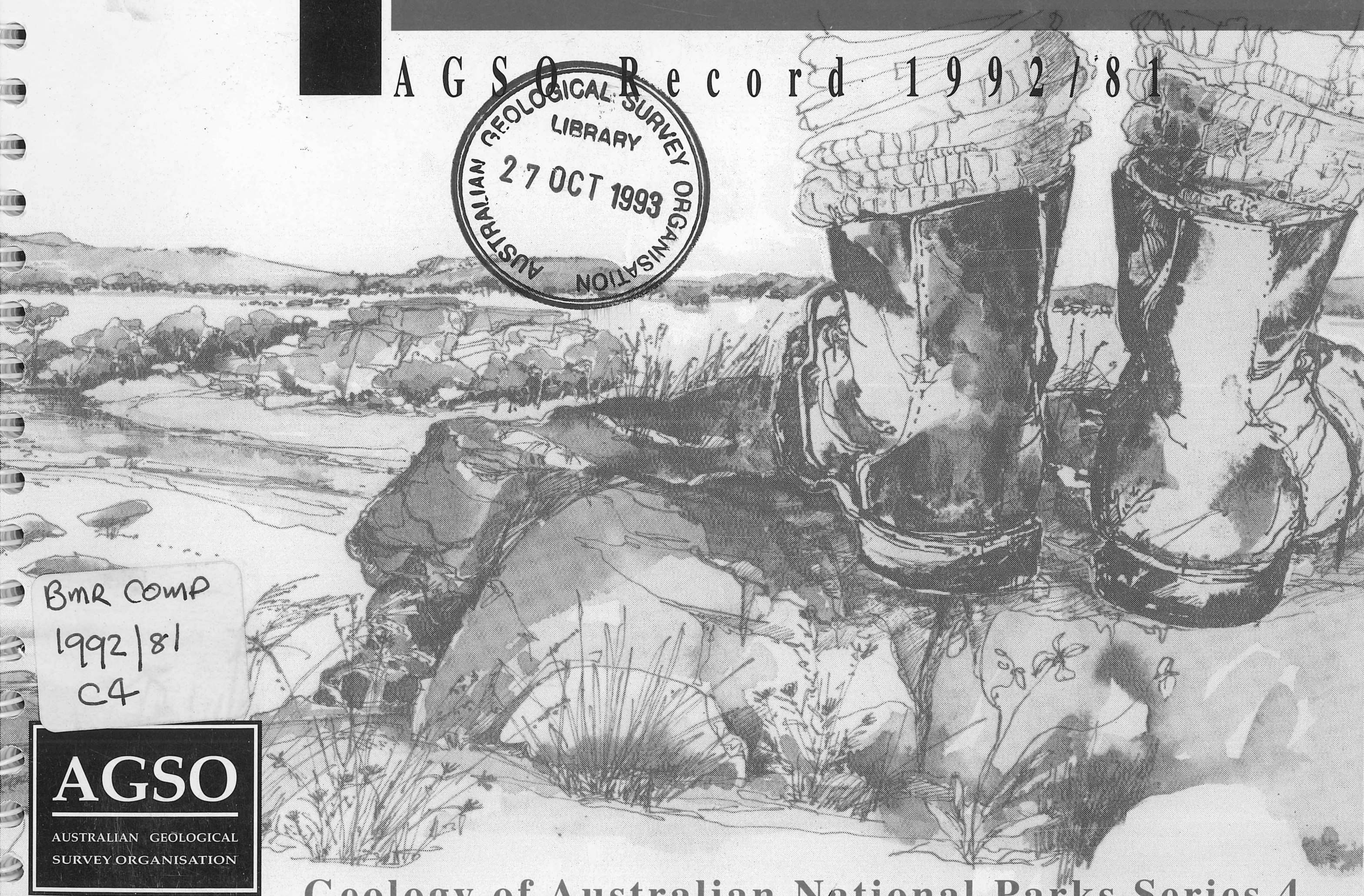
Geology of the walking trails in *Kakadu National Park*

- Nourlangie area

by R.S. Needham

AGSO Record 1992/81



AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Geology of Australian National Parks Series 4

GEOLOGY OF THE WALKING TRAILS IN KAKADU NATIONAL PARK

- NOURLANGIE AREA

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RS Needham

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Geology of Australian National Parks Series #4

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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.

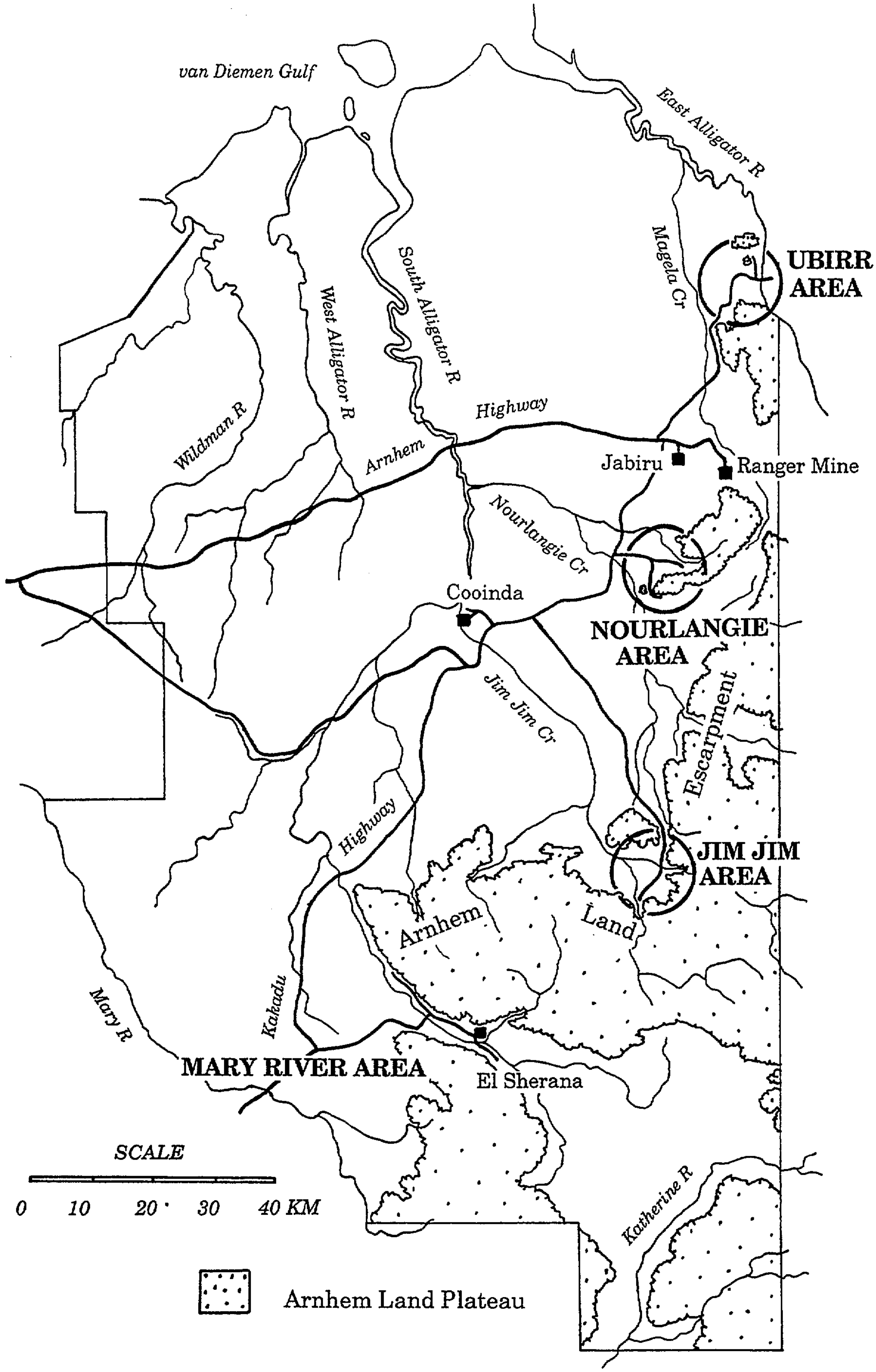

Figure 1. Location of the Kakadu walking trails

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 the Nangulwur walk 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

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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*

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.

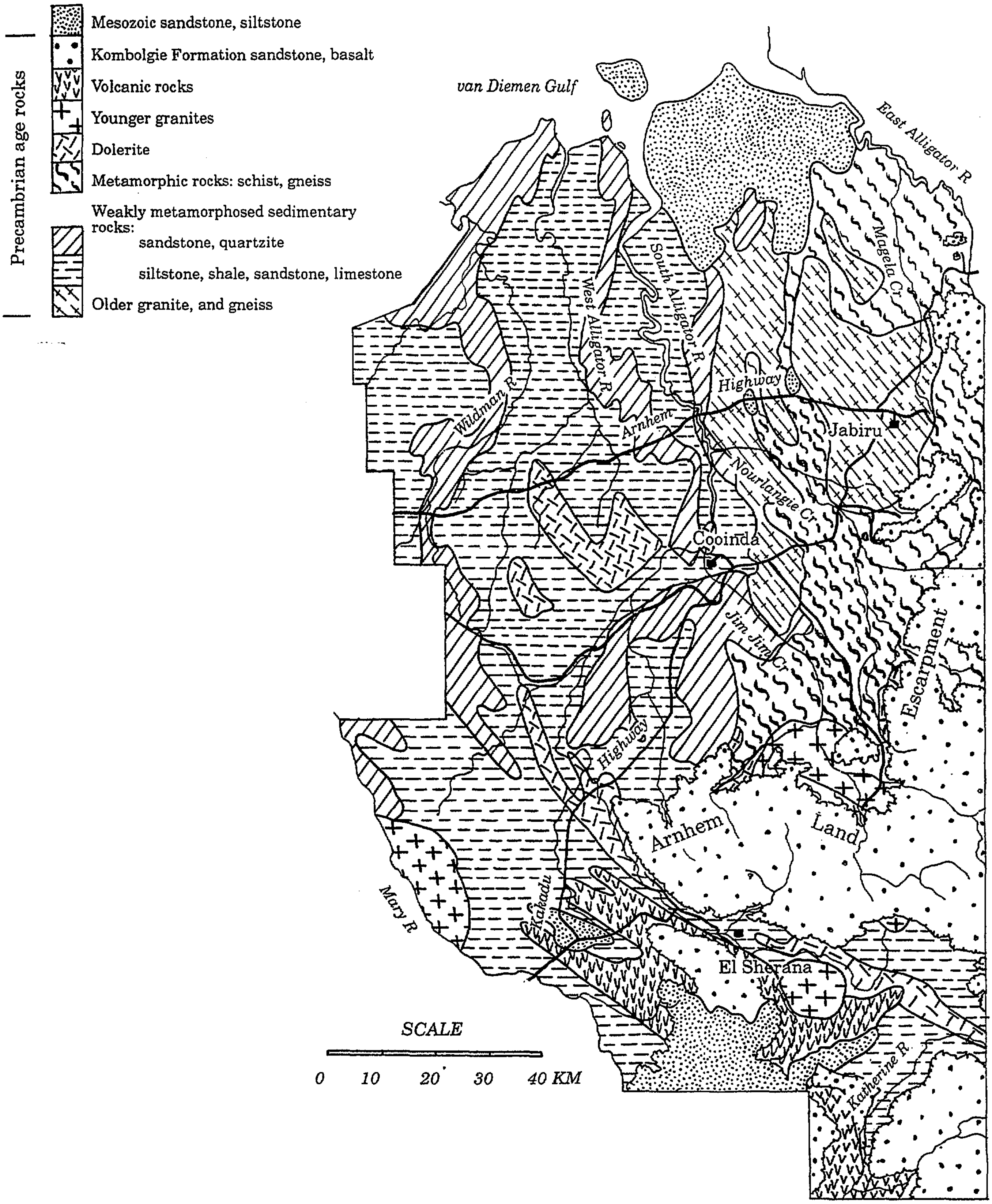


Figure 2. Generalised geology of Kakadu National Park

GEOLOGY OF THE WALKING TRAILS IN THE NOURLANGIE AREA OF KAKADU

There are six walking trails in the Nourlangie area - the Anbangbang and Nanguluwur Gallery Walks, the Kunwardehwarde Lookout, and the Barrk, Gubarra and Nawurlandja trails. They explore the sheer cliffs and massive boulders of the Arnhem Land escarpment and nearby sandy plains, and offer intriguing insights into the lifestyles and beliefs of traditional Aboriginals through their art and habitation sites.

