

DISCOVERY TRAILS TO EARLY EARTH

a traveller's guide to the east Pilbara of Western Australia

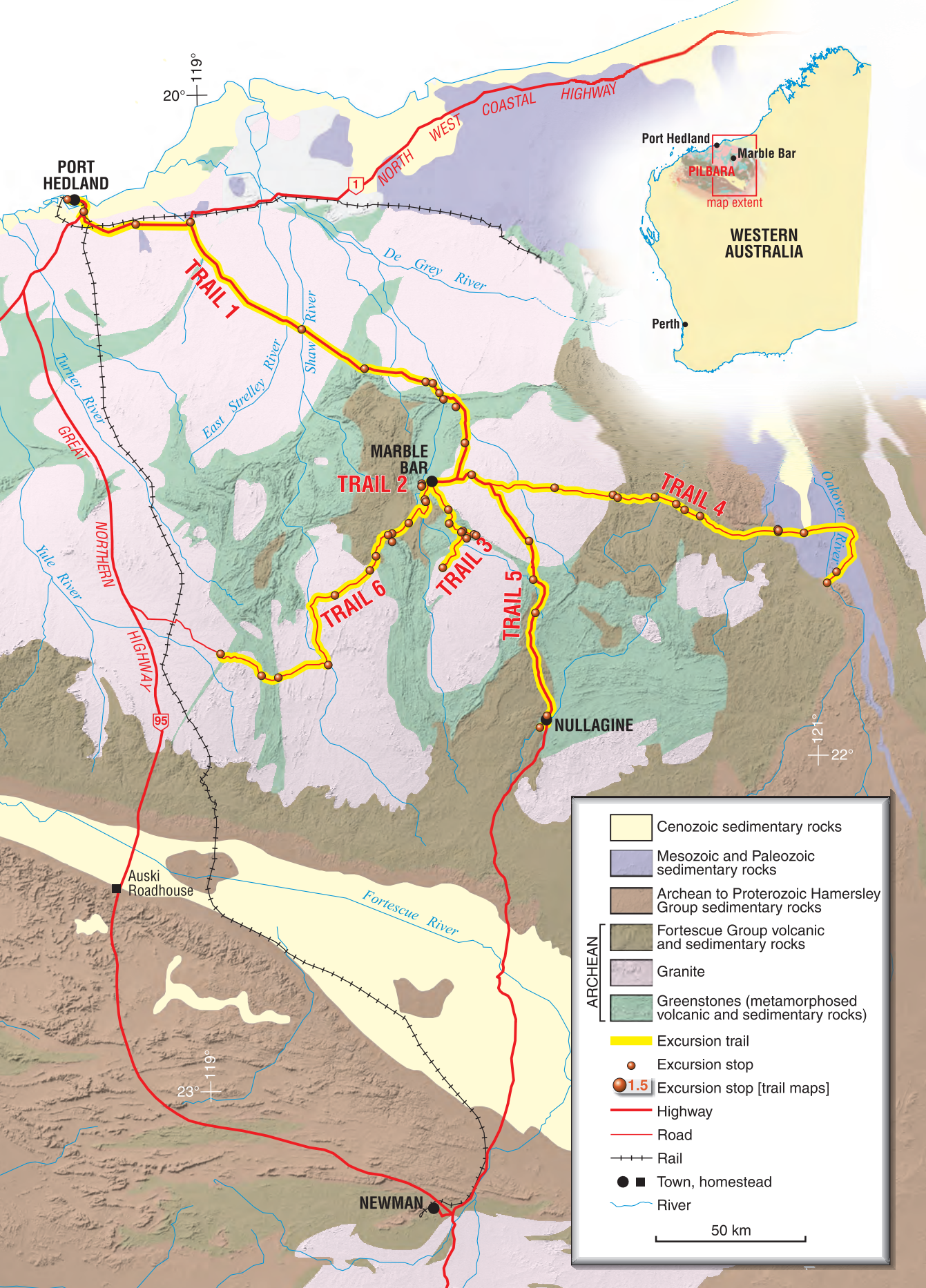


Government of Western Australia
Department of Mines and Petroleum

**MARTIN VAN KRANENDONK
and JEAN JOHNSTON**

Geological Survey of
Western Australia





	Cenozoic sedimentary rocks
	Mesozoic and Paleozoic sedimentary rocks
	Archean to Proterozoic Hamersley Group sedimentary rocks
	Fortescue Group volcanic and sedimentary rocks
	Granite
	Greenstones (metamorphosed volcanic and sedimentary rocks)
	Excursion trail
	Excursion stop
	Excursion stop [trail maps]
	Highway
	Road
	Rail
	Town, homestead
	River
50 km	





Discovery trails to early Earth

— a traveller's guide to the east Pilbara
of Western Australia

by

MJ Van Kranendonk and JF Johnston

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Cover photograph:

Red rocks and blue sky reflected in the calm waters of a Pilbara pool provide a sense of timelessness

Inside front cover:

Geology map of the six Discovery Trails around Marble Bar

Frontispiece:

Author, Dr Martin Van Kranendonk, points the way across a typical Pilbara landscape

Inside back cover:

Locations of all the Stops along the Trails

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Front endpaper: Map of the six Discovery Trails around Marble Bar

Back endpaper: Locations of all the Stops along the Trails





Welcome travellers,

...to the east Pilbara region, a place renowned for its wide-open spaces, turquoise coasts, hottest town, long trains, big ships, and spinifex — lots of spinifex. These are the features that most visitors to the region see. But the east Pilbara is much more and has one other feature that makes it unique within Australia and — except for a part of southern Africa — anywhere else in the world. It is a feature that is difficult to see without guidance and that very few of the general public would ever recognize: the east Pilbara is a window into Deep Time. This special place offers a glimpse of what the world was like 3.5 billion (3 500 000 000) years ago, or three-quarters of the way back in time to the formation of the planet, long before European settlement, before its Aboriginal inhabitants arrived, before marsupial megafauna and dinosaurs, before fish climbed out of the sea, even before multicellular life.

This guidebook will help you to open that window, help you to see, appreciate, and understand the secrets that are locked in the hills and flat expanses of this region and will give you a sense of the processes and vast time frames involved in the formation of the planet we live on, and the landscapes we see around us today.

We hope that you enjoy the journey!

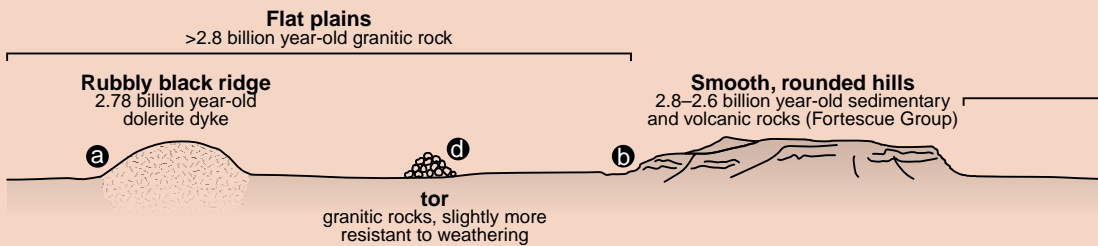
MJ Van Kranendonk and JF Johnston

June 2009

What is in this book?

This book introduces you to the landforms, rocks, and geological processes that helped shape this ancient landscape, through thousands, millions, and even billions of years:

- *Six Discovery Trails* cross the east Pilbara, centred on Marble Bar, designed to look at the ancient rocks, and allow you to appreciate the formation of different landscapes, marvel at their longevity, and enjoy the ambience of this ancient and harsh, but beautiful, environment.
- After the trails, *a series of chapters* focuses on: 1. Deep Time — the story of the Universe, our solar system and early Earth over billions of years; 2. rocks, minerals, and landscapes; 3. the geological history of the east Pilbara; and 4. the history of the people of the Pilbara.
- A *Glossary* will help you understand the geological terms used to describe the rocks, the processes that change the rocks, and the structures and minerals contained within them. Throughout the text, geological and technical terms are in **bold type like this**, and are defined in the Glossary at the end of the book.
- *Further reading* offers a list of books and articles that go into more detail on some of the concepts and the localities in this book.
- Inside the *front cover* is the geology map showing the six Discovery Trails. Inside the *back cover* is a listing of the locations of all the Stops along the six Discovery Trails.



What you will see

The Discovery Trails across the east Pilbara described in this book will introduce you to some of the oldest rocks on the planet — almost 3 500 million years old — that in many places, are so well-preserved that they look as if they were deposited only yesterday. These include:

- deposits from volcanic eruptions
- sediments deposited on ancient land surfaces and seafloors
- granite rocks emplaced deep within the Earth’s crust, and
- magmas emplaced into giant fractures as the crust was pulled apart during periods of plate movement.

You will witness the long history of the development of the Western Australian landscape (see below), through periods of uplift and erosion, glaciation, and tropical weathering as the Australian plate migrated its way across the face of the globe, driven by tectonic forces deep within the Earth’s interior over the past 300 million years. The panorama below combines sketches of the many landscapes you will encounter, together with photographs of a typical example of some of them.

And finally, you will also see some of the recent history of this region, including evidence of Aboriginal life over the past 40 000 years and colonization by European miners only 100 years ago.



Broad valley
glacial valley, filled with boulders of many different rock types, and polished rock outcrops; often steep-sided valley walls

Razorback ridges
>3 billion year-old sedimentary and volcanic rocks (Pilbara Supergroup)
Recent scree slope
Cenozoic alluvial fan

Active creeks and rivers

Inverted topography
Phanerozoic lake or river deposits, formerly in depressions, but now elevated due to erosion of softer flanking rocks



What will you need?

The east Pilbara is a harsh environment, even in winter. Summers, which start in October and extend till May, are hot to very hot (40–50°C), with occasional cyclones. Winters (June to September) are warm to hot (20–35°C), with cooler evenings and cold nights, and sometimes strong, cool winds. Travellers are advised to visit in the winter months only. Even then, you will need a hat, sunglasses, sunscreen, hiking boots, and long trousers or leg gaiters to protect your lower legs from the sharp needles of the ubiquitous spinifex grass. A **Global Positioning System** (GPS) unit is strongly advised to help you to locate the Stops along the roads, and measure distances precisely. If you are planning to be away from your vehicle for any time, carry plenty of drinking water. A backpack with a compass, GPS, safety matches, and a personal **EPIRB** are also good safety measures for longer walks. Remember that fuel and water are precious commodities in the Pilbara region.

Outback etiquette (or ... please close the gate)

The Stops described in this guidebook are all on pastoral cattle stations and sheep stations and it is the proper etiquette to close all gates as you pass through them, unless already open when you arrive. If travelling in early morning or late afternoon and especially in the evening or at night, take extreme care while driving to avoid a collision with stray cattle and kangaroos. *You are responsible for your own safety at all localities and are cautioned to take appropriate care for yourself and your party, as well as for others you may happen to meet.* A few of the Stops are on main roads and tracks that may have light to moderately heavy traffic, including ore-hauling road trains. Be cautious where you park along the side of these roads so that your vehicle and yourselves are clearly visible at all times. Please remember to take out all rubbish and leave only footprints at the sites, so that others may also enjoy this region.

Using this book

Each Discovery Trail comprises several Stops, each is described on a 2-page spread — see example on next page. Directions on how to get from the previous Stop to each new Stop are given at the start of each section, *in italic type, like this*. Locality positions are given in degrees and minutes (to 3 decimal places) measured by GPS, and distances between points are indicated in kilometres (km) or metres (m), measured using the trip meter in the vehicle. Directions may be followed using only the distances indicated, but a GPS unit is also very handy to ensure that you are at the correct, and best, place to view each Stop.

These are the icons used at each Stop to show the type of feature being visited:



Cliffs or roadside cutting



Fossil locality



Mine site



Outcrop



Panorama



Pool



Vista



Walking track

And here is a sample double-page spread from one of the Trails, with annotations:

Trail number and Stop number

Icons for each Stop

Stop name

Red arrows show age of rocks at each Stop, set on the time scale

GPS reading for this Stop

Directions from previous Stop

What you see at this Stop

Stop 1.12 — The Sisters and Mount Edgar Granitic Complex
21°03.391' S 119°51.220' E

Directions to Stop 1.12: Return to the Marble Bar Road. Turn right, heading south towards Marble Bar. Continue for 17 km until you see a ridge of white-capped hills on your right (21°03.391' S 119°51.220' E). Pull over with care, well off the road, as road trains commonly pass by.

What you see here
The white-capped hills on the right-hand (west) side of the road are called The Sisters. They are made of white quartz that was intruded as a thick vein system along a fault that encircles the Mount Edgar Granitic Complex.

Could there be gold in the quartz?
Such quartz veins are quite common along faults and represent the effects of relatively late upper crustal movement in structures that originate from much deeper in the crust. Fault structures filled with quartz veins commonly host gold mineralization, because they provide channels for mineralizing fluids to move through the crust. Gold is carried in solution in these fluids and precipitates out when rapid fault movement releases pressure and the fluids instantly freeze and crystallize in place. Gold is generally present at very low concentrations, but as the fluids in the veins pass through the rocks they scavenge the gold and it is precipitated in the veins, and along vein contacts with the surrounding rock.

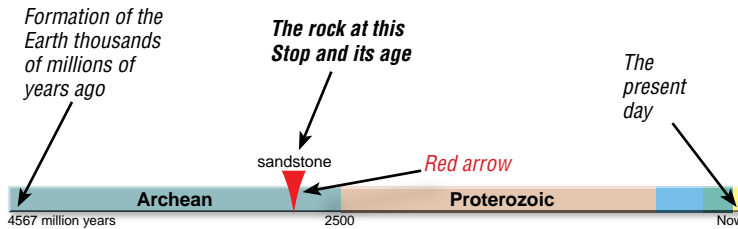
View to the distant greenstone mountains
The view across the road to the east looks right across the Mount Edgar Granitic Complex (see panorama), which is a 60 km-diameter, broadly circular dome of granitic rocks that were emplaced into the upper crust as a result of a long series of deformation events, commencing about 3470 million years ago and continuing until 2630 million years ago. Several different pulses of granitic magma (at 3470 Ma, 3300 Ma, 3240 Ma, and 2630 Ma) make up the Mount Edgar Granitic Complex.

Return to your car, and continue towards Marble Bar. At 18.3 km, notice in front of you and curving off into the distance to the left, the Warrawoona Range, made up of volcanic and sedimentary rocks uplifted and tilted to the south (away from the Mount Edgar Granitic Complex) during the ballooning and uplift of the granite (noted earlier). We will travel into the heart of the Warrawoona Range in Trail 3.

This is the last Stop on Trail 1. Continue to Marble Bar.

Looking south across the flat 'downs' of the Mount Edgar Granitic Complex to the Warrawoona Range of tilted greenstones

The time scale — shows just where you are throughout time:



In the top right-hand corner for each Stop is a time-scale bar that indicates the age of the feature at each Stop. The bar spans the entire history of the Earth from its formation 4 567 000 000 years ago to today (as shown above) and the red arrow will slide along the bar to give an immediate picture of the relative ages of the rocks.

Because this is a roadside geology guide and not a geological story through time, localities are described as they are encountered along the roads, not as they fit into the geological history of the region.



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	km
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Travelling Trail I

Port Hedland to Marble Bar

The 200-km drive from Port Hedland southeast to Marble Bar takes you from coastal limestone reefs, sandy beaches, and tidal river inlets, through broad, flat sandplains formed in recent times by the action of wide, seasonal rivers, and on to the ancient rocks of the Pilbara Craton. Along the way, you will see evidence of Australia's dramatic journey through time, when it experienced periods of uplift and erosion, sandstone deposition during the time of the dinosaurs, periods of deep, intense weathering under tropical climatic conditions, and the development of some recent landforms.





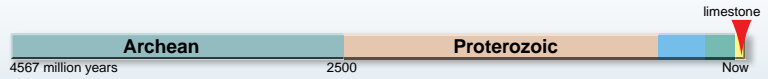
Stop 1.1 — Coastal limestone, Port Hedland

20°18.548'S | 118°34.737'E

Directions to Stop 1.1: Start your journey at the Port Hedland Visitor Centre in Wedge Street (20°18.752'S 118°34.576'E). Set trip meter to 0.0 km. Head northwest along Wedge Street, turn right into Richardson Street, and travel east for 400 m to Captain Bert Madigan Memorial Park. This is the best place to view the loading of the iron ore ships. Proceed to far southeastern corner of the car park (200 m). Walk down the moderate slope onto the beach, past mangroves, to the limestone platform.



General view of the limestone pavement right at the water's edge. Slabs broken off the pavement during storms have been flung high up on the beach at the foot of the grass-covered dunes. Loading of iron ore into huge ships is taking place in background



Platform by the sea

What you see here is a gently sloping, etched platform of pinkish **limestone** that was formed when the sea level was much higher than today, between 60 000 and 10 000 years ago.

The platform now has a hackly or irregular and broken surface where it is being weathered and eroded by the waves. Seawater trapped in the indentations is evaporating, leaving salt-filled depressions.

What is limestone?

Limestone is a chemical sedimentary rock made of calcium carbonate (with the chemical formula CaCO_3). Limestones like the Bossut **Formation**, here, are mostly formed by animals, such as corals and oysters, which are able to use calcium carbonate dissolved in seawater to make their skeletons or shells. When such organisms die, their shells accumulate on the sea floor as limy mud which, over time, hardens to form the limestone.



Notice the salt-filled indentations and the hackly surface of the limestone pavement



Stop 1.2 — Salt evaporation ponds

20°20.753'S | 118°37.819'E

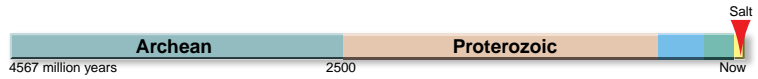
Directions to Stop 1.2: Return to the car. From the car park, turn right into Richardson Street, travel past the Customs House to The Esplanade. On the right is Port Authority building. Notice the salt piles stark white against the red-brown iron ore. Turn right onto Wedge Street (1.7 km). Turn left at stop sign to Wilson Street to get out of town. Proceed along Wilson Street. Just opposite the race track, the ridge on your right is made of limestone (Bossut Formation once again) deposited on the former sea floor. Aboriginal petroglyphs have been inscribed into the surface of this soft rock in places. Iron ore trains with about 300 wagons (hailed by up to six diesel engines) are often visible behind this ridge on their way to the unloading and loading facility at Port Hedland. Further along the road, salt piles belonging to Dampier Salt Limited come into view. At 10.9 km, turn left into the photo lookout parking bay. Walk up to the viewing platform overlooking Dampier Salt's stockpiles (20°20.753'S 118°37.819'E).

Did you know?

Western Australia produced 9 million tonnes (Mt) of salt in 2008 (valued at A\$200 million) from evaporation ponds such as these. Salt has many industrial uses: it is vital for the petrochemical industries, it is used to preserve food, for curing leather, and is added to glass, plastics, paper, and soap.



View of the white piles of salt and the salt evaporation ponds from the viewing platform



What you see here

From the viewing platform, you can see a mix of products from ancient and modern geology, with 2.5 billion year-old iron ore in rail wagons being shipped from the Hamersley Range, some 250 km south, and salt, a mineral that has **crystallized** from the **evaporation** of seawater over the past few weeks or days. This duality exemplifies the incredible diversity of processes and time that is involved in geology.

Evaporation of seawater

The large white pile of salt (NaCl) is the product of evaporation of seawater that has been pumped from the Indian Ocean into shallow, man-made ponds. Seawater has an average salinity of approximately 3.5%, which means that every one kg of seawater contains 35 grams of dissolved salts. The salts consist mostly of sodium (Na) and chlorine (Cl), but magnesium (Mg), sulfur (S), calcium (Ca), and potassium (K) are also present in lower concentrations. As the seawater in these ponds evaporates, Na and Cl combine to form salt — the mineral **halite**.

This man-made evaporation process is similar to the natural process of formation of rock salt, which happens when large seas or saline lakes become barred from the open ocean (as a result of **faulting**, mountain building, or changes in sea level), and water circulation ceases and evaporation commences, forming **evaporative minerals**.

Salt deposits in the Mediterranean Sea

The Mediterranean Sea, separating Europe from Africa, is a good example of a barred saline water body, with restricted access to the Atlantic Ocean through the Strait of Gibraltar, which is only 14 km wide. At times in the geological past when sea levels were lower, or the straits were blocked, the Mediterranean Sea was completely closed off and experienced extensive evaporation — and thick salt deposits were formed. The same process occurred across parts of Western Australia about 800 million years ago, when much of central Australia was covered by a shallow, evaporative sea.



Stop 1.3 — View of Robe Pisolite

20°23.222'S 118°47.846'E

Directions to Stop 1.3: Return to vehicle. Set trip meter to 0.0 km. Turn left onto main road, continue on for 1.2 km, and take the turn off to Great Northern Highway at 20°21.387'S 118°37.419'E.

*Reset trip meter to 0.0 km. At 5.1 km (20°23.233'S 118°39.400'E), notice the stockpiles of grey-black ore on the right. This is **manganese** that has been trucked from Woodie Woodie, some 180 km east of Marble Bar. The manganese is derived from sedimentary rocks deposited from seawater during a period of oxygen-enrichment of the atmosphere and oceans. Continue on for a total of 21.2 km (20°23.222'S 118°47.846'S). Pull well over to the side of road.*

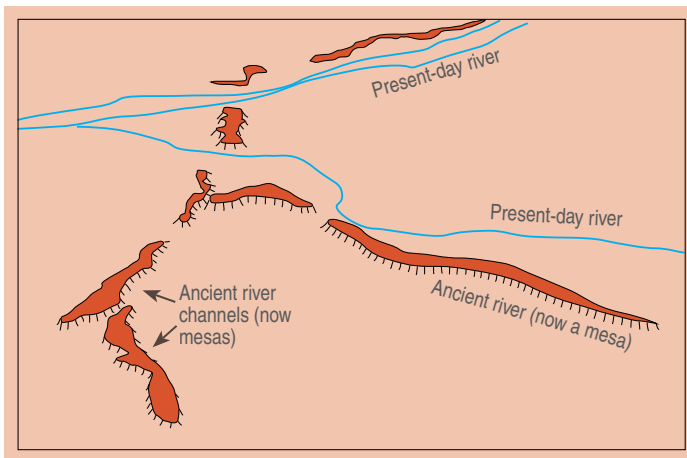
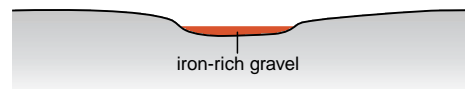


Figure 1: This sketch shows present-day mesas made up of channel-iron deposits. The sinuous form of the mesas reflects ancient rivers, now perched on hills and cut by recent drainage

Figure 2: The stages of mesa formation: a) iron-rich gravels are laid-down in stream beds; they solidify and become much harder than the surrounding granites; b) modern erosion cuts down through the granites, but the gravels are resistant; c) the iron-rich rock remains in place and forms a sinuous mesa shape

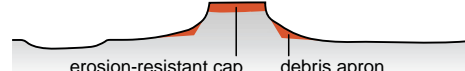
a) Iron-rich gravel deposited in river beds

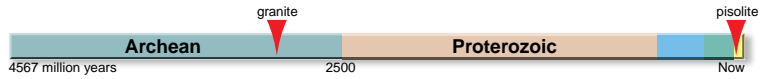


b) Landscape eroded by meandering stream



c) Cap of iron-rich rock more resistant to erosion





What you see here

The dark flat-topped hills, or **mesas**, that you see about 7 km to the south of the highway are examples of ‘inverted topography’, where old stream channels (formerly in the lowest part of the landscape) now form ridges, as a result of recent erosion that has weathered away the surrounding rocks and left the more-resistant, **iron-cemented** river gravels upstanding (Fig. 1).

Ribbons of iron

These mesas are made of sinuous ribbons of ironstone, known as channel-iron deposits (CID), that some 30 to 60 million years ago were deposited in rivers and creeks long since dried up (Fig. 2). The mesas are the remnants of

an earlier land surface that was formed after a major Ice Age (in the Permian, 250 million years ago). The CID mesas mark the last years of the ancient plateau, after the dinosaurs had become extinct.

Good enough to export

The channel-iron deposits are named the Robe Pisolite, and are composed of iron-rich **pisoliths** (pea-shaped grains) cemented together by brown **limonite**, an iron-rich mineral. The Robe Pisolite is an important source of iron ore for Western Australia’s export markets.

Small amounts of broken rock fragments are also in these rocks, as well as scattered fragments of fossil wood.



View, looking south of the highway, at the ‘train’ of mesas made by the Robe Pisolite; termite ‘airconditioners’ in the foreground



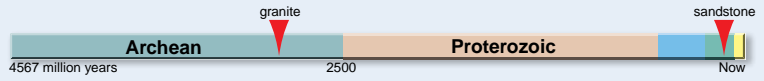
Stop 1.4 — Cretaceous mesas

20°22.946'S | 118°58.430'E

Directions to Stop 1.4: Continue driving east along the Great Northern Highway for about 30 km. Just before the turn off for the Marble Bar Road on the right (20°22.946'S 118°58.430'E), pull over to the (left) side of the road and look across the Great Northern Highway to the northeast to the claw-like hill. You are now commencing your journey back into Deep Time.

Hand-sized sample from the sandstone capping containing mineralized fragments of Cretaceous wood





What you see here

The claw-like hill and its neighbours visible to the north of the Great Northern Highway (see vista) are mostly made up of 2950 million year-old **granite** (light-orange rock at the base of the hills) of the **Pilbara Craton**, with a flat capping of dark brown to black-weathering **sandstone** between 146 and 66 million years old — formed in **Cretaceous** times. The sandstone is made up of coarse, angular **quartz** sand grains and rock fragments cemented together by black iron-rich material. Wood fragments may be found in the sandstones, still showing original woody textures despite their age and the original wood material having been replaced by minerals once carried in solution by groundwater (see photo).

Fossil plants

Some of the fossils have been identified. They come from a variety of plants, including: ferns (called *Cladophlebis*, *Sphenopteris*,

Dictyophyllum, and *Ruffordia*); seed ferns (plants that are fern-like but have seeds not spores, e.g. *Pachypteris*); large trees like modern-day pines (*Pagiophyllum* and *Brachyphyllum*); and large deciduous trees like the modern Ginkgo (*Ginkgoites*). Such a grouping suggests a damp, broadleaf forest where birds, pterosaurs, mammals, marsupials, and even dinosaurs would have thrived.

The sandstone is interpreted to have been laid down in a fluvial (river) or deltaic (delta) setting, near the southern or southwestern margin of a freshwater lake. In the geological past, broad river systems deposited sands (forming sandstones) in just the same way as large braided rivers are doing on the flat plains today (See Stop 1.5).



Vista at the Marble Bar Road turnoff. Ancient (Archean) granite lies underneath Cretaceous sandstone

Stop 1.5 — Shaw River

20°42.610'S | 119°19.730'E

Directions to Stop 1.5: Take the turnoff to the right, towards Marble Bar. Set trip meter to 0.0 km and head south along the Marble Bar Road.

At about 27.5 km, note the raised gravel ridge running parallel to the road on the right hand side. This is all that remains of the former railway line that ran from Port Hedland to Marble Bar between 1911 and 1951. At about 42 km, are the first glimpses of the ancient rocks that form the geological heart of the Australian continent — the ultimate goal of our journey. At about 56 km, cross the signposted Shaw River (20°42.610'S 119°19.730'E). Park the vehicle.

What you see here

The flat plains you have been travelling across, are the recent floodplains of rivers on their journey to the sea. These floodplains are covered with sediment that has been washed down from the highlands in the south and east by a series of broad sandy rivers. The Shaw River before you is about one km wide and flows for more than 205 km — it rises in the Chichester Range in the south and eventually reaches the Indian Ocean about 75 km east of Port Hedland.

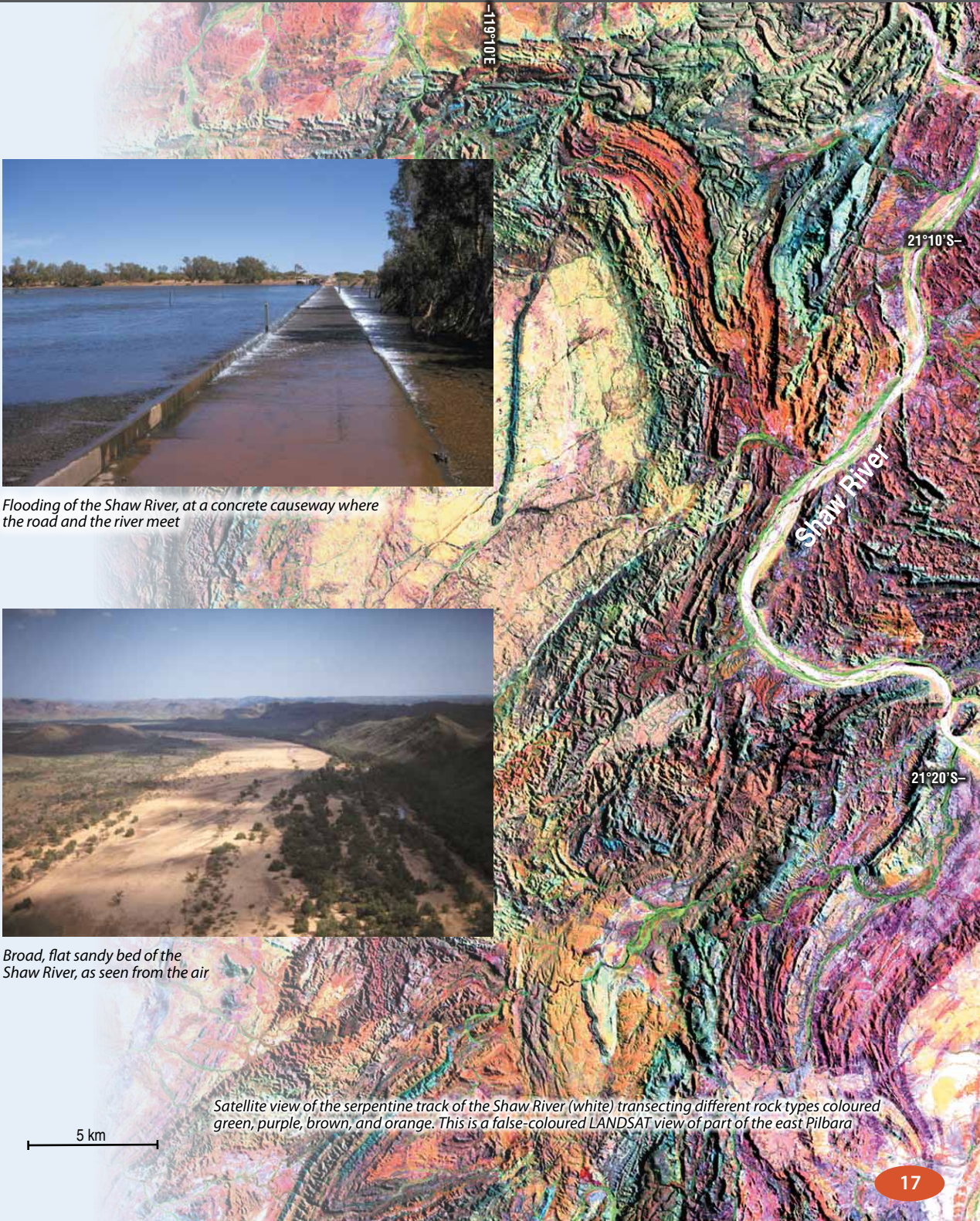
Dry winters and summer cyclones

The flow of the Shaw River reflects the climate of the region. The river is almost completely dry on the surface for most of the winter, except for isolated deep pools along river bends. It only flows occasionally, when a tropical cyclone passes over its catchment area in the summer (rainy months). As the river drains a large catchment and cyclones can drop a huge volume of rainwater over a short time, the river can fill up quickly and flow rates can be high. It is common to see debris from floods stuck high up in the branches of the river red gums lining the river banks; sometimes even large branches or whole tree trunks (see photo)!

Much of the sandplain that you have driven across since leaving Port Hedland is the result of large floods (maybe one in every 100 years), when the rivers flood to a depth of about 10 m, burst their banks and spread their suspended load of eroded rock material (sand) over this broad flat area. As well, the roads and highways are closed until the floodwaters recede.



Once the floodwaters subside, the debris is left stranded high and dry in the trees



Flooding of the Shaw River, at a concrete causeway where the road and the river meet



Broad, flat sandy bed of the Shaw River, as seen from the air

Satellite view of the serpentine track of the Shaw River (white) transecting different rock types coloured green, purple, brown, and orange. This is a false-coloured LANDSAT view of part of the east Pilbara

Stop 1.6 — Ancient beaches and a dried-up lake

20°49.821'S | 119°31.831'E

Directions to Stop 1.6: Continue for about 23 km on the Marble Bar Road, to the Des Streckfuss rest area (at 79.4 km cumulative distance from the turnoff to Marble Bar from the Northwest Coastal Highway, 20°49.527'S 119°30.547'E); stop and reset the trip meter to 0.0 km.

First view of an ancient land

Looking to the north of the highway, you can see the first exposures of ancient, 3.5 to 3.2 billion year-old **greenstones** of the **Pilbara Supergroup**, striking (or trending) away from the highway to the northeast and north, **dipping** almost vertically into the ground, and with the tops of the beds facing west, indicating they get younger to the west. These rocks were tilted and **deformed** into a tight, south-plunging **syncline**, prior to deposition of sedimentary rocks of the overlying 3 billion year-old Gorge Creek Group, which forms the large ridge of hills to the south of the highway (Fig. 1). Between these two groups of rocks there is an **angular unconformity**, which represents a long period of time when sediments were not being deposited at this locality (Fig. 2).

Continue for 2.4 km past the Des Streckfuss rest area (20°49.821'S 119°31.831'E), and stop on the roadside.

Archean beaches

There is a good view, looking south across the highway, of the Gorge Range, which strikes (or trends) east-southeast, parallel to the Marble Bar Road. The range itself is composed of 3 billion year-old quartz **sandstones** of the Gorge Creek Group

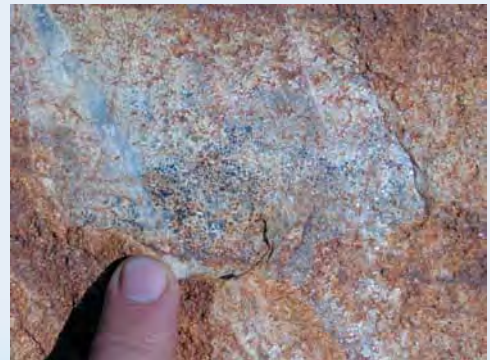


Figure 3: Close-up view of 3 billion year-old beach sands (now sandstone) of the Gorge Creek Group

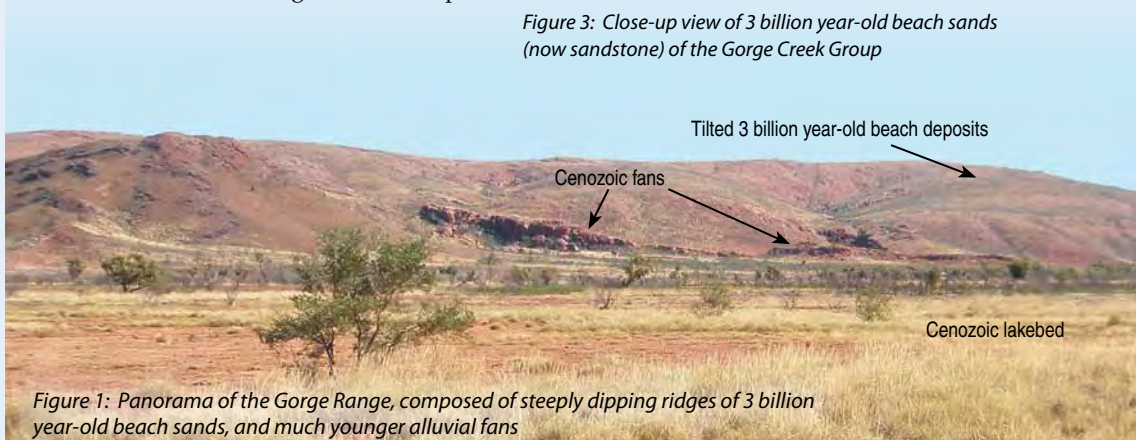
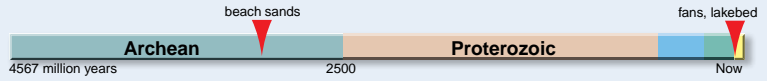


Figure 1: Panorama of the Gorge Range, composed of steeply dipping ridges of 3 billion year-old beach sands, and much younger alluvial fans



(Fig. 3) deposited on an ancient beach that have been tilted and **overturned** so that, while they dip steeply towards you, the tops of the beds **face** away from you towards the south. The **bedding** is visible as subhorizontal stripes on the hills.

Young shorelines

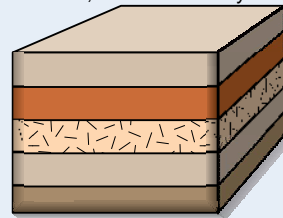
As you continue driving east, you will notice three lobes of coarse sandstone and **conglomerate** rocks coming down off the tops of the hills and fanning out from valleys in the Gorge Range onto the flat plain below. These are **Cenozoic** (<66 million years old) **alluvial fans** that were deposited during more tropical climatic conditions. The fans contain cobbles and boulders (derived by erosion of the old Gorge Creek Group sandstones), which have been cemented together to form a new rock. These fans flowed down from the hilltops onto the flat plain which the road crosses, and which represents a dried-up lake bed.

At 5.9 km past the rest area (20°50.063'S 119°33.762'E) is the best view of a single fan; then at 9.8 km past the rest area (20°50.327'S 119°35.894'E) there is a fine view of the three fans from the road.

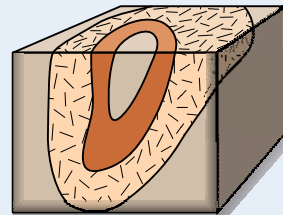
Traces of bedding in 3 billion year-old rocks



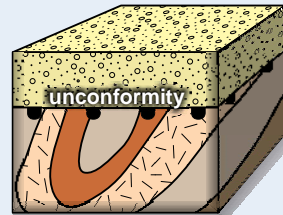
a) Volcanic and sedimentary rocks, 3.5–3.2 billion years old



b) Tilting and folding, uplift and erosion, 3.2–3.07 billion years ago



c) Deposition, 3.02–2.94 billion years ago



d) Tilting and folding, 2.94 billion years ago

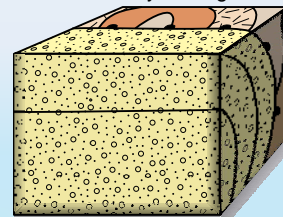


Figure 2: Stages in the formation of the unconformity at this Stop



Stop 1.7 — Sheared granite gneiss

20°52.309'S | 119°43.714'E

Directions to Stop 1.7: Continue for a total of 24.5 km from the Des Streckfuss rest area. Pull right over to the side of road. The outcrop is on right hand (south) side of road, just before a tree-lined creek (20°52.309'S 119°43.714'E).

What you see here

The **outcrop** of rock right beside the road is on the bank of One Mile Creek. The rocks are **sheared granite gneiss** that form the southern margin of the Muccan **Granitic Complex**, where the **granite–greenstone** story begins. This outcrop consists of a number of different types of granite, **emplaced** over several hundreds of millions of years. The oldest components are dark-coloured and finer grained than the younger granites and have been **intruded** by coarse-grained, light-coloured granitic **veins**. **Deformation** gives the rock a gneissic texture.

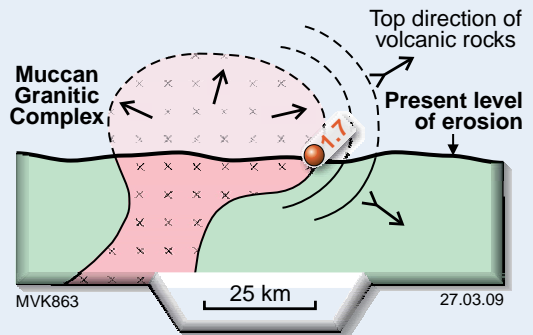
Did you know?



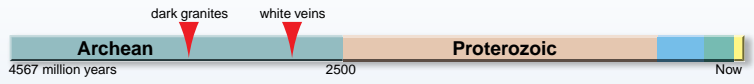
The Muccan Granitic Complex is a 75 km-diameter, ovoid body of granitic rocks. The rocks have been dated at between 3.47 and 2.94 billion years old, and have been affected by **shearing** and **metamorphism**. The Muccan Granitic Complex is one of several ovoid granitic complexes in the east Pilbara. They are so large that they are visible from space (see Landsat image in Chapter 3). Like the other complexes, the Muccan Granitic Complex is flanked by arcuate **greenstone belts** that wrap around the complex, like a ring of mountains. The complexes are like giant, crustal 'boils' that rose up from deep in a much hotter Earth.

Uplifted granites act like dough rising in a bread tin

Look closely at the outcrop, and you may be able to recognize **planar features** in the rocks that dip to the north. Together with evidence from **overturned bedding** in volcanic rocks at Stop 1.9, this **fabric** is used to indicate that the Muccan Granitic Complex ballooned outwards at this point and over-steepened its margin during uplift and emplacement — just like bread dough that rises up and over the top of the bread tin.



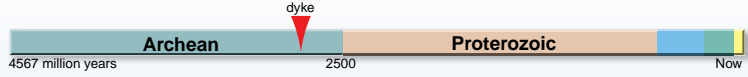
Sketch showing the ballooning granites (looking just like rising bread dough)



Close-up view shows gneissic banding formed during deformation at high temperatures deep within the crust



Author sitting on outcrop of sheared granite gneiss



Stop 1.8 — Dolerite dyke

20°52.584'S | 119°45.079'E

Directions to Stop 1.8: Continue east along the Marble Bar Road. At 27.0 km from the Des Streckfuss rest area, pull over just before the road crosses a ridge of dark brown-weathering rocks (20°52.584'S 119°45.079'E).

