

Context:

Geology, Gabriola, tectonic fractures

Citation:

Doe, N.A., Gabriola's fractures—their origins, *SHALE* 20, pp.3–12, April 2009.

Copyright restrictions:

Copyright © 2009: Gabriola Historical & Museum Society.

For reproduction permission e-mail: [nickdoe@island.net](mailto:nickdoe@island.net)

Errors and omissions:

Later references:

N/A.

Date posted:

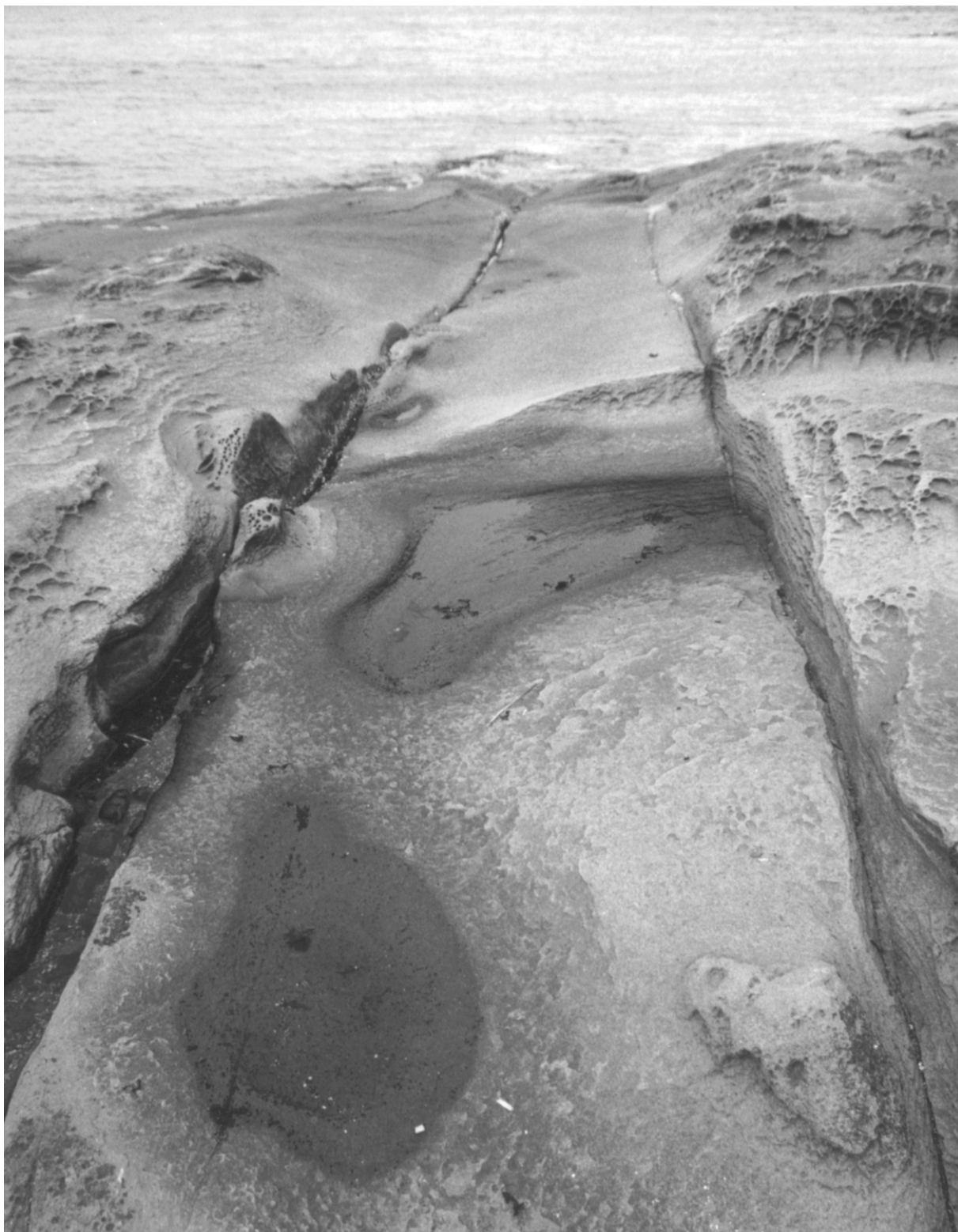
September 10, 2011.

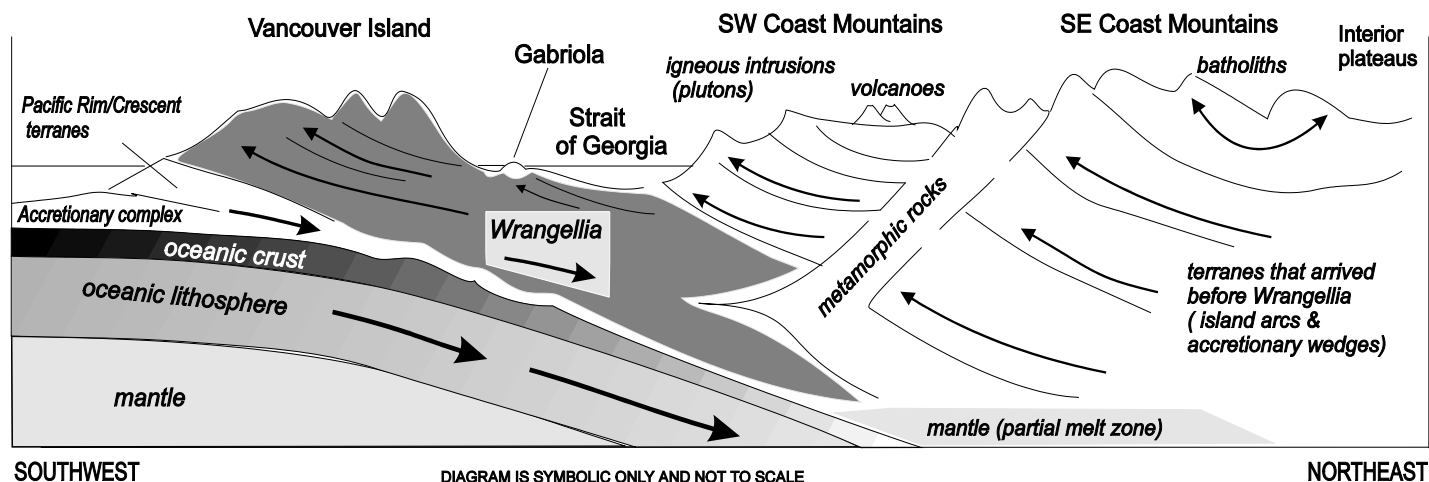
Author:

