**A GEOLOGIC AND OCEANOGRAPHIC JOURNEY ACROSS THE SALISH SEA (SOUTHWESTERN CANADA AND NORTHWESTERN USA)**

Alice S. Chang and Arun Kumar

The Salish Sea is also an active waterway for fisheries, industry, transportation, and recreation..... The year 2020 marks the tenth anniversary of the official naming of the Salish Sea..... The rocks of Wrangellia are mainly represented by the Karmutsen Formation, a 6,000-meter thick pile of flood basalts (flows and pillow lavas) and volcanic tuffs that were part of an oceanic plateau some 230 million years ago (late Triassic)..... Several hypotheses have been proposed to explain the origin of the Georgia Depression. These include Cretaceous–Tertiary (66 million-year-old) downwarping or down faulting of the crust, eastward tilting of the Vancouver Island block, and crustal weakening between the Insular and Coast belts.

The Strait of Georgia, the Strait of Juan de Fuca, Puget Sound, and the surrounding waterways of southwestern British Columbia (BC), Canada, and northwestern Washington State, USA, are collectively called the Salish Sea (Figure 1). As one of the world’s most productive ecosystems, the Salish Sea is also an active waterway for fisheries, industry, transportation, and recreation. Scenic port cities (Vancouver and Seattle) and provincial and state capitals (Victoria and Olympia, respectively) call the shores of the Salish Sea home, as do 70% of BC’s and 60% of Washington’s populations.

We decided to write this popular science article because as earth scientists, we have a long association with this region through recreation, as well as research at the universities of BC (Vancouver) and Victoria (Vancouver Island), and at Carleton University (Ottawa, Canada), where one or both of us were involved. We have crossed the Salish Sea many times, whether aboard passenger ferries (e.g., BC Ferries, MV *Coho*, *Victoria Clipper*) or research vessels (e.g., Canadian Coast Guard Ship (CCGS) *John P. Tully*, CCGS *Vector*, MV *Strickland*), and have gained an appreciation and respect for the natural beauty of this area.

With this article, we also hope that readers will learn more about the Salish Sea as a cohesive geographical region. The year 2020 marks the tenth anniversary of the official naming of the Salish Sea. Yet in May 2019, the Sea Doc Society and Oregon State University surveyed 2,405 participants and found that only 9% of Washingtonians and 15% of British Columbians could identify the Salish Sea when shown a map of its boundaries (Trimbach and Gaydos, 2019). While
scientists have accepted the new concept, these results show that further steps are required to educate the general public about the shared histories—both cultural and natural—of this place.

We offer this article as a small step toward familiarizing our audience with the Salish Sea through the lens of geology and oceanography. We first discuss how the Salish Sea name came to be. Then we describe the geological processes, from plate tectonics to ice ages, that shaped the land and modern waterways. Throughout the article, we use our ferry trips across the Salish Sea as platforms for observation, and also describe excursions to points of interest on land.

**A BRIEF HISTORY OF NAMES**

The Strait of Juan de Fuca was named after a Greek pilot, Apostolos Valerianos—better known as Juan de Fuca—who sailed with the Spanish navy and was the first European to enter the strait in 1592. The Strait of Georgia was incorrectly named “Gulf of Georgia” in 1792 by Captain George Vancouver for King George III of England, even though the strait was named a year earlier by the Spanish naval officer Francisco de Eliza. The Spanish name, “Gran Canal de Neustra Señora del Rosario la Marinera,” did not stick. What did stick was the name “Gulf Islands” in the Strait of Georgia from when the strait was called a gulf. Also in 1792, Captain Vancouver entered Puget Sound and named it after one of his lieutenants, Peter Puget.

The name “Salish Sea” was first proposed in 1989 by Bert Webber, a Canadian-born professor of marine biology at Western Washington University (Bellingham). He recognized the shared oceanography and ecology of these waterways and proposed the name to honour the Coast Salish peoples who have lived in the area for millennia. In 2008, the Stz’uminus (Chemainus) First Nations proposed to rename the Strait of Georgia as the Salish Sea and the idea gained momentum. By 2009, renaming the three waterways collectively as the Salish Sea was endorsed by the government of British Columbia, the Geographic Names Board of Canada, the Washington State Geographical Names Board, and the US Board on Geographic Names. Although the name was officially adopted in 2010, the original names of the individual waterways are still retained.

**GEOLOGIC HISTORY**

In order to understand the natural history of the Salish Sea, we must first step back and take a look at the geology of the larger picture.

**Exotic Lands**

The Canadian Cordillera can be divided into five northwest to southeast trending zones based on bedrock geology. The two westernmost zones, the Insular and Coast belts, are of interest in this article (Figure 2, inset).
Figure 1. The Salish Sea, with location names and ferry routes discussed in this article. Inset map shows the entire Salish Sea boundary; yellow box shows the location of the larger image. Satellite images courtesy of Microsoft.
British Columbia and Washington State are mostly composed of distinct strips of the earth’s crust, called terranes, each with its own geological history (see reviews in Johnston, 2008; Gibson and Monger, 2014; Hildebrand, 2015). These terranes, composed of either volcanic island chains (island arcs), or metamorphosed rocks, or pieces of sea floor with ancient tropical fossils, were formed far away from where they would eventually end up.

