Early Fractures in Limestones: an example from Bermuda

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Fractures and joints are common features of all rock-types but the majority form during burial as a result of overburden pressure and response to regional and local tectonic stresses of compression and extension. With limestones however, fractures can form very early in the carbonate sediment's history, and close to the surface, although the actual processes involved are less certain. Fractures are important conduits for fluids flowing through rocks, including water, oil, gas and mineralising fluids, and some waters may lead to dissolution of the limestone and the formation of cave systems. This short article describes some prominent fractures formed in young (Pleistocene) limestones, up to several 100,000 years old, from Bermuda and reviews the possible reasons for their formation, which are not straightforward.

Geological background to Bermuda

The Bermuda islands occur upon a volcanic ridge formed through a mantle plume active in the mid-Tertiary, from 45-35 million years ago, which created a massive edifice (the Bermuda Rise) upon the Atlantic Ocean floor at a depth of 4000 metres. The seamount is oval in shape with a SW-NE elongation, about 100 km long by 60 km across, parallel to the Mid-Atlantic Ridge, which is located some 1500 km to the southeast. It is likely that the original volcanic complex rose to about 1000 m above sea level, by about 30 Ma ago, and since then it has been eroded down to create the extensive platform where shallow-water carbonate sediments have been deposited. There are no volcanic rocks exposed across the Bermuda pedestal but they have been proved in drilling, occurring at a depth of several 10s of m below sea level, beneath the carbonate cap.

Overall, the islands of Bermuda form a sort of rectangular shape, 23 x 4 km, with a long straight southeastern side, a shorter straight northwestern side at the NE end, and a short straight northeastern end (Figure 1); many of these shorelines have low rocky cliffs. The southwestern end is curved, as a result of longshore movement of lime sand, enclosing a large lagoon (the Great Sound). Reefs of coralline algae and corals are developed around much of the platform, very close to shore off the southeastern side, but much farther offshore on the NW side (Figure 1). There are 6 major limestone formations on the island, each deposited during an interglacial highstand, and separated by a palaeosoil. Most of the carbonates are aeolianite, that is lime sand derived from the beach, deposited by wind, with large-scale cross bedding. Shallow-marine to foreshore facies are far less common, and thin (a few metres); they are exposed at the base of several units, passing up into aeolianite which may reach several 10s of metres in thickness (Rowe 2020). These limestone packages were deposited from around 800,000 years ago during interglacial Marine Isotope Stages (MIS) 17(?), 11, 9, 7, 5e and 5a.

The young carbonates on Bermuda are cemented and many are extremely hard. The lithification took place soon after deposition, notably through the effects of meteoric (fresh) water, dissolving less stable (aragonitic) grains and precipitating calcite cement. Some foreshore-shallow-marine sediments were cemented by seawater.

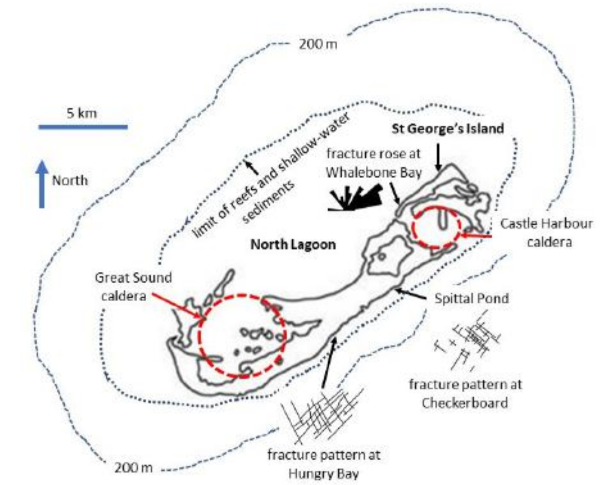

Fig. 1. The islands of Bermuda with the location of Spittal Pond and the fracture pattern there at Checkerboard Rock, as well as at Hungry Bay (from Scheidegger in Rowe et al. 2014) and Whalebone Bay (from Hartstock et al. 1997). Also shown are the locations of the 2 volcanic calderas, the outer limit of reefal and shallow-water carbonates, and the position of the 200-metre depth contour.

