FRIENDS OF VULKATHUNHA-GAMMON RANGES NATIONAL PARK

BOLLA BOLLANA BOULDER BEDS.

GEOLOGICAL HISTORY FROM 720 MILLION YEARS AGO

PRESERVED IN THE WEETOOTLA GORGE

A geological guide by Peter Briggs

The brown outcropping Bolla Bollana formation that forms the Weetootla Gorge

As you hike into **Weetootla Gorge**, some of the rock boulders you will see in the creek bed and in the cliffs of the Gorge itself are unusual in that they contain a mixture of different rocks and boulders within a broader mass or matrix, as seen in **Photo 1**. In the Gammon Ranges we have one of the best examples of this type of formation in the World.

Photo 1 Mass of different cemented boulders

These rocks are part of the **Bolla Bollana Formation**, a world-renowned example of a massive Sturtian Glaciogenic deposit. **The Pan Sturtian Glaciation** began ~717–660 million years ago and lasted ~57 million years, the longest known ice age in Earth's history. It was considered the first major **Cryogenian glaciation**, and is thought to have been a near-global "Snowball Earth" event with ice almost reaching equatorial regions. Its geographic record is particularly well-preserved here in the Gammon Ranges. Similar Sturtian glacial deposits have been recorded around the world on every continent except Antarctica.

The climate around this time was freezing and hence is called the **Cryogenan Period** (720 – 635 My). Practically the whole Earth was covered in ice sheets, giving the impression of a snowball Earth. Instead of a blue sphere when viewed from space, the Earth appeared as a white snowball. **Mid–Cryogenan** is referred to as the **Sturtian Glaciation** period. The rocks at the base of the Sturt Gorge at Eden Hills, the **Sturt Tillite,** also formed at this time.

Another later glaciation period lasting ~15 million years, called the **Marinoan Glaciation,** represented by the **Elatina Formation**, began later, ~650–635 million years ago, the second Cryogenian glaciation, and the last before the **Ediacaran Period**. It was also considered a "Snowball Earth," but possibly less severe and shorter-lived than the **Sturtian**.

These two periods spanning 72 million years of widespread glaciation separated in between by 10 million years, are well represented here in South Australia. Since we have globally significant examples of both, it gave rise to the local naming of these two Global Geological Periods.

The **Bolla Bollana Formation** is an exceptionally thick example of this type of glacial deposit (1500 metres) and was first recognised by *Douglas Mawson* in 1941 & 1949, later studied by *Dr Vic Gostin & G. M. Young (1991), Wolfgang Priess (2011) and D.Heron, M.Busfield and A. Collins in 2013*. All have contributed as source material for this guide.

Closer study of the rocks encased in these rocks reveals a variety of types and sources. One will find **Sandstones**, **Quartzites**, **Metasiltstones**, **Gabbros**, **Granites**, **Dolerites** and **Basalts**. This collection of rocks has been scoured and scooped up by moving Ice Sheets over hundreds of square kilometres and then funnelled into a lake or marine environment. Some rocks show scratch marks or lineations due to movement by the ice sheet, while others have been rafted out enclosed in ice bergs, floated out into lakes and later seas, which then melted and dropped their rock load.

Photo 2 Outcropping Bolla Bollana Formation in background and foreground

The Bolla Bollana formation is identified as being the large dark brown cliff outcrops on either side of the gorge which extend at least a kilometre or more (**Photo 2).** Inspection of the outcropping rocks in the first km of the trail path, reveal Bolla Bollana Formation rocks, some classified as **Diamictite** or **Tillite**. An explanation of these two terms is given later. The boulders contained within Bolla Bollana have origins ranging from Sedimentary, Metamorphic to Igneous, both Intrusive and Extrusive.

Photo 3 Mt Fitton Formation

Soon after the beginning of the walk into the gorge from the trail head, one walks over a fault associated with the **Paralana Fault**, a major fault in the region that can be seen at **Italowie Gorge** and continuing all the way up to **Paralana Hot Springs**. The fault separates **the Angepena Calcerous siltstone** (rocks in hills next to Balcanoona Station and at the Bonython Lookout), and the **Mt Fitton Formation** (**Photo 3**). The Mt Fitton Formation is only approximately 20m wide here, and is possibly a deep freshwater lake deposit before glacial sediments poured in off the land.

