Context:
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Errors and omissions:
A recent (April 2011) review of the literature on Riedel fractures shows no support for the description of "stand-alone" P and X shears in transtensional strike-slip faults on page 28. When described, they are secondary fractures accompanying R and R' shears. More investigation of this particular fault is needed.

Later references:
N/A.

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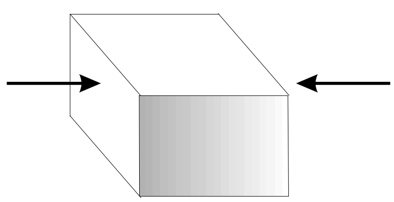
Stress on Gabriola

by Nick Doe

For millions of years, Gabriola has been sporadically squeezed, stretched, and rotated by tectonic forces generated by the heat in the earth's mantle. These forces are called "stress" and are measured in units of pressure—"megapascals", or if you're hopelessly old-fashioned, millions of "pounds per square inch" (psi).

Squeeze and pull-apart

When geologists think about stress, they always have in mind that what's being stressed is not moving. If we think of a cube of rock for a moment, this means there must be *equal and opposite forces* applied to the sides of the rock. The rock is being *stressed* by the forces, but they're not moving it because they exactly cancel each other out.

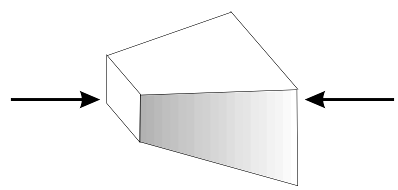


I sometimes use the term "stress pair" when writing about stress to remind the reader that there are *always* two equal and opposite forces involved, but that's not usually done, and the word "pair" is really unnecessary once you get the hang of it.

Although the two forces that compose a stress are always equal in magnitude, they commonly have different physical origins. The stress applied to the soles of your shoes, for example, comprises the force of gravity pushing down (your weight) and an entirely different, but exactly equal force, pushing up. This upward force is the electrostatic force generated by the billions of molecules in the floor, which, being similarly electrically charged, are resisting being squeezed together.

Stress can be *compressive*—it can squeeze—as in the diagram of a cube, *left*, or it can be *tensile*—it can pull apart—which it would be if we reversed the directions of the two arrows. Stress can also twist, like when you unsuccessfully try to unscrew a rusty bolt.

In the diagram of the cube, because the equal and opposite forces are acting on equal areas, the *pressures* on the two faces are the same. But this is not always so.



Stress can be concentrated. In the diagram of stress *above*, the *forces* remain equal and opposite, but there is more *pressure* on the left than on the right because the force on the left is acting on a smaller area than on the right. There's a dramatic illustration of the effects of "stress concentration" in Leboeuf Bay and we'll come to that later.

No matter how many stresses are acting on a rock, they can always be reduced for the purposes of analysis to two stresses (normal and shear) in two dimensions, or three (the principal stresses, σ_1, σ_2, σ_3) in three.[1] These composite stresses always act at right angles to each other.

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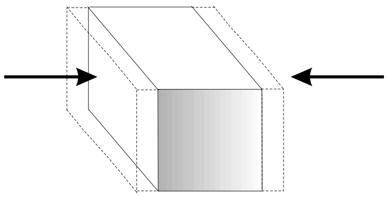
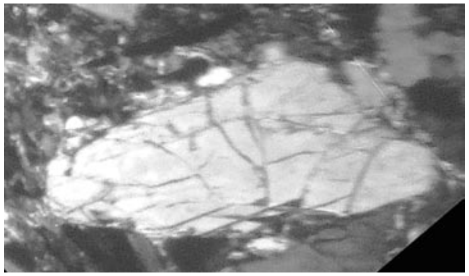
1 Several forces can be considered to form a single composite force even in three dimensions, but you can't do that with stress.

Responses to stress

Compressive stress

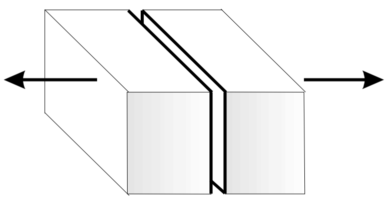


Rocks have several responses to compression. One obvious one is to contract. Shrinkage of rocks is small and is not something one often notices, but in granular rocks like sandstone, the effects can be very apparent under a microscope. Boulders that are quarried sometimes crack spontaneously after being brought to the surface. This is because the rock was compressed when it was buried. When dug up, it tries to expand too quickly to its original size.



Even individual grains of sandstone can be fractured. Those on this 1-mm grain of *hornblende* are easily seen, but other grains nearby are fractured too. Even though microscopic, a rock's bulk properties, its permeability for example, may be altered by such fractures.

Tensile stress

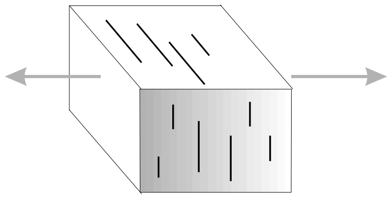


If the stress is tensile, a simple, although not common response is for the rock to split apart. The fracture planes in such cases often show a "plumose" or >> chevron pattern on their surfaces.

Left: A classical "pull-apart" or tensile fracture plane in a block of sandstone in central Gabriola Island. The rock face is about 2.5 metres (8 ft.) high. Ignore the vertical bars; these are black lichen living in the rainwater runoff.

The "plumose" pattern is the pattern of chevrons (>>), a common feature of this type of fracture. The chevrons are actually many thousands of microfractures.

These types of fracture are common in quarries and on construction sites, but what exactly happened here, I don't know. Possibly a portion of the sandstone snapped off when it was undermined by erosion and left protruding from a cliff face.



