NOTE: The text below was contributed by officers of the Department of Mines and Energy (MESA) to *Explore the Flinders Ranges* first published by The Royal Geographical Society of South Australia Inc. in 1995.

The legacy of time

Mountains never grow old, they simply fade away.
Douglas Mawson, geologist and Antarctic explorer

Visitors to the Flinders Ranges are invariably impressed by the majestic sandstone capped peaks, and the long, twisting ridges formed by upturned layers of rock in a rich diversity of colours. Ramparts such as Rawnsley Bluff and the Elder Range, the curious Great Wall of China, and the beautiful chasms of Alligator, Edeowie and Chambers Gorges have inspired painters, photographers and tourists. The beauty of the ranges provided backdrops for movies such as *Robbery under Arms*, *Bitter Springs* and *The Lighthorsemen*.

The Flinders Ranges have been shaped by geological processes that, over hundreds of millions of years, have built the stage upon which the drama of biological interactions is being performed.

The Flinders Ranges form part of a highland chain extending from Kangaroo Island in the south through the Mount Lofty Ranges and Flinders Ranges to Marree and beyond in the north, to Olary in the east, and to Spencer Gulf and Lake Torrens in the west. Like many other mountain chains, they began their history as a subsiding sedimentary basin.

During the late Precambrian era, the Earth's crust in South Australia consisted of granitic, metamorphic, sedimentary and volcanic rocks formed between 2600 and 1400 million years ago. In the present Flinders, the only rocks from that time are exposed near Arkaroola, including what are now known as the Freeling Heights Quartzite, Terrapinna Granite (Terrapinna Tors Walk) and Mt Neill Granite. Rocks that now constitute the eastern states of Australia were yet to form and the ancestral Pacific Ocean may have had its shores in South Australia. To the south, Australia was still joined to Antarctica.

The main area in South Australia then lay west of an approximate line from Adelaide to Oodnadatta; a smaller one existed in the vicinity of Lake Frome. The intervening area, where the Flinders and Mount Lofty Ranges now stand, became a long-lived basin known as the Adelaide Geosyncline, in which sediments accumulated 800 to 500 million years ago.

A great depression

The formation and evolution of the Adelaide Geosyncline are still only partly understood. Initially stretching and thinning of the Earth's crust below this region formed depressions, which developed into a series of troughs that eventually were invaded by the sea. With no vegetation to protect the adjacent land masses from violent storms, large volumes of rock debris were washed into the shallow seas and lakes of the geosyncline to form sandy plains, alluvial fans and river deltas.

Different parts of the basin floor subsided at different rates, accompanied by faulting, so that sediment type and thickness varied—from hundreds of metres to many kilometres. The older basement, which formed the basin floor, is exposed only around Arkaroola. Above this basement granite are the oldest sediments—the Paralana Quartzite and limestone of the Wywyana Formation.* Sediment usually accumulated at about the

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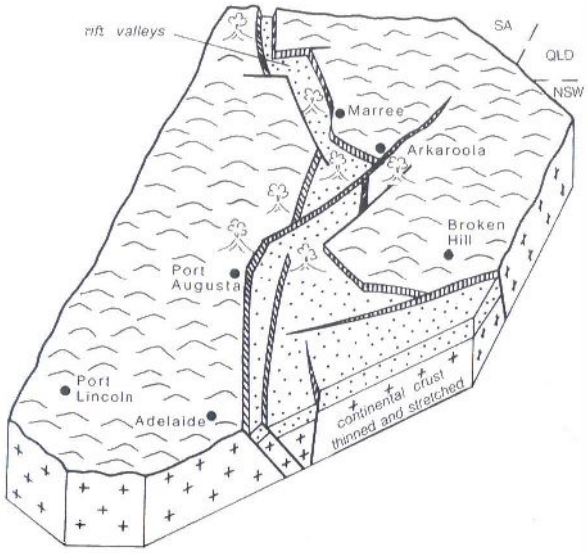
** Stratigraphic columns are helpful for following the sequence in which sediments were laid down.*

rate as the land subsided and water depth rarely exceeded a few tens of metres. The major faults shown on geological maps as flanking the Flinders Ranges had their origin at this time e.g. Paralana Fault (Italowie walk).

