

Context:

Geology, tafoni, Gabriola, sandstone, cavernous weathering, salt weathering

Citation:

Doe, N.A., What makes holes in sandstone, *SHALE* 9, 2d ed., pp.12–40, August 2004.

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Errors and omissions:

This is the 2nd edition which contains a few corrections on pages 25 & 39.

Later references:

“[Salt-weathering](#) of upper Nanaimo Group sandstone” is in *SHALE* 23.

“Holes at great heights” and “Windy New Mexico”, <http://www.nickdoe.ca/pdfs/Webp239c.pdf>

“[The geometry of honeycomb weathering of sandstone](#)” explains the relationship between honeycomb polygons and Thiessen polygons. Why the holes have the shape they do.

“[Colonial corallites and honeycomb holes in sandstone](#)” explores in an informal manner the origin of honeycomb holes and why the patterns resemble some forms of coral.

Date posted:

August 1, 2008.

Author:

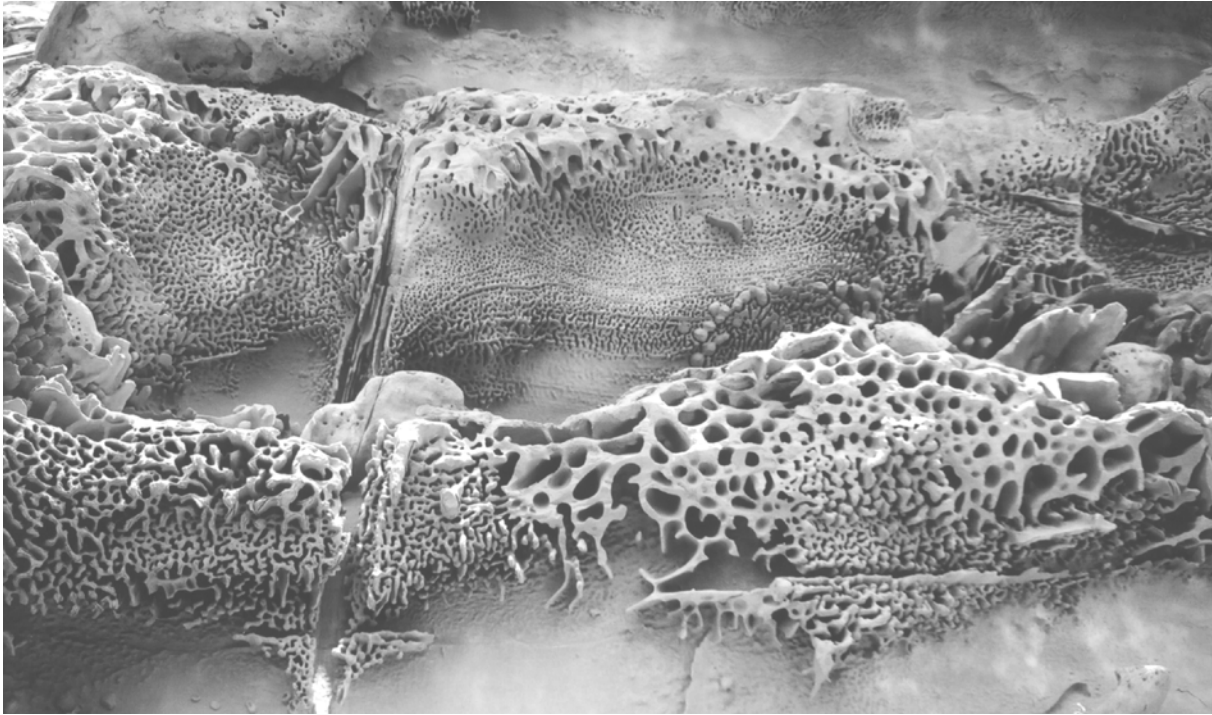
Nick Doe, 1787 El Verano Drive, Gabriola, BC, Canada V0R 1X6

Phone: 250-247-7858, FAX: 250-247-7859

E-mail: nickdoe@island.net

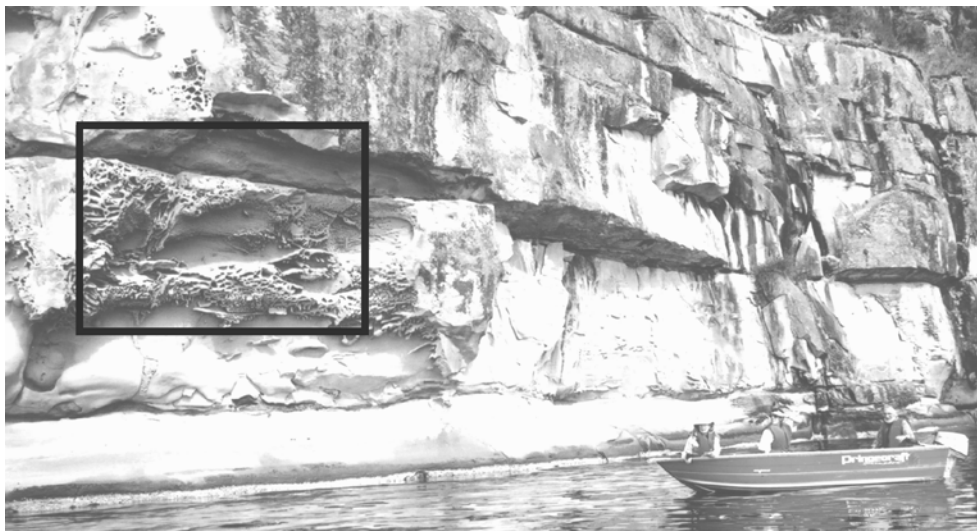
What makes holes in sandstone

by Nick Doe



Above: Honeycomb weathering in the sandstone cliffs on Valdes Island [endnote 5]. The rock has the appearance of rotting away from the inside, which in a sense it is.

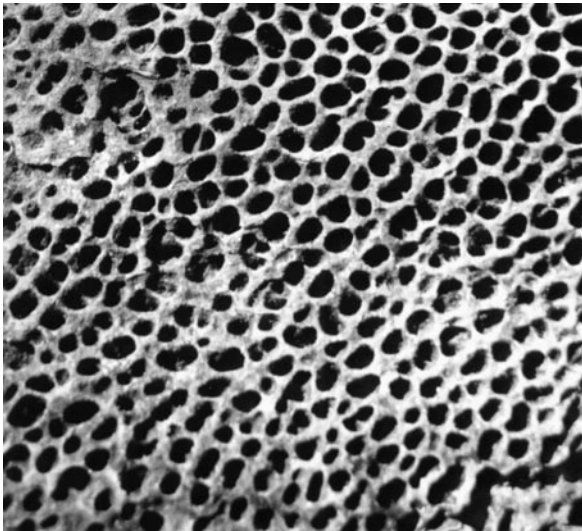
Below: Many boaters pass by these spectacular formations seemingly oblivious to their presence, unlike our friends, bottom right. The black rectangle identifies detail above.



Hexagons

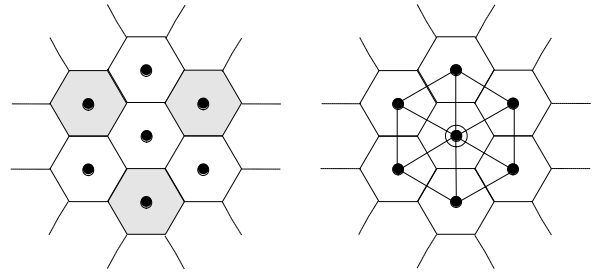
Here's something to think about. Twenty of the 50 states in the United States are inland states—they have no oceanic coastline. If you count the number of state and international borders that each of these inland states has, you'll find that the average is 5.9—let's just call it six. A typical example is the inland state of Utah. Going round clockwise, its borders touch those of Wyoming, Colorado, New Mexico, Arizona, Nevada, and Idaho—six borders in all.

That the number is six, and not four or eight or some other number, is not an accident. If you've ever looked at the little holes that riddle the sandstone on Gabriola's beaches (*below*) and got the feeling that they too are not randomly organized, you'd be right. The twenty inland US states, and the holes, have been distributed according to the "hexagon solution", which is the answer to the question: how do you distribute *service centres* evenly over a flat surface that extends indefinitely in all directions?



Above: Honeycomb holes in sandstone. This weathering pattern is common in the Gulf Islands in locations near to the sea.

Right: One possible explanation for the holes. Too many geologists!

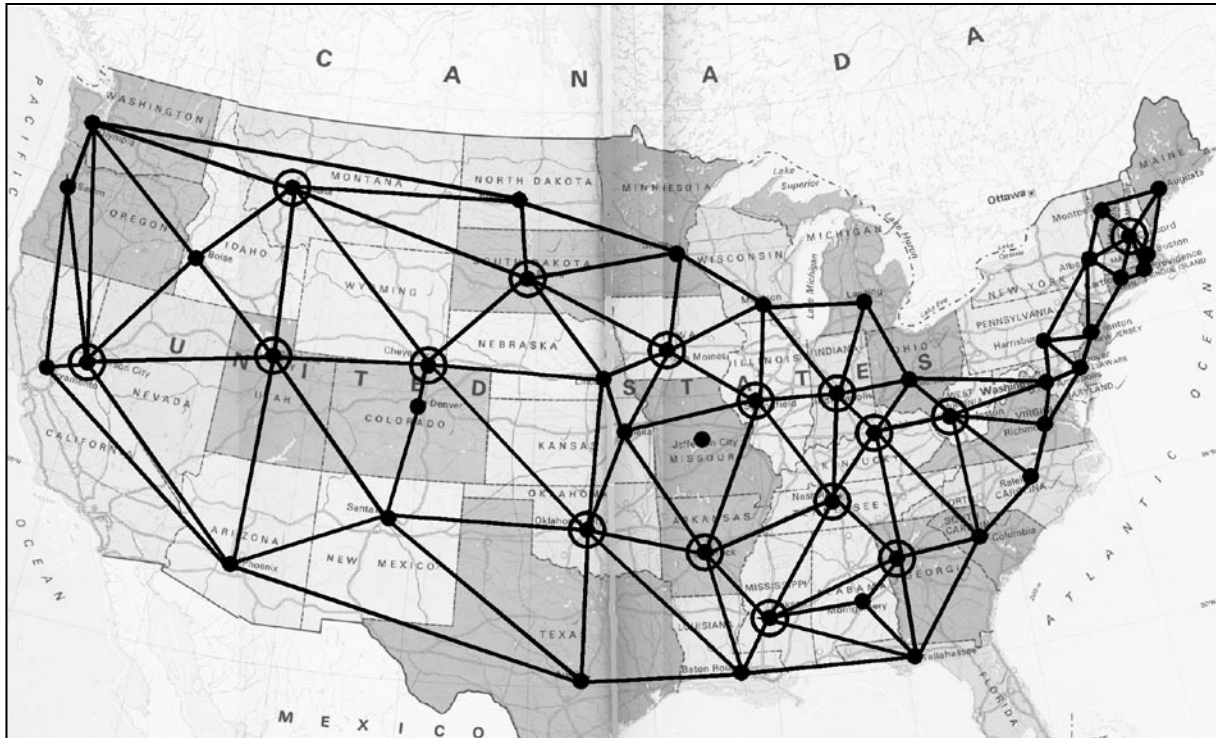


Left: Dividing the surface of a plane of unlimited size into hexagons is a way of distributing *service centres* in such a way that everyone on the plane has easy access to a centre. *Right:* The centres themselves also form hexagons with links to six neighbours

This task confronts many people, including those who decide where to locate schools, pubs, Canadian Tire stores—that sort of thing—especially on prairies.

