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Passes of the Aleutian Islands: First detailed description

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Abstract

We derived the first detailed and accurate estimates of the location, cross-sectional area, length, and depth of the Aleutian Island passes, which are important bottlenecks for water exchange between the North Pacific Ocean and the Bering Sea. Our pass descriptions utilized original bathymetric data from hydrographic smooth sheets, which are of higher resolution than the navigational chart data used for earlier pass size estimates. All of the westernmost Aleutian passes, from Kavalga to Semichi, are larger (18%–71%) than previously reported, including Amchitka Pass (+23%), the largest in the Aleutians. Flow through Chugul Pass, previously reported as the largest pass in the Adak Island area, is blocked on the north side by Great Sitkin and several other islands. Collectively, these smaller passes (Asuksak, Great Sitkin, Yoke, and Igitkin) are only about half the size of Chugul Pass. The important oceanographic and ecological boundary of Samalga Pass occurs in a location where the cumulative openings of the eastern Aleutian passes equal the minimal opening of Shelikof Strait, carrier of the warmer, fresher water of the Alaska Coastal Current that eventually flows northward, through Samalga and the other eastern passes, into the Bering Sea and Arctic Ocean.

KEYWORDS
Aleutian Islands, Aleutian passes, bathymetry, Bering Sea, North Pacific Ocean

1 | INTRODUCTION

There are thousands of islands in the Aleutian Archipelago arranged in a 1,740 km long arc that crosses 25 degrees of longitude, but only a few dozen passes among those islands limit water circulation between the North Pacific Ocean and the Bering Sea (Figure 1). Our project sought to add inshore details to an older bathymetry model (Zimmermann et al., 2013) for complete shore-to-shore pass descriptions. For decades, oceanographers and ecologists have studied water flow through these passes for a better understanding of the ecosystem impacts of the warmer, fresher water flowing from the North Pacific and into the Bering Sea, which supports fisheries harvests worth US $2 billion annually (Fissel et al., 2019), but those flow estimates were based on rough pass sizes. This northward transport also makes a significant contribution of heated fresh water for melting of Arctic ice, making it important for climate change considerations, and global ocean circulation (Woodgate et al., 2006).

The passes of the Aleutian Islands are important oceanographic features, some of which have been charted for centuries, but only with vague indications about their locations. For example, passes are defined as occurring between two islands, but this navigational generality was inadequate for this project, as we were interested in the exact linear or curvilinear path between two islands that results in the smallest amount of cumulative depth. The passes have been described by size and depth estimates, by official place name locations, and by placement of oceanographic moorings, but there is no source for the location of the minimal cross-sectional areas of the passes. Favorite (1967) defined the cross-sectional area for 36 Aleutian passes in units of 0.1 km^2 by planimetering on low-resolution navigational charts. He also estimated maximum sill depth

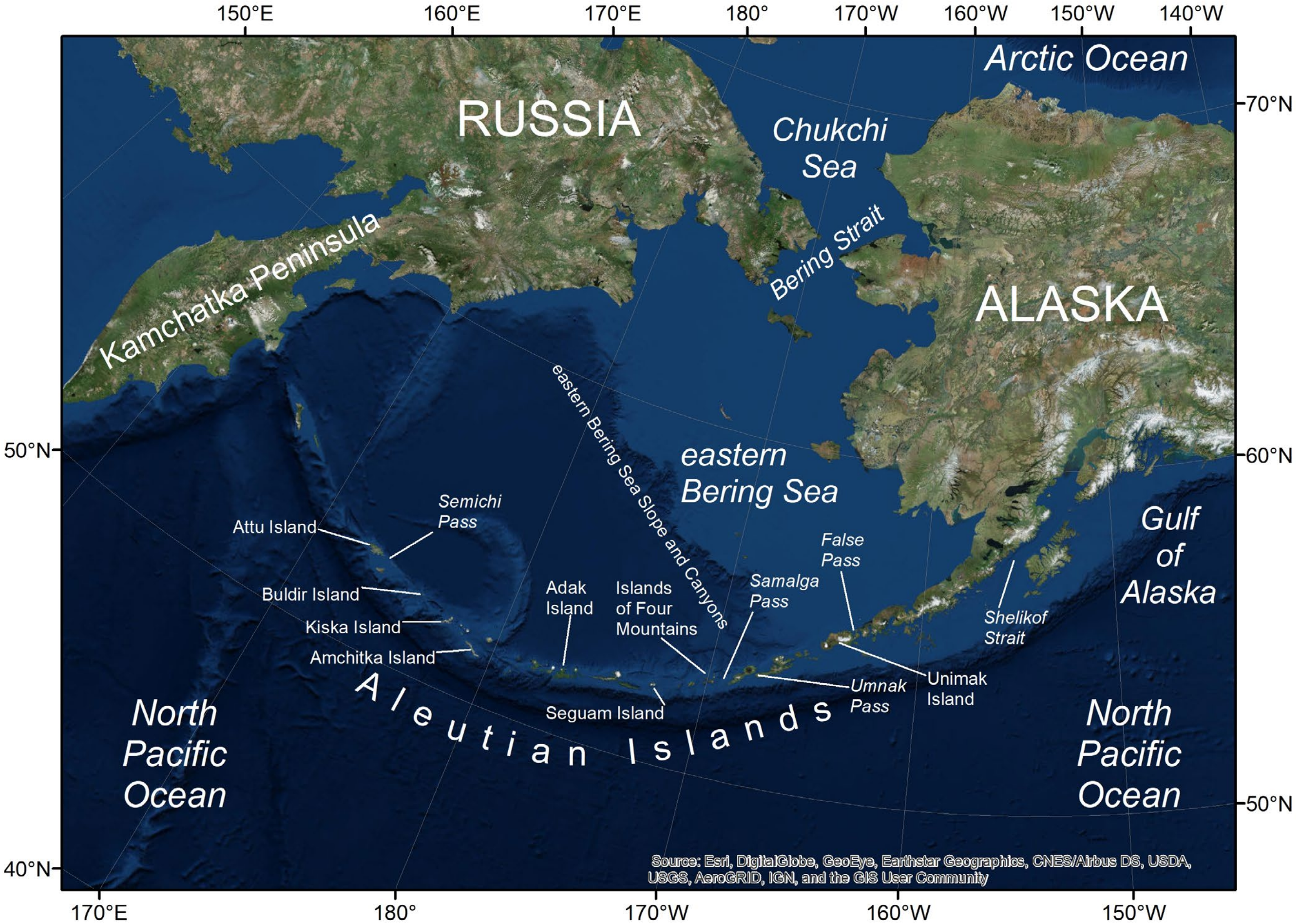

FIGURE 1 Overview map of the region showing location of Aleutian Islands separating the North Pacific Ocean from the Bering Sea

in 5-m intervals, presumably from the same charts, but it is unclear whether the sill depth metric refers to the maximum depth within the pass or refers to the deepest depth contour that crosses the pass (through depth). Favorite (1967) mapped pass locations (see Figure 4 in Favorite, 1967) at a coarse scale but did not publish positions of the passes. Ladd et al. (2005) also estimated cross-sectional areas in units of 0.1 km^2 for seven passes, noting that the available bathymetry was inadequate, and indicating the general location of three passes in multiple figures. The US Board on Geographic Names (USBGN: https://www.usgs.gov/core-science-systems/ngp/board-on-geographic-names) defines the single cartographic location of numerous passes within the Aleutians. Oceanographic publications report the position of moorings deployed to measure water flow through several passes, but without explanation about how locations were chosen (Reed, 1990; Reed & Stabeno, 1997; Stabeno et al., 2005, 2016; Stabeno & Hristova, 2014). This project is the first to define the location of minimal cross-sectional area across each Aleutian Island Pass that significantly contributes to the flux of North Pacific water into the eastern Bering Sea.

To quantify the passes of the Aleutians, we built upon our previously published bathymetry map of the Aleutians (Zimmermann et al., 2013), derived primarily from historical hydrographic survey documents called smooth sheets (Zimmermann & Benson, 2013). Originally available only as archived paper documents, the smooth sheets were scanned into digital form and the depth soundings were digitized into text files (National Centers for Environmental Information: https://maps.ngdc.noaa.gov; Wong et al., 2007). We digitized the MHW (mean high water) shoreline from the smooth sheets and annotated cartographic features, as inshore features such as rocks, islets, and rocky reefs sometimes have depths associated with them, but were often missed or digitized incorrectly at NCEI (Zimmermann & Benson, 2013). Some areas of the Aleutians have never been charted (Zimmermann et al., 2013), so we added non-hydrographic single-beam data to increase coverage and also some higher quality multibeam data which superseded older, lower-quality smooth sheet and single-beam soundings. A single-beam echosounder, originally known as a fathometer, is a device usually affixed to a ship's hull that emits a short blast of sound toward the seafloor, at a particular frequency, and then converts the resulting seafloor echo into a depth estimate based on lapsed time and the speed-of-sound traveling vertically through the water column. Most of the smooth sheet soundings were collected with fathometers or single beams. A multibeam is essentially a collection of single-beam units arranged along the ship's hull in a line that is perpendicular to the path being traveled, so that the resulting seafloor reflections map a linear swath of the seafloor, sometimes with hundreds of depths. The various data types were combined into a new, detailed Aleutian Pass map.

Oceanographers have been using low-quality estimates of bathymetry to examine flow from the North Pacific Ocean to the Bering Sea (Ezer & Oey, 2013; Favorite, 1974; Ladd et al., 2005) and to the Arctic (Ezer & Oey, 2013; Woodgate et al., 2006). There are three major bathymetric features that influence this northward water flow from the North Pacific to the Arctic: the Aleutian Island passes, the canyons incising the Bering Sea slope, and the shallow waters of Bering Strait. We have not yet made a detailed bathymetric map of the Bering Strait. In 2018, we published a map and defined the canyon thalwegs of the eastern Bering Sea slope (Zimmermann & Prescott, 2018), which are important conduits for deep-water flow onto the Bering Sea shelf (Clement-Kinney et al., 2009). We published a draft Aleutian bathymetry map in 2013 (Zimmermann et al., 2013), and here, we update that map with a more complete bathymetric surface, pass locations, and accompanying new pass size estimates for use in recalculating pass flow estimates.

