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False Pass, Alaska: Significant changes in depth and shoreline in the historic time period

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Abstract

Global ocean circulation is limited partly by the small passes of Alaska's Aleutian Islands, which restrict North Pacific Ocean water from flowing north into the Bering Sea and eventually to the Arctic, but the size and shape of these Aleutian passes are poorly described. While quantitatively redefining all of the Aleutian passes, we determined that the easternmost pass, with the cryptic name of False Pass, and with an unusual configuration of having both northern and southern inlets, had two or more inlets to the Bering Sea in the recent past, but that it has only a single northern inlet now (15,822 m^2), roughly equivalent in size to the southern inlet, Isanotski Strait (15,969 m^2). Navigational charts depict the opposite: two inlets to the Bering Sea now, but just one in older charts (1926–43). This discrepancy inspired a thorough review of the hydrographic history from which we concluded that the second northern inlet did exist and hypothesize that it was a remnant of multiple former openings, or a single large opening, potentially allowing greater northward flow of warmer, fresher Alaska Coastal Current water. While the shoreline changes that we document here are often regarded as minor, ephemeral events, we document similar, nearby, permanent shoreline shifts which changed Ikatan Island into a peninsula and which shifted the Swanson Lagoon outlet over 3 km to the east.

KEYWORDS
Aleutian Islands, Aleutian Passes, bathymetry, Bering Sea, False Pass, Isanotski Strait, North Pacific Ocean

1 | INTRODUCTION

The Aleutian Islands are the first of three partial barriers to water flow from the North Pacific Ocean to the Arctic Ocean (Figure 1). This geographically complicated and lengthy water route between the Aleutian Islands, up the canyons of the Bering Sea slope, and through the Bering Strait is the only connection between the Pacific and Arctic oceans. Net flow carries warmer, fresher water from the Alaska Coastal Current (ACC) northward, increasing ice melt by providing approximately one-third of the heat to the Arctic (Woodgate et al., 2006). Thus, the Aleutian Island passes, the Bering Sea slope canyons, and the Bering Strait shallows all play a role in limiting the contribution of northward Pacific water flow to global ocean circulation. Unfortunately, oceanographers have only had low-resolution maps of these underwater obstructions for estimating water flow (Aleutian Island passes: Favorite, 1974; Stabeno et al., 2005; Ladd et al., 2005, Bering Sea slope canyons: Clement-Kinney et al., 2009, Bering Strait: Woodgate et al., 2006). We recently published a detailed and accurate map of the Bering Sea slope (Zimmermann & Prescott, 2018) and are updating a bathymetry map of the Aleutian

FIGURE 1 Regional map and place names of the False Pass area of Alaska

Islands (Zimmermann et al., 2013), for shore-to-shore cross-sectional pass measurements (Zimmermann & Prescott, In Review). False Pass, which we examine in this current manuscript, is just the first of dozens of Aleutian passes that we are redefining (Zimmermann & Prescott, In Review), updating the first estimates from 50 years ago (Favorite, 1967).

Northward flow through only the eastern Aleutian passes, from False Pass through to the much larger Samalga Pass, consists of the fresher and warmer ACC, while the saltier and colder Alaska Stream (AS) dominates western passes (Hunt & Stabeno, 2005). These ACC and AS flows bring different levels of macronutrients northward, impacting primary production of the Aleutian and Bering Sea ecosystems, supporting neritic zooplankton species in the east and oceanic species in the west (Hunt & Stabeno, 2005). The species richness and growth rates of fish decline from east to west, most piscivorous birds nest in the east and most planktivorous seabirds nest in the west, and Unimak and Samalga passes denote major geographic divisions in multiple cetacean populations, while Samalga Pass defines a division between Steller sea lion (*Eumetopias jubatus*) diets and population trends (Hunt & Stabeno, 2005).

The easternmost Aleutian pass, Alaska's False Pass—the body of water between Unimak Island, in the Aleutian Islands, and the western tip of the Alaska Peninsula—is a nautical enigma with little published information. Despite its name, it is a real pass, and it is the only Aleutian pass with constricted northern and southern openings. It has dangerous shallows that limit passage of deeper draft vessels through the north, a narrow, winding channel that limits passage of longer vessels in the south, tides influenced by the Pacific Ocean and Bering Sea (Chu & Chen, 1985), strong currents (4–7 kts or 2.1–3.6 m/s; Chu & Chen, 1985), and wandering channels (Pe'eri et al., 2015). The bathymetry of the northern section of this body of water is poorly defined due to extensive mudflats and

FIGURE 2 Old and new navigational charts of the False Pass area, Alaska. (a) Navigational chart 8701 from 1926 showing a wide, short, and unbroken but poorly defined Cape Krenitzen. (b) Navigational chart 16535 from 2015 showing a slender, long, and more defined Cape Krenitzen broken by a single inlet

(a)

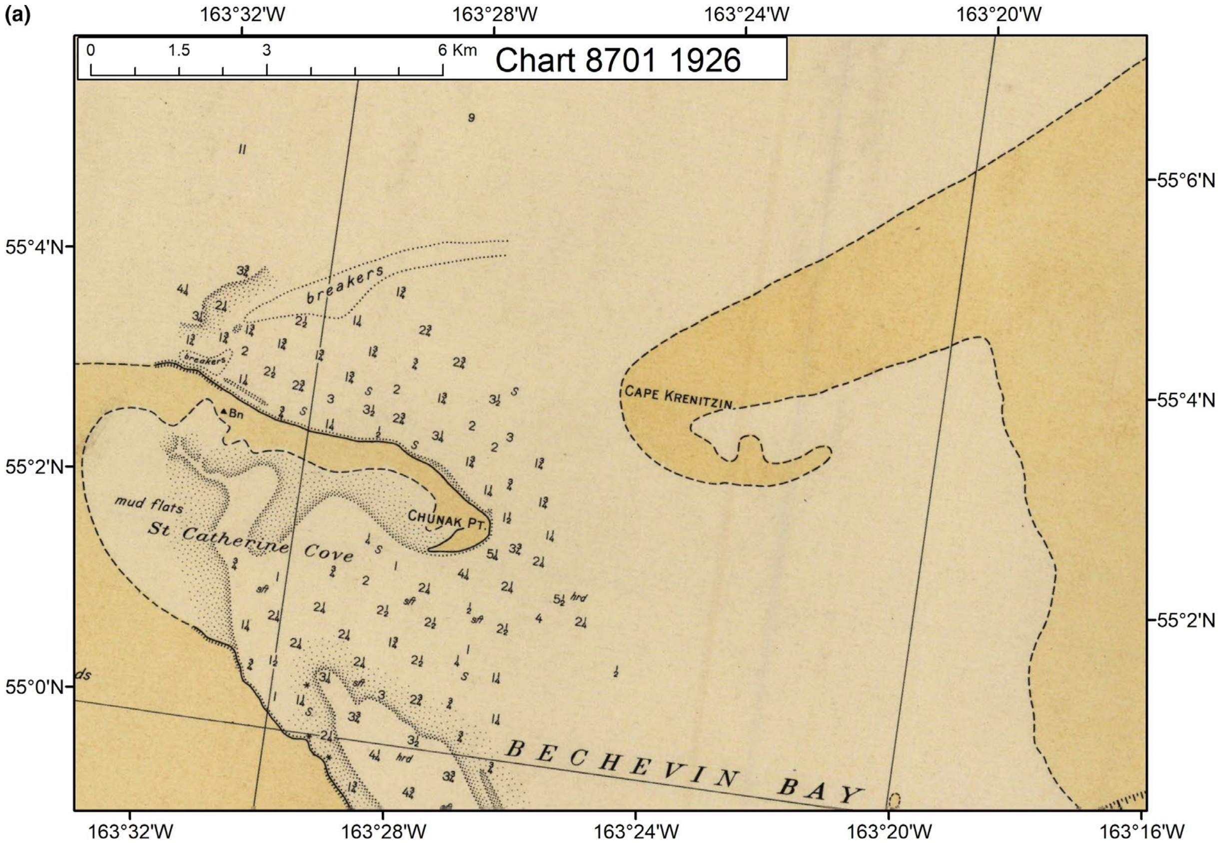
Chart 8701 1926
0 1.5 3 6 Km
163°32'W
163°28'W
163°24'W
163°20'W
163°16'W
55°6'N
55°4'N
55°2'N
55°0'N
breakers
CAPE KRENITZIN
CHUNAK PT
mud flats
St Catherine Cove
BECHEVIN BAY

(b)

