FOWLERS GAP ARID ZONE RESEARCH STATION

GEOLOGY, ENGINEERING GEOLOGY AND HYDROGEOLOGY OF FOWLERS GAP STATION

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GEOLOGY, ENGINEERING GEOLOGY AND HYDROGEOLOGY OF FOWLERS GAP STATION

A Contribution to the Evaluation of the Basic and Applied Geology of the Station from the School of Applied Geology, University of New South Wales.

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CHAPTER 1 INTRODUCTION

1. Location and Topography

Fowlers Gap Arid Zone Research Station is located across the Silver City Highway, about 100 km north of Broken Hill, New South Wales. The study described here was undertaken to provide up-to-date information on the geology of the Station, and to collate all of the research carried out in pure and applied geology, on the Station, since 1963. In particular, a succession of extremely dry seasons prompted renewed investigation into the siting of water storages, and the exploitation of groundwater resources. Neither of these investigations could be undertaken, profitably and efficiently, until a reliable geological map of the Station area had been prepared, and the basic geology - lithology, structure, and weathering - properly assessed and understood. It may possibly be argued that the study might have been extended beyond the boundaries of the Station. However, the detail which it was considered would be required precluded this, unless the study were to be extended for an indefinite period.

Apart from the more immediate purposes of the study, it was used to test the idea that it might be possible to develop engineering geology and hydrogeology maps to assist in the location of water storage sites and of productive water bores. If this idea proved to be a possibility, and in fact it has, the technique could be extended from the pilot scale of the Station, to a regional scale, in this part of the Australian Arid Zone.

Topographically, the area consists of three units, corresponding approximately to the main stratigraphic units. The Precambrian areas are hilly uplands with generally gentle slopes and rather broad valleys. In this unit, landforms are controlled by structure and lithology: the more resistant quartzites, limestones and dolomites forming more or less well defined ridges, and the phyllite ("shale") areas being occupied by valleys. The Upper Devonian area is one in which control tends to be lithological, with a dip slope-escarpment type topography, and with occasional mesa-like forms, capped by silcrete. The boundary between the Precambrian and Devonian is, for much of its length, faulted; the boundary fault has had a topographic influence, with stream development strong along the fault. The whole of the eastern sector of the Station is a plain on Quaternary and Tertiary sediments. The boundary between these sediments and the Upper Devonian rocks is frequently marked by aprons of alluvium and colluvium. Overall, the topography tends to be gentle and open.

II. Survey Methods

Since the existing geological map of the Station, at the beginning of the study, was small scale, based on a sketch topographic base map, and the geology itself determined almost exclusively on air photo interpretation with little ground control, complete geological re-mapping of the area was undertaken. The base map used was the Central Mapping Authority, Department of Lands, New South Wales 1:25 000 contour map of Fowlers Gap. Geological mapping for the basic studies was carried out at this scale.

Geological mapping involved air-photo interpretation, followed by field traverses. These were initially east-west at 1 km intervals, although, as the occasion required, traverses were made at much closer intervals, in some cases as little as 50 m, where relationships were critical. Observations were recorded directly onto base maps, but again, where necessary, compass and tape traverses were made. In preparing site maps, compass and tape, and tacheometric methods were adopted. The preparation of the engineering geology and hydrogeology maps was based on the recognition of units, each of which had more or less common engineering (especially water storage engineering) and hydrogeological characteristics. The boundaries of these units often, but not always, correspond to stratigraphic boundaries.

Studies of weathering in the Precambrian rocks were made possible only by the drilling of five diamond drill holes to depths of about 70 to 100 m. All cores were logged in the field, and in the laboratory, and were used for mineralogical, fabric, petrographic and geomechanical study. Three percussion bores were drilled in the Devonian sediments for hydrogeological purposes, and to obtain data on the weathering of these rocks. Cuttings were logged in the field, and examined and tested in the laboratory. Pump tests for aquifer parameters were made in the field on these three bores. Additionally, water from the bores was chemically analysed. Analyses of waters from other bores, from tanks and from streams were carried out during the study.

For a proper examination of the engineering soils, over 30 test pits were excavated on the Station. These were logged, and both disturbed and undisturbed samples taken for laboratory testing. One test cut was made adjacent to Frieslich Dam for the purpose of field testing compaction characteristics of the soil used in the dam. All laboratory tests used standard procedures laid down by the International Association of Rock Mechanics and the American Society for Testing Materials.

III. Previous Studies

The most recent general work in the Fowlers Gap area is the "Geology of the Torrowangee and Fowlers Gap" by Cooper et al (1978). This work, actually completed in 1974, is a regional study, which added little to our knowledge of the Station area. Two points were raised, however, which call for later discussion. These were that the dolomite in the west of the Station is to be correlated with the Corona Dolomite, and that the quartzite of the Frieslich Ridge represents a silicified fault zone. Earlier summaries of the geology, and applied geology of the Station are those of Ward and Sullivan (1973) based largely on previous work by Taylor (1967), Ward, Wright Smith and Taylor (1969) and Wright Smith (1967). The geomorphology of Fowlers Gap has been described by Mabbutt (1973) and the water resources, including hydrogeology, by Bell et al (1973).

Soils of Fowlers Gap were described by Corbett (1973), but this study was largely pedological, and did not consider the soils as engineering materials. Weathering studies of the dolomite (Beavis, 1981), and of the phyllites (Beavis et al, 1982), have been completed recently, while a study of the engineering characteristics of the soils has also been completed (Akpokodje, 1982).

The geological factors involved in the construction of the Frieslich Tank-Dam system were reported by Beavis et al (1978). Results of hydrogeological investigations of the Devonian Sandstones, with particular reference to aquifer characteristics are contained in a thesis by Udofia (1980).

IV. Acknowledgments

Many people, in some way, have contributed to this project. The basic geological mapping was carried out by the authors. Other aspects of the study were undertaken, or supervised, by the senior author. Assistance from the several Officers-in-Charge at the Station has always been given willingly. Staff at the W.S. and L.B. Robinson University College, Broken Hill, have analysed water samples, and members of the School of Geography, University of New South Wales have freely discussed many aspects of the work, especially relating to soils. Special thanks are due to Diane Blank and Marianna Horvath for their meticulous typing and drafting, respectively. Drilling and boring on the Station was supported financially by the Australian Rural Development Fund, the Australian Research Grants Commission and the University of New South Wales.

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CHAPTER 2 STRATIGRAPHY

I. General Statement

Four distinct stratigraphic units are exposed on Fowlers Gap Station:

4. Tertiary-Recent unconsolidated to poorly consolidated sediments, and silcretes, calcretes, and ferricretes.

3. Mesozoic sediments - conglomerates, sandstones and shales.

2. ?Upper Devonian sediments - conglomerates, quartzites, sandstones and shales.

1. Precambrian low and medium grade metamorphic rocks - dolomites, limestones, metaquartzites, phyllites, greenschists and amphibolites.

The Precambrian rocks are in part faulted against the Upper Devonian sediments, in part unconformably overlain by these sediments. Locally, Mesozoic sediments overlie Precambrian rocks with marked angular unconformity; on the eastern boundary of the Upper Devonian, Mesozoic conglomerates, sandstones and shales overlie the Devonian with slight angular unconformity, or with a disconformity.

In assigning ages to the rocks, lithological and field relationship criteria, generally, have been used. A few fossils have been found in the so called Upper Devonian rocks, but these have no real stratigraphic value. Plant fossils, preserved in silcrete near Sandstone Tank have, however, proved to be of considerable value in dating the Tertiary rocks. In assigning Upper Devonian and Mesozoic ages to two of the units, the ideas of previous workers have been followed, since no new evidence of age has been found.

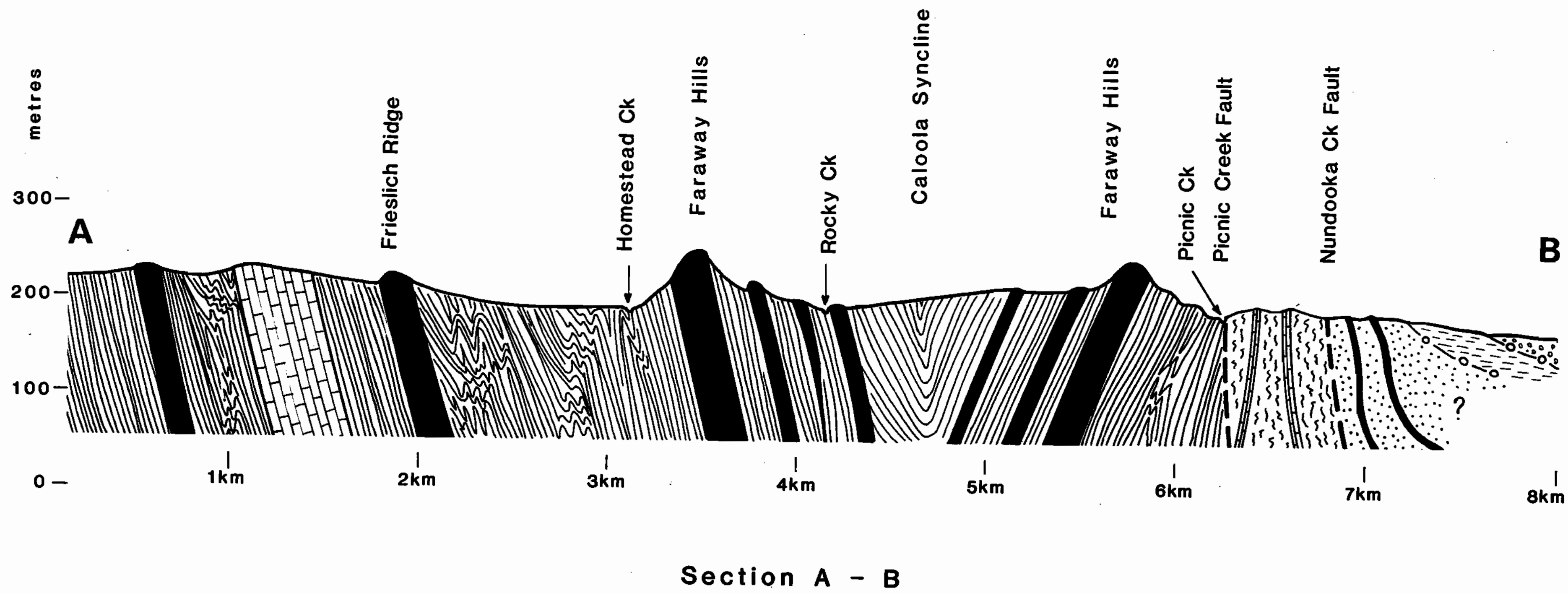

Fig. 1a. Geological cross-section.

The sequence of stratigraphic units is shown on Table 1 and their distribution and relationships, one with the other, are shown on Figure 1, prepared from the 1:25 000 geological map.

II. Precambrian Metamorphic Rocks

As a result of the detailed geological mapping by the authors, the stratigraphic sequence of previous workers (e.g. Ward et al, 1969; Cooper et al, 1978) has been modified. In particular (?)Willyama metasediments and amphibolites have been recognized, while the Frieslich Quartzite and Western Creek Dolomite are given distinct stratigraphic status.

The Picnic Creek Metamorphics, the oldest unit on the Station, is represented by a narrow belt of crushed greenschist and phyllonite, with amphibolite dykes, and several well defined beds of buff coloured crystalline limestone, which are exposed along the eastern margin of the Precambrian belt, in the valleys of Picnic Creek and Conservation Creek. The rocks of this Complex, unlike the other Precambrian metamorphics on the Station, have undergone several periods of folding deformation, and both F_1 and F_2 folds can be clearly distinguished in limestones near Picnic Creek, 1.5 km north of the Silver City Highway, and again in limestones and metaquartzites about 0.5 to 1.0 km south of the Highway, in Conservation Creek.

