A field guide to

THE GEOLOGY OF HALLETT COVE

First Edition

FIELD GEOLOGY CLUB OF SOUTH AUSTRALIA, INC.

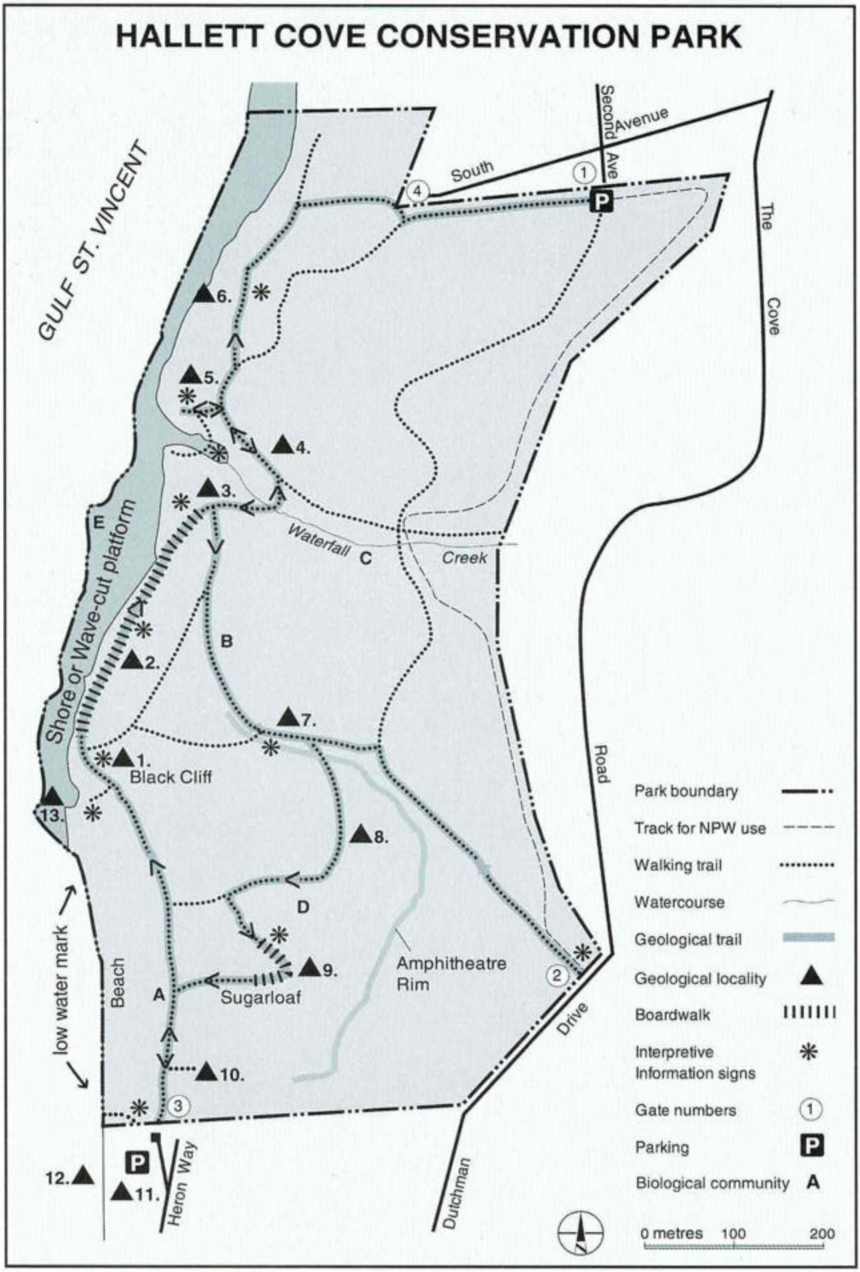

Figure 1: Sketch map of Hallett Cove Conservation Park showing car parks, entrances, walking trails and geological localities. (Modified from base map supplied by National Parks and Wildlife Service, 1997, reproduced with permission of Department of Environment, Heritage and Aboriginal Affairs).

KEY TO GEOLOGICAL LOCALITIES AT HALLETT COVE

IN THE PARK

Locality 1: BLACK CLIFF – Proterozoic siltstone and sandstone bedrock. Folds. Glacial Pavement.

Locality 2: ALONG THE CLIFF TOP WALK – Contact between bedrock and Permian glacial sediments.

Locality 3: GLACIAL ERRATICS – Quartzite boulders transported by Permian ice sheet.

Locality 4: WATERFALL CREEK – View of contacts between Proterozoic, Permian, Pliocene marine and Pleistocene alluvial sediments.

Locality 5: VIEW OF SHORE (WAVE CUT) PLATFORM – Contact between Proterozoic and Permian sediments.

Locality 6: SANDSTONE BLUFF – Fossil bearing Hallett Cove Sandstone. Contact with Permian sediments.

Locality 7: NORTH RIM OF THE AMPHITHEATRE – View of natural amphitheatre eroded in Permian glacial and Pleistocene alluvial sediments.

Locality 8: LEDGE OF HALLETT COVE SANDSTONE – Contact between Pliocene marine and Permian glacial sediments.

Locality 9: THE SUGARLOAF – Permian glacial sediments capped by Pleistocene alluvial clays.

Locality 10: GRADED BEDS IN PERMIAN LAKE SEDIMENTS – Turbidites. Ripple mark.

ALONG THE BEACH

Locality 11: LARGE ERRATICS – Rocks transported by the Permian ice sheet.

Locality 12: FIRST PERMIAN SEDIMENTS – Lodgement till and flow till complex. First glacial sediments.

Locality 13: SHORE (WAVE CUT) PLATFORM – Eroded folds in Proterozoic bedrock sediments.

KEY TO BIOLOGICAL COMMUNITIES

A: LOW COASTAL DUNES: Salt and wind-tolerant sandbinding plants

B: VIEW OF CLEARED LANDS: Kangaroo thorn and grasses. Revegetation with native trees and shrubs

C: WATERFALL CREEK: Bulrushes and sedges in alluvial sediments.

D: AMPHITHEATRE: Native and introduced trees and shrubs. Introduced grasses.

E: SHORE (WAVE CUT) PLATFORM: Invertebrates and algae colonising folded and eroded Proterozoic bedrock.

This book is dedicated to
MAUD McBRIAR
Patron of the Field Geology Club of South Australia Incorporated

and

passionate preserver of our geological heritage,
particularly that at Hallett Cove.

A FIELD GUIDE
TO THE
GEOLOGY OF HALLETT COVE
AND OTHER LOCALITIES WITH
GLACIAL GEOLOGY ON
FLEURIEU PENINSULA

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A Field Guide to the Coastal Geology of Fleurieu Peninsula 1986. P. Hasenohr and D.W.P. Corbett (eds).

A Field Guide to the Geology of Yorke Peninsula. Second Edition 1997. R. Giesecke (ed.).

Cover Photo: The Sugarloaf in the Amphitheatre at Hallett Cove – a conical hill of white, glacial sand from the waning stages of the Permian Ice Age (about 270 million years ago) overlying beds of red sands and clays with boulders deposited in a Permian lake of glacial meltwater and capped by brown alluvial sands and clay deposited in the Pleistocene age (about 1-2 million years ago). Photo: R Major

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USING THIS BOOK

Hallett Cove provides enjoyment for many, including walkers, students and natural historians. This book caters for those interested in the natural environment at Hallett Cove and provides an insight into the geological processes by which it developed – but it is not a highly technical book.

It describes Hallett Cove's geology with particular emphasis on its glacial history, using illustrations from localities which are easily accessible from the geological trail in the Park and on the beach. To provide as complete a story as possible photographs have been included from some areas in the Park which are not readily or safely visited. Two geological walks starting from the southern entrance to the Conservation Park (where there is a car park, some toilets and the picnic facilities of the Heron Way Reserve) are described.

There are three chapters to the book. The first might appeal more to the casual visitor for it provides a general overview – the big picture – of the Hallett Cove environments through time and the processes by which the landscape changed. The reader is able to view the successive landscapes through word pictures ('snapshots') with descriptions of the major factors which initiated the changes.

The second gives a more detailed description of the geology at various locations throughout the Park. These locations can be found on the walking trail map inside the front cover. This might appeal more to those who wish to understand how geologists determined what happened in the past, the story behind the spectacular scenery. The two chapters may be read in succession or independently. For this reason repetition between the two is intentional. Brief notes are also included on the vegetation throughout the Hallett Cove Park and on the invertebrate populations on its shore platform for those interested in natural history. However, visitors with a specific interest in identifying the plants would find it helpful to take with them the book *It's Blue with Five Petals – Wildflowers of the Adelaide Region* (Prescott, 1988) and read Darrell Krahenbuehl's book *Pre European Vegetation of Adelaide: A survey from the Gawler River to Hallett Cove* (1997) which gives an historical aspect to the clearing of vegetation in the area and describes the flora of the Conservation Park and the coastal cliffs to the south.

The third chapter, on other localities on Fleurieu Peninsula which have glacial origins and which share some of the geological history of Hallett Cove, complements the first two chapters. A road map is included to these popular tourist spots on the Peninsula and brief notes are given on their particular glacial geology.

To help the reader understand the meaning of geological terms used a glossary is provided on page 57. The events which were important to the evolution of Hallett Cove and the Peninsula are summarised inside the back cover.

The bibliography includes key references as well as a selected reading list of publications available on Hallett Cove and Fleurieu Peninsula geology.

PREFACE

In the century and a quarter since Ralph Tate discovered evidence of past glaciation at Hallett Cove, geologists and other scientists through their ongoing investigations, have come to recognise this small area, so close to the city of Adelaide, as a site of supreme scientific importance. Not only has it been the focus of detailed research, but also by virtue of the splendid exposure of key geological sections it provides an ideal open air classroom which has long been utilised by students at all educational levels.

In the late 1950s, when the development pressures around the margins of the Cove were already becoming apparent, the first moves toward conservation of the area were made and during the 1960s were to develop into a protracted and hard fought battle – a classic confrontation between the forces of conservation and development which only ended with the establishment of the Hallett Cove Conservation Park in 1976.

In what became the fight to save Hallett Cove no one fought harder than Maud McBriar, to whom this book is most fittingly dedicated. With her geological knowledge, keen negotiating skills and calm reason she has been a tireless advocate for preserving the geological integrity of the Cove. Her interest has been carried into the activities of the Field Geology Club and this book is a logical outcome of the Club's long involvement with the area and includes information from its own field trips to Hallett Cove and Fleurieu Peninsula as well as published research on the region.

In this book, as in its two earlier publications, *A Field Guide to the Geology of Yorke Peninsula (1976, and 2nd edition 1997)* and *A Field Guide to the Coastal Geology of Fleurieu Peninsula (1986)* the Club has distilled scientific knowledge into a form which encourages a greater understanding and enjoyment of our natural heritage.

David Corbett

ACKNOWLEDGEMENTS

This book represents contributions from many people who have an interest in Hallett Cove, its preservation, its tourist potential and its value as an open air classroom – not only in geology but also in other aspects of natural history.

The fragile ancient landscapes of Hallett Cove have been a source of interest and activity for the Field Geology Club, particularly since the mid 1970s when it became one of the many groups lobbying for the site to be preserved against suburban development. This new field guide is a logical outcome of that interest and involvement.

Responsibility for developing the book lay with the Publications Subcommittee chaired by Robin Giesecke. The provision of high quality photographs and illustrations was the work of subcommittee members Bob Major, Bob Whatmough, Dennis Rice, Jill Streich and Robin Giesecke. The text was developed by Robin Giesecke, Pam Hasenohr, Bob Major, Joan Rogasch, and Bob Whatmough. The complementary summary table showing the major geological events at Hallett Cove, on Fleurieu Peninsula and the Australian continent was the particular and exacting work of Dennis Rice. The sources of the information used in its compilation include *Hallett Cove, A Field Guide* (Cooper, H.M., Kenny, M. and Scrymgour, J.M., 1976), *The Management Plan for the Hallett Cove Conservation Park* (National Parks and Wildlife Service, Department of Environment and Planning, 1986), *Biology for the 1990s project, the Common Threads, Part 2* (The Australian Academy of Science, 1991) and *Australia Through Time* (Australian Geological Survey Organisation, 1998). Thanks are given to the publishers for permission to use that material.

Other members of the Club have contributed: Rex Hosking with a database of published work on the area, Brian Brock with notes on sites of biological interest at Hallett Cove, Maud McBriar with advice on conservation and Frances Williams and Cynthia Pyle for critically reading the final draft. Cynthia Pyle also provided the figure of turbidites (Figure 21). Francis Taylor drew Figure 10 which first appeared in the Club's publication *A Field Guide to the Geology of Yorke Peninsula*. Ray Hunt provided the photo of the rock platform (Plate 22). Club members also road tested an early draft of the book, providing comment on the style and sites for inclusion in the book.

Dr Neville Alley, Director of Mineral Resources in the Department of Primary Industries and Resources South Australia (PIRSA) and Professor Bob Bourman from the University of South Australia were willing and inspiring consultants throughout the production of the book. Artwork (Figures 2, 3, 12, 16) was provided by courtesy of PIRSA with technical assistance provided by Dr Alley, J. Drexel and B. Frost. Permission to use figures 8, 21 and 24 was given by Dr Alley and Professor Bourman. Their contributions are gratefully acknowledged.

Dr Allan Holmes, Director of Heritage and Biodiversity in the Department of Environment, Heritage and Aboriginal Affairs (DEHAA), and staff members P. Brennan and T. Gregory gave permission to use and modify artwork from that Department's publications, including *The Management Plan for the Hallett Cove Conservation Park 1986* (Figures 1, 7, 9, 17, 19), with advice on Hallett Cove Conservation Park and Sturt Gorge Recreation Park.

Jim Gehling, formerly of the University of South Australia, is thanked for his permission to use illustrations on the successive environments of Hallett Cove. (Figure 5). Dr Geoff Fraser, formerly of the Department of Geology and Geophysics at the University of Adelaide, is thanked for his photograph of an eastern Antarctic icescape (Plate 1 and back cover). Bill Lyne is thanked for permission to use his excellent photograph of crescentic gouges (Plate 2).

Opportunity to write a new field guide on Hallett Cove arose when the original field guide on Hallett Cove authored by Cooper, Kenny and Scrymgour and published by the South Australian Museum in 1976 went out of print. This book had been the most used and quoted guide to the area, introducing generations of South Australians to Hallett Cove. The word pictures and easily assimilated presentations of complex geological issues by June Scrymgour in this publication have remained educational models. In acknowledgement of their continuing value, excerpts have been included, with her permission, in this book ('Snapshots' 4, 5). The provision of her early research and photographic material from Hallett Cove is hereby acknowledged and her role in the early interpretation of Hallett Cove geology recognised.

Permission to use some of the clear diagrams (Figures 11, 12) from *The General Drift SASTA-ESTA Geology Revision Guide 1994* was given by the executive officer of the South Australian Science Teachers Association. Penguin Books are thanked for permission to use the portion (Figure 22) of their diagram of ripple marks from p.129 of *The Penguin Dictionary of Geology* (D.G.A. Whitten with J.R.V. Brooks, Penguin Books Ltd, Hermondsworth, Middlesex, England, 1972). Permission to use a modification of the Fleurieu Peninsula road map from Geological Society of Australia brochure *Pathways to the Past* was provided by Pam Hasenohr.

In the early stages of the book's development, comments were sought from a range of educators, tourism personnel and bookshop proprietors on the needs of their groups in such a publication. Comments provided by Stuart Nicoll of RAA, Bronte Nicholls of the State Secondary Schools Assessment Board and Lyn Schubert of the SA Museum bookshop were most helpful in this regard.

Significantly, thanks must also go to Maud McBriar for introducing Club members and many others to the fascination of Hallett Cove and the value of preserving South Australia's geological heritage as well as for her continuing advice and encouragement throughout the development of this book.

The input by all contributors was melded into this book with the assistance, advice and technical expertise of the staff of Gillingham Printers. Their role in producing a quality publication is acknowledged with thanks.

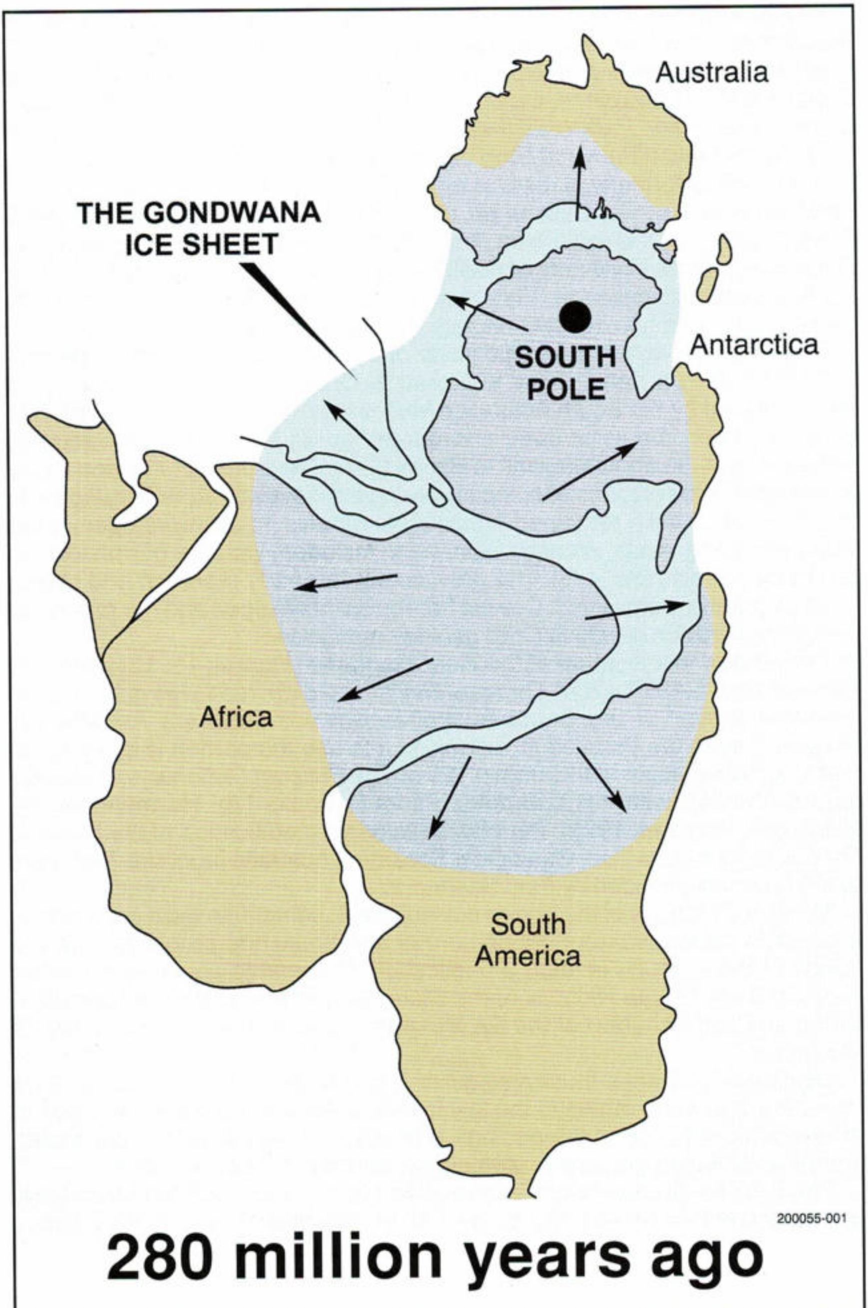


Figure 2: The second, or Gondwanan, ice sheet which moved on to Australia during the Permian Ice Age, 280 million years ago. (Courtesy: PIRSA).

INTRODUCTION

Three glacial periods (ice ages) have influenced South Australian landscapes and coastline. The first (Sturtian) occurred about 750 million years ago, the second (Permian or Gondwanan) about 280 million years ago (Figure 2) and the third (Great) peaked about 18,000 years ago. The first two of these occurred while Australia was part of Gondwana, the southern supercontinent, and left evidence in the rocks and landscapes of southern Australia. The third occurred after Australia had separated and drifted northwards. In the southern hemisphere the major effect of this ice age was a change in sea levels and corresponding alterations to the coastlines of Australia in the Pleistocene times.

Evidence that glacial ice had moved on to the Australian continent was first found at the site known as Glacier or Selwyn's Rock, in Inman Valley on Fleurieu Peninsula, in 1859.

Further evidence was found at Hallett Cove in 1875. Subsequently it was found that these belonged to the Permian glaciation. In 1901 glacial sediments belonging to the even earlier glacial period, the Sturtian, were found in the banks of Sturt Creek in the Adelaide Hills.

Why go to Hallett Cove?