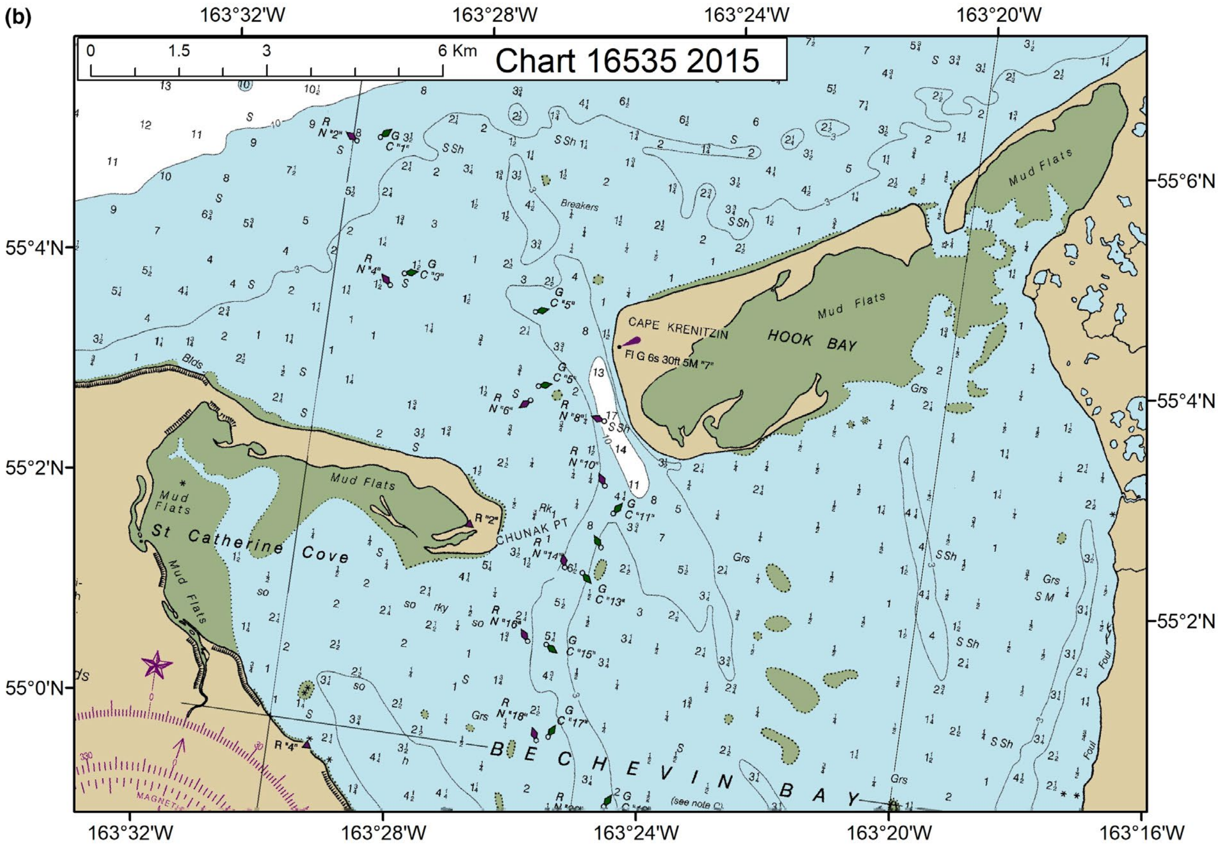
Chart 16535 2015
0 1.5 3 6 Km
163°32'W
163°28'W
163°24'W
163°20'W
163°16'W
55°6'N
55°4'N
55°2'N
55°0'N
Mud Flats
CAPE KRENITZIN
HOOK BAY
Fl G 6s 30ft 5M "7"
Breakers
CHUNAK PT
St Catherine Cove
BECHEVIN BAY

shifting sediments (Pe'eri et al., 2015). Favorite (1967) published the only cross-sectional area estimate of False Pass—at 0.1 km^2—the same general, rounded estimate as for eleven of the other smallest Aleutian passes. Additionally, the False Pass name is not officially recognized by the US Board on Geographic Names (https://www.usgs.gov/core-science-systems/ngp/board-on-geographic-names). Instead, False Pass is officially the name of a settlement on the eastern shore of Unimak Island, located near the north end of Isanotski Strait (http://unimak.us/city_false_pass.shtml). By examining the hydrographic and nominal history of this area, we sought to dispel some myths, better define this misunderstood body of water, and provide some insights to understand better the flow dynamics impacting Aleutian and Bering Sea productivity.

This entire body of water is known as False Pass informally because the northern opening is too shallow for larger vessels (APIA, 2014: https://www.apiai.org/tribes/false-pass/). Here and in the remainder of this paper, we refer to this body of water as the False Pass area, refer to the northern opening as False Pass, the full or partial waterways through Cape Krenitzen as Cape Krenitzen Inlet(s), and the southern opening as Isanotski Strait. Favorite (1967) seems to indicate that it is the northern opening of Bechevin Bay, bracketed by western and eastern capes, that is the location of False Pass, but Chu and Chen (1985) refer to this as Bechevin Inlet while Pe'eri et al. (2015) refer to it as Bechevin Bay Channel. Adding to the nominal confusion, the western cape is not named but ends in Chunak Point and the eastern cape is named Krenitzen but may have been divided by inlets into barrier islands until recently. In the south, the deep but narrow opening between Isanotski Strait and Ikatan Bay also does not have an official name, but McCormick (1906) and Orth (1967) both indicate that this is the location of False Pass, due to shallowness, but this area is at least 20 m deep.

As the easternmost of the Aleutian passes, the False Pass area offers a tempting but risky short cut for mariners transiting between the Gulf of Alaska and the Bering Sea, instead of rounding Unimak Island 100–150 miles to the west (Chu & Chen, 1985). Every spring, the US Coast Guard replaces navigational buoys in the deepest channel of Bechevin Bay (Pe'eri et al., 2015) because the channel moves so much due to shifting sediments.

Hydrographers initially charted the False Pass area in a piecemeal fashion (1924–57), perhaps because of the combined size (~300 km^2) of its three main bodies of water—Bechevin Bay in the north, Protassof Bay in the center and Isanotski Strait in the south. The US Coast and Geodetic Survey (C&GS: now the National Ocean Service, NOS; and the National Geodetic Survey, NGS) sounded the southern and western areas of the False Pass area in the 1920s and produced the first US navigational chart of the area in 1926. This chart and several later editions depicted Cape Krenitzen as wide (~2.1 km), short (~6.1 km), and unbroken, but with a dashed shoreline indicating uncertainty (Figure 2a) until more surveys in 1957 documented a complete and a partial inlet through a slender (<1.0 km) and long (~9.8 km) Cape Krenitzen. The most recent hydrographic charting surveys occurred in 2014, but were incomplete, and the 2015 version of the navigational chart repeats that same depiction of Cape Krenitzen as being broken by a single inlet about midway along its length (Figure 2b). Building on these newer hydrographic surveys, Pe'eri et al. (2015) experimented with a method to derive bathymetry of shallower waters from satellite-derived water turbidity, but sediments suspended in the water column limited the method's success, so we did not use his bathymetry in this project. His Bechevin Bay study area just missed mapping the Cape Krenitzen Inlet (see Figure 4 in Pe'eri et al., 2015); however, a closer examination of other non-hydrographic satellite imagery available in mapping applications such as ESRI's ArcMap (v.10.6, ESRI: Environmental Systems Research Institute, Redlands, CA) and airplane-based terrestrial radar mapping from the US Geological Survey (USGS) (IFSAR: https://elevation.alaska.gov/) shows that Cape Krenitzen is still slender and long, but unbroken, indicating that substantial, undocumented, longshore sediment deposition has occurred since the 1957 hydrographic survey.

Thus, some of the hydrographic records indicated that there was an inlet through Cape Krenitzen, connecting Hook Bay to the Bering Sea and making the western portion of Cape Krenitzen a barrier island, but recent non-hydrographic satellite imagery, IFSAR, and the earliest hydrographic records showed that there was no such inlet through Cape Krenitzen. Which version was correct? Were there multiple False Passes? We resolved the cartographic confusion of Cape Krenitzen by carefully reviewing, proofing, editing, georeferencing, digitizing, and displaying all available information in a common horizontal datum (North American Datum of 1983 or NAD83) in a Geographic Information System (GIS). We also quantified the minimal cross-sectional openings of all inlets of the False Pass area.