Starting in the mid Jurassic (175 million years ago), through the processes of plate tectonics and continental margin subduction, the terranes began accreting one after another to the western edge of Laurentia—the proto-North American continent—which moved westward following the earlier break-up of the supercontinent Pangaea. Around this time, the Cascadia Subduction Zone was born: extending offshore from northern Vancouver Island to northern California, the ancient Farallon plate and today’s Juan de Fuca plate (both oceanic) plunge beneath the continental North American plate. Melting of the subducting plates is responsible for forming the Coast Plutonic Complex, which is the largest granite outcrop in North America, and related volcanoes (e.g., Mt. Baker) (Figure 2). Crustal faulting and large earthquakes also result from subduction. By Cretaceous time (100 million years ago), the accretion of major terranes to western Laurentia was complete, although accretion of minor terranes continued into the Eocene epoch (40 million years ago).

Table 1. Physiography and Oceanography of the Main Waterways in the Salish Sea.

<table>
<thead>
<tr>
<th></th>
<th>Strait of Georgia</th>
<th>Strait of Juan de Fuca</th>
<th>Puget Sound</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physiography</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length (km)</td>
<td>222</td>
<td>160</td>
<td>161</td>
</tr>
<tr>
<td>Width (km)</td>
<td>28 – 58</td>
<td>18 – 40</td>
<td>16 (maximum)</td>
</tr>
<tr>
<td>Surface area (km²)</td>
<td>6,800</td>
<td>4,068</td>
<td>2,632</td>
</tr>
<tr>
<td>Mean water depth (m)</td>
<td>156</td>
<td></td>
<td>63</td>
</tr>
<tr>
<td>Max. water depth (m)</td>
<td>447 (south of Texada Is.)</td>
<td>250 (mouth of strait)</td>
<td>286 (Central Basin)</td>
</tr>
<tr>
<td><strong>Oceanography</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow type</td>
<td>estuarine</td>
<td>estuarine</td>
<td>estuarine</td>
</tr>
<tr>
<td>Min. surface salinity</td>
<td>15 (freshet) – 29.5 (spring)</td>
<td>26 (spring, east)</td>
<td>27 (summer, South Basin)</td>
</tr>
<tr>
<td>Max. bottom salinity</td>
<td>31 (winter)</td>
<td>33.5 (winter, west)</td>
<td>31 (winter, Admiralty)</td>
</tr>
<tr>
<td>Tides</td>
<td>semidurnal</td>
<td>diurnal/semidurnal</td>
<td>semidurnal</td>
</tr>
<tr>
<td>Tidal range (m)</td>
<td>2.3 – 3.35</td>
<td>1.85 – 2.45</td>
<td>2.4 – 4.6</td>
</tr>
<tr>
<td>Max. current speed (cm/s)</td>
<td>&gt;50 (southern)</td>
<td>250 (Port Angeles)</td>
<td>340 (Deception Pass)</td>
</tr>
</tbody>
</table>

Units: km: kilometers, km²: square kilometers, m: meters, cm/s: centimeters per second

Sources:
Figure 2. Geologic terranes and units discussed in this article. Inset map shows the main geological belts. Unshaded map areas represent geologic units not discussed in this article. CPC: Coast Plutonic Complex. Based on Brown et al. (2007), Gibson and Monger (2014), Wells et al. (2014), Wheeler et al. (1991), and Yorath and Nasmith (1995). Satellite images courtesy of Microsoft.
Main Terranes and Geologic Units

We observed several terranes and geological units during our travels of the Salish Sea. Wrangellia (part of the Insular Superterrane) makes up most of the bedrock for Vancouver Island (Figure 2), and extends north to parts of the Coast Mountains of southwestern BC, the islands of Haida Gwaii (formerly called the Queen Charlotte Islands), and southeastern Alaska (Wrangell Mountains). The bedrock in the Crescent Terrane (part of the larger Siletzia Terrane) is found on the southern tip of Vancouver Island, and on the Olympic Peninsula and around Puget Sound in Washington State (Figure 2). Sandwiched between Wrangellia and the Crescent Terrane on Vancouver Island is the Pacific Rim Terrane, bounded by two north-dipping faults.

The rocks of Wrangellia are mainly represented by the Karmutsen Formation, a 6,000-meter thick pile of flood basalts (flows and pillow lavas) and volcanic tuffs that were part of an oceanic plateau some 230 million years ago (late Triassic). Other rocks in Wrangellia include the Wark and Colquitz gneiss complex that were metamorphosed during the early Jurassic (200 million years ago) but were probably derived from early Devonian (400 million-year-old) granitic and volcanic rocks of the Sicker Group. The city of Victoria sits atop the gneiss complex (Figure 3A). Paleomagmatic and fossil evidence suggest that Wrangellia originated far to the south of its present location and accreted to North America around 140 million years ago (late Jurassic or early Cretaceous; Monger et al., 1994). Collision with the continent caused Wrangellia to fold and uplift into mountains on Vancouver Island. Erosion of these mountains between 90 to 65 million years ago (late Cretaceous) produced the Nanaimo Group, a thick sedimentary sequence that accumulated in the broad basin to the east of Vancouver Island and in the Georgia Depression (Yorath and Nasmith, 1995) (Figures 2 and 3). In the city of Nanaimo, these strata also contain coal seams.