2 | METHODS

The smooth sheets used for the 2013 Aleutians bathymetry compilation provided additional information that was the focus of this effort to define the passes, particularly for the inshore area. Smooth sheet hydrographic soundings were collected in the mean lower low water (MLLW) tidal datum, defined as a depth of zero. Few soundings are collected shallower than zero depth so annotated cartographic features and the shoreline supplemented the inshore area.

The cartographic information for the easternmost pass—False Pass—was so confusing and contradictory that we analyzed it in a separate project (Zimmermann & Prescott, in review). False Pass is unusual as it is the only Aleutian Pass that directly connects the shelves of the western Gulf of Alaska and eastern Bering Sea, it has constricted northern and southern openings with two extensive capes blocking most of the northern opening, and some information indicated that there might be an additional inlet through one of those capes (Figure 1). The other Aleutian passes were more straightforward to define as they are mostly deeper.

2.1 | Cartographic features

Inshore cartographic features were proofed, edited, and digitized along with depth or elevation measurements, generally in units of feet (0.305 m). Cartographic features such as rocky reefs, rocks, and islets sometimes have accompanying depth information, while features such as kelp beds never do.

2.2 | Shoreline

A new shoreline was digitized from the smooth sheets and annotated with MHW. In general, tidal variations, ranging from high to low tides, were recorded as marigrams during the course of each smooth sheet survey so that soundings could be adjusted deeper or shallower according the state of the tide at the time the soundings were collected. MHW is recorded in units of 0.1 feet and is always a negative number, meaning that it is elevated (depths are positive numbers).

2.3 | Single-beam soundings

Non-hydrographic quality single-beam echosounder data and navigational data from biennial Alaska Fisheries Science Center (AFSC) Aleutian Island bottom trawl survey fisheries research cruises (2004, 2006, 2010, 2012, 2014, 2016, 2018) were edited for errors including missed positions, repeated depths, and lost bottom. GLORIA (Geological Long Range Inclined Asdic: https://coastalmap.marine.usgs.gov/gloria/) surveys for mapping the US Exclusive Economic Zone on the *Farnella* in 1986–88 also produced underway files with depths that we utilized for deeper areas around the Aleutians. National Ocean Service (NOS) cruises on the *Pioneer* 1961–63 and *Surveyor* 1963–64 provided offshore depths south of the Aleutians.

2.4 | Multibeam soundings

Multibeam data sets from multiple sources were aggregated, if needed, and generalized into 100 m horizontal resolution point shape files prior to incorporation in the final depth surface. Nine deep-water multibeam surveys, ranging from Seguam Island to Stalemate Bank, provided seafloor details of 9,700 km^2 for the University of South Carolina's Western Aleutian Volcano Expedition (WAVE) project on the R/V *Thompson* in 2005 (https://www.seoe.sc.edu/yogodzinski/Genes_Web_Site/SeafloorVolcanism.html) (Coombs et al., 2007). About 8,900 km^2 of the northern flank of Bowers Ridge was mapped by the U.S. Extended Continental Shelf Task Force (USECSTF) for the United Nations Convention on the Law of the Sea (UNCLOS) project on the R/V *Davidson* in 2003 (http://ccom.unh.edu/data/bering-sea-bowers-ridge-bathymetry), http://ccom.unh.edu/sites/default/files/publications/Gardner_03_cruise_report_DA0301.pdf). Another 2,700 km^2 at 17 coral garden sites were mapped by the R/V *Davidson* in 2003 (Woodby et al., 2009). The Consortium for Risk Evaluation with Stakeholder Participation (CRESP) mapped a mostly shallow (<100 m) area ~17 km long north of Amchitka Island for assessment of offshore radionuclide leakage from three nuclear test sites (http://www.cresp.org/Amchitka/Amchitka_Final_Report/index_FinalReport.html). The NOS conducted 44 inshore multibeam surveys around Unimak and Unalaska islands (https://maps.ngdc.noaa.gov). In 2004, a R/V *Roger Revelle* cruise investigated potential tsunamigenic landslides south of Unimak Pass (Rathburn et al., 2009) and collected about 3,500 km^2 of underway data along the north side of Umnak and the Islands of Four Mountains (IOFM) (Woodby et al., 2009).

2.5 | Creation of depth raster

We combined the smooth sheet soundings, annotated cartographic features, newly digitized MHW shoreline, and single-beam and multibeam data into a TIN (triangulated irregular network). Potential depth or position errors of individual sounding were investigated by examining TIN slope anomalies. Any sounding errors were corrected according to the source data or deleted. After numerous iterations, the TIN was converted into a 100-m horizontal resolution grid using local area weighting or natural neighbors.

2.6 | Pass definition and cross-sectional area

Rather than draw a straight line across the 100-m horizontal resolution depth surface for each pass in an attempt to intersect the shallowest depths by hand (Interpolate Line tool), we utilized a Cost Distance tool in ArcMap (v.10.2.2; ESRI: Environmental Systems Research Institute) to select algorithmically the shallowest curved path of each pass, thus defining the pass location and cross-sectional opening at the same time. The Cost Distance tool method for defining passes requires multiple steps. First, numerous potential starting points are created from the edge of the 100 m depth raster along the shore of one island. Second, numerous potential ending points are created along the shore of the next neighboring island. Third, the Cost Distance tool derives a curved path connecting the two groups of potential starting and ending points, minimizing cumulative areal opening of the pass across the depth raster. When the smallest (flow limiting) pass was not obvious in an area because there were multiple islands, several test runs determined which pass, or combination of passes, limited water flow between the North Pacific and the Bering Sea. The Cost Distance tool draws the path through the centers, not the edges, of the 100-m grid cells. Thus, the smallest pass has a length of 100 m and is drawn between two 100-m raster cells that share a border, and a single 100-m raster cell cannot qualify as a pass. Paths can change course and follow eight possible directions: the four cardinal and the four inter-cardinal directions.

2.7 | Maximum pass and through depth

We used the Cost Distance path to select the depths of raster cells along the path to determine the maximum pass depth. Some of the maximum pass depths are blocked by shallower depths on one or both sides of the pass; thus, these depths may not define the maximum depth of water that can freely move through the pass. Therefore, the deepest depth contour that completely transited each pass defined the deepest through depth.

2.8 | Pass tortuosity

We measured the curved length of each Cost Distance path and a straight-line distance from the starting and ending points of each pass in ArcMap. Dividing the curved Cost Distance path length by the straight-line distance yielded tortuosity, a measure of how much each path deviated from a straight line. Thus, curved or zigzagged passes scored higher tortuosity values. A tortuosity of 1.1 means that a curved path is 10 percent longer than the corresponding straight path.

3 | RESULTS

Differences between our new pass size estimates and those previously published vary by pass size (large > 10 km^2; medium > 1–10 km^2; small > 0.3–1.0 km^2, and tiny > 0–0.3 km^2) and by location (eastern or western) (Figure 2a–d; Tables 1–7). Our estimates of the three largest passes (Figure 2a) and most of the medium-sized passes (Figure 2b) were greater than the estimates of Favorite (1967). The Aleutian's largest pass, Amchitka (+13.8 km^2), was the greatest difference among all passes estimated in this study compared with Favorite (1967). Differences between small pass estimates were mixed, with minor positive and negative differences (Figure 2c). Differences between tiny pass estimates were minor but had the greatest percent differences due to Favorite's (1967) limitation in using units of 0.1 km^2 (Figure 2d). All of our pass size estimates, including the large-sized pass of Amukta, three of the four medium-sized passes (Samalga, Tanaga, and Seguam), and the small-sized pass of Umnak, were less than the estimates of Ladd et al. (2005), except for the medium-sized Unimak Pass (+7%) and the tiny-sized Akutan Pass (nearly double). Several of the passes we measured were not reported by Favorite (1967), presumably because they were too small to estimate with the data available at the time, deemed too small to matter, or were combined with larger, neighboring passes. There are regional differences in how pass sizes compared with Favorite (1967), with our eastern pass size estimates both lesser and greater than Favorite (1967) but all of our western pass size estimates (from Kavalga through Semichi) greater than Favorite (1967). Compared with Ladd et al. (2005), our two eastern pass size estimates are greater, while our five central Aleutians passes are smaller.

3.1 | Regional results

3.1.1 | Unimak area passes

Our estimate of the sum of the eastern passes in the Unimak area (2,140,609 m^2, Figure 3a,b) matches closely with the 2.0 km^2 estimate

TABLE 1 Unimak Pass area characteristics

Pass	Area km^2	Max sill depth (m)	Max through depth (m)	Cost path dist. (m)	Straight dist. (m)	Tortuosity	Favorite (1967) km^2	Ladd et al. (2005) km^2
Unimak	1.078915	73	66	20,050	18,926	1.059	0.9	1.0
Ugamak (includes Aiktak and Kaligagan)	0.290826	88	49	8,025	7,548	1.063	0.2	
Derbin	0.097728	70	50	2,497	2,302	1.085	0.1	
Rootok	0.056780	59	55	2,514	2,100	1.197		
Avatanak	0.311160	120	75	5,404	5,004	1.080	0.4	
Akun	0.009364	14	13	1,949	1,500	1.299	0.1	
Akutan (includes Baby and two passes within the Baby Islands)	0.194643	65	57	7,999	7,294	1.097	0.2	0.1
Unalga	0.101194	42	42	3,280	3,002	1.093	0.1	
Total	2.140609						2.0	N/A

Note: Area is the minimal cross-sectional opening as determined by the Cost Distance method, with comparisons to the literature. Maximum sill depth is the deepest location along the Cost Distance-derived curved path. Maximum through depth is the deepest contour that completely crosses the pass. Cost path distance is pass curved length, and tortuosity is curved divided by straight pass length.