The Anbangbang Gallery walk twists between and beneath huge sandstone blocks to form sheltered shady places used as living areas by traditional Aboriginals. The massive forces of nature are brought into focus by the sheer size of the blocks which fell away from the main cliffs in an ancient period of *scarp retreat.* Over the last few thousand years however the area has been geologically stable, which has allowed a rich archaeological heritage of Aboriginal art and soil accumulations to develop and be preserved.

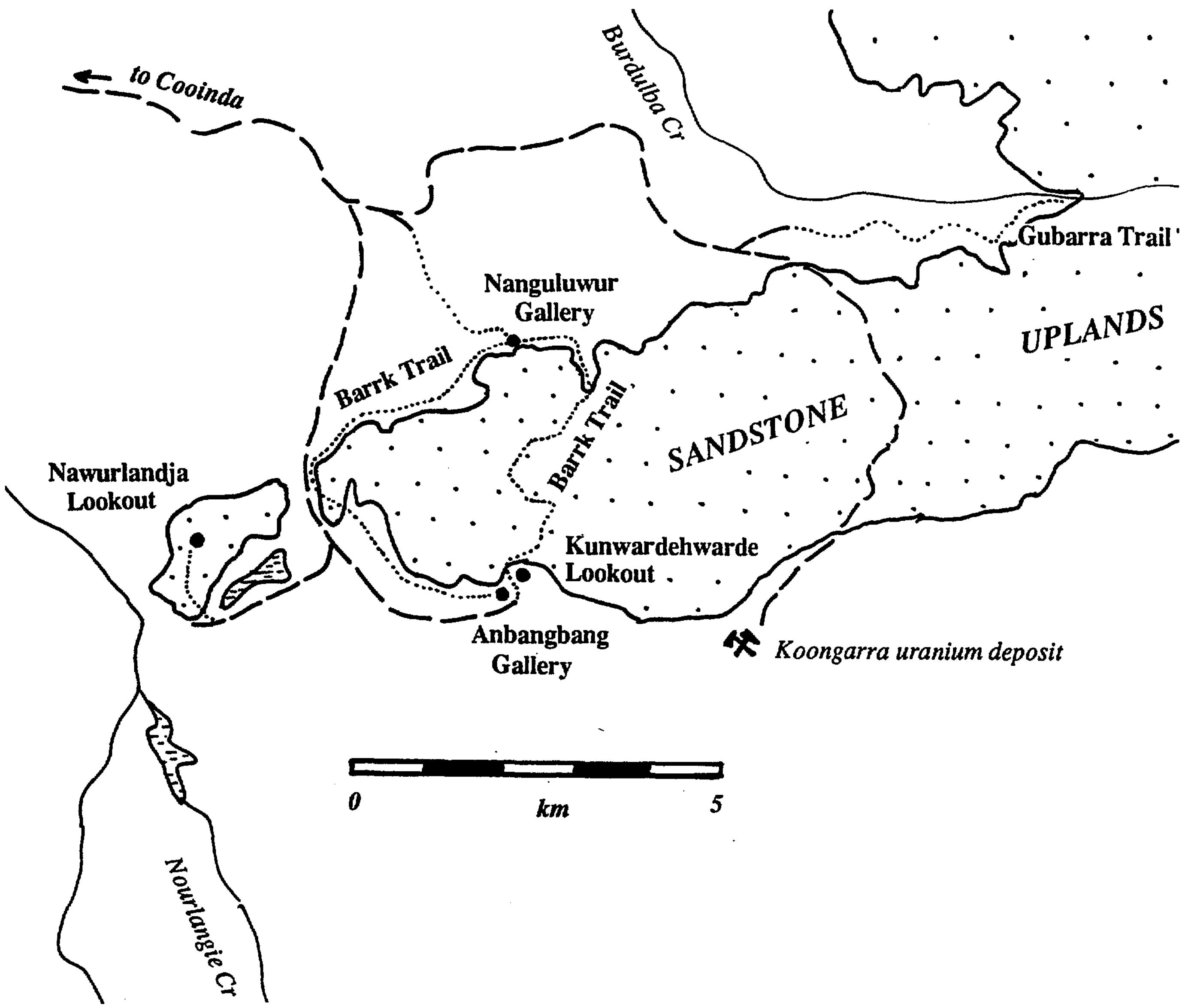


Figure 3. Location of the walking trails in the Nourlangie area

The short walk to the Kunwardehwarde Lookout provides magnificent views to the cliffs of the Arnhem Land Escarpment, which tower above the fallen sandstone blocks of Anbangbang. The main line of escarpment, marking the edge of the Arnhem Land Plateau, can be seen in the far distance to the east and southeast, beyond the sand plains of Nourlangie Creek.

The Barrk trail is a challenging walk which climbs up the spectacular cliffs above Nourlangie, across the plateau top and down the other side, returning along the base of the cliffs past the Nanguluwur Gallery. Many features of the sandstone country can be seen, reflecting changes in the rock, the different ways in which it is being weathered, and the variety of plant communities that can flourish in these harsh rocky environments.

The Nanguluwur walk is on the northwest side of the sandstone plateau, and crosses undulating sandy plains which show evidence in places of the different sorts of rocks concealed beneath. The Nanguluwur Gallery is an excellent example of how the face of the sandstone cliff is "armoured" by silica to protect it from erosion, and how quickly the sandstone can erode once this surface is broken.

The Gubarra trail exhibits a different, less severe mood along the edge of the sandstone uplands of Nourlangie. Here the cliffs are low and more eroded, and because the base of the sandstone sequence lies below ground level, the cliffs reach right down to the sandy plains without the steep boulder-strewn slopes common elswhere. The trail ends at a tranquil permanent creek which can be followed up to its source along a flat, rocky bed.

The Nawurlandja walk climbs to the top of a small *outlier* of sandstone west of Nourlangie Rock. This hill is the last outcrop of *Kombolgie Formation* sandstone which makes up the Arnhem Land Plateau, giving way to endless sandy plains which stretch to the horizon to the north, west and south. The effects of *erosion* are clear here, with the bare, craggy sandstone and *conglomerate* pavements, tilted up by *faulting* showing the effects of rapid erosion by water.

ANBANGBANG GALLERY WALK

Huge blocks of sandstone and conglomerate have tumbled down from the Nourlangie cliffs, and the shady areas beneath overhangs and close to water have been favourite habitation sites for traditional Aboriginals. The rock art is threatened not only by damage from ant trails, hornets' nests and physical flaking off of the pigment, but also by the growth of mineral salts on the rocks. These salts are more common on the roofs of overhangs, forming green, white, yellow or black, encrustations, and in the main gallery look like sooty stains on the ceiling.

The Anbangbang Shelter is made up of enormous boulders, some weighing over 20 000 tonnes, which fell from the main cliffs many thousands, perhaps millions, of years ago. They are made of quartz *sandstone* and *conglomerate,* and are slab-shaped because of the *bedded* nature of these rocks, which were formed as sandy and pebbly sediments laid down on an ancient river plain about 1 800 million years ago.

They fell from the main cliff as the softer rocks beneath the sandstone and conglomerate were eroded away, just as we see around our coastline in many places today. Examples of these softer, red-brown micaceous *siltstones* can be seen on the path up to the shelter (Figure 4); they are stained red from hematite, an iron oxide mineral, and the silvery flecks are small flakes of white mica. The siltstones form relatively thin beds between the more massive sandstone and conglomerate beds, and can be seen clearly from Anbangbang Billabong and Nawurlandja Lookout as weathered-out recessive red notches in the main cliffs of Nourlangie. Where some of these beds are very rich in iron and stained deeply red, they have been used by Aboriginals as a source of red ochre (Figure 5). On the path between the shelter and the gallery, about 100 m west of the gallery, one of these siltstone beds can be seen beneath an overhang of sandstone and conglomerate (Figure 6), and shows how the softer siltstone is readily eroded away so that eventually the sandstone above it will collapse.

The huge slab of rock which forms the roof of Anbangbang Gallery was once a flat-lying overhang halfway up the main cliff above a soft bed of siltstone. When it collapsed, it fell onto smaller boulders to end up jutting upwards at an angle of 30^{o} from the horizontal (Figure 7). Trees have grown on the shaded side, and the site provides shelter from the harsh sun and from wet season rains.

The sandstone and conglomerate in the boulders are indurated with silica which makes the rock stronger and more resistant to erosion. On some surfaces the matrix of the rock has weathered away to expose the pebbles in the conglomerate, which are rounded white quartz river pebbles (Figure 8). Some of the faces of the boulders at the shelter and along the path to Anbangbang Gallery are splitting away along *joints* which cut vertically through the rock. The joints formed before the boulders fell from the cliffs, and provide pathways for rainwater to percolate down through the rock, and over millions of years gradually widen the cracks so that eventually pieces spall off the sides of the boulders (Figure 9).

The roof of the shelter and the underside of other overhangs in the area are marked with black, cream, grey and pale green stains, and the black stains have often been interpreted as sooty deposits from old cooking fires. These deposits are made up of mineral salts (salt, gypsum, whewellite [pronounced hew-el-ite]). Their chemistry is different from the chemistry of the sandstone and conglomerate, and so the salts must be derived from some other source. Research has shown that rainwater in this region contains relatively high levels of nutrients (e.g. calcium, magnesium, potassium, sodium, phosphorus and nitrogen); organic acids are also present, especially early on in the Wet Season. The mineral salts are deposited on the surface of the rock either from water seeping through the rock or over its surface, or from atmospheric moisture.

In some places the mineral salts contain extremely thin layers of carbon which probably represent ash blown onto the rock faces during bushfires and subsequently covered by more mineral salts. It is possible therefore that the black stains on the ceiling of the shelter may result from carbon from campfires being incorporated into the mineral salts.

Figure 4. Red siltstone on the path up to Anbangbang Shelter. The red colour is from hematite, an iron oxide mineral, and the silvery flecks are flakes of white mica (muscovite)

Figure 5. The deep notches in the Nourlangie Rock cliffs are weathered-out beds of red, iron-rich (hematitic) siltstone. They continue around to Anbangbang, where they dip down to ground level and can be seen forming outcrops near the Gallery and on the path up to the Shelter

Figure 6. Bed of red siltstone beneath sandstone and conglomerate near Anbangbang Gallery.

Figure 7. The Anbangbang Shelter, formed from a huge sandstone/conglomerate block which fell from the main cliff and is now resting on smaller blocks and is tilted about 30^{o} from the horizontal

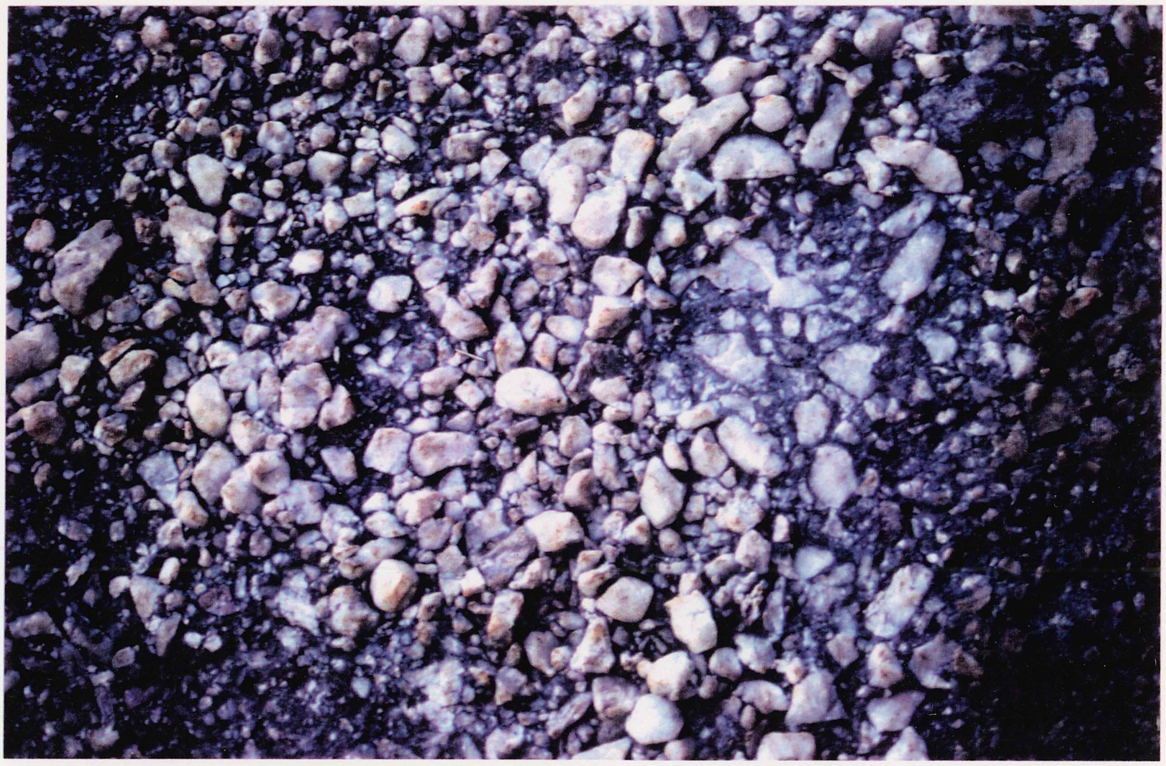


Figure 8. Rounded white pebbles of quartz which were laid down to form conglomerate beds on a large floodplain 1800 million years ago, to form the Kombolgie Formation

