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Australian Radiation Laboratory

Tietkens Plain Karst - Maralinga

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A report of a site visit from the 15th - 21st November 1986.

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ABSTRACT

The Tietkens Plain karst is located to the north of Maralinga village which is on the crest of the Ooldea Range on the north and east margin of the Nullarbor Plain in western South Australia. In this report the geology of the carbonate rocks in the Maralinga area is summarised. The area has an annual rainfall of less than 200 mm and hence the karst falls into the category arid to semi-arid. Evidence for a palaeokarst on Tietkens Plain is produced. The sealing of the karst surface, against the penetration of meteoric waters, by calcretes and case-hardening of the dolomite is suggested. The karst features of Tietkens Plain are described and an explanation of their origins presented. A comparison is drawn between the dolomite surface of Tietkens Plain and the limestone surface of the Nullarbor Plain.

On Tietkens Plain from 1955 to 1963 nuclear weapons tests dispersed radioactive materials over the Maralinga area. Six nuclear devices were detonated in the air and one was exploded a few metres below the surface. The effect such explosions have on the karst and the possible rate of recovery of its surface are discussed.

Results of the measurements made in order to assess water quality and water contamination by radioactive nuclides are presented. The implications arising from the presence of radioactive materials on the surface and the possibility of them entering and contaminating the groundwater in the area are discussed in the context of the chemistry of uranium and plutonium. The potential for transmission of contaminants through groundwater conduits and aquifers in the dolomite is discussed.

Any accumulation of aeolian radioactive materials from Maralinga in the caves and blowholes of the Nullarbor Plain could be a potential hazard to cave explorers. Evidence is produced to show that the caves are not contaminated at present and are unlikely to be so in the future.

INTRODUCTION

The Maralinga village is located (Fig. 1) on the crest of the Ooldea Range on the north and east margin of the Nullarbor Plain in the western part of South Australia. To the south of Maralinga lies the karst surface of the flat and very extensive limestone Nullarbor Plain and to the north lies the much smaller but equally flat dolomite Tietkens Plain. It was on Tietkens Plain that the nuclear experiments at Maralinga were carried out.

Between 1955 and 1963, the United Kingdom Atomic Weapons Research Establishment conducted a program of nuclear weapons development trials at Maralinga. These included seven major nuclear trials involving atomic explosions and many other smaller scale experiments which dispersed radioactive materials on the test range, Tietkens Plain. An account of this program has been given by Symonds (1985).

In 1964 and 1967 clean-up operations were undertaken (Lokan, 1985). The rehabilitation processes involved burying radioactive materials and rubbish in pits, removing top soil, adding extra top soil and ploughing various sections of the karst. All of these operations have changed the karst surface and some may have changed the hydrological characteristics of the dolomite plain.

This report is the record of a visit to the Maralinga area from the 15th - 21st November 1986 which involved an inspection of the karst surface together with collection of water, soil and rock samples. This brief visit enabled a description of the karst to be prepared and a preliminary assessment to be made of the maturity of the Tietkens Plain karst. The investigation of the possible routes of meteoric waters into the groundwater system was made considerably easier by 7 mm of precipitation falling in the area at the beginning of the visit. The waters and soils collected were analysed at the School of Chemistry, University of Sydney and at the Australian Radiation Laboratory, Melbourne.

The results of these preliminary studies enable some conclusions to be drawn as to the water quality in the Maralinga area and its possible contamination by radionuclides. It was also possible to examine whether radioactive materials were accumulating in the aeolian deposits in the caves of the Nullarbor.

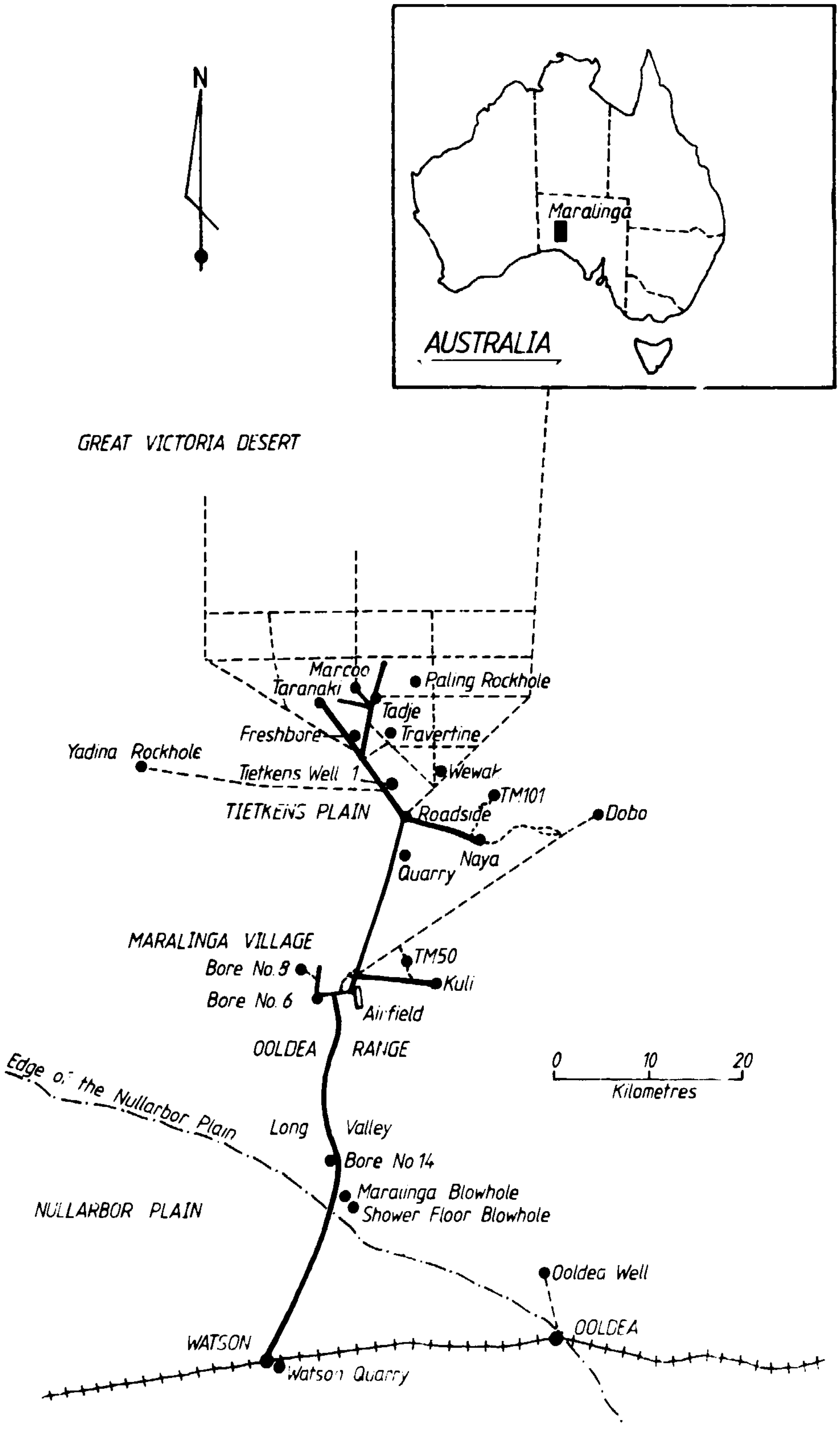

Figure 1. The Maralinga area

GEOLOGY OF THE MARALINGA KARST AREAS (FIGURE 2) (BENBOW, 1986)

The Maralinga area lies just within the east margin of the late Proterozoic-Palaeozoic Officer Basin and the northeast margin of the Cretaceous-Tertiary Eucla Basin. The Ooldea Range forms a divide between the Tietkens Plain and Nullarbor Plain. This aeolian coastal range is one of the prominent topographic features of western South Australia. The range stands 150-180 m above the very extensive Nullarbor Plain and some 90-110 m above Tietkens Plain; an equally flat but much smaller plain.