Evidence from all three ice ages can be found at Hallett Cove, though much of the spectacular landscape had its origin in the Permian. The Cove is recognised world-wide for being one of the most important and visibly interesting records of the second (Permian) Ice Age. Hallett Cove Conservation Park preserves this time capsule and also provides magnificent coastal scenery, good walking trails, and a grassed picnic area, for public enjoyment.

To the casual visitor today Hallett Cove may present many puzzles. For instance – why is the seafront littered with so many rocks of different sizes and shapes? Why doesn't the beach carry as much sand as nearby swimming beaches and why is it so slippery at low tide? Why are there hills of sand and shelly marine fossils inland? Using this book you can discover the answers for yourself.

Two hundred and eighty million years ago, while Australia was attached to Antarctica and part of the vast southern supercontinent called Gondwana, the Permian ice sheet, up to 1000 metres thick, moved over the area now known as Fleurieu Peninsula, and beyond to Yorke Peninsula. After 10 million years the ice sheet melted, leaving vast lakes of meltwater covering the land. With the passing of time the rocks over which the ice moved were exposed by erosion. These rocks were the eroded stumps of the very first Mt Lofty and Flinders Ranges, 500 million years old. After the Permian ice age long periods of erosion, the laying down of new sediments, and a brief incursion by the sea further changed the landscape.

At Hallett Cove there are reminders of that ice age – spectacular hills of sand and a moonscape which was once a vast glacial lake. There is a natural amphitheatre cut out of glacial sediments laid down as early as 270 million years ago. There are also rocks which were deposited after the ice age – sandstones carrying fossils four million years old from the time the sea invaded the land. There are representatives of plant families which evolved in Gondwana and provide another link with Australia's Gondwanan heritage.

Preservation of Glacial Features at Hallett Cove

When marks made by ice were found on the hard rocks of the cliff top at Hallett Cove by Ralph Tate, Professor of Natural Science at the University of Adelaide, in 1875, the discovery was deemed highly significant – so much so that 'the largest scientific excursion ever held in the Southern Hemisphere' was arranged to Hallett Cove in 1893 by the Australian Society for the Advancement of Science.[1]

There was considerable debate about the age of the ice which had left the marks on the cliffs. Professor Walter Howchin, also from the University of Adelaide, published in the Transactions of the Royal Society of South Australia,[2] the results of his research between 1893 and 1924, concluding that the marks had been made by Permian ice – a fact later confirmed by correlation with fossils found in similar glacial deposits in Victoria. The glacial sediments preserved at Hallett Cove are now recognised as the best record of Permian glaciation in Australia and attract the interest of earth scientists from around the world. South Australian scientists continue to research the Hallett Cove geology and information from their recent investigations is included in this book.

Preserving this record against the creep of suburban development has been an arduous task. In 1960 the clifftop land, including 'Tate's Rock' containing the marks left by the Permian ice, was donated to the National Trust by beneficiaries of the estate of George Sandison. With some small parcels of adjoining land this became the nucleus of the Sandison Reserve which is now marked by a National Trust plaque. The State Government added a further 20.76 hectares as a 'site of scientific interest' in 1969. Subsequent lobbying by the National Trust, the South Australian Division of the Geological Society of Australia, the Field Geology Club of South Australia, other natural history groups and concerned citizens resulted in the acquisition of more land and the whole area of 50.48 hectares was declared a Conservation Park in 1976. Since that time the Park and the Sandison Reserve have been managed by the National Parks and Wildlife Service in the Department of Environment, Heritage and Aboriginal Affairs – preserving this area of geological heritage from development.

Hallett Cove has been placed on the National and State Heritage Registers and is a designated Geological Monument. Under the care of the Department of Environment and Natural Heritage, walking trails and boardwalks have been installed making access safer, viewing of features easier and preservation of the fragile environments within the Park better. The Division of Mineral Resources (formerly Mines and Energy of South Australia and now within the Department of Primary Industries and Resources of South Australia) have added excellent descriptive signs along the trails. Friends of Hallett Cove assist in the management of the Park and its assets.

Being a conservation area, collection of rocks, fossils, or biological specimens is not allowed and clear indications of this are shown on the signage in and around the Park. It is up to visitors to respect measures which have been put in place to preserve the fragile environments, heeding warning signs and taking responsibility for their own safety, especially on clifftops and on rubbly surfaces by staying on the well marked walkways and paths.

With book in hand walk in the Park, or stroll along the beach, finding clues to past events left in the rocks. You can journey back through 600 million years to when Australia was part of Gondwana. You can see the evidence left by the ice ages, by the invasion of the sea and by erosion by wind and water. Anyone with a keen eye and a little geological knowledge can rediscover these ancient events for themselves at Hallett Cove (and further afield on the Peninsula).

Preparing for your Visit

Some of the best geological features are exposed high on the cliffs above the beach so it is advisable to wear good walking shoes and suitable clothing, take a hat and use sunblock cream. As there are no shops it is wise to take your own drinks. Toilets are present only at the Surf Life Saving Club outside the southern entrance of the Park where there is a public car park.

To walk from one end of the Park to the other could take more than two hours but it is possible to do shorter walks to individual features (see map of geological features inside front cover). Some of the paths are covered with small loose stones and cliff edges are very unstable. For this reason it is advisable to keep to the marked paths and boardwalks. On the beach at low tide glacial clays exposed amongst the boulders tend to be extremely slippery. If you are considering spending some time on the beach or on the shore platform consult the tide times published daily in *The Advertiser*. The tide peaks at Hallett Cove are similar to those for Port Adelaide.

Getting There ...

The Park is easily accessed by road and rail (Figure 3).

If travelling by road take South Road from Adelaide. The eastern and southern entrances to the Park are reached from South Road, then Majors Road at the top of Tapleys Hill, then Lonsdale Road to the left. After approximately four kilometres turn right into The Cove Road where there is a sign directing you to the Park. Turn left into Dutchman Drive (also sign-posted) at a roundabout just past the railway. This takes you to the boundary and eastern entrance of the Park. If you wish to enter the Park here, cars may be parked on the roadside. The walking trail from this entrance takes you into the Park across the rim of the Amphitheatre.

The southern entrance of the Park is recommended as there is a large car park, toilet facilities in the Surf Life Saving Club and better access to the beach. To reach this entrance continue down Dutchman Drive to the coast.

Turn right into Heron Way, then left, to reach the car park at the Hallett Cove Surf Life Saving Club. The Park entrance is just beyond the car park.

To reach the northern entrance of the Park take Brighton Road south and follow the signs. Turn right into Scholefield Road then turn left into Newland Avenue. Turn right into Jervois Terrace and cross the railway line. The first turn left takes you into The Cove Road which follows the rail line. Three kilometres on, near the Hallett Cove Railway Station, take South Avenue on the right (west), then Second Avenue on the left (south) and follow to the car park at the northern entrance. This entrance is the closest to the path to the northern end of the shore platform, but entails a longer walk to the other geological localities. To travel between the three entrances of the Park take The Cove Road which runs around the landward side of the Park.

If travelling by train, take services going to Noarlunga Centre. Easy access to both ends of the Park allows a one-way walk through the Park. To reach the southern entrance alight at Hallett Cove Beach Station and walk down Gwen Street (across the car park from the subway) to Dutchman Drive, which leads to the coast. The Park is to the right, just beyond the Hallett Cove Surf Life Saving Club. To reach the northern entrance, alight at Hallett Cove Station and head west down South Avenue and Second Street.

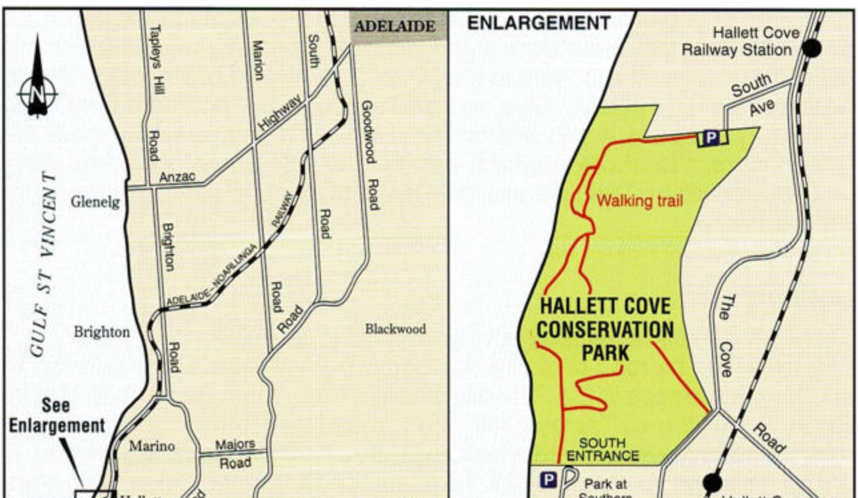


Figure 3: Road and rail access to Hallett Cove. (Courtesy: PIRSA).

Chapter 1

HALLETT COVE – 'SNAPSHOTS' THROUGH TIME

Overview of the Geological History of Hallett Cove

The landscapes of Hallett Cove have evolved through a continual process of deposition, burial, uplift, weathering and erosion (Figure 4).

By interpreting the evidence left in the rocks by past events geologists have shown that the present Hallett Cove landscape has been evolving for more than 600 million years – from tidal flat on a continental shelf, to a mountain range, an ice blanketed landscape, a shallow sea, alluvial plains, to the eroded coastline we recognise today (Figure 5).

In this chapter the environments are depicted through a series of seven 'snapshots' accompanied by a description of the climatic factors and

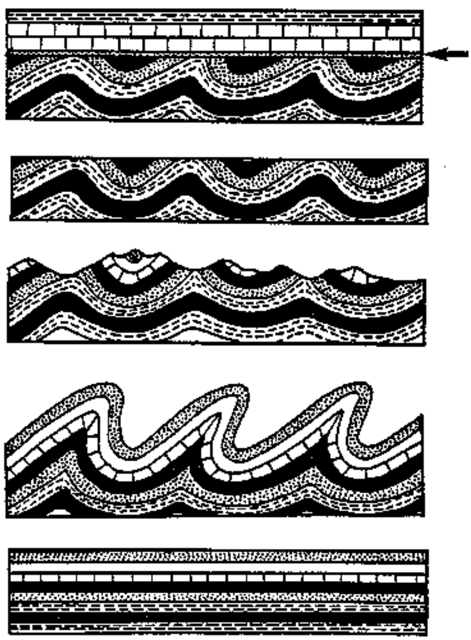


Figure 4: The cycle of deposition, uplift, weathering and erosion by which landscapes evolve. Unconformities are contacts between two periods of deposition separated by a period of erosion which has removed evidence of geological events. (After McDonnell, Massey and Tebbutt, 1977).

Coastal Erosion
Recent
Snapshot 7

Shallow Sea
4my
Pliocene
Snapshot 5

Glaciation
280my-270my
Permian
Snapshots 3 and 4

Mountain Building
500my
Ordovician
Snapshot 2

Continental Shelf
600my
Proterozoic
Snapshot 1

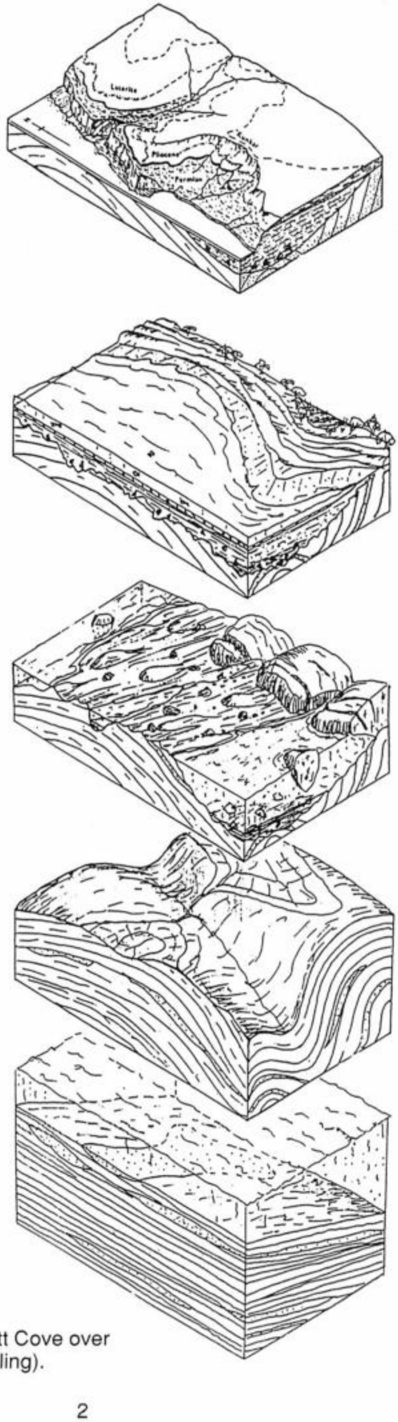


Figure 5: The landscapes at Hallett Cove over the past 600 million years. (After Gehling).

processes which were responsible for the changes. The sites at Hallett Cove where clues to the geological history of the area can be seen are also listed. The time scale over which these changes occurred is summarised in the table on the inside back cover, with information showing what else was occurring on Fleurieu Peninsula and on the Australian landmass. The meaning of geological terms used can be found in the glossary (page 57).

As the processes which created the past landscapes are continuous you will also be able to see some of them at work in the present landscape.

Snapshot 1: A Continental Shelf – 600 million years ago (Proterozoic times)

A broad shallow sea stretches to the northern and eastern horizons. Way to the west is a low land across which rivers meander, depositing their sand and silt in to the sea. Ripples created by tidal currents can be seen in the sediments settled on the sea floor. The land is bare – plants and animals have not yet evolved, but there are some algae and jellyfish in the sea.

At this time Australia was part of Gondwana. Over millions of years sands and silts have eroded from the land and deposited in a series of shallow marine depressions and lakes, thought to extend from the position of present day Kangaroo Island through into Central Australia. This area is now known as the Adelaide Geosyncline (Figure 6). The sediments subsided under their own weight as the depressions filled. In the process sandy sediments settled in shallower water and the finer silts as mud in deeper water. As the sediments became buried by later additions their water content was reduced. Sands became sandstones and quartzite; silts and muds siltstones and shales.

At Hallett Cove these 600 million-year-old sediments are represented in Black Cliff, the cliff line to its north and the shore platform below. They are the oldest rocks exposed in the Park and were deposited well before there was life on land.

Snapshot 2: Mountain Building – 500 million years ago (Ordovician times)

An enormous mountain range stretches over the horizon to the north and the east. The craggy heights reach skywards and their flanks are covered with loose rock. Rivers roar down the steep narrow valleys carrying boulders, sand and silt.

About 100 million years after the sediments were laid down on the continental shelf movements within the earth's crust deformed them, creating a mountain range similar to the modern Alps or Himalayas. In South Australia the sediments of the Adelaide Geosyncline were squeezed in a north-westerly direction, folded and uplifted to form the

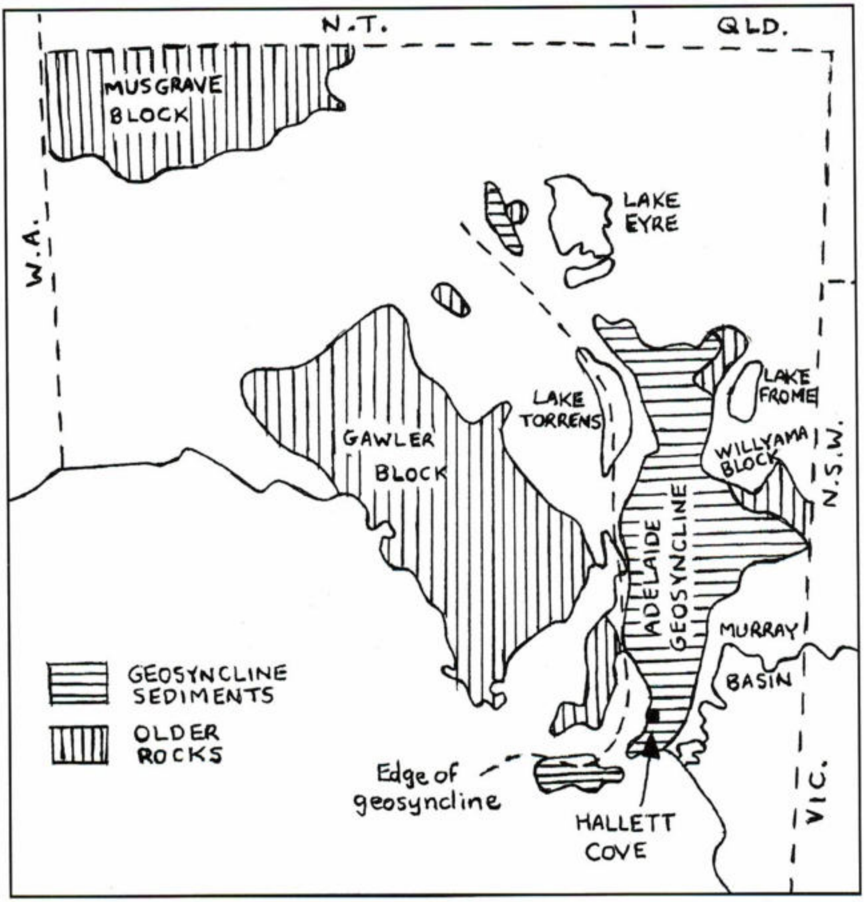


Figure 6: Sketch map of South Australia showing the position of Hallett Cove in relationship to the geosynclinal sediments and the even older rocks which formed the geological building blocks of the State.

original Mount Lofty and Flinders Ranges. These formed part of a mountain range which stretched north into central Australia and south into Gondwanan Antarctica which lay adjacent to South Australia. Through folding – in which rocks are bent and twisted (as a mat folds when the ends are pushed together), faulting – (in which layered sediments or rocks break, allowing other sediments or rocks to slide over or past them) and uplift, the land was transformed.

Heat and pressure building up in the more deeply buried sediments have been altering the sediments to hard rock. At Hallett Cove the sediments were changed to siltstones, sandstones and quartzite. The eroded stumps of these folded rocks now form the cliff line including Black Cliff and the shore platform.

The position of the Adelaide Geosyncline sediments, one of the geological building blocks of South Australia, is shown in Figure 6. This sketch map also shows the position of present day Hallett Cove in relationship to these sediments. The folded sediments formed the original Mount Lofty Ranges, sometimes referred to as the Delamerian Mountains.

Over the following 220 million years clues to geological events at Hallett Cove were removed by severe erosion of the mountain ranges. Elsewhere in Australia the Great Dividing Range was uplifted on the east coast, where there was extensive volcanic activity. Central Australia was covered by sea. Life emerged on to the land – plants evolving from seaweeds. Amphibians walked onto the land. Forests of trees established in swampy areas (table, inside back cover).

The next event for which a record exists in the rocks at Hallett Cove was a major ice age or period of glaciation. This was the second time the southern polar ice sheet had moved on to the Australian land mass – still part of the supercontinent of Gondwana (Figure 2). This second ice age is referred to as the Gondwanan or Permian Ice Age.

Plate 1: A continental ice sheet blanketing the landscape in eastern Antarctica today. A similar ice sheet covered Hallett Cove 280 million years ago. Photo: G. Fraser.

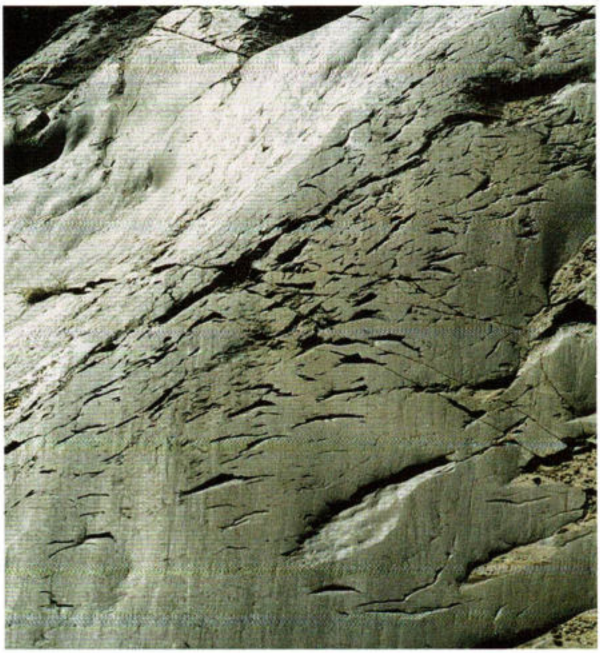


Plate 2: Friction marks (crescentic gouges) left in bedrock by the passage of ice containing rock debris. The ice flowed over this horizontal pavement from south-east to north-west (from bottom to top of photo). Photo: W. Lyne, reproduced with permission.

Snapshot 3: During Glaciation about 280 million years ago (Permian times)

Just the peaks of the mountain ranges can be seen poking through the thick blanket of ice which covers the land filling in the valleys and flattening the landscape. There is no plant or animal life to be seen, for it has been buried under the ice. It is intensely cold and bleak.