2 | METHODS

The navigational charts provide a broad view of this area but are relatively coarse in scale (~1:80,000) in comparison with the more detailed (~1:20,000) shoreline (topographic or T-sheets) and hydrographic smooth sheets (H-sheets). We examined the available T-sheets and smooth sheets, supplemented with aerial imagery in the era between hydrographic surveys, to explain changes in the depiction of False Pass area over time. Next, we compared newer (2014) to older (1924–57) hydrography to quantify any erosion and deposition that may have occurred.

We shifted all of the False Pass area hydrographic documentation into a common, modern horizontal datum (NAD83) in ArcMap, as described in Zimmermann and Benson (2013). The first phase of nautical charting is the establishment of triangulation stations and the creation of topographic maps or T-sheets (see NOAA Shoreline Data Explorer: (https://www.ngs.noaa.gov/NSDE/, and Non-georeferenced NOAA Shoreline Survey Scans: https://nosimagery.noaa.gov/images/shoreline_surveys/survey_scans/NOAA_Shoreline_Survey_Scans.html) showing shorelines drawn from plane table traverses (older) or aerial photography (newer), and the triangulation stations plotted along the shore. The second phase is the hydrographic survey that utilizes the triangulation stations for marine navigation while updating the T-sheet shoreline through ground truthing. Hydrographic surveys produce a paper document called a smooth sheet that includes depth soundings, a ground-truthed shoreline, inshore features such as rocks and kelp beds, and surficial sediment observations. Digital versions of smooth sheets (see National Centers for Environmental Information or NCEI: https://maps.ngdc.noaa.gov/viewers/bathymetry/) from Alaska were typically digitized incorrectly, including missing and duplicate soundings and incorrect horizontal datums (Zimmermann & Benson, 2013), and often need multiple corrections. Descriptive Reports (DRs) are text documents that accompany each smooth sheet and describe the hydrographic surveying methods and materials. The final phase of hydrographic documentation is utilizing the new T-sheets and smooth sheets for creating or updating a navigational chart. Aerial- or satellite-derived shorelines are sometimes utilized instead of field work (see Continually Updated Shoreline Product or CUSP: https://www.ngs.noaa.gov/NSDE/) for chart updates.

2.1 | T-sheets

The T-sheet T-08536 (1950) is the first to depict Cape Krenitzen and T-11478 (1960) is the only other T-sheet of the area (Table 1). No T-sheets were made in conjunction with the 2014 hydrographic surveys but an updated shoreline was depicted in CUSP (2014), derived from satellite imagery of the Cape Krenitzen area collected from 2011 to 2012. Instead of utilizing the T-sheets for shorelines, we digitized the smooth sheet shorelines, as these are ground-truthed and align well with the smooth sheet soundings.

2.2 | Smooth sheets

Hydrographic surveys (https://maps.ngdc.noaa.gov/viewers/bathymetry/) range from 1924 to 2014 within the False Pass area (Table 2). The southern and the western parts of the area were first hydrographically surveyed in 1924 (H04391 and H04394), while the southeastern portion (H04500) was completed in the following year. It was not until 1957 that the northeastern part of Bechevin Bay (H08373) and the Cape Krenitzen area (H08375) were surveyed. We carefully corrected the digitized NCEI soundings against the handwritten soundings on the georeferenced smooth sheets.

We digitized a complete shoreline from the older smooth sheets (1924–57) for use in creating a comprehensive "before" bathymetry surface, and annotated that shoreline with MHW (Mean High Water) values recorded in the DRs. A MHW value of −0.19 ft (−0.06 m) MHW from H04394 near Rocky Point was discarded as being out of range of all the other values (Table 2). Instead, the MHW value of −4.3 ft (−1.3 m) from nearby smooth sheet H08373 was substituted. Additionally, we digitized the outlines of mud flats from H08373 and H08375 and annotated these boundaries with a depth of 0 ft (0 m) for MLLW (Mean Lower Low Water). Together the corrected depth soundings of these five surveys (1924–57), the digitized shorelines (MHW) and the digitized tide flat boundaries (MLLW), with hydrographic observations extending from shore to shore, constitute the "before" bathymetry in our study. Errors associated with depth observations, navigation, tides, and currents are discussed in the DRs but no error surface was produced.

In 2014, three overlapping hydrographic surveys (H12630-2) operating in NAD83 covered much of the deeper water of the study area with multibeam and singlebeam at a horizontal resolution of 4 m but avoided much of the shallows. Instructions in the DRs limit the use of multibeam to depths > 8 m and the use of singlebeam to > 4 m, presumably because of likely danger to the surveyors and their vessels. Error sources and calibration of equipment are discussed at length in the DRs, but no error surface was produced from these surveys. No smooth sheets were created from the 2014 multibeam surveys, and therefore, no comparable shoreline was available for comparison to the earlier smooth sheet surveys. The CUSP shoreline, also in NAD83, was created from satellite imagery but did not include MHW annotation, tide flats, nor ground truthing. No T-sheets were created, and no MHW values were available from the DRs or Tide Note. Therefore, due to the sparse inshore multibeam and singlebeam coverage, lack of tide flat delineation, and lack of MHW shoreline, we were not able to create a shore-to-shore depth surface from the 2014 bathymetry data. Thus, the "after" depth surface was just the 4 m horizontal resolution depth surface, generally deeper than 8 m.

TABLE 1 Topographic (T-sheet) surveys for Cape Krenitzen of the False Pass and Swanson Lagoon areas

Location	Topographic sheet survey	Year	Scale	Datum
Cape Krenitzen	T-08536	1950	1:20,000	Unalaska
	T-11478	1960	1:20,000	NAD27
	CUSP	2014	Unknown	NAD83
Swanson Lagoon	T-04028a	1923	1:10,000	Unknown
	T-06858a	1940–41	1:20,000	Unalaska
	T-11478	1960	1:20,000	NAD27

Note: The Continually Updated Shoreline Product (CUSP) is remotely derived from aerial or satellite imagery. Horizontal datums ranged from unknown, Unalaska, NAD27 (North American Datum of 1927), to NAD83 (North American Datum of 1983).

TABLE 2 Hydrographic surveys and methods used for charting the False Pass area of Alaska

Smooth sheet survey	Year	Scale	Mean high water	Sounding method	Navigation method	Datum
H04391	1924	1:10,000	−7.8 ft (−2.4 m)	Shallow: hand lead	Visual	Unknown
				Deep: sounding machine	Visual	
H04394	1924	1:20,000	−0.19 ft (−0.06 m)	No methods mentioned	Visual	Unknown
H04500	1925	1:20,000	−6.5 ft (−2.0 m)	Shallow: hand lead	Visual	Unknown
				Deep: sounding machine		
H08373	1957	1:20,000	−4.3 ft (−1.3 m)	Fathometers	Shoran	NAD27
H08375	1957	1:20,000	−4.3 ft (−1.3 m)/ −6.8 ft (−2.1 m)	Fathometers	Shoran	NAD27
H12630	2014	1:40,000	None	Shallow: singlebeam	GPS	NAD83
				Deep: multibeam		
H12631	2014	1:40,000	None	Shallow: singlebeam	GPS	NAD83
				Deep: multibeam		
H12632	2014	1:40,000	None	Shallow: singlebeam	GPS	NAD83
				Deep: multibeam		

Note: Visual triangulation utilized hydrographic sextants. Short Range Navigation (Shoran) was early radio signal navigation. Global Positioning System (GPS) has been the standard since the 1990s. Horizontal datums ranged from unknown, NAD27 (North American Datum of 1927), to NAD83 (North American Datum of 1983).

2.3 | Bathymetry comparison

We compared the bathymetry between the earliest hydrographic surveys (1924–57) to the most recent surveys (2014) using ArcMap (Zimmermann & Benson, 2013). The older smooth sheet soundings were combined with depths from inshore cartographic features, digitized MHW shoreline points, and digitized MLLW mudflat points to create a TIN (Triangulated Irregular Network). The TIN was converted into a 4 m horizontal resolution depth raster using Natural Neighbors (Local Area Weighting) to match the spatial resolution of the "after" data set. This "before" depth raster was further trimmed by the MHW shoreline to eliminate all land areas. We used the Mosaic tool in ArcMap to combine the three overlapping 4m horizontal resolution rasters from 2014 into a single 4 m horizontal resolution "after" depth raster that is limited to the spatial extent of the three input rasters. Finally, the "after" depth raster was subtracted from the "before" depth raster to reveal depth change over time.

