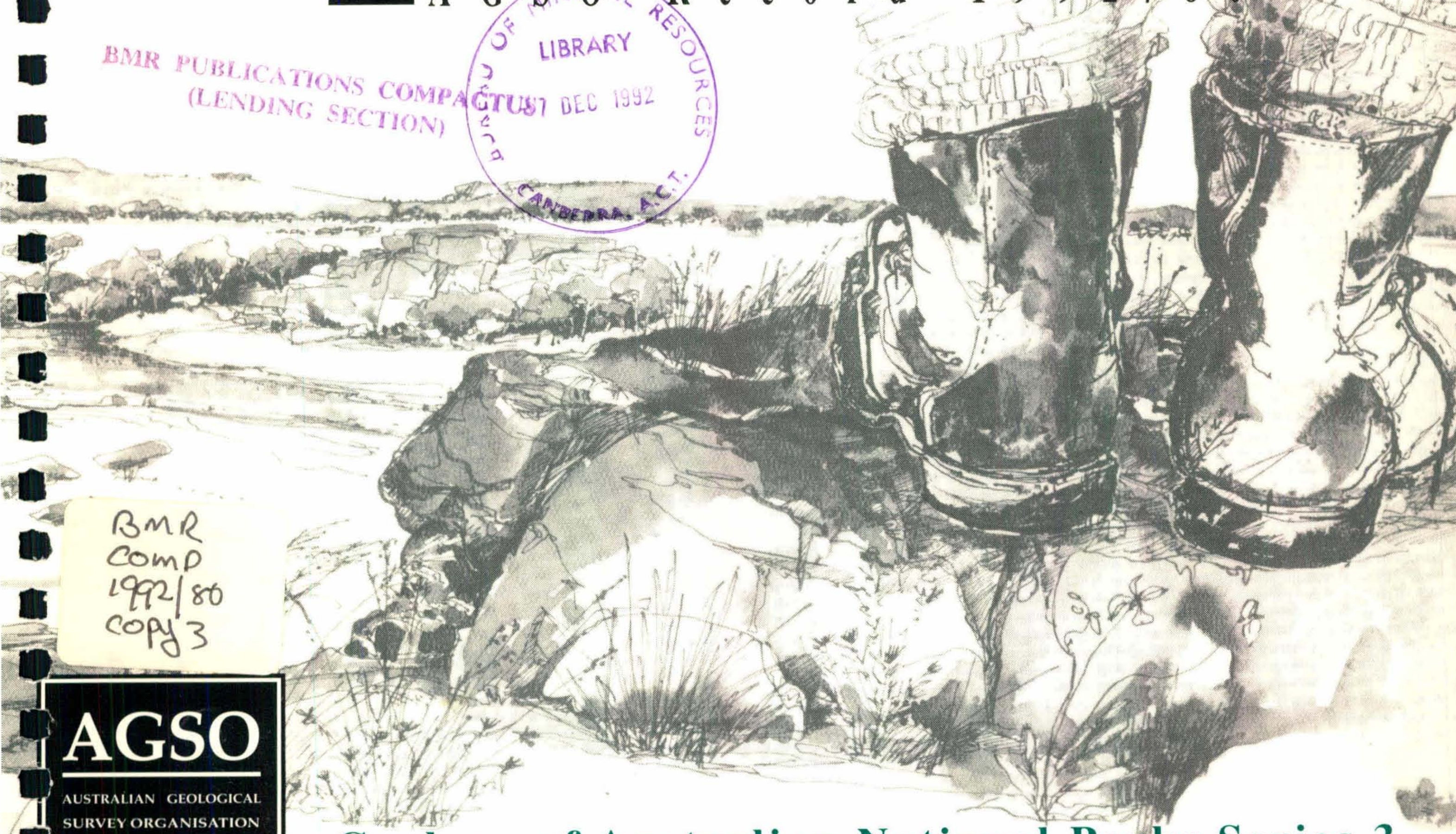
Geology of the walking trails in *Kakadu National Park*

- Jim Jim Falls area

by R.S. Needham

AGSO Record 1992/80



AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Geology of Australian National Parks Series 3

GEOLOGY OF THE WALKING TRAILS IN KAKADU NATIONAL PARK - JIM JIM FALLS AREA

by

RS Needham

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Geology of Australian National Parks Series #3

DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

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cover artwork courtesy Australian National Parks & Wildlife Service; drawn by Jane Moore

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INTRODUCTION

HOW AN UNDERSTANDING OF GEOLOGY CAN HELP US APPRECIATE THE NATURAL DEVELOPMENT OF OUR NATIONAL PARKS

Most of Australia's National Parks have been established to protect areas of natural beauty. In many instances this natural beauty owes itself to a landscape dominated by rock (e.g. Uluru, Bungle Bungles, Warrumbungles). Over millions of years, interaction between the rocky landscape and the climate has produced a unique assemblage of environments for each park, and the variation between these determine the plants and animals which live in each area.

Therefore National Parks offer the opportunity to study the landscape and the rocks from which it was carved. By knowing more about the rocks, we can come to understand how the park landscape and ecosystems evolved. The rocks represent stages in the development of our Earth, and so by understanding the geology of our National Parks, we can improve our knowledge of the unique and ancient processes by which our planet and its multitude of environments has evolved.

The natural beauty of Kakadu National Park is focussed on and around the sandstone cliffs of the Arnhem Land Escarpment and the adjacent wetlands. This report is one of a series developed to describe the geology of the walking trails which explore the sandstone country in the Ubirr, Nourlangie, Jim Jim Falls, and Mary River areas.

