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Abstract

We assembled approximately 230,000 U.S. National Ocean Service (NOS) bathymetric soundings from 39 lead-line and single-beam echosounder hydrographic surveys conducted from 1896 to 2005 in Norton Sound, Alaska. These bathymetry data are available from the National Geophysical Data Center (NGDC: http://www.ngdc.noaa.gov), which archives and distributes data that were originally collected by the NOS and others. While various bathymetry data have been downloaded previously from NGDC, compiled, and used for a variety of projects, our effort differed in that we compared and corrected the digital bathymetry by studying the original analog source documents - digital versions of the original survey maps called smooth sheets. Our editing included deleting erroneous and superseded values, digitizing missing values, and properly aligning all data sets to a common, modern datum. We incorporated 3 multibeam surveys, and added an additional 6,992 single-beam soundings from the 2010 Northern Bering Sea bottom trawl survey to fill in where smooth sheet data were lacking. We proofed and digitized 312 cartographic features, comprised mostly of rocks and islets and also digitized 4,305 verbal sediment descriptors, and digitized or adapted 2,142 km of mainland and 837 km of island shoreline. These data are not to be used for navigational purposes.

Contents

Introduction

Our smooth sheet bathymetry covers Norton Sound, west to the eastern point of St. Lawrence Island, south to the Yukon River delta, and north along the Seward Peninsula and around the point of Cape Prince of Wales (Fig. 1). The earliest hydrographic surveys in Norton Sound were conducted in the late 1890s and early 1900s; more recent work started again in 1950, and a few modern multibeam surveys have also been conducted in the region.

Observed by Captain James Cook in 1778, Norton Sound was named after Speaker of the British House of Commons, Sir Fletcher Norton (Griffith 1999). The oldest outpost in the area was a Russian trading post at St. Michael founded in 1833, the first Russian settlement north of the Aleutians (Collier et al. 1908, Whymper 1868). Prior to the 1898 discovery of gold at Anvil Creek on the Seward Peninsula, only a few non-Natives were present in the area (Schrader and Brooks 1900). The subsequent gold rush led in 1901 to an influx of 12,000-20,000 people into the area which would eventually become Nome. In just 13 years, over $60 million in gold was recovered from the gold mines at Nome and surrounding sites on the Seward Peninsula (OCS 1990). As of 2010, there were less than 3,600 people living in Nome and less than 10,000 people living in the entire region (U.S. Census Bureau 2010).

Travel to Nome at the time of the gold rush was quite difficult. Aside from a few local trails there were, and currently are, no roads or railroads connecting Nome to any of the other major cities in Alaska, Canada, or the lower 48 states of the United States. The distance to Nome is more than 4,000 km by sea from the port of Seattle, and sea access is only available from June to November due to ice cover. The rest of the year travel within and to the region relied on dog sled, a method tested in the early history of Nome. During the winter of 1925, Nome was ice bound and its residents were in the middle of a diphtheria outbreak. The nearest stock of medicine was in Anchorage, where it was placed on a train to Nenana, the nearest station to Nome, still over 600 miles away. The rest of the distance was covered by dog sled, using 20 different mushing teams over the course of just 6 days, a feat that would normally take 30 days (Borneman 2003). The Annual Iditarod Sled Dog Race follows some remnant trails from the gold rush and commemorates the 1925 delivery of diphtheria serum to the isolated city of Nome (OCS 1990).

The major landmarks that fall within the Norton Sound region are St. Lawrence Island on the western boundary, St. Michael Island, Stuart Island, Besboro Island, Sledge Island, and King Island, as well as Norton Bay, Golovnin Bay, Port Clarence, Imuruk Basin, Safety Sound, and the Yukon River delta, while the main towns are Nome, Unalakleet, and St. Michael (Fig. 1). The important fisheries, both commercial and subsistence, in Norton Sound include red king crab, *Paralithodes camtschaticus*, five species of Pacific salmon, *Oncorhynchus* spp., and Pacific herring, *Clupea pallasii* (OCS 1990).

Recently, Nome has been selected as the potential site for a new deep water port in the Arctic; currently the nearest deep-draft port is nearly 2,000 km to the south in Dutch Harbor. Creating a deep water port in the region will support increasing vessel traffic and bolster economic development in the remote Arctic region (U.S. Army Corps of Engineers 2015).

While mariners have routinely used the small-scale NOS navigational charts (1:100,000) for about a century, the source data - the original, detailed hydrographic surveys - remained relatively unknown to those outside of the NOS. In 2005, the National Geophysical Data Center (NGDC) began hosting electronic copies of the hydrographic surveys. This project focused on working with the original bathymetric survey data available from NGDC and combining them into a single data set, digitizing the sediment information, as well as adding and correcting any features. In Norton Sound, these surveys date as far back as the late 1890s and early 1900s because they are the best, and often only, surveys available. These data are not to be used for navigation.

Methods

We downloaded and examined single-beam and lead line hydrographic survey smooth sheet data sets available in whole or in part from the NGDC (http://www.ngdc.noaa.gov), to create a bathymetry map of Norton Sound.