Photo 4 Angular crushed fault breccia, Mt Fitton Sandstone. Paralana Fault,

Movement along this fault has created a fracture zone with broken sharp jagged fragments jumbled up and recemented together.

Photo 4. This is called fault breccia and although it looks similar to the Bolla Bollana rocks, its origin is not Glacial. Notice that the fragments are sharp and angular indicating that they have been broken up in-situ and have not been transported.

The following is a selection of different rock types found in the Bolla Bollana Formation can easily be found in the creek beds and in the outcrops that make up the gorge. Normally the rocks and boulders present in creek beds represents the surrounding landscape rock geology, which is the case here, but there are also rocks within rocks in the Bolla Bollana. These rocks did not originate in the surrounding geology but come from afar.

Photo 5 Diamictite boulder lying creek bed opposite the camp ground.

Photo 5 is a mass of different boulders collected up by a moving ice sheet. These would have accumulated at the nose of a glacier and pushed forward by its slow movement. This is called a **glacial moraine**. Eventually it gets pushed into a water basin, tumbling down the edge, getting mixed up and enclosed in fine sediment which finally acts as the matrix cement.

Geologists call a rock mixture like this a **Diamictite**, which is a descriptive term and refers to a poorly sorted sedimentary rock with a wide range of grain sizes, from clay to boulders, all embedded in a finer-grained matrix. **Diamictites** can form from many processes: glacial action, submarine mass flows and volcanic debris flows, whereas a **Tillite** is a special type of Diamictite formed by glacial action.

Photo 6 Brown iron stained vesicular Basalt boulder with trapped air bubbles, found in the creek opposite the campground..

Photo 6 is vesicular **Basalt** boulder (Igneous intrusive) enclosed by a mudstone matrix. Weathering of the iron minerals (Olivine & Pyroxene) give a brown surface stain. Also visible are small trapped gas bubbles (vesicles) as the basalt quickly cooled. It also has angular edges, suggesting it has not been transported by tumbling down a river but dropped by a floating ice berg into the muddy sediment. This would make it a **Tillite.**

Photo 7 Protruding Granite boulder with pitted weather surface, 1km into gorge.

Photo 7. This protruding rounded **Granite** boulder is of Intrusive Igneous origin and like all the boulders seen, must be older than the rock it sits in, which is estimated to be 717 My. Its surface is pitted from recent weathering with the typical orange-brown staining found on exposed granites. The boulder shape is also typical of granite boulders, splitting along orthogonal joints. This boulder was scooped up by a moving ice sheet and incorporated into the ice, only later to be released after moving many kilometres when the ice melted.

Photo 8 Tillite with different dropstones, in creek bed opposite campground

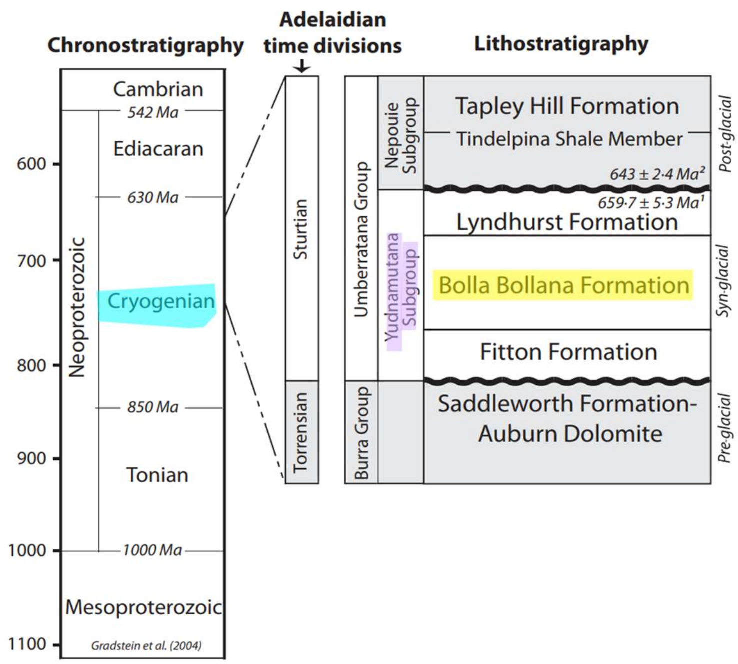
Photo 8 shows a fined grained green/grey mudstone/siltstone embedded with five different boulders that appear to have dropped from a floating ice berg. These **dropstones** have distorted the once horizontal bedding by their impact. Look at the curvy bedding that bends around the large **quartzite** boulder at the base. There is also a mid-sized **granite** boulder and a darker pinky **quartzite** boulder above that. In the middle right of the boulder are rounded Olive-green **Dolerites** (Intrusive Igneous) boulders. All these boulders have completely different geological origins, meaning that they have been gathered up by the ice sheet over many square kilometres. All these features have been outlined in white in the photo.