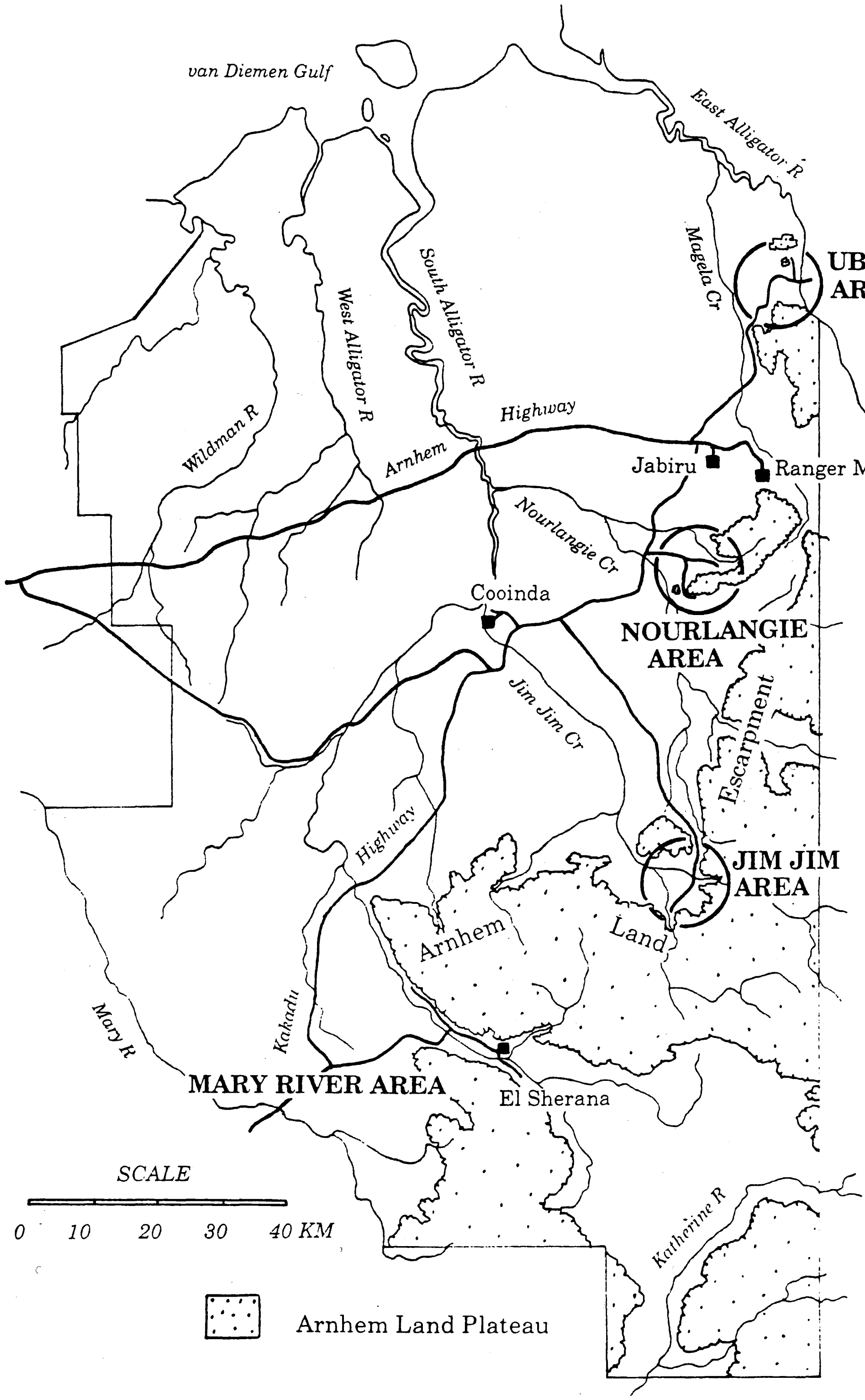


Figure 1. Location of the Kakadu walking trails

A BRIEF OUTLINE OF THE GEOLOGY OF KAKADU AND ITS LANDSCAPE

The cliffs which dominate the landscape of Kakadu are made of ancient sandstone which was deposited by large rivers flooding across a wide, flat plain. The sandstone is about 1000 metres thick, and the lowest 200 m or so are exposed as the Arnhem Land Escarpment. The higher parts of the sequence form the Arnhem Land Plateau, which extends up to 100 km east of the escarpment. The sandstone is known scientifically as the Kombolgie Formation [1], and formed 1 700 million years ago in *Precambrian* [2] times.

The plain over which the sandstone was laid down was formed from a long period of erosion and weathering of even older rocks. These are *granites* and *metamorphic rocks (schist, gneiss, quartzite and amphibolite)* which formed 1 800 million years ago as a result of the earth's crust sagging down to form a large depression or *geosyncline,* in which an inland sea formed which gradually filled up with sediments washed in from the surrounding higher ground. The geosyncline slowly sagged down under the weight of the sediments, and eventually about 10 km thickness of sediments accumulated. This weight on the Earth's crust caused great pressure and temperature increases, and as a result the sedimentary rocks of the geosyncline were strongly folded and recrystallised in a mountain building or *orogenic event,* changing them into metamorphic rocks. Different kinds of *magma* intruded these rocks, forming bodies of *granite and dolerite.*

The mountains of metamorphic rocks, granite and dolerite were gradually worn down by erosion and weathering for 100 million years, until the area was reduced to a wide, flat plain. A few small hills and ridges dotted the plain, and some are still preserved, for example as Mirray (Mount Cahill) and the Mount Partridge Range. The best exposures of these older rocks are commonly near the base of the escarpment, and they can be seen on several of the walks described in this report.

The sandstone rocks of the Kombolgie Formation covered all of Kakadu until a sea invaded the area in *Mesozoic* times, 100 million years ago. Wave action progressively eroded back the sandstone to form sea cliffs, and once again exposed the older metamorphic rocks which had been covered by the sandstone for 1 100 million years. So these older rocks extend beneath the lowlands of Kakadu, but they are mostly poorly exposed because they have been deeply weathered and covered over by sand, gravel and *laterite* in relatively recent geological times.

The landscape of Kakadu is therefore truly ancient, because its major features are little changed from when they were first sculpted 100 million years ago. Shallow seas have covered parts of the lowlands from time to time as sea levels have fluctuated, and climate patterns have changed significantly. The most recent of these changes are documented in rock art, which shows that the sandstone country of the escarpment and its *outliers* have provided shelter for Australian Aboriginals for perhaps as long as 40 000 years.

[1] *geologists give different rock formations names so it is easier to understand which rocks in which general location are meant when describing them. The name usually starts with a geographical term (e.g. "Kombolgie") which refers to a creek, hill, homestead etc where the rock unit is well exposed. The end of the name is commonly a rock type (e.g. "Granite, Schist"), but if the unit being described is a mixture of rock types, then the term "Formation" may be used instead. An Australian register is maintained to ensure that each unit is defined properly and that each name is unique in Australia.*

[2] *scientific terms explained in the glossary at the end of this report are shown in italics*

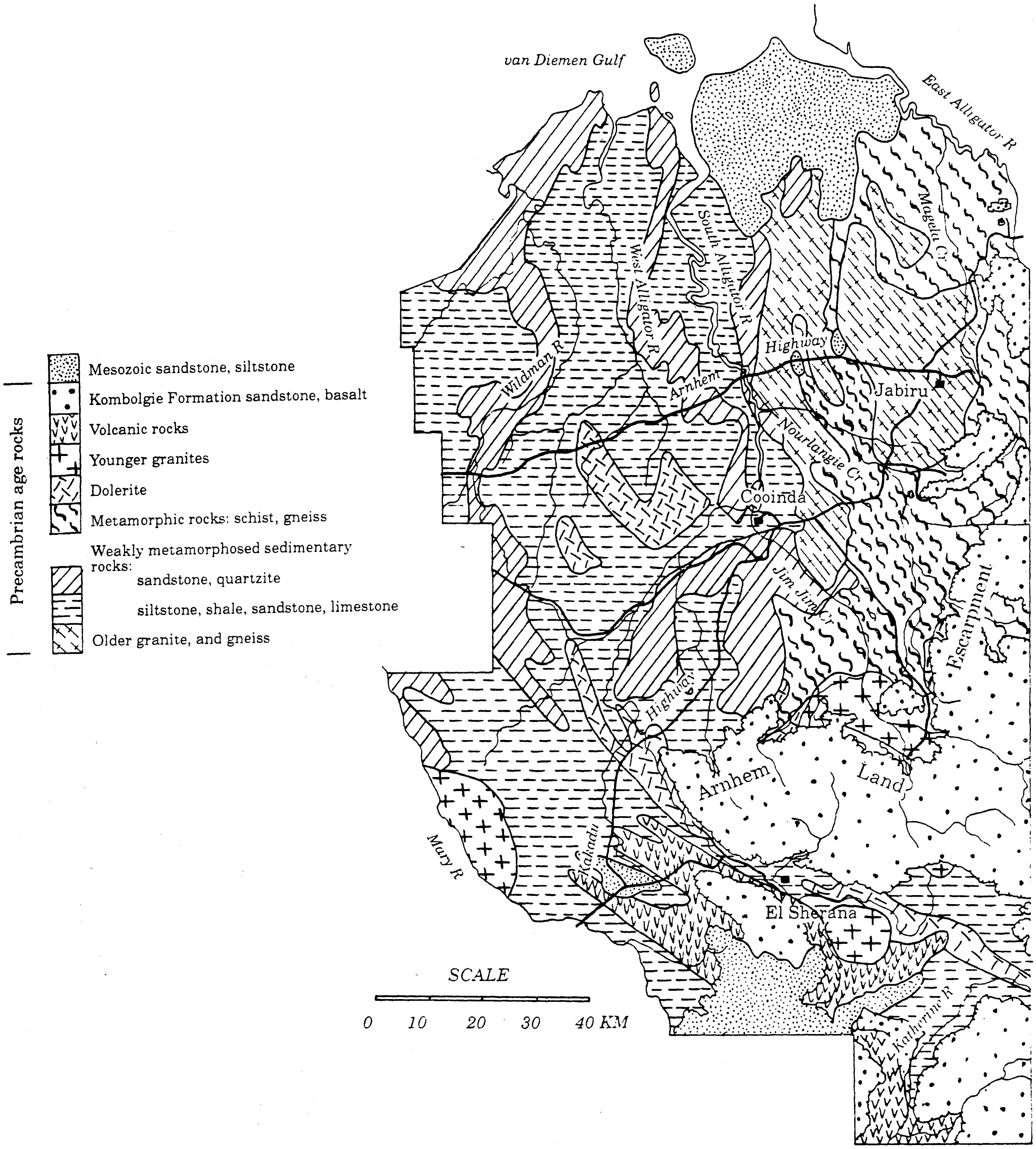


Figure 2. Generalised geology of Kakadu National Park

There are three walking trails in the Jim Jim Falls area - the Budgmii, Plunge Pool, and Barrk Marram trails. In different ways, they explore how the majestic scenery of Jim Jim Falls was formed.