Each data set provided by NGDC generally consists of three parts: a typed or hand-written document called the Descriptive Report which contains much of the survey metadata, a nautical chart called the smooth sheet which depicts the geographical placement of the soundings written as numerals, and a text file of the soundings from the smooth sheet (Wong et al. 2007). Some of the more modern surveys were accompanied by an original text or data file of the soundings, which contained more points than were written on the final smooth sheet, making proofing difficult at times. Older surveys that predated the computer era did not have an original file, and these were digitized from the smooth sheets (Wong et al. 2007). A paper smooth sheet with muslin backing was the final product of a hydrographic survey (Hawley 1931). The text file of soundings is a modern interpretation of the smooth sheet, produced in a vast and expensive digitizing effort to salvage millions of hydrographic soundings from thousands of aging paper smooth sheets in U.S. waters, done largely without any error-proofing (Wong et al. 2007).

To produce a continuous, interpolated, bathymetric surface, it is simplest to download and plot the digitized soundings in a Geographic Information System (GIS), this can be accomplished in a matter of hours or days. This is the goal of most users. A generalized surface which shows the central bathymetric tendency is a valuable product in the relatively unknown and unexplored Alaskan waters, but such efforts have limited value in that they tend to smooth errors and blur seafloor features. Our goal was to describe the individual features (flats, bumps, and dips) that create the bathymetry, and we have found that there are too many errors in the digitization process to ignore. Therefore, over the course of several months, we made very careful comparisons between the smooth sheet soundings and the digitized soundings, correcting any errors, and producing an edited version of the NGDC bathymetry. We accomplished this error-proofing in a GIS by georeferencing the smooth sheets, custom datum-shifting them into a common, modern datum, and making comparisons to the digitized text file provided by NGDC. Details of the methods are described in Zimmermann and Benson (2013).

Norton Sound is generally well covered by smooth sheet surveys, except for four gaps in the coverage. In an attempt to fill in these gaps we also analyzed single-beam data from the NMFS (National Marine Fisheries Service) bottom trawl survey in 2010 (Lauth 2011) and USGS (U.S. Geological Survey) cruises taking place from 1977 to1983, and examined the NOAA charts in the region. Ultimately a subset of the 2010 data was added, but the USGS cruise data could not be reconciled with the smooth sheets or within itself, and the NOAA charts presented the same gaps.

Bathymetric features, such as rocks and islets, were also proofed, edited, and digitized. Verbal sediment descriptions were also digitized from the smooth sheets. Short abbreviations such as "S" and "M" were translated into their full names of "Sand" and "Mud". Position of the sediment points were centered on the written description.

Mainland and island shorelines were digitized mostly from the smooth sheets using the Editor in ArcMap. Gaps in the smooth sheet shorelines were filled with other sources: the King

Island shoreline was digitized from NOS Chart 16204; the Brevig Lagoon shoreline was adapted from the National Shoreline (http://www.ngs.noaa.gov/NSDE/); the Nome Harbor shoreline was adapted from the Continually Updated Shoreline Product (http://www.ngs.noaa.gov/NSDE/); and the Yukon Delta shoreline was digitized from JPEG images of T-sheets (http://nosimagery.noaa.gov/images/shoreline_surveys/survey_scans/NOAA_Shoreline_Survey_Scans.html). The Mean High Water (MHW) value was obtained from the smooth sheets or the smooth sheet descriptive reports, which often noted that wind strength and direction had a significant impact on sea level.

Results

Our efforts resulted in the inclusion of 39 smooth sheet surveys from which we proofed, edited, or digitized 91,192 soundings and cartographic features. Of the 40 surveys in the region, survey H02263 was not incorporated due to sparse coverage and no identifying coordinate system/geographic reference; survey H02462 was only partially used, its poor quality from aging and warping left only the middle section legible enough to be included. We fully or partially digitized 6 surveys (Table 1). Several surveys had cartographic features fully or partially missing, which we digitized. There are four significant areas of missing data (Fig. 2). The largest gap is in the south along the Yukon River delta between Kawanak and Apoon passes. The second gap, along the coast north of Sledge Island, is only sparsely filled with soundings from an old, low resolution survey, no other data appears to be available for the region. The other two gaps are smaller, located in the inner portion of the sound, with the upper gap located near the entrance to Norton Bay and the lower gap off the coast of Unalakleet.

Proofing and editing were variable among smooth sheet data sets. We encountered most of the characteristic and random errors described in Zimmermann and Benson (2013) so each smooth sheet needed to be read and interpreted individually. For example, H02450 had mistakenly digitized an “S” sand label as a 5 m sounding, and had numerous “deeper than soundings,” soundings indicating the lead line was not deep enough to reach the bottom, denoted by fractions with zero in the numerator and the length of the rope in the denominator. H09179 had more soundings than labels, which made proofing more difficult, but it was clear, based on the surrounding soundings, that several of these unlabeled soundings were in error, so they were taken out of the compilation. Due to the datum shift, several of the sounding files had to be shifted to accommodate the new alignment; some such as H02450 and H02478 required shifting in sections. Even fully digitizing surveys had to be done carefully; H02499 and H02505 were charted in both feet and fathoms, switching from fathoms to feet in waters shallower than 3 fathoms.