Most of the Pacific Rim Terrane is composed of the Leech River complex, which consists of 135 million-year-old (early Cretaceous) metamorphosed mudstones and sandstones, and basaltic metavolcanics (see review in Rusmore and Cowan, 1985) (Figure 4A). Sometime before 55 million years ago (early Eocene), the Pacific Rim Terrane accreted to the southern edge of Wrangellia. During subduction, the rocks of the Leech River complex became folded and eroded. The products of this erosion accumulated into the Sooke Formation sandstones around 25 million years ago (late Oligocene) (Figure 4B).

The Crescent Terrane consists of mainly gabbro and pillow basalts (Lyttle and Clarke, 1975). These basalts erupted on the ocean floor, possibly forming a volcanic island arc, around 54 million years ago (early Eocene) before being accreted to North America and uplifted about 42 million years ago (late Eocene; Beck and Engebretson, 1982). These uplifted rocks make up most of the northern and eastern Olympic Mountains whose highest peaks are visible from Seattle, Richmond and Victoria (Figure 4C, D). Another consequence of the collision of the Crescent Terrane was the folding and faulting of the Nanaimo Group sedimentary rocks and the creation of the Gulf Islands (Yorath and Nasmith, 1995).
Figure 3. Wrangellia and the Nanaimo Group. Geologic column illustrates the stratigraphic relation of units observed (bold names) in this article (based on Mustard, 1994). Ma: age of deposition, millions of years ago. A. In Victoria’s Inner Harbour, condominiums sit atop the Wark and Colquitz gneiss complex of the Sicker Group. (Photo: A. Kumar, 2019, from aboard the Victoria Clipper V.) B. Contact between underlying dark mudstones of the Haslam Formation and the overlying conglomerates of the Extension Formation at Beddis Beach, Saltspring Island (see Figure 8A for location). (Photo: A. Chang, 1992.)
The geology of northwestern Washington State is more complex. Around 110 to 80 million years ago (Cretaceous), the Coast Plutonic Complex was created and the San Juan Islands–Northwest Cascades thrust system was accreted to North America (see review in Brown et al., 2007) (Figure 2). The thrust system is considered to be a composite terrane because it is a pile of nappes, or sheets of rock with different geologic origins, that are separated by faults. The oldest nappes (Devonian–Permian, 400 to 280 million years ago) contain island arc sedimentary and volcanic rocks. Higher up are nappes of Permian to Jurassic age (280 to 180 million years ago) composed of cherts, schists, oceanic basalt, and limestones bearing fossil fusilinids (extinct, tropical, single-celled marine life). These rocks likely represent an accretionary mélangé, which is a wedge of materials scraped off the sea floor and stuck to the continent’s edge as the oceanic slab subducted beneath the continent. The youngest nappes consist of late Jurassic (150 million-year-old) ophiolitic plutonic rocks, mid-ocean-ridge basalts, cherts, marine mudstones and sandstones.

During the Eocene, the Straight Creek–Fraser River Fault displaced the southern end of the Coast Plutonic Complex by around 170 kilometers (Figure 2).

ORIGINS OF THE SALISH SEA

The Salish Sea as we know it today lies within the Georgia Depression, a northwest to southeast trending trough that lies between the Insular and Coast belts, and runs down the length of the Strait of Georgia and Puget Sound (Figure 2, inset).

Several hypotheses have been proposed to explain the origin of the Georgia Depression. These include Cretaceous–Tertiary (66 million-year-old) downwarping or down faulting of the crust, eastward tilting of the Vancouver Island block, and crustal weakening between the Insular and Coast belts. A current model suggests that the Georgia Depression began forming around 90 million years ago (late Cretaceous) as the Juan de Fuca plate subducted beneath the North American plate (see Westnedge, 2011). Subsidence of the depression and complementary uplift of the Coast Mountains, the Vancouver Island Ranges, the Olympic Mountains and the Cascade Mountains then led to the formation of the Strait of Georgia, Strait of Juan de Fuca and Puget Sound (Nelson, 1976, and references therein; Thomson, 1981). Details of the natural histories of these waterways are described below.

STRAIT OF GEORGIA

The largest waterway in the Salish Sea is the Strait of Georgia (Table 1). The strait is connected to the Pacific Ocean in the north via the narrow Discovery Passage and Johnstone Strait, and to the south by the Strait of Juan de Fuca via channels around the San Juan Islands (Figure 1). The eastern margin of the Strait of Georgia is flanked by long and steep-sided fjords indented into the coast of the BC mainland.
Figure 4. Pacific Rim Terrane at Botanical Beach (A, B), and Crescent Terrane (C, D). A. Northwest-tilted metasedimentary rocks of the Leech River Complex. The Strait of Juan de Fuca opens to the Pacific Ocean, with the tip of the Olympic Peninsula at left. B. Sea cliffs formed by the horizontally bedded Sooke Formation sandstones. C. Panorama of the Olympic Mountains and the Strait of Juan de Fuca at dusk, as seen from southeast Victoria. D. The Olympic Mountains at Hurricane Ridge, elevation 1,598 meters. (Photos: A. Chang, 2006–2009).
Ice Sheet Advance

The Strait of Georgia took on its modern dimensions after the end of the last glaciation 11,000 years ago (early Holocene). Before that, the region was locked in the deep-freeze of the Fraser Glaciation. This cold period started 29,000 years ago (late Pleistocene) when mountain glaciers grew and coalesced to form the Cordilleran Ice Sheet, which covered Alaska, the Yukon, BC, Washington, Idaho and Montana (Figure 5). This ice sheet was much smaller than the better-known Laurentide Ice Sheet, which covered much of northern North America east of the Rocky Mountains at the same time.