The Picnic Creek Metamorphics consist of three distinct lithological units: the more easterly unit comprises chloritic phyllites and phyllonites. To the west, this passes into a unit of calcareous phyllites and limestones, with amphibolite intrusions. The most westerly exposed unit is a quartzite with some chloritic phyllite. Detailed relationships are uncertain: more detailed mapping of the formation is required, and is in progress.

The rocks, apart from the complex folding, are intensely crushed, in association with faulting. The relationship to the

TABLE 1

Stratigraphic Sequence at Fowlers Gap

Age	Group	Formation	Member	Approximate Thickness (m)
Quaternary				
Tertiary				100
?Mesozoic		Telephone Creek Sandstone		50
Devonian		Nundooka Sandstone		1,800
		Coco Range Formation		750
Precambrian	Farnell	Fowlers Gap Formation		850
		Faraway Hills Quartzite		100
		Sturts Meadows Siltstone	Frieslich Quartzite Member Western Creek Dolomite Member	100 3,000 400
	?Willyama	Picnic Creek Metamorphics		?

Devonian sediments varies. In the uppermost reaches of Picnic Creek, the Picnic Creek Metamorphics are overlain with angular unconformity by the Upper Devonian Coco Range Formation, which, less than 100 m to the east, is faulted against the Upper Devonian Nundooka Sandstone. Further downstream, near the boundary fence between Connors and South Ridge paddocks, an excellent exposure of the contact is seen, where the Nundooka Sandstone is separated from the Picnic Creek Metamorphics by 50 cm to 1 m of fragmental material dipping 15^{o}W. This relationship has been interpreted as an angular unconformity modified by the Nundooka Creek Fault. On the north side of the Silver City Highway, conglomerates of the Coco Range Formation rest directly on the Picnic Creek Metamorphics, and this relationship was observed to persist to the south for about 3 km.

The relationship between the Picnic Creek Metamorphics and the younger Precambrian rocks is not as clearly exposed, although excellent relationships can be seen at isolated localities, where the Picnic Creek Metamorphics are faulted against the Sturts Meadows Siltstone on the Picnic Creek Fault. The fault comprises 1 to 3 m of completely crushed rock, which dips very steeply east. Both the Sturts Meadows Siltstone and the Picnic Creek Metamorphics are intensely sheared for up to 100 m on either side of the main crush belt.

The recognition of the highly deformed and crushed limestones, greenschists, phyllonites and amphibolites as possible Willyama Complex has been purely on lithological grounds and on the basis of the relationship to the younger Adelaidean Farnell Group of very low grade, simply folded, metamorphic rocks. Whether this correlation is totally justified is uncertain; nonetheless, these rocks are certainly older than the Adelaidean of the area. Multiple deformation has not been observed in the Farnell Group on the Station, apart from localized strain slip cleavage, nor have amphibolites been observed elsewhere on the Station. The greenschists and phyllonites are of a distinctly higher grade than any of the Farnell Group metamorphics.

The Farnell Group is here divided into five units, with the Frieslich Quartzite and the Western Creek Dolomite recognized as distinct lenses within the Sturts Meadows Siltstone. The Group comprises a sequence of marine sediments deposited under varying conditions. The presence of authigenic pyrite in some of the sediments, especially low in the Sturts Meadows Siltstone, suggests a restricted environment. Sedimentary structures are not common: in fact, they tend to be restricted to the upper part of the Fowlers Gap Formation. In this formation, limestones, often graphitic, are associated with highly graphitic phyllitic siltstones, suggesting that the limestones may be of organic origin. The upper part of the Sturts Meadows Siltstone and part, at least, of the Fowlers Gap Formation, are strongly calcareous. Towards the top of the latter, the sediments become coarser and more quartzitic.

The general nature of the rocks indicates quiet conditions in relatively deep water. That shallowing occurred is indicated by the presence of carbonate rocks higher in the sequence, and the coarser texture of the sandy siltstones.

It is possible that the Sturts Meadows Siltstone should be divided into two formations at least, since the phyllites (locally referred to as "shale") to the east of the Frieslich Quartzite, are calcareous; thin beds of limestone occur, and quartzites appear to be absent, while to the west of the Frieslich Quartzite, the phyllites are less calcareous, often dolomitic, and beds of dolomite and quartzite are common. Nonetheless, on a regional scale, these differences might not persist; moreover, field separation is not easy on a formation which, generally, has poor outcrop.

Two bores drilled in the Sturts Meadows Siltstone, as well as exposures in Western Creek, indicated very close minor folding. It is highly probable, in view of this, that the thickness of 3,000 m, suggested in Table 1, is well in excess of the true thickness. It is impossible accurately to determine thickness on the Station, but it is considered that thickness may be closer to 2,000 m.

The Western Creek Dolomite, with a maximum thickness of 400 m, has excellent outcrop on a more or less well defined ridge. Pale fawn in colour, finely crystalline, it is highly silicified in outcrop, although it is known from bores FG1a and FG1 that silicification extends to depths of only a couple of metres. In outcrop, karst features are prominent, and equally prominent are abundant folded veins of quartz. Cooper et al (1978) correlated this dolomite with the Corona Dolomite, and interpreted it as a basement feature. However, both surface exposures and drilling show that it is a conformable unit within the Sturts Meadows Siltstone, having uniform dip and strike with the beds of this formation, and in bore FG2 showing a slow gradation (over about 10 m) into the phyllite on its upper surface.

Despite its prominent outcrop, in common with the other rocks of the area, exposure terminates abruptly on Fowlers Creek, to the south of which is alluvium only. It has been postulated by Bell et al (1973) that a major fault may occur here. Apart from the abrupt termination of rock exposure at the creek, no evidence of faulting was found.

The Frieslich Quartzite, a highly fractured, sometimes ferruginized, belt trending north-south has been referred to by Cooper et al (1978) and by Tuckwell (personal communication) as a silicified fault zone. It cannot be dismissed that the rock is highly fractured, and has undergone considerable secondary silicification. Despite these features, clearing and excavation for the Frieslich Dam exposed a bed of phyllite within the quartzite, and this was traced, although poorly exposed, for several hundred metres north and south of the dam. Both upper and lower surfaces of the quartzite are conformable with the phyllite of the enclosing Sturts Meadows Siltstone. Moreover, a small anticline occurs in the quartzite on the south abutment of the dam. All of these features strongly suggest that the quartzite is a distinct stratigraphic unit. This does not preclude the possibility of strike faulting within the unit.

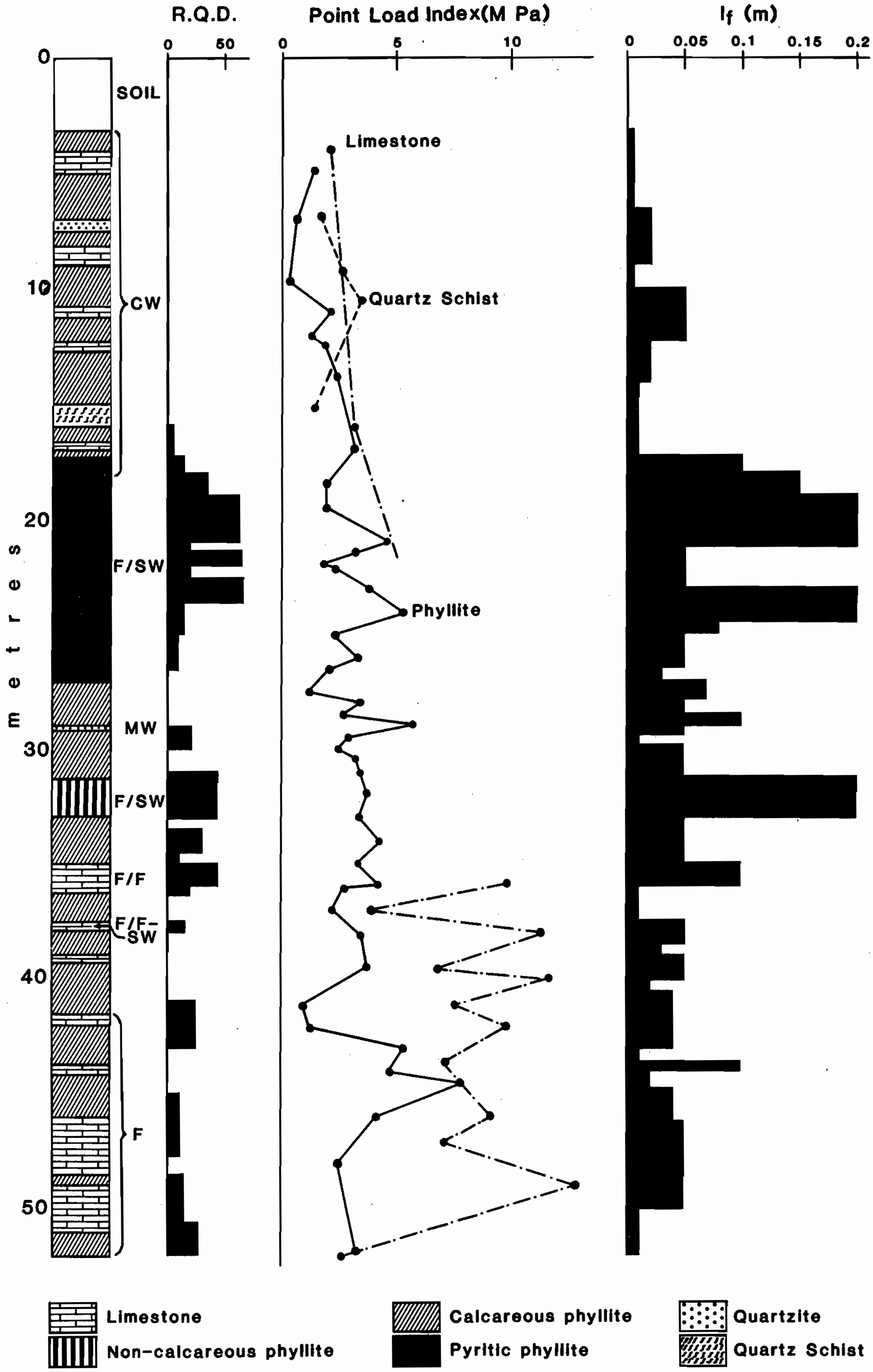

Fig. 2. Lithological log of Bore FG5, Fowlers Gap.

Conformably overlying the Sturts Meadows Siltstone is the Faraway Hills Quartzite, a unit not more than 100 m thick, and probably less, of quartz biotite schist, metaquartzite and thin phyllites. This unit forms a distinct erosion resistant ridge, and constitutes an excellent marker. Outcrop occurs on both limbs of the Caloola Syncline, but the most northerly section is obscured by silcrete and other Tertiary deposits. In the extreme south of the Station, 1 km north of Nelia Dam, the unit is unconformably overlain by conglomerates of the Coco Range Formation which are here overturned.

The uppermost formation of the Farnell Group on the Station is the Fowlers Gap Formation. This consists of a maximum thickness of 3,500 m in the south, but, because of the southerly plunge of the Caloola Syncline, the centre of which it occupies, the thickness in the north is much less. A measured section about 1 km south of the North Homestead - South Ridge paddocks fence gave the following:

Phyllite with thin metaquartzite	240 m
Metaquartzite	75 m
Phyllite with thin metaquartzite	300 m
Metaquartzite*	80 m
Phyllite	160 m
Total	855 m

* This metaquartzite passes along strike to the south into a dark grey crystalline limestone, which persists for 2 km, and then passes back into metaquartzite.

Elsewhere, thin dolomites and limestones occur. Bore FG5, admittedly drilled close to the limestone bed, shows the lithological variation which can occur in the phyllite units, which is not obvious in natural exposure (Figure 2).

III. Upper Devonian Sediments

Two distinct formations of possible Upper Devonian sediments are exposed on Fowlers Gap Station:

Nundooka Sandstone
Coco Range Formation.