We used 2010 single-beam echosounder data (Lauth 2011) to fill in some of the gaps that the smooth sheets did not cover. This led to an additional 6,992 soundings, adding data to the northeastern gap in the coverage (Fig. 2). It is unknown if any corrections were made to this data before we obtained it; its incorporation into our coverage fit reasonably with surrounding smooth sheet data, and no editing was done on our part. We also examined USGS data to fill in gaps, but could not reconcile the USGS data with the smooth sheet data (USGS CMG InfoBank). The USGS data contradicted itself at different passes and disagreed with overlapping smooth sheet data (Fig. 3). Because there was no obvious pattern to the discrepancies and we could not reconcile the USGS data with the smooth sheet data, we chose to leave it out of the coverage.

Bathymetric Surface

The edited smooth sheet bathymetry points, along with the features with elevations, the single-beam and multibeam data, and shoreline point data were processed into a solid surface of variably-sized triangles (Triangular Irregular Network or TIN) which utilized the points as corners of the triangles. The TIN was then converted by linear interpolation into a solid surface of 100 m squares (GRID). Those grid cells that appeared on land, or outside of the area covered by the smooth sheets, were eliminated and a new grid was made which only covered the water (Fig. 1). Norton Sound is relatively flat with a depth ranging from -1.3 to 63 m. The average depth of the coverage is 22. 3 m, while the average depth within the sound itself, taking from the western point of the Yukon delta and eastward, is only 13 m. The surface area of the sound is 31,379.3 km^2, while the volume is 435.8 km^3. There are two deeper zones within the sound: one flowing out from Golovnin Bay and the other running parallel to the coast off Nome. The causes of these two deeper regions are unknown.

Shoreline

We digitized or adapted 2,142 km of mainland and 837 km of island shoreline. The total study area, ranging from the mainland shoreline to the offshore boundary, covered 78,852 km^2, with a total of 328 islands occupying 837 km^2 of that area. MHW of the shoreline was low, ranging from -1.28 m in the Norton Bay area to -0.18 m north of Sledge Island.

Features and Sediment

There are a total of 312 cartographic features in the Norton Sound region, with 14 of the 39 surveys containing features. They were predominantly rocks (n = 254) and islets (n = 41) (Fig. 4).

We digitized 4,305 verbal sediment descriptions present in 32 of the 39 surveys, with 120 unique categories. Hard (n = 1623), Soft (n = 1289), and Sticky (n = 591) were the most prevalent. In addition, there were descriptions which provided more detail about a sample. For example, aside from the simplistic description of Sand (n = 125), there were also numerous instances such as Fine Gray Sand (n = 41), Hard Sand (n = 98), and many others that combined color and/or shape of the sediment, each getting their own unique label. There were also numerous, complicated, or specific sediment descriptions with 71 of the 120 categories having only a single occurrence. The majority of these sediments were concentrated along the shorelines, with relatively few in the center sound or offshore (Fig. 5).

Age of Surveys

Most of the surveys (n = 23) were completed in the late 1890s to early 1900s coincident with the 1898 gold rush in the area. The newer surveys, from 1950 through 2005 (n = 16), accounted for just over 80% of the smooth sheet soundings, superseding several of the older surveys in the center of Norton Sound, while the older surveys filled the shallower and inshore regions.

Datums and Datum Shifts

All the surveys conducted in the late 1890s to early 1900s lacked information describing which horizontal datum was used. The more modern surveys from the 1950s to the 1970s were conducted in North American Datum of 1927 (NAD27), while the most recent smooth sheet surveys from 2005, and the multibeam surveys, were conducted in North American Datum of 1983 (NAD83). We calculated unique datum shifts for each smooth sheet, aligning them with North American Datum of 1983 High Accuracy Reference Network (NAD83 HARN), so that the original datum, even if it was unknown, did not affect how the data could be accurately compared and combined. This was done by comparing locations of triangulation stations between the original datum and the modern NAD83, as detailed in Zimmermann and Benson (2013). Due to the age of some of these surveys, not all had modern triangulation stations and this led to difficulties in shifting datums. Some were aligned by using already shifted, neighboring surveys and quality checking with the neighboring surveys and a land coverage map. Other surveys such as H02263 had to be abandoned because there were no markings, stations or coordinates to allow for comparison with other surveys or to allow proper georeferencing and datum shifting.

Soundings

The soundings downloaded from NGDC were plotted in a GIS to determine if their positions corresponded to the sounding numerals written on the georeferenced and datum-shifted smooth sheets. We defined agreement between the digital soundings and the soundings on the smooth sheet to be when the digital soundings were "on or near" the written soundings on the smooth sheet. In general, there were numerous substantial differences between many of the digital sounding data sets and the smooth sheets, which required shifting the soundings as a group to align with the smooth sheets. Some of these shifts corresponded to the difference between the original smooth sheet datum and NAD 1983 HARN (a few hundred meters). However, since some data sets aligned perfectly, each needed to be checked individually.

This comparison between the soundings and the smooth sheets also served the purpose of checking for errors or incompleteness in the soundings files. Errors in the soundings, such as those misplaced, missing, incorrectly entered, or otherwise in disagreement were corrected (Zimmermann and Benson 2013). Sometimes there was little or nothing to correct. Other times there were numerous or significant errors, which made this a tedious and time-intensive error-checking process.