On the southern margin of the Ooldea Range, south of Maralinga, on the Nullarbor Plain the outcropping rocks are Nullarbor Limestone (Early - Middle Miocene) which in the area of Watson Quarry (Fig. 1) are about 40 m thick. These fossiliferous carbonates are very porous in part, the result of prolonged weathering. The formation is renowned for its cavernous nature, with the formation of blowholes and caves.

Tietkens Plain is the surface expression of the Garford Formation (Miocene) and is underlain by an indurated dolomite from 10-20 m thick. It is exposed over a large area and can be best observed in Roadside Quarry (Fig. 1). At this locality at least, the formation has been fragmented and recemented by secondary calcium carbonate. In fact there has been a complex history of weathering of these rocks, resulting in a marked porosity. Tietkens Wells (No. 1 and 2) and nearby drillholes indicate green clay interbeds at the base of the dolomite.

The Wilsons Bluff Limestone (Middle - Late Eocene) does not have surface exposure in the Maralinga area but must be considered in the groundwater studies. This unit is up to 11 m thick and comprises yellow brown very fine to fine grained limestone. This marine fossiliferous limestone is indurated, particularly at the base where it is recrystallised, as observed in Tietkens Well 1. The chalky beds of this limestone have high porosity but low permeability.

Veneering the Maralinga area are the aeolian sands of the Great Victoria Desert. These are up to 30 m thick in the longitudinal dunes which run NW-SE to SW-NE in the northern section of the Maralinga test site. Within the upper part of the sand ridges is a calcrete which varies from soft to very hard and is up to five metres thick.

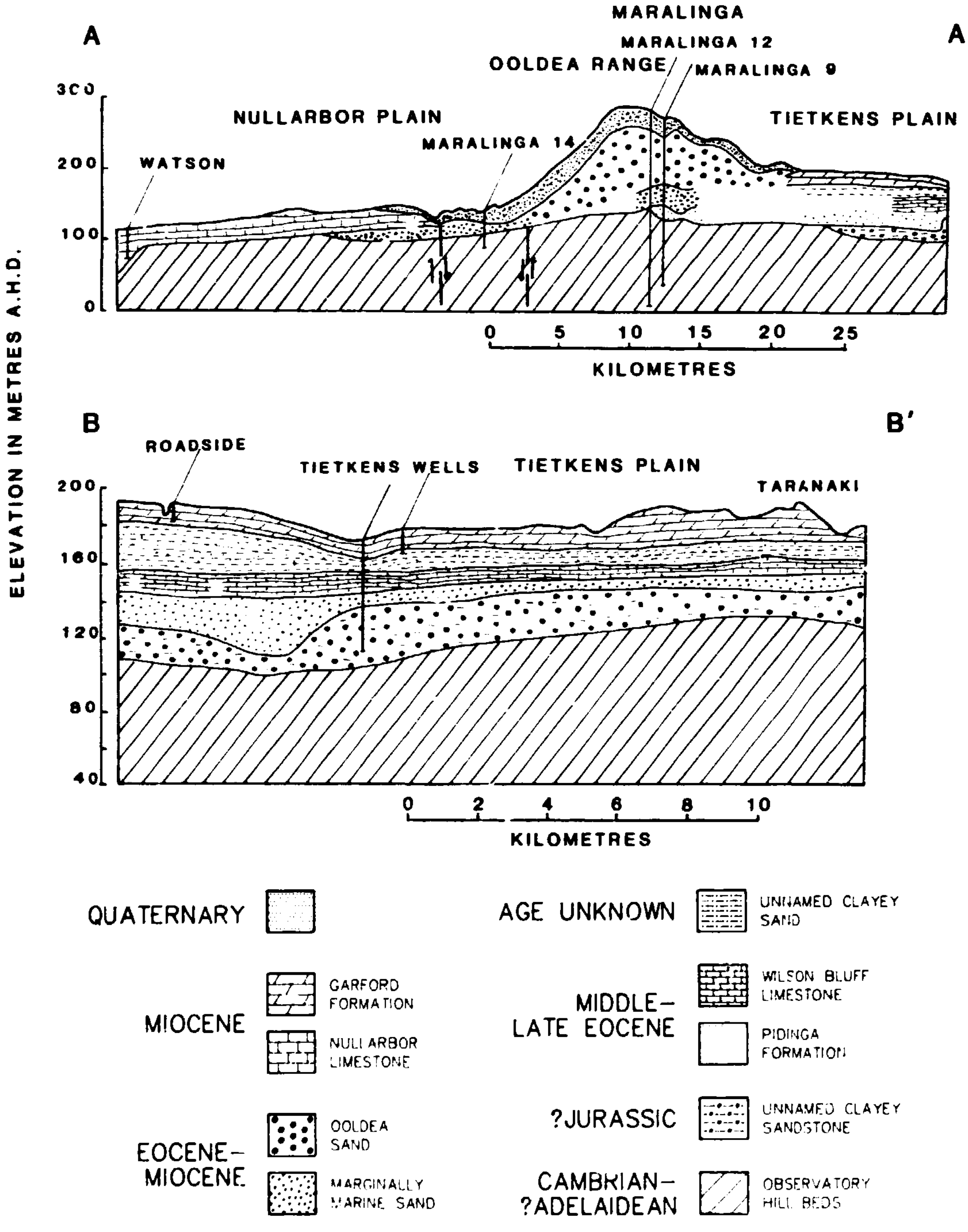

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Figure 2. Geological cross sections, Maralinga area (after Benbow, 1986)

TIETKENS PLAIN KARST

Arid and Semi-arid Karst

Tietkens Plain is borderline between an arid and semi-arid karst with an annual rainfall of less than 200 mm per year (I. Thomas, pers. comm.). Maralinga has a warm to hot non-seasonal desert climate with short cool to cold winters. The rainfall is unreliable and has no seasonal pattern, with plant growth constrained to sporadic intervals as a result. Temperatures show both seasonal and diurnal ranges as a result of continentality. In this climatic regime karst processes are limited because of low and erratic precipitation, high evaporation and little biogenic carbon dioxide, consequently there is poverty in active surface karst forms.