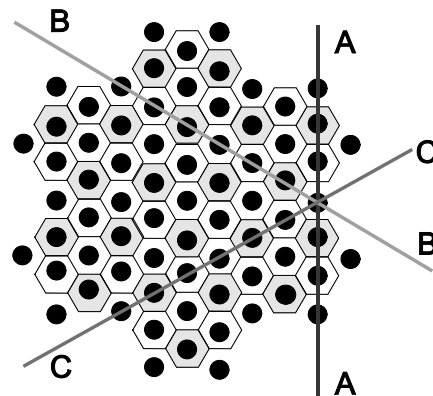
A very popular way of distributing centres is to assign each of them to a hexagonal area, as shown in the diagram, *above*. What's nice about this pattern, is that you can extend the coverage as far as you like in any direction, leaving everyone within easy reach of one of the centres.





State capitals of the United States. All the capitals that are shown as a black dot enclosed by a circle are located with links to exactly six other capitals. Those that do not have a circle, don't miss the target of six by much. Several have links to five capitals. International borders, coasts, and, on the east coast, history, obviously distort the pattern, but the underlying principle is clear. Nobody planned it this way of course, any more than anyone plans where to put holes in rocks.

You'll notice on looking at this pattern, that not only does each centre service its own hexagonal area, but six of the seven centres themselves outline a hexagon, with one of the centres, at its centre, making it a potential "super-centre". Among geographers, Christaller (1933) and Skinner (1964)¹ are famous for noticing such a hierarchical pattern in the distribution of cities (*landstädte*) in southern Germany and of villages in rural China.



When you look at the bigger picture of such a distribution (*right*), the centres appear to run in straight lines. Each of these "lines" is parallel to line AA, line BB, or line CC.

Identifying hexagonal patterns by looking for these linear alignments is usually far easier than looking for the hexagons themselves, especially when they are distorted, mixed with other polygons, and otherwise imperfect, as in the real world they often are.

¹ Brian J.L.Berry, Edgar C. Conkling, D. Michael Ray, *Economic Geography*, pp.379–397, Prentice-Hall, 1987.

The three diagrams *right* for example shows the result of a search for such linear alignments in the locations of the state capitals.

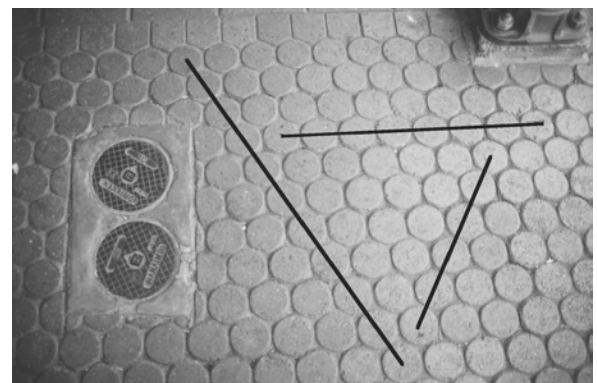
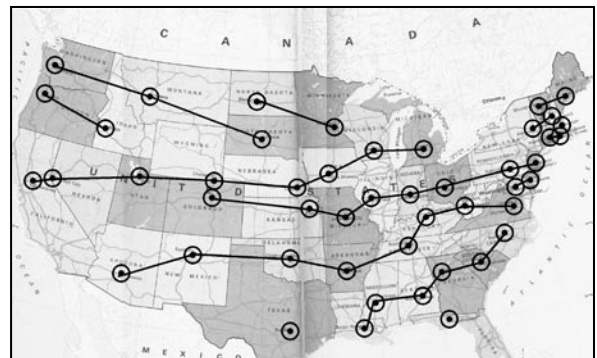
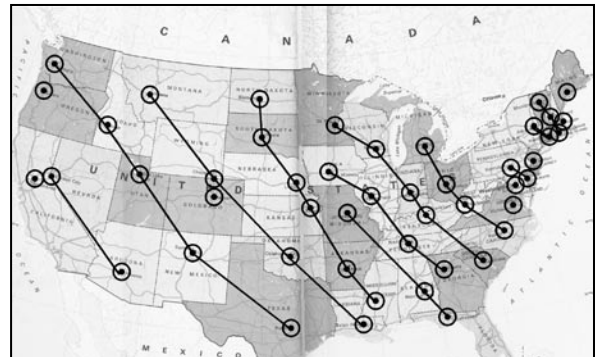
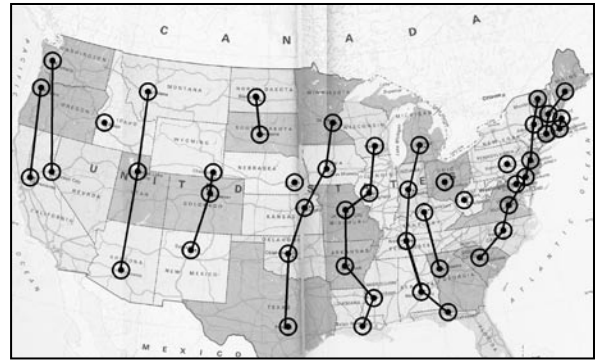
Now, it is of course well known that joining up dots to make a line is a highly subjective process. I always feel that the real test of whether or not such alignments are really “real”, and not just imagined, is to ask a group of children to draw the lines for you. I don’t do this because I like my theory too much to run the risk of having it shown to be nonsense, but there’s nothing to stop you having a go.

OK, now that we’ve taken care of the United States, let’s look at Gabriola’s rocks.

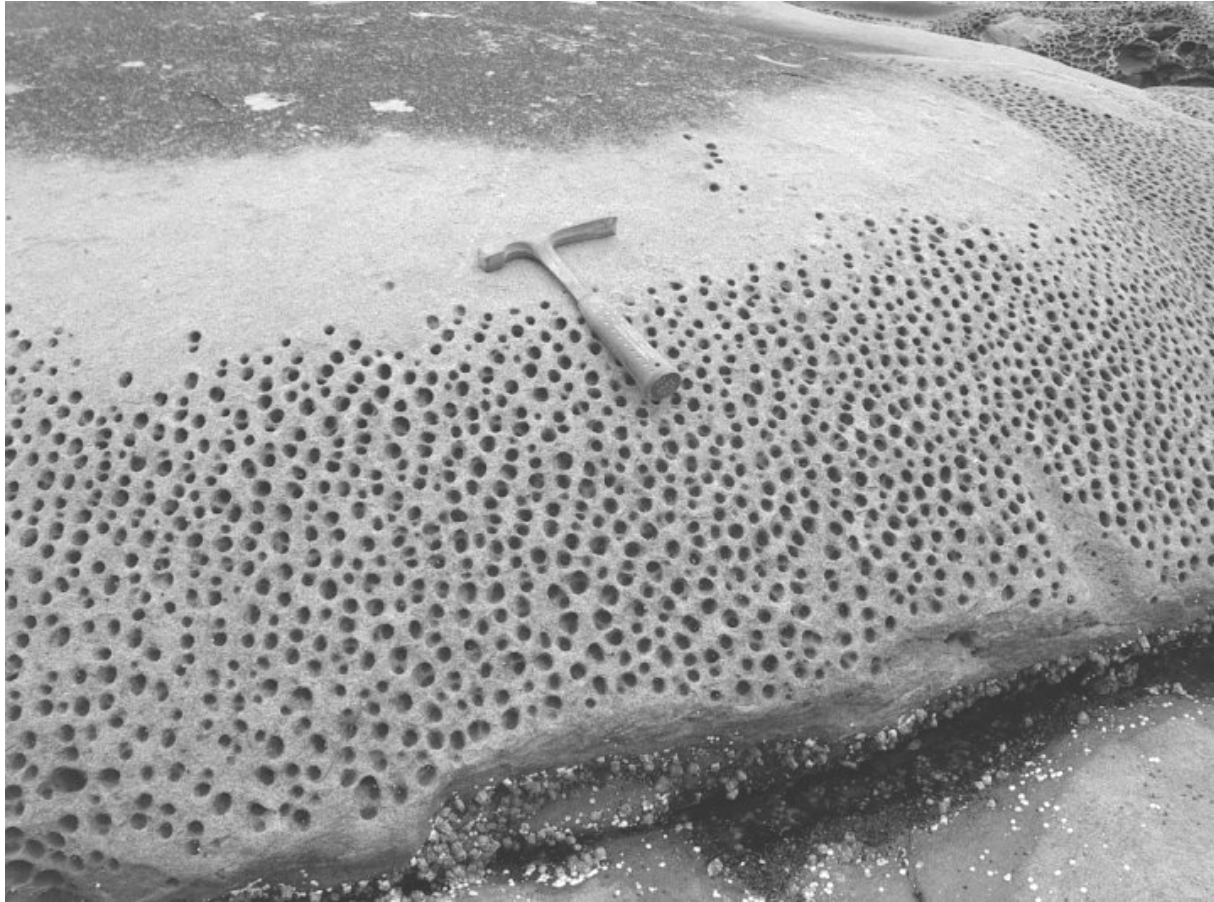
On the next page is a honeycombed rock. At first glance, the holes may appear to be randomly distributed. But are they? Well, no. For starters, there are no holes on the top of the rock, which is a bit odd, isn’t it?

Some people think that this has something to do with the black lichen, which you can see on the top of this particular rock. But I don’t think so. I think it has more to do with the fact that the lichen like rainwater, which gathers on the top, and the holes don’t. Notice the little groove on the side of the rock, on the right. What’s the betting that water runs down that gully and helps keep the gully free of holes?

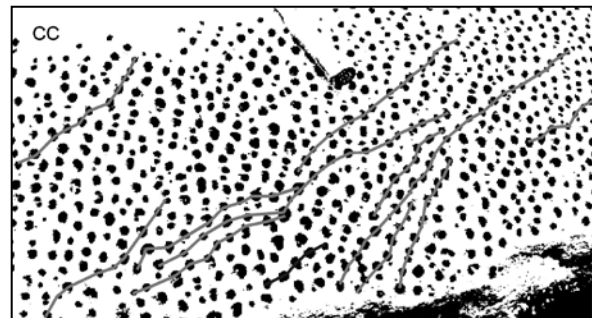
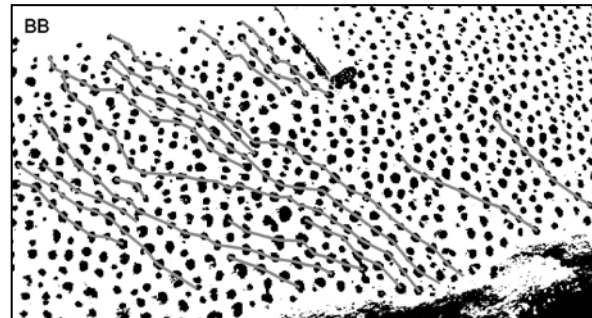
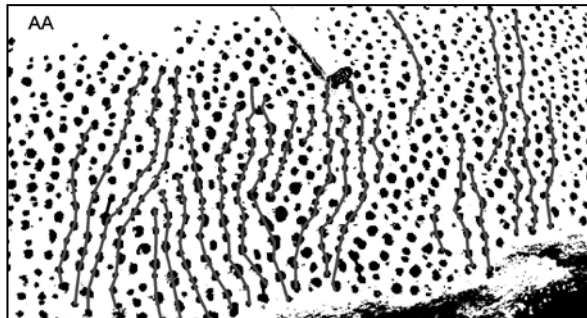
And are the holes in lines? Well I think so. I don’t think the holes are randomly distributed at all. They’re distributed in a hexagonal-like pattern, just like service centres. What *service* do the holes perform? My guess is that the holes allow water trapped *within* the rock to escape when the rock gets hot in the sun. They’re exhaust holes. Each hole relieves the internal water pressure in its immediate vicinity, thereby making it unnecessary to have another hole too close to it. Just like pubs on islands.



Hexagonal paving on Nanaimo’s downtown sidewalks easily passes the three-line test.