Scale and Coverage

The scale of the surveys was quiet variable (Table 1). The survey scales were spread fairly evenly between 1:20,000 (n = 11), 1:40,000 (n = 7), 1:80,000 (n = 6), and 1:100,000 (n = 4), with extremes at 1:10,000 and 1:1,000,000.

Data Quality

Data quality is quite variable on the smooth sheets. Some are barely legible and the inshore area is a confusing array of amorphous islands, marshes, sparse features, and isolated soundings in otherwise blank water. Others appear crisp, clean, well-organized, and reveal surprising details.

Discussion

We consider this smooth sheet bathymetry compilation a rough first draft, detailing the bathymetry, features, and sediments of Norton Sound. Our slow method of data editing and compilation, which relied on comparing the digitized soundings to the smooth sheets in a GIS, was critical to the discovery and elimination of numerous errors, such as incorrect, misplaced and missing soundings. Properly accounting for the horizontal shift from the original datum to NAD 1983 HARN was the most important part of our error-checking.

Our digitized coastline was compiled from many of the older smooth sheet data. We compared our shoreline to modern satellite imagery and noticed a shift in the Yukon River delta (World Imagery ArcGIS, Esri®). The western portion of the delta has accreted as much as 2 km while the eastern portion of the delta has eroded about 500 m.

Norton Sound is very shallow. Looking at a comparison with our compilation in Cook Inlet, Norton Sound has a larger surface area, 31,379.3 km^2 to Cook Inlet's 20,540 km^2, but less than half the MHW volume, 435.8 km^3 compared to 1,024.1 km^3 (Zimmermann and Prescott 2014).

This Norton Sound bathymetry compilation is part of a GAP (Groundfish Assessment Program) effort to create more detailed bathymetry and sediment maps to provide a better understanding of how studied animals interact with their environment, to identify Essential Fish Habitats (EFH), and to aid GAP scientists who conduct stock assessment bottom trawl surveys in survey planning by using the information to delimit areas that cannot be sampled effectively with bottom trawls. The results from this project may result in a separate survey conducted by another method, such as underwater cameras or acoustics, to assess the abundance of fish in the untrawlable areas. More detailed and accurate bathymetry and sediment information was requested in the EFH request for proposals because the NOAA, NMFS Alaska Regional Office was interested in "a new predictive modeling effort examining Norton Sound red king crab and potential effects of offshore marine mining activities on their habitat." The Alaska Regional Office may also investigate use of the bathymetry and sediment information to oversee sustainable fisheries, conduct EFH reviews, and manage protected species.

Acknowledgments

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Table 1. -- List of smooth sheet bathymetry data sets for Norton Sound.

Survey	Scale	Year	Vessel	Datum
H02263*	20000	1896	*Bear*	Unknown
H02362	20000	1898	*Yukon, Taku*	Unknown
H02363	80000	1898	*Yukon, Taku*	Unknown
H02382	30000	1899	*Patterson*	Unknown
H02416	10000	1899	*Patterson*	Unknown
H02449	80000	1899	*Yukon, Taku*	Unknown
H02450	20000	1899	*Taku*	Unknown
H02452	20000	1899	*Taku*	Unknown
H02462**	200000	1899	*Patterson*	Unknown
H02477	20000	1900	*Pathfinder*	Unknown
H02478	80000	1900	*Pathfinder*	Unknown
H02479	80000	1900	Unknown	Unknown
H02480	80000	1900	Unknown	Unknown
H02481	80000	1900	Unknown	Unknown
H02482	40000	1900	*Pathfinder*	Unknown
H02499	40000	1900	*Patterson*	Unknown
H02505	40000	1900	*Patterson*	Unknown
H02508	40000	1900	*Patterson*	Unknown
H02516	20000	1900	*Patterson*	Unknown
H02517	10000	1900	*Patterson*	Unknown
H02518	40000	1900	*Patterson*	Unknown
H02519	40000	1900	*Patterson*	Unknown
H02604	1000000	1902	*Patterson*	Unknown
H07835	20000	1950	*Explorer*	NAD 27
H07837	20000	1950	*Explorer*	NAD 27
H07838	20000	1950	*Explorer*	NAD 27
H07840	40000	1950	*Explorer*	NAD 27
H07849	20000	1950	*Pioneer*	NAD 27
H07844	20000	1950	*Pioneer*	NAD 27
H09020	100000	1968	*Surveyor*	NAD 27
H09022	100000	1968	*Surveyor*	NAD 27
H09025	100000	1968	*Surveyor*	NAD 27
H09026	100000	1970	*Surveyor*	NAD 27
H09048	100000	1970	*Surveyor*	NAD 27
H09164	100000	1970	*Rainier*	NAD 27
H09165	100000	1970	*Rainier*	NAD 27
H09166	100000	1970	*Rainier*	NAD 27
H09179	243000	1970	*Rainier*	NAD 27
H11453	10000	2005	*Bristol Endeavor*	NAD 83
H11454	10000	2005	*Bristol Endeavor*	NAD 83

Multibeam (Combined at 5 m Resolution)				
	Resolution			
H11273	5 m	2005	*Bristol Endeavor, Peregrine*	NAD 83
H11274	5 m	2005	*Bristol Endeavor, Peregrine*	NAD 83
H12232	5 m	2010	*Fairweather*	NAD 83
Trawl Survey**	Unknown	2010	*Vesteraalen*	Unknown

