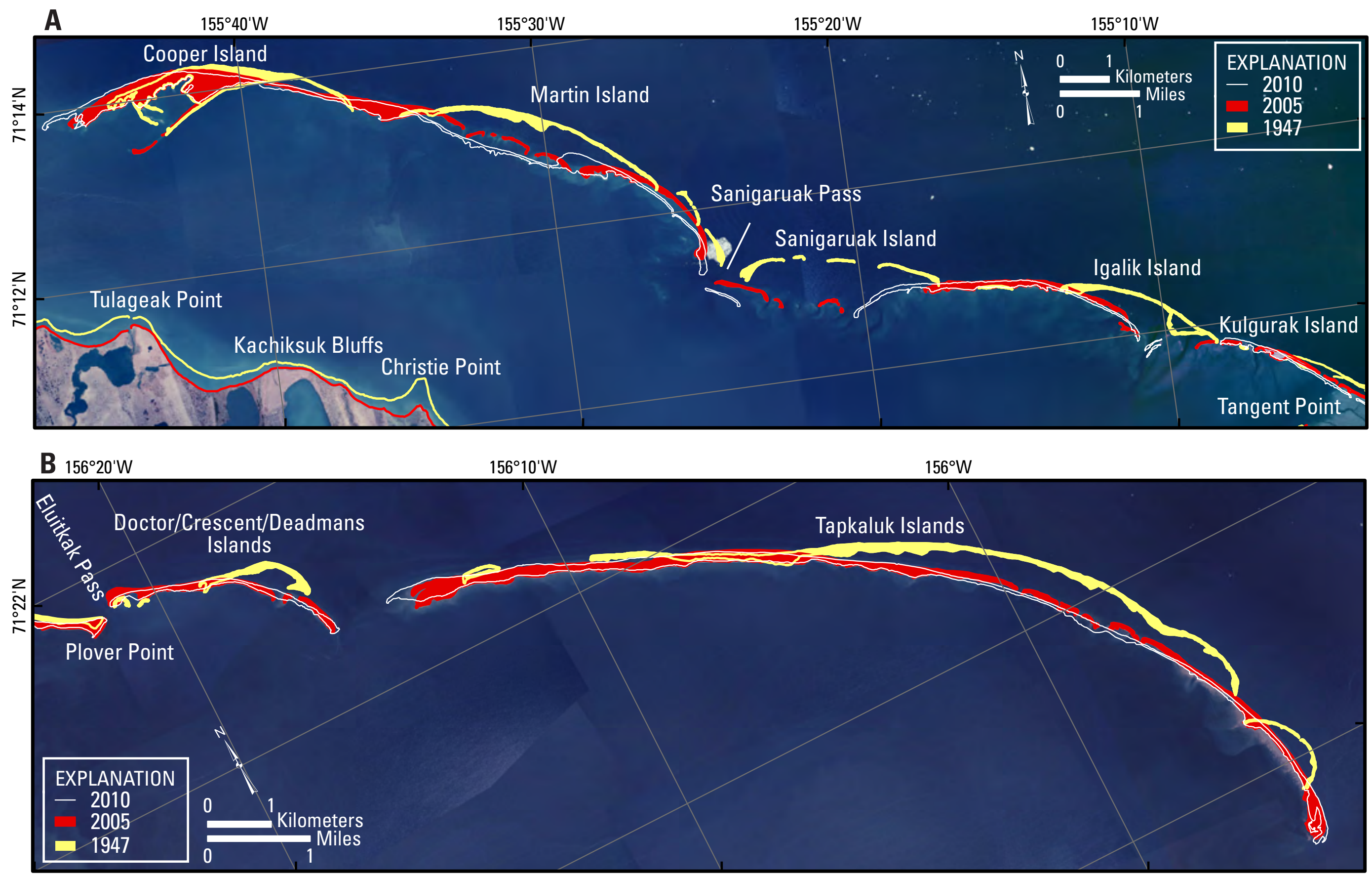


Figure 58. Top: Graph of shoreline change rates for exposed open-ocean coast of Region 8, Dease Inlet to Barrow, northern Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 8 indicating distances measured alongshore.

Table 8. Total barrier island area in Region 8, Dease Inlet to Barrow, north coast of Alaska, for each era and total change during analysis period, in square meters.

Island	1940s	2000s	2000s–1940s
Igalik Island	241,881	482,859	240,978
Sanigaruak Island	125,724	59,408	-66,316
Martin-Cooper Islands	1,777,350	2,153,391	376,042
Tapkaluk Island	996,898	1,768,424	771,526
Deadmans Island	188,041	334,831	146,790
Total	**3,329,893**	**4,798,913**	**1,469,020**



Background image USGS DOQQ (http://earthexplorer.usgs.gov)

Figure 59. Detailed map showing shorelines of Plover Islands fronting Elson Lagoon for time periods 1947, 2005, and 2010. Note how barriers migrated landward and segmented into multiple islands. Lightest line is shoreline derived from 2010 lidar DEM; this shoreline, which was not used for DSAS analysis in this study, shows that between 2005 and 2010, Martin, Tapkaluk, and Doctor/Crescent/Deadmans Islands reformed into a single continuous island.

unnamed smaller islands. 1947 T-sheets show a 5.7 km long Martin Island, 5.5 km long Cooper Island, and 3 smaller unnamed islands. By 2002, the central part of Martin Island had migrated over 600 m landward and segmented into several islands. The unnamed islands west of Sanigaruak Pass merged with the eastern part of Martin Island forming a ~3.5 km long island, and the inlet between Martin and Cooper Islands closed forming one continuous island. The central part of Cooper Island, one of the only vegetated landscapes within the Region 8 barrier chain, remained relatively unchanged throughout the study period, although the western end of the island extended nearly 800 meters to the west (figs. 55 and 59). Average rates of shoreline change for the islands between Sanigaruak Pass and the Ekilukruak Entrance average -3.3 m/yr and range between -13.2 and +4.1 m/yr (table 5), although these rates do not include the considerable accretion associated with the closure of the inlet between Martin and Cooper Islands, nor the westward extension of Cooper Island. During the same time period, the total surface area of the Martin and Cooper Islands increased by 224,033 m^2 (table 8).

Ekilukruak Entrance to Eluitkak Pass

The reach between Ekilukruak Entrance and Eluitkak Pass includes the Tapkaluk Islands chain, and Deadmans, Crescent, and Doctor Islands. Between 1947 and 2002, the eastern part of the Tapkaluk Islands migrated ~500 m landward and extended southeast about 800 m into Ekilukruak Entrance while the western part of the island migrated on the order of 125 m landward and extended ~800 m to the northwest. Deadmans, Crescent, and Doctor Islands coalesced into one island separated by two small, ephemeral inlets. Average rates of shoreline change for the islands between Sanigaruak Pass and the Ekilukruak Entrance average -3.9 m/yr and range between -10.5 and +3.6 m/yr (table 5), although these rates do not include the considerable accretion associated with the northwestward and southeastward extension of the Tapkaluk Islands and coalescence of Deadmans, Crescent, and Doctors Islands. During the same time period, the total surface area of the Tapkaluk and the coalesced Doctors Islands increased by 691,627 m^2 (table 8).

Plover Point to Barrow Peninsula

The barrier spit coast between Plover Point and the Barrow Peninsula shows a much less dynamic shoreline change history compared to the Plover Islands to the east. Between 1947 and 2005, the NE, Beaufort Sea-facing shoreline between Plover Point and Point Barrow, the migrated 75-200 m (average -2.2 m/yr) to the southwest, while maintaining a similar overall morphology. At Point Barrow, erosion has exposed and continues to threaten numerous ancient burial and archeological sites.

Along the NW, Chukchi Sea facing spit, the shoreline at Point Barrow shows both erosion (<200 m) and accretion (up to 400 m) as the tip appears to have migrated to the south. Southward from Point Barrow, shoreline change rates are initially accretional then transition to predominantly erosional (average, -0.6 m/yr). Erosion rates are highest about 2/3 of the way down the spit along the low-lying and narrow portion of the spit near the western extent of Region 8.