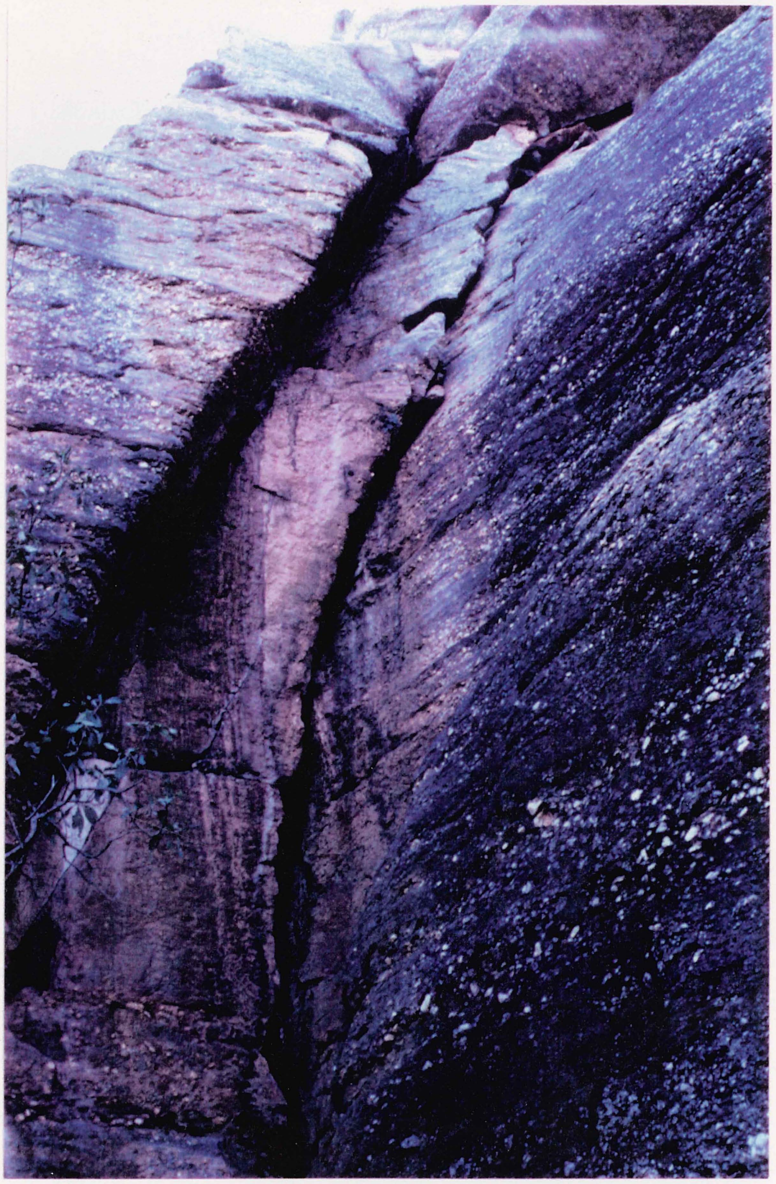


Figure 9. Erosion along steep joints in the sandstone/conglomerate eventually leads to slabs breaking off the main block

KUNWARDEHWARDE LOOKOUT

The lookout is on a low hill of sandstone and conglomerate which is part of the same sequence as the rocks of the Nourlangie cliffs. The cliffs form a semi-circle around the lookout, which is therefore an ideal spot to admire the dramatic shapes, shadows and profiles of the cliffs from a variety of angles. There are also views across a broad sandy plain, underlain by the older metamorphic rocks, to the main Arnhem Land Plateau.

The hill which forms the Kunwardehwarde Lookout is part of the same Kombolgie Formation sequence which makes up the main cliffs of Nourlangie. Unlike the large slabs at the Anbangbang Shelter, the rocks at Kunwardehwarde are "in situ", that is they are still roughly flat-lying in their original position, and have not fallen from the main cliffs. The rocks here are coarser-grained sandstone, pebbly sandstone, and conglomerate, which indicates that they are close to the base of the Kombolgie Formation sequence, and not far above the *unconformity contact* which separates these rocks from the older *metamorphic rocks* beneath. Like the rocks at the Anbangbang Shelter, there are many pebbles of *vein quartz* in the sandstone and conglomerate, which were swept up from an old, deeply weathered plain and then mixed with sand grains by flooding rivers to deposit extensive sheets of pebbly sandstone, and where the pebbles dominate over sand grains, conglomerate.

There are magnificent views of the Nourlangie cliffs from the lookout (Figures 10, 11). Notches cut into the profile of the cliffs above Anbangbang Shelter have been formed where softer *siltstones* interbedded with the *sandstones* have been weathered away. The curved shape of the cliff line is a result of the rocks breaking away along vertical *joints* and *faults* which formed after the rocks had become solidified and were warped and slightly folded as a result of flexing of the Earth's crust. Vertical clefts in the rock face (e.g. Figure 11) are examples of other joints which cut through the rocks perpendicualr to the cliff line. The Kombolgie Formation sequence once covered all of the low sand plains which can been stretching far to the south from here, but have mostly been eroded away. One theory is that a shallow sea covered the low plains during the *Mesozoic Period* about 100 million years ago, and that wave action gradually eroded the Kombolgie Formation sequence away through a process of *scarp retreat*, similar for example to the coastal erosion taking place on the Portland coast in Victoria today.

Looking out across the plain to the southeast, the main cliff line of the Arnhem Land Plateau can be seen in the far distance. The low valley in between (about 12 km across) consists of a thin sandy veneer over the older metamorphic rocks - mostly *schist, quartzite and dolerite*. In many places this sand veneer is only a metre thick, and on aerial photographs the folds in the underlying rocks can be clearly seen (Figure 12).

The Nourlangie cliffs form the western end of an *outlier*, or a separate upland of sandstone, divided from the main Arnhem Land Plateau by sandy lowland plains overlying the older metamorphic rocks (Figure 12). These older metamorphic rocks are exposed at the base of the sandstone cliffs 3 km east of Kunwardehwarde Lookout, near the Koongarra uranium deposit, where the older rocks have been brought up into contact with the sandstone along a *fault* (Figure 13). Near the fault the rocks are broken up ("brecciated") and veined with quartz. At Nourlangie the fault and contact between the sandstone and the metamorphic rocks lie several hundred metres to the south of the cliffs beneath sandy soils, and so the brecciation of the sandstone, and the older metamorphic rocks, is not visible here.

Figure 10. View from Kunwardehwarde Lookout towards the cliffs above Anbangbang

Figure 11. View from Kunwardehwarde Lookout north towards the sandstone cliffs ascended by the Barrk trail

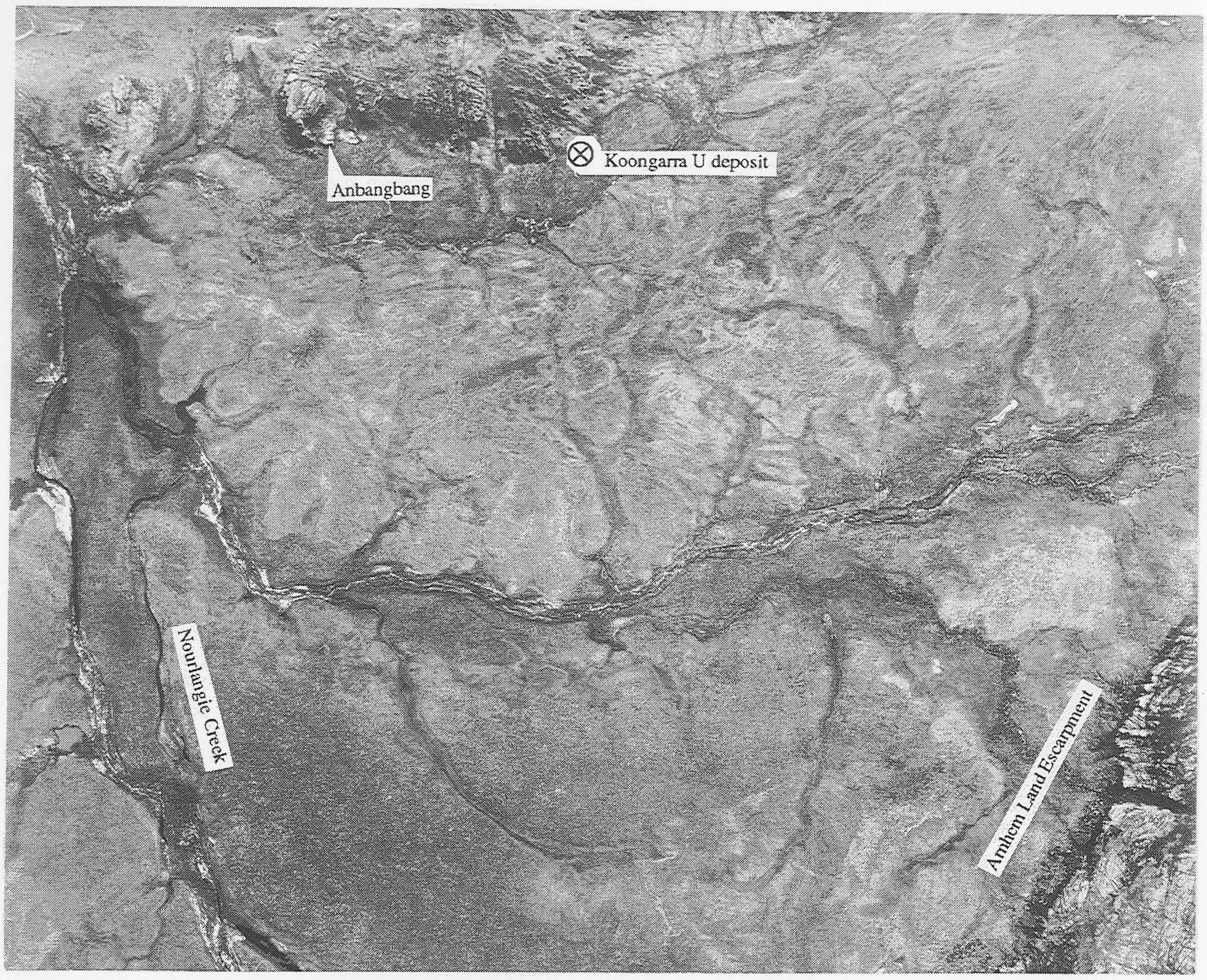


Figure 12. Aerial photograph of the low valley between the Arnhem Land Plateau (bottom right), and the Nourlangie sandstone outlier (top)