*Left out of compilation
**Only partial use

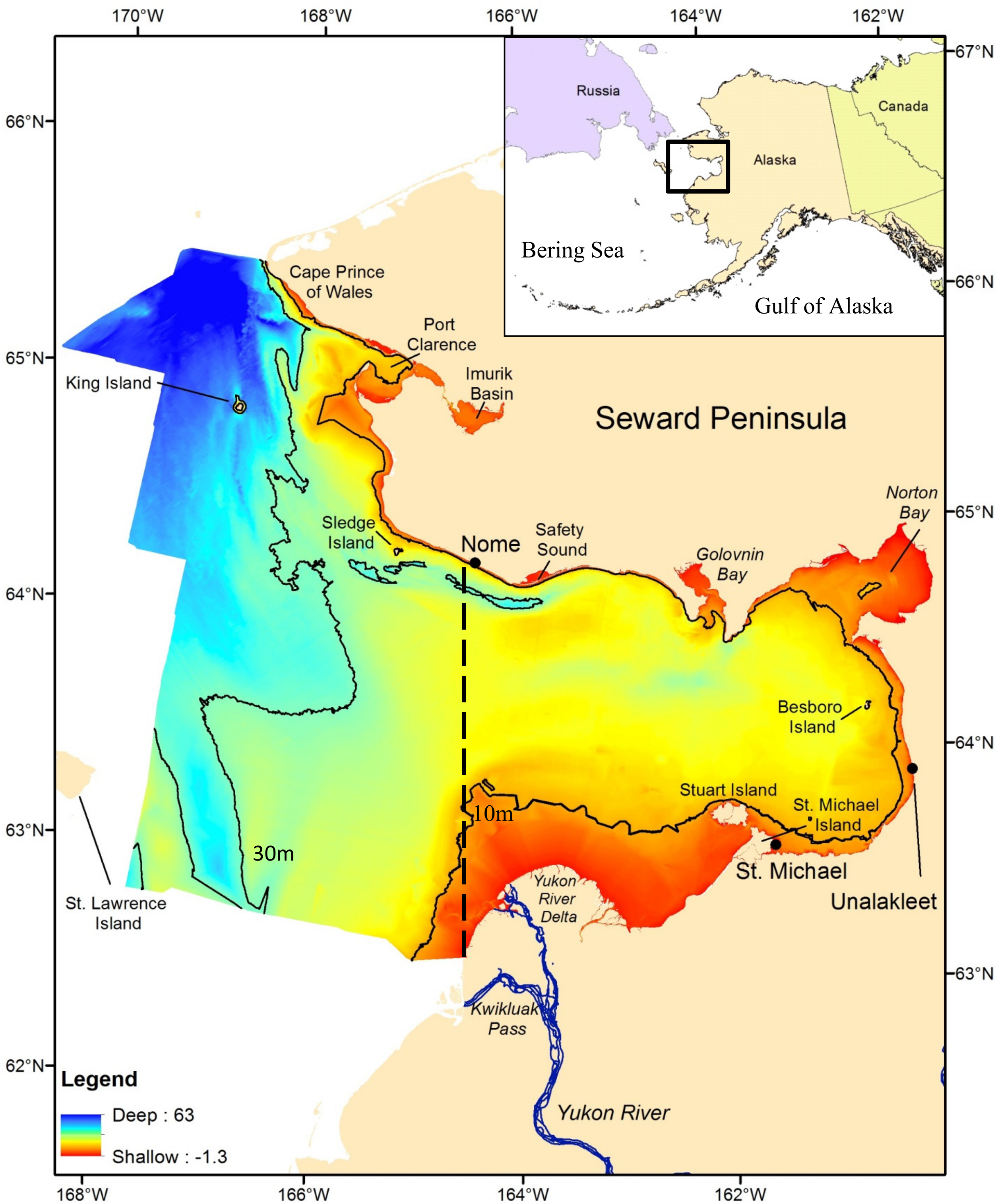

Fig. 1. -- The bathymetric coverage of Norton Sound and important locations within the region. Contour lines mark depths of 10 m and 30 m. The dashed line shows our boundary for Norton Sound, itself. Not to be used for navigational purposes.