As stretching continued, the crust spilt in several places about 800 million years ago, allowing molten rock to come to the surface through fissures and vents (volcanoes). The best examples of the resultant lavas are now exposed as the Wooltana Volcanics near Wooltana and on Arkaroola near Bararrana Gorge and on the Echo Camp road. Other volcanics occur near Port Augusta and Marree.



Stretching and thinning of the earth's crust formed depressions and rift valleys that were invaded by the sea. Molten rock came to the surface through volcanoes and fissures. (MESA)

Sedimentation resumed with sand and gravel, which were later consolidated to form the Humanity Seat Formation and Blue Mine Conglomerate. Sand and lime deposited in a near-shore environment were later consolidated into the Wortupa Quartzite and Opaminda Formation Acacia Ridge Walk. In the deepest parts limy (calcium carbonate) and dolomitic (calcium magnesium carbonate) minerals were chemically precipitated from calm lake and marine waters (as continues today in the Coorong lagoon), when no eroded material was carried into the basin. The characteristic Skillogalee Dolomite, so well exemplified on Arkaroola (Oppaminda-Nudlamutana Walk), developed at this time, and the included magnesite (magnesium carbonate) is now mined at Witchelina for the manufacture of refractory bricks.

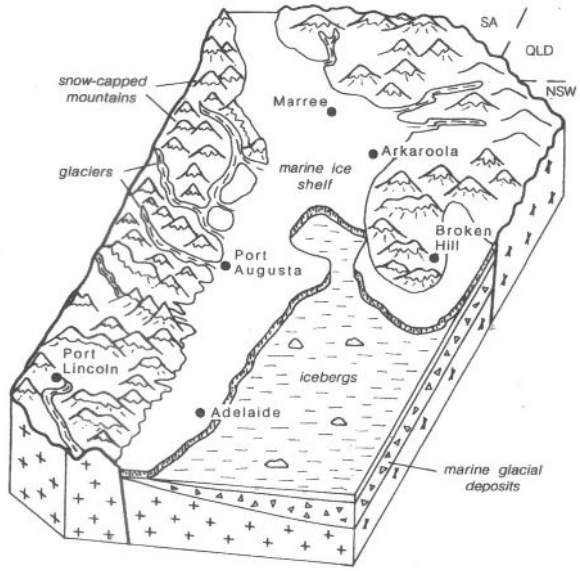
The only life at this time were bacteria and 'blue-green algae' (Cyanobacteria) that formed dense mats and laminated mounds and columns known as stromatolites (still forming in lakes in Innes National Park, Yorke Peninsula and at Shark Bay in WA). Examples of fossil stromatolites occur near the town of Melrose, in the Flinders Ranges National Park and in many other places in the Flinders (Haywards Huts and Wilkawillina Walks).

Two ice ages

A severe climatic cooling about 700 million years ago caused a major ice age over much of Australia. Glaciers, possibly joining to form a continuous ice sheet in the Lake Frome region, disgorged their loads of scoured rock debris into the sea. These sediments consist of thoroughly mixed clay, silt, sand, pebbles and boulders with little sedimentary layering. Icebergs dropped occasional boulders into fine-grained marine sediments.

Later consolidation of glacial debris formed a sedimentary rock known as tillite, which is well-preserved and spectacularly exposed in the northern Flinders Ranges near Arkaroola and in Vulkathunha-Gammon Ranges National Park, where Bolla Bollana Tillite reached a maximum thickness of 3 km (Weetootla and Italowie Walks). Tillite is also widespread from eastern Kangaroo Island and Fleurieu Peninsula, throughout the Mid-North, to the Olary region in the north-east.

