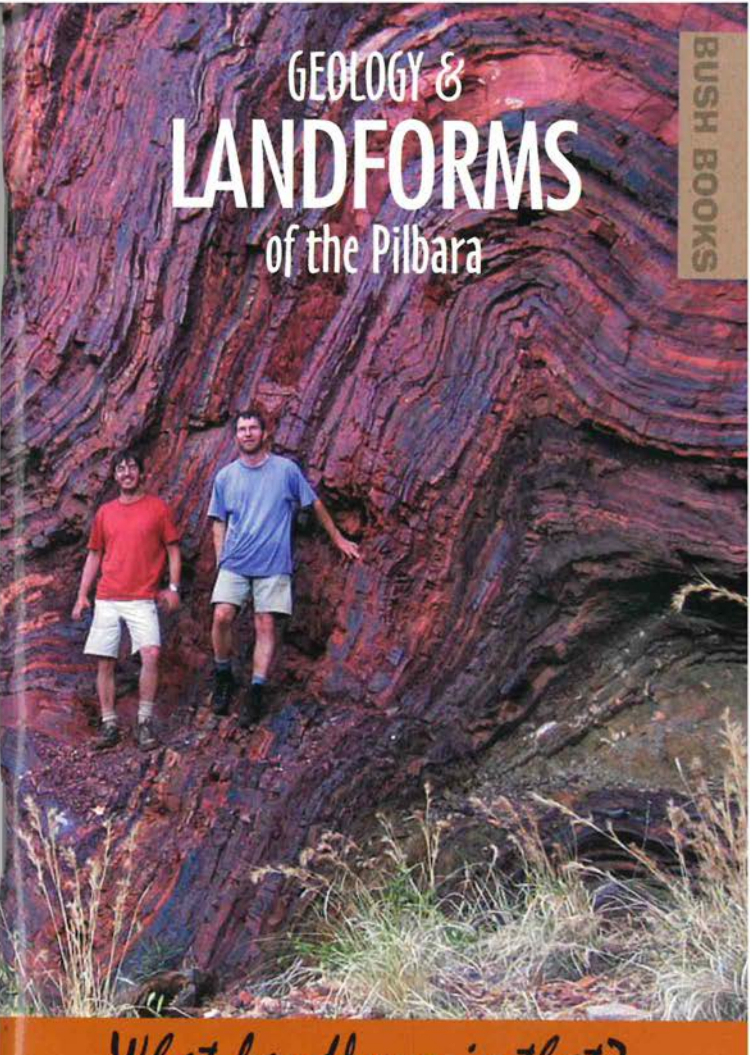
GEOLOGY &
LANDFORMS
of the Pilbara

BUSH BOOKS



What landform is that?

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ABOUT THE AUTHOR

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Publisher: Department of Conservation and Land Management, 17 Dick Perry Avenue, Kensington, WA 6151.

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Front cover:
Folded banded iron-formation, Hamersley Gorge, Karijini National Park.
Cover photo: Mark van Zuilen

ISBN 07307 5556 8

GEOLOGY & LANDFORMS of the Pilbara

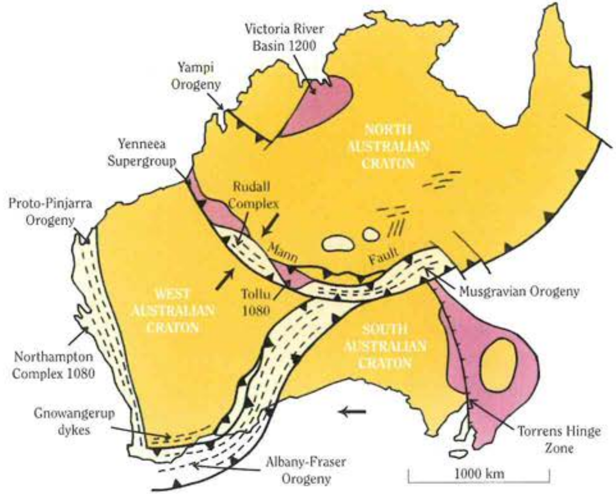
by Iain Copp

GEOLOGICAL HISTORY OF THE PILBARA

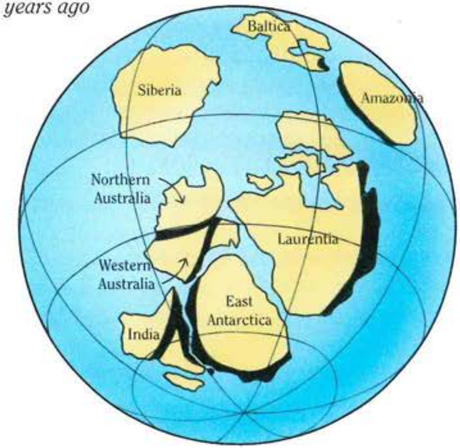
The Pilbara is geologically one of the oldest regions in Australia, containing rocks that are more than 3600 million years old. These formed when the Earth was still very young, during the Archaean, and belong to the Pilbara Craton. This represents one of the world's best preserved fragments of ancient continental crust – one of Earth's earliest continents.

The oldest part of the craton is made of greenstones, a mixture of volcanic and sedimentary rocks, intruded by granite magma to form 'granite–greenstone terrain'. The greenstones continued to be deposited, and were intruded by more granite throughout the following 800 million years. During this time, huge stresses within this newly formed crust caused many rocks to be severely sheared, folded and faulted. Large volumes of hot fluid were generated deep within the craton as a result, and many rocks and faults became mineralised with gold, copper, nickel, zinc, tin and tantalum. The Earth's surface was a hostile place during this time, with little oxygen in the atmosphere, and only simple microbial life that formed stromatolites. Some of these are up to 3490 million years old – the world's oldest fossils and the first visible evidence of life on Earth. The world's oldest evidence of meteorite impacts also occurs in the Pilbara during this time (3460 to 2490 million years ago).

By around 2800 million years ago, the formation of granite–greenstone terrain had ended, and a major period of uplift and erosion took place throughout the Pilbara. The Pilbara Craton at this time was part of a larger continent that began to break apart along what is today its southern margin. As the crust stretched and became thinner, an extensive rift was formed that ran in a west-north-westerly direction. Consequently, around 2770 million years ago, a huge volume of molten rock from the underlying mantle was extruded along this zone, forming a 'sea of basalt lava'



Above: *The assembly of Australian cratons between 1760 and 1000 million years ago*



The supercontinent Rodinia, about 750 million years ago, showing the main areas of mountain building (in black) that buried the older granite-greenstone terrain landscape. These lava flows are preserved as part of a thick succession of volcanic and sedimentary rocks, known as the Fortescue Group. This was the beginning of the deposition of the vast Hamersley Basin, the youngest part of the Pilbara Craton.

As the main period of crustal extension came to an end by about 2690 million years ago, the Hamersley Basin then began to fill with sediments deposited on a shelf or platform that opened to an ocean. During this time, extensive deposits of banded iron-formation (BIF) were laid down, such as those in the Hamersley Range.

Between about 2200 and 1800 million years ago (during the Proterozoic), the ocean that lay to the south of the Pilbara Craton was closed during a series of collisions with other ancient continents that included the Yilgarn Craton. This caused the rocks of the Hamersley Basin to be deformed into large folds, as they were squeezed between the two continents. Together, the landmasses formed the vast new West Australian Craton. Extensive mountain building took place along this collision zone, leading to another major period of erosion and the formation of a sedimentary basin called the Ashburton Basin.

Soon after, at around 1760 million years ago, the West Australian Craton collided with another continent to the north-east, called the North Australian Craton. This continental collision brought together most of what is now the western and central parts of the Australian continental landmass. Further collisions brought together a much bigger assemblage of cratons that formed the Rodinia supercontinent by 1000 million years ago.

Following the collisions, the crust then sagged over the junction between the cratons, allowing an immense basin to develop that filled with sediments deposited by shallow seas, rivers and glaciers. In the eastern part of the Pilbara, where the Little

Sandy Desert is today, this part of the basin is called the Officer Basin. By about 750 million years ago, towards the end of the Proterozoic, Rodinia began to break apart and, although the Australian continent remained mostly intact, old 'joins' between cratons were reactivated. Consequently, about 550 million years ago, substantial faulting and folding took place in the Rudall area.

North-east of the Pilbara, where the Great Sandy Desert is today, a huge basin called the Canning Basin began to form around 490 million years ago. As it slowly filled with marine and continental sediments, it partly covered older rocks at the edge of the Pilbara Craton and in the Rudall area. Glaciers formed some of these deposits around 295 million years ago during the Permian. Australia was then part of the Gondwana supercontinent and lay close to the South Pole. The glaciers deeply scoured the landscape, carving huge glacial valleys that are recognisable today in the north-eastern part of the Pilbara.

Around 170 million years ago, a large rift developed within the crust off the northern side of the Pilbara, where the present day North West Shelf now is. This marked the beginning of the break-up of Australia from Gondwana, and as the continental crust pulled apart, a sedimentary basin called the Northern Carnarvon Basin developed along this rift. Slowly, it filled with an enormous thickness of sediment, some of which was transported by rivers from the eroding rocks of the nearby Pilbara Craton.

During the last 90 million years, thick deposits of limestone have accumulated over the North West Shelf, some of which is now exposed as islands and coastal ranges.

With such ancient rocks, the Pilbara is now internationally known as the best 'field laboratory' for studying the early history of the Earth. Research is carried out by scientists from Japan, France, the USA (including NASA), the United Kingdom and Australia.

EVOLUTION OF THE PILBARA LANDSCAPE

The Pilbara region has a spectacular landscape of plateaus, gorges, ranges, razor-backed hills and ridges, narrow steep-sided valleys, low hills, plains, deserts, coastal flatlands and islands. This diverse landscape is very old, and much of it probably began to form at least 295 million years ago during the Permian period. During this time, Australia was part of the Gondwana supercontinent and was situated close to the South Pole. Glaciers carved broad deep valleys into the landscape, particularly on the north-eastern side of the Pilbara. After the glaciers retreated, the surface continued to be eroded as rivers cut down through the landscape.

Around the late Jurassic (about 170 million years ago), as Australia began to break apart from Gondwana, the Pilbara was probably gently uplifted. This caused an extensive interior drainage system – the ancestral Ashburton River – to develop. By the Late Cretaceous (around 100 million years ago), warm and humid climatic conditions prevailed over the Pilbara region, and the underlying rocks consequently underwent deep weathering. A blanket of iron-rich sediments slowly accumulated over the landscape to form the Hamersley Surface, which today is preserved over much of the Hamersley Range. Soon after, the Pilbara was gently tilted towards the north-west and rivers then began to cut back and down into this newly formed plateau, and a network of gorges developed. Material that was eroded at the higher levels was transported to the sides and floors of valleys, to form thick iron-rich deposits. As erosion continued, these deposits were themselves dissected, and are now preserved as mesas and tablelands, like those at Deepdale near Pannawonica. By around 40 million years ago, as Australia began to drift northwards after separating from Antarctica, the Pilbara probably began to dry out, leading to lakes forming in old river valleys, such as those of the Fortescue and the Oakover.

Photo – Jiri Lochman

Aerial view of dunes in the Great Sandy Desert

During the last two million years, successive ice ages made the climate throughout Western Australia extremely arid. Between about 25,000 and 13,000 years ago during the last ice age, aridity was at a peak, probably causing the last significant activity of the dunefields in the Great Sandy Desert and Little Sandy Desert. As the polar ice caps contracted for the last time, about 18,000 years ago, and the climate became warmer and more humid, sea level began to rise and coastal areas were flooded, leaving behind higher areas as islands, like the Dampier Archipelago and Barrow Island.

SEQUENCE OF GEOLOGICAL EVENTS

GEOLOGICAL EVENT/FEATURE	INTERVAL	YEARS
coastal tidal flats and mangroves	Holocene	less than 10,000
Ningaloo Reef	Holocene	less than 10,000
Millstream	Holocene	less than 10,000
dunefields	Pleistocene	25,000–13,000
Montebello Islands	Pleistocene	less than 1 million
Cape Range	Miocene	20 million
pisolitic iron-ore deposits	Oligocene	30 million
Karijini Gorges	Late Cretaceous	100 million
Barrow Island oilfield	Early Cretaceous	130 million
Fortescue River alluvial plain	Late Jurassic	150 million
glaciation	Permian	295 million
Officer Basin	Proterozoic	800-550 million
continental collision with North Australian Craton	Proterozoic	1760 million
iron-ore deposits	Proterozoic	1800 million
continental collision with Yilgarn Craton	Proterozoic	2200–1800 million
Hamersley Range banded iron formation	Proterozoic	2500 million
gold deposits	Archaean	3400 to 2700 million
granite–greenstone terrain	Archaean	3600–2800 million

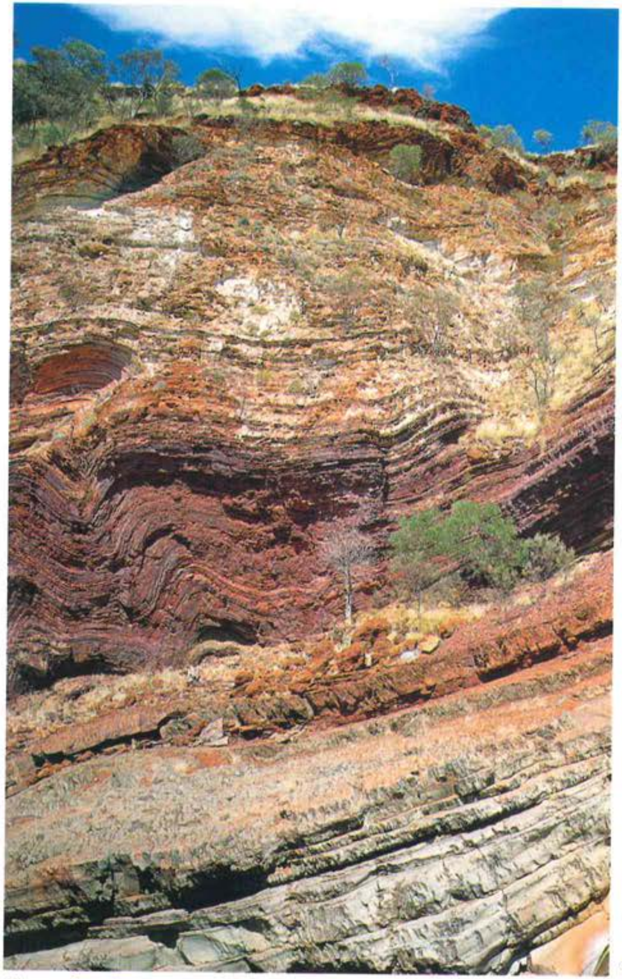


Photo – B L Downs

Hamersley Gorge in Karijini National Park

TYPES OF ROCKS

Rocks are classified into three types, according to their origin.