Nick Doe, 1787 El Verano Drive, Gabriola, BC, Canada V0R 1X6

Phone: 250-247-7858

E-mail: [nickdoe@island.net](mailto:nickdoe@island.net)





The basic structural geology of Vancouver Island, the Strait of Georgia, and the Coast Mountains on the adjacent mainland.

On the left (southwest), Pacific Ocean seafloor (oceanic crust and oceanic lithosphere) descends into the earth's mantle (asthenosphere) below Vancouver Island and the adjacent mainland. Patches of less dense, continental-type rocks are detached from the surface of the seafloor and added to the underside of Vancouver Island (the accretionary complex). The drag of the sinking floor, pushes Vancouver Island to the right (northeast) which invokes counter-thrusts buttressed by the mountains on the mainland, and ultimately by the North American tectonic plate, which is moving to the left (west) because of the expansion of the floor of the Atlantic Ocean. The squeeze raises mountains on Vancouver Island and on the mainland. This continuous uplift is countered by erosion, with one sometimes prevailing over the other.

The high ground on the landward side to the east of the original late-Cretaceous Nanaimo Basin, which was wider than the present-day Georgia Basin, was primarily uplifted and thickened continental rock, namely the SE Coast Mountains. At our latitude, these are on the east side of the Fraser Canyon. The basin then was a *foreland basin*. Subsequently, as a result of partial melting of the mantle, the SW Coast Mountains arose (at our latitude on the west side of the Fraser Canyon) and these mountains have more of the character of a volcanic edifice built by intrusion, but with some extrusion also (Mt. Meager, Mt. Garibaldi, Mt. Baker, etc.). The Coast Mountains, which are mostly granitic rocks, are the "glue" that holds the *Wrangellia* terrane to the North American plate and give the present-day Georgia Basin its *forearc basin* characteristics. The Georgia Basin, the Tertiary (Chuckanut) Basin in NW Washington, and the late-Cretaceous Nanaimo Basin owe (and owed) their existence to the downward flexing of the lithosphere in response to the weight of the mountains built up on both sides of the basin.

It is because of all this activity that many fractures on Gabriola run parallel to the direction of the thrusting and counter-thrusting and the island's bedrock is folded along an axis that runs at right angles to it (roughly NW–SE).

Sketch from information provided by Monger and Journeay, 1994, Geological Survey of Canada, Open File 2490.  
GPS data from Dragert, Schmidt, Henton, and Lu, 2001, *Western Canada Deformation Array Project*, GSC, Natural Resources Canada.

---

# Gabriola's fractures—their origins

by Nick Doe

Fractures in the sandstone on Gabriola's beaches are intriguing, especially "tramlines" like the ones in the photograph on the *front cover*. "Has there been an earthquake here recently?" is the usual enquiry. Well, yes... there has. We had a megathrust earthquake on January 26, 1700 AD—but it's not recent earthquakes that created most of these fractures. Many date back millions of years to the geological epoch known as the Eocene, 56- to 34-million years ago, when Vancouver Island was pushed up against the Coast Mountains reducing the width of what is now the Georgia Basin by up to 30% (10–30 km). In the process, the by-then-ancient seafloor was folded and uplifted to create the rolling hills that were destined, much later, to become the Gulf Islands.

One of the several fascinating things about fractures is that they occur on such a wide range of scales. The fracture patterns seen in stones in the yard, or even under a microscope, can also be seen in features which, in some parts of the world, run for hundreds of kilometres across the landscape. Evidence of what might be fractures crossing the whole island can be seen in aerial photographs, satellite imagery, and

*Front cover.* Fractures in sandstone on the beach near Seagirt Road at the north end of the island. The fractures are millions of years old and appear to be the result of tensile (pull-apart) stress but with some strike slip too.

These transtension (or wrench) fractures are members of a set that, along this beach, has an average orientation of N 26° E (the A set), which is a common orientation, not only on Gabriola, but throughout the Gulf Islands. What is unusual here however, is that they are accompanied by another set that runs more easterly at N 71° E (the F set) *see below*.

Why and when these two sets of fractures were formed are not easy questions to answer—it's not only petroglyph carvers that have created enigmas in stone on Gabriola.



*Right.* Another fracture in sandstone near Seagirt Road looking toward Entrance Island, which is just beyond the point. The set of which this is a member runs N 71° E (the F set). If you look the other way, it points, quite startlingly, directly at Mount Benson.

Unlike the N 26° E set (the A set), one of which is visible bottom left, these fractures are slip fractures and are heavily mineralized.

The two sets *might* have been formed at different times by different events, or they may be conjugates formed at the same time but modified since by new stress.

earthbound observations of the relief of the terrain, but, because they are so heavily eroded, or so deeply buried, these features can rarely be studied in the same detail as “minor fractures” like those shown in the picture on the *first page* and on the *front cover*. You can seldom walk more than a few metres along our sandstone beaches without seeing one.