Fractured carbonates of Bermuda

At many outcrops on Bermuda, fractures can be observed in the limestones, but one locality where they are especially well developed is Checkerboard Rock at Spittal Pond Reserve (Figures 1, 2).
Here, the limestones belong to the Belmont Formation (i.e. MIS 7, age around 200,000 years) and the most prominent fractures occur in the lower part, in shallow-marine facies; they are less common in the higher units, of low-angle beach facies and overlying aeolianite (Figure 3). Two sets of fractures are developed in the marine facies, roughly at right angles, oriented in approximate SW-NE and NW-SE directions (see Figure

Fig. 2. Prominent near-vertical SW-NE fractures with minor offset and cross-cutting NW-SE fractures in shallow-marine facies. Checkerboard Rock, Spittal Pond, Belmont Formation.

1, measurements made from an aerial photograph). The SW-NE orientation is parallel to the rocky coastline, which extends in this direction for about 18 km. The fracture spacing is 40-60 cm, and fracture continuity extends for 10s of metres, with minor offsets. Most fractures appear close to vertical. In this upper intertidal zone exposure, the fracture pattern in the marine facies has been exploited by wave erosion-dissolution to generate a striking clints and grikes pattern (Figure 4), just as present on Carboniferous limestone surfaces in the Yorkshire Dales.

Fig. 3. Rectilinear fractures in foreground in shallow-marine facies, overlain by beach-foreshore facies, 1 metre thick (low-angle lamination dip to right, i.e. seawards) and aeolianite above (high-angle lamination dipping to left, i.e. onshore, 1.5 m thick), with fewer fractures.

Fig. 4. Fractures weathering to give a distinctive clint and grike feature.

The fractures are less common (and more widely spaced) in the higher aeolianite units (Figures 3, 4), which themselves are less tightly cemented and still quite porous. The fracture fills can be observed here and they are 10-15 mm wide and consist of cemented lime sand grains, with a central crack (Figures 5, 6). Elsewhere, there are calcite crystals within the fractures. and some contain laminated calcrete where there are palaeosoils not far above the bed. These features indicate that the fractures are dilational and suggest episodic opening. The fracture fills commonly stand proud of the adjacent rock (Figure 5).

Fractures are also documented from Hungry Bay, 5 km SW of Spittal Pond, and these have similar orientations to Checkerboard Rock, parallel and normal to the shoreline (Figure 1)(Scheidegger in Rowe et al. 2014). Fractures on the northwestern coast of Bermuda, in the vicinity of Whalebone Bay, St George's Parish (Fig. 1), were described by Hartsock et al. (1997) in the Rocky Bay (MIS 5e) and Belmont (MIS 7) formations. They recorded the presence of a primary, dominant set of fractures oriented in a generally SW-NE direction (coinciding with the orientation of the 4-km-long straight rocky coastline there), but with several secondary, subordinate sets at large angles to this (see rose diagram, Figure 1).

Fig. 5. Three prominent near-vertical fractures in aeolianite facies with their more tightly cemented fills weathering out.

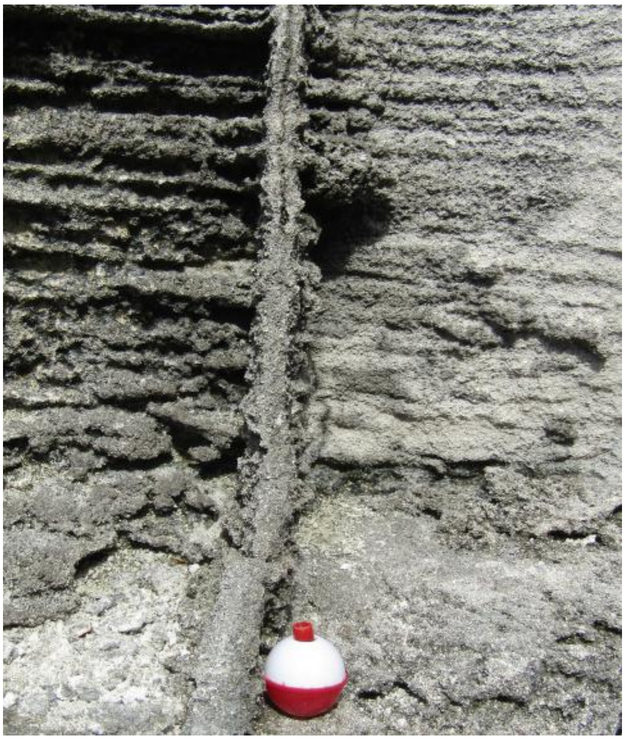

Fig. 6. Fracture cutting aeolianite with comminuted lime sand fill and calcite cement. Note central crack suggesting a later phase of movement (dilation). Fish float 4 cm diameter for scale.