Igneous rocks have solidified from molten rock (magma) formed deep within the Earth, which then moves upwards along cracks and faults. It may break through the Earth's surface and pour out as lava, forming volcanic rocks such as basalt or rhyolite. Pyroclastic deposits are the accumulations of ash and other material (including pumice) produced by explosive volcanic eruptions. Basalt erupted under water forms distinctive pillow structures. Magma that does not reach the Earth's surface is injected ('intruded') into pre-existing rocks. Just below the Earth's surface this may take place along cracks to form 'dykes', or along layers in sedimentary rocks to form 'sills'. These rocks take longer to cool and the mineral crystals have time to grow larger, forming medium-grained rocks such as dolerite. Deeper in the Earth's crust, magma may accumulate in large chambers that act as feeders to volcanoes at the surface. Such bodies take a very long time to solidify, forming coarse-grained rocks such as granite and gabbro.

Photo - Ian Williams

Basalt pillow lava

Sedimentary rocks form when rocks are broken down by weathering, mostly by the action of water, wind and ice. Fragments of rock are then transported by rivers, tides or currents, by the wind, or by glaciers and ice sheets to be deposited as sediments in river channels, floodplains, seas, oceans, lakes or deserts, or by retreating glaciers and ice sheets.

These sediments may then be buried by succeeding layers and, over time, harden into solid rock. Rocks made up of boulders, cobbles and pebbles are called conglomerates, those made up of sand are sandstone, and those formed of silt and mud are siltstones, mudstones and shales. Sedimentary rocks also form by the accumulation of animal and plant remains, forming limestone or coal.

Photo - Dennis Sarson

Jasper chert

Metamorphic rocks are formed when igneous or sedimentary rocks are altered by heat and/or pressure: turning sandstone and mudstone into schist and gneiss; basalt into amphibolite; limestone into marble; and granite and gabbro into granitic gneiss, amphibolite and granulite. Metamorphism may occur when major earth movements bury rocks deep in the Earth's crust, or through heating next to an igneous intrusion. New minerals, such as garnet, grow as the rock recrystallises.

Photo - Ian Williams

Schist

CAPE RANGE NATIONAL PARK

The impressive, long, broad peninsula of Cape Range lies between Exmouth Gulf and Ningaloo Reef. Its arid, rugged terrain contrasts with the adjacent sea, coral reefs and sandy beaches.

DESCRIPTION: Cape Range is about 100 kilometres long, 20 kilometres wide and up to 330 metres above sea level. Dozens of small creeks run perpendicular from its ridgelines.

ROCK TYPES: The range is made of limestone deposited during the Oligocene to Pleistocene (30 to 2 million years ago). It consists mostly of sandy and silty limestone, which contains broken fossil material that includes corals, gastropods, echinoids, bivalves, sponges, bryozoans, nautiloids, calcareous algae, worms and crustacean fragments. The rocks are also rich in calcareous (carbonate-rich) microfossils. The limestone was formed by the accumulation of these fossil organisms, which thrived in the warm shallow marine water that once covered most of the area. Sand bars, shoals and dunes also formed in this environment and are preserved as cross-bedding within the limestone.

LANDFORM FORMATION: A series of large faults, which developed in the Jurassic when the Australian continent began to split away from Gondwana, run in a north-north-east direction throughout the Exmouth Gulf area. Since the Eocene (55 million years ago) these faults periodically moved, and a large area of ground was very slowly uplifted and gently compressed to form an A-shaped fold, or anticline. This process continued through to the Pleistocene so that the anticline was eventually exposed as the low broad range that we see today. At the end of Shothole Canyon, which is in the centre or axis of the anticline, the fold can be clearly seen; the beds dip towards the east on one side and towards the west on the other. Deep weathering and erosion have carved out steep-sided gorges, and rainwater has percolated down through the limestone, slowly dissolving it to form more than 400 caves.

On the western side of Cape Range, a series of scarps and

Photo – Wade Hughes/Lochman Transparencies

Cape Range

terraces run the length of the anticline for about 90 kilometres. They were formed by wave action successively cutting back the coastal cliffs of limestone. Each successive scarp or terrace has been lifted progressively higher above sea level as the range rose. This erosion took place during the Pliocene and Pleistocene, when the polar ice caps periodically contracted and the sea level rose.

NOTABLE FEATURES: Within much of the limestone are abundant disk-shaped grains, about the size of a small fingernail. These are foraminifera – single-celled organisms that secrete a calcareous shell. They were the main source for much of the lime sand and silt that was eventually transformed into the limestone of Cape Range. Foraminifera still survive today, and their remains can often be seen in beach sand along the Western Australian coast.

BARROW ISLAND NATURE RESERVE

Barrow Island, 56 kilometres offshore from the Pilbara coast, is WA's largest oilfield and its second largest island. West Australian Petroleum Pty Ltd discovered oil there in 1964, though geological investigations on Barrow Island began in 1954. More than 850 oil wells have since been drilled on the island, with more than 290 million barrels of oil and 4700 million cubic metres of gas extracted since production began in 1966. It is estimated that more than 103 million barrels of oil and over 927 million cubic metres of gas are still recoverable from the reservoirs below Barrow Island. At present rates of production, the life of the oilfield may continue until 2020.

DESCRIPTION: Barrow Island is a continental island that is gently folded into a broad, very low anticline. It is 25 kilometres long, up to 10 kilometres wide, covers 234 square kilometres and reaches up to 65 metres above sea level. The island's terrain is undulating except for some ravines on the western coast, and is covered by clay, limestone gravel and weathered limestone outcrops. Reefs and tidal flats partly surround it.

ROCK TYPES: Most of the island is covered by silty and sandy Trealla Limestone, similar to that in Cape Range. It contains abundant microfossils such as foraminifera, shell fragments, bryozoan, corals and calcareous algae. These organisms were deposited during the Miocene (14 million years ago) on a marine shelf, where they were slowly transformed to limestone as further sediment accumulated on top of them. Beneath Barrow Island are the rocks that are reservoirs to the massive oilfield. They consist of permeable and porous Cretaceous and Jurassic sandstone, the deepest beds of which lie nearly 3500 metres below sea level.

FORMATION AND DISTINCTIVE GEOLOGICAL FEATURES: The reservoir rocks of the oilfield were originally deposited as sand on river deltas, shallow marine shelves and deep-sea fans. This took place in the Jurassic and Cretaceous, as Australia rifted from the supercontinent Gondwana. Continued faulting and uplift led to the formation of the


Photo – Marie Lochman

Oil pumps ('donkeys') on Barrow Island

Barrow Island anticline, which continued to develop through the Miocene. The oil and gas below the island began to form from nearby organic-rich rocks during the Early Cretaceous, then migrated along porous rocks and faults before becoming trapped in the reservoir sandstones in the newly formed anticline.

During the Pleistocene ice ages, when the sea level was lower, the Barrow Island anticline was a low hill on a broad coastal plain. After the last ice age ended around 18 000 years ago, the rising sea level began to flood the coastal plain, eventually stranding Barrow Island on the newly formed continental shelf around 8000 years ago.

NINGALOO MARINE PARK

Ningaloo Reef stretches down the western coast of Cape Range Peninsula. It is the second largest reef in Australia and one of the world's major coral reef systems, supporting a community of marine plants and animals that is typical of Indopacific coral reefs.

DESCRIPTION: Ningaloo Reef is a barrier reef that protects a shallow sandy lagoon. It stretches for about 260 kilometres, forming a nearly continuous wall of coral that creates a system of habitats: the high wave-action zone of the reef front, the intertidal reef-flat zone, the sheltered back-reef edge and the quiet lagoon. The 220 species of corals that inhabit the reef feed on microscopic plants and animals called plankton that wash over them. The corals produce complex structural and biological habitats for other invertebrates such as sea stars, feather stars, fish and other animals.

ROCK TYPES: The corals and shells of many other organisms of the Ningaloo Reef are composed of calcium carbonate (lime), and form the building blocks of limestone. When these plants and animals die they slowly add to an accumulating layer of limey sand, silt and rubble, which over millions of years will be compacted by overlying deposits and transformed to limestone. Such reefs are preserved in the geological record, like the 375-million-year-old Devonian reefs in the Kimberley.

LANDFORM FORMATION: Ningaloo Reef began to form about 125,000 years ago during the Pleistocene. The pioneer corals settled on rocky ridges at the edge of Cape Range Peninsula (see pages 12–13). The reef gradually built up by the accumulation of generations of corals and other organisms with calcareous skeletons. Along the western edge of Cape Range Peninsula the continental shelf is very narrow, and heavy ocean swells wash clear, warm ocean water over the reef – ideal conditions for the growth of coral.

NOTABLE FEATURES: Many of the reef's corals owe their vibrant colours to a community of microscopic green algae, called

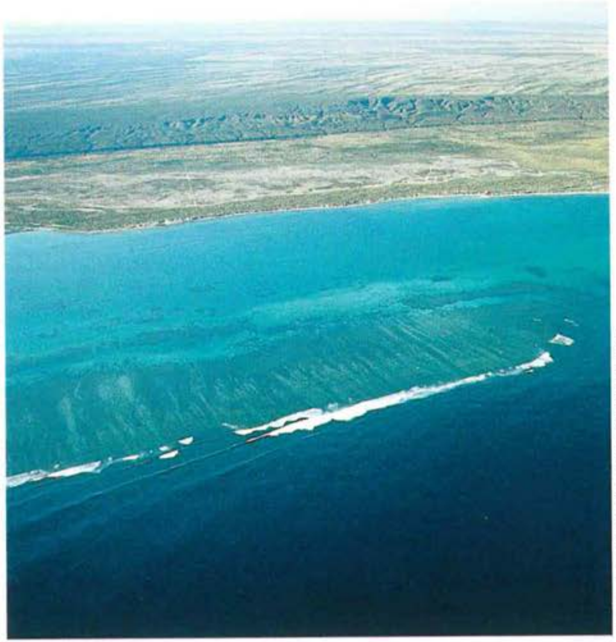


Photo – Geoff Taylor/Lochman Transparencies

Ningaloo Reef

zooxanthellae, which share the coral's skin tissue. During daytime these symbionts photosynthesise and produce supplementary nutrients for the host corals. If the water temperature becomes too warm, due to unusual oceanographic conditions, the zooxanthellae may die, causing coral bleaching. It may then take several years before the symbionts again become established.

Coral death is quite widespread on the reef as a result of infestation of the marine snail *Drupella*. This small, knobbly snail has had a devastating effect, stripping the living tissue from the coral to leave a calcium carbonate skeleton. This snail has stripped coral cover by more than 75 per cent in some parts of the reef.

MONTEBELLO ISLANDS

The Montebello Islands, about 120 kilometres north-north-west of Dampier near Barrow Island, are among WA's most distant continental islands. In 1952 and 1956, the British detonated three atomic weapons on Trimouille and Alpha islands and in the bay that separates them. Consequently, the islands were a prohibited area under Commonwealth legislation until July 1992. Public access to some areas near the test sites is still prohibited, but other areas may be visited by permission from the Navy.

DESCRIPTION: More than 100 flat islands, ranging from 1000 hectares to less than a hectare in size, are surrounded by numerous bays, wave-cut platforms and sandy beaches, and are covered mostly by sand and coastal heath.

ROCK TYPES: The islands are made of limestone, similar to that which lies along parts of the Pilbara coast. The rock contains a high proportion of lime sand derived from seashells and minute marine organisms originally deposited as sand dunes and beach deposits during the last million years. The lime sand was slowly dissolved by rainwater, then deposited again when the water evaporated, cementing the sand grains together and turning the dunes into limestone.

LANDFORM FORMATION: At the end of the last ice age, some 18,000 years ago, the sea level was much lower than it is today, reaching about 130 metres below its current level. The Montebellos and nearby Barrow Island were a low range of hills on a wide coastal plain during much of this time, probably caused by a broad anticline in the underlying rocks. Around this time, the limestone that forms the Montebellos was probably deeply weathered, creating a rugged karst landscape (see below). As the icecaps began to contract following the end of the last ice age, the sea level rose, drowning the coastal plain and stranding these hills as islands.