The Budgmii trail, west of the campground, presents a general view of the Arnhem Land Escarpment and of the mouth of Jim Jim Gorge. The Budgmii lookout is at a fine example of the base of the sandstone sequence *(the Kombolgie Formation)* which forms the cliffs and plateau of the Arnhem Land Escarpment. This type of geological contact, known as an *unconformity,* divides the sandstone from much older "basement" rocks on which the

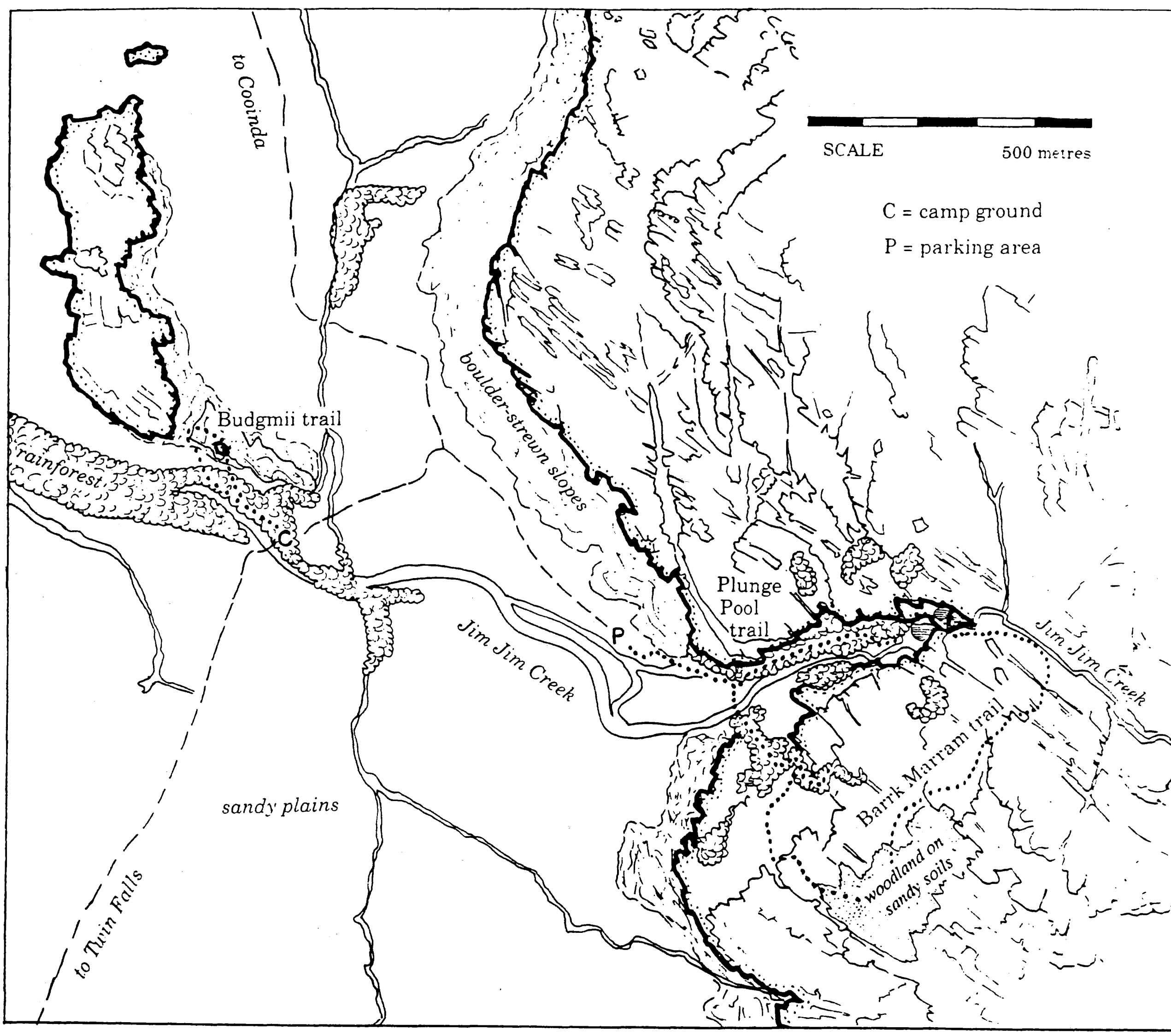


Figure 3. Location of the Budgmii, Plunge Pool, and Barrk Marram walking trails in the Jim Jim Falls area

sandstone was deposited. This sharp contact between the two rock types represents a time gap of 100 million years between the 1 700 million year old sandstone and the older basement rocks, which in the Jim Jim Falls area consist of granite.

The Plunge Pool trail follows the north side of Jim Jim Gorge to the plunge pool at the base of Jim Jim Falls. The trail clambers over and between enormous blocks of sandstone which have fallen down from the cliffs as they have been eroded back. The sandstone has broken away from the cliffs along vertical cracks or *joints*, and along horizontal *bedding planes,* and these surfaces can be seen in places in overhangs and sheer faces in the cliffs. The water-laid origin of the sandstone is evident from *ripple marks* on some of the fallen blocks, and from *cross-bedding* in the cliffs.

The Barrk Marram trails climbs to the top of Jim Jim Falls, and ends with magnificant views along the gorge and across the lowland plains beyond. The end of the trail looks down into the upper section of the falls which is about half the height of the main cascade seen from the Plunge Pool trail. The trail crosses part of the rugged, bare rock pavement landscape typical of the 16 000 square kilometre Arnhem Land Plateau, which extends from Katherine to near Milingimbi on the north coast of Arnhem Land. This landscape consists of bare sandstone pavements and rugged sandstone crags separated by patches of thin soils supporting spinifex and other grasses, and stunted acacia and eucalyptus scrub. Pockets of tangled rainforest survive in the deep shady ravines which cut across the plateau in many directions. These ravines are caused by weathering along *joints and faults,* where the rocks have been cracked and sometimes displaced by bending of the earth's crust.

BUDGMII TRAIL

From the Jim Jim campground the trail follows the north bank of Jim Jim Creek for 300 m then winds northwards up to a hill of ancient and deeply weathered granite. At the lookout on the top of the hill, the *Kombolgie Formation* sandstone sits directly on the granite, defining a geological *unconformity* which represents a time gap of 100 million years between the granite and the younger sandstone.