Photo 9 Rounded sandstone boulder with striations, in gorge wall.

Photo 9 shows a rounded **sandstone** boulder with a number of scratch marks caused by being dragged over a rough surface by the ice sheet. These are called **striations**. Solid rock at the base of the glacier which remains in-situ also suffer striations caused by the moving above ice sheet. These are seen at Hallet Cove and Glacier Rock in the Inman Valley, and are called striated glacial pavements. They indicate the movement direction of the ice sheet.

GEOLOGICAL ORIGINS AND ENVIRONMENT FOR THE BOLLA BOLLANA FORMATION

The following is a geological description of how this massive Bolla Bollana glaciogenic formation came into existence some 700 million years ago when Australia was still part of a supercontinent called Rodina.



In the stratigraphic the **Bolla Bollana Formation** sits in the middle of the **Yudnamutana Sub-Group.** Its equivalent in the Adelaide region is the **Sturt Tillite** at Eden Hills. Above it is the **Lyndhurst Formation** and then the **Tapley Hill Formation** which is seen in the cuttings of the Southern Expressway at Darlington. Below it is the **Mt Fitton Formation** seen 100m from the start of Trail head and then the **Saddleworth Formation** (not seen here), which is present in cuttings of the SE Freeway as it ascends to Crafers.

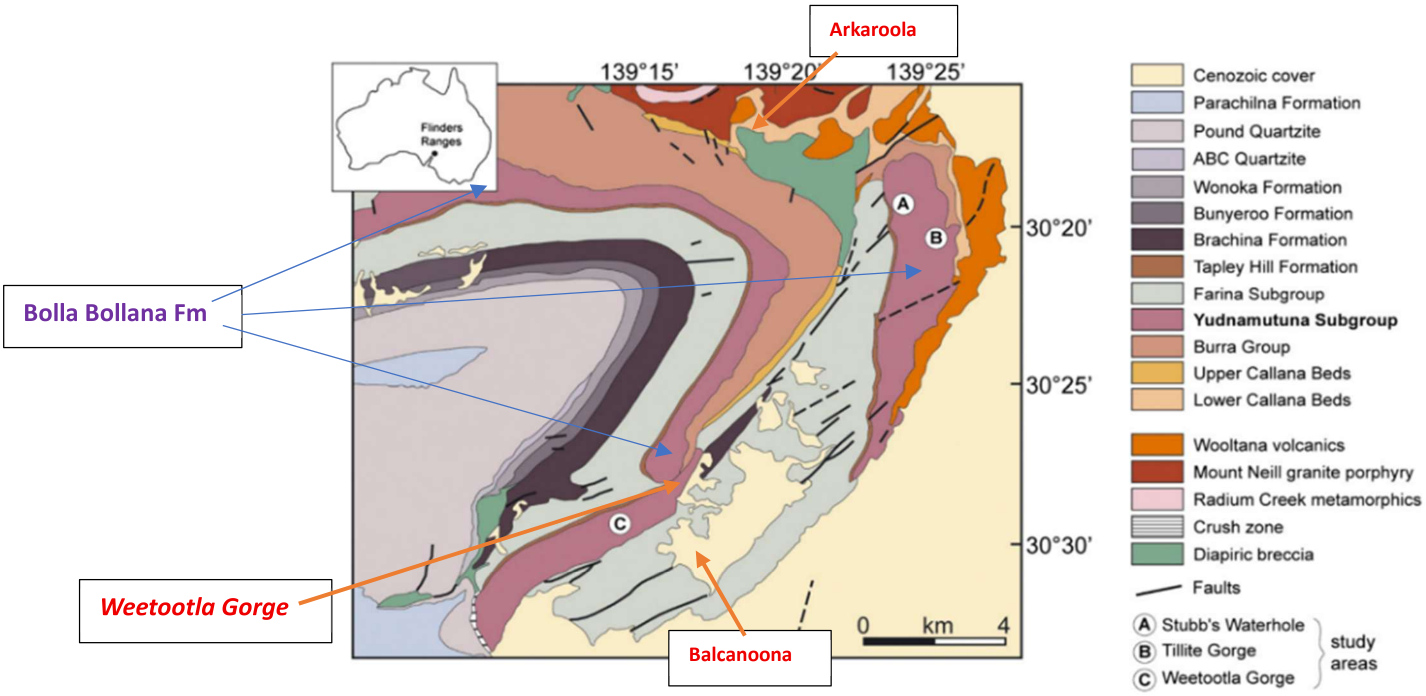


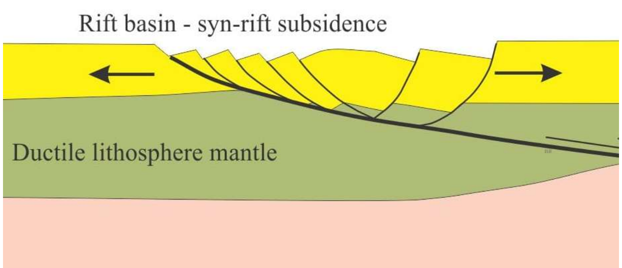
Fig. 1. Geological sketch map of the Arkaroola region (modified and simplified after Coats, 1973). Note the location of the Tillite Gorge, Stubb's Waterhole and Weetootla Gorge sections which are shown in Fig. 4.

The **Bolla Bollana Formation** is coloured purple on the map and being on the eastern rim of a syncline, as it arcs around. It also appears in the Arkaroola area, best seen in **Stubbs Waterhole** (A) and **Tillite Gorge** (B)