The assignment of the Upper Devonian age by Ward et al (1969) appears to have been on the basis of the discovery of scales of *Bothriolepis* in the sandstones. Whether or not this is a reliable indicator of age is uncertain; however it does indicate, together with the nature of the sediments, a fresh water origin for these rocks.

The Devonian sediments occupy the whole of the northerly and north-westerly section of the Station. They unconformably overlie, or are faulted against, the Precambrian metamorphics, and are disconformably overlain by Mesozoic sediments and disconformably and unconformably overlain by Tertiary and Recent sediments.

At the type locality of the Coco Range Formation, outside the mapped area, the sediments are faulted against the Nundooka Sandstone, and overlie unconformably the Precambrian rocks. The sequence for the Coco Range Beds at this locality is:

Quartzose sandstone	180 m
Green-grey to fawn siltstone	1 m
Pebbly sandstones and conglomerates	3 m
Quartzose sandstone	92 m
Pebbly sandstone and conglomerate	185 m
Orthoquartzite	1 m
Quartzose sandstone and orthoquartzite	275 m
Total	737 m

The Coco Range Formation outcrops intermittently along the eastern margin of the Precambrian rocks. Here, due to faulting, much of the sequence is lost, but not uncommonly, the sequence begins with a distinctly conglomeratic bed. At the type locality, the beds are folded into a broad, east plunging anticline on an east-west axis. No folding of these beds was observed elsewhere.

The Nundooka Sandstone is an extremely important unit from the point of view of groundwater resource development, a fact recognized by Bell et al (1973). For this reason, the Nundooka Sandstone has been subdivided into a number of units; however, formal naming and description is not warranted. The sequence is shown on Table 2. Note that this sequence is not fully exposed throughout the Devonian area of the Station; some of the sequence is cut out by faulting, and some is obscured by the cover of younger rocks.

Near the top of the exposed section is a relatively thick white fine sandstone with a distinct fine internal lamination. This rock is strongly current bedded, sometimes shaly. It is conformably to disconformably overlain by Mesozoic (? Cretaceous) grits and conglomerates.

Throughout the sequence, the beds are gently dipping, except near faults, where steep, often almost vertical dips were recorded. Some evidence exists of broad, open folding along east-west axes.

Through the courtesy of Planet Oil, the log of Bancannia South oil exploration well was made available. This is shown, in summary form, on Table 3, together with a tentative stratigraphic correlation. Assuming horizontal dip, the total thickness of the Nundooka Sandstone in this bore is 1,780 m, and of the Coco Range Formation 650 m. This compares with the surface exposures of 1,800 m and 740 m respectively.

TABLE 2

Sequence of Units in the Nundooka Sandstone

Unit	Description	Approximate Thickness (m)	Remarks
G	Sandstone, with white shaly inclusions	500	Aquifer
F	Quartzite	20	Aquiclude
E	Sandstone, minor shale	260	Aquifer
D	Quartzite	50	Aquiclude
C	Sandstone	300	
B	Sandstone	330	Possible Aquifer
A	Sandstone	360^+	

TABLE 3

Summary Log of Bancannia South No. 1 Oil Well and Stratigraphic Interpretation

Age	Formation (Tentative)	Lithology	Thickness (metres)	Depth (metres)
Tertiary - Recent		Sands, clays, gravels	123.75	0-123.75
Lower Cretaceous		Shale	24.38	148.13
		Sand and minor coal	36.58	184.71
		Shale	25.60	210.31
Upper Devonian to Post Devonian		Red shale	22.86	233.17
Upper Devonian	Nundooka Sandstone	Interlaminated siltstone, sandstone and shale	593.15	826.32
Middle to Upper Devonian		Porous sandstone grading to siltstone (Aquifer?)	391.67	1,217.99
		Hard sandstone minor shale	259.08	1,477.07
		Sandstone, minor shale	131.66	1,608.73
		Hard pebbly sandstone, minor siltstone, shale	703.49	2,312.22
		Poorly sorted feldspathic sandstone, minor siltstone	222.51	2,534.73
		Feldspathic sandstone, minor shale	70.10	
	Coco Range Formation	Calcareous sandstone and shale	234.70	2,769.43
		Conglomerate, sandstone and minor shale	21.34	2,790.77
		Thinly bedded quartzitic sandstone - lesser shale	323.10	3,113.87
		Poorly sorted cross-bedded sandstone, minor shale	69.50	3,183.37
		Volcanics	151.50+	3,334.87

Note: The sequence from 210.31 m to 3,183.37 m is known as the "Red Bed Sequence".

It should be noted that, in the field, no direct conformable relationship was observed between the two Devonian formations. In every case, where the two are in contact, the boundary between them was faulted.

IV. Mesozoic Sediments: Telephone Creek Sandstone

Two areas of Mesozoic rocks have been observed. The more extensive occurs on the eastern margin of the Devonian belt, where they are largely overlain by the Recent apron deposits; the smaller, less extensive, generally unmappable at the scale used, and of less certain relationships, occurs beneath Recent and Tertiary sediments at the southern margin of the Sandstone Tank alluvial area.

In both cases, the rocks exposed are conglomerates and grits. In the eastern belt, these overlie Devonian rocks apparently conformably or with slight disconformity. In the Sandstone Tank exposures, they overlie the Precambrian rocks with angular unconformity, and are overlain by Tertiary sediments conformably. Thickness is difficult to determine. The greatest thickness observed was about 15 m. The thickness of the Mesozoic rocks penetrated by the Bancannia No. 1 well was of the order of 85 m.

V. Tertiary Sediments

Like the Devonian, these sediments have some considerable significance as a potential source of groundwater. Planet Camp bore and Mandelman bore exploit aquifers within this sequence. However, without drilling, it is impossible to study these sediments. On the plains, they are covered by Quaternary sediments of uncertain thickness. It is known from the Bancannia No. 1 well that the Tertiary sediments consist of two units:

2. An upper stiff clay, with sandy to gravelly lenses and beds, and, towards the base, swelling clays: 75 m

1. A lower clay, interbedded with coarse sand with lignitic material and bands of dolomitic material in the clay: 20 m

It is the gravel and sand beds which constitute the aquifers.

The silcrete cappings which occur mainly in the north of the Station are of Tertiary age. Plant fossils of the Cinnamomum flora preserved in the silcrete south of Sandstone Tank indicate clearly the age of this material. It is likely that the sands, clays and gravels beneath the silcrete in this area are also of Tertiary age. They show less compaction than the underlying Mesozoic remnants.

VI. Quaternary Sediments

These constitute four main groups:

1. The extensive plains deposits in the west of the Station area;

2. The pediment like deposits on the western margins of the plains, and which grade into the finer textured deposits of the plains;

3. Isolated areas of alluvial deposits such as those of Sandstone Tank and Gap Creek paddock.

4. Stream deposits in stream beds and forming occasional terraces.

No purely aeolian deposits of sand or silt occur.

The most extensive of the Quaternary sediments are those of the plains. At the surface these tend to be finer textured types which become coarser to the west. The pediment-like sediments are bouldery to gravelly sandy types, while the isolated areas of alluvial sediments are fine textured silty sands. The stream bed and terrace sediments are sandy, with boulders and gravels.

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CHAPTER 3 STRUCTURAL GEOLOGY

I. General Structural Statement

Four major structural features dominate: the Caloola Syncline; the Nundooka Fault; the Picnic Creek Fault; and the Precambrian-Devonian unconformity which is modified by the Nundooka Fault. Apart from these major structures, smaller scale folding and faulting are characteristic of the Precambrian rocks, while all of the Precambrian and Devonian rocks are quite intensely jointed.

Because of the importance of structural defects in the various rocks in relation to engineering geology and hydrogeology, the study of such features as bedding planes and joints has been somewhat detailed. Faulting, and folding, while of some importance, generally do not have a significant role in the applied geology of the Station. However, for completeness, these structures have been studied as an essential part of the basic geology.

II. Folding

The Caloola Syncline, developed in the Farnell Group metamorphics, is a relatively symmetrical, south plunging structure. Measurements of lineations give consistent plunges of from 5^{o} to 12^{o}S. The dip of beds on the limbs averages 65^{o}, but dips of from 30^{o} to 90^{o} have been recorded, with dips S at 10^{o} in the hinge zone of the fold. The hinge line of the fold trends a few degrees east of south, with minor variations usually associated with transverse faults. The style of the fold is similar.

On the limbs of the fold, minor folds are common, especially in the less competent phyllites. These folds, in general, have the same plunge as the main fold, and are

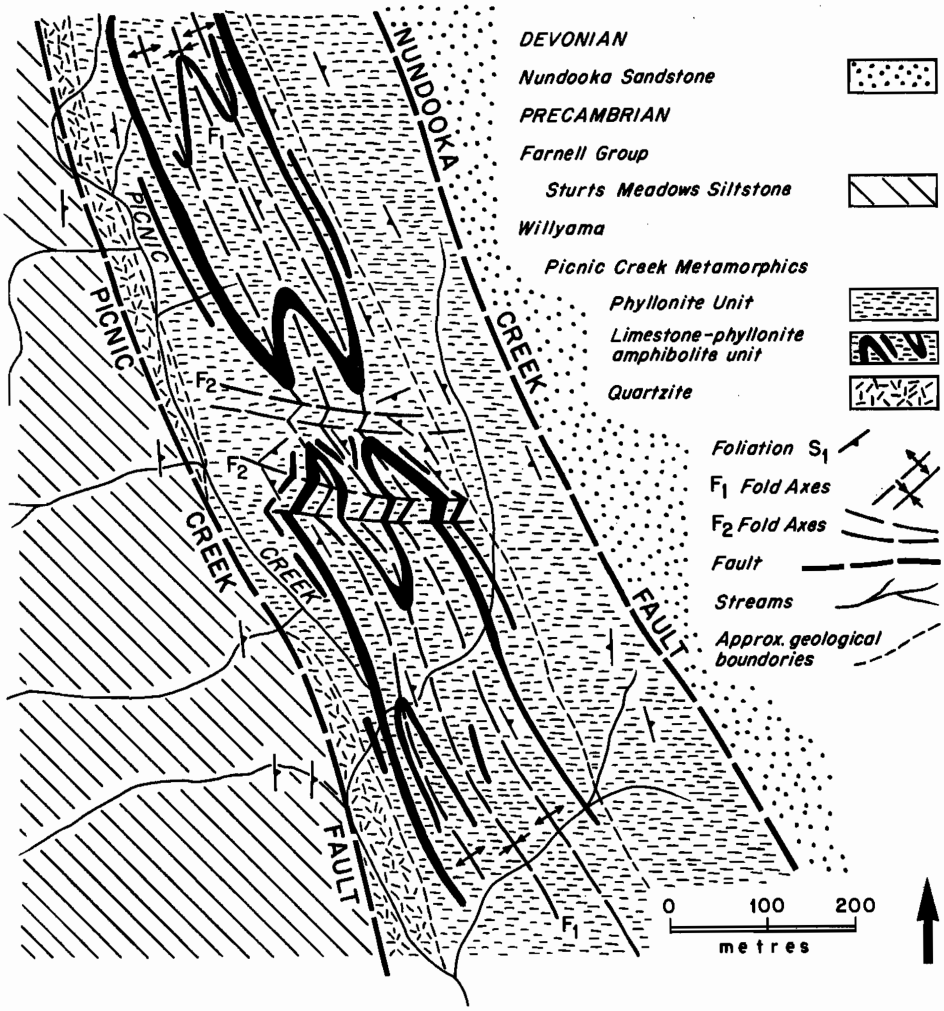


Fig. 3. Folding in Picnic Creek Metamorphics near Picnic Creek.

symmetrical, with similar style. Throughout the pelitic rocks, slaty cleavage is highly developed, parallel to the axial surfaces of both the minor folds and of the main syncline. Within some of the impure quartzites and quartz schists, a fine schistosity, parallel to the slaty cleavage of the phyllites, has been developed, apparently due to the preferred dimensional orientation of the fine micas and of the quartz grains. All of the rocks involved are strongly lineated, even the limestones, which suggests a definite preferred orientation of the calcite crystals.