TABLE 2 Islands of Four Mountains area pass characteristics

Pass	Area km^2	Max sill depth (m)	Max through depth (m)	Cost path dist. (m)	Straight dist. (m)	Tortuosity	Favorite (1967) km^2	Ladd et al. (2005) km^2
Umnak	0.271224	68	48	9,036	7,029	1.285	0.2	0.5
Samalga (includes Sagak)	3.761077	246	185	36,283	33,413	1.086	3.9	6.7
Chuginadak	0.871502	276	197	5,760	5,354	1.076	1.0	
Herbert	5.647562	439	227	31,255	27,909	1.120	4.8	
Yunaska	6.202953	517	463	20,144	18,595	1.083	6.6	
Chagulak	0.306540	79	71	6,350	5,941	1.069	0.3	
Total	17.060856						16.8	N/A

Note: Area is the minimal cross-sectional opening as determined by the Cost Distance method, with comparisons to the literature. Maximum sill depth is the deepest location along the Cost Distance-derived curved path. Maximum through depth is the deepest contour that completely crosses the pass. Cost path distance is pass curved length, and tortuosity is curved divided by straight pass length.

of Favorite (1967), although there are some significant differences between individual passes (Table 1). For example, our Akun Pass estimate is 9,364 m^2 (or about 0.01 km^2), but Favorite (1967) estimated it to be almost eleven times larger (0.1 km^2 or 100,000 m^2). Favorite (1967) estimated the size of Ugamak Pass, which we assumed spanned the 7 km gap between larger Ugamak and Tigalda islands. Instead, we found that the minimal pass in this area runs between smaller islands within the pass, from near Aiktak to Kaligagan island. Thus, smaller passes flank Ugamak to the east (Aiktak) and west (Kaligagan) (Figure 3b), and we assume that Favorite's (1967) Ugamak Pass size estimate also included them, but our combined estimate of these passes is about 45% larger. Favorite (1967) did not recognize Rootok Pass, which we estimate is larger (56,780 m^2) than some of the passes for which he estimated sizes. Perhaps his placement of Avatanak Pass between Avatanak and Akun Islands, and about 8 km to the east of our location between Rootok and Avatanak islands, meant that he interpreted Rootok Pass as unimportant for measuring water flow (Figure 3a).

Stabeno et al. (2016) placed a mooring for Unimak Pass that is in close agreement with our location of Unimak Pass (Figure 3a). Stabeno et al. (2005) placed moorings to measure water flow on the north and south sides of Akutan Pass, but her published positions are misreported (Personal Communication, Carol Ladd, Pacific Marine Environmental Laboratory (PMEL), March 11, 2020), placing the moorings on land. If the latitudes of these two moorings are swapped (Personal Communication, Carol Ladd, PMEL, March 11, 2020), then the moorings plot in water, similar to her map (see Figure 3; Stabeno et al., 2005). However, the corrected positions of the moorings are both more than 10 km away from our definition of Akutan Pass.

3.1.2 | Islands of Four Mountains (IOFM) area passes

Our sum of the IOFM passes (17,060,856 m^2, Table 2; Figure 4a,b) is similar to Favorite's (1967) estimate (16.8 km^2), as in the Unimak area, but again with some significant individual differences. Samalga Pass, which we combine with a tiny pass occurring between Umnak Island's Sagak Cape and Samalga Island, is about equal to the estimate of Favorite (1967) but 44% smaller than the estimate of Ladd et al. (2005). Umnak Pass is isolated, occurring between the Unimak and IOFM areas (Figure 1), and therefore, it is not shown in Figures 3a and 4a but only depicted in the graph in Figure 4b. Our size estimate of 271,224 m^2 for Umnak is 36% larger than Favorite (1967) and 46% smaller than Ladd et al. (2005). Umnak is the second-most tortuous pass (1.285) in the Aleutians (Table 2).

Moorings placed to measure water flow to the north, center, and south of Samalga Pass are well-situated (Stabeno & Hristova, 2014) (Figure 4a). Moorings placed north of the islands to measure the Alaska North Slope Current (Reed & Stabeno, 1997) and placed south of the islands to measure the Alaska Stream (Stabeno & Hristova, 2014; Stabeno et al., 2005) are located far away from the passes and appear well-suited to measuring offshore water flow.

3.1.3 | Seguam area passes

Amukta Pass was regarded by Favorite (1967) as the third largest in the Aleutians and our results confirmed that, although our size estimate (21,369,326 m^2, Table 3; Figure 5a,b) is about 10% larger than his estimate (19.3 km^2) but 14% smaller than Ladd et al. (2005). Favorite (1967) did not provide a size for tiny Agligadak Pass (not in USBGN) so we combined it with the much larger, neighboring Seguam Pass and our combined pass size is about 31% larger than Favorite (1967) but 45% less than Ladd et al. (2005).

Moorings placed by Stabeno et al. (2005) for measuring water flow through Amukta Pass are well-placed if one of the latitudes is adjusted to align with the other three moorings (a misreported latitude; Personal Communication, Carol Ladd, PMEL, March 11, 2020) (Figure 5a). Their north mooring for Seguam Pass is close to the pass location, but their mooring for measuring water flow on the south side of the pass is about 21 km away. The Reed and Stabeno (1997) Alaska Stream mooring off of the north side of Atka Island is well away from any passes.

3.1.4 | Adak area passes

Favorite (1967) determined that Chugul Pass was the largest pass in the Adak area and our size estimate (604,417 m^2) agrees with his

TABLE 3 Seguam Pass area characteristics

Pass	Area km^2	Max sill depth (m)	Max through depth (m)	Cost path dist. (m)	Straight dist. (m)	Tortuosity	Favorite (1967) km^2	Ladd et al. (2005) km^2
Amukta	21.369326	451	439	77,881	69,633	1.118	19.3	24.4
Seguam (includes Agligadak)	3.044047	175	160	32,323	28,855	1.120	2.1	4.4
Amlia	0.027844	29	29	2,207	2,062	1.071	0.1	
Total	24.441217						21.5	N/A

Note: Area is the minimal cross-sectional opening as determined by the Cost Distance method, with comparisons to the literature. Maximum sill depth is the deepest location along the Cost Distance-derived curved path. Maximum through depth is the deepest contour that completely crosses the pass. Cost path distance is pass curved length, and tortuosity is curved divided by straight pass length.

TABLE 4 Adak Pass area characteristics

Pass	Area km^2	Max sill depth (m)	Max through depth (m)	Cost path dist. (m)	Straight dist. (m)	Tortuosity	Favorite (1967) km^2	Ladd et al. (2005) km^2
Atka	0.245388	47	41	8,328	7,640	1.090	0.2	
Oglodak	0.011370	21	19	1,183	1,118	1.058	0.1	
Fenimore (includes Ikiginak)	0.197538	51	48	6,663	6,286	1.060	0.2	
Tagalak	0.051016	37	32	3,149	2,927	1.076	0.1	
Chugul	0.604417	89	87	8,773	8,448	1.038	0.6	
Chugul reroute (Igitkin, Yoke, Great Sitkin, and Asuksak)	0.325402	109	101	10,969	10,378	1.057		
Umak	0.020700	25	20	1,190	1,140	1.044	0.1	
Little Tanaga	0.075779	58	55	2,466	2,300	1.072	0.1	
Kagalaska	0.009444	28	27	500	500	1.000	0.1	
Adak	0.569785	64	60	13,389	12,552	1.067	0.5	
Kanaga	0.149744	46	27	8,743	7,938	1.101	0.1	
Total	1.656167						2.1	N/A

Note: Area is the minimal cross-sectional opening as determined by the Cost Distance method, with comparisons to the literature. Maximum sill depth is the deepest location along the Cost Distance-derived curved path. Maximum through depth is the deepest contour that completely crosses the pass. Cost path distance is pass curved length, and tortuosity is curved divided by straight pass length.

TABLE 5 Amchitka Pass area characteristics

Pass	Area km²	Max sill depth (m)	Max through depth (m)	Cost path dist. (m)	Straight dist. (m)	Tortuosity	Favorite (1967) km²	Ladd et al. (2005) km²
Tanaga	4.179038	372	286	35,551	32,961	1.079	3.6	5.3
Skagul	0.001731	7	6	641	608	1.054		
Ogliuga (includes Sea Otter)	0.032769	11	10	6,467	5,744	1.126	0.1	
Kavalga	0.500767	59	59	13,354	12,167	1.098	0.3	
Amchitka	59.542836	1,268	1,096	120,733	105,414	1.145	45.7	
Total	64.257141						49.7	N/A

Note: Area is the minimal cross-sectional opening as determined by the Cost Distance method, with comparisons to the literature. Maximum sill depth is the deepest location along the Cost Distance-derived curved path. Maximum through depth is the deepest contour that completely crosses the pass. Cost path distance is pass curved length, and tortuosity is curved divided by straight pass length.

estimate (0.6 km^2) (Table 4), but he did not realize that Great Sitkin and other islands on the north side of Chugul Pass partially block the flow of water through Chugul Pass (Figure 6a,b). Together, the small passes of Igitkin, Yoke, Great Sitkin, and Asuksak (325,402 m^2) are only about half the size of Chugul Pass. Thus, Adak Pass, which we estimate to be about 12% larger than Favorite (1967), is the largest pass of importance in this area. Favorite (1967) did not provide a size estimate for Ikiginak Pass so we combined it with neighboring Fenimore Pass, and together, they roughly equal Favorite's estimate of Fenimore. Our total for passes in this area (1,656,167 m^2) includes the smaller passes of the Great Sitkin Island reroute and not Chugul Pass, but Chugul is contained within the total estimate (2.1 km^2) for Favorite (1967) (Table 4).