What you see here

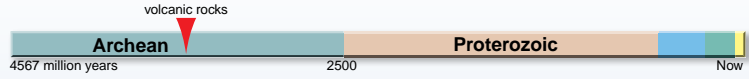
The ridge of dark brown to black-weathering rock that the highway crosses at this locality is a **dolerite dyke**, a sheet of dark **igneous rock** injected into a vertical **fracture** in the **crust** about 2772 million years ago. This is one of a swarm of dykes that cut across the older **granite–greenstone** rocks of the **Pilbara Craton**. Dykes such as this were the feeders to **basalt lava flows** of the Fortescue Group, a 2775 to 2630 million year-old **succession** of volcanic and sedimentary rocks (see Trail 4) that lie on top of the granite–greenstone rocks of the Pilbara Craton.

Is that chocolate icing on top?

The dolerite dykes are long, sinuous, knobby lines of dark-brown hills cutting across the countryside — the weathered rock looks just like chocolate icing coating the tops of the hills (photo, below). Dolerite dykes are a common sight and are easily recognizable as you drive across the east Pilbara region.



Characteristic landforms made by weathering of the cross-cutting dolerite dykes



Stop 1.9 — Overtured bedding

20°54.340'S | 119°46.362'E

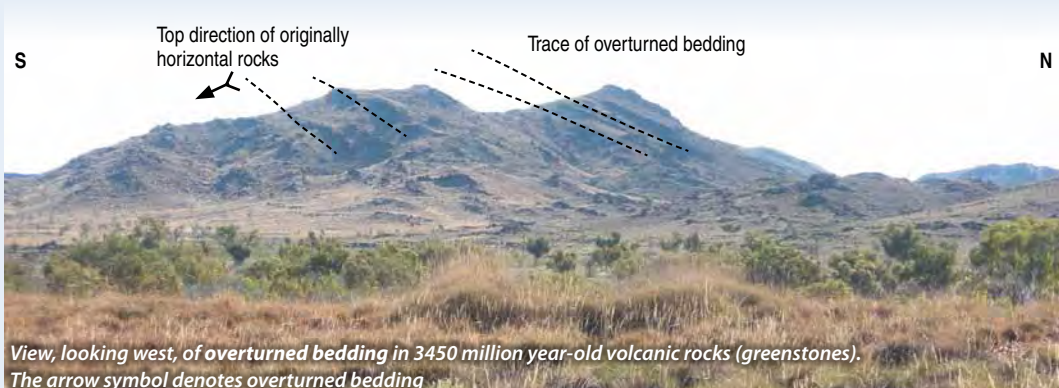
Directions to Stop 1.9: Continue along the Marble Bar Road for a total distance of 31.1 km from the Des Streckfuss rest area, and pull over just past a small creek. Turn right at the track; continue about 200 m to view the next locality (20°54.340'S 119°46.362'E).

What you see here

First, have a look back towards the road (to the north-east), to get a stunning view of another, much larger, dolerite dyke, which makes a knobbly black trail across the landscape. This dyke reappears southwest of Marble Bar as the Black Range, which can be seen in Trail 6.

Striped hills

Looking towards the west, you will see a distinctive striped pattern in low dark hills about one km in the distance that **dips** to the north (to your right). The stripes in the hills represent rocks of different compositions, with the general background rocks representing **basaltic rocks**, and the darker stripes thin ridges of silicified **sedimentary** or **ultramafic** rocks. The striping represents the **bedding** that was originally horizontal when the rocks were first deposited on the Earth's surface about 3450 million years ago. The gradual rise (over hundreds of millions of years!) of the Muccan **Granitic Complex** to the north (see Stop 1.7) has first tilted these rocks to vertical and then **overtured** them, so that the tops of the beds in these hills now face to the south, into the ground. This dramatic feature of the geology gives a good sense of the **tectonic** forces involved in the formation of this piece of **crust** so long ago.



View, looking west, of overturned bedding in 3450 million year-old volcanic rocks (greenstones). The arrow symbol denotes overturned bedding



Stop 1.10 — Doolena Gap

20°55.525'S | 119°47.127'E

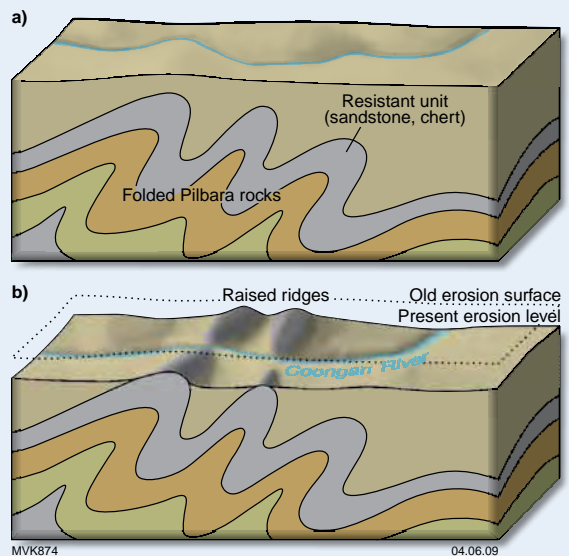
Directions to Stop 1.10: Retrace your tracks to the Marble Bar Road, turn right and continue southeast for 1.4 km. Take the dirt track on the right (20°54.827'S 119°46.979'E) and meander along the western bank of the Coongan River for 1.3 km, past steep cliffs, to Doolena Gap (20°55.525'S 119°47.127'E).

What you see here

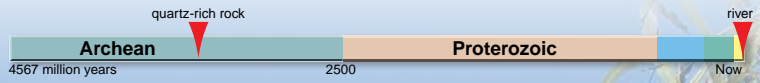
At this locality, the Coongan River flows northwards through a resistant ridge made of 3400 million year-old **quartz-rich sedimentary rocks** named the Strelley Pool Formation. The Strelley Pool Formation **unconformably** overlies the older, bedded **volcanic rocks** of the last Stop, but has also been steeply **tilted** during ancient episodes of **deformation**.

A narrow gorge

During flooding events, the Coongan River becomes constricted between the steep sides of the Gorge Range and sets up turbulent backflow on the down-stream (north) side of the ridge, resulting in a slightly deeper channel that retains water throughout most of the dry season. In fact, although most of the rivers in the east Pilbara region are dry at the surface, water continues to flow beneath the river beds, sometimes only a few metres below ground.



Sketch showing the stages in the formation of the Doolena Gap:
a) erosion commences with a small stream;
b) uplift of the rocky plateau causes further erosion. The more resistant rocks erode more slowly and remain as standing ridges



The ridge of resistant quartz-rich sedimentary rocks cut by the Coongan River forms the Doolena Gap. The pool is a permanent rock pool in the Coongan River



Stop 1.11 — Rocks from an ancient giant volcano

20°56.894'S | 119°49.520'E

Directions to Stop 1.11: Return to the Marble Bar Road. Reset the trip meter to 0.0 km. Turn right and head towards Marble Bar. You will be driving through greenstone ranges, with pillow basalts on either side of the road. Once through the ranges, at 7.4 km, turn right onto a small dirt track (20°56.424'S 119°50.229'E). Follow the track, heading southwest and keeping right, for 1.6 km through a right and a left turn. Just past the left turn, pull over and walk to a small hill on the right, just next to the track (20°56.894'S 119°49.520'E).

What you see here

The rock in this hill is a **volcanic conglomerate**, made up of coarse, rounded blocks and pieces of a variety of volcanic rocks set in **volcanic ash**, all **erupted** from a huge volcano some 3470 million years ago (much larger than the 1980 Mount St Helens eruption, in the USA) .

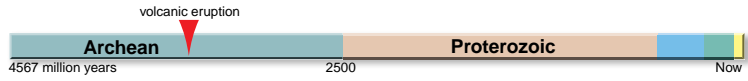
You are near a volcanic vent

At this point, you are standing in the middle of an 8 km-thick **succession** of **dacite**, belonging to the Duffer Formation, one of the main units of the **Pilbara Supergroup**. It is a key **tectonic** indicator for the geological evolution of this area. The thickness of the rocks here, combined with evidence for **faults** bounding the **formation** to the south and north of this locality, indicate that these rocks were **deposited** in a basin, most likely a volcanic **caldera**, when the rocks were being erupted. The coarse nature of the blocks in this outcrop, and through much of the 8-km thickness of this unit, indicates that the eruptive vent of the volcano was nearby.

You can see more of the Duffer Formation at the start of Trail 2.



A large eruption of an active volcano (Mount St Helens): ash and fragments flow down the side of the mountain, and ash is erupted high up into the air. Photo courtesy of USGS



Close-up view of the volcanic conglomerate, showing blocks and pieces of rock ejected from the volcano welded together by fine-grained volcanic ash. Several fragments are outlined



*Sketch: showing the remnant of a volcano, called a **caldera**, after the top of the volcano has been blown apart by a major eruption. Steam issuing from the floor of the caldera shows that hot magma lies just below the surface*



Stop 1.12 — The Sisters and Mount Edgar Granitic Complex

21°03.391'S | 119°51.220'E

Directions to Stop 1.12: Return to the Marble Bar Road. Turn right, heading south towards Marble Bar. Continue for 17 km until you see a ridge of white-capped hills on your right (21°03.391'S 119°51.220'E). Pull over with care, well off the road, as road trains commonly pass by.

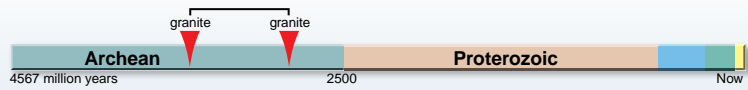
What you see here

The white-capped hills on the right-hand (west) side of the road are called The Sisters. They are made of white **quartz** that was intruded as a thick **vein** system along a **fault** that encircles the Mount Edgar **Granitic Complex**.

Could there be gold in the quartz?

Such **quartz veins** are quite common along faults and represent the effects of relatively late upper crustal movement in structures that originate from much deeper in the **crust**. Fault structures filled with quartz veins commonly host **gold mineralization**, because they provide channels for mineralizing fluids to move through the crust. Gold is carried in **solution** in these fluids and **precipitates** out when rapid fault movement releases pressure and the fluids instantly freeze and **crystallize** in place. Gold is generally present at very low concentrations, but as the fluids in the veins pass through the rocks they scavenge the gold and it is precipitated in the veins, and along vein contacts with the surrounding rock.





View to the distant greenstone mountains

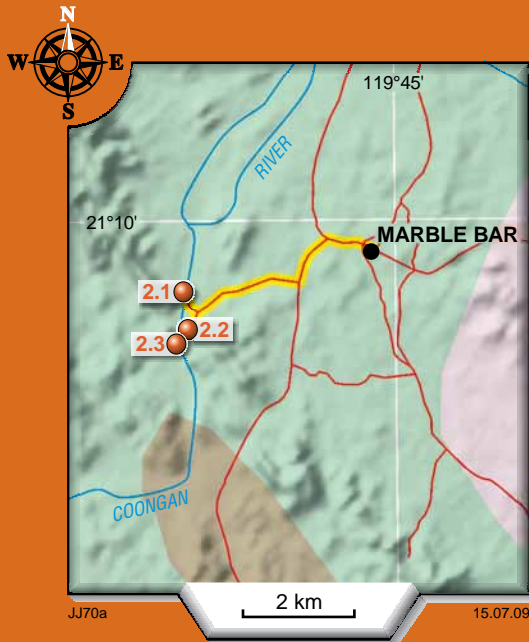
The view across the road to the east looks right across the Mount Edgar Granitic Complex (see panorama), which is a 60 km-diameter, broadly circular dome of granitic rocks that were **emplaced** into the upper crust as a result of a long series of **deformation** events, commencing about 3470 million years ago and continuing until 2630 million years ago. Several different pulses of **granitic magma** (at 3470 Ma, 3300 Ma, 3240 Ma, and 2830 Ma) make up the Mount Edgar Granitic Complex.

Return to your car, and continue towards Marble Bar. At 18.3 km, notice in front of you and curving off into the distance to the left, the Warrawoona Range, made up of volcanic and sedimentary rocks uplifted and tilted to the south (away from the Mount Edgar Granitic Complex) during the ballooning and uplift of the granite (noted earlier). We will travel into the heart of the Warrawoona Range in Trail 3.

This is the last Stop on Trail 1. Continue to Marble Bar.



Looking south across the flat 'downs' of the Mount Edgar Granitic Complex to the Warrawoona Range of tilted greenstones



●	MARBLE BAR	km	0
●	2.1 A volcanic breccia at Chinaman Pool		4
●	2.2 Pillow basalt		4
●	2.3 The Marble Bar		5



See inside front cover for map legend

Travelling Trail 2

Around ‘the Bar’

This Trail stays within a short distance of the town of Marble Bar, visiting Chinaman Pool and the famous Marble Bar. The first two Stops show a cross section up through a 3500 million year-old piece of the sea floor, now tilted on edge — and indeed up, and over, its edge — by the effects of granite doming about 3400 to 2700 million years ago. A visit to ‘the Bar’ just on dusk is a breathtaking experience.





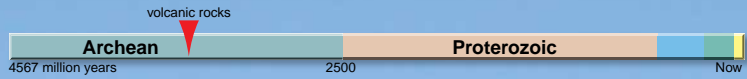
Stop 2.1 — A volcanic breccia at Chinaman Pool

21°10.678'S | 119°42.788'E

Directions to Stop 2.1: Set the trip meter at 0.0 km at the Ironclad Hotel (21°10.286'S 119°44.671'E), and head west for about 900 m through town along the main street, past the government buildings on your left (constructed in 1896), up and over a small rise and turn left at the sign pointing to Marble Bar Pool. Continue for about 900 m along the paved road, then turn right to Chinaman Pool and Marble Bar Pool. Follow this road for about two km, through the first range of orange hills, taking the sharp turn to the left and turning immediately right onto a dirt track leading to Chinaman Pool. Follow the track down to the river and as far along to the right as you can go, until the road loops back. Park the car and walk parallel to the riverbank (heading north) for a few metres to a large, low outcrop of rock (21°10.678'S 119°42.788'E).



Close-up view of the volcanic breccia showing rounded and angular fragments (clasts) within a matrix originally of fine-grained ash. Note the large clast of red chert



Enjoy the view!

The large exposure of rock here is made up of **felsic volcanic** and **volcaniclastic** rocks. This **formation** is very thick — up to 8 km — in this area, and consists largely of coarse **conglomerate** and **breccia**, rocks which formed as a direct result of volcanic **eruptions** between 3474 and 3463 million years ago. Imagine a gigantic volcano, 8 km high (almost as high as Mount Everest), which is spewing out a mixture of gas, ash, and rock fragments, all dumped onto the flanks of the volcano.

What you see here

The rock at this locality contains well-rounded to sub-angular boulders, cobbles, and pebbles

of felsic volcanic rock within a finer grained **matrix** of **felsic ash** and other fine **volcanic** material (see close-up view, left). Less common are more angular **clasts** (pebbles) of banded red-and-white **chert**, similar to the Marble Bar Chert (Stop 2.3), but derived from an even older unit of chert not visible at this locality. **Bedding** is poor, in part because of the coarse nature of the deposit, which was probably **deposited** quickly in response to a sudden **debris flow** following or accompanying an eruption. This rock type is typical of **pyroclastic flows** deposited on the flanks of a **stratovolcano** after a violent eruption — for example the Mount St Helens (USA) eruption of 1980 that blew away the top part of the volcano.



Stop 2.2 — Pillow basalt

21°11.042'S 119°42.831'E

Directions to Stop 2.2: Return to the car and retrace your route along the dirt track to the paved road. Turn right and follow the road for about 300 m to a small turnoff on the right (21°11.042'S 119°42.831'E). Park the car at the end of this short track.

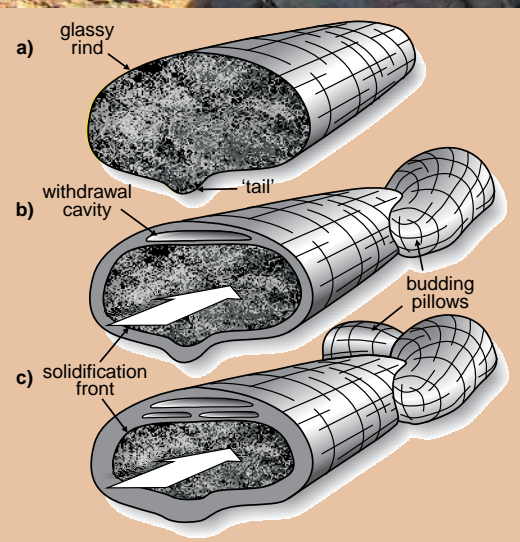
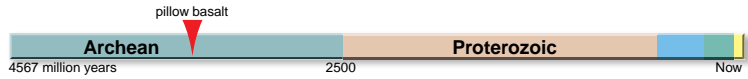


Figure 1 (above): Large oval-shaped pillows, formed originally on the sea floor, are now slightly squashed and misshapen. The rinds or rims are light-green and trace the margins of each pillow; the centres of the pillows have been altered to a mass of overgrown spherules that look like beads, each about 5 to 10 mm across. White arrows outline the main pillow

Figure 2 (left): Sketch showing how pillows form, and how they get their characteristic shapes



What you see here

This large low outcrop in front of you, towards the Coongan River, is an excellent example of **pillow basalt**, a type of **mafic volcanic rock** that was **erupted** under the sea about 3465 million years ago.

The rocks are visible in cross section and display a variety of interesting textures. The largest and most obvious textures are called ‘**pillows**’ — broad, irregular oval shapes defined by slight changes in colour between dark greenish-brown weathering rock, thin rinds of lighter greenish-weathering rock, and irregular-shaped patches of lighter rock with brecciated textures (Fig. 1).

How pillows form

The pillows formed when hot **magma** was erupted under the sea. When the magma enters the water its hot surface instantly cools to form a skin (glassy rind, Fig. 2, part a). Continued magma pressure

forces the magma to extrude out from under the skin, forming a new pillow-shaped bulge at the end of the first pillow (Fig. 2b). Within a short time the magma moves to another locality to form another pillow (Fig. 2c). The areas in between the pillows are filled by shards of broken pillow rims (Figs 3, 4).



Figure 3: Close-up view of the broken volcanic glass shards between the pillows — see if you can find them in the outcrop!

Where was the top?

Pillows form on the sea floor, so their orientation today can indicate to geologists how much the rocks have been tilted. Pillows have a distinct shape, with smooth round tops that form at the free surface interface with water, and more irregular ‘tails’ that fill-in the irregular underlying surface (Fig. 2). Pillows sometimes contain elongate, flat-bottomed internal withdrawal cavities, where magma has passed through on its way to making a new pillow (Figs 2b, 2c). At this outcrop, withdrawal cavities can be seen in some pillows, but these have been filled-in later by white **quartz** brought in by circulating fluids, and the pillows have also been slightly **deformed** into more oval shapes when the rocks were squashed during tilting.

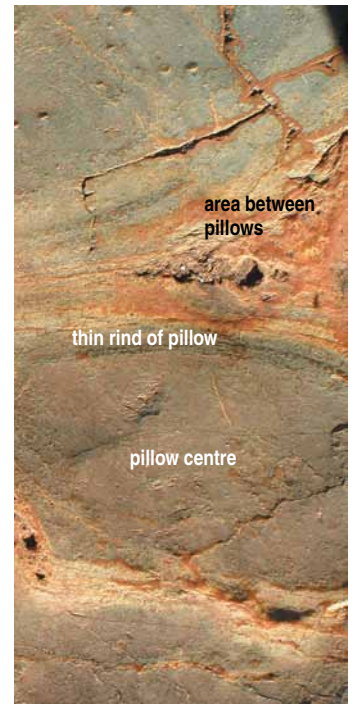


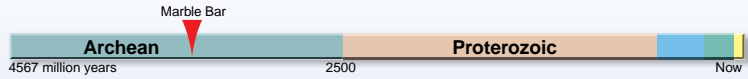
Figure 4: Close-up view of centres, rinds, and interpillow areas



Stop 2.3 — The Marble Bar

21°11.182'S 119°42.710'E

*Note that there
is no collecting
here. Put away
your hammers.*



Directions to Stop 2.3: You can walk across the outcrop to the next locality, following the river for 200 m, or return to your car, drive back to the dirt track, turn right, and drive to the car park at Marble Bar Pool (21°11.182'S 119°42.710'E). This is a lovely spot for a swim and a picnic.

What you see here

This spectacular red, white, and blue-black striped rock is 'the Marble Bar' (locally referred to as 'the Bar'), named by the early pastoralists because they thought it was composed of marble and because it blocked the flow of the Coongan River (literally, a bar); see main photo.

'The Bar'

'The Bar' is part of a **sedimentary** deposit that can be traced for more than a hundred km along **strike**. The prominent **layering** that you can see today (Fig. 1) is **sedimentary bedding** in rocks that were laid down on the sea floor about 3460 million years ago (Fig. 2, part a). However, you will notice that the layering now **dips** steeply to the east-northeast, or under your feet and back towards Marble Bar as you walk towards the river. This steep dip of the bedding reflects the effects of the long geological history of this region — the originally flat-lying rocks have been tilted up on edge and moderately **overturned** as a result of **uplift** and **doming** of the Mount Edgar **Granitic Complex** to the east of Marble Bar (Fig. 2b).



Figure 1: Fine-scale layering of the Marble Bar Chert

The Marble Bar is really jasper

The Marble Bar is not composed of **marble**, but of **jasper** or, more correctly, very fine grained **silica** (SiO_2). The Bar is much harder than the surrounding volcanic rocks and is exceedingly difficult to erode; hence it forms a prominent ridge in the region. The different colours in the rock come from trace amounts of fine-grained mineral impurities, including iron (**hematite**) making the red layers, and **pyrite** and carbonaceous material that makes the blue-black layers. The white layers are pure silica (Fig. 1).

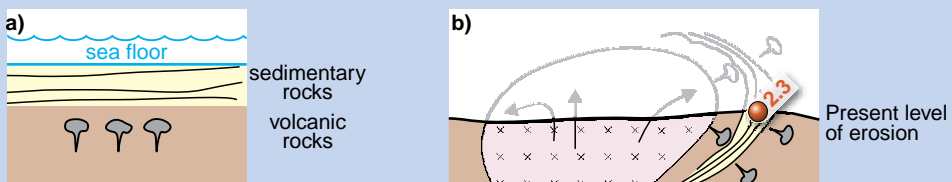


Figure 2: Effects of granite doming: a) sedimentary rocks form on the sea floor; b) much later, doming of the granite tilted and overturned the layers, which is what we view today

Stop 2.3 — ‘the Bar’ (continued)

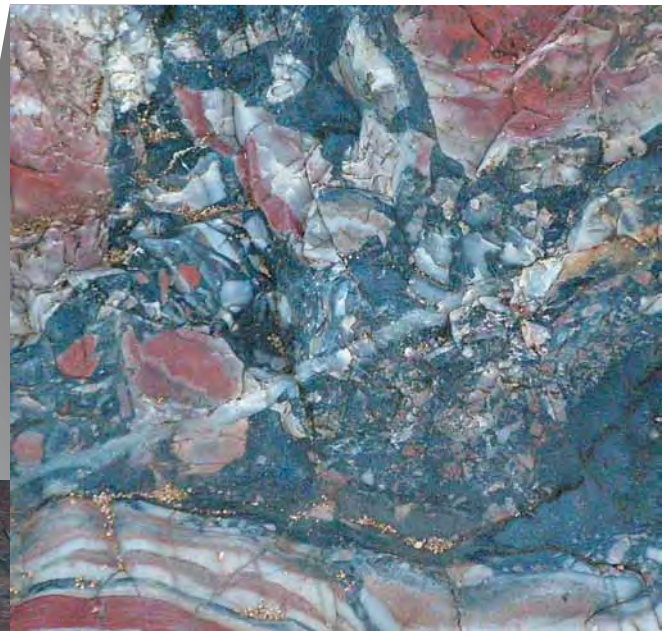
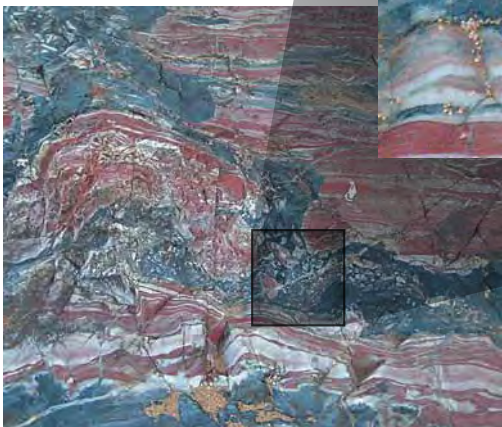
Putting the marble back into ‘the Bar’

In a rather nicely ironic twist, recent studies have found that part of the chert that now makes up the rock was introduced during complete replacement of what was once a fine-grained, slightly iron-bearing **carbonate rock (limestone)**. **Silica** was introduced into the rock dissolved in seawater. This circulated down into the crust and was heated up by **magma**s lower in the crust. The heated waters then moved back up to the surface along a series of **fractures** during episodes of **faulting** (Figs 3, 4).

These fractures can be observed cutting across the layering of the rock throughout the Bar; the fractures are filled by massive blue-black chert that commonly contains angular pieces of the layered chert broken off from the fracture walls (Fig. 3).

Remember to take a bucket to the Bar, to splash water onto the rocks

Figure 3: Blue-black silica breccia vein cutting through layered jasper chert. Veins like this were originally hot fluids that carried dissolved silica, which crystallized from solution when the fluids broke through the layering, boiled, and froze almost instantly



Enlarged photo (above) is of a small portion of the silica breccia vein, showing the broken and jagged jasper fragments

In some layers, fluid pressures were so high that original bedding was completely destroyed. The silica replacement almost completely masks the original rock — limestone. Limestone, when heated and put under pressure, recrystallizes (or metamorphoses) into marble.

So, it turns out that the old-timers were not so wrong after all when they named it the Marble Bar!

This is the end of Trail 2. Return to Marble Bar.

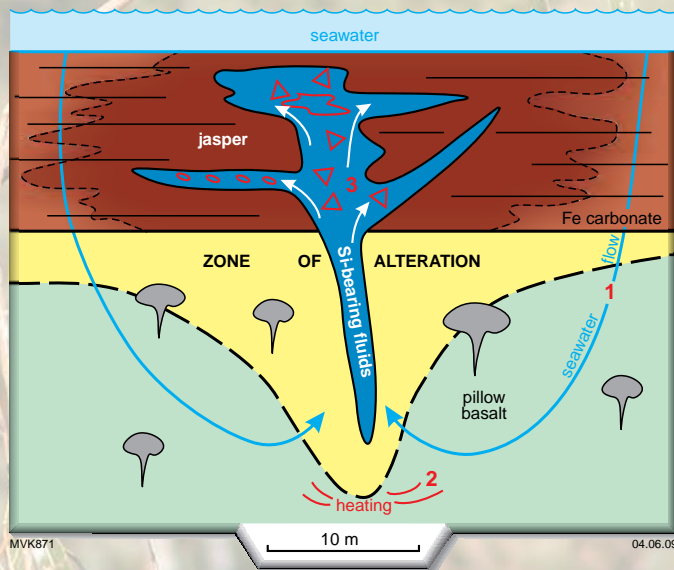





Figure 4: Cross-sectional sketch of the Marble Bar Chert showing:
1) downward-circulating seawater that heats up from below;
2) heated water is forced back up to the surface along fractures cutting through the chert;
3) as the rock fractures, silica floods into the fractures



●	MARBLE BAR	km 0
●	3.1 Vista to greenstones	12
●	3.2 Vista: oblique deformation in the Warrawoona Syncline	17
		
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Travelling Trail 3

Marble Bar to Corunna Downs

This trip is a neat half-day journey right across a greenstone belt, showing how the greenstones have been squeezed by the rising granites on both the north and south sides of the belt. The old Warrawoona Mining Centre is an interesting diversion, and the former Corunna Downs air base offers a little-known fragment of Western Australian history.





Stop 3.1 — Vista to greenstones

21°15.416'S | 119°47.878'E

Directions to Stop 3.1: Set trip meter to 0.0 km at the Ironclad Hotel. Drive east along Francis Street, out of town towards Port Hedland, for about 1 km. Then, just past a fence line, turn right onto the Corunna Downs Road (21°10.516'S 119°45.159'E), following the sign to the old Corunna Downs air base (about 58 km with diversions).

Old stone walls

At 0.6 km along the Corunna Downs Road, observe the stone walls built by the old miners. Then, as you come over a rise, you will see the Warrawoona Range appear in front of you, curving around to the left. This range is underlain by the continuation of the Duffer Formation (from Stop 2.1), including the Marble Bar Chert (Stop 2.3), as well as other volcanic and sedimentary rocks that are more resistant to weathering than the surrounding granitic rocks, which have weathered away to form the flat plains.

You are driving deep into the Earth's crust

As you continue south towards Corunna Downs, you are effectively driving deeper into the Earth's **crust** as it was over 3000 million years ago. From the well-preserved rocks seen at Marble Bar and Chinaman Pools you are moving into depths where the same sorts of rocks were squeezed and heated to form **metamorphic 'schists'**. These metamorphosed volcanic and sedimentary rocks (called **greenstones**) become more and more **deformed** as they become pinched between two very large **domes** of granite — the Mount Edgar **Granitic Complex** over which you have driven, and the Corunna Downs Granitic Complex (Stop 3.7) on the other side of the ranges.

Continue on for 11.1 km to a low rise (21°15.416'S 119°47.878'E).

Tilted rocks

The orange hills to the right and in front of you at this locality (Fig. 1) show tilted **bedding** — geologists call this **dipping** — and the rocks are dipping away from you to the right. The beds were originally horizontal (Fig. 2, part a), but they have been tilted up by the force of the **intrusion** of the adjacent **granites** (Fig. 2b shows how the volcanic rocks are dipping today).



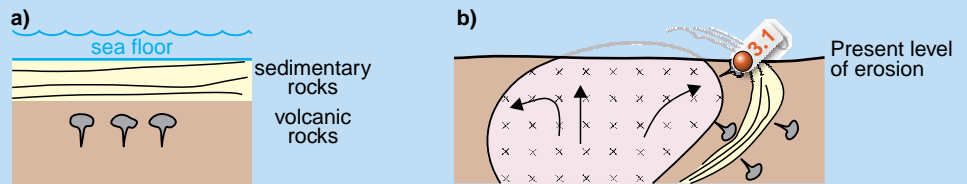
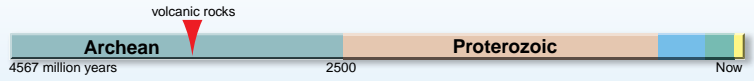


Figure 2: Formerly flat-lying rocks are now tilted
 a) sedimentary and volcanic rocks laid down horizontally;
 b) now tilted and metamorphosed by the force of the upwelling granite

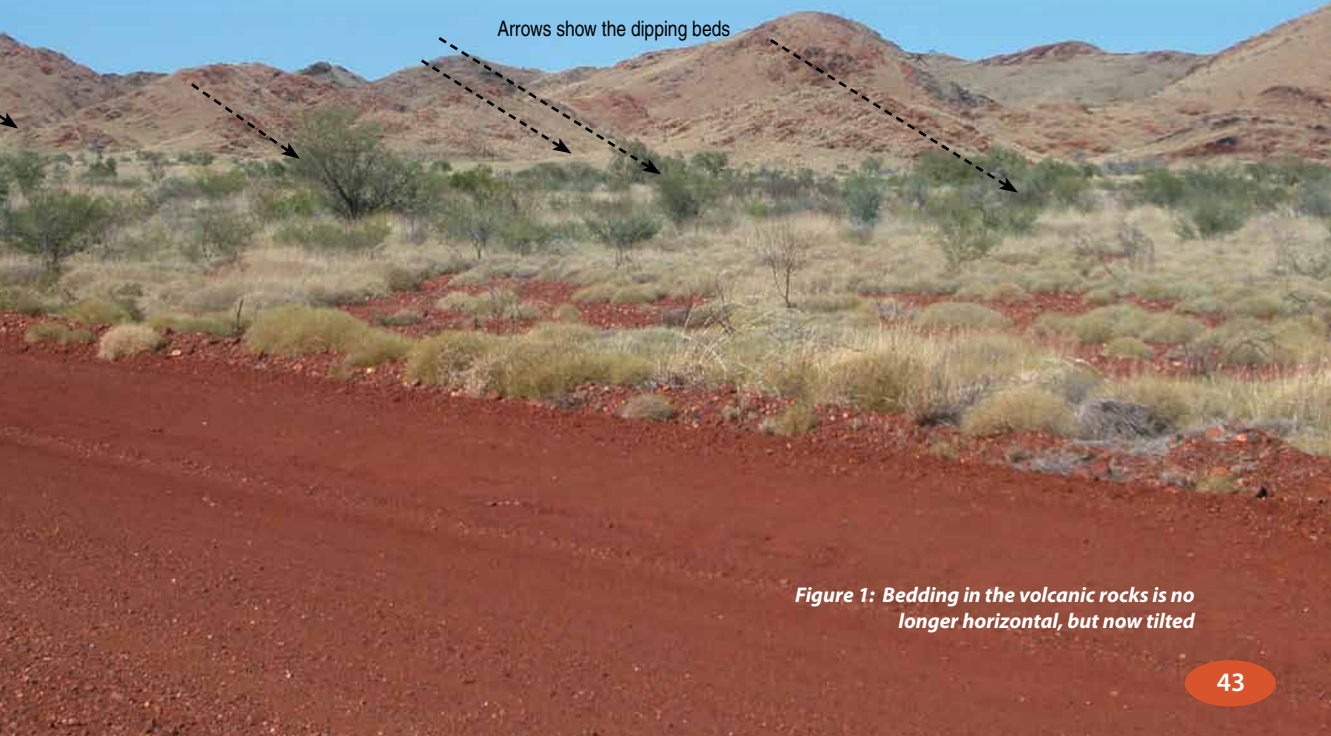


Figure 1: Bedding in the volcanic rocks is no longer horizontal, but now tilted



Stop 3.2 — Vista: oblique deformation in the Warrawoona Syncline

21°17.948'S | 119°48.046'E

Directions to Stop 3.2: Continue on for 6 km and stop at the high cliff face (21°17.948'S 119°48.046'E).

What you see here

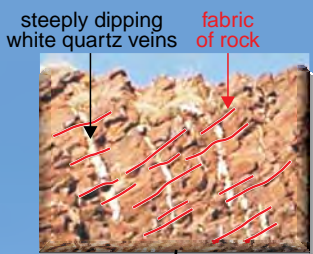
The high cliff face in front of you at this locality contains a number of different, strongly **deformed** rock types. At the base are **chlorite schists**, formed by the **metamorphism** of **pillow basalts** such as those at Stop 2.2. However, at this Stop **deformation** has completely **sheared** out all of the original rock **textures**, and heat and pressure have caused the rocks to **recrystallize** to an assemblage of fine-grained **metamorphic** minerals. These metamorphic changes did not occur at the surface of the Earth, but at depths of between 5 km and 10 km in the Earth's **crust**. Because these rocks are now visible at the surface of the Earth proves that they have been **uplifted** and deeply eroded over time.

Part way up the cliff are ridges of a more-resistant grey **metachert**, whereas at the top of the cliff is a dark-brown **ultramafic rock** (Fig. 1).

A unique style of deformation

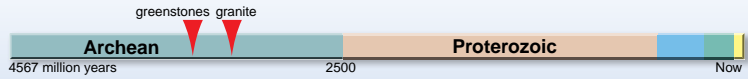
The rocks here mark the start of an unusual style of crustal deformation that no longer occurs on our planet: it is unique to rocks that are older than about 2500 million years. Between here and Stop 3.6, rocks have sunk down deep

Figure 1: Steeply dipping white quartz veins contrast with the dark-brown ultramafic rocks; the veins are perpendicular to the fabric of the rock



Dark-brown ultramafic rocks

Grey metachert



into the crust into a vertical zone of sinking between rising **granitic domes** (Fig. 2). At this locality, you are standing at the edge of that zone, where the rocks are just starting to be inclined towards that vertical zone located some 5 km to the east (see Stop 3.6).

Can you see two features in the cliff?

- at the top of the cliff (Fig. 1) can you see a set of **quartz veins** (white lines) cutting through the rocks at 90° to the **fabric** of the rock, and **dipping** steeply to the west. These **veins** formed when the stiff **ultramafic** rocks were stretched too far and broke apart as they were brought towards the surface and cooled, allowing **silica** to flood into the cracks to form the quartz veins;
- a second, very subtle, feature is that all the minerals in the rocks, and folds of layering in the chert are elongated towards the east. They plunge into the hill at about 20° from the horizontal, perpendicular to the quartz veins. You can see this **fabric** in the chlorite schist and grey **metachert**.

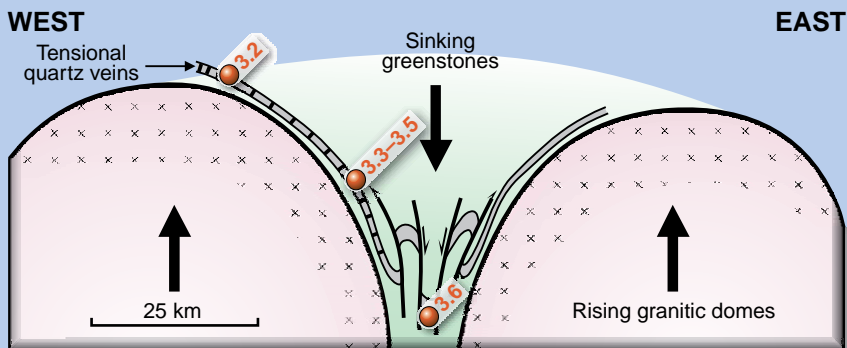


Figure 2: This diagram shows how the rock structures seen at Stops 3.2 through to 3.6 formed — through the sinking of dense, thick greenstones into underlying more buoyant granite. Sinking of the greenstones was made easier by partial melting of the granites



Stop 3.3 — Vertically plunging schists

21°19.301'S | 119°50.725'E

Directions to Stop 3.3: Continue along the Corunna Downs Road. Note at 18.2 km (21°18.216'S 119°48.625'E) the waste dump from the first of many small gold mines along the Warrawoona Range. This was the Copenhagen mine.

Linear structures in the rocks (the **fabric**) high on top of the hill still plunge to the west, but more steeply here (at about 35°) than at the previous Stop. The quartz veins are still at right angles (perpendicular) to the rocks. You can also see steeply dipping rocks in the side of the open-cut.

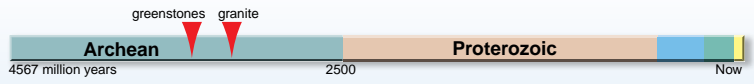
At 22.1 km (21°19.285'S 119°50.226'E) turn left onto a dirt track, marked by a green drum. At 23 km, continue straight ahead through a small creek bed (21°19.280'S 119°50.668'E) for 100 m (21°19.301'S 119°50.725'E). Park the vehicle here.

What you see here

On the right side of the track (Fig. 1) and further up the hill in the distance, near-vertically plunging **schists** look very spiky, like spinifex grass or long spindles. As at the last Stop, this texture is due to the vertical stretching of the rocks as they sank down deep into the **crust**. If you look at the higher hills in the distance to the south, the white quartz veins are now almost flat-lying, but they still remain perpendicular to the **fabric** of the rocks (Fig. 2).



Figure 1: Vertically plunging schists



White quartz veins are now almost flat-lying



Figure 2: White quartz veins are now nearly flat-lying, but are still perpendicular to the rock fabric



Stop 3.4 — Klondyke Boulder mine and ruins

21°19.951'S | 119°52.865'E

From here, the track to Stops 3.4 and 3.5 is very rough and has some deep rocky gullies to negotiate; it is only suitable for 4WD vehicles.

Directions to Stop 3.4: Continue east along the track. At 27.8 km (21°20.219'S 119°52.942'E), turn left. After about 100 m take the left-hand track, and at 28.2 km take the left track again (21°20.046'S 119°53.005'E), and stay on the left track towards some old mine workings at 28.4 km. Park at 28.5 km (21°19.951'S 119°52.865'E).

CAUTION: THERE ARE OLD MINE SHAFTS AND OPEN PITS HERE. TAKE GREAT CARE!

What you see here

There are ruins of an old stone and cement building here (Fig. 1), and remnants of shafts, gouges, and small pits. In the 1890s, the old timers were chasing gold in the **quartz veins** in strongly **sheared mica schist** containing fuchsite. Fuchsite is the bright-green, chrome-rich shiny mica mineral that is common here (Fig. 2). Gold was found along the sides of quartz veins that were **emplaced** within the schists during **deformation** about 3300 to 3200 million years ago. If you (with care) have a look at some of the shafts, you can see the quartz veins that the miners were following and mining. Also in the vicinity is the casing to more-recent drill holes, the bagged samples laid out neatly next to the hole they came from. This ground is currently under lease, so removal of samples by visitors is not permitted.



Figure 1: Mining ruins

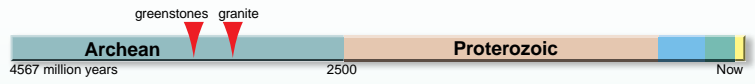


Figure 2: Large boulder of fuchsite schist. The green fuchsite looks as if it has been smeared over the rock



Figure 3: Old house of stone 'logs' abutting the strongly deformed schists



Stop 3.5 — Klondyke Queen mine

21°20.146'S | 119°53.268'E

Directions to Stop 3.5: Backtrack until you get to the old ruins marked by rusted barrels and the partial wall of a building at 29.1 km (21°20.190'S 119°52.986'E). Turn sharply left. Continue on to 29.5 km (21°20.246'S 119°53.161'E). Take the track to the left, then turn left after 100 m, cross the creek, and take a sharp left turn. At 29.8 km (21°20.146'S 119°53.268'E) park the vehicle.