Long fractures nevertheless have a lot to do with the shape of Gabriola Island. Go down to Brickyard Beach when the tide is low and you'll see at the entrance to False Narrows, a low ridge of sandstone protruding out of the shale. The sandstone is fractured and breaking up into oblong blocks, the short sides of which tilt gently upward towards Mudge, and the long sides of which point almost directly at the Gabriola ferry terminal in Nanaimo (N 74° W), which is close to the orientation of the central axis (syncline) of Gabriola over much of its south-central length (N 68° W). Now turn around with your back to Nanaimo and you'll find yourself looking along the shoreline of False Narrows—a pretty good indication that it was ancient fractures, such as these, that made it easy for ice to gouge a channel in that direction and while at it, provide a path down to the beach from the cemetery.<sup>1</sup>

But it doesn't stop there. If you are a reader who considers *SHALE* altogether too parochial, I'll point out that False Narrows just happens to run almost exactly parallel to the Juan de Fuca Strait (N 69° W) and that's not entirely a coincidence either.<sup>2</sup> And if

you want more, the Juan de Fuca Strait, as you will shortly see, arguably runs the way it does due to stress patterns that involve the entire floor of the Pacific Ocean.

## Geological history

The history of Gabriola's fractures is, as far as we know,<sup>3</sup> as follows. Vancouver Island has been docked alongside North America for about 90 million years. It is part of a terrane brought here by moving seafloor from the tropics far away in the Pacific, perhaps close to where Indonesia is now. Many of the rocks that make up Vancouver Island are old seafloor or volcanic and sedimentary rocks formed in a shallow-marine environment. When the island first arrived here, it was probably just below sealevel.<sup>4</sup> It is the collision with North America that has created mountains.

Seafloors move because seafloor is continuously being created and consumed. Nowhere on earth are there oceanic rocks more than 250-million years old, yet continental rocks have been found that are more than 4000-million (4-billion) years old. Seafloor is created from lava erupting along mid-ocean ridges running through all of the world's oceans. Old seafloor is removed by subduction into the earth's mantle beneath the edges of continents, or into deep-sea trenches. This circulatory motion is driven by heat generated mostly by radioactivity in the mantle. Cycling the seafloor allows this heat to escape, which is otherwise difficult for it to do because the earth's crust is such a good insulator.

---

<sup>1</sup> In this article, a fracture orientation given as N 45° W (northwest) could equally well be described as being S 45° E (southeast). In these articles, I'm arbitrarily using the more northerly of the two possibilities.

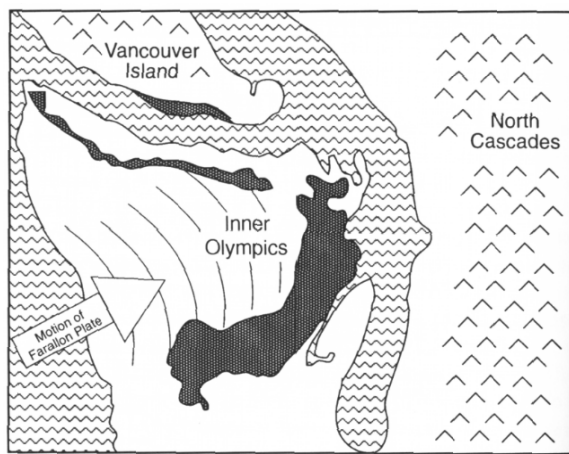
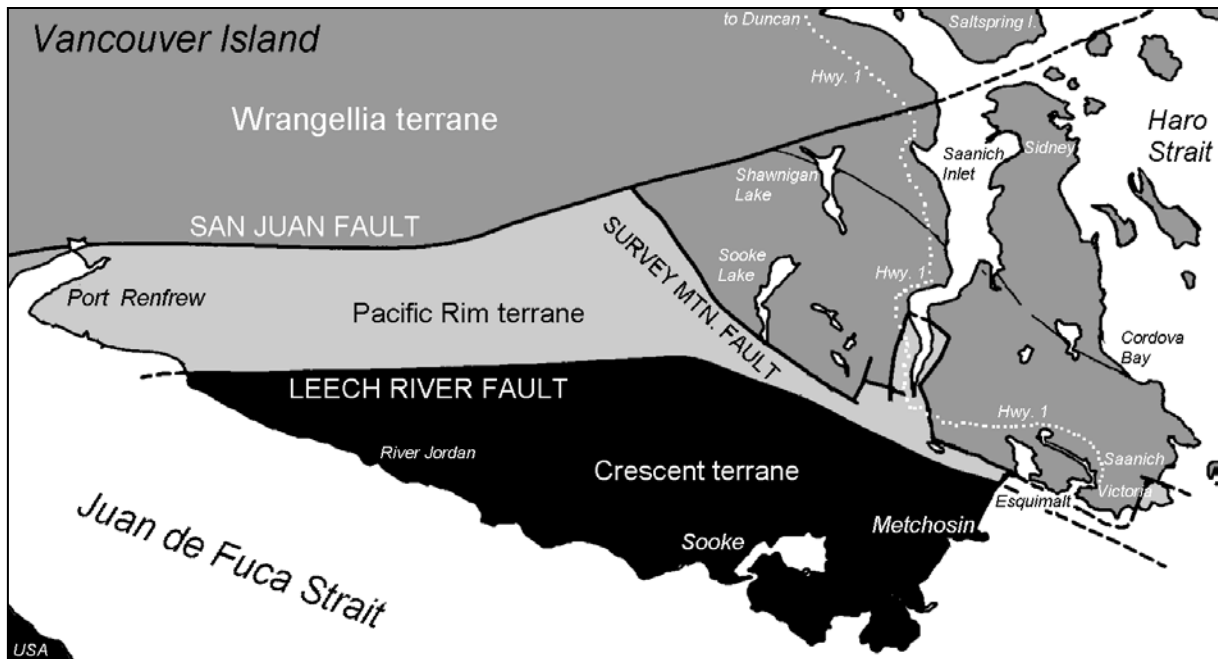
<sup>2</sup> N 22° E, which is the complement of N 68° W, is a popular orientation for bedding-perpendicular joints

---

throughout the southern Gulf Islands (Macke, 2002, p.106, Trend 1).