No convincing evidence of more than one period of folding was found in the Farnell Group rocks. Some localized strain slip cleavage, making an angle with the slaty cleavage was observed in bore core from bores FG2 and FG3, and in several surface outcrops. This cleavage has produced lineations on bedding planes and slaty cleavages which have orientations different from those of the lineation associated with the main folding. These obviously superposed planar and linear features are quite localized, and are certainly not penetrative on more than sub-mesoscopic scale.

The Picnic Creek Metamorphics tentatively correlated here with the Willyama Complex have certainly undergone at least two folding deformations. However, because of the restricted outcrop, no attempt could be made to correlate either of these with the folding of the Farnell Group rocks. The folding of the Picnic Creek Metamorphics is quite complex (Figure 3); F2 folds, which have amplitudes from a few cm to 10 m are clearly recognized, especially when thin limestone and quartzite beds are involved.

Folding in the Upper Devonian sediments is generally broad and open. In the Coco Range area, the Coco Range Formation is folded into a broad, gently east-plunging syncline, with dips of about 20^{o} on the limbs. A weak east-plunging anticline has been developed on an east-west axis

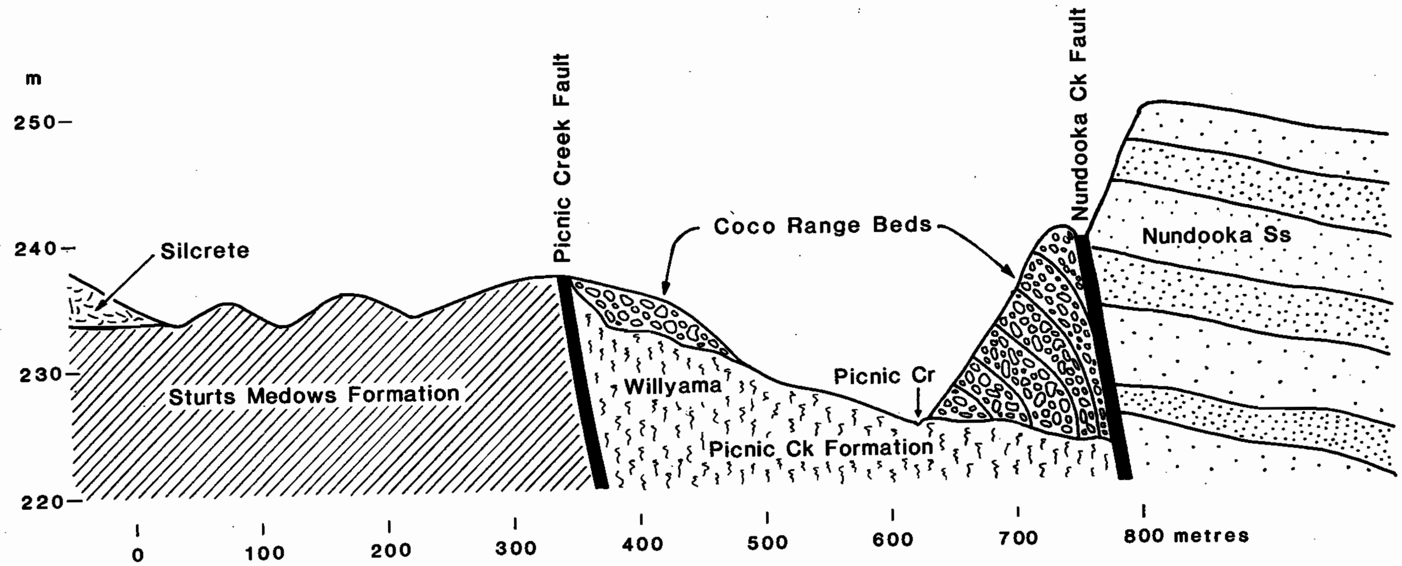


Fig. 4. Geological cross-section, Nundooka Creek Fault, in the headwaters of Picnic Creek.

east of Sandstone Tank. Here dips may be as low as 10^{o}. In general, dips in the Devonian sediments are low - 20^{o} or less, except near the Nundooka Creek Fault, where drag has induced dips of 60^{o} to 90^{o}, with local overturning of beds.

III. Faulting

The Nundooka Creek Fault is one of the major fault structures of the area. The description of this structure as a normal fault, with downthrow to the east, by Ward et al (1969) is an oversimplification, since at several localities, notably in the Picnic Creek area, clear evidence of localized low angle thrusting on the fault has been obtained. Where the fault zone is clearly exposed in the headwater region of Picnic Creek, it consists of several metres of fragmental ironstone, with an easterly dip of about 80^{o}. Dips in the Coco Range Formation steepen from 20^{o}-30^{o}E in the Creek to 80^{o}E in the saddle in which the fault zone outcrops. The Nundooka Sandstones, abutting against the fault dip 20^{o}E (Figure 4). Further downstream in Picnic Creek, the fault forms the boundary between the Picnic Creek Metamorphics and the Devonian sediments. Here the fault has near vertical dip, as do the beds of the Nundooka Sandstone. However, the fault is modified by low angle (15^{o}) thrusting.

The Picnic Creek Fault, which forms the boundary between the Picnic Creek Formation and the Sturts Meadows Siltstone is a north-south steeply east dipping structure, marked by 1 to 3 m of completely crushed phyllite and phyllonite. This structure is tentatively interpreted as a high angle thrust. It has been traced from the headwaters of Picnic Creek, south for some 7 km, when it is overlain by sediments of the Coco Range Formation. Its age is clearly pre-Devonian and post-Adelaidean.

Other faults, some of them of considerable magnitude and importance, have been mapped. These are mainly NW-SE striking structures, with a significant component of horizontal movement along them. The Gap Creek Fault is a NW-SE fault, marked by crushed quartzite, crushed dolomite and ironstone breccia, along which strike slip movement has caused displacement of the Frieslich Quartzite and Western Creek Dolomite to the west, on the south wall of the fault, by some 850 m. The Faraway Hill Fault, a north-south structure, has produced a repetition of the Faraway Hills quartzite by upthrust movement to the west. The fault is a high angle structure, dipping about 80° to the east.

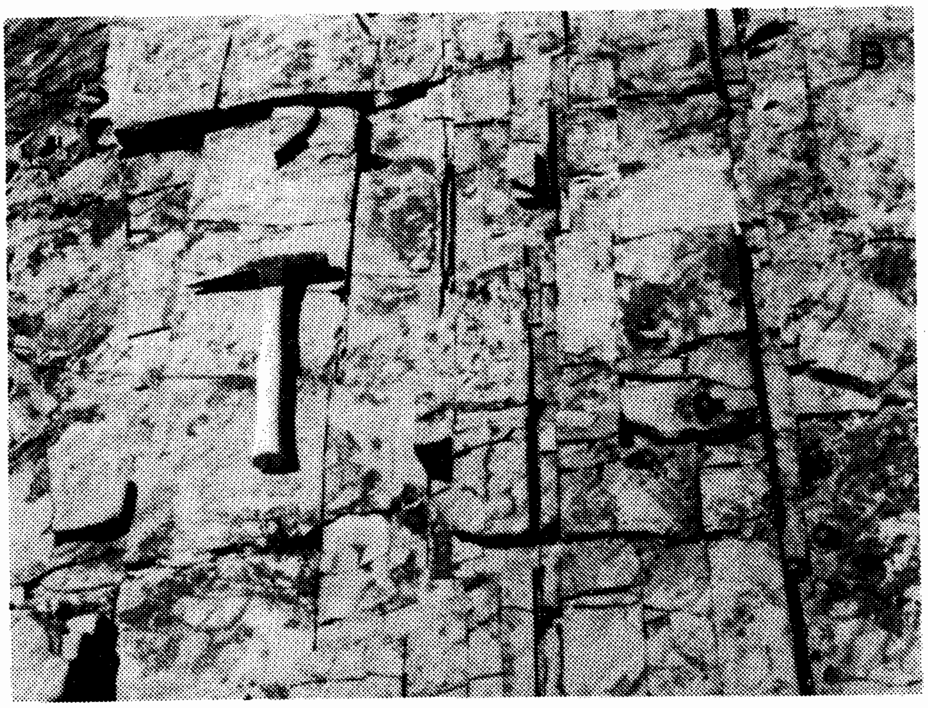
The Faraway Hills Quartzite on the eastern limb of the Caloola Syncline is terminated in the south by the Nelia Fault and Warren Fault which have produced a dextral rotation in the beds of the Fowlers Gap Formation. Little is known of these structures. On the same limb of the Caloola Syncline, but in the northern sector, a small fault has displaced the Faraway Hills Quartzite by about 100 m, and is probably responsible for the broad, open cross folds produced nearby.

Minor faults are numerous; many can be observed in outcrop with displacements of only a few cm; others have displacement of the order of tens of metres. The more important of these are shown on Figure 1.

Bell et al (1963) postulated a major fault in, or close to, Fowlers Creek, in the south western sector of the Station. No evidence of this postulated fault could be found, either in the field or on air-photos. It is difficult to explain the sudden termination of such prominent, erosion-resistant, units as the Frieslich Quartzite and Western Creek Dolomite without recourse to faulting. It is preferred, however, to avoid ascribing this outcrop feature to the effects of faulting unless, and until, some evidence is obtained.

Fig. 5. Photographs of joints in two lithological types in the Fowlers Gap Formation:

(a) Close jointing in calcareous phyllite - note also bedding and cleavage.



(b) ac joints in phyllite.

IV. Jointing

Jointing is a feature present in all of the Precambrian and Devonian rocks. Spacing and orientation are very much a function of lithology, so that, in a sequence of varying lithologies, such as occurs in the Fowlers Gap Formation, the pattern of the joint system, and the fracture spacing index, vary considerably (Figure 5). The structural analysis of the joint system is further complicated by the development of weathering fractures, especially in the more crystalline rock types such as dolomite, limestone and quartzite.

Joints in the Precambrian rocks comprise a general system with sets striking 50°, 60°, 145° and 165°. These are all very steeply dipping; flat, near horizontal joints also occur. Spacing varies from 0.1 m to 1.5 m; but overall, the most frequent spacing is from 0.1 m to 0.2 m. The most closely spaced joints are those with a 60° trend in the quartzites, where the spacing is almost invariably less than 0.2 m and may be as low as 0.05 m.

In the Devonian sediments, the system comprises three dominant sets of steeply dipping to vertical joints, with strikes 90°, 100° and 120°. Flat joints also occur, while locally sets with strike 50°, 110°, and 140° are prominent. Joint spacing is fairly consistent at from 0.1 to 0.4 m, although, near the Nundooka Creek Fault, jointing is much more closely spaced, and much more complex in pattern.

Continuity of joints in the Precambrian rocks is difficult to determine, but certainly the more prominent structures can sometimes be traced, if outcrop is good, for from 50 to over 100 m. On the other hand, continuity is much less in the Devonian sediments, where, on the average, an individual joint can rarely be traced for more than 15 or 20 m.

The development of joints in both groups of rocks is clearly the result of tectonic stresses, with later weathering fractures superimposed on the tectonic system. Weathering processes have been responsible for the open condition of joints in surface exposures. Weathering along joints has been found to depths of up to 80 m. The tectonic joints bear a definite geometric relationship to folding and faulting; on this basis, a similar genesis is assumed. The dominance of easterly-westerly joints in a fold and fault system which is north-south in orientation points to the tensile nature of these joints. Those with NE-SW and NW-SE strikes are clearly shear structures, and these frequently carry slickensides.