2.4 | Minimal cross-sectional openings

We attempted to use ArcMap's Cost Distance tool to derive algorithmically the minimal cross-sectional openings of the False Pass area, as we did for all of the other Aleutian passes (Zimmermann & Prescott, In Review). This method is different than the user drawing straight lines (Interpolate Line tool) across a depth surface, which we have utilized in past analyses (e.g., Zimmermann et al., 2019). The Cost Distance tool groups together raster-derived points from the edge of the depth raster near one shore (potential starting points), groups together a second set of raster edge points from the neighboring shore (potential ending points), and then determines the minimal path by summing depths between the two groups of points (https://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/understanding-cost-distance-analysis.htm). Our efforts eventually resulted in the elimination of extraneous (negative depth) inshore soundings and the reduction in the number of input data points, which we describe in the Results.

2.5 | Navigational charts

Navigational chart editions (all scale 1:80,660) of the False Pass area provide almost a century of history (digital copies available: https://historicalcharts.noaa.gov/search.php). The USC&GS created the older chart editions (8701: 1926–73), and the NOS created the newer chart editions (16535: 1976–2015).

2.6 | Imagery

Aerial imagery from the USGS (https://earthexplorer.usgs.gov/) was of sufficient resolution to show the status of the Cape Krenitzen Inlet in the time period between the "before" (1924–57) and "after" hydrographic surveys (2014). In this black and white USGS imagery, land along the shore is white, interior land, presumably higher in elevation and more colonized with vegetation, is patchy and gray, mud flats and sand bars are a darker gray, and deep water is nearly black. The oldest imagery showing the Cape Krenitzen Inlet area is from 1962 (Scale 1:47,473; elevation 20,000 ft). The next available observations are from 1974 (Scale 1:76,000; elevation 38,000 ft). Satellite imagery from this era is too coarse to resolve clearly the status of the Cape Krenitzen Inlet.

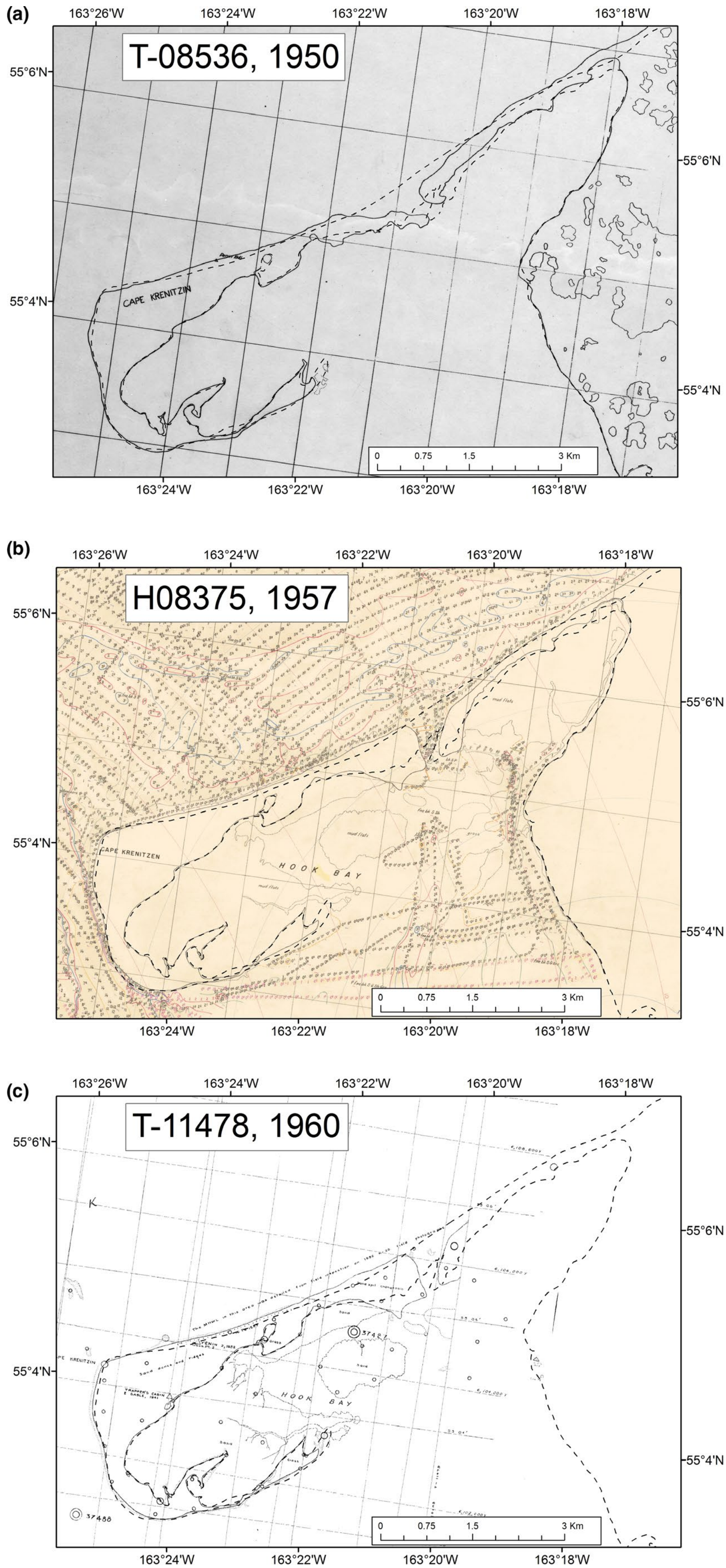

FIGURE 3 Cape Krenitzen depicted by (a) T-sheet T-08536 (1950), (b) smooth sheet H08375 (1957), and C) T-sheet T-11478 (1960). The CUSP (2014) (Continually Updated Shoreline Product) is shown as a dashed black line on all three panels. The T-sheets and smooth sheet show the inlet through Cape Krenitzen but the CUSP shoreline does not

2.7 | Changes in Ikatan Bay and Swanson Lagoon

A thorough history of the oldest charting of the Ikatan portion of the False Pass area is available on the Isanotski Strait section (http://unimak.us/isanotski_strait.shtml) of the Unimak Island Area web page (http://unimak.us/index.shtml). The Swanson Lagoon shoreline was mapped by T-sheets in 1923, in 1940–41, and in 1960 (Table 1). Hydrographers have never surveyed this small and shallow lagoon, so there are no smooth sheets.

3 | RESULTS

Georeferencing (Zimmermann & Benson, 2013) brought all of the T-sheets, smooth sheets, navigational charts and aerial imagery into a common GIS framework (NAD83) for comparison. Older maps were created in unknown, Unalaska, or NAD27 (North American Datum of 1927) datums (Table 2) and shifted to NAD83 by subtracting or adding latitude and longitude differences from a common triangulation station with old datum and NAD83 positions (Zimmermann & Benson, 2013). The USGS aerial imagery could only be roughly georeferenced by using approximate corners, as the corners are rounded in the imagery, and by using corner positions contained within the metadata: There were no graticules, triangulation stations, or definitive landmarks in the imagery that could be used as alternative georegistration points.

3.1 | T-sheets

T-08536 (1950) depicts the inlet through Cape Krenitzen but does not depict mud flats or channels in Hook Bay (Figure 3a), all of which are shown in more detail in smooth sheet H08375 (1957: Figure 3b). T-11478 (1960) depicts the same Cape Krenitzen Inlet but with greater detail and a different shape: The inlet is about 250 m wide on the Hook Bay side and widens to about 750 m on the Bering Sea side, with “sand” areas along and near the Hook Bay side of Cape Krenitzen, but no soundings to define deeper channels (Figure 3c). Both T-08536 and T-11478 also depict the partial inlet farther west on Cape Krenitzen: T-08536 shows it as a round pond with a small outlet stream draining into Hook Bay while T-11478 depicts it as a small bay about three quarters of the way across Cape Krenitzen. In the western portion of Hook Bay, T-11478 shows two channels of deeper water extending through the mud flats toward the south side of Cape Krenitzen; the larger of the two nears the partial inlet across Cape Krenitzen. The CUSP shoreline (dashed black line Figure 3) clearly indicates that the inlet has disappeared by 2011–2012, but there was no fieldwork conducted to corroborate this significant change.

3.2 | Smooth sheets

Smooth sheet H04394 (1924) depicts a survey around St. Catherine Cove, the west side of Bechevin Bay and only has a very simple depiction of the western tip of Cape Krenitzen (not shown in Figure 3). Apparently, the possibility of an inlet through Cape Krenitzen was a concern at the time of this survey, as the H04394 DR states that “Sufficient time was not available… to search for a possible channel on the eastern side of Bechevin Bay and off Cape Krenitzen… It is doubtful if there is a practicable channel… for local fishermen running to east to Port Moller use the passage to the west of Chunak Point.” (p. 3: https://data.ngdc.noaa.gov/platforms/ocean/nos/coast/H04001-H06000/H04394/DR/H04394.pdf).