What you see here

Explore! This old mining area is full of surprises. There is an old boiler close to one of the shafts (Fig. 1), a locked tunnel, and long costeans (or trenches) down the side of the hill where the old miners traced gold in **quartz veins**. Above the entrance to the main tunnel are several thin quartz veins within **sheared schists** (Fig. 2).

Devil's dice and Liesegang rings

Along the walls of the tunnel entrance, you can see black cubic **pyrite crystals** that the old timers called 'devil's dice' and used as a tracer for gold (Fig. 3). You can also see fibrous quartz growing around some of the pyrite cubes, showing how rocks **recrystallize** and mineral-bearing fluids become mobile within highly sheared schists.

Liesegang rings are also evident on the wall of the tunnel. These ring-like structures of alternating light and dark-brown bands derive from recent weathering of the rocks, when rainwater percolates through the soft porous rock and transports dissolved iron, which then **precipitates** within the rock as a series of rings (Fig. 4).



Figure 1: Long-abandoned machinery. Local stone was used to eke out the precious concrete for the footings for local buildings

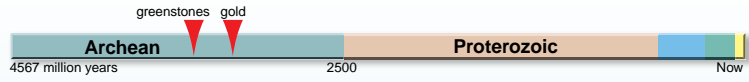


Figure 2: Gold-bearing quartz veins in sheared schists at the entrance to the locked tunnel



Figure 4: Brown and white Liesegang rings in the wall of the tunnel. Lens cap for scale

Figure 3: Close-up view of black pyrite cubes (called 'devil's dice') embedded in the entrance wall to the tunnel



Stop 3.6 — Centre of Warrawoona Syncline

21°19.520'S | 119°50.400'E

Directions to Stop 3.6: Retrace your route to the main Corunna Downs Road, a total distance of 36.1 km from the start of the Trail. Once back on the road, reset the trip meter to 0.0 km. Continue south for 0.5 km to the base of a small round hill at a curve in the road. Park well off the road.

What you see here

Climb the small hill on the left to look at vertically plunging, **lineated schists** in the centre of the vertical zone of sinking (Fig. 1, opposite). The rocks are highly siliceous or silica-rich (they are **metamorphosed felsic volcanic rocks**) and a band of **chert** occupies the high centre point of the hill.

A rare spectacle

This type of structure — of vertically plunging rods of highly **deformed** rocks — is found in only a few places in the world, and indicates vertical downward transport of the rocks within a **deformation** regime of constriction from all sides; much like squeezing toothpaste from a tube, as it points downward (Fig. 2, below).

The map at the beginning of Trail 3 nicely shows the **greenstones** at Stop 3.6 being caught between the northern Mount Edgar **Granitic Complex** and the southern Corunna Downs Granitic Complex.

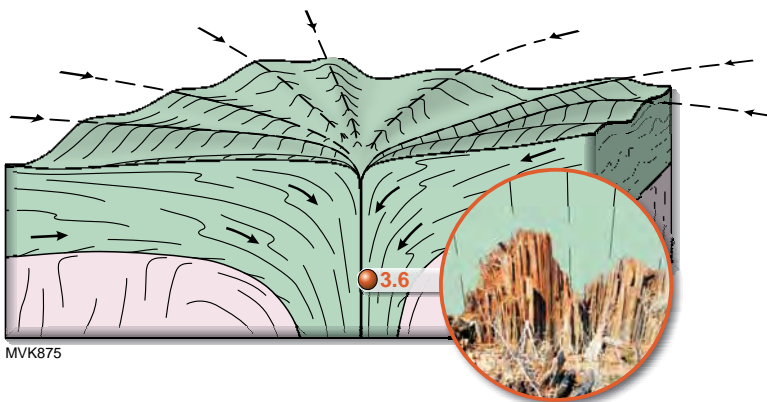


Figure 2: The greenstones are being drawn down and squeezed between two upwelling granites

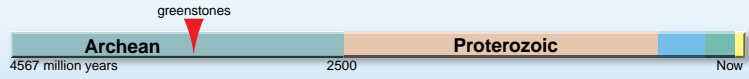


Figure 1: Vertically plunging rods of silica-rich metamorphic rocks indicate the centre of the syncline. Knocking two of these rods together makes a strong 'chinking' sound, characteristic of hard, highly siliceous rocks



Stop 3.7 — Corunna Downs Granitic Complex

21°20.654'S | 119°51.420'E

Directions to Stop 3.7: Continue southeast along the Corunna Downs Road. From this point on, we are now on the other side of the ranges of the greenstone belt, heading out towards Corunna Downs (see map for Trail 3). The rocks quickly become less deformed. At 2.4 km (21°20.680'S 119°50.515'E) turn left, just after a cattle grid. Continue along this track for 1.7 km, and park near a group of light-orange boulders (21°20.654'S 119°51.420'E).

What you see here

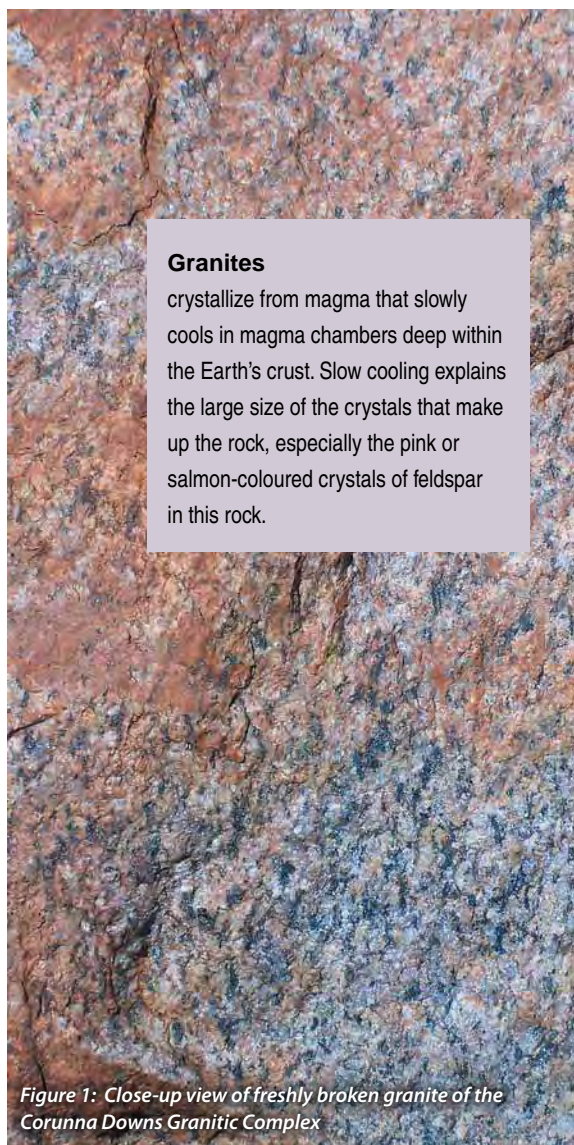
You are now sitting on the flat 'downs' of the Corunna Downs **Granitic Complex**, which is about 60 km across. On the far horizon on your left and right and arcing all the way round are the **greenstone** ranges. On a clear day you can see the entire encircling **greenstone belt**.

Crack open a rock

The Corunna Downs Granitic Complex consists almost entirely of granitic rocks 3310 million years old — still showing their original **igneous textures**, including large **feldspar** crystals (Fig. 1). If you crack open one of the brown boulders found here, inside you will see it is a typical grey speckled granite containing the minerals **quartz**, **feldspar**, and **biotite**, and looking quite different from the brown, drab rock visible on the outside (Fig. 2). The brown boulders result from weathering over millions of years. The sketch in Figure 3 shows how the boulders form.

A contact

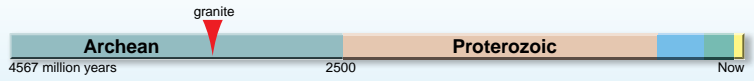
At the base of the hill (through the fence), you may be able to make out the **granite–greenstone contact**, where granitic rocks were **intruded** into the older greenstones. A structural **fabric** in the granites is related to their **uplift**, but it is much milder here than in the Mount Edgar Granitic Complex to the north, showing just how greatly geological systems can vary, even over short distances.



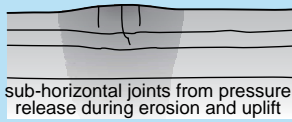
Granites

crystallize from magma that slowly cools in magma chambers deep within the Earth's crust. Slow cooling explains the large size of the crystals that make up the rock, especially the pink or salmon-coloured crystals of feldspar in this rock.

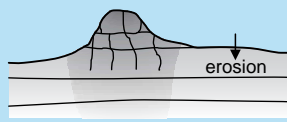
Figure 1: Close-up view of freshly broken granite of the Corunna Downs Granitic Complex



a) Old erosion surface



b) Vertical joints during erosion



c) Spheroidal weathering along joints

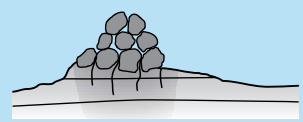


Figure 3: Sketch showing how round boulders of granite are formed

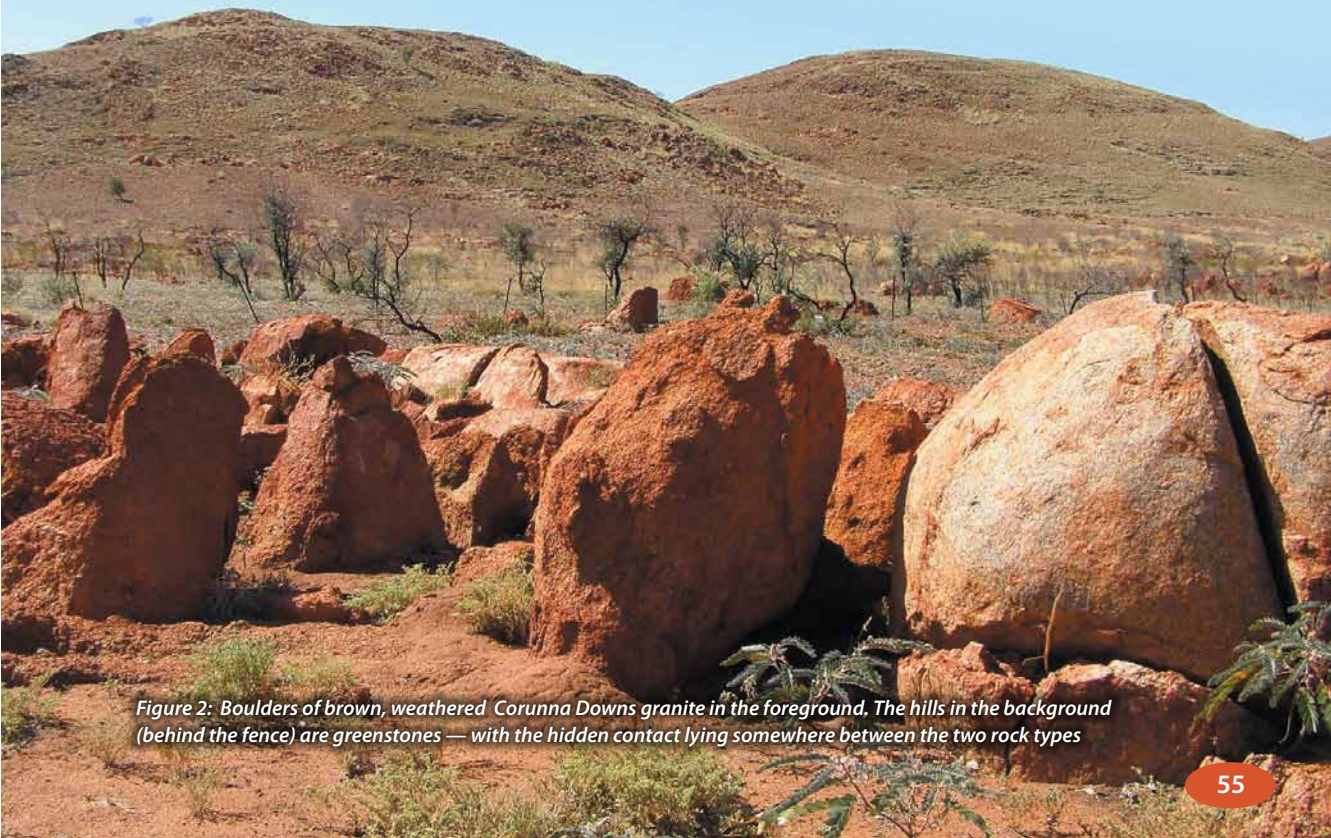


Figure 2: Boulders of brown, weathered Corunna Downs granite in the foreground. The hills in the background (behind the fence) are greenstones — with the hidden contact lying somewhere between the two rock types



Stop 3.8 — Runway, Corunna Downs air base

21°25.929'S | 119°46.721'E

Directions to Stop 3.8: Return to the main road and turn left towards Corunna Downs. After 4.5 km (21°22.486'S 119°48.869'E) follow the sign and turn right towards the old air base. Passing a black ridge formed by a dolerite dyke, the track traverses a gap in two hills of dolerite-capped granite. At 6.3 km (21°22.760'S 119°48.165'E) dolerite intrudes the Corunna Downs granite: see if you can recognize the two different rock types. Continue on to 13.0 km (21°25.929'S 119°46.721'E).

A secret air base

You are driving through the now-abandoned Corunna Downs air base. It was the most remote and secret of Australia's defence airfields during the Second World War. From this remote plain, the 380th United States Army Air Force Bomber Group and the RAAF No. 25 Squadron flew bombing sorties to blast Japanese bases in Indonesia, and harass Japanese shipping moving supplies and troops. It was far from the coast and considered to be safe from Japanese sorties over Australian soil.

Runways and scrap iron

The No. 73 Operational Base Unit at Corunna Downs once had all the facilities of a bustling air base, but today foundations, scattered debris, a loading ramp, and revetments (or barricades) are all that remain. The intersecting, flat runways can still be discerned, formed apparently of bitumen on a crushed granite base. There were two runways: one running approximately east–west about 2300 m long, the other running north–south about 1700 m long, with a 20-m wide taxiway linking them. Some 20 camouflaged revetments (to disperse aircraft and minimize bomb damage) were constructed at Corunna Downs.

Flat granites make good runways

Weathering of the **granite** has resulted in very flat topography, and this was a critical factor in the location of this remote air base. Explore around the runways. **Dolerite dykes** abound around the margins of the area — the dykes are sinuous ridges or hills with blackish-brown rubble tumbling down their sides. At 13.6 km (21°26.238'S 119°46.721'E) are the remnants of the main buildings.

The Coongan River about a kilometre further along the track makes a nice shady lunch stop.

This ends Trail 3. Travel back to Marble Bar.

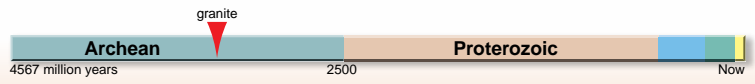


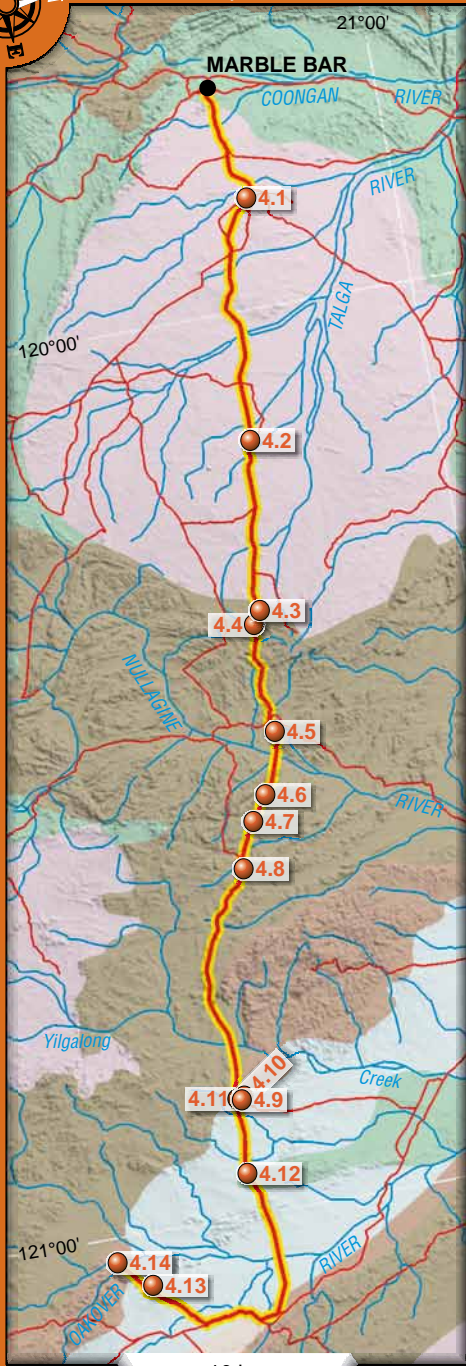
Figure 1 (top): Huts and tents at the air base, 1942

Figure 2: 1943, view past the 'Black Swan' Liberators, across the Corunna Downs Granitic Complex, towards the encircling greenstone mountains

(Photos courtesy of Aviation Heritage Museum of Western Australia, Bullcreek)



NOTE: Journey is west to east



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	km
● MARBLE BAR	0
● 4.1 Moolyella tin workings	15
● 4.2 Mount Edgar Granitic Complex	45
	
● 4.3 Granite–greenstones	66
● 4.4 Ignimbrite	68
	
● 4.5 Conglomerate	81
● 4.6 Limestone bed with stromatolites	89
● 4.7 Roadside cutting, Kylenea Basalt	93
● 4.8 Vista to stromatolites	99
● 4.9 Glacial valley	128
● 4.10 Meteorite impact breccia	129
● 4.11 Glacial erratics	129
● 4.12 Ancient lake deposits	138
	
● 4.13 Polished glacial pavement	183
● 4.14 Carawine Pool	188

See inside front cover for map legend

Travelling Trail 4

Marble Bar to Carawine Pool

Trail 4 is a comfortable day trip, but the addition of an overnight camp at the scenic oasis of Carawine Pool makes it a memorable journey. The flat expanse of the Mount Edgar Granitic Complex is traversed first, then some spectacular ancient rocks are exposed in roadside cuttings. Young glacial deposits at the end of the trail bring a nice symmetry to this geological journey.

NOTE THAT THERE IS NO FUEL AVAILABLE ALONG THIS TRAIL, AND WATER SUPPLIES ARE LIMITED TO SEASONAL POOLS. YOU NEED TO BE SELF-SUFFICIENT.





Stop 4.1 — Moolyella tin workings

21°09.161'S | 119°52.529'E

Directions to Stop 4.1: Set trip meter to 0.0 km at the Ironclad Hotel. Head east out of town, towards Port Hedland. At 8.6 km (21°09.795'S 119°49.240'E), turn right onto the Nullagine–Telfer–Newman Road. Reset trip meter to 0.0 km. Watch out for stray cattle on the road.

You are now crossing the Mount Edgar **Granitic Complex**, with broad low **outcrops** and remnant boulders of **granite**. The complex is easy to find on the map for Trail 4 — it is the large pink circular area close to Marble Bar.

At 6.4 km (21°09.161'S 119°52.529'E) pull over to the side of the road.

What you see here

To the north and northeast of the road on your left are the Moolyella **tin** workings. Most mining here was **alluvial** 'dredging' for tin in drainage channels, but there was also one hard-rock mine. The original tin mineralization is associated with a 'young' (relatively, for the Pilbara) **granite** that intruded into the older granites only 2850 million years ago. This young granite forms the hills to the northeast and is fringed by **veins** and **dykes** of a rock called **pegmatite**.

The tin was in the pegmatite

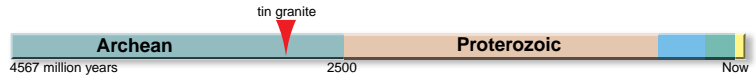
The pegmatite crystallized slowly from metal-rich fluids in the granite and has very large crystals of **feldspar** and **quartz**, and smaller crystals of black **cassiterite** (tin). Over millions of years the pegmatites were broken down by **weathering** to release the crystals of tin. Being heavier and harder than the feldspar the tin was naturally concentrated in the creek beds draining the area. Such channel deposits provided miners with most of the tin.



Figure 1: Tin granite at Moolyella. The yellow pen (arrowed) marks the sharp boundary between younger tin granite (top left) and the older granite (bottom)

Tin — a useful metal

Modern-day uses for tin are: for tin-plating (tin cans are made from tin-coated steel), for alloying with other metals for soft solder, for type metal (but that is a dying use), and for making pewter and bronze.



Early discovery of tin

The Moolyella tin field was discovered in 1898, with a reported 76 t of tin concentrate mined that year. Tin was found as the mineral cassiterite, an oxide containing 70% tin metal. The heavy black grains, pebbles, or fragments of cassiterite were easily visible in the greenish-coloured **alluvium** and initially hand-tools or simple concentrating equipment were used. Later mining relied on earth-moving machinery and centralized treatment plants to mine and concentrate the tin (Figs 2, 3). The lake covered with reeds here is the result of damming of the creeks in worked-out areas to ensure a water supply for the treatment plant.



Figure 2: Extensive tin workings at Moolyella in 1971



Figure 3: Looking towards the dam on Moolyella Creek in the middle distance



Stop 4.2 — Mount Edgar Granitic Complex

21°11.636'S 120°08.641'E

Directions to Stop 4.2: At 14 km, continue on the Ripon Hills Road, towards Woodie Woodie and Telfer. At about 19 km, you will get the first glimpses of Mount Edgar to the south of the road, but continue on to 22 km for the best viewing locality (21°11.636'S 120°08.641'E).

What you see here

Here is a typical **outcrop** of the Mount Edgar **Granitic Complex**, which forms the flat ground in this area spreading out in all directions over a distance of about 30 km (see Trail 4 map). The **granite** (actually a granite with a little bit more sodium than normal and therefore a **granodiorite**) has minerals characteristic of granites the world over: white and pink **feldspar** crystals, glassy **quartz**, and **biotite mica** (the black mineral). Faint **igneous layering** gives the rock a striped appearance. The layering formed as the magma flowed into the **magma chamber** from its source deep below. These rocks are 3300 million years old, but are remarkably fresh and similar to rocks much younger, illustrating that the Earth processes making such rocks have not changed since ancient times.

Desert varnish

The hard, shiny brown skins coating the light-grey granite are known as '**desert varnish**' and are peculiar to arid terrains (Fig. 1). No one is sure exactly how the varnish forms, but some researchers suggest that microbes may be involved. The light-grey patches of rock are exposed when hot bushfires sweep through the area and crack the brown outer skins to expose the fresh grey granite beneath. Geologists call this '**spalling**'. Some of the boulders look as if they have been cleaved in two by an axe — another **weathering** feature typical of arid regions, which results from extreme diurnal temperature variations, i.e. very hot days, then temperatures below freezing at night. The variations in temperature cause expansion and contraction of the rock, weakening the rock until it eventually fractures or cracks.

Is this a volcano?

Solitary Mount Edgar rises to the south of the road, looking just like a volcano (Fig. 2). But it is not a volcano. In fact, this small mountain represents the granitic magma chamber *below* the throat of an ancient volcano (now eroded away) that erupted about 1800 million years ago. The **magmatism** was the result of geological events quite far to the east from here, but which caused a small part of the Earth's **mantle** to melt and form this younger granite.

Figure 2: The younger granite making up Mount Edgar has a different composition from the surrounding flat granite 'downs'



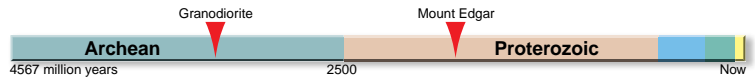


Figure 1: Fresh, grey granite is exposed when the brown desert varnish cracks and spalls off





Stop 4.3 — Granite–greenstones

21°12.952'S 120°20.029'E

Directions to Stop 4.3: Continue east along the road, crossing the Talga River. The boulder-strewn landscape forms the backdrop for some roadside graffiti. Stop at 57.5 km (21°12.952'S 120°20.029'E) and pull over to the side of the road.

What you see here

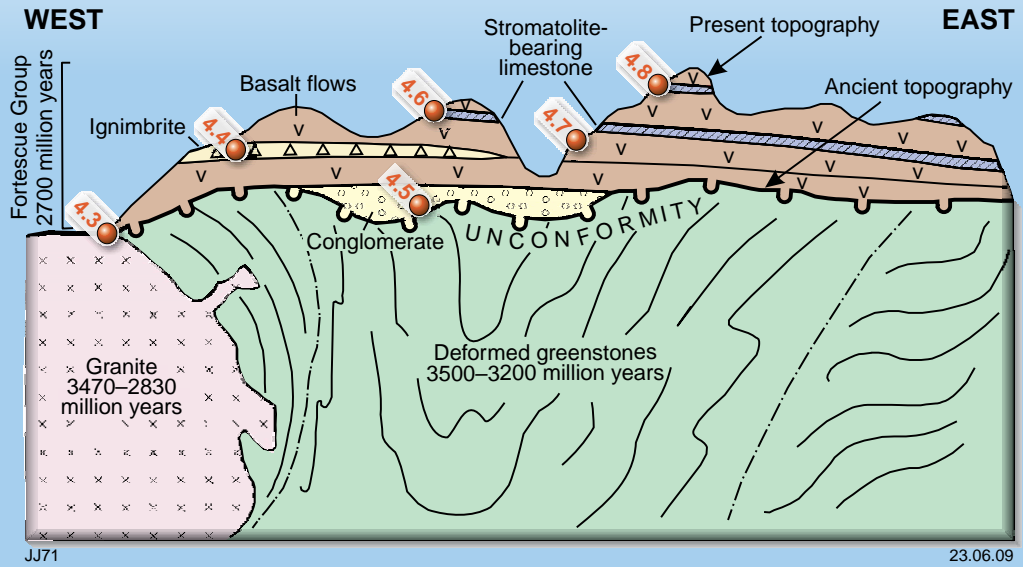
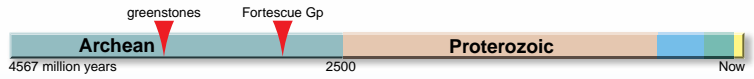
You have now crossed the Mount Edgar **Granitic Complex**, and are starting to climb up into the **greenstone** ridges that flank the eastern edge of the complex (see map of Trail 4). To the right of the road are **granites** with their characteristic orange and brown skins, but to the left are steeply **dipping** dark-brown to black **schists**, derived from **metamorphosed basalts**, of the ancient Warrawoona Group (3500 million years old). Straight ahead are younger rocks making up the Ripon Hills that belong to the 2700 million year-old Fortescue Group. They are only weakly **deformed** and **tilted** by younger **folding** and **faulting**, but otherwise remain pretty much as they formed, so long ago.

The contact between the ancient greenstones and the Fortescue Group is one of the world's best examples of an '**unconformity**'. The surface of the unconformity represents the surface of the Earth 2 800 000 000 years ago.

A marker in Earth's history

In terms of early Earth, the Fortescue Group represents really the first modern-style geological **succession** in the world deposited on a **basement** of thick **continental crust**. It reflects an important transition in Earth history. Elsewhere in the world the rocks that formed at a similar time are now highly **metamorphosed** and strongly deformed, showing that in the ancient past, as in the modern day, different continents have their own unique history.

Photo: Gently-rounded hills show off the flat-lying sedimentary and volcanic rocks of the Fortescue Group (marked in brown, yellow, and blue on the sketch above)



Diagrammatic cross section (not to scale) of some of the Stops along Trail 4, showing the Fortescue Group rocks deposited on an older basement of granites and greenstones across an unconformity surface developed 2700 million years ago





Stop 4.4 — Ignimbrite

21°13.479'S 120°20.907'E

Directions to Stop 4.4: Sweep around the big curve in the road and continue to 59.5 km (2 km). Stop right beside the outcrop on the left-hand side of the road (21°13.479'S 120°20.907'E).

Hidden riches

This pile of white, cream, and brownish rubble at the side of the road looks unremarkable at first glance (Fig. 1). But, if you pick up hand-sized pieces, you will see that each is a little treasure! The rocks are streaky, white, and greenish-black in colour with a little bit of iron staining. This streaky rock goes by the rather grand name of **rheomorphic ignimbrite** — a rock that was made during the **eruption** of **felsic magma** from a large volcano 2760 million years ago.

Volcanic glass

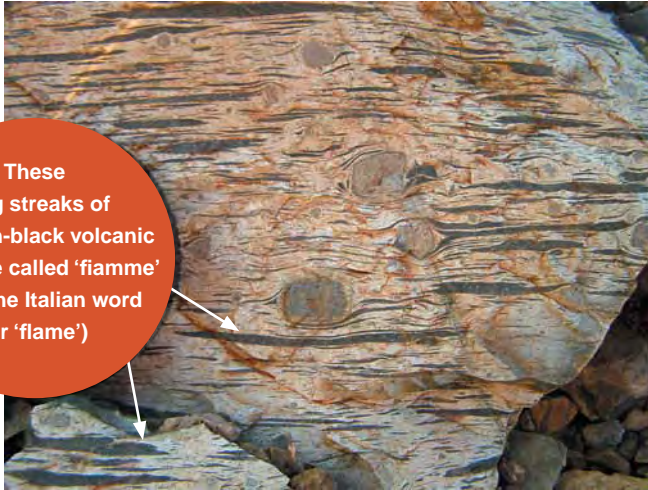
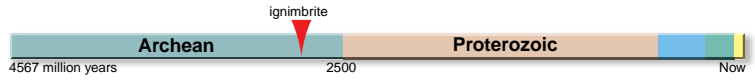
During the eruption, pieces of dark-green **volcanic glass** were thrown high up into the air, together with **crystals** ejected from the **magma chamber** deep in the **crust**, and enveloped in a huge cloud of very fine grained **volcanic ash** (Fig. 2). All of this material fell back down onto the side of the volcano whilst still hot and fused into the rock you see here (Fig. 3). But, as the ash, the glass, and the magma cooled, it started to flow down the side of the volcano and in the process smeared out the dark glassy fragments and rotated the crystals so that in places the rock looks as if it is strongly **deformed** (Fig. 3).



Figure 2: Hot fiery deposits of ash and lava flow down the side of this erupting volcano, producing the same type of deposits that you see at Stop 4.4 — which formed 2700 million years ago. Photo courtesy of Patrick Taschler

Lapilli and fiamme!

If you look closely at the texture, you will see that the dark-green fragments (called **lapilli**) have ragged and pointy edges, which indicate that originally they were hot, glassy fragments spewn out from the volcano into the air. The heat from the volcanic eruption slightly **metamorphosed** the rock so that the glass has **devitrified** to a very fine aggregate of crystals, and the original **matrix** of volcanic ash has fused together into a finely **crystalline** rock. After the ignimbrite formed, it was covered up by younger deposits, then **uplifted**: it has only been exposed to **weathering** in more recent times. This is an example of how weathering of the rock has actually enhanced its texture: you will notice that freshly broken surfaces of the rock are much duller and more homogeneous in colour and are thus more difficult to 'decipher' than the weathered pieces.



These long streaks of greenish-black volcanic glass are called 'fiamme' (from the Italian word for 'flame')

Figure 3: Close-up view shows the green streaks of volcanic glass, and the rotated and dragged crystals as the hot ignimbrite flowed down the side of the volcano. For scale, the lens cap = orange circle



Figure 1: Rubby, unremarkable outcrop right beside the road belies the treasure within



Stop 4.5 — Conglomerate

21°13.397'S 120°28.221'E

Directions to Stop 4.5: Reset trip meter to 0.0 km. Continue on past lower Fortescue Group sedimentary and volcanic rocks (there are thick sandstones deposited by rivers, as well as limestone reefs: they are very widespread units) for 13.7 km. Stop at the roadside cutting on the north (left-hand) side of the road (21°13.397' 120°28.221'E).

What you see here

This road cutting exposes a unit of **sedimentary conglomerate** deposited 2760 million years ago, but looking remarkably fresh for its age. Note the large, very well rounded pebbles, cobbles, and boulders are of different rock types, such as **granite** (light grey) and **vesicular basalt** (green, with round holes) and are set in a fine-grained **matrix**. Some boulders in the conglomerate are up to 30 to 40 cm in diameter (Fig. 1). The conglomerate was deposited in a high-energy stream, or braided stream channel.

Basalt clasts are short-lived

The presence of many basalt **clasts** suggests that the time between the volcanic eruption (to form the basalts), erosion of the basalts, and **deposition** of this rock was not very long. Basalt clasts were easily eroded under the harsh chemical **weathering** conditions that were then present on Earth, when the atmosphere had almost no oxygen (O), but higher carbon dioxide (CO₂), and perhaps even methane (CH₄).

Small faults

The long, flat, steep surfaces at some places in the road cutting are small **faults**; you can see they cut right through some of the pebbles and cobbles of the conglomerate. Some surfaces are smeared with yellowish **calcium carbonate**. These faults are the distant effects of the collision of **tectonic plates** in the distant past, some 1800 million years ago. The effects of this collision become more apparent as you drive further east (and are very well demonstrated in the highly **folded** and faulted rocks in the Rudall River National Park, should you have a chance to go there).

Continue along the road.

Notice that the next road cutting also exposes conglomerate. At this second site, weathering has enhanced the differences between the matrix or background material and the clasts (the boulders and pebbles); and, as well, the clasts are extremely well rounded.

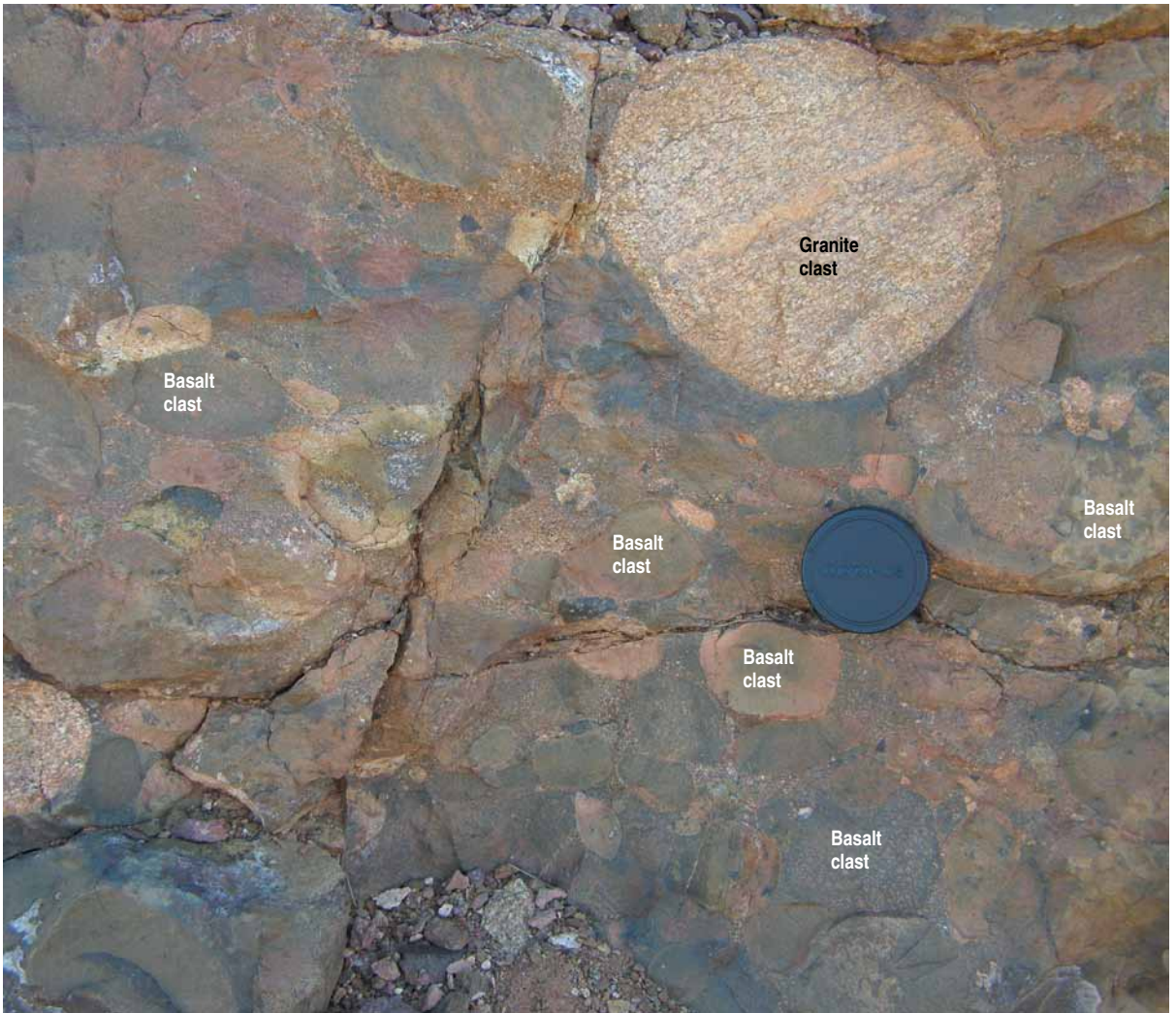
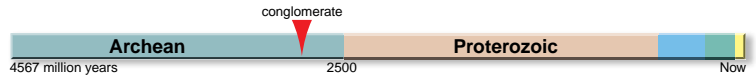


Figure 1: Clasts of granite and basalt set in a fine-grained matrix. Lens cap for scale



Stop 4.6 — Limestone bed with stromatolites

21°14.689'S 120°32.316'E

Directions to Stop 4.6: Continue driving and stop at a distance of 21.5 km from Stop 4.4. Walk across to the outcrop of dark-brown rocks on the south side of the road (21°14.689'S 120°32.316'E).

What you see here

From this locality, looking to the south of the road, notice the prominent horizontal black stripe of rock that meanders across the hills (Fig. 1). This is an **outcrop** of a thin **limestone reef** filled with **stromatolites**, laid down in a shallow sea 2740 million years ago, during a **hiatus** in volcanism.

Ancient life

Stromatolites of this age were once regarded as the oldest-known life forms on Earth and were used to illustrate the antiquity of life on this planet. However, we now know there is a geological record of life on Earth (including much older stromatolites) that reaches as far back as 3500 million years — from evidence also preserved elsewhere in the east Pilbara!

A rock full of gas bubbles

As you walk up to the outcrop on the south of the road for a closer look, you will walk over **basaltic rocks** full of what were once gas bubbles, but that are now infilled with white **calcite**, a calcium carbonate mineral that crystallized from ancient seawater percolating down into the basalt as the rocks were flooded by a rising sea that made the limestone reef.

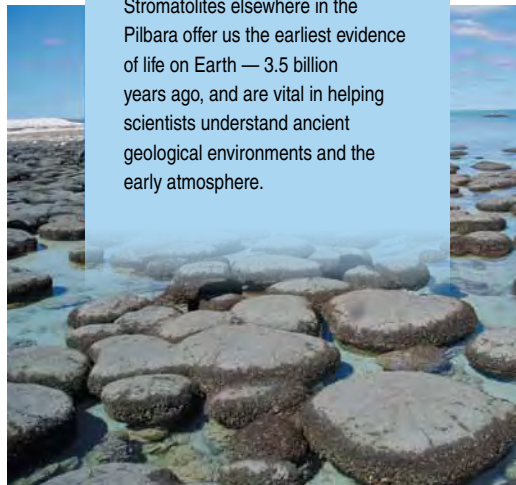
Did you know?

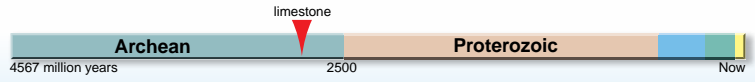
Stromatolites are

organosedimentary deposits; that is, sedimentary rock structures made not just by physical means, but also with the help of micro-organisms — most commonly cyanobacteria. The cyanobacteria use two processes to build layered, domal, cone-shaped, or branching structures: they either trap and bind sedimentary particles and/or they precipitate minerals as a result of photosynthesis.

Stromatolites thrived between 2800 and 1000 million years ago, but competition from other organisms in more recent times has restricted their occurrence. Living stromatolites survive in super-saline waters of the World Heritage area at Hamelin Pool in Shark Bay, Western Australia.

Stromatolites elsewhere in the Pilbara offer us the earliest evidence of life on Earth — 3.5 billion years ago, and are vital in helping scientists understand ancient geological environments and the early atmosphere.





This is the same limestone bed

Figure 1 (top photo): Vista to the horizontal dark stripe visible half-way down the hillside, which is a limestone bed full of stromatolites

Figure 2: Close-up view of the limestone bed. The wrinkly and dome-shaped textures were formed by colonies of micro-organisms (microbes) in very shallow seawater



Stop 4.7 — Roadside cutting, Kylena Basalt

21°15.698'S 120°33.976'E

Directions to Stop 4.7: Continue along the road and stop at a cumulative distance of 25.1 km from Stop 4.4 (21°15.698'S 120°33.976'E).

What you see here

The road cutting on the north side of the road displays a section through two, almost flat-lying, very thick **basalt flows** of the Kylena Formation (2740 million years old), one overlying the other. About two-thirds of the way up the cutting is a zone where the lower basalt becomes highly **vesicular** (full of gas bubbles) and is bleached to a pale brown. This marks the top of the lower basalt flow (Fig. 1). The surface is bleached because in ancient times it was exposed to **weathering** before the upper basalt flowed over the top. This weathering stripped the rock of many elements, including iron (Fe), magnesium (Mg), and silica (Si). Evidence of such chemical stripping lends support to the idea that the Archean atmosphere had very little (or even no) free oxygen and was entirely composed of carbon dioxide and methane: we would not have been able to live in such atmospheric conditions!