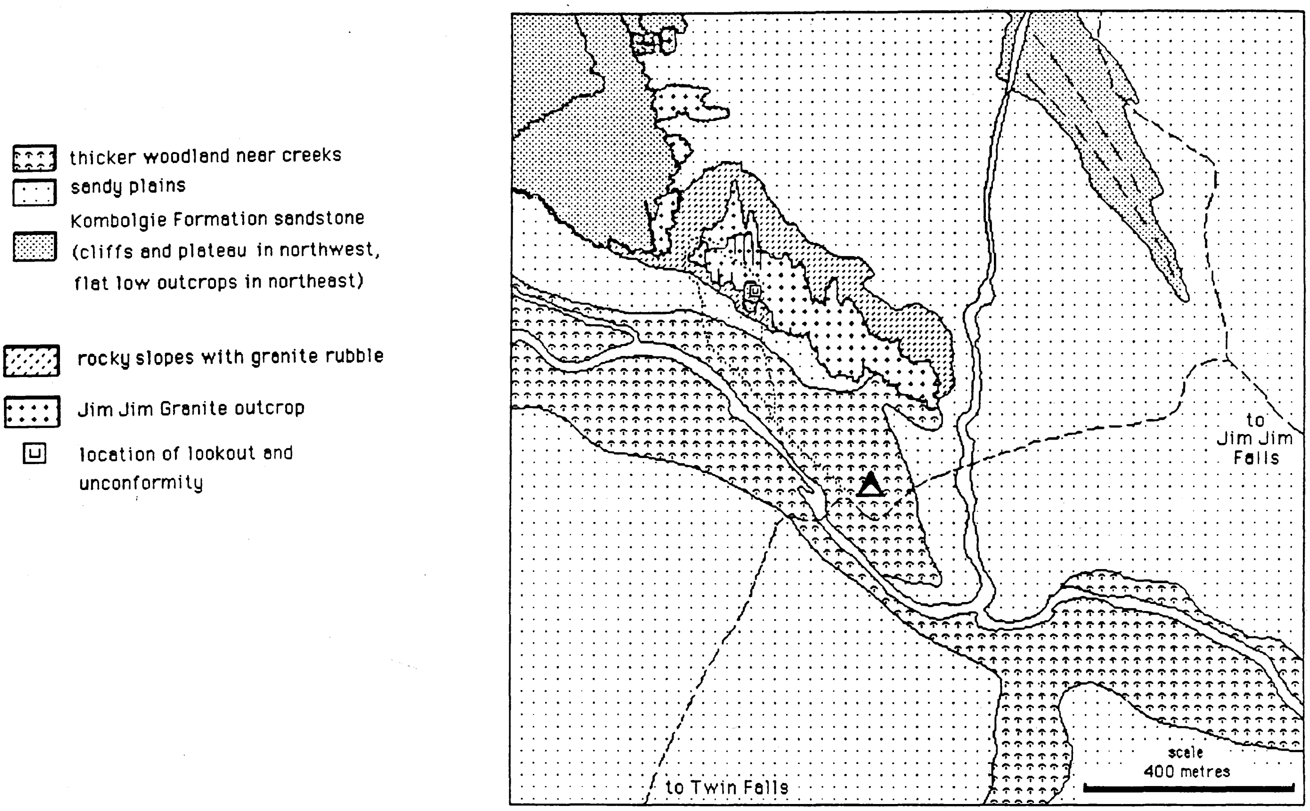


Figure 4. The Budgmii walking trail

The sandy soils along Jim Jim Creek have been washed down from the Arnhem Land Plateau, and sands persist down the creek for about another 20 km. After the track leaves the creek, it climbs up over a coarse gravelly-looking red or mottled red-green rock (figure 5) which is a very deeply weathered granite known as the *Jim Jim Granite*. The granite extends down to Twin Falls, and to the headwaters of Gimbat Creek in the southern part of Kakadu about 30 km farther south, but it is mostly unexposed or covered over by the *Kombolgie Formation* sandstone.

The granite at Budgmii is very crumbly because it was deeply weathered for many millions of years before the Kombolgie Formation sandstone was deposited. Deeper parts of the granite were strongly leached and the surface areas enriched in iron oxide (hematite) which gives the rock its blotchy purple and cream colour. This leaching process is similar to the process which has led to the formation of *laterite* in relatively recent times in Kakadu.

Granite consists of three essential minerals - quartz, feldspar and mica. In this rock, the feldspar and mica have rotted to clay, which is stained red by the hematite and green by chlorite, a mineral rich in iron and magnesium. The only original mineral left intact is quartz, which forms angular glassy grains up to 1 cm across.

Where the trail tops the saddle between the lookout and the sandstone tableland farther west, the granite forms rounded boulders (figure 6) distinct from the more angular and commonly flat, slab-shaped blocks of Kombolgie sandstone. The granite is cut by long veins of a fine grey rock which is altered very fine grained granite or "microgranite", which was injected along cracks in the granite after the granite itself had crystallised from a *magma* deep in the earth (figure 7).

At the lookout, sandstone of the *Kombolgie Formation* sits directly on the granite. This contact is known geologically as an *unconformity,* and it represents a time break and major change in the type of geological process below and above the contact (figure 8). From dating of the minerals in the granite we know it was intruded into the earth's crust about 1850 million years ago. Its coarse grain size tells us it cooled slowly (i.e. crystals have longer to grow and are therefore bigger) and so was probably at least 1 km below the surface - at shallower depths it would have cooled quickly and would be finer grained.

This 1 km of covering rock, then some of the granite, was eroded away and the granite surface then deeply leached and chemically altered by ancient weathering, all before the Kombolgie sandstone was laid down on top 100 million years later. The great length of this period even by geological standards, can be better appreciated when you consider that the age of the dinosaurs ended "only" 65 million years ago!

The view from the lookout shows the sandstone cliffs of the main escarpment with individual thick beds of sandstone continuing each way for several kilometres. The beds generally rise and fall over slight fault movements in the basement rocks. The sandstone gets thinner looking south to Twin Falls, and in the southwest towards Graveside Gorge the basement rocks form high ridges with only a thin capping of sandstone on top - less than 50 m, compared to the 200 m at Jim Jim Falls.

The sharp conical hill in the middle distance looking west is a pinnacle of *Jim Jim Granite* with a little cap of *Kombolgie Formation* sandstone. The large *outlier* of sandstone immediately west and northwest of the lookout is also a capping of sandstone on granite. Because the sandstone is relatively thin over the granite we can tell that the granite formed a low plateau on the landscape before the sandstone was laid down, rising about 30 m above the softer *schists* and *siltstones* around the granite.

Figure 5. Weathered, crumbly granite on the trail up the hill towards the lookout.

Figure 6. Rounded, irregularly jointed outcrop of weathered granite at the top of the hill, looking towards the lookout.

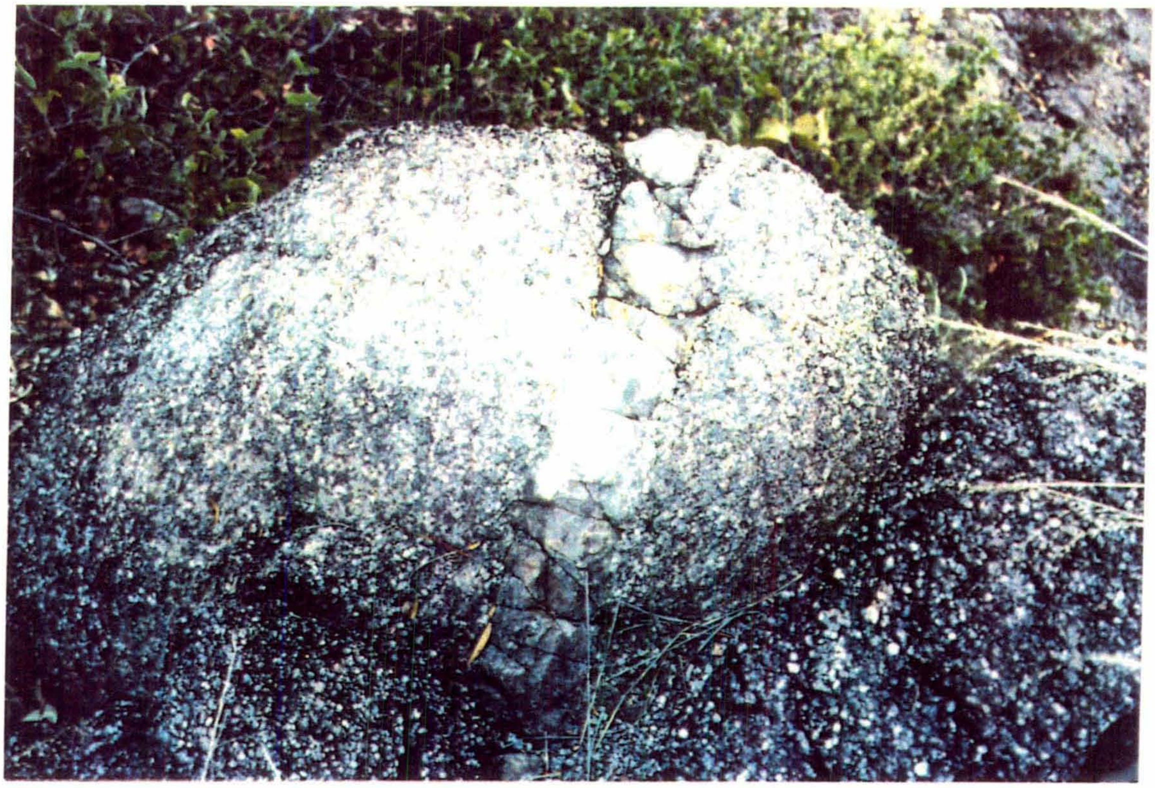


Figure 7. A pale grey vein of microgranite cuts through the Jim Jim Granite.

Figure 8. The granite / sandstone contact about 30 cm above the sign is an unconformity representing a major break in the rock record spanning 100 million years; and a change in geological processes from magma intrusion deep in the earth's crust, to land surface weathering, to sand deposition on a wide river plain.

This walk climbs through a jumble of sandstone boulders to the tallest sheer cliff face in Kakadu. Ripple marks and cross-beds demonstrate the method of deposition of the*Kombolgie Formation* sandstone, which is cut by many deep vertical *joints* controlling the shape of the gorge and the rock face at the falls.