NOTABLE FEATURES: Many of the islands, particularly Hermite Island, contain distinctive curved shorelines and semicircular bays

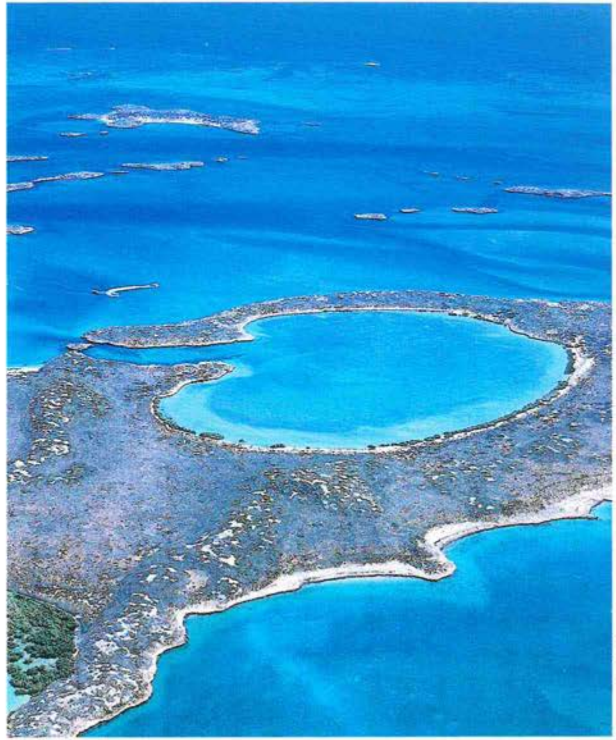


Photo – Col Roberts

Montebello Islands

that are almost cut off from the sea. These probably reflect a Pleistocene karst surface, produced when the sea level was lower and percolating rainwater dissolved the limestone. Large circular sinkholes (or dolines), which typically join up with subterranean caves, are a common feature of this weathering process. With the rising sea level following the last ice age, these dolines would have then slowly filled with seawater, their outlines now partially reflected by the many curved shorelines and bays.

DAMPIER ARCHIPELAGO AND BURRUP

North-east of Karratha is a group of rocky islands known as the Dampier Archipelago. The Burrup Peninsula was once part of this island group, but is now joined to the mainland by several causeways. Since the early 1960s, the area has become the hub for some of Australia's largest resource projects, including a major iron-ore shipping port, liquefied natural gas (LNG) treatment plant, and the world's largest solar salt operation. Twenty-five islands are nature reserves managed by the Department of Conservation and Land Management, protecting the likes of northern quolls, turtles, migratory birds, Rothschild's rock-wallabies and water rats.

DESCRIPTION: The 42 islands of the archipelago range from a hectare (Enderby Island) to 3290 hectares (Dolphin Island) and rise up to 120 metres above sea level. Most are steep and rugged, with sea cliffs and large rock piles separated by valleys, beaches and coastal sandplains.

ROCK TYPES: Most islands are made of dark-coloured volcanic rocks – andesite and basalt – of the Fortescue Group. The rocks have all been weekly metamorphosed and contain a mixture of minerals such as feldspar, biotite mica, hornblende, pyroxene, quartz, chlorite and calcite. Thin beds of sandstone and conglomerate can also be found interbedded with these volcanic rocks. Less common are areas of gabbro and dolerite of the much older greenstone succession (see pages 56–59). They contain pyroxene and feldspar, which have been partly altered to minerals such as amphibole, chlorite and epidote.

The Burrup Peninsula is geologically quite different, comprising mostly granophyre (a fine-grained granite) and gabbro that intruded as a sill of magma between layers of surrounding volcanic and sedimentary rocks. The sill is at least two kilometres thick and was formed around 2717 million years ago. The granophyre consists of feldspar and quartz, whereas the

Photo – Dennis Sarson/Lochman Transparencies

Above: *Dampier Archipelago* Below: *Deep Gorge, Burrup Peninsula*

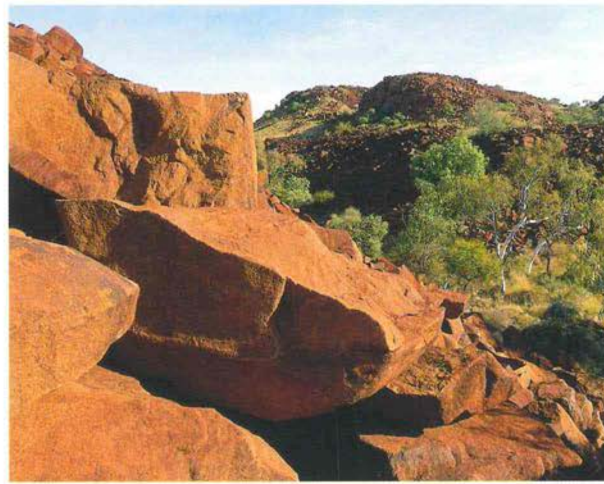


Photo – Jiri Lochman

gabbro contains mostly pyroxene. Some islands, such as Hauy, Delambre and Legendre comprise mostly limestone known as the Bossut Formation, which also forms much of the submerged archipelago. On these submarine plains there are also vast sheets of shell gravel and muddy lime sand.

LANDFORM FORMATION: The Dampier Archipelago and the Burrup Peninsula formed during the last 5000–6000 years when sea level was rising following the last ice age. Consequently, this once very hilly area was flooded, leaving just the hilltops and ridgelines as islands. Coastal dunes of shelly lime-sand then accumulated around and partly over the newly formed islands. Soon after, percolating rainwater dissolved some of the lime, reprecipitating it as cement that bound the grains together to form limestone.

NOTABLE FEATURES: The Burrup Peninsula and the islands of the archipelago tend to be aligned in a north-east orientation. This is because the dominant grain and structures of the rocks run in this direction. Most of the channels, straits and embayments (such as Flying Foam Passage, Searipple Passage and King Bay) owe their origin to fractures and joints that crosscut the rocks in various orientations. Such geological features encouraged erosion and weathering and major valley systems to form in their place, segmenting the area into a series of hills.

Right: *Hearsons Cove on the Burrup Peninisula*

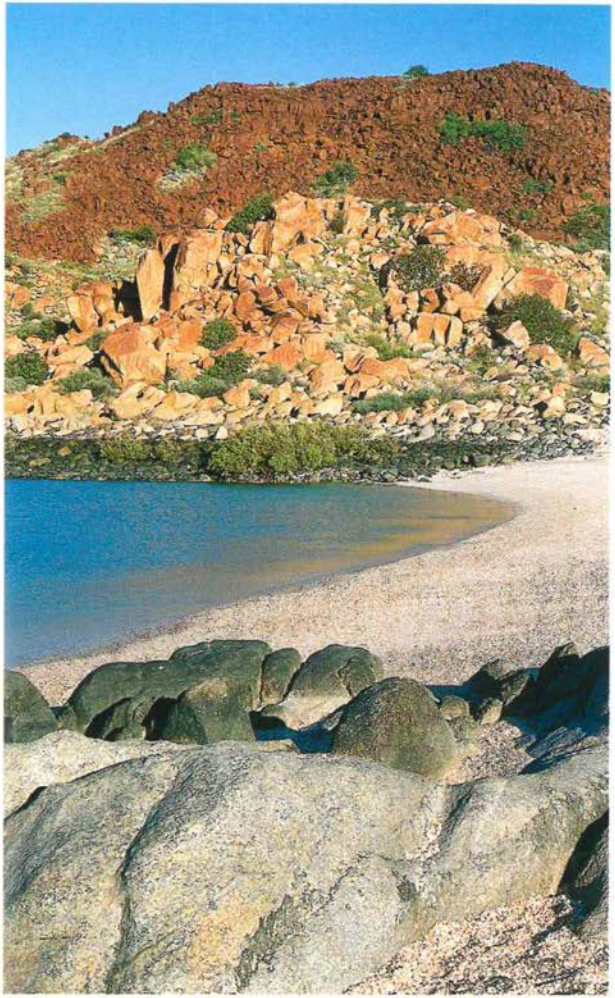


Photo – Dennis Sarson/Lochman Transparencies

MILLSTREAM

Along the base of the Chichester Range near Millstream are several large pools such as Deep Reach Pool, Crossing Pool and Chinderwarriner Pool. They owe their origins to the Fortescue River system, which developed during the last 150 million years.

DESCRIPTION: Up to 14 metres deep, the pools lie along the course of the western part of the Fortescue River. The pools are permanent and water level is maintained by springs from an aquifer beneath the Fortescue River alluvial plain. Consequently, a number of ecosystems are unique to this water-rich area, including sedgelands and woodlands of cadjeput and Millstream palm. The palms are a relic from a tropical rainforest that has since retreated, after the climate became drier and more arid about five to10 million years ago.

ROCK TYPES: The aquifer consists of dolomite, calcrete, silcrete and clay, and is known as the Millstream Dolomite. The dolomite and clay were probably deposited in lakes that developed in the Fortescue River alluvial plain about 40 million years ago (see pages 30–33). Calcrete and silcrete are weathering products, formed close to the surface by the action of water through sand and gravel, cementing the grains together by calcium carbonate (calcrete) or silica (silcrete). Because the aquifer is made mostly of calcareous (carbonate-rich) rocks, the water is very hard.

LANDFORM FORMATION: The Millstream Dolomite contains abundant cavities formed when carbonate- and silica-rich minerals dissolve by percolating surface water, the same process that forms limestone caves. These dissolved minerals may then precipitate out to form silcrete and calcrete. The interconnecting cavities allow water to travel through the aquifer, like an underground stream, flowing out to form springs where the aquifer is exposed at the surface. It is continually recharged with water from the Fortescue River and small tributaries that drain the northern flank of the Hamersley Range, and from rainfall.

Photo – Jiri Lochman

Chinderwarriner Pool in Millstream–Chichester National Park

The Fortescue River follows a braided course along its alluvial plain as far west as Millstream. Here, the river becomes constricted and infilled with sand and silt, and diverts to the north-west through a series of rocky gorges incised into the Chichester Range. This constriction has led to the formation of several isolated hollows, which have filled up with water from the springs to form the pools.

NOTABLE FEATURES: Groundwater pumped from the Millstream Dolomite aquifer has been used as a public water supply for towns in the west Pilbara since 1968. The Harding Dam, constructed in 1985, will eventually help to supply water to these towns and take the pressure off the aquifer.

CHICHESTER RANGE

The Chichester Range lies to the north of the Fortescue River, roughly parallel with the Hamersley Range. The rocks that make up this landform were deposited during the Archaean, about 2775–2630 million years ago. They are very different to the granite–greenstones (see pages 56–59) in the north, and mark a major change in the geological evolution of the Pilbara.

DESCRIPTION: The Chichester Range is a narrow plateau, about 300 kilometres long by 33 to 40 kilometres wide, and more than 570 metres above sea level. It extends from near Pannawonica in the west to near Bonney Downs Station in the east, where the range becomes ill-defined and forms dissected hills, breakaways and mesas. Dozens of tributaries to the Fortescue River drain the Chichester Range, adding sediment to the vast alluvial plain that separates it from the Hamersley Range (see pages 34–39).

ROCK TYPES: A succession of southerly dipping volcanic and sedimentary rocks – known collectively as the Fortescue Group – make up most of Chichester Range. In the Pilbara, this group of rocks is up to 6.5 kilometres thick and overlies the granite and greenstones exposed in the north. Good exposures of the Fortescue Group can be seen in the range on the Great Northern Highway and on the Roebourne–Wittenoom Road. Basalt is the dominant volcanic rock, and was deposited as lava flows ranging from less than a metre to more than 60 metres thick. It tends to be dark green to grey and weathers over much of the range to a red, very clay-rich soil called gilgai. This type of soil is easily recognisable because it forms characteristic expansion crevices and depressions, known as 'crabholes'.

Towards the southern side of the range the rocks are dominated by sandstone, shale, chert and some dolomite. These commonly form very hard outcrops because silica has cemented the grains together, a process known as silicification. The original

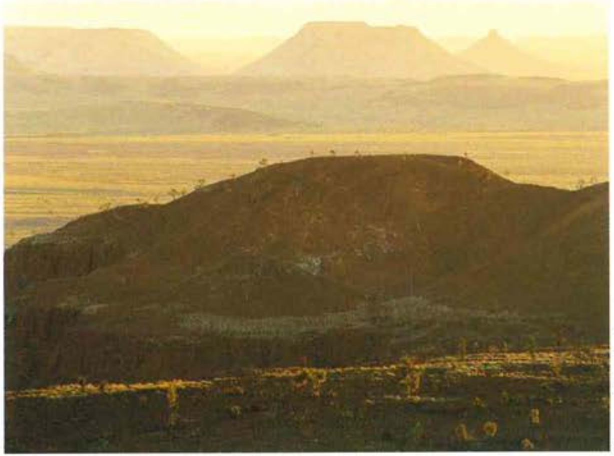


Photo – Marie Lochman

Above: *View of dissected hills and mesas from Mt Herbert*
Below: *The gentle slopes typical of the Chichester Range*


Photo – Marie Lochman

sediments were deposited in a marine environment close to the shoreline and also further offshore, with the coastline running approximately in the same orientation as the Chichester Range does now. Cross-bedding within the sedimentary beds resulted from water current movement, where small sand dunes have moved across the sea bed. When the intensity or the direction of water flow changed, such as when the tide changes or a river changes direction, inclined sand layers were deposited at a different angle to those below.