Gas cavities in the basalt

In the middle of the lower basalt flow are very large, irregular, elliptical or flat, gas cavities that are now filled-in by two white minerals — an outer zone of greyish-white, glassy **quartz** and a core of white **calcite** with a pearly lustre that splits into perfect rhombs (Fig. 2). The gas cavities reflect the fact that most volcanic **eruptions** contain a significant amount of gas which, in this case, was trapped within the **viscous magma** during eruption. The gases escaped through very fine **fractures** that cut through the rock as it cooled, and the cavities were later filled up by minerals **precipitated** out of fluids that percolated through the rocks.

YOUNG AND ANCIENT BASALTS

Compare the ancient basalt flow in Figure 1 with a modern-day basalt erupted in Hawaii (photo below of ash flows and basalt flows). The ancient basalt looks remarkably similar — just a little weatherbeaten.



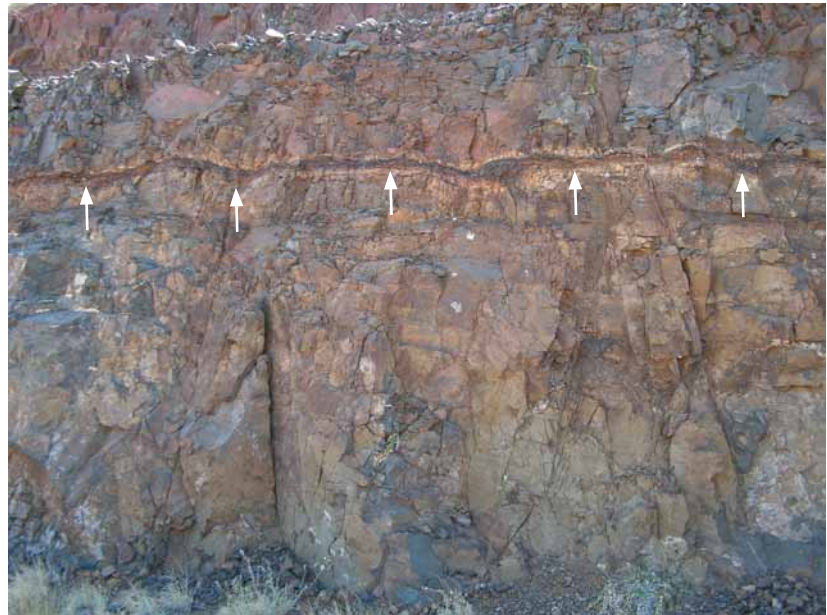
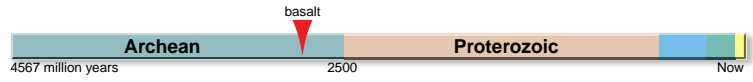


Figure 1: Vertical roadside cutting. Arrows show bleached and weathered top of lower basalt flow



Figure 2: Calcite and quartz have filled in large gas cavities in the basalt



Stop 4.8 — Vista to stromatolites

21°16.843'S 120°36.990'E

Directions to Stop 4.8: Continue driving east along the road, and stop at a rest area, 31 km total distance from Stop 4.4 (21°16.843'S 120°36.990'E).

What you see here

The dark-brown and black-weathering rocks of the 2720 million year-old Tumbiana Formation form low, flat-topped, slightly sloping, black hills to the north of the rest area. This is another, more widespread, unit of **limestone** (compare with Stop 4.6), containing densely packed **stromatolites**; in fact, the whole rock is known as a **microbialite** (i.e. **precipitated** by **micro-organisms**). If you walk up to the low hill flanking this rest area, you can see an array of large and well-preserved stromatolites in the loose boulders and **outcrops**. Stromatolites in this unit have shapes that vary from flat, wrinkly mats, to domical shapes and conical shapes (Figs 1–3). Non-biological carbonates have very flat, regular **laminations**, but you can see here the added complexity that living organisms have given to the formation of the rocks.

Continue driving east.

About one km further along the road, you can see well-developed sedimentary **layering** in the 2700 million year-old rocks (Fig. 4) in the hills to the north of the road, formed by the slow accumulation of sand and gravel over millions of years, during fluctuating sea levels and erosion. These rocks have lain essentially undisturbed for 2700 million years!

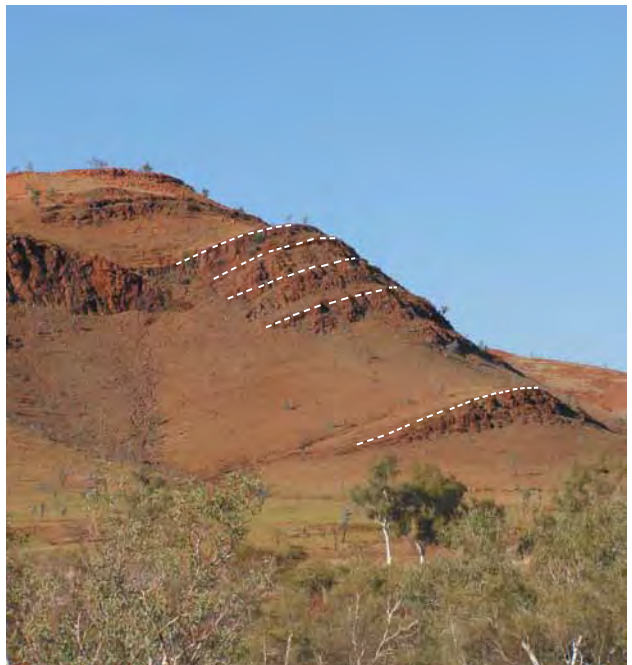


Figure 4: White dashed lines mark the sedimentary layering in undeformed rocks that make up the Fortescue Group

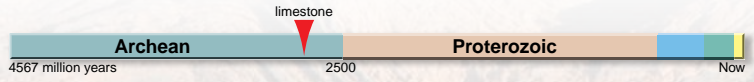


Figure 1: Cross-sectional view of domical stromatolites with wavy algal mats sitting below

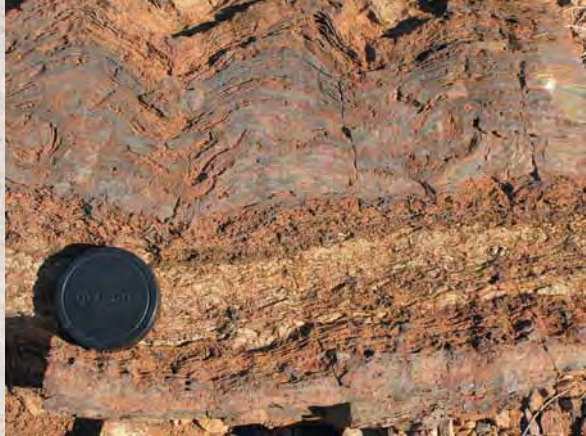


Figure 2: Looking down on to the top of a domal stromatolite



Figure 3: Cross-sectional view of domal stromatolites and wrinkly algal mats



Stop 4.9 — Glacial valley

21°19.698'S 120°52.187'E

Directions to Stop 4.9: Continue driving east and stop at a cumulative distance of 60.3 km from Stop 4.4 (21°19.698'S 120°52.187'E).

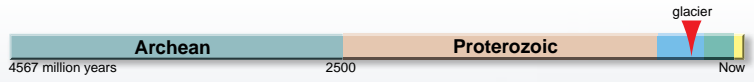
What you see here

Stretching out before you is a wide, flat valley. Hills on the far side of this valley, about 30 km away, are just visible in the distance. The valley was carved out by an ancient glacier, some 300 million years ago, when Australia was near the South Pole and covered with a continental ice sheet several kilometres thick. It is this ice sheet that is responsible for the generally very flat topography of most of Western Australia. As the massive ice sheet slowly ground down the continent with its great weight, lobes of this ice sheet flowed to the north, carving out valleys just like this.

Erratic boulders

The valley is covered with glacially transported boulders (glacial erratics), which were sourced from between tens to hundreds of kilometres south, and transported by the ice to this locality, where they dropped out from the ice as the glacier retreated. Glaciation waxed and waned several times over tens of millions of years, before Australia eventually moved northwards into a warmer climate. Some of the boulders have smooth polished surfaces, and even some scratches from the glacial ice. At Stop 4.11 you will see rock surfaces polished smooth by the movement of glaciers.





Creaking and grinding its way across the landscape, this present-day glacier in Iceland shows just how glaciated valley is formed



Stop 4.10 — Meteorite impact breccia

21°19.263'S 120°52.093'E

Directions to Stop 4.10: Turn left (north) from Stop 4.9 and reset trip meter to 0.0 km. Turn left at 600 m (21°19.388'S 120°52.331'E) and head towards the windmill. Park at the windmill. Walk towards the outcropping rocks, and then up the small, but steep-sided, gully for about 150 m (keeping above the spinifex grass) to a point at 21°19.263'S 120°52.093'E.

What you see here

Notice, as you walk up the gully, the very regularly **layered** brown **limestone** in the walls. It differs from the limestones at Stop 4.6 and Stop 4.8 in having no **stromatolites**, and geologists have interpreted this to indicate **deposition** of the limestone in deep water some 2600 million years ago. As you continue up the gully, and around a sharp bend, you will notice that the limestone changes character to a rock that contains no obvious layering but has many scattered bits and pieces and fragments, some up to 30 cm across, of black, white, grey, and red siliceous rocks (Fig. 1). This is highly unusual for a limestone, and indicates extremely high-energy conditions during deposition, something that only happens during a major storm (cyclone), an earthquake-generated tsunami, or the impact of a meteorite.

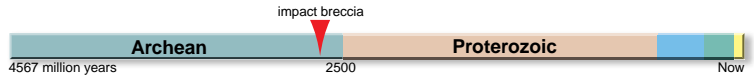
Tiny glass spheres hold the key

It was discovered through minute observation of the **matrix** of the rock that this unit was, in fact, deposited as the result of a giant **meteorite** impact 2630 million years ago. The key piece of evidence for this was the observation that tiny spheres of altered glass are distributed through the unit: you can find these if you search the rocks very carefully. They are beige, one mm-diameter spheres, but they are not common (see Fig. 2, to the right of pen-tip).

These tiny spheres formed when the meteor crashed into Earth and vaporized the surface rock (Fig. 3). The force of the impact threw the vapour high up into the atmosphere, where it condensed into tiny spherical droplets, cooled, and fell back to Earth, to become embedded in the rocks in front of you. The force of the meteorite impact also caused a giant tsunami, which broke up pieces of rock (i.e. the coloured siliceous fragments) from elsewhere and transported them several kilometres to this location, where they became part of the thick bed of limestone. We infer from these separate pieces of evidence that the whole **breccia** unit you see here was deposited almost instantaneously.



Figure 3: Image of giant meteor hitting Earth and vaporizing the surface rock



Was this a global event?

An identical bed in rocks of identical age has also been discovered in South Africa, suggesting that the impact event may have had an influence at a global scale.

Retrace your steps to the vehicle.



Figure 2: A tiny sphere of altered glass embedded in the limestone is evidence of a meteorite impact



Figure 1: Megabreccia of massive limestone with large fragments of chert and limestone. Bedded limestone can be seen at base of cliff in centre foreground (arrowed)

Stop 4.11 — Glacial erratics

21°19.476'S 120°52.295'E

Directions to Stop 4.11: Drive back along the track, towards the road, but only for about 100 m, to a barren plain strewn with boulders (21°19.476'S 120°52.295'E).

What you see here

Here you will see boulders of **granite**, **basalt**, **conglomerate**, and **limestone**, strewn across the plain, none of which come from the local vicinity. These rocks were deposited by a passing glacier a mere 300 million years ago. Such boulders are called **glacial erratics** or **glacial boulders**. Some of the boulders show polished and striated surfaces (**striae**) formed by the heavy glacier scratching and scraping over the rocks, or dragging the rocks beneath it.

Manganese pebbles tell the story of the atmosphere

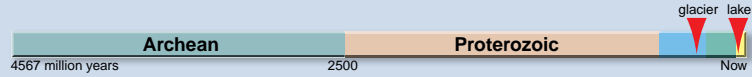
This plain is also littered with heavy, shiny black pebbles of **manganese**, similar to that mined at Woodie Woodie, further east along the Ripon Hills Road, and trucked to Port Hedland. Woodie Woodie is an interesting deposit, because manganese is dissolved in seawater when there is no free oxygen, but **precipitates** out when ocean waters become oxygenated. In fact, manganese deposits like those at Woodie Woodie are common throughout the world in rocks deposited about 2400 to 2000 million years ago, and geologists use this to infer that oxygen in the atmosphere and oceans started to increase at about this time, during what has been called the **Great Oxidation Event**. Many other lines of evidence are used to infer that the oxygen came from photo-synthetic microbes that were able to use sunlight, water, and carbon dioxide (CO₂) to produce carbon for their bodies, but gave off oxygen as a waste product. It is this waste, from countless billions of microbes over billions of years, that we breathe today.



Boulder showing striations or grooves made by a glacier



Figure: Glacial erratic (lone boulder). Black manganese pebbles strewn across the plain are visible in the right foreground



Stop 4.12 — Ancient lake deposits

21°19.911'S 120°57.219'E

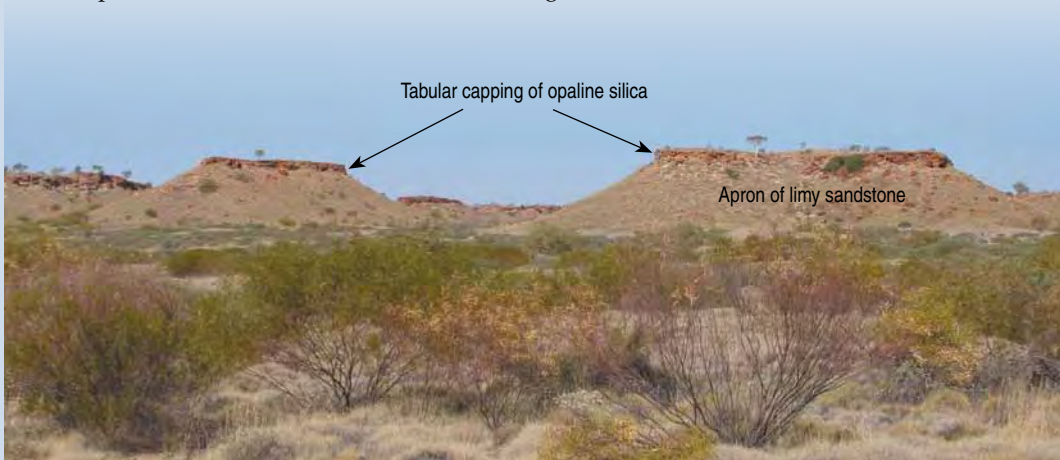
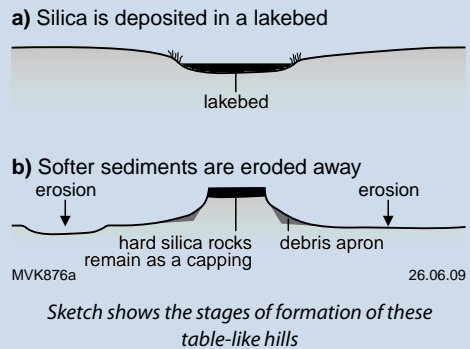
Directions to Stop 4.12: Head back to the main Ripon Hills Road. Turn left and reset the trip meter to 0.0 km. At 3.1 km there is a roadside stop on the south side of the road, but continue on to 9.0 km exactly (21°19.911'S 120°57.219'E).

What you see here

Surrounding you at this locality, is a set of low, flat-topped hills (the hills are actually best viewed when driving back westward on your return trip). On the north side of the road here, the tops of the hills are made of a resistant rock (called **opaline silica**) that forms a protective capping. This **vuggy**, whitish-grey silica protects **scree** slopes of blue-grey limy (**calcareous**) **sandstone** that form an 'apron' below the capping, giving the hills a very distinctive sharp-edged, table-like appearance (see photo). The hard, opaline silica (**microcrystalline quartz**), with a strong conchoidal fracture, is of interest to lapidarists for tumbling and polishing to yield attractive gemstones.

A lake in the sky!

Together, the two types of rocks form the Oakover Formation, deposited about 20 million years ago, below shallow lakes that once filled the **glacial valley**. Since they were **deposited**, the ancient lakebeds have been **uplifted**, and **erosion** of the softer rocks has left these former depressions now on the tops of hills. The sketch above shows the stages of formation of the hills.



Distinctive tabular landforms formed by differential weathering of the hard silica (top) and softer limy sandstone underneath

Stop 4.13 — Polished glacial pavement

21°26.933'S 121°03.591'E

Directions to Stop 4.13: Continue driving east. Cross the Onkover River. At 26.7 km, take the Woodie Woodie Road to the south (not the Telfer Road, which is a private road). At 35.7 km (21°24.062'S 121°06.784'E), turn right onto the track leading into Carawine Pool. Reset the trip meter to 0.0 km. At 8.1 km, at the first cliff on your left with huge boulders tumbling down the slope (21°27.223'S 121°03.975'E), turn right onto a faint track taking you across a gravel plain to a low outcrop, which shines brightly in the afternoon light. At 0.8 km along the track you have reached the first outcrop (21°26.933'S 121°03.591'E).

What you see here

All the rock surfaces here glint and glisten in the sun (Fig. 1). They are smooth, polished surfaces with long grooves or **striae** gouged by the grinding, rasping, and scratching of glaciers as they passed over this area some 300 million years ago (Fig. 2). You may also see small **chattermarks**, which are sets of horseshoe-shaped **fractures** gouged into the bedrock by rocks carried along by the glacier. There are two rock types at this outcrop: a layered, fawnish-coloured **dolomite** (2630 million year-old Carawine Dolomite), and a peculiar red **hematite–quartz breccia** (Figs 3, 4). The breccia unit was deposited in **solution** cavities in the dolomite, which was dissolved away by acidic waters. The fluids contained iron and silica, which **precipitated** out and replaced the original dolomite. The red colour of the iron

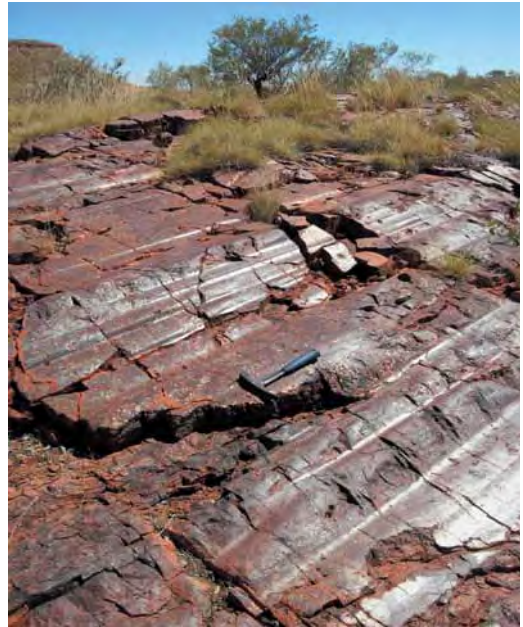
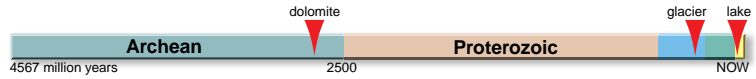


Figure 2: Polished and grooved rock surfaces are tell-tale signs that a glacier has been at work



Figure 1: Rock surfaces polished by a continental glacier glisten in the afternoon sunlight. Note the tabular hills in the background (Stop 4.12)



coatings indicates that the fluids were highly oxidized, and therefore must be post-Archean in age — which is when the atmosphere became oxygenated.



Figure 4: Close-up view of the hematite-quartz breccia. Note the large clast of chert near the lens cap

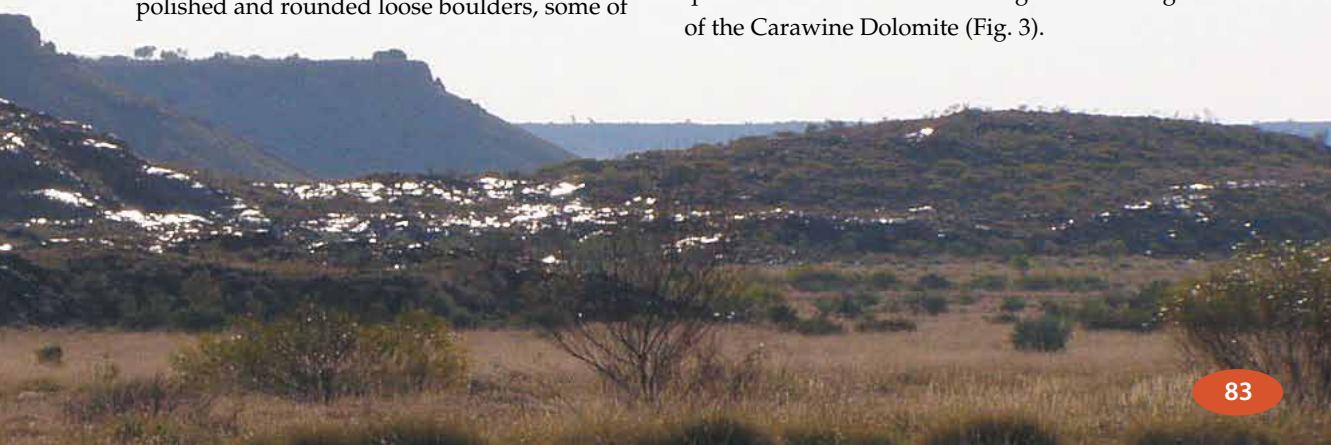


Figure 3: Fawnish-coloured layered Carawine Dolomite and the hematite-quartz breccia

Walk around the first outcrop and continue on to the second (northern) outcrop.

The Carawine Dolomite here is well preserved and locally full of **stromatolites** — ranging from very small to very large domes. At the top of some of the **outcrop**, and up against the flank of the hill to the northwest, you can see numerous polished and rounded loose boulders, some of

which are striated and **faceted**, again the work of the glacier. There are also broken crusts of white **limestone** lying about on the surface, which are from much younger lake deposits that filled this valley after the glaciation, about 20 million years ago. At some places along the edges of this outcrop, you can see how the iron-quartz breccia cuts down through the bedding of the Carawine Dolomite (Fig. 3).





Stop 4.14 — Carawine Pool

21°28.865'S 121°01.682'E

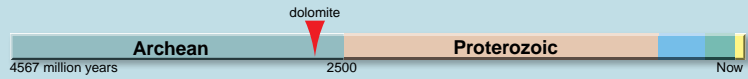
Directions to Stop 4.14: Return to the Carawine Pool track. Turn right and continue for 5.3 km to Carawine Pool (21°28.865'S 121°01.682'E). This is an excellent camping spot and you can swim in the pool.



Cabbage-like stromatolites are visible in the wall of the cliff (outlined). The large stromatolite is about 20 m wide



View across Carawine Pool to the cliff of Carawine Dolomite. It is beautifully calm, but flash-flooding is common. River gravels brought down by the flooded river are heaped up next to the pool



What you see here

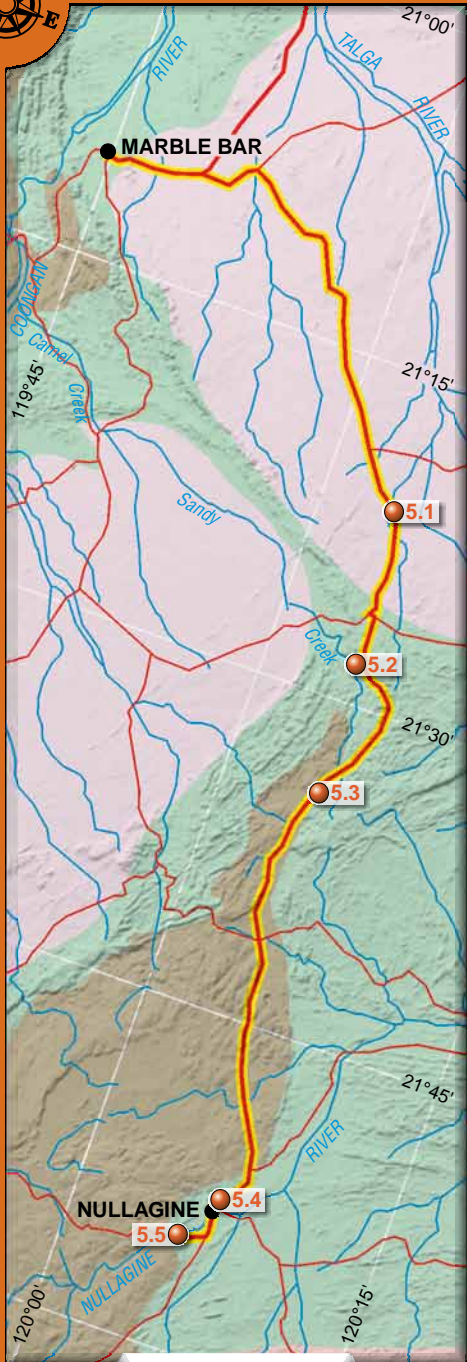
This spectacular locality affords a view across Carawine Pool to the steep cliff of Carawine **Dolomite**. For most of the cliff section, the **bedding** is quite flat and regular. However, in the middle of the cliff, a very large **stromatolite** dome — about 20-m across — is visible, one of the largest such structures known in the world. Smaller domes are also visible on the flanks of the big dome.

The calm after the storm

Carawine Pool itself is a good example of the vagaries of geological processes. For most of the year, and sometimes even for several years in a row, the Oakover River is quiet and mostly dry, except for permanent pools like this. However, during the cyclone season, large rainstorms cause the river to surge and flow, carrying suspended sediment, pebbles, and even large rocks to erode the stream, and then dump its load. Erosion can be devastating and fast during such times, reverting to quiet conditions perhaps after only a few days. For example, the site used to be covered by large, mature, river red gums, but the trees were snapped off or uprooted, and washed away during a cyclone in 2006. This cycle is quite typical of many geological processes — intense bursts of activity followed by longer periods of relative quiescence— think of volcanoes and earthquakes and how quickly they rage then cease.

This is the end of Trail 4. Return to the main road, turn left and head back towards Marble Bar.





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Travelling Trail 5

Marble Bar to Nullagine

This is a pleasant day trip. The journey to Nullagine is only about 120 km, but there is a variety of Stops on the way.

The stromatolites of Stop 5.2 form the centrepiece of the journey — they are rare, delicate, and ancient fossiliferous rocks that should not be sampled. Nullagine is an interesting historic gold town and the Nullagine gold mining areas warrant a visit.



Stop 5.1 — Hidden riches: kimberlite dyke

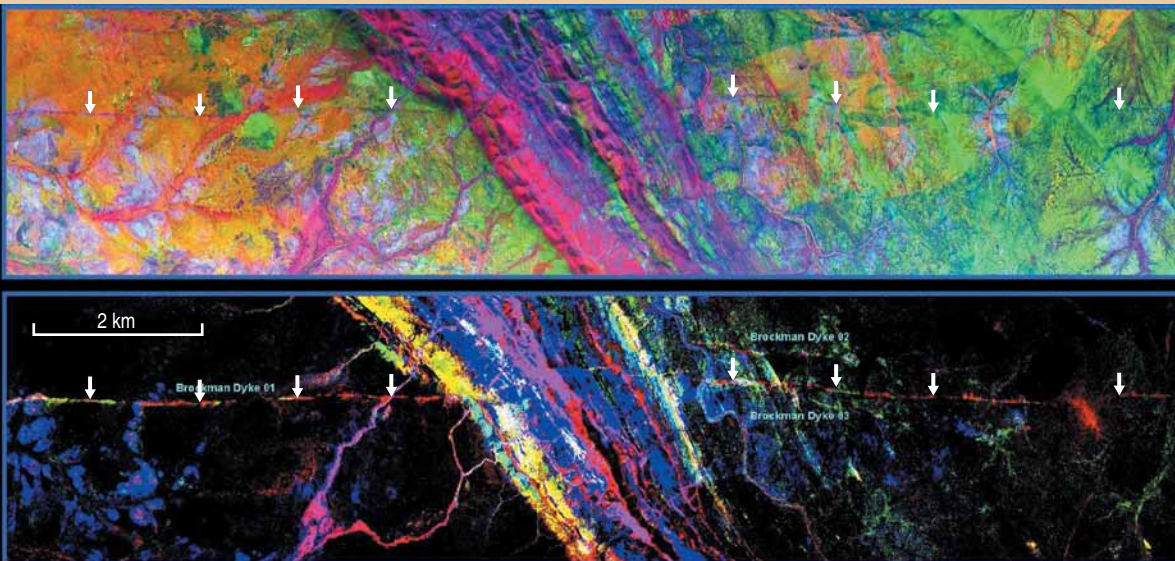
21°21.221'S 120°03.604'E

Directions to Stop 5.1: Set trip meter to 0.0 km at the Ironclad Hotel in Marble Bar. Head out of town, east along Francis Street, towards Port Hedland. At 8.6 km (21°09.795'S 119°49.240'E), turn right onto the Nullagine–Telfer–Newman Road. At 22.5 km, turn right (south) on to the Nullagine Road. Continue south for 24.5 km to 47.0 km and pull over to the side of the road. Watch out for stray cattle.

What is a dyke?

A long, thin body of rock that results when magma intrudes and cools in a vertical crack or joint in the Earth. Here the magma formed a kimberlite, a rare rock type that may host diamonds.

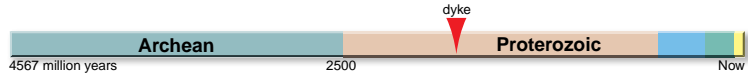
Follow the white arrows to trace-out the dyke



Two different views of the Brockman dyke:

Top panel: False-colour Landsat view, in which greenstones are bright pink, granites are orange to green, and branching creeks are clearly visible

*Bottom panel: The same area as the top panel, but seen as a Hyperspectral image that emphasizes reflected light of specific wavelengths that correspond to individual minerals. Note how much more clearly the dyke shows up in this view
Image courtesy of Mark Mitchell, DeBeers Australia Exploration Ltd*



Can you see it?

On the right-hand side of the road, extending to the west-southwest for 30 km, is an unusual **dyke**.

Can't you see it? C'mon, look harder!

Actually, there's absolutely nothing visible to the naked eye; the dyke is completely hidden from view by a covering of soil and **regolith**. However, the Brockman dyke is visible through **remote sensing**, which, in this instance, is an aeroplane- or satellite-based spectrographic technique that can analyse the ground surface for different wavelengths of light that reflect off different mineral species in the soil. The image below (top panel) shows the dyke as a thin trace cutting across many different rock types. The dyke is a rare, and possibly extremely valuable, **kimberlite intrusion** that contains diamonds. It was **emplaced** into the **crust** about 1800 million years ago and is one of the oldest kimberlites in the world.

Diamonds

The diamonds found within the dyke are probably much older still, possibly 3500 to 3000 million years old. The dyke was discovered by analysing the soil reflectance for high values of magnesium hydroxide (MgOH) (see image), which is a characteristic feature of weathered kimberlite, but is only found in very low concentrations in the surrounding **granite**. So the high values of magnesium traced out a long thin feature — which is the Brockman dyke.

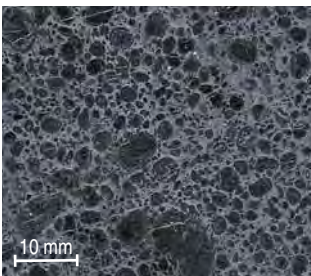
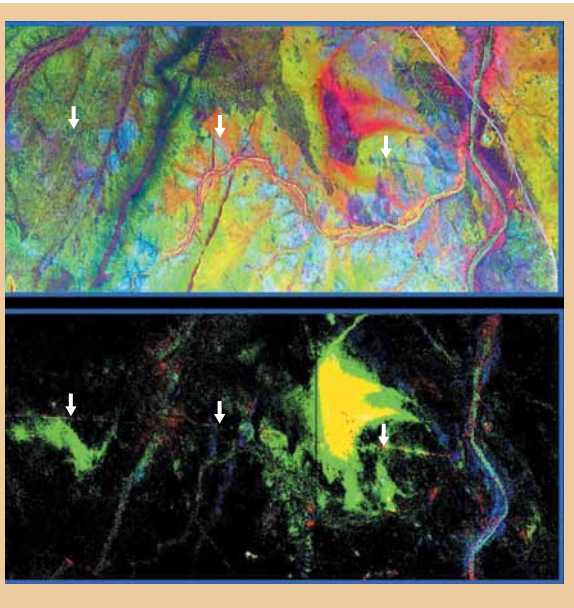
Geophysics can see beneath the surface

This aspect of the whole discipline of geology is known as **geophysics** — the study and analysis of the physical properties of the rock, such as density, magnetic signature, radiometric

properties, spectrometry, electrical conductivity, and seismic properties. From such studies much more about the 3D geometry of rock units in the crust can be deciphered.

Left: Kimberlite sample with pebbly texture of olivine crystals;

Right: Rough diamonds (x3 enlarged)





The rocks at this locality are rare and precious.
Take only photos, leave only footprints.

Stop 5.2 — Ancient life (stromatolites)

21°28.200'S 120°04.344'E

Directions to Stop 5.2: Continue to 38.3 km (21°28.045'S 120°04.777'E), turn right at a small rock cairn on the left-hand side of the road, onto a slightly overgrown 4-wheel drive track. NOTE: This track is not suitable for caravans! Reset trip meter to 0.0 km. Travel 1.1 km along the winding track, which includes a small gully crossing. Park the car at a small cairn (21°28.200'S 120°04.344'E). Walk uphill about 75 m to the white and grey rocks half-way up the hill (point 1 is at 21°28.238'S 120°04.315'E). For point 2, continue just behind the ridge for about 40 m to the edge of a small, shallow gully (21°28.252'S 120°04.321'E).

Famous fossils

The grey- and white-weathering rocks of this unassuming ridge are a **faulted** remnant of what was once a 3400 million year-old **reef** on which thrived some of the oldest life on this planet (Fig. 1). This formation consists of **carbonate rocks**, similar to those found in reefs on Earth today, deposited in shallow water, near the shoreline of an ancient sea.

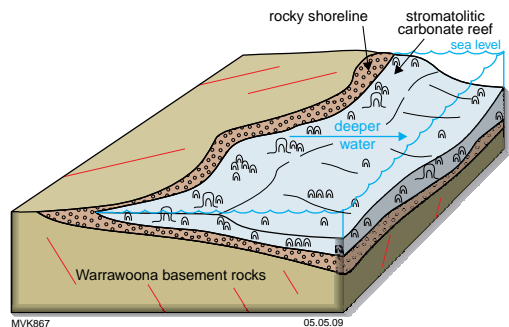


Figure 1: Environment of growth of stromatolites in a shallow sea, some 3400 million years ago

The features you can see in parts of this ridge (Fig. 2) are **stromatolites**, fossil structures created by colonies of microscopic organisms that represent the precursor to all of the more complex forms of life on this planet today. Stromatolite occurrences like these have made the east Pilbara a world-famous geological locality. Researchers from universities around the world come to these outcrops to study the oldest evidence of life on Earth.

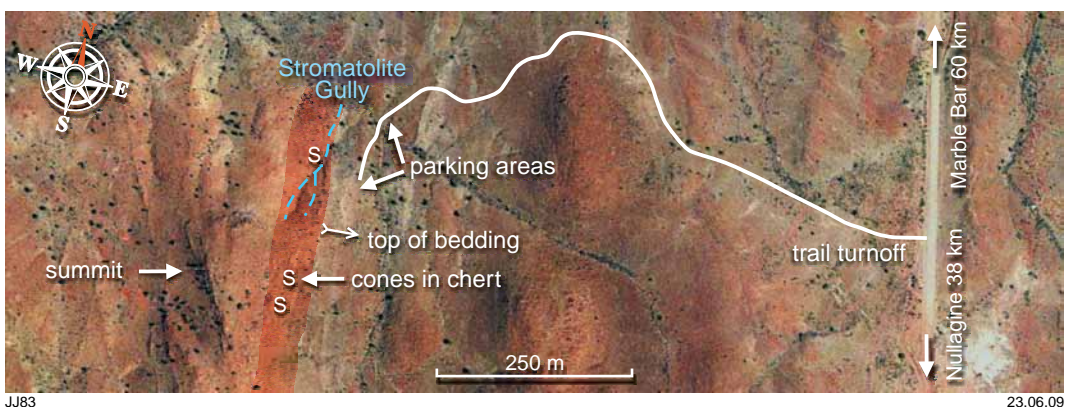
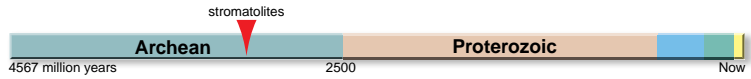


Figure 2: The stromatolite locality today — now far from the sea in rugged terrain



Point 1

The **bedding** in the rocks **dips** slightly downhill (back towards your vehicle), so it is best to walk up over the ridge and look at the rocks facing back downhill to see a cross section through this unit. The grey- to dun-coloured rocks show thin, wavy layers about a millimetre thick, which represent original bedding in the carbonate sediment (Fig. 3).

What are stromatolites?

Much of the **layering** in these rocks is flat and planar, but in places — if you look closely at the rocks — you will see that the **laminations** define columns of what in cross section look like stacked $\wedge\wedge\wedge$ s (Fig. 3). However, in some places you can see that these columns are actually three dimensional inverted cones (Fig. 4), and it is these structures that are interpreted to be stromatolites (see also Stop 4.8).

Such structures are not known to form through any purely physical process and reflect the activity of living organisms, which interact and shape their surroundings — just as we do.

Elsewhere, there are spectacular outcrops that contain much more complicated and diverse structures that show evidence of branching, asymmetrical growth, and other features which, collectively, are absolutely diagnostic evidence of ancient life (Fig. 5). These rocks have



Figure 3: Flexures represent conical structures — the stromatolites. This is a cross-section view showing thin layers of sediment that represent original bedding in the ancient reef. Original carbonate minerals are now quartz



Figure 4: Oblique 3-dimensional view of a conical stromatolite

This Stop tells the story of ancient life on a fringing reef — a reef just like the modern-day Great Barrier Reef in Queensland, but that existed long before corals evolved to colonize a reef.



Stop 5.2 — Ancient life (stromatolites) continued

21°28.200'S 120°04.344'E



Figure 5: This small, branched, columnar stromatolite about 5 cm across, fondly known as Mickey Mouse ears, comes from another locality

experienced a long and complex **alteration** process and the carbonates have been replaced by **silica**. We infer that the rocks were once carbonates because in some places we see original carbonate textures preserved.

Point 2

At this locality you can see a typical section through several different types of rocks (Fig. 6). Rocks are **dipping** moderately downhill to the east, so the oldest part of the **formation** is on the western side of this small ridge, closest to the ground. At the base of the formation is a thin **conglomerate**, a **sedimentary rock** containing rounded to angular pieces or clasts of grey chert 0.5 to 3.0 cm in diameter (layer 2 in Fig. 6, and a sample is shown in Fig. 7). This rock type was deposited from rivers or in a beach environment on top of much older rocks of the Warrawoona Group (layer 1 in Fig. 6), which are hidden beneath the rubble and not visible here.

Overlying the conglomerate is a unit, about 50 cm thick, of light-grey and brown (silicified) carbonate with thin, even laminations (layer 3 in Fig. 6). Layer 4 is a 50 to 60 cm-thick

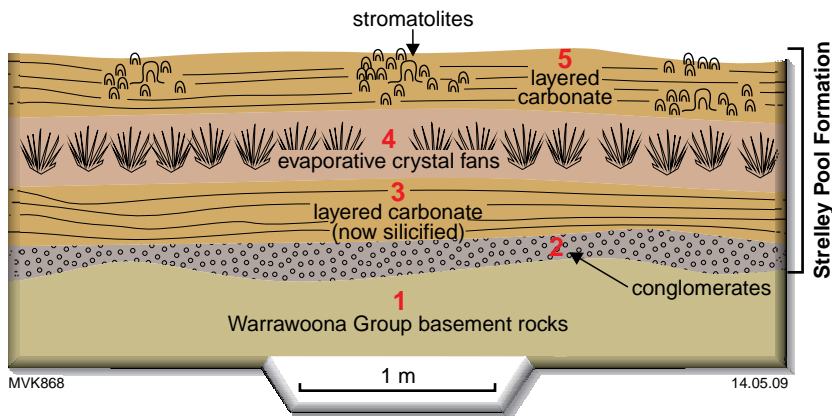


Figure 6: Section through the stromatolite-bearing reef from this locality



Figure 8: (Above) Cross-sectional view of coarse, weakly upward-radiating crystal fans (dark grey) in light grey weakly bedded carbonate. These grey crystals indicate evaporation of an ancient shallow sea

Figure 7: (Left) Close-up view of the conglomerate from the base of the formation, showing the cherty clasts. Lens cap for scale

unit of light grey to dark brown carbonate (not replaced by silica) that has 10 cm-long, upward-radiating crystal fans that cut across the layering (Fig. 8). These radiating crystals grew in the bedded carbonates when they were still soft and exposed to very shallow-water conditions. Such crystals formed when there was a high level of **evaporation** that concentrated sodium (Na) and calcium (Ca) in the remaining briny seawater. The sodium and calcium combined with carbonate or sulfate in the rocks to form the **evaporative minerals**.

Draping over the layer of crystal fans is a 40 to 50 cm-thick unit of well-layered carbonate, orangey-brown in colour, that is full of wavy laminations of the conical stromatolites (layer 5 in Figure 6).

These stromatolites are almost the oldest, but certainly the best-preserved, traces of early life ever found. They are 3400 million years old! They are widespread throughout the east Pilbara, and tell us that, for perhaps the first time, a carbonate reef flourished on an ancient piece of continental crust.