Origin of fractures in young limestones

The fractures seen widely on Bermuda in the limestones occur within well-lithified carbonates, as young as 80,000 years, which have not been buried to any extent. Like many carbonate sediments they were cemented early, on contact with freshwater especially, and this could have taken place within 100s of years of deposition. Thus, competent rocks would likely have been produced soon after sedimentation, and these would have been liable to brittle failure if subjected to stress. Their near-surface location, the vertical to subvertical nature of the fractures, their orthogonal pattern and sediment-cement fills suggest the limestones were responding to strong horizontal tensile stresses.

Fractures in young (Quaternary) limestones have been described from many places in the Bahamas (e.g. Aby 1992; Whitaker & Smart 1997) and elsewhere, and in most cases they are oriented parallel to the local shelf margin, with another set at right angles. Fracture sets have commonly been exploited to form cave systems, including blue-holes. With many of these locations, the shallow-water to aeolian limestones are close (a few 100 m) to the shelf margin, which in many places is relatively steep, descending to 1000s of m. In the geological record, many steep-sided reefal platforms show a similar pattern of synsedimentary fractures parallel to the shelf margin, good examples being described from the Devonian in the Canning Basin of Western Australia and the Permian Capitan reef in Texas. Such fractures may be filled with contemporaneous sediment, giving rise to so-called neptunian dykes.

The formation of the margin-parallel (and normal) fractures in the Bahamas has been related to phases of sea-level lowstand, during glacial periods, when the platform would have become lithified as sea level fell. The cemented limestones would have been exposed up to 100 m above the lowered sea level for many 10s of 1000s of years, and then subjected to horizontal tensile stresses as hydrostatic pressure in the carbonates was lowered. On the southeast side of Bermuda, the drop-off to ocean depths, marked by a line of reefs, is only 100 m offshore (Fig. 1). Thus, the fractures in limestones along the SE side of the island, plus the linear nature of the coastline itself there (20 km long in the direction 050-230, Figure 1), is likely to be related to the presence of the nearby steep shelf. However, on the NW side of the island, in the St George's Parish area where there are also SW-NE fractures and a 4-km long straight section of rocky coast (Figure 1), there is an extensive shallow shelf lagoon extending for 10 km to the NW before the drop-off. Could this area have also been affected by the slope on the SE side of the island or is there another explanation? It is noteworthy that the NE end of Bermuda also has a conspicuous straight coast, at right-angles to the NW and SE coastlines, thus, also fracture controlled.

To account for the somewhat variable subordinate fracture orientations on the NW coast, Hartsock et al. (1997) suggested that the underlying topography of the upper surface of the volcanic edifice may have been influential. A volcanic caldera located beneath Castle Harbour, at a depth of 60 m below sea-level in the centre and 30 m at the margin, has been detected from seismic, and another larger one occurs beneath Great Sound (both shown on Figure 1). The interpretation is that massive dissolution of carbonates took place at the volcanics-limestone contact during sea-level lowstands, creating large cavern systems which collapsed and gave rise to the fractures in higher limestones. Such a process would certainly give rise to fractures in overlying carbonates but would probably not account for the clear SW-NE fracture-controlled coastline there.

The majority of fractures in rocks, generally, result from the effects of the regional stress field. However, in the case of the Bermuda Rise, this stress regime is complex, reflecting several processes including ridge-push forces related to sea-floor spreading at the Mid-Atlantic Ridge, relict thermal stresses from cooling of the volcanics and stresses from loading of the edifice (Vogt & Jung 2007; Rowe et al. 2014). However, it is difficult to see how these stresses would affect such near-surface limestones, and the compressive, shear fractures to be expected are not observed.

In summary then, the dominant orientation of the fractures on Bermuda, SW-NE, parallel to the southeastern shelf margin of the carbonate platform (plus their associated, orthogonal, NW-SE fractures), most likely relates to the tensile stresses affecting the lithified carbonates during sea-level fall and exposure, adjacent to a steep shelf margin. Other fracture directions may well be related to collapse of underlying caverns and topography of the volcanic subsurface caldera, but once formed, fractures will lead to further cave development through focussing dissolution. The regional stress regime is unlikely to be responsible for these early near-surface fractures.