A more muted consequence of tensile stress is the creation of stretch marks, or *tension gashes*. These are common in sandstone. Often the gashes appear alongside a bigger fracture, and so give a clue as to the nature of the bigger fracture. On Gabriola, the gashes frequently have "thick-lips" of orange-brown stained sandstone, a result of weathering by rainwater. The stain is iron oxides (*limonite*). The scene is Drumbeg Park. The sandal, for scale, is size 9. I used it because the dog wouldn't sit still.

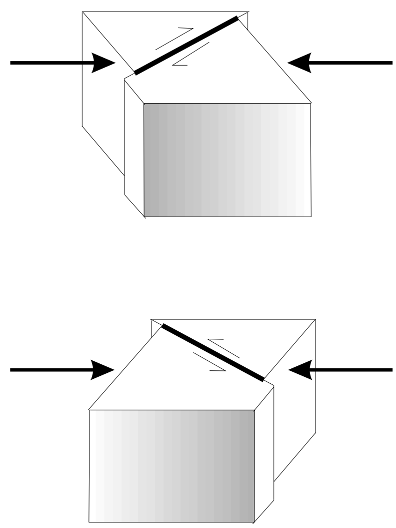
Strike-slip faults

Once rock has shrunk as much as it's going to in response to compressive stress, it can do two things. It can ***shear*** or it can ***fold***.

If the stress due to gravity is somewhere between the two horizontal stresses, shear creates a *strike-slip fault*.[2]

Upper diagram: a right (dextral) strike-slip fault. No matter on which side of the fault you stand, the other side of the fault appears to have slipped to the right.

Lower diagram: the mirror image, a left (sinistral) strike-slip fault. The fault on Gabriola that runs from the Maples, close to the Community Hall on South Road, to Dragon's Lane (near the old Grande Hotel) on the north side is a left strike-slip fault. The south of the island has moved about 200 metres to the northeast compared with the rest of the island.



Strike-slip faults. Right (*top*), left (*below*).

[2] "Strike" is the compass direction of the line marking the intersection of a fault plane with the horizontal, so 10° = just east of north, etc. The "dip" is the angle the fault plane makes with the horizontal, so 10° = almost horizontal, etc. There are two strike directions. For example, a line running SE also runs NW. It's customary to select, if possible, the direction where the fault plane dips to your right.

Left: A block of sandstone forming a wall along the east side of the gravel pit at the end of Dorby Road.

It has been pushed into flat mudrock country—the Boultons' farmland—by the left strike-slip fault that runs across the southern end of the island.

Left: Deposits of pearly white mineral on the faces of sandstone boulders on Gabriola (compass for scale) are easily dismissed as being just *calcite* left by groundwater. Chemical analysis however shows some of them to be a mix of *calcite* and *zeolite* mineral(s). *Zeolites* are only formed in the presence of water at high temperature and high pressure.

This face must have been part of a water-filled slip fracture that once got very hot during the prolonged shaking and grinding of a major earthquake.

Gabriola's sandstone contains a few crystals of a fairly rare mineral that belongs to a class of minerals known as *zeolites*.[3] Zeolites are interesting because they are never found in the granite that was originally ground up to make the sand.

They have been added to the sandstone after it was formed. Because they require heat and pressure for their formation, they are commonly associated with geothermal sites, but on Gabriola, it is a reasonable guess that

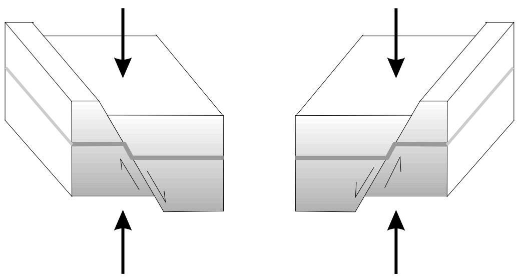
[3] Whole rock analysis gave $Ca_4NaAl_{11}Si_{28}O_?.22H_2O$, which is closest to $Ca_4Al_8Si_{28}O_{72}.24H_2O$, *calcium heulandite*. There are at least 45 zeolites, but *heulandite* and *laumontite* (Parkard 1972) are the only ones I've seen reported in Nanaimo Group sandstones. See the Appendix.

the zeolites were formed on fracture surfaces heated by friction during seismic events.

Single strike-slip faults develop when there is relatively little additional stress acting perpendicular to the major stress axis. If there is a confining stress in this direction, the rock may respond by shearing in *both* directions. Such shear fractures are called *conjugate fractures*.[4]

Dip-slip faults

If the stress due to gravity is stronger than either of the two horizontal stresses, then we get a *normal* fault.

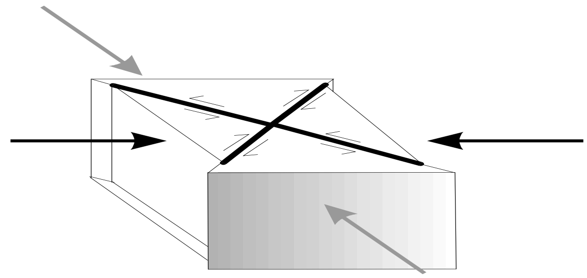


Normal faults—one fault-block falls away from the other either to the right or left.

It's fairly common for a series of normal faults in the same direction to produce a hill that has a series of step-like inclines—cyclists and joggers know these well.

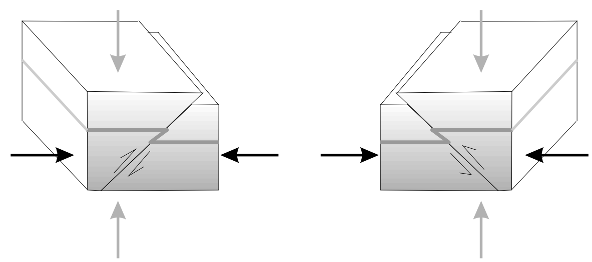
If the stress due to gravity is weaker than both horizontal stresses, then we get a *reverse* fault. One fault-block is pushed up over the other. These are rare on Gabriola but common elsewhere.