Ladd et al. (2005) did not estimate any pass sizes in the Adak area. There were no mooring locations available from the literature for comparison to our Adak area pass locations.

3.1.5 | Amchitka area passes

Amchitka Pass, reportedly the largest in the Aleutians (Favorite, 1967), must span a gap of about 100 km across the 180° longitude line, but the pass location was not clear from the geographic distribution of islands nor from the literature (Figure 7a). After testing several possibilities, we determined that the minimal opening extended for 120.7 km between Unalga and Amchitka islands, making Amchitka the second longest pass in the Aleutians after Buldir. The eastern two-thirds of Amchitka Pass is relatively shallow but highly variable in depth, with minima of 240 and 108 m, and maxima of 492 and 899 m (Figure 7a,b). The western portion of Amchitka is much deeper, with a maximum depth of 1,268 m only 8 km from Amchitka Island's eastern shore, and the greatest through depth (1,096 m) among all Aleutian passes (Table 5, Figure 7a,b). Because of its length and deeper western side, we confirmed that Amchitka is the largest Aleutian Pass, accounting for 38% of the cross-sectional area of all passes through to Attu Island. Tanaga Pass should probably include Ugidak Island, but the shoreline of this island was not drawn on the smooth sheets that we used, and hence, it is omitted in our map (Figure 7a) and analysis.

The only oceanographic mooring (Reed, 1990) was about 19 km to the north, and the USBGN place name was about 28 km to the north of our Amchitka Pass location (Figure 7b). Thus, flow through Aleutian's largest pass is a good candidate for reanalysis. Starting with Kavalga Pass, and continuing through to the westernmost Aleutian Pass, all of Favorite's (1967) pass size estimates were smaller than our estimates. Ladd et al. (2005) only provided a pass size estimate for Tanaga in this area, and our estimate is 27% smaller.

3.1.6 | Kiska area passes

Our estimate for Kiska, the largest pass in this area, is 19% larger than Favorite (1967), even though we determined that the pass follows a shallow ridge (Figure 8a,b). Favorite's (1967) Rat Pass must be a combination of several smaller passes (Krysi, Sea Lion, Tanadak, and North or South passes) that occur between Rat ("Hawadax") and Kiska islands because the USBGN does not recognize a Rat Pass (Table 6). Krysi and Sea Lion passes are supposedly divided by Sea Lion Rock, but, according to the smooth sheets, this feature is below MLLW and therefore does not completely obstruct water flow (Figure 8b). Tanadak Island is less than a kilometer in size, making a very small division between Sea Lion and Tanadak passes. Finally, the gap between Little Kiska and Kiska islands is named North Pass on the north side and South Pass on the south side by the USBGN, while our derived pass occurs between them, suggesting name substitutes such as "Middle" or "Little Kiska" for "North" or "South." Collectively, our estimate for this group of passes is 41% larger than Favorite's (1967) Rat Pass estimate, perhaps because we found that Krysi/Sea Lion had a maximum depth of 62 m and maximum through depth of 59 m in comparison with his estimate of 15 m sill depth for Rat Pass (Table 6).

The namesake for Favorite's (1967) Rat Pass, Rat Island, originally called "Hawadax" by the Unangax̂, earned its post-contact name when rodents were accidentally introduced from a 1,780

TABLE 6 Kiska Pass area characteristics

Pass	Area km^2	Max sill depth (m)	Max through depth (m)	Cost path dist. (m)	Straight dist. (m)	Tortuosity	Favorite (1967) km^2	Ladd et al. (2005) km^2
Oglala	0.947095	74	72	22,166	19,761	1.122	0.8	
Rat combined	1.023744	62	59	40,367	37,287	1.083	0.6	
Kiska	8.388953	118	118	113,273	104,580	1.083	6.8	
Total	10.359792						8.2	N/A

Note: Area is the minimal cross-sectional opening as determined by the Cost Distance method, with comparisons to the literature. Maximum sill depth is the deepest location along the Cost Distance-derived curved path. Maximum through depth is the deepest contour that completely crosses the pass. Cost path distance is pass curved length, and tortuosity is curved divided by straight pass length.

shipwreck, decimating the native ground-nesting bird populations. In 2008, the aerial application of 46 tons of rodenticide put an end to two centuries of rat occupation (Buckelew et al., 2011), and in 2012, the rat-free island was officially renamed Hawadax by the USBGN, to commemorate the island's return to more natural conditions. Perhaps that Unangax̂ name of Hawadax can be extended to the pass too.

All of our pass size estimates in this area were larger than Favorite's pass size estimates (1967) (Table 6). Ladd et al. (2005) did not provide any pass size estimates in this area. There were no mooring locations available from the literature for comparison to our Kiska area pass locations.

3.1.7 | Buldir area passes

All of the passes between Buldir and Attu islands are relatively straight, with tortuosities < 1.1 (Table 7), due to a narrow shelf connecting the islands (Figure 9a,b). Buldir Pass is the longest (132.7 km, 10 km longer than Amchitka) and second largest pass in the Aleutians, with our cross-sectional area estimate 17% larger than Favorite (1967). Favorite (1967) did not provide pass size estimates for the short, small, and shallow Shemya and Nizki passes although they are both clearly separated by larger islands and recognized by the USBGN (Table 7, Figure 9a,b). Located between Alaid and Attu islands, Semichi Pass is the westernmost pass included in our analysis.

All of our pass size estimates in this area are larger than Favorite (1967). Ladd et al. (2005) did not provide any pass size estimates in this area. There were no mooring locations available from the literature for comparison to our Attu area pass locations.

3.1.8 | Shoreline

We digitized the shoreline of the largest 3,009 islands from the smooth sheets. In general, the Aleutians Islands are small and only four islands are larger than 1,000 km^2: Unimak (4,082 km^2), Unalaska (2,707 km^2), Umnak (1,770 km^2), and Atka (1,056 km^2). There are only 17 islands greater than 100 km^2 but less than 1,000 km^2. Thus, 2,988 islands are smaller than 100 km^2. The average, unweighted MHW of the digitized shoreline segments is −1.1 m and ranged from −0.8 to −2.1 m.

3.1.9 | Cartographic features

We proofed, edited, and digitized 187,177 cartographic features from the smooth sheets (Zimmermann & Benson, 2013). There are 18 types of features, such as kelp beds, rocky reefs, rocks, and islets. Depths or elevations are included whenever they were available (most cartographic features do not have associated depths or elevations).

TABLE 7 Buldir Pass area characteristics

Pass	Area km^2	Max sill depth (m)	Max through depth (m)	Cost path dist. (m)	Straight dist. (m)	Tortuosity	Favorite (1967) km^2	Ladd et al. (2005) km^2
Buldir	33.594189	1,050	657	132,745	121,382	1.094	28.0	
Shemya	0.009424	10	7	1,956	1,865	1.049		
Nizki	0.000330	2	1	283	283	1.001		
Semichi	2.104970	112	108	32,614	30,166	1.081	1.7	
Total	35.708913						29.7	N/A

Note: Area is the minimal cross-sectional opening as determined by the Cost Distance method, with comparisons to the literature. Maximum sill depth is the deepest location along the Cost Distance-derived curved path. Maximum through depth is the deepest contour that completely crosses the pass. Cost path distance is pass curved length, and tortuosity is curved divided by straight pass length.