With Tietkens Plain as with all arid and semi-arid karsts, the assessment has to be made as to whether the landscape is the cumulative product of repeated, sporadic modern events or is relict from former periods more favourable to karst development (Jennings, 1983).

Palaeokarst

There is extensive evidence in the quarry at Roadside (Fig. 1) that the Tietkens Plain is a palaeokarst. In the quarry walls there is piping opening up large cavities that are now filled with sands and soil breakdown products (Plate 1). These cavities are caves and blowholes that formed when the karst was active, that is, when karst development was faster. A past warm-wet interval has been claimed in South Australia presenting the possibility of faster karst development at that time. More water leads to faster karst development and is likely to generate open conduits in the dolomite. These cavities would have infilled in drier times.

Calcretes and Case-hardening of Dolomite

Calcretes: calcrete occurs extensively on Tietkens Plain both within the dunes and in the sand sheets. A layer of calcrete nodules up to one metre thick has been exposed during quarrying at Roadside (Plate 2). Calcrete, as laminar sheets, is found at Travertine (Fig. 1). One manifestation of calcretisation at Maralinga is the formation of pseudo anticlines. The calcrete builds up on high points, giving the ridges and corridors in the dune area in the north of Tietkens Plain.

The calcrete nodules and sheets have a layered structure indicating that deposition and solution occur intermittently. The deposition of calcite as calcrete is complex, both carbon dioxide degassing and evaporation can control the process (Goudie, 1983); at Maralinga evaporation is likely to be dominant.

Given their wide distribution and the controversy as to their formation, it is not surprising that contrary views are taken as to whether calcretes are active or relict and what the climatic implications are if they are relict. Commonly they are taken to relate to wetter phases but they are also attributed to drier phases - both inferences may be valid in different contexts.

On Tietkens Plain the limited evidence indicates that the calcretes are forming. After 7 mm of rainfall a number of holes were dug in the bottom of closed depressions, after they had drained, in order to find the depth of penetration of the water. The rain water had only moistened soil to a depth of approximately 200-300 mm. At the limit of the damp area there was a deposit of calcium carbonate oolites (small nodules), the precursors of calcrete nodules.

Case-hardening of the dolomite: the surface of the bedrock on Tietkens Plain has been altered to give a hard capping of calcium carbonate as calcite. Without excavation it is difficult to establish whether the rock outcrop is case-hardened dolomite or calcrete. As calcretes only form in soils and sands, they are a feature of the desert rather than the karst surface.

Case-hardening is usually accepted as a feature of tropical limestones (Sweeting, 1973), however an identical mechanism for the process is possible on Tietkens Plain. Short-lived torrential rainstorms thoroughly soak the upper dolomite beds with slightly acidulated water, followed almost immediately by almost complete evaporation. The indurated layer forms a rim-rock protecting the softer dolomite.

Case-hardened dolomite, calcrete nodules and sheets form a protective layer which prevent meteoric waters reaching deep groundwater. Tietkens Plain presents an ideal situation for a study of calcrete formation and case-hardening. The possible inclusion of uranium from the nuclear tests into the carbonate structure could give a rate of formation for both under the present climatic conditions, particularly at a site such as Kuli where approximately 7000 kg of natural and depleted uranium was explosively dispersed to the environment in a series of minor trials over the period 1956 to 1963.

Karst Forms

Dongas: dongas occur both on Tietkens Plain and the Nullarbor Plain. They are mostly circular in plan, typically a few metres to a few hundred metres in diameter and up to several metres deep. There are many such depressions on Tietkens Plain, the largest being at Taranaki. They nave a silty floor of windblown sand and distinctive vegetation because of the local concentration of run-off. The larger dongas are modified and have lost their simple roundness through gentle centripetal gullying. This may be attributed to decreased permeability and greater runoff as a result of sealing by soil. The dongas would have been a focus for drainage in any previous karst development.

Pipes: there are numerous solution pipes ending in domed tops or open to the surface in Roadside Quarry; all are earth filled. The Watson Quarry also exhibits numerous pipes, some of which have no fill (the earth may have washed out after they have been exposed by quarrying). The pipes form as open structures and the number of open pipes would have been greater during periods of higher rainfall. It has been suggested by Lowry, 1967, that such cavities form from below by upward solution. There is an increase in the aggressivity of groundwater to carbonate rocks at the fresh/saline water interface. These features would have been water filled at the time of formation, drained as the water table lowered and if there was access would have subsequently filled with sand and soil.

If pipes form from below, there may be an undefinable number below Tietkens Plain and these will be continuous to the base of the dolomite. Tietkens Plain is a shallow mature karst and karst processes will have opened up fracture lines throughout the dolomite. The pipes form a possible route for the access of meteoric waters into any shallow water storage.

Minor karst features on dolomite surface: most of the dolomite on Tietkens Plain is covered. However, the dolomite/limestone surface, where it has been case-hardened, outcrops around Yadina and Paling waterholes and in regions where the plain has had the top soil ploughed and/or removed. On these flat rock surfaces there is small irregular rain pitting, multiple fracturing/crazy paving (Plate 3) and larger solution pans (Plate 4), some filled with vegetation. There are no features on the dolomite surfaces that can be directly attributed to wind erosion.

Minor karst features from under soil cover: the smoothing, perforation and pocketing of the dolomite beneath the soil by solution can be observed where the interface has recently been exposed or deliberately revealed. Where dolomite fragments have been embedded in the soil, the buried surface shows solutional smoothing (Plates 5 and 6). Around Marcoo, there are fragments from the surface explosion scattered over a wide area. These thirty year old fragments show little signs of weathering, which indicates that at the present time the karst processes (solution processes) are slow.

Rockholes (gnamma holes): there are two such holes on Tietkens Plain -

Yadina Rockhole (Fig. 1)

Yadina Rockhole is located 25 km to the west of Tietkens Well 1. It can also be reached by a track from the Oak Valley Road. It is in the centre of a donga which has been modified by gullying. Around the small hole (diameter less than 1 m) is a dolomite/limestone pavement which has numerous subaerial solution features on it that indicate the pavement has been exposed for a considerable time period. The bedrock has been case-hardened. The rockhole was dry when located by I. Thomas immediately prior to the November site visit and could have been excavated. After 7 mm of rain it was full of muddy water and thus its depth to bedrock could not be assessed.

Paling Rockhole (Plate 7, Fig. 1)

Paling Rockhole is situated in a donga that has hardly been modified by rainfall runoff. The small hole is in an area of dolomite outcrop, the pavement area is small and has little evidence of subaerial weathering. It is case-hardened and has smoothed forms indicating subsoil modification in the past. The hole was excavated and found to contain damp dark brown humus. This damp dark environment was the residence of a pathetic specimen of a frog, which was photographed and returned to its underground home. In and around the hole there were numerous crickets and one specimen was captured for identification. The hole was excavated to a depth of 1 m before becoming too uncomfortably small for further excavation.