The dip of the fault plane of a reverse fault is usually steep (more than 45º). If it is less than 45º, the fault is sometimes called a *thrust* fault. Reverse faults often have a lesser strike-slip component.

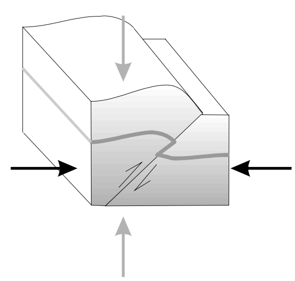


Conjugate fractures—a combination of right and left shear fractures that may develop if there is confining stress at right angles to the main stress. The strongest stress axis (shown here left-right) always bisects the narrower angle of the >< intersection which is commonly around 60° degrees.

Contraction in the highest-stress direction is accommodated by crushing at the crossover and expansion in the weakest-stress direction.

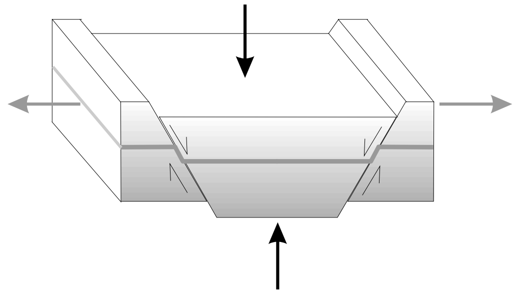


Reverse faults. One fault-block is thrust up over the other, again, either to the right or to the left. The strata have a characteristic Z or mirrored-Z shape. Reverse faults are described as being "*x*-vergent" where *x* is the compass direction of the up movement.



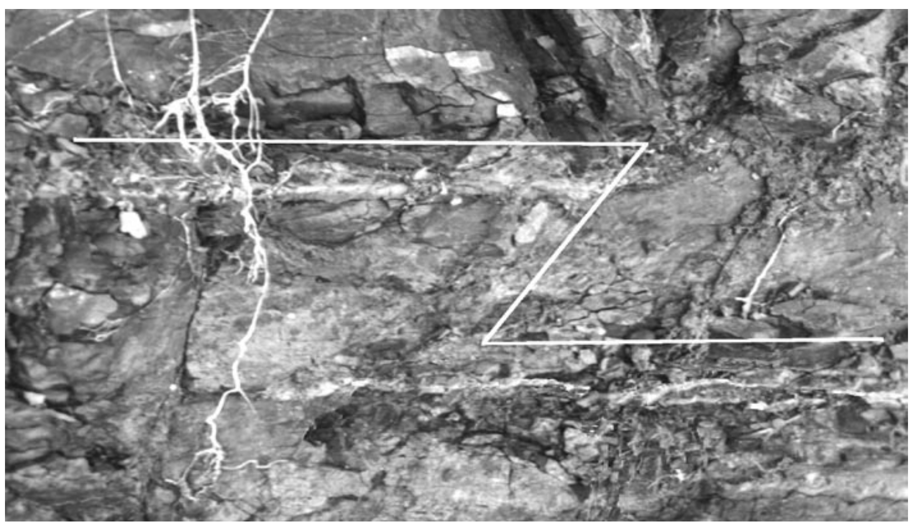
A reverse fault may appear as a fold. It was only recently discovered that the so-called "Lock Bay anticline" is the result of a reverse fault running into nearby Leboeuf Bay.

4 *SHALE* 7, pp.26–31.

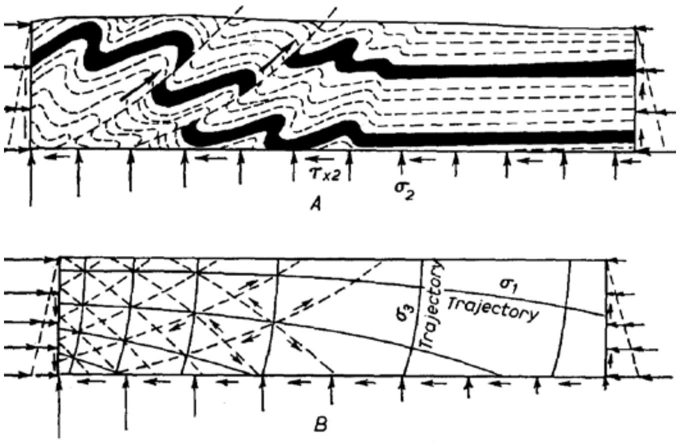


Above: A pair of small normal faults about 10 metres apart, each side of the path down to the beach from the Community Cemetery on South Road. The faults are marked by a thin interbed of sandstone in shale. On the *left*, the right-hand fault-block has fallen away; on the *right*, the left-hand fault-block has fallen away. The drop in this example is a very modest 30 centimetres, but there is a series of them. This is a typical pattern left after rocks have been stretched horizontally. The valley of the Rhine and the East African rift valley are famous examples.

Right: Reverse faults range in scale from small (those are tree roots in the photograph) to continental as, for example, in the Rocky Mountains. This fault is at the southeast end of El Verano, Gabriola where there is a curious mélange of faults, probably of great age.