The duration of glaciation is not known, but a warming of the climate led to the melting of ice sheets and renewed marine inundation of the landscape. The highlands west of the



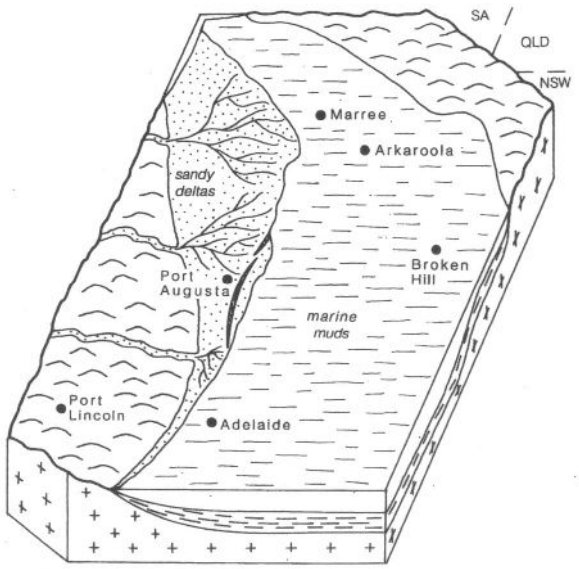
Glaciers, sometimes forming an ice sheet, disgorged loads of scoured rock debris into the sea and icebergs dropped stones into marine sediments, which became consolidated to form tillite. (MESA)

geosynclines had by now been levelled and the sea was able to extend far west of the present Lake Torrens. Black silt, rich in fine organic material derived from algae and bacteria, was deposited as laminations (each less that 0.5mm thick) in the calm shelf sea. The total thickness of this silt blanket (known as the Tapley Hill Formation) (Weetootla Geology Walk) increased from a few tens of metres in the west to about 3km in the ranges east of Hawker, around Holowiliena Station. Here depth of water and rate of subsidence of the basin floor were greatest. As silt built up, the water around the margins of the basin became shallow enough for stromatolites and oolite banks to form; these are exposed near Port Augusta and Balcanoona.

A second though probably less severe, ice age occurred about 650 million years ago, again associated with a drop in sea level. Tillite deposited at this time is exposed in Etina creek, where it is crossed by the Bunyeroo-Wilcolo walk and the Heysen Trail (Haywards Huts, Trezona circuit).

Remarkable events

Again melting of ice sheets caused a rise in sea level and the whole basin was inundated. A widespread blanket of silt and clay extended from near Kingoonya across the entire eastern half of the State, later to become the Brachina Formation. Deposition of these fine grained sediments was briefly interrupted by sandy deltas once again building out from the rivers flowing east from high land in the west. These sediments now constitute the ABC Range Quartzite exposed throughout the Flinders Ranges, notably in the ABC Range on the eastern flank of the Aroona and Bunyeroo valleys in Flinders Ranges National Park.



Late in the development of the Adelaide Geosyncline sandy deltas built out from easterly flowing rivers. (MESA)

With renewed marine flooding came the deposition of the fine-grained silts which later became the red shales of the Bunyeroo Formation. These uniform shales contain a remarkable rock debris layer, only a few centimetres thick, which is evidence of a huge meteorite impact on northern Eyre Peninsula (see *The space connection* at end). Later, limy mud and silt were deposited on top of the Bunyeroo Formation, resulting in the calcareous rocks (Wonoka Formation), which form a characteristic white-weathering band that can easily be traced around the outer slope of Wilpena Pound and at the foot of the Heysen and Elder Ranges.

Another remarkable feature then developed in the Flinders Ranges region. Submarine 'canyons', some over 1 km deep, were cut into the sea-floor sediments by currents and underwater landslides; these were also filled with limy mud and silt of the Wonoka Formation. They may be easily seen in satellite photographs, but they are not easily observed on the ground. There is one at the foot of Mount Brown (crossed by Mount Brown Summit Walk) and another near Patsy Springs is crossed by the road from Copley to Arkaroola.

About 600 million years ago, red then white sand sheets were deposited as the rate of sedimentation caught up with the rate of subsidence, almost to exclude the sea from the Central Flinders area. The beach-like ripple marks now so evident in some place are an indication of the shallowness of the seas. The resulting red sandstone (Bonney Sandstone) can be seen at the base of Wilpena Pound where it is exposed near the Chalet. The white sandstone, known as Rawnsley Quartzite, forms the highest peaks of the Flinders Ranges, such as St Mary Peak, Mount Aleck and Benbonyathe.