Stop 5.3 — Contact

21°34.188'S 120°04.741'E

*Directions to Stop 5.3: Return to the car and drive back out to the main road. Reset trip meter to 0.0 km and turn right onto the Nullagine Road. You are now driving across **greenstone belt** topography. At 6.4 km you can see ahead of you large **laterite-capped hills** (red and brown) representing an old erosion surface from the tropical-weathering period during **Cenozoic** times (see Chapter 2). The laterite capping is iron-rich and is shedding big boulders down **scree** slopes. At 8.4 km, laterite is also visible. Such hills are very different from the more rounded hills of layered greenstone topography that you are now passing through. At 14.2 km (21°34.188'S 120°04.741'E), stop the vehicle half way down the hill.*

What you see here

On the left (east) side of the road is an **outcrop** of reddish-brown rocks near the base of the 2700 million year-old Fortescue Group, a thick **succession** of **volcanic** and **sedimentary** rocks that lies **unconformably** on top of the older Warrawoona Group rocks (forming the rugged hills just to the north, see explanation at Stop 4.3). The broad flat area to the south is all made up of these younger Fortescue Group rocks (shown on map for Trail 5).

Keeping in touch

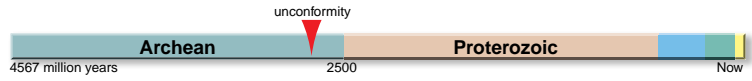
At this outcrop you can trace the irregular **contact** between two rock types of the Fortescue Group (Fig. 1). Basaltic **lava flows** are dark brown and massive rocks, with round holes or **vesicles** that are now filled by secondary white minerals. Lying just above the **basalt** is a light yellowish-weathering unit of **conglomerate** packed with rounded pieces of grey and white **chert**, ranging from pebbles to cobbles in size (Fig. 2). The conglomerate was deposited by streams during a **hiatus** in the **eruption** of the lavas. Big boulders of the conglomerate are weathering out and rolling down the slope here, repeating the **weathering process** that formed the original sedimentary rock. A small **fault** is visible in the outcrop — as a smooth, flat plane lined with yellowish and orange mineral streaks (Fig. 3).



Figure 2: Conglomerate with rounded clasts of white and grey chert



Figure 3: Smooth fault plane in basaltic lavas. Lens cap for scale



Can you find the contact?

See if you can find the actual **contact** between the lavas and the conglomerate. Figure 1 may help you find this feature — now you are practising geology!



Figure 1: The contact between conglomerate and the basaltic lavas is shown in the photograph above



Stop 5.4 — Gold and diamond workings

21°52.779'S 120°06.863'E

Directions to Stop 5.4: Return to your car, reset the trip meter to 0.0 km, and continue driving south. The road continues through Fortescue Group rocks (shown on map for Trail 5). At 38.1 km, turn right onto a cleared area just past a parking bay on the left.

What you see here

This locality has a fine view of the Beatons Creek Conglomerate. Scrapes on the hill and mine **tailings** dumps are evidence of past mining activity for **alluvial** gold and diamonds in these ancient (almost 2800 million years old) **conglomerates**, which lie near the base of the Fortescue Group. Exploration drilling has shown that this locality once marked the edge of a 1000 m-high cliff (**fault-scarp**) over which streams cascaded into a deep lake.

Turn right along the track for a few metres to view the workings, both current and from 100 years ago (see photos above and below). These conglomerates offered rich pickings



Author inspecting the ancient gravels of the Beatons Creek Conglomerate, looking for traces of gold

for the old prospectors and once again, today, are of great interest to companies looking for gold.

Shape of the gold

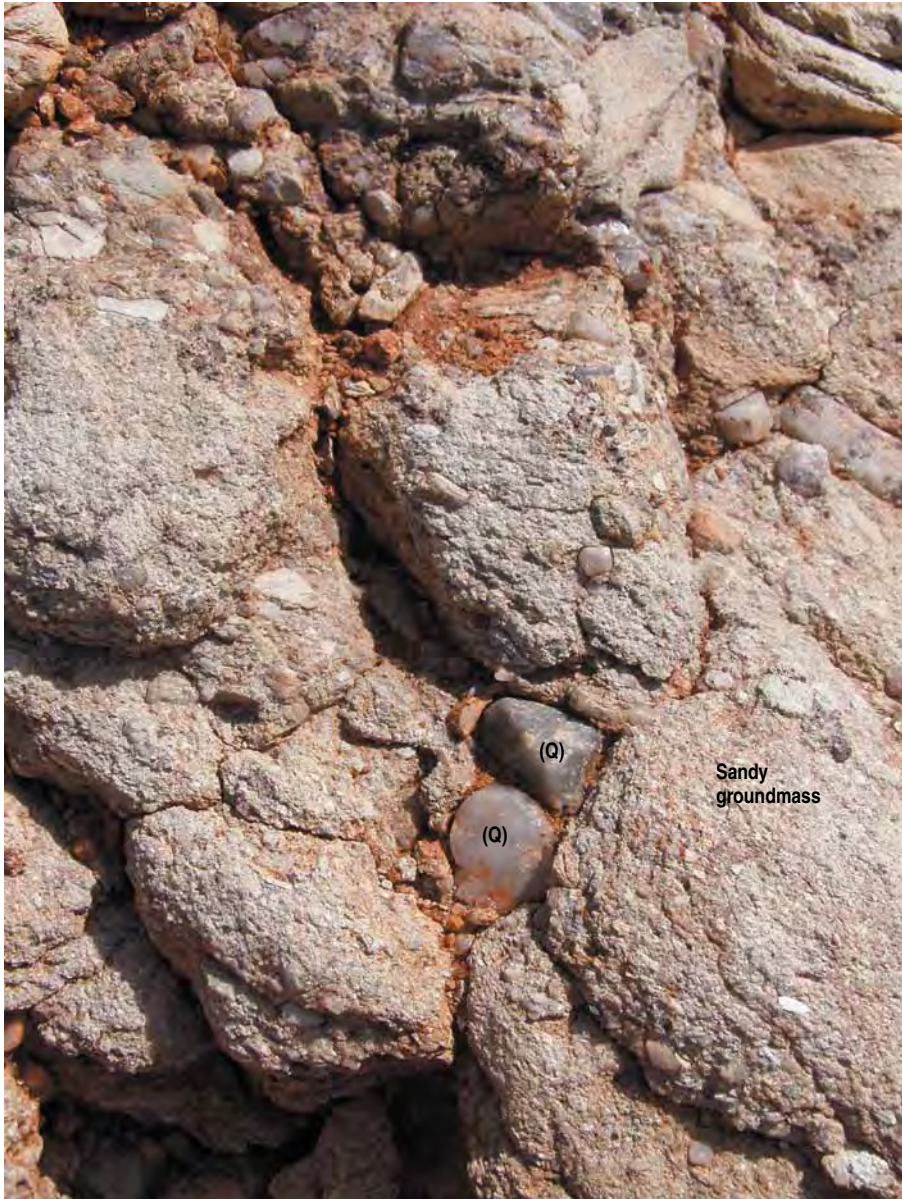
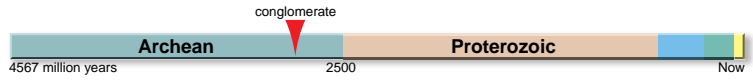
The gold nuggets in these deposits have a unique shape; they are flattened and look as if they have been pounded by a large mallet. Indeed, that is pretty much what did happen, as the gold swirled around, being hammered by big pebbles and boulders in the turbulent streams.

Where did the gold come from?

Diamonds and gold were eroded from the underlying older bedrock during a period of **uplift** and **erosion**. The gold probably originated in the underlying 2940 million year-old Mosquito Creek Formation, from just east of Nullagine, where there are numerous gold mines. You will see the unconformity between the older rocks of the Mosquito Creek Formation and younger rocks of the Fortescue Group at Stop 5.5.



Vista across the Nullagine gold diggings



Close-up view of the gold-bearing Beatons Creek Conglomerate, showing white quartz pebbles (Q), 2 to 10 cm across, in a sandy matrix



Stop 5.5 — Angular unconformity

21°54.899'S 120°05.482'E

Directions to Stop 5.5: Return to the road and continue into Nullagine (about 800 m). At the Roadhouse, reset the trip meter to 0.0 km and head south towards the Conglomerate Hotel. Turn left onto the Newman Road, travel 1.8 km then turn right onto Garden Pool Road (at 21°54.046'S 120°06.868'E). Keep left on the track, go as far as the high outcrop on the left (3.2 km), and park just in front of the pool on the Nullagine River (21°54.899'S 120°05.482'E).

Contorted rocks

The rocks at this locality are part of the 2940 million year-old Mosquito Creek Formation. They are brown-red **sandstone** and brown-black **siltstone** and **mudstone** in very thin layers. These rocks are very contorted and have been **folded** and **cleaved** during a **deformation event** about 2905 million years ago (Fig. 1).

Walk around the corner

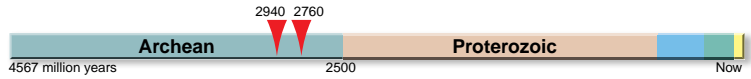
If you walk around the corner of this high **outcrop** and along the river to the west for about 50 m and scramble part way up the hill for about 5 to 10 m, you will get to a point where these older, steeply **dipping** rocks are overlain by similar-looking, but almost 200 m.y. younger, more gently **dipping** rocks (dipping away to the right as you face the hill) that are not folded or contorted in any way (Fig. 2). These overlying rocks include sandstone and conglomerate of the Hardey Formation, part of the Fortescue Group.



Figure 1: Contorted, folded, and cleaved rocks below the unconformity

Sit on the unconformity

This angular relationship between older and younger rocks is called an **angular unconformity**, and it is an important concept for geologists (see Chapter 2 and Fig. 3). The first published observation of an unconformity was by Scotsman James Hutton in 1788 (the year the First Fleet arrived in New South Wales to settle Australia), which led to the understanding that geology involved vast expanses of time and that this contradicted the literal interpretation of the Bible. Hutton challenged the established philosophical and theological order



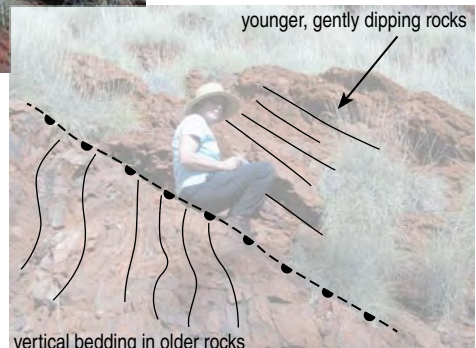
when he 'looked through the abyss of time and found no vestige of a beginning and no prospect of an end' and realized that the rocks he found required the Earth to be very old indeed.

'Hutton's unconformity', together with Charles Darwin's publication 'On the Origin of Species' (1859), started a profound social revolution and heralded the onset of the modern scientific age.

This is the end of Trail 5. As you travel back to Marble Bar across the flat Mount Edgar Granitic Complex you are encircled by greenstone mountains.

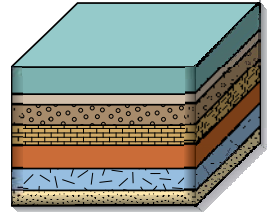


Figure 2: Author marks the **angular unconformity** — vertically dipping rocks (below) and gently dipping rocks (above unconformity)

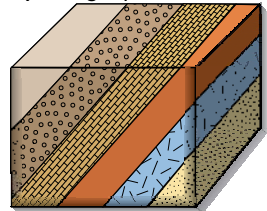


Formation of an angular unconformity

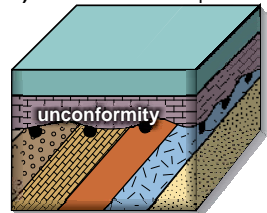
a) Deposition



b) Tilting, uplift and erosion



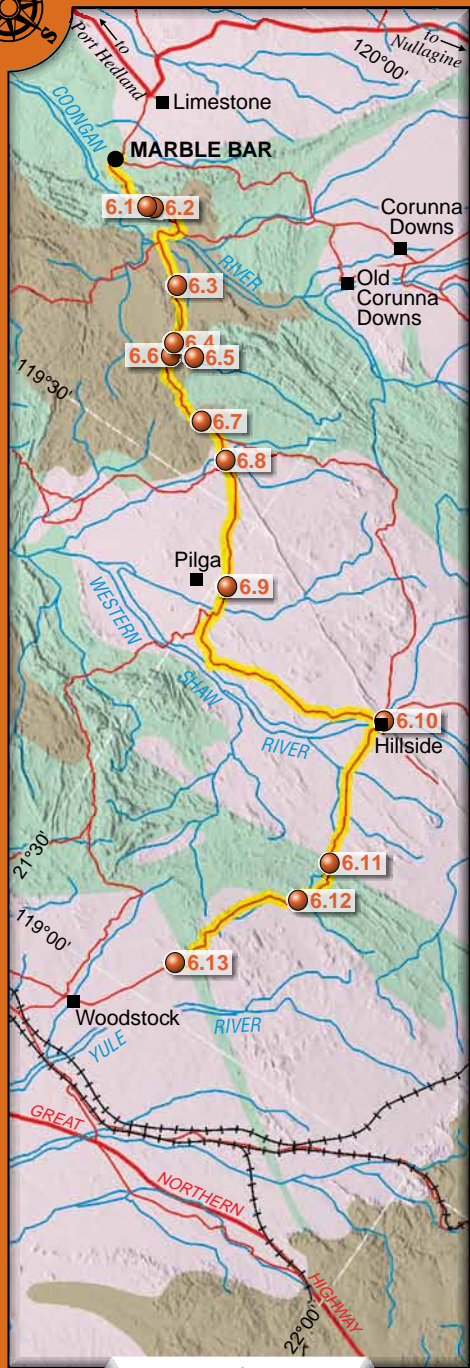
c) Subsidence and deposition



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Figure 3: The making of an unconformity —

- a) sediments are deposited on the sea floor;
- b) they are tilted and eroded;
- c) a new layer is deposited, unrelated to the layers below, to form the **unconformity**



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See inside front cover for map legend

Travelling Trail 6

Marble Bar towards the Great Northern Highway — along the Hillside Track

This drive along the Hillside Track, from Marble Bar towards the Great Northern Highway, takes you through the heart of the Pilbara and provides an opportunity to see a wide variety of world-class geology. This Trail has thirteen Stops and may take more than a single day to complete in comfort, but there are numerous good camping spots that will allow you to extend your stay to fully appreciate the grandeur of this region.





Stop 6.1 — A 2.7 billion year-old valley

21°13.566'S | 119°43.353'E

Directions to Stop 6.1: Set trip meter to 0.0 km at the Ironclad Hotel. Travel west along General Street, and turn left onto the Hillside Track. At about 2.9 km (21°12.044'S 119°43.461'E) along the Hillside Track is a turn off to the left to the Jasper Deposit, which is the collecting locality for the Marble Bar Chert (not at Marble Bar Pool). Continue for about 600 m to the turn off to the Flying Fox Lookout on the right (21°12.325'S 119°43.301'E), which affords a spectacular view over the Coongan River. Continue on the Hillside Track for 2.4 km, just before the Comet Mine, and park by the side of the road (21°13.566'S 119°43.353'E). Walk about 50 m to the left, to the first low ridge of dark brown rocks.

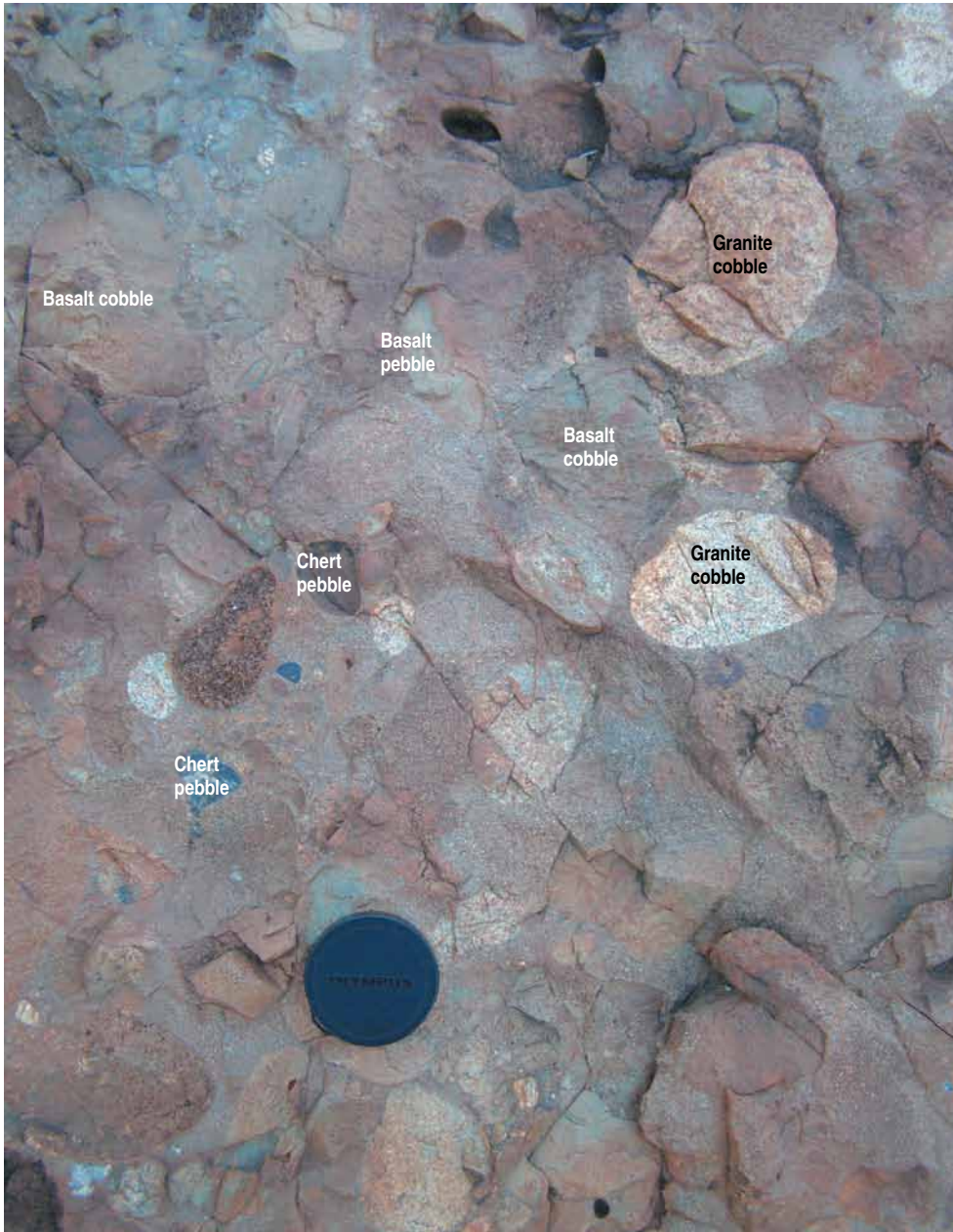
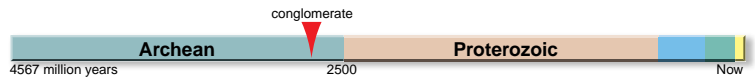
What you see here

The sedimentary **conglomerate** (see photo) in the low ridge at this Stop was deposited in an ancient valley that formed part of the landscape here 2700 million years ago. This ancient valley would have looked much the same as the valley you are standing in today, minus the spinifex and trees.

A mixture of pebbles and boulders

The conglomerate was deposited by water and contains pebbles, cobbles, and boulders of a variety of rocks: **granite**, **chert**, and **schist** from the older (about 3000 million years old) **basement** rocks, as well as large boulders of **basalt** from a younger (2780 million year-old) **lava flow** that lies immediately beneath this unit. The mix of different rock types and the roundness and sphericity of the cobbles suggests that the material originally came from quite far away — meaning that the cobbles have had time to become smoothed and rounded. The valley is situated over an ancient **fault** line, and this fault continues on to the Comet Mine, where it was mined for gold (see Stop 6.2).

Cobbles and pebbles?				What's the difference?		
Geologists measure the size of grains in a sedimentary rock, and rank them (from largest to smallest) like this:						
Boulders →	Cobbles →	Pebbles →	Granules →	Sand →	Silt →	Clay
>25 cm	25–6 cm	60–4 mm	4–2 mm	sand-sized grains	small grains	tiny grains



The conglomerate has a mixture of subangular to well-rounded pebbles and cobbles of granite, basalt, and chert



Stop 6.2 — Comet Mine

21°13.958'S | 119°43.521'E

Directions to Stop 6.2: Return to the vehicle. Proceed 800 m and turn left in to the Comet Mine Tourist Centre.

A once-in-a-lifetime strike!

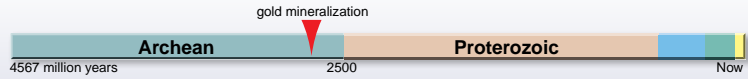
Local prospector Tommy Starr and his two partners discovered the Comet Mine in 1936, thus it was quite a late find, and not part of the initial gold rush to the region in the late 1880s and early 1890s. Tommy originally named the mine 'Halley's Comet' (at that time, last seen in 1910), as he felt it was appropriate with the name Starr and considered it was a once-in-a-lifetime strike. He was correct. It was a very rich find, going about 10 oz (more than 300 g) of gold to the tonne near the surface.

A long-lasting mine

The prospectors sold their leases to the Claude de Bernales Company, which had the mine fully operational and the little settlement and processing plant well-established by 1938; they operated the rich underground mine for about ten years. About 100 men worked there, attracted by generous facilities that went some way to compensate for the harsh conditions and isolation. Stuart Stubbs purchased the Comet in 1948, and the Stubbs family continued mining over the years, also expanding their activities into other commodities and installing various mineral treatment plants at the mine. More recently, Haoma Mining NL bought the mine as part of its regional gold-mining tenements in the Pilbara, and now operates the Comet Mine as a seasonal tourist complex, with



Figure 1: The Comet Mine nestles into the landscape. Notice the tall smokestack



shop, mineral and ore displays, demonstrations, and accommodation. The smokestack that still presides over the mine was deemed to be the tallest structure in the southern hemisphere when it was erected in 1938 (see Fig. 1).

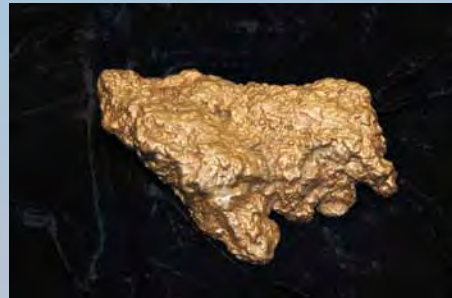
Gold is in a shear zone

The Comet Mine has produced over 400 kg of gold from about 22 000 t of ore. Gold mineralization is in a two metre-wide zone of strongly **sheared** chlorite–fuchsite–carbonate rock impregnated with fine **pyrite** and traversed by small veins of **quartz** and **carbonate** minerals. The ore horizon **dips** southward at about 70° and has been mined to a depth of 110 m below the opencut. The main ore shoot is controlled by the intersection of a series of **fractures** developed during late-stage **faulting** associated with the relatively late displacement of Fortescue Group rocks.

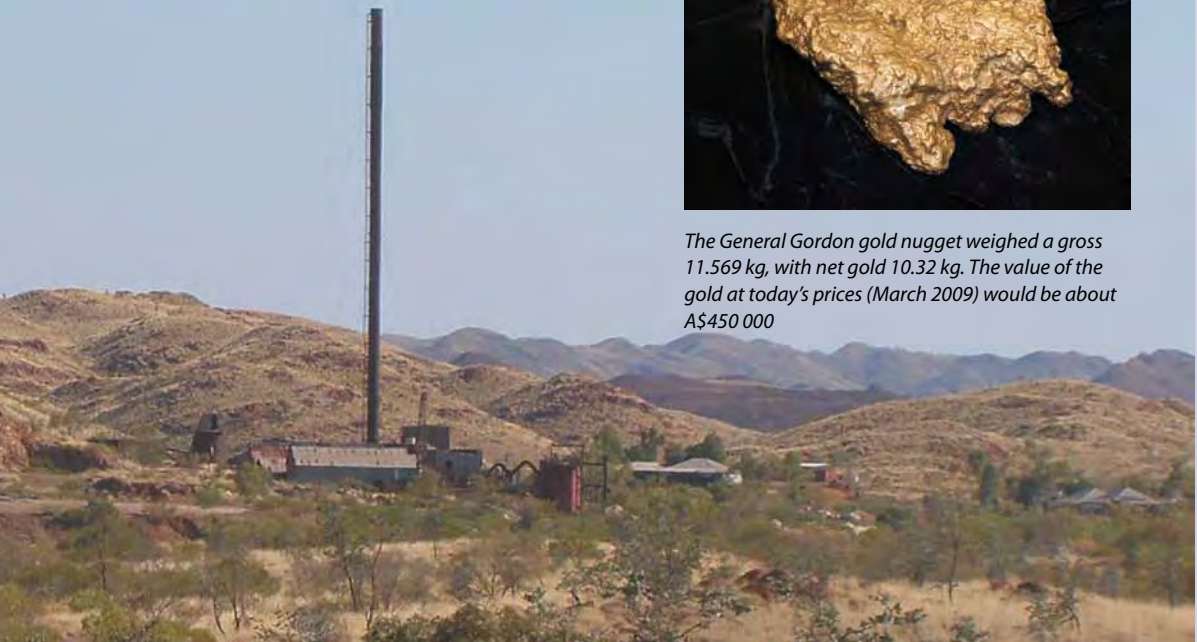
Gold in the Pilbara

In the east Pilbara, production from the most significant centres of Bamboo Creek, Marble Bar, Nullagine, North Pole, Sharks, and Warrawoona peaked in the 1940s then fell away, until a resurgence in the gold price in the early 1980s (together with modern mining and treatment methods) saw a sharp increase in gold production from this region.

Sharks Gully, about 48 km southwest of Marble Bar, produced many large nuggets. Two of the most famous are: the General Gordon nugget (see below), found in 1895, which weighed 11.569 kg; and the Bobby Dazzler nugget, found in 1899, which weighed in at 15.15 kg.



The General Gordon gold nugget weighed a gross 11.569 kg, with net gold 10.32 kg. The value of the gold at today's prices (March 2009) would be about A\$450 000





Stop 6.3 — Geological panorama

21°17.819'S | 119°40.173'E

Directions to Stop 6.3: Reset the trip meter to 0.0 km. Travel for 14.2 km along the Hillside Track to Stop 6.3 and pull well over to the side of the road (21°17.819'S 119°40.173'E).

What you see here

This Stop provides a broad overview of very characteristic geology of this area. The gently rounded hills ahead of you on the right are made up of thick **lava flows** that **erupted** about 2740 million years ago. The flows can be seen on the side of the hill as horizontal terraces (Fig. 1, opposite), and they **dip** gently away from you, as you can see when you swivel around to the left (Fig. 2). Each flow is up to several metres thick and erupted onto, and spread over, the ancient land surface.

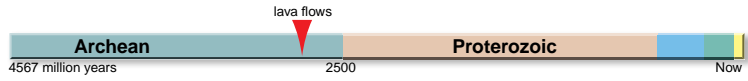
'Pretend' mountains

The higher, reddish hills ahead of you on the left and sweeping back behind you (shown in the panorama of Fig. 3) consist of older **greenstones** and **banded iron-formation (BIF)** of the **Pilbara Supergroup** (3500 million to 3160 million years old) and slightly younger rocks to 2940 million years old. These rocks are more **silica-rich** than the **siltstones**

South



Figure 3: Panorama showing the ancient land surface (shown by the dashed line)



of the Fortescue Group that lie beneath your feet here (but are not **exposed**) and are thus more resistant to **erosion**. An interesting feature of these higher hills is that they are generally flat-topped and almost all are at the same height (Fig. 3). They are thus very different from 'real' mountains formed along collisional plate boundaries (such as the Alps and the Himalayas), which are towering and quite jagged mountains. This difference is because 'real' mountains are thrust up by the collision of **tectonic plates**, whereas these Pilbara mountains are the remnants of an ancient land surface that has been **uplifted** and then carved down by **erosion** over many thousands and even millions of years.

Figure 4 shows the rock history from about 3000 million years ago to the present day.

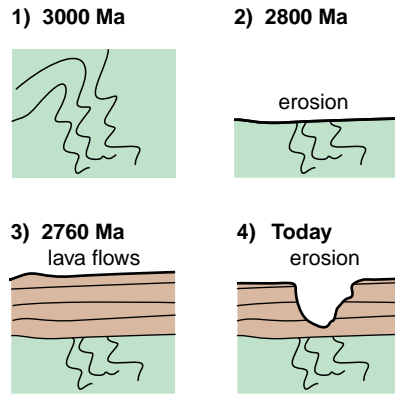


Figure 4 (sketch): Stages in the development of this landscape

- 1) folding of sedimentary rocks;
- 2) erosion cuts down to deeper levels;
- 3) lava flows out over the exposed rocks;
- 4) once again erosion is cutting down through the rocks

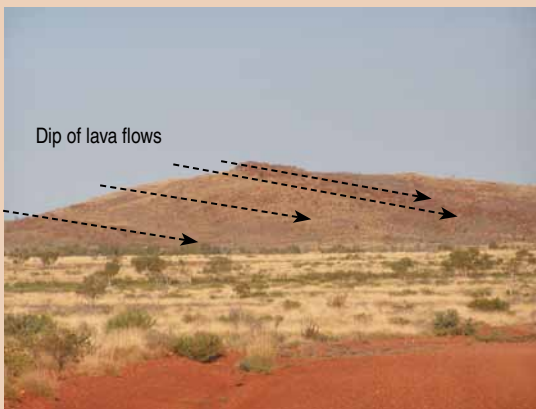


Figure 2: Side view of the lava flows, gently dipping to the north

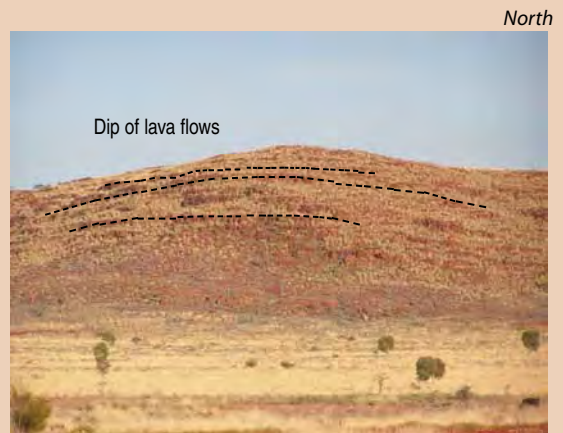


Figure 1: Front view of the lava flows, dipping gently away from viewer



Stop 6.4 — Basaltic pillow breccia

21°19.629'S | 119°36.927'E

*Directions to Stop 6.4: Reset the trip meter to 0.0 km and drive west along the Hillside Track. At 7.2 km (21°19.629'S 119°36.927'E), pull over to side of the road as far as possible, just before a group of white-trunked gum trees. The smooth rock surface of the orange rocks on the south side of the road is the top of a **sandstone** unit within the Fortescue Group. The **dip** of the slope indicates the present-day dip of the originally flat-lying **bedding** surface, which was tilted as a result of **tectonic** forces some 2700 million years ago. Cross the road and walk about 70 m uphill to the north, to a craggy outcrop just past some very weathered, low-lying green rocks.*

What you see here

This spectacular craggy **outcrop** is made up of large light-orange fragments set in a dark brown rock. It is a **basaltic pillow breccia** that formed from a very rapid and huge **eruption** of basaltic **lava** under the sea some 2770 million years ago that covered an area of more than 175 × 200 km in the Pilbara.

Pillows formed, then broke up

The lava was cooled by the water, forming **pillows** (compare with Stop 2.2), some of which are still preserved as large (25–120 cm), round or oval, light-coloured blobs in this rock (Fig. 1). However, these pillows, instead of remaining in place (as at Marble Bar Pool, Stop 2.2), became detached from their lava source and rolled down a steep slope, breaking up into large angular pieces. These are now the light orange parts of the outcrop (see Fig. 2). The smaller dark fragments in between the larger pillow breccia fragments are pieces of basaltic **glass** that broke off from the chilled rinds of the pillows and then fell into place after flying through the air during the violent gaseous eruption. This distinctive unit can be traced for 50 km to the north from here.

Where did all this lava come from?

This basaltic pillow breccia was erupted from the Black Range **dolerite dyke**, a linear **intrusion** that looks like a long black scar on the Earth, and extends for 150 km across the Pilbara (see Stop 6.10).

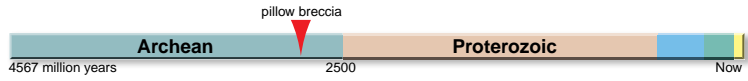


Figure 1: Outcrop of basaltic pillow breccia. Author is indicating a large oval pillow still preserved in the rock



Figure 2: Close-up view showing angular broken fragments of former pillows



Stop 6.5 — Glen Herring Gorge

21°21.169'S 119°36.881'E

Directions to Stop 6.5: Return to your car. Reset the trip meter to 0.0 km. Continue west along the Hillside Track for 1.3 km (21°19.945'S 119°36.294'E) and turn left onto a smaller dirt track into Glen Herring Gorge. Follow this track almost due south for 2.5 km and take a sharp turn left (21°21.207'E 119°36.561'E), downhill into the gorge. Follow the track for 375 m, crossing a small creek near the end, and park on the gravel (21°21.169'S 119°36.881'E). There are camping spots here and it is a lovely spot for a rest and a walk. Sometimes there is a pool in the creek to the north of here that can be used for a dip, but take care as it is shallow and has a rocky bottom.

An ancient gorge revealed today

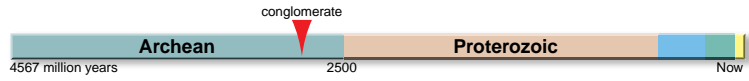
Glen Herring Gorge is of geological interest because it contains sediments that were deposited in a gorge 2775 million years ago that would have looked almost the same as it does today. The ancient gorge would have had steep-sided cliffs and a narrow stream flowing through it, with steep narrow hills and valleys to the south. The only difference between the ancient and modern-day gorges is that there would have been no vegetation covering the ancient hillsides, although the water probably contained **microbial** life, possibly even photosynthesizing bacteria and algae.

What you see here

As you walk north from the parking area along the creek bed, you will walk over **vesicular basalt flows** of the 2775 million year-old Mount Roe Basalt of the Fortescue Group. These smooth, white-weathering rocks have been polished by the flow of the creek and carved into odd shapes. If you look closely at these rocks, you will notice they contain numerous small, white, round- to irregular-shaped blebs (called **amygdales**). The amygdales represent gas bubbles (**vesicles**) in the original basalt that are now filled by secondary minerals (**quartz, calcite**) **precipitated** out of **solution** from later circulating fluids. You will also notice red **fractures** and stains in the rock, which reflect the passage of highly oxidized groundwater through the rock, during more recent episodes of **faulting**.

Boulder conglomerate

As you walk further north, down the gorge, you will notice that the rocks change from smooth-textured basalts to very rough, irregular-textured rocks that are full of cobbles, boulders, pebbles, and sand grains (see Fig. 1). This rock is a **conglomerate** and was deposited from running water, under very high-energy conditions on a steep slope — probably conditions that were much the same as those you see around you today. The boulders in the



conglomerate are large, indicating that high topography was involved, as water alone would be unlikely to transport boulders of this size. Some of the fragments in the conglomerate are very large and probably derived from episodes of faulting, possibly the same fault that formed this gorge. It is fun to see if you can find the **contact** between the basalts and the conglomerates in the floor of the creek — now you are really practising geology!

What is remarkable about this area is that the present land surface has been eroded back to the same level it was over two and a half billion years ago!

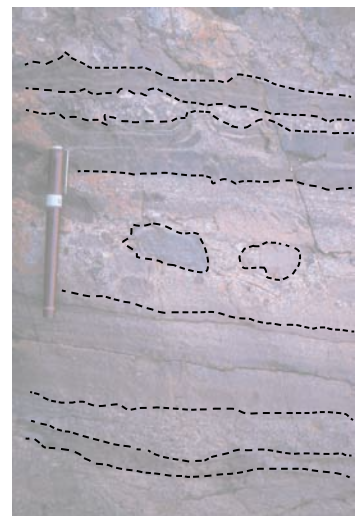
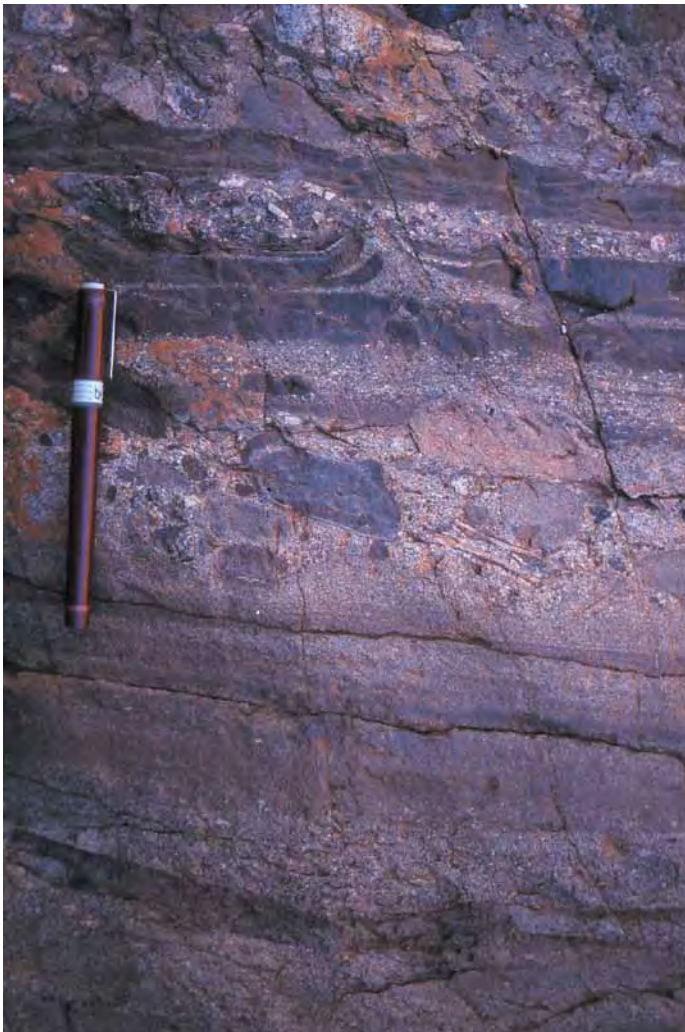


Figure 1:
Bedded conglomerate and sandstone
in Glen Herring Gorge. The different
sedimentary layers are still easily
recognizable (and outlined here)



Stop 6.6 — Ripple-marked siltstone

21°19.916'S 119°36.112'E

Directions to Stop 6.6: Retrace your route out of the gorge back to the Hillside Track. Reset the trip meter to 0.0 km and turn left. Continue for 250 m to Stop 6.6 (21°19.943'S 119°36.127'E). Park the car at the side of the road. Cross the road (north) and walk about 50–100 m up the small stream (left, or west) to a small outcrop in the stream bed (21°19.916'S 119°36.112'E).

What you see here

You can see a small rock pavement or platform in the stream with a series of ripples on the surface of fine-grained **sandstones** and **siltstones** that were deposited under the quiet flow of shallow water across here 2760 million years ago. The ripples are beautifully preserved (Fig. 1).

Beach ripples

Like modern ripples you see when you visit the beach, these ancient ripples are asymmetrical, with one long, low slope and one shorter, steeper slope, as shown in the sketch (Fig. 2). The sand grains were carried up the back of the ripple, and cascaded over the foreset. The steeper slope is on the downstream side of the current, indicating that water flowed to the southeast at this spot such a very long time ago.

'Elephant skin'

If you look around carefully you may even find evidence of early life in the very fine grained **sedimentary rocks**. Some of the surfaces of the siltstones show what is called 'elephant skin' texture, a wrinkly, leathery-looking rock texture (see Fig. 3), which is indicative of a sedimentary surface bound by a thin film of **microbes**. When these **microbial** surfaces are exposed to air, they dry up and wrinkle just as mud dries and forms mud cracks.

As you walk further up the creek ...

If you walk up the creek, heading west-northwest, to the base of the hill, you will see **outcrops** of white pebble **conglomerate**. These rocks are also part of the Hardey Formation and formed in a higher energy depositional environment than the rippled siltstones at the start of this locality. These conglomerates were probably also deposited from streams or rivers, the difference in grain size representing a change in flow regime either within a single stream system, or over time.



Figure 3: Sample of wrinkly 'elephant skin' texture on the surface of a siltstone. Sample is 12 cm wide

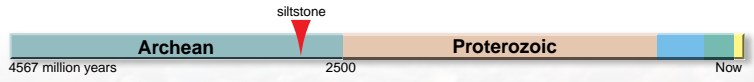
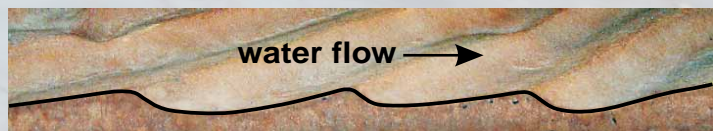


Figure 1: A flat pavement showing beautifully preserved ripple marks in fine-grained sedimentary rocks

Figure 2: Cross sections of asymmetric wave ripples, showing the flatter back slope and the steeper foreset of each ripple



Stop 6.7 — Shaw Granitic Complex and the Black Range

21°23.728'S | 119°33.697'E

Directions to Stop 6.7: Return to your vehicle and follow the Hillside Track to the west and south for about 9.82 km, until you are out of the dark rocks, onto a flat rise overlooking a broad view to the south (21°23.728'S 119°33.697'E). Park at the side of the road.