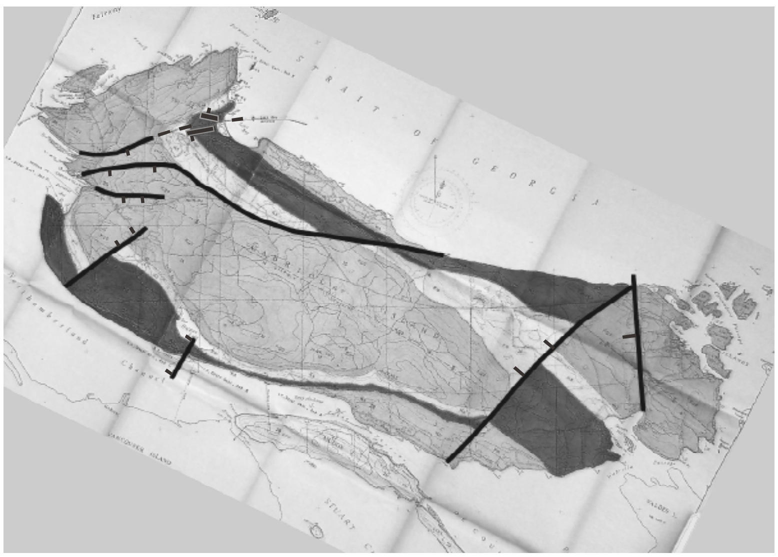


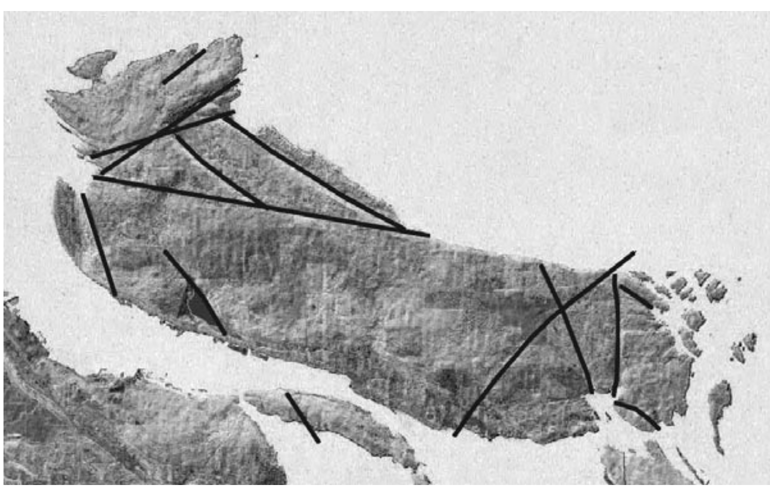
There are also hybrid faults such as *rotational faults, oblique slip faults* (mixed strike-slip and normal faults); *transtension and wrench faults* (mixed strike-slip and pull-apart faults); and *transpression faults* (mixed strike-slip and reverse faults).



Left: Textbook example of stress concentration resulting in reverse faults. The hypothetical block is 100 km wide and 10 km deep. The highest compressive pressure is applied to the left, the weakest to the right. The forces are balanced by a shear force acting right-to-left on the bottom surface. Diagram B shows the patterns of the strongest and weakest principal stress, σ_1 and σ_3 respectively (solid lines), and the trajectories of maximum shear stress (dashed lines). Hills, 1963, p.83

Below: Leboeuf Bay, Gabriola. There's not so much folding (it's a smaller structure) but several other features of this cliff and its (northwest vergent) reverse faults match the diagrams very well. Hammer in picture *right* for scale.





When is a fault not a fault? It is common on Gabriola to see what appears to be a fault, and may once have been, but is now a topographical feature due to differential erosion. Sandstone and conglomerate weather more slowly than shale. These three diagrams show that attempts at identifying major faults on Gabriola don't always result in agreement among the experts.

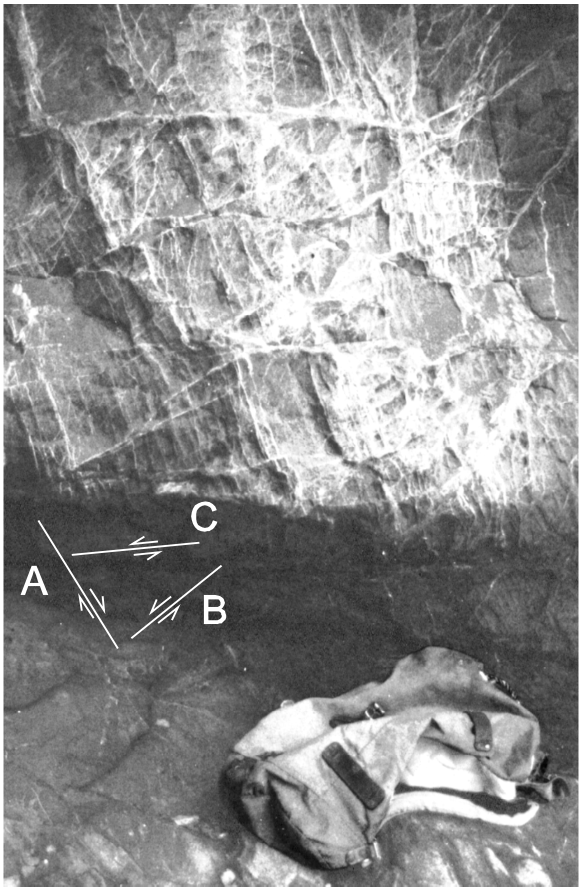
Top: map produced by hydrologists (Brown & Erdman, 1975) based mainly on aerial photographs.

Middle: map produced by geologist (Packard, 1972) based only on field observations.

Bottom: map produced by lineament analysis of satellite imagery, a digital elevation model (DEM), and editing based on reported field observations (courtesy Natural Resources Canada, Murray Journeay).