(9) Barrow to Peard Bay

Introduction

The coast of Region 9 extends from the northern extent of the tundra backed coast of the Barrow Peninsula near North Salt Lagoon nearly 90 km southwest to Tachinisok Inlet on the east side of Peard Bay (fig. 60). In contrast to the Beaufort Sea coast to the east, this coastal stretch generally faces northwest, trends southwest to northeast, and fronts the Chukchi Sea. The reach includes the village of Barrow, the largest city (with a 2010 census population of 4,346; State of Alaska, 2015) and economic center of the North Slope Borough, and marks the seaward boundary of the NPR-A. Much of the village of Barrow is fronted by a low berm or bluff (1–2 m high) seaward of the coastal road and in many locations coastal protection structures are present (fig. 61A). The reach is characterized by a low-lying coast (< 3 m high) northeast of the Wiley-Post-Will

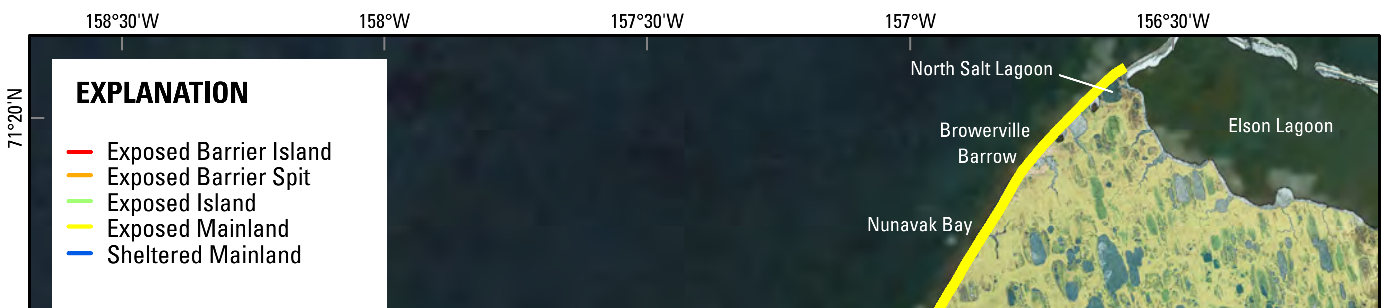


Figure 60. Map showing color-coded shoreline types within Region 9, Barrow to Peard Bay, north coast of Alaska.

Rogers Memorial Airport where it transitions to coastal bluffs ~5–25 m high segmented by numerous small creeks, drainages, and bays. No major rivers reach this section of coast although many smaller creeks and the large Walakpa Bay reach the coast. Bluff heights generally increase from north to south; the highest bluffs in the study area (~25 m high) are found near Skull Cliff (figs. 61A–D). Narrow (<40 m wide) sand and gravel beaches are common along this coast and are absent only fronting the high bluffs near Skull Cliff. Wider (<150 m) beaches and spits typically front the coastal creeks and bays.

Exposed Open-Ocean Shoreline Change

Shoreline change rates for Region 9 were determined from three data sets, 1947 T-sheets, DOQQ imagery from 2005 and the 2010 lidar DEM (table 2; fig. 4). The region only includes exposed open-ocean shorelines (fig. 60). Shoreline change rates along this coast are the lowest in the study area, with maximum erosion and accretion rates of -1.2 m/yr and +0.7 m/yr, and respectively. The reach is predominantly erosional (86 percent of transects) with an average shoreline change rate of is -0.3 m/yr, which is at the limit of the analytical uncertainty on individual transects (fig. 62; table 5). Highest accretion rates (+0.7 m/yr) were measured between Walakpa River and Nunavak Bay. Highest erosion rates (-1.2 m/yr) were measured between Oyagatut Creek and Killi Creek. There is a relative increase in erosion rates about 2.5 km north of Nulavik where average rates nearly double from -0.2 m/yr to the north to -0.4 m/yr to the south (figs. 62 and 63; table 5).

Figure 61. Aerial photographs showing typical examples of coast of Region 9, Barrow to Peard Bay, north coast of Alaska. A, Town of Barrow, Alaska. Shore-protection structures are common and beaches are narrow along this low-lying coastal stretch. View to southeast. B, Highest bluffs in study area present within Region 9 at Skull Cliff, where they reach nearly 25 m high. Relatively resistant layer is present at base of bluffs, and beaches are rare along this section of coast. C, Nearly vertical bluff faces north of Skull Cliff. D, Faceted, sloping, and vegetated bluffs between the Walakpa River and Nunavak Bay, indicating differences in geology and erosional history. (Photographs A and C taken in 2006, and B and D taken in 2009; Gibbs and Richmond, 2009, 2010).

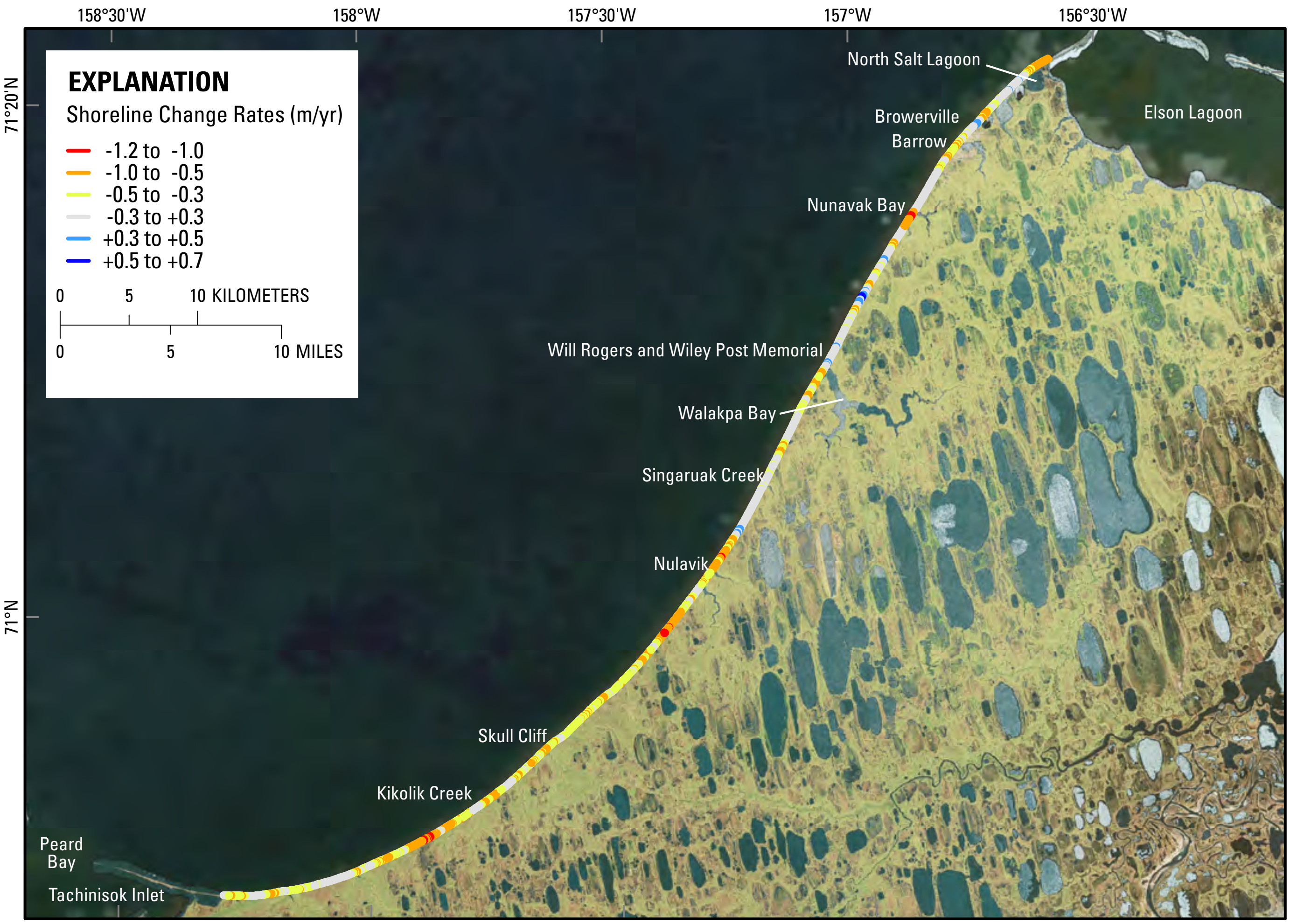
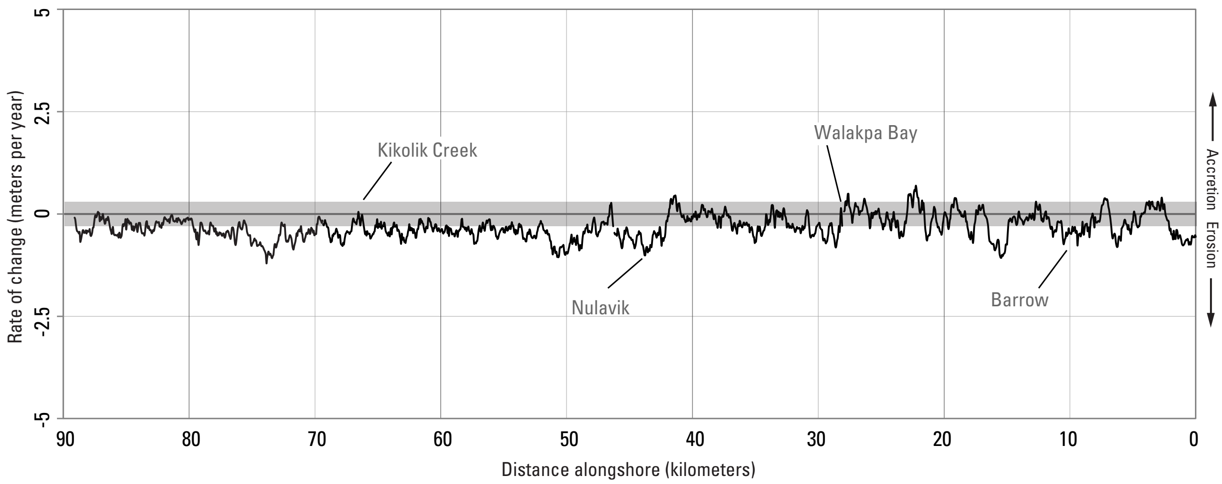


Figure 62. Map showing color-coded shoreline change rates in Region 9, Barrow to Peard Bay, north coast of Alaska. Width of line represents shoreline change envelope, or total shoreline change over analysis period, and distance between historical shorelines. Note change in in rate legend compared to other shoreline change maps and relatively higher erosional rates south of Nulavik compared to north of Nulavik.



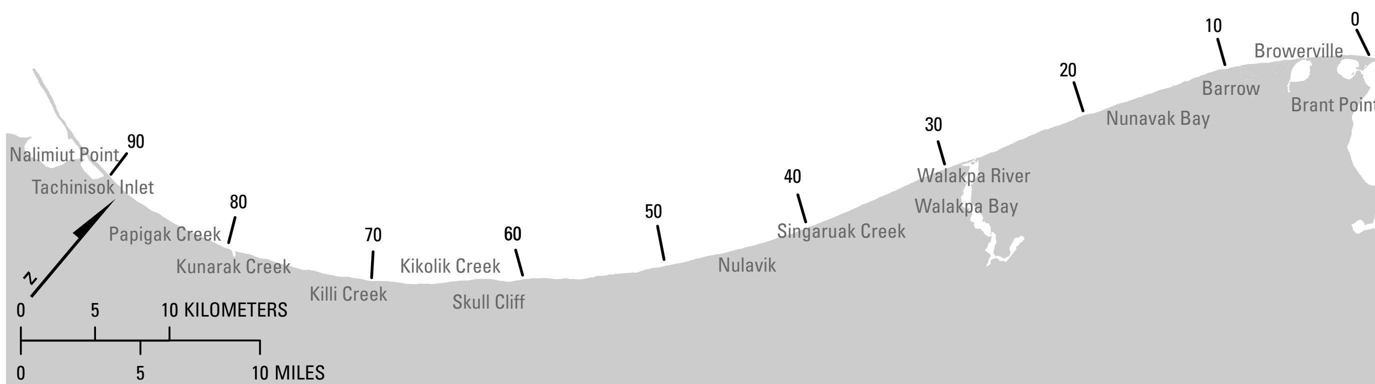


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Figure 63. Top: Graph of shoreline change rates for exposed open-ocean coast of Region 9, Barrow to Peard Bay, north coast of Alaska. Gray bar is total shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 9 indicating distances measured alongshore.

(10) Peard Bay to Icy Cape

Introduction

The coast of Region 10 extends approximately 180 km southwest along the coast of the Chukchi Sea from the east end of Peard Bay to the western boundary of the study area at Icy Cape Pass (fig. 64). The Native Village of Wainwright, with 556 residents (2010 census; State of Alaska, 2015), is the only population center and infrastructure development along this stretch of coast.

Region 10 includes exposed open-ocean and sheltered lagoon coasts. The coastal plain includes low to relatively high tundra with numerous, large, thermokarst lakes generally elongated in an NW-SE orientation. Two large estuaries, Wainwright Inlet and Kugrua Bay and, five large rivers (Kugrua River which drains into Kugrua and Peard Bays, and the Sinaruruk, Kuk, which feeds Wainwright Inlet, Nokotlek and Avak Rivers) segment the coast. Barrier spits and islands front the coast of Peard Bay and between Kilmantavi and Icy Cape Pass. Narrow barrier beaches connected to the mainland at both ends and enclosing lagoons, are present near Point Belcher and between the Kuk River and Kilmantavi.

Shoreline change rates for Region 10 were determined from several datasets, 1947 and 1949 T-sheets; 2010, 2011, and 2012 lidar DEMs; and 2010 and 2011 SPOT5 satellite orthoimagery (table 2; fig. 4). Shoreline change rates for parts of the lagoon coast near Icy Cape were not included in the analysis because the shoreline could not accurately be delineated from the 2000s era data sources (fig. 65). Comparison of 2010 SPOT5 satellite imagery (http://www.alaskamapped.org; accessed November 22, 2014) with shorelines derived from the 2011 lidar DEM shows this area is a very low-lying with a poorly defined shoreline which presents difficulties in deriving a lidar shoreline (fig. 65). Region 10 is predominantly erosional (71 percent of transects) with combined shoreline change rates for both the exposed open-ocean and sheltered mainland-lagoon coasts averaging -0.3 m/yr, which is equal to the total shoreline change rate uncertainty at individual transects. Average rates of change for the sheltered mainland-lagoon coast compared to the exposed open-ocean coast are not

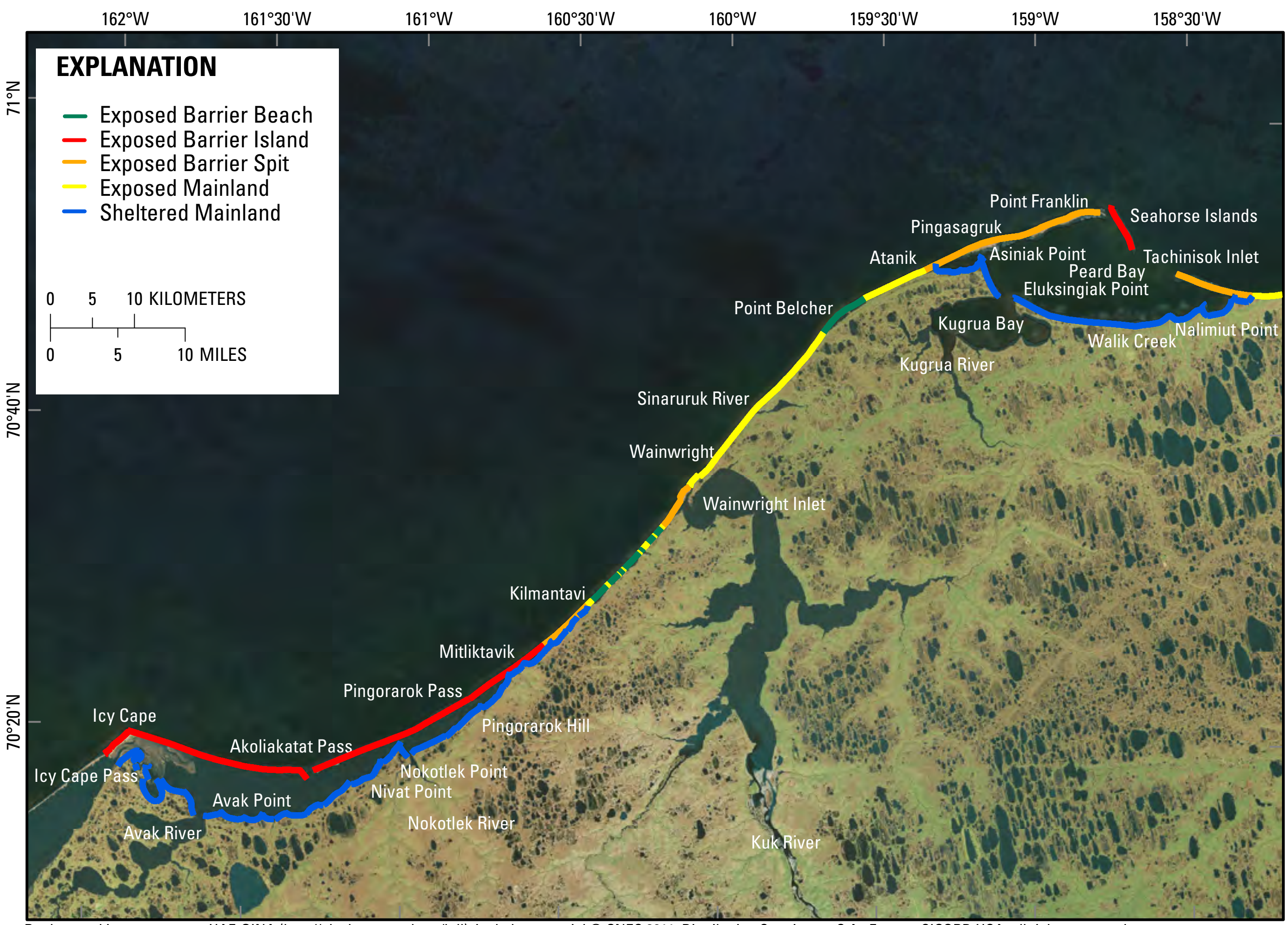

Figure 64. Map showing color-coded shoreline types within Region 10, Peard Bay to Icy Cape, north coast of Alaska.

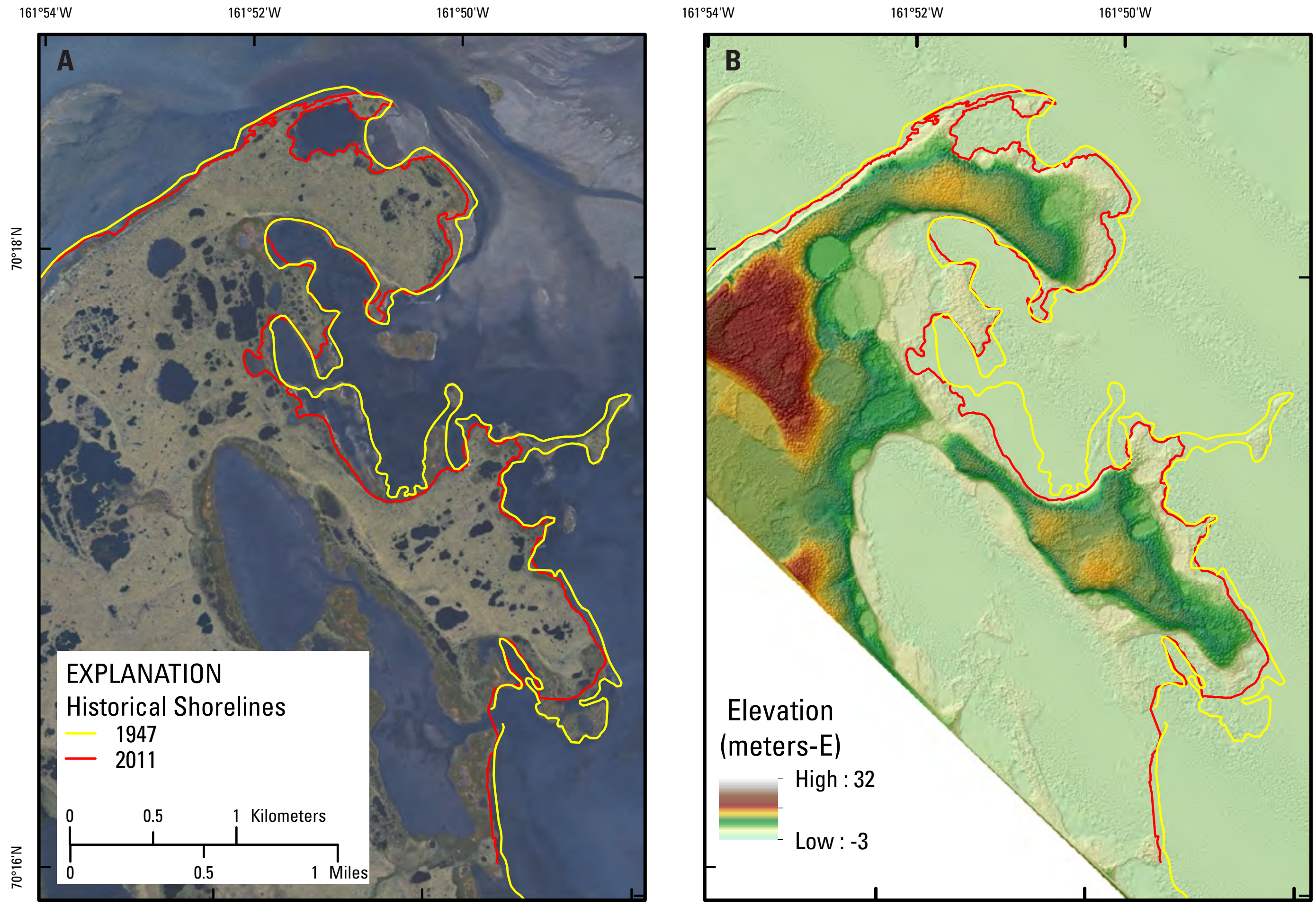

Figure 65. Map showing historical shorelines plotted over A, 2010 satellite image, and B, 2011 Digital Elevation Model of Icy of the lagoon coast near Icy Cape. Low elevation and discontinuous remnant tundra islands precluded reasonable shoreline change rates from being determined for this area.

significantly different, (-0.3 and -0.4 m/yr, respectively), however, the overall range in rates along the mainland-lagoon coast (-2.2 to +2.0 m/yr) is considerably lower compared to the open-ocean coast (-8.5 to +8.0 m/yr) (table 5). These higher rates along the open-ocean coast reflect erosion and accretion at the ends of barrier spits and islands associated with island breaching, infilling and inlet migration (figs. 66–68).

Sheltered Mainland-Lagoon Shoreline Change

The sheltered mainland-lagoon coast of Region 10 includes a ~40 km stretch within Peard Bay and a ~60 km stretch between Kilmantavi and Icy Cape Pass (fig. 64). The exposed mainland lagoon coast of Region 10 is predominantly erosional (77 percent of transects) with shoreline change rates averaging -0.3 m/yr, and ranging between -2.2 and +2.0 m/yr (table 5). The highest and lowest erosion rates along this stretch of coast are associated to the erosion and migration of barrier islands and their adjacent inlets (figs. 66 and 67; table 5).

Peard Bay

Within Peard Bay, the mainland coast is characterized by tundra bluffs varying between 3 and 8 m high except within Tachinisok Inlet and fronting the numerous small drainages and tapped thermokarst lakes near Kugrua Bay where no bluffs are present. Beaches are generally less than 25 m wide except along cuspate headlands, at Nalimuit Point, Walik Creek, Eluksingiak Point, and Asiniak Point where wider beaches occur (fig. 69A). The average rate of shoreline change for this coast is the same as the regional average of -0.3 m/yr but with a range between -2.2 and +1.7 m/yr (table 5). Relatively higher rates of change, both accretion and erosion, were measured near the headlands mentioned above.

Kilmantavi to Icy Cape

The lagoon coast between Kilmantavi and Icy Cape is similar to the Peard Bay coast, although bluffs reach up to 12 m high near Pingorarok Hill. The coast between the Nokotlek

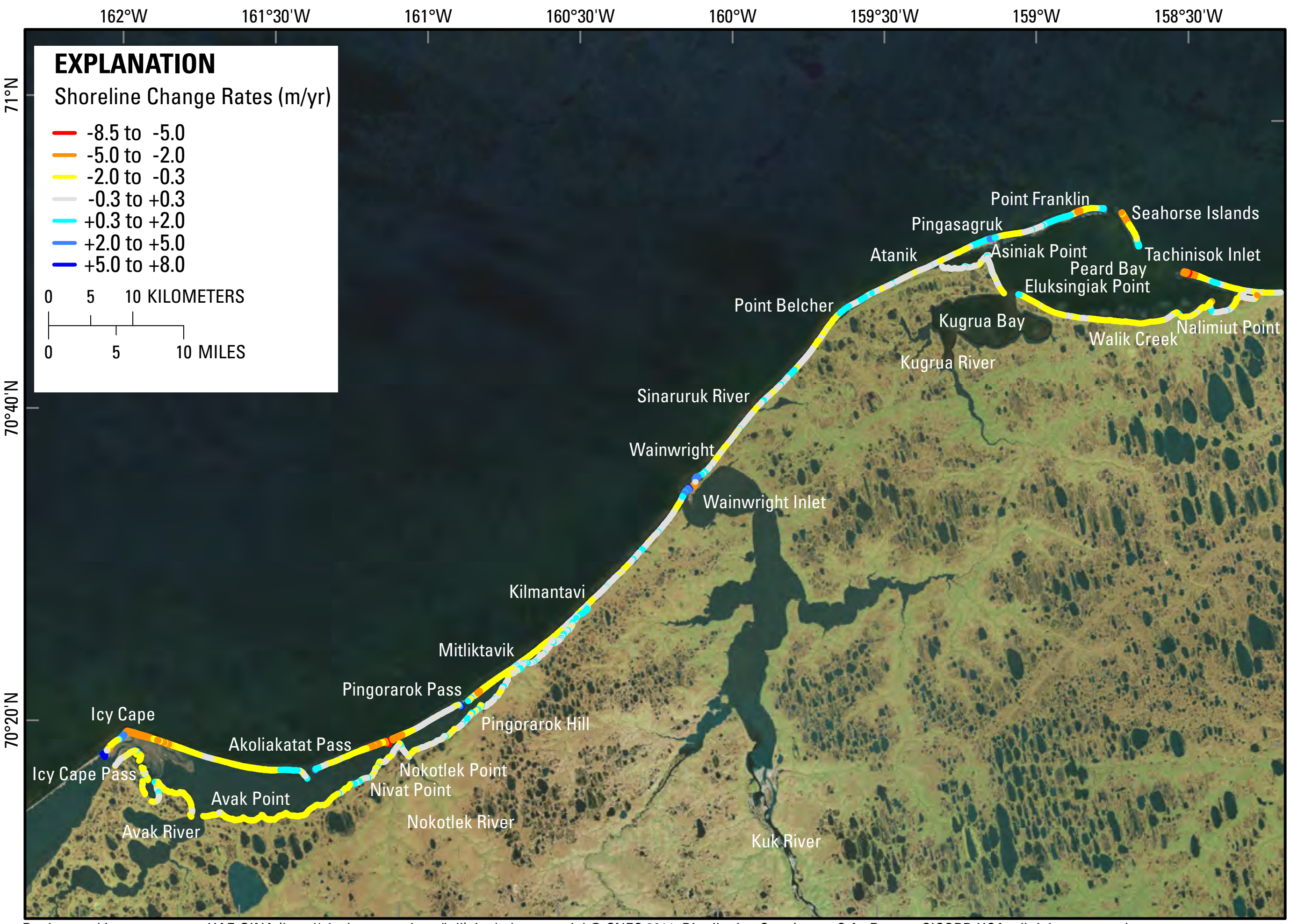

Figure 66. Map showing color-coded shoreline change rates in Region 10, Peard Bay to Icy Cape, north coast of Alaska. Width of line represents shoreline change envelope, or total shoreline change over analysis period, and distance between historical shorelines.

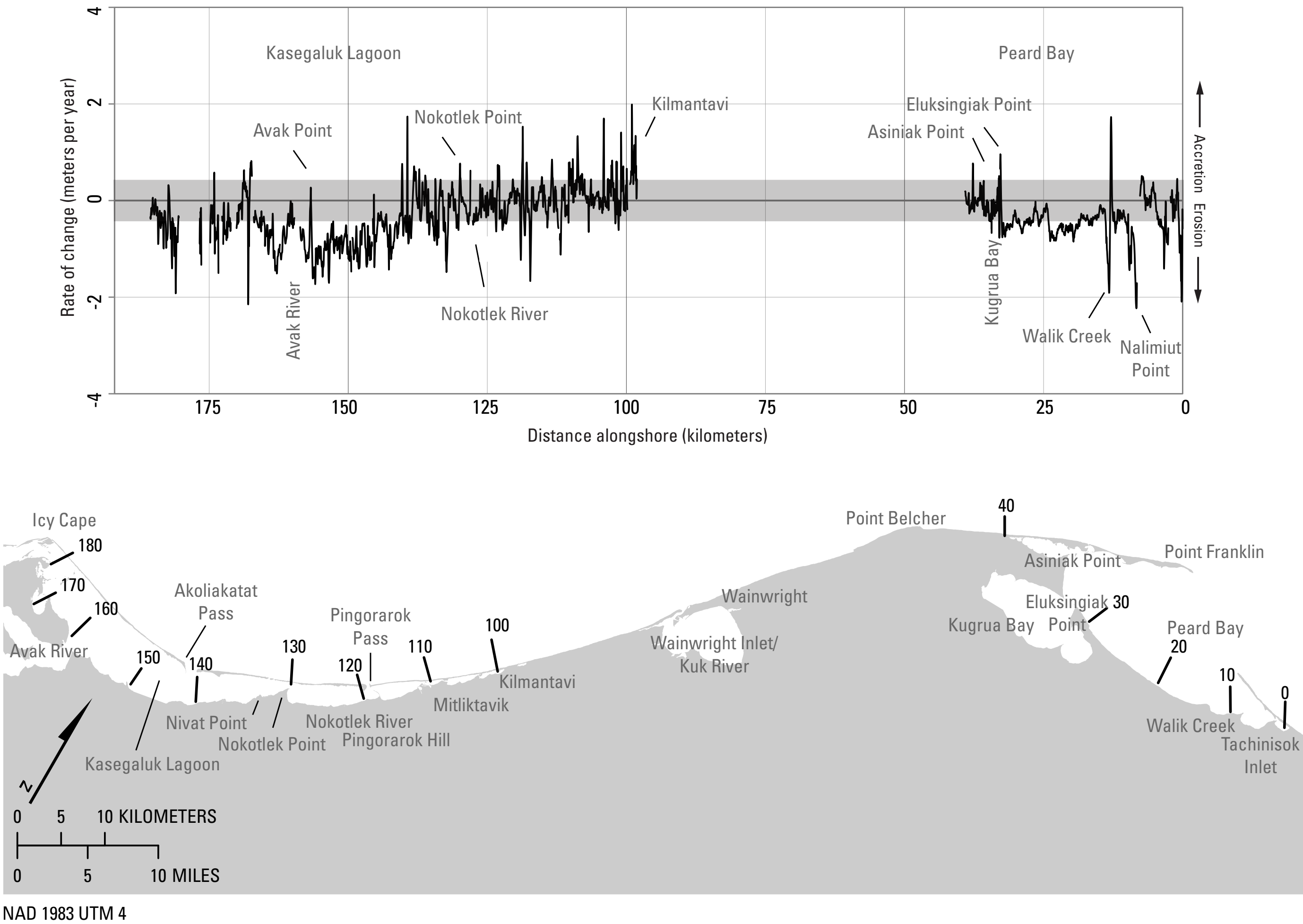

Figure 67. Top: Graph of shoreline change rates for sheltered mainland-lagoon coast of Region 10, Peard Bay to Icy Cape, north coast of Alaska. Gray bar is shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 10 indicating distances measured alongshore.

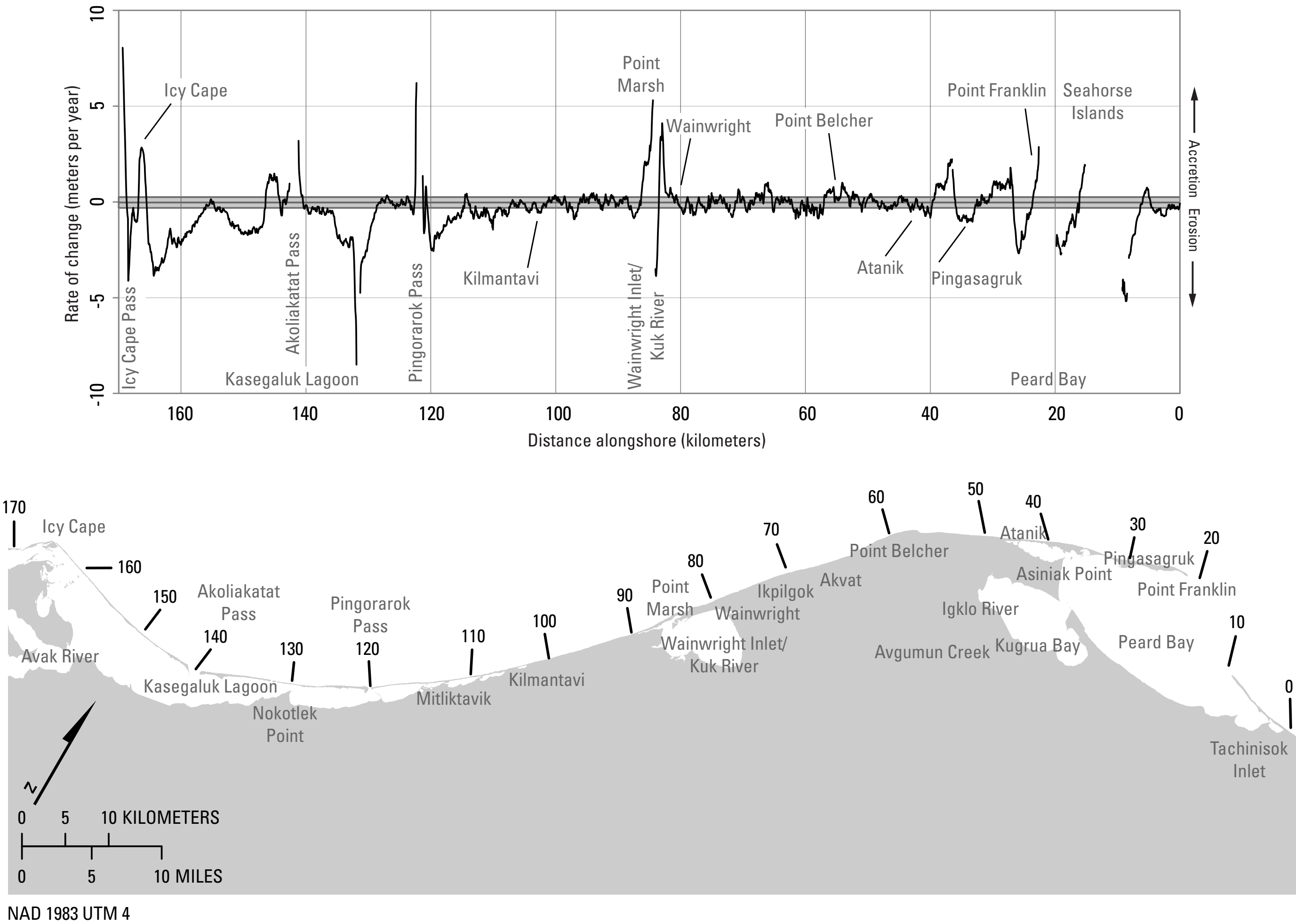

Figure 68. Top: Graph of shoreline change rates for exposed open-ocean coast of Region 10, Peard Bay to Icy Cape, north coast of Alaska. Note high rates of erosion and accretion at inlets, and increase in erosion rates west of about kilometer 145. Gray bar is the shoreline change rate uncertainty (±0.3 m/yr) for individual transects. Bottom: Map of coast of Region 10 indicating distances measured alongshore.

Figure 69. Aerial photographs showing typical examples of sheltered mainland-lagoon coast of Region 10, Peard Bay to Icy Cape, north coast of Alaska. A, Nalimiut Point, a cuspate headland on the mainland-lagoon coast of Peard Bay. Moderately-high tundra bluffs are visible in the background, view to southeast. B, Low to moderately high tundra bluffs near Nokotlek Point, view to the southeast. C, The low-lying coast near Avak Point with narrow beaches and numerous, large, thermokarst lakes on coastal plain, view to south. D, Low-lying coast near Icy Cape with inundated tundra and exposed mudflats. (All photographs taken in 2009; Gibbs and Richmond, 2010).

River and Icy Cape is lower-lying and the adjacent coastal plain comprises numerous and considerably larger thermokarst lakes. Beaches along this section are relatively narrow although several cuspate headlands are present such as Nokotlek Point and Nivat Points (fig. 69B). Shoreline change rates along this section of coast average -0.3 m/yr and range between -2.1 and +2.0 m/yr. Approximately 6 km west of Nivat Point, near Akoliakatat Pass, and continuing west toward Icy Cape the shoreline change trend becomes almost entirely erosional (94 percent of transects) and the average rate of shoreline change for this segment nearly doubles to -0.6 m/yr (figs. 66 and 67; table 5). In contrast to the coast to the east where >2 m high coastal bluffs are common, this section of coast is characterized by low-lying bluffs (<2 m) and numerous tapped thermokarst lakes (figs. 69C and 69D).

Exposed Open-Ocean Shoreline Change

The exposed open-ocean coast of Region 10 comprises barrier islands, barrier spits, barrier beaches, and tundra-bluff backed mainland beaches (fig. 64). Barrier islands include the Seahorse Islands, which mark the east side of Peard Bay, and a chain of islands starting between Kilmantavi and Mitliktavik and continuing west to the cuspate headland at Icy Cape and Icy Cape Pass. Barrier spits extend west from Tachinisok Inlet into Peard Bay, between Point Franklin and the abandoned site of Atanik, fronting Wainwright Inlet, and west from the abandoned site of Kilmantavi toward Mitliktavik. Barrier beaches front lagoons near Point Belcher and between Wainwright Inlet and Kilmantavi. Between Atanik and Kilmantavi the coast is predominantly mainland, high-tundra backed beaches.

The barrier islands, spits, and beaches in this region are low-lying (< ~2.5 m high), generally < 150 m wide, and mostly unvegetated to sparsely vegetated (figs. 70A–C). Wider, higher, and more well-vegetated areas are found near Icy Cape, Akoliakatat Pass, the spit south of Wainwright Inlet, Point Belcher and Pingasagruk, a pre-historical whaling village and Inupiat winter-house site (Reinhardt, 1993). The presence of well-developed vegetation on the barriers suggests historical stability and limited overwash of these locations relative to unvegetated portions of the barrier islands. Along the exposed, open-ocean

Figure 70. Aerial photographs showing typical examples of exposed open-coast shore types of Region 10, Peard Bay to Icy Cape, north coast of Alaska. A, Sparsely vegetated barrier spit near Point Franklin with coal deposits in the nearshore. B, Unvegetated barrier spit fronting a narrow lagoon between Kilmantavi and Mitliktavik. C, Densely vegetated, remnant tundra barrier island near Pingasagruk. D, Village of Wainwright fronted by shore protection structures. All views are to south. (All photographs taken in 2009; Gibbs and Richmond, 2010).

mainland coast between Atanik and Kilmantavi, beaches front bluffs, which reach up to 10 m high, and lagoons such as those near Point Belcher and southwest of Wainwright Inlet. The beaches are generally less than 100 m wide along this coast, but are relatively narrow fronting the village of Wainwright (<20 m), where shore protection structures are common (fig. 70D).

The exposed open-ocean coast of Region 10 is erosional (66 percent of transects, with shoreline change rates averaging -0.4 m/yr and ranging from -8.5 to +8.0 m/yr) (table 5). The barrier island and spits along the coast of Region 10 show little change over the study period (averaging -0.5 m/yr) except adjacent to inlets and are only slightly higher compared to the exposed mainland shorelines (0.0 m/yr) or the regional average (-0.3 m/yr). The coastal reach between Kilmantavi and Icy Cape Pass has a higher average rate of erosion (-0.8 m/yr) compared to other coastal segments in the region (figs. 66, 68; table 5). Many of the barrier islands and spits have migrated landward from their 1940s location, but maintained a similar overall morphology and orientation. The spit between Point Franklin and Atanik shows a regular, alongshore pattern of alternating erosion and accretion, with up to 170 and 180 m of shoreline erosion and accretion, respectively, but an overall average rate of change of 0.0 m/yr (table 5; fig. 71A). Patterns of inlet migration at Wainwright Inlet, Pingorarok Pass, and Icy Cape Pass, suggests a dominant easterly littoral transport direction along this section of coast (fig. 71). The spit at the southern shore of Wainwright Inlet accreted over 200 m and migrated nearly 400 m to the northeast, resulting in over 250 m of erosion the northeast bank of the inlet. The spit at Pingorarok Pass migrated over 1,300 km to the east and the inlet narrowed from 950 m in 1949 to less than 200 m in 2011. The spit at Akoliakatat Pass migrated to the southwest and narrowed the inlet from 1,300 m in 1949 to about 600 m in 2011. Two inlets formed between 1949 and 2011, near Nokotlek Point and north of Mitliktavik. The spit west of Icy Cape Pass migrated nearly 1,500 m to the northeast narrowing the channel from 700 to 180 m.

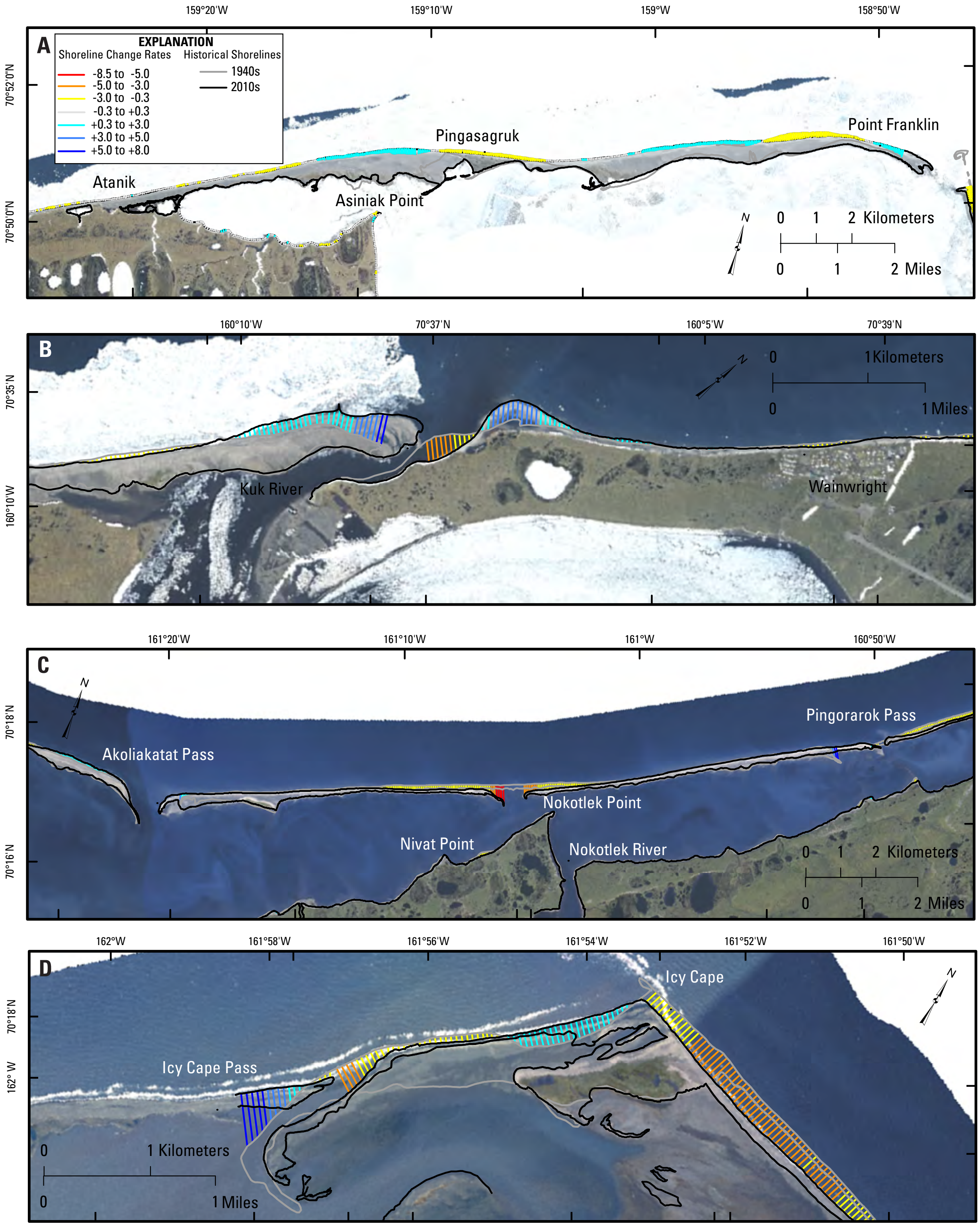

Figure 71. Detailed maps showing four examples of shoreline change patterns on barrier islands and spits within Region 10, Peard Bay to Icy Cape, north coast of Alaska, between 1947/49 and 2010/11. A, Regular, alternating patterns of shoreline erosion and accretion near Pingasagruk. B, Nearly 400 m of northeastward migration of Wainwright Inlet. C, Akoliakatat Pass migrated to the southwest and narrowed by nearly 700 m, an inlet formed in the barrier island near Nokotlek Point breached between 1949 and 2011, and Pingorarok Pass migrated more than 1,300 km to the east and the inlet narrowed by over 700 m. D, Spit west of Icy Cape Pass migrated nearly 1,500 m to northeast, narrowing the channel by over 500 m.

Discussion and Additional Considerations

The total length of coastline evaluated along the north coast of Alaska between the U.S.- Canadian border and Icy Cape is approximately 1650 km. Due to data gaps, typically around river deltas, or where historical data are lacking, the shoreline change analysis presented in this report covers approximately 80 percent of the coast. Shoreline change was found to be highly variable alongshore, with widely ranging rates of erosion and accretion common over short distances.

In order to maintain consistency with other NASC reports, the term erosion as used in this study indicates the measured landward movement or retreat of the shoreline. No distinction was made between physical erosion and land loss or shoreline retreat as a result of breaching of coastal lake shorelines or flooding of the coast due to sea-level rise and/or land subsidence; in this context erosion and retreat are interchangeable. Accretion as used in this study indicates the measured seaward progradation of the shoreline and, particularly in case of barrier islands and spits, may also represent the migration alongshore of a landscape feature.

Where shoreline change rates were quantified, the average rate of shoreline change for the entire study area was -1.4 m/yr with a range between -18.6 and +10.9 m/yr (fig. 72). This rate is based on 26,567 individual transects of which 84 percent were determined to be eroding (table 9). The calculated uncertainty on all shoreline change rates is ±0.3 m/yr. Average shoreline change rates along the Beaufort Sea coast, which represents 72 percent of the study area, is more than 5 times higher than along the Chukchi Sea coast (-1.7 and -0.3 m/yr, respectively).

The highest rates of both erosion and accretion in the study area were measured within Region 6, with rates of erosion greater than 18 m/yr between Cape Halkett and Pogik Bay and rates of accretion greater than 10.5 m/yr on the west side of Pogik Bay. The highest average rates of shoreline change (-6.3 m/yr) were measured within Region 6 and the lowest (-0.3 m/yr) along the Chukchi coast in Regions 9 and 10 (fig. 72).

Shoreline type and exposure is an important factor in observed shoreline change rates (table 9). Sheltered shorelines comprise 42 percent of all transects and 88 percent are erosional. Open-ocean exposed shorelines comprise 58 percent of all transects and 81 percent are erosional. Average shoreline change rates along exposed shorelines are twice as high (-1.8 m/yr) compared to sheltered shorelines (-0.9 m/yr). Barrier shoreline transects (including barrier islands, spits, and beaches) comprise 29 percent of the total transects and 50 percent of all exposed shoreline transects. Average shoreline change rates on barrier shorelines are not significantly different than exposed mainland shorelines (-1.7 and -1.8 m/yr); however, mainland shorelines (sheltered and exposed) have the lowest percent of erosional transects (12 percent) of all shoreline types. As discussed in the regional descriptions above, considerable migration and translation in the position of the barrier islands and spits resulting in substantial erosion and accretion was observed over the study period. Because of the lack of corresponding shoreline positions, some of these changes could not be measured using the DSAS method of analysis, particularly in Regions 3, 4, and 8. In those regions, there was a nearly 10 percent net increase (1,737,529 m^2) in total barrier island surface area during the study period.

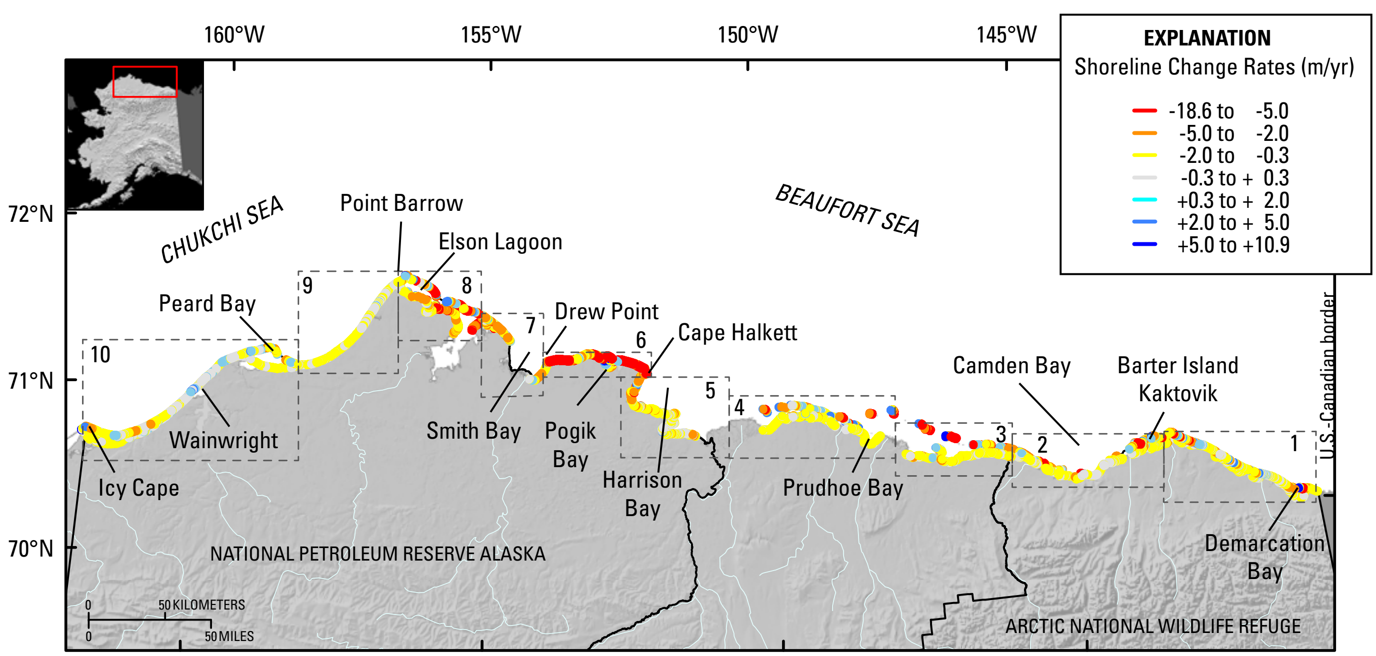

Figure 72. Map showing color-coded shoreline change rates for the north coast of Alaska, U.S.-Canadian border to Icy Cape and the boundaries of the ten analysis areas discussed in this report (dashed boxes and numbers).

Table 9. Summary of shoreline change rates for study area and each region relative to shoreline type.
[m/yr, meters per year]

Shoreline type	Number of transects	Average of rates (m/yr)	Maximum rate (m/yr)		Percent of transects		Percent of study area
			Erosion	Accretion	Eroding	Accreting	
Study Area: U.S.-Canadian border to Icy Cape							
All transects	26,567	-1.4	-18.6	10.9	84	16	100
Beaufort Sea coast	19,222	-1.7	-18.6	10.9	88	12	72
Chukchi Sea coast	7,345	-0.3	-8.5	8.0	74	25	28
All sheltered shorelines	11,199	-0.9	-16.4	10.9	88	11	42
All exposed shorelines	15,368	-1.8	-18.6	9.6	81	19	58
All mainland shorelines	18677	-1.2	-18.6	10.9	12	88	70
Only exposed mainland	7,478	-1.8	-18.6	7.3	87	12	28
Only exposed barriers (island, spit, beach)	7,725	-1.7	-17.9	9.6	75	25	29
Only exposed islands	165	-1.0	-2.6	0.9	92	8	0
Region 1: U.S.-Canadian border to Jago River							
All Transects	3,673	-1.0	-13.5	5.5	86	14	14
Sheltered shorelines	1,705	-0.5	-3.0	1.7	90	9	6
Exposed shorelines	1,968	-1.4	-13.5	5.5	82	18	7
Region 2: Jago River to Staines River							
All Transects	3,464	-1.1	-16.5	9.6	84	15	13
Sheltered shorelines	1,749	-0.5	-4.5	1.9	85	14	7
Exposed shorelines	1,715	-1.6	-16.5	9.6	83	17	6
Region 3: Staines River to Sagavanirktok River							
All transects	2,162	-1.5	-16.8	6.7	89	11	8
Sheltered shorelines	1,439	-0.8	-4.4	2.7	93	6	5
Exposed shorelines	723	-3.0	-16.8	6.7	81	19	3
Region 4: Sagavanirktok River to Colville River							
All transects	2,973	-1.1	-14.7	7.0	85	15	11
Sheltered shorelines	1,918	-0.8	-4.2	1.2	95	5	7
Exposed shorelines	1,055	-1.6	-14.7	7.0	66	34	4
Region 5: Colville River to Cape Halkett							
All transects (all exposed)	1,989	-1.1	-9.6	5.0	92	8	7
Region 6: Cape Halkett to Drew Point							
All transects	1,545	-6.3	-18.6	10.9	90	10	6
Sheltered shorelines	202	-0.5	-5.7	10.9	62	38	1
Exposed shorelines	1,343	-7.1	-18.6	7.3	94	6	5
Region 7: Drew Point to Dease Inlet							
All transects	1,315	-2.4	-16.4	3.4	92	8	5
Sheltered shorelines	457	-3.2	-16.4	0.6	96	4	2
Exposed shorelines	858	-1.9	-6.8	3.4	90	10	3
Region 8: Dease Inlet to Barrow							
All transects	2,228	-2.5	-17.9	7.0	90	10	8
Sheltered shorelines	1,406	-2.1	-9.9	4.9	95	5	5
Exposed shorelines	822	-3.2	-17.9	7.0	82	18	3
Region 9: Barrow to Peard Bay							
All transects (all exposed)	1,779	-0.3	-1.2	0.7	86	14	7
Region 10: Peard Bay to Icy Cape							
All transects	5,439	-0.3	-8.5	8.0	71	29	20
Sheltered shorelines	2,323	-0.3	-2.2	2.0	77	23	9
Exposed shorelines	3,116	-0.4	-8.5	8.0	66	33	12

Influence of Human Activities

The influence of local human activities on the Arctic coast is relatively modest compared to the remainder of the U.S. coastline. Coastal development is limited to 3 villages (Barrow, Wainwright, and Kaktovik), 13 DEW radar sites and the extensive but spatially restricted infrastructure associated with oil and gas extraction activities. Seasonal fish camps and whaling villages are scattered along the coast and barge landing sites are common adjacent to the villages and oil and gas sites. Native Inupiat utilize the coast and nearshore waters extensively for subsistence hunting, fishing, and trapping.

Shore protection structures, primarily sand bags and rock-filled gabion revetments, discontinuously front the bluffs in the villages and at some oil and gas developments. Buildings and municipal infrastructure are located within several hundred meters of the coast and many primary roads, commonly artificially elevated, run along the coast behind the primary berms. Sand and gravel mining in the nearshore littoral environment around the villages, particularly Barrow and DEW sites was common practice historically, but has for the most part ended (Jorgenson, 2011).

The first large-scale development in the region began in the 1950s with the construction of the Distant Early Warning (DEW) Line system. Thirteen sites were built on the Arctic coast between Icy Cape and the U.S. Canadian border. Most sites were deactivated in the early to late 1960s, however, several sites were rebuilt as North Warning System sites (Wainwright, Barrow, Lonely, Oliktok, Flaxman Island, Barter Island). Only Barrow, Oliktok, and Barter Island are still active. The sites produced large amounts of hazardous waste. Several of the sites are now threatened by coastal erosion and clean-up and remediation are presently underway. The landfill at Barter Island was relocated landward in the late-2000s although some I-beams and structures previously emplaced to protect the old landfill remain in the nearshore environment. Remnant gravel pads and airstrips remain at most of the abandoned locations.

Coastal development associated with oil and gas activities started in the late 1960s with the discovery of the Prudhoe Bay fields in 1968. Numerous exploration wells drilled in the 1970s are scattered across the landscape and are becoming increasingly vulnerable to coastal erosion. Several causeways and artificial islands have been constructed along the coast near Prudhoe Bay and gravel pads and roads supporting development facilities are widespread. Few of the production sites sit right on the coast, however where present, significant modification to the coasts and beaches have occurred.

The warming of the Arctic and decline in the extent of summer sea-ice is leading to an increase in both commercial and recreational shipping traffic in the region. Development of offshore oil and gas leases in the Chukchi and Beaufort Seas is also intensifying. The combination of these two activities may result in considerable coastal development along the Arctic coast in the near future.

Planned Updates

During the course of this study, two additional regional shoreline data sets, circa-1979 Alaska High Altitude Photography and 2009–2012 high-resolution coastal lidar surveys, were identified. They are currently being processed and will be incorporated into the shoreline change data base and analysis and released as an update to this study when completed. The USGS typically to revises and update rates of shoreline change every 5 to 10 years, or when new data sets are identified and acquired. Therefore, this report and associated data are a work in progress. The revision interval will depend on the availability of new shoreline data and technological advances. Continued monitoring of shoreline change is vital in the coming decades as the dynamics of the coastal environment that lead to beach erosion (for example, sea-level rise, storms, and waves) are likely to change with changing climate.

Acknowledgments

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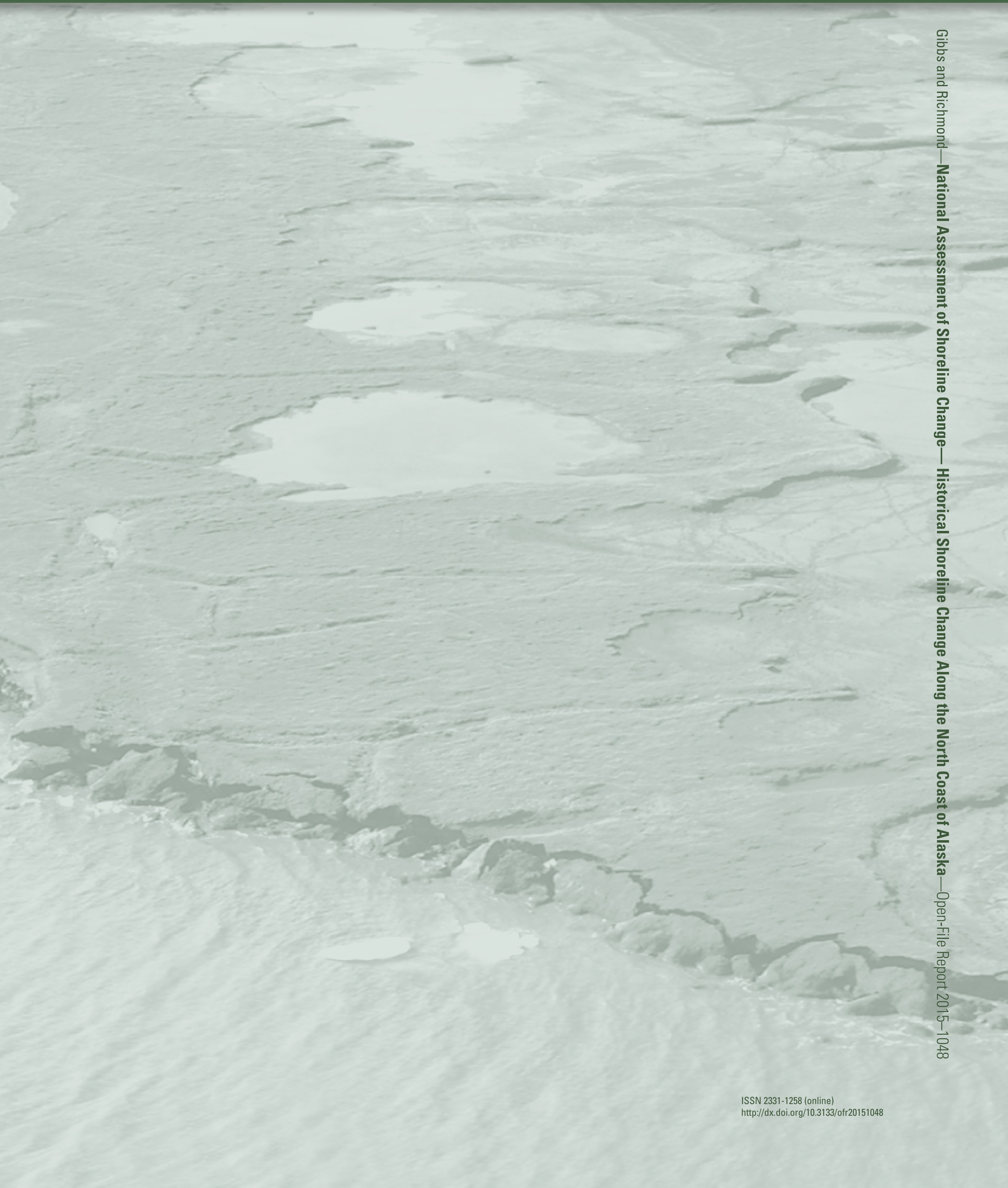

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