What you see here

This vantage point affords an unparalleled view over a large tract of the east Pilbara, looking south to the Chichester Range in the far distance, which obscures the valley of the Fortescue River even further south. The flat expanse is entirely underlain by the Shaw **Granitic Complex**, one of the broad **granitic domes** that characterize the east Pilbara (see satellite image in Fig. 1). This dome extends for 90 km from north to south, and 40 km from east to west. It is coloured pink on the map at the beginning of Trail 6. Several of the following Stops will look at discrete components of this dome.

Black Range

The other feature you will notice as you look south is the Black Range, a long line of black hills heading away from this viewpoint (Fig. 2). The range is formed by the Black Range **dolerite dyke**, a single **intrusion** of **mafic magma** into the **crust** that is more than 200 km long, and dated at 2772 million years. This magma was **emplaced** along a great crack in the crust, as it was split apart by the effects of **continental drift**, and represents the feeder conduit to **basalt flows** of the Mount Roe Basalt at the base of the Fortescue Group.



Figure 2: The ribbon-like Black Range dolerite dyke

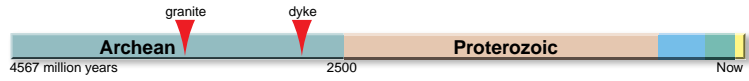


Figure 1: Huge granitic complexes (the yellow shapes) are visible from space!
 This image, captured by satellite, shows the yellow granitic complexes fringed by deformed (striped) greenstone belts.
 Abbreviations: (E) = Mount Edgar Granitic Complex (see Trail 1); (C) = Corunna Downs Granitic Complex (see Trail 3);
 (S) = Shaw Granitic Complex



Stop 6.8 — A most unusual conglomerate

21°26.239'S | 119°32.499'E

Directions to Stop 6.8: Continue southwest along the Hillside Track for about 5.5 km and pull over to the side of the road in the shady bed of Coolyia Creek (21°26.239'S 119°32.499'E).

What you see here

Just north (10–40 m) of the road, in the bed of Coolyia Creek, are a couple of smooth, river-washed **outcrops** of a very unusual boulder **conglomerate** (Fig. 1). The conglomerate forms a linear band extending along **strike** to the northeast away from the tip of the Black Range **dolerite dyke** (see geological sketch, Fig. 2). These rocks look superficially similar to conglomerates deposited by water, except for a few subtle, but telling, differences that can be used to infer a completely different environment of formation; that is, in a hot **fracture** at the propagation tip of the Black Range **dolerite dyke**.

A strange conglomerate

Three of the significant differences between this conglomerate and a **sedimentary conglomerate** are:

- all the large boulders are very highly rounded, whereas the smaller clasts (<2 cm in diameter) within the rock are highly angular (Fig. 3). This is just the opposite of a normal conglomerate deposited by water, where the finer grained material has been transported the furthest and is thus the most rounded;
- there is no **bedding** in this, or any other, outcrop of this particular unit, a feature which distinguishes it from similar rocks deposited by water;
- there are very well rounded pieces of black, fine-grained **basalt** (Fig. 4). These basaltic rocks are quite delicate compared with granitic rocks and would certainly have been completely destroyed if they were transported long distances together with the granitic boulders in water. This suggests that the basaltic clasts were somehow introduced at a late stage in the formation of the conglomerate.

How did such a rock form?

The origin of this conglomerate is directly related to the **emplacement** of the Black Range dolerite dyke: the dyke is thought to have been emplaced along a **fracture** growing from the south-southwest to the north-northeast. As it grew, the dyke opened up an empty fracture in front of it, into which granitic boulders (sourced from across the Shaw Granitic Complex to the south) fell. Gases released from the **magma** mixed with **groundwaters** to form high-pressure steam in the fracture, which mixed and milled the granitic boulders to their highly spherical shapes. Minor additions of basaltic magma formed the darker blobs in this unusual rock.

Figure 1: An unusual conglomerate made up of poorly sorted and highly rounded granite boulders

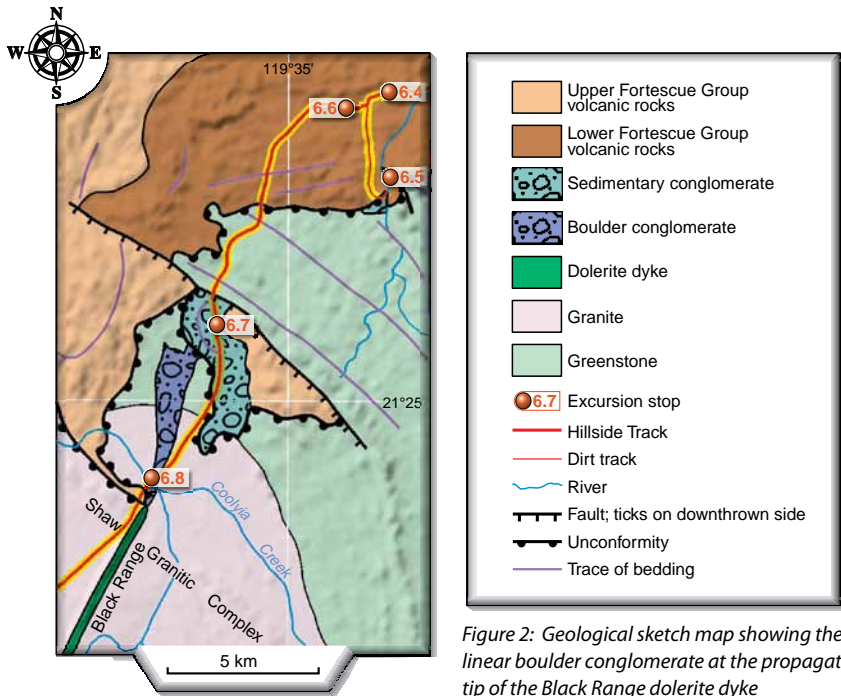
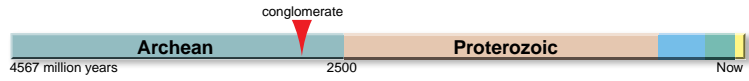


Figure 2: Geological sketch map showing the linear boulder conglomerate at the propagation tip of the Black Range dolerite dyke



Figure 3: (above left) Detail of boulder conglomerate, showing rock flour (dark, smooth area) between granitic clasts, the result of very high degrees of mechanical milling

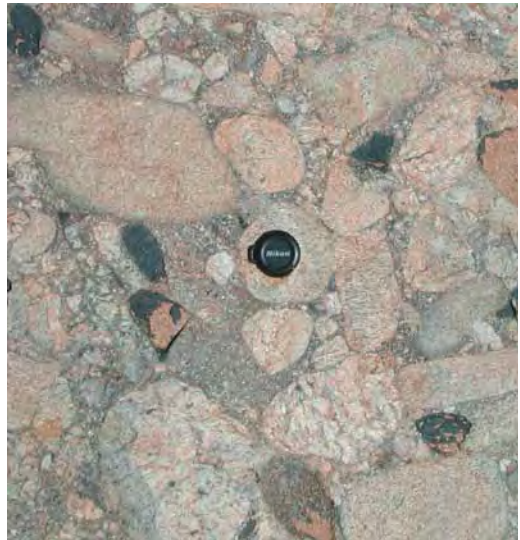


Figure 4: (above right) Detail of boulder conglomerate, showing rare basaltic pebbles (black) and the highly angular nature of the smaller granite pieces (white)



Stop 6.9 — Alluvial tin–tantalum mining

21°30.721'S | 119°25.624'E

Directions to Stop 6.9: Drive south along the Hillside Track, following the Black Range dolerite dyke, then continue to the southwest for a total of about 14.77 km (21°30.721'S 119°25.624'E).

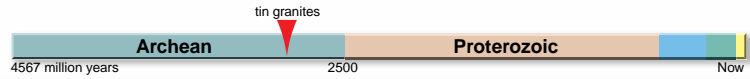
What you see here

To the south of the road here you can see low hills of red gravel that were pushed up by bulldozers from the creek beds during the heyday of **tin–tantalum** mining in the east Pilbara, between the 1950s and 1980s. Almost 16 000 t of **cassiterite** (tin oxide, SnO_2) was produced from the entire **Pilbara Craton** up to 1977, for a total value of A\$18.5 million. Some 900 t of tantalite concentrate and 82 t of **columbite** was also mined. The miners found that the minerals were concentrated in gravels in the creek beds around the edges of 'late' **granites**, such as the granite exposed at Spear Hill (see Fig. 1 opposite). The creeks essentially acted as mineral concentrators, transporting pieces of the heavy black tin ore (Fig. 2) eroded from the coarse-grained granite **veins** that emanated from the margins of these large bodies of granite.

This area is part of the Pilga Mining Centre, and there were several other mining centres within the Shaw Granitic Complex, dotted around the edge of the large **dome** of granite.



Figure 2: Alluvial cassiterite



Go to the tin-bearing granite

To see the Spear Hill Monzogranite continue for 2.7 km along the Hillside Track and stop in the sandy bed of Cooglegong Creek. (21°31.128'S 119°24.129'E).

Walk about 50 m south to a low outcrop in the middle of the creek bed (21°31.156'S 119°24.125'E).

The large size of the **K-feldspar crystals** scattered through the granite is indicative of a slow rate of cooling of the **magma**. Cutting across the granite are thin veins of light-grey **quartz**, filling a small network of **fractures**. In one of the veins can be seen a black mineral, about 0.5 cm wide, which is the tin-bearing mineral cassiterite.

Age dating of the zircons from these tin–tantalum granites has shown that the granites were emplaced about 2850 million years ago. These tin-bearing granites were the last of several **melting** events in the **crust** that started some 3490 million years ago. Multiple melting events concentrated elements that are normally only sparsely distributed in granites: indeed, it is through this gradual concentration of rare elements that many ore deposits are formed. **Emplacement** of these 'young' tin granites was the last event to affect the east Pilbara **basement terrane** and resulted in its stabilization, which has lasted up to the present day.



Figure 1: View of the Spear Hill Monzogranite, one of the sources of the tin mineralization in the east Pilbara



Stop 6.10 — Black Range dolerite dyke

21°43.255'S | 119°24.136'E

Directions to Stop 6.10: Continue west along the Hillside Track for 4.14 km from Cooglegong Creek (at 21°31.128'S 119°24.129'E), taking the left, less prominent, fork in the road (21°31.214'S 119°21.796'E), and head due south for a further 19.36 km (total of 23.5 km), to the turnoff sign to Bamboo Springs on the left (21°42.801'S 119°23.914'E), just before the Hillside Track turns to cross the Shaw River. Continue driving south for about 900 m into the bed of the Shaw River, with a hill of dark rock to the north (21°43.255'S 119°24.136'E).

What you see here

As you look across the river to the north from this position you can see good **exposures** and large, loose angular blocks of black, medium- to coarse-grained dolerite of the Black Range **dolerite dyke** which, at this point, is approximately 250 m wide. A sample taken from this locality was age dated at 2772 million years. To form the dyke, the dolerite fills up a long, sinuous **fracture** in the Earth's **crust**. There are many such dykes leaving rocky traces across the whole of the Pilbara (e.g. Zebra Hill dyke in the west Pilbara shown in Fig. 1).

A further 250 m along the track, you will see a large hill of treated river gravels and two of the old concentrators used by the alluvial tin miners to separate the tin from the waste gravels (Fig. 3).



Figure 1: Typical weathering pattern of dolerite dykes. Blocks of dolerite tumble down the hillslopes making spectacular patterns amongst the spinifex

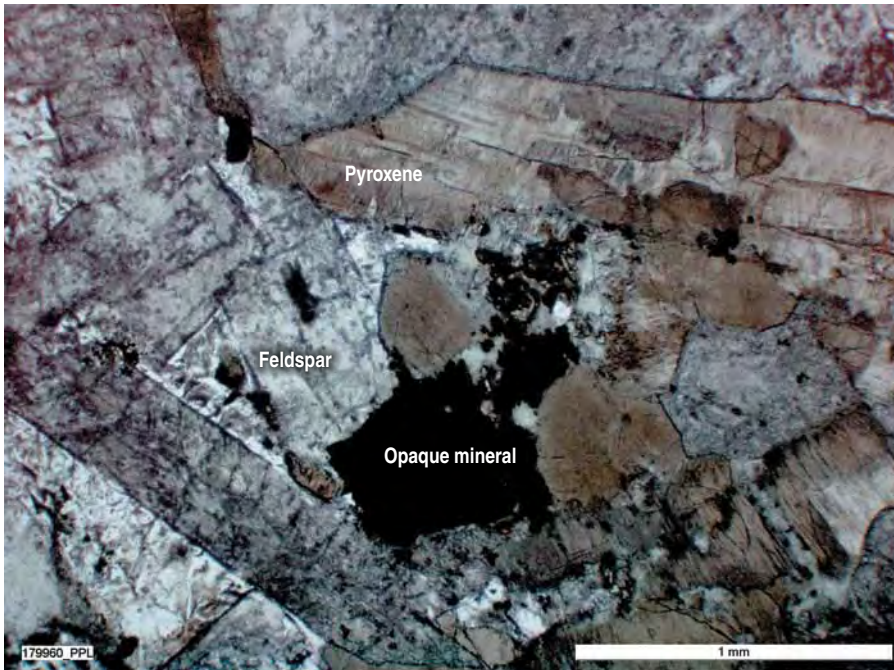
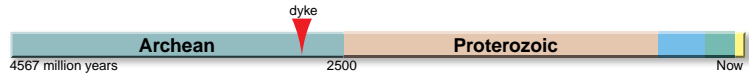


Figure 2: This is a **thin section of dolerite** — a sliver of rock ground down so thin it becomes translucent, allowing the rock to be studied with a microscope. This dolerite is made up of several minerals typical of dolerites the world over: feldspar (greyish), pyroxene (brown), and a black (opaque) mineral, possibly ilmenite or magnetite. Notice the scale



Figure 3: Abandoned spiral concentrators formerly used to separate the heavy tin minerals from waste material



Stop 6.11 — Mylonitic gneiss, Tambourah Creek

21°45.410'S | 119°14.357'E

Directions to Stop 6.11: Return north to the Hillside Track and turn left. Cross the Shaw River, drive west along the track for 13.77 km. Notice that westward from here, the rocks are becoming like knife blades, sticking up vertically from the flat plains. Continue west for a further 4.13 km (total 17.9 km) to a turnoff on the right onto a small track (21°45.468'S 119°14.514'E) that leads for 140 m to the top of a low hill on the south bank of Tambourah Creek. Park the car. Walk down into the creek and head west (left, upstream) for about 100 m and clamber over the rocks onto a large, low stream-washed outcrop (21°45.410'S 119°14.357'E).

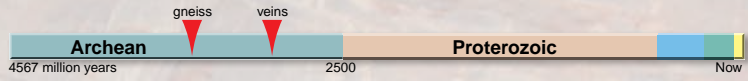
Since the last Stop, you have driven across the western half of the 40 km-wide Shaw **Granitic Complex** and are very near its western **contact**, where it is **sheared** and **faulted** against the Western Shaw **greenstone belt** (see map at beginning of Trail 6).

What you see here

This spectacular **outcrop** of striped blue-grey and white rock is a wonderful example of what happens to **granitic rocks** when they become sheared within the middle part of the Earth's **crust**; they are heated to such a degree that they start to melt and flow. If you walk to the northeastern corner of this outcrop, you can see less-deformed examples of 3420 million year-old blue-grey **granites** that are cut by a random network of white **veins** of younger (about 2940 million years old) coarse-grained granite containing large crystals of **feldspar** (Fig. 1). As you walk to the west, you will notice that the white granite veins become narrower, the **crystals** within the veins become smaller and more rounded, and the veins all become parallel to one another. If you look closely, you will notice that some of the veins are folded into tight 'S' shapes (Fig. 2), and that individual rounded feldspar crystals have been rotated (Fig. 3). Such textures indicate the rocks have been highly **deformed**.

Deformed rocks

The **shear deformation** happened 2940 million years ago, and resulted from a **craton-wide deformation** event that affected the Pilbara **crust** from this point westward, for about 250 km, all the way to Karratha and beyond. This major period of deformation is called the **North Pilbara Orogeny** and resulted in the movement of large fault-bound packages of rock within the crust for several tens of kilometres along **strike** of one another. During this mountain-building event, fluids were circulating through the crust, mobilizing and concentrating gold to form many significant gold deposits, as well as an emerald mine.



This sequence of photos shows the changes in textures in the granite as deformation increases.

Figure 1: Undeformed granite veins cutting granite gneiss about 3420 million years old

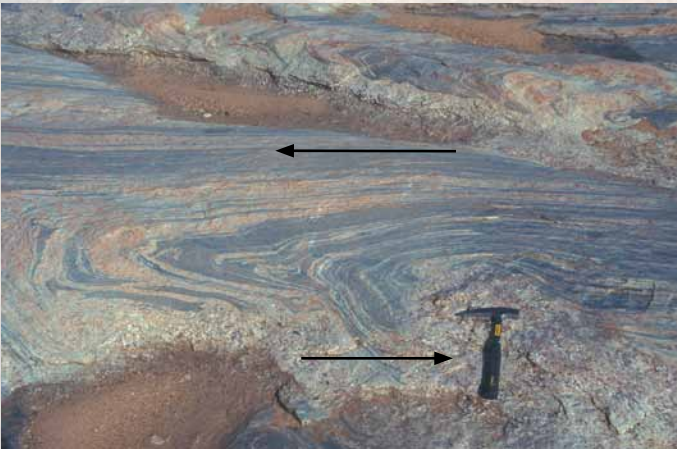
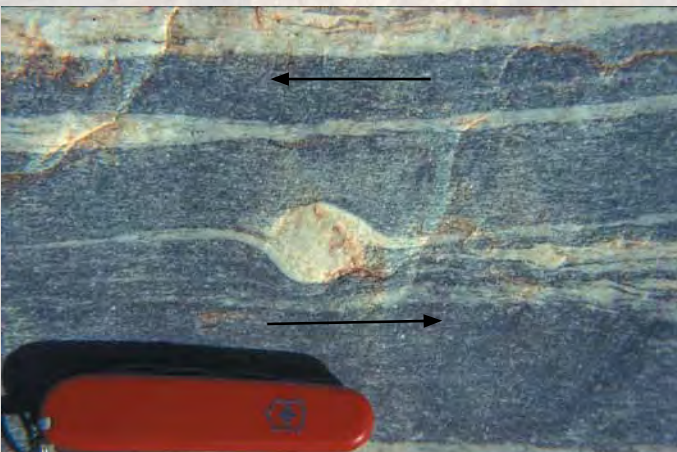


Figure 2: Sheared granitic gneiss, deformed into half of an 'S'-shaped fold. Arrows show direction of shearing



*Figure 3: Sheared granitic gneiss (now a **mylonite**) with a rotated crystal of K-feldspar (white circular grain in centre). The asymmetry of the grain indicates sinistral (top to left) shear movement, shown by the arrows*



Stop 6.12 — Granite–greenstone contact

21°45.073'S | 119°11.063'E

Directions to Stop 6.12: Return to the Hillside Track and turn right, heading west. Continue for some 6.56 km, across the dark, ridged terrain of the Western Shaw greenstone belt and onto the orange-weathering rocks and flat topography of the Tambourah Dome, another granite of the Yule Granitic Complex (21°45.073'S, 119°11.063'E). Pull right off to the side of the track and look back east towards the hill.

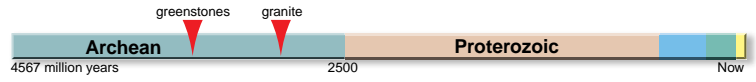
Geologists search for **contacts** between two different rock types to help them confirm relationships and ages between adjacent rock packages. Because they are rare, an **Archean** contact between **granite** and the surrounding **greenstone belt** is an exciting find!

What you see here

Looking back to the east on the side of the hill, you can see thick sheets of deep-orange granite of the Tambourah **Dome** interlayered with the dark greenish-black **metabasalts** of the Western Shaw greenstone belt. The granitic rocks represent **crystallized magmas** that were **emplaced** within the greenstones some 2900 million years ago. The greenstones themselves, were originally **volcanic rocks** that **erupted** onto the Earth's surface 3450 million years ago.

Tambourah Mining Centre

To the east of the contact, just on the other side of the hill, is a zone of significant gold mineralization known as the Tambourah Mining Centre. Reports from the early 1890s gave values of 1 oz (31 g) of gold to the tonne or better on very long quartz **reefs**, and the area has continued to be a site for gold prospecting ever since. Gold mineralization is associated with a series of granitic **veins** emanating from the Tambourah Dome into the greenstones.



Orange granite dykes (dotted) cut through dark hills of metamorphosed greenstone



Stop 6.13 — Granite tors

21°40.964'S | 119°03.052'E

Directions to Stop 6.13: Return to your vehicle and proceed west for about 18 km through a series of twists and turns across the Tambourah Dome, through a re-entrant of the Western Shaw greenstone belt, and out onto the flat expanses (or 'downs') of the main part of the Yule Granitic Complex (21°40.964'S 119°03.052'E).

What you see here

As you drive west from this point, you will notice that the landscape has changed dramatically and that the flat plains are broken by several pyramid-shaped hills of **granite** (Fig. 1). These hills are made up of rounded granitic boulders that have seemingly been piled one atop the other by some industrious, Virgoan giant, intent on cleaning up the neighbourhood! However, appearances can be deceptive and these **tors** are actually remnants from a time past when the landscape was less deeply eroded and the land surface higher than it is today — level with the tops of the pyramid-shaped hills. Over many tens of thousands of years (a blink of an eye in geological time), most of the terrain has been eroded down to ground level, but some of the more resistant granites have weathered more slowly, remaining as hills.



Figure 1: Granite tors north of the Hillside Track result from arid weathering

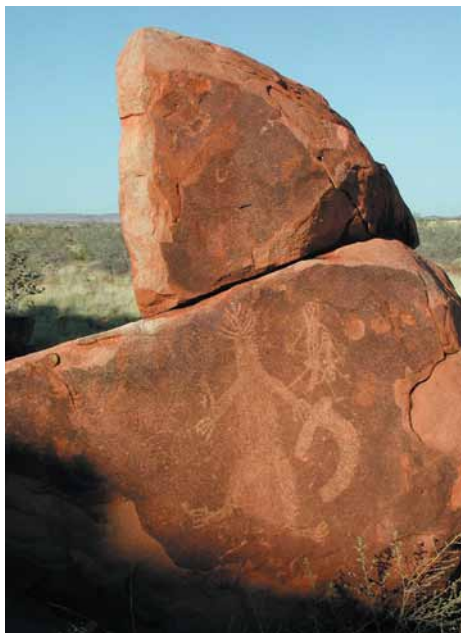
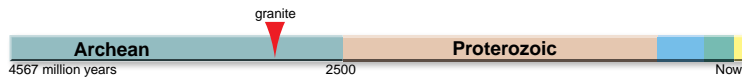


Figure 2: Tors (granite hills) with Aboriginal petroglyphs inscribed into the brown desert varnish

Arid weathering

The piles of boulders arise from a peculiar style of arid weathering, whereby the extreme cold-hot variation of the night-day cycles (up to 35°C over nine hours) causes the granitic rocks to expand and contract, and eventually **fracture** into large blocks along what are sometimes perfectly straight, even fractures through the rock. These fractures allow the rains and dry sand to penetrate along all sides of the rock, wearing away the edges and eventually forming rounded boulders. Over time the fractures penetrate down through the hill, allowing the spheroidal weathering to proceed through a thick column of rock.

Petroglyphs

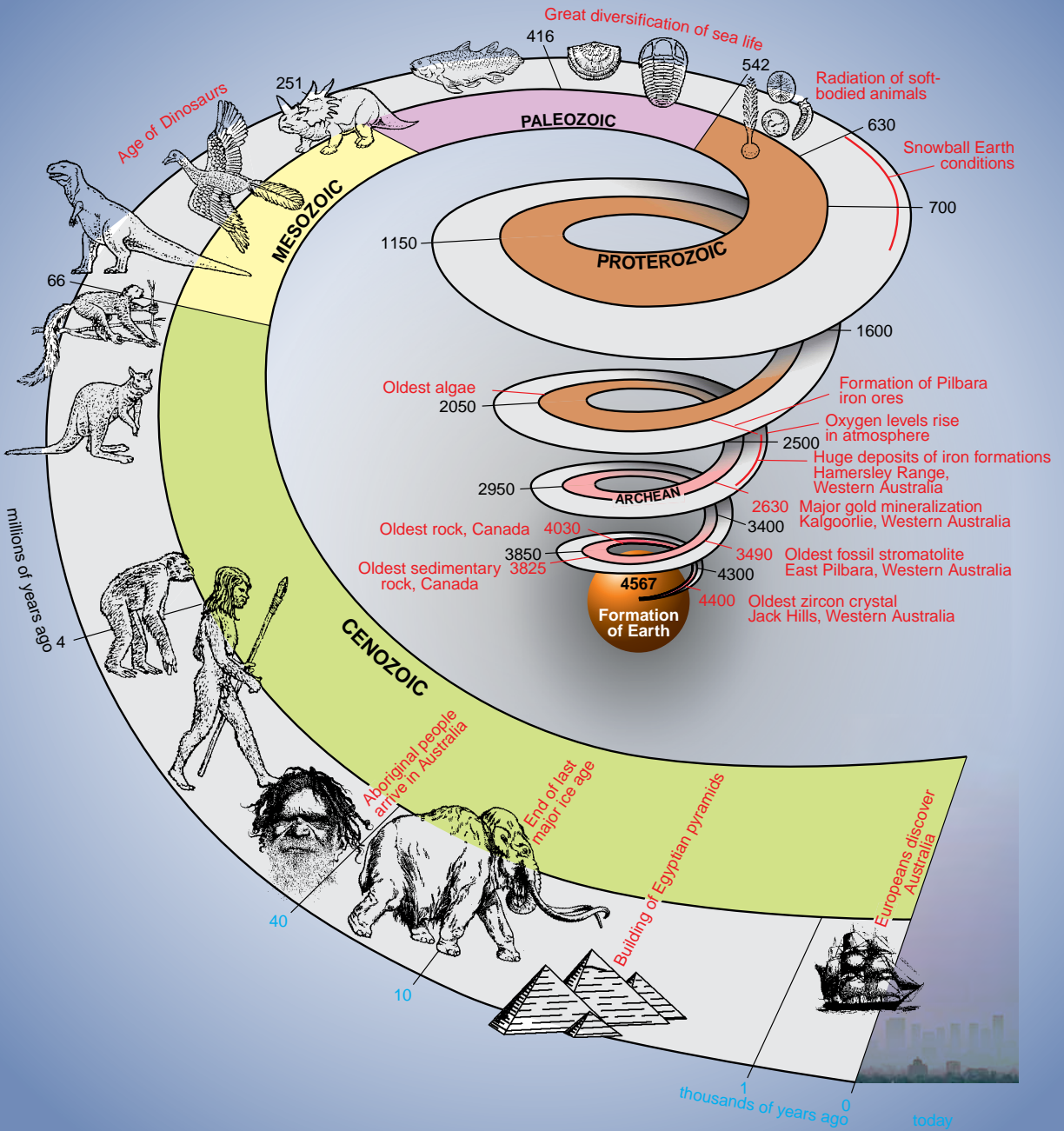
Most of these pyramidal hills are festooned with Aboriginal petroglyphs, or rock carvings

(Fig. 2). The weathered boulders contain a particularly clean dark surface, called **desert varnish**, and light-grey fresh granite that is only a few millimetres below the surface (Fig. 3). The carvings were made by tapping a stone against the dark desert-varnish surface and exposing the fresh rock beneath. Attempts have been made to date these rock carvings, but it is a difficult and imprecise science, with some estimates suggesting they are as much as 17 000 years old.

This ends Trail 6. There are several options: drive to the Great Northern Highway, travel to Newman, head northwest to Port Hedland, or return to Marble Bar to travel another of the stunning Pilbara Trails.



Figure 3: Outcrop of granite, showing the effects of arid weathering in the Pilbara. 'Desert varnish' is everywhere



Spiralling back right to the beginning of the Earth, this time-scale ribbon shows just how long ago the Earth formed and how recently man appeared on the scene

Knowing Chapters 1 to 4

Chapter 1 Deep Time and the early Earth

Four pages tell the story of the Earth from the Big Bang right up to the present day

Chapter 2 The Earth around us

Some background knowledge of rocks and minerals, and some of the concepts important to geologists

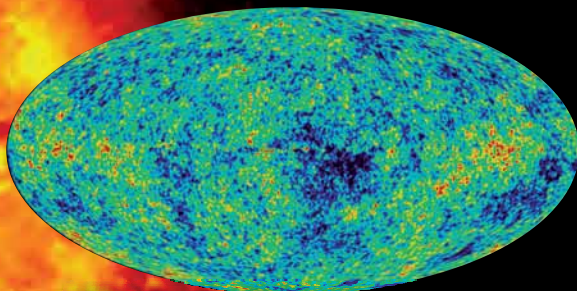
Chapter 3 Where did it all begin? The ancient geological history of the east Pilbara

The geological story of the east Pilbara: a billion-year saga

Chapter 4 The people of the Pilbara — Aboriginal people, pastoralists, and miners

A short history of the people of the Pilbara: the earliest peoples, the characters of the past, and modern-day inhabitants

In the beginning
13.7 billion years ago
the Big Bang
formed the Universe



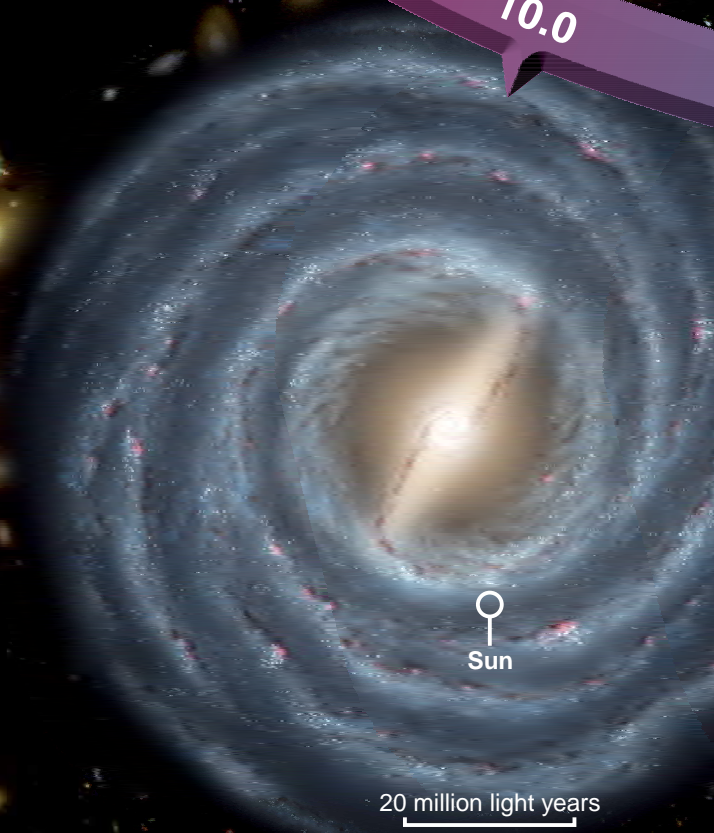
The afterglow light pattern from the
big bang, showing the beginning
of material for galaxy formation

13.7

13.3

12.7

10.0



Sun

20 million light years

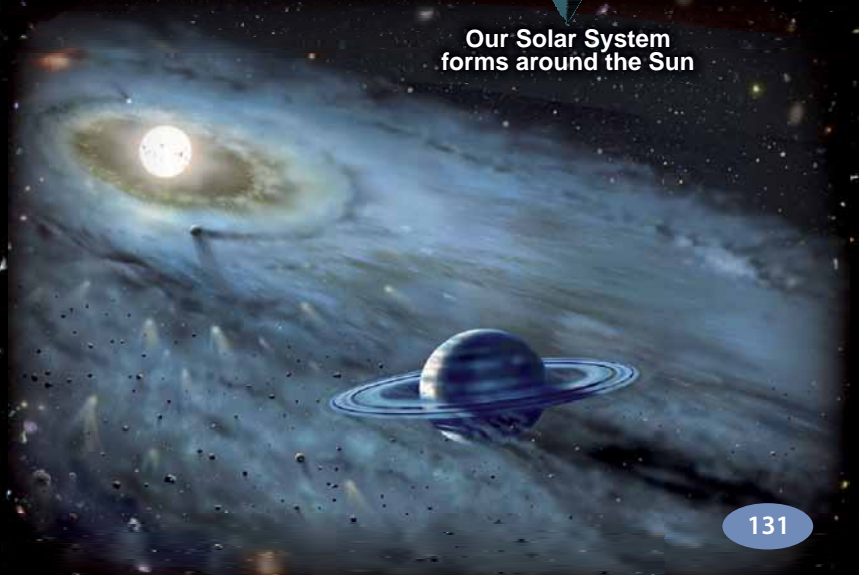
Chapter 1



Earth collides with an asteroid, the size of Mars, and the Moon is created (4.5 billion years ago)

4.567

Our Solar System forms around the Sun



The Milky Way galaxy is formed

billions of years ago



The first tiny pieces of crust are preserved on the surface of a much hotter Earth, and life establishes a foothold (3.5 billion years ago)

Pilbara geology starts here



Life gains a firm foothold (2.7 billion years ago)

3.85

3.5

2.7

2.5

Earth experiences a period of heavy bombardment by large meteorites, preventing the preservation of large continental plates (4.0 to 3.85 billion years ago)





Earth plunges into a prolonged cold period called Snowball Earth where glacial conditions prevail over most of the globe (800 to 650 million years ago)

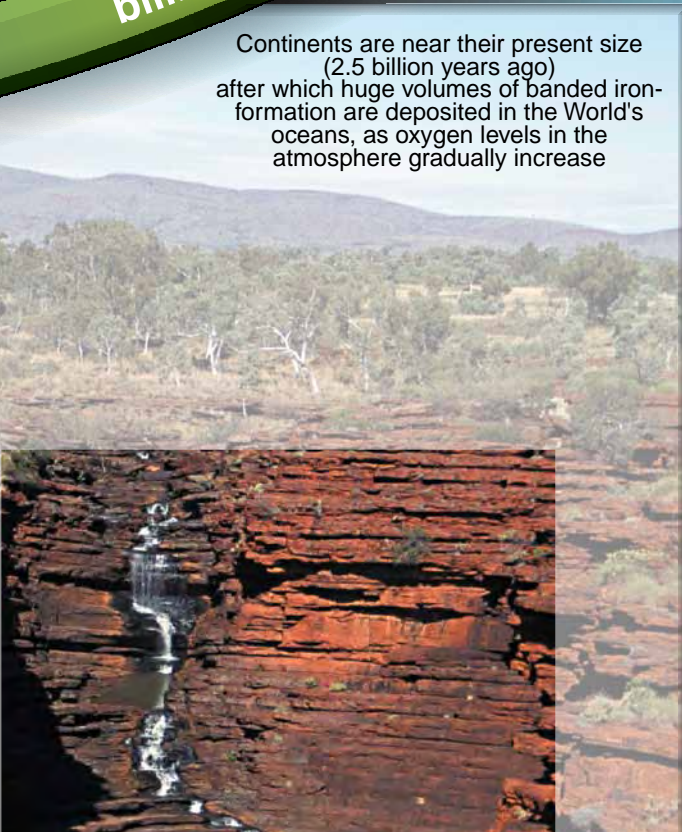
billions of years ago

0.8

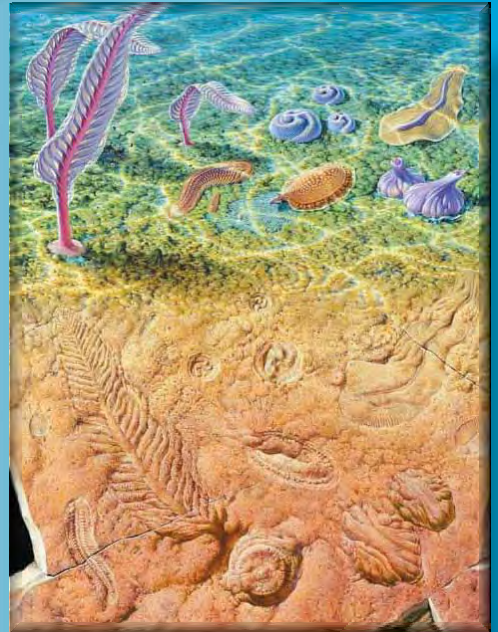
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Today

Continents are near their present size (2.5 billion years ago) after which huge volumes of banded iron-formation are deposited in the World's oceans, as oxygen levels in the atmosphere gradually increase



The rise of animals (542 million years ago)



Knowing

Chapter 2 The Earth around us

The ancient Greeks realized that our environment is made up of four components: earth, water, air, and living things. Scientists call these the **lithosphere**, the **hydrosphere**, the **atmosphere**, and the **biosphere**. But these do not exist in isolation; they interact and are affected by each other. For instance, rocks are **altered** or **weathered** by water, air, and by living things; volcanoes affect the hydrosphere, the atmosphere, and the biosphere, including mankind.

Searching for clues

The lithosphere — the rocks and minerals that make up the Earth — is the domain of geologists, scientists who study the Earth. The study of geology is a bit like doing a complex puzzle with lots of the pieces missing. The Earth has had a long history and only a few fragments of old rocks exist, the fossil record is incomplete, and younger rocks obscure much of what is below. Geologists search for clues to the long distant past by studying how the rocks are forming today, and how they are **eroding**. By understanding geological processes happening today (see Fig. 1), and through mapping of ancient rocks and the application of scientific techniques (Fig. 2), geologists are able to unravel the past.

Figure 1: With awesome power, an ash cloud blasts up into the sky from an erupting volcano. Guagua Pichincha, Quito, Ecuador. Image courtesy of Getty Images



Figure 2: The author mapping steeply dipping sedimentary rocks (shown by the dashed lines) deposited 2700 million years ago



The rock cycle

The formation of **igneous rocks**, then their **erosion**, **transport**, and **deposition** as clastic **sedimentary rocks**, and their **metamorphism** during **collisional mountain building**, is an ongoing process that may take millions of years. This is known as the **rock cycle**.

Can a rock have a 'life' cycle?

The 'life' cycle of a rock may be something like this:

- an *igneous rock* (e.g. granite) slowly **crystallizes** from a **magma** deep within the Earth
- during **uplift**, the overlying rocks are eroded and the granite is exposed to wind, rain, and ice that erode and break down the granite into small rock particles
- these rock particles are transported by rivers to the sea and deposited on the sea floor, where they are compacted and hardened to form a *sedimentary rock*
- this rock may be subsequently buried under younger rocks and subjected to heat and pressure, forming a *metamorphic rock*
- this rock may then be ready for remelting or weathering again — the next phase of the rock cycle.

The rock cycle has come full circle: from formation, to disintegration, to deposition, burial, and formation once again. On and on, this cycle has continued for millions, and even billions of years. The wonder of the Pilbara is that although some rocks are ancient, dating back more than 3500 million years, they are still relatively fresh and have escaped disintegration. They show easily recognizable **textures**, structures, and fossils that developed when the rocks first formed, giving us a 'window' back through time. Part of the reason the very ancient Pilbara rocks have been well

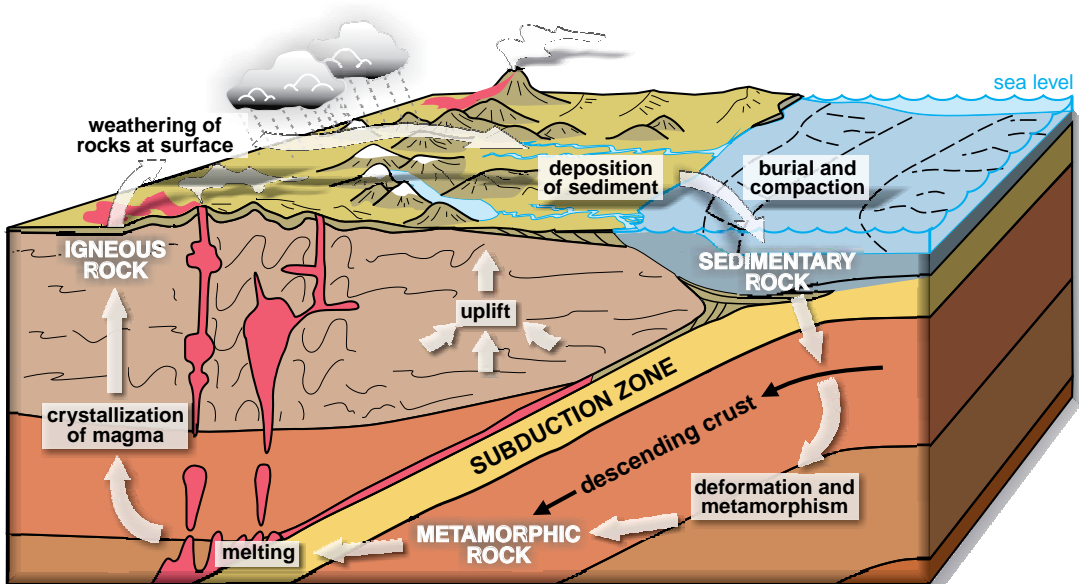


Figure 3: The rock cycle. Follow the white arrows on a continuous journey through rock formation and then destruction

preserved for so long is that they have been covered by younger rocks (some 2700 to 2200 million years old) that have only recently been weathered away as a result of Australia's northward drift and collision with Indonesia and Papua New Guinea that is depressing the northern part of our continent, and uplifting the south-southwest part and the Pilbara region.