Ice entered the Strait of Georgia from the Coast Mountains via river valleys on the mainland coast. As the ice advanced south down the strait, poorly consolidated, well-sorted and cross-stratified glacial outwash known as Quadra Sand was deposited in layers up to 75 meters thick at the front and margins of the glaciers (Clague, 1976). The Cordilleran Ice Sheet eventually displaced the sea entirely, filling the Strait of Georgia down to the bedrock and weighing down the land. During the last glacial maximum 19,000 to 17,000 years ago (late Pleistocene), the ice was up to 2 kilometers thick within the Strait of Georgia (James et al., 2000).

Ice Sheet Retreat

Around 17,000 years ago, the climate and ocean began to warm. In response, the marine edge of the Cordilleran Ice Sheet destabilized and calved, dumping coarse sediments scoured by the ice into the Pacific Ocean off the west coast of Vancouver Island. When marine water flooded the Strait of Juan de Fuca (see next section), the Cordilleran Ice Sheet began retreating rapidly and the Strait of Georgia began filling with seawater (Taylor et al., 2014, and references therein).

Melting and retreat of the ice between 17,000 and 14,800 years ago (late Pleistocene) resulted in rapid rebound of the land as the weight of the ice was removed. As a result, sea level within the Strait of Georgia dropped by 130 to 150 meters in less than 2,000 years, and sea levels were as much as 50 meters below present levels (Clague and James, 2002; Hutchinson et al. 2004; James et al., 2000, 2005). By 11,000 years ago, the Strait of Georgia became ice-free.

Today, the crust beneath the Strait of Georgia is still rising due to residual effects from the ice sheet’s retreat. We cannot feel this uplift but we can see evidence left behind by the former ice sheet. These include fjords (e.g., Jarvis and Alberni inlets and Howe Sound) that were carved out by ice in former river valleys on the west coasts of the BC mainland and Vancouver Island (Figure 1), the Gulf Islands that were sculpted by glacial scouring of the Nanaimo Group sandstones, and the thick deposits of glacio-fluvial sediments (Quadra Sand, Vashon Till) throughout the strait (Figure 6A). Where the ice sheet scoured the bedrock, striations were left behind, such as on Saltspiring Island (Figure 6B).
Figure 5. Extent of Cordilleran Ice Sheet cover during the last (Fraser) glaciation (29,000 to 11,000 years ago). Inset shows the Cordilleran and Laurentide ice sheets during the last glacial maximum (19,000 to 17,000 years ago). Based on Clague and James (2002) and Hendy and Cosma (2008). Satellite images courtesy of Microsoft.
Modern Oceanography within the Strait of Georgia

As the largest river in British Columbia, the Fraser River has headwaters in the Rocky Mountains and delivers an estimated 75% of the total freshwater runoff and up to 17 million tonnes of sediment to the Strait of Georgia annually. Most of the sediments are delivered during the spring freshet that begins in April when mountain snowpacks melt, continues with high flow from late May to July (up to 11,000 cubic meters per second, compared to 1,000 cubic meters per second during winter), and recedes in August and September (McLean et al., 1999; Thomson, 1981). The Fraser River plume is visible from space and on the water’s surface when one travels across the strait (Figure 7). The sediments are eventually deposited on the floor of the strait while the freshwater slowly makes its way to the Pacific Ocean via southern channels.

The remaining sources of freshwater and sediment into the Strait of Georgia come from smaller rivers, including the Squamish River that discharges through Howe Sound north of Vancouver (Figure 7A), and from the Cowichan, Chemainus, Nanaimo and Courtenay rivers on Vancouver Island. Salinity within the Strait of Georgia therefore depends on the season and proximity to river sources. Surface waters are fresher closer to river runoff and during the spring/summer freshet, while deeper waters are saltier away from freshwater sources and during the winter (Table 1). This water column structure drives estuarine circulation, where a net seaward flow of fresher, low-density surface water offsets landward flow of deeper saline water.

Tides within the Strait of Georgia are semidiurnal, meaning that high and low tides cycle twice per day. Within the strait, the tidal stream (horizontal tidal currents) flows to the southeast during an ebb and to the northwest during a flood, with speeds reaching up to 50 centimeters per second. During an ebb, the Fraser River plume will flow to the southwest towards the Gulf Islands (as in Figure 7A), overriding the normal southeasterly current in the strait due to the momentum of the river discharge. During a flood, the Fraser River plume will take a sharp turn to the right, due to a combination of currents and the Coriolis effect from the earth’s rotation (Thomson, 1981).