The fractures on Bermuda, as elsewhere in similar limestones only 10s to 100s of 1000s of years old, clearly show that fractures can form very early in a sediment's history and near-surface. Synsedimentary – early diagenetic cementation to form brittle rocks is a major factor, as well as the proximity to a steep shelf margin, with major falls in sea level exposing the carbonate platform and changing pore-fluid pressures also involved.

Look carefully at fractures in sedimentary rocks and their orientations; they may be younger than you think!

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References

Aby, S.B. (1992) Relation of bank-margin fractures to sea-level change, Exuma Islands, Bahamas. Geology 22, 1063-66.

Hartsock, J.K. et al. (1997) Fracture systems in northeastern Bermuda. Geological Society of America Special Paper 300, 325-334.

Rowe, M.P. (2020) Bermuda Geology: an Explanation of the Geology of Bermuda. https://bermudageology.com/11-field-guide/

Rowe, M.P. et al. (2014) Anomalous MIS 7 sea level recorded on Bermuda. Quaternary Science Reviews 90, 47–55.

Vogt, P.R. & Jung, W.Y. (2007) Origin of the Bermuda volcanoes and the Bermuda Rise: history, observations, models and puzzles. Geological Society of America Special Paper 430, 553-591.

Whitaker, F.F. & Smart, P.L. (1997) Groundwater circulation and geochemistry of a karstified bank-marginal fracture system, South Andros Island, Bahamas. Journal of Hydrology 197, 293-315.

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‘Blow, blow thou watery wells’ (with apologies to W. Shakespeare!)

By Charles Hiscock

On a cold winter’s day on the coast of Lincolnshire when a north east wind blows off the grey North Sea, the correct title of William Shakespeare’s poem from ‘As You Like It’ is very applicable. However, with apologies to Shakespeare, the first line of the poem came to mind on another visit to the Tetney Blow Wells and immediately became ‘corrupted’ to give the title of this article.

The village of Tetney is situated 6 miles south of Grimsby and 3 miles inland from the sea wall from Immingham south to the Wash that protects this low-lying stretch of coast. In an otherwise almost flat expanse (in spite of the caravan site nearby being called ‘Windy Ridge’) the superficial tidal flat deposits of clays and silts are intensively farmed as in fig. 1 which shows two clumps of trees and the distant Lincolnshire Wolds.

Fig. 1 Trees at Tetney Blow Wells and distand Wolds

The area of tall trees, mainly aspen and willow with a few oak and birch, surround a number of pools and marshy ground within which are the Tetney Blow Wells, major artesian springs with an interesting and surprising geological explanation. In an area of about half a square mile there are four large pools, each surrounded by marshy ground and reed beds filled with pale blue slightly cloudy water. Between 1948 and 1961 the wells were cultivated as watercress beds but there is little of this left except for watercress growing in the pools, waterways and some concrete. At one point in each pool a sluice siphons the water off into the Anglian Water Companies water supply, each sluice being clearly marked with a sign saying ‘Deep Cold Water. No swimming. Hazards include Entrapment. Drowning. Shock. Weil’s Disease’! (fig. 2).

Fig. 2 Safety sign by Well 3

The water flow from each pool is significant as judged by the current that noisily flows under the metal grids over each sluice and even after the very dry summer of 2018 the flow did not seem to have diminished compared with previous visits (fig. 3). These springs are not the only supplies of water to well up through the Pleistocene clays but they certainly are one of the most significant, so much so that the area was one of the first to be designated an SSSI by the Lincolnshire Wildlife Trust soon after its foundation. The Blow Wells are an important nature habitat particularly for birds migrating across the North Sea. During a visit in October 2018 numerous large flocks of the ‘winter thrush’, the Fieldfare, were seen around the trees feeding on the abundant hawthorn berries. In the warm autumn sunshine, numerous dragonflies and damselflies were skimming over the reed beds. In an earlier springtime visit the trees were alive with Chiffchaff, Willow Warbler, Blackcap and resident species such as Chaffinch, Goldfinch, and Greater Spotted Woodpecker while ducks and grebes were seen on the water. In the extensive reed beds Sedge Warbler and Reed Bunting are regularly seen. The meadow areas support profuse cowslips in spring and are cut later for hay to preserve the flowers.

Fig. 3 Blow well 4