Ages of rocks

Australia has the longest preserved rock record anywhere on Earth. This record includes the oldest Earth *material*: tiny grains of the mineral **zircon** ($ZrSiO_4$), dated to 4404 million years old, recovered from 3000 million year-old sedimentary rocks from Jack Hills in the northwestern part of Western Australia (Fig. 4). The oldest *rocks* in Australia are 3730 million year-old **gneisses** and metamorphosed igneous rocks found near Mount Narryer, also in the northwestern part of Western Australia. The east Pilbara is home to rocks some 3500 million years old. The youngest rocks are forming along the coast right now, as **limestone reefs** such as Ningaloo Reef and those at Rottneest Island (Fig. 5). Rocks of all ages in between these two extremes are found throughout the rest of Western Australia.



Figure 4: Photo of Jack Hills sedimentary rocks, which contain tiny grains of ancient zircon



Figure 5: Young limestone reefs at Rottneest Island

Do the continents really move?

In the early twentieth century a young German, Alfred Wegener, proposed the theory of **continental drift** to explain the apparent jigsaw-fit of the continents and identical fossil finds across several continents. But without any mechanism to explain such massive movement of the continents, his theory foundered.

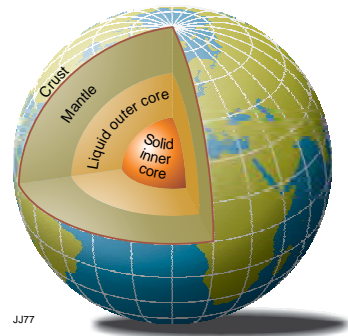
Underwater discoveries

Things changed in the 1950s and 1960s when discoveries of mid-ocean ridges as high as Mount Everest, and deep trenches more than 10 000 m beneath the surface of the oceans suggested the formation and destruction of **oceanic crust**. This evidence, together with the discovery (using geophysical techniques) of stripes in the magnetic anomaly pattern on the sea floor, led to development of a new model, called **plate tectonics**, which described the dynamic forces operating on Earth and accounted for the movement of the continents.

Floating plates

We now know that Earth is divided into several rigid, but mobile **plates** that float on the **mantle**. The mantle is the semi-solid, middle layer of the Earth with strong convection currents heated from the Earth's core (Fig. 6).

Most plates consist of a combination of oceanic and **continental crust**, except for the Pacific Plate, which consists entirely of oceanic crust (Fig. 7). The tectonic plates of Earth move relative to one another at a slow, but measurable, rate of about 10 mm per year.



JJ77

Figure 6: Cutaway view, showing the layers within the Earth

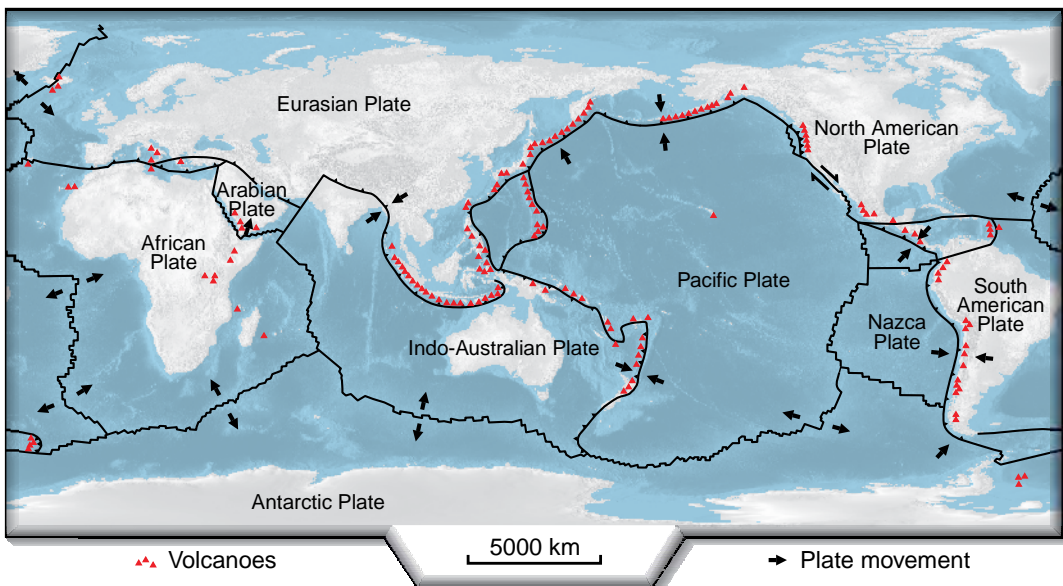


Figure 7: Map of the Earth showing the various tectonic plates. Black arrows show the direction of movement of the plates relative to one another

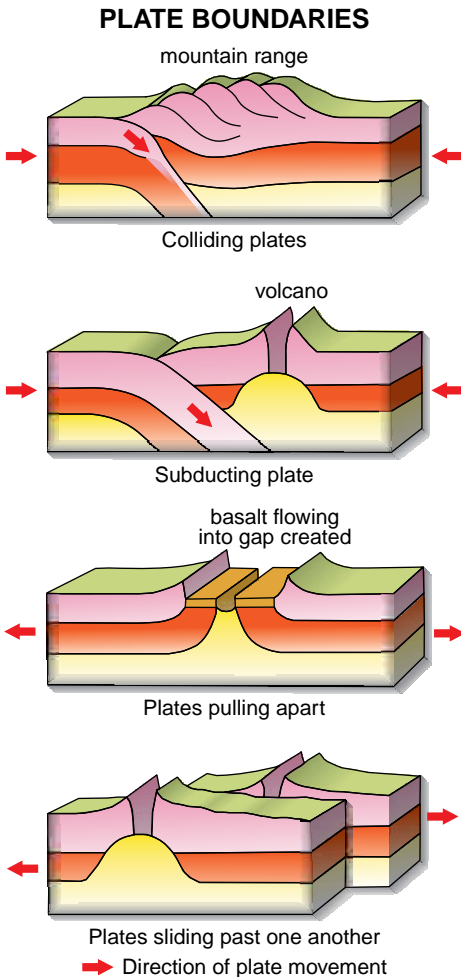


Figure 8: Sketch showing four types of plate boundaries (as shown by the arrows in Figure 7)

Figure 8 shows the different types of plates. The margins of neighbouring plates may be:

- crashing into each other at convergent plate boundaries (e.g. Indian and Eurasian plates, producing the Himalayan Mountains);
- subducting under one another (another type of convergent plate boundary, for example the Pacific Plate subducting under the North American Plate);
- pulling apart from one another at spreading zones, such as the mid-Atlantic Ridge and East Pacific Rise; or
- sliding past one another at transform plate boundaries (e.g. San Andreas fault in California).

Solving some geological puzzles

The plate tectonics model answers many of the 'big' questions posed in geology, such as the origin of mountain ranges, the distribution of earthquakes and volcanoes (for example, the Pacific Ring of Fire you can see on Fig. 7), and the jigsaw fit of some continents to one another (e.g. South America and Africa).

This model explains how new oceanic crust is formed above upwelling, hot mantle at oceanic spreading centres, where the crust is tearing apart (Fig. 8). At the other end of the cycle, **subduction** explains how oceanic crust is recycled back into the mantle and why earthquakes and volcanoes are concentrated along the zones where plates converge at deep-sea trenches (Fig. 8).

Just what are rocks and minerals?

Rocks

Rocks are a mixture of one or more, but usually several, minerals. Geologists identify different types of rocks by the combination of their minerals, their shape, and their texture. Once the rock is identified, this tells the geologist *how* the rock was formed.

Three types of rocks

Rocks are classified into three types — **igneous**, **sedimentary**, and **metamorphic** — depending on how the rock was formed.

Igneous rocks are produced when liquid rock — called **magma** — from deep within the Earth cools and solidifies, either on the Earth's surface (e.g. as **lava** flowing from a **volcano**) or deep within the crust (e.g. as **granite**; see Fig. 9). You can recognize igneous rocks because they are made up of interlocking minerals, or of glass. A common type of **extrusive igneous rock** is **basalt**, which forms by the solidification of lava: it makes up nearly all of the oceanic crust and oceanic islands, such as Hawaii and Iceland (Fig. 10). **Granite** is the most common **intrusive igneous rock** crystallizing deep within the Earth. The minerals of granite are: **feldspar**, **quartz**, **hornblende**, and **biotite** (Fig. 11). Granite appears at the Earth's surface when the rocks lying over the top of it have all been eroded away. You will get to know granite very well during your travels in the Pilbara!

Sedimentary rocks are rocks that have been **deposited** by water. **Clastic sedimentary rocks** are rocks made up of particles of older rocks and/or mineral grains that have been weathered by wind, water, or ice. The particles can be boulders, cobbles, pebbles, gravel, sand, silt, or clay transported to new locations and deposited in layers in rivers and lakes, on beaches, and in oceans. These layers are slowly



Figure 9: Rectangular crystal of feldspar (about 1 cm long) in granite from the east Pilbara



Figure 10: Fresh Hawaiian basalt has flowed across the Island, into the sea. You can see the individual flows as layers in the cliff

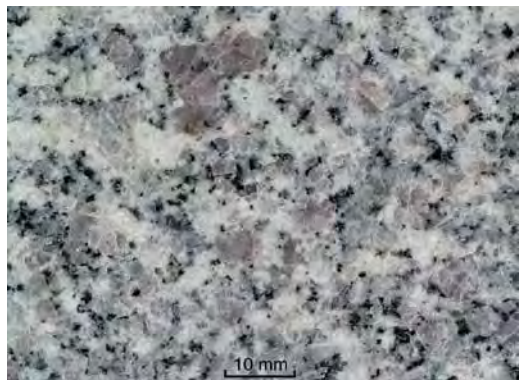


Figure 11: Polished slab of fresh granite showing interlocking crystals of feldspar (white and pink), quartz (grey), hornblende (black), and biotite (black)

compacted and hardened to form a sedimentary rock, e.g. **conglomerate** (see Fig. 12), **sandstone**, and **shale** are some examples. Fossils (remnants of living creatures) may be found in sedimentary rocks, as well as features such as wave ripple-marks (Figs 13, 14), footprints, mudcracks, burrows, and even raindrop impressions that give a great deal of information about how and where the rock formed.



Figure 12: A conglomerate

A second type of sedimentary rock is a **chemical sedimentary rock**, such as **limestone**, **chert**, and **banded iron-formation** (Fig. 15). These rocks have been **precipitated** from **solution** in seawater, by **evaporation**, or by microbes and other living organisms, such as corals.

Metamorphic rocks result from the transformation of either igneous or sedimentary rocks by heat and pressure deep within the Earth's crust. Metamorphic rocks form when pre-existing rocks are buried by overlying rocks, most commonly within zones of mountain building where tectonic plates collide. The great pressures and temperatures in these zones cause the rocks to fracture, buckle, and even melt (Fig. 16). New minerals are formed during this process, and sometimes these minerals are aligned to give a prominent **fabric** or **layering** in the rocks, giving them a strongly banded or streaky appearance. **Schist**, **gneiss** (pronounced 'nice'), **marble**, and quartzite are common examples of metamorphic rocks.

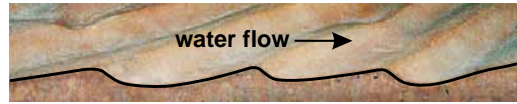


Figure 13: Cross sections of asymmetric ripples, showing the flatter back slope and the steeper foreset slope of each ripple



Figure 14: Beautifully preserved ancient ripple marks in siltstone (you will visit this locality at Stop 6.6)



Figure 15: Banded iron-formation



Figure 16: Contorted and melted metamorphic gneiss

Minerals

Minerals are natural, inorganic (not living), uniform chemical substances with a crystal structure and certain characteristic properties. Of the thousands of minerals that have been identified, only about 100 are common, and these are easily identified by their physical properties — such as colour, shape or form, crystal structure, how the crystal breaks or cracks when hit with a hammer, its feel, hardness, and density (specific gravity); geologists may also sniff or lick minerals to help identify them! A common mineral we all know is salt (its mineral name is '**halite**'). Halite is made up of the elements sodium and chlorine (with the chemical formula NaCl), it has a cubic crystal structure, it is most often white, and it also has a salty taste! This is a unique combination of features enabling it to be identified (Fig. 17). Other minerals have other combinations of properties that allow the mineral to be identified. For example, another common mineral is **quartz**, but it has different properties from halite, being much harder, pseudo-hexagonal, tasteless, and with a glassy lustre (Fig. 17).



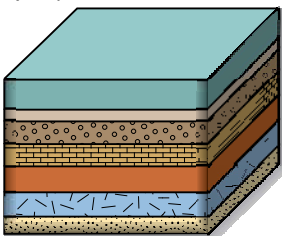
Figure 17: Selection of white minerals, from top — halite, quartz, and calcite show their individuality

The dating game

The Earth is very, very old

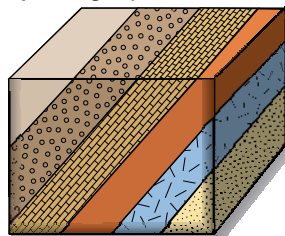
The idea that the Earth was very old arose through detailed observation by geologist James Hutton, who, in 1785, recognized that a group of rocks in northern Scotland had been tilted, uplifted, eroded, and then overlain by younger, flat-lying rocks. Based on his knowledge of the rates of geological processes, he concluded that the **angular unconformity** (Fig. 18) between these distinct rock packages must represent a great period of missing time.

a) Deposition

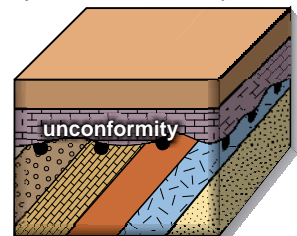


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b) Tilting, uplift and erosion



c) Subsidence and deposition



15.07.09

Figure 18: Stages in the formation of an angular unconformity. A (black) geological symbol marks the unconformity

This seminal discovery was supported by other observations by a great number of people (including Charles Darwin) that older, underlying sedimentary rocks contained a different fossil assemblage from younger, overlying rocks and that there had been a change in the forms of life over time. As well, it was recognized that many of the more ancient life forms were now extinct — including giant dinosaurs whose fossilized remains left such a strong impression on young Darwin and influenced him in developing his theory of **evolution**.

Natural radioactive decay

Additional evidence for the long history of the Earth came with the discovery of **radioactivity** and the development of radiometric dating of rocks. Age-dating techniques are based on the fact that some naturally occurring (parent) **isotopes** of some elements, such as uranium,

are radioactive and decay to (daughter) isotopes *at a known rate*. A highly sensitive instrument, known as a mass spectrometer, is used to count the relative amounts of parent and daughter isotopes in a rock sample. From the ratios of these isotopes, it is possible to calculate how long the radioactive ‘clock’ has been ticking, and to thus obtain the age of the rock.

Geochronologists love zircons

To date very old rocks, geochronologists collect rock samples and search for trace minerals, such as zircon ($ZrSiO_4$), which incorporate minor amounts of uranium when they **crystallize** (Fig. 19). The rocks are carefully crushed and the zircon crystals extracted. The tiny zircon crystals (commonly less than the width of a human hair) are then analysed on a Sensitive High-Resolution Ion MicroProbe (colloquially called ‘the SHRIMP’).

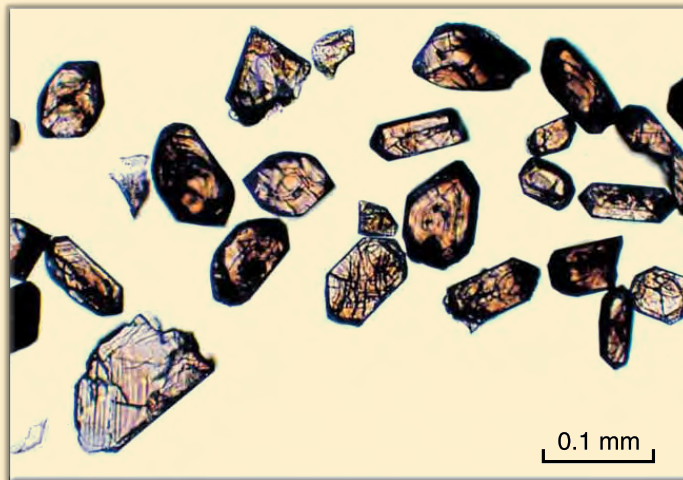


Figure 19: Tiny zircon crystals ready for age dating. Notice the scale

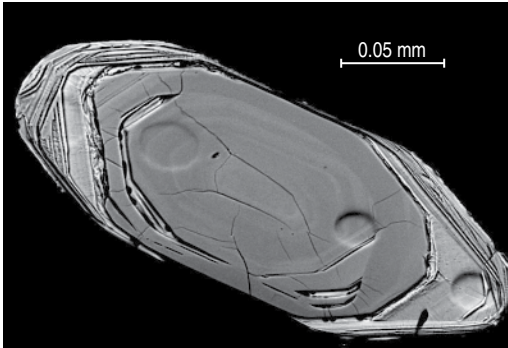


Figure 20: Close-up view of a zircon crystal showing older core (dark grey) and younger light-grey rim, evidence the zircon has kicked around for a long, long time! The round pits within the grain are areas that have been analysed by the SHRIMP

How can a SHRIMP help?

Zircon crystals are exceptionally robust, and they can survive recycling through many geological processes, and can even appear as older cores within younger crystals (Fig. 20). Because of this, the SHRIMP was designed to analyse very tiny amounts of uranium, and its radioactive decay daughter product lead, within individual crystals to determine the different ages of zircon crystals, or even parts of crystals (Fig. 21).

Geochronology, noun, the science of dating and determining the time sequence of events in the history of the Earth

Geochronologist, noun, the person who practises the science of geochronology



Figure 21: This high-tech SHRIMP machine at Curtin University is used for dating zircon crystals

Knowing

Chapter 3 Where did it all begin? Ancient geological history of the east Pilbara

The east Pilbara crust has survived for eons

The east Pilbara geological region covers an area of about 200 km from east to west, centred on Marble Bar, and about 200 km from Port Hedland on the northwest coast, south to Nullagine. This area belongs to the Pilbara Craton*, a piece of very ancient continental crust that has survived relatively intact for about 3500 million years, withstanding a long geological history of younger mountain-building events that have chipped off its edges (Fig. 1).

* For this chapter, technical words are not in bold type

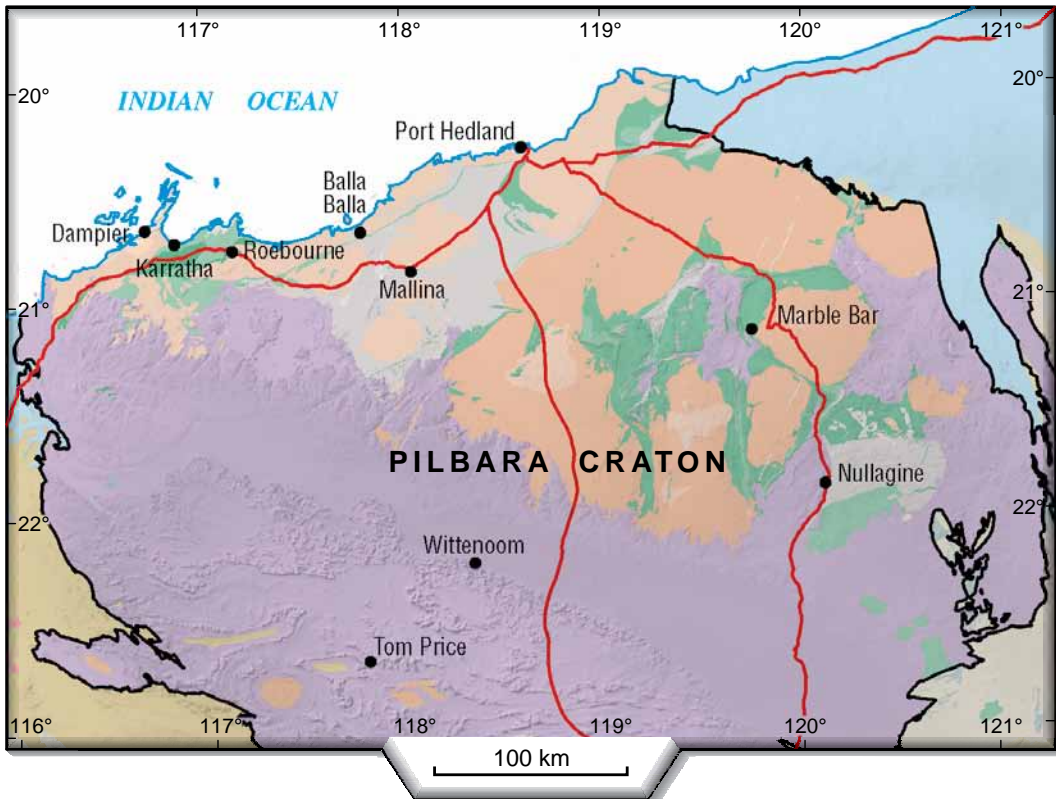


Figure 1: Tectonic map of the Pilbara region. The Pilbara Craton extends across most of the area shown and consists of Archean granite (pinkish orange), greenstones (green), and sedimentary rocks (light grey) that are exposed in the northern part of the region, and in some smaller outliers in the south and southeastern parts.

A large part of the craton is covered by sedimentary and volcanic rocks of the 2780–2300 million year-old Fortescue and Hamersley Groups (purple), and even younger sedimentary rocks overlie the northeastern part of the region (blue)

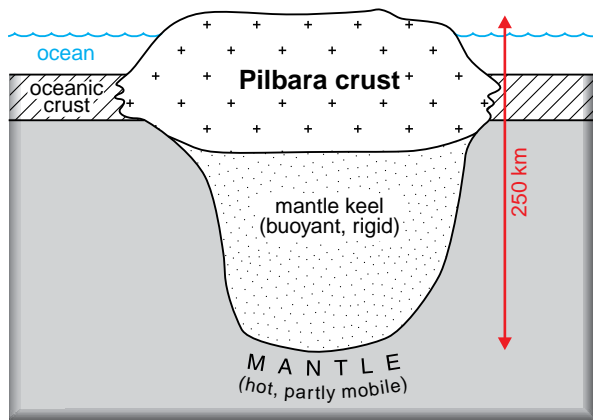


Figure 2: Pilbara Craton riding on a thick buoyant keel of rigid upper mantle

The ability of the Pilbara Craton to survive this long geological onslaught and resist subduction (see Chapter 2) back into the mantle — the fate of most oceanic crust and much of the younger continental crust — is because the crust of the Pilbara Craton rides on a thick, buoyant keel (>250 km deep) of rigid upper mantle material (Fig. 2). This combination of physical properties means that the Pilbara Craton (crust + upper mantle keel) rides on the crust of the Earth much like an iceberg rides on the surface of the ocean, bobbing its way through geological ups and downs and losing its edges along the way, but retaining its essential core region relatively intact over the eons. This has allowed us to view a part of the early Earth very much as it was when the rocks were first erupted (as volcanic rocks), deposited (as sedimentary rocks), and intruded (as igneous rocks) some 3500 to 2830 million years ago, and provides us with a unique window into this ancient period of Earth history, back into Deep Time.

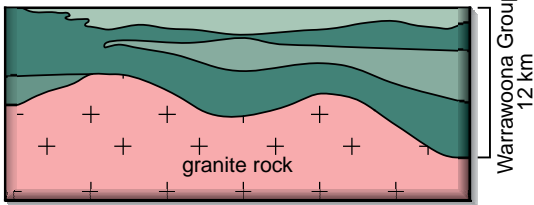
In the beginning there were lavas

The first major crust-forming event continued for 100 million years, from about 3530 to 3430 million years. During this period, large volumes of melt were extracted from the mantle and erupted onto the surface of the Earth as a series of lavas reaching a total of 12 km in thickness, known as the Warrawoona Group (Stage 1 shown in Fig. 3). These lavas were deposited on a basement of even older crust that had formed as a result of poorly understood geological events between at least 3740 and 3650 million years, the traces of which survive as rare rocks and zircon crystals in younger igneous and sedimentary rocks. Intrusion of large volumes of granite accompanied volcanism. Heat from the newly erupted lavas helped to drive circulation of seawater down into the rocks (Fig. 4). The heated water was driven back up towards the surface along faults that formed during extension of the crust that accompanied volcanism. Hydrosulfuric acid leaching liberated the very low concentrations of metallic elements dissolved in the volcanic rocks and concentrated them within faults on the way back up to the surface, in this way forming many of the ore deposits we mine today for so many commodities (Fig. 4). Evidence has been found that these ancient hydrothermal environments were colonized by primitive microbes, whose traces are preserved as microfossils in the frozen hydrothermal fluids, or as stromatolites in the sedimentary rocks deposited during interruptions in outpourings of volcanic material (see a good example at Stop 5.2).

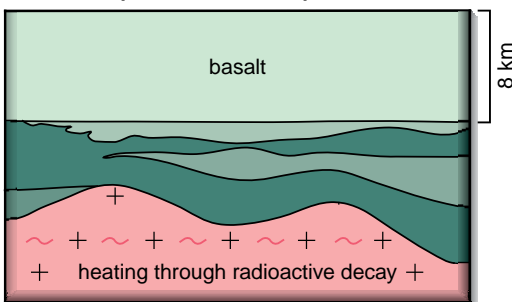
Then came erosion

This early piece of proto-continental crust then sat around for about 75 million years and was exposed above sea level for at least part of that time, when it was subjected to weathering and erosion by wind and rain. The ancient land surface was eroded to a nearly flat plain, although some low-relief topography was preserved in areas where more resistant rock layers were exposed.

Stage 1: Early crust formation (3530–3430 Ma)



Stage 2: Basaltic eruptions and heating (3350–3325 Ma)



Stage 3: Dome-and-keel architecture (c. 3325 Ma)

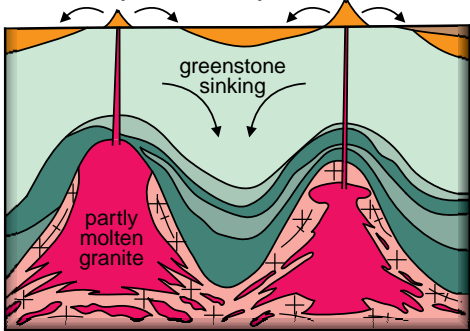


Figure 3: Stages showing the development of 'dome-and-keel' map pattern in the east Pilbara:

Stage 1: Formation of early crust, with eruption of Warrawoona Group lavas and intrusion of granites

Stage 2: Eruption of a thick, dense basalt buries hot granites deeper into the crust, where they start to melt

Stage 3: Melting of granitic middle crust results in sinking of dense greenstones, which push up the lighter granitic melts into domes

More stirrings deep in the craton

About 3350 million years ago, the mantle beneath the Pilbara Craton began to stir again and commenced a second major period of melting. At first, the arrival of the plume of mantle melt from below caused the east Pilbara crust to rise, and this very likely was the cause for at least some of the erosion mentioned above. But as the melts erupted through to the surface, the east Pilbara 'iceberg' slowly subsided and the surface once again sank below the surface of the ocean. At least 8 km of new basaltic lavas were deposited on top of the older crust over the next 25 million years, all of it below water (Fig. 3, stage 2). During the final stages of this eruptive episode (at 3325 million years), the composition of lavas changed from mafic and ultramafic (dark and very dark, and rich in iron and magnesium silicate minerals) to felsic (light-coloured, rich in aluminium and calcium), reflecting the slow, cumulative effects of magma differentiation and assimilation of older granitic crust.

'Dome-and-keel architecture' is generated

One of the major effects of this second melting event was the initiation of a unique crustal pattern called 'dome-and-keel architecture', which is characterized by large, ovoid domes of granitic rocks and narrow, intervening

keel-like structures of greenstones that wrap around the domes (Fig. 5). This geological pattern is present almost exclusively in crust older than 2500 million years, the geological period called the Archean.

Indeed, the east Pilbara is the best-exposed and best-studied piece of crust with this distinctive type of map pattern, but paradoxically — due to the arid weathering conditions in the Pilbara — the landforms (resulting from erosion processes) are opposite to the original geological pattern defined by the different rock types, because the granite domes that weather more readily, have been eroded into flat plains (called ‘downs’ by the early pastoralists, as at Corunna Downs, a pastoral station just southeast of Marble Bar, see Trail 3), whereas the greenstone keels, containing more-resistant rocks, form upstanding ridges (Fig. 6). This ‘dome-and-keel architecture’ is the direct result of a hotter Earth.

What happened to generate such architecture?

- the addition of a thick lid of dense volcanic rocks on top of older, less dense, granitic rocks produced a gravitationally unstable crustal architecture;
- the buried granitic rocks rich in radiogenic elements produced heat, so that when this mass of ‘hot’ granitic rocks was pushed down into the middle part of the crust by the addition of the thick basaltic lid on top, the decay of radiogenic elements heated the middle crust until it was near melting point;
- heat from the melting mantle passed up through the base of the crust into the middle crust (as a result of conduction) and, together with the heat from radioactive decay (see above), caused the less dense granitic rocks in the middle crust to soften through partial melting.

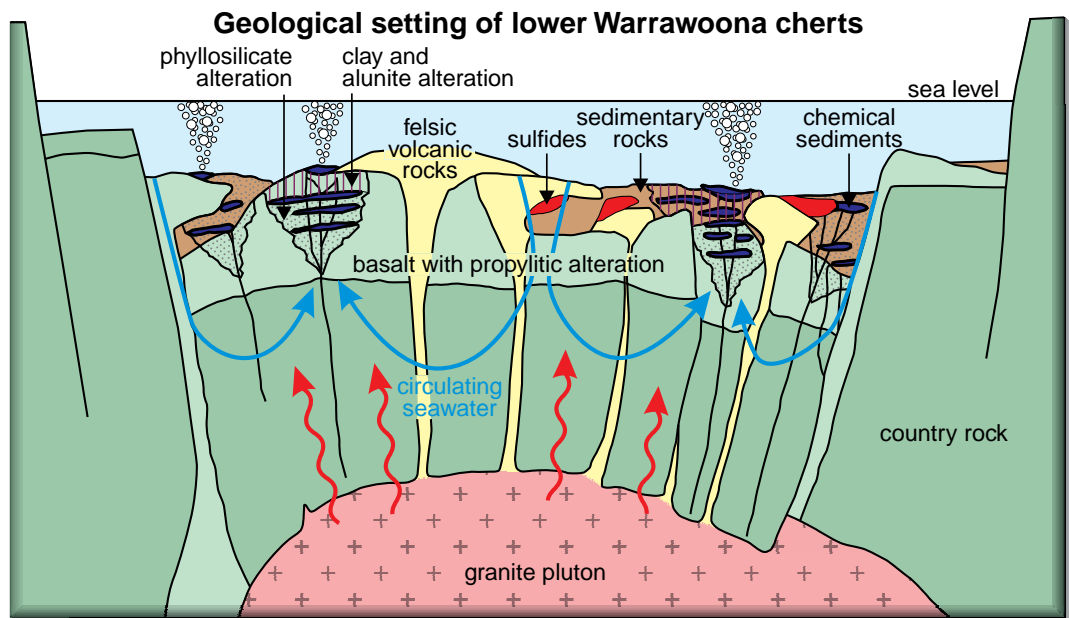


Figure 4: Depositional setting of Archean cherts in the East Pilbara Terrane in basins developed during volcanism. Sediments deposited in the basins were replaced by silica that was mobilized from underlying volcanic rocks during downward circulation of seawater along growth faults, and heating of this fluid by underlying granitic plutons

When the middle crust started to melt, the cold, dense basaltic rocks of the upper crust sank down into the softened middle crust in response to gravity, and in the process pushed aside the newly melted granitic material and forced it up into the cores of broad domal structures (Fig. 3, Stage 3). In the east Pilbara, the first component of this process occurred at around 3325 Ma, after 25 million years of mantle melting and crustal softening, putting in place the architecture of the east Pilbara crust that remains to this day.

The reason that this type of geological map-pattern does not occur in modern geology is due to the Earth’s mantle being much cooler now than it was 3500 or 2500 million years ago, and also because most of the radioactive elements in granitic rocks have already decayed. However, this is not the case everywhere and, indeed, Australia is investigating the potential for obtaining geothermal energy from hot granitic rocks, whose heat is being generated by the decay of concentrated radioactive elements deep below the surface.

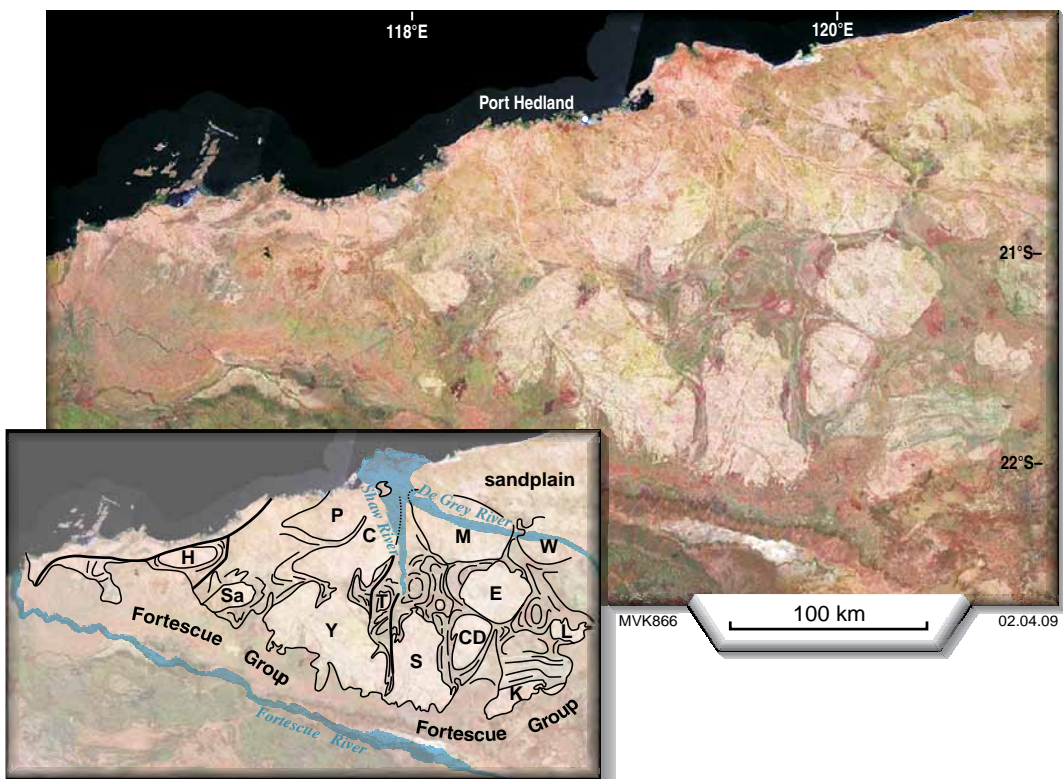


Figure 5: Landsat image (main) and an annotated version highlighting the granite–greenstone geology ('dome-and-keel architecture') of the Pilbara Craton. Archean granitic rocks are light-coloured, often circular, structures, separated by darker areas of greenstones. In the south, these rocks are covered over by younger rocks, called the Fortescue Group. Light-coloured granitic complexes are labelled: C = Carlindi; CD = Corunna Downs; E = Mount Edgar; H = Harding; K = Kurrana Terrane; L = Yilgalong; M = Muccan; P = Pippingarra; S = Shaw; Sa = Satirist; T = Strelley; W = Warrawagine; Y = Yule

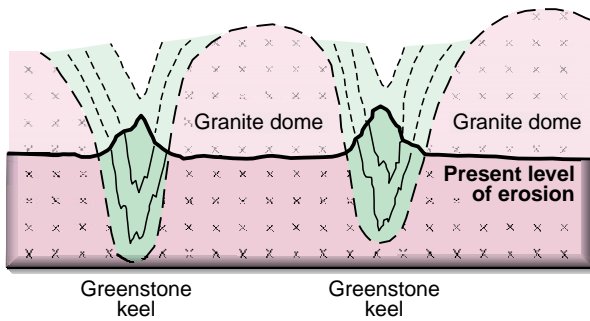


Figure 6: Sketch of granitic 'domes' and greenstone 'keels' — the remnants at the present-day level of erosion

A third cycle of mantle melting

The east Pilbara crust was subjected to a third cycle of mantle melting, from 3270 to 3240 million years ago. This cycle was similar to the cycle described above, and consisted of:

- lava eruption
- intrusion of granitic rocks, and
- amplification of the previously formed 'dome-and-keel architecture'.

At the end of this event, the upper mantle keel beneath the east Pilbara crust had fully formed and was very highly depleted of melt components and thus buoyant and hard to disrupt.

Rifting and collision

After a short period of relative quiet, the east Pilbara crust experienced tearing apart of its margins as a result of rifting, at about 3200 million years ago. This rifting caused thinning of the margins of the crust and was first accompanied by deposition of sedimentary rocks derived largely from erosion of the uplifted granite domes. As rifting progressed, lavas were erupted and parts of the crust were separated from the east Pilbara parent, e.g. parts of the west Pilbara, around the town of Karratha, and southeast of the town of Nullagine. Geological activity then switched to the western part of the Pilbara, and did not seriously affect the eastern Pilbara until the formerly rifted fragments of east Pilbara crust, together with newly created crust in the west Pilbara, collided with the eastern Pilbara 3070 million years ago.

Relaxation

Following this collision event, the crust relaxed again and a thick sequence of sedimentary rocks was deposited between 3020 and 2904 million years, the latter part of which was accompanied by the widespread emplacement of granitic rocks and re-amplification of the 'dome-and-keel architecture' of the east Pilbara crust. The last granitic rocks of the basement were emplaced 2830 million years ago, and are host to tin–tantalum and lithium mineralization.

Summary

The east Pilbara took over 700 million years to form a stable piece of continental crust, the same length of time as the whole history of more complex life on Earth (the Phanerozoic). Ever since, this piece of crust has withstood the ravages of time — immense amounts of time! — and geological upheaval to provide us with a window into Deep Time.

Knowing

Chapter 4 People of the Pilbara — Aboriginal people, pastoralists, and miners

The east Pilbara region has one of the longest records of life on the planet, from Earth's oldest fossil **stromatolites** in 3490 million year-old rocks, to the plants, animals, and people living there today.

The Aboriginal people

The oldest human occupants are the Aboriginal people, who have lived in the Pilbara for more than 40 000 years. Today there are some 30 Aboriginal cultural and language groups. Each group had a traditional location where their people practised a hunter-gatherer and fire-stick farming lifestyle. These people moved over the land depending on seasonal foods and water and, like many other groups of Neolithic man across the globe, left a permanent mark on the landscape: in the form of petroglyphs and other art forms, created on rock surfaces (Fig. 1).

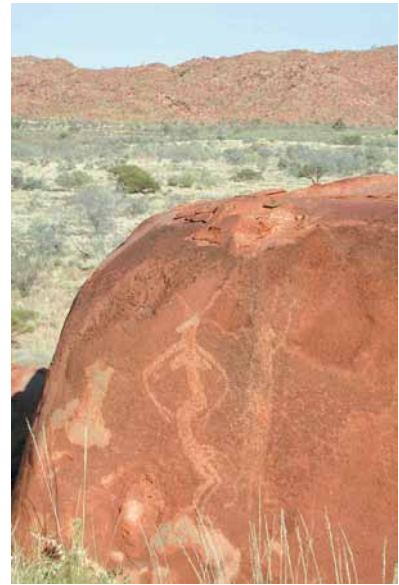


Figure 1: Aboriginal petroglyph inscribed into the desert varnish coating on granite

Exploring for the 'inland sea'

In 1861 surveyor and explorer Francis Gregory and his North West Australian Exploring Expedition were the first Australian colonists to travel through the Pilbara. Gregory was desperate to find east-flowing rivers leading to what was believed to be Australia's 'inland sea': a mirage that had brought many an explorer death or ruin. Gregory's expedition discovered more than a dozen great rivers, including the Turner, Sherlock, and De Grey — all flowing west or north to the Indian Ocean, but none inland. Gregory opened the way for colonial settlement of the Pilbara, as he estimated that two to three million acres (800 000 to 1.2 million ha) of excellent grazing for sheep and cattle were on offer. For the struggling young Swan River colony (Perth) these newly discovered rich grazing lands of the North West beckoned.

Graziers followed

The De Grey River area was settled first, and De Grey Station became a well-equipped and permanent property in the Pilbara. Fanning out from the De Grey, a series of pastoral stations were settled along the river systems between about 1869 and the early 1890s — Pardoo on the coast, Mulyie, then Muccan and Yarric; elsewhere were Ettrick, Warrawagine, and Braeside. Then on the Coongan River, Warralong, Coongan, and Eginbah were developed. Pioneers built up flock numbers and continually expanded their land holdings. By about 1890 sheep numbers were a phenomenal 2.5 million. The great drought of the 1890s decimated the flock, but the old De Grey

lease still remained viable as it was also a central location for the Pilbara pearling fleet. Many famous names in Western Australian public life started out in the Pilbara: names such as Padbury, Withnell, Edgar, Coppin, Drake-Brockman, Anderson, Mackay, and Grant.

Nathaniel Cooke from Mallina Station was the first to bring back tales of the fabulous bar of ‘**marble rock**’ in the Coongan River (after which the townsite of Marble Bar is named). He was wrong though — the bar is not of marble, but of **jasper**, spectacular striped red, white, and grey jasper forming a large rock bar in the river (see Stop 2.3). Nowadays, few visitors or locals worry about the veracity of the name.

Gold!

Gold was first discovered in the east Pilbara in 1888 at Nullagine, leading to about 1000 men working there briefly. Some diamonds were also found. In 1891 gold was discovered by Ted Francis, Harry Jenkins, and Jim Edmondstone at Prospectors Gully, near the present site of the Marble Bar township — this was **alluvial gold**, giving easy pickings for the early arrivals. In 1892 there was a gold rush to Just-in-Time, 8 km south of Marble Bar. Other alluvial finds followed, but were often quickly exhausted. And it was still the Pilbara — hot, rugged, lonely, and inhospitable. There are many solitary gravesites scattered amongst the gold shows, some of which are memorialized on plaques in Marble Bar. Rich **alluvial** finds, particularly large nuggets, came from the Shaw River, Sharks Gully (413 fine ounces [equal to 1.28 kg] in the famous Bobby Dazzler nugget), McPhees Patch, and Talga Talga (Fig. 2). Nuggets continue to be unearthed today.