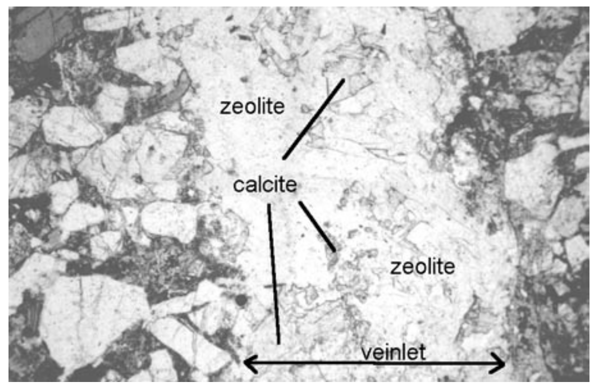
Hydrologists are quicker than structural geologists to identify cliffs and inclines as eroded fault scarps. Because the effect on groundwater is similar, hydrologists can afford to neglect the possibility that such features may not in fact be faults, but may have other origins. Hydrologists too have less interest in knowing whether a fracture is due to purely local circumstances or has regional significance.

For the structural geologist on the other hand, labelling every cliff or incline as a fault is not useful if there are no accompanying observations of the geometry of the conjectured original or underlying fault.



Left: Veins looking like a cobweb in sandstone in Cox's Bay. Backpack for scale; left is NW. This is the shear zone between the blocks of a large strike-slip fault. Chaotic though it may seem, the basic pattern is just conjugate normal faults (A and B) later cut by bedding-plane faults (C). The embellishments developed as local stresses changed magnitude and direction (Engelder, 1987), possibly rapidly and severely.

Below: Under a microscope, the veins appear to be packed *zeolite* and *calcite* crystals likely formed from hot water injected under pressure during an earthquake. Field-of-view is 2.5 mm.



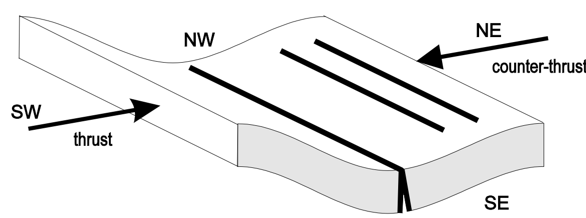
Folding

Shearing is one way the rock may respond to compressive stress, but it can also *fold*.

Because of their granular natures, sandstone, and to a lesser extent shale, are *competent* rocks, that is, given lots of time, they can flow into any shape required to accommodate the applied forces.

Folding can produce several different types of fracture, both compressive and tensile. Gabriola sits in a trough, or ∪-shaped *syncline*, which is one of a series of folds on the east side of Vancouver Island.[5]

Tensile stress due to folding opens up fractures that run parallel to the fold axis. I call these *longitudinal fold fractures*. On Gabriola these are oriented roughly SE-NW.



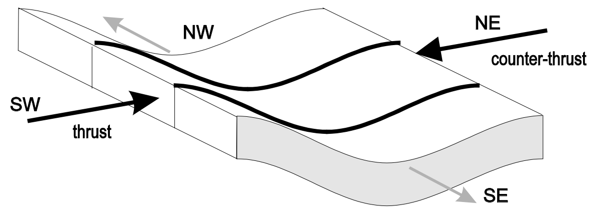
Fractures resulting from the tensile stress created by folding run parallel to the fold axis, which on Gabriola means NW-SE. Although fractures start where the stress is highest, they go on to crack the slab completely because of progressive stress concentration. It's like breaking a bar of chocolate

[5] Crests, ∩-shaped folds, are called *anticlines*. There is one running up the Stuart Channel towards Dodd Narrows. The folds are about 4 miles (6.5 km) across (crest-to-crest).

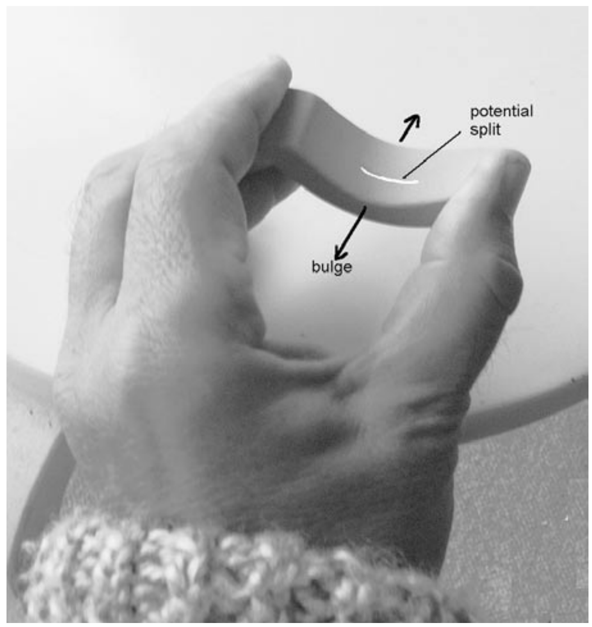
Brickyard Beach looking at Nanaimo. The long fractures in the sandstone are longitudinal fold fractures. They run parallel to the axis of Gabriola's syncline [∪-fold]; hence the dip to the right toward the centre of the island.

Compressive stress due to folding causes the rock to be squeezed outward along the axis of the fold (try this with a rubber eraser, see *photo right*).

This expansion along the axis produces tensile stress fractures that run across the fold perpendicular to the axis and parallel to the compression. I call these *lateral fold fractures* because they run from one side of the fold to the other. Such fractures are very common on Gabriola's beaches and are oriented roughly SW-NE.



Compression can also created tensile stress that runs at right angles to the fold axis. On Gabriola, the resulting fractures are oriented roughly NE-SW. Extension fractures like this often develop in cheap rubber boots.