<sup>3</sup> Despite research over several decades, no consensus has emerged on the detailed paleogeography of the coast—the Baja-BC controversy continues.

<sup>4</sup> Johnstone, Mustard, & MacEachern, 2006.



As the seafloor moves, it carries with it patches of “scum”—lightweight, granitic rocks, rich in silica and aluminum (*quartz* and *alkali-feldspars*) compared to the basaltic rocks of the seafloor that are rich in iron, magnesium, and calcium (*pyroxenes*, *olivine*, *anorthite*).

Continents, terranes (micro-continents), and lesser patches of “scum” called “accretionary complexes” (mélanges of oceanic, andesitic, metamorphic, and sedimentary rocks) remain on the surface where they jostle together, coalesce, split, and meander across the earth, rather like

Above: The *Pacific Rim* and *Crescent* terranes were added to SW Vancouver Island (*Wrangellia*) during the Eocene.

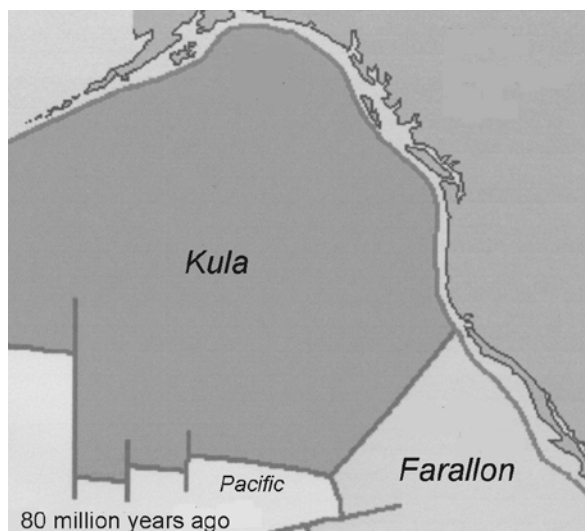
Adapted from GSC 1553A by J.E. Muller

Left: Canadian maps often don't show that the *Crescent* terrane (black) forms the heart of the Olympic Mountains. The Olympic Peninsula is mostly basalt, the stuff seafloors are made of, which was pushed aloft about 42-million years ago.

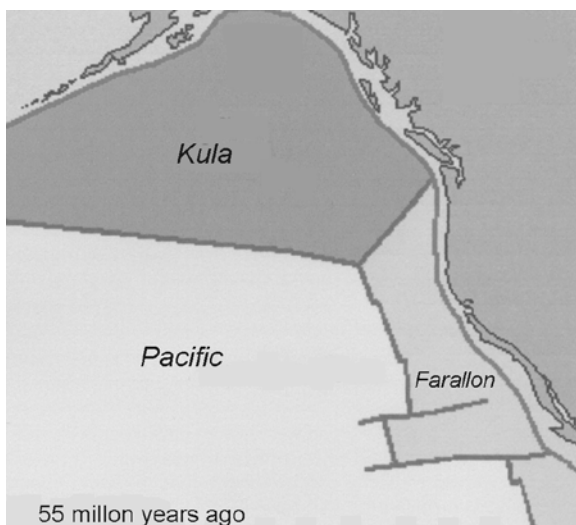
The geography shown here is more symbolic than actual. Nobody knows what the San Juan Islands looked like back then—they could have been mountains—and the Strait of Georgia was dry land, the sea having retreated at the end of the Cretaceous period.

Drawing from Hill Williams, *The Restless Northwest—A Geological Story*, Washington University Press

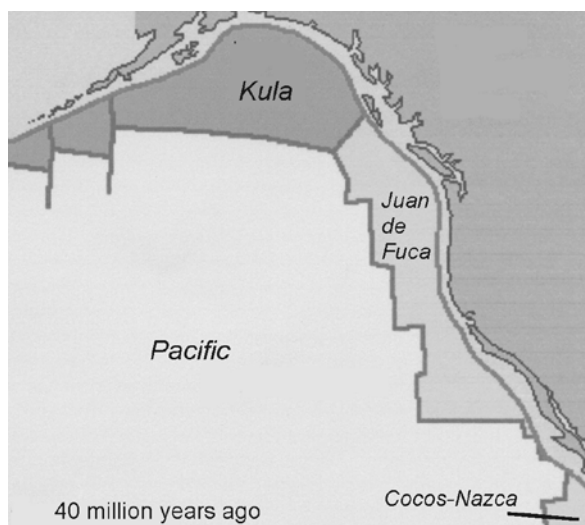
blobs of olive oil on the surface of water in a pot being heated to cook spaghetti. Enough time has elapsed since the earth was formed for any one piece of this “scum” to have drifted completely around the world more than once.



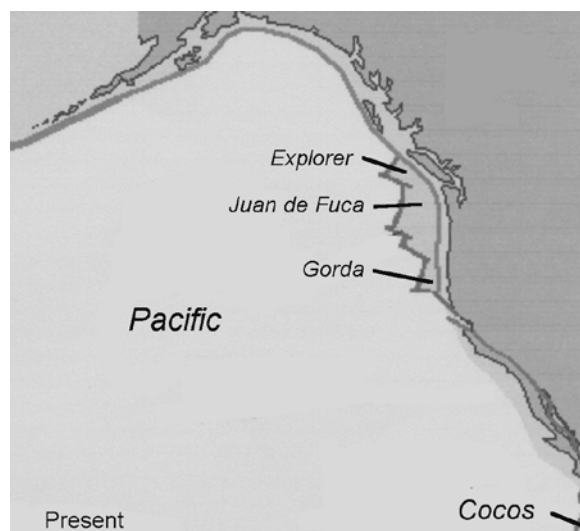
Map 1: One giant tectonic plate, the *Farallon* plate, once dominated the Pacific, much as the *Pacific* plate does today, but, by 80-million years ago, it had split, creating a separate *Kula* plate. The *Kula* plate was moving rapidly north, parallel to the coast, bringing relative seismic tranquility to the Nanaimo Basin where the sediments that now form our bedrock were first laid down.