The study of jointing presented here has, of necessity, been general. Much more detailed study is required at any water storage site, while detailed study of the joint system for the whole of the Devonian area is essential, since Udofia (1980) regards jointing in these rocks as being the most important structures controlling the movement of groundwater. This is probably the case, also, for the Precambrian rocks, but Hussein (1975) suggested, while drilling has confirmed, that groundwater development of these rocks would not be an economic undertaking.

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CHAPTER 4 PETROLOGY

I. Precambrian Metamorphic Rocks

The narrow inlier of the Picnic Creek Metamorphics consists of greenschists and phyllonites, with thin impure metaquartzites, and thin limestones, intruded by small bodies of amphibolite. All of the rocks show evidence of shearing; in particular, the greenschists are frequently phyllonitic. The limestone is very fine textured, with crystal size less than 0.01 mm. The rock is sheared, with fine shear planes spaced at 1 mm; these constitute axial planes to microscopic folds in veins of coarser secondary calcite. The impure metaquartzite has a greywacke-like texture, with rounded to highly angular grains of quartz, often poikiloblastic, lesser plagioclase, and rare microcline and white mica, in a very fine matrix of calcite and sericite. Shearing is evident, with the larger grains elongated in the plane of shearing. All of the feldspars and quartz exhibit strain polarization, while the feldspars are frequently fractured. The greenschist is an extremely fine grained aggregate of chlorite and quartz, with very rare fine, indeterminate feldspar. A very fine, completely penetrative foliation has been imposed.

Amphibolites are very coarse textured; they consist primarily of hornblende and abundant ilmenite with lesser twinned plagioclase in the range An_{50} to An_{90}. Much of the hornblende is replaced by pale green chlorite in the exposed material, while large crystals of secondary calcite may be present. Le Couteur (1977) recognized two types of Willyama Complex amphibolites: those with garnet, and those without garnet. The amphibolites examined are of the latter type. Much of the alteration observed in near-fresh material appears to be the result of retrograde metamorphism rather than to weathering.

All of the rocks of the Picnic Creek Metamorphics exposed at Fowlers Gap show strong evidence of shearing and, to some degree, of retrograde metamorphism. The belt exposed almost certainly constitutes part of a major shear zone in which shearing postdated the F2 folding.

Within the Sturts Meadows Siltstones, the original siltstones, shales, sandstones, quartzites, limestones and dolomites have undergone low grade regional metamorphism, raising them to the Chlorite Zone. The pelitic rocks are very strongly foliated by a fine, microscopically penetrative slaty cleavage. In some cases, a fine, later strain slip cleavage has been imposed locally. All of the pelitic sediments tend to be either calcareous or dolomitic; the former occur to the east of the Frieslich Quartzite, the latter to the west. In the fresh condition, the pelitic rocks consist of quartz, feldspar, sericite, chlorite, primary calcite and/or dolomite, and, in one recorded case, a vermiculite-like clay mineral. Certain beds are distinctly pyritic, and others are relatively rich in magnetite. Graphite is occasionally present.

Both the dolomites and limestones are very fine textured rocks, which, in the hand specimen may show evidence of cleavage, but this is not always apparent in thin section. The dolomites contain abundant secondary quartz, and occasionally some secondary calcite. Very occasionally, pyrite occurs in the limestone.

The metaquartzites are relatively coarse textured, with grain size up to 2 mm or more. They consist almost exclusively of quartz, with very rare feldspar, rarer tourmaline, and some sericite.

The rocks of the Faraway Hills Quartzite are quartz schists with thin beds of quartzite, which is indistinguishable from the quartzites of the Sturts Meadows Siltstone, but which differs sharply in texture from the Frieslich Quartzite, which is exceptionally fine grained. Unlike the quartzite, the quartz schist is strongly foliated, with equidimensional and elongated grains of quartz, and equidimensional grains of feldspar, An_{70}-An_{90}, and microcline. The elongated grains are oriented dimensionally in the plane of foliation. These larger grains are set in a very fine matrix of elongated quartz and very rare feldspar. Margins of the larger grains tend to be sutured. Pale green chlorite occurs rarely, and detrital tourmaline may be present.

The Fowlers Gap Formation consists of finely laminated phyllitic shales and siltstones, limestones, dolomites, quartzites and sandstones. Within some of the sandstone units, slump breccias occasionally occur. Several features are of importance in this Formation: the rocks are low grade (Chlorite Zone) metamorphics, with locally a strong development of pyrite and graphite, usually associated with strongly calcareous metapelites, meta-arenites, and limestones. Throughout, all of the rocks are calcareous to varying degrees. The dolomites differ from those of lower formations in their darker colour.

The quartzites are composed almost exclusively of quartz, with rare sericite. The texture is generally considerably finer than that of the quartzites of the Faraway Hills Quartzite. The limestones, however, are coarser textured, and in some cases contain large areas (up to 5 cm^2) of black calcite, which owes its colour to graphite.

All of the pelitic rocks consist of very fine chlorite, sericite and quartz, with, in some cases, abundant graphite. Calcite is almost invariably present. The fine penetrative cleavage is perfectly developed, and where large porphyroblasts of calcite occur, these are elongated in the plane of foliation. The pure pelites often grade down into semipelites, with numerous equidimensional to elongated grains of quartz. These metasediments may contain lenticular plates of strongly pleochroic, very pale fawn mica.

The texture is frequently almost mylonitic, with closely spaced shears (0.5-1.0 mm) which curve around the quartz, and around the calcite aggregates, which are lenticular. Authigenic pyrite occurs in both the pelitic and arenaceous rocks as anhedral to euhedral crystals up to 3 mm long. Sandstones, invariably, are strongly calcareous, with equidimensional to elongated grains of quartz and feldspar (and occasionally calcite) in a quartz-sericite-calcite matrix. A coarse foliation has been developed.

The nature of the sedimentary sequences, and the lithologies, suggest strongly a marine origin for the Farnell Group rocks. The abundance of graphite suggests the presence of carbonaceous organisms. Most of the calcite and of the pyrite appears to be of primary origin, although both secondary pyrite and secondary calcite occur. The metamorphism, associated with the folding, has not been severe, the rocks being raised only to the Chlorite Zone. Locally, more intense movement has produced mylonitic textures, sometimes with pressure fringes developed on the harder minerals such as magnetite and pyrite. These pressure fringes are not restricted to rocks with a mylonitic texture, but have been observed in the phyllites of the Sturts Meadows Siltstone where mylonitic textures do not occur (Beavis, Roberts and Smith, 1982). The presence of mylonitic textures in well defined zones, as for example near the hinge of the Caloola Syncline, points to localized areas of more intense deformation. Scope exists for a much more detailed study of the petrography and petrology of the metamorphic rocks than has been warranted here.

II. Upper Devonian and Mesozoic Sediments

Apart from basal conglomerates, these sediments are dominantly sandstones, with very rare shales and siltstones, and with two prominent units of orthoquartzite in the Nundooka Sandstone, and one in the Coco Range Formation. The conglomerates consist of rounded pebbles of quartzite in a sandy to silty-sandy matrix. The sandstones, in the fresh condition, are white in colour, but are pale fawn to dark reddish-brown when weathered. They are generally well sorted, although, near the upper surface of some of the beds, sorting is poor. Values obtained for effective size range from 0.003 to 0.018, with uniformity coefficients varying from 1.88 to 62.5. For three separate beds examined in detail, the following values were obtained:

a) Effective size 0.03-0.085, Uniformity coefficient 1.53-1.88
b) Effective size 0.006-0.048, Uniformity coefficient 4.69-10.7
c) Effective size 0.0026-0.018, Uniformity coefficient 8.61-62.5

Further details are shown on Table 4. The influence of effective size on hydrological parameters is discussed in Chapter 7.

The sandstones are composed essentially of quartz and feldspar, both occurring as angular to subangular and rounded grains, and displaying a fine network of microfractures, cemented by limonite stained clay minerals in the weathered rock, and by white clay minerals in fresh rock. Occasional rare flakes of pale brown mica occur, and tourmaline is a relatively abundant accessory. The quartz and feldspar grains lack the strain characteristics which these minerals exhibit in the Precambrian rocks; the derivation from these, of the Devonian and Cretaceous sediments, is therefore extremely unlikely. On the other hand, the highly angular nature of the grains suggests transport over only a short distance. Another important aspect is the apparently total absence of calcite, which is a significant constituent of most of the Precambrian rocks of the area. The orthoquartzites are medium grained, with angular to subangular and rounded grains of quartz which show secondary enlargement cemented by very fine quartz. Again the quartz shows none of the characteristics of this

TABLE 4

Effective Size and Coefficient of Uniformity of some Nundooka Sandstones

Sample No.	Sample Interval (m)	Effective Size (D_{10})	Coefficient of Uniformity (Cu)
NSB1-1	0-1	-	-
17	44-45	0.038	4.21
38	97-98	0.035	4.14
39	101-102	0.04	3.75
43	110-112	0.085	1.88
50	123-125	0.03	5.33
NSB2-1	0-0.5	0.006	30.8
16	43-44	0.032	4.69
33	98-99	-	-
35	103-104	-	-
39	110-111	0.013	10.7
43	119-120	0.048	3.54
NGB1-1	0-1	0.004	62.5
26	84-85	0.0026	61.54
27	85-86	0.018	9.17
35	101-102	0.018	8.61
40	114-115	-	-
42	124-125	-	-

mineral in the Precambrian rocks. Feldspar is very rare, and detrital tourmaline is sometimes present.

III. Tertiary Silcrete

The silcrete is grey in colour, and consists of fine grains of quartz, often with strain characteristics, in a cryptocrystalline matrix of silica. Occasionally, pebbles of quartzite are included in the silcrete. The fossiliferous silcrete is much finer textured and appears to be largely cryptocrystalline silica.

The silcretes, and the much rarer ferricretes, are clearly of duricrust origin, although one occurrence of a subsurface ferricrete (Beavis, 1981) has been recorded. Subsurface silcretes were not observed on the Station.

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CHAPTER 5 ROCK WEATHERING

I. General Statement

Recent, very detailed, studies of rock weathering on the Station have been completed. In particular the dolomites, the pelites of the Sturts Meadows Siltstone, the calcareous pelitic and arenaceous rocks of the Fowlers Gap Formation, and the Nundooka Sandstone were examined with respect to the mineralogical and fabric changes which accompanied weathering. At the same time, the effect of weathering on the engineering properties of the rocks was studied, and engineering classifications proposed. Since the published research is readily available, only brief summaries will be included here. Because the main purpose of the geological work reported here was to serve as a basis for engineering geology and hydrogeology, weathering profiles are discussed primarily in engineering geological terms. Representative samples are preserved in the collections of the School of Applied Geology for reference by workers whose interests lie elsewhere.