On the southern edge of the range, above the large fans of scree that border the Fortescue alluvial plain, is the Marra Mamba Iron Formation. This iron-rich rock formation belongs to the Hamersley Group, which is part of a succession of rocks that form the Hamersley Range to the south. The Marra Mamba Iron Formation hosts the Marandoo iron-ore deposit east of Tom Price and some of the orebodies at Newman. It is a very hard rock known as banded iron formation (BIF), which consists of layers of yellow to yellow-brown chert, quartz and carbonate minerals, interbedded with brown to black iron-oxide minerals. Its origin is complex and controversial, but it most likely formed by the precipitation of iron and silica in seawater, with deep-sea volcanoes as the probable source of this material.

LANDFORM FORMATION: Bedding in the Fortescue Group runs in an approximately west-north-west direction, so weathering and erosion has preferentially preserved this orientation to give us the Chichester Range. The sharp southern margin of the range is also a result of preferential erosion. In this case, a more easily weathered rock formation, called the Wittenoom Formation, lies between the Hamersley and Chichester ranges. It weathered faster than the iron formations above and beneath it, eventually forming a valley (the ancestral Fortescue River alluvial plain) with the two parallel ranges on either side.

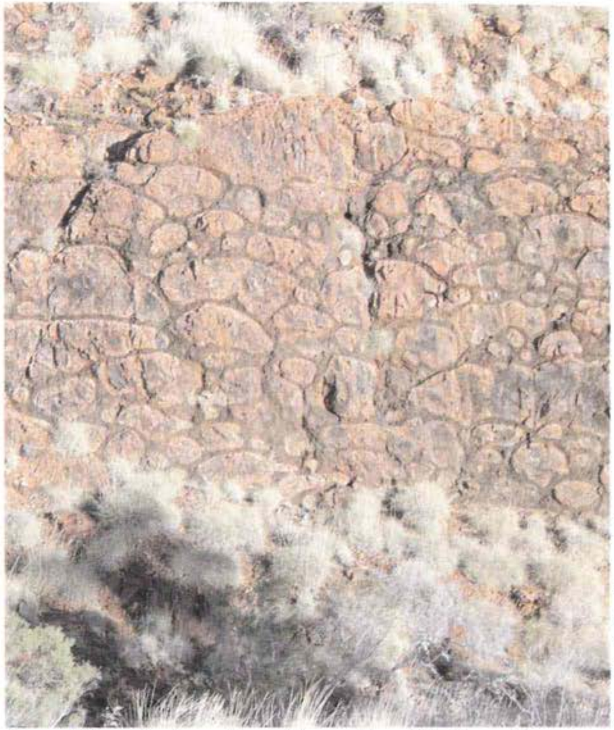


Photo – Martin Van Kranendonk

Above: *Pillow structures formed by eruption of Fortescue Group basalts underwater*

NOTABLE FEATURES: Layers of abundant, very small, spherical or irregularly shaped cavities, called amygdales, are commonly found in the basalt of the Chichester Range. When molten rock reaches the Earth's surface, the lower pressure allows gas bubbles to form in the lava flows, just like when a lid is taken of a bottle of carbonated water. The top part of lava flows usually contains most of the amygdales.

FORTESCUE RIVER ALLUVIAL PLAIN

On the Great Northern Highway between Newman and Port Hedland a vast, low-lying area runs approximately north-west to south-east, bisecting the Pilbara region. This is the Fortescue alluvial plain, an ancient river valley that has slowly filled up with sediment.

DESCRIPTION: The alluvial plain occupies a broad valley between the steep scarp of the Hamersley Range to the south and the gentle slopes of the Chichester Range to the north. The Fortescue River follows a braided course along most of this plain as far west as Millstream, where the river becomes constricted and diverts to the north-west through a series of gorges. In the east, the river flows from the south, where it cuts through the Ophthalmia Range.

The plain is about 450 kilometres long, up to 72 kilometres wide and is covered by spinifex, annual grasses and scattered trees and shrubs. Woodlands and open forest fringe the Fortescue River. In the east, at its widest point, the plain opens out onto the Little Sandy Desert, whereas in the west it narrows to about eight kilometres in width ending near Deepdale, south-west of Pannawonica.

ROCK TYPES: The alluvial plain is underlain by a complex pattern of clay, silt, sand, gravel and conglomerate, sourced from rivers and creeks, nearby slopes and ancient lake systems, during the Cretaceous to Holocene. Today, most of the sediment is deposited by the Fortescue River, which usually flows in the summer months following thunderstorms and cyclonic rainfall. Creeks that drain the Chichester Range commonly join the Fortescue River and add to this sedimentation. The large fans of rubble that fringe the Hamersley Range scarp also add sediment to the plain.

LANDFORM FORMATION: The Fortescue River alluvial plain has its origins during the Late Jurassic (about 150 million years ago),

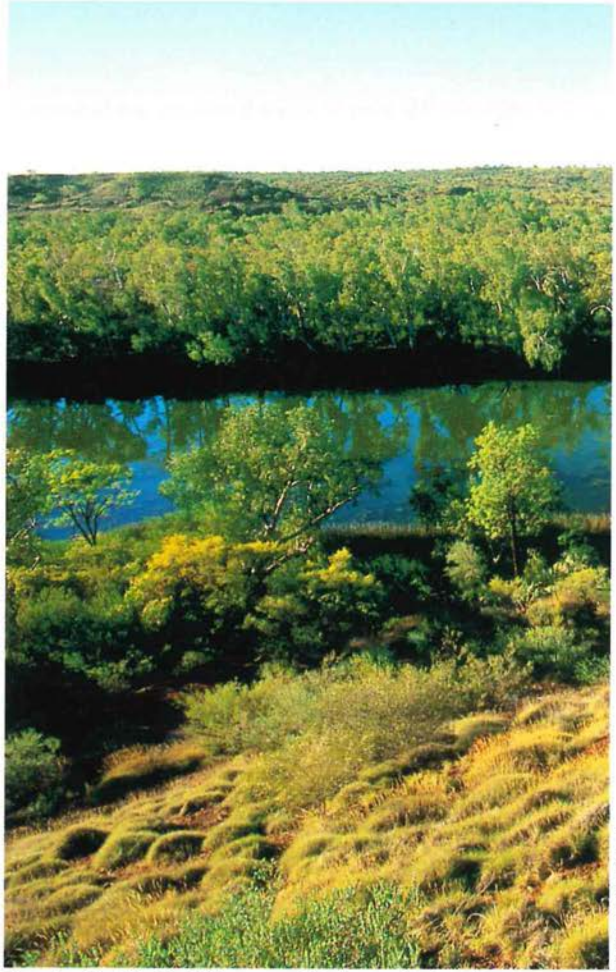


Photo – Jiri Lochman

Crossing Pool in the Millstream–Chichester National Park when a valley began to form in a rock formation (the Wittenoom Formation) that now underlies it. These rocks, which run in a north-westerly to south-easterly direction, were preferentially weathered over the surrounding very hard banded iron formation and chert that dominate the Hamersley and Chichester ranges.

Erosion of the valley during this time resulted in a vast amount of sediment being transported westward off the WA coast and deposited as a delta (now underlying the Barrow Island area). During the Early Cretaceous, the Pilbara was then thought to be gently tilted towards the north-west, and the nearby Robe River 'captured' the ancestral westerly flowing Fortescue River, hence altering its course towards the north-west. Later, possibly in the Oligocene (about 40 million years ago), the climate became more arid and a lake system formed within the original Fortescue valley, depositing dolomite and clay on the lake bottom. This 'ponding' of water may have occurred because the Robe River's course became constricted with sediment as a result of decreasing water run off.

At the end of the Pleistocene or the beginning of the Holocene, the ancestral Fortescue River was again 'captured' by another north-westerly flowing river – today's western end of the Fortescue River.

NOTABLE FEATURES: The Wittenoom Formation, which was the foundation of the original Fortescue River course, is today a major water reservoir for the Pilbara district. It is present in many valleys within the Hamersley Range and, where it has been karstified (partly dissolved and containing solution cavities), it allows large quantities of water to pass through it. Consequently, it is now used as a source of water for the Tom Price and Marandoo iron-ore mines. The much younger lake deposits now also form an aquifer and are the source of the water at Millstream (see pages 24–25).

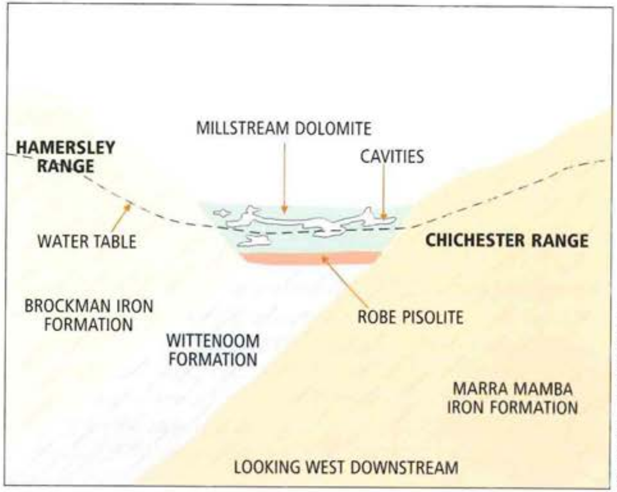


Illustration – Ian Dickinson

Above: *The Millstream aquifer has formed because the Millstream Dolomite contains abundant cavities that allow water to travel underground like a stream*

HAMERSLEY RANGE

The Hamersley Range runs approximately north-west to south-east through the central Pilbara. It is famous both for its spectacular gorges in Karijini National Park and giant world-class iron-ore deposits, such as Mt Whaleback near Newman. Rocks of the Hamersley Range are part of the 2775 to 2470 million-year-old Hamersley Basin that once covered much of the Pilbara.

DESCRIPTION: The Hamersley Range is a large plateau, 400 kilometres long by 32 to 64 kilometres wide, extending from near Pannawonica in the west to near Mt Newman in the east. The top of the range is a series of rounded, dome-shaped hills up to 1245 metres above sea level (Mt Meharry). The plateau forms the watershed between the Fortescue River to the north and the Ashburton River to the south. It has been deeply dissected by numerous rivers and streams, which have carved out gorges and broad scree- and rubble-filled valleys.

ROCK TYPES: The slightly metamorphosed rocks consist mostly of banded iron formation (BIF), chert, pelite (metamorphosed siltstone) and dolomite. They belong to the Hamersley Group, a package of rock formations that is about 2500 million years old. The BIF weathers to the rusty red colour characteristic of the Pilbara landscape. In the Hamersley Range, these rocks contain alternating thin layers of fine-grained quartz, iron oxides, carbonate minerals and chert. They are hard and resistant to weathering. Spectacular examples of BIF are seen in the road cuttings in Munjina Gorge as the Great Northern Highway descends the northern side of the Hamersley Range to the Fortescue River alluvial plain.

LANDFORM FORMATION: The structure and composition of the rocks closely controls the shape and distribution of the hills within the Hamersley Range. For example, in the northern part, where the beds dip gently in broad U- and A-shaped folds, or synclines and anticlines, the hills are also broad. The southern part is more tightly folded and the hills consequently form narrower

Photo – Bill Belson/Lochman Transparencies

The Hamersley Range

ridges. The position of rivers and creeks are mostly controlled by the position of less resistant rock types, because these are easier to erode. BIF is highly resistant to weathering, and tends to form conspicuous cliffs where there are vertical joints and fractures in the rock. These structures were therefore important in controlling where gorges developed within the range.

NOTABLE FEATURES: BIF is a very distinctive looking sedimentary rock, which mostly formed during the earliest part of Earth's history, in the Archaean. Although its origin is controversial, it seems likely that it formed by the precipitation of iron and silica in seawater, with the probable source of this material coming from deep-sea volcanoes. The rocks of the Hamersley group have thin layers of sand-sized spherules of melt material, thrown into the atmosphere by ancient meteorite impacts.

GORGES OF KARIJINI NATIONAL PARK

There are many gorges in the Hamersley Range, but the most spectacular are in Karijini National Park. Here, the plateau that forms the range has been deeply dissected to reveal magnificent vertical exposures of 2500-million-year-old red rocks known as banded iron formation (BIF). These rocks record a time during the Archaean when little oxygen filled the atmosphere and the only forms of life were simple bacteria and algae.

DESCRIPTION: The eight main gorges in the national park are up to 100 metres deep and form steep-sided chasms. Dry for most of the year, the rivers that flow through the gorges are tributaries of the Fortescue River, which flows on the northern side of the Hamersley Range. They flow in a north-north-easterly direction, changing dramatically from small creeks to sheer-sided chasms, with a waterfall commonly marking this sharp transition.

ROCK TYPES: The rocks exposed in and around the gorges are mostly BIF, which is made of alternating thin layers of fine-grained quartz, iron oxides, carbonate minerals and chert, and is hard and very resistant to weathering. It is commonly weakly magnetic and can be tested by a compass or a magnet. The rocks belong to the Brockman Iron Formation, from which iron-ore is mined elsewhere in the Pilbara. Dolomite, a grey or pale brown rock with a sugary appearance where freshly broken, is also present. Distinctive beds of purple or pink shale, which are faintly laminated and very soft, can also be seen.