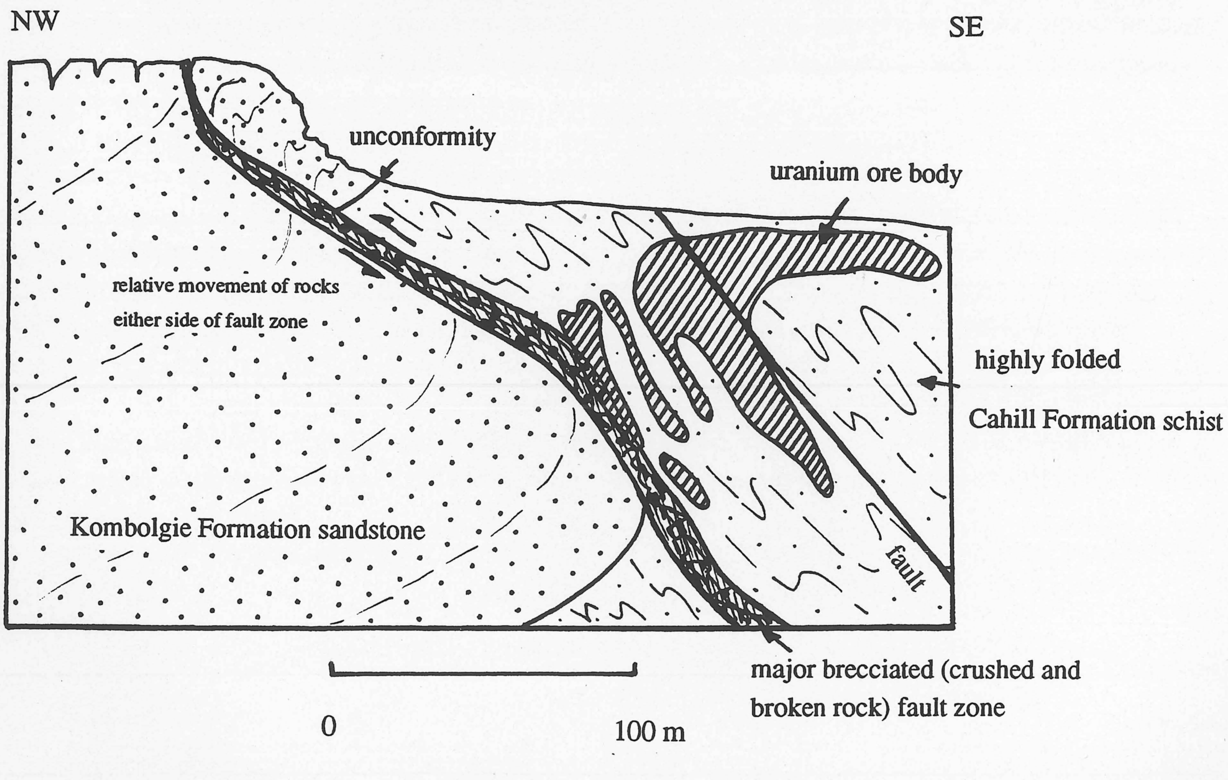


Figure 13. Schematic cross section through the Koongarra uranium deposit, 3 km east of Kunwardehwarde

BARRK TRAIL

This trail climbs over more than 200 m of vertical section of the Kombolgie Formation and contains many examples of sculpturing of the sandstone by weathering, joint and fracture formation and alteration of the rock along these joints, and natural colouring of the rock surface from brown, red, orange, pink, cream, yellow and grey. The return part of the walk passes huge sandstone boulders which have fallen down from the main cliff, and outcrops of dolerite and vein quartz which make up part of the basement strata beneath the Kombolgie Formation sandstone.

The first part of the climb, between the main cliffs of Nourlangie and the Kunwardehwarde Lookout is across "pudding stone rock" or quartz pebble *conglomerate* of the *Kombolgie Formation.* The pebbles were originally angular chunks of *vein quartz,* but during transport in rivers and creeks they were eroded into regularly rounded and sized pebbles. They therefore travelled farther from their source area to be deposited in the *sandstone* than did the more angular pebbles in the sandstone and conglomerate lower down in the sequence near the Anbangbang Shelter.

The sheer thickness of these conglomerate beds also tells us that enormous quantities of sand and pebbles were transported simultaneously and dumped suddenly, as if from massive flash floods across a vast alluvial plain. If they were deposited in lakes or on the bed of an ancient sea, or in meandering rivers, the pebble beds would not be so thick, continuous, or devoid of internal variations such as river bank deposits etc.

About a third of the way up, the conglomerate is overlain by brick red fine and medium grained sandstone with flakes of white mica (muscovite), which sparkle in the sunlight. This rock type represents a much lower energy environment than the flash floods of the conglomerates below. The much thinner beds also tell us that the sedimentation style was much gentler.

Above the red sandstones, the rock type changes to a pale grey to white pebbly sandstone, and then settles down to an even grained sandstone with only occasional pebbly beds, which makes up the rest of the sequence along this walk and which is the commonest rock type throughout the Arnhem Land escarpment and plateau.

By now there are magnificent views across to the main cliffs above the Anbangbang Gallery and shelter (Figure 15). The natural pale grey and white sandstone is strongly stained orange and brown by limonite, an iron oxide leached out by groundwater percolating through the sandstone, which is then precipitated on the rock face as the water finds the way out of the rock along cracks and bedding surfaces and runs down the cliffs. The red micaceous sandstone forms dramatically streaked cliffs with darkly shaded overhangs closer to the walking trail (Figure 16).

Other black and white streaks add drama to the colourful rock faces. The black streaks show where water courses down the cliffs in the wet season, and are caused by algae growing in these wet, nutrient-rich zones.

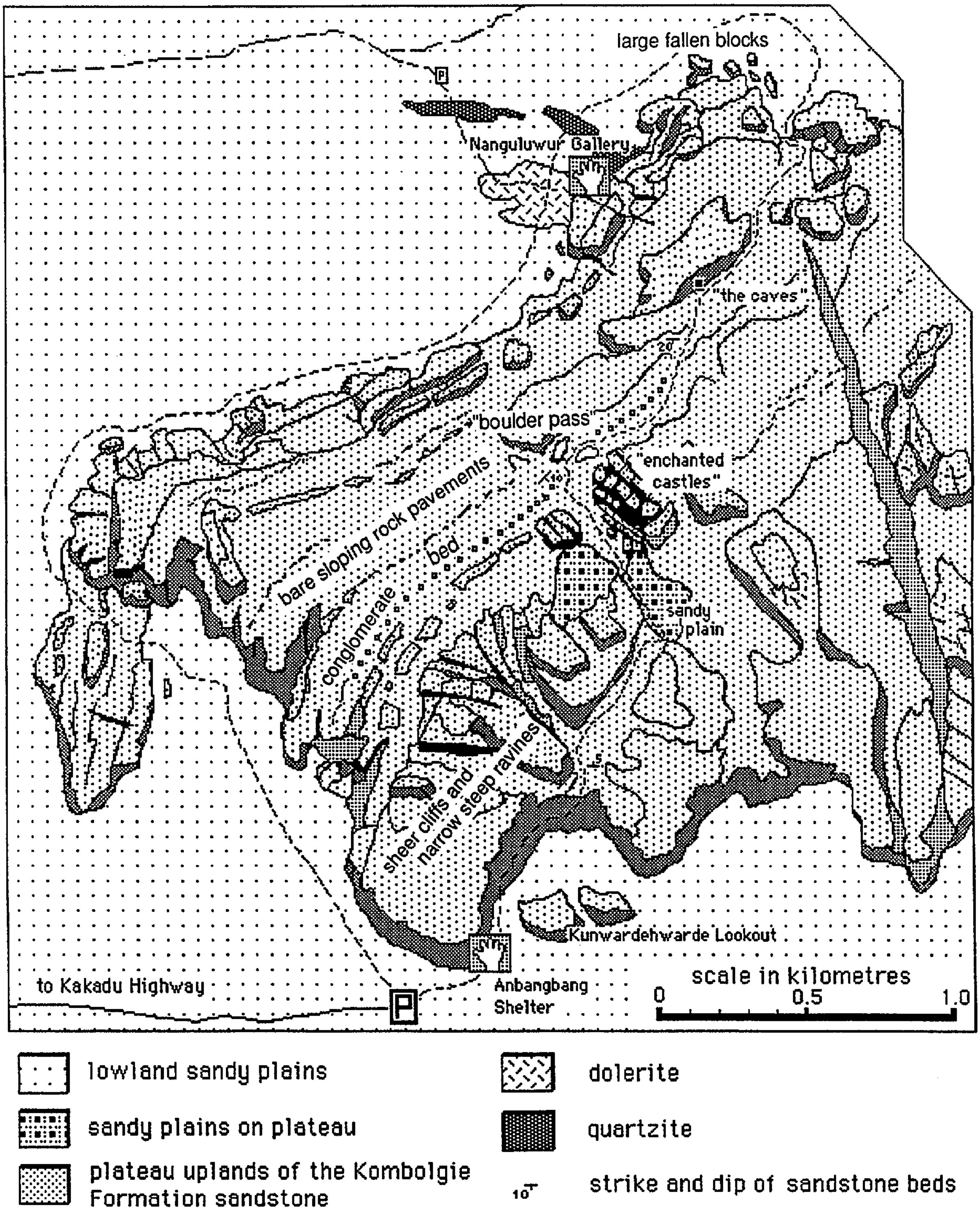


Figure 14. Barrk Trail

White streaks often form a contrasting edge to the black marks, and are caused by minerals - mostly gypsum and salt - precipitating on the rock as a result of dust and rainwater containing these minerals interacting with the surface of the rock. The organic acids generated by the nearby algae growing on the rock face probably assist in these chemical reactions taking place.

The black organic encrustation is also well developed in shaded parts of the rock face, such as on the conglomerate cliffs next to the footbridge at the beginning of the Barrk Trail (Figure 17).

At the section where the trail climbs out of the trees and follows a path at the base of a cliff on the right hand side, unusual markings can be seen on the rocks which at first glance look like aboriginal stick figure paintings (Figure 18). These are formed by water which has percolated through the sandstone, dissolving small amounts of silica from the quartz grains and iron from the clayey material between the grains. The water eventually finds a crack in the rock, and as it flows along the crack the silica and iron are precipitated on either side of the crack to change the rock's colour. Where there is a criss-cross fracture set, the resultant alteration and colour change along the cracks can produce patterns like human figures.

Also in this area, plants such as the pandanus palm hold tenaciously onto the bare rock, braced by pyramids of aerial roots which seek out moisture in the rock crevices (Figure 19).

After the top of the steep climb the trail passes into a wooded and shrubby sandy plain. A different style of rock alteration to the "stick figure" type can be seen in the sandstone cliff on the southwestern side of the sand plain. Here, the alteration occurs around small grains or patches in the rock, forming coloured spots (Figure 20). The difference in colours, especially white and brown/red, are related to changes in the oxidation state of iron-bearing minerals in the rock, or "redox reactions" (i.e. iron in the reduced or oxidised state).

Farther along, this cliff is very straight, showing it to be an exposed *joint* or *fault* surface (Figure 21). In places the rock surface is very smooth because of silicification along the pre-existing joint structure, and at times the silicification is apparent as tiny quartz crystals on the rock face glinting in the sunlight. Fractures in the rock parallel to the main face give further evidence of the formation of the cliff from old joint surfaces. In fact most of the major rock faces in the Nourlangie cliffs are exposed joint or fault surfaces which have been armoured by silica to make them resistant to erosion.

The soils of the sand plain are derived only from breakdown of the Kombolgie Formation sandstone, and nutrients can only be added by rotting plant material. There is no clay to bind the sand grains together to develop a loamy soil, so the soil remains a loose sand deposit coloured grey by organic matter.

After the sand plain, the track passes through natural rock formations weathered into shapes like enchanted castles and arches (Figures 22 and 23). These sandstone columns developed as a result of weathering of the sandstone along vertical weak joints; there are two sets of joints roughly at right angles to one another, and so as erosion has worked its way down the joints, it formed a series of rectangular columns. Therefore the joints in this area must not have been strengthened by silica as were those that form the sheer cliff faces above Anbangbang. The weakness of the rock surfaces is also demonstrated by some small areas of "honeycomb weathering" (roughly circular pits developing in weak sandstone from deflation of the rock surface by water and wind erosion) in the cliff on the left of the track after the "enchanted columns".

When we started on the Barrk climb, the sandstone beds dipped northwards by 5 or 10^{o}, and then on the top of the climb they levelled out. Notice now how the *bedding* (the lines portraying the layers in which the sandstone was laid down under water) is again dipping, but to the east by about 10^{o}.

The rocks are also becoming pebbly again, and soon the trail emerges onto a wide pavement of conglomerate which has clasts of *vein quartz* up to 12 cm across, with a few banded *quartzite* (a *metamorphic* rock) and red mica *schist*, pebbles (Figure 24). The pebbly nature of this rock bed suggests we are now climbing down the rock sequence, and approaching the same level in the Kombolgie Formation sequence as at Anbangbang.

The sandstone bed resting immediately on top of the conglomerate pavement shows examples of *cross-bedding,* formed when the water flowed in channels and dropped sand in layers sloping down along the river bed in the direction of water flow. With very good exposures of cross bedding, geologists can measure which way the water was flowing when the sandstone was deposited, and hence the direction towards the land mass from which all this sand was derived.

Soon the trail passes between some large blocks of sandstone. The one on the right is in place, but the ones on the left of the trail have fallen off that block and landed on their sides, so the once-horizontal bedding is now vertical. This is a good example of cliff *retreat,* with large blocks breaking off and tumbling down as weaker beds beneath are eroded away.