II. Climate and Weathering

One important fact to note is the relatively great depth of weathering. This may possibly reach 100 m, but averages about 50 m. A second important fact is that the weathering of the rocks has been determined not only by present and past arid climates, but also by past humid climates. Considerable evidence of humid weathering has been obtained from the mineralogy of the weathered rock. The age of the weathering is uncertain. Bowler (1976) has shown that, during the Quaternary, several periods of humid climatic conditions occurred interspersed with arid periods. However, it seems likely that the weathering profile at present in existence on the Station, dates back to Tertiary

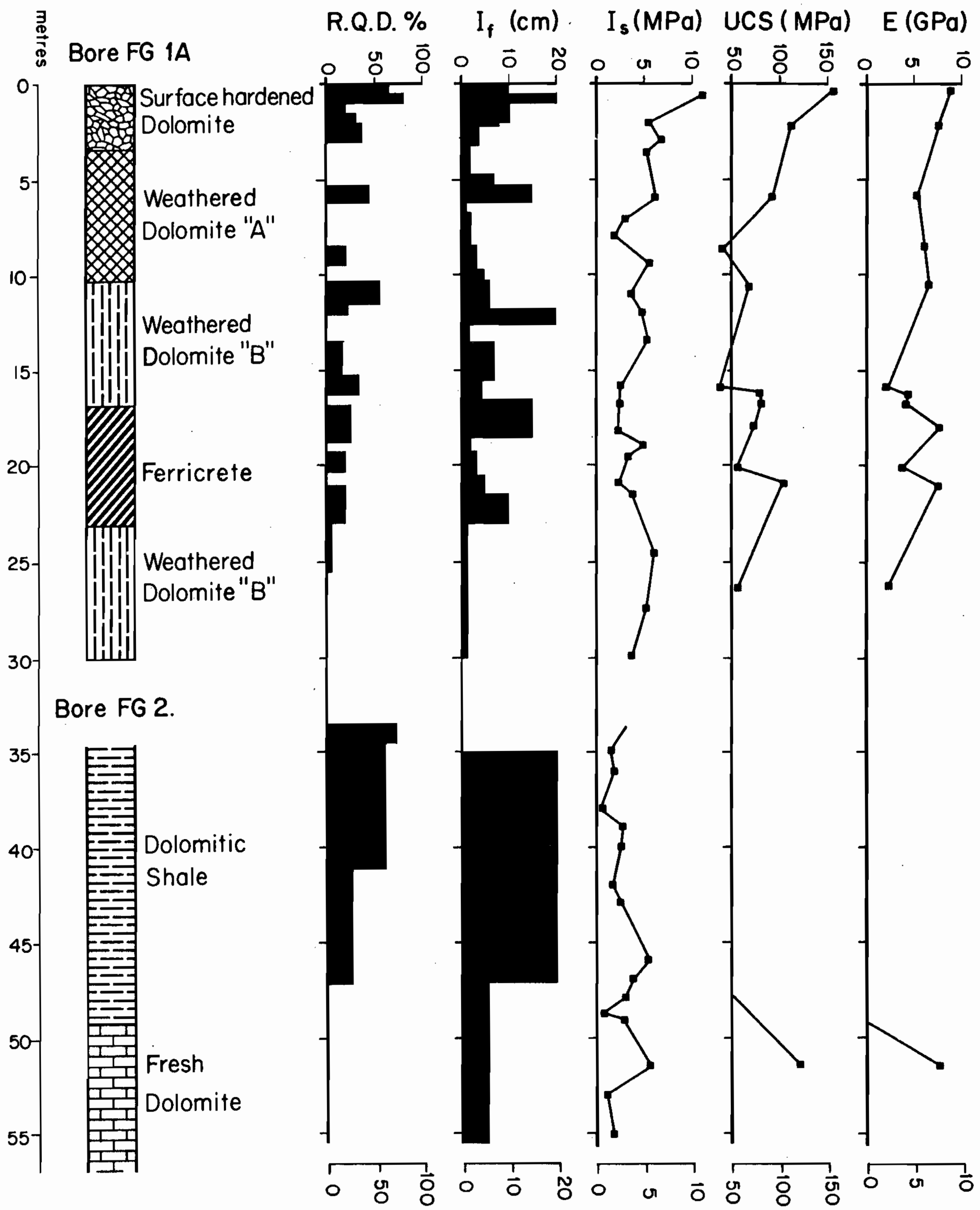

Fig. 6. Weathering profile, Western Creek Dolomite.

times, as evidence of which is the existence of the Tertiary silcretes and ferricretes. These imply quite humid conditions for much of the period of weathering. Since lower Tertiary sediments occur, sometimes beneath the silcrete, it is suggested that the weathering probably dates from the Upper Tertiary.

It is believed, then, that weathering has been in progress since Upper Tertiary times under alternating arid and humid conditions. Under these circumstances, the sometimes unusual and complex weathering profiles developed are not unexpected. In some profiles it has proved to be possible to distinguish between the effects of the two climates. In other profiles, such a distinction is difficult or impossible.

III. Weathering Profiles and Patterns

One of the most unusual weathering profiles observed on the Station has been developed on the Western Creek Dolomite. This is shown on Figure 6, which is based on bores FG1, FG1a and FG2. The profile comprises two major units: Weathered Dolomite and Fresh Dolomite. However, the former can be divided into four sub-units or horizons; with a total thickness of weathering of about 50 m:

Surface hardened dolomite		3.30 m
Weathered dolomite	Type A	6.80 m
	Type B	6.65 m
Ferricrete		6.30 m
Weathered dolomite.	Type B	7.45 m+
Fresh dolomite.		

Surface hardened dolomite represents surface and near surface weathered rock - probably originally completely weathered - which has undergone surface silicification, almost certainly during the period when the silcretes of the area were developed. The silicified, surface hardened dolomite is composed of dolomite, illite, mixed layer clays, and kaolinite, with extremely fine quartz replacing much of the dolomite.

The ferricrete occurs as a distinct subsurface horizon, with sporadic outcrop, indicating its development before the present erosion. It is probably of similar age to the silcretes and surface silicification. The ferricrete consists of irregular fragments of dolomite set in a cement of goethite, hematite, amorphous iron oxides, illite, chlorite, kaolinite and quartz.

Weathered dolomite of both types A and B consist of dolomite, quartz, calcite, together with illite, mixed layer clays, occasional kaolinite, and goethite, hematite and chlorite. The only distinction between the two types is based on the darker colour of type A, due to a somewhat higher concentration of iron oxides. That type B occurs above and below the ferricrete suggests leaching of the iron oxides from the type B horizons with accumulation of these oxides in the ferricrete.

Within the fresh dolomite, the main constituents are dolomite, with quartz and calcite. Illite is relatively common and may indicate some slight chemical weathering even in the apparently fresh rock. Potash feldspar is a rare constituent. In the apparently fresh rock, small solution cavities also occur. Such cavities are found throughout the weathering profile, while the rock, in outcrop, displays karst features.

Any soils developed on the dolomite are thin and stony, except on slopes, where a distinct profile is developed.

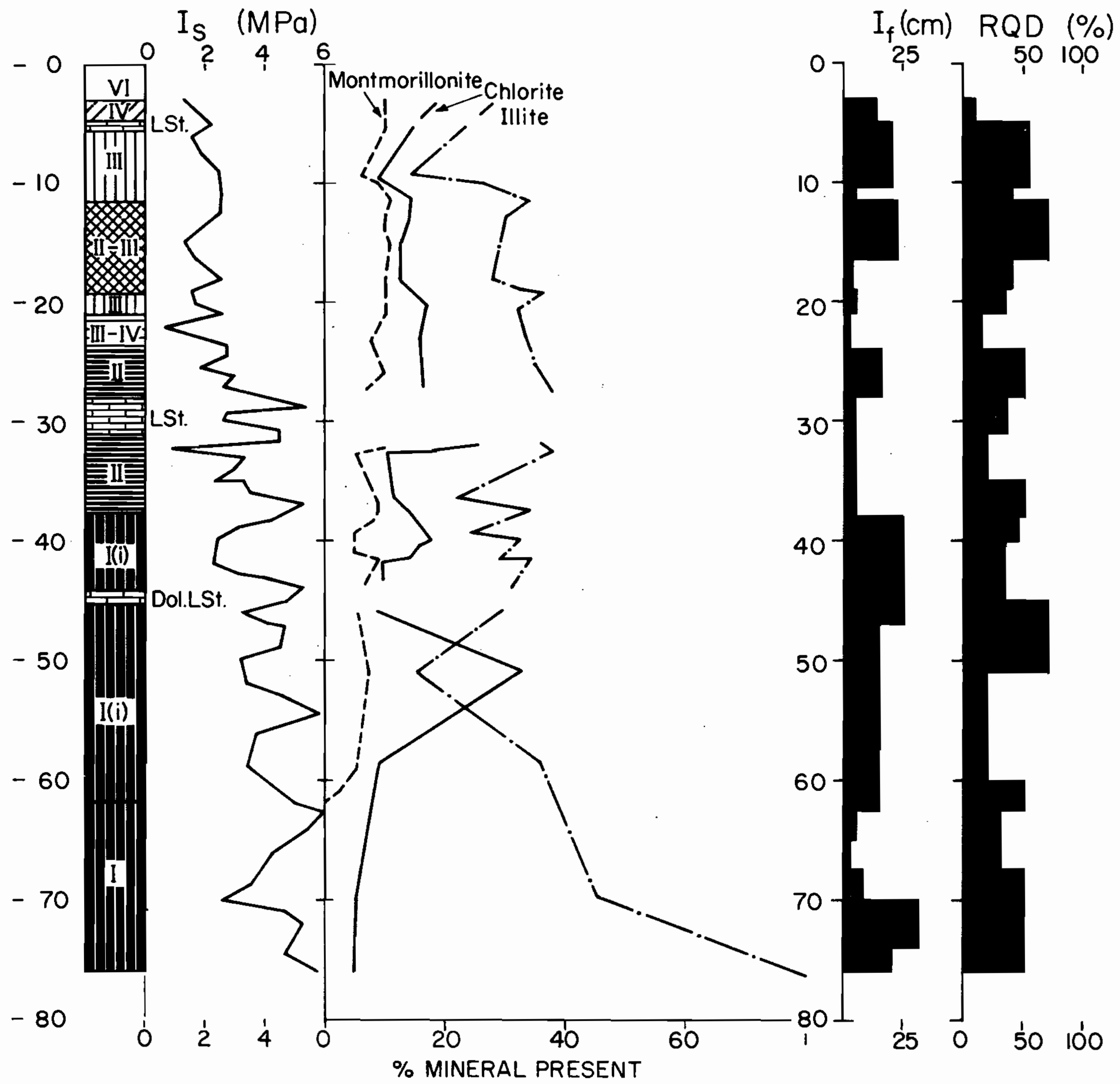

Fig. 7. Weathering profile, Sturts Meadows Siltstone, Unit Elb.

These soils, however, are to be regarded largely as colluvial, rather than residual types.

The profile of weathering in the Sturts Meadows Siltstones varies. In the calcareous rock to the east of the Frieslich Ridge, the profile is:

Soil	3.0 m
Highly weathered rock	2.5 m
Moderately weathered rock	5.5 m
Moderately to slightly weathered rock	9.0 m
Moderately weathered rock	2.0 m
Moderately to highly weathered rock	2.5 m
Slightly weathered rock	14.5 m
Essentially fresh rock	11.5 m
Fresh rock	

The total thickness of the weathered zone is a little over 60 m (see Figure 7).

In the dolomitic phyllite to the west of Frieslich Ridge the profile is:

Soil	5.0 m
Completely weathered rock	5.0 m
Highly weathered rock	3.0 m
Moderately to highly weathered rock	6.5 m
Slightly weathered rock	3.0 m
Moderately to completely weathered rock	5.5 m
Moderately weathered rock	4.5 m
Slightly weathered rock	2.3 m
Essentially fresh rock	15 m+

The total thickness of the weathered zone is about 50 m (see Figure 8).