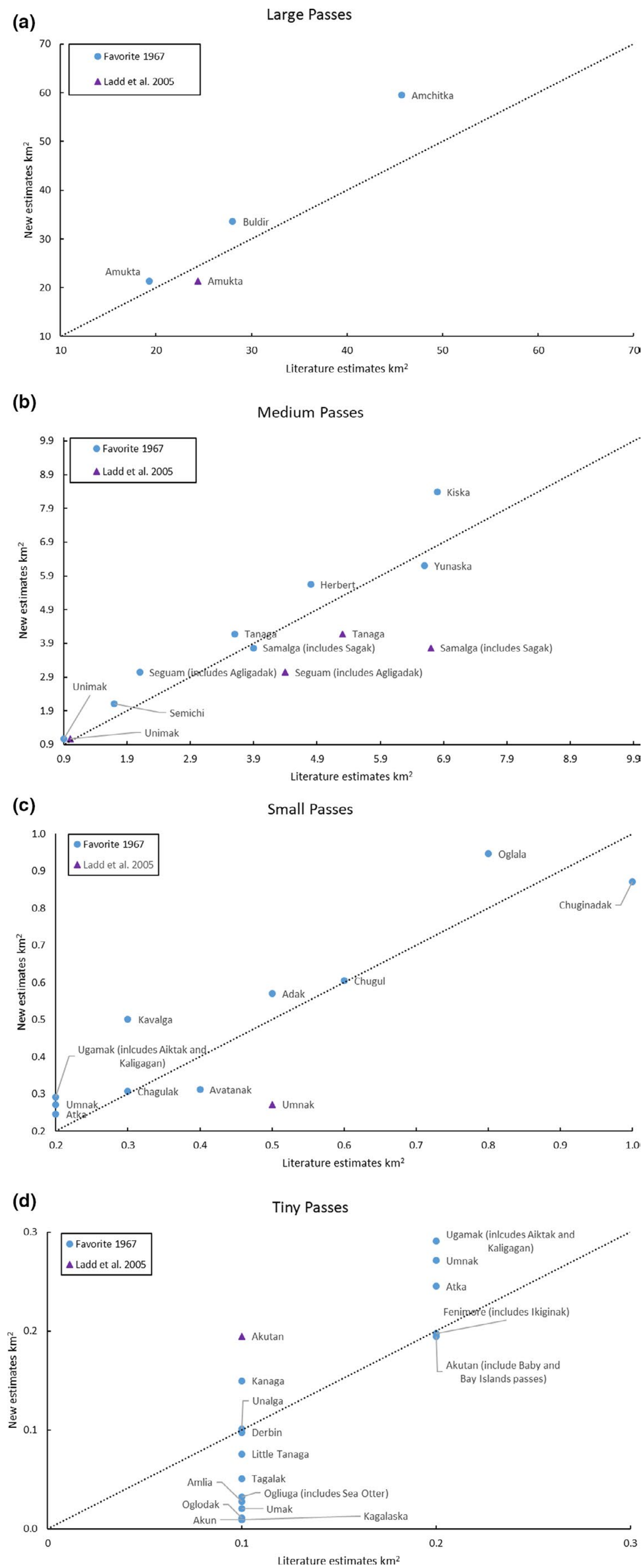

FIGURE 2 Graph comparison between literature values (x-axis, in km^2) and estimates from this study (y-axis, in km^2) for the minimal cross-sectional size opening of (a) large, (b) medium, (c) small, and (d) tiny passes in the Aleutian Islands. Comparisons with literature values from Favorite (1967) are shown as blue circles and with Ladd et al. (2005) are shown as purple triangles. A dashed line starting at the origin and running through the data points at 45 degrees, indicating where$x = y$, shows how to judge differences in pass size estimates. Points falling on the trend line indicate equivalent estimates from the literature and this study. Points above the trend line indicate larger pass size estimates from this study, and points falling below the trend line indicate smaller pass size estimates from this study

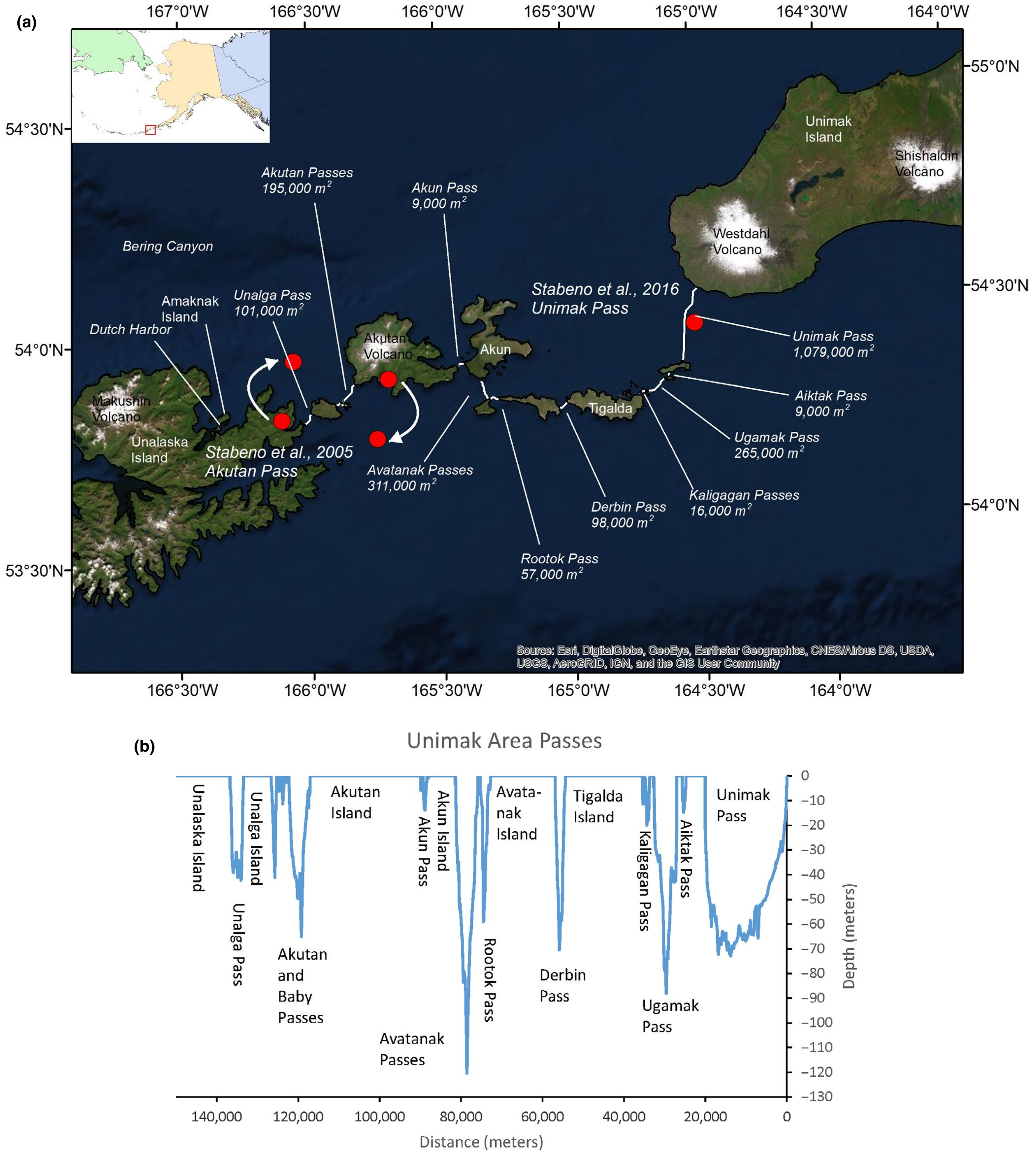

FIGURE 3 (a) Pass locations and sizes in the Unimak area. Pass location as defined by the Cost Distance tool denoted as white line. Reported mooring locations are shown as red circles along with reference. (b) Graph showing horizontal arrangement of islands and passes, with pass depth shown in meters

3.1.10 | Pass curvature

The curved length of the flow limiting passes totaled 849 km, nearly half of the 1,740 km long arc of the Aleutian Islands. Straight length of the passes, perhaps more of a comparable metric to the total length of the Aleutian Archipelago, added up to only 44% of the length. Thus, if the Aleutians are viewed as a picket fence, the total width of the slats and the total width of the openings between the slats are roughly equal. Tortuosity generally was low, with 30 of the passes less than 10% longer than straight paths, and

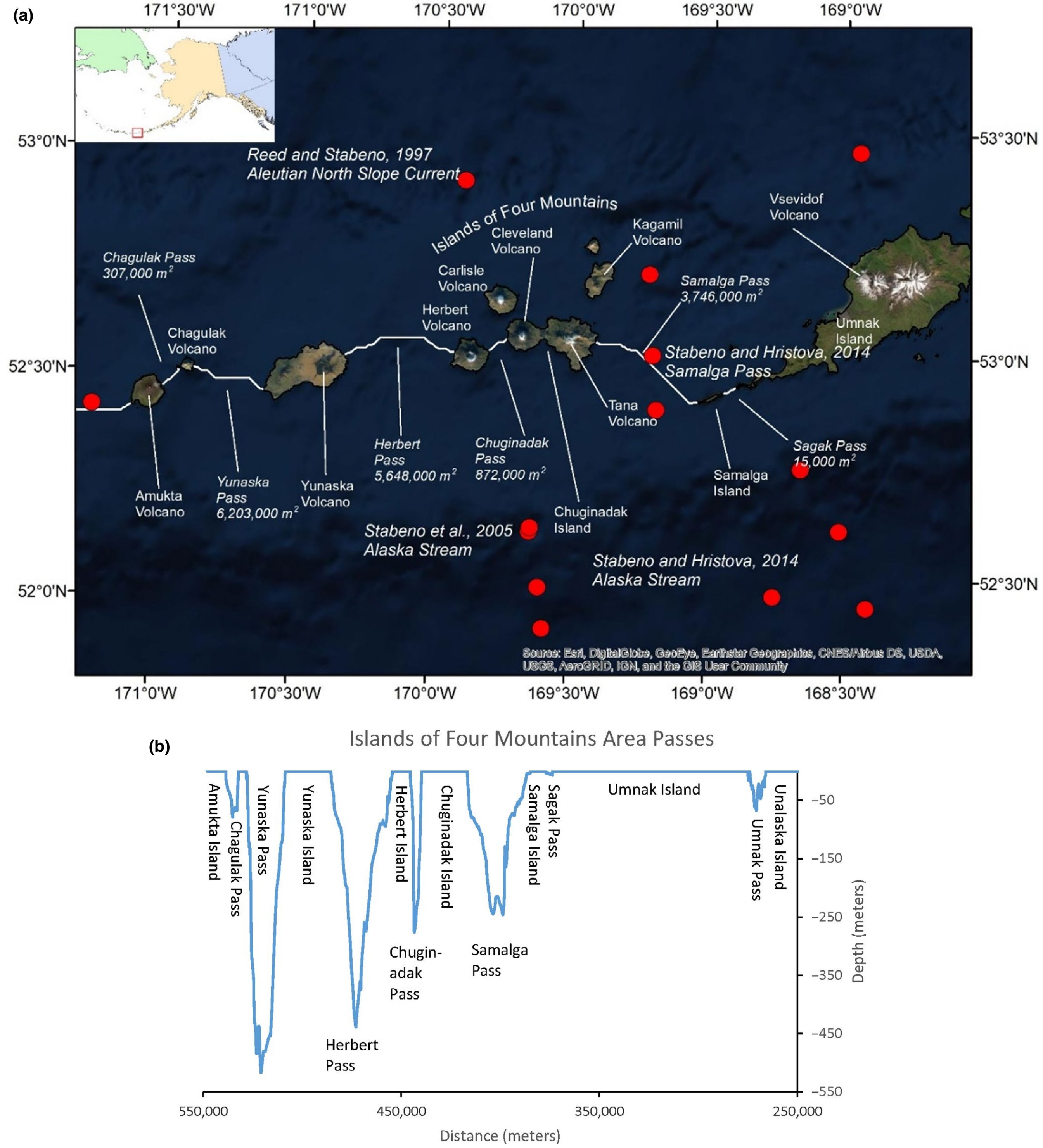

FIGURE 4 (a) Pass locations and sizes in the Islands of Four Mountains (IOFM) area except for Umnak Pass, which is not shown due to its isolation between the IOFM and Unimak areas. Pass location as defined by the Cost Distance tool denoted as white line. Reported mooring locations are shown as red circles along with reference. (b) Graph showing horizontal arrangement of islands and passes, with pass depth shown in meters. Umnak Pass, which occurs far to the east of Samalga Pass, is included

an additional eight 10%–20% longer than straight paths. Only Akun (1.299) and Umnak passes (1.285), both smaller, shallower, eastern passes, had higher tortuosities. Akun Pass has a high tortuosity because it zigzagged but generally did not change direction, while Umnak Pass has a high tortuosity because it forms a distinctive U shape.