In the field of Geology, it is regarded as a globally significant formation and forms the **'Type'** section for this unit in the global stratigraphic register. The outcrops appear as a solid jumble of rocks grading from small pebbles to large boulders held together by a matrix cement of finer sediment. This could represent an underwater landslide where a mass of debris has tumbled down a slope to a more stable layer in the sedimentary basin. The trigger for this could be gravity after a rapid inflow of sediment, or an earthquake trigger. In both cases, there is a chaotic tumbling flow down a slope. These flows range from 1m to 20m in thickness, and subsequent later debris flows can stack up on each other. It is quite an energetic environment.

In the beginning

The origin of this formation began when the supercontinent **Rodina** was beginning to fragment (Continental Drift). Australia as a continent didn't exist then; it was part of a huge global landmass called **Rodina**. When a continent splits apart due to moving tectonic forces inside the Earth's mantle, it results in the brittle crust becoming stretched, then sagging, and then slipping down along faults (graben faults) to form rift valleys. In this area, a side rift valley trough developed as a sub-basin, to the larger **Adelaide Superbasin**. These rifts valleys act as accumulation basins for incoming water carrying sediment, and hence the beginnings of a

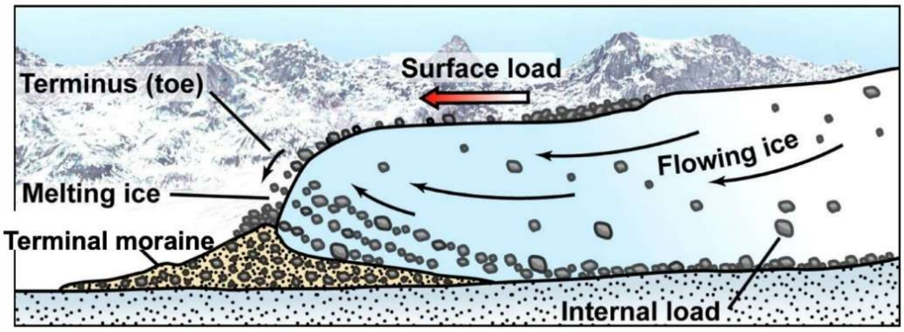


sedimentary basin. It began as a freshwater lake. St Vincent Gulf is an example of a present-day sedimentary basin. The **Adelaide Superbasin** is roughly 1,000 km long and up to 200 km wide, filled with up to 10–12 km of sedimentary rocks deposited between about 870 and 500 million years ago. These rocks now make up the Flinders and Mt Lofty Ranges. Its previous name was the **Adelaide Geosyncline**.