The right hand side boulder also has an interesting story to tell about how the *joints* in the rocks develop. Some obviously have formed suddenly as large cracks, probably related to ancient earthquakes and so on. But in this boulder, some beds have narrow vertical cracks in them. As these cracks provide an easy passage for water seeping through the rock, water begins to course along these cracks and eventually stains them with the iron (yellow and brown limonite) the water has picked up along the way (Figure 25). As more water flows along the cracks, they widen and lengthen and provide the main attack points for erosion.

These cracks are perpendicular to the main "through" joints in the Barrk trail area, which trend north/south. The "enchanted columns" area developed where both sets of joints are very well developed, and provided two lines of attack for erosion.

The rocks now steepen to a dip of about 20^{o} to the east, and below the conglomerate the trail starts to descend over grey pebbly sandstone in which the bedding gradually swings around so that after a while the bedding dips towards the south. Therefore, overall the beds in the sandstone sequence from Anbangbang to the northern part of the Barrk trail form a gradual basin shape or "syncline". In this area, colourful fine circular and irregular banding in the sandstone is "liesegang banding" produced from different amounts of oxidation (rusting) of small amounts of iron minerals in the rock matrix (Figure 26).

Farther down, especially on a brownish dip slope of pebbly sandstone, subtle scallop-shaped depressions forming slight troughs in the rock surface are the tops of *cross-beds* in the sandstone, where each "scallop" represents an ancient flow channel within a river. These cross-beds clearly show that the sandstone was deposited from water flowing towards the northeast.

The descent is in fairly homogeneous quartz sand. A good example of orange, limonite (i.e. iron oxide) crusts can be seen at "The Caves" locality (Figure 28).

The second half of the Barrk Trail skirts the base of the sandstone escarpment, and meanders between many large sandstone blocks which have tumbled down from the top of the cliff. Therefore the bedding planes in the blocks vary from flat to vertical. The biggest block we pass measures about 24 x 14 x 48 m and is calculated to weigh 42 000 tonnes - and it made it to the bottom of the cliff in one piece!

Some of the blocks have Aboriginal paintings on them, but they are mostly poorly preserved because the rock faces are exposed to the sun and the rain with little or no protection from overhangs. This is because overhangs form where the bedding in the rock is close to horizontal, and softer rocks are being eroded from underneath to cause undermining and collapse. As there is no active erosion at the base of the scree slope, no overhangs have formed around the sandstone blocks. In places, the surfaces of some blocks are stained bright orange as a result of iron oxides being precipitated out of water that has percolated through the rocks (Figure 29); black, brown and dark green encrustations are also evidence of mineral salts such as gypsum and whewellite being precipitated as a result of chemical reactions on the surface of the rock between minerals in airborne dust, algae growing on the rock, and moisture from rainwater.

Partly because the cliffs are mostly made up of silicified or armoured *joint* surfaces, the present day rate of cliff *retreat* is very slow. One theory is that most of the present cliff line developed as coastal cliffs around the margin of Mesozoic seas, in the age of the dinosaurs 100 million years ago, and that there has been very little retreat of the cliffs since. This would explain why there are very few boulders more than 100 m from the base of the cliff, and virtually none beyond the base of the scree slope.

On the walk back to Nourlangie there are a couple of examples of the old rocks which formed the land surface on which the Kombolgie sandstone was deposited. These are a "blow" of milky white *vein quartz* before, and black round boulders of *dolerite* after, the Nanguluwur art site. Most of the basement rocks below the Kombolgie Formation are *schist,* but because it is relatively soft and so easily eroded, it is not often exposed. The harder quartz and dolerite which intrude the schist therefore give a false impression of what these older rocks consist of. Geologists have therefore had to drill rows of shallow holes across the plains to find out the true nature of the rocks below the sand plains.

The Barrk Trail ends with magnificent views of the Kombolgie Formation forming the west face of the Nourlangie cliffs (Figures 30 and 31). The red and purple colours near the base of the cliffs result from iron-rich hematitic *sandstone* and *siltstone.* Most of the iron was obtained by "reworking" (rivers and creeks picking up fragments of older rocks and then depositing them to form new rocks) the "basement" schists which had formed an ancient flat land surface for millions of years before the Kombolgie Formation rivers spread across this region. During this long period the land surface was deeply leached and iron was concentrated on the surface, similar to the process which has formed *laterites* on the present day land surface in Kakadu. The hematitic (iron-rich) material from the old surface was reworked and mixed with sand to form the hematitic sandstone in the red and purple layers in the lower parts of the Nourlangie cliffs.

Figure 15. View to the cliffs above Anbangbang from the first stage of the Barrk Trail climb.

Figure 16. Armoured joint and fault surfaces form sheer cliffs above the Anbangbang galleries which are streaked white and black by mineral salts deposited where water runsdown the rock surfaces in the wet season.

Figure 17. Dramatically shaded red cliffs rise abruptly above the trees close to the Barrk Trail ascent.

Figure 18. Black, algae-covered pebbly sandstone at the base of the sandstone cliffs at the footbridge near the start of the Barrk walking trail.

Figure 19. "Stick figures" formed by natural chemical reactions in the sandstone along cracks and joints.

Figure 20. A pandanus clings precariously onto the bare rock with its pyramid of aerial roots.

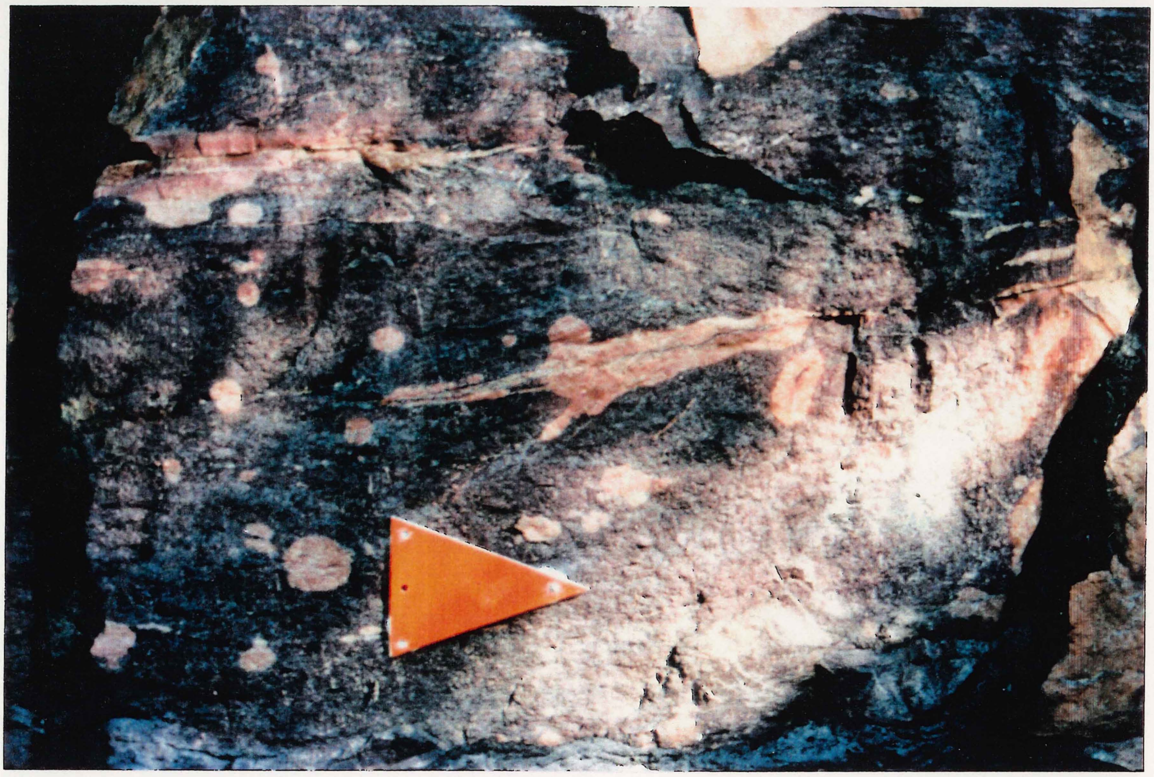


Figure 21. "Redox" spots formed by oxidation of iron in the matrix of the sandstone.

Figure 22. The joint-controlled straight cliff line forming the southwest edge of the wooded sand plain.

Figure 23. Erosion along two intersecting sets of joints has formed craggy peaks and arches resembling an enchanted castle.

Figure 24. Vertical sides on these pillars clearly show the original joint surfaces which have controlled downward erosion of the sandstone in the "enchanted castle" area.

Figure 25. Close to the north side of the Barrk sandstone upland, the rocks dip to the south and pebbly sandstone and conglomerate are encountered once more as the lower part of the sandstone sequence is re-entered.

Figure 26. Vertical joints in the sandstone are pathways along which water readily seeps through the rock; iron oxides have been precipitated out where the water flowed out of the joints.

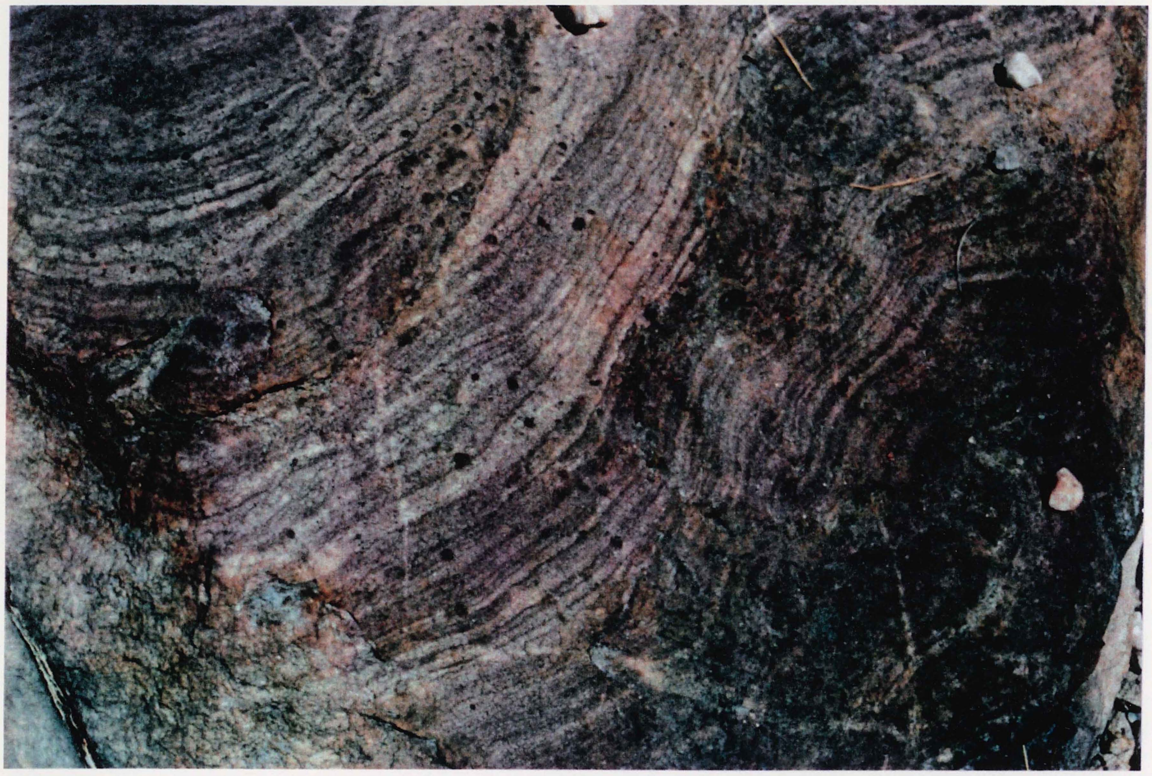


Figure 27. Finely colour-banded sandstone formed by the oxidation of iron-bearing minerals in the matrix of the rock.

Figure 28. Thick encrustations of limonite on sandstone at "The Caves" near the top of the Barrk trail descent.

Figure 29. Bright orange iron-stained faces on sandstone blocks at the base of the scree slope below the sandstone cliffs.