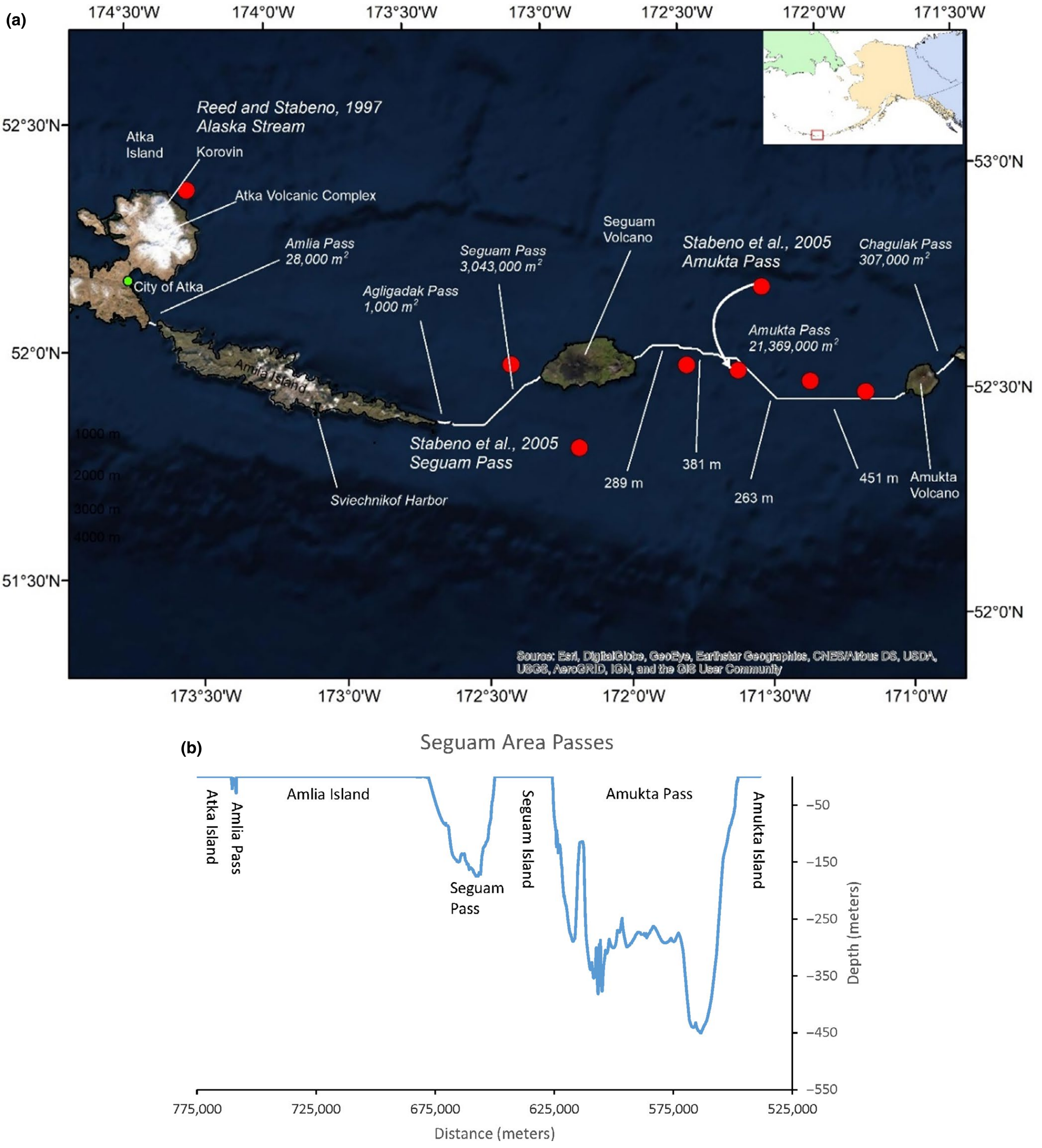

FIGURE 5 (a) Pass locations and sizes in the Seguam area. Pass location as defined by the Cost Distance tool denoted as white line. Reported mooring locations are shown as red circles along with reference. (b) Graph showing horizontal arrangement of islands and passes, with pass depth shown in meters

3.1.11 | Pass depths

In general, the maximum sill depth and through depth were similar at each pass, with an average depth difference of about 15%. Notable exceptions occurred at Herbert (212 m difference or 48%), Ugamak (39 m or 44%), Kanaga (19 m or 42%), Avatanak (45 m or 38%), and Buldir (393 m or 37%), all locations where the Cost Distance algorithm chose a shorter path that crossed a deep spot. Favorite's (1967) "sill depth" is most similar to what we defined as through depth.

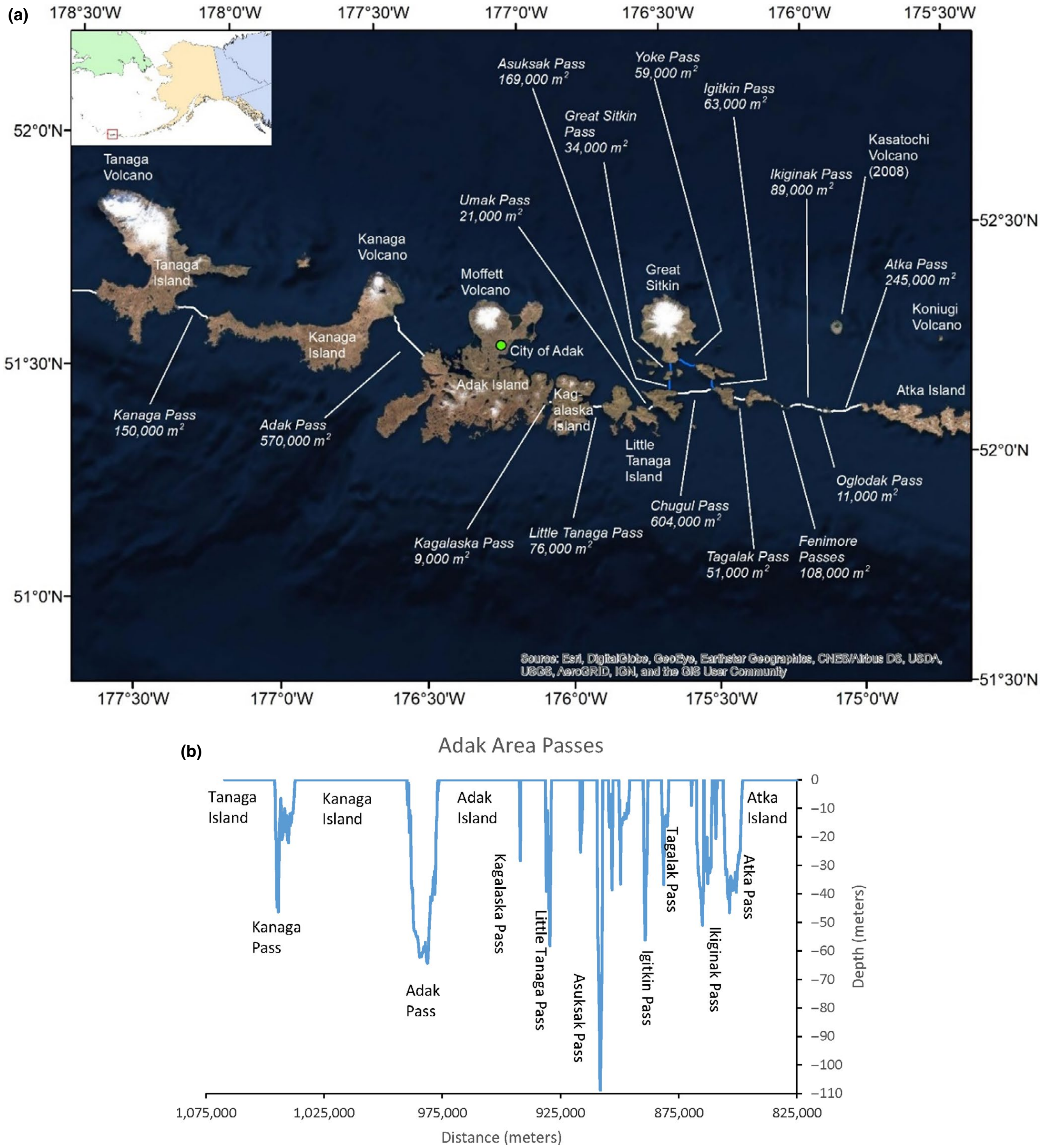

FIGURE 6 (a) Pass locations and sizes in the Adak area. Pass location as defined by the Cost Distance tool denoted as white line. (b) Graph showing horizontal arrangement of islands and passes, with pass depth shown in meters

4 | DISCUSSION

We consider our new pass size measurements a significant update of the previous estimates (Favorite, 1967; Ladd et al., 2005). We utilized sources of bathymetry such as smooth sheet soundings, cartographic features, and digitized shorelines that were not available for earlier pass size estimations. The NOS navigational charts previously used for pass size estimates are coarser versions of the smooth sheets. Without knowing the exact paths traced or soundings utilized on navigational charts for previous pass characterizations, it is difficult to understand methodological differences.