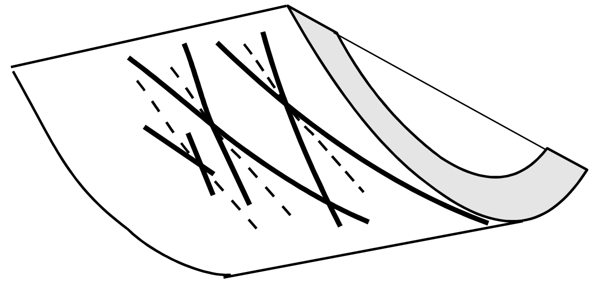


Fractures parallel to the compressive stress, often called *cross-faults*, may also be a result of unevenly distributed thrust or unevenly distributed resistance to the thrust.

There are several more ways that fractures can develop from folds than are shown here, but I'll only mention one, and that because it is fairly common.

The diagram *opposite* shows *lateral fold fractures* that have developed as conjugate fractures. This pattern represents compression at the surface in the dip direction; elongation parallel to the fold axis; and no change normal to the bedding.

Fractures due to folding always reflect the folding, not the regional stress that caused the folding. If you look at the way that some of your clothes and carpets crumple in response to simple compression you can appreciate how complicated folding-induced fracture patterns can be.



Compression at the surface of a trough (not visible in this sketch) may create conjugate fractures that propagate downward.

Joints

Parallel fractures caused by folding are usually interconnected by *joints*, sometimes called *cross-joints* in this context. It's easy to distinguish these from the main fractures because they're short, irregularly distributed, terminate in T-junctions, and often wander, especially if the sandstone contains concretions.

Once a crack has opened up, it can no longer transmit stress from one side to the other; it forms a stress barrier because the rock on one side of the joint is neither pushing nor sliding against the rock on the other.[6] This changes the stress pattern from being a regional pattern to a local pattern.

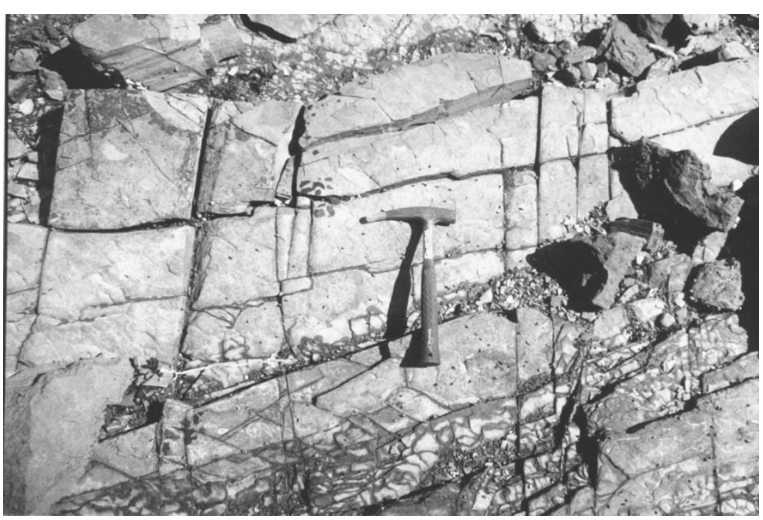
Note the smaller but similar fractures in the bottom right-hand corner of the picture. A larger version of what might be an asymmetric conjugate fracture arguably extends over the whole width of the island. The offset of the crossover indicates the rock was stressed again after the first fracture was formed though the offset is too small to be of any regional significance. That's my size 9 shoe again. View is looking NE.

[6] Assuming the crack is not just a surface feature. Stress patterns vary with depth because, for the same reason, there is no vertical stress at the top surface.

Not all joints have been created by tectonic forces, sometimes gravity plays a role. An example is as follows.

Beds of sandstone on Gabriola have near-horizontal bedding planes. When the beds rest on soft mudrock, erosion leaves them protruding from cliff faces and the sandstone subsequently break off, parallel to the cliff face, in long slabs, see *photo below*. Vertical joints in these slabs form when support of the weight of the slab becomes uneven. The spacing of the joints is related to the thickness of the bed—the thicker the bed, the wider apart are the joints. Vertical joints in sandstone probably play a major role on Gabriola by allowing groundwater to move downward.

Above: There was once a whole lot of shaking going on…the only explanation most beach walkers need for fracture patterns composed entirely of small joints. Bit like what happens when you drop a plate on the kitchen floor.



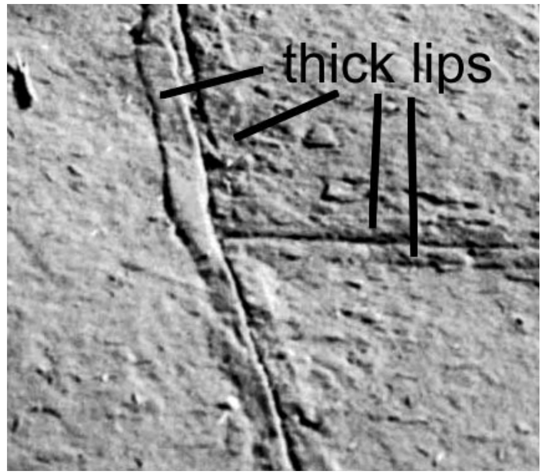
Top left: Sandstone slab on Gabriola with vertical joints (Percy Anchorage). Joints like these are formed when support of the weight of the slab becomes uneven, in this case by movement of the underlying beach sand. The spacing of the joints is related to the thickness of the bed—the thicker the bed, the tougher it is, and the wider apart are the joints.

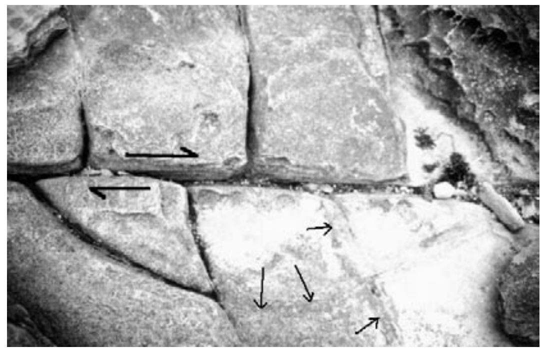
Bottom left: A thin layer of siltstone in mudrock (shale) (Leboeuf Bay). The slab has been tilted—the handle of the hammer points 17° down N 45°W). If you think of the tilt as part of a fold, then the horizontal fractures in the picture represent longitudinal faults, and the vertical ones, lateral faults or cross-fractures parallel to the stress that caused the fold.