Map 2: About 55-million years ago, seafloor spreading along the *Kula-Pacific* ridge waned leaving the *Farallon-Pacific* ridge as the only active ridge. The *Kula-Farallon* boundary was moving north past Oregon, Washington, and BC, causing many changes to the region's geography. The change from north-moving *Kula* to east-moving *Farallon* may have added terranes to Vancouver Island.



Map 3: Around 40-million years ago, the *Kula* plate was subducting into the newly opened Aleutian Trench, and seafloor spreading at the *Kula-Pacific* ridge had practically ceased. By 30-million years ago, the *Kula* was gone. Meanwhile, the *Farallon* split again, this time into the *Juan de Fuca* and *Cocos-Nazca* plates. Both plates subsequently split again into the fragments we see today shown in Map 4.



Map 4: The present configuration of the tectonic plates in the North Pacific. The assembly is dominated by the giant *Pacific* plate; the others are small remnants. The *Juan de Fuca* and *Gorda* plates are today subducting beneath Vancouver Island and the North American continent.

Diagrams from Steven Dutch's website, University of Wisconsin, based on ideas of Tanya Atwater, Stanford University.

Vancouver Island and the rest of the terrane called *Wrangellia*—which included Haida Gwaii, mountains in Alaska, and possibly a fragment in western Idaho—wasn't the last terrane to impact the coast. Around 55-million years ago, a small terrane known as the *Pacific Rim* terrane dug into the southwest corner of Vancouver Island. It's the Pacific Rim terrane that forms the walls of the narrow canyon you pass through on the descent from the summit of the Malahat Drive on the way to Victoria.

Then, around 42-million years ago, a much larger terrane, the *Crescent* terrane, the size of Iceland, added the land of Sooke, Metchosin, and Colwood to the Island, and the Olympic Peninsula to Washington State.

A third deformation event, about 24-million years ago (Neogene), involved the very southern part of what is now the Strait of Georgia and Puget Sound and was a result of large-scale decoupling of accreted material beneath Vancouver Island, the San Juans, and the Cascades from the surface of the subducting oceanic plate. This moved the compression margin 70 km southwest, creating abrupt changes locally in the strength and direction of the tectonic stress.<sup>5</sup>

Many fractures that we see on Gabriola are the more gentle by-products of these tumultuous events. If we look at the Pacific Ocean today, we see, at most, only small remnants of the oceanic tectonic plates that were instrumental in creating our landscape.

## Gabriola's link to the whole Pacific Ocean

Earlier, I said that the Juan de Fuca Strait, and False Narrows, arguably run the way they do due to stress patterns that involve

the entire floor of the Pacific Ocean. Let's now see how this might be.<sup>6</sup>

About 5500 kilometres west of Gabriola, and 3000 kilometres east of Tokyo, way out in the Pacific Ocean in the middle of nowhere, there is a seamount called *Kammu*. Seamounts are submarine volcanoes that either never made it to the surface of the sea, or once did but have since subsided or been worn away.

Travelling away from Kammu, almost due north (N 10° W), you can follow a chain of seamounts, 2600 kilometres long, all the way to the coast of Kamchatka. And travelling away from Kammu in a southeast direction (S 61° E), you can similarly follow a chain of seamounts and occasional small volcanic islands, 3100 kilometres long, all the way to Hawaii. Kammu is famous not because it is unique, but because it is situated at the “big-bend” in the Hawaiian-Emperor Seamount Chain, *see map on next page*.

As one travels along the chain starting from Hawaii, the lavas become older and older—Maui (1 million), Oahu (3 million), Kauai (5 million)... Numbers in circles on the map indicate age in millions of years. The oldest lavas, near the Russian coast, may be 80-million years old.

There are two theories as to what happened at the time the seamount called *Kammu* was forming at the “big bend”. One theory supposes that the moving seafloor changed direction over a more-or-less stationary “hotspot”; the other postulates that the hotspot travels along pre-existing fractures and that where it shows itself is controlled

<sup>5</sup> Journeay and Morrison, 1999.

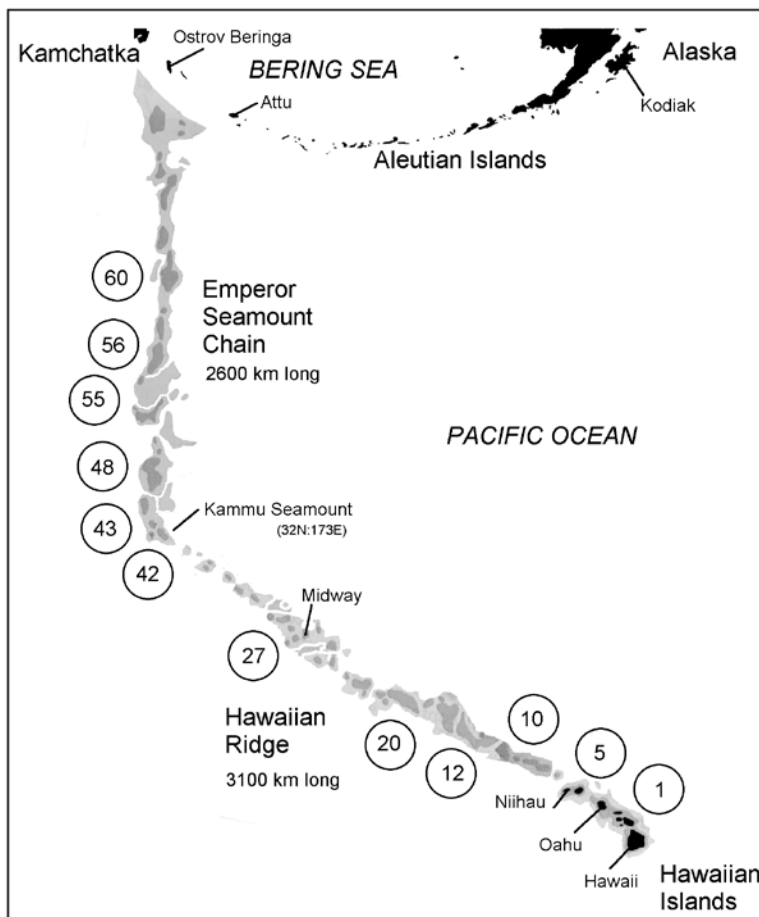
<sup>6</sup> The history of the tectonic plates is a topic of on-going research, and you should be warned that by the time you read this, some of the details may have been substantially revised. This account is also a simplification of a complex process.