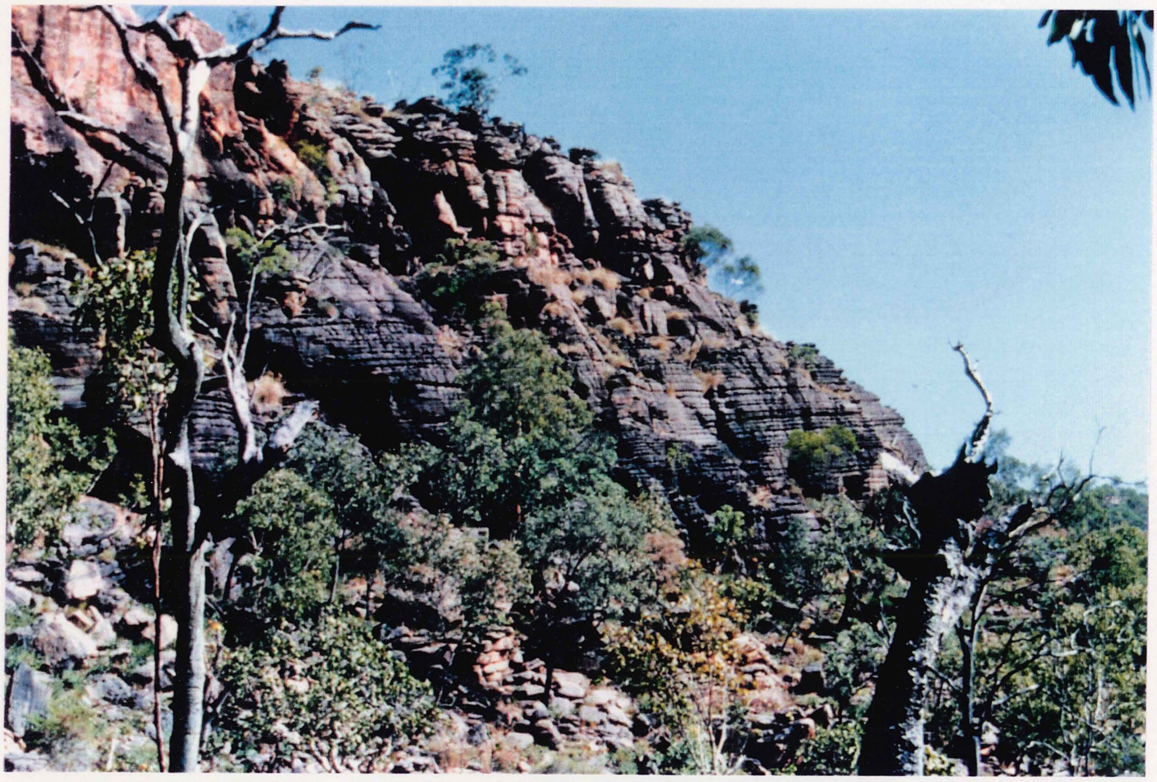


Figure 30. Purple and red sandstone cliffs at the western end of the Barrk trail.

Figure 31. Wide bedding surfaces sweep down towards the red and purple sandstone cliffs on the west side of Nourlangie, close to the end of the Barrk trail.

Several examples of the old "basement" rocks which lie beneath the Kombolgie Formation sandstone are exposed along the track to the gallery. At the gallery there is evidence of nature's way of forming a smooth and durable surface suitable for Aboriginal paintings.

along the walking trail ....

At the parking area, the ground surface is made up of sandy soil forming a thin veneer over *laterite*. The laterite forms dark brown blocks near the track in a few places (Figure 33). The blocks are full of holes and so this sort of laterite is called "vermicular laterite" (i.e. worm like). The holes are not worm burrows, but were formed by intense leaching during prolonged *weathering*. The leaching also concentrated iron near the surface to form the laterite.

In a laterite profile, the rocks beneath the brown, iron-rich cap are usually mottled pink, cream, pale brown and white, indicating differential leaching and movement of minerals in the rock related to water saturation (rainfall) and water removal (dry season evaporation). If you look carefully, you will see a couple of examples of this multicoloured rock along the track. This lower, variegated part of the laterite profile is called "mottled zone laterite".

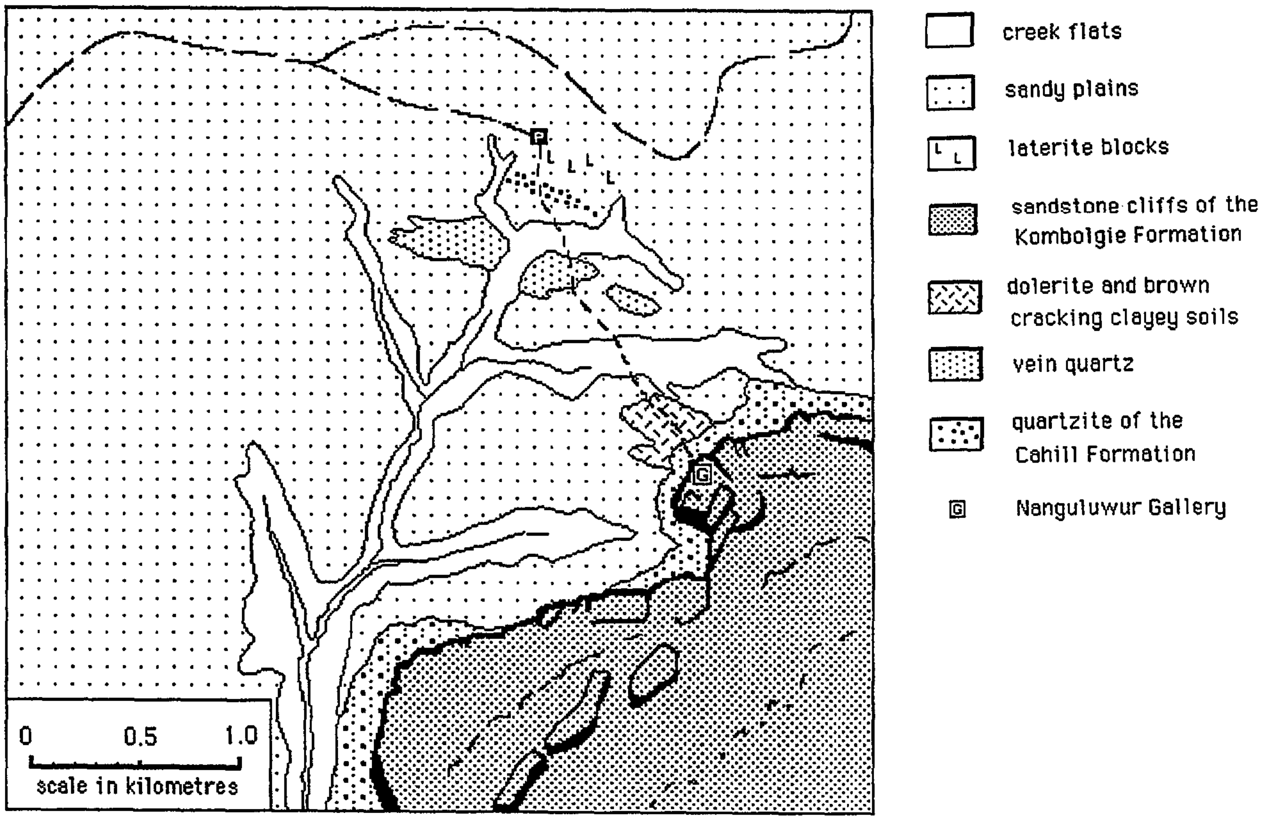


Figure 32. Map of the Nanguluwur walking trail.

About 150 m from the parking area a low blocky outcrop of glassy grey-brown *quartzite* crosses the track (Figure 34). This rock, like the sandstone of the *Kombolgie Formation,* is made up of quartz grains, but can be distinguished from it because of it has a recrystallised texture which indicates that it has been *metamorphosed* by heat and pressure. As the Kombolgie Formation and younger rocks are essentially unmetamorphosed, this quartzite must therefore be older than Kombolgie Formation age.

The *quartzite* on this trail is part of the *Cahill Formation.* This formation is mostly made up of *mica schist and quartz schist,* but because these are easily weathered, only harder rock interbeds such as this quartzite, form outcrops. Because of this differential resistance to weathering a rock such as the quartzite which makes up less than 5 percent of the Cahill Formation may commonly form over 80 percent of the outcrops. This formation contains the Ranger, Koongarra and Jabiluka uranium deposits of the Kakadu region, and so it has been closely studied by geologists. The poor exposure means that drilling had to be done to discover the full range of rock types in this formation.

Further along the trail after the first creek flat, the country rises up to a stony ridge which is strewn with angular blocks of white or glassy *vein quartz* (Figure 35). The quartz has spread out from several quartz veins which trend along the ridge about E-W, and although the quartz veins themselves are quite narrow (less than 5 m), the "float" has spread out over 100 m either side so as to cover the whole ridge with white vein quartz rubble. These quartz veins formed by precipitation from hot silica-rich fluids which flowed along lines of weakness (faults) in the *Cahill Formation schists* as they were being *folded and metamorphosed.*

We know that vein quartz rubble was strewn across the landscape almost 1 800 million years ago before the Kombolgie Formation *sandstone* was deposited, just like it is today. This is because angular fragments of quartz just like these are preserved in pebbly sandstone near the base of the sandstone - for example, near Anbangbang. Most of the quartz pebbles in the Kombolgie Formation are rounded, and must have been transported much further in rocky river beds to be worn smooth before being deposited along with the much finer grained sands.

Some of the vein quartz is stained a shiny orange-brown, like a glaze. The glaze has been produced by resins released from vegetation as it has burnt during many bush fires, and the resins have baked onto the quartz fragments.

After crossing the second creek flat, the soil changes markedly from sand to an orangey-brown clay. This clay shows rough hexagonal cracking, produced by shrinkage as the clay dries out at the beginning of the dry season (Figure 36).

This colour clay is typical of the deep clayey soils which develop on mafic (dark, low in silica, high in iron and magnesium) *igneous rocks* generally called *dolerite.* As you continue up the track, outcrops of the dolerite become common, and weathered round brown lumps in an iron-rich crust are scattered around in places like potatoes. Where it is fresh it is a dark rock (Figure 37), and platey silver-green crystals of the mineral olivine stand out on the surface and glint in the sun. The rock belongs to the *Oenpelli Dolerite,* a rock suite only rarely exposed in Kakadu but which is common in Arnhem Land, where it often forms long ridges in valleys cut into the sandstone plateau (e.g. in Deaf Adder Gorge).

This dolerite body continues east under the Kombolgie Formation cliffs, and forms a ridge about

250m south of the Nanguluwur gallery.

The dolerite forms a *dyke* about 200 m thick, intruding the *Cahill Formation schists.* Although the schist is not well exposed like the dolerite, a few pieces of red, iron rich schist with silvery flakes of mica are scattered on the ground near the gallery.

at the gallery ....

Like all the other galleries in Kakadu, the Nanguluwur paintings are on *sandstone* of the *Kombolgie Formation.* Often the surface has been chosen for painting because of its smoothness, and the reason for this is well documented here.

At the northern end of the gallery the sandstone is being eroded into thin, soft beds of friable (loose) sand, except for a 1 centimetre thick layer parallel to the face of the cliff (Figure 38). It is this layer which forms the strong, smooth surface most suitable for painting.

This surface formed as a result of water percolating through the rock and dissolving *silica* on the way. The silica was then precipitated out in zones of concentrated fluid movement which developed along cracks or *joints* in the rock. Therefore two hard siliceous zones formed either side of the joint. Some of the joints are long and straight and represent major weaknesses in the rock, and cliff collapse is commonly controlled by them. The surface left after collapse is however "armoured" as a result of silica impregnation, and is a smooth, impermeable surface ideal for painting because the silicification has sealed up the voids between the sand grains.

The thickness of this armoured surface can be seen at the northern end of the gallery, where the friable sandstone behind the silicified surface is being eaten away by naturally occurring erosion. The armoured rock face is resistant to erosion, and as long as the cliff is not undermined it will be stable for a very long time. The joint controlling this rock face is slightly enriched in hematite (an iron oxide mineral), which gives a pale red colour to the silicified zone.

In places below the paintings different coloured crusts cover the rock surface (e.g. a black crust below the ship painting). The crusts are made up from minerals formed by weak chemical reactions on the rock surface. These reactions took place between dust, weakly acidic rainwater, and organic compounds which settled or seeped across the rock face. Some black marks may have originated as soot from camp or bush fires, but regardless of their colour (variously green, cream, white or black), these crusts are mainly made up of a group of mineral salts called oxalates, containing calcium, carbon, oxygen and water.