LANDFORM FORMATION: Although rocks in the Hamersley Range have existed for hundreds of millions of years, most of the landscape has formed in the last tens of millions of years. Geologists call this deeply dissected plateau 'The Hamersley Surface'. It is uncertain when and how this erosion took place, but it was probably during the Late Cretaceous or Early Cainozoic when the Pilbara was gently tilted towards the north-west. This caused rivers in the range to downcut through the rocks, rapidly eroding the softer shale and

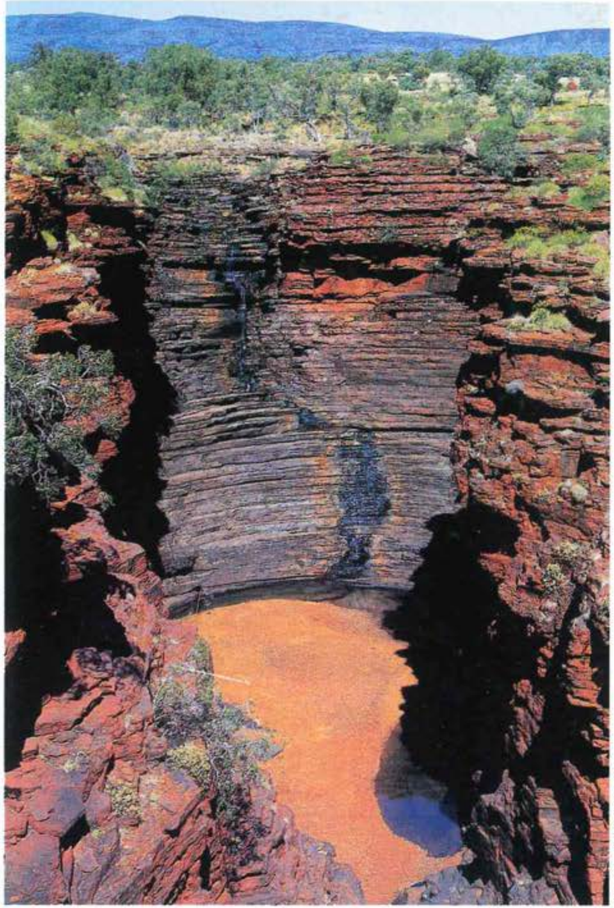


Photo – Bill Bachman

Joffre Falls. A combination of joints and easily eroded shale and dolomite beneath the iron formations have enabled the creeks to cut deeply into the range

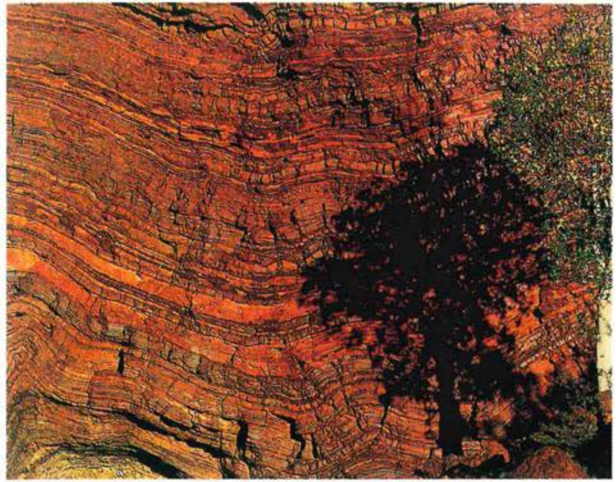
Photo – Jiri Lochman

Dales Gorge in Karijini National Park

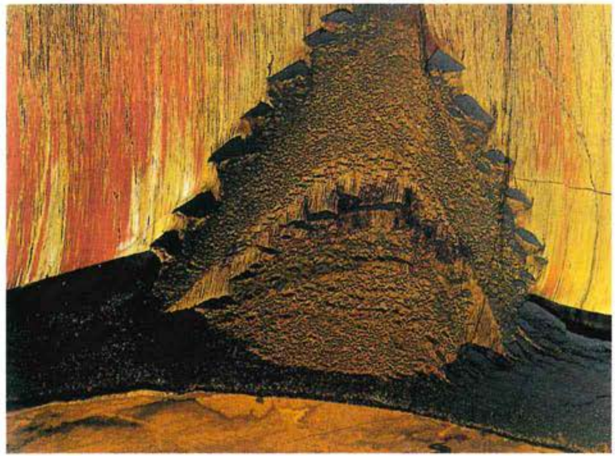
dolomite beneath the BIF, giving rise to spectacular gorges and waterfalls. Lines of weakness within the rocks, such as faults and joints, would have aided this headward erosion. This process was enhanced by the onset of an arid climate in WA, depleting the vegetation available to cover and protect the valley sides.

NOTABLE FEATURES: Many creeks have exploited joints and other fractures cutting across the rocks. These watercourses are characteristically straight and commonly parallel to neighbouring valleys, such as the lower Wittenoom Gorge and Bee Gorge. Angular creek junctions form in areas where two or more directions of jointing are present. A good example of this is where Weano, Red, Hancock and Joffre Gorges intersect.

Where the gorges aren't deep chasms, they often have a slope and step appearance. This reflects an alternation of weak and resistant rock types – the more easily eroded shale and dolomite form the gentle slopes, and the very resistant BIF forms steep cliffs.



Above: *Banded iron formation at Hamersley Gorge*



Photos – Bill Bachman

Above: *The semi-precious stone tigereye is found at Karijini*

IRON-ORE MINING

"This is essentially an iron country...there is enough to supply the whole world should present sources be worked out", wrote Government Geologist Harry Page Woodward in 1890. However, iron-ore was produced solely for the domestic market for the next 70 years, because of economic considerations and a Commonwealth Government embargo on iron-ore exports. The lifting of the embargo in 1960 heralded an exploration boom that saw the discovery and development of giant iron-ore deposits in the Pilbara, which became one of the largest iron provinces in the world. It seemed that Woodward's prediction had come true. With nearly 15 per cent of the world's total iron-ore production, WA is today one of the world's leading iron-ore producers. Most of this ore, which in 2000 was around 156 million tonnes, comes from the Pilbara and is shipped to Japan.

Most of the mines lie within the Hamersley Range, and the ore is transported by train to the coastal shipping ports of Port Hedland, Cape Lambert and Dampier. At present, BHP Iron Ore Pty Ltd, Hamersley Iron Pty Ltd, and Robe River Iron Associates are mining 15 deposits, including Mt Whaleback and its satellite ore bodies near Newman, Tom Price, Paraburdoo, Yarrie north-east of Marble Bar, and Mesa J near Pannawonica. Several large new deposits such as West Angelas, Area C, Hope Downs, Nammuldi/Silvergrass are waiting to be developed.

The giant Mt Whaleback mine near Newman started in 1969, and is the largest remaining resource of high-grade ore in the Pilbara. It contains a massive 759 million tonnes of ore. Other deposits are much smaller. Yarrie, for instance, contains only 37 million tonnes of ore and was developed in 1993 to replace the depleting resources of nearby Shay Gap and Nimingarra.

ROCK TYPES: Two types of iron-ore deposits are present in the Pilbara. The most common is formed by the iron enrichment of two

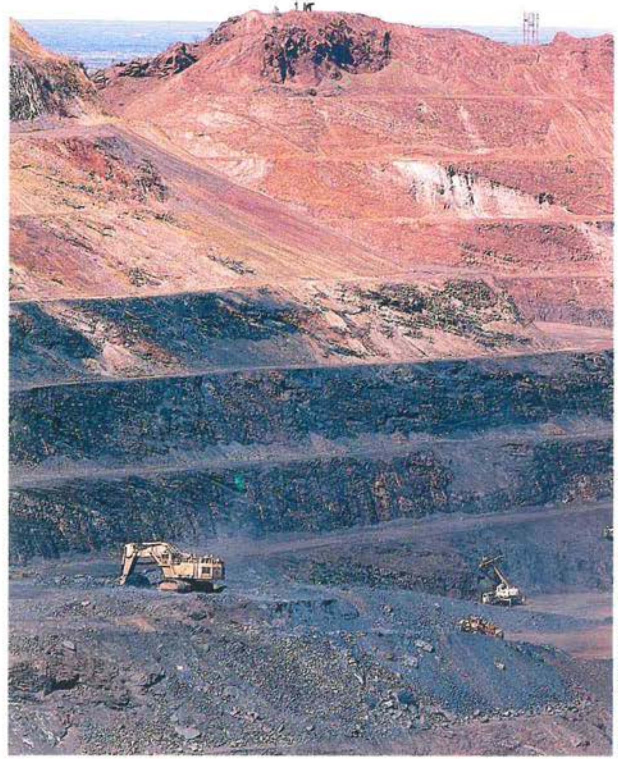


Photo – Bill Belson/Lochman Transparencies

Open cut iron-ore mine at Mount Newman

rock units of banded iron formation (BIF) – the Marra Mamba Iron Formation and the Brockman Iron Formation. The Mt Whaleback, Marandoo and Paraburdoo deposits are of this type. The Brockman Formation is very widespread in the Hamersley Basin, and forms most of its hills and gorges, but only parts of it are enriched in iron. The minerals in this ore type are mostly haematite and goethite.

The second type of deposit is formed in ancient river channels of major drainage systems, and is commonly called pisolitic iron-ore, channel iron-ore, or Robe Pisolite. The deposits at Robe River, such as Mesa J, are of this type. The main minerals are haematite and hydrated oxides of iron, which form cemented masses of very small (less than two millimetres) spherical concretions.

FORMATION AND DISTINCTIVE GEOLOGICAL FEATURES: The iron-enriched ore probably began to form about 1800 million years ago. Although the exact timing and processes of its formation are uncertain, geologists consider that a weathering mechanism called 'supergene enrichment' was most likely involved. This takes place mainly by the action of groundwater leaching BIF, converting iron-rich minerals in the rock, such as magnetite, to iron-rich minerals forming the ore, such as haematite and goethite. Faults and folds within the iron formations acted as pathways for this water to travel through. Some iron-ore deposits, like Mt Whaleback, may also have undergone metamorphism, which also helped to enrich the BIF with more iron.

The pisolitic iron-ore formed in a very different way. Although the process is still not completely understood, it is likely that the spherical concretions formed around 30 million years ago, in swampy channels of broad meandering rivers. In these riverbeds were accumulations of iron-rich fragments eroded from outcrops of BIF and laterite. These then acted as nuclei for the precipitation of dissolved iron that had leached from the iron-rich landscape into the river system. Consequently, wide sheets of iron-rich spherical concretions gradually replaced the mud and sand in the rivers. This new land surface was then eroded, but its remnants were preserved as mesas and benches. Mining this type of surface deposit is done by strip-mining techniques.

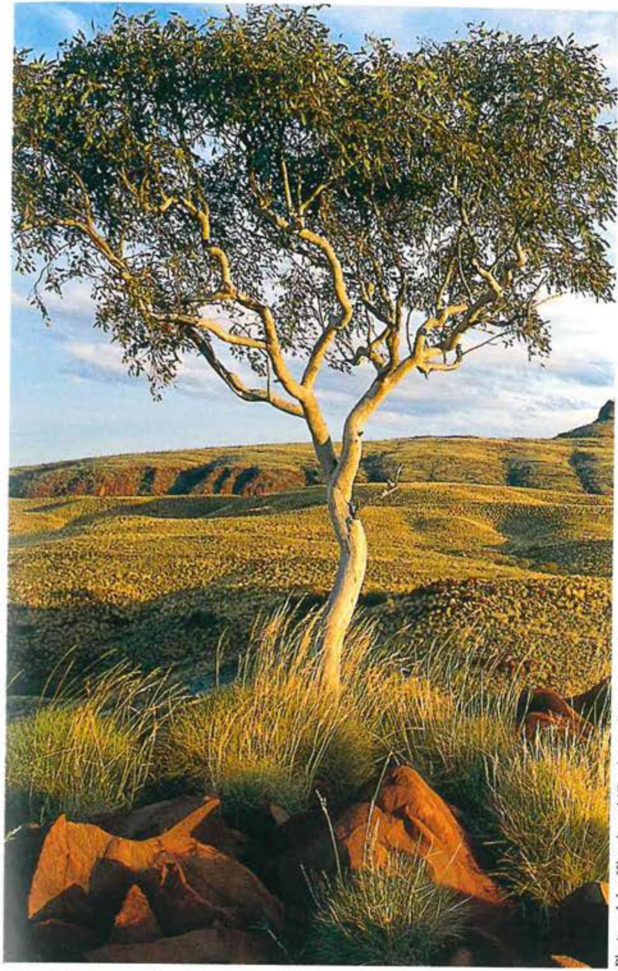


Photo – John Kleczkowski/Lochman Transparencies

Mount Newman in the Ophthalmia Range

DESERT COUNTRY

A vast expanse of desert country borders much of the eastern Pilbara. This is the edge of the Little Sandy Desert and the Great Sandy Desert.

DESCRIPTION: Desert country comprises dune and dune-free sandplains, isolated hills and ranges, salt lakes, claypans, lakes and floodplains. Longitudinal or seif dunes, up to tens of kilometres long, 20 to 30 metres high, and four kilometres apart, trend in an easterly to south-easterly direction and cover much of the desert country.

ROCK TYPES: The deserts have a recent veneer of quartz sand that overlies a succession of much older rocks. The Great Sandy Desert, which extends north-eastward to the Kimberley, is one of the world's largest deserts. It overlies the vast Canning Basin to the north-east of the Pilbara, which formed in the last 490 million years during the Phanerozoic. The basin is up to 15 kilometres thick and was formed as a north-westerly trending rift slowly filled with sediment. Most of the Pilbara was a landmass during this time and the sediments essentially onlapped the edge of it. The Permian rocks deposited by glaciers at Rudall River, Shay Gap, and Carawine Pool belong to this basin. Sandplains cover most of the Canning Basin, but just below the surface, and outcropping as scattered mesas and buttes, are Cretaceous rocks (about 144 to 113 million years old) that consist of sandstone, siltstone, and claystone, all of which were deposited by a vast sea that covered much of inland Australia.