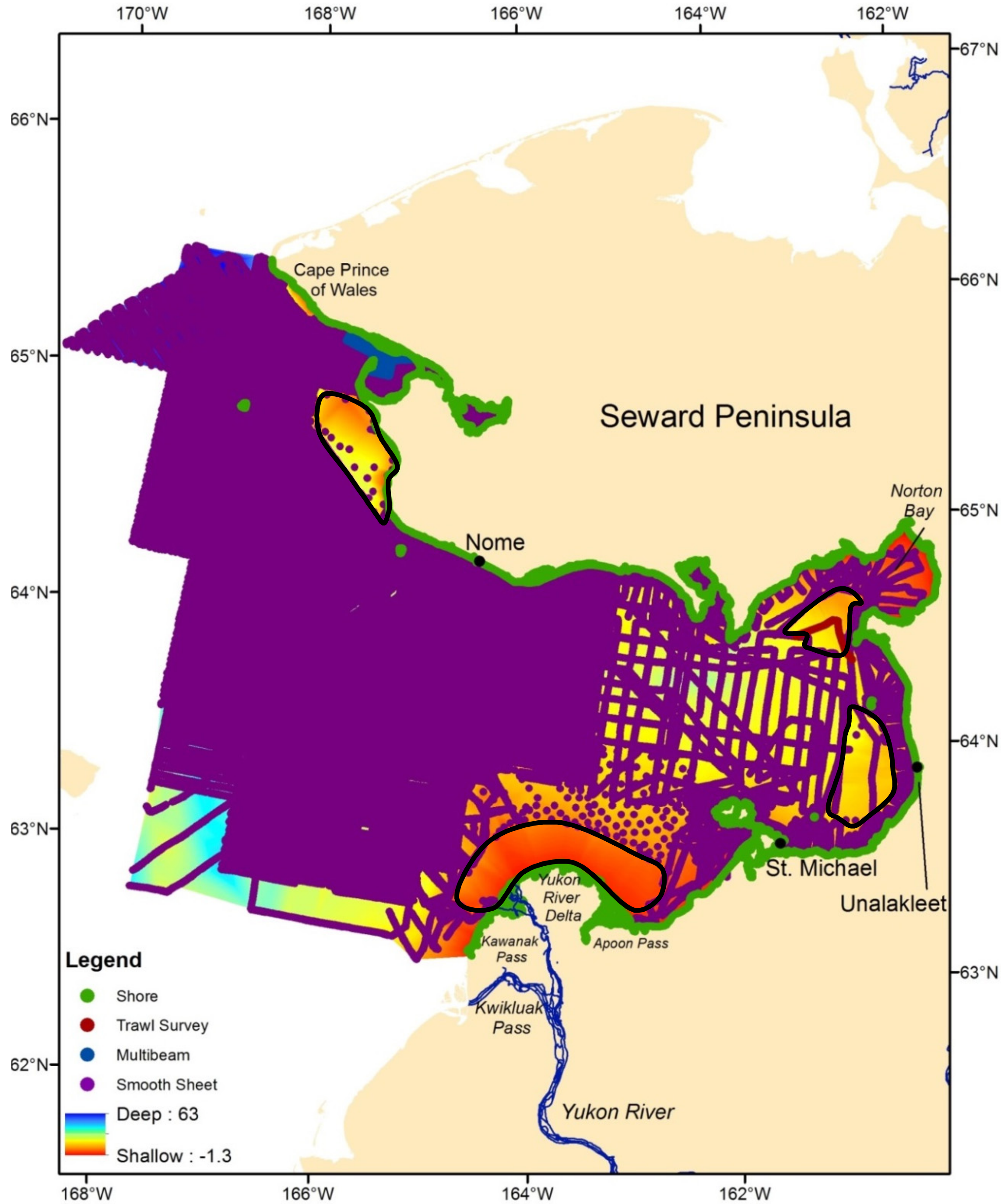

Fig. 2.--The coverage of individual data points used to build the Norton Sound bathymetry coverage. Smooth sheet data are shown in purple while the supplementary trawl data are displayed in red, multibeam in blue, and shoreline points in green; the regions circled in black are noted to be areas of missing data even though surrounding areas have dense coverage. Not to be used for navigational purposes.