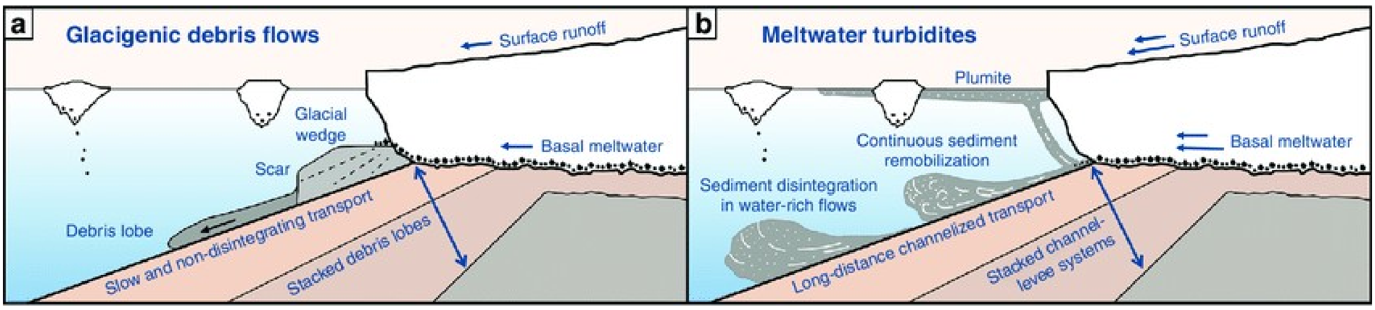
The **Arkaroola – Gammon Ranges** zone is thought to be a sub-basin off this main Super Basin, and it was into this sub-basin that the **Bolla Bollana Formation** was deposited in a time referred to as the '**Sturtian Pan Glacial event'**

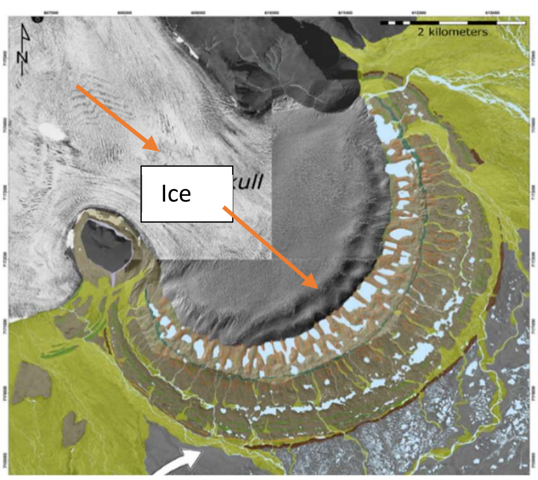
With this background in place, we can describe the **environment** that led to the rocks we find in **Weetootla Gorge.**

The sub-basin was at the edge of an ice sheet/glacier that was slowly moving towards it, melting when it reached the shoreline. It was most likely a freshwater and later a marine basin. Glaciers, driven by gravity as they slowly move to lower regions, are powerful eroding agents. So powerful in fact that they can carve out huge U-shaped valleys, plucking out rocks that later become incorporated into the glacier itself. The grinding nature of the moving ice sheet also creates gravels, sands, and rock flour, all the ingredients we see in the **Bolla Bollana Boulder Beds**.