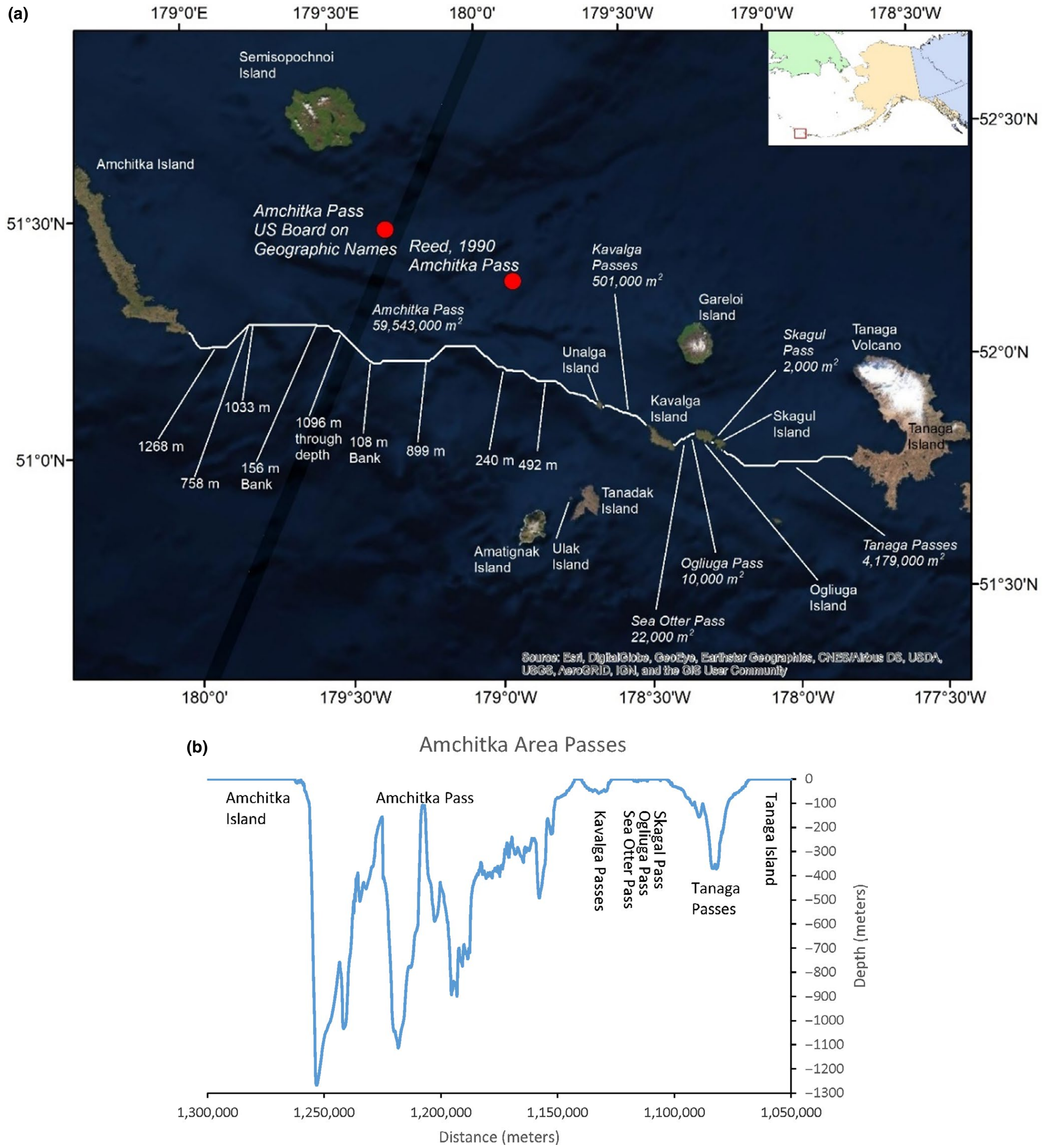

FIGURE 7 (a) Pass locations and sizes in the Amchitka area. Pass location as defined by the Cost Distance tool denoted as white line. A single reported mooring location is shown as red circle, along with reference, and the US Board on Geographic Names location is also shown as a red circle for Amchitka Pass. (b) Graph showing horizontal arrangement of islands and passes, with pass depth shown in meters

Most of the smooth sheets from which we derived our bathymetry are old, with the majority of them from the 1930s–40s (Zimmermann et al., 2013), and this age might cause concern that they provide outdated information, even though they are the only hydrographic information for most of the Aleutian navigational charts. Still, some well-known volcanic and tectonic events reshaped Aleutian seafloor areas since the smooth sheet surveys. Significant, recent eruptions such as Kasatochi (2008) and Bogoslof (2016–17) resurfaced and expanded these island volcanoes (https://avo.alaska.edu/), but seafloor changes have not been quantified. Fortunately,

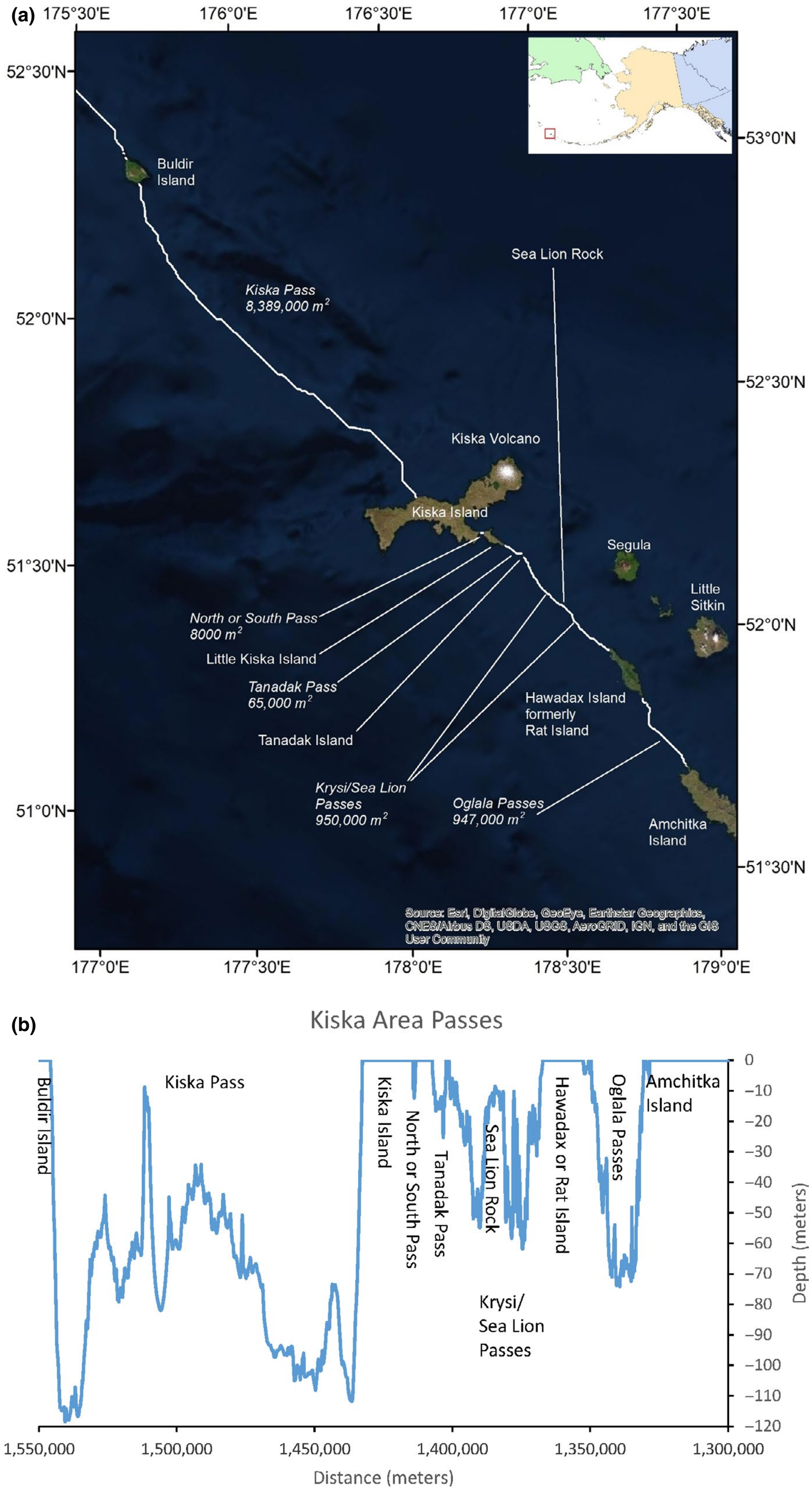

FIGURE 8 (a) Pass locations and sizes in the Kiska area. Pass location as defined by the Cost Distance tool denoted as white line. (b) Graph showing horizontal arrangement of islands and passes, with pass depth shown in meters

none of our pass definitions involved these two islands. The 7.1 magnitude Unimak earthquake of 1946, which created an unexpectedly large tsunami that destroyed property in Alaska and Hawaii, was thought to have been aided by a deep (~>2,000 m) underwater landslide of about 200–300 km^2 occurring south of Unimak Island (Fryer et al., 2004), but this finding was later discounted (Rathburn et al., 2009), leaving potential seafloor slides or fault line shifts undescribed. A 1957 magnitude 8.6 earthquake in the Andreanof Islands