by the pattern of stresses around the edges of the tectonic plates. What will fascinate Gabriolans about this, is that Kammu dates back to the Eocene, exactly the same age as many of the fractures on Gabriola. Clearly, back then, “something” was going on to the floor of the Pacific Ocean that wasn't just local to the Gulf Islands.<sup>7</sup>

The thought that the chain of seamounts record the movement of the seafloor over a stationary “hot-spot”—rather like the scorch mark you could trace out by moving a sheet of paper slowly over a candle flame was once popular. However, if it were correct, the big bend would represent an enormous change in direction of the ocean floor's movement (50° counterclockwise) and it's not clear what forces could have caused this.

The second idea is that it is wrong to assume that the hot-spot, which is currently under Hawaii, is stationary. Instead, it is suggested, the chain of seamounts represent the movement of a “leak” along pre-existing fractures, the movement being driven by changes in stress around the rim of the

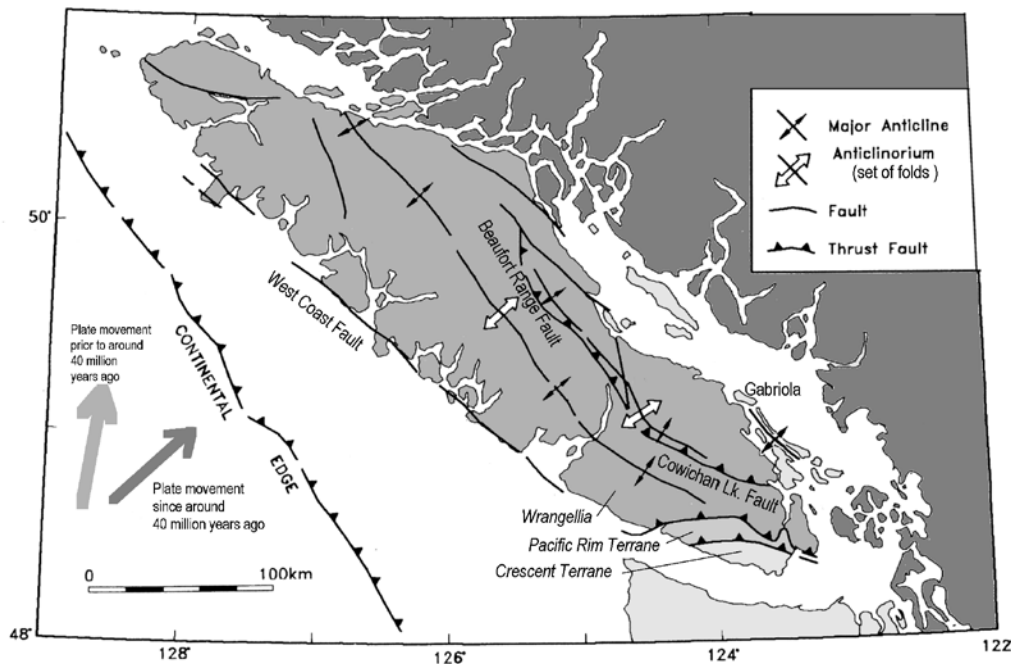


The Hawaiian Islands stretch 650 kilometres northwest from the Big Island to tiny Niihau, but under the sea, the chain continues for thousands of kilometres, all the way to Kamchatka. Circled numbers are ages in millions of years.

Pacific Ocean. This is rather like the way that the direction a slowly developing crack in a car's windshield may be controlled by flexing around the edges of the glass. Anybody who's learnt to cut stained glass will know too how you can control the direction of a crack by subtly changing the pressure you exert while holding the piece by its edges. If this idea is right, then the bend represents movement of the hot-spot from one pre-existing fracture to another.<sup>8</sup>

<sup>7</sup> South of the border, this time is known as the “Challis Episode”, named after a small town in Idaho. Large regions of the US Pacific Northwest were folded, faulted, and rearranged, all the while hosting a chain of volcanoes running diagonally across Washington and Idaho. At the end of this period, a large piece of ocean floor (now the Olympic Peninsula) was uplifted and forced beneath the edge of the continent, extending the continental margin to its modern western limit (Townsend & Figge, 2002).

<sup>8</sup> Smith, 2003. Recent research supports the idea that the hot-spot moves. The movement was rapid during the Cretaceous.



Folding, and fracturing of Vancouver Island and the late-Cretaceous Nanaimo Basin was a result of drag from the oceanic tectonic plate descending beneath North America from the southwest. Uplift of Vancouver Island began shortly after it arrived off the coast around 90-million years ago, but the most severe distortion occurred during the Eocene, 56–34 million years ago when new terranes arrived at the south end of the island.

Adapted from Yorath and Nasmith, 1995.

Whatever the reason for the bend however, it seems a reasonable surmise that what caused it is intimately linked to the events that, in effect, created our island.