H08375 (1957) is the only smooth sheet to show all of Cape Krenitzen, confirming the same inlet in the T-sheets (Figure 3b). Furthermore, this smooth sheet shows that there are groups of soundings defining deeper pools, generally ≥2 fathoms (3.7 m) within and to the north and south of the inlet. A large mud flat nearly obstructs a connection between the deeper water within the Cape Krenitzen Inlet to the other deeper pools within Hook Bay. Outlines of Hook Bay mud flats to the east of the inlet show channels of deeper water extending toward to the south side of Cape Krenitzen. We interpret the shallow inlet depicted completely though Cape Krenitzen, and the nearby pools of deeper soundings, to indicate that there was an inlet about 2 fathoms (3.7 m) deep here before it was mostly obstructed by Hook Bay mud flats at the time of the H08375 survey.

Smooth sheet H08375 (1957) also depicts the partial inlet in Cape Krenitzen, to the west of the complete inlet (Figure 3b). H08375 shows that the partial inlet extends more than half way across Cape Krenitzen, similar to what is shown on the T-sheets. Aligned with the partial inlet are three soundings ≥2 fathoms (3.7 m) in the Bering Sea extending away from the Cape Krenitzen shore. Additionally, there is a deeper channel of water through the mud flats leading up to this partial inlet on the Hook Bay side. We interpret these results as indicating that this partial inlet was also a complete inlet prior to H08375 (1957), also with a channel of perhaps two fathoms (3.7 m) before silting in.

3.3 | Bathymetry comparison

The “before” bathymetry ranges from shore to shore within the False Pass area, to a depth of 172 m in Protassof Bay, and extends several km into the Bering Sea and a small distance into the Gulf of Alaska. This “before” bathymetry shows five larger channels extending north from Protassof Bay to Chunak Point, False Pass, and to the south side of Cape Krenitzen, with the two central channels merging into a single channel between the capes and becoming the deepest part of False Pass. The union of the two central channels occurs much closer to Cape Krenitzen (~250 m distant) than Chunak Point (~2,500 m distant), and the deepest soundings of 18 fathoms (32.9 m) occur about midway along the western shore of Cape Krenitzen, well north of Chunak Point (Figure 4). A deep pool isolates these deepest soundings from other areas up to the 14 m depth contour. The two central channels merge at a depth of about 12 m to form an inverted Y, a configuration that continues up to the 6 m depth contour. Smaller relic channels, originating from the north ends of the five larger

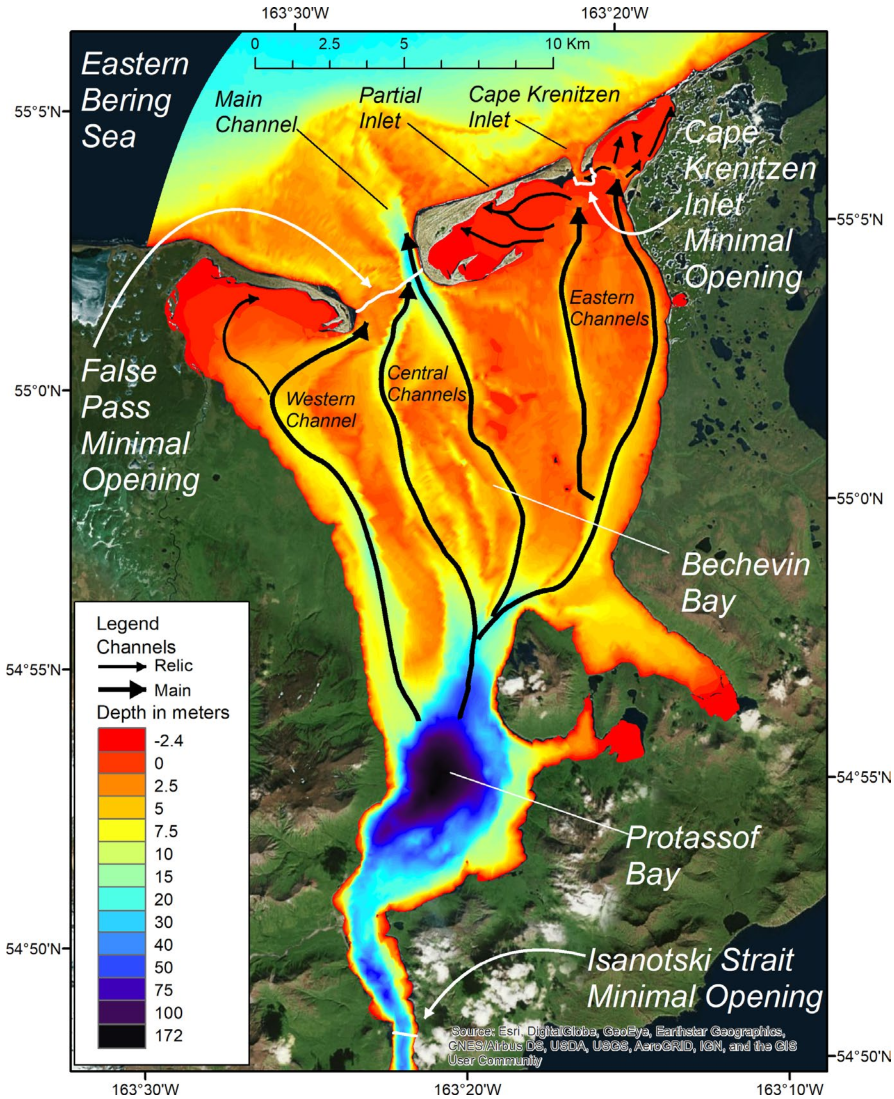

FIGURE 4 False Pass bathymetry with main channels indicated with thick black arrows and relic mud flat channels indicated with thin black arrows, using the "before" bathymetry (1924–57). The "after" bathymetry of 2014 was incomplete, without soundings in much of the shallows and without a shoreline

channels, are also visible in the shallows on the south side of both capes. Shallows extend north from False Pass and into the Bering Sea in a bell-shaped curve, about 4 km in width from the northwest tip of Cape Krenitzen but less than 1 km in width from the base of each cape. These Bering Sea shallows are a continuation of the shallows within the False Pass area, suggesting that sediment has been transported from within and been deposited immediately outside of the False Pass area through the capes.

The "after" bathymetry also extended into the Bering Sea and Gulf of Alaska, and to a depth of 171 m within Protassof Bay, but avoided much of the shallows, confounding a straight comparison about changes over time within the False Pass area (Figure 5). Therefore, we sought to make some inference about depth change over time by quantifying the mismatch in overlap between the "before" and "after" depth rasters and also by limiting our analysis to within the False Pass area, as bounded by the minimal areal openings at False Pass, Isanotski Strait, and the Cape Krenitzen Inlet.

Within this reduced study area, there were about 15 million raster cells (Mean depth = 10.3 m, *SD* = 21.6) in the "before" bathymetry; 10 million of those (Mean depth = 2.4 m, *SD* = 2.4) were not resurveyed while about 5 million (Mean depth = 28.3 m, *SD* = 32.3) were resurveyed. Overall, those 5 million resurveyed raster cells deepened slightly (−0.01 m, *SD* = 2.8) but an analysis in one meter depth intervals showed that depth change varied according to the "before" depth. On average, the shallowest (<12 m) 2 million raster cells deepened while the deepest 3 million raster cells (≥12 m) shallowed. We interpret these results as indicating that shifting sediments made 2 million shallow raster cells deep enough to be resurveyed, while 10 million raster cells remained too shallow, and the 3 million deepest raster cells shallowed.