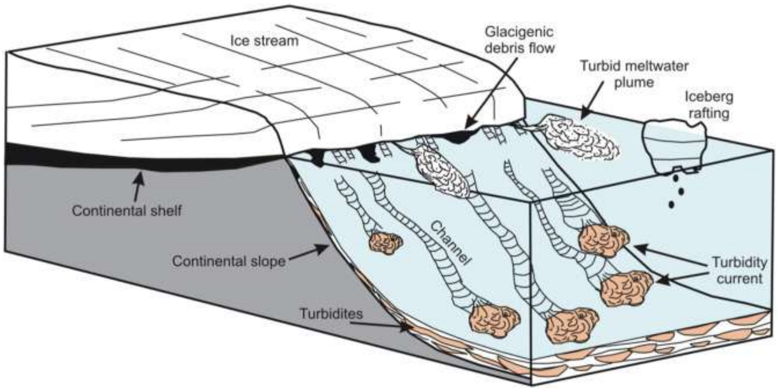
When this mixture of Ice and rocks/sediments moves to lower altitudes, it begins to melt, and the meltwater travels towards a depression (the sub-basin). The movement of the ice sheet also creates a build-up of rocks and boulders in the front of the glacier, called a **moraine**. The downward-moving ice is bulldozing this moraine at its toe. This movement of ice and moraine can flow all the way to the shoreline of the basin, where ice rafts can break off and float out to deeper water. A flow of fine sediments, rocks, and boulders into the basin, initially freshwater, but as it expanded it was transgressed by the sea, becoming **glaciomarine**. Driven by enormous amounts of meltwater, which fans out into the basin, these deposits are unusually thick, indicating a rapid, energetic depositional environment.





As the deposit fans out into deeper water, it slumps and slides downslope as a slurry called '**glaciogenic debris flow'.** Rather than a basin wide sheet flow, they are confined to fingering lobes that spread out and then regenerate in another direction. A sudden unstable movement caused by the buildup of sediments can result in a slip downwards as a chaotic flow. These remobilisations are called **Turbidty Currents** and result in a jumbling up of the sediments when they eventually come to rest. This produces a mixture of **clasts** and **lodestones** set in a mud matrix, which will produce the **Diamictite** rock.

Once settled, over time they compress, consolidate, and squeeze out water to form a **Diamictite** rock that we see today. Small fast-moving rivulets of meltwater also enter the basin, scouring out channels which later become filled with sands and muds. These channel deposits can be seen preserved in the exposed rocks.



As the front of the glacier pushes the **moraine debris** into the marine basin, large lumps of Ice can also break off and float out to sea. These icebergs would also contain rocks and boulders of all sizes that have been scraped off the land surface as the Ice sheet moved across it. This is called **Ice Rafting** of rocks and boulders. As they move out into deeper water, the ice melts, releasing the rocks and boulders, which immediately sink to the bottom where finer sediments (sands, muds, and silts) have been deposited. As the boulders drop into these finer sediments, their impact **deforms** the fine sediment layers. We call this type of Diamictite a **Tillite.**

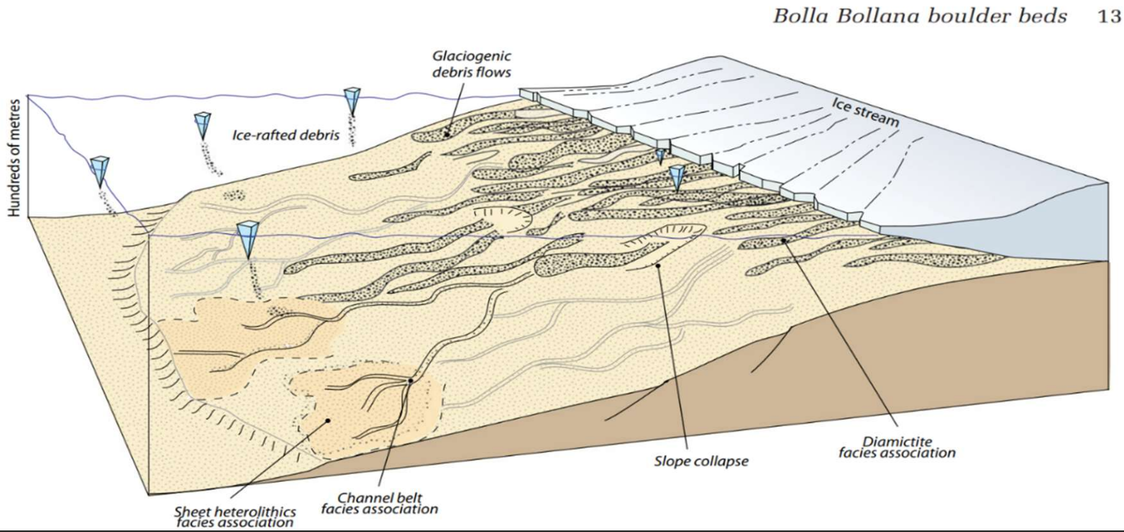
A **Tillite** is a genetic term and specifically refers to a lithified glacial till (i.e. a Diamictite that formed directly from glacial deposition). Characteristic features can include faceted and striated clasts (rocks), lack of sorting, and association with other glacial deposits (**dropstones**, **varve beds** (alternating seasonal deposited beds in glacial lakes from melting).