Spray formation, Gabriola Island. Courtesy Dr. Steven Earle

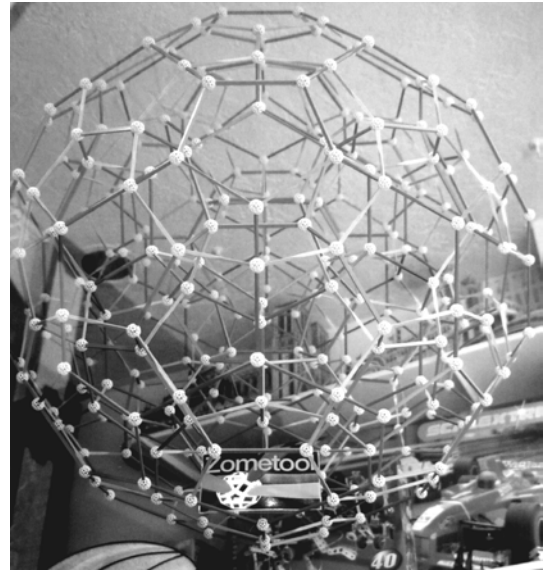


Now you may object that if you look carefully at the pattern of holes in the rock, you don't see perfect hexagons everywhere. And this is fair enough. There are several excuses for this, which I won't go into in detail, but they all boil down to the fact that surfaces in nature are usually far more complicated (and interesting) than a flat sheet of paper. Here's a simple example.

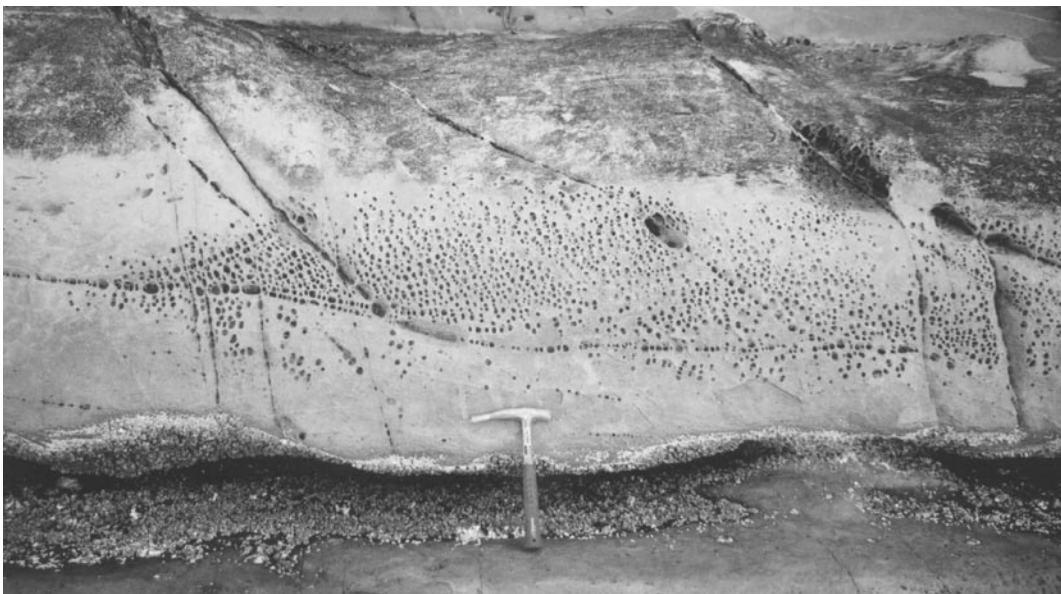
Take another look at the map of the USA again, and note that some of the state capitals have only five links, not six. Now, take a look at the simple geodesic dome shown *top right*. Many of the “centres” on this dome do have six links, but if you look long enough you’ll spot two with only five (*one is on the lefthand side, halfway up*). You just don’t get perfect hexagons on surfaces that aren’t flat.



The picture *opposite right* shows a geodesic dome (made by Zometool) that I spotted in the window of a toyshop in Victoria. It has all kinds of polygons, but the important point is that they are nevertheless all interrelated. And if we can see such patterns in the holes in the rocks, it means the holes are interrelated, and if the holes are interrelated it can only be because they are a property of the rock itself; they are not just the result of random splashes of some corrosive liquid on the surface. Note also, that when it comes to a rock surface, we’re not talking here about the surface being *optically flat*, we’re talking about it being *hydraulically flat*, that is, with a uniform internal water pressure, and the internal water pressure is not something the human eye can see. Note in the picture *below*, that the holes cluster around fractures, and



fractures in sandstone, even those not visible, are often conduits for water.



OK, so the holes provide an exit for water trapped inside the rock when the rock gets hot in the sun. But why doesn't water just seep out through the myriads of minute pores in the sandstone? I don't know why it doesn't, but here's a simple experiment that shows that nature doesn't work that way. It's best done when all members of the family who aren't interested in geology are out of the way.

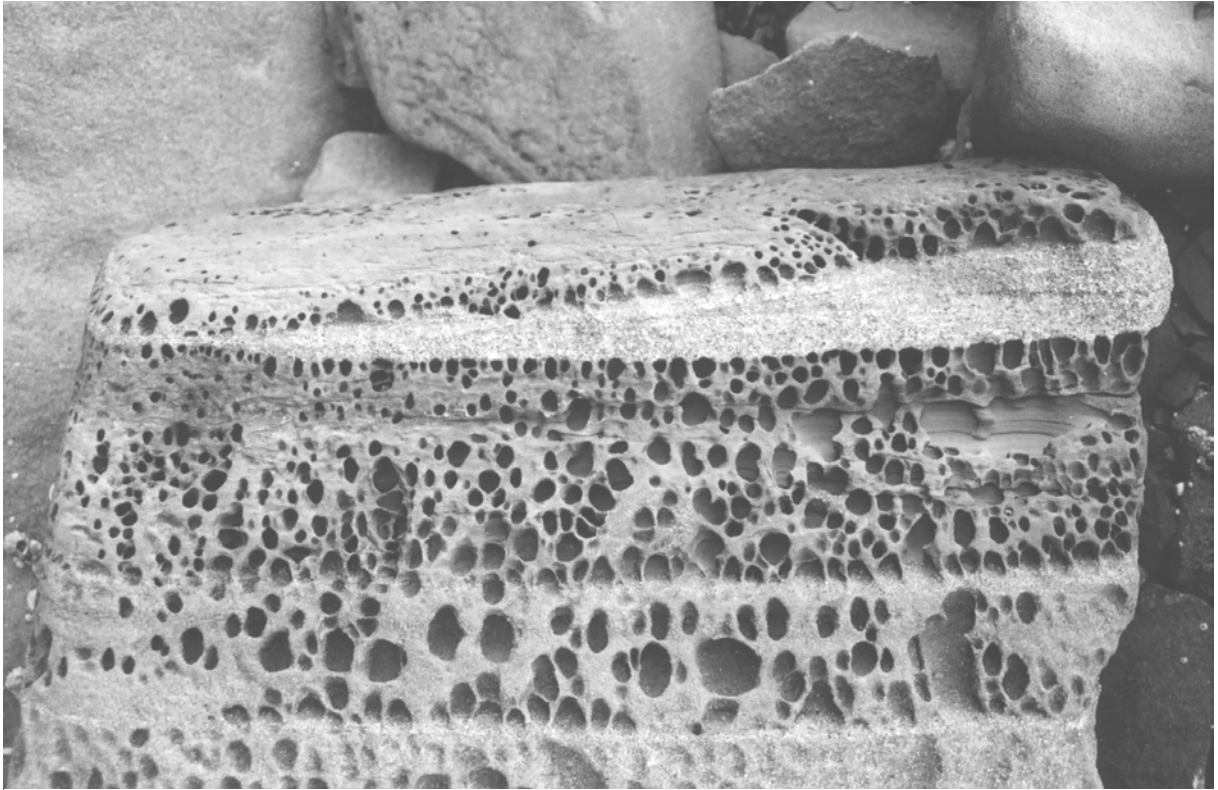
Go to the kitchen and choose the largest fine-meshed sieve you can find. Set it up so you can see its underside. As you can see in the photograph *below*, I used a brick to hold the sieve on the tray of a step-ladder. Now pour in some honey. The stickier kind is best so long as it doesn't contain any sugar crystals. You have to use honey because we want the flow to be laminar, not turbulent, which it would be if we tried to use water.



What you will notice is that the flow divides itself up into several streams spread out evenly over the surface of the sieve. All of the streams are considerably larger than the mesh of the sieve. This is what must happen in honeycombed sandstone.

The sandstone has such a low permeability that water within it behaves as though it were viscous, like honey. Water diffusing from the wet interior of the rock toward the bone-dry evaporation surfaces forms streams (as does spilt water on a concrete slope), each of which is considerably larger in diameter than the pores of the rock. I bet if you could find a way to photograph the honey streams without getting your camera in a mess, you'd find that their distribution on the mesh is similar to the distribution of honeycomb holes on the surface of a rock.





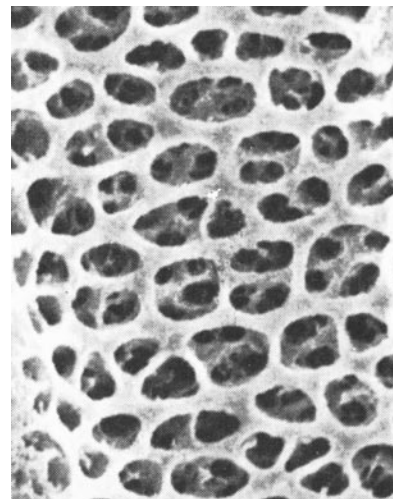
A sandwich of sandstones with different grain sizes. The bright wedge-shaped bed near the top without honeycomb holes is very-coarse sandstone with grains of between 1 and 2 mm.

The size of the holes actually appears to be related to several factors. Honeycombs in “marginal” locations (low rockwater supply, shaded, facing north, or some distance from the sea) always seem to be larger than usual [endnote 6]. Some inland honeycombs are just a single large cavity, and scarcely recognizable as a honeycomb hole. Another factor is the grain size of the sandstone. The photo *above* shows thin beds of honeycombed sandstone, each bed with a different size of grain—and, presumably as a consequence, a different size of honeycomb hole. One wedge-shaped layer of very-coarse sandstone (1–2 mm), near the top, actually has no holes at all!

Now here’s a question for you. Do you see anything unusual about the honeycomb rock shown on the *right*?

Not really?

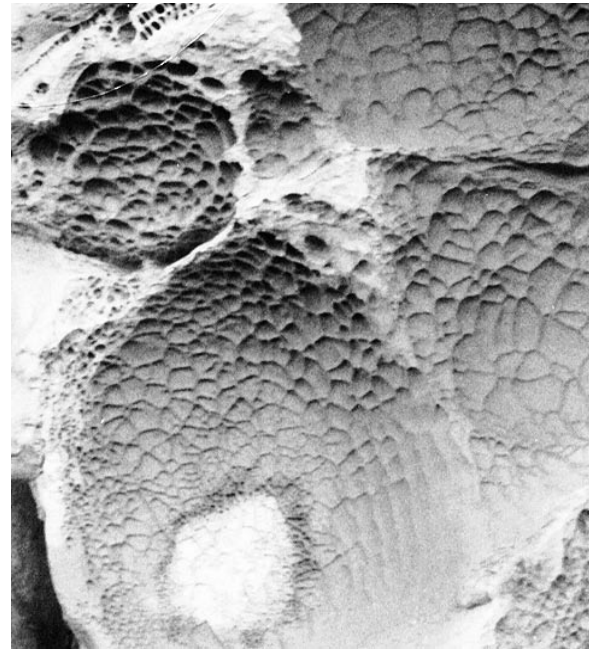
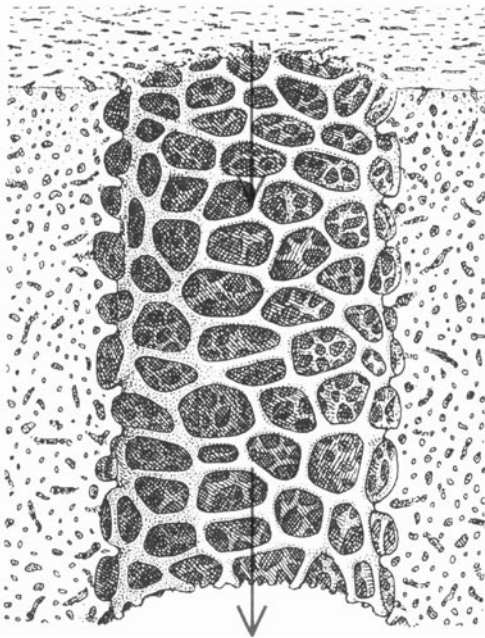
Well, what is unusual about it is that it isn’t a rock at all. It’s a scanning-electron microscope picture of a bird’s lung. Which leads me to the next part of the story....