Crossing the Strait of Georgia

The British Columbia Ferry Services corporation (BC Ferries) operates 35 vessels that cross the Strait of Georgia at various points, dozens of times per day. One of the major routes is the Tsawwassen–Schwartz Bay crossing. For this article, one of us (AC) made oceanographic and geological observations aboard the MV Spirit of British Columbia in June 2019 (Figures 7B and 8). This ferry began service in 1993, is 167 meters long and 32.9 meters wide, and can travel at a maximum speed of 19.5 knots (36 kilometers per hour). A typical crossing takes one hour and 35 minutes. In 2018, the ferry was refitted with a dual-fuel engine that can use either marine diesel oil or cleaner-burning liquefied natural gas. The ferry’s capacity is 2,100 passengers and crew, and 358 vehicles (BC Ferries, 2019).
Figure 6. Evidence of the Cordilleran Ice Sheet. A. Quadra Sand (upper half of outcrop) at Pt. Grey, Vancouver. Cobbles in the Vashon Till are visible in the uppermost 2 meters of the outcrop. People for scale at bottom of outcrop. B. Glacial striations in Comox Formation sandstone at Ruckle Park, Salt Spring Island (Figures 3 and 8A). Striations have a northwest-southeast direction; field of view ~1 meter wide. (Photos: A. Chang, 1992.) C. Esperance Sand in bluffs on Whidbey Island, as seen from Puget Sound aboard the Victoria Clipper V. The dip in the bluffs is a kettle, a depression caused by a large piece of ice (see Figure 10A for location). (Photo: A. Kumar, 2019).
On a clear day, one can look across the strait toward the Gulf Islands (Figure 8B). If you travel at the right time of year, the Fraser River plume is visible partway across the strait (Figure 7B). At the eastern entrance to Active Pass, a narrow channel between Mayne and Galiano islands with two blind turns (Figure 8A), the ferry slows to half-speed and blows its horn to warn oncoming watercraft that may be approaching around the first turn. Another BC Ferry, in this case the sister vessel Spirit of Vancouver Island, is usually the other vessel inside the pass (Figure 8C). The ferries pass closely enough that passengers can feel the other vessel’s wake and wave to each other. During slow-speed westward travel inside Active Pass, passengers on the starboard side of the ferry can appreciate the Nanaimo Group sedimentary strata in the exposed cliffs on Galiano Island (Figure 8D). On the port side is a view of the cliffs on Mayne Island but they are tree-covered almost to the waterline. Once the ferry exits Active Pass on the west, it gains speed in the open waters towards Schwartz Bay but must navigate carefully around the numerous smaller Gulf Islands (Figure 8E). The only other large island visible from the starboard side of the ferry is Saltspring Island with its sandstone exposures (Figures 3B and 6B).

**STRAIT OF JUAN DE FUCA**

The second largest waterway in the Salish Sea is the Strait of Juan de Fuca (Table 1). The underwater Victoria sill splits the strait into eastern and western basins (Figure 9A). East of the sill, the bottom topography of the Strait of Juan de Fuca is complex as it interfaces with the Strait of Georgia to the north via Haro and Rosario straits, and with Puget Sound to the south via Admiralty Inlet. West of the sill, the cross-channel bottom topography of the Strait of Juan de Fuca is simpler and U-shaped, and the coastline lacks fjords.

**Cordilleran Ice Sheet Influence**

The portion of the Cordilleran Ice Sheet that overtopped southern Vancouver Island is called the Juan de Fuca lobe because ice was also transported westward through the Strait of Juan de Fuca toward the continental shelf in the Pacific Ocean (Figure 5). During the last glacial maximum, the Juan de Fuca lobe was up to 2 kilometers thick with ice that was supplied from the Coast Mountains (Booth, 1986). As the climate warmed 17,000 years ago, warm seawater entered from the Pacific and began melting the Juan de Fuca lobe. At the same time, water depth within the strait increased abruptly from 100 meters to over 250 meters relative to the continental shelf and further destabilized the ice sheet (Taylor et al., 2014, and references therein). When melting outpaced ice supply within the Strait of Juan de Fuca, ice retreat became rapid and irreversible, and the strait became ice-free around 16,200 years ago (Mosher and Hewitt, 2004).

As the crust rebounded from the removal of the weight of ice between 17,000 and 14,800 years ago (late Pleistocene), sea level within the eastern Strait of Juan de Fuca dropped by 150 meters within 2,500 years. Sea levels fell to as much as 60 meters below present levels at around 11,000 years ago (early Holocene) and eventually settled at modern elevations around 6,000 years ago (mid Holocene) (Mosher and Hewitt, 2004).
Figure 7. Fraser River plume in the Strait of Georgia. A. View from the International Space Station. Astronaut photograph ISS040-E-138806, taken September 6, 2014 (courtesy of NASA). B. A line in the water: the silty Fraser River plume (right) meets marine waters of the strait (left). View looking northwest from aboard the MV Spirit of British Columbia. (Photo: A. Chang, taken June 3, 2019.)
Evidence that ice once occupied the Strait of Juan de Fuca includes its U-shaped cross-section where ice carved out the bedrock during advance. Thus, the strait can be considered a glacially formed submarine valley (Holbrook et al., 1980). The Victoria sill is likely a terminal moraine (a ridge of glacial debris pushed by the toe of a glacier) that marks the southernmost advance of an ice sheet that predates the Fraser Glaciation (Thomson, 1981).