In the Little Sandy Desert, on the south-eastern edge of the Pilbara, the rocks that underlie the sandy veneer are much older, between 800 and 520 million years old, and belong to the Officer Basin. Here, the desert is formed of dunes and low hills, ridges and plateaus of sandstone, siltstone, and dolomite. Shallow seas, rivers and deltas deposited most of these sediments.

Photo – Marie Lochman

The Durba Hills in the Little Sandy Desert

LANDFORM FORMATION: The dunefields formed in the last few million years and were last active around 25,000 to 13,000 years ago, during the last ice age. This was a time of great aridity in much of Australia, when lower rainfall and stronger atmospheric circulation encouraged dunes to develop. The sand was derived from erosion of the quartz-rich sandstones of the Canning and Officer Basins.

NOTABLE FEATURES: The distinctive longitudinal shape of the dunes is thought to have formed when strong prevailing winds from the south-south-east moved horizontally across the land surface. This caused a thin turbulent air layer to form just above the surface, and with it pairs of whirling wind eddies, or vortices that move in the direction of the prevailing wind. Sand consequently built up between these vortices to form the dunes, which then slowly migrated in a south-south-easterly direction to form the longitudinal shape. Network dunes formed in areas of complex windflow.

RUDALL RIVER

On the eastern edge of the Pilbara, between the Great Sandy Desert to the east and the Little Sandy Desert to the west, is the remote and spectacular Rudall River National Park. The area contains significant mineralisation, including the Kintyre uranium deposit discovered in 1985.

DESCRIPTION: The Rudall River area is a north-westerly trending belt of rocky plateaus, ridges, low hills, rocky pavements, valleys and flattish plains, about 180 kilometres long and up to about 60 kilometres wide. Dissected plateaus with cliffs and steep escarpments predominate in the northern part, with plateaus interspersed with low hills and valleys in the south.

ROCK TYPES: The Rudall area contains a variety of metamorphic, igneous and volcanic rocks. In the southern part of the Rudall area the rocks are at least 1790 million years old, are more varied than in the north and have been considerably metamorphosed. Those in the Fingoon Range, for example, were originally mostly alternating beds of sandstone, siltstone and shale deposited in deep ocean water, but have now been transformed to quartzite, schist and gneiss. Quartzite is a very hard rock and commonly forms the steep escarpments and cliff faces. Low hills of gneiss are also interspersed with these metamorphosed sedimentary rocks. They were originally granite that intruded the newly deposited rocks when two continental landmasses collided, later undergoing metamorphism under extremes of pressure and temperature. Other rock types include banded iron formation (BIF) and amphibolite (a dark greenish-black rock made mostly of hornblende, feldspar and, in places, garnet).

Towards the north, in the Throssell and Broadhurst range areas, sandstone is the major rock type and is around 1250 to 900 million years old. It has been slightly metamorphosed, resulting in the recrystallisation of the original quartz grains, and the clay between the grains has been replaced by sericite mica. Although

Photo – Marie Lochman

Desert Queens Bath Gorge

the rocks have been quite altered, the original bedding is still preserved, with cross-bedding common throughout the ranges. These rocks were deposited in rivers and deltas near a shoreline, and later metamorphosed. The Desert Queens Bath waterhole in the Broadhurst Range is formed within this sandstone, close to the intersection of two faults, as are the Three Sisters.

LANDFORM FORMATION: The north-westerly orientation of the Rudall area is a result of the grain (foliation) and structures (faults and folds) within the rocks. The rock type also influences the form of hills, for example, the gneiss characteristically produces rounded hills and the quartzite produces more rugged country. Many of the valleys were formed by the action of glaciers during the Permian, about 295 million years ago when Australia was in the grip of a major ice age. These valleys, like that which contains Compton Pinnacle, were carved out by advancing glaciers, grinding up the rocks beneath to form tillite deposits of boulders, clay and sand.

NOTABLE FEATURES: Geologists are not sure how the Rudall area formed, but it is thought that the rocks may once have been part of the Armadeus Basin and the Arunta Orogen, which lie more than 400 kilometres eastward in central Australia. An extensive fault system that operated about 550 million years ago may be responsible for this sideways movement, effectively displacing a large belt of rocks from central Australia and moving it towards the eastern margin of the Pilbara Craton where the Rudall area lies today.

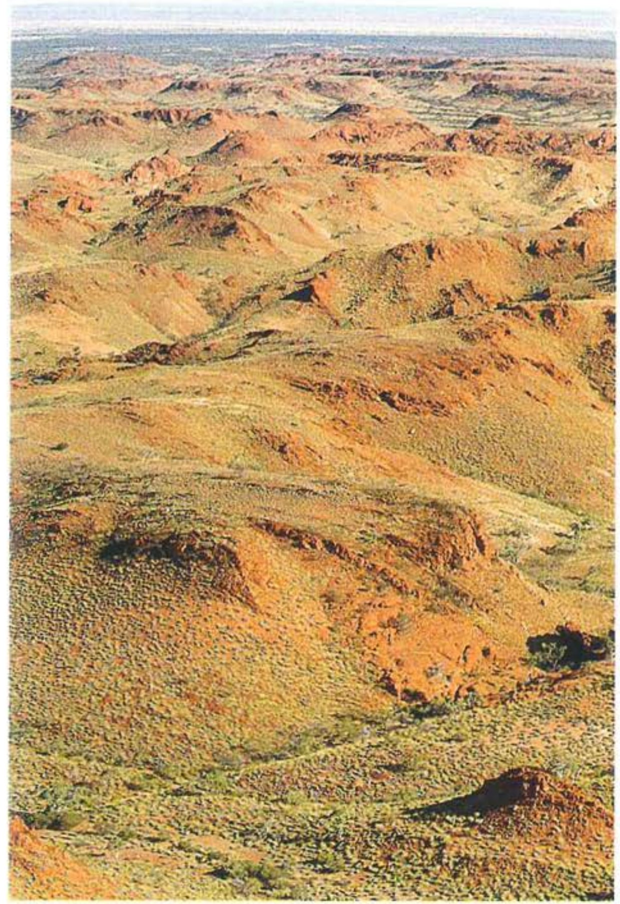


Photo – Jiri Lochman

Fingoon Range

CARAWINE POOL

Spectacular Carawine Gorge lies at the southern end of the Oakover River Valley in the eastern Pilbara. It contains a two-kilometre-long, S-shaped rock pool known as Carawine Pool.

DESCRIPTION: Spinifex-covered low hills, mesas, buttes and dissected tablelands are interspersed with the ephemeral braided Oakover River. Semi-permanent and permanent rock pools lie along the river.

ROCK TYPES: The brown-weathered Carawine Dolomite is the main rock type that forms Carawine Gorge. Dolomite is a carbonate rock, containing calcium and magnesium. The Carawine Dolomite formed in warm, shallow water during the Archaean, at least 2500 million years ago. Within these rocks geologists have also found evidence of intertidal and lagoonal environments, and inland settings where floodwater was rare called supratidal flats. These types of environments are similar to those along the present day Pilbara coastline (see pages 68–69). There are spectacular examples of fossil stromatolites on the western side of the gorge. These large hemispherical shapes, up to five metres high, are built of successive layers of what was originally calcium carbonate deposited by cyanobacteria. Similar modern forms are growing today at Shark Bay.

Along the four-wheel-drive track into Carawine Pool are low hills of much younger rocks. These comprise sandstone, siltstone and mudstone, with scattered pebbles, cobbles and boulders up to two metres across. They were deposited during the Permian (295 million years ago) when glaciers covered much of the continent. The great weight and force of moving ice ground up rocks from the valley floor and walls, redepositing them as beds of sediments, or tillite, when the ice melted. Similar deposits are also found at Shay Gap (see pages 54–55) and Rudall River (see pages 46–49).

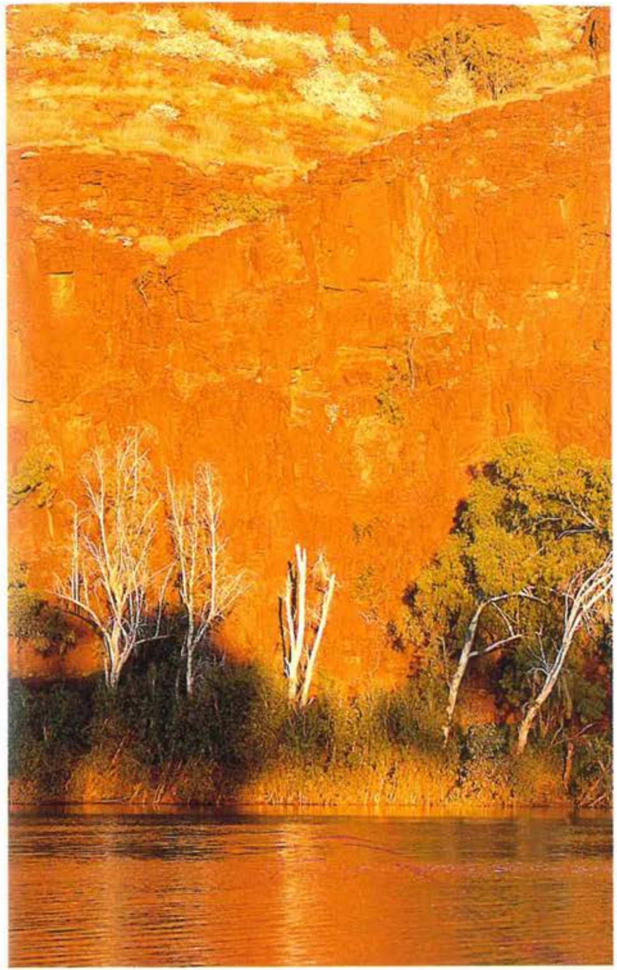


Photo – Marie Lochman

Carawine Gorge on the Oakover River

Near Carawine Pool, on both sides of the track, are very young rocks known as the Oakover Formation, which were deposited as lake sediments during the Miocene to Pliocene (25 to 2 million years ago). They form mesas and buttes of blue, grey and fawn limestone and calcareous sandstone, with cliff-forming tops of very hard chalcedony and opaline silica. Chalcedony is also a silica-rich mineral, and like opaline silica is a weathering product that formed close to the surface.

LANDFORM FORMATION: The Permian glaciers carved huge ice-scoured valleys into the landscape, one of the largest in the Pilbara being the Wallal Embayment. This wedge-shaped area, nearly 150 kilometres long, extends in a south-easterly direction from east of Shay Gap, where it is about 50 kilometres wide, and ends just south of Carawine Pool, roughly paralleling today's Oakover River valley. The ancestral Oakover River may have in fact originated when the Permian glaciers began to melt.

During the Miocene and Pliocene, much of the river valley became a lake, similar to what happened in the Fortescue River alluvial plain (see pages 30–33). Subsequent headwater erosion by the De Grey River in the north of the valley broached the lake and drained it. The modern Oakover River has since slowly dissected these lake deposits and the underlying glacial rocks, leaving remnants as hills, mesas and buttes. It has also incised the underlying Carawine Dolomite, possibly following fractures or joints within the rock.

NOTABLE FEATURES: Some of the rock surfaces near Carawine Pool are highly polished with sets of parallel grooves, called striations. These resulted from scouring by rocks embedded in the moving glaciers. From their orientation, geologists have determined that the ancient glaciers were moving in a north-north-westerly direction at this locality.

Above: *Glacial striations* Below: *Mesa in the Oakover Valley*

Photos – Ian Williams

SHAY GAP

On the north-eastern edge of the Pilbara, a prominent plateau rises abruptly from low-lying plains and valleys. The plateau is dissected by Coonieena Creek to form a short gorge called Shay Gap. Iron-ore has been mined close to the nearby town of Shay Gap since the early 1970s. It was closed and dismantled in 1993 when the Yarrie mine was developed further to the east and mining operations declined near Shay Gap.

DESCRIPTION: This sparsely vegetated north-westerly trending plateau, up to 250 metres above sea level, is incised by a northerly flowing tributary of the De Grey River. Ranges, small buttes, mesas and tablelands lie on the northern side of the plateau. Low-lying plains and valleys occupy the southern side.

ROCK TYPES: The plateau that Shay Gap dissects comprises banded iron formation (BIF), jaspilite, shale, mudstone and chert, similar to the rocks of the Hamersley Range (see pages 34–35). There are more than 30 opencut iron-ore mines (the Shay Gap, Sunrise Hill, Nimingarra, and Yarrie operations) in these rocks, which are known as the Nimingarra Iron Formation. On the southern side of the plateau granite has weathered to form low-lying plains and valleys, whereas on the northern side basalt forms low ranges. This combination of rock types, known as granite–greenstones (see pages 56–59), formed more than 3300 million years ago.

The buttes, mesas and tablelands are substantially younger and are made of sandstone and conglomerate. Known as the Callawa Formation, they were laid down in swamps, lakes, rivers and intertidal areas during the Early Cretaceous (about 144 million years ago). Just north and east of Shay Gap are scattered boulders and cobbles of various rock types. Although they are not well exposed, these are glacial deposits, or tillite, laid down during the Permian (about 295 million years ago) and are similar to those at Carawine Pool and Rudall River (see pages 50–53 and 46–49).