Some of the white sand was deposited rapidly, probably by storms, thereby trapping and preserving some of the oldest known animals on Earth—the Ediacara fauna.

The sea withdrew completely from the Adelaide Geosyncline at the end of the Precambrian era and terrestrial erosion occurred for an unknown length of time. When water again flooded in during the Cambrian period about 540 million years ago, abundant animal life had already evolved, including mollusks, brachiopods, and the extinct sponge-related archaeocyaths; characteristic trilobites appeared soon after. These animals lived in shallow-marine, lime-precipitating environments; their fossil remains are now preserved mainly in limestone; see for instance, the outcrops of Wilkawillina Limestone near the western end of Brachina and Parachilna Gorges and in Wilkawillina Gorge (Wilkawillina Walk).

About 520 million years ago, sheets of silt and sand largely coloured by red oxides of iron, flooded in from the exposed margins of the Adelaide Geosyncline. These, its youngest sediments, accumulated to several kilometres in thickness and are preserved as siltstone and sandstone south of Wirrealpa in the Grindstone Range, Prism Hill and Reaphook Hill.

The mountains emerge

Sedimentation ended when major movements and heating within the Earth's crust began about 500 million years ago. By now the accumulated sediments had been compacted and cemented to form sedimentary rocks (mudstone, siltstone, sandstone, conglomerate, tillite) 10-15 km thick. Movement of the original stable land masses of the Lake Frome region and west of the Flinders caused buckling and upthrusting of rocks.

Sinuous ridges, such as those west of Hawker around Warren and Buckaringa Gorges, saucer-shaped structures such as Wilpena Pound, and domes like that at Blinman, had their origin at this time. The landforms seen today result from deep erosion of these structures. Thus, the variously-coloured rock layers now seen in the Flinders Ranges are cross-sections through the different sedimentary rock types originally laid down as successive layers on the sea floor. The buckling that began 500 million years ago has in many places tilted the layers so that they are nearly vertical (e.g. Warren Gorge) or inclined (e.g. Brachina and Bunyeroo Gorges where the youngest layers are at the western end and the oldest in the east).

Faulting was another result of the crustal movements. Small faults can be seen throughout the Flinders Ranges today, but the largest are hidden by alluvial fans where the ranges rise dramatically out of the plains. Faults that originally caused the troughs to form during the Precambrian era underwent reversal of movement, now uplifting rocks of the geosyncline.

Soft ductile sediments near the floor of the troughs were so severely squeezed that they became plastic and flowed upwards and outwards in massive bodies known as diapirs.

Brittle rocks were broken into fragments ranging in size from less than a millimetre to hundreds of metres; the broken rock is known as breccias. Blinman Mine is located on a copper ore body within one massive breccia-block of a diaper. The usually soft and broken nature of the rocks often gives diapirs in the Flinders a subdued topography. This is best seen immediately east of Oraparinna and in the well-known Hills of Arkaba.

Further north at Arkaroola, molten rock intruded the ancient rocks of the basin floor to form the granite exposed on Mawson plateau, which is now juxtaposed against the very ancient quartzite of Freeling Heights.

Sweeping plains . . . and ragged mountain ranges

Thus the ancestral Flinders Ranges were born. But weathering and erosion immediately began to reduce the mountains as they arose. Large rivers carried away vast amounts of eroded rock, to feed developing sedimentary basins in eastern Australia. The land surface was lowered by several kilometres; for example the site of Blinman would have been originally covered by 5-6km of rock. The region south of Port Augusta was more deeply eroded than that to the north so that most of the upper sediments, sometimes to below that ABC Range Quartzite, have been removed even from the highest peaks such as Mt Remarkable. Most of this would have been removed before the Permian period (about 280 million years ago), when debris from another ice age was dumped locally on the landscape.