In the southern part of the gallery, many of the boulders scattered on the flat area close to the base of the cliff have a smooth shiny surface or "patina". This is also the result of a crust of oxalate minerals forming on the surface of the sandstone rock, forming a skin up to 1 centimetre thick. Because these very shiny, smooth surfaces occur only on relatively flat rocks beneath shady overhangs, commonly with evidence of Aboriginal habitation, it is possible that the formation of the patinas is related to people sitting and climbing over the rocks for many thousands of years.

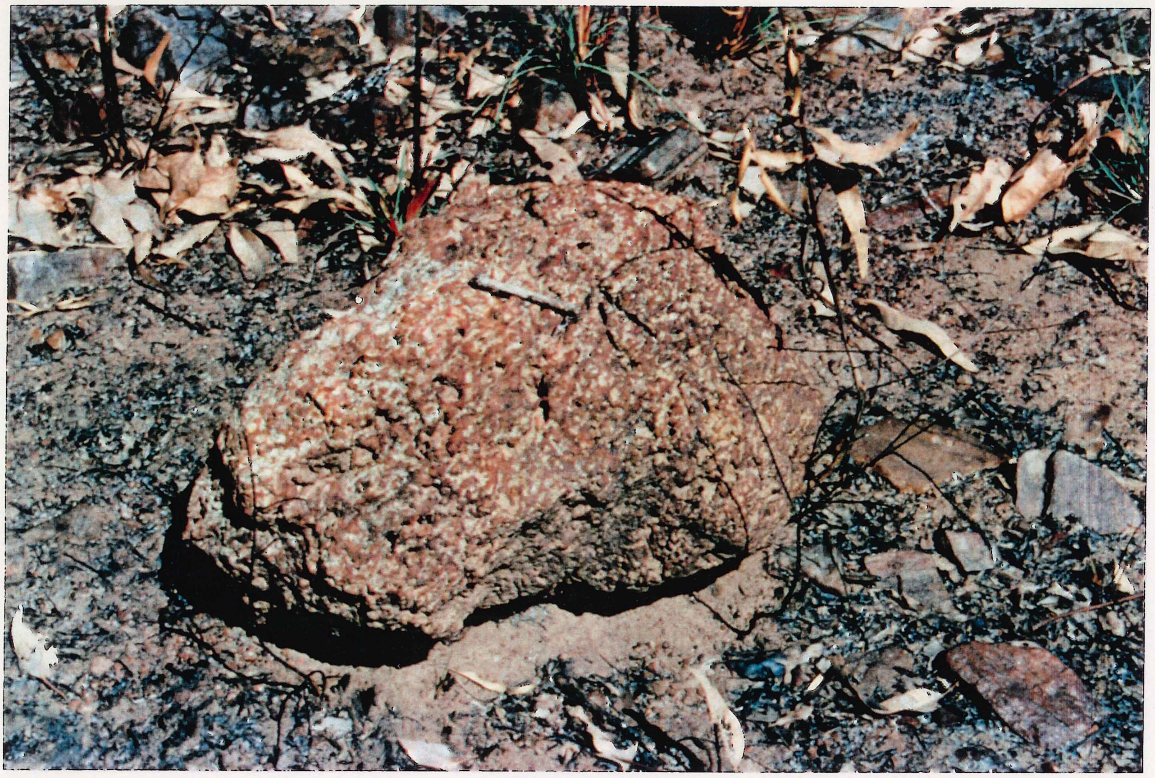


Figure 33. Laterite block beside trail near parking area.

Figure 34. Angular blocks of reddish-brown quartzite (Cahill Formation) on track about 150 m from parking area.

Figure 35. Quartz "blow" - hard glassy white vein quartz is scattered widely around large boulders which represent the position of the actual quartz vein. The vein cuts through the unexposed older rocks (quartzite and schist) in a straight line about east-west.

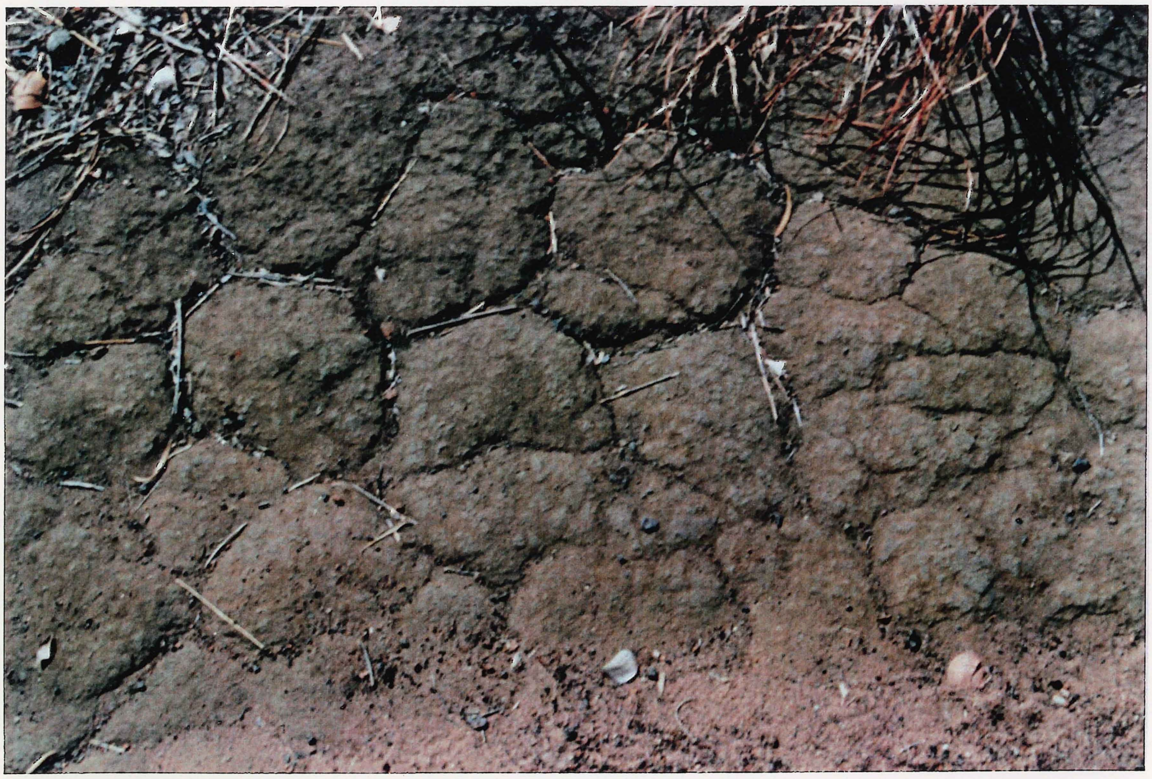


Figure 36. Hexagonal shrinkage cracks in clayey soils developed over dolerite rocks.

Figure 37. Outcrop of fresh dolerite rock (Oenpelli Dolerite).

Figure 38. The paintings are on a joint surface in sandstone, which has been made hard and smooth as a result of silica impregnation. The hard coating is 1 - 2 cm thick. Soft sandstone is exposed behind it at the north end of the gallery. The red and brown colours are from iron staining.

Figure 39. Black lumpy crusts on the sandstone below the ship painting, and the smooth brown patina on the boulders at the southern end of the gallery, are all composed of oxalate minerals containing calcium, oxygen, carbon and water.

GUBARRA TRAIL

The harsh environment of the sandy plains in the early stages of the walk contrast vividly with the cool tranquility of the rocky permanent stream bed of Burdulba Creek. In this area the base of the Kombolgie Formation sandstone sequence is buried below ground level, and so the cliffs are lower and lack the bouldery footslopes common where the base of the sandstone sequence is exposed.

The sandy soils of the first part of the trail overlie a 10 to 25 metre layer of poorly consolidated sandstone washed down from the *Kombolgie Formation sandstone* cliffs in the *Tertiary* geological period, about 1 million years ago. The bedrock below this layer is not exposed along the trail, but is *schist* and *quartzite* of the *Cahill Formation.* Some outcrops of Komblogie Formation sandstone dip below the sand plain, suggesting that in places the Kombolgie Formation extends underneath the plains beyond the cliff line (figure 40). In the later part of the trail the sandy soils give way to darker, more organic-rich soils around the creeks, some of which are fed by springs which rise at the base of the cliffs.

The Kombolgie Formation sandstone is very commonly *cross-bedded* at an angle of 10 to 20^{o} degrees to the normal bedding. In some sandstone blocks the normal bedding and cross-bedding are at much steeper angles than those in the main cliffs, indicating that these blocks have tumbled down from the main cliffs and no longer rest in their geologically correct attitude (figure 41).

The unconformity which marks the base of the *Kombolgie Formation* and its contact with the older *schist and quartzite* cannot be seen in this area, because the basal part of the sandstone sequence is buried beneath the land surface. It is because of this that the sandstone cliffs are relatively low, and they come right down to the level of the sand plains without a footslope of rubble such as at Nanguluwur (figure 42).

Although a tranquil place in the dry season, creeks such as this one at the end of the Gubarra Trail can become ferocious torrents in the wet season, especially if cyclonic depresions pass upstream. The size of the boulders transported from farther up the creek, and kettle holes formed by cobbles wearing away holes into the sandstone bed, are a quiet testimony to more turbulent times in the continuing evolution of Burdulba Creek (figures 43, 44).

By following the creek upstream into the sanstone plateau country and then climbing up its banks, it is possible to see areas of spinifex-dominated sandy clearings and bare rock pavements typical of the Arnhem Land Plateau farther east (figure 45). This type of country is explored by the trail which climbs to the top of Jim Jim Falls.

Figure 40. The Kombolgie Formation sandstone dips down beneath the sandstone plains.

Figure 41. This sandstone block has tumbled away from the cliff, and so the bedding is steeper than that seen in undisturbed outcrops. This block also shows cross-bedding at an angle to the main bedding layers.

Figure 42. The cliffs here lack the steep rubbly footslopes which are developed where the softer, older metamorphic rocks are exposed beneath the sandstone.

Figure 43. The large, rounded boulders in the creek are evidence of the powerful forces of the water flow during the wet season.

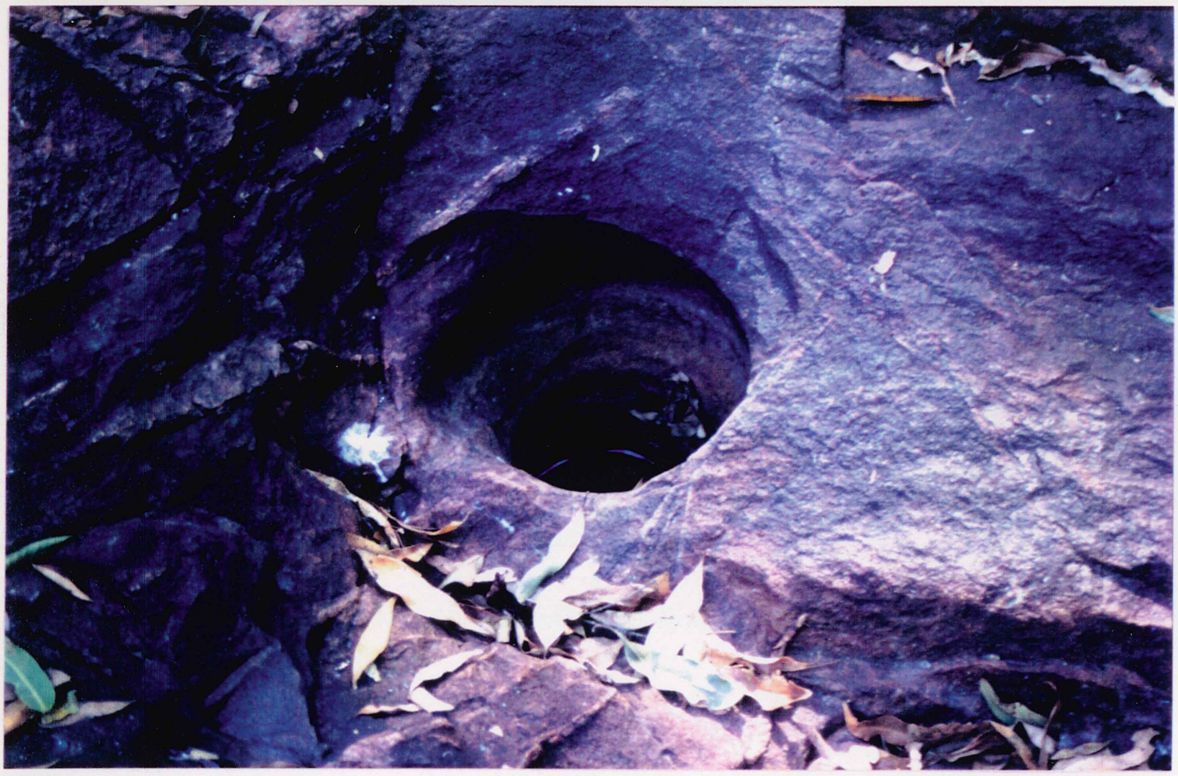


Figure 44. "Kettle holes" formed by cobbles tumbling on the creek bed in the wet season and wearing holes into the sandstone bed of the creek.