Both Yadina and Paling Rockholes are believed to be of biological and cultural importance on the otherwise waterless Tietkens Plain. Neither of the two rockholes stores sufficient water to last reliably through the unpredictable intervals between rain. They have not been used for a considerable time period and probably need regular maintenance to be viable water sources even for a limited period. Paling Rockhole is possibly the waterhole that the Milpuddie family found dry and subsequently stumbled upon water in the Marcoo crater. Around the Yadina Rockhole are quantities of worked stone tools, old fireplaces and burnt bone as well as recent garbage. This rockhole was visited by Brady and Palmer, 1987 who noted its cultural significance to the aborigines of Oak Valley and Yalata.

Caves and Blowholes: appendix I describes the caves found close to Maralinga - they are south of the Ooldea Range and in the Nullarbor Limestone. There are no open cavities in the dolomite Tietkens Plain. Blowholes are so named because of the strong air draughts which frequently blow in and out of them. Lowry, 1967, suggests that blowholes form by extension upwards of blind pipes in shallow cave roofs until they breach the limestone pavements or cause subsidence in the overlying soil. The Maralinga Blowhole (Fig. 1) appears to have formed by this mechanism with the shaft entrance being exposed during the construction of the Watson-Maralinga road. The cave contains nests of the stick-nest rat which has been extinct in that region of the Nullarbor for at least 70 years (A. Spate, pers. comm.). These animals must have entered the cave by routes other than the present entrance shaft. Old and new soil was collected from this cave.

A Comparison of the Nullarbor Plain Karst with that of Tietkens Plain:

Tietkens Plain has morphological features similar to those seen on parts of the karst surface of the Nullarbor Plain; however, it is a distinct physiographic karst region and thus is separate from the Nullarbor Plain. The

Garford Formation which immediately underlies Tietkens Plain is geologically similar in age and lithology to the Nullarbor Limestone. The major difference is that on Tietkens Plain the underlying carbonate rock is dolomite and on the Nullarbor it is limestone.

As a karst rock dolomite behaves in a similar way to limestone, that is, it is soluble in natural waters containing carbon dioxide and its stability at equilibrium is much the same. However, its solution kinetics differ markedly, bringing equilibrium much more slowly (White, 1984). This means that the cavities in dolomite will develop more slowly, even though there has been adequate time for cavern development below Tietkens Plain. It is expected that similar but smaller caverns to those which lie below the Nullarbor Plain will lie below Tietkens Plain.

Tietkens Plain is a covered karst, the covering being largely aeolian sands from the Great Victoria Desert. The sands appear to have filled all the open cavities on Tietkens Plain. Where the soil is shallow or exposed, the surface of the dolomite has been case-hardened. Where it is deep, layers of calcrete or calcrete nodules have formed. These layers of calcrete and case-hardening protect the rock from further erosion by descending meteoric waters. No wind erosion features were found on Tietkens Plain.

The Nullarbor Plain south of Maralinga is only partially covered and has considerably less vegetation than Tietkens Plain. It is in part protected from being covered by aeolian sands by the Ooldea Range to the north. Hence on it there is more exposed rock and many of the caves and blowholes are open. There are solution and wind erosion features on exposed rock surfaces on the plain.

The open nature of the Nullarbor karst leaves it free for penetration by meteoric waters, which on entering the limestone get transmitted through the porous rock into aquifers. In the caves there is still some solution erosion taking place. In contrast the closed nature and low porosity dolomite in its natural state has been aided in its sealing against penetration by meteoric waters by the aeolian sand, calcrete and case-hardening, and thus closing almost all of the cavities on Tietkens Plain.

Changes to the Karst Surface

No comparison can be made in this report between the state of the karst on Tietkens Plain prior to the nuclear experiments and that presently observable. However, the following are believed to be changes that have occurred on the karst surface as a result of the nuclear experiments.

Karst surface at Taranaki: on the 9th October 1957, a 27 kiloton balloon-borne nuclear device was exploded 300 m above the Taranaki surface. After the airborne explosion the Taranaki donga was cleared of vegetation and even beyond the rim of the donga there is evidence of nuclear pruning of the trees. A few large trees have now grown within the donga and miniature vegetation is establishing itself and stabilising the calcrete and sand surface.

In places the topsoil has been ploughed causing rainwater to be channeled into the furrows and form limited drainage routes. Extra soil has been added to cover contaminated soil and this is still unconsolidated by either vegetation or calcrete. A large depression is developing over what is possibly a burial pit on the south side of the man-proof fence. Within the fenced area there appears to be local influxes of water into the underground in the vicinity of some of the 21 burial pits, many of which contain plutonium. Aeolian sands are accumulating against the fence.

Karst surface at Wewak: the karst surface at Wewak has been disturbed both by the building of platforms for the explosions associated with the minor trials and by the heavy machinery that has moved through the area. Caterpillar tracks can be seen clearly after twenty years and in places the calcrete/case-hardened dolomite surface has been scraped free of soil. Some parts of the area appear to be close to the natural state with the dongas having well established vegetation.

Karst surface at Marcoo: on the 4th October 1956, a 1.5 kiloton nuclear device was exploded on the ground surface at Marcoo. It is here that the karst exhibits the greatest damage, with many dolomite boulders scattered over a large area extending beyond the blasted area into the nuclear pruned trees. Any damage of hydrogeological significance cannot be observed. The Marcoo underground explosion created a crater approximately 12 m deep and 50 m in diameter with water at its base. This crater was filled in with debris, some radioactive, and soil. The result is that the karst in this region provides an easy access route for meteoric waters into the underground. It is impossible to comment on the damage to the karst surface close to the crater because much of this has been covered with explosion and rehabilitation materials. The explosion is expected to have caused additional fracturing to the dolomite bedrock.

In general the preparation of a road network and buildings, the nuclear experiments and the clean-up operations have created artificial catchments and channeled water into small streams. The accumulated waters have the potential to reopen the filled solution pipes and access the underground. The numerous pits in which radioactive materials were buried, at the trial sites at Taranaki, TM50, TM101, Kuli, Dobo and in the Tietkens Plain and Airfield Cemeteries, and especially the crater at Marcoo, provide a potentially more direct route for meteoric water to enter the groundwater system.

KARST HYDROLOGY

The Tietkens Plain hydrology is one of low relief, and horizontal structure. There are no surface streams in the Maralinga area. There are no springs and the only surface water is found in the semi-permanent rockholes. During rainfall lakes of water accumulate in most of the dongas (Plate 8) but these disappear, rapidly draining or drying up in less than 24 hours after the rain has ceased.