Since montmorillonite was recorded in the fresh rock, it is perhaps better to regard this as essentially fresh, so

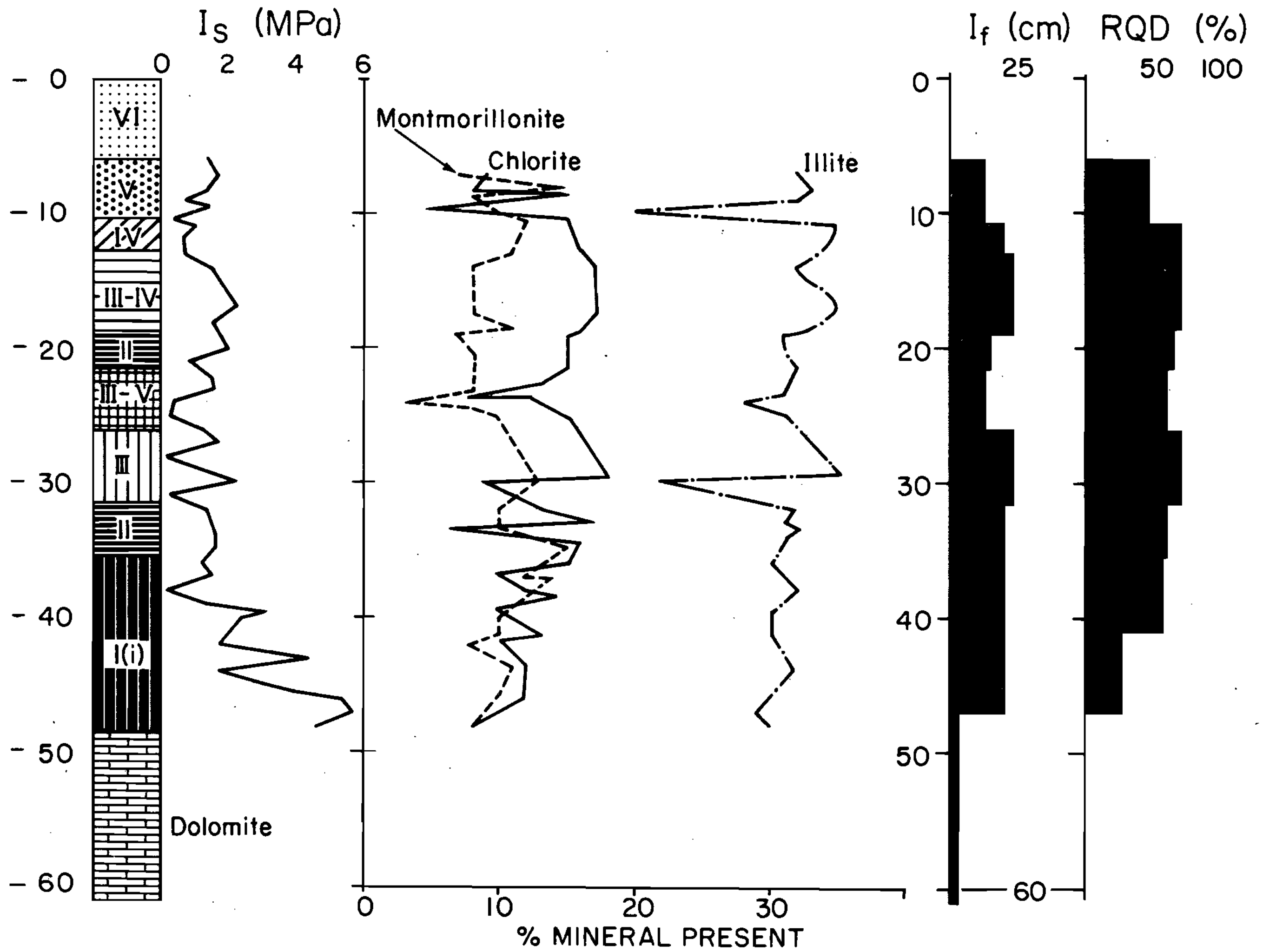

Fig. 8. Weathering profile Sturts Meadows Siltstone, Unit Ela.

that the true thickness of the weathered zone would be over 50 m.

Mineralogical changes due to weathering in these profiles are discussed in the next section of this Chapter since, unlike those of the dolomite, the changes tend to be progressive.

Because of the relatively thin bedding and variable lithologies of the Fowlers Gap Formation, the weathering profile is even more complex than that noted in the Sturts Meadows Siltstones, where lithology is more or less constant. The profile examined by drilling consisted of a series of thin limestones, pyritic and graphitic shales, calcareous sandstones and quartzites. Since the expression of each of these lithological types, for any one grade of weathering, is different, considerable difficulty was experienced in determining the weathering profile. The profile, shown on Figure 2 is one possible interpretation of the data.

The generalized profile is:

Soil	3.0 m
Completely weathered rock	15.0 m
Fresh to slightly weathered rock	16.5 m
Fresh rock.	

The total thickness of the weathered zone is about 35 m. In the lower part of the Fresh to Slightly Weathered horizon, the rock material is fresh, but rock mass weathering is indicated by stained joints and bedding planes.

The Devonian sediments all show a certain amount of surface silicification and ferruginisation. From the data of three percussion bores (NSB1, NSB2, NGB1) material weathering appears to be quite shallow. Below a thin silicified horizon, a few cm thick, the rock is completely weathered for about 3 m. There is then an apparently rapid transition to fresh rock material within about 2 m. However, weathering along joints was found to persist to depths of almost 100 m. This weathering is indicated by iron staining and the development of ferruginous veins along joint planes. Fine details of the profile such as were obtained from the Precambrian rocks was made difficult because of the nature of the boring. A typical profile is:

Silicified sandstone	0.05 m
Highly weathered sandstone	2.0 m
Slightly weathered sandstone	3.0 m
Fresh sandstone with ironstained and weathered joints	86.0 m
Fresh sandstone with no staining of joints.	

The few bores drilled in both the Precambrian and Devonian rocks suggest that, while the material constituting the former is weathered to greater depths than the latter, the mass weathering has penetrated to a greater depth in the sandstones than in the metamorphic rocks. Too little data is available to determine the weathering pattern. However, the evidence suggests that this pattern is unrelated to the present land surface. Similarly, groundwater level is known only from a few bores. In November, 1980, this was about 100 m below the surface at Sandstone Bore, and 80 m at New Gorge Bore. Taking into account the elevations, the water table at both sites is at about 90 m: close to the limit of rock mass weathering.

IV. Mineralogical and Fabric Changes with Weathering

Detailed study has been made of the mineralogical changes which were produced by weathering in the Precambrian rocks (Beavis, 1981; Beavis, Roberts and Smith, 1982). It has been shown that the changes are the result of weathering under both humid and arid conditions. The presence of montmorillonite, goethite and kaolinite and the extensive solution of the more soluble minerals indicates weathering under humid conditions. On the other hand, the presence of halite, gypsum and "lime" in the near surface section of the weathering profile indicates arid type weathering. High concentrations of silica in many of the surface rocks and of iron and manganese at depths of from 10 to 20 m are due to the alternation of arid and humid conditions in the past.

It appears that chlorite first breaks down to a vermiculite-like mineral, then to a montmorillonite; ultimately, the montmorillonite is broken down to kaolinite. Unlike chlorite, sericite remains unaltered, except in the highly and completely weathered rocks and in the soils where it is replaced by illite. Degraded illite also occurs in some soils.

One excellent guide to the degree of weathering, especially in the shales, is the progressive replacement of such minerals as magnetite by calcite. Such replacement appears to begin with the onset of weathering; it is about 50% complete in the moderately weathered rock, 70-80% in the highly weathered rock, and 100% in completely weathered rock.

Weathering currently in progress under arid conditions involves, largely, oxidation reactions, with the water table at depths of from 70 to over 100 m.

The fabric of weathered rocks has been investigated at the macroscopic scale, and at the microscopic (and sub-microscopic) scales. The macrofabric, i.e. the spacing of fractures, can be described quantitatively using the fracture spacing index I_f (cm). Microfabric, i.e. the spacing of microfractures, again can be expressed quantitatively using the microfracture index $I_{f_{mi}}$ (mm/cm^2). Very fine fabric, studied by scanning electron microscopy, can be described only qualitatively.

In the rocks under investigation at Fowlers Gap, fracture spacing index, in general, showed no consistent variation with weathering. However in the completely weathered rock, where desiccation produced shrinkage cracks in the phyllites, and where surface quartzites showed thermal fracturing, I_f showed a marked increase. On the other hand, the microfracture index was a sensitive indicator of degree of weathering in the dolomites, with density of microfractures highest in the (Completely Weathered) surface hardened rock. Similar results were obtained for limestones and quartzites; the metapelites, however, showed little microfracturing at any level of weathering. The shales and schists showed a distinct opening along foliation in the completely weathered rock, while the greenschists of the Picnic Creek Formation break into flat, rhomboid particles, on ? thermal cracks, spaced at about 2 mm.

At the sub-microscopic level, scanning electron microscopy was used to study fabric changes with weathering. The most valuable results were the demonstration of solution to produce increased porosity, especially in the case of the more soluble minerals, and in the disruption of foliation with granular disintegration due to the production of clay minerals along grain boundaries.

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CHAPTER 6 ENGINEERING GEOLOGY

I. Introduction

Engineering geology investigations were aimed at producing a rational basis for the siting of future water storages on the Station, and at developing, on an experimental level, water storage siting evaluation maps. It was, in fact, towards these ends that the basic geological studies were undertaken. It is clear that, from the engineering geological point of view, the three dominating factors are:

(1) Weathering of the rocks, and the type and thickness of soil development. This is closely related to -

(2) Geological condition of catchments

(3) Structural defects in the rock mass.

The basic geological studies of most significance, therefore, were the distribution of rock types, rock weathering, and structural geology.

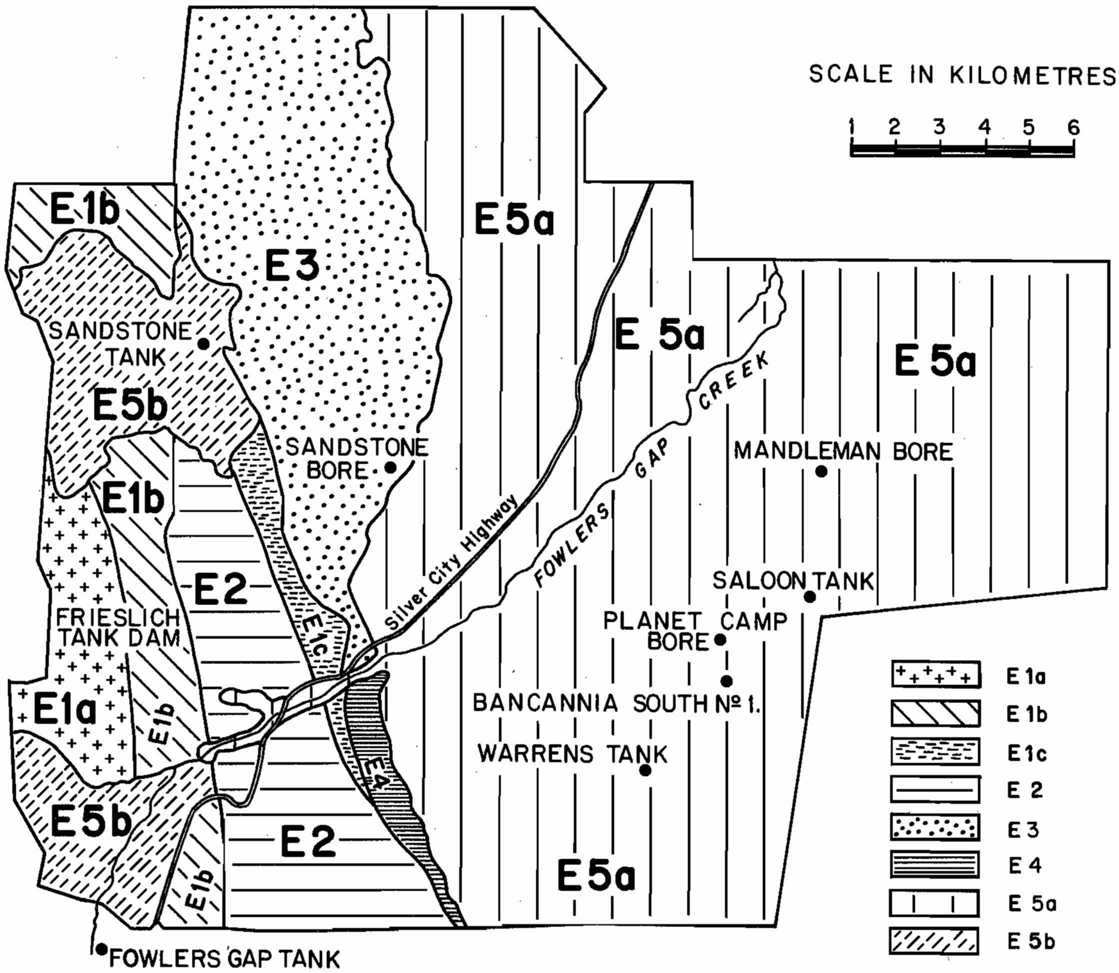
Geological criteria relating to the siting and construction of both tanks and dams were examined for the region as a whole, by a study of both successful and failed storages. The excavated tank is constructed using a bulldozer; the excavated material is either pushed aside, or used for the construction of auxiliary structures. The tank is located in, or close to, a stream channel; when the water is supplied from catch drains, wing walls, or paved areas, a silt trap must be incorporated in the design. A spillway or overflow chute may be an essential part of the structure. The tank is the preferred solution for the retention of surface runoff in areas of low relief, low rainfall and high evaporation. Because of the high evaporation rate, the surface area-depth ratio must be low, and the excavation must therefore be deep. Hence, it is an important requirement that the tank be located where low cost excavation to the required depth is possible. Ingles (1974) has suggested that the tank is the most economical solution for sandy soils, provided these contain a significant proportion of clay.