**Modern Oceanography within the Strait of Juan de Fuca**

While freshwater input and salinities in the Strait of Juan de Fuca vary seasonally, the effects between the seasons is not as pronounced as those in the Strait of Georgia (Table 1). The primary freshwater source to the eastern basin of the Strait of Juan de Fuca is the Fraser River freshet (Herlinveaux and Tully, 1961). The remaining sources of freshwater originate from Puget Sound via local river input, along the Olympic Peninsula, and from rivers on the west coast of Vancouver Island during the winter rainy season (Masson and Cummins, 1999). Thus, the water column in the Strait of Juan de Fuca is saltier in the winter, and west towards the Pacific Ocean and along the seafloor in the shape of a “salt wedge.” This structure creates a weakly layered, partially mixed estuarine flow in the strait (Holbrook et al., 1980; Thomson, 1981).

Tides within the Strait of Juan de Fuca west of Port Angeles are mainly semidiurnal, but in the eastern strait are mainly diurnal (one cycle of high and low tides per day). This difference is due a combination of how the tide heights cancel each other out, along with the declination of the moon throughout the month. Thus, tides around Victoria are diurnal around 20 days of the month, whereas tides around Vancouver are predominantly semidiurnal, and tides around Seattle (next section) are always semidiurnal (Thomson, 1981).

Currents within the Strait of Juan de Fuca are strong and depend on tidal streams, wind direction, seasonal freshwater runoff, and the Coriolis effect. Flood streams flow northward along the Pacific coast of Washington State, enter the mouth of the strait and continue eastward. During maximum flood, currents attain speeds of 75–130 centimeters per second along the axis of the western basin, and reach speeds of 180 centimeters per second during large spring tides (Thomson, 1981). Where the strait narrows near Port Angeles, flood currents can accelerate to 250 centimeters per second. During maximum ebb, currents reverse their flow and move westward toward the Pacific Ocean.

**Crossing the Strait of Juan de Fuca**

The only vessel that can take passengers and their vehicles across the Strait of Juan de Fuca between Victoria and Port Angeles is the MV Coho, Black Ball Ferry Line’s sole ferry, which was named after the salmon that migrates through the Salish Sea. In service since 1959, the Coho is 104.1 meters long and 21.95 meters wide, and has an average speed of 15 knots (28 kilometers per hour). A typical crossing takes 90 minutes. The Coho has twin propellers and rudders, and in 2004 was refitted with two diesel engines. The vessel’s capacity is 1,000 passengers and 115 vehicles (Black Ball Ferry Line website).
Figure 8. Crossing the Strait of Georgia. A. Map of the southern Gulf Islands and ferry route. VI: Vancouver Island. B. The Gulf Islands, as seen from the Tsawwassen ferry terminal. C. The Spirit of Vancouver Island entering Active Pass at Collision Point (width less than 450 meters), as seen from the Spirit of British Columbia. D. Wave-cut notch in conglomerate and sandstone cliffs of the Gabriola Formation (Figure 3), Galiano Island, as seen from inside Active Pass. E. Emerging from Active Pass. (Photos by A. Chang, 2019. Satellite image courtesy of Microsoft.)
Because this crossing is relatively straight with no islands, the Coho can chug along at a constant speed. One of us (AC) made the crossing in November 2007. During the autumn, the strait and Port Angeles are often shrouded in fog, which is not ideal for photography (Figure 9B). A lengthwise crossing of the strait between Victoria and the Pacific Ocean by AC aboard the CCGS Tully in October 1999 was similarly gloomy. On the contrary, a summer crossing seems more pleasant, and large cruise ships transiting from Alaska to Seattle often stop in Victoria because of the spectacular scenery (Figure 9C). Through a direct connection with the Pacific Ocean, the Strait of Juan de Fuca is home to many types of marine life, both local and migratory. These include jellyfish, salmon and sea birds, along with sea urchins, sea lions, and the endangered southern resident killer whales who feed on migrating salmon in the Salish Sea during the summer and fall (Figure 9D–F).

**PUGET SOUND**

As the smallest of the three main waterways in the Salish Sea (Table 1), Puget Sound is the second largest estuary by area in the USA after Chesapeake Bay on the east coast. Puget Sound contains five basins separated by underwater sills: North Puget Sound (Admiralty Inlet), Whidbey Basin, Central Basin, South Basin and Hood Canal. The sound is connected to the Pacific Ocean in the north by the Strait of Juan de Fuca via Admiralty Inlet and the much narrower Deception Pass north of Whidbey Island (Figure 10A).

**Cordilleran Ice Sheet Influence**

The portion of the Cordilleran Ice Sheet that was funneled south between the Olympic Peninsula and the Cascade Mountains is called the Puget lobe because ice covered Puget Sound and the surrounding Puget Lowland (Figure 5). During the last glacial maximum, ice was 450 meters thick near Olympia and 1 kilometer thick near Seattle (Thorson, 1980). When the climate warmed 17,000 years ago (late Pleistocene), the rapid eastward retreat of the Juan de Fuca lobe decapitated the Puget lobe, starving it of ice supply. A series of proglacial lakes formed across the Puget Lowland south of the receding ice when meltwater collected in troughs eroded by the ice sheet during its advance. Whenever the terminus of the Puget lobe retreated northward across a deep proglacial lake, iceberg calving occurred. By around 16,000 years ago, Puget Sound became ice-free and was inundated with sea water after the ice terminus retreated north of Admiralty Inlet (Porter and Swanson, 1998; Thorson, 1980).