Not all fractures are due to tectonic or seismic activity, especially in shale. For examples due to weathering, see *SHALE* 12, pp.7–29.

Beach at the south end of Gabriola across from Breakwater Island.

Parallel fractures due to regional stresses in brittle sandstone are interconnected with joints. They may be at right angles or oblique, or they may gently curve indicating that they developed in response to local stresses that changed rapidly as the fracturing progressed.





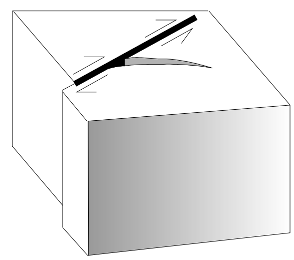
Top: Fractures allow the entry of water and this hastens the weathering of iron-rich minerals (*hornblende*, *biotite*, *magnetite*) to a mix of if iron oxides (*hematite*) and hydoxides (*limonite*). I call this “thick-lip” weathering.

Bottom: While many fractures widen to become joints, others, as in the fault-block lower right (*arrows*), may be “healed” by such weathering. The righthand strike-slip along the central fracture is an inch or two.

While we tend to think of joints as being just a few millimetres wide, this is not always so. On Valdes Island, there is a series of caves consisting of a network of fractures with joints that are wide enough for spelunkers to scramble through.

Secondary fractures

Secondary fractures are common and often have several plausible explanations—they can be great time-wasters if you’re into trying to explain them all. A simple and common example, shown on the *right*, is



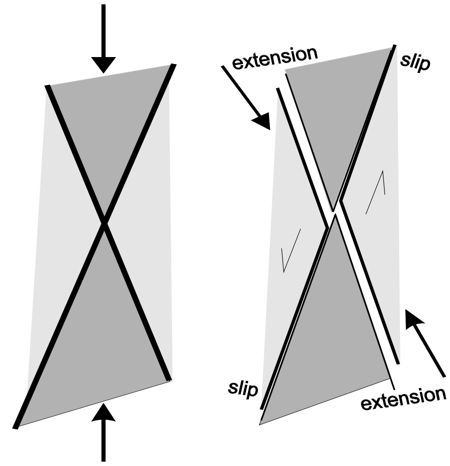
Unevenly distributed slip along a slip fault is just one of many ways secondary fractures develop. If you think this is just textbook stuff, take a look at the picture on the cover of Gabriola’s shore north of Descanso Bay.

where the slip along a strike-slip fracture is unevenly distributed (in this case zero at the back right-hand corner). The uneven slip results in a secondary pull-apart fracture that is oblique to the main fracture.

Reactivation

If this were not Gabriola, we could leave it at that—we don't want to get too stressed!—but one of the interesting complexities of life on Gabriola is that the island has clearly been stressed more than once, and not always in the same direction.

Apart from the apparent circular deformation seen in air photographs (*front cover*), one of the hints that direction-changing stress may have been at work here is the asymmetry of some fractures that may be conjugate. It is fairly common on Gabriola to find one-half of such fractures appearing as (compressive) slip fractures, and the other half as tension (pull-apart) fractures with mild slip. The diagram *opposite* shows how varying compression stress might cause this.



Left: Fault blocks with conjugate fractures. The original compression, indicated by the arrows, acted parallel to the long axes of the fault blocks.

Right: New stress in a different direction, or old stress applied after rotation of the blocks, generates compression and slip on one set (*bottom left-top right*) and tension and "pull-apart" on the other set (*bottom right-top left*). Asymmetric northeast-trending fractures looking like they may be conjugate are common near Berry Point and Seagirt Road, and there are some in Drumbeg Park.

Earthquakes

Fractures are commonly caused by earthquakes, and the best place to look for direct evidence of major earthquakes is on Whalebone beach and the beach at False Narrows. On both beaches, dykes of fine-grained and very well-sorted sandstone can be seen in several locations cutting up through the near-horizontal bedding planes of the shales of the Northumberland Formation. This sandstone is the result of earthquake liquefaction and has been forced upward from the underlying De Courcy Formation—the stuff Mudge is made from. If the dykes had been formed by in-filling by debris of an extension fracture, the sandstone would have a much more varied composition than it does. Contrary perhaps to popular opinion, we on Gabriola live in very stress-filled country. ◊

Appendix 1

Analysis of the white deposit commonly seen on fracture planes

The white deposit found on the surface of fracture planes is mainly *calcite* [$CaCO_3$] with perhaps *dolomite* [$CaMg(CO_3)_2$] and similar minerals; however, although these minerals react to warm dilute hydrochloric acid, other minerals present do not react at all. Even very strong acid does not completely dissolve the deposit. To find out what the non-carbonate component might be, a whole rock analysis was conducted with the following results.

This particular sample collection site was Valdes Island (448600,5440350). (Sample 21, Valdes I., Geoffrey Fm.). Norwest Labs File: 267038. ACME File: A305584.

Methods

DILEACH: one gram of sample added to 50mL de-ionised water, shaken for at least 1 hour. Filtered solution was analysed by Ion Exchange Chronomatography (IEC) for anions. A whole rock analysis was then done using an inductively coupled plasma (ICP) ion generator and mass spectrometer (MS), plus LECO analysis for C and S. Loss on ignition (LOI) was assumed to be due to loss of water, CO_2, and SO_2 , which enabled concentrations of C, S, and H to be assessed as for the other elements.