The Maralinga area in its natural state lacks any active drainage network because rainfall and runoff are not sufficient to counteract high rates of evaporation or percolation into the soil and underlying aquifers. Under earlier climatic conditions of more effective rainfall surface drainage channels could have developed. There is evidence of a palaeochannel system (Pitt, 1979) converging on the Nullarbor Plain from surrounding areas. At this time there could have been active drainage on Tietkens Plain. Any such drainage channels would now be infilled by the aeolian sands of the Great Victoria Desert. If there has been active drainage on Tietkens Plain and conduits developed in the past, then the modern waters will take these preferred routes.

Percolation into the sands at the drainage centres of the undisturbed dongas after 7 mm of rain was only minimal (200-300 mm) and much of this rain lay on the surface awaiting evaporation (Plate 8). There was no surface water remaining in the Marcoo area.

Within the fenced area at Taranaki the rainwater appears to have direct access to the underground. Inside the man-proof fence there are numerous small solution pipes that are open and take water from embryo drainage networks (Plates 9 and 10). The water chemistry of Freshbore indicates that meteoric water is reaching an aquifer at the base of the dolomite (see Water Chemistry). Comparison with the chemical water analyses from the Nullarbor Caves, where meteoric waters are known to enter the aquifers, indicates that those on Tietkens Plain are slightly more saline but of similiar composition (Wigley and Hill, 1966).

WATER CHEMISTRY

The water chemical results shown in Table 1 are not expected to be truly representative of their sources. The samples from boreholes were taken after they had been abandoned for some twenty years and only duplicate samples of the surface waters were taken. To obtain a complete chemical picture of these sources the bores should be pumped and an extensive sampling program carried out to enable characterisation of the bore waters at various stages of drawdown. Yadina Rockhole should be sampled regularly, as it dries up, to obtain information on how this water ages. In parallel with the water chemical study on water quality there should be a microbiological study. The water chemical analyses of the bore waters from boreholes No. 8 and 14 have unsatisfactory ion balances. No further samples have been collected to improve the quality or quantity of the chemical data. With these limitations in mind the following comments can be made on the quality of waters in the Maralinga area.

Superfical waters: during rainfall lakes of water accumulate in most of the dongas but these disappear, rapidly draining or drying up less than 24 hours after the rain has ceased. The closest water sample to rainwater that was collected was the tap water at the hospital. This water was, at the time of collection, runoff from the airport. It is acceptable drinking water.

Yadina Rockhole: this water is a potable carbonate water containing low levels of all minerals. It is the only water sampled that contained phosphate; probably resulting from leaching of the fireplaces and burnt bone within its catchment. The Yadina Rockhole water analysis was similar to the Maralinga tapwater. The calcium/magnesium ratio indicated that its composition is largely influenced by drainage across calcrete or case-hardened rock and not through dolomite.

Paling Rockhole: contained no water, only saturated soil. Digging failed to accumulate enough water for chemical analysis.

Freshbore: Freshbore is approximately 5.5 km south of the Taranaki site (Fig. 1) which is extensively contaminated with plutonium and uranium. The water level was at 27 m and the sample was collected from just below the surface. The aquifer is probably directly above or in an unnamed clay and sand bed at the base of the dolomite. Its calcium/magnesium ratio and salinity indicate that it is not entirely percolation waters from the dolomite. It is possible that this water storage is in hydraulic connection with saline groundwater. Wilson Bluff Limestone lies 10-20 m below the base of the dolomite, and is recognised as a source of saline waters (Lowry and Jennings, 1974).

Freshbore is not an acceptable drinking water without some desalination or dilution. If the Freshbore hydrological system is stressed by pumping it may be possible to drag radioactive contamination through from the nuclear test sites. The radioactive nuclides would have to travel in soluble or suspended forms through relict conduits. In addition, as fresh water floats on saline water, this source may well become more saline as water is drawn from deeper in the system. The size of the tank base at Freshbore indicates that the bore had only a low yield when in operation.

Borehole No. 8: is a deep bore and penetrates into the Observatory Hill Beds (Cambrian) and its analysis indicates that it does not receive any drainage from limestone aquifers. (A limestone aquifer is one in which carbonates are dominant in providing or developing the resource (Smith, 1987)). The high salinities obtained from these deep bores in Maralinga Village are typical of connate water and the supply is unlikely to be recharged by meteoric waters and is therefore not subject to contamination by radioactive nuclides from the Maralinga tests.

TABLE 1. WATER CHEMISTRY, MARALINGA

Samples	Freshbore 17-11-86	Tap Water 21-11-86	Yadina Rockhole 16-11-86	Bore No. 8 18-11-86	Bore No. 14 13-11-86
dO_2 mg L^{-1}	4.3	8.5	8.5	0.3	0.5
Field pH	8.14	6.90	7.32	8.16	4.36
Lab pH	8.0	7.0	6.5	7.6	3.5
ANIONS (mg L^{-1})					
Cl^-	1498	10.1	9.0	12264	15988
SO_4^{2-}	129.0	7.9	7.7	584	4728
HCO_3^- (as $CaCO_3$)	547	156	164	3340	-
NO_3^-	5.0	0.29	0.48	23.8	-
F^-	2.5	-	-	-	-
PO_4^{3-}	-	-	1.4	-	-
CATIONS (mg L^{-1})					
Ca^{2+}	399.0	22.46	21.00	26.9	626.5
Mg^{2+}	116.9	3.897	4.410	352.7	1387
Na^+	717.9	8.307	7.726	8517	10320
K^+	117.6	4.285	10.63	414.5	364.7
Si	25.2	2.409	5.076	21.3	5.0
Fe^{3+}	9.7	0.099	0.126	9.60	155.9
B	0.00	0.021	0.000	0	3.10
Zn^{2+}	2.0	0.046	0.029	1.50	2.40
Sr^{2+}	0.00	0.119	0.032	0.00	8.40

For methods see Appendix II

Borehole No. 14: is a shallow bore in Long Valley on the Watson-Maralinga road and only just penetrates into the Observatory Hill Beds. Its analysis is very different to that obtained from Borehole No. 8 and thus, most probably, draws its waters from the Tertiary marine sands. The Tertiary sequence contains silicified or ferruginized layers, limestones and calcretes. This rock and mineral composition would give the chemical analysis for the water presented in Table 1. The presence of boron is a particularly sensitive indicator of a marine environment (Swaine, 1971). This water has an unusually low pH.

It is believed that this is the bore from which the State Water Laboratory of South Australia has found high readings for α and β activity (G. Wood, pers. comm.). The radioactivity is most likely to come from natural sources rather than contamination from the tests. However, the Tertiary marine sands could easily transmit contaminants, which could be tested for by examination of the water for radioactive nuclides that are characteristic of the nuclear experiments.

These water chemical results add further information to the hydrogeology put forward by Morris and Benbow, 1986 who summarised the work of T. A. Barnes and R. G. Shepherd.