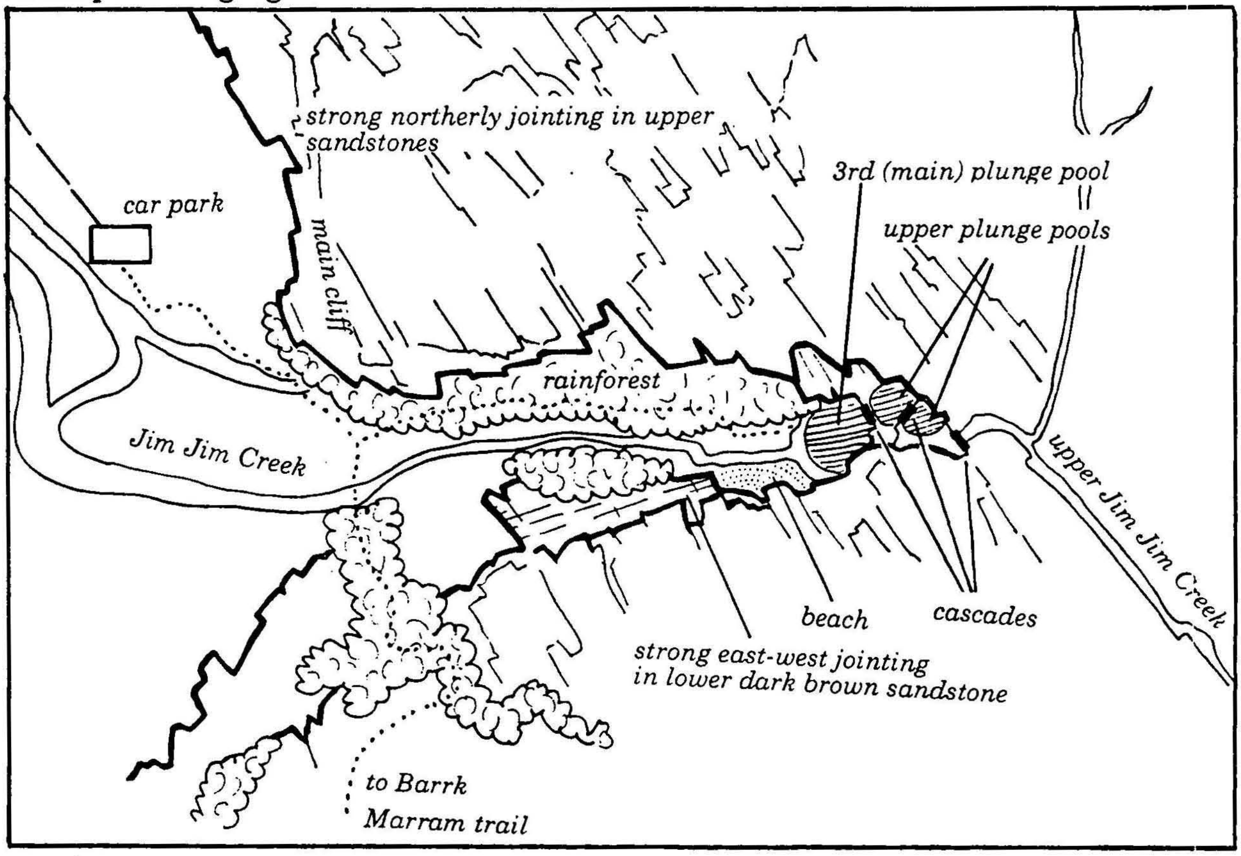


Figure 9. The Jim Jim Falls plunge pool trail

The path from the car park picks its way through sandstone blocks which have fallen from the cliff up to the north (left) of the track. Depending on how far up the cliff face the sandstone fell from it is either red and pebbly (the lower part of the cliff) or pale brown to white and fine grained from the top part.

The Kombolgie sandstone lies on top of a deeply weathered granite in this area called the *Jim Jim Granite.* Although the contact between the sandstone and granite is covered by rubble up the slope, a few small boulders of the red, very crumbly granite (breaking open to mottled cream, brown or pale green) have rolled down to the track. This rock looks similar to the coarse red sandstone, but lacks the bedding structures and the pebbles that the sedimentary sandstone contains.

The sandstone boulders in the creek are slab shaped (figure 10), because they have split away from the cliff face along the near-horizontal *bedding planes,* which represent the layers in which the sandstone was laid down during floods across a vast alluvial plain which stretched across Kakadu 1 700 million years ago. Some of these bedding surfaces are *ripple marked* (figure 11), demonstrating clearly that these sands were laid down in water.

Another indicator of the water currents which deposited the sandstone is a feature called *cross bedding*. These cross beds slant down between bedding surfaces in the direction that the water used to flow, and are very clearly preserved in the dark stained rocks at the sandy beach (figure 13). The crossbeds are best developed in the thicker beds, and ripple marks on the surfaces of the thinner bedded parts of the sandstone sequence. The crossbeds slope down towards the falls, telling us that the rivers which deposited the sands flowed to the east.

The lowest 40 m of the sandstone cliffs is dark because it is stained by iron minerals picked up by the ancient rivers from the deeply weathered and iron-enriched plain as it flowed across. These minerals were mixed up with the sand and deposited with it in the earlier stages of Kombolgie sandstone deposition.

The upper 160 m of the cliff is made up of fine white quartz sandstone with few pebbles and very little iron. There is enough iron in the rock however for water seeping through the sandstone to stain the cracks through which the water has passed.

The many cracks in these towering and seemingly teetering cliffs were formed by fracturing and *faulting* of the sandstone, mainly in southeast and southerly lines (figures 14 & 15). Water seeping along them has also deposited silica along the walls of some of these fractures, so "armouring" the sandstone with a few centimetres of very strong silica in place of the weak clays which normally hold the sand grains together.

Because of this "armour plating" the current surface of the cliffs at the falls is very stable. The rate of weathering back (or *retreat*) of the falls is consequently very slow. Indeed, many scientists believe that the cliffs formed as sea cliffs in the *Mesozoic* era, about 100 million years ago; this would explain why there are few large blocks away from the base of the cliffs on the plains, because they would have been broken down by wave action. In many places there has been very little *scarp retreat* since the sea cliffs were formed.

Jim Jim Falls is so high because there is a thick section (200 m) of sandstone here, rising from only about 20 m above the level of the plains. By comparison, at Twin Falls a relatively thin cap of sandstone (120 m) covers the basement rocks. There also the creek flows along a fracture in the rocks to form a long, narrow gorge. Here at Jim Jim Falls the creek flows across the fractures and plummets down armoured rock faces and two sheer drops (only the lower drop of about 150 m can be seen from the plunge pool; the upper drop is about a 50 m fall and can be seen on the Barrk Marram trail).

Although the larger boulders have probably not moved for hundreds or thousands of years, the smaller ones are jostled each wet season. Very heavy rains from tropical cyclones passing over the Jim Jim Creek system on the plateau periodically produce unusually heavy flows which can change conditions in the gorge considerably. Such a cyclone may have been the cause of accumulations of iron-rich sand over the area now occupied by the plunge pool. This sand cemented the boulders into a weak *conglomerate* rock, and remnants of it are still evident in places around the pool (figure 16).

Jim Jim Falls cascade over the highest sheer cliff section in Kakadu (figure 17). The total thickness of the *Kombolgie Formation* is about 1000 m, but only the basal sections are exposed in the Arnhem Land Escarpment. The higher parts of this geological formation continue across the plateau for about 80 km east of Jim Jim Falls, and the Arnhem Land Plateau covers 16 000 square kilometres.

Figure 10. Sandstone blocks, many weighing hundreds of tonnes, form a jumbled mass at the base of the cliffs near the plunge pool. The flatter surfaces are once-horizontal bedding surfaces along which the rock broke away.

Figure 11. Ripple marks on some boulders are relics of the deposition by water of these sandstones. The ripples are mostly asymmetrical (steeper on one side than the other), but cannot be used to determine the direction of water flow because the boulders are not in place.

Figure 12. Some rocks have been polished by sand-laden water abrading them and by minerals precipitated on the surface of the rocks from percolating water.

Figure 13. Cross-bedding in the dark-stained sandstone beds above the sandy beach on the south side of the gorge show that the depositional currents flowed towards the east (i.e. from right to left in the photo).