Photo – Jiri Lochman

Above: *Hillocks near Shay Gap*

LANDFORM FORMATION: BIF is an extremely hard rock compared to those rocks lying to the north and south at Shay Gap. It was thus preferentially preserved by weathering and erosion, leaving a prominent ridge. Shay Gap was probably formed by glaciers, which covered much of the continent during the Permian. As glaciers moved over the landscape they slowly ground up the underlying rocks. Possibly following a weakness in the BIF ridgeline, they formed a narrow glacial valley. Since then, rivers have further cut down the valley to form the gap we see today.

NOTABLE FEATURES: Shay Gap contains a succession of rocks of vastly different ages. On top of the plateau, the very young Callawa Formation overlies the ancient Nimingarra Iron Formation – thus more than 3000 million years separates their formation! This unusual situation arose because the BIF plateau was originally a very high range of hills when sediments of the Callawa Formation were deposited. As sea level rose, the sediment slowly built up, eventually burying the hills. Erosion has since exposed the hills again and preserved patches of Callawa Formation that once covered them.

GRANITE–GREENSTONE COUNTRY

Throughout much of the northern Pilbara – such as at Marble Bar, along the northern part of the Newman–Port Hedland Road, and the coastline north of Roebourne – the landscape is dominated by distinct granite and greenstone landforms. These rocks formed during the Archaean, approximately 3600 to 2800 million years ago, and contain many mineral deposits, including gold, nickel, tantalum, tin, copper, lead, zinc, silver and iron-ore.

DESCRIPTION: Granite–greenstone country tends to form a mixture of low undulating hills, monadnocks (large isolated hills that stand above a generally flat plain), sandy plains, and rugged hills and ridges with narrow valleys that may be very steep-sided.

ROCK TYPES: Granite, the dominant rock type of the two in the northern Pilbara, forms several vast ovoid intrusions, up to 120 kilometres in diameter. Granite is mostly a coarse-grained rock consisting of quartz, feldspar and mica, and commonly weathers to a smooth surface. In places it may contain scattered crystals of feldspar that are much larger (up to several centimetres) than the other grains. Called porphyritic granite, it is thought to form when magma moved from deep in the Earth's crust, where it was cooling slowly and forming large crystals, to a higher level where the magma cooled faster and smaller crystals then formed.

Greenstones are a mixture of volcanic and sedimentary rocks, which in the Pilbara include rhyolite, basalt, komatiite, banded iron formation (BIF), shale, siltstone, conglomerate and chert. They contain a variety of minerals such as quartz, feldspar, mica, pyroxene, olivine, talc, tremolite and chlorite. The greenstones lie between the large granite intrusions, as extensive linear or curved belts, tens of kilometres long. In cross-section, these belts are commonly V-shaped folds, or synclines, and have very steeply dipping beds. At Cleaverville Beach, north-east of Roebourne, wave-cut platforms provide excellent exposures of greenstones. The rocks here belong to the 3015-million-year-old Cleaverville Formation, and consist of BIF, chert, (red, black,

Photo – ACRES, Geoscience Australia

Above: *Landsat imagery showing the dome and basin pattern of granite–greenstones in the northern Pilbara*

Photo – Ian Williams

Above: *Rock outcrop of schist in granite–greenstone country* and greyish-white), shale, siltstone and some volcanic sedimentary rocks. The dark-coloured BIF, which exhibits fine-scale (less than a millimetre) alternations of iron-oxide and chert layers, alternates with bleached sedimentary beds. Other good exposures of greenstones can be seen in the hills just south of Karratha. Here, metamorphosed basalt contains globular structures (up to about a metre in diameter) called 'pillow lava'. They formed when magma erupted onto the sea floor, cooling very quickly as it made contact with the water, to form pillow-shaped rocks.

LANDFORM FORMATION: The type of rocks present in this part of the Pilbara commonly controls the shape of hills that have formed. For example, porphyritic granite weathers to form 'humpback' hills, whereas granite with lots of fractures, a strong alignment of grains (foliation), or which is sheared (has undergone extreme stress) tends to form more rugged hills. Many of the sandy plains in the northern part of the Pilbara also indicate granite underneath.

In contrast, the jagged 'razorback' hills and narrow ridges are mostly steeply dipping greenstones. Erosion has removed beds of the more readily weathered rock types to give the 'razorback' profile. Where the greenstones are more flat lying, they also form low hills like granite.

NOTABLE FEATURES: There is an excellent exposure of greenstones at Maree Pool, where the North West Coastal Highway crosses the Maitland River. At the southern end of the pool is a highly flattened and stretched rock type called mylonite. It formed when a major fault, called the Sholl Shear Zone, sheared and ground the granite and greenstones deep within the Earth's crust under extreme pressure. This is one of the major faults within the Pilbara, extending for at least 250 to 350 kilometres in a roughly north-east to south-west direction. Geologists believe that, at one stage, movement along this fault zone caused the rocks on the northern side to be displaced 150 to 200 kilometres to the left, relative to those on the southern side.

Photo – Ian Williams

Above: *Pillow basalt*

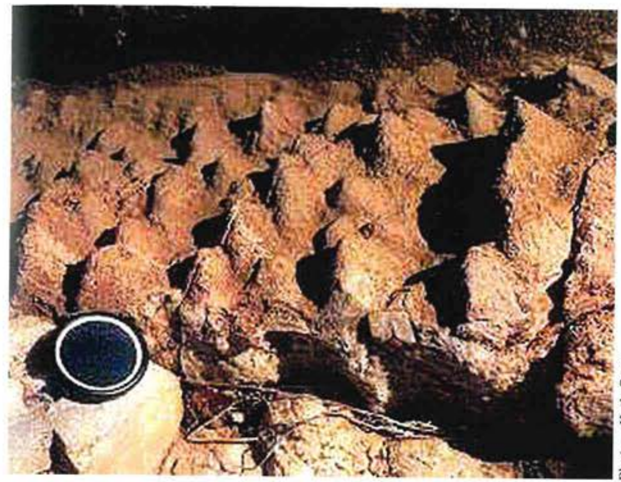


Photo – Kath Grey

Above: *Egg carton-shaped stromalolites 3.4 billion years old*

PILBARA MINERAL DEPOSITS

Some of the earliest mineral discoveries in WA were made in the Pilbara, soon after the European settlement of Roebourne and Cossack and nearby pastoral leases in the 1860s. Copper was discovered in 1872, followed in the same year by lead and silver, and then gold soon after, leading to the Pilbara goldrush (see pages 62–63). By the early 1890s, it was apparent that the Pilbara was a very prospective area. The first Government Geologist, Harry Woodward, stated that "...the North-west district as a whole is rich in minerals". Over the next century, there were hundreds of mineral discoveries that included gold, copper, lead, zinc, silver, manganese, tin, tantalum, chromium, tungsten, uranium, platinum and diamonds. Vast resources of iron-ore were discovered in the 1960s, which is now the Pilbara's main mineral export. Today, apart from gold and iron-ore mining (see pages 62–63 and 40–42), mineral production is mostly tantalum (at Wodgina), copper (at Nifty), manganese (at Woodie Woodie) and nickel (at Radio Hill).

ROCK TYPES: Most mineral deposits in the Pilbara (apart from iron-ore) are within the greenstone belts (formed in the Archaean, 3500 to 2900 million years ago) that surround the large ovoid granite intrusions (see pages 56–59). Most of the mineralisation is in faults and veins within these rocks.

The Hamersley Group (about 2500 million years old) that overlays the granite–greenstones contains most of the iron-ore deposits, and consists of slightly metamorphosed banded iron formation, chert, pelite (metamorphosed siltstone) and dolomite. The manganese deposits at Woodie Woodie are also found in these rocks.

Less commonly, mineral deposits are also found in much younger rocks that lie at the eastern edge of the Pilbara. These rocks are about 1070 to 630 million years old and are mostly

Photo – Ian Ruddock

Above: *Radio Hill nickel mine*

sedimentary rocks such as sandstone, siltstone and dolomite. The Telfer gold deposit and the Nifty copper deposit are found within these rocks.

FORMATION AND DISTINCTIVE GEOLOGICAL FEATURES: Many of the deposits in the Pilbara, such as the tantalum and tin deposit at Wodgina 130 kilometres south of Port Hedland, are the oldest of their type in the world. Wodgina contains the world's second largest reserves of tantalum, used mainly in the manufacture of mobile phone and laptop computer electronics. The minerals here were formed around 2800 million years ago. Most mineral deposits in the Pilbara are associated with shear zones – intensely deformed features deep within the earth's crust that formed under extreme stress. These zones, common throughout the granite–greenstones, allowed hot mineralising fluids to travel along them, precipitating out a variety of minerals at favourable sites within the rocks.

PILBARA GOLDFIELDS

Since gold was first discovered near Roebourne in 1877, the Pilbara has had a long history of gold prospecting, exploration and mining. More than 1000 occurrences of gold have been reported in the region so far, and more than 183,000 kilograms of gold has been mined, most of that coming from Telfer on the edge of the Great Sandy Desert. At first, early Pilbara prospectors found only small amounts of gold, but in 1888 a substantial discovery at Mallina, east of Whim Creek, led to the Pilbara goldrush. Further discoveries at nearby Egina and Pilbara Creek, which included a 3.95-kilogram nugget, led to the proclamation of the Pilbara goldfield in October that year. The government quickly recognised the new goldfield's economic importance, so geological investigations commenced to assist private companies that had begun to develop these deposits. It is not known how much gold was produced during these early days, as it is likely that many thousands of ounces were not declared to avoid the gold tax, which was 2/6d per ounce.

Other significant discoveries over the next century included Warrawoona, Pilgangoora, Pilbara, Hong Kong, Station Peak, Lower Nickol, Nullagine, Marble Bar, Bamboo Creek and North Pole. The largest of all was at Telfer, about 100 kilometres north of the Rudall River area. Discovered in 1971, mining began in 1976 and it is one of the richest gold deposits in Australia.

ROCK TYPES: Most gold occurs in the granite–greenstone country in the northern Pilbara (see pages 56–59). The rocks here are Archaean, around 3600 to 2800 million years old. At Telfer, gold is found in much younger rocks that belong to the Paterson Orogen, a south-easterly trending belt of sedimentary and granitic rocks along the eastern edge of the Pilbara. These were deposited during the Neoproterozoic, around 1070 to 630 million years ago.

FORMATION AND DISTINCTIVE GEOLOGICAL FEATURES: Most gold mined in the Pilbara occurs in native form, but is commonly alloyed with silver and, in some cases, other metals. Gold grains range in size

Photo – State Library

Above: *Men and horses near Marble Bar's mining township circa 1897*

from microscopic particles to large nuggets, such as the Bobby Dazzler (found at Sharks mining centre, south-west of Marble Bar) weighing a massive 15.15 kilograms and about 30 centimetres in diameter. Most of the gold, however, is present in quartz veins, up to two metres wide, within shear zones. Hot gold-bearing fluids travelled along these intensely deformed zones, which formed under extreme stress deep within the earth's crust, precipitating out gold at favourable locations. The Comet Mine near Marble Bar is situated along such a shear zone. Before mining began, the mineralised zone was 40 metres long and dipped steeply towards the south. It was a significant producer, mainly during the 1930s to 1950s, recovering about 3818 kilograms of gold.

At Telfer, the gold formed in sandstone and siltstone, probably when hot mineralising fluids that travelled upwards through faults were trapped in the crest of a large A-shaped fold, or anticline. This structure, known as the Telfer Dome, is easily identified from the air.

STROMATOLITES

The Pilbara contains the world's oldest known examples of fossil stromatolites – around 3.45 billion years old. They help scientists understand the evolution of life and the creation of Earth's early biosphere.

DESCRIPTION: Stromatolites are laminated biological structures built mainly by cyanobacteria (single-celled organisms too small to be seen by the human eye). They were the earliest forms of life on Earth and dominated the fossil record between about 2000 and 1000 million years ago.

Stromatolites and similar life forms known as thrombolites also form today, but are much less common than in the past. They are found in some saline lakes and hot spring environments, typically where other organisms cannot exist. The best example of living stromatolites is at Hamelin Pool in Shark Bay. Scientists study modern stromatolites to help interpret fossil stromatolites such as those in the Pilbara.

FORMATION: Stromatolites are formed by bacteria that precipitate or trap and bind sediment to create layered structures. These are dome- or cone-shaped or branching, and fossil stromatolites range in size from smaller than a finger to larger than a house. Fossil stromatolites are found throughout the Pilbara and are extremely important in helping scientists determine the environments in which the rocks were formed.

The world's oldest stromatolites, discovered in the late 1970s, are found in the North Pole area of the Pilbara. These exceptionally well-preserved 'egg-carton'-shaped stromatolites grew around 3.45 billion years ago (3450 million years ago) in shallow water fed by hot springs associated with volcanoes.

SIGNIFICANCE: The Pilbara is recognised as one of the most significant regions in the world for studying ancient stromatolites. Some modern stromatolitic bacteria are photosynthetic, that is, they

Photo – Arthur Hickman

Above: Ancient stromatolites in the Pilbara

use sunlight as an energy source that creates oxygen as a waste product. Organisms that build stromatolites, such as those now found as fossils in the Pilbara, were probably responsible for oxygenation of Earth's early atmosphere. Understanding how and where stromatolites grew in the Earth's ancient past has also been of great interest to scientists looking for possible fossil life on Mars – a planet considered to have a similar early evolution to that of Earth.