Figure 45. By climbing up the sides of the creek's valley, you can see glimpses of the landscape typical of the vast expanse of the Arnhem Land Plateau, which stretches east of the Kakadu region into Arnhem Land.

NAWURLANDJA LOOKOUT

Nawurlandja Rock is the most westerly remnant of a once extensive cover of Kombolgie Formation sandstone, and the lookout offers an extensive view of the low, flat plains which now cover much of Kakadu. The sandstone and conglomerate are rapidly eroding and the lack of soil development has prevented vegetation from establishing itself, leaving a stark rock surface in places worn into bizzare shapes by the forces of nature.

The rock is made up of interbedded *sandstone* and *conglomerate,* with pebbles of *vein quartz* and *quartzite* mainly 2 - 4 cm but in places up to 10 cm across. The surface of the rock is an extensive *bedding surface* which dips at 15^{o} to the east figure 46), and this surface is the top of a conglomerate bed about 1.5 m thick interbedded with sandstone and more conglomerate. The rocks are *cross-bedded* here and there, for example near the lookout sign. The surface of these cross beds is curved into a shallow trough formed by the direction of water flow as these rocks were deposited, and in places these troughs have been weathered out forming shallow gullies in the rock surface trending about eastwards. Evidence such as this tells geologists that the water which deposited these rocks came from the west and northwest.

Nawurlandja is made up of the lowermost part of the *Kombolgie Formation* sequence, and on the west side at the base of a sheer cliff the base of the sequence is exposed as an *unconformity* exposure above highly contorted *biotite chlorite schist* of the older *Cahill Formation.* The schist is very deformed because it is close to a major geological *fault* a few hundred metres farther west. Rocks in the fault zone have been weathered away and are not exposed, but the direction and position of the fault are preserved in the linear northwesterly trend of Nawurlandja Creek, which has preferentially followed the weaker rocks in the fault zone.

In the wet season, the rapid flow of water across the rock slope of Nawurlandja Lookout washes away any loose material, so very little soil accumulates and vegetation is almost non-existent. Hollows on the rock surface form little ponds which remain moist for long periods and are crusted with black algae. The rock is also cut by straight and curved joints, and these are opened up by water flowing down them and taking some minerals into solution (figure 47). Sometimes a lower, weaker *bed* has been dissolved away more quickly, resulting in collapse of the main surface.

The same disolving action by rainwater attacks the upper surface of the rocks, and the sandstone surfaces are worn into strange gargoyle-like projections (figure 48).

The broad, flat plain stretching to the north, west and south was once covered by the same *sandstone* and *conglomerate* rocks, but these have all been removed by erosion probably about 100 million years ago when the region was covered by a shallow Mesozoic sea. A few hills stood up as small islands, including Mirray (Mount Cahill) on the Kakadu Highway to the west, and Mount Basedow (close to the road to Jim Jim Falls) which can be seen to the southwest.

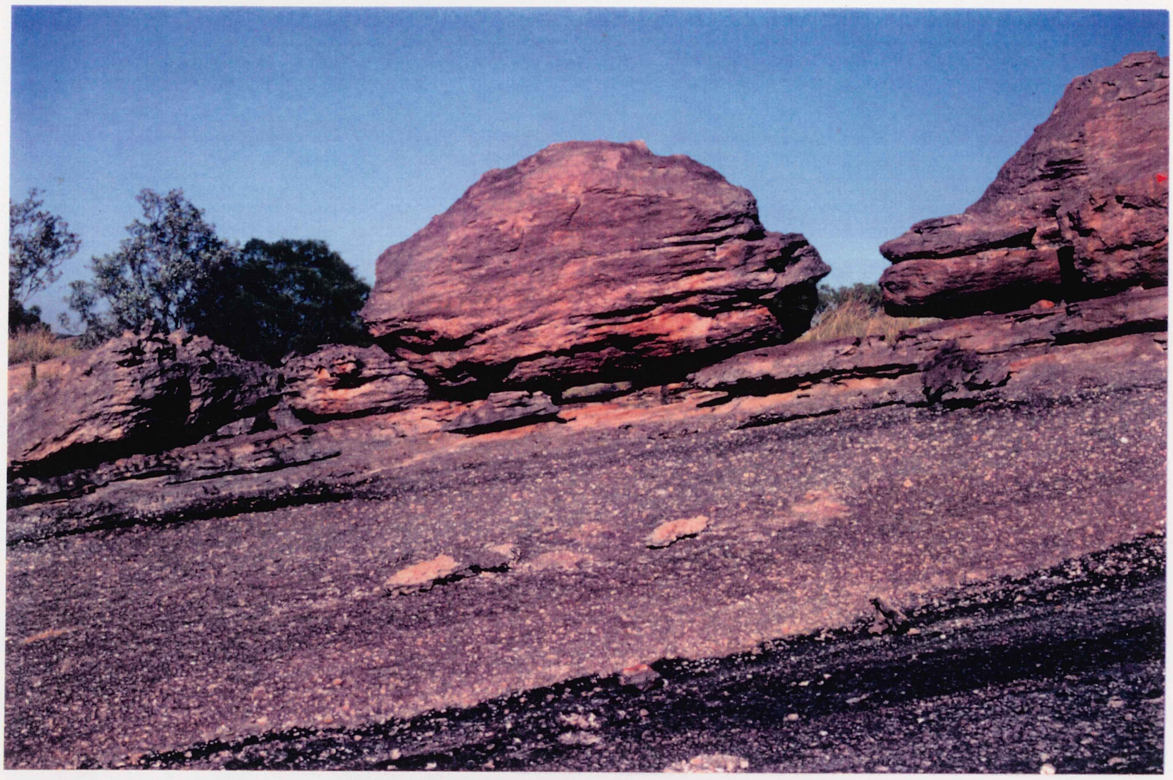


Figure 46. Sandstone blocks perched on top of the conglomerate bed are the remains of continuous sandstone layers. Water cascades off the 15^{0} rock slope in the wet season, preventing any build-up of soil or vegetation.

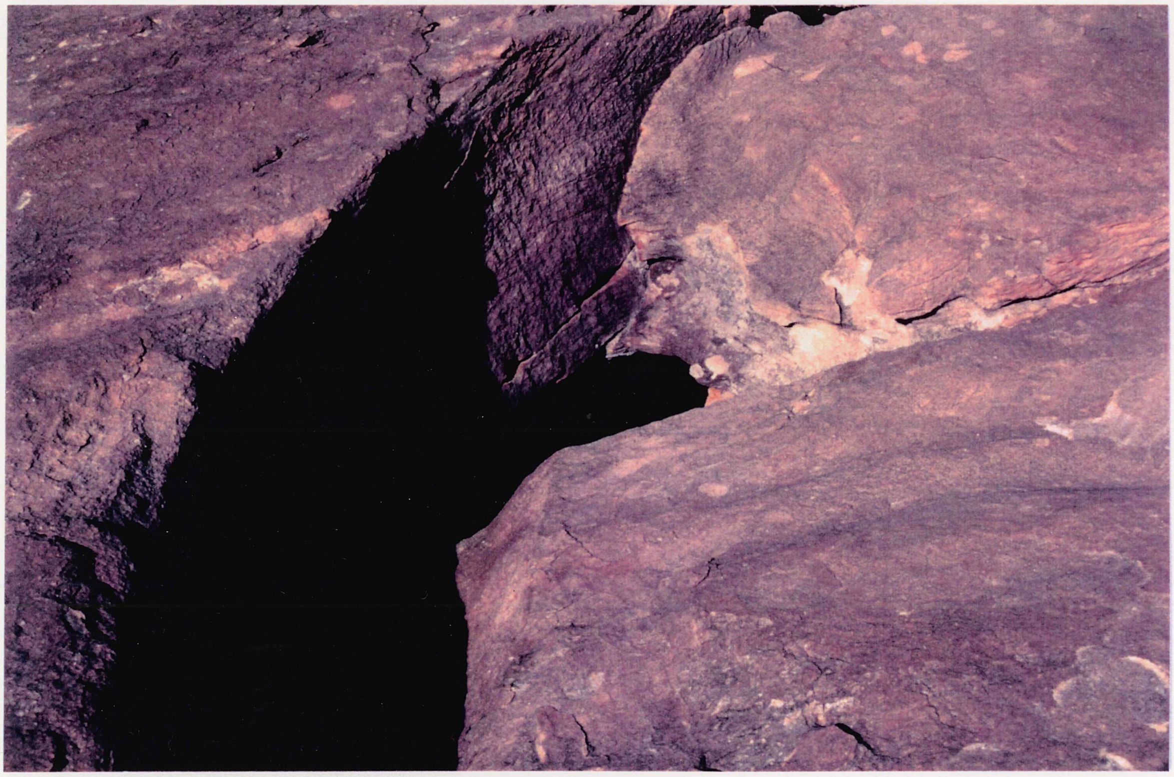


Figure 47. Curved and straight joints provide pathways for rainwater flow; the rock surfaces of the joints, and softer rock layers below, are gradually dissolved away and small collapse craters form in places.

Figure 48. Sandstone "gargoyles" formed by the weathering away of the rock as some minerals are taken into solution by the rainwater.

GLOSSARY OF GEOLOGICAL TERMS

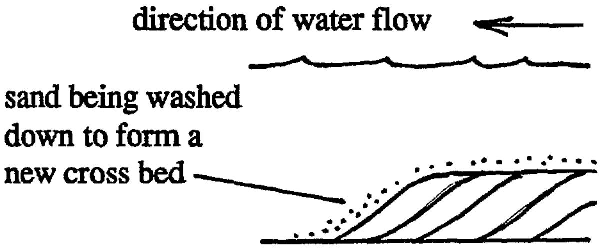
Amphibolite - a fine-grained metamorphic rock formed by the recrystallisation of dolerite or marble.

Bedding, bedding planes, bedding surfaces - planes of weakness in a sedimentary rock which are formed mostly 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.

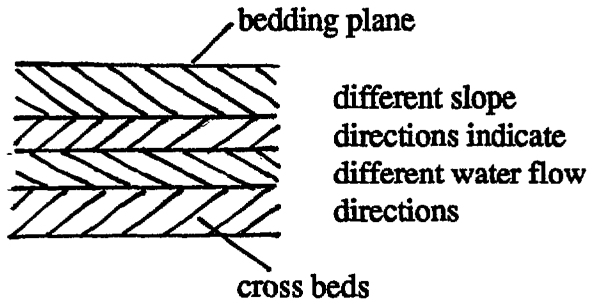
Cahill Formation - the formal scientific name for the sequence of schist, quartzite and amphibolite which lies beneath the Kombolgie Formation and sand plains of the Nourlangie area. The rocks were laid down as sediments about 2000 million years ago, and were later metamorphosed to their current rock types in the orogenic event about 1800 million years ago. This formation contains the large, rich uranium deposits of the Alligator Rivers Region.

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.

Dyke - a usually near-vertical and narrow body of igneous rock which intrudes older rocks and solidified from magma or hot fluids and gases.

Faults, faulting - 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 recrystallisation 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.

Igneous rocks - rocks which formed by cooling and crystallising of a magma, either on the Earth's surface (i.e. volcanic rocks), or in the Earth's crust (i.e. intrusive rocks such as granite or dolerite.).

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 1760 million years old, 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, involving 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.

Oenpelli Dolerite - the formal scientific name for usually very long bodies of 1700 million year old dolerite, up to 250 m thick, which intrude the Precambrian rocks of the Kakadu and Arnhem Land Plateau regions. Exposures outside the Arnhem Land Plateau are rare.

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.

Scarp retreat - see "retreat"

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 characteristic 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 become 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.

Tertiary - a relatively young geological period between 65 and 2 million years ago, when Northern Australia was geologically very stable and the Earth's surface was eroded to extensive plains and deeply weathered.

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.

Weathering - a combination of natural agents which cause the breakdown or alteration of rocks at the Earth's surface. Agents are physical (e.g. washing away by water, abrasion by sand grains blown by the wind, cracking resulting from expansion and contraction caused by temperature fluctuations), and chemical (e.g. leaching and dissolving of minerals by surface and near-surface waters, oxidation etc).