Evidence of ice sheet activity in the region includes thick outcrops of poorly consolidated, moderately well-sorted and cross-bedded outwash called Esperance Sand, especially on Whidbey Island (Easterbrook, 1968). This unit is equivalent to Quadra Sand in age and composition (Clague, 1976), and both units show erosion and slopes that have a low angle of repose typical of unconsolidated materials (up to 35°, above which the slope destabilizes) (Figure 6A, C). The dip in the Whidbey bluff is a cross-section of a kettle (Figure 6C), a once bowl-shaped depression in the land made by a large piece of ice before it melted and before the bluffs eroded back (Easterbrook, 1968). Esperance Sand is overlain by poorly sorted glacial drift (Vashon Till) and
glacio-marine sediments. Today, these glacio-marine sediments are found between 40 and 60 meters above sea level. If sea level was 60 to 70 meters below present sea level when the last ice retreated, then between 100 and 130 meters of crustal rebound and tectonic movement in this region has occurred since (Thorson, 1980).

**Modern Oceanography within Puget Sound**

Of the annual average riverine discharge of 1,350 cubic meters per second into Puget Sound, one-third comes from the Skagit River, which empties into Whidbey Basin; the remaining runoff comes from thirteen other major tributaries (Figure 10A). Maximum runoff from rivers such as Skagit and Snoqualmie (Figure 10B, C), whose headwaters are in the Cascade Mountains, occurs in May and June when snowpacks melt, although runoff also occurs during the winter (December to March) due to increased rainfall. Lowland rivers without mountainous headwaters have highest discharge only during the winter (Megia, 1956; Staubitz et al., 1997).

Salinity within Puget Sound therefore varies seasonally but also becomes fresher southward, reflecting reduced amounts of marine waters coming in from the Strait of Juan de Fuca (Table 1). Because circulation within the Puget Sound is estuarine, and because of its glaciated past, the sound is considered to be a fjord estuary.

As explained previously, the eastern part of the Strait of Juan de Fuca experiences predominantly diurnal tides throughout the tidal cycle. However, this effect decreases to the south toward Puget Sound where tides are always semidiurnal around Seattle (Thomson, 1981). Within the sound, the tidal stream generally flows to the south during a flood as water is pushed in from the Strait of Juan de Fuca, and to the north during an ebb as water is pulled back out.

Currents within Puget Sound are complicated due to the complex coastlines, bathymetry and estuarine circulation. Where the sound is both narrow and shallow, current velocities are the highest. Maximum currents in Admiralty Inlet range from 240–300 centimeters per second (Guerra et al., 2019 and references therein). At the narrower Deception Pass (Figure 10A), current speeds reach up to 340 centimeters per second. In the southern end of the Central Basin, currents of up to 260 centimeters per second have been measured at the Narrows (Kruckeberg, 1995), site of the famous Tacoma Narrows suspension bridge collapse in 1940 due to gusty winds and poor engineering design.

**Crossing Puget Sound**

Ferry service across Puget Sound and the Strait of Juan de Fuca between British Columbia and Washington State is operated separately by Washington State Ferries (22 vessels) and the Clipper Vacations company (2 vessels). For this article, one of us (AK) boarded the latter company’s *Victoria Clipper V* in March 2019 for the round-trip voyage between Seattle and Victoria. Built in 2003 and acquired in 2018, this ferry is 51 meters long and 12.3 meters wide, and reaches top
speeds of 36 knots (67 kilometers per hour). A typical crossing takes two hours and 45 minutes. The Clipper V is a catamaran that uses waterjet propulsion and is the one of the fastest passenger vessels in the Western Hemisphere (Clipper Vacations, 2019). The ferry can carry 532 passengers and crew but no vehicles. As a larger and faster vessel, the Clipper V replaced the Clipper IV (Figure 11A), which retired in 2018 after 22 years of service.

![Figure 9. Crossing the Strait of Juan de Fuca. A. Map of the strait and ferry route. B. Leaving Victoria aboard the MV Coho in November 2007. C. The Coho (center) enters Victoria’s Inner Harbour, with two cruise ships in the strait (June 2019). View looks south across the strait toward the Olympic Mountains. D. Purple sea urchins bore pits into Sooke Formation sandstone in shallow water at Botanical Beach. E. A sea lion visits the Oak Bay Marina in east Victoria. F. Killer whales migrating through Haro Strait, as seen from a whale-watching vessel. (Photos: A. Chang, 2006–2019. Satellite image courtesy of Microsoft.)](image-url)
Figure 10. Puget Sound and tributaries. A. Map of basin names, rivers and ferry route. Yellow dotted lines separate the basins. Not all rivers are labeled. B. A Snoqualmie Falls Park sign explains local geology. The falls cascade over an 82-meter andesite cliff made by a 20 million-year-old volcano that was fed by the Snoqualmie Batholith (ancient magma chamber inside the Earth). Adjacent to the batholith are the San Juan Islands–Northwest Cascades thrust system nappes (Figure 2). C. The Snoqualmie Falls were popularized in the American TV mystery series Twin Peaks (1990–1991). (Photos: A. Kumar, 2019. Satellite image courtesy of Microsoft.)
Figure 11. Crossing Puget Sound. See Figure 10A for ferry route. A. The now-retired Victoria Clipper IV in Victoria’s Inner Harbour. (Photo: A. Chang, 2007.) B. Aboard the Victoria Clipper V in Elliot Bay, departing Seattle from Pier 70 (maroon-coloured building). The Space Needle at left is a Seattle landmark. C. The majestic Olympic Mountains, as seen from Puget Sound. The central peak is Mount Olympus (elevation 2,432 meters). D. Another view of the Esperance Sand on Whidbey Island. (Photos: A. Kumar, 2019.)