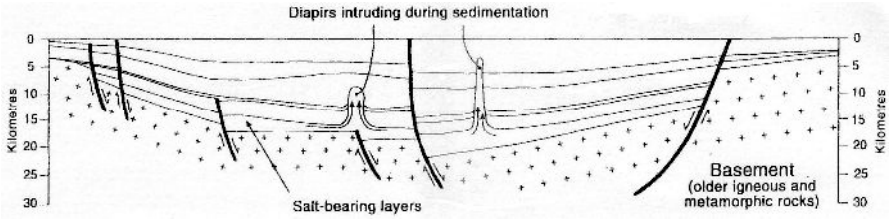
By the Mesozoic area (230 to 65 million years ago), the climate was generally warmer and wetter than today and the ancestral ranges had probably been weathered to a low, gently undulating landscape. Coal seams formed from the dense vegetation in mostly fresh-water lakes and swamps within and around the ranges. The best known at Leigh Creek where coal, accumulated about 170 million years ago, now provides much of the State's electricity from power stations at Port Augusta,

Approximately 140 million years ago the sea inundated large areas of central Australia for over 60 million years to form the Great Artesian Basin. Here sand and mud accumulated from rivers draining the subdued Flinders Ranges and other areas. These sediments contain numerous fossils such as molluscs, wood, and locally, marine reptiles such as plesiosaurs and ichthyosaurs.

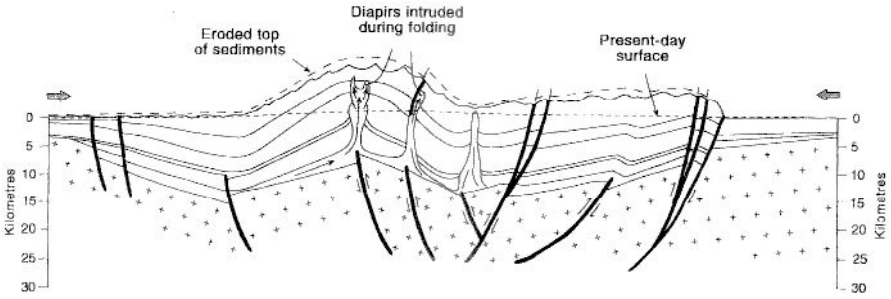
Earth movements related to the breakup of Australia from Antarctica then caused further uplift of the ancestral ranges. During the last 40-50 million years, the Flinders Ranges have been rising steadily, and persistent small earth tremors in the region indicate that this is a continuing process. During uplift, softer rocks such as mudstone were eroded to form valleys while harder rocks such as sandstone remained as peaks and ridges. The highest peaks around Wilpena Pound and in the Elder, Chace, Heysen and Gammon Ranges have formed where resistant stone layers were thickest. The present spectacular canyons such as Brachina, Bunyeroo and Parachilna Gorges were cut through the ridges where streams exploited joints and small faults in the sandstone layers.

As weathering proceeded, eroded material accumulated as sediments which are preserved beneath the Willochra and Walloway Plains. Lakes Frome, Torrens and Eyre are isolated, dehydrated remnants of former larger lakes that deposited clay and dolomite around the periphery of the Flinders Ranges between 30 and 2 million years ago.

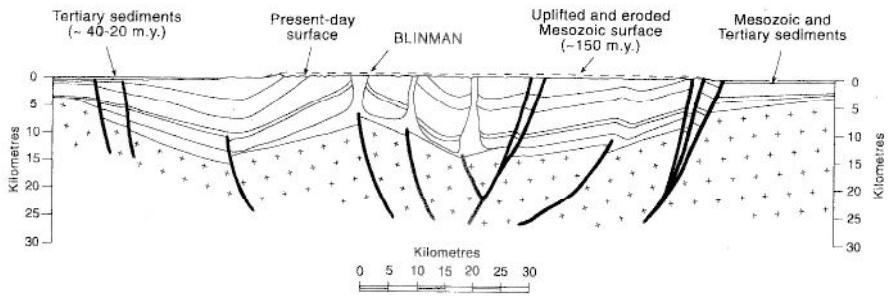
What of the future for the Flinders Ranges? The rocks are being weathered, and eroded during heavy rainfall. The debris is being deposited on the surrounding plains, thus gradually levelling out the difference between the peaks and the plains. At the same time crustal movements continue to push up the ranges. If uplift ceases at some time in the future, the Flinders Ranges will eventually again be reduced to a subdued topography such as they have had in the past.