RADIOACTIVITY ANALYSES ON BORE WATERS AND SOILS

TABLE 2A. RADIOACTIVITY ANALYSES ON 3.9 LITRES OF WATER FROM FRESHBORE, NOVEMBER 1986

^{210}Pb	0.05(3)	Bq L^{-1}
^{228}Ra	0.07(3)	Bq L^{-1}
^{228}Th	0.01(1)	Bq L^{-1}
^{40}K	1.5(2)	Bq L^{-1}

TABLE 2B. RADIOACTIVITY ANALYSES ON 7.1 LITRES OF WATER FROM NO. 6 BORE AT THE HALF-WAY TANK, MARALINGA VILLAGE, NOVEMBER 1987

^{210}Pb	0.2(1)	-	Bq L^{-1}
^{226}Ra	1.6(1)	*0.022(3)	Bq L^{-1}
^{228}Ra	6.07(5)	*0.088(5)	Bq L^{-1}
^{228}Th	0.24(1)	*0.012(2)	Bq L^{-1}
^{40}K	not obtained		

* After treatment by reverse-osmosis

Notes:

1. The e.s.d.'s in parentheses are based on counting statistics alone. All other radioactive nuclides were below the limits of detection for long counts by high-resolution gamma-ray spectrometry.

2. After purification by reverse-osmosis, the levels of radioactivity in No. 6 Bore water were of an acceptable level for drinking water. These results show that water from both No. 6 Bore and Freshbore exhibit no radioactivity that is characteristic of contamination by fallout from the nuclear weapons tests.

TABLE 3. RADIOACTIVITY ANALYSES ON SOILS FROM ROCKHOLES AND CAVES

Activities (in mBq g^{-1}) of radionuclides detected in sediment samples from the Maralinga area by high-resolution gamma-ray spectrometry. ND indicates not detected. The counting errors, expressed as estimated standard deviations, are given in parentheses and refer to the least significant digits (N.B. the actual errors are probably somewhat greater than these values).

Sample	^{238}U	^{226}Ra	^{210}Pb	^{228}Ra	^{228}Th	^{40}K	^{137}Cs	^{241}Am
Paling Rockhole 16/11, mud.	10(4)	4.6(8)	53(4)	6.3(9)	8.5(5)	68(10)	121(1)	26.6(7)
Paling Rockhole 19/11, second sample.	4(2)	5.7(7)	51(5)	10(2)	7.9(7)	67(9)	121(2)	23.8(7)
Yadina Rockhole 16/11, 2.5 cm depth.	8(4)	8.0(6)	101(3)	14(1)	13.9(5)	69(10)	19.7(7)	ND
Maralinga Blowhole, 18/11, old soil.	10(4)	7.1(7)	ND	10(1)	7.2(8)	297(9)	ND	ND
Maralinga Blowhole, 18/11, new soil.	5(1)	7.5(4)	17(2)	11(1)	2.8(3)	89(10)	2.3(3)	ND

DISCUSSION

From the data presented in Table 3, the following points can be made:

1. The levels of naturally occurring ^{238}U, ^{226}Ra, ^{228}Ra and ^{228}Th are typical for soils in this region.

2. The levels of naturally occurring ^{210}Pb in three of the samples are typical for soils from this region, with the value for Yadina Rockhole being significantly high and the old soil from Maralinga Blowhole showing no ^{210}Pb.

3. Naturally occurring ^{40}K levels are typical for these soils, the exception again being the old soil from Maralinga Blowhole.

4. ^{137}Cs levels in this area, from global fallout, are typically 2-12 mBq g^{-1}, so Yadina Rockhole is a fraction high and Paling Rockhole shows enhanced ^{137}Cs from the Maralinga tests.

5. ^{241}Am is the pointer to ^{239}Pu, with the ^{239}Pu/^{241}Am activity ratio varying between ca. 7 and 42 depending on the source of the plutonium (Johnston *et al.*, 1988). Paling Rockhole is within the Maralinga test sites area, and would be expected to be contaminated by fallout from the major nuclear trials. Hence a ratio of between 23 (One Tree trial) and 42 (Tadje trial) is currently appropriate for converting the observed ^{241}Am activities to activities of ^{239}Pu.

The new soil from the Maralinga Borehole shows no radioactivity that can be attributed to contamination from the nuclear tests. It is the closest known cave to the test site but is directly south of it. The nuclear tests were all carried out with the winds coming from a southerly direction so that fallout would be spread over uninhabited desert. It has already been stated that the Ooldea Range acts as a barrier and in part protects the Nullarbor plain from invasion by the red sands from the Great Victoria Desert. The Ooldea Range would also protect the Nullarbor from any wind-borne radioactive contamination from the north. Some cave explorers visiting the Maralinga Blowhole and Shower Floor Blowhole (Appendix I) have, in the past, been afraid to enter because of possible radioactive contamination (A. Davey, pers. comm.). Such fears are unfounded.

Old Maralinga Blowhole soil has a high potassium content; it has been noted by Spate *et al.*, 1984, that sands collected from other caves on the Nullarbor Plain containing red aeolian sand deposits have a high percentage of potassium. The high potassium in the Maralinga Blowhole could result from its occupation by stick-nest rats or from the saline waters that formed it (Appendix I). The saline water could come from a similar source to that in Borehole No. 14, which also has a high potassium content.

URANIUM AND PLUTONIUM CHEMISTRY IN A CARBONATE TERRAIN

The contamination remaining in the local Maralinga area from the seven major nuclear weapons trials, involving atomic explosions, consists of trace amounts of cobalt-60, europium-152, strontium-90, caesium-137 and europium-155 (all of intermediate half-lives of 30 years or less), as well as trace amounts of long-lived plutonium particularly at the Tadje site. However, by far the most significant radioactive contamination in the area results from the hundreds of "minor trials", most of which involved explosive (non-nuclear) dispersal of radioactive materials and/or beryllium to the local environment (Williams *et al.*, 1987). There are five main regions at Maralinga where these minor trials took place, and the types and quantities of materials dispersed are given below.

Taranaki: about 22 kg of plutonium, 47 kg of uranium (both isotopes ^{238}U and ^{235}U) and 18 kg of beryllium were dispersed during the Vixen B series of minor trials over the period 1960-63. It is estimated (Lokan, 1985) that between 2 to 4 kg of this plutonium remains on the ground in the Taranaki vicinity, with the remainder either contained in the 21 shallow burial pits within the fenced area of Taranaki or dispersed over a much wider area.

Wewak: approximately 0.6 kg of plutonium, 47 kg of uranium and 4 kg of beryllium were dispersed in minor trials.

Naya: approximately 1.2 kg of plutonium was dispersed but subsequently 0.5 kg was collected and eventually returned to the United Kingdom. As well, over a fairly wide area centred on Naya, 469 kg of uranium and 2.4 kg of beryllium were dispersed.

Kuli: in the sandhills to the east of Maralinga village a total of 7489 kg of uranium and 75 kg of beryllium were dispersed. Most of the uranium is presumed buried in shallow pits alongside the Kuli and TM50 firing sites. However, the Kuli area in particular is littered with yellow crumbly fragments of oxidised uranium, as well as with small pieces of uranium metal.

Dobo: is the eastern-most site of the Maralinga Range and in its vicinity 28 kg of uranium was dispersed into the immediate environment.