In the Southern Hemisphere the climatic changes became very severe. An alteration in the arrangement of the Gondwanan land mass and the sea has disrupted global weather patterns, causing temperatures to drop. The polar ice caps grew bigger.

Australia was still part of Gondwana, together with the landmasses which were to become Antarctica, India, Africa, South America and New Zealand, but had moved closer to the South Pole. Antarctica lay immediately to the south. Gondwana was progressively covered by a wet-based continental ice sheet (Plate 1). On the Australian land this ice sheet covered much of the area of Tasmania, Victoria, part of South Australia and extended into the other States (Figure 2). In South Australia Fleurieu Peninsula was covered by the ice (Figure 7).

As the ice flowed it tore away soil and rock from the surface of land over which it passed. The rock debris frozen into the base of the ice gouged, scratched and polished the bedrock. A variety of the friction marks so created remained on bedrock surfaces when the ice melted, providing proof of the passage of ice and sometimes also to the direction of flow. These marks fall into two groups – scratches (striae) and grooves, and friction cracks including crescentic gouges (Plate 2) and chatter marks.

Chatter marks, or small indentations, were caused by the vibration of small rock fragments in the base of the ice. They occurred at right angles to the direction of flow. Crescentic gouges were created by indirect pressure applied to the bedrock, perhaps by a rock fragment cushioned by sand, or by direct pressure applied at an angle to the bedrock. The bedrock fractured near vertically and a wedge of rock was removed as ice moved forward. Gouges thus tended to form at right angles to the direction of flow, deepening in the direction of ice movement. The 'horns' of the crescent pointed away from the direction of flow. Lunate fractures were created in a similar way but the horns pointed in the direction of flow. Crescentic cracks were simpler vertical surface fractures.[3] At Hallett Cove scratches predominate on the fine grained siltstones, sandstones and quartzites of Black Cliff (Locality 1) where there is a polished glacial pavement (Plate 5). Small crescentic gouges are also present there.

Larger rocks trapped deeper in the ice were often transported many kilometres from their place of origin. These much travelled 'erratic' rocks were dumped when the ice melted. Their structure and composition were often different from the locally derived rocks. Determining their structure and matching it with known rock outcrops provided an indication of the

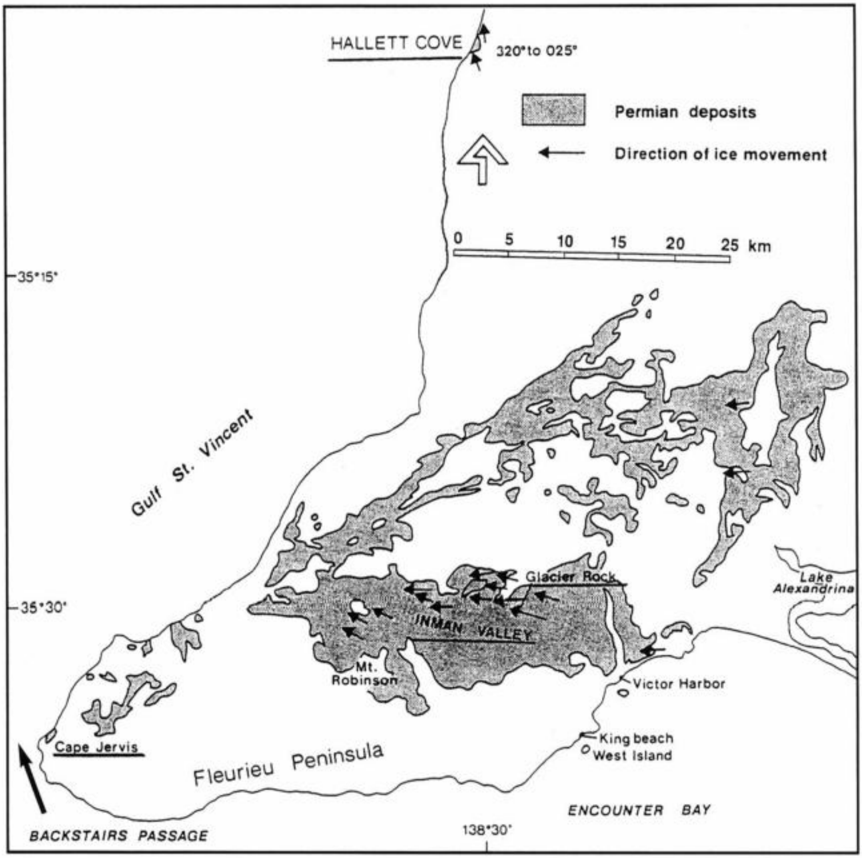


Figure 7: Outcrops of Permian glacial sediments on Fleurieu Peninsula indicating the extent of the ice. Arrows indicate the direction in which the ice was flowing. (After Hallett Cove Conservation Park Management Plan, National Parks and Wildlife Service, 1986) and Geology of South Australia, Volume 2, Mines and Energy, 1995).

origin of the rock and the direction from which the ice came. Erratics are found along Hallett Cove Beach (Locality 11) and on top of the cliff (Locality 3) a little north of the glaciated pavement.

As the ice moved over the landscape it entered, deepened and widened former valleys into U-shaped valleys by plucking away the softer rock and exploiting joints or cracks in harder rock. Rock fragments were plucked from the downward (lee) side of harder rock. (Figure 28, page 54). At Hallett Cove the zig-zag shape of the present day cliffs north of Black Cliff was shaped by the sea, eroding soft valley sediments. Just to the landward side of Black Cliff a former valley (fossil or palaeovalley) was deepened by ice and filled with sediment as it melted. A small branch of this valley is seen along the cliff top walk north of Black Cliff (Plate 7, page 22). Along the coastline to the south of the Park the end of a small U-shaped valley can be seen.

Snapshot 4: About 270 million years ago (late Permian times)

'Around us the dark folded Precambrian (Proterozoic) rocks break through a frozen mantle of white, while below lies a long lake on whose still waters float rafts of melting ice. Embedded in these rafts are pebbles and rock fragments of all sizes, some so fine that the ice itself looks grey and dirty. A large boulder suddenly detaches itself and falls into the water, sending ripples across the surface. To the south lies a wall of the retreating ice sheet, reflected in the quiet water of the lake.

Small streams of meltwater have cut a path through rock fragments heaped in confusion on the polished bedrock; laden with milky white rock flour, they drain into a patchwork of pools and lakes, in depressions and temporary dams of rock and sediment.

A crackling roar breaks the silence as a huge iceberg breaks away from the wall of ice and crashes into the lake. Once again the reflections shiver – then break into waves of turbulent water.'[4]

The warming climate caused the ice to thin and melt. Meltwater, laden with fine rock flour and some coarser material, flowed from the surface and from under the ice, creating deltas and fans of sediment. These sediments, mostly sands and clays, accumulated in layers on the floor of meltwater lakes dammed against the ice. Previously trapped rocks and debris were released from floating icebergs (Figure 8) and dropped on to lakebed sediments.

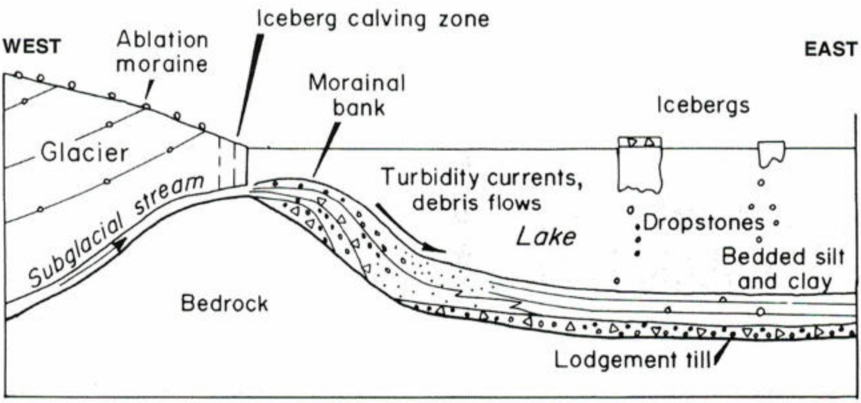


Figure 8: As the ice melted entrapped rock fragments, silt and sand were shed into meltwater lakes dammed against the remaining solid ice sheet. Icebergs calved from the ice sheet and floated on the lake waters, releasing rocks (dropstones) and finer rock debris. (From Bourman and Alley, 1990).

At Hallett Cove the Permian glacial sediments are exposed throughout the Park (Figure 9) – draped over Black Cliff (Localities 2 and 5), filling an ancient valley south of Waterfall Creek (Locality 4), and in the Amphitheatre (Localities 7 and 9). Dropstones are seen in the sediments of the Sugarloaf (Locality 9). A small hillock just inland from the beach at the lower end of the Amphitheatre, demonstrates the effects of turbidity currents and graded bedding created by flows of sediment-laden melt-water coming off the ice (Locality 10).

After the ice melted a 'gap' of about 160 million years occurred in the geological record at Hallett Cove. Erosion removed much of the evidence

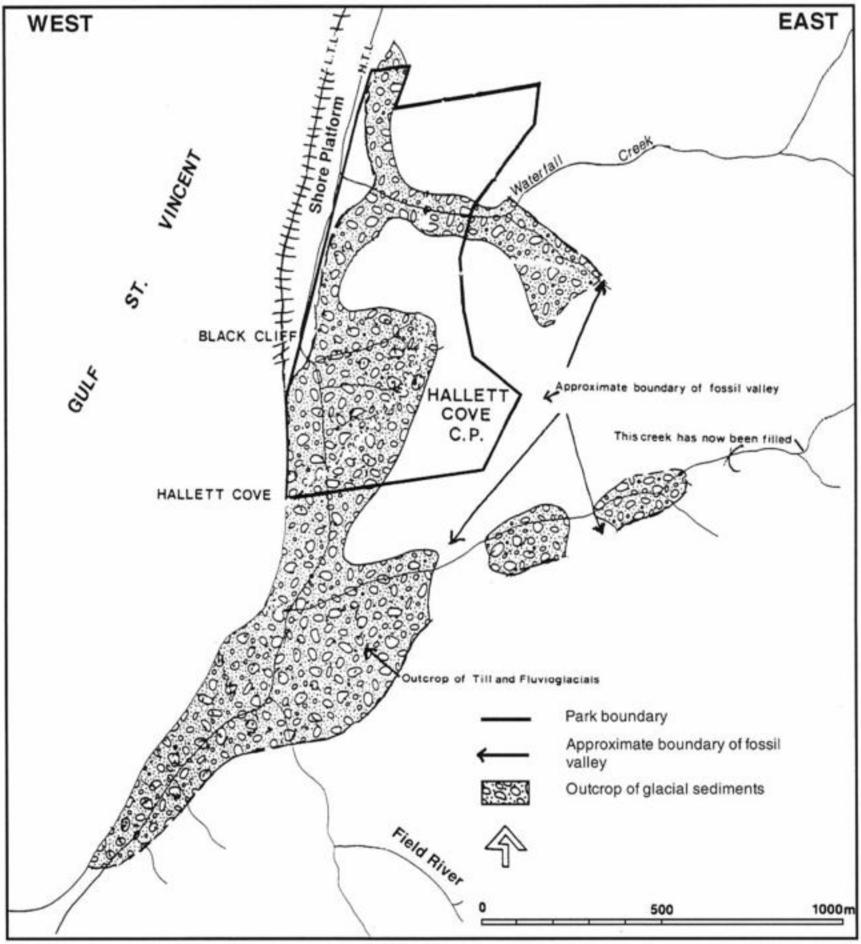


Figure 9: Outcrops of Permian glacial lake sediments in the Hallett Cove area. (Modified from Hallettt Cove Conservation Park Management Plan, National Parks and Wildlife Service, 1986).

of any geological events during this time. Elsewhere in Australia the forests which had evolved in the swamps were buried to become the basis of coal deposits. Vast seas covered most of the inland areas and teemed with fish and plesiosaurs.

Earth movements had begun to break up the Gondwana supercontinent and the rifting finally separated Australia about 45 million years ago. Australia then drifted northward alone. Plants which had evolved in Gondwana and extended onto the Australian landmass began to develop characteristics which enabled them to survive the changing climate. The sea flooded into a broadening rift valley between Antarctica and southern Australia covering low lying land on the margin of South Australia and creating Gulf St Vincent and Spencer Gulf. Clues to this event can be found in the deposition of fossiliferous sandstones at Hallett Cove around four million years ago.

Snapshot 5: About four million years ago (late Pliocene times)

'Shallow seas lap against the foot of the Mount Lofty Ranges. The air is warm, the water clear and we can see the Permian rock rubble lying on the sea floor, half buried beneath the accumulating yellow sands. On some of these rocks coral-like algae are growing; in a cranny lies a heap of shells – big round cockles and broken fragments of many smaller bivalves piled together with coiled gastropod shells.

A meandering trail marks the path of a sea snail ploughing its way along just below the surface of the sand. A scallop swims vigorously by, its valves snapping shut and opening again as it propels itself erratically through the water: other scallops rest quietly on the sandy bottom. Here and there lie disc-shaped objects, some quite small, others an inch or more in diameter. They are many – chambered shells of *Marginopora*, a single-celled organism which inhabits these seas in large numbers. Oysters grow clustered together in a colony nearby'.[4]

About four million years ago a warm and shallow sea briefly covered low lying parts of the land on the eastern side of what is now Gulf St Vincent. Sand eroded from the surrounding dry land accumulated on the seabed. The many-chambered forams or foraminifera called *Marginopora* spp (Figure 10), and shellfish, thrived in the waters and in death accumulated on the sandy sea floor. These sandy sea floor sediments were altered to hard sandstone and the remains of the organisms in it were fossilised. About two million years later they were exposed when the present Mount Lofty Ranges were uplifted. At Hallett Cove this fossiliferous sandstone (the Hallett Cove Sandstone) forms a bluff along the cliff top in the north-western part of the Park, (Locality 6) and a discontinuous ledge within the Amphitheatre (Locality 8).

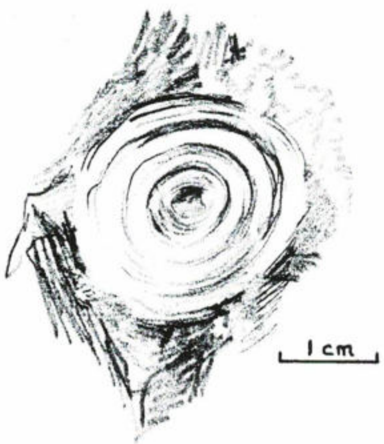


Figure 10: The fossil foram *Marginopora*. (From A Field Guide to the Geology of Yorke Peninsula, Field Geology Club of South Australia Inc, 1997).

Forams are single celled marine organisms related to amoebae, but differing from them in creating a shell from calcium carbonate. They are frequently less than two millimetres in size, are very sensitive to changing environments and so are valuable for dating sediments. The fossilised forms of *Marginopora vertebralis* in the Hallett Cove Sandstone are some of the largest, being more than one centimetre in diameter.

Then, for a third time in the evolution of the Hallett Cove landscape, erosion removed clues to geological events, this time for a period of about two million years. During this time Australia continued its drift northwards and became warmer and drier. Rainforests started to die out and were replaced by grasslands and Eucalypt forests. With the extending grasslands came the first grazing animals and the marsupials – a giant kangaroo and diprotodonts (large hippo-sized animals) (Figure 11). The first humans, Aboriginal people, arrive from the Indonesian archipelago.

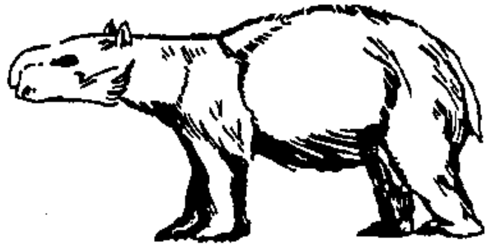
Snapshot 6: About half a million years ago (Pleistocene times)

To the east the Mount Lofty Ranges tower over the flat landscape covered with Eucalypt woodland. Rivers rush out of the ranges dumping their load of sand and silt from the eroding ranges onto the plains. Giant kangaroo abound in the woodland and diprotodon slosh along the riverbanks, browsing on the vegetation.

The South Australian climate became cold, windy and generally dry, but there were many very wet periods which caused deep erosion of high ground. During these wet periods sands and silts and clays eroded off the still rising Mount Lofty Ranges and were carried down to Hallett Cove in streams. There they were deposited as thick alluvial sediments on the exposed fossiliferous Hallett Cove Sandstone. In places where the sea had not previously flooded the land the alluvial sediments were laid down directly on the even older Permian glacial sands. The contact between these latter sediments was an unconformable or non-sequential one. Soils developed in the alluvial sediments. Through seasonal wetting and drying, calcium carbonate was dissolved from the soil and redeposited near the ground surface as a hard layer known as calcrete ('kunkar'). At Hallett Cove a layer of this rubbly limestone can be seen just below the rim of the Amphitheatre (Locality 7).

South of the Park, on the north bank of Field River (Hallett Creek on some maps) a partial skeleton of a diprotodon and portion of the paw of a giant kangaroo have been found in the alluvial sediments laid down 50-60,000 years ago.

Figure 11: The now extinct marsupial *Diprotodon australis* (N. Pledge, S.A. Museum) – a hippo-sized marsupial, remnants of which were found in Pleistocene alluvial sediments south of the Hallett Cove Park. (From SASTA-ESTA Geology Revision Guide, 1994).



There were many global climate changes, with waxing and waning of the polar ice caps and falls and rises in sea level, particularly toward the end of this period. The northern hemisphere was gripped by a very severe ice age (often referred to as the Great Ice Age) but in the south only small areas of the Australian continent, such as the present Snowy Mountains and Tasmania, and the high mountains of New Guinea, were covered by ice. The sea level changes associated with this third ice age altered the coasts around Australia, including those around Fleurieu Peninula and at Hallett Cove.

Snapshot 7: 10,000 years ago (Recent times)

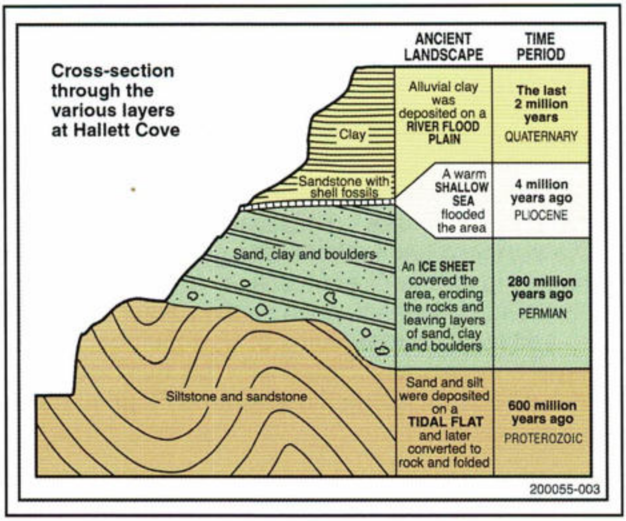
Waves crash against the stumps of the mountain range. The sea is now bordered by a tall rocky cliff. The outline of folds from the old mountain range can be seen along the base of the cliff.

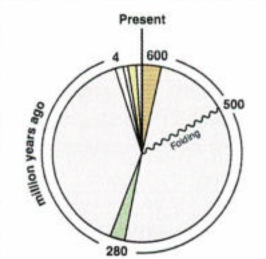
A beach with very little sand but with many boulders lies south of the cliffs. Beyond the cliff the unprotected soft sediments are being cut down by streams flowing off the uplifted high land forming badlands and a huge natural amphitheatre in which trees, shrubs and grasses grow.

With the melting of the northern hemisphere ice cap, sea levels rose more than 100 metres. The shoreline moved in from the region of Kangaroo Island to its present position. Erosion by the sea cut into folded sediments of the original Mount Lofty Ranges creating the cliffs, removing vast quantities of rock and leaving a rocky shore platform at their base. Erosion by the sea also exposed many Permian erratics on the beach. The land surface was uplifted also. Erosion of this dry land continued. Sediment-laden water flowing down the creeks and gullies from the modern Mount Lofty Ranges cut through the softer sediments near the coast and unprotected by Black Cliff. This erosion formed the Amphitheatre and its gullies. Fans of alluvial sediment formed along the seaward side of the Amphitheatre and sand built up into low coastal dunes along the beach. This is the landscape with which we are now familiar.

In summary: These seven snapshots have shown how Hallett Cove changed from a tidal flat on a continental margin of Gondwana to a heavily eroded coastal environment in South Australia over a period of 600 million years. The cycle of deposition, uplift, weathering and erosion which created the Hallett Cove landscape continues today...

The major landscape elements at the Cove are summarised in Figure 12.