Birds are thought to have evolved from dinosaurs, appropriately enough given the topic at hand, in the Cretaceous Period, exactly when Gabriola's sandstone rock was formed. The bones of birds are hollow, which reduces their weight. They are also connected to the bird's respiratory system—it's actually possible for a bird to breathe through its bones.

The lungs of birds are different from ours. Instead of air passing into the lungs and then out again, air is drawn directly into two "input" sacs. From there, it is pushed and pulled through the lungs themselves into two "output" sacs, from which the air is expelled. The flow of air through the lungs

is one-way, and is rather like water flowing continuously through a sponge.



Air-tubes (parabronchi) of birds' lungs have a lace-like pattern. The purpose of this is to present as much surface area to the air as possible without obstructing its flow. The holes in the lacework shown here *above left* are about 0.1mm in diameter.

Similar patterning occurs in weathered sandstone, especially when conditions for forming honeycombs are marginal. The photograph (*top right*) shows about 50 feet (15 metres) of cliff on the north coast of Gabriola. Most of these cliffs are honeycomb free, but here and there, there is a large cavity that has honeycomb or lace-like patterns on its inner wall. On the *bottom right* is a close-up of the cavities. The holes in the lacework are roughly 80 mm across on average.

Bird lung pictures are from Knut Schmidt-Nielsen, *How Birds Breathe*, Readings from Scientific American, *Vertebrate Structures and Functions*, pp.161–167, Dec. 1971

The lungs consist of fine tubes (parabronchi), the walls of which are honeycombed. The whole construction is designed to expose as much surface as possible to the air so that oxygen can be absorbed, while at the same time creating as little resistance to the flow of air as possible. Perhaps there's a lesson here. Are the honeycomb holes in rocks designed to create as much evaporation surface as possible, while at the same time decreasing the pressure needed to bring the flow of rockwater to the evaporation surface?

It's the salt

Now, while we have a reasonable hypothesis as to why the holes are distributed the way they are, we haven't explained yet why the escaping water should create holes. The simple answer is that the evaporating water on the surfaces inside the holes leaves behind "salt", and it's the salt that does the damage.

The evidence that salt brought by "rockwater" to the erosion surface causes honeycombing is very persuasive. It provides the following explanations for the observed features of honeycombing:

- honeycombing is most active on south-facing rocks because it is there that evaporation is highest in summer
- it is most active deep inside the rock, not on the more exposed outer surfaces because the source of the salt is inside the rock
- honeycomb weathering only occurs near the sea (at least our kind does)
- the salt deposit on the dried clay in the roofs of galleries occurs on the *inside* of the flakes of clay, not on the *outside*.

Rockwater:

"Rockwater" is a term I use for water that has soaked into the rock through pores and crevices during winter, and is in slow transit to either an evaporation surface, discharge point, or, less likely when the site is near the sea, an aquifer. Rockwater on the coast contains sodium chloride, not because of saltwater intrusion into an aquifer, but because the rain falling on cliffs and beaches in winter is accompanied by sea-spray and saltwater aerosols carried by gale-force winds. Trees may help in this by capturing high-flying spray. I dislike calling this water "groundwater" because that term conjures up far too static an image of well-established zones with varying degrees of moisture saturation. It's also an inappropriate term to apply to individual boulders. In the intertidal (midlittoral) zone, some rockwater may be absorbed directly from the sea at high tide.

The erosion needs no external supply of brine during the summer months because the mixture of sea-spray and rain that has percolated into the rock over winter is the source of the salt.

Technical analysis shows that the walls separating the honeycomb holes are identical to fresh unweathered rock [endnote 1]. There's nothing unusual about them, and they aren't being protected in any way. They remain intact because none of the rockwater reaches the walls; it is instead moving from the interior of the rock to the bottom of the holes, this being the shortest route to an evaporation surface. This process makes the holes deeper.

Chemical analyses that I have done of the soluble salt in the loose sand and silt in the holes show that the salt is not pure sea-salt, as it would be if it were there as a result of saltwater splash [endnote 2]. There is always a groundwater evaporite component.

The backwalls of galleries, despite their “dry” appearance in summer, often show evidence of the presence of rockwater in winter. White evaporite deposits are common, even when the galleries are in sheltered locations and not especially prone to being splashed directly by sea-spray in winter. Vertical-inclined fractures behind the erosion face are an important source of rockwater, especially for galleries like the Malaspina Galleries.

How?

How does salt erode the sandstone? A simple experiment provides a clue.

Take chips of unweathered sandstone and immerse them in brine for 24 hours.

Then take the chips out and let them dry out for another 24 hours.

Then immerse them again, and dry again, and do this for two or three weeks.

What happens is that the brine gets cloudy. At first, clay, and then silt and sand particles accumulate at the bottom of the jar of brine, and the surface of the sandstone acquires that gritty feel that the inside of holes and the backwalls of galleries do.

What was for me a surprise, is that the soaking-drying cycle did *not* initially produce sand. The theory that salt crystals pry apart the particles of sand is wrong. What happens is that the brine impregnates the clay that is bonding and cementing the particles of sand together, and it is this clay that the salt attacks (if that’s the right word, see *endnote 7*). This may explain why if you look for salt crystals with a microscope, as researchers including myself have done, you don’t see any. Possibly the crystals are just too small to be seen with a regular optical microscope.

This experiment by the way works equally well using sodium sulphate (Glauber’s salt)

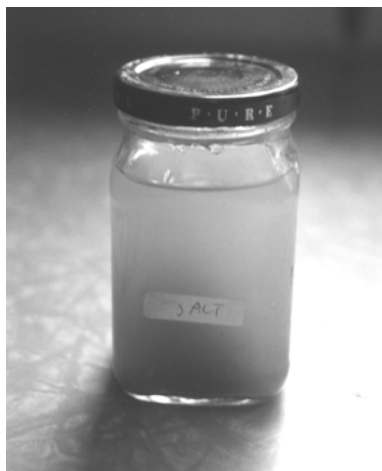


Step 1: *left*, soak in brine for 24 hours.

Step 2: *middle*, Allow to dry for 24 hours.

Step 3: repeat many times.

Step 4: *bottom*, loose sand and clay.



as it does with sodium chloride (table salt), which supports the idea that the weathering is mechanical rather than chemical.²

² Though, as Dr. Steven Earle points out, this should be tried with potassium chloride. If sodium were responsible, honeycombing would be more common.

Soaking, without drying, the rock in some strong solutions of household corrosive chemicals did nothing; with others, a green coloration developed and there were slight signs of weathering, but only after several months [endnote 4].

X-ray diffraction analysis of the clay from the roof of a gallery surprisingly showed that the clay (*kaolinite*) contains lots of calcium sulphate (*gypsum*). Other researchers looking at the weathering of sandstone buildings in cities, have also found *gypsum* in the weathering debris, so maybe it plays a role.

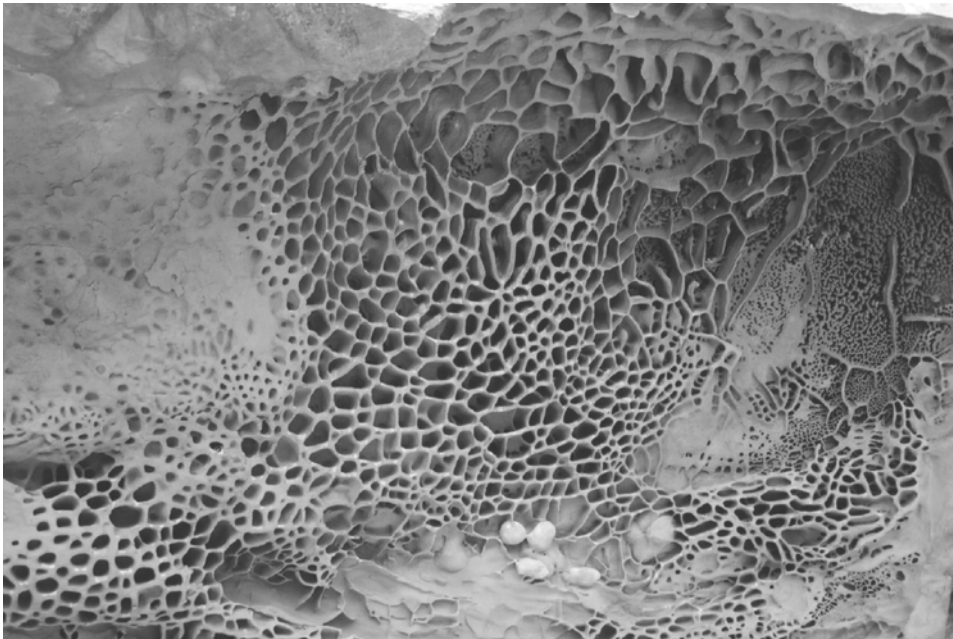
No holes?

One last thing. Why are there no holes in some sandstone? One of the impressive features of the Malaspina Galleries is the roof. It provides a solid platform for the kids to jump off into the sea in summer, and it remains much as it was when the Spanish visited over two hundred years ago. What protects the roof “visor” from weathering in the same way as the backwall of the gallery

below it?

The short answer is that it resists salt-crystallization erosion because the bonding agent for the sand particles is not the original clay, but iron oxide or *hematite*. Soak a piece in oxalic acid if you don't believe me. Oxalic acid is sold in hardware stores for removing rust and bloodstains and cleaning bathroom porcelain—it dissolves iron. Within a month, oxalic acid reduces a small chip of “case-hardened” sandstone to a pile of mud and sand, while having no visible effect on unweathered rock [endnote 4].

The iron comes from iron-rich minerals in the sandstone. When conditions for oxidation are good within the sandstone, these minerals weather to *hematite*, which coats the grains and more firmly cements them together. *Hematite* is very insoluble and so effectively protects the sandstone from further weathering. What's the betting, do you think, that the Island's petroglyph carvers were aware of this? ◇

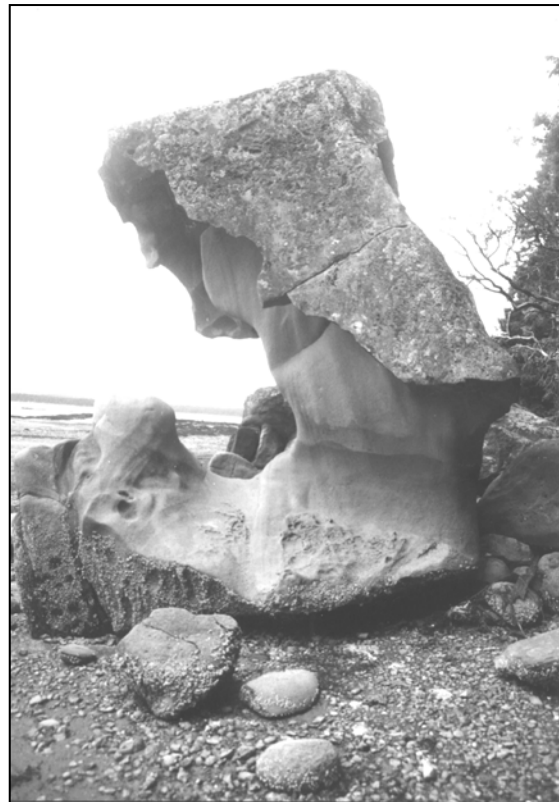


Honeycomb weathering in sandstone cliffs on Valdes Island. Salt encrustation from evaporating water from inside the rock is visible *top left*.