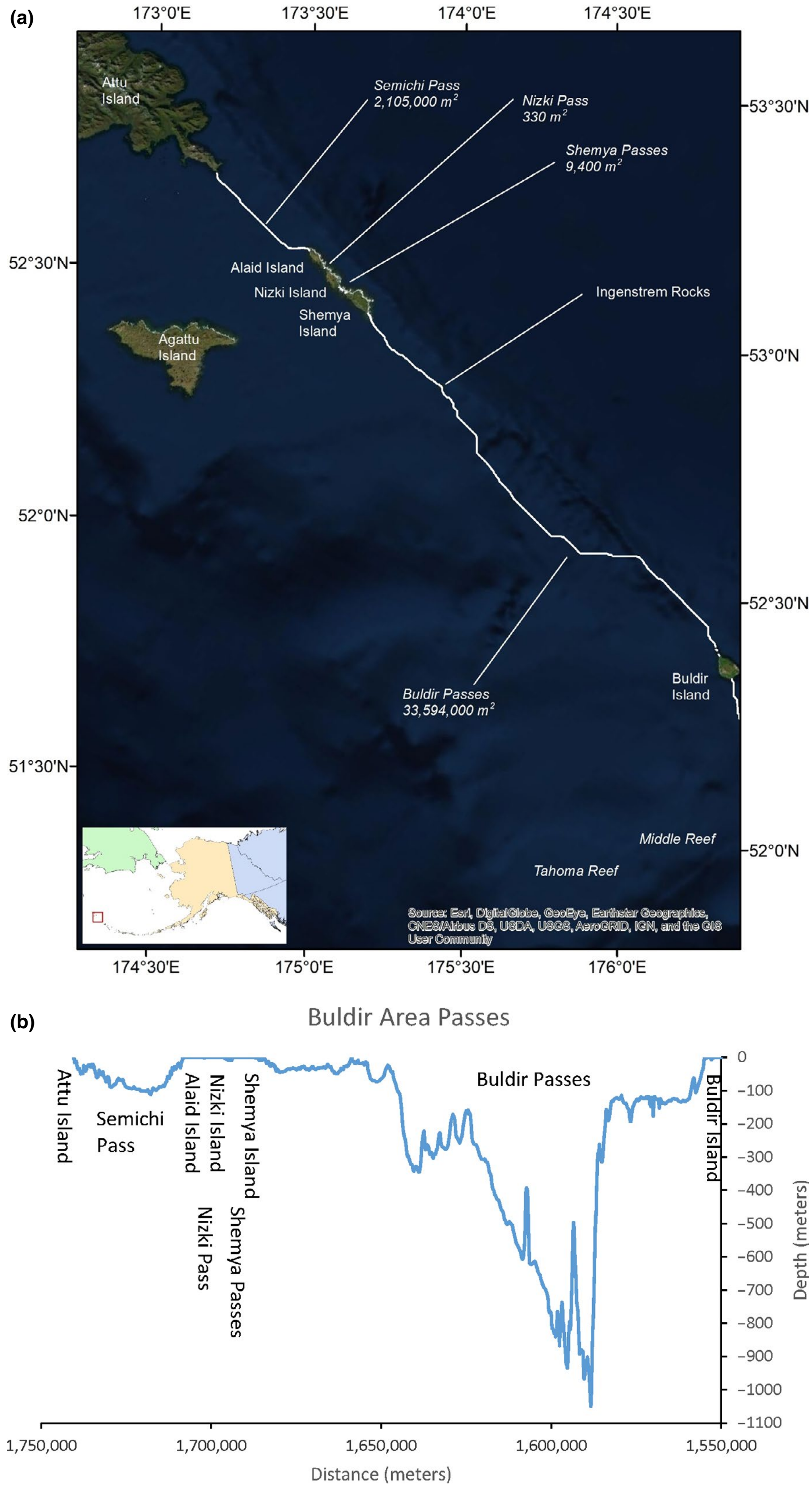

FIGURE 9 (a) Pass locations and sizes in the Buldir area. Pass location as defined by the Cost Distance tool denoted as white line. (b) Graph showing horizontal arrangement of islands and passes, with pass depth shown in meters

also caused tsunamis and property damage on Adak and Umnak islands, California, Hawaii, and was detected in Chile, El Salvador, and Japan (https://earthquake.usgs.gov/earthquakes/eventpage/official19570309142233_30/impact, Johnson et al., 1994), but changes in the seafloor have not been described. When available, we used newer non-hydrographic quality bathymetry data to supplement the older smooth sheet data sets, but these more modern data sets only cover small areas. Oceanographic, ecological, and bathymetric projects such as this one would greatly benefit from a new, comprehensive, high-quality Aleutians seafloor map. Such a mapping effort would be expensive and take multiple ship-years to complete, but provide a detailed and accurate bathymetry map that could be used to develop a better understanding of the connections between the North Pacific Ocean and Bering Sea.

There is confusion in the literature about the location of Amchitka Pass, the largest pass of the Aleutians. Favorite (1967) is not specific enough to make a determination between which islands this pass occurs. While we agreed that this is the largest Aleutian Pass, Favorite's (1967) estimate is sufficiently low to raise doubts that he selected the location correctly for measurement (Table 5). Favorite (1974, fig. 1.13) shows vertical profiles of water for Amchitka Pass as occurring between Tanaga, Semisopochnoi, and Little Sitkin islands—a route of passes that is to the north of the pass location we determined and cumulatively even larger than our pass size. Favorite's (1974) location for Amchitka Pass is similar to the USBGN and Reed (1990). Reed's (1990) mooring, placed on the north side of Amchitka Pass, is blocked from measuring water flow through the pass by shallow seafloor (Figure 7a). It occurs about 45 km to the northeast of the portion of the pass with the greatest through depth. Thus, the transport measurement from Reed (1990) at Amchitka Pass should be re-evaluated, along with Akutan and Seguam passes which also had misplaced moorings.

Oceanographic research has identified Samalga Pass as an important boundary between water masses in the Gulf of Alaska, with warmer, fresher, and nitrate-poor water to the east and colder, saltier, and nitrate-rich waters to the west (Ladd et al., 2005). This eastern water is from the ACC (Alaska Coastal Current), which moves through Shelikof Strait, hugs the southern shore of the Alaska Peninsula, and then moves northward only through the eastern Aleutian passes (Ladd et al., 2005; Stabeno et al., 2005). Hunt and Stabeno (2005) summarize several significant ecological impacts of this western/eastern division in water masses at Samalga Pass, including differences in primary production; zooplankton species composition; species diversity of cold-water corals; groundfish species richness, abundance, diet composition, and growth rates; seabird foraging guilds; Steller sea lion diets (*Eumetopias jubatus*); and cetacean distributions. The location of this division of water masses at Samalga Pass makes bathymetric sense because the minimum opening of Shelikof Strait (6.504 km^2: Zimmermann et al., 2019) is approximately equal to the sum of the eastern Aleutians passes through Samalga (6.189 km^2, including the 15,800 m^2 estimate of False Pass from Zimmermann & Prescott, In Review). Samalga is by far the largest and deepest of these eastern passes, accounting for 61% of the group's cross-sectional area, and thus, its size may dictate the importance of its location. West of Samalga, the next two passes of Chuginadak (0.872 km^2) and Herbert (5.648 km^2) more than double the total capacity of these eastern passes, perhaps easily accommodating any overflow of ACC water. A new volumetric analysis of water transport, taking into account ACC depth and speed, along with our new pass size and shape estimates, might improve our understanding of this important oceanographic process. The oceanographic connection between the narrowest opening of Shelikof Strait is about 1,200 km to the east of Samalga Pass, across the glacially sculpted western Gulf of Alaska (Zimmermann et al., 2019), so it is highly unlikely that there is a direct, one-to-one relationship between water flow through these two features.

The smooth sheet shorelines that we digitized for this project are not the official NOS Topographic sheet or T-sheet shorelines utilized for navigational charts. Instead, hydrographers drew these smooth sheet shorelines in coordination with the inshore cartographic features and soundings, providing a horizontally homogenous and ground-truthed data source that distinguishes between islands, rocks, rocky reefs, and kelp beds (Zimmermann, 2019). Additionally, the smooth sheet record of MHW provided a consistent vertical datum, while T-sheet shorelines are also defined as MHW but not annotated with the measurement of MHW.

We anticipate that our new pass size measurements from our new bathymetry compilation will be used for reconsidering previous current mooring observations and for planning the placement of new moorings. The Aleutian passes are important, but small and rarely studied oceanographic features that impact the ecosystem of the far larger Bering Sea, ultimately influencing the Arctic and contributing to global ocean circulation (Woodgate et al., 2006). Better Aleutians bathymetry should lead to better oceanographic observations, more precise and finer-scale current modeling, and improved understanding of some very local Aleutian ecosystem processes as varied as primary production (Mordy et al., 2005), bird feeding aggregations (Jahncke et al., 2005), and coral distribution (Woodby et al., 2009). Better bathymetry may also be an important investigative tool for understanding the origins of tsunamis (Fryer et al., 2004; Johnson et al., 1994; Rathburn et al., 2009). While this project is our latest effort to create better bathymetry for understanding and management of the valuable fisheries resources of Alaska (Fissel et al., 2019), this is the first project in many years to critically re-examine seafloor influence of transport through the Aleutian passes. We also expect that our pass size estimates and bathymetry will be refined in future years when better seafloor data become available.

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data. The findings and conclusions in the paper are those of the authors and do not necessarily represent the views of the National Marine Fisheries Service, NOAA. Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA. The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Mark Zimmermann is the corresponding author, did most of the manuscript preparation and interpretation of data, and participated in some of the data collection. Megan Prescott created most 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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