The Time Chart

The geological history at Hallett Cove can be represented on a 600 million year time chart.

Figure 12: A cross-section through the sediments at Hallett Cove summarising the periods of deposition and erosion of the past 600 million years. (Courtesy: PIRSA).

For a description of the geological features of Hallett Cove, the evidence left of the past landscapes and the clues which geologists have used to interpret this evidence, read on...

Chapter 2

HALLETT COVE – DESCRIPTIVE GEOLOGY

Some of the best features of the Permian (Gondwanan) Ice Age in the world are preserved at Hallett Cove. It is also possible to see exposures of the Proterozoic sedimentary rocks over which the ice moved, and of Pliocene and Pleistocene sediments which were laid down after the ice had sculpted the landscape. Together they create the spectacular scenery within the Park.

Thirteen localities have been selected to provide the visitor with the clues which geologists have used to tell the story of Hallett Cove. The locality numbers used in this book are used to identify specific features. There is no numbered marking on the trail but some localities are marked with an interpretive sign. Where access to localities is not recommended to the public, photographs have been included to show the features. In this chapter detailed notes are provided on each of the localities which are shown on the map inside the front cover.

The localities have been arranged on two walks – one within the Park and one along the beach – both starting from the southern entrance of the Park. The walk within the Park can take at least two hours. Starting at Black Cliff, it will take the visitor from the oldest (600 million-year-old) rocks up through the sequence of sedimentation and erosion to the present day. If less time is available a visit to Localities 1, 2, 8, 9 and 10 would give the visitor an appreciation of the extent of landscaping caused by the passage of ice and by the major processes which gave rise to it – sedimentation, uplift and erosion.

Boardwalks are provided in some areas to make walking easier and to protect the environment. For your own safety it is recommended you stay on the marked paths. As the area is a National Park the collection of specimens – rocks, fossils or plants, is forbidden.

The walking trails also pass through some interesting vegetation. Brief notes have been included on the major plant communities to provide the visitor with a greater appreciation of the interdependence of rocks, soils, plants and animals and of some of the mechanisms used by them in adapting to a particular environment. The book *It's Blue with Five Petals* (Prescott, 1988) would be useful for identifying the individual plants. Seeds, plant segments, animal fossils, fossil pollens and other microscopic organisms have all been used by geologists to date the sediments in which they lie. The visitor to Hallett Cove can see how these might be preserved in today's sediments for geologists to interpret in the future.

The walk along the beach can be made independently of that in the Park. The specific localities are not signposted but are shown on the map inside the front cover. It is recommended that Localities 12 (the glacial tills) and 13 (the rock platform) only be visited at low tide. The tide times are published daily in *The Advertiser.* A description of some of the invertebrates which colonise the zones on the rock platform is included in this chapter also to demonstrate the creation and colonisation of the separate environments there.

The meaning of geological terms used in this chapter can be found in the glossary (pages 57 to 60).

The Walk within the Park

The first locality to visit on this walk is Black Cliff – approached by taking the main path in from the southern entrance of the Park and which runs parallel to the beach.

En route notice the present day vegetation colonising the low coastal dunes. Species included here are the dark green bushy boobialla or water bush *(Myoporum insulare)* whose leaves carry resin glands that combat salt desiccation. In very exposed sites on the dunes, however, these bushes are often severely stunted through both salt and wind damage. Along the dunes and the eastern side of the path there are examples of coastal saltbush *(Atriplex cinerea)*, native lily *(Dianella revoluta)* and coastal lavender *(Olearia axillaris)* which is also resistant to salt-laden winds. In this area plantings of coastal wattle (*Acacia sophorae)*, nitre bush *(Nitraria billardierei)* and she-oak *(Allocasuarina sp.)* have been made to restore some of the native species. You may be lucky to see Wanderer butterflies feeding on the nectar of the Cape Dandelion *(Arctotheca calendula)*. Their larvae feed on the leaves of the introduced broad-leafed cotton bush *(Asclepias rotundifolia)* which has caustic milky sap and duckling-shaped fruits.

Many coastal lavender *(Olearia)* bushes can be seen. On the dunes the compact smokey-grey cushion bush *(Calocephalus brownell)* can also be seen. An isolated athel or tamarix tree *(Tamarix aphylla)* may be seen growing west of the path, marking the site of beach shacks which once occupied the area. These woody plants are salt and drought tolerant.

A slight diversion down an old path to the beach along here will show zonation of the vegetation associated with the degree of wind and salt tolerance. Closest to the beach is the sand-binding grass *(Spinifex hirsutus)*, the triangular-leafed pigface *(Carprobrotus aequilateralis)* and a *Euphorbia* species. The more salt and wind resistant *Olearia and Myoporum* colonise the crest of the dunes. In the more sheltered areas inland, both *Myoporum* and dry country tea trees *(Melaleuca lanceolata)* grow. On the left of the main track, just past the large gully near the base of Black Cliff, note the low spreading bush with flat serrated-edged leaves. This is a fan flower *(Scaevola crassifolia)* – a very common coastal shrub in South Australia and one of several plant species at Hallett Cove which have a Gondwanan origin.

Glance ahead to the northern end of the beach where Black Cliff, a dark rocky headland, can be seen. Continue toward the cliff. Pause at the sign 'From Seabed to Mountain Range' at its base and note the erratics on the beach to the south, and the eroded shore platform at the base of the cliff. Climb to the top of Black Cliff using the main path, which is quite steep.

Plate 3: Black Cliff from the beach showing the shore platform exposed at the base and the cliff consisting of 600 million-year-old sandstones and siltstones – the eroded stump of the folded geosynclinal sediments which formed the core of the original Mount Lofty Ranges. The ketch 'Falie' stands off to the left. Photo: R Major.

Locality 1: Black Cliff

Black Cliff is an exposed anticlinal fold of the 600 million year old sediments (Plate 3), deposited originally as upper layers in the shallow marine trough which became known as the Adelaide Geosyncline (Figure 6, page 4). While the Australian landmass was still part of Gondwana these sediments had been laid down continuously over millions of years and been buried by later sediments as the trough filled. The sediments exposed now in Black Cliff were some of the later sediments to be deposited in this trough. Changed by heat and pressure as they were buried they became sandstones, quartzites and siltstones, and were folded by movements in the earth's crust about 500 million years ago to form the original Mount Lofty and Flinders Ranges. They are the oldest rocks exposed in the Park and formed the bedrock over which the Permian ice sheet moved.

From the top of the cliff a panoramic view of the area can be seen. Looking south along the coastline beyond Field River you can see the end of a small ice-gouged valley and an erratic embedded in the cliff face. Coming back toward Black Cliff along the shoreline, the pebble bank at the mouth of the River, erratics (ice-transported boulders) strewn along the beach, the effects of erosion on the beach, the strand lines of flotsam and jetsam and the zonation and pruning of vegetation by salt-laden winds can also be observed. At low tide a compact layer of clay can be seen stretching along the the length of the beach above the low water mark.

At the base of the cliff portion of the shore platform folded Proterozoic siltstones and sandstones can also be seen at low tide. The folds, like the one forming the cliff itself, were created when the sediments were squeezed up to form the original mountain ranges. Here the folds are dipping to the south, creating M-shaped figures (Plate 4). The M-shaped folds have been exposed by the eroding action of the sea. The descriptive elements of a simple fold are shown in Figure 13.

Plate 4: Looking south from the top of Black Cliff. M-shaped folds (outlined) are exposed at the base of the cliff. Photo: R. Major.

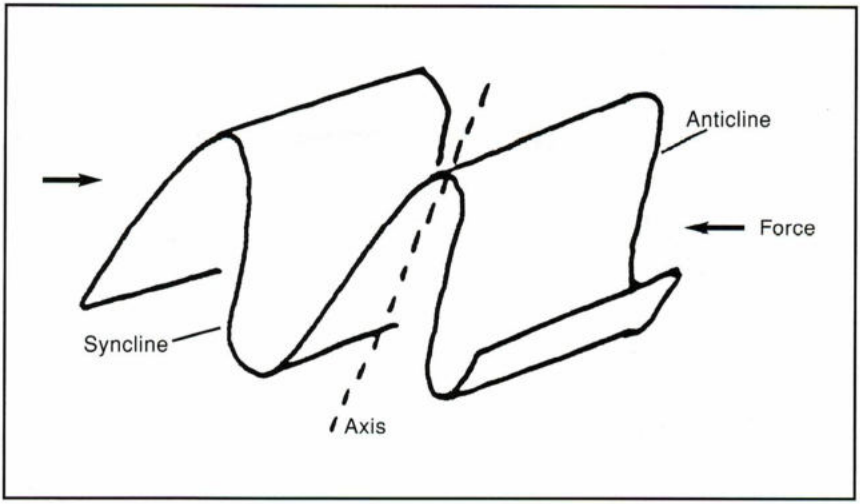


Figure 13: Diagrammatic representation of a simple fold. Anticlines are upward trending folds and synclines downward trending folds. The force is that which deforms the sediments, in this case compression or squeezing by movements within the earth's crust. (After SASTA-ESTA Geology Revision Guide, 1994).

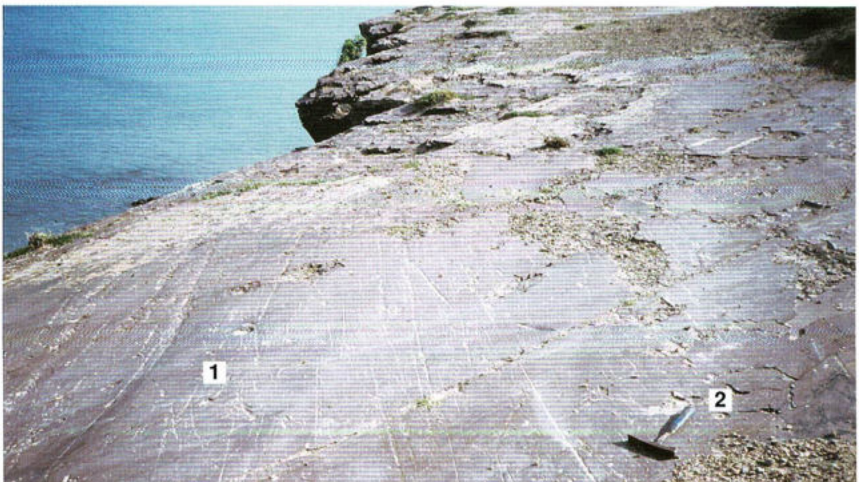


Plate 5: The glacially smoothed and striated pavement developed in the fine siltstone on the top of Black Cliff. On this surface striations (1) predominate, but when the light plays across the surface at a low angle, small crescentic gouges (2) and the faint impressions of grooves can be seen. Photo: R. Major.

Plate 6: Enlargement of crescentic gouges showing the horns and the general shape created by the removal of a wedge of rock between two fractures. These friction marks can provide an indication of the main direction in which the ice travelled; here indicated by the pencil. The ice moved acoss the top of Black Cliff in a north-westerly direction – that is, from left to right. The steeper part of the gouges formed in the downstream flow of the ice. Photo: R. Whatmough.

The top of Black Cliff is the crest of a large fold, eroded and planed off by the Permian ice sheet. On the siltstone surface a glaciated pavement has been exposed – testimony to the passage of ice (Plate 5). Note the smoothing and scratching caused by rock debris frozen into the base of the Permian ice sheet as it moved over the land, grinding down hills and gouging out valleys about 280 million years ago. In this location the ice moved over the land in a north-westerly direction, but what and where are the clues which show this?

Look first at the polished surface, then at the general direction of the scratches which predominate on this pavement. At this location the marks are of varying lengths and appear to trend in a north-westerly direction, but there are some which go in different directions – indicating that there were varying local ice movements associated with local obstructions. Very fine scratches are made by fine sands and silts in the ice and even finer material, called rock flour, embedded in the ice provides the polish on the pavement. Striae or scratches predominate on the fine grained bedrock.[3] Grooves are larger scale features created by boulders embedded in the ice. At low light angles, faint impressions of grooves can be seen on this pavement.

Small chatter marks and crescentic gouges can be seen more distinctly if the sun shines across the pavement at a low angle. Chatter marks are series of crescent-shaped friction cracks lying at right angles to the direc-

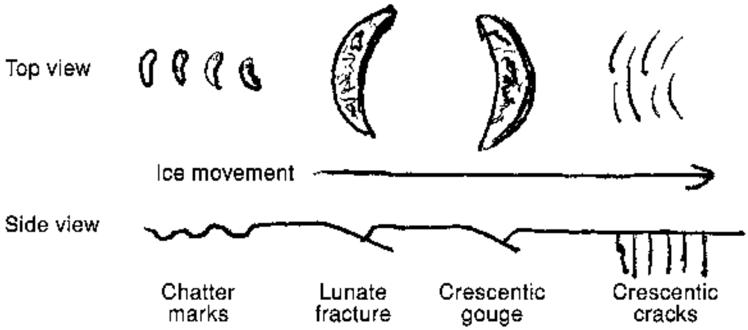


Figure 14: Marks left on bedrock by the ice consist of scratches and friction cracks. Friction cracks include chatter marks, lunate gouges and crescentic gouges. The top and side views of these help to identify them. The steeper parts of the cracks occur on the lee (downstream) aspect of the ice flow. (After Embleton and King, 1975).

tion of movement with ends pointing in the direction of flow (Figure 14). Crescentic gouges are usually single, steep-sided and curved, with ends turned away from the direction of movement. They are also aligned at right angles to the direction of ice movement and the deepest part of the hollow is usually on the lee side, in the same direction as the flow of advancing ice[3] (Plate 6).

These friction marks are the clues which geologists have used to show that the ice was moving from the south and trending in a north-westerly direction over the cliff line.

It may be necessary to distinguish marks made by moving ice from other marks present on rock surfaces – such as those made by windblown gravel, weathering or by the movement of rock over rock along a fault. The latter are called slickensides. Below the southern end of the Black Cliff glaciated pavement a small area of exposed rock shows a series of grooves which are slickensides and could be mistaken for marks of glacial origin. They are ridges and grooves caused by friction created during folding.

From the pavement continue on the walk northward along the top of the cliff on the railed boardwalk.

Plate 7: View of Black Cliff looking south from the cliffop walkway. The red brown Proterozoic sandstones and siltstones of the cliff form the western limb of an anticlinal fold. The crest of the fold has been planed off by the ice and a sharp contact can be seen with the overlying pale Permian glacial sediments. Between the contact and the boardwalk, the gully is a small pre-existing valley which has filled with glacial sediments. Black Cliff forms the western rim of this valley. A period of 220 million years elapsed, with no remaining record, between the folding of the Proterozoic sediments and the passage of the Permian ice, making this contact an unconformity. Photo: R. Major.

Locality 2: Along the Clifftop

As you walk northward turn around occasionally and look back toward Black Cliff – which will be seen as one limb of a large, tilted anticlinal fold (Plate 7). Note that the top of the fold has been planed off, leaving the flat surface on which the glaciated pavement is situated. As the ice moved over the Hallett Cove area it ground flat this crest of the fold and also deepened a valley which lay just to the east of it. This, and other branch valleys, were filled with glacial sediments when the ice melted. The main valley is thought to have extended along the cliffline just inland of Black Cliff (Figure 9, page 10). On top of Black Cliff the western rim of a small valley (pre-existing, fossil, or palaeovalley) can be seen (Plate 7).

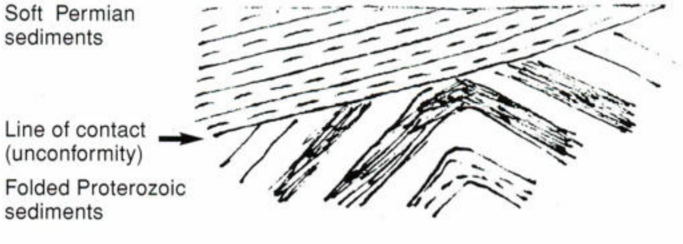


Figure 15: Elements of the unconformity

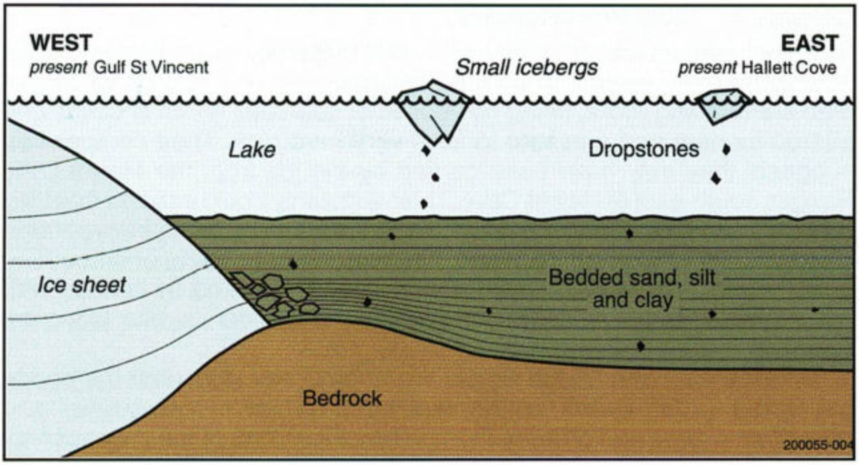


Figure 16: Diagrammatic representation of the deposition environment toward the end of the Permian Ice Age. Sediments are deposited in lakes of meltwater dammed against the thinning ice sheet. Small icebergs calve off the ice and float on the lakes, releasing entrapped rock debris. The falling debris (dropstones) often deform the soft sediment on to which they fall. (Courtesy: PIRSA; after Bourman and Alley, 1990).

The contact between the dark siltstones of Black Cliff and the pale soft glacial sediments here is an unconformity, as a time span of about 220 million years separates them with no record remaining of any events occurring during that time (Figure 15). The original Mount Lofty Ranges may have been about ten kilometres high before erosion by ice, water and wind reduced them to the stumps that are now represented by Black Cliff.

Heading further north along the pathway, note on the landward (eastern) side of the path, the glacial sediments which deposited in a melt-water lake dammed against melting ice sheet (Figure 16). Graded bedding, sequences of sedimentation in which coarser particles are deposited first and are followed by deposition of progressively finer particles, can be seen in these sediments. They are now considered to be turbidites – beds deposited sporadically by turbid (sediment-laden) water coming off the ice.[5] A better example of such turbidites can be seen at Locality 10.

As you continue north on the boardwalk along the clifftop the zig-zag or sawtooth-shaped cliff line can also be glimpsed. This shaping has been created by the sea exploiting joints and removing softer rock.

There is also a variety of rocks scattered over the exposed top of the cliffs. These were once embedded in, and transported here, by the ice. The finer, softer sediments have been eroded away leaving these foreign rocks (erratics) in the landscape.

Ahead are two large quartzite boulders dropped with other rock debris from the Permian ice sheet as it melted.

Locality 3: Quartzite Boulders

It can be seen on closer examination that these boulders (erratics) differ from other rocks nearby. They are paler in colour and coarser in texture than surrounding rocks, being composed of quartzite, which is sandstone altered by heat and pressure to form very hard rock. Their composition suggests they may have been carried by the ice from the Mount Lofty Ranges south-east of Hallett Cove. Their angularity could indicate that they had not been exposed to the elements for long before being incorporated deeply in the advancing ice sheet. As there is no rounding or smoothing of the edges it is also unlikely that they were reworked by contact with other rocks or by water, as were the majority of boulders strewn along the beach.

Take the path and bridge across Waterfall Creek. Just near the bridge are some broad-leafed cotton bushes *(Asclepias rotundifolia)* and bulrushes *(Typha* sp.*)* growing in the creek. Cushions of the grey cushion bush *(Leucophyta brownii)* can be seen growing near the mouth of the creek.

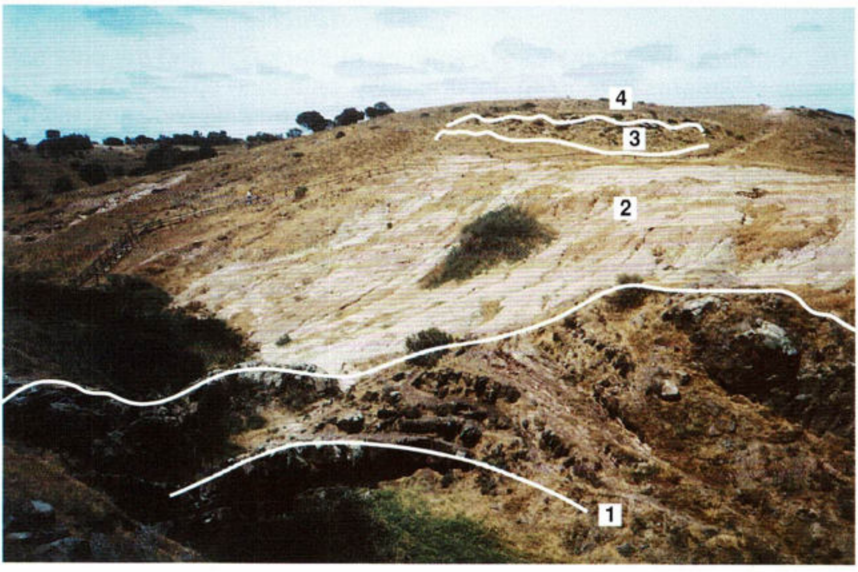


Plate 8: View south from the bank of Waterfall Creek. The dark reddish-brown Proterozoic siltstones and quartzites forming the arch (1) at the waterfall are overlain by a thick layer of pale pink and white glacial sediments of Permian age deposited in a pre-existing valley (2). Near the top of the pale sediments a lens of harder grey white sandstone (3) – the Hallett Cove Sandstone of Pliocene age – can be seen. These are overlain by Pleistocene clays (4). This view provides an excellent summary of the four periods of deposition which created the Hallett Cove landscape. Photo: R. Whatmough.