Fossil stromatolites also help geologists determine the age of the rock formations, and also their potential role in mineralisation and petroleum formation.

Please remember that many stromatolite sites are fragile and easily damaged and it is illegal to collect them.

MARBLE BAR

About three kilometres west of the town of Marble Bar is a spectacular outcrop of jasper chert, originally thought to be marble, after which the town was named. The jasper chert is part of the Marble Bar greenstone belt, a 12-kilometre-thick succession of volcanic and sedimentary rocks that formed during the Archaean, about 3490 to 3430 million years ago.

DESCRIPTION: Marble Bar is an unusually large and impressive water-polished rock bar across the Coongan River, surrounded by rugged hills and ridges.

ROCK TYPES: Marble Bar was at first mistakenly thought to be red and white banded marble, a metamorphic carbonate rock. It is actually chert, a sedimentary rock composed of microscopic silica grains. The red chert, or jasper, is well bedded, at intervals of between one and 10 millimetres, whereas the lower part is less banded and is white and bluish-black. Some of the bands are broken and form chaotic beds of elongate and angular fragments of chert. This is known as a breccia, and probably formed by slumping of the siliceous sediment soon after it had hardened. It is thought that the finely bedded jasper originated from hot silica-rich fluids emanating from deep within the crust about 3460 million years ago, during a period of submarine volcanism. The silica was then slowly deposited as a gel-like substance on the seabed in very deep and quiet water. The white and bluish-black chert intruded the jasper while the jasper was still soft.

Evidence of volcanic activity can be seen on the northern side of the bar, just north of the parking lot and on the eastern side of the river. Here, basalt underlying the chert contains beautifully preserved 'pillow structures'. These formed when lava was extruded in deep water then quickly cooled to form 'pods' of basalt.

LANDFORM FORMATION: The beds of volcanic and sedimentary rocks near Marble Bar Pool run in an approximately north-westerly direction, cutting across the Coongan River. Because the

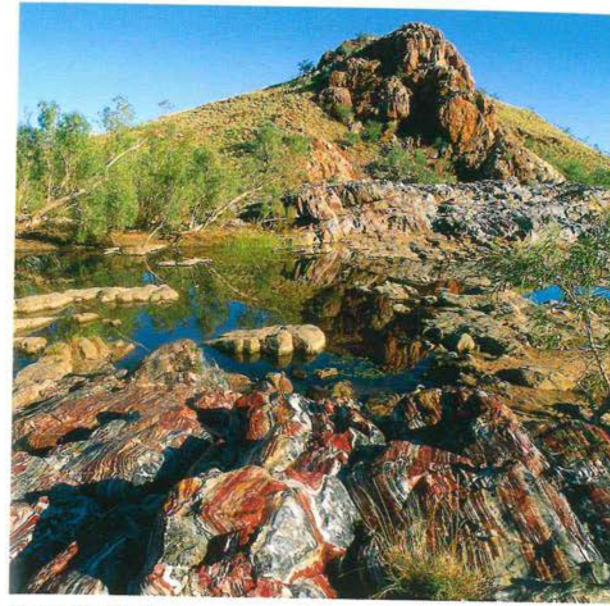


Photo – Dennis Sarson/Lochman Transparencies

Above: *Marble Bar*

chert is highly resistant to weathering, the flowing water has preferentially preserved it relative to surrounding less resistant rocks. A chert bar has therefore remained across the river, and allowed a pool to form on its northern side. Chinaman Pool and the Chinaman Pool Chert just to the north have a similar origin.

NOTABLE FEATURES: Investigations of Earth's early environment have recently been carried out in the Pilbara as part of 'The Archean Biosphere Drilling Project'. Samples of rock-core between 3500 and 2700 million years old were analysed from drilling carried out at Marble Bar. This important study, by scientists from Japan and Australia (including the Geological Survey of Western Australia) hopes to understand Earth's early climatic, atmospheric and oceanic conditions as well as the types of ancient organisms.

COASTAL TIDAL FLATS AND MANGROVES

The Pilbara coastline is mostly fringed by tidal flats, mangrove swamps and claypans. Near Dampier, a large area of tidal flats has been converted to the world's largest solar evaporation ponds. Dampier Salt Pty Ltd currently produces more than four million tonnes of salt a year from these renewable deposits. Also along the coastline are several large rivers, like the Ashburton, which empty their sand and silt laden waters onto the coast to form deltas. Some of the sand is then transported alongshore by currents, and helps to build sandy beaches and dunes.

DESCRIPTION: Drainage channels, floodplains, tidal flats, salt lakes, mangrove swamps, dunes and lagoons form a complex pattern along the Pilbara coastline. Most of the material deposited comprises mud and silt, making the ground waterlogged during wetter weather and impassable by vehicle. In dry weather the ground is broken by expansion crevices and depressions known as 'crabholes'. This type of clay and silt deposit is termed 'gilgai'. Vast amounts of mud and silt are also emptied onto the surrounding tidal flats by the many rivers that meander towards the coast from the inland Pilbara.

LANDFORM FORMATION: Most of the deposits along the Pilbara coast formed in the Holocene, during the last 10,000 years, following the last ice age. As the icecaps began to contract, the slowly rising sea level flooded low-lying areas, reworking older coastal deposits, and depositing sand and silt in its wake. The rivers continued to supply sediment onto the new coastal plain, which was also reworked by the shifting tidal channels. Where floodwaters have temporarily ponded before completely evaporating, claypans have formed. The hot and dry climate of the Pilbara periodically dries out much of this area, producing an environment where salt-tolerant plants survive.

NOTABLE FEATURES: The more inland part of the tidal flats, where floodwater is rare, is called the supratidal area. Here,

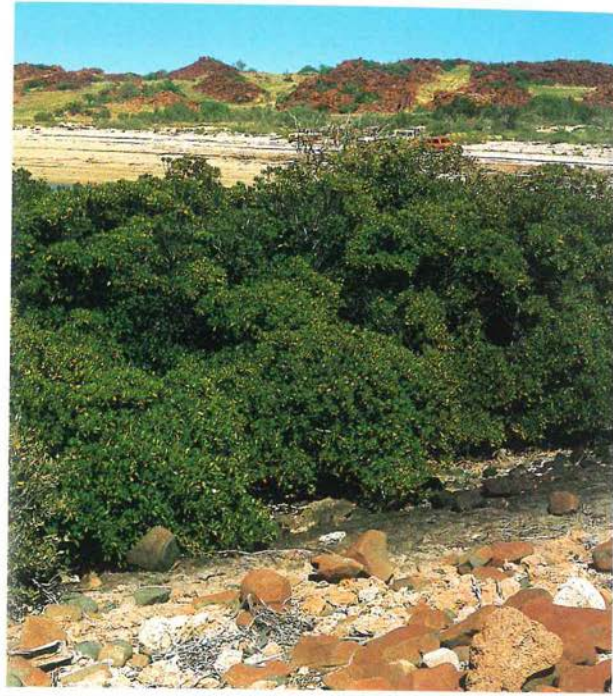


Photo – Kevin Kenneally

Above: *Mangroves (mainly* Rhizophora stylosa*) along the Pilbara coast*

because evaporation exceeds the amount of incoming water, salt crusts form at the surface. Below, larger crystals of gypsum are found growing within the saline-rich sediment. The giant solar salt operations at Dampier have enhanced this natural salt-forming process by maximising the balance between the amount of seawater that flows over the supratidal and intertidal areas with the fluctuating evaporation rate. Presently, more than 1.1 billion litres of water is evaporated daily from the 19 500 hectares of ponds.

GEOLOGICAL SURVEY OF WA

The Geological Survey of Western Australia (GSWA) is a division of the WA Department of Industry and Resources (DOIR) Resources. For over 100 years the GSWA has carried out geological and geophysical studies of the State, with the aim of revealing its mineral and petroleum wealth. The information gathered forms maps, reports, evaluations and data summaries. These help the mineral and petroleum industries, the public and other government departments in exploration, mining and land use planning.

Between 1847 and 1888, before the establishment of the GSWA, a series of Government Geologists were appointed to investigate mineral discoveries in the new Colony. Some of this early work led to the State's first gold rush at Halls Creek in 1885–86. Based on this contribution to the Colony's development, the government established the GSWA in 1888, headed by Government Geologist Harry Page Woodward. It was essentially a 'one-man band' with very limited funds. Over the next 60 years, although only a handful of staff were added, more than half of WA was mapped, many mining centres investigated and areas of potential mineralisation identified. In 1961, under the direction of Joe Lord, the first systematic mapping of the State began, taking 20 years to complete. This resulted in the first real understanding of the geological framework of WA and set the groundwork for major mineral and petroleum discoveries. During the last 20 years, more detailed studies and mapping have been carried out, resulting in further discoveries and a better understanding of which areas are the most prospective.

The GSWA is now one of the largest and most respected geological surveys in the southern hemisphere. Employing nearly 150 staff, including more than 65 geologists, it serves a minerals and petroleum industry that spends more than $1 billion a year on exploration in WA.

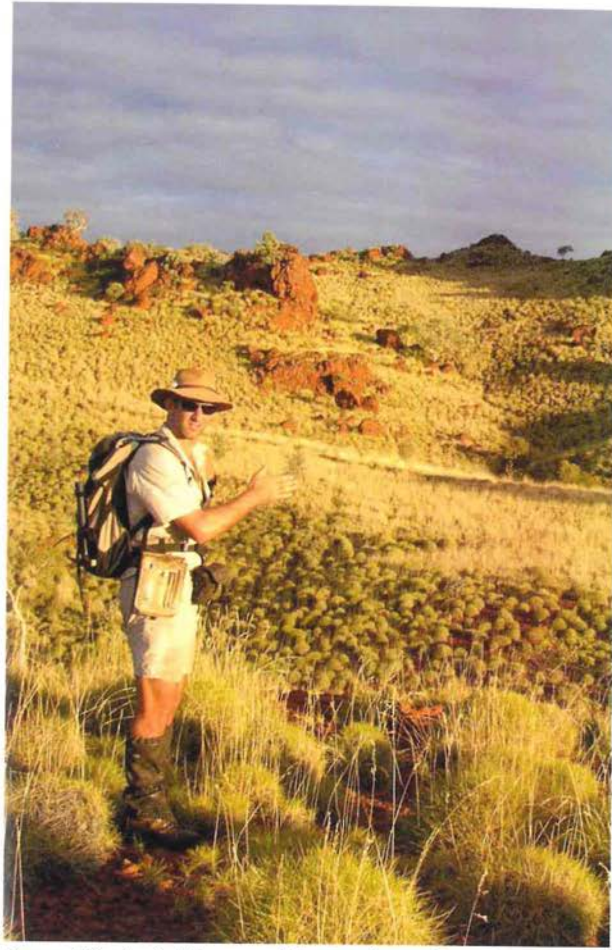


Photo – Eben Rose

Above: *A Geological Survey of Western Australia geologist in the field in the Pilbara*

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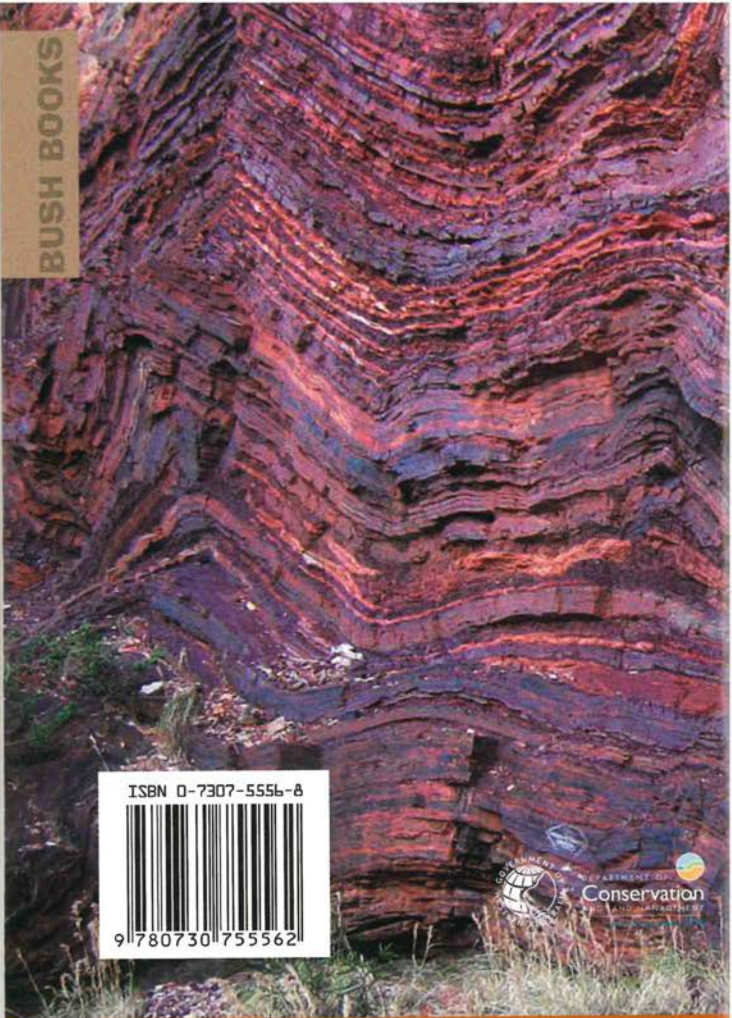

ISBN 0-7307-5556-8
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