During weathering in the oxidising environment of such a carbonate terrain, uranium is readily oxidised to U^{6+} and combines with oxygen to form the uranyl ion, UO_2^{2+}, which forms several soluble complexes. In contrast Be^{2+} ions, because of their high charge density, are quickly absorbed or precipitated. Once in solution in the groundwaters within a carbonate terrain, uranium is transported as the very soluble anionic complex $(UO_2[CO_3]_3)^{4-}$. On entering the underground system, these waters may precipitate as calcium carbonate, coprecipitating a small amount of the uranium complex. The exact mechanism of uranium incorporation into calcite is not well understood.

The dispersion of plutonium into the groundwaters at Maralinga will depend on its speciation on the surface and in the soils. Williams ***et al.***, 1987, have classified the types of plutonium contamination as finely dispersed material, discrete oxide particles and contaminated fragments. Each of these presents its own particular hazard. They note that it is essential to establish the chemical nature of these materials.

Plutonium at Maralinga is expected to be largely in the oxide form. However, plutonium oxides have a reactivity which is usually strongly influenced by their thermal history, being much more inert if they have been ignited (Greenwood and Earnshaw, 1984). The various forms of plutonium (plutonium metal protected by oxide layer and plutonium oxides) will have the following relative activities with the groundwaters:

plutonium metal >> plutonium oxides >> plutonium as refractory oxides.

In a karst area the plutonium equilibria of environmental concern are largely those associated with acid-base properties and especially the formation of complex compounds. The ligands present in the Maralinga groundwaters that are likely to complex with plutonium are: carbonate, sulfate, chloride, fluoride and organic acids from the soil. All of these ligands are known to complex with plutonium in its various oxidation states, and some of them such as carbonate will form very stable complexes (Cleveland, 1979).

Once complexed, plutonium is available to the groundwater system and it will move with those waters through the system. It is also possible for the oxides of plutonium, themselves, to be flushed into open dolomite conduits and travel through the system as suspended solids. This may occur faster [illegible] a stress, such as pumping, is placed on the water storage.

CONCLUSIONS

It is believed that Tietkens Plain is a palaeokarst that is currently undergoing minimal solution activity at its dolomite surface. There is some evidence that indicates that relict passages in the karst are being rejuvenated. Below ground level, solution of the dolomite may still be taking place at the fresh-saline water interface, creating new cavities. The karst before it infilled was mature and thus conduits will extend to the impervious beds below. These conduits will form a network of preferred routes for the groundwaters and they may be open, flooded or earth filled.

At present there is no evidence of contamination of the groundwater within the karst. Where the karst surface is sealed contamination has no access. Where the integrity of the karst surface has been destroyed soluble contaminants can enter the groundwater. There is a reasonable probability that in the areas of Marcoo and Taranaki the shallow and thus low salinity groundwater is contaminated although it must be emphasised that plutonium oxide is very insoluble and only ca. 30 years have elapsed since the plutonium was introduced to the area. This contamination can only be established by drilling to reach the groundwater and subsequent analysis; an expensive project. These waters do not present a hazard to the fauna or to man unless they are tapped for a water supply.

With the very limited information available, the precaution should be taken of not using water on Tietkens Plain from either the Garford Formation or the Wilsons Bluff Limestone. The high natural radioactivity of the Long Valley water makes it suspect. The water that is safest to use for any long term supply, for desalination, is the water from the deep bores in Maralinga Village, that is, those that draw their water from the Observatory Hill Beds.

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APPENDIX I. CAVES

MARALINGA BLOWHOLE (Matthews, 1985)

N155 Ooldea 750E 6641N (YDS E 462.6, YDS N 1243.4)

A one metre diameter tube in a square hole at the centre of a 2.75 m x 2.85 m concrete slab, drops three metres and then steps down to -10 m. The cave lies 20 m off the Watson - Maralinga Road, was probably exposed during roadmaking, and had been vandalised by rubbish and graffiti. Extensive faecal deposits from the stick nest rat (believed to be extinct in this area of the Nullarbor for at least 70 years (A. Spate, pers. comm.)) were also present.

Soil deposits of fresh wind blown red sands and an apparently much older dark soil (see soil radioactivity analyses, Table 3) were present in the cave. The cave is entirely in Nullarbor Limestone, and appears to have been formed by phreatic action at the fresh - saline water interface. At that time the saline groundwater was higher and the three distinct levels in the cave indicate that there may have been three rest levels in its dropping. The only decorations in the cave are extensive roof and wall coverings of poor quality dog tooth spar. An interesting piece of graffiti was found in the cave

April 1960

We have some photographs of the caves, if you are interested.

D.H. Summers (D.O.W.)
Justin Avenue,
Northfield Adelaide SA

Beard (DOW)
24 Second Street,
Wingfield Adelaide SA

We found no tunnel from the first cavern, and have not found one on this level yet.

SHOWER FLOOR BLOWHOLE (Mathews, 1985)

N183 Ooldea 751E 6639N (YDS E 463.3, YDS N 1242.2)

A blowhole which has been used as a disposal pit for wastes from Maralinga construction camp (not visited). A concrete apron surrounds the entrance.

APPENDIX II. METHODS OF CHEMICAL ANALYSES

SAMPLING - Duplicate water samples were collected in acid washed plastic bottles from the following sites. The location of the sites are shown on Figure 1.

Yadina Rockhole
Tapwater at Maralinga Village
Bore No. 8 in Maralinga Village
Bore No. 14 in Long Valley
Freshbore on Tietkens Plain

ANALYTICAL METHODS -

pH - was measured at the site using an Orion Model 211 Digital pH meter and measured in the laboratory using an Orion Ionanalyser/901.

Dissolved oxygen - was measured at the site using an Orion Model 97-08 oxygen electrode; correction was made for salinity.

Alkalinity - was determined at the site by titration with 0.01M HCl using methyl orange as the indicator and by pH titration to 4.5.

Cation, anion and molecular species analyses - anions were measured on a Dionex Ion Chromatograph Model No. 2000 isp. Cations were measured on an Applied Research Laboratories Inductively Coupled Plasma (ICP) spectrophotometer Model No. 34000 at the New South Wales Water Resources Commission Laboratory.