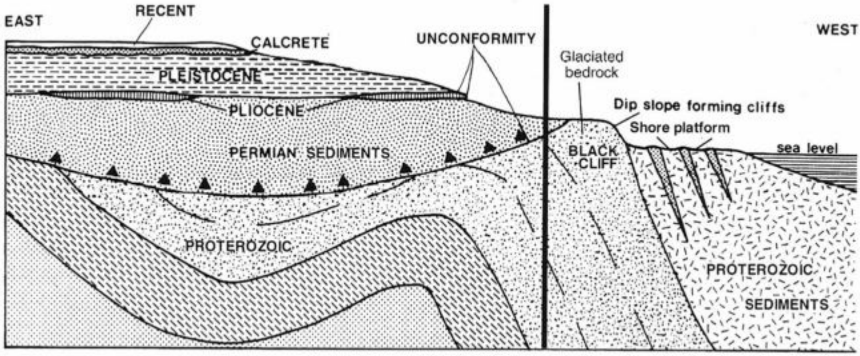


Figure 17: Diagrammatic representation of the four depositional periods and the three unconformities exposed south of Waterfall Creek. Area to left of the vertical line corresponds with view shown in Plate 8. (Adapted from The Hallett Cove Conservation Park Management Plan, National Parks and Wildlife Service, 1986).

Locality 4: Waterfall Creek

Near the sign 'A Gap In Time' look southwards. This locality provides the best visible summary of the geology and evolution of Hallett Cove – showing the four periods of sedimentation (deposition) and the three unconformities (gaps in the geological record) which separate them (Plate 8 and Figure 17).

In cutting down through soft glacial sediments Waterfall Creek has exposed the contact with the underlying Proterozoic sediments (the dark sandstones and siltstones) which represent the first period of deposition at Hallett Cove. These dark sediments form the arch or fold at the waterfall. The line of the contact between the sediments can be followed up from the waterfall on the south side of the creek and almost to the boardwalk on the top of the cliff to the right. The younger, paler glacial sediments, representing the second period of deposition, now make up most of the hillside (Plate 8) but were originally deposited in a glacial lake which formed in a pre-existing valley on this site. These sediments – mostly sands, shales and clays – are softer because they have never been buried sufficiently deeply to be hardened by heat and pressure. Being soft they weather very quickly. A period of 330 million years separates these two periods of deposition and the contact between them is an unconformity. Very extensive weathering and erosion during the time of separation is thought to have reduced the height of the ranges created from the folded Proterozoic sediments by many kilometres.

Still looking south, but further up toward the top of these sediments, an overlying layer of grey weathered sandstone can be seen. This sandstone – the fossiliferous Hallett Cove Sandstone – represents the third period of deposition, occurring when a shallow sea covered the area about four million years ago. The contact between this layer and the glacial sediments is also an unconformity, representing another gap in the record, or period of erosion, this time of about 266 million years.

Overlying the sandstone is a thin layer of alluvial silts and clays laid down between one and two million years ago by sediment-laden streams flowing down from the Mount Lofty Ranges. This layer represents the fourth period of deposition. The contact between the sandstone and these recently deposited silts and clays is also an unconformable one.

Leave this viewpoint by the path which continues toward the coast, noting the thicket of kangaroo thorn *(Acacia paradoxa)* growing on the hill-side north of Waterfall Creek and the clumps of the grey cushion bush *(Calocephalus brownii)* growing near the mouth of the Creek. Take the lower (left) path to the cliff to where there is an excellent view of the shore platform. If you wish to visit the shore platform there is a lesser path down the cliff from here.

Plate 9: The view south along the shore platform from the cliff above Waterfall Creek. The ice-flattened top of Black Cliff and the western limb of the anticlinal fold which forms the cliff can be seen in the mid-distance. The eroded sediments which form the platform can be seen to be continuous with those of Black Cliff. All consist of the 600 million-year-old Proterozoic sediments – siltstones, sandstones and quartzites. The sharp contact between these sediments and the pale glacial sediments draped over the cliff line can be clearly seen. Photo: R. Major.

Locality 5: View to the Shore Platform

From the top of the cliff the shore platform can be seen extending southwards at sea level back to Black Cliff (Plate 9).

In perspective, it can be more easily appreciated that the platform is composed of the same dark Proterozoic siltstones as Black Cliff. Following the melting of the northern hemisphere ice cap the sea reached its present level about 6000 years ago. Erosion by the sea progressively undercut the cliff removing layers of rock. This fallen rock has eventually washed away leaving a platform at beach level and bringing the shoreline closer to its present shape.

Notice how the layers in Black Cliff dip steeply towards the sea and curve over near the top, exposing one limb of a massive anticlinal fold. This folding took place about 500 million years ago when the geosynclinal sediments were squeezed up by pressures within the earth's crust. The glaciated pavement is developed on the crest of this fold. Another fold forms the arch seen at the nearby waterfall. Other smaller folds can be seen on the shore platform. These folds can be examined more closely by visiting the platform at the base of Black Cliff at low tide (see Plates 4, 22 and description for Locality 13). The line of contact between the dark siltstones and the pale Permian glacial sediments can be easily traced along the cliff line.

Take the main path north which continues along to the National Trust plaque which denotes the clifftop as part of the Sandison Reserve. Note the changes between pale soft Permian sediments in the small gullies and an overlying layer of hard greyish white fossil-bearing rock.

Locality 6: A Bluff Capped by Fossil-Bearing Sandstone

Above the path this hard greyish white fossil-bearing sandstone forms a bluff only about one metre thick. (Plate 10). The Hallett Cove Sandstone was laid down as sandy sediment about four million years ago, in the shallow warm sea which thinly covered exposed glacial sediments. The sea had inundated the St Vincent basin, which had gradually developed by downfaulting of blocks of Proterozoic geosynclinal sediments, and entered high bays such as Hallett Cove. The sea only shallowly covered the land – which may account for only a thin layer of sandstone occurring in the area.[6] About 266 million years elapsed between the deposition of the Permian glacial sediments and their covering by the sandy marine sediments. As no record remains of events in that period, this contact is also an unconformity.

The sea supported life in the form of forams such as *Marginopora* spp (see Figure 10, page 12) and molluscs (shellfish) (Plate 9). The species of fossilised *Marginopora* at Hallett Cove may have enabled geologists to define the age of these sandy sediments. The sediments containing the remains of these organisms were buried, altered to sandstone, uplifted and exposed about two million years ago. This sandstone bluff is the type section of Hallett Cove Sandstone. At the foot of the bluff there are fallen boulders of the fossil-bearing sandstone which clearly show several different types of shelly marine fossils – the only place in the Park where these are plentiful. These are also exposed in a rock near the path (Plate 11).

The sandstone layer can be traced southwards as a ledge above Black Cliff and around into the Amphitheatre, where it disappears at a point near the Sugarloaf. A very clear contact between the underlying Permian sediments and the sandstone can be seen at Locality 8, within the Amphitheatre.

Plate 10: Above the path are blocks of the Hallett Cove fossiliferous Sandstone which have fallen from a ledge which rested on the pale glacial lake sediments. At this point the ledge forms a bluff of sandstone about one metre thick. The sandstone carried fossil shellfish and other marine organisms called *Marginopora* which occupied a shallow sea about four million years ago. The contact between the sediments is an unconformity (arrowed) at the base of the bluff. Photo: R. Major.

Plate 11: Shelly fossils of marine origin in Hallett Cove Sandstone. Photo: R. Whatmough.

Retrace your steps to Waterfall Creek, cross the bridge and take the left fork which branches off the main pathway before reaching the two large glacial erratics seen at Locality 3.

Near the bridge, on a rising part of the path, note the fibrous corms of the thread iris *Gyandiris setifolia.* Boxthorn *(Lycium ferocissimum)*, the prickly shiny ground-berry *(Acrotriche patula)*, felted wallaby bush *(Beyeria lechenaultii)* and ruby saltbush *(Enchylaena tomentosa)* grow nearby. Follow the left fork in the path, which takes you to the viewing point on the north rim of the Amphitheatre. You may pass people flying kites and model gliders at this upland where the rising winds from the south west can be quite strong. Note also the wind sculpting of the vegetation and the more healthy growth of shrubs sheltered from the wind.

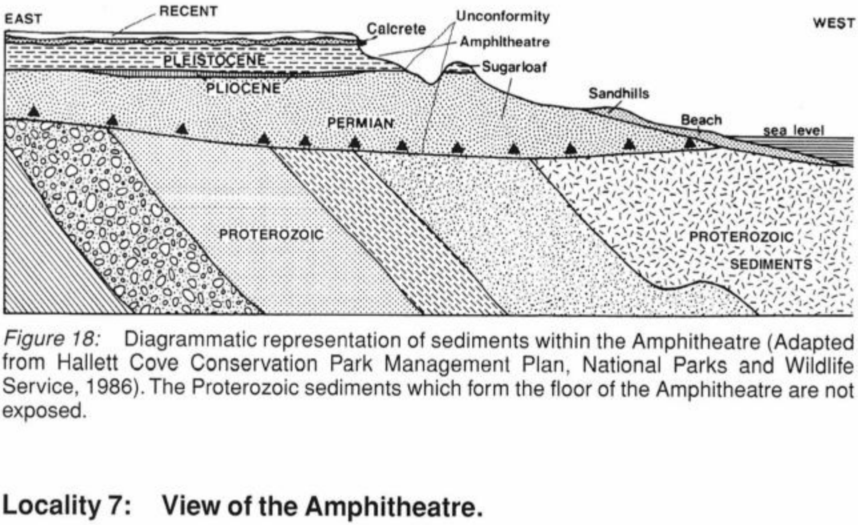


Figure 18: Diagrammatic representation of sediments within the Amphitheatre (Adapted from Hallett Cove Conservation Park Management Plan, National Parks and Wildlife Service, 1986). The Proterozoic sediments which form the floor of the Amphitheatre are not exposed.

Locality 7: View of the Amphitheatre.

From this viewpoint on the northern rim the sediments from three of the four main periods of deposition at Hallett Cove can be seen. These sediments, originally laid down within a basin formed in the Proterozoic rocks have been exposed by deep erosion and carved out to form the Amphitheatre (Plate 12) (Figures 18 and 19).

The lowest visible layer of sediments are the soft, light coloured Permian sands and silts which were deposited in a meltwater lake formed in a depression, or basin, in the Proterozoic rock toward the end of the glacial period, about 270 million years ago. The glacial sediments were deposited, unconformably, on exposed Proterozoic sediments, as they had been elsewhere within the Park. The prominent white conical hill seen in the middle distance – the Sugarloaf – also lies within this layer of glacial sediments, capped by Pleistocene clay.

Above the glacial sediments is the thin, discontinuous layer of the hard greyish-white Hallett Cove Sandstone. These sediments were originally deposited about four million years ago. The contact between the glacial sediments and the sandstone is also an unconformity – about 266 million years separating the two periods of deposition. (See description at Locality 6). The sandstone layer thins out and disappears just south of the Sugarloaf.

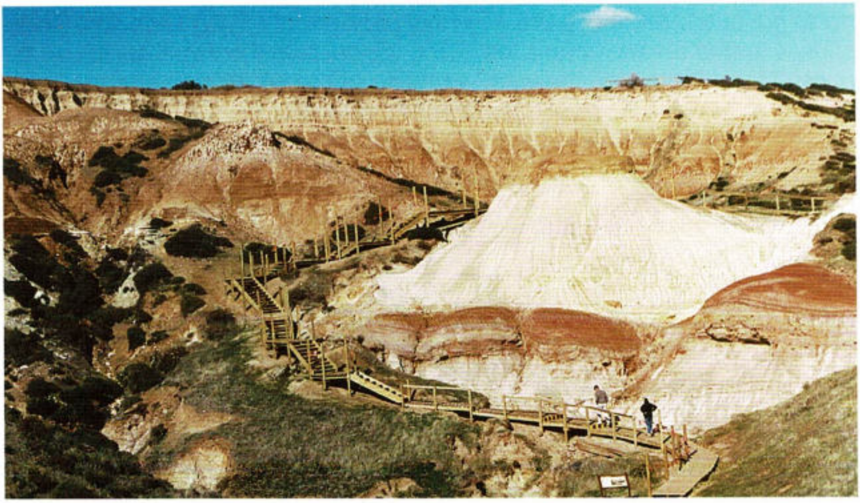


Plate 12: View from the north rim of the Amphitheatre toward the Sugarloaf, showing the Permian glacial, Pliocene marine and Pleistocene alluvial sediments which infilled a former valley developed in the Proterozoic bedrock. The Proterozoic sediments are not exposed. Photo: R. Giesecke.

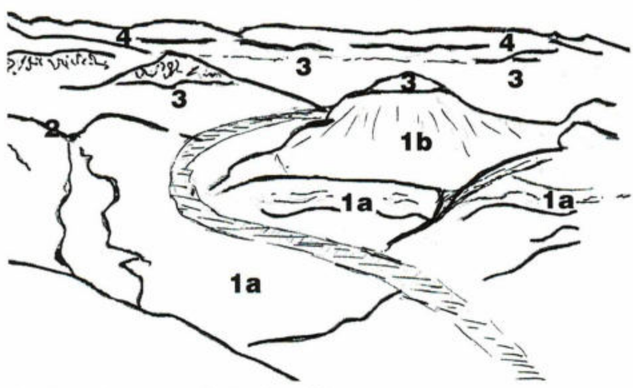


Figure 19: Sediments exposed in the Amphitheatre.
(1a) Permian glacial lake sediments including red coloured beds containing erratics and dropstones; (1b) Light coloured Permian windblown sands of the Sugarloaf; (2) The discontinuous ledge of Pliocene Hallett Cove Sandstone; (3) Red brown Pleistocene alluvial silts and clays. Ferruginous mottling present in the pale sandy clay; (4) Light coloured Recent sandy soil containing bands of calcrete.

Overlying the sandstone is the third layer of sediments – a thick layer of mainly soft red and khaki silts and clays deposited over the last 1-2 million years (in Pleistocene times). They are the alluvial sediments derived from the erosion of the present Mount Lofty Ranges as they were uplifted. The Hallett Cove area was then a wide flood plain crossed by rivers carrying the silts and clays eroded from the rising ranges. The climate was then much wetter and giant marsupials including diprotodon and kangaroo roamed the nearby savannah woodlands.

Within the alluvial sediments some soils have developed. On the slopes on the landward side of the Amphitheatre and behind the Sugarloaf, prominent red mottling identifies one of these soils. While the overall red colour of this soil is due to varying concentrations of iron oxides, the mottling is associated with the weathering process. Mottles are an indicator of rising and falling water levels within the soil. During wet periods minerals are leached from the soil and during dry times solutions of leached minerals evaporate, leaving behind the more resistant iron salts. This iron-rich, or ferruginous mottling can be seen in the red sediment behind and to the east of the Sugarloaf (Plate 12). The iron containing sediments are magnetic and such sediments have been used by geologists to measure changes in the earth's magnetic field.

In the topmost layer of the alluvial sediments bands of calcrete – a hard nodular limestone formed in soil also through alternate wetting and drying, and solution of contained calcium carbonate – can be seen (Figure 20). In the Amphitheatre there is a thin layer of recent clay and sand deposited above the calcrete (kunkar).

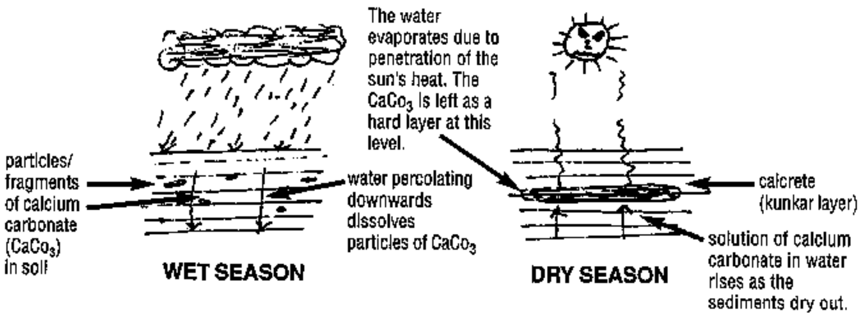


Figure 20: The formation of calcrete through alternate wetting and drying. Rainwater percolating downwards through the soil dissolves particles of calcium carbonate from the soil. In dry periods the soils dry, water evaporates and the calcium carbonate forms a dense band in the top layers of the soil.

The Hallett Cove landscape with which we are now familiar – the eroded gullies of the Amphitheatre, the beach, the shore platform and the cliff line, have only been created within the last ten thousand years as sea levels rose with the melting of the Pleistocene (northern hemisphere) ice sheets. Although this ice age was not one associated with presence of ice in this area the associated rising sea levels changed the coastline to its present position and created the shore platform. This is the evidence left at Hallett Cove by the third ice age.

Before leaving this viewpoint notice the changes in vegetation cover within the Amphitheatre. On the floor, where the soil is more fertile, introduced grasses and herbs form a fairly complete sward. Above these is a dense cover of shrubs and in the gully below the viewpoint trees are growing. Among the small native trees present in the Amphitheatre are the native peach or quandong *(Santalum acuminatum),* native apricot *(Pittosporum phylliraeoides)* and black tea tree *(Melaleuca lanceolata).* Wattle *(Acacia racinacea)*, wild rosemary *(Dampiera rosmarinifolia)* and the cut-leaved yellow goodenia *(Goodenia pinnatifida)* are also present. *Goodenia* belongs to the same family of Gondwanan origin as *Scaevola* and *Dampiera.*[7]

Now take the path down into the Amphitheatre. There are two localities where it is possible to more closely examine the layers that make up the walls of the Amphitheatre. The first of these is a prominent ledge to the left of the path where there is an exposure of the hard sandstone unconformably lying on the Permian glacial sediments. The second is the spectacular conical hill known as the Sugarloaf.

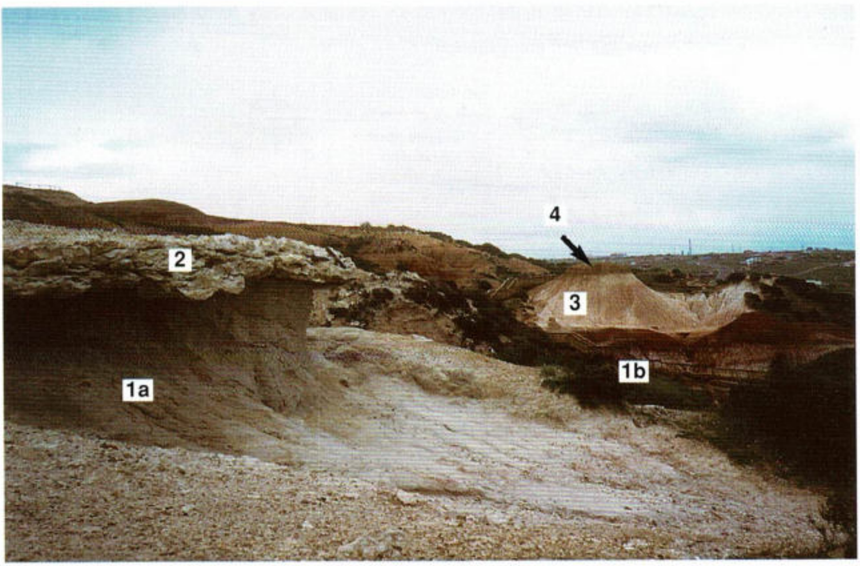


Plate 13: On the left the ledge of Hallett Cove Sandstone (2) unconformably overlies Permian glacial sediments (1a). In the middle distance the red beds of Permian glacial sediments (1b) can be seen at the base of the Sugarloaf. Above the red beds the Permian wind-blown sands which make up the pale coloured middle layer of the Sugarloaf (3) can be seen with the cap of alluvial clay (4). Photo: R. Major.