The location of excavated tanks is determined by the requirement to achieve stable, impervious walls, with a catchment of suitable gradient, area and condition. Soils with a clay content of less than 10 per cent are difficult to seal at low cost. Since the clay content of many soils in arid regions tends to increase with depth, the lower level soils can be used to seal the higher levels of the tank walls. However, salinity also tends to increase with depth (Stace, 1969); if this is the case, the transfer of low level soils to a higher level is undesirable. At Fowlers Gap no clear evidence of a consistent variation of salt concentration with depth has been obtained, however. Seepage losses through the floor and walls of a tank can be quite serious, and this is especially so if the soils contain expansive clays. Under these conditions, cracking occurs when the tank empties, and on refilling, seepage losses are aggravated. Although every attempt must be made to minimize seepage losses, compensation for these is possible, and the reliability of the tank increased by increasing the catchment area-storage capacity ratio.

The storage capacity of the tank, the quantity and quality of the water, and the development of soil erosion in the catchment will all be influenced by the surface conditions and soils of the catchment. Lewis (1964) cited the catchment requirements per 4.5×10^6 litres of storage as:

Grassed catchments	100 acres (40.5 ha)
Roaded catchments	25 acres (10 ha)
Rocky catchments	10 acres (4 ha)

Fig. 9. Engineering Geology Map of Fowlers Gap Station



These estimates assume a minimum catchment gradient of 1:400. The catchment condition is an important factor since insufficient yield can result in hydrological failure. In Australian arid regions, no substantial runoff generally occurs for rainfall events of less than 0.5 in (12 mm).

The ring tank or turkey's nest dam consists of a peripheral embankment constructed either by pushing soil outwards (ring tank) or inwards (turkey's nest dam). Since no real excavation is involved, construction is not costly. However, the low surface area-depth ratio demands a very high embankment, and, with compaction being carried out by a bulldozer only, the chance of bank failure is very high. For the most satisfactory construction, a clay-rich soil is required and careful construction is necessary to avoid failure by piping. The soil used should contain at least 12 per cent clay size material.

The combination of excavated tank and earth dam requires a site having all the criteria necessary for the tank, with additionally, a suitable dam site. This latter demands a relatively steep sided and narrow valley and implies some degree of topographic relief. For water economy the topography and geology should be such that the tank can be located as close as possible to the dam, i.e. in the deepest water.

II. Engineering Geology Units

Within the Station area, the basic geological studies suggested that a number of engineering geology units could be recognized, within each of which the catchment characteristics, weathering, and the engineering features of the rocks and soils were, in general, constant. These broad units are shown on Figure 9. Some of the units could be further subdivided, for example, Units E1 and E5. The units define water storage site suitability in terms of catchment characteristics, site characteristics and availability of construction materials. The Units are:

Unit E1: Thick, highly cleaved, moderately to completely weathered "shales", thin bedded, and moderately to closely jointed. Thin beds of quartzite, limestone and dolomite occur, with one thick bed of dolomite. The equivalent stratigraphic unit is the Sturts Meadows Siltstone. The Unit is divided into:

E1a: The "lower" section of the Sturts Meadows Siltstone, marked by generally poor outcrop, except along quartzite and dolomite beds. Weathering is deep, and is known to be in excess of 15 m, at which depth the rock is moderately weathered. Dolomites are hard and tough due to surface silicification. Catchments are characterized by thick soil cover, comprising both residual and colluvial soils.

Catchment conditions suggest low to moderate runoff, while the deep weathering indicates suitability for excavated tank construction. Ample materials are available for earth dam construction, but the colluvial soils should be rejected.

E1b: The "upper" section of the Sturts Meadows Siltstone, marked by more extensive outcrop than E1a; the exposed rock is less weathered (MW-HW), and the weathering is shallower (MW-SW at 5 m). The "shales" tend to be surface-hardened in outcrop. In general, slopes are flat; runoff is estimated to be moderate. However, no suitable dam sites were recorded, nor are adequate supplies of soil available, while the shallow weathering militates against low cost construction of excavated tanks.

Elc: This comprises Picnic Creek Metamorphics greenschist, limestone and amphibolites. Physical weathering appears to be extensive. Catchments are rocky, and runoff is moderate. A number of dam sites exist, but construction materials are not available. No sites suitable for excavated tanks were observed.

Unit E2: This Unit comprises the stratigraphic units Faraway Hills Quartzite and Fowlers Gap Formation. The Unit consists of thin quartzites, quartz schist, cleaved "shales", limestones, and dolomites. The thicker quartzites and limestones form prominent ridges, and are MW in outcrop. Other rocks are CW to MW in outcrop. Weathering, generally, is shallow. Runoff is estimated to be moderate, and several good dam sites were noted. However, suitable soils for dam construction are not readily available, nor is the mass suitable for excavated tank construction. At dam sites, rocks are intensely jointed and would require treatment to prevent high seepage losses.

Unit E3: The corresponding stratigraphic units are the Nundooka Sandstones. At the surface the sediments are MW-SW, with some surface hardening. Runoff appears to be moderate. Some good dam sites were noted, but construction materials would have to be transported. Excavated tanks could be constructed, but the sandstones are highly permeable.

Unit E4: This is not a significant unit: it corresponds to the Coco Range Formation, which have very limited distribution.

Unit E5: Unconsolidated sands, clays and gravels of Tertiary to Quaternary age.

E5a: This sub-unit comprises the thick deposits which occupy most of the eastern section of the Station. Runoff is extremely low to zero. The whole area is suitable for the construction of excavated tanks, although any particular site considered would require investigation. No dam sites exist.

E5b: This occupies two areas, the Sandstone Tank area and the area south of Fowlers Creek in the western section of the Station. It consists of thin Tertiary-Quaternary deposits. Tank sites are numerous, but again, each site would require investigation.

Perhaps to be included in Unit E5 are the river sands. These are usually restricted in extent both laterally and vertically. However, they are important as a potential source of filter material for dam construction.

III. Rock Properties

Two aspects are important: the properties of the rock mass, such as weathering and structural defects; and properties of the rock and soil materials. Rock mass and rock material properties are considered in this section; soil mass and material properties are discussed in Section IV.

In terms of water storage engineering geology on the Station, the geological structures of significance are the fractures: pattern, spacing, and condition; also of importance are the degree, pattern and depth of weathering. The former control the water-tightness of dam and tank storages; the latter control the suitability of possible excavated tank sites in terms of economic construction, and the availability of dam construction materials.

The nature, and degree of weathering are significant, since these, together with the nature of the parent rock, will control the clay mineralogy of the soil, and hence, to a great extent, the engineering properties of the soils. The weathering may be controlled, also, by the fracture characteristics of the rock mass. For each of the defined engineering geology units on the Station, the following are the structural and weathering features:

Unit Ela: The combination of bedding, cleavage and a near rectangular jointing system results in a rock mass made up of rhomboidal blocks. Fracture spacing index varies from 20 cm to 5 cm so that these blocks have average dimensions of 20 x 7.5 x 5 cm. In the CW, HW and MW this facilitates ripping and excavation, while the fragments disintegrate readily under a roller so that CW and HW rock is suitable for embankment construction.

Bedding and foliation strike N-S, with steep dips. Foliation dips almost vertically, and bedding dips at 50°-70°. Joints have a variety of dips and strikes, but the most prominent sets are N-S and E-W with vertical dip, and horizontal to sub-horizontal. Down to depths of 20 or more metres the joints and major bedding planes are open, with clay material, iron oxides, pyrite and pyrolusite deposited on them.

The weathering pattern is not known in detail, but bores la and 2 indicate weathering in both the dolomite and "shale" to depths of up to 40 to 50 m. The weathering pattern, and the products of weathering in the dolomite are unusual (Beavis, 1981); solution cavities occur throughout the profile, and even in fresh rock, these have been observed. Secondary silicification of the dolomite has produced a very strong surface rock, while ferricrete is developed as a distinct layer at about 20 m.

Unit E1b: In general terms, the remarks made in relation to sub-unit E1a apply also to this unit, except that the "shale" of E1b is much less weathered at the surface. Weathering is to approximately the same depth. In some areas, for example near the air strip, the exposed "shale" has suffered secondary silicification. Because of the lower degree of weathering, excavation by ripper alone would be difficult below 3 to 4 m, while rock fragments do not break down under the action of rollers.

Unit E2: All of the rocks of this Unit are foliated, bedded and jointed, with, in quartzites, secondary weathering fracturing due to thermal effects. As a result, fracture spacing index for quartzites (5 cm) is lower than in the other rock types. Joints are open to depths of up to 30 m; coatings and infillings include clay minerals, pyrite, goethite, and pyrolusite. Seepage losses along fractures would be considerable. Weathering at the surface depends on rock type: the limestones, quartzites and dolomites are SW to MW; the quartz schist MW-HW; shales CW to MW. All of the conditions point to difficult excavation; in many areas, explosives would be required.

Weathering depth appears to be about 30-35 m. In bores 4 and 5 rocks at this depth were fresh to essentially fresh, the only evidence of weathering being traces of montmorillonite.

Unit E3: In the relatively thick sandstones, and thinner quartzites and shales, the joints are very widely spaced - up to 10 m - due largely to the fact that these rocks have not been subjected to intense deforming stresses. Close to major faults, the fracture spacing index is much lower - about 20 to 50 cm - but this is localized. Fractures are not continuous, and there is only a moderate degree of interconnection (Udofia, 1980).

On the basis of three bores, it can be concluded that weathering, especially along joints, persists to about 50-60 m; surface material shows secondary silicification, and the rock material is fresh at depths of from 35 to 40 m. At the surface, all rock is SW to MW; surface material would require explosives for excavation, but the silica depleted zone from 1 to 5 m thick could be excavated by ripper.

Units E4 and E5:

No study has been made of Unit E4 because of its restricted distribution. Unit E5 is, in engineering terms, composed of soils, and is considered later.

The engineering properties of the rock materials are of no great relevance to the likely engineering works on the Station. However, a summary is given here for completeness. The only property of significance is permeability; this was determined for jointed rock, and is therefore more or less applicable to the rock mass. Detailed information on engineering properties of rock materials is contained in published papers (Beavis, 1981; Beavis, Roberts and Smith, 1982).

Typically, strength and elasticity decrease with increasing grade of weathering; density decreases, and porosity increases. No consistent relationship exists between degree of weathering and coefficient of permeability. This last property, of greatest significance in terms of water storages has been determined for a number of rock materials, each sample tested containing one joint. The permeability measured