Thus, there have been large shifts of sediment within the False Pass area. A new deposit, as deep as 15 m and in the shape of an inverted Y, occupies the main channel, between the capes. This deposit is almost exactly on top of a wider area of erosion that is also in the shape of an inverted Y. Because of the slightly offset deposition and erosion, the main channel deepened by up to 13 m and shifted even closer to Cape Krenitzen. Extending to the northwest from the convergence of the two central channels, an area that was shallower than 2 m eroded substantially, creating a new channel deeper than 6 m in some places. The erosion and deposition is dividing the north end of the main

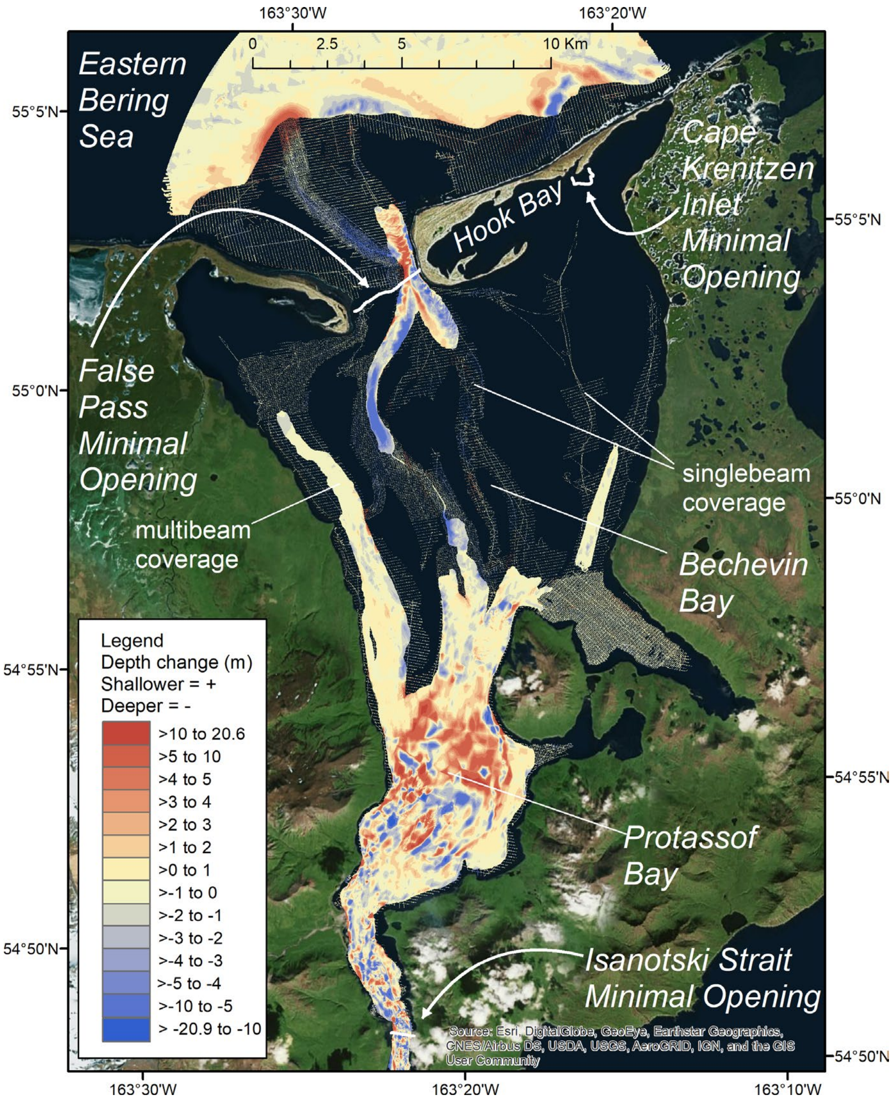

FIGURE 5 Depth change of ±20 m between the "before" (1924–57) and "after" (2014) bathymetry. The area of the comparison is restricted to the extent of the 2014 hydrographic surveys, which avoided the shallower waters

channel into two channels, one very narrow and edging closer to Cape Krenitzen and one broader and nearly in the middle of the pass. The northern half of Protassof Bay shallowed by as much as 20 m while portions of the bay center deepened by an equivalent amount.

3.4 | Minimal cross-sectional openings

The ArcMap Cost Distance tool was initially unable to derive the minimal cross-sectional openings of False Pass, Cape Krenitzen Inlet, and Isanotski Strait because much of the nearshore "before" raster depths were negative (shallower than MLLW) and the Cost Distance tool needs positive values. To mitigate this problem, we experimented with running the Cost Distance tool farther offshore, avoiding the wide band of negative depths along each shoreline, and this succeeded for False Pass (15,822 m^2) and Isanotski Strait (15,969 m^2) (Figures 4 and 5), but not for Cape Krenitzen Inlet, as all of the depths along the mudflats within Hook Bay were zero or too close to zero. Instead, we drew a curved, minimal opening (7 m^2) using the Interpolate Line tool, along the edge of the mud flat that nearly blocks the southern opening (Figures 4 and 5). As a contrast to this minimal opening for the Cape Krenitzen Inlet, we also drew a straight line across the deep pool in the center of the inlet, showing that it was about 400 m^2 in cross-section at its greatest.

Since the "after" depth raster was missing much of the shallower water depths, we did not attempt to derive the location of new minimal openings. Instead, we compared the "after" depths to the "before" depths along the same minimal opening paths for False Pass and for Isanotski Strait, but only at raster cell locations where there was an "after" depth for comparison. Thus, across depths generally >8 m, False Pass deepened a total of 875 m^2 or about 5.5%, due mostly to the channel deepening and shifting east, while Isanotski Strait deepened a total 1,226 m^2, or about 7.7%. This deepening may have been offset by shallowing in waters <8 m in depth.

3.5 | Navigational charts

The earliest USC&GS and NOS charts (1926, 1927, 1929, 1940, 1942, and 1943) all show a solid and relatively wide but crudely drawn

Cape Krenitzen (Figure 2a). The 1949 chart is the first to show a thin Cape Krenitzen, broken by a single inlet, but with no nearby soundings and no obstruction of the inlet from Hook Bay mud flats. The 1969, 1973, 1976, 1990, and 2015 (Figure 2b) chart editions add greater definition to Cape Krenitzen by including soundings within and around the inlet, show substantial mud flats nearly closing off the inlet at MLLW from the Bechevin Bay side, and also indicate deeper channels within Bechevin Bay.

3.6 | Imagery

The 1962 USGS aerial imagery clearly confirms the inlet extending all the way through Cape Krenitzen and other channels within the shallows of Hook Bay (Figure 6a). These images also show a partial inlet through Cape Krenitzen farther to the west of the complete inlet, extending about three quarters of the way across Cape Krenitzen, terminating in a deep pool connected to Hook Bay by a shallow, narrow channel. The land surrounding both the Hook Bay and the Bering Sea ends of this partial inlet is white, and therefore presumably lower than the surrounding landscape. Along the eastern side of this partial inlet through Cape Krenitzen is a nearly linear feature that we interpret as a relic shoreline, extending all the way from Hook Bay to the Bering Sea, adding evidence that this partial inlet was originally a second inlet through Cape Krenitzen.

The 1974 USGS imagery clearly confirms the Cape Krenitzen Inlet is closed and that the partial inlet is nearly occluded on the Hook Bay side (Figure 6b). The linear feature along the eastern side