Locality 8: Ledge below North Rim of the Ampitheatre

The lower sediments of clay, sand and pebbles exposed here (Plate 13) were deposited in a Permian glacial lake about 270 million years ago. The layers, once nearly horizontal, have now been tilted at angles up to 40 degrees, perhaps by an underwater landslide. Embedded in the sediments are fine tubes of limestone carried in solution from the overlying hard limey Hallett Cove Sandstone layer. The tubes apparently formed around the roots of shrubs that grew here much as they do along the rim today. The top of these Permian sediments (along with any younger rocks) was removed by erosion in the 275 million years between the retreat of the ice and the advance of the sea, creating a gap in the record of events in this time.

Overlying the glacial sediments is the hard grey-white fossiliferous Hallett Cove Sandstone. In this locality there are a few fossils present, whereas in the same sediments at Locality 6 they are much more prevalent.

The shrubland here contains examples of stiff western rosemary *(Westringia rigida)*, twining glycine *(Glycine clandestina)* and a yellow pea flowered shrub *(Pultenaea tenuifolia)*. Pigeons and starlings can often be seen flying in the Amphitheatre, where they nest in the cliffs. Further down, the path passes through shrubland containing the felted wallaby bush *(Beyeria lechenaultii)*, shiny ground berry *(Acrotiche patula)* and creeping boobialla *(Myoporum parvifolium)* on which the Wanderer butterfly feeds. In places along this path the pest plant bridal creeper is present. Near the interpretive sign for the Sugarloaf examples of native flaxlilly *(Daniella revoluta)*, native apricot *(Pittosporum phylliraeoides)* and sea box *(Alyxia buxifolia)* can be seen. Just to the north is a she-oak *(Allocasuarina* sp.*)* tree. Note that the shrubs on the facing slope of the hill to the north are severely wind sculptured.

Before taking the boardwalk around the Sugarloaf, pause to examine the layers in this conical hill.

Locality 9: The Sugarloaf

Of all the geological localities in the Park, the Sugarloaf (Plate 14) is perhaps the best known and one of the most spectacular. Even its name is interesting. Why would it be called the Sugarloaf? There is also some controversy as to its origin and its survival, particularly when it consists of soft glacial sediments that have been very heavily eroded elsewhere in the Park. You may have the answers after examining it more closely.

The lowest bed here consists of the whitish glacial sand. The bed is of variable thickness and contains thin beds of gravel, sands and some dropstones. There is some evidence of graded bedding and turbidite beds. With this composition the bed is considered to be glacial lake sediment.[5]

A very distinct bed of red silty sand and clay containing pebbles and ice-transported, striated boulders (dropstones) of Proterozoic siltstone and

Plate 14: The Sugarloaf within the Amphitheatre. At the base is a layer of white sands, clays and boulders (erratics and dropstones) deposited from the Permian ice into a glacial meltwater lake. Overlying these beds is a layer of red sands with dropstones ('red beds') and then a thick bed of pale glacial sands containing white windblown sand probably of late Permian age. The brown capping is alluvial sand and clay of Pleistocene age deposited one to two million years ago. Photo: R. Whatmough.

sandstone overlies the pale sand and gravel layer. The presence of dropstones of Proterozoic origin, indicates that the sediments were also glacial in origin and that the lake in which they were deposited was sufficiently deep to allow icebergs to float. Dropstones at this locality are also striated suggesting direct contact with ice. The red colour of the sediments is due to the presence of iron oxide, probably absorbed from the weathering siltstones. The layer is often referred to as the 'red beds'.

Not only is the origin of these red beds controversial. Their position here is also a matter of speculation. The red colour and contained dropstones suggest that the sediments were derived from the local Proterozoic siltstones. The striation on these dropstones suggests direct contact with the ice. As the beds above and below the red beds are so similar it has been suggested that this red layer is a lens, or package of sediments, which could have been transported in as a whole bed at a single period of time.[5] Some small faults present in the clay at the base of the bed and irregularity of the top surface of the bed, indicating some erosion, could support this. It has been suggested that these beds may have been deposited in a lake situated elsewhere and transported as a single unit of either exposed, dried out lake sediments or as a partly frozen block of sediments from an area to the north of the Sugarloaf.[5]

The greater portion of the Sugarloaf consists of the thick layer of pale sand which is similar to that immediately below the red bed. There is some evidence of bedding. At the base the sand is coarser in texture and contains small clay balls. Small dropstones are present throughout the sediments, indicating that it is of glacial origin.

It has recently been found that this layer contains aeolian (wind blown) sands. Under the microscope larger quartz grains in the white sand are rounded, polished and 'frosted', indicating a windblown, rather than glacial origin. On the basis of this, the presence also of smaller angular quartz grains and of clay balls, it has been suggested that these are mixed sediments containing sand which was blown into a lake which formed in the later stages of of the Permian ice age.[5]

Above the white sand is a thin capping of brown alluvial silt and clay deposited in Pleistocene times (1-2 million years ago). The contact between the white sand and this overlying cap of silt is an unconformity – representing a period of erosion lasting about 265 million years. It is apparent that, in this location, the capping has been sufficiently hard to protect the underlying soft glacial sediments from rapid erosion.

Now, for the name! Look at the shape of the hill. If this doesn't suggest an answer try an older style dictionary or the glossary.

The layer of fossiliferous sandstone deposited elsewhere in the Park about four million years ago is missing at this location – suggesting that the sea either did not cover the sediments at that time or that they were extensively eroded before the brown silt was deposited.

Take the boardwalk around the back of the Sugarloaf and return to the main path which leads to the southern entrance of the Park. The prominent plant in this vicinity is the yellow flowered pig face *(Carbrotus* sp.*)* whose fruits are edible when ripe. Note also the prominent red mottling in the upper segments behind the Sugarloaf.

From the main path a small diversion to the left leads to the next locality – an exposure of Permian glacial sediments in which the graded bedding and turbidite beds are more easily seen.

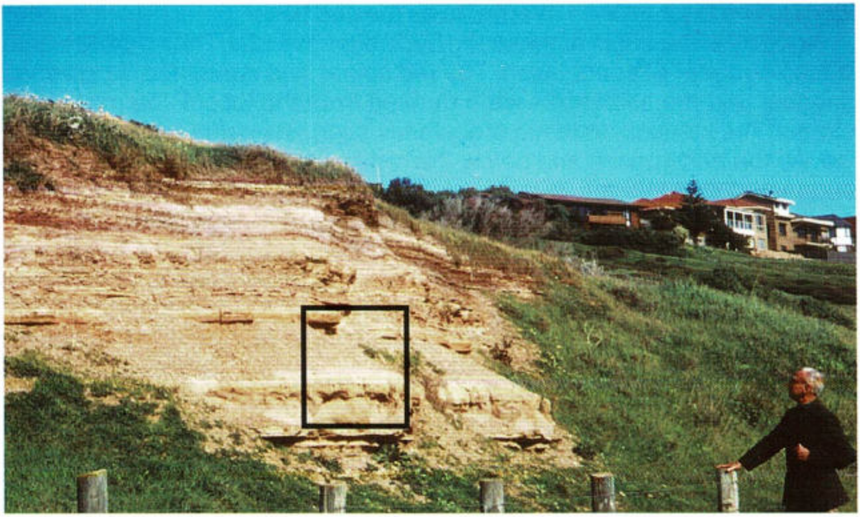


Plate 15: Graded beds of Permian lake sediments.
These beds of sandstone and siltstone were derived from layers of sand and silt deposited off the Permian ice sheet about 270 million years ago. The structures exposed include graded beds, slump structures and ripple marks. For enlargement of these structures (boxed area) see Plates 16 and 17. Photo: R.Major.

Locality 10: Graded Beds of Permian Lake Sediments

This exposure shows a slice through sediments deposited in a glacial lake toward the end of the Permian ice age (Plate 15). It is an excellent location for examining some of the small scale features associated with sedimentation and glaciation – such as graded bedding and ripple marks.

The environment under which these sediments were deposited is shown in Figure 21. It has been suggested[5] that such beds were created by rock debris and finer material slumping off the stagnating ice sheet to the west and being carried into a meltwater lake by water flowing off, and from under, the ice.

The sediment beds here are graded upwards from coarser gravel to finer sand to even finer clay particles (Plate16). From the slurry of material shed from the ice the heavier particles and small pebbles settled first. The finer layers at the top formed from material falling more slowly through the water column and settling more slowly. Still finer particles settled as beds which are now laminated (Figure 22).

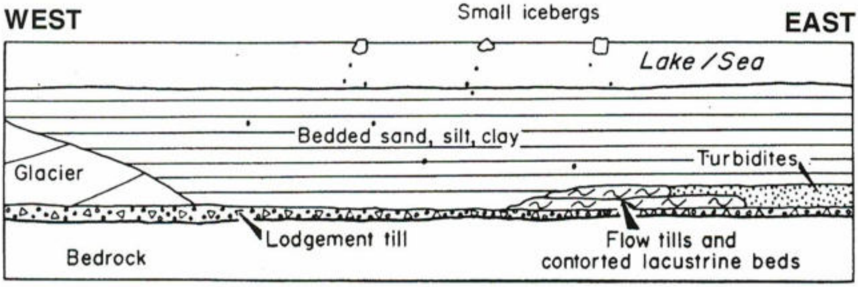


Figure 21: Deposition of sediments from melting ice in the later stages of the Permian ice age. (After Bourman and Alley, 1990).

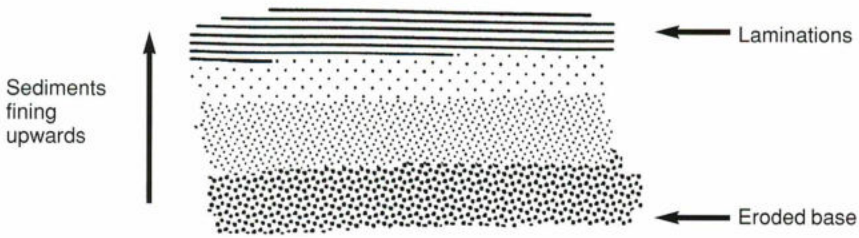


Figure 22: Elements of a graded bed. (After Pyle, 1998).

Plate 16: Detail of graded beds within the Permian sediments. The coarser particles settled out first creating the lower bed (1). The finer sediments settled out more slowly forming beds of progressively finer sediments (2). This sequence is called a graded bed, in which the sediments fine upwards. Photo: R. Whatmough.

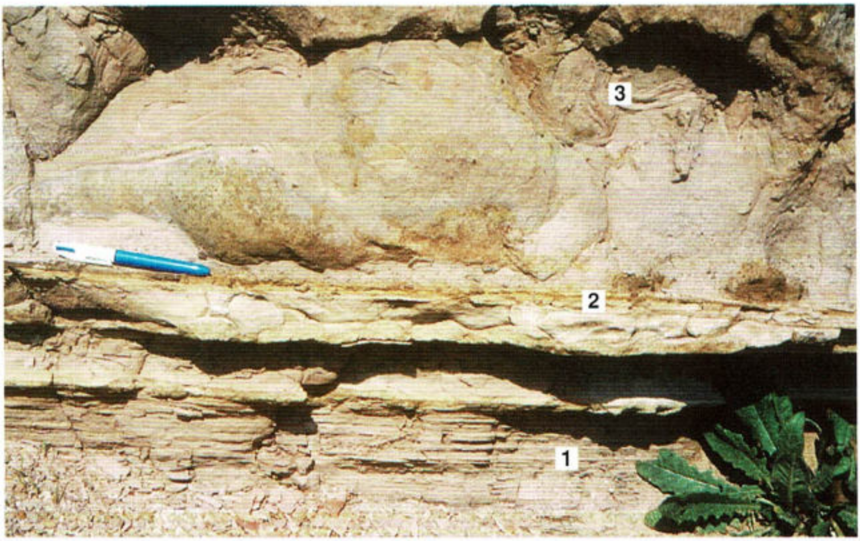


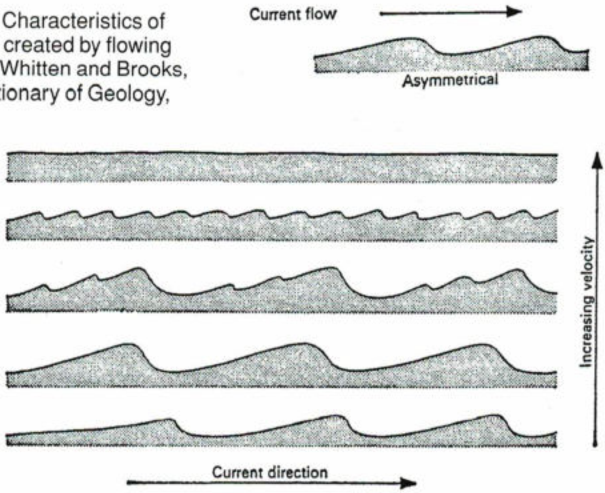
Plate 17: Detail of structures within the Permian lake sediments including laminated beds (1) ripple mark (2) and slump structures (3). The biro rests on ripple marked sandstone pointing in the direction of the current which caused the ripples – here moving from left to right: north to south. The ripple mark is asymetrical. Above the biro are strands of pink shale and sandstone derived from sediments which slumped in a plastic state into surrounding soft sediments. Photo: R. Major.

The difference between turbidites and varves (which these sediments have been called) is not easy to define. Both are graded beds. The presence of convolutions and slumps in these graded sediments (Plate 17) has been used to distinguish them as turbidites rather than varves, which are graded beds laid down more on a seasonal rather than sporadic basis. Varves tend to be consistent across an area and do not thin out to the sides as some of the layers do here. It is the presence of convolutions which have provided the clue to the origin of sediments here – suggesting currents highly charged with rock debris flowing off the stagnating ice and down the surfaces of underwater fans into a lake.

Flowing water also causes ripples in the top layer of sediment. An asymetrical ripple mark can be seen on a bed near the base of the outcrop (Plate 17). The crests or peaks of ripples advance in the direction of current flow and the height of crests decrease with the speed of the flow (Figure 23). The ripple mark preserved in these sediments indicated that the flow at the time was from left to right (from north to south). When you visit the beach look for ripple marks in the sands after the tide has turned.

This completes the walk in the Park. Return to the main path and continue southward to the Park entrance. For those wishing to explore the beach descriptions of the large erratics, the first glacial tills and the shore platform follow.

Figure 23: Characteristics of ripple marks created by flowing water. (After Whitten and Brooks, Penguin Dictionary of Geology, 1972).



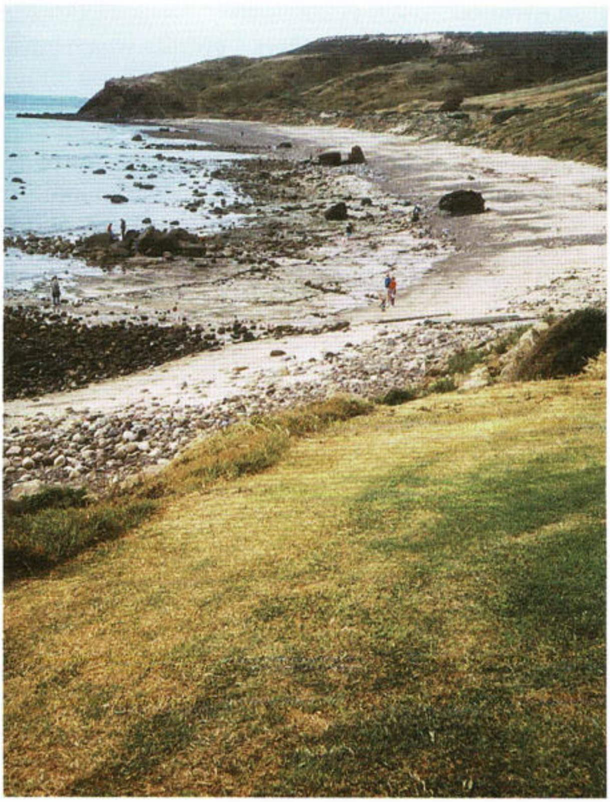


Plate 18: View north along the beach to Black Cliff. At the low water mark glacial clays representing the first advance of the ice on to Hallett Cove about 280 million years ago are exposed. Along the sands, below the grassed area and half submerged in the water are boulders of varying sizes and shapes – erratics dropped from the melting ice about 10 million years later and exposed by erosion of the softer glacial sediments surrounding them. Photo: R.Major.

The Walk along the Beach

A walk along the beach at Hallett Cove can be full of interest. On the beach there are numerous large and small erratics, some of local rock – others of differing composition and transported from many kilometres south by the Permian ice (Plate 18). At the low water mark there is evidence of the very first advance of the ice to this area. This locality, which extends the length of the beach to the base of Black Cliff, consists of clay and is slippery to walk on when wet. Ripple marks can often be found in the sands between the boulders. For those interested in exploring rock pools a visit to the shore platform, which can be approached from the beach or from a point near the mouth of Waterfall Creek at low tide, is well worthwhile.

It would be wise to obtain information on tide times before visiting these area as they can only be safely visited at low tide. Tide times are published daily in *The Advertiser*. The tides at Hallett Cove are similar to those at Port Adelaide (Outer Harbour).

From the southern entrance of the car park go down to the beach. The first large erratic can be seen just below the Surf Life Saving Club and the rest are scattered along the beach to the south.

Locality 11: The Large Erratics

Hallett Cove beach (Plate 18) is strewn with boulders – erratics which have been eroded from local bedrock or transported by the Permian ice about 280 million years ago and reworked by the sea. Most of the smaller boulders have been eroded from the dark sandstone cliffs to the south and tumbled northwards by the waves. On the beach in front of the Surf Life Saving Club there is a boulder of pink Encounter Bay granite transported by the ice from the Victor Harbor area. About 150 metres south, below the picnic shed there is a single large dark coloured boulder of Sturt Tillite (Plate 23, page 50). This rock is a relic of the first ice age to involve South Australia – the Sturtian – which moved over South Australia about 750 million years ago. Further south again are a number of large boulders, situated close together (Plate 19) consisting of the reddish brown Proterozoic

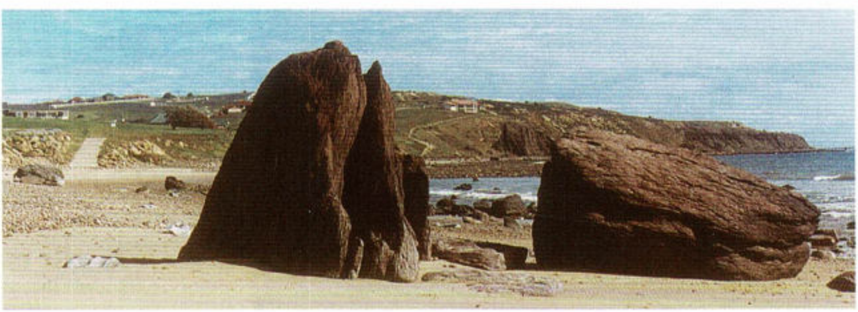


Plate 19: Two large erratics composed of red-brown Proterozoic sandstone and siltstone. These were probably stripped from the bedrock south of Hallett Cove and carried deep in the Permian ice. Photo: R. Whatmough.

(600 million-year-old) sandstone and siltstone – the same rock types as seen in Black Cliff. In contrast to the quartzite erratics on top of the cliff, these erratics show more rounded edges indicative of weathering and reworking by the sea. It is probable that these erratics were carried deep in the ice and dropped into a lake of meltwater from floating icebergs toward the end of the Permian ice age. Erosion later removed the sediments into which they had fallen.

Some of the smaller boulders were probably rock derived from the underlying Proterozoic bedrock during the first movement of the ice on to the Hallett Cove area.

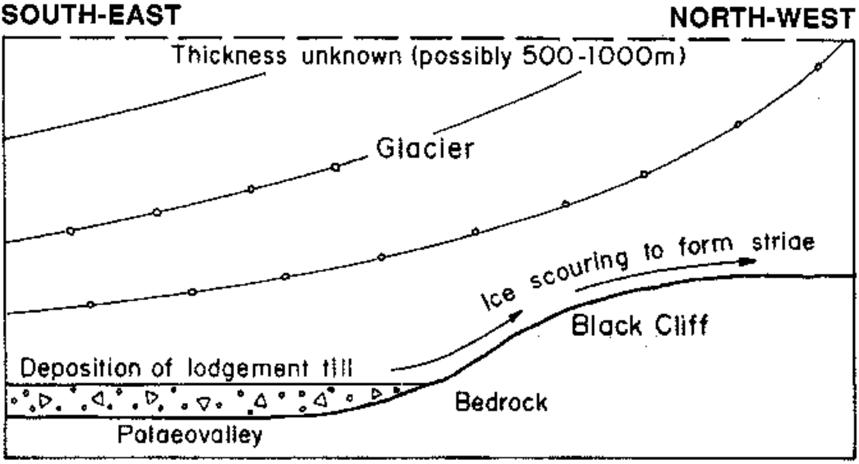


Figure 24: Deposition of sediments during the first advance of the Permian ice on to Hallett Cove. (After Bourman and Alley, 1990).