This “something” was likely the point during the Eocene when the old *Farallon* plate, which had once dominated the entire eastern half of the Pacific Ocean, finally gave up its status as the major tectonic plate and became a minor player on the edge of a rapidly growing *Pacific* plate. The upheaval was thus due to the changes in the subduction direction, and subduction angle of the plates beneath the westward moving American plates that this change entailed. It was the change in tectonic plates off the west coast of Vancouver Island from the northward-moving *Kula* plate (now disappeared into the Aleutian trench) to the

eastward-moving *Farallon* plate (now split into fragments that include the *Juan de Fuca* plate) that added the Pacific Rim and Crescent terranes to Vancouver Island. These changes determined much of the present-day coastal geography of BC and western Washington and Oregon states.

Today, the Pacific Ocean is dominated by the *Pacific* plate, most or all of the other original oceanic plates having been subducted in the “ring of fire”—the *Izanagi* under the Eurasian plate; the *Phoenix* under the *Indo-Australian* and *Antarctic* plates; and the *Farallon* under the *North America* and *South America* plates save only for the *Nazca* fragment in the southeast, and tattered remnants in the northeast: the *Explorer*, *Juan de Fuca*, *Gorda*, and *Cocos*.

Although plates like the *Juan de Fuca* are small on a global scale,<sup>9</sup> their movements have very significant seismic effects locally.

## Uplifting Vancouver Island

When Vancouver Island first arrived off the mainland coast, all of it was probably slightly below sealevel. Subsequent uplift formed, and then divided, the late-Cretaceous Nanaimo Basin between Vancouver Island and the mainland. The west coast of the basin may at one time have run through the Port Alberni and Cowichan Lake area where Nanaimo Group outcrops are found today, or maybe even west of there—nobody knows. The Nanaimo coalfields were thus likely formed on the east coasts of emergent islands or peninsulas lying between central Vancouver Island and the present-day Strait of Georgia.<sup>10</sup>

All this happened though, long before Gabriola was around. The Northumberland Formation is the oldest of the Nanaimo Group formations found on Gabriola, but at the time that the muddy sediments that comprise it were being laid down, Vancouver Island had already been here for some 15–25 million years. Nevertheless, we can see practically everywhere on our shale beaches the signs of the major earthquakes that accompanied ongoing uplift and tectonic activity in the ancient Nanaimo Basin.<sup>11</sup> And it hasn't stopped; the

mountains on Vancouver Island are currently being uplifted at a rate of 1–2 mm per year, and those on the mainland at between 1–3 mm per year. Meanwhile, Gabriola, along with the floor of the southern Strait of Georgia and the Fraser valley, is either stable or sinking slightly at rates of between 0–1 mm per year due to subsidence caused by the increasing weight of the Fraser delta. This locally-relative tectonic tranquility, which has lasted for millions of years, in part, accounts for the fact that most of the fractures we see in the sandstone on our island are very old.

## Structure of the Georgia Basin

That Vancouver Island has been shoved up against the mainland from the southwest is perhaps not a surprise for the axis of the big island runs diagonally northwest, N 51° W.<sup>12</sup> If you think all this shoving was in the past, you should take note that the present-day movement of Nanoose, just north of us, is still exactly in line with this thrust.

According to GPS measurements made over the past 20 years or so, Nanoose is moving at 4.6 mm/year N 39° E, that's N 51° W + 90°, relative to Penticton on the mainland. If you view Mount Benson, which is made up of lava from the floor of the Pacific Ocean, as “looming” over Nanaimo, there's good reason for this perception. It probably is still moving our way.

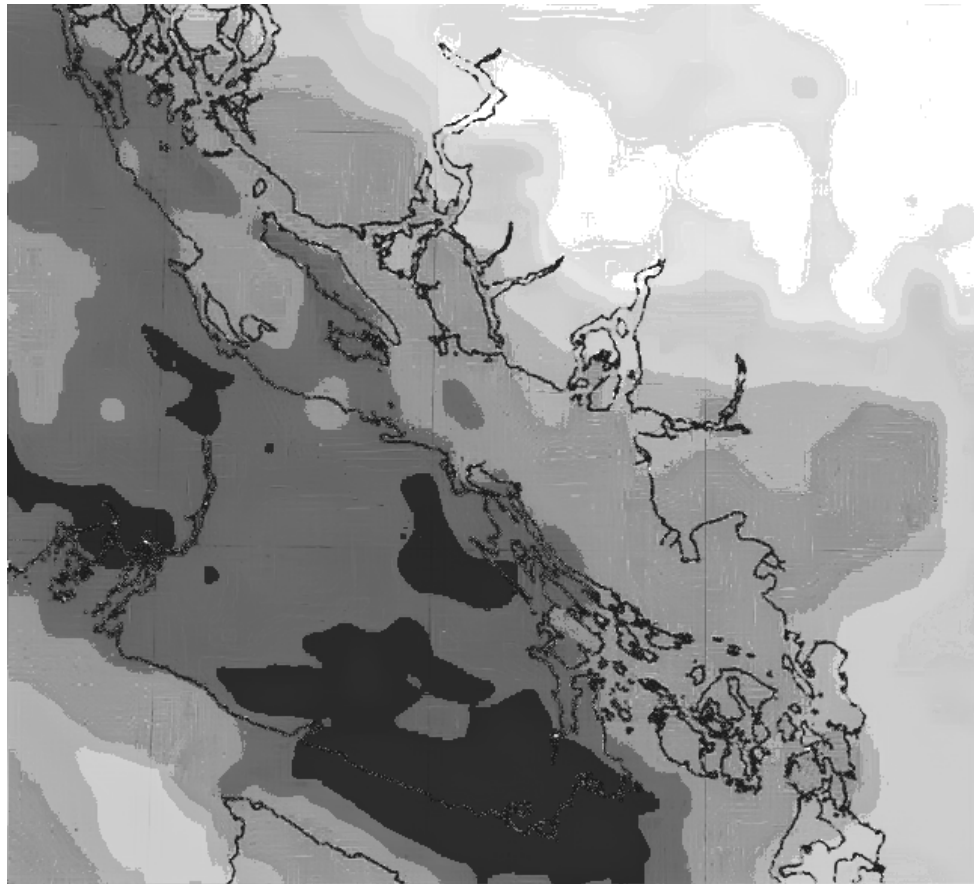
<sup>9</sup> Some people think that the *Explorer*, *Juan de Fuca*, and *Gorda* are too small to be designated tectonic plates, but they are moving in different directions.