Figure 2: Bobby Dazzler gold nugget

Marble Bar

The discovery of **reef** or lode gold enabled Marble Bar to survive, and it became the administrative centre for the region, and a town in 1893. In 1894 the Perth to Marble Bar telegraph opened up, giving the Pilbara real-time contact with the outside world. Imposing stone government buildings were erected in 1896 and are still in use today. In 1911 Marble Bar was linked by rail to Port Hedland and, with massive subsidies, the little Spinifex Express train operated until 1951. In its heyday, this parched, forgotten little town once housed two pubs, three stores, a fizzy drink factory,



Figure 3: Beautiful old stone Government buildings in Marble Bar

a saddler, barber and blacksmith, two butchers, the inevitable rooming house for the single miners, a bakery, a weekly paper, a doctor and solicitor, as well as Government offices such as the court house, police station, post office, Mines Department, and a railway station (Fig. 3).

Plenty of other mining and prospecting localities had brief lives — places such as Bamboo Creek, Warrawoona, Chinamans Gully, and Cooglegong. The town of Nullagine, about 110 km southeast of Marble Bar, survives with sporadic bursts of mining activity centred on gold, diamonds, and **antimony**. Government-owned crushing plants for gold ore (called State Batteries) were erected at Marble Bar, Nullagine, and Bamboo Creek to crush small parcels of ore for the prospectors still scattered around the Pilbara. In 1890 the Pilbara had 16 000 people, but by 1899 this had been reduced to 11 000, and by 1912 only 2000 people remained.

Marble Bar is known as the hottest town in Australia, famously reaching the old 100°F (37.8°C) for 160 days in a row between October 1923 and April 1924 — there was no air conditioning in those days either. The hottest day recorded reached 49.2°C (120.4°F) in January 1955. The Ironclad Hotel, which is still open today, is a famous Marble Bar landmark that once served Rot Gut or OP Rum rather than hot beer.

The depression years and the war

By 1929 (the centenary of the first settlement in the Swan River) the south of the State was optimistic, wealthy, and successful. It was not so in the north: easy alluvial gold had dried up and there were shortages of manpower and money to develop or continue mining underground; the wool price remained static; transportation costs to the North West were huge, despite subsidies to the railway and State ships; a bright note was Norman Brearley's air service.

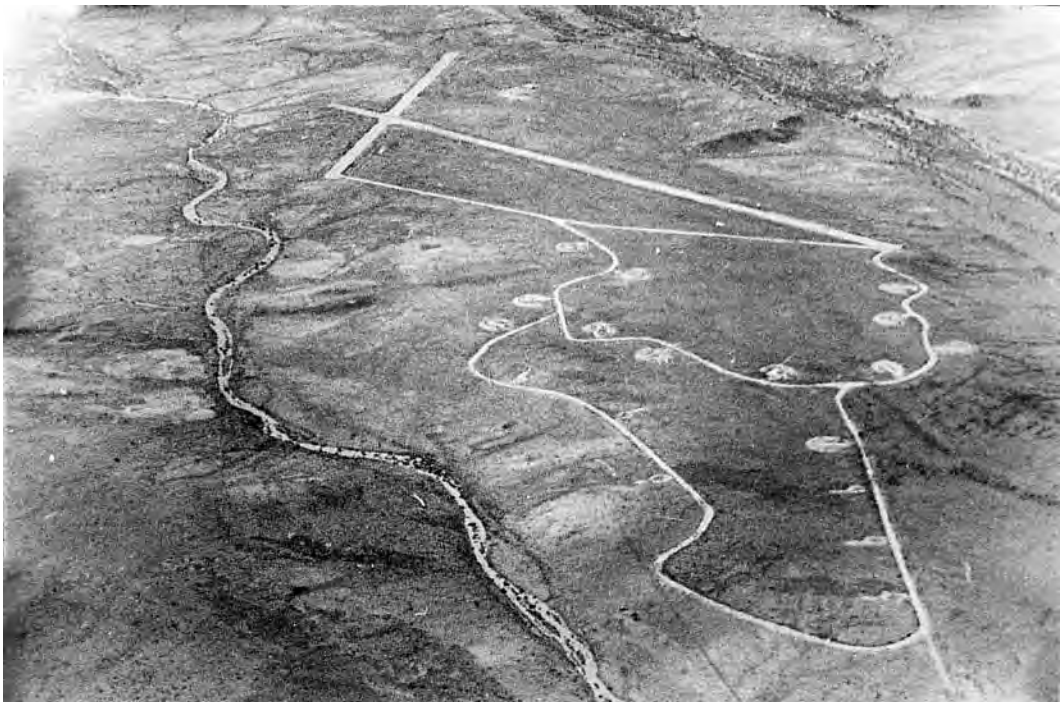


Figure 4: Aerial view of Corunna Downs air base, 1944. Photo courtesy of the Aviation Heritage Museum of Western Australia

The Wall Street crash of October 1929 hit the south of the State hard, but in the Pilbara things stayed much as they had been — self-sufficient vegetable gardens, sheep for mutton, the wool clip, and sundry mineral exports. A gold prospecting bonus, paid to keep men prospecting and in employment, did much to keep the northerners afloat.

During the Second World War Corunna Downs Station became Corunna No. 73 Operational Base Unit (OBU) for both the US Army Air Force and Royal Australian Air Force crews, for bombing sorties to the Japanese-occupied Dutch East Indies islands (Fig. 4 and Stop 3.8).

A famous incident was the Pilbara ‘strike’, when the Aboriginal people — essential labour on the pastoral stations for shearing, shepherding, fencing, and as fine stockmen — withdrew their labour from all the stations between 1946 and 1949. Their complaints centred on injustices over their status and inadequate rewards for their labour, and were the first stirrings about ‘land rights’. Their actions led ultimately to reform.

Recent prosperity

Throughout the 1940s, 1950s, and 1960s the Pilbara was remote and forgotten. The mining of iron ore changed all that. In the early 1960s the Federal Government’s embargo on exporting iron ore was lifted and the mountains of iron ore in the Pilbara were ripe for mining, railing to port, loading onto huge ships, and sending to Japan, Korea, Taiwan, and China. The names of Lang Hancock, Peter Wright, Stan Hilditch, Ken McCamey, Charles Warman, Bruno Campana, Tom Price, and politicians Charles Court and David Brand are inextricably bound-up in the story of the huge iron ore developments in the Pilbara that commenced in the late 1960s. Today there are myriad mines, several high-speed heavy-duty railway lines to cart the ore 450 km to the coast, and huge deepwater ports to service this remote region and send Western Australian iron ore to the steel-making furnaces of the world.



Figure 5: Loading of iron ore at Port Hedland

Finishing

Acknowledgements

Images for Chapter 1 are courtesy of HubbleSite <<http://hubblesite.org>>. Material created by STSci (Space Telescope Science Institute) and NASA.

Photos of Coronna Downs air base are courtesy of the Aviation Heritage Museum of Western Australia, Bullcreek.

Landsat imagery is Copyright to Commonwealth of Australia, National Earth Observation Group, Geoscience Australia, Canberra <<http://www.ga.gov.au/remote-sensing/>>

Brockman Dyke image courtesy of Mark Mitchell, DeBeers Australia Exploration Ltd, used with permission.

Ediacaran fauna image is from a painting by Peter Trusler. Permission to publish courtesy of Australia Post.

An Archean landscape of stromatolites, hot springs, and volcanoes. Painting is by Dave Smart and Ted Jones, based on the original mural in the Smithsonian Institution.

Photo of the Tungurahua eruption (Ecuador) is courtesy of photographer Patrick Taschler, France, and used with permission.

Several photographs courtesy of Liesma Kukuls and Eben Rose.

Photos of the Moolyella tin granites are courtesy of John Blockley.

Mount St Helens eruption (1980) photo courtesy of United States Geological Survey.

The photo of the eruption of Guagua Pichincha, Quito, Ecuador (7 October 1999) is by photographer Pablo Corral Vega (National Geographic Collection, Getty Images).

Aerial photos are courtesy of Landgate (formerly Department of Land Information) Western Australia.

Finishing

Glossary

Where possible, definitions are from Neuendorf et al. (2005), but may have been modified and simplified

* divisions of geological time, see time scale on page 128

Accrete, accretion	to grow or join together. The welding together of small parts to make a larger body, particularly in the formation of the planets, including Earth
Acid volcanic rock	volcanic rock comes from a volcano, and an acid volcanic rock is a light-coloured volcanic rock that contains lots of silica (Si) and aluminium (Al)
Alluvium	clay, silt, sand, and gravel carried by a stream then deposited either in the stream or on its flood plain; alluvial fan = deposits on the flood plain of a stream
Alteration	physical or chemical changes to a rock, especially by hydrothermal solutions
Amygdale	vesicle or gas bubble in basalt that has been filled with calcite or quartz
Angular unconformity	see unconformity. Diagram at Stop 5.5
Anticline	folded rocks that are arch-shaped or convex upward
Antimony	antimony (the white metallic element, Sb) is produced as a by-product of gold mining, particularly from the Nullagine area of the east Pilbara
Archean*	the earliest part of Precambrian time, from 3600 to 2500 million years ago. Most of the Stops on the Trails look at the Archean rocks of the east Pilbara
Ash (volcanic)	fine, unconsolidated material thrown out of a volcano during an eruption
Ash flow	turbulent blend of unsorted fragments and high-temperature gas explosively thrown out of a volcano, fissure, or crater
Atmosphere	the mixture of gases that surround the Earth, chiefly nitrogen and oxygen
Banded iron-formation	(BIF) chemical sedimentary rock with alternating bands of iron-rich and silica-rich layers. Bands are multi-coloured red, white, pink, cream, black and brown. Hematite iron ore formed from the BIF is mined in the Pilbara
Basalt	fine-grained, dark volcanic rock, rich in iron (Fe) and magnesium (Mg) that pours out of a volcano during an eruption; basaltic = adjective
Basalt flow	liquid lava that pours out of a volcano and hardens to basalt
Base level	water flows downhill toward sea level, which is base level
Basement	undifferentiated rocks that lie below the oldest known rocks in an area
Bedding	layering in a sedimentary rock
Billion years	1 000 000 000 years (a thousand million years); abbreviated to b.y.
Biosphere	the area of the Earth that supports life (now includes ocean deeps)
Biotite	a soft, flaky, silvery-brown mineral that peels into thin, tough paper-like sheets; part of the mica family
Breccia	coarse-grained rock composed of large angular rock fragments cemented together by a fine-grained matrix
Calcareous	describes a substance that contains calcium carbonate
Calcite	a white mineral with a pearly lustre that splits up into rhomb shapes and is made up of calcium carbonate (CaCO ₃)
Calcium carbonate	Three elements, calcium (Ca), carbon (C), and oxygen (O) together make up calcium carbonate or calcite

Caldera	a circular depression left when the top of a volcano has either been blown off during an eruption, or has subsided after an eruption. See sketch for Stop 1.11
Carbonate rock	sedimentary rock (e.g. limestone) composed of calcium carbonate
Cassiterite	a mineral, tin oxide (SnO ₂), the major ore of tin; it is black or brown, heavy, commonly found as small pebbles or fragments in streams draining tin-bearing granites and pegmatites. Photo at Stop 6.9
Cenozoic*	the youngest Era of geological time, from 66 million years ago to the present
Chattermark	evidence of glaciation, it is a small, short, curved scar or crack chipped into the bedrock by rocks trapped in a glacier as the glacier moved across the rocks
Chert	hard, dense, very fine grained sedimentary rock made of silica. Impurities such as iron, calcium, or manganese give chert a variety of colours, such as white, red, cream, grey, and black. Famous example at Stop 2.3 — Marble Bar
Chlorite schist	schist is a metamorphic rock, and this type contains the greenish, soft, flaky mineral chlorite; see schist
Clast	an individual grain, fragment, pebble, or cobble in a sedimentary rock
Clastic	sedimentary rock from from fragments of older rocks and minerals
Cleavage	the splitting of a rock along particular planes; a mineral may split (or cleave) along particular planes that reflect its crystal structure
Collisional mountain building	The formation of mountains through the collision, thickening, and uplift of tectonic plates on the surface of the Earth
Columbite	heavy black mineral that is related to tantalite; found in granites and pegmatites with cassiterite (tin)
Concretion	a little ball of rock made up of concentric layers; pea gravel or laterite gravel are good examples
Conglomerate	coarse-grained sedimentary rock made of large rounded rock fragments cemented together by a fine-grained matrix. Photo in Chapter 2
Contact	junction or margin between two different rock types
Continental crust	see crust
Continental drift	theory that continents have moved around the surface of the Earth; now superseded by plate tectonics
Convection, convection cell	the upward or downward circulation of liquid or gas, typically in swirling columns, driven by heating or cooling
Costean	shallow pit or trench dug to expose the bedrock
Country rock	general term for the rocks surrounding an igneous intrusion
Cover	something that obscures the crystalline rocks below — can be sand, regolith, or young rocks
Craton	piece of continental crust that has been stable for billions of years, e.g. Pilbara Craton
Cretaceous	the youngest Period of the Mesozoic Era, ranging from 146 million years ago to 66 million years ago. There are rocks of Cretaceous age at Stop 1.4
Crust	outermost shell or layer of the Earth. See diagram in Chapter 2
Crust, continental	the largely granitic, less dense, part of the Earth's crust that is under the continents and continental shelves. It is about 35 km deep, and may be 60 km deep under mountain ranges
Crust, oceanic	the mostly basaltic, denser part of the Earth's crust that is under the oceans. It is about 8 km thick and only rarely thrust up onto land by faulting
Crystalline	describes a rock made up of crystals

Crystallization	important process in geology where minerals form as magma cools. If the magma cools very slowly the minerals have time to grow very large resulting in a coarse-grained rock, if the magma cools quickly the minerals are tiny, giving a fine-grained rock. Coarse-grained granite is at Stop 3.7
Dacite	light-grey, fine-grained volcanic rock with lots of quartz and feldspar
Debris flow	moving mass of rock fragments, mud, and water that can result from a volcanic eruption or from flooding
Deep Time	the world as it appeared 3 500 000 000 years ago
Deformation	stresses on the rocks in the Earth that cause folding, cracking (or faulting), or shearing; the result of deformation is that a rock becomes deformed
Deformation event	certain times in the Earth's history when deformation has taken place
Deposition	accumulation of rock fragments (e.g. sand or silt or chemical precipitates) to form a sedimentary rock; also accumulation of lavas
Desert varnish	hard film or coating of iron oxide that forms on the outside of a rock as it weathers. Wind and water may 'polish' the coating. See Stop 4.2
Devil's dice	miners' name for pyrite crystals weathered to hematite, but which still keep their cubic pyrite shape
Devitrification	the process of volcanic glass changing to crystal material during weathering
Differentiation	geological process in which parts of a magma separate, usually by crystallization and mineral settling (or floating) of its minerals
Dip/dipping	downward slope of a rock or layer
Dolerite	dark-grey to black, fine-grained igneous rock, common in dykes. The east Pilbara is criss-crossed with dolerite dykes
Dolomite	carbonate mineral, similar to calcite, but made up of calcium and magnesium; also the rock made up of dolomite
Doming	rocks being pushed up into a bulge or dome
Dyke	large crack or fissure in the Earth that is filled up with magma. Black Range dyke in the Pilbara is a magnificent example of a dolerite dyke. See Stop 6.10
East Pilbara Terrane	a distinct tectonic region of the Pilbara Craton, with rocks that are older and have a different history from adjacent terranes or regions
Element	a pure chemical substance, e.g. two elements silica (Si) and oxygen (O) join to make up the mineral quartz (SiO ₂)
Emplacement	another word for intrusion, it is magma rising through the crust and flooding into new locations
EPIRB	Emergency Position Indicating Radio Beacon; for sending out a distress signal
Erosion	the actions of wind, water, and ice that wear away then carry away rock fragments on the Earth's surface
Erratic	boulder or large rock that has been carried a considerable distance by a glacier then dropped; also = glacial boulder. Good example at Stop 4.11
Eruption	volcano actively spewing out ash, gas, lava, or fragments
Evaporative minerals	minerals formed by the evaporation of seawater. Example at Stop 1.2
Evolution	theory that life on Earth has developed gradually, from simple organisms to very complex organisms
Exposure	an outcrop
Extension	process in which the crust is stretched
Extrusion	igneous material flowing onto the surface of the Earth, perhaps through a volcano or a fissure
Fabric	texture within a rock

Faceted	boulder or pebble that has been ground flat on one or more sides, in some cases by a glacier
Facing	the direction in which sedimentary or volcanic rocks get younger
Fault	zone of rock fracture. A crack in the Earth's surface where rocks may be sheared
Fault bound	areas or packages of rocks with faults around their margins
Feldspar	a common rock-forming mineral, colour = white, cream, pink, or greenish; it has perfect cleavage, and a pearly lustre; feldspars occur in all kinds of rocks, particularly granites, and weather to clay. Example at Stop 3.7
Felsic magma	a magma that light-coloured igneous rocks rich in feldspar and quartz will crystallize from; opposite to mafic magma
Felsic volcanic rock	rock that comes from a volcano, made up of lots of feldspar and quartz
Fiamme	flame-like, wispy fragments of glass in a volcanic rock. Beautiful example at Stop 4.4
Fissure	crack in the Earth's surface
Foliation	layered or felted texture in a rock, commonly from the alignment of minerals
Formation	formal name given by geologists to a rock unit that is different from rock units next to it, can be traced for some distance, and is easily recognizable. Example is Duffer Formation, Stop 1.11
Fracture	crack in a rock, it could be a joint, or a fault
Geochronology	the science of dating rocks. For more details see Chapter 2
Geophysics	the study and decoding of the physical properties of rocks, such as density, magnetics, radiometrics, spectrometry, electrical conductivity, and seismic properties. See example of the use of geophysics at Stop 5.1
Glacial boulder	boulder carried by a glacier, then dropped when the ice melted; also = erratic
Glacial valley	valley scoured by a glacier or filled with sediments dropped from a glacier
Gneiss	a hard, metamorphic rock that may have coarse banding, or alignment of dark and light minerals, giving it a foliated texture
Gold mineralization	highly sought-after by old and young prospectors! Found in alluvial deposits and quartz veins in greenstones in the east Pilbara
GPS	Global Positioning System (GPS readings for Stops in this book are in degrees and decimal minutes)
Graben	an elongated trough or basin, bounded by faults
Granite, granitic rock	common intrusive igneous rock made up of crystals of quartz, feldspar, biotite, and hornblende. It forms deep within the Earth
Granitic complex	group of related granites that crystallize at roughly the same time, e.g the Mount Edgar Granitic Complex at Stop 4.2
Granitic dome	large circular convex bulge of granite
Granitic magma	magma from which light-coloured igneous rocks, such as granites, will crystallize
Granodiorite	granite-like rock rich in sodium
Great Oxidation Event	the time when Earth gained an oxygen-rich atmosphere, about 2350 million years ago
Greenstones	rocks deposited on the Earth's surface in Archean times. They are volcanic and sedimentary rocks that have been metamorphosed
Greenstone belt	package of metamorphosed volcanic and sedimentary rocks, generally wrapping around granite domes, particularly in crust of Archean age. The east Pilbara is home to many of these greenstone belts. See satellite image in Chapter 3
Hackly	rough or jagged

Halite	a mineral, made up of the elements sodium (Na) and chlorine (Cl); common salt
Hematite	common iron mineral, gun-metal grey and with a distinctive cherry red streak. Common ore of iron
Hiatus	a gap or interruption in rocks being laid down or deposited
Hornblende	a green, greenish brown, or black mineral, part of the amphibole family. A common mineral in granites
Hydrosphere	waters of the Earth, including oceans, rivers, lakes, glaciers, and snow
Hydrothermal	relating to heated water percolating through rocks
Igneous layering	as a magma 'porridge' cools to form igneous rocks, similar types of minerals will crystallize out together and settle in bands, giving a banded or layered look to the rock
Igneous rock	rock formed from magma — can be extrusive or intrusive. An extrusive igneous rock erupts from a volcano; an intrusive igneous rock forms by the cooling and consolidation of magma deep in the Earth, allowing minerals to crystallize. Igneous , along with sedimentary and metamorphic rocks make up the three major classes of rocks
Ignimbrite	volcanic rock formed by the violent eruption of a volcano, when showers of gas and lava drops race down the slopes of a volcano at great speed, then solidify. The resulting rock is made up of glass, crystals, and ash welded together. Beautiful example at Stop 4.4
Intrusion	the process of a magma moving up into the crust to slowly cool, crystallize, and harden into a rock. Granite is formed by intrusion; also a noun
Iron cemented	gravels bound together by iron
Isotope(s)	two or more forms of a chemical element, depending on variations in mass
Jasper	variety of banded chert with iron-oxide impurities that colour the chert red, but also yellow, green, brown, grey, and black. See the classic Marble Bar Chert at Stop 2.3
Joint(ing)	a fracture or parting in a rock
K-feldspar	feldspar mineral rich in potassium
Kimberlite	ultramafic igneous rock, defined in South Africa, that hosts diamond deposits. Is found as a narrow plug or dyke
Komatiite	distinctive type of ultramafic volcanic rock rich in magnesium, with unusual spinifex texture, made up of criss-crossing needles of minerals (named after the growth pattern of stems of spinifex grass). May host nickel and chrome deposits; komatiitic = adjective
Lamina; plural = laminae	thin layer (or layers) in a sedimentary rock
Laminated	said of a rock that can be split into thin layers, especially a shale
Landsat	Satellite orbiting Earth and sending back images of its travels. Gives a very high 'bird's eye view' of Earth. See image at Stop 1.5
Lapilli	small rock or glass fragments (between 1 and 60 mm in size) ejected from a volcano
Laterite	an informal term for highly weathered red soil containing lots of iron and silica; may have a surface of pea-gravel
Lava	molten material flowing or bursting from a volcano; also the solidified rock
Lava flow	the trail of lava flowing out from a volcano
Layering	concentration of certain minerals in bands or layers in a rock — may be from igneous settling during crystallization, due to metamorphism, or to bedding in sedimentary rocks
Liesegang rings	a pattern of brown rings or bands caused by iron-rich fluids seeping through the weathered rock. See example at Stop 3.5

Limestone	common sedimentary rock made of calcium carbonate
Limonite	yellowish-brown or brown earthy material made of iron oxide
Lineation, lineated	a line-like fabric in a rock, ranging from striations to minerals that are aligned; lineated = texture created by the lines
Lithosphere	the crust of the Earth, as distinct from the atmosphere or hydrosphere
Lithium	element (Li); lithium ores are found with tin and tantalum in pegmatites
Ma	1 000 000 years (million years); also written as m.y.
Mafic rock	a dark-coloured igneous rock that is rich in magnesium and iron; opposite of felsic. Dolerite is an example
Mafic volcanic rock	dark-coloured igneous rock flowing out of a volcano. Basalt is an example
Magma	molten or partially molten rock material (similar to hot 'porridge') formed deep within the Earth, capable of being intruded (to make granite) or extruded (to make basalt)
Magma chamber	a staging post where magma collects before it erupts out of a volcano; it has already moved up into the crust from deep within the Earth
Magmatism	the act of magma moving to higher levels in the crust from deep in the mantle
Manganese	the element Mn. Manganese is mined at Woodie Woodie in the east Pilbara
Mantle	one of the zones of the Earth, below the crust and above the core. Chapter 2 has diagram
Marble	new rock that forms when limestone is metamorphosed and recrystallized
Matrix	in a sedimentary rock this is the fine-grained material holding together the large grains or pebbles
Melt	fluid or liquid magma, derived from melting of rocks
Mesa	flat-topped, table-like hill formed by erosion. See Stop 1.3
Mesozoic*	the Era older than the Cenozoic, starting 251 million years ago, and finishing 66 million years ago
Metabasalt, metachert	meta = short for metamorphosed; this is basalt or chert that has been metamorphosed, changing its appearance and the minerals in it
Metamorphic rock	a sedimentary or igneous rock that has been melted and buckled by high temperatures and high pressures deep within the Earth to form a new rock. Metamorphic , along with sedimentary and igneous rocks make up the three major classes of rocks
Metamorphism	processes (melting and buckling) that change an igneous or sedimentary rock into a metamorphic rock; past tense = metamorphosed
Meteorite	a fragment of asteroid that has fallen to Earth from space
Mica	flaky, soft mineral coloured greenish-white, silver, or pale brown that peels into tough, paper-thin sheets; a common rock-forming mineral; biotite and muscovite are the well-known micas
Microbialite	a layered or non-layered rock made by micro-organisms, through mineral precipitation, or through trapping and binding of particles; stromatolite is one type of microbialite. See example at Stop 4.6
Microcrystalline	Said of the texture of a rock with crystals so small they can only be seen under a microscope
Million years	1 000 000 years; shortened to Ma or m.y.
Mobile crust	crust that has been heated and softened by geological processes
Mudstone	mud that has hardened to form a fine-grained sedimentary rock
Mylonite	folded, sheared, and deformed rock

North Pilbara Orogeny	ancient mountain-building event in the Pilbara, about 2 940 000 years ago
Oceanic crust	see crust
Opaline silica	silica or quartz that looks like opal, or has an opal lustre
Outcrop	area of rock jutting out at the surface, also termed 'an exposure'
Overtuned	said of a folded rock when it has tilted beyond the perpendicular; thus the sequence of rocks is no longer younger layers over the top of older layers
Pea gravel	see pisoliths
Pegmatite	an exceptionally coarse-grained igneous rock found in veins or small dykes. Crystals in the pegmatite are large (and can be huge!), their size due to the slow rate of cooling of the magma. Pegmatites are an important source of economic minerals such as barite, fluorite, tin, tantalum
Period	one of the subdivisions of the geological time scale
Permian	the youngest Period of the Paleozoic Era, starting 299 million years ago and finishing 251 million years ago. A time of glaciation, see Stops 4.9, 4.11
Phanerozoic*	major subdivision of geological time, starting at the end of the Proterozoic, 542 million years ago, and continuing to present day
Pilbara Craton	tectonic name for the (ancient) Archean portion of the Pilbara region. See diagram in Chapter 3
Pilbara Supergroup	sequence of metamorphosed volcanic and sedimentary rocks in the East Pilbara Terrane of the Pilbara Craton
Pillow basalt, pillow lava	mafic lava poured out from a volcano under the sea that makes pillow-like structures or bulges. Good example at Stop 2.2
Pillow structure	balloon-like bulge formed when mafic lava is extruded under water. See above
Pisolith(s)	pea-shaped grain(s), about 1–3 cm in diameter, and spherical or oval in shape, with concentric layering inside; also called pea gravel
Planar fabric	textural features of a rock, lying or arranged in a plane
Plate tectonics	theory of global tectonics that divides the Earth into several large 'plates' or blocks that float on a thick under-layer in the mantle. More details in Chapter 2
Precipitate	a solid separating out from a solution; noun = the resulting solid
Precipitation	process where mineral phases separate out from a solution, for example seawater or magma
Proterozoic*	major subdivision of geological time, from 2500 million years ago to 542 million years ago
Pyrite	another name for fool's gold, an iron sulfide mineral (FeS ₂) greenish-gold in colour that weathers to form devil's dice
Pyroclast	piece of hot, liquid rock (magma)
Pyroclastic flow	flowing volcanic rock, made up of pyroclasts and volcanic ash, erupted from, and deposited on the flank of, a volcano
Pyroclastic rock	rock composed of pyroclasts, literally pieces of hot, liquid rock (magma), erupted from a volcano
Quartz	very common rock-forming mineral made of silicon dioxide (SiO ₂). It is hard, glassy (or vitreous), white, grey, or clear. Common in granites and veins
Quartz veins	erratic, narrow cracks in granites or greenstones filled by quartz that may or may not also have gold. Good example at Stop 3.5
Radioactive decay	natural breakdown of radioactive elements due to their inherent instability. The process generates heat
Radioisotope	radioactive isotope
Recrystallization	process, especially during metamorphism, where rocks can be changed, and new minerals can crystallize

Reef	sedimentary ridge built of the skeletons or fossils of masses of corals. Ancient reefs were built up by stromatolites. Also a miner's term for gold-bearing veins
Regolith	weathered rocks and soils visible in the landscape
Remote sensing	gathering and interpreting data from the full electromagnetic spectrum without being in contact with what is being measured. Includes data from satellites, radar, aerial photography, magnetics, etc.
Rheomorphic ignimbrite	(pronounced ree-oh-mor-fic) an ignimbrite on the slope of a volcano that developed flow textures due to high temperatures. Fine example at Stop 4.4
Rift	long, narrow trough or graben, bounded by normal faults and resulting from tectonic extension in continental or oceanic crust (e.g. mid-Atlantic rift)
Sandstone	a common sedimentary rock composed of sand grains bonded together by silica, iron oxide, or calcium carbonate
Schist	metamorphic rock with flaky minerals that are aligned, allowing the rock to be split. Mica and chlorite are common minerals in schist, giving the rock a sparkly look and a slightly greasy feel
Scree	mass of broken rock fragments that lie on a slope, or tumble down a hillside
Scree slope	the hillslope formed by scree
Sedimentary rock	one of the three major classes of rocks (with igneous and metamorphic). Sedimentary rocks are formed in two ways: (i) loose grains are compacted and solidified to form a new rock, or (ii) a rock is formed by chemical precipitation or by evaporation
Shale	sedimentary rock of compacted clay, silt, and mud that form layers or laminae so that the rock will split into thin sheets
Shear	deformation or fracturing of a rock by sliding one section against another
SHRIMP	S ensitive h igh-resolution ion m icroprobe (SHRIMP). A sophisticated instrument used for determining the ages of rocks. Further details in Chapter 2
Silica	silicon dioxide (SiO ₂) that occurs naturally as crystals (quartz), or in cryptocrystalline form (chert) or amorphous form (opal); it is an essential component of many rocks
Sill	intrusion of magma along a horizontal path (as distinct from a dyke, which is commonly vertical)
Siltstone	sedimentary rock of compacted silt, mud, and clay
Solution	a liquid containing dissolved minerals
Spall	a thin, curved slab that falls off the surface of a rock
Stratovolcano	volcano that erupts alternating layers of lava, fragments, and ash
Striae	scratches on a rock surface
Strike	the trend or direction of the rocks of an area
Strike and dip	slope (dip) of rocks measured at right angles to the trend (strike)
Stromatolite	a laminated or layered rock built by the activities of micro-organisms, mainly cyanobacteria, either through mineral precipitation or trapping and binding of particles (sand). An example of the development of early life on Earth. Further details at Stop 4.6, excellent examples at Stop 5.2.
Subaqueous eruption	eruption of lavas under water
Subduction	the relative movement of two tectonic plates — instead of colliding, one plate slides under the other. See Chapter 2
Succession	a sequence of rock units (formations) in chronologic order
Syncline	fold that is basin-shaped or concave upwards, the opposite fold to an anticline
Tailings	ground-up waste rock left over after ore has been treated
Tantalum	the element (Ta) in tantalite. Is found with alluvial tin ore in the east Pilbara

Tectonics	study of the outer part of the Earth, particularly the tectonic plates
Tectonic plate	rigid piece of continental or oceanic crust; see Chapter 2 for more details
Terrane	ancient part of the crust, with faults around its margins. The east Pilbara is made up of granite–greenstone terrane about 3 billion years old
Texture	fabric of a rock
Thin section	fragment of rock ground down so thinly that it becomes translucent or transparent, allowing the rock to be studied with a microscope. Example at Stop 6.10
Tin ore	usually refers to the mineral cassiterite, found in the east Pilbara in pegmatites and alluvial deposits. See photo for Stop 6.9
Tor	a pile of rocks, especially of weathered granite boulders. Example at Stop 6.13
Transport	shifting of material from one place to another on the Earth's surface by natural means, such as moving water, ice, or wind
Ultramafic rock	very dark igneous rock very rich in magnesium and iron. Komatiite is an example
Unconformity	a gap in the rock record, where one rock layer overlies another that is much older. The gap may be due to non-deposition of rocks or to erosion of the earlier layer; unconformable = adjective. See also angular unconformity . Example at Stop 5.5
Undeformed	rocks that are not folded or altered, opposite of deformed
Uplift	where rocks in the crust are thrust up or raised
Vein	erratic, narrow crack in granite or greenstone filled up by quartz. It may also contain gold. Good example at Stop 3.5
Vesicle	gas bubble or round hole left by gas escaping from a basalt; vesicular = adjective. See also amygdale
Viscous magma	sticky, 'porridge-like' molten rock that doesn't flow easily
Volcanic ash	fine material ejected from a volcano during an eruption. See Chapter 2
Volcanic breccia	volcanic rock made up of angular volcanic-rock fragments
Volcanic conglomerate	volcanic rock made up of rounded volcanic-rock fragments. See Stop 1.11
Volcanic glass	natural glass formed by the cooling of molten lava that happened so quickly crystals couldn't form; an example is obsidian
Volcanic rock	rock formed by a volcano
Volcaniclastic rock	sedimentary rock composed mainly of volcanic-rock particles
Vug	small cavity in a rock, which may be lined with crystals; vuggy = adjective
Weathering	physical and chemical breakdown of rocks when they are exposed to Earth's atmosphere; happens to people too — they become weatherbeaten
Weathering process	as soon as a rock forms, the agents of weathering — wind, water, and ice— start their work to eventually destroy the rock. See rock cycle in Chapter 2
Zircon	a mineral ($ZrSiO_4$) found in minute quantities in many rocks, particularly granite. Used for age dating

* part of the geological time scale, see page 128

These are BIG numbers ...

1 million years = 1 000 000 years, also Ma, m.y.

1 billion years = 1 000 000 000 years, also b.y.

Finishing

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Finishing

Who are we?

Geological Survey of Western Australia

For more than 100 years the Geological Survey of Western Australia (GSWA) has collected and published the results of geological, geophysical, geochemical, and geochronological studies of the State, with the aim of revealing its mineral and petroleum potential.

The information published takes many forms: maps, reports, evaluations, and digital data, nearly all of which is available free of charge via the Department of Mines and Petroleum website. The information is for many users — the mining and energy industries, Government departments, the general community, and urban and land use planners.

From the heady days of Western Australia's gold rushes and the development of Kalgoorlie's 'Golden Mile', to the first oil discoveries at Cape Range, the huge iron ore developments of the 1960s, then the 1970s nickel, diamond, and uranium booms, and the massive expansion in iron ore production in the 2000s, Western Australia's fortunes continue to be intimately linked to the resources industry, and GSWA has had a direct role to play.

Today, GSWA continues the tradition of providing high-quality, field-based regional geological mapping, combined with database compilation, mineral economics reviews, and mineralization studies for the resources industry. As well, GSWA has geological expertise in new fields such as geothermal energy, tight gas, and carbon capture and storage.

As part of the Department of Mines and Petroleum, GSWA employs more than 130 staff, including 61 geoscientists, and serves a resources industry that spent more than A\$2 billion on exploration in Western Australia in 2007–08.

About the authors:

Dr Martin J Van Kranendonk was born and raised in Canada, where he undertook his geology studies (PhD 1992). He came to Australia in 1994 as an Australian Post-doctoral fellow at the University of Newcastle to study the geology of the Pilbara. In 1997 he moved to Perth to join GSWA. Since then he has been exploring the Pilbara, appreciating its beautiful places, and uncovering its geological secrets. He is a specialist in Precambrian geoscience and a world authority on early life and Archean tectonics.

Jean F Johnston is a geologist and has worked in the Editing and Publishing group of GSWA for many years. She is passionate about making geology accessible to non-technical readers.

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Locations of all the Stops along the Trails

Trail	Stop No.	Description	Latitude °S Longitude °E	Km from start
1		From Port Hedland		0
	1.1	Coastal limestone, Port Hedland	20°18.548'S 118°34.737'E	2
	1.2	Salt evaporation ponds	20°20.753'S 118°37.819'E	11
	1.3	View of Robe Pisolite	20°23.222'S 118°47.846'E	34
	1.4	Cretaceous mesas	20°22.946'S 118°58.430'E	55
	1.5	Shaw River	20°42.610'S 119°19.730'E	112
	1.6	Ancient beaches and a dried-up lake	20°49.821'S 119°31.831'E	138
	1.7	Sheared granite gneiss	20°52.309'S 119°43.714'E	160
	1.8	Dolerite dyke	20°52.584'S 119°45.079'E	163
	1.9	Overtuned bedding	20°54.340'S 119°46.362'E	167
	1.10	Doolena Gap	20°55.525'S 119°47.127'E	169
	1.11	Rocks from an ancient giant volcano	20°56.894'S 119°49.520'E	178
1.12	The Sisters and Mount Edgar Granitic Complex	21°03.391'S 119°51.220'E	193	
	Marble Bar	21°10.286'S 119°44.671'E	215	
2		From Marble Bar		0
	2.1	A volcanic breccia at Chinaman Pool	21°10.678'S 119°42.788'E	4
	2.2	Pillow basalt	21°11.042'S 119°42.831'E	4
2.3	The Marble Bar	21°11.182'S 119°42.710'E	5	
3		From Marble Bar		0
	3.1	Vista to greenstones	21°15.416'S 119°47.878'E	12
	3.2	Vista: oblique deformation in the Warrawoona Syncline	21°17.948'S 119°48.046'E	17
	3.3	Vertically plunging schists	21°19.301'S 119°50.725'E	23
	3.4	Klondyke Boulder mine and ruins (4WD track)	21°19.951'S 119°52.865'E	29
	3.5	Klondyke Queen mine (4WD track)	21°20.146'S 119°53.268'E	30
	3.6	Centre of Warrawoona Syncline	21°19.520'S 119°50.400'E	37
	3.7	Corunna Downs Granitic Complex	21°20.654'S 119°51.420'E	41
	3.8	Runway, Corunna Downs air base	21°25.929'S 119°46.721'E	58
	From Marble Bar		0	
4	4.1	Moolyella tin workings	21°09.161'S 119°52.529'E	15
	4.2	Mount Edgar Granitic Complex	21°11.636'S 120°08.641'E	45
	4.3	Granite–greenstones	21°12.952'S 120°20.029'E	66

Trail	Stop No.	Description	Latitude °S Longitude °E	Km from start	
4	4.4	Ignimbrite	21°13.479'S 120°20.907'E	68	
	4.5	Conglomerate	21°13.397'S 120°28.221'E	81	
	4.6	Limestone bed with stromatolites	21°14.689'S 120°32.316'E	89	
	4.7	Roadside cutting, Kylenea Basalt	21°15.698'S 120°33.976'E	93	
	4.8	Vista to stromatolites	21°16.843'S 120°36.990'E	99	
	4.9	Glacial valley	21°19.698'S 120°52.187'E	128	
	4.10	Meteorite impact breccia	21°19.263'S 120°52.093'E	129	
	4.11	Glacial erratics	21°19.476'S 120°52.295'E	129	
	4.12	Ancient lake deposits	21°19.911'S 120°57.219'E	138	
	4.13	Polished glacial pavement	21°26.933'S 121°03.591'E	183	
	4.14	Carawine Pool	21°28.865'S 121°01.682'E	188	
	5		From Marble Bar		0
		5.1	Hidden riches: Kimberlite dyke	21°21.221'S 120°03.604'E	46
		5.2	Ancient life (stromatolites)	21°28.200'S 120°04.344'E	61
5.3		Contact	21°34.188'S 120°04.741'E	75	
5.4		Gold and diamond workings	21°52.779'S 120°06.863'E	113	
5.5		Angular unconformity	21°54.899'S 120°05.482'E	119	
6		From Marble Bar		0	
	6.1	A 2.7 billion year-old valley	21°13.566'S 119°43.353'E	7	
	6.2	Comet Mine	21°13.958'S 119°43.521'E	8	
	6.3	Geological panorama	21°17.819'S 119°40.173'E	22	
	6.4	Basaltic pillow breccia	21°19.629'S 119°36.927'E	28	
	6.5	Glen Herring Gorge	21°21.169'S 119°36.881'E	30	
	6.6	Ripple-marked siltstone	21°19.916'S 119°36.112'E	33	
	6.7	Shaw Granitic Complex and the Black Range	21°23.728'S 119°33.697'E	45	
	6.8	A most unusual conglomerate	21°26.239'S 119°32.499'E	51	
	6.9	Alluvial tin–tantalum mining	21°30.721'S 119°25.624'E	66	
	6.10	Black Range dolerite dyke	21°43.255'S 119°24.136'E	97	
	6.11	Mylonitic gneiss, Tambourah Creek	21°45.410'S 119°14.357'E	115	
	6.12	Granite–greenstone contact	21°45.073'S 119°11.063'E	122	
6.13	Granite tors	21°40.964'S 119°03.052'E	140		

About this guide

The east Pilbara region in the northwest of Western Australia has one of Earth's best-preserved remnants of ancient crust — crust that is more than 3 500 000 000 years old! The book takes you on a journey through this iconic ancient land. You will see remnants of gigantic volcanic eruptions, rocks virtually untouched by time, the famed 'Marble Bar', and the most ancient traces of life on Earth — stromatolites. All sites are close to the road, readily accessible, and located for you by GPS. Come travel these six trails, radiating out from Marble Bar, and delve back into Deep Time ...



This book will be of interest to:

- Tourists travelling around Australia — scratch beneath the surface for some hidden secrets
- School children and teachers — there is much to interest you in this book
- Those with an interest in the Pilbara region, its rocks, and its landscapes
- Locals wanting to deepen their knowledge of the region, and perhaps see some areas with new insight
- Geoscientists on holiday