Locality 12: First Permian Glacial Sediments

At low tide, on the beach straight down from the Clubrooms, the sediments which mark the first advance of the Permian ice on to the Hallett Cove area can be visited. The environment in which these early sediments were deposited is shown diagrammatically in Figure 24.

Visible only at low tide is the lowest of these sediments, called by geologists a lodgement till (Plate 20). It is a bed which extends well out to sea with only the upper surface exposed at the low water mark. The sediments consist of very fine grained, compacted, grey sandy clay containing unsorted (variably sized) clasts or pebbles of rock. Most of these are angular but a small number are rounded. The majority of the pebbles consist of red siltstone or sandstone torn from the underlying Proterozoic bedrock by the advancing ice, but a small number consist of quartzite, granite or rocks of volcanic origin.[8] Some have been polished, faceted and striated and some of the larger pebbles are oriented in a south-east to north-west direction. Fossil pollens identified in these sediments,

Plate 20: The first Permian glacial sediments at Hallett Cove. This lodgement till consists of hard grey sandy clay with embedded pebbles of the underlying Proterozoic siltstone and sandstone. The sediments have been hardened by contact with the moving ice. The clay content makes them very slippery when wet. Photo: R. Giesecke.

though not age specific, suggest that the sediments were early Permian in age.[5]

These sediments appear to have been deposited by moving ice directly on the basement of Proterozoic siltstones and sandstones, the orientation of the larger pebbles contained in the debris indicating the direction of ice movement. It is the clay content of these sediments which makes them very slippery when wet.

Exposed along the beach to the south, and again only visible at low tide, is a layer of sediments known as a flow till (Plate 21). This layer was deposited later and overlies the lodgement till, extending shorewards, where it is covered by the sand of the beach. It contains a greater number of rocks than the underlying lodgement till and shows convoluted and contorted, interbedded sands, silts and clays with embedded pebbles[5]. This layer is considered to be a flow till created by debris flowing from the ice into a lake. The contortions and slumps may have been created by the draining of the lake and subsequent collapse of the contained sediments.[5] While the same rock types present in the underlying layer are represented in this bed, there is a greater percentage of granite and rock of volcanic origin brought in from elsewhere.[8]

It has been suggested that most of the larger boulders strewn along the beach were derived from this group of sediments.

As you walk along the beach note that there is little sand here compared to most Adelaide beaches. The sand here is also frequently eroded during winter storms and replenished during summer. Coastal erosion is

Plate 21: The second layer of glacial sediments at Hallett Cove. This flow till overlies the lodgement till and consists of convoluted and contorted beds of sands silts and clays containing pebbles of granite and gneiss which were transported from areas south of Hallett Cove by the advancing ice. Photo: R. Giesecke.

greater where the softer sediments are exposed south of Black Cliff[9], forming the Cove.

Locality 13: The Shore Platform

The heavily folded and eroded Proterozoic (600 million-year-old) sandstones and siltstones underlie the glacial sediments on Hallett Cove beach and are exposed only at the base, and to the north of, Black Cliff as the shore platform (Plates 3, 4, 9 and 22) at low tide. The best place to appreciate the extent of the platform, study the geological features and the variety of invertebrate life that colonises it, is north of Black Cliff, approached at the base of the cliff or from a path near the mouth of Waterfall Creek. (See map inside front cover).

During the third (Pleistocene) ice age, which was at its maximum about 18,000 years ago the sea level was 100-130 metres lower and the shoreline was south of Kangaroo Island. The Hallett Cove area was probably undulating low hills with rivers draining west on to alluvial plains. As the northern hemisphere ice sheets melted about 10,000 years ago the sea levels rose around the world reaching their present level in the southern hemisphere about 6000 years ago.

Storms and high tides during these last 6000 years became agents for erosion and the cliffs were eroded eastwards in response to the battering waves. The sea undercut the cliffs and removed large quantities of the dark siltstones, buff coloured quartzites and pink dolomites which make

Plate 22: The rock platform at the northern base of Black Cliff consisting of Proterozoic sandstones, siltstones and quartzites. A prominent hard upturned band of quartzite protrudes above the eroded sandstone layer, exposed to the left. This band is also continuous with that in the fold of the cliff itself. Fallen slabs of the sandstones and siltstones can be seen around the base of the cliff. The rock debris on the platform provides the rock pool environment in which many invertebrates thrive. Photo: R. Hunt.

up the bulk of the Proterozoic sedimentary rock here. Rock rolled around by wave action increased the degree of erosion of the remaining rock, levelling it at the current low tide mark. The erosive energy of the waves was limited and did not go beyond the wave base at high tide. Consequently, the rock was eroded down to a flat platform out from the base of the cliffs. A cross section of the steep westerly-dipping beds of Proterozoic rock has been exposed by the wave action and on the platform today, the exposed bedding, folds and faults within the Proterozoic Geosynclinal sediments can be clearly seen.

M-shaped folds are best seen at the base of Black Cliff (Plate 4, page 18) while S-shaped folds are more prevalent on the platform north of Black Cliff. To the north of the cliff the quartzite layers, being more resistant to erosion, protrude above the siltstone layers (Plate 22). Small faults can be found by walking along these quartzite layers and noticing where the quartzite layer appears to be displaced (Figure 25).

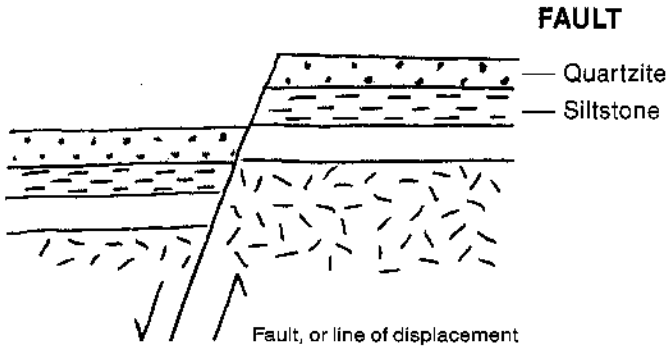


Figure 25: Small scale faulting giving rise to displaced beds in the quartzite and siltstone.

Weathering of the softer rock has provided the crevices which offer refuge for the many invertebrates and algae colonising the platform.

At the base of the cliff – but above the spray or supra littoral zone – note the orange and grey lichens. Where a little soil has accumulated, the round-leaved pig face grows. In crevices at the base of the cliff can be found a little blue grey snail *Littorina unifasciata*. The production of acids and the rasping action of snails and limpets feeding on microscopic algae contribute to the erosion of the rock surface. In particular, limpets will rest in one spot, hastening the breakdown of the rock.

On some of the erratic rocks strewn over the mid range of the platform bands of calcareous grey-white tubes of the tube-dwelling segmented worm *Galeolaria caespitosa* can be found. Old bands lying at unusual angles or levels may indicate that these rocks have been displaced, toppled or turned. Red-brown sheets of the alga *Porphyra* are more tolerant of exposure to air and occur at a higher level than the pink feathery coraline alga *Coralina* which can be seen in pools further down toward the sea.

Also seen at this level are the little brown conical snail *Bemicium*, then black periwinkles, barnacles, small black mussels, the segmented worm *Galeolaria* and the warrener snails (the 'doors' of whose shells are seen as 'eyes' in beach sands). All occupy a preferred zone.

As you walk back along the beach to the southern entrance look inland and up on the cliffs. You can now see some of the modern age housing development which surrounds the Hallett Cove Park, and evidence of some of the massive earth-shaping events which have taken place over the last 600 million years – virtually in residents' front yards.

In summary: these earth-shaping events, the preserved evidence of which you have seen in your walk in the Park and along the beach, were, firstly, evidence of sediments laid down in shallow depressions on a continental shelf in Gondwana about 600 million years ago. Then their folding which created the first Mount Lofty Ranges about 500 million years ago. A long period of erosion followed, during which these ranges were reduced to stumps. Then the Gondwanan ice sheet, up to 1000 metres thick, flowed over Fleurieu Peninsula about 280 million years ago, leaving evidence of its passing in the glacial sediments and erratics throughout the Park and on the beach.

Then you saw the evidence of climate changes which affected southern Australia after tectonic forces finally separated Australia from the Gondwanan land mass about 45 million years ago and allowed the continent to drift northwards alone. The climate warmed. About four million years ago a warm shallow sea invaded the southern margins of Australia, including the coastline of South Australia. Organisms and shellfish living in this sea became fossilised as the seafloor sediments were buried. This left a ledge of sandstone extending from the coast and around to the Amphitheatre.

Then the effects of further uplift, weathering and erosion were seen as the present Mount Lofty Ranges were uplifted and became weathered two million years ago and the seafloor sediments were exposed. You saw evidence of another ice age, which affected the northern hemisphere more than the south, caused northern polar ice sheets to re-form; sea levels around the world to wax and wane but nonetheless, left evidence at Hallett Cove. The climate became warmer and wetter. Erosion and a wetter climate created vast alluvial plains on which giant kangaroo, diprotodon and Aboriginal Australians roamed. Finally you saw how the coastline was changed and the modern shape of the Hallett Cove landscape emerged. Rising seas flooded the coastal plains and a glacial valley across the toe of the mountain range, thus separating Kangaroo Island from the mainland and bringing the coastline to its present position. Coastal erosion became a factor. Wave action over the last 6000 years created Black Cliff and the shore platform extending to its north.

The scenery at Hallett Cove has an interesting past. Added to the forces of deposition, folding, uplift and erosion which created, and are continuing to change, the landscape, there is now an additional force – human activity. Will it be a force for destruction or preservation?

With your new-found knowledge of the power of ice to sculpt the landscape, you may wish to visit other places on Fleurieu Peninsula where the effects of past ice ages can be seen.

In the following chapter notes are provided on the glacial features at Sturt Gorge, Cape Jervis, The Bluff (Rosetta Head) and Glacier Rock in the Inman Valley. A road map, with these places highlighted, is included.

You may wish to take a copy of *A Field Guide to the Coastal Geology of Fleurieu Peninsula* (Field Geology Club of South Australia, Inc, 1986) with you, as it has detailed notes on the interesting and scenic coastline of the Peninsula.

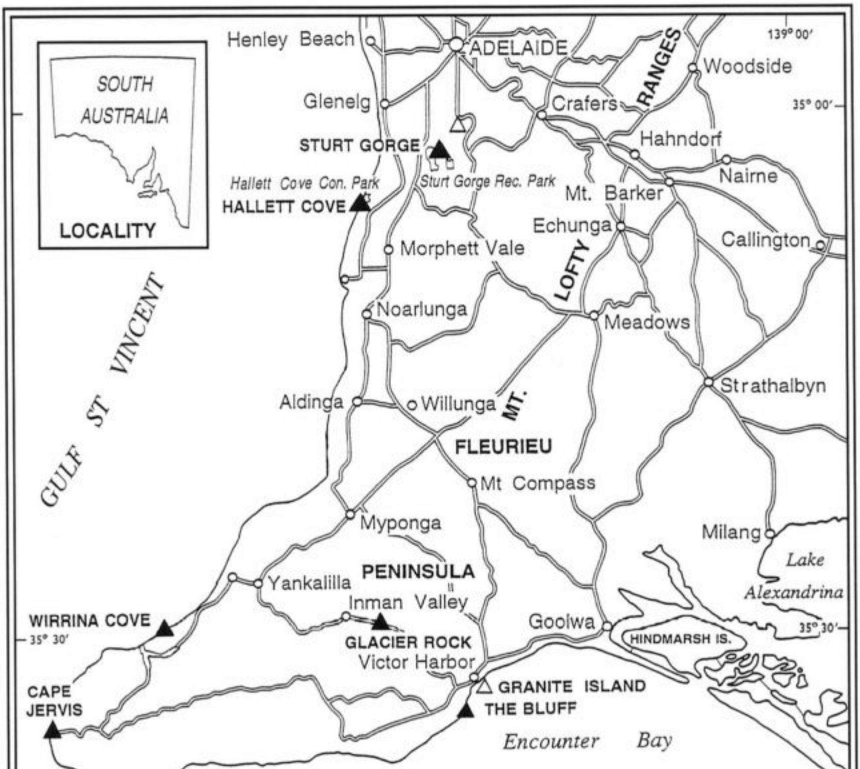


Figure 26: Fleurieu Peninsula, with localities showing features of glaciation highlighted. (After Geological Society of Australia, 1996).

Chapter 3

OTHER LOCALITIES WITH GLACIAL GEOLOGY ON FLEURIEU PENINSULA

For those whose interest and curiosity have already been aroused by their discoveries at Hallett Cove, there await other sites on Fleurieu Peninsula where they may pursue their hunt for clues left by the ice ages. The important features of these localities are briefly described in this chapter. The localities where the ice ages have left evidence of their passing on and around the Peninsula are highlighted in Figure 26.

As previously mentioned, the Peninsula has been affected by three ice ages – the Sturtian of about 750 million years ago, the Permian (Gondwanan) of about 280 million years ago and the Great (northern or Pleistocene) of about 18,000 years ago. The sequence of geological and climatic events which affected the Peninsula and Australia during the time frames over which the Hallett Cove landscape evolved is given in the table inside the back cover. Exposures of the Permian glacial sediments on the Peninsula are shown in Figure 7 (page 8).

A walk along the river bank in the Sturt Gorge Recreational Park will provide rewarding glimpses back in time to the oldest – the Sturtian ice age, while the (more recent) Permian glaciation can be traced by the keen investigator along the coastline at Cape Jervis, Encounter Bay, and in the Inman Valley. These two ice ages, which involved sculpting of the landscape by ice, have left clear traces of their passage on the Peninsula and South Australia. The third and most recent ice age, the Pleistocene, left its mark on the Peninsula's coastline.

The earliest ice age occurred about 750 million years ago, and was first recognised by Professor Walter Howchin of the University of Adelaide in 1901, when he examined rocks of the Sturt River Gorge south of Adelaide. Evidence of this glaciation was to be found later elsewhere in South Australia, the Northern Territory and in other parts of the world. Known world wide as the 'Sturtian', this ice age is thought to have been one of the most severe and widespread ever to have occurred on Earth. In South Australia tillite associated with this glaciation has been found in the Flinders Ranges. The southern exposure is best seen at Sturt Gorge and can also be seen at Anacotilla Beach, Wirrina Cove. A large erratic composed of Sturt Tillite is also present on the beach at Hallett Cove, having been transported there by the later Permian ice sheet.

Plate 23: Large erratic of Sturt Tillite exposed on Hallett Cove beach showing the typical composition of variably-sized pebbles of quartzite and gneiss derived from the Gawler block embedded in grey brown mudstone. The tillites from this 750 million-year-old ice age were later stripped and transported to Hallett Cove by the Permian ice sheet 280 million years ago. Photo: R. Major.

Sturt Gorge

The Sturtian glacial sediment, called tillite, is found in the deep gorge created by the Sturt River and exposed in the Sturt Gorge Recreation Park, which lies in the foothills of the Mount Lofty Ranges, within the suburbs of Bellevue Heights and Flagstaff Hill, about 13 kilometres south of Adelaide.

The best approach to the river and to good exposures of the tillite is by a steep walking track and fire track entered from a small car park on Broadmeadow Drive, Flagstaff Hill. The walking tracks are less well developed than in the Hallett Cove Conservation Park and there are no facilities available. Water should be carried as that in the Sturt River is not suitable for drinking.

The tillite is hard rock and forms the walls and floor of the gorge. It is also exposed on the upper slopes of the gorge in the north-west bend of Broadmeadow Drive. The glacial beds, which are about 750 million years old are believed to have been deposited by melting icebergs which had floated out to sea from an ice-covered continent, as is happening off the coast of Antarctica today.

The exposure in the Sturt Gorge is the type section for Sturtian glacial sediments but there are also exposures at Hallett Cove and Wirrina Cove.

The tillite has a very distinctive appearance – being a grey, gritty mudstone containing numerous erratics of varying sizes from small pebbles to large boulders up to one and a half metres in diameter randomly scattered throughout the fine material (Plate 23). The enclosed erratics consist of granite, quarzite and gneiss resembling those of the Gawler Block (see Figure 6, page 4) to the north-west, from which they were transported by the ice.

At Sturt Gorge some of the erratics show evidence of stretching and fracturing likely to have occurred after their deposition, during the Delamerian period of mountain building about 500 million years ago. Others have become aligned in one direction within the tillite (Figure 27). The Sturt Tillite exposed at Hallett Cove and Wirrina Cove does not show these features.

STRETCHED AND ALIGNED PEBBLES

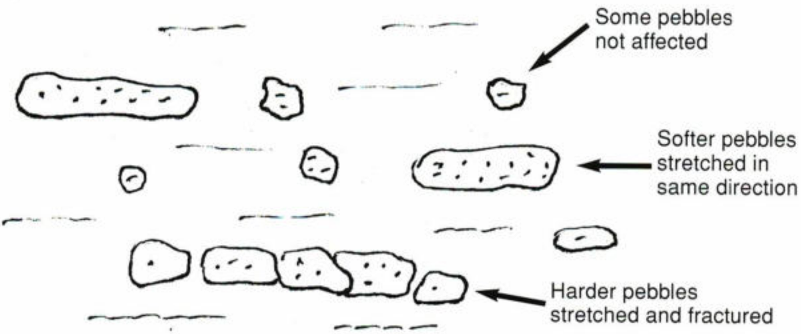


Figure 27: The response of erratics within the Sturt Tillite at Sturt Gorge to mountain building forces applied to the tillites after their deposition.

Cape Jervis

At Cape Jervis, on the toe of the Peninsula, there are extensive deposits of Permian glacial till. It has been suggested that this area may have been the junction of two tongues of ice or glaciers, one of which moved westwards across the Peninsula and the other moving northwards through what is now Backstairs Passage (Figure 26), then a glaciated valley.

The low and comparatively flat area of the Cape, which extends back from the coast about three kilometres, is possibly due to the eroding force of this northward moving ice. The coastal shore platform and the lower part of the coastal cliffs consist of grey, altered Cambrian (520 million-year-old) sandstones. Lying directly upon these rocks to the north of the lighthouse, the glacial sediments form hills up to 30 metres in height. The lower sediments can be distinguished by their paler colour from the younger reddish clay sediments which overlie them. Fossil forams found in the clay layer indicated that the glacial sediments on the Peninsula were of early Permian age. As they were of the type found in low temperature and possibly slightly saline environments it suggested that the clay sediment was deposited from the ice into an estuarine or shallow marine environment toward the end of the glaciation period. The Permian Cape Jervis Beds are the type section for Permian sediments in South Australia and were probably deposited at the same time as those at Hallett Cove.[8]

In the gullies between the hills fresh exposures of glacial till can be seen. The sediments range from very fine silts to much larger pebbles and boulders (dropstones). Many of the larger erratics have been faceted and striated. Most have been torn from the underlying Cambrian bedrock. The tills therefore carry a higher proportion of sandstone than those at Hallett Cove.[8] The large boulders scattered on the shore platform below the coastal cliffs are erratics which have eroded out from the till (Plate 24). Some of these consist of Encounter Bay granite.

The great variety of sediments seen here suggests that they were deposited from the melting ice sheet, streams from which formed constantly changing lakes and streams in the local area.

Encounter Bay and The Bluff

Another site to examine Permian glacial sediments and ice sculpting is Encounter Bay, on the southern coast of the Peninsula.

The sea cliffs from Port Elliot to The Bluff (Rosetta Head) on Encounter Bay are all composed of glacial deposits of the Permian Ice Age. They contain many large and prominent granite erratics, some of which can be seen lying in the shallow water off the shoreline near the Bluff. Most consist of the granite which forms the Bluff and have been transported from it and from the granite islands scattered offshore. The erratics have been dropped, then exposed, as the sea has eroded away the cliffs formed of the glacial deposits.

The distinctive granite erratics derived from the Port Elliot and Encounter Bay areas provide wonderful evidence for tracing the direction

Plate 24: Granite erratics dropped from the Permian ice sheet, exposed on the shore platform north of the Cape Jervis lighthouse. The platform was created by recent erosion of Cambrian (520 million-year-old) sediments. Photo: P. Hasenohr.