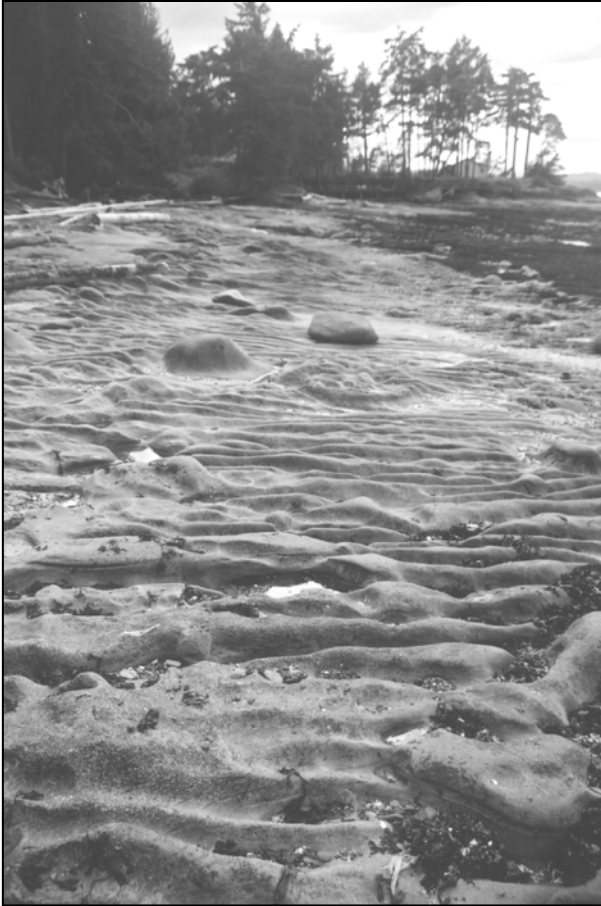


Holes in the mill stone quarry on Gabriola. Am I seeing things, or do I see holes being surrounded by six others? Even old-timers knew about hexagons.

Postcard bought at the former B&K Store at Twin Beaches



Left and right. Case hardening helps preserve the skin of sandstone boulders, but not forever. Rock on the left is in Drumbeg Park; rock on the right is in Descanso Park.



Left: It's not true that the wind and the waves don't ever cause erosion of sandstone of course. This beach at Lavender Bay on the northeast end of Gabriola catches the full force of northwesterly storms blowing down the strait, and the runnels seem to have been created at least in part by the backwash of the surf. The concentration of concretions, which are slightly soluble, is very high here, which might also be a factor.

(Note: this is probably incorrect, for a better explanation, see *SHALE* 10, pp.37-44).



Familiar barnacles on a rock surface. Unlike honeycomb holes, they distribute themselves more or less randomly. I don't think you'll have much luck finding arrays of polygons here.



Holes that only narrowly avoided getting written about. They're in mudrock (silt- or claystone) and were bored by shellfish called *piddocks*, which are common around Gabriola.

ENDNOTE 1—Bulk chemical analyses

Case hardened sandstone compared to unweathered rock:

“hardened-12” sample results obtained by averaging the “hardened surface” Site 1 and Site 2 data from Mustoe, 1982. “Unweathered-12” sample results obtained by averaging the “fresh rock” Site 1 and Site 2 data from Mustoe, 1982. Sandstone from the Chuckanut Formation.

Cavity walls (the thin walls between adjacent honeycomb holes) compared to unweathered rock:

“cavity wall-34” sample results obtained by averaging the “cavity wall” Site 3 and Site 4 data from Mustoe, 1982. “Unweathered-34” sample results are a reference obtained by averaging the “fresh rock” Site 3 and Site 4 data from Mustoe, 1982. Sandstone again from the Chuckanut Formation.

Cation (metal) % weight [% number].				
	unweathered-12	hardened-12	unweathered-34	cavity wall-34
aluminum	39 [52]	41 [51]	41 [50]	44 [51]
sodium	13 [20]	14 [20]	14 [20]	14 [19]
iron	11 [7]	16 [9]	14 [8]	14 [8]
potassium	8 [8]	8 [7]	8 [7]	10 [8]
calcium	7 [6]	8 [7]	9 [7]	9 [7]
magnesium	4 [6]	4 [6]	5 [6]	5 [6]
titanium	1 [1]	1 [1]	1 [1]	1 [1]
manganese	<u>0</u> [0]	<u>0</u> [0]	<u>0</u> [0]	<u>0</u> [0]
	83 %	92 %	92 %	97 %
others	<u>17</u> %	<u>8</u> %	<u>8</u> %	<u>3</u> %
	100 %	100 %	100 %	100 %

All figures rounded to nearest integer.

Comment

Mustoe comments as follows:

“Exposures of Chuckanut arkose [*feldspar*-rich sandstone] in both coastal and inland environments commonly display a hardened surface layer, ranging in thickness from a few millimetres to several centimetres and dark grey or reddish in contrast to the light-coloured unweathered material from which it is derived. Microscopic examination of thin sections and hand specimens indicates the hardened layer results from dissolution of iron minerals, particularly *biotite*, within the arkose. While unaltered *biotite* flakes are visible in fresh rock, this mineral is absent in the hardened zone. Instead, ferric oxides or hydroxides are observed as grain coatings and as interstitial cement. In samples where the hardened layer is well developed, chemical analyses show a small enrichment of iron and aluminum content, but the increased durability of the rock seems to result mostly from the redistribution of these elements rather than from a high degree of accumulation.... Walls separating cavities do not show mineral alteration characteristic of hardened outer surfaces. Microscopic examination of freshly broken specimens shows that even very thin walls are identical in appearance to unweathered rock. *Biotite* flakes show no signs of alteration or dissolution, and interior surfaces of cavities are devoid of iron stains or ferruginous cement. Chemical analyses of samples from a number of sites indicate that cavity walls are identical in bulk composition to fresh rock collected from the same outcrop.”

These observations are consistent with my own observation that “case-hardened” rock readily breaks up in a solution of oxalic acid (an iron solvent), but not in hydrochloric acid (a calcite solvent).

ENDNOTE 2—Honeycomb “salt”

This a record of an attempt to pin down where the “salt” responsible for de-cementing the sandstone in honeycomb holes is coming from. Samples of the weathering debris were collected at three sites. The samples were then leached with de-ionised water and the extract analyzed as if it were groundwater. The three sites were varying distances from the sea.

The results were compared with those obtained for groundwater from observation wells on Gabriola; ordinary seawater; and a white deposit left by groundwater seeping out of a sandstone cliff face, see *endnote 3*.

The results are shown here on three trilinear (Piper) diagrams (Deutsch, 1997) showing:

cation ratios: $[\text{Na}^+ + \text{K}^+]: \text{Ca}^{2+}: \text{Mg}^{2+}$

anion ratios: $\text{SO}_4^{2-}: \text{Cl}^-: [\text{CO}_3^{2-} + \text{HCO}_3^-]$; and

cation/anion ratios: $[\text{Ca}^{2+} + \text{Mg}^{2+}]$ (as % of cations): $[\text{SO}_4^{2-} + \text{Cl}^-]$ (as % of anions).

Percentages were calculated in terms of the number of ions, atoms, or molecules present, not by their weight.

Trilinear diagrams show the relationships between different water samples in a very visual way—it is not necessary to study the details of the data in order to be able to classify the groundwater. White *et al.* (White, 1963) provide an extensive compilation of groundwater analyses from a wide variety of aquifer host rocks.

Measuring carbonate and bicarbonate anion concentrations require a special technique that was not available at Norwest Labs, so instead, the value was calculated from the cation and other anion concentrations on the basis that the solution must be electrically neutral overall, and bicarbonate is always a major constituent of groundwater.

Groundwater

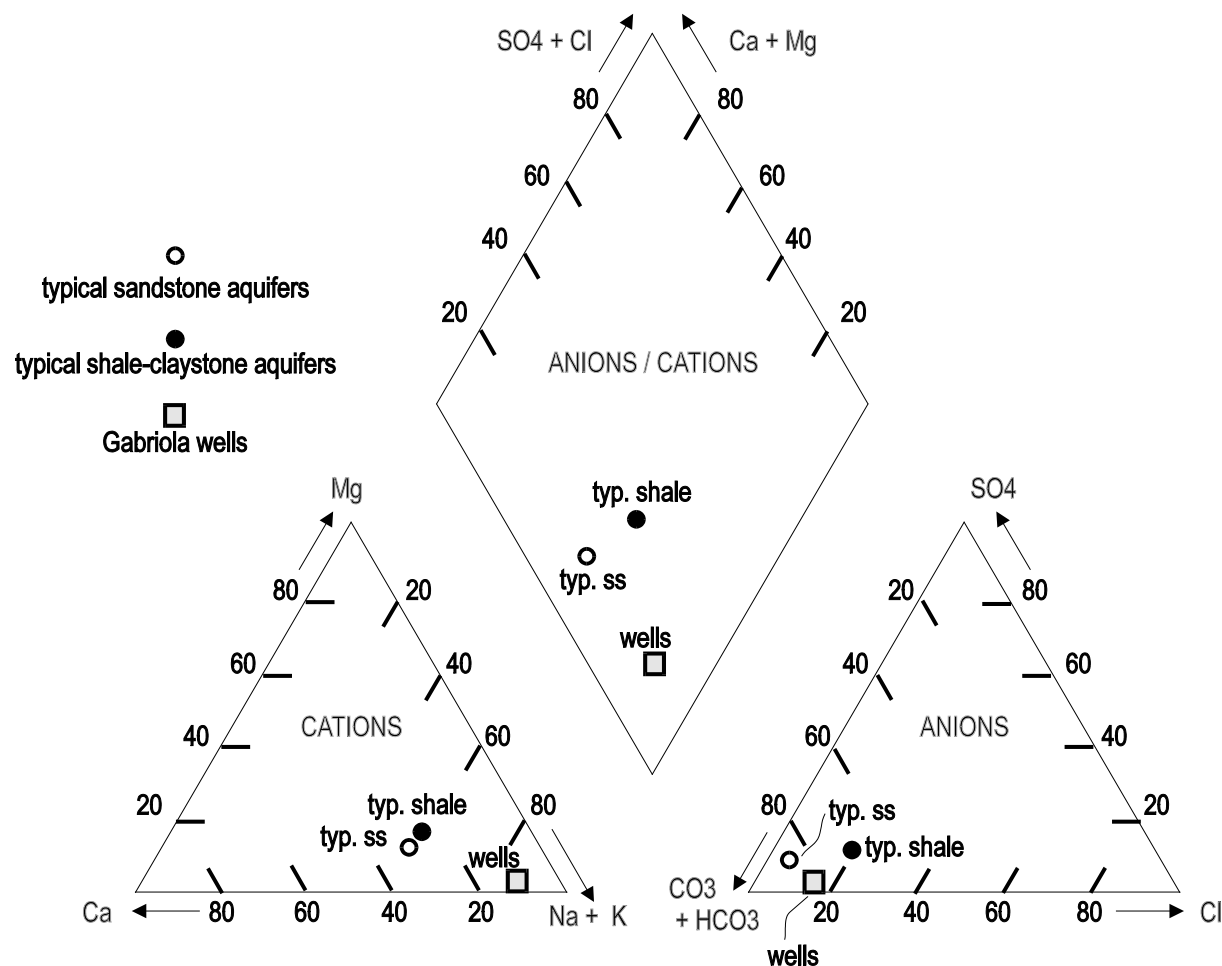
The “groundwater” result was obtained from calculations based on published data (Piteau, 1993). Averages were taken of 13 arbitrarily-chosen wells on Gabriola, including five observational wells maintained by the provincial government.