Results

Nothing significant was detected in the water: chloride <5mg/L , fluoride <10mg/L, nitrate 1mg/L, nitrite <10mg/L, sulphate <10mg/L. This result was deemed to rule out the prime suspect, *gypsum* [$CaSO_4.nH_2O$].

The whole rock analysis result was as follows. Ratios are relative number of atoms of each element present in the sample, not including oxygen:
calcium 19.0; **silicon** 21.8; **aluminium** 8.5; **hydrogen** 34.1; **carbon** 15.9; others 0.7.

Comments

The presence of both carbon and calcium means there is *calcite* present. The insoluble calcium/silicon/aluminium mix suggests a calcium aluminosilicate or *zeolite*; most probably $CaAl_2Si_6O_{16}.5H_2O$ (*heulandite*) or $CaAl_2Si_4O_{12}.4H_2O$ (*laumontite*). Both can be formed from Ca-feldspar, but by processes usually associated with hot water and deep burial, but my guess is that such conditions can be produced in fractures during earth movements.

This best fit to the data is 15.7 parts $CaCO_3$ (*calcite*) plus 3.5 parts $CaAl_2Si_6O_{16}.5H_2O$ (*heulandite*) = **calcium** 19.2; **silicon** 20.9; **aluminium** 7.0; **hydrogen** 34.9; **carbon** 15.7.

John Packard however identified the *zeolite* mineral *laumonite* rather than *heulandite* by X-ray diffraction analysis in samples of Geoffrey and Gabriola Formation sandstones, and although he didn't associate his samples selected for analysis with fracture planes—he simply chose those with the highest concentration of *zeolite*—the possibility that they were so associated clearly exists.

Acknowledgements

Chemical analysis by Norwest Labs, Surrey BC, and I am grateful to Bill Warning and John Davidson for their help. Whole rock analysis by ACME Analytical Laboratories, Vancouver BC. Thanks also to Mike Hale who met John Packard when here and loaned me his copy of John's thesis.

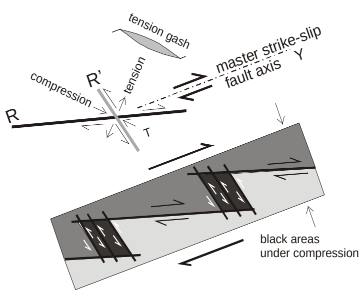
Appendix 2

Microfractures

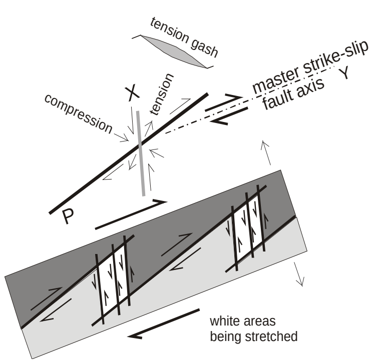
Not too any people on Gabriola spend their time wondering about the origin of microfractures. The most common examples you see on the beach are seemingly-delicate tangled threads of white quartz-filled veins in smooth, fine-grained, igneous stones or boulders. These were brought here by ice, and their history is very different from that of the bedrock of our island. However, here's an instance where microfractures gave clues as to the nature of the stress on the rock, and hence the nature of a major fault. The diagrams are idealized—the fracture patterns are never seen with such clarity in the real world.

When rock shears, the fracture surfaces are pulverized and deformed. For small faults, the contact surfaces are subsequently weathered and are rarely a centimetre or two wide. For larger faults however, the contact becomes a shear zone several metres wide containing within it, microfractures with characteristics of their own.

Riedel microfractures are conjugate strike-slip faults that develop in shear zones. They appear to form interlocking sawteeth that oppose the stress causing the shear.

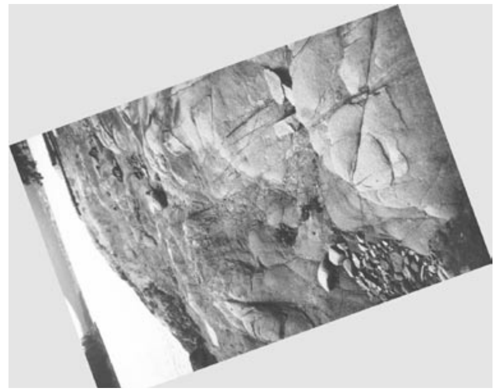


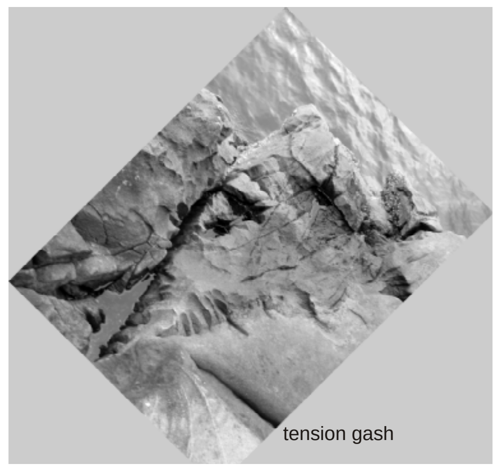
If the shear zone is being pulled apart however, the interlocking sawteeth may swing around and appear to be dragged along by the stress causing the shear.



The photos show one certain (*top*), and one suspected (*below*) shear zone, oriented so that north is at the top. If you look closely at both pictures, you'll see pairs of conjugate microfractures with the same orientation.

The inclination of these (), I think, shows that the master fault is a tensile right strike-slip fault.





This is interesting because the rock *below* is at the west tip of Descanso Bay and the one at the *top* is in Cox's Bay. Evidently, a large hybrid fault may run N70°E across Descanso Bay. I talk more about that in a companion paper. ◊

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