<sup>10</sup> The Beaufort Range and its continuation south. There is a map in *SHALE* 7, p.12.

<sup>11</sup> Another very tangible sign of ancient uplift is the conglomerate that makes up some of the Geoffrey Formation. The cemented and beautifully rounded cobbles you can see at the top of Brickyard Hill likely came from the San Juan Island area, certainly from due south of us. Patos Island shows an

excellent record of a large river delta that existed there during late-Cretaceous times. This would have been at a time when the San Juan terranes (*Decatur*, *San Juan*, and *Lopez*) had been uplifted in response to the easing of the downward pressure of the subduction zone as it moved from the west coast of the continent to the outer coast of Vancouver Island and by the violent collision with *Wrangellia*.

<sup>12</sup> North (Cape Sutil, 50°53' N); East (Cadboro Point, 123°16' W); South (Christopher Point, 48°19' N); West (Cape Scott, 128°26' W); 470 km SE to NW.



Adapted from Lowe, Dehler, Zelt, NRC, Canada, 2003

Variations in the strength of gravity in the Strait of Georgia region. The darker the grey, the stronger the gravity, and hence by implication, the denser the basement rocks. Note the lobe of denser rocks, probably belonging to the *Wrangellia* terrane, underlying the Fraser lowlands.

Studies of the variation of the strength of the gravitational field, and hence the density of the rocks lying below the sediment and sedimentary rocks, provide a fascinating glimpse of the geological structure of the Strait of Georgia. Because of their marine component, the rocks of the *Wrangellia* terrane are denser than the volcanic and intrusive igneous rocks of the mainland, and so a “gravity” map provides details of the boundary between the Coast Mountains and Vancouver Island, as it exists up to 13 kilometres below the surface. Perhaps too there are clues here as to why Gabriola has the geographic orientation that it does, something I’ll write about later.

Although glaciation has shaped our landscape, glaciers were often guided in this by fractures. One of many examples of this is the Malaspina galleries, where sometime in the last two-million years, a glacier has removed a large “sliver” of sandstone to create the bay between McConvey Road and Malaspina Drive. This “bay” extends a fair distance inland as a wide gully, filled with clay, glacial débris, and, now, small gardens. Despite its being created only recently however, the face of the galleries and the gully run N50° W, which is a common trend of fractures not only on Gabriola, but throughout the Gulf Islands. Like its human history, Gabriola’s geological history is but a part of the history of the whole globe. ◇

## References

- Nick Doe, *Sandstone and shale— Gabriola's origins*, *SHALE* 1, pp.26–35, November 2000; *How Gabriola came to be*, *SHALE* 7, pp.5–14, January 2004; *The Malaspina Galleries*, *SHALE* 9, pp.53–6, August 2004.
- Stephen Earle, *The Geology and Geological History of Vancouver Island*, web.viu.ca/earle/mal-cut/geology-of-vancouver-island.ppt.
- T.D.J. England, *Late Cretaceous to Paleogene evolution of the Georgia Basin, Southwestern British Columbia*, Ph.D. thesis, Memorial University of Newfoundland, 1989.
- C. Lowe, S.A. Dehler, and B.C. Zelt, *Basin architecture and density structure beneath the Strait of Georgia, British Columbia*, *Canadian Journal of Earth Sciences*, 40: pp.965–81, 2003.
- P.D. Johnstone, P.S. Mustard, & J.A. MacEachern, *The basal unconformity of the Nanaimo Group, southwestern British Columbia: a Late Cretaceous storm-swept rocky shoreline*, *Canadian Journal of Earth Sciences*, 43: pp.1165–81, 2006.
- J.M. Journeay & J. Morrison, *Field Investigation of Cenozoic structures in the northern Cascadia forearc, southwestern British Columbia, Canada*, *Geol. Survey of Canada, Current Research*, pp.239–50, 1999-A/B.
- J.W.H. Monger & J.M. Journeay, *Basement geology and tectonic evolution of the Vancouver region*, *Geol. Survey of Canada, Bulletin* 481, pp.3–25, 1994.
- James W.H. Monger & J. Murray Journeay, *Guide to the geology and tectonic evolution of the southern Coast Mountains*, *Geol. Survey of Canada, Open File* 2490, 1994.
- J.E. Muller and J.A. Jeletzky, *Geology of the Upper Cretaceous Nanaimo Group, Vancouver Island and Gulf Islands, British Columbia*, *Geol. Survey of Canada, Paper* 69-25, 1970.
- Peter S. Mustard, *The Upper Cretaceous Nanaimo Group, Georgia Basin*, *Geological Survey of Canada, Bulletin* 481, pp.27–95, 1994.
- June Ryder, *Physical Geography of BC*, *Encyclopedia of British Columbia* (Ed. Daniel Francis), pp.549–59, 2000.
- Alan D. Smith, *A re-appraisal of stress field and convective roll models for the origin and distribution of Cretaceous to Recent intraplate volcanism in the Pacific Basin*, *Int. Geol. Rev.*, 45, pp.287–302, 2003.
- Catherine L. Townsend and John T. Figge, *Northwest Origins—An Introduction to the Geologic History of Washington State*, <[http://www.washington.edu/burkemuseum/geo\\_history\\_wa](http://www.washington.edu/burkemuseum/geo_history_wa)>
- C.J. Yorath, A. Sutherland Brown, & N.W.D. Massey, *Lithoprobe, Southern Vancouver Island, British Columbia, Canada*, *Geol. Survey of Canada, Bulletin* 498, 1999.
- C.J. Yorath and H.W. Nasmith, *The Geology of Southern Vancouver Island—A Field Guide*, Orca Book Publishers, Victoria, 1995.