Gabriola wells: dissolved cation and anion % weight [% number].

	cations		anions
sodium	76 [84]	bicarbonate	62 [59]
calcium	17 [11]	carbonate	20 [19]
magnesium	4 [4]	chloride	9 [14]
potassium	<u>1</u> [1]	silicate	6 [4]
	98.2 %	sulphate	<u>3</u> [4]
iron	1.3		99.9 %
manganese	0.2	fluoride	0.1
aluminum	<u>0.2</u>		<u>100.0 %</u>
	99.9 %		

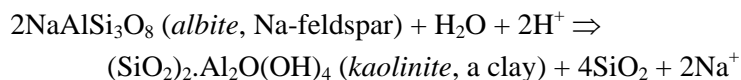
Figures for individual major components are rounded.

Two “benchmark” results are also included. These are figures obtained by White *et al.* for sandstone aquifers and shale/claystone aquifers (Deutsch, 1997).



Comment

The composition of Gabriola well-water is not too different from the typical pattern for sandstone and claystone aquifers. There is more sodium than usual (Earle, 2004), possibly due to remnant seawater in the rock (Allen, 2001), and also as a weathering product of *albite* which is commonly detected in X-ray diffraction analyses of the clay of Nanaimo Group sediments:



The presence of sodium in Gabriola groundwater means that sodium is not a particularly good indicator of the presence of seawater. It also means that whatever is de-cementing the sandstone within honeycombs is unlikely to be sodium alone, because otherwise honeycombing would be more widespread.

Site 1

The first sample was collected from the floor of a very marginal honeycomb site, almost one kilometre from the sea in a forested area facing southwest. The “honeycomb” was a large single cavern. The sample was loose dry sand, silt, and clay.

Gabriola Island (445650,5442550). (Sample 04-01, Gabriola I., Geoffrey Fm.). Norwest Labs File: 251521-1.

Site 1: distilled water leach: cation and anion % weight [% number].

	cations		anions
sodium	4 [6]	bicarbonate	7 [10]
calcium	80 [73]	carbonate	- [-]
magnesium	12 [18]	chloride	5 [11]
potassium	<u>3</u> [3]	sulphate	<u>88</u> [79]
	99.2 %		100.0 %
aluminum	0.3		
iron	0.2		
manganese	0.0		
strontium	<u>0.3</u>		
	100.0 %		

Figures for individual major components are rounded.

Site 2

The second sample was collected from the roof of a gallery. Although close to the sea, the sample was taken from a spot within the gallery very sheltered from rain and salt-spray. The sample was dry sand, silt, and clay that was barely hanging on to the surface. It was removed with fingertips.

Gabriola Island (437600,5447350). (Sample 04-02, Gabriola I., Gabriola Fm.). Norwest Labs File: 251521-2.

Site 2: distilled water leach: cation and anion % weight [% number].

	cations		anions
sodium	40 [50]	bicarbonate	7 [7]
calcium	44 [32]	carbonate	- [-]
magnesium	14 [16]	chloride	39 [61]
potassium	<u>2</u> [2]	sulphate	<u>54</u> [32]
	99.4 %		100 %
aluminum	0.1		
iron	0.1		
manganese	0.0		
strontium	<u>0.4</u>		
	100.0 %		

Figures for individual major components are rounded.

Site 3

The third sample was taken from the floor of a deep, fist-sized, honeycomb hole in a rock on the beach. The rock was a few metres above the high-water mark, and fairly exposed to saltwater-splash, though dry, and moderately sheltered from anything but driving rain. The sample was loose dry sand, silt, and clay.

Gabriola Island (444000,5442200). (Sample 04-03, Gabriola I., Northumberland Fm.). Norwest Labs File: 251521-3.

Site 3: distilled water leach: cation and anion % weight [% number].

	cations		anions
sodium	59 [69]	bicarbonate	5 [4]
calcium	26 [17]	carbonate	- [-]
magnesium	8 [9]	chloride	54 [75]
potassium	<u>7</u> [5]	sulphate	<u>41</u> [21]
	99.3 %		100 %
aluminum	0.3		
iron	0.1		
manganese	0.1		
strontium	<u>0.2</u>		
	100.0 %		

Figures for individual major components are rounded.

Seawater

The “seawater” result was obtained from the “textbook” composition of seawater.

Seawater: cation and anion % weight [% number].

	cations		anions
sodium	84 [86]	bicarbonate	1 [1]
calcium	3 [2]	carbonate	- [-]
magnesium	10 [10]	chloride	87 [94]
potassium	<u>3</u> [2]	sulphate	<u>12</u> [5]
	99.9 %		100 %
aluminum	0.0		
iron	0.0		
manganese	0.0		
strontium	<u>0.1</u>		
	100.0 %		

Figures for individual major components are rounded.

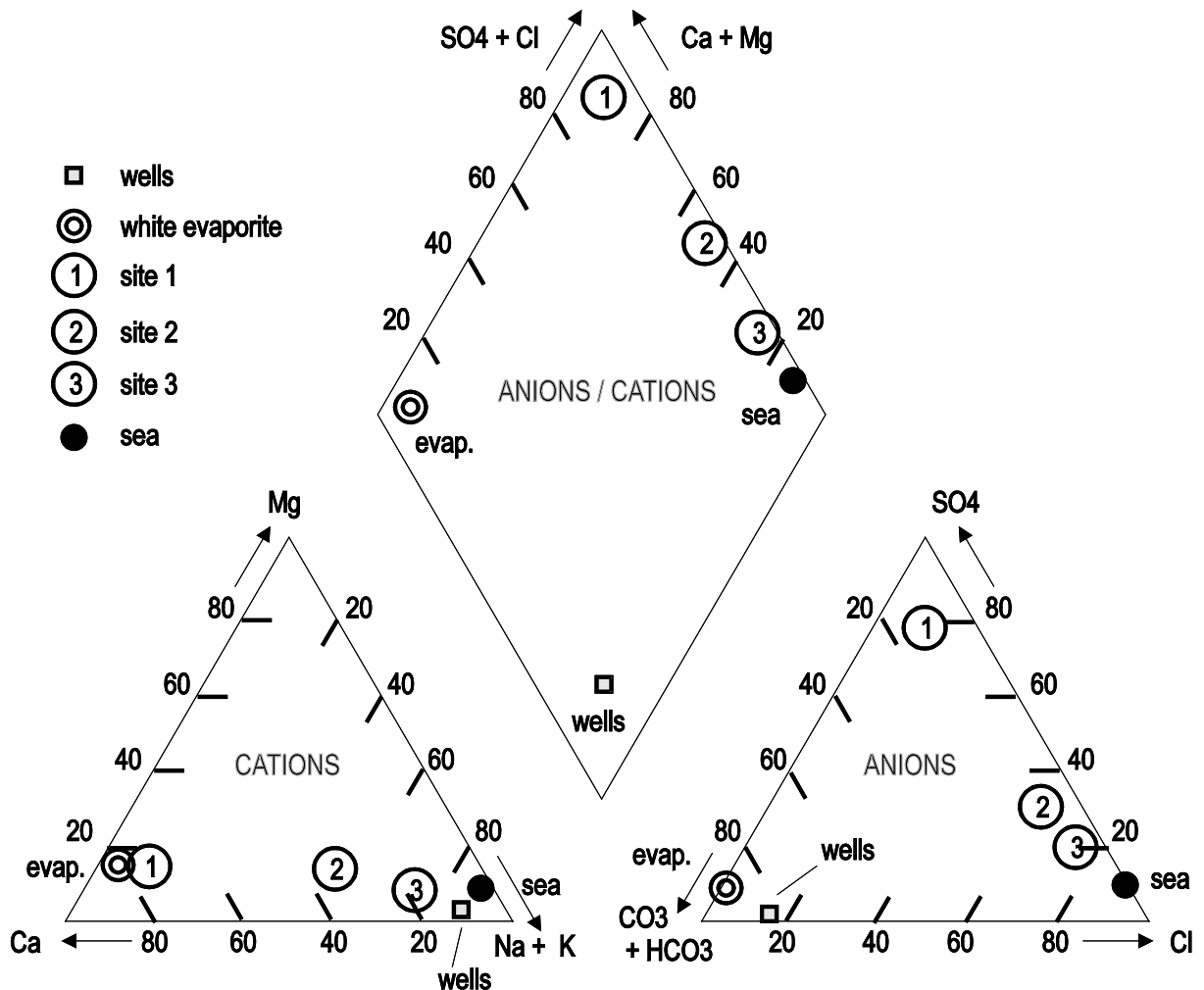
White evaporite

See *endnote 3*.

White evaporite: cation and anion % weight [% number].

	cations		anions
sodium	2 [3]	bicarbonate	83 [93]
calcium	78 [74]	carbonate	- [-]
magnesium	8 [13]	chloride	0 [0]
potassium	<u>2</u> [2]	sulphate	<u>17</u> [7]
	90.3 %		100 %
aluminum	3.1		
iron	5.6		
manganese	0.3		
strontium	<u>0.7</u>		
	100.0 %		

Figures for individual major components are rounded.



In the first trilinear diagram showing cation ratios (bottom left):

- the white groundwater evaporite appears in the bottom lefthand corner. This is because it is rich in calcium
- well-water and seawater appear close together in the bottom righthand corner. This is because both are high in sodium
- the three sites are strung out along the bottom of the diagram, indicating increasing amounts of sodium and decreasing amounts of calcium. Site 1, the marginal honeycomb site, most closely matches the groundwater evaporite; Site 3, the site on the beach, most closely matches seawater.

In the second trilinear diagram showing anion ratios (bottom right):

- well-water and white groundwater evaporite appear close together in the bottom lefthand corner. This is because both are relatively high in carbonates
- seawater appears in the bottom righthand corner. This is because it is rich in chloride

- the three sites are strung out along the righthand side of the diagram, indicating decreasing amounts of sulphate, and increasing amounts of chloride.

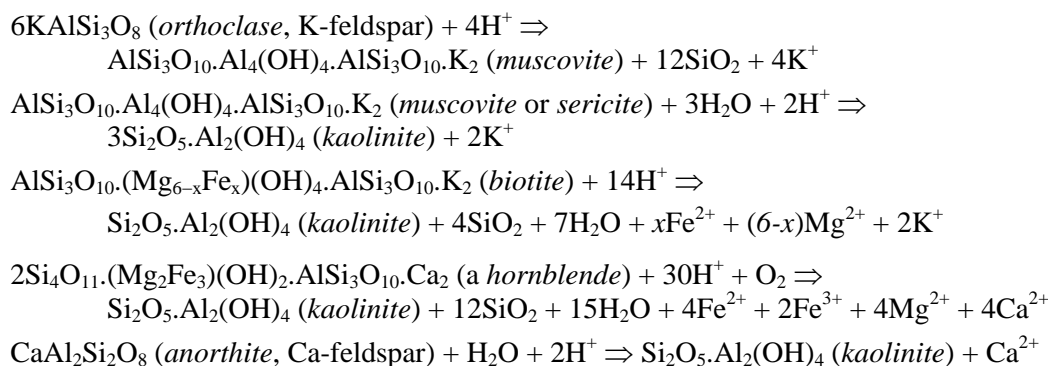
In the third trilinear diagram showing anion/cation ratios (upper centre):

- white groundwater evaporite appears on the middle left. This is because it lacks chloride anions, and is rich in calcium and magnesium
- seawater appears on the middle right. This is because it is rich in chloride anions, but lacks calcium and magnesium
- well-water appears at the bottom. This is because it lacks sulphate and chloride anions, and lacks calcium and magnesium
- Site 1, the marginal honeycomb site, appears at the top. This is because, unlike the evaporite, it does not lack chloride anions; yet, is rich in calcium and magnesium
- Site 3, the site on the beach, again most closely matches seawater. The calcium and magnesium proportion is depressed by the presence of sodium
- Site 2, the gallery roof site, sits midway between the other two sites.