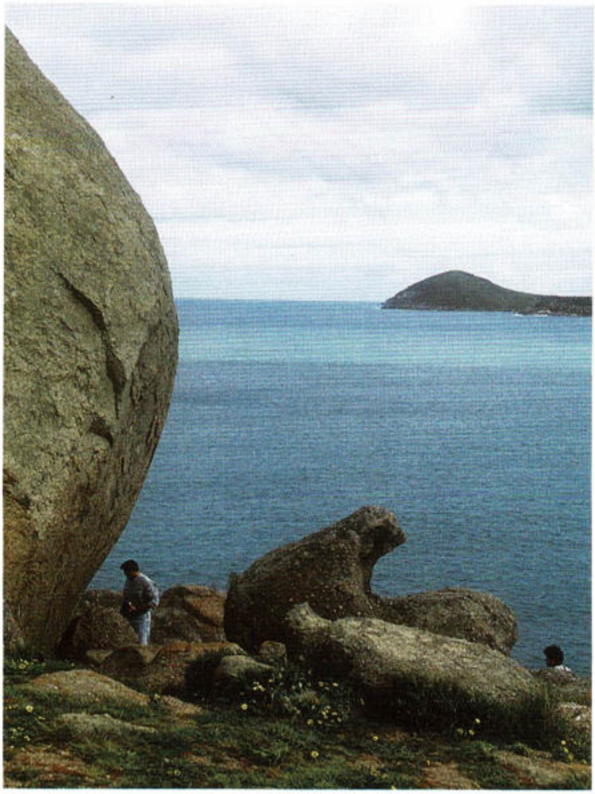


Plate 25: The Bluff (Rosetta Head) seen from Granite Island, Encounter Bay. While the Bluff has the shape of a *roche moutonnée* possibly created by ice moving from the south (left) no marks left by the passage of ice have been found on the weathered granites which form this headland. In the foreground are typically smoothed and rounded boulders of Victor Harbor (Encounter Bay) granite. Photo: R. Whatmough.

and movement of the glacial ice. They can be discovered right across the Fleurieu Peninsula as far as Cape Jervis, further north along the coastline to Hallett Cove, and on the southern half of Yorke Peninsula, proving that the ice moved in a westerly direction.

Note the rounded and smooth shape of the Bluff (Plate 25). Once thought to be a typical glacial feature called a *roche moutonnée* (so named for structures shaped like sheep lying down) there is now some doubt about this. Despite the presence of erratics on the beach at its base and the presence of glacial moraine at Kings Point west of Victor Harbor, no evidence of glaciation has been found on the headland itself. In this locality it would have been expected that a northward moving ice sheet or glacier would have left striae on the southern face of the headland and evidence of the plucking of softer rock and steepening of the northern face (Figure 28) but no striae or friction cracks have been found in the weathered granites of the Bluff to confirm either the passage, or direction, of the ice in this locality.

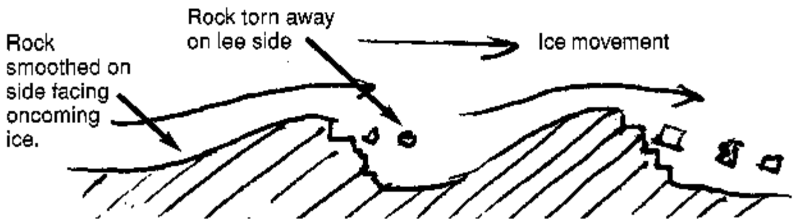


Figure 28: Movement of ice over a slope to create a *roche moutonnée*. The side facing the oncoming ice is usually smoothed and marked by the ice while the side away from the direction of the ice movement (lee side) is steepened by the plucking of rock by the ice.

Inman Valley and Glacier Rock

From known exposures of sediments the Permian ice sheet appears to have crossed the Peninsula (Figure 7, page 8) through the east-west trending Inman Valley.

Inman Valley was an ancient valley. Today it stretches from Victor Harbor to Normanville – a distance of about 32 kilometres. It is approximately 16 kilometres in width and is traversed by the road from Victor Harbor to Yankalilla. It was in the Inman Valley that glacial features were first recognised on the Australian continent by A.R.C. Selwyn, a Victorian geologist, in 1859.

The undulating and rolling landscape of today is created by erosion of glacial sediments – mostly soft clays and sandy clays – deposited by the westerly moving Permian ice on Cambrian bedrock as it moved through the pre-existing valley which traversed the Peninsula. The valley was deepened in the process and filled with a great thickness of glacial deposits. Following the 200 million year period of erosion which occurred at the end of the glaciation period the floor of the valley was eventually exposed. The area was uplifted and watercourses were re-established, cutting down through the glacial sediments. These soft sediments, which form the slopes in the valley, are particularly susceptible to erosion. For a time the sediments in the deeper valleys were protected but are now eroding at a rapid rate.[10]

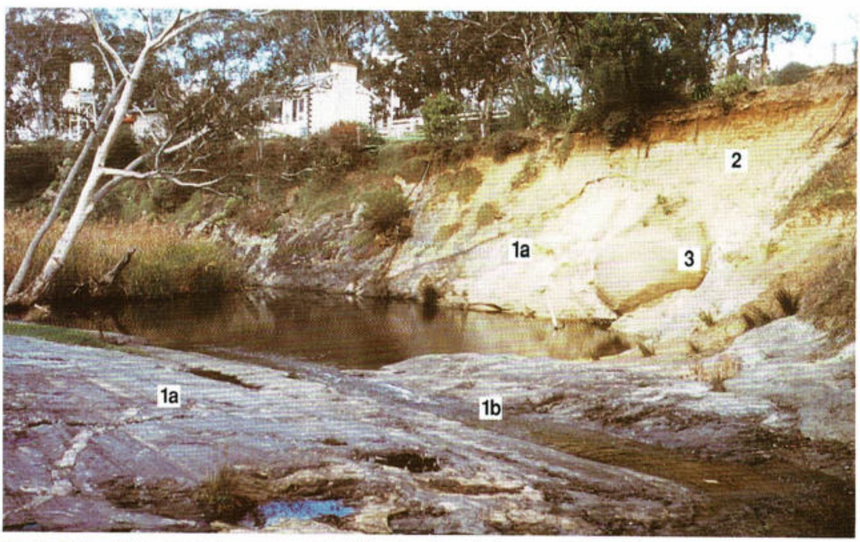


Plate 26: The glacial pavement at Glacier Rock, Inman Valley, looking east. The pavement of Cambrian bedrock is striated (1a) and grooved (1b) showing that the Permian Ice sheet was moving from east to west in this locality. Permian tills (2) form the south bank of the Inman River. A large erratic of Encounter Bay granite (3) lies exposed in the till. Photo: R. Major.

Numerous erratics can be found dotting the landscape and lying on the bed of the Inman River. Some are very large, and are composed of the same type of granite that occurs along the southern coast in the Encounter Bay area.

A site well worth visiting is the Glacier Rock cafe, about 14 kilometres from Victor Harbor, where refreshments can be obtained and a visit made to the glaciated pavement discovered by Victorian geologist A.R.C Selwyn in 1859. This is Glacier Rock – a site recognised for its geological heritage.

Like the glaciated pavement at Hallett Cove, the bedrock surface here exhibits a polished, and striated surface scoured by the great thickness of ice which passed over it. However, this pavement features deep grooves created by boulders held in the ice. The grooves and striae here trend east-west. In the south bank of the river, which consists of soft glacial sediments, there are many embedded erratics. One particularly large boulder of Encounter Bay granite hangs out of the sediment halfway up the bank (Plate 26).

In summary: Through visiting Hallett Cove and these other sites on Fleurieu Peninsula you have been able to see the dramatic effects of moving ice in shaping the Peninsula and South Australian landscapes. While the Permian ice sheet extended westward to Yorke Peninsula it is on Fleurieu Peninsula that more of the glacial sediments have been exposed, enabling closer study. At Hallett Cove where, in those Permian times, 280 million years ago, the landscape would have resembled that of Eastern Antarctica today (Plate 1 and back cover), you have been able to see both the landscaping effects and the smaller scale features which enabled geologists to interpret sediments as glacial in origin.

GLOSSARY OF GEOLOGICAL TERMS

Ablation moraine: Rock fragments concentrated on the ice by its melting.
Aeolian: Formed of particles transported by wind.
Alluvial: Transported by river or stream.
Alluvial fan: A low conical hill of sediment formed where the rapidly flowing stream enters a flatter area and deposits the rock material that it is carrying. The shape is produced as the stream divides or varies its direction to find its way through what it has already deposited.
Anticline: An upward or 'A' shaped fold.
Calcrete: Calcium carbonate that has been formed into a hard layer in soil, by dissolving in ground water that regularly accumulates there in wet seasons and evaporates in dry seasons. Also known as 'kunkar'.
Cement: A material that links grains of sediment together to form a harder material. Common examples are quartz, calcium carbonate and various forms of iron oxide. Usually brought into the sediment in solution in water.
Chatter marks: Friction cracks in the form of a series of small crescent-shaped hollows aligned at right angles to the ice movement, with 'horns' pointing in the direction of ice movement.
Clast: A fragment of rock contained in another material, possibly ice or a younger rock of which it now forms part.
Claystone: A rock formed by the hardening of clay, especially by compaction or the linking of its grains by a cement.
Contact: A surface where rocks of different types or ages meet. See also unconformity.
Convolution: Distortion of a sedimentary layer by a series of upward and downward folds usually produced by high velocity currents or by disturbance of beds after deposition.
Crescentic cracks: Friction cracks in the form of a series of curved near-vertical cracks at right angles to the ice movement with their ends turned in the direction of ice movement.
Crescentic gouge: A friction crack in the form of an isolated, sometimes large crescent-shaped depression at right angles to the ice movement, with horns pointing in the direction opposite to the movement. The depression has a steep edge on the downstream side. (See also lunate fracture).
Deformable: Structure which can be changed in shape or volume after its formation or deposition.
Differential weathering: A process whereby rocks of differing composition break down *in situ* at different rates according to their mineral composition, grain size or hardness.
Dolomite: Rock containing magnesium carbonate. Formed through evaporation of very saline water.
Dropstone: A rock carried by floating ice and dropped into water as the ice melts. It depresses the sediments where it lands. The same rock may also be an erratic.
Erosion: The removal of rock material by mechanical action (eg running water, wind, wave impact, ice) or chemical action (eg solution in water). Hard rocks may require weathering before they are so affected.
Erratic: A rock carried by ice from a different area. Larger examples may weigh many tonnes. The same rock may be a dropstone.
Faceted: Worn by a mechanical process (eg abrasion by rock fragments embedded in ice) so that flat faces, meeting at sharp angles, are formed.
Fault: A break in the material of a rock when one side has moved past the other. Usually visible when materials on opposite sides don't match in the expected way. Faults can be formed by various forces including compression (squeezing) and stretching.
Faulting: The formation of faults. When it occurs on a large scale it may be associated with the uplift of mountains.

Fault line: A fault at least hundreds of metres long, especially one formed by earth movements that have affected the landscape in an obvious way (eg by raising the ground surface on one side to form a hill).

Ferruginous: Containing iron.

Flow till: Material flowing from the ice and deposited in layers.

Fold: A bend in the material of a rock, usually made visible by the bending of layers in the rock. Folds are most often produced by compression and include anticlines with an arch (or 'A') shape and synclines with a trough (or 'V') shape.

Folding: The formation of folds. When it happens on a large scale (tens of kilometres or so) it is often associated with the formation of mountains.

Foram (Foraminifera): Single celled protozoan organisms related to amoeba but differing from them in being covered with a shell containing calcium carbonate. Are sensitive indicators of changing environments, particularly levels of salinity, and are useful for dating sediments. See Figure 10.

Fossil: Evidence of life, found in rock.

Friction cracks: Marks left on bedrock by the passage of ice containing rock fragments. Include chatter marks, crescentic gouges, crescentic cracks and lunate fractures

Frosting: Surface etching caused by abrasion.

Geosyncline: An area of sinking where sediments accumulate to a great thickness. It is often long and narrow and may be hundreds of kilometres in extent. In the last stages it may be folded and become a mountainous area.

Glacial (glaciated): Associated with ice.

Gneiss: Banded and highly altered rock. Often of granite composition.

Graded bedding: The arrangement of sediment in layers in which the particle size decreases upwards from coarse to fine. Each layer is formed in a separate event in which particles of different sizes settle from water, the coarser settling more quickly, finer more slowly. Fine beds at top.

Granite: Rock of igneous origin containing quartz and feldspar. May be light coloured and granular in composition.

Grooves: Larger scale parallel markings on a rock surface formed by a mechanical process. Glacial furrows formed by abrasion by boulders in the ice.

Joint: A break formed in a rock by shrinkage or minor deformation of the material without significant movement between the sides. Such breaks may form a regular pattern.

Kunkar: see *Calcrete.*

Lacustrine: Pertaining to lake; ie sediments deposited in a lake.

Laminated sediments: Thin layers of sediment.

Leaching: Weathering by the chemical action of acids dissolved in rainwater.

Lee: The side of a rock or feature that is downstream of the approaching flow (of ice, wind, etc).

Limestone: A rock composed mostly of calcium carbonate which may also include sand, clay or other impurities.

Littoral: The beach area between high and low tide marks. Supra-littoral is above high tide mark, sub is below low tide mark.

Lodgement till: Fine grained, compacted material and non-stratified sediment deposited beneath the moving ice. Contains unsorted rock fragments torn from the underlying bedrock. Early glacial sediment. See Plate 20.

Lunate fracture: A friction crack in the form of isolated, sometimes large crescent-shaped depression at right angles to the ice movement. The depression has a steep edge on the lee side. 'Horns' point downstream. See Figure 14.

Metamorphic rock: A rock formed by the alteration of another rock by some combination of heat, pressure and chemical action.

Moraine: A stream of rock fragments carried along by a glacier and deposited along the margin or at the end of the ice.

Nodule: A hard lump of material formed within a rock by chemical action, sometimes showing concentric layers when broken.

Orogeny: Mountain building episode, usually associated with faulting or folding at a specified time.

Outcrop: An exposure of rock.
Palaeovalley: A former, pre-existing or fossil valley, now filled with younger rocks.
Pavement: A hard, flat rock surface.
Polished: Worn by a mechanical process until very smooth.
Quartz: The mineral silica or silicon dioxide
Quartzite: Altered sandstone. Through heat or pressure sand grains recrystalise and form a dense interlocking structure of quartz cement, resulting in a very hard rock.
Ripple marks: Wave like shapes formed on the surface of sand or silt by the movement of water or wind over it. Often seen on beaches. Can be preserved in solid rock.
Roche moutonnée: A rock or feature of any size shaped by the passage of ice over it, so that it has a gentle rise on the side of the approaching ice and a steep irregular drop on the lee side. So named because of the forms shaped like recumbent sheep. See Figure 28.
Rock flour: Very fine silt or clay derived from the grinding of larger rock fragments.
Sandstone: A rock formed by the hardening of sand, especially by the linking of its grains with a cement less hard than the sand grains.
Sedimentary rock: Rock formed from the deposition of material without a great amount of chemical alteration. Often forms distinct layers.
Shore platform: A flat, but possibly rough area of the shore below the level of extreme high tides, carved from hard rock by the mechanical or chemical action of the sea and biological activity.
Silt: Moderately fine particulate material derived from rock by weathering or erosion of pre-existing rocks. Particle sizes are between sands and clays.
Siltstone: A rock material formed by the hardening of silt especially by the linking of its grains by a cement.
Slickensides: Parallel marks made on the surface of a rock by its movement against another rock, especially along a fault or fold.
Slump: Structure produced by sediments erratically flowing down a slope. A contorted bed.
Striations (Striae): Small scale linear and parallel marks on a rock surface formed by mechanical process (eg abrasion).
Sugarloaf: A bare conical hill. Named after a moulded lump of refined sugar (now rarely made).
Syncline: A downward or 'V' shaped fold.
Till: A mixture of rock fragments of greatly varying size transported by ice. Includes clay, sand, pebbles and boulders.
Tillite: Rock formed by the hardening of till.
Tension crack: A break formed in the rock by stretching of the material in one direction, usually accompanied by contraction in other directions. May be filled with quartz.
Turbidite: A sedimentary rock formed under water by the settlement of material from turbidity (sediment-laden) currents. Graded beds of sediment.
Turbidity current: A rapid movement of water with suspended rock particles down the sloping floor of a sea or lake. The underwater equivalent of a landslide.
Type section: The site of a rock outcrop which has been chosen to define a particular rock type or succession.
Unconformity: A surface where sedimentary rocks have formed in contact with much older rocks and where there has been no continuing sequence of deposition. Often marks a period of intense erosion.
Varves: Graded bedding formed by deposition of sediment in a lake in which the inflow of sediment-laden water is seasonal or annual and each bed represents a seasonal or annual input. Coarser sediments tend to form in summer and finer in winter. Ice melts more slowly in cooler weather, and faster in warmer weather.
Weathering: The chemical breakdown of rocks that makes them soft and able to be removed by erosion. Includes the formation of soil.

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NOTES

NOTES

SUMMARY OF EVENTS AT HALLETT COV

Era	Period	Epoch	Mya	Hallett Cove: Events	Hallett Cove: Stratigraphy
CAINOZOIC	Quaternary	Holocene	0.01		sandy soil Bakers Calcrete
		Pleistocene	1.8	DEPOSITION Alluvial sands and clays	fossil soils of Amphitheatre Keswick & Hindmarsh Clays
	Tertiary	Pliocene	5	DEPOSITION Limey sands & shells deposited beneath shallow seas: uplift: river-transported land deposits	cream fossiliferous Hallett Cove Sandstone
		Miocene	24		
		Oligocene	34	Most of glacial deposits removed during second long period of erosion	
		Eocene	55		
		Palaeocene	65		
MESOZOIC	Cretaceous		141		
	Jurassic		205		
	Triassic		251		
PALAEOZOIC	PERMIAN		298	DEPOSITION Glaciation: rocks polished & grooved: huge quantities of rock debris left behind when ice melted:reworked by streams	windblown pale yellow to white quartz sand of Sugar Loaf; glaciolacustrine silts and clays, sandy clay of lodgement till on beach at low tide.
	Carboniferous		354	Mountains worn down by weathering and erosion during most of Palaeozoic.	
	Devonian		410		
	Silurian		434		
	Ordovician		490	Major earth movements in the OrdovicianCambrian buckled & uplifted sediments of the Geosyncline into mountain ranges.	
	Cambrian		544		
PROTEROZOIC			2500	DEPOSITION silts & sands deposited beneath shallow seas of ADELAIDE GEOSYNCLINE	red mauve siltstones (Brachina Group) Black Cliff
ARCHAEAN			4500		

N FLEURIEU PENINSULA AND IN AUSTRALIA

Fleurieu Peninsula	Australian	
Events	**Climatic & geological features**	**Features of biological evolution**
	similar to present	similar to present
	cool,dry low sea levels alternate with warm and wet high levels	aborigines arrive. Extinction of the giant marsupials
uplift of present Mt Lofty Ranges	Australia drifts north, cools and dries after a warm start	rainforests decline while eucalypts and grasslands spread. Giant forms of kangaroos and wombats
	warm & wet	lush rainforests, reef growth in northern waters
	Gap widens between Australia & Antarctica	Modern groups present, Acacias, eucalypts, koalas and possums
	New coastlines form with the separation from Antarctica	Temperate forests, marsupials, bats, frogs .Forests and non-marine mammals in Antartica
	Australia and Antarctica separate	New flowering plants, mammals & birds diversify after the decline of the dinosaurs; primates appear
	shallow inland seas	flowering plants evolve and spread; dinosaurs abound but are extinct by the end of the period; first appearance of snakes , monotremes
	warm & wet, Australia & Antarctica begin to separate	conifers, cycads & ferns abound, plant eating aquatic reptiles, birds
	Gondwana begins to break up	insects, reptiles, dinosaurs, Dicroidium flora in Gondwana
Inman Valley sediments & glaciated pavement, glacial till (Cape Jervis beds)	cold period with glaciers followed by global warming	swamp-forests present, insects fish & early amphibians; Glossopteris flora in Gondwana; first mammal like reptiles ; Major extinction at end of period. [> 80% of known life-forms]
	warm at first then glaciers develop as Gondwana drifts across south pole	club mosses replaced by hardier plants; first forests, conifers; winged insects
	inland seas	tree sized land plants; many fish; first amphibians; insects; Major extinction middle period
	mountain building along east coast,volcanism	vascular land plants, first fish with jaws
	warms seas cover central Australia	marine invertebrates [bivalves & crinoids], graptolites jawless fish evolve; first land plants (bryophytes)
uplift of first Mt Lofty Ranges, intrusion of Victor Harbor granites...... [Delamerian Orogeny]	land that will form Australia lies north of the equator	no life on land, but seas teem with jellyfish, trilobites sponges & molluscs
Sturtian glaciation	Oxygen becomes abundant and life diversifies, single cell eukaryotes evolve[2.1 billion years], then multicellular organisms [600 million years.]	
	formation & development of earths crust, atmosphere and oceans,life formed as early as 3.8 billion years ago.some bacteria produce oxygen, ozone layer begins to shield the Earth from UV rays.	

The continental ice sheet in Eastern Antarctica today. This is how Hallett Cove may have appeared during the Permian Ice Age, 280 million years ago. Photo: G. Fraser.

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