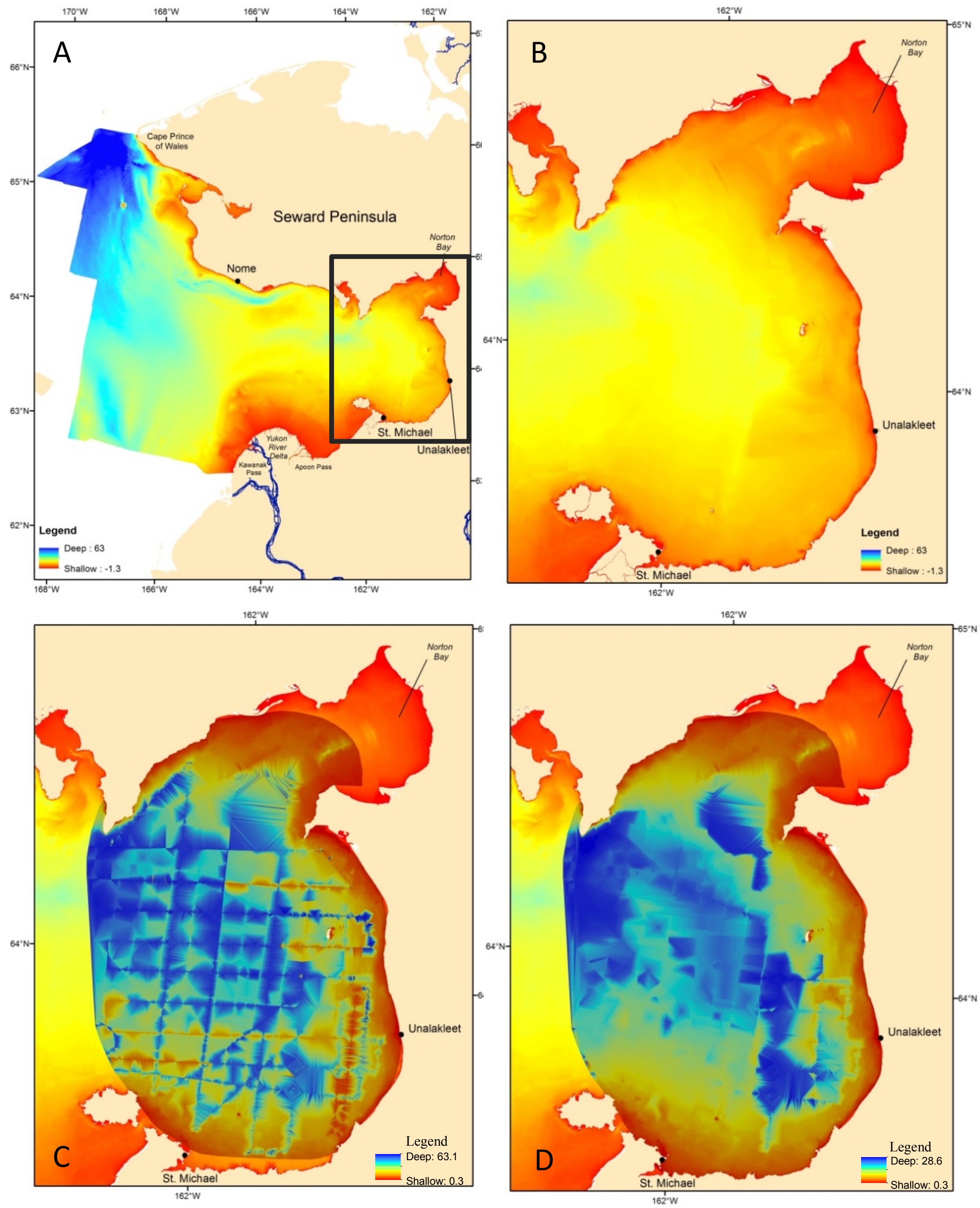

Fig. 3. -- A. Showing the region within the coverage where the USGS data could fill in gaps. B. Zoomed in version showing the area of note. Edited and finalized with no USGS data. C. Shows the coverage when USGS data are added to the smooth sheet data. Note that it has a different depth range, to show clearly the presence of bad data. D. That same region after extensive attempts to edit out bad data from the USGS surveys, which still could not sufficiently clean and reconcile the data with the smooth sheets. Not to be used for navigational purposes.