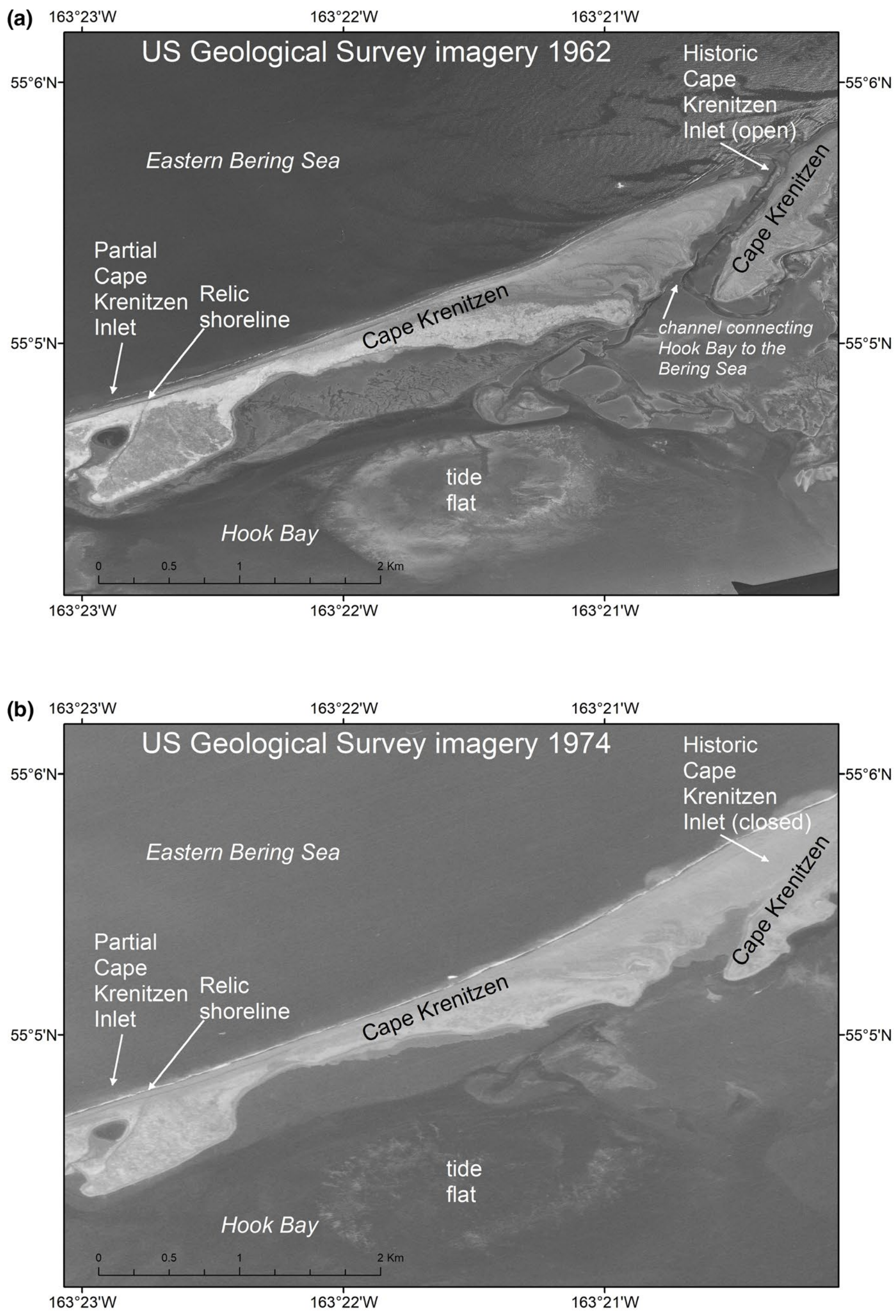

FIGURE 6 US Geological Survey imagery of Cape Krenitzen showing the inlet open in (a) 1962 and the inlet closed in (b) 1974. Both (a) and (b) show another partial inlet occurring to the west

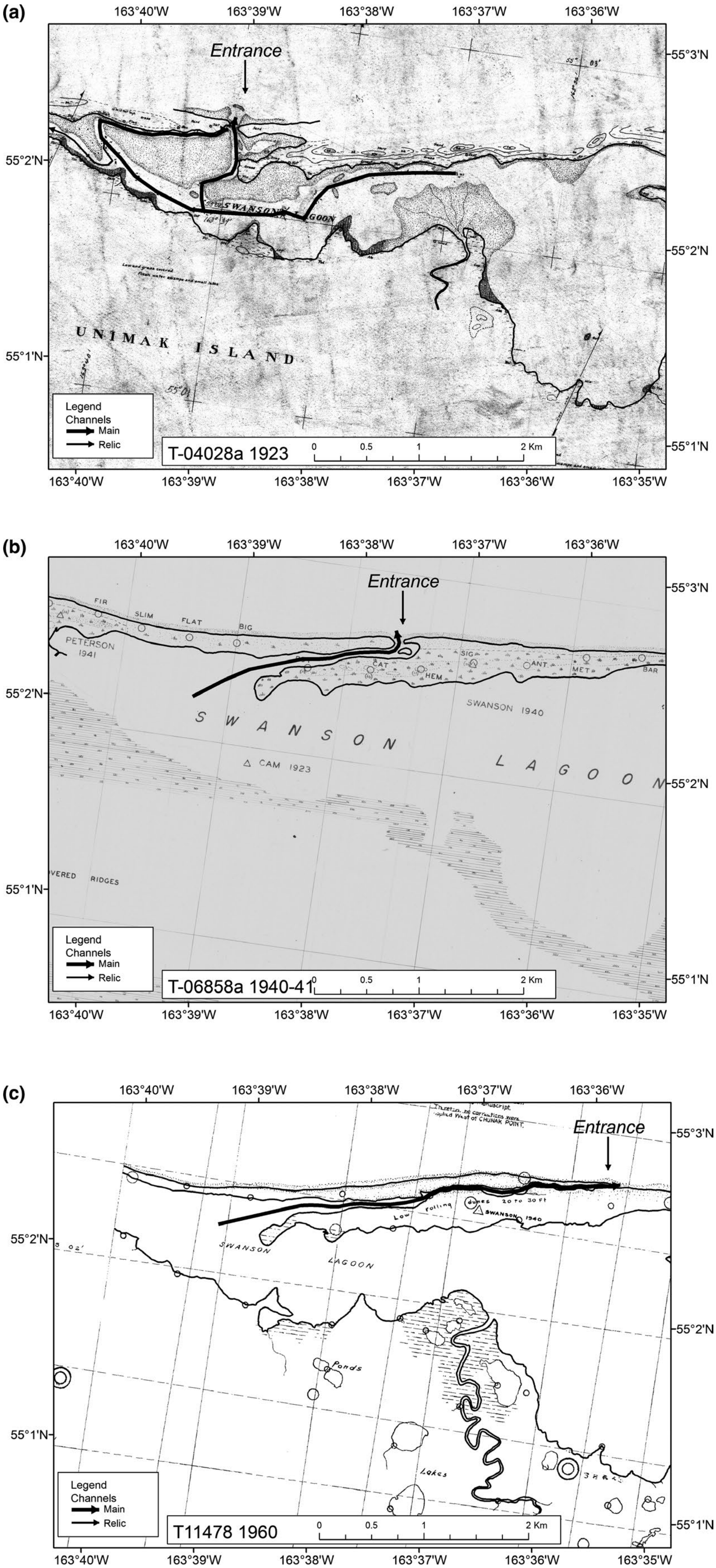

FIGURE 7 Changes in Swanson Lagoon from Topographic surveys or T-sheets (a) T04028a (1923), to (b) T06858a (1940–41), to (c) H11478 (1952/1956/1957/1960). Each shoreline has been digitized in black, and the location of the Lagoon entrance has been indicated for greater clarity

of the partial inlet that we interpreted from the 1962 imagery as a relic shoreline is still intact. While time of the imagery and tidal state is not known, it appears that the 1962 imagery, which shows the Cape Krenitzen Inlet is open, was taken at low tide, while the 1974 imagery, which shows the Cape Krenitzen Inlet is closed, was taken at high tide.

3.7 | Changes in Ikatan Bay and Swanson Lagoon

Ikatan Island shifted geomorphologically into a peninsula (http://unimak.us/isanotski_strait.shtml): Russian charts in 1802 and 1826 label Ikatan as an island, separated by water from the southeastern corner of Unimak Island. A chart labeled as an 1883 tracing of an 1849 Tebenkoff atlas also shows Ikatan as an island (https://historicalcharts.noaa.gov/image=547-00-1849). The Unimak web page shows details from an 1882 US chart (https://historicalcharts.noaa.gov/image=3N806-82) that for the first time shows Ikatan connected to Unimak by a sandbar and labeled as a peninsula. Oral history states that a solid connection from Unimak to the island developed around 1895 (http://unimak.us/isanotski_strait.shtml). A US chart depicts the peninsula connection as solid land in 1908 (https://historicalcharts.noaa.gov/image=CP2992C), and ArcMap imagery shows that this connection has remained and thickened to at least 500 m in width (Figure 1). Having lasted for over a century, this change from an island to a peninsula appears to be permanent.

The 1923 T-sheet of Swanson Lagoon (T-04028a) shows a large area of open water about 2.5 km × 1.5 km at the east end separated by a river's flood plain from shallow channels in the central and western areas (Figure 7a). A relic, western channel dead ends before nearly reaching the Bering Sea, another western channel turns back east along the shore before joining with another channel and exiting to the Bering Sea in a 70 m wide gap between two sand spits. Twenty years later, T-06858a (1941) shows that the western channels have consolidated into a single channel about 75 m wide, exiting the lagoon about 1,600 m to the east of the original outlet (Figure 7b). After another twenty years, T-11478 (1960) shows the same general configuration of the lagoon but now the single channel that drains to the Bering Sea is about 3,600 m to the east of the original outlet, and about 10 m wide at its narrowest (Figure 7c). As with the geomorphological changes we documented at Cape Krenitzen and Ikatan Bay, evidence indicates that the shoreline changes at Swanson Lagoon are the results of deposition and are permanent.