The Bolla Bollana Tillite contains boulders many metres across lying in a fine-grained sediment, being deposited by Ice Rafting (**dropstones**).

Quite clearly, this sedimentary sequence of rocks is distinctively different from common sedimentary rocks, which similarly contain a range of muds, silts, sands, gravels, and boulders (conglomerates), transported by rivers into an aqueous basin, with water being the main transport agent of erosion. The main **transport agent of erosion in the Bolla Bollana is both Ice and water**, making it a glaciomarine deposit.

In this environment, huge amounts of sediments and rocks (**moraines**) are being pushed into the basin, with extensive energetic meltwater, washing in debris and ice rafting of rocks and boulders. The weight of this massive, fast filling, and thick deposit can cause the sedimentary basin to subside even more. This, in turn, can create weakness in the underlying basin basement and, combined with tectonic stretching of the crust, causes more **graben faults** to develop at the same time as sediments are being deposited. This makes the basin sink further down, creating even thicker deposits. This accounts for the variation in thickness in **Bolla Bollana Formation**, with **Weetootla Gorge** being the thickest and **Stubbs Waterhole** and **Tillite Gorge**, north (see geological map) in the Arkaroola Conservation Area being less thick.

Given the extensive amount of time these icy conditions existed on the Earth's surface, the Ice sheet or glacier would have advanced and retreated into the sub-basin many times as climatic conditions changed, moving the deposition of glaciomarine back and forth.



Above is a simple depositional model of the Bolla Bollana Glaciomarine deposit. (Ref: **Sedimentology 2013.** *Bolla Bollana boulder beds: A Neoproterozoic trough mouth fan in South Australia? DANIEL P. LE HERON *, MARIE E. BUSFIELD * and ALAN S. COLLINS†.*

This is what you see in the rocks at **Weetootla Gorge**.

TILLITES: *masses of different types of rocks and boulders that have been dropped by floating Ice bergs into a fine-grained cement matrix. These boulders are called '**dropstones**' and will make a depression when they sink into the basin sediment*.

DIAMICTITES: *Similar to Tillites, but the rocks and boulders have been emplaced by gravity mud and debris flows into the basin, fanning out into the trough, plus, the pushing out of rock moraines into the basin when the ice sheet meets the water's edge. Later turbidity currents would add to this jumble of rocks.*

GRAVEL CHANNEL DEPOSITS: *Incoming excessive meltwater can carry in sands and gravels, which, by their erosive force, scour out previously deposited sediments. These later become infilled by sediments, are not obvious, and hard to find.*

SANDSTONES, SILTSTONES AND MUDSTONES*: Lesser energetic meltwater can carry these lighter, finer sediments out into deep water to produce sedimentary layers.* ***Dropstones*** *can sink into these. In addition, at the end of this period in time, when the ice sheet retreats, continuous meltwater carrying finer sediments can flood across the whole basin to give a blanket layer of conglomerates, sandstones, siltstones, shales, and* ***dolostones*** *(dolomite). Interestingly, the final topping of dolostones indicates perhaps a warming of the climate, as these are formed by the precipitation of calcium, magnesium carbonates. Not seen at Weetootla.*

Keep a lookout for these rocks the next time you walk the Weetootla Gorge.

Acknowledgements: The development of this guide was assisted by Henry Pecanek and Julian Evanochko in the field work.

Ref: **Sedimentology 2013.** *Bolla Bollana boulder beds: A Neoproterozoic trough mouth fan in South Australia? DANIEL P. LE HERON *, MARIE E. BUSFIELD * and ALAN S. COLLINS†.* An Informative paper used in forming this guide, plus a few general diagrams sourced from the internet.