Plate 1. Cavity filled with earth in Roadside Quarry

Plate 2. Calcrete nodules and calcrete sheets in Roadside Quarry

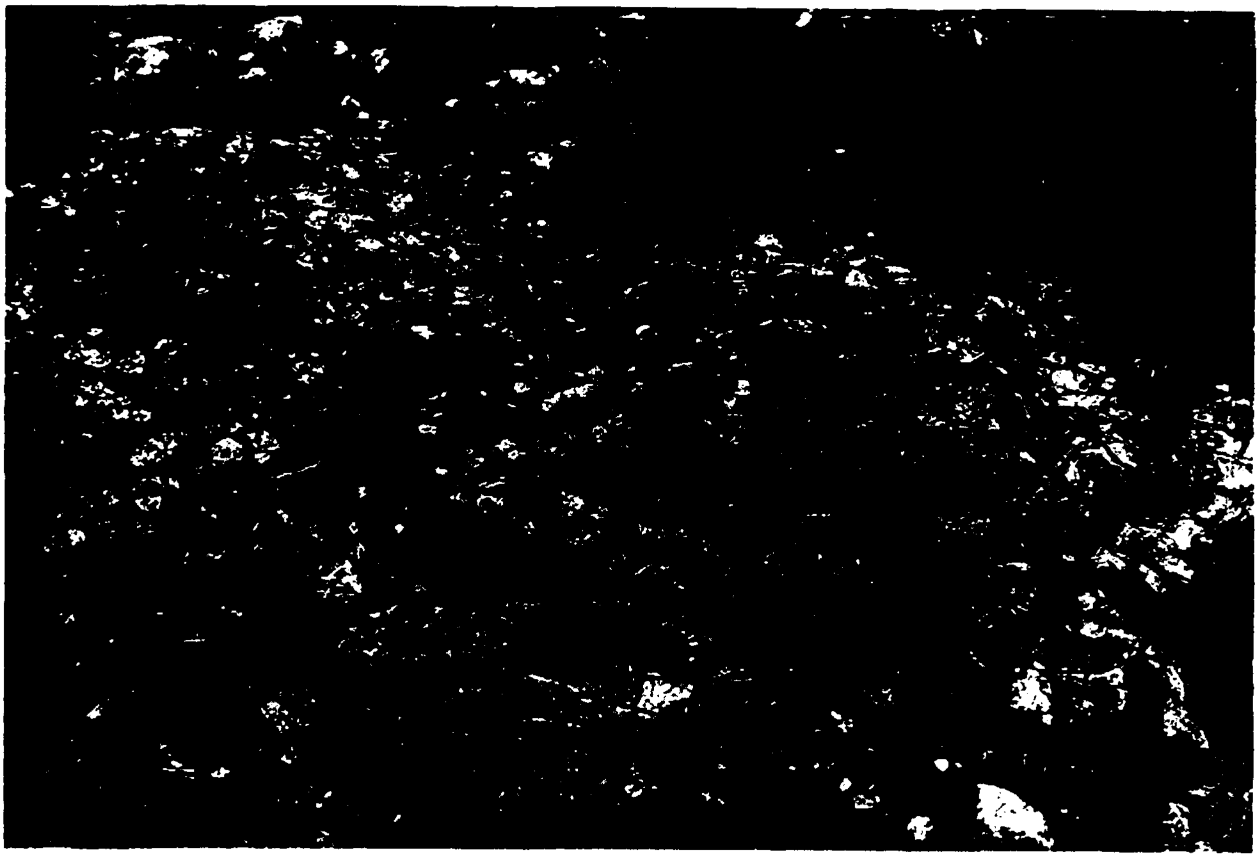

Plate 3. Multiple fracturing of the indurated carbonate rock surface at Yadina Rockhole

Plate 4. Solution pan without vegetation at Yadina Rockhole

Plate 5. Subsoil weathering of a dolomite boulder

Plate 6. A dolomite boulder with an unweathered surface

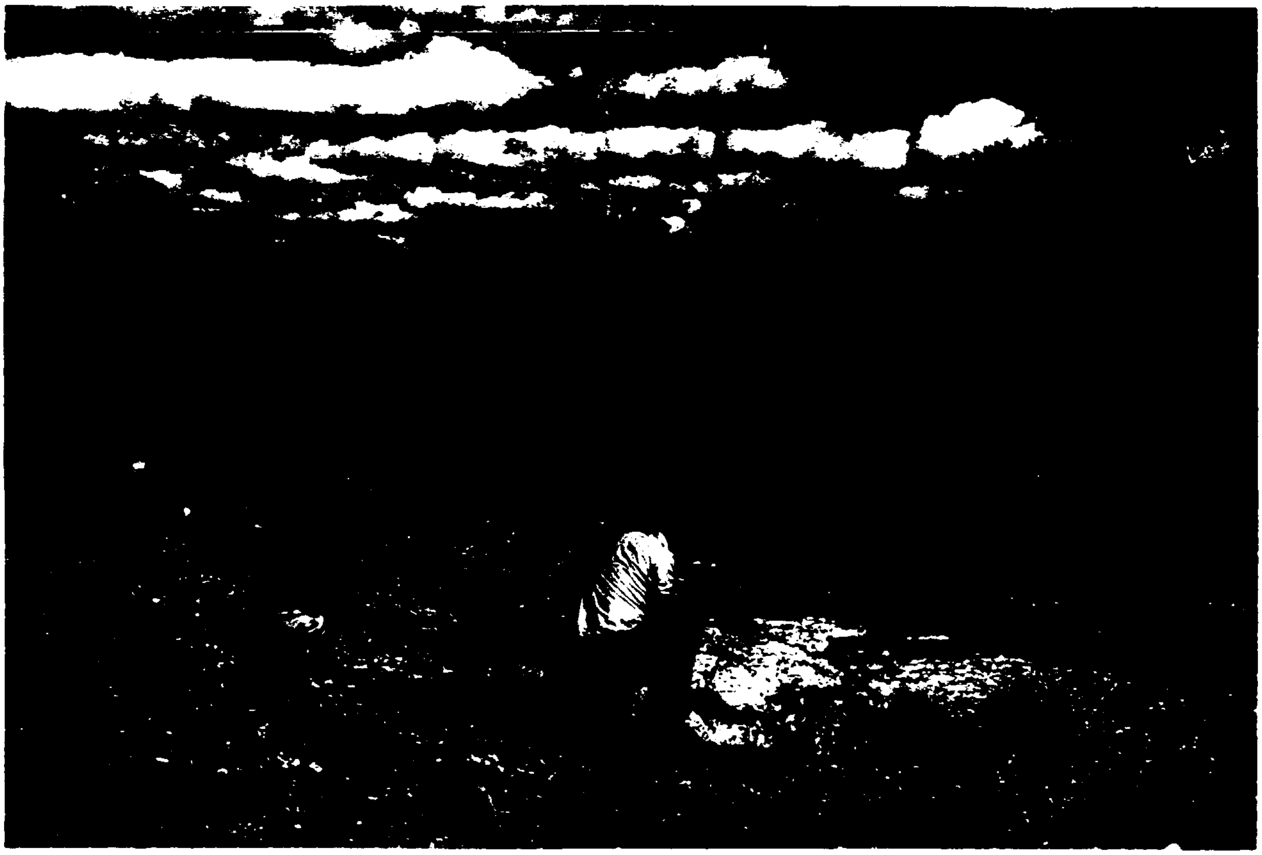

Plate 7. Paling Rockhole

Plate 8. Taranaki donga after a rainstorm

Plate 9. Small solution hole within the man-proof fence at Taranaki

Plate 10. Hole into which water sinks within the man-proof fence - this hole may have been a rabbit burrow initially