4 | DISCUSSION

We conclude that the geomorphology of the False Pass area was substantially different before the early charting surveys that we examined in this project. We propose that before the capes existed, the north entrance was deeper and up to 18 km wide, fully exposing Bechevin Bay to the Bering Sea. Over time Bechevin Bay shallowed due to sedimentation, but channels running through northern tide flats maintained deeper inlets to the Bering Sea. As the tide flats developed into sandbars, barrier islands, and capes, the Cape Krenitzen Inlet closed before 1974. The remaining inlet—today's False Pass—has narrowed and deepened into a channel, roughly at equilibrium in size with the southern inlet, Isanotski Strait, and both are only about 16% of the size previously estimated (Favorite, 1967). We hypothesize that these geomorphological changes are permanent, as at nearby Swanson Lagoon and Ikatan Peninsula. Sedimentation will likely continue within Bechevin Bay until only one of the five main channels remain, connecting Isanotski Strait more directly to False Pass. Twenty year Bering Sea storm waves of 7.75 m, and frequent, annual 4–5.5 m storm waves (Chu & Chen, 1985) may ultimately close the single remaining inlet of False Pass.

Another possibility is that False Pass has reached some stability with its decline in size. With two deep pools extending down to 58.5 and 62.2 m (smooth sheet H04391), almost twice the maximum depth of False Pass (32.9 m, H08375), we had initially assumed that Isanotski Strait was a much larger inlet than False Pass. Eventually, exploratory analysis with the Cost Distance tool found a cross-sectional opening between Isanotski Strait's two deeper pools, roughly equal in size to the minimal opening of False Pass. Thus, if these northern and southern inlets are similar in size, perhaps the water flow through Isanotski Strait is maintaining a minimal opening at False Pass. Our depth comparison showed a mixture of deepening and shallowing within Isanotski Strait, suggesting that its capacity is not changing, but large areas of shallowing in northern Protassof Bay, and to the north of False Pass (Figure 5) may be gradually slowing this northerly flow.

Additional northward flow of water through a wide open Bechevin Bay, or through several northern inlets, may have impacted the southern Bering Sea ecosystem more in the past than it does today (presently ~ 1.34×10^8 m^3 during each tidal cycle: Chu & Chen, 1985). Warm water flow through False and Unimak passes (Hunt & Stabeno, 2005) delays ice formation (See Figure 2, Nghiem et al., 2012), and loss of typical winter sea ice formation due to warmer winters in recent decades is of great concern for the Bering Sea ecosystem (Gramling, 2019). The southern Bering Sea area was the focus of early (1940–61) red king crab (*Paralithodes camtschaticus*) research (Zimmermann et al., 2009), the location of the Unimak broodstock (Dew & McConnaughey, 2005), a major spawning area for Pacific cod (*Gadus macrocephalus*) (Shimada & Kimura, 1994), and a migration route for the largest sockeye salmon (*Oncorhynchus nerka*) run in the world (Burgner, 1991), as it returns to Bristol Bay (French & Bakkala, 1974).

Several larval fish and oceanographic studies demonstrated the importance of shallow nursery areas along the Bering Sea side of Unimak Pass and the western end of the Alaska Peninsula, potentially owing to transport of larval fish from the Gulf of Alaska onto the shallow Bering Sea shelf. Northern rock sole (*Lepidopsetta polyxystra*) larvae are abundant in this southern Bering Sea area in some years, and satellite drifters show that transport through Unimak Pass is consistently to the north (Lanksbury et al., 2007). Ichthyoplankton sampling determined that this area is also likely a spawning area for walleye pollock (*Gadus chalcogrammus*) (Bachelor et al., 2010), and is important for transport of larval Pacific sand lance (*Ammodytes hexapterus*), *Sebastes* spp., and Pacific cod (Siddon et al., 2011). Inshore growth rates and densities of age-0 Pacific cod were higher in comparison with farther offshore (Hurst et al., 2018).

Reviewers of these bathymetry projects are often focused on the calculation of error surfaces so that changes in depth can be judged for statistical significance. Unfortunately error surfaces were never constructed for these bathymetry data sets and, without a substantial amount of very specific information regarding methods of each depth sounding, we are not able to construct such error surfaces. Instead, we focus on correcting each data set according to the source documents, such as the smooth sheets and descriptive reports. We have found it to be far more important to resolve horizontal datum errors that occurred at NCEI so that the soundings do not plot on land (See fig. 17; Zimmermann & Benson, 2013) and to correct digitization errors than to estimate measurement errors.

About two-thirds of the False Pass area was not resurveyed due to shallow water, and we hypothesize that much of this area had shallowed since the “before” surveys, such as at the former inlet through Cape Krenitzen. On average, only a small minority of shallow areas which deepened due to shifting sediments were able to be resurveyed, while the deeper waters shallowed. Significant deposition of sediment in the shallow waters in the False Pass area may be linked to extensive eelgrass beds, as they accrete silt (Bos et al., 2007). Hogrefe et al. (2014) mapped large, dense eelgrass beds covering about 34% of Hook Bay and about 18% of St. Catherine Cove, and also mapped smaller eelgrass beds in Hotsprings Bay and Traders Cove (Figure 1). About 350 km to the east of False Pass in the Chignik area, gradual sedimentation of eelgrass beds reduced the depth within 5 of 6 bays examined (Zimmermann et al., 2018).

Similar to the results found at Chignik (Zimmermann et al., 2018), we hypothesized that sedimentation is responsible for the geomorphological changes we note at False Pass, Ikatan, and Swanson Lagoon. As mentioned previously, the False Pass area has not been thoroughly studied, so a definitive sedimentation analysis is not available, but there are other informative data sets, such as land movement measurements and sea level trends, from nearby stations. The nearest UNAVCO (University NAVSTAR Consortium: https://www.unavco.org/) land movement station at King Cove (https://www.unavco.org/instrumentation/networks/status/nota/overview/AC25) shows no vertical land movement (<1 mm) in the last year and last decade, but a total upward movement of 1 mm over the last two decades. However, the land has moved downward 16 mm over the last century. Thus, the land in this area is vertically stable. The nearest NOAA tide gauge in this area is also at King Cove (https://tidesandcurrents.noaa.gov/map/index.html?id=9459881). With records spanning only the last 15 years, verified monthly mean water level has risen a total of 0.058 m or 3.9 mm/year at King Cove, which would have partially mitigated the sedimentation we observed. NOAA has not calculated longer term (>15 years) relative sea level trends at the King Cove tidal station, but has done so for the Sand Point station (1.21 mm/year ± 0.87 mm/year, 1972–2019, Gulf of Alaska) and the Port Moller station (3.15 mm/year ± 1.94 mm/year, 1984–2017, Bering Sea) both occurring to the east, and for the Unalaska station (−4.63 mm/year ± 0.51 mm/year, 1957–2019, Bering Sea), occurring to the west (https://tidesandcurrents.noaa.gov/sltrends/). Since False Pass falls in between these small positive and negative sea level changes, it seems reasonable that sea level rise or fall is also not a likely cause of the changes we noted here. Therefore, our hypothesis of gradual sedimentation combined with episodic Bering Sea storm events remains a likely explanation.

5 | CONCLUSIONS

From our review of the GIS information for this area, it seemed most appropriate that the single, remaining northern opening of the False Pass area should be named False Pass. Clearly, from our review of the hydrographic documentation of this area, it is the northern opening, between Bechevin Bay and the Bering Sea, along with the wandering channels within Bechevin Bay, which is the bottleneck for safe navigation. The inlet that we documented through Cape Krenitzen no longer exists and can be removed from NOS chart 16535. It also would be simplest if no passes are named in association with Isanotski Strait.

This project occurred during a revision (Zimmermann & Prescott, In Review) of our original Aleutians bathymetry (Zimmermann et al., 2013), which played an important role in defining coral and sponge habitats (Rooper et al., 2014) and also in defining Essential Fish Habitat (EFH) (Turner et al., 2017). Our new Aleutians bathymetry will further improve our understanding of coral, sponge, and EFH, along with tides and currents modeled in oceanographic studies. It would be interesting to model the different tidal and current regimes that might have existed with a deeper Bechevin Bay that was fully exposed to the Bering Sea.

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AUTHOR CONTRIBUTIONS

Mark Zimmermann is the corresponding author, did most of the manuscript preparation, interpretation of data, and data collection. Megan Prescott created some of the project data and was involved with its statistical interpretation and manuscript preparation. All authors approved the manuscript version to be published and have agreed to be accountable for all aspects of the work.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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