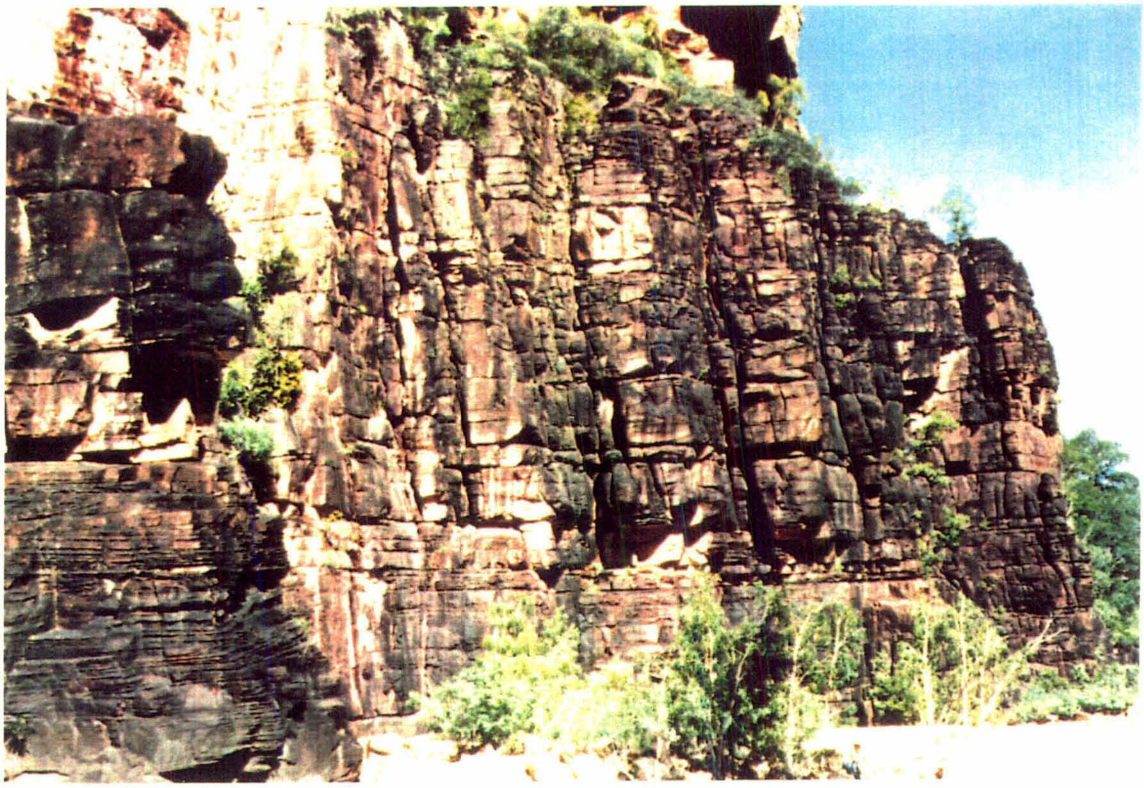


Figure 14. By looking back at the lower darker part of the southern cliff, an east-west set of steep joints can be seen which parallel the direction of Jim Jim Creek and which are controlling the direction of formation of the Jim Jim gorge.

Figure 15. The dominant joint set which controls the northerly line of the escarpment forms sheer vertical faces which are best developed in the lighter-coloured rock higher in the cliffs. "Armouring" of these faces by a layer of silica strengthens them and makes them more resistant to erosion.

Figure 16. In places near the plunge pool, clasts of subangular to rounded vein quartz and sandstone are cemented by iron oxides (limonite and hematite) to form pebble conglomerate, and probably formed at a time when the plunge pool was filled with iron-rich sand.

Figure 17. The height of the cliffs above the plunge pool and the bedding in the cliffs appear to dip down towards the waterfall, but the true dip of the plateau top and bedding in the sandstone is to the east, 'into' the main cliff.

BARRK MARRAM TRAIL (to the top of Jim Jim Falls)

This trail climbs up the entire sandstone section from Jim Jim Creek below the Plunge Pool, to the top of the Arnhem Land Plateau. The walk finishes with magnificent views of the sandstone faces of Jim Jim gorge from the top of the upper waterfall. The clefts formed in the sandstone by *faulting and jointing* can be clearly seen and experienced as the trail winds along, through and across many of these features. On the plateau top the track crosses extensive bare sandstone pavements with only scattered soil and vegetation. This starkly beautiful land form extends over 16 000 square kilometres of the Arnhem Land Plateau, mainly east and north of Jim Jim.

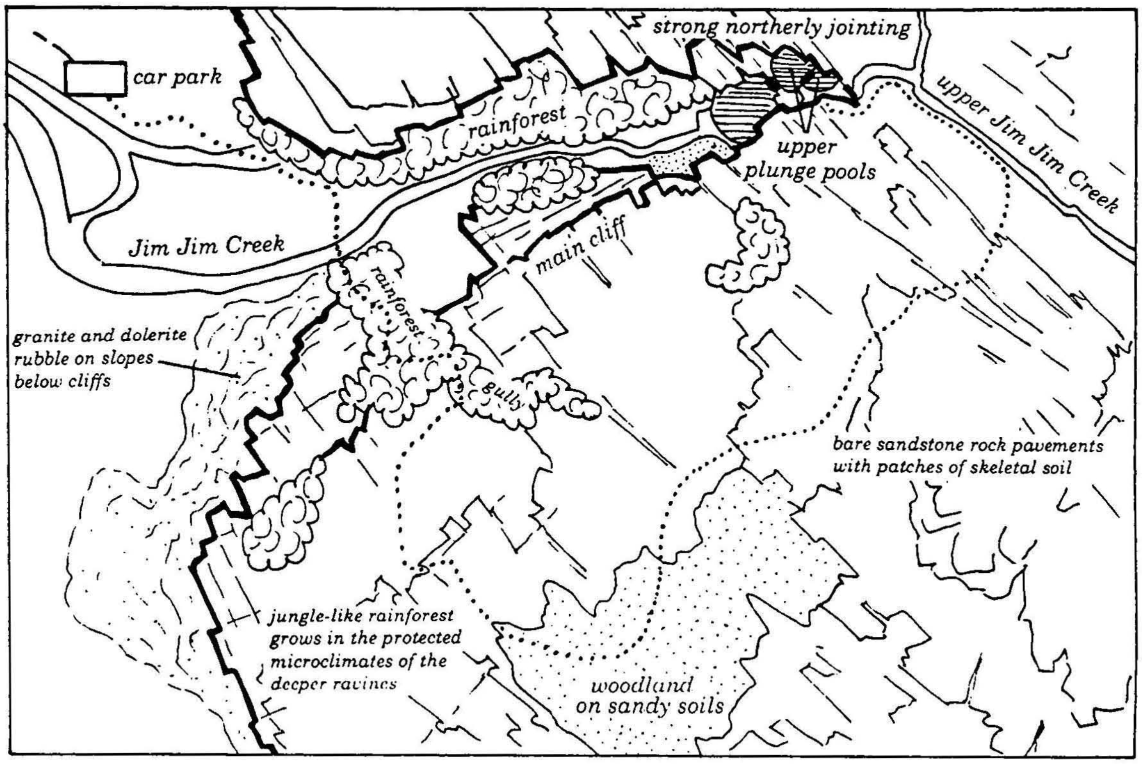


Figure 18. The Barrk Marram trail to the top of Jim Jim Falls

The track begins by crossing Jim Jim Creek where the creek bed is filled with 1-2 m sized blocks of sandstone and a few blocks and outcrops of *Jim Jim Granite* (figure 20). The granite here is relatively fresh, but all of the original minerals except the quartz are altered to clays and stained red, purple and brown by iron.

The climb .....

Between the creek and the rainforest gully, more blocks and outcrops of the granite lie near the track (figure 21). Here they are very crumbly and stained red by hematite, and this red alteration indicates that these granite outcrops formed a deeply weathered land surface before the Kombolgie sandstone was deposited about 1 700 million years ago. The contact between the sandstone and the older rocks is called an *unconformity,* but it is not exposed here because of sandstone rubble which has fallen down the cliffs. The *unconformity* is clearly exposed at the lookout on the Budgmii walking trail west of the Jim Jim camping ground.

The granite outcrops of the rainforest gully are overlain by a coarse gritty or pebbly red sandstone derived from and therefore very similar in appearance to the granite. The sandstone can be easily distinguished from the granite because it contains rounded pebbles, and is bedded into roughly horizontal layers.

The freshly broken granite surface reveals highly altered feldspar minerals which are mottled purple or green and cream, but iron has been leached during weathering to form a dark red skin a few millimetres deep which changes the surface colour of the rock. Algae grows on the surface too, making the rock look even darker.