An analysis of the ratios of various cations shows similar differences to those exhibited in the trilinear diagrams. In the table below, s1 = Site 1, and so on.

	most	cation ratios % by number present				least
$K^+ / (K^+ + Na^+)$	ev. = 34	s1 = 34	s3 = 6	s2 = 3	sea = 2	well = 1
$Ca^{2+} / (Ca^{2+} + Na^+)$	ev. = 96	s1 = 93	s2 = 39	s3 = 20	well = 11	sea = 2
$Mg^{2+} / (Mg^{2+} + Na^+)$	ev. = 81	s1 = 77	s2 = 25	s3 = 11	sea = 10	well = 5
$Ca^{2+} / (Ca^{2+} + Mg^{2+})$	ev. = 85	s1 = 80	well = 72	s3 = 67	s2 = 66	sea = 16

As a general rule, potassium and magnesium in soil derive chiefly from the dissolution of *orthoclase*, *biotite*, and *hornblende*. *Plagioclase (anorthite)* is the principle source of calcium (Bowser, 2002).



Comment

The results clearly show that the salt leached from the loose deposits of sand is neither evaporated seawater nor evaporated groundwater alone, but a mix of the two. It is not possible to say that the results show conclusively that the mix was arrived at by groundwater and seawater travelling through the rock together, but it does seem likely that this is so, and certainly so at the inland Site 1.

Other researchers have remarked on the “mixed” nature of the water-soluble salts in the sand deposits in honeycomb holes. In his 1982 paper, Mustoe makes the following comments:

“Samples collected in late summer after several weeks of calm weather are similar in action content to samples collected from the same site during an autumn storm characterised by strong winds. Thus deposition of salts by wave splash is a continual process rather than a result of episodes of unusually strong wave action.”

My own interpretation of this observation would be that the deposition is not by wave splash at all.

“Weathered debris from areas not exposed to wave splash have much lower concentrations of soluble Na^+ , but other cations are present in amounts similar to samples from honeycomb cavities. Soluble cations from inland sites probably represent elements released by dissolution of constituent minerals....”

“Relative abundances of Na^+ , K^+ , Ca^{2+} , and Mg^{2+} in samples from honeycomb cavities are somewhat variable, and do not always correspond closely to the ratio of these elements in seawater. To some extent these cations may represent dissolution of minerals, but some cavities contain shreds of seaweed, wood fibers, mollusc shell fragments, and organic debris introduced by wave splash and wind action; the material probably makes a contribution to the cation content.”

Bearing this in mind, I took care not to collect “contaminated” samples. That this does nothing to reduce the variability, is evidenced by the results shown in the trilinear diagrams. Again, these observations are consistent with the hypothesis that the water in the honeycomb is primarily “salty groundwater” (rockwater), not sea splash.

ENDNOTE 3

Groundwater evaporite analysis

Groundwater seepage is often marked on cliff faces by a white deposit, not to be confused with whitish dust lichen (*Lepraria* sp.), or bird excrement. Similar deposits are sometimes seen on the sides of sandstone boulders, indicating that these were formerly fracture planes. The “white stuff” (efflorescence) is also seen in dry locations beneath large boulders and inside rock cavities. Knowing what these deposits are might tell us something about the way the rocks are weathered.

Collecting enough deposit for an analysis was difficult because it is often little more than a stain. This problem was solved by analysing both collected scrapings of the deposit, and the host rock itself, thereby giving us a basis for compensating for the “contamination”. The contamination was taken to be the amount that reduced the concentration of at least one of the thirty-three measured concentrations of metals to zero after compensation. The hand sample reacted strongly to cold, dilute HCl, indicating CaCO_3 .

The sample collection site was Valdes Island (448600,5440350). (Sample 02, Valdes I., Geoffrey Fm.). Norwest Labs File: 251521-4 (deposit), 251521-5 (host sandstone). No active honeycombing.

Cation-element % weight [% number]. Strong acid extractables.

	white deposit	sandstone	corrected white deposit	
calcium	76 [71]	3 [3]	78 [74 as Ca ²⁺]	
magnesium	9 [14]	5 [8]	8 [13 as Mg ²⁺]	
iron	6 [5]	12 [8]	6 [4 as Fe ³⁺]	
aluminum	4 [5]	7 [10]	3 [4 as Al ³⁺]	
sodium	2 [3]	0 [1]	2 [3 as Na ⁺]	assuming 10%
potassium	2 [2]	2 [2]	2 [2 as K ⁺]	contamination
strontium	1 [0]	0 [0]	1 [0 as Sr ²⁺]	of deposit with
manganese	<u>0</u> [0]	<u>1</u> [0]	<u>0</u> [0 as Mn ²⁺]	sandstone
	100 %	30 %	100 %	
others	* <u>0</u> %	** <u>0</u> %	<u>0</u> %	
	100 %	30 % (rel. to deposit)	100 %	

Percentages of anion-elements on the same basis were:

	white deposit	sandstone	corrected white deposit
carbon (<i>calculated, see text</i>)			28 [88 in CO ₃ ²⁻]
sulphur	6 [7]	0 [0]	6 [7 in SO ₄ ²⁻]
phosphorus	4 [5]	0 [0]	4 [5 in PO ₄ ³⁻]
titanium	0 [0]	1 [1]	0 [0 in TiO ₃ ³⁻]
silicon	0 [0]	0 [0]	<u>0</u> [0 in SiO ₄ ⁴⁻]
			38 %

* Ba > Zn > Cr > V > Ni > Cu > Li > As > Co > Sn > U > Se > Cd > Sb = Bi > Mo > Be = Pb = Th = Zr > Ag

** Ba > V > Zn > Cr > Li > Ni > Cu > Co > Zr > Sn > As > Th > U > Pb = Se > Sb = Bi > Be > Mo > Ag > Cd

Figures for individual major components are rounded.

Anion concentrations were not measured; however, the content of sulphur, phosphorus, titanium, and silicon was. If we *assume* that these are present as SO₄²⁻, PO₄³⁻, TiO₃³⁻, and SiO₄⁴⁻ and that the missing anion required for electrical neutrality is CO₃²⁻, then the number of anions present per 100 cations (column in [] on the far right of the table) is 88 CO₃²⁻, 7 SO₄²⁻, and 5 PO₄³⁻.

Comment

The white deposit is thus likely to be at least 70% CaCO₃ (*calcite*) with some 10% CaMg(CO₃)₂ (*dolomite*) or MgSO₄.nH₂O (*epsomite etc.*), CaSO₄.nH₂O (*gypsum etc.*), and minor amounts of sulphates, and phosphates of iron and aluminum (*alunogen*, Al₂(SO₄)₃.nH₂O, perhaps). Chloride, Cl⁻, was not measured, making it impossible to comment on the nature of the sodium and potassium minerals. Phosphates commonly have an organic origin. The presence of ferric sulphate might explain the pale pink colour sometimes seen, although *dolomite* can also be pink.

Methods and acknowledgements

The procedures were: STRONG ACID EXTRACTABLE: One gram of sample leached with 1.5mL HCl and 3.5mL HNO₃ at 90°C for 1 hour (BC MOE SALM method). No HF was used. Then analyzed by ICP (inductively coupled plasma) for metals. Chemical analyses, not all routine, were

done by Norwest Labs of Surrey BC, and I am grateful to Bill Warning and John Davidson for their help in doing these.

ENDNOTE 4—De-cementing agents

Some “garden-shed” experiments were made to find out what de-cements sandstone. Samples were chips of rock weighing about 10 gm., and the lab glassware was a set of tea-light glasses.

1. **Soaking in water:** This was the control experiment using unweathered sandstone. After soaking in pure water for about two months, the rock showed a slight change in colour from grey to buff, but remained intact.

2. **Freeze-thaw cycle:** The unweathered sandstone was put in the freezer for about 12 hours and then soaked in water for 12 hours. This was repeated for a couple of weeks. This was a moderately successful way of breaking up the sandstone. The first evidence of de-cementation was the water going cloudy. After a few more days, micro-cracks became visible and small chips started breaking off. It didn't seem however that individual grains of sand were being loosened in the way that they are in honeycomb holes.

3. **Salt soak & dry cycle:** The unweathered sandstone was soaked in a strong brine (sodium chloride) for a couple of days, and then put in a warm oven to dry out for a few hours. This was repeated four or five times (until my wife came home). Nothing happened.

A modified version of this experiment was tried for about three months. Every day the sample was alternately removed from the solution and allowed to dry out for 24 hours, and returned to the solution to soak for 24 hours. Both sodium chloride and sodium sulphate were tried. This was more successful. After a few weeks, both solutions went murky and the samples acquired a loose gritty feel. The sample immersed in sodium chloride underwent some surficial colour change, going brown in places. The de-cementation rate was not startlingly high but it was unmistakable and continuous.

4. **Acids and alkalis:** Strong solutions of common corrosive chemicals such as oxalic acid, hydrochloric (muriatic) acid, CLR (calcium–lime–rust) cleaner, and sodium hydroxide (lye or caustic soda) all had a similar effect on unweathered sandstone. The solutions turned yellowish and, after several weeks, small flakes were seen breaking off here and there. The samples eventually disintegrated, but the process was very slow and judged to be unlikely to occur in nature as such strong solutions were used. The oxalic acid solution rapidly disintegrated “case-hardened” sandstone, but the hydrochloric acid didn't, which rules out the possibility of *calcite* being the cement.

ENDNOTE 5—Honeycomb weathering—observations

The most striking characteristic of the sandstones in the Nanaimo Group formations is their weathering pattern on exposures that are close to the sea. Often called “honeycomb weathering” or *tafoni*, the erosion of the sandstone takes many strange and wonderful forms including large single cavities; arrays of small closely-packed holes; lattice and lace-like patterns; fretting; and large “galleries” like Gabriola's tourist attraction, the Malaspina Galleries.³

The common feature of all these forms is that the sandstone inside the cavities in the rock is being de-cemented while at the same time the outer surfaces exposed to the wind and rain remain durable and for the most part intact. The difference between surfaces that are being eroded inside the cavities, and those that are on the outside and are not, is readily apparent:

³ The Malaspina Galleries appear in official charts, topographical maps, and gazetteers as the “Galiano Gallery”; however, this name is not in common usage in the Gulf Islands.

The **erosion surfaces** in summer appear fresh, clean, and dry; light in colour; and covered with grit. Running a finger lightly across the surfaces never fails to dislodge a few grains. The erosion surfaces are seldom below the supralittoral fringe (splash zone). Lichens and algae are rarely found on them.⁴ The erosion surfaces, particularly those forming the roofs of larger cavities, may be caked with friable, gritty, dried-out mud. Minor patches of thin coatings of evaporite (white) are not unusual.

In contrast, the **“case-hardened” surfaces** are smooth, mostly unpitted with no loose surface grit; characteristically darker in colour; no evaporite unless obviously from a recent tide in summer; fully exposed to the rain; and often the host of black crustose lichens that are dormant in summer, or, at the intertidal level, the attachment surface of barnacles and seaweeds. These surfaces frequently preserve the original profiles of boulders and cliffs, while the honeycombed inside of the rock has the appearance of having “rotted” away.

Environmental factors conducive to honeycombing

The commonly observed environmental factors that appear to promote honeycombing are:

- proximity to the sea. Honeycombing always occurs along the shore. The furthest away from the shore that any trace of honeycombing was found during the study was about one kilometre
- lack of wave action. Contrary to a persistent popular theory on the cause of honeycombing, there is abundant evidence that being washed by waves or regularly doused in sea spray prevents, not causes, honeycomb weathering. Erosion surfaces are only rarely populated by the barnacles or periwinkles, and when they are, they are clearly not the main site of the weathering.
- lack of exposure to rain. There is abundant evidence that being exposed to rainwater hinders the development of honeycombing. Marvellous honeycombs often form on the roofs and backwalls of deep cavities in places least likely to be reached by rain. In this area, surfaces at the top of the supralittoral fringe and landward that are washed by winter rain attract black crustose lichens. These are probably *Verrucaria maura* and other species, which are common throughout the Pacific Northwest. As a general rule, surfaces covered with black crustose lichen are not honeycombed. It is particularly noticeable that the tops of boulders on the beach are often black with lichen because rainwater gathers there. These tops remain almost free of honeycombs, while the near-vertical surfaces around the sides are eroded away.
- sun. The “best” honeycombs seem always to occur on the south and southwest facing shores of the islands.⁵ The northeast side of De Courcy is almost devoid of honeycombing; yet, there are spectacular formations along the side facing Vancouver Island.