Section showing sediments in the geosyncline compressed to form sedimentary rocks with developing faultlines.



Section showing rocks being folded to form high mountains



Section showing profile of the Flinders Ranges as they are today.

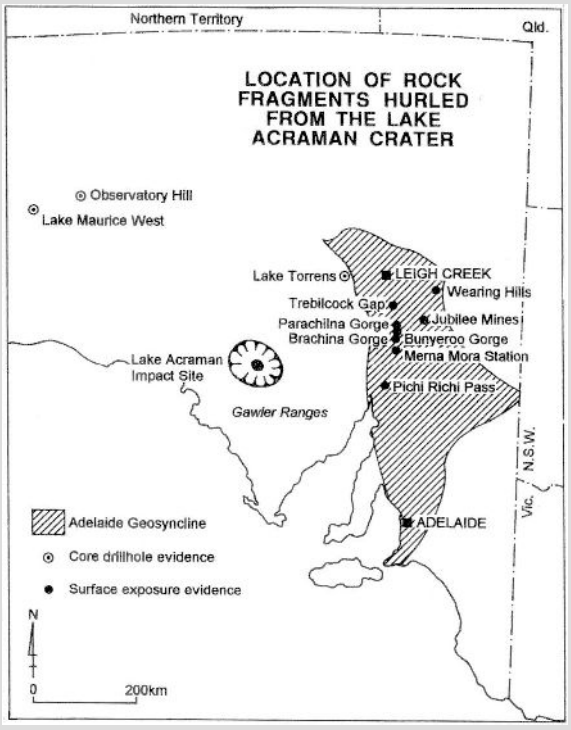
The space connection

Scientific detective work during 1983 by geologist Dr Vic Gostin and his colleagues revealed a surprisingly continuous layer of volcanic rock debris throughout much of the Flinders Ranges. The layer ranges in thickness from 0.4m in Brachina Gorge, where rock fragments (or clasts) are up to 0.3m across, to only a few tens of millimetres in the Wearing Hills 100km to the east, where the rock fragments are the size of coarse sand. The thinning of the layer and decrease in size of the fragments towards the east suggested that the debris had its origins in the west.

The fragments are of similar composition to volcanic rocks found in the Gawler Ranges, hundreds of kilometres to the west on Eyre Peninsula. Even more intriguing is the age of the rock fragments – 1575 million years – and this within sedimentary rocks that were deposited only 600 million years ago.

Another Adelaide geologist, Dr George Williams, suspecting he had the answer to this puzzle, examined newly available satellite pictures of Eyre Peninsula. In 1985 he found that Lake Acraman a lonely salt lake in remote northern Eyre Peninsula, is surrounded by a series of concentric rings ranging in diameter from 30 km to almost 160km. He knew that rock samples from the lake contained structures known as shatter cones, and microscopic examination of the rock had revealed irrefutable evidence of intense shock deformation. The jigsaw could now be reassembled and the complete picture revealed

Approximately 600 million years ago, sediments of the present Flinders and Mount Lofty Ranges were being deposited in a shallow sea that covered much of eastern and north-western South Australia; Eyre Peninsula as we know it, with its very much older rocks, was above sea level. At that time an extraterrestrial object – asteroid, comet or meteorite – approximately 4 km in diameter and travelling at almost 100 000km/hr, plunged into the ancient volcanic rocks of the Gawler Ranges. The immense force of the collision blasted a crater at least 30 km wide and several kilometres deep. Rock not vaporized was hurled outwards at velocities several times the speed of sound, to splash down in shallow seas at least 500km away. Finer material and dust blown into the upper atmosphere probably took months to settle back to earth.



In the hundreds of millions of years that followed, this debris layer was buried by thousands of metres of marine sediment, folded then uplifted during development of the Flinders Ranges and finally re-exposed by weathering and erosion.

At the lake Acraman impact site, only the very roots of the crater remain below the level of the original crater floor – testimony to an immense explosion in South Australia before the Flinders Ranges existed.