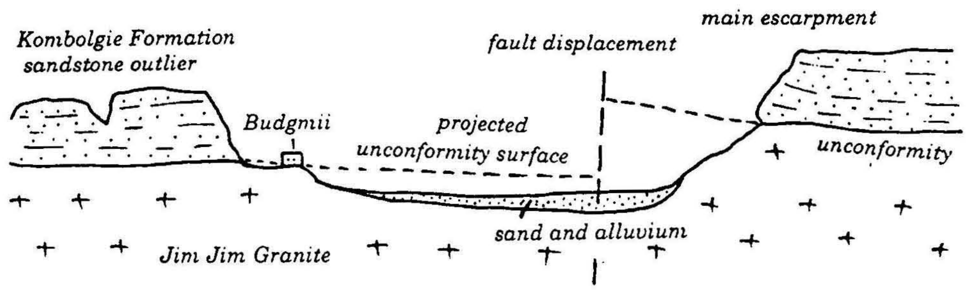


Figure 19. Sketch cross section from Budgmii to main escarpment near Jim Jim Falls showing the projected fault displacement of the granite/ sandstone contact (unconformity).

Climbing further up the trail, glimpses across to the Budjmii Lookout and the sandstone *outlier* beyond can be seen (figure 22). The *Jim Jim Granite* formed a low plateau about 60 m high on the plains before the *Kombolgie Formation* sandstone was deposited, and the sandstone forms a uniformly flat cap about 140 m in thick in the *outlier,* above this ancient and now mostly buried feature. Budjmii is at the edge of this plateau, and the granite surface can be seen sloping down away from the buried plateau towards Jim Jim gorge. A *fault* running north between the main escarpment and the *outlier* has pushed up the granite to a higher elevation on the eastern side, so that granite underlies the base of the cliffs at the mouth of the gorge at higher elevation than at Budjmii.

In the main cliff on the trail up to the top of Jim Jim Falls the sandstone becomes lighter in colour and fine and even grained, with only few pebbles of milky *vein quartz.* The sandstone remains like this for the rest of the climb. This change in rock type and colour from red and coarse at the bottom to white and fine grained further up the cliffs is also easily seen on the Plunge Pool trail.

The plateau top .....

The trail scrambles upwards through clefts in the sandstone formed by erosion along *joints and fractures* in the rock. The steel footbridge near the top of the climb crosses an 18 m deep crack formed this way (figure 23); the rocks either side have not moved apart, but a section of the rock has been removed by erosion along these fractures, which are lines of weakness where water has most effectively been able to at first soak through and then break down the rock. The water does this by removing the clay which sticks the sand grains in the rock together.

This process can work horizontally as well as vertically, and so weaker beds of sandstone are wasted away forming "pancake" stacks of alternating weaker and stronger beds of sandstone (figure 25).

Weathering also moves many elements from the rock, particularly iron and silica. Iron forms a skin on many horizontal rock surfaces, especially where water sits on the surface for a long time, soaks down into the rock to leach out the iron, and then when the water is removed by evaporation during the dry season from the rock's surface, the iron is left behind as a reddish brown or orange rim (figure 26).

In places this process has also acted on the thin soils that have accumulated on the plateau surface, and here the iron accumulates as small brown nodules of *laterite*.

Even though the top of the plateau is 200 m higher than the base of the sandstone sequence near the beginning of the trail, the sand from which the sandstone rock was formed was still being transported and deposited in the same way. Numerous *ripple marked bedding surfaces* prove the water-laid origin of these sands. *Ripple marks* themselves are commonly asymmetrical (steeper on one side than on the other), and tell us the direction of water flow on that bed at that place. The steeper face of the ripple is on the downstream side. However, ripple marks are a poor guide to the overall direction of water flow, as any day on the beach would tell you. Therefore *cross-bedding* structures such as those at the base of the sandstone sequence on the Plunge Pool trail are used as a more reliable guide to the main direction of water flow (these are formed by individual channels of water flowing along and depositing sand as it goes).

In this area of the plateau top however there are very few *cross beds* developed, suggesting that the depth of the water during sand deposition was very shallow. This is borne out by the frequency of *ripple marks,* which trend to almost all points of the compass here.

The black surfaces along the creek bed just before it plunges over the edge of the cliff are caused by algae growing on the wet rocks during the rainy season. In some places, sand being transported along the creek in the wet season has abraded the rocks on the creek bed and banks to a smooth polished surface.

At the top of Jim Jim Falls .....

The two levels at the top of Jim Jim Falls indicate that at some stage the armoured *(silicified)* surface of the main rock face was breached, allowing erosion of the upper cliff face, back to another strong vertical surface also armoured by *silicification* along a *joint* in the rock. During this retreat, the blocks from the top plunge pool area would have fallen 150 m into the lower Plunge Pool. Without doubt, most of these would have weighed several hundred tonnes each.

Looking over the falls, the *joints* in the sandstone which control the shape of the cliff faces, can be seen as deep narrow fissures being gradually deepened and widened by erosion (figure 27). The fissures and the cliff faces are stained orange and brown by iron leaching out of the rock onto these surfaces, transported by water slowly seeping through the rocks. The black streaks are caused by algae growing on the rock in the wetter areas.

The view west from the top of Jim Jim Falls (figure 28) takes in the large sandstone *outlier* resting on *Jim Jim Granite* (the sandstone outcrop on the Bugmii walking trail forms the very eastern tip of this *outlier*). The low mountain range on the horizon is the Mount Partridge Range, near Barramundie Gorge. These quartzites are part of the basement sequence beneath the Kombolgie sandstone, and form part of the *folded and metamorphosed* sedimentary rock sequence into which the *Jim Jim Granite* was intruded.

These quartzites can therefore be easily distinguished from the *Kombolgie Formation* sandstones, which have not been significantly *folded or metamorphosed* and so remain essentially unchanged since they were deposited 1700 million years ago, except for them becoming lithified (i.e. hardened into rock), and surface alteration effects.

It's worth pondering that fossils with hard shells first appeared "only" 600 million years ago, and that when the Kombolgie sands were laid down there was no vegetation or complex life of any sort yet evolved on this planet, except perhaps for primitive single-celled organisms. In fact, scientists now believe that oxygen was only just beginning to build up in our atmosphere at that time.

Figure 20. Roughly rounded boulders of grey Jim Jim Granite mixed with more angular brown sandstone boulders in the bed of Jim Jim Creek.

Figure 21. Crumbly outcrops of deeply weathered and altered Jim Jim Granite in the rainforest gully. The weathering took place mostly before the sandstone was laid down on top of the granite, about 1 700 million years ago.

Figure 22. Glimpses from the climb up the sandstone cliffs across to the outlier west of the Jim Jim campsite. The Budgmii trail lookout is a small low knob at the base of the outlier, near Jim Jim Creek.

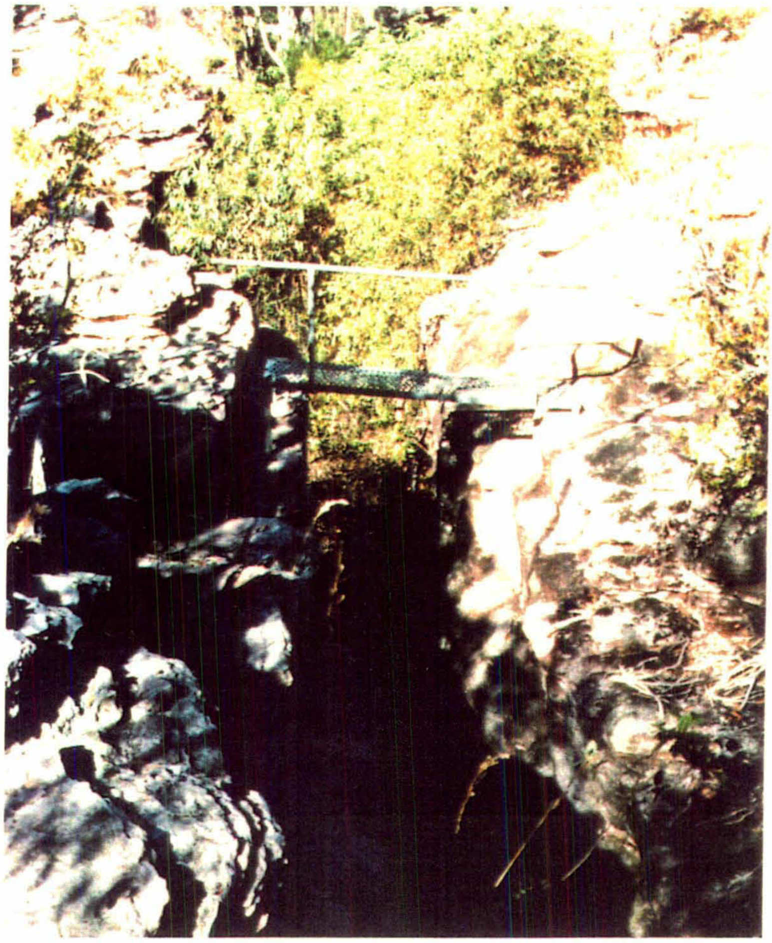


Figure 23. The steel footbridge spans a crevasse formed by weathering out along a sandstone joint. The cool, shady crevasse floors provide a variety of microclimates which support markedly different vegetation to the sandstone surface of the Arnhem Land Plateau.