After pulling out of Pier 70 from Seattle, the Clipper V enters the Central Basin of Puget Sound (Figure 11B). The ferry then begins its northerly journey through the Central Basin and into Admiralty Inlet. Along the way, passengers get a magnificent view on their port side of the snowcapped Olympic Mountains (Figure 11C). On the starboard side, the western bluffs of Whidbey Island, the largest island in Puget Sound, then come into view (Figures 6C and 11D). For several kilometers of Whidbey Island’s coastline, one can see exposed the volume and extent of the Esperance Sand glacial outwash that was deposited during the last ice age. Once the Clipper V emerges from the mouth of Admiralty Inlet and heads into the open Strait of Juan de Fuca, the ferry increases speed on its way to Victoria.
SUMMARY

We hope you have enjoyed traveling with us across the Salish Sea and through geologic time. You can see that this region’s integrated natural history and shared oceanography, as well as the common heritage of the Coast Salish peoples, transcend national borders and should be appreciated as a whole.

If you have not visited this region before, come explore and take in the scenery and culture. If you have been here previously but a long time ago, come back and see the Salish Sea in a new light. The name is becoming more common (Figure 12), and hopefully before long, it will be well known by everyone.

ACKNOWLEDGEMENTS

AK would like to thank his daughter Anita K. Maisuria and son-in-law Paresh Maisuria of Seattle for taking him to several geologically interesting places in the northwestern USA and various places in BC, including Vancouver Island. These visits resulted in many articles (see references). As described earlier, the latest adventure was a ferry crossing from Seattle to Victoria and back in March 2019, during which the idea for this current article sprang to life.

Figure 12. A sign of acceptance? Directional signage installed in 2016 shortly after the Tsawwassen Mills shopping center opened in Tsawwassen (Figure 1). The sign guides motorists and educates the general public about the Salish Sea name. Thank you for reading our article! (Photo: Tanya Lefebvre, 2019; used by permission.)
AUTHORS’ CONTRIBUTIONS TO THE GEOLOGY OF THIS REGION

Alice S. Chang

Alice was born and raised in Vancouver, and earned BSc and MSc degrees in Geology from the University of British Columbia (UBC) in Vancouver. She completed a PhD degree at Carleton University (Ottawa, Canada), and participated in a weeklong research cruise to Effingham Inlet (Figure 1), west coast of Vancouver Island, aboard the CCGS Tully in October 1999. During the cruise, a suite of sediment cores was collected. From core samples, she examined seasonal and annual changes in sediment patterns and diatom (single-celled phytoplankton) populations from 5,000 years ago (mid-Holocene) to the present. This work was followed by a post-doctoral fellowship at the University of Victoria in Victoria, BC. Here, Alice focused on the geochemistry and paleoceanographic history of the western North American margin from Vancouver Island to Guaymas Basin, Mexico, from 50,000 years ago (late Quaternary) to the present. Alice lives in Richmond, BC, and is a project coordinator in the Department of Earth, Ocean and Atmospheric Sciences at UBC.

Arun Kumar

Arun studied Quaternary sediments of Saanich Inlet (Figure 1), southeastern Vancouver Island, during his doctoral research at Carleton University. He examined sedimentology, stratigraphy and benthic foraminifera as proxies for paleoceanography, paleoecology and earthquake history for this region. For post-doctoral research at Carleton University, he studied environmental controls over the distribution of dinoflagellate cysts in the surface sediments of Effingham Inlet. This project was extended to include the study of sedimentology, stratigraphy, dinoflagellate cysts, fish scales and diatoms from various shallow and deep cores in this inlet. Additional research involved visiting the Seymour-Belize inlet complex on the central coast of mainland BC aboard the CCGS Vector. Here, sediment cores were extracted and sampled in a research program similar to the work
done for Effingham Inlet. In 2006, Arun’s daughter and her family settled down in suburban Seattle. Family visits became opportunities to go on field trips to the local volcanoes of the Cascade Mountains in Washington State, and to Crater Lake in Oregon.
REFERENCES and SUGGESTED READINGS

Geologic History and Terranes


*Cordilleran Ice Sheet*


*Salish Sea General References and Naming*


Strait of Georgia


Strait of Juan de Fuca


Puget Sound


Photo Credit


Selected Authors’ Research Contributions


For a full list of Alice’s and Arun’s research papers, conference abstracts, and popular science articles, visit their ResearchGate pages at https://www.researchgate.net/profile/Alice_Chang5 and https://www.researchgate.net/profile/Arun_Kumar605.