⁴ Lichens are sometimes seen inside cavities, but these surfaces appear “old” and no longer active, or they are inside honeycombs of the “midlittoral” variety.

⁵ I say “southwest” because observers often mention this, but no statistical analysis was done to see if it is true. If confirmed, a possible explanation is that southwest facing vertically-inclined surfaces both capture summer sunshine and avoid getting washed down by rain, which is often driven in from the southeast.

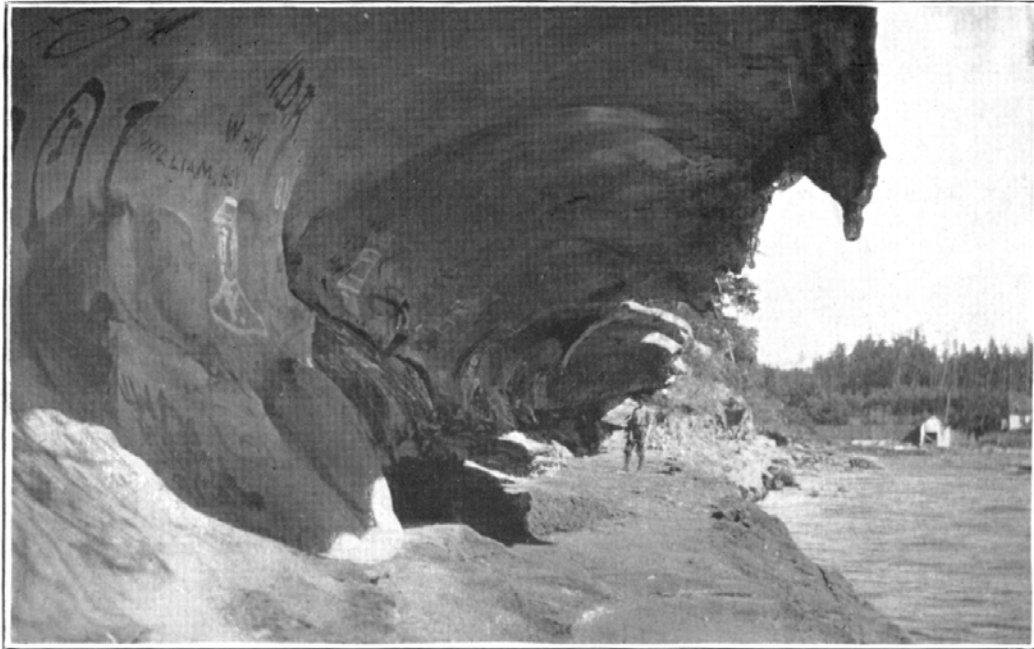


Plate III.—Malaspina gallery, showing the effect of wind and wave erosion on a sandstone of the Nanaimo series, its current having been loosened by the solvent action of the salt-water spray.

Photograph with its original caption by Charles H. Clapp, 1912



"It's-due-to-the-wind-and-waves" has been a popular explanation for the formation of *tafoni*, particularly large holes and galleries like the Malaspina Galleries, for many years, above (Clapp, 1912) and left (notice 2003).

The question is however, if it is the work of the wind and waves, why don't the "best" honeycombs form in the windiest and most wave-washed places? For example, the only honeycombs I've seen in Sandwell Park, which is on the north side of Gabriola, is at the top of a forested cliff, 56 metres above the beach. Why only there? The waves don't often get that high. True, the floor of the Malaspina Galleries is sometimes covered by winter-solstice spring tides, but the backwalls of the galleries are, as Ted Wilson notes, very rarely, if ever, exposed to surf.

ENDNOTE 6—Marginal and paleo- honeycombing

In environments only marginally favourable to honeycombing, it is noticeable that the “preferred” form of weathering is the large isolated cavity. In some cases, the inner wall of the cavity is mildly honeycombed (lattice patterns), but in the most borderline cases, even this is absent and there is just a hole or cave with loose sand on its floor. That weathering is still active can be confirmed by running a finger over the inner walls and roof of the cavity. This readily loosens grains of sand in a way that does not occur on other nearby surfaces.

“Marginal” honeycombing conditions are those with one or more of the following characteristics:

- facing north with the proviso that north-facing sites that are sheltered by trees are practically never honeycombed
- facing south and sheltered by trees
- some distance vertically or horizontally from the surface of the sea, but usually still within sight of it unless the rock is facing south or southwest.

White efflorescence, particularly on the undersides of boulders where rain seldom if ever reaches, is common at inland marginal sites.

Paleo-honeycombing

A couple of examples of paleo- or “fossil” honeycombs were pointed out to me during the study. These were mostly away from the present shoreline or high up on cliffs. They were usually offered as being evidence of former higher sea-levels, but in all cases, these “fossil” sites turned out on examination to be active but marginal honeycomb sites of the type described above. In a few cases, honeycombing may have been more active in the past because the area had been logged and the rock more fully exposed to the sun for a while.

Like rainbows, galleries sometimes have secondary, less well developed, version above them. The Malaspina Galleries do, and on Valdes Island, even tertiaries are visible. “Stacked” galleries appear to be a result of the rock strata alternating between massive sandstone and thin beds of mudrock. I very much doubt that honeycombs could have survived the ten thousand years since sea-levels were substantially higher than they are now. Even at a scarcely-visible erosion rate of one grain of sand every ten years, a rock that continues to be lightly weathered would lose one metre of surface in that time. However, I have been told that honeycomb-like caverns are present below sea level in the area around Gabriola Passage and these are not so easily dismissed as paleo-honeycomb candidates.

ENDNOTE 7—De-cementing mechanism

Exactly why sandstone within honeycomb holes loses its competency is the central remaining question. That rockwater is involved, there can, I would submit, be no doubt; however, what the rockwater does to the sandstone is not clear to me. There are two classes of theory: that the cause is entirely physical; and that the cause is entirely chemical.

The case *for* the cause being physical rather than chemical is as follows:

- in experiments, “salt” crystallization (or hydration/dehydration) was shown to de-cement unweathered sandstone. No chemical experimental method was found that did the same thing

- one would expect a chemical change to result in staining of the weathering surfaces, particular if iron were involved, but no such staining is observed. On the contrary, the surfaces often have a fresh clean look to them.

The areas of the theory that need further explanation are as follows:

- the honeycombing is clearly a result of exposure to seawater, yet although sodium chloride, the main constituent of seawater, has a large crystallization pressure, it is not the only salt to exert crystallization pressure. The question is why don't groundwater salts do the same thing?

Crystallization pressures in atmospheres of some evaporite minerals are:

<i>halite</i> , NaCl	554	
<i>gypsum</i> , CaSO ₄ .2H ₂ O	282	
<i>hexahydrate</i> , MgSO ₄ .6H ₂ O	118	
<i>epsomite</i> , MgSO ₄ .7H ₂ O	105	
<i>natron</i> , Na ₂ CO ₃ .10H ₂ O	78	
<i>mirabilite</i> , Na ₂ SO ₄ .10H ₂ O	72	(Bland, 1998, p.98)

- what is the role, if any, of calcium sulphate, which always seems to be present in the honeycomb weathering debris? The change between *anhydrite* CaSO₄ and *gypsum* CaSO₄.2H₂O involves a change in volume and although equilibrium between these two minerals occurs at a temperature in pure water of 44°C, this temperature is considerably lowered by the presence of NaCl, and also of Na-, Mg-, K sulphates and their hydrates (Deer, 1992, p.614)
- if salt corrodes sandstone, why is Gabriola still here? [A qualitative answer *might* be that for long periods in its history, Gabriola was nowhere near the sea. The present-day Georgia Basin was a dry-land valley for most of the Tertiary Period.]
- why doesn't the weathering surface "case harden"? [Is oxidized iron (Fe³⁺) being "locked up" in *hydrobiotites*? If so, what environmental factors are controlling this?]
- petrographic observations of weathering sandstone from honeycombs show abundant short intergranular microfractures, but, within the microfractures, no sign of halite (or carbonate). Why is the halite (salt) so difficult to observe?
- petrographic observations of weathering sandstone show some complex alteration reactions, some of which are usually associated with hydrothermal conditions. Are these reactions contributing to the effect?
- anions and cations common in salt- and groundwater are known to cause flocculation (clumping) and peptization (dispersion) of clay particles (vanOlphen, 1987). Is one of these two mechanisms de-cementing the sandstone? If so, what peculiarity of rockwater facilitates this?

References

D.M. Allen & M. Suchy, *Geochemical evolution of groundwater on Saturna Island, British Columbia*, Canadian Journal of Earth Science, 38, pp.1059–1080, 2001.

A.C. Bishop, A.R. Woolley, & W.R. Hamilton, *Guide to minerals, rocks, and fossils*, Cambridge University Press, 1999.

Will Bland & David Rolls, *Weathering—An introduction to the scientific principles*, Arnold, 1998.

Carl Bowser, & Blair Jones, *Mineralogic controls on the composition of natural waters dominated by silicate hydrolysis*, American Journal of Science, 302, pp.582–662, 2002.

Charles H. Clapp, *The Geology of the Nanaimo Coal District*, The Transactions of the Canadian Mining Institute, XV, pp.334–353, 1912. Also, *Geology of the Nanaimo Map-Area*, Canada Geological Survey, Memoir 51, 1914.

W.A. Deer, R.A. Howie, and J. Zussman, *The rock forming minerals*, 2nd. edition, Prentice Hall, 1992.

William J. Deutsch, *Groundwater geochemistry—Fundamentals and applications to contamination*, Lewis Publishers, 2004-06-24.

Steven Earle & Erik Krogh, *Geochemistry of Gabriola's groundwater*, *SHALE* 7, pp.35–42, 2004.

Paul LeBlond & Andrew Loveridge, *Tafoni: Jewels of the Gulf Islands*, *ISLAND TIDES*, p.7, March 29, 2001.

D.N. Mottershead, *Spatial variations in intensity of alveolar weathering of a dated sandstone structure in a coastal environment, Weston-super-Mare, UK*, pp.151–174, in (Robinson, 1994).

G.E. Mustoe, *The origin of honeycomb weathering*, *GSA Bulletin*, 93, pp.108–115, February 1982.

A.C.D. Newman (ed.), *Chemistry of clay and clay minerals*, Wiley & Sons, 1987.

Piteau Associates Engineering, *Assessment of Groundwater Supply—Weldwood Lands, Gabriola Island, BC*, Islands Trust Report, 1993.

D.A. Robinson & R.B.G. Williams (ed.), *Rock weathering & landform evolution*, Wiley & Sons, 1994.

Ken'ichi Takahashi, T. Suzuki, & Y. Matsukura, *Erosion rates of a sandstone used for a masonry bridge pier in the coastal spray zone*, pp.175–192, in (Robinson, 1994).

H. vanOlphen, *Dispersion and flocculation*, pp.203–4, in (Newman, 1987).

D.E. White, J.D. Hem, & G.A. Waring, *Chemical composition of subsurface water*, in *Data of Geochemistry*, 6th ed., USGS, 1963, cited in (Deutsch, 1997). ◇



Honeycomb weathering features are often known as *tafoni* (“tah-phone-ee”, *plural*, and *tafone* “tah-phone-ay”, *singular*), which means little holes (alveoli), a word from the old language of Corsica. The picture however is not from Corsica, but from Capo d’Orso in neighbouring Sardinia. The rock is granite, and the holes are said to have been carved “by the wind”.... Hmmm?