Figure 24. In areas where the sandstone plateau surface is covered by thick residual sands, tall grasses grow in an open woodland of tall eucalypts.

Figure 25. Differential erosion of harder and softer sandstone beds produces "pancake stacks" of bare rock. The thin, poor sandy soils support mainly spinifex grasses and acacia scrub.

Figure 26. Crusts of iron oxides (hematite and limonite) are precipitated on the bottom of clear rock pools in the wet season.

Figure 27. Vertical cracks formed by the weathering out of joints in the northern cliff face above the upper plunge pool clearly show how jointing controls the shape of the cliff face as the sandstone cliffs gradually retreat.

Figure 28. View of the south cliff face above Jim Jim Falls; splitting along joint surfaces has caused blocks to fall away, leaving overhangs. On the horizon, a thin layer of Kombolgie Formation sandstone overlies quartzites of the Mount Partridge Range.

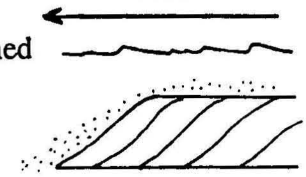
GLOSSARY OF GEOLOGICAL TERMS

Bedding, bedding planes, bedding surfaces - planes of weakness in a sedimentary rock which are formed under water and which separate the individual layers or beds from which the rock was formed. When formed, the bedding was horizontal or very nearly horizontal.

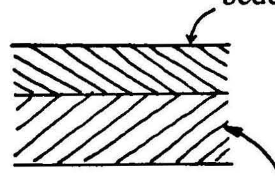
Amphibolite - a fine-grained metamorphic rock formed by the recrystallisation of dolerite or marble.

Conglomerate - a sedimentary rock made up of rounded pebbles of older rocks stuck together by sand and smaller rock fragments.

Cross bedding - layers within a sedimentary rock bed which slope at an angle to the bedding planes; the cross bedding surfaces slope down towards the direction in which the water was flowing.



FORMATION OF CROSS BEDS



CROSS BEDS PRESERVED IN ROCK

Dolerite - a black igneous rock formed by the cooling down and solidifying of a magma which is low in silica and relatively enriched in iron and magnesium.

Faults - fractures caused by stresses in the earth's crust along which the rocks either side have moved relative to one another.

Folding - bends in rock strata caused by stresses in the earth's crust; usually shortening of the crust forces the rocks to fold so as to take up less lateral space, and the increase in vertical space may be great enough to constitute 'mountain building'.

Geosyncline - a large, shallow depression on the Earth's crust which becomes filled with sediments washed in from the surrounding higher ground. It forms from stretching of the crust, and this thinner, weaker crust commonly sags under the weight of the sediments so that a sequence of new rocks can form in the geosyncline which is much thicker than the original depth of the shallow depression.

Gneiss - a metamorphic rock formed from recrytallisation of an older sedimentary, metamorphic or igneous rock, which is usually strongly banded or foliated and fine to coarse grained.

Granite - an igneous rock, mostly medium to coarse grained and light-coloured, formed by the cooling and solidification of a magma rich in silica and relatively low in iron and magnesium.

Jim Jim Granite - the formal scientific name for the granite outcrops in the Jim Jim Falls area. It is mostly covered by sand and alluvium in the lowlands, and it continues beneath the sandstone cliffs east and south of Jim Jim Falls and Twin Falls.

Joints - a fracture in rocks caused by stress release; unlike faults, the rocks either side have not moved relative to one another. Joints often are the focus of weathering, and water passing through the rocks mostly travels along open joints.

Kombolgie Formation - the formal scientific name for the sandstone which makes up the cliffs, plateau country and outliers of Kakadu and western Arnhem Land. It is about 1 000 m thick, and near the top contains two basalt lava flows. Only the bottom 250 m are exposed in the Arnhem Land Escarpment.

Laterite - a dark red-brown rock formed at or near the land surface as a result of leaching of iron and other elements during weathering of the underlying rock and/or loose materials. In Kakadu it generally forms a 1-2 m crust of nodular (pebbly) or vermicular (wormhole-like) rock, overlying a deep, pale yellow, cream or white bleached zone from which the iron has been removed by fluctuating groundwater levels.

Magma - molten rock material formed deep within the earth which has become mobilised into the upper crust where it may cool and solidify to form igneous rocks. If it cools within the crust it forms *intrusive* igneous rocks such as granite and dolerite, and if it reaches the surface it forms *extrusive* volcanic rocks. Different chemical compositions of the magma result in the formation of different rock types.

Mesozoic - a geological era embracing time from 65 to 250 million years ago, and including the Triassic, Jurassic and Cretaceous periods; commonly known as "the age of the dinosaurs".

Metamorphic rocks, metamorphism - rocks formed by the recrystallisation of older rocks as a result of extreme heat and pressure in the earth's crust, mostly related to mountain building episodes. Different minerals are formed at different temperatures and pressures, so the minerals that make up metamorphic rocks can be used to estimate the temperature and pressure conditions under which they formed.

Orogenic event - a "mountain building" episode, involoving folding, faulting and metamorphism. Commonly some of the deeper rocks are melted to form magma, which along with magma originating from deeper inside the earth, are intruded or extruded to form a variety of igneous intrusions and volcanic rocks.

Outlier - an outcrop of younger rocks surrounded by older rocks. In Kakadu, "islands" of Kombolgie Formation sandstone left behind as the main escarpment was eroded back form a series of outliers surrounded by basement rocks west of Jim Jim Falls, between Nourlangie and Ranger mine, and in the Ubirr area.

Precambrian - all of earth history before the evolution of life forms with hard body parts in the Cambrian period 540 million years ago. The earth is thought to have formed about 4 500 million years ago, so that Precambrian time embraces more than 85% of earth history. Almost all of the rocks of Kakadu formed in Precambrian times.

Quartzite - a sedimentary or metamorphic rock completely made up of quartz; commonly, the quartz grains are originally mixed in with a clay matrix, but the clay is later replaced by quartz deposited in the rock from percolating silica-rich groundwater.

Retreat - the process by which a landscape feature moves over a long period of time as a result of erosion and weathering, e.g. a cliff or escarpment (hence **scarp retreat**), river bank, creek headwaters.

Ripple marks -an undulating bedding surface in a sedimentary rock formed by movement and deposition of grains during sedimentation, by wind, water currents, or wave agitation. The ripple marks in the Kombolgie Formation were formed by water currents in rivers and flood waters.

Sandstone - a sedimentary rock made up of small grains, usually mostly quartz. The grains are generally stuck together by very fine clay particles.

Schist - a strongly foliated and mica-rich metamorphic rock formed usually by the recrystallisation of a fine-grained sedimentary rock (e.g. mudstone or shale).The mica minerals form thin plates which are squeezed into the same orientation during metamorphism, which gives the rock its characterisitic strong foliation. Schist has undergone higher temperatures and pressures than shale or slate, in which mineral grains have also been aligned but there has been no recrystallisation of minerals.

Silicification - The process by which rocks have silica added to them, mostly by precipitation from circulating groundwater which took the silica into solution whilst percolating through a silica-rich rock. In the Kombolgie Formation, silicification is concentrated along some joints and the quartz grains in the rock have becme cemented by silica to form a hard, weathering-resistant, quartzite.

Siltstone - a usually brown, red or yellowish soft sedimentary rock which is made up mostly of silt-sized particles, that is between clay-sized and sand-sized.

Unconformity - a surface of erosion or non-deposition that separates younger sedimentary rocks from older rocks. The base of the Kombolgie Formation is a spectacular unconformity exposed in many places at the base of the Arnhem Land Escarpment, representing a time break of about 100 million years.

Vein quartz - mineral quartz, mostly white or glassy, which was deposited from very hot fluids or gases coursing through cracks in cooler rocks from areas of magma intrusion or metamorphism.