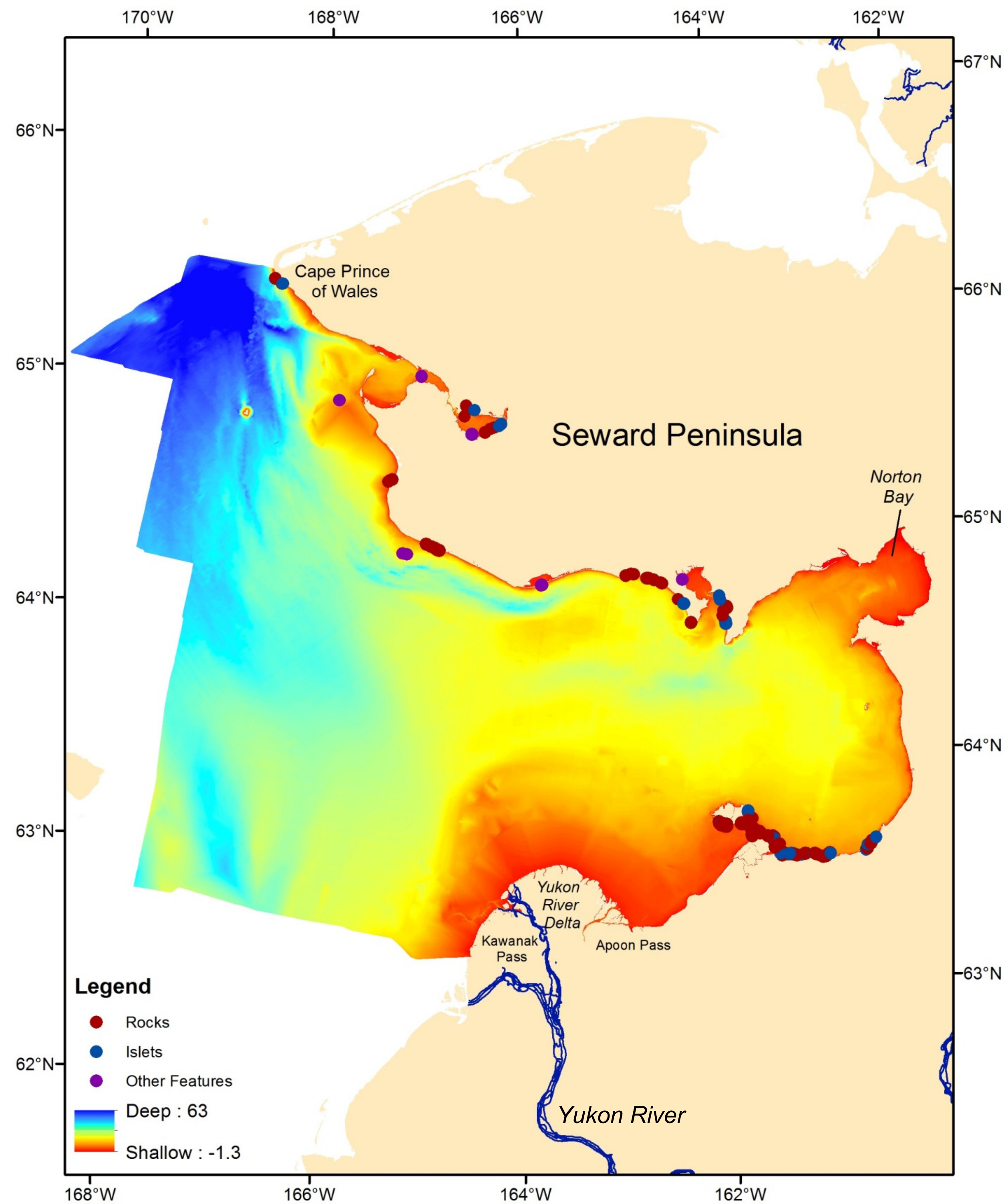

Fig.4. -- The features contained within the Norton Sound coverage. The majority of features were rocks (red), with islets (blue) being the second most common. All other features are grouped together (purple). Not to be used for navigational purposes.

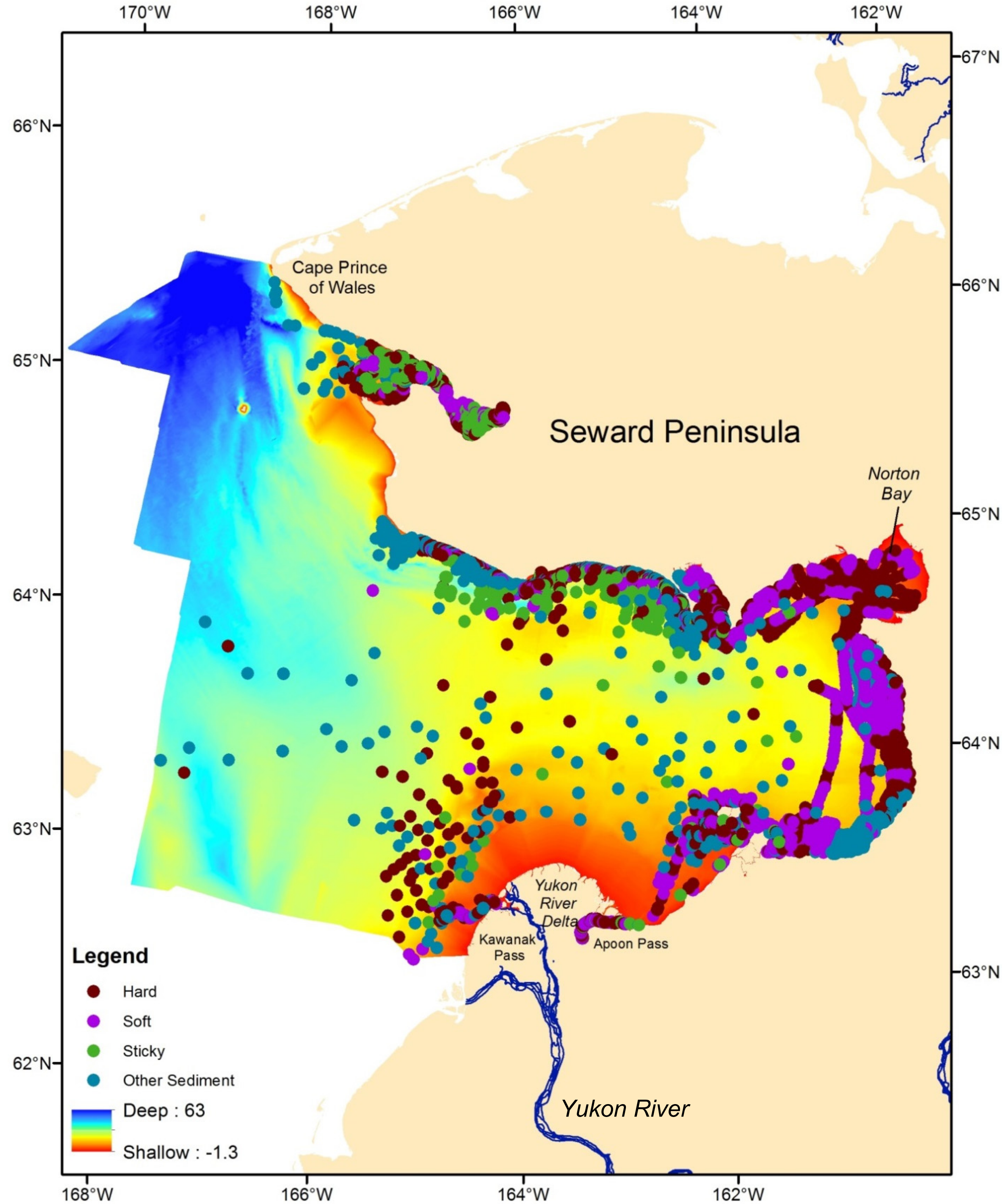

Fig. 5. -- The distribution of sediments in Norton Sound, highlighting the most common; Hard, Soft, and Sticky, with all other sediment categories combined into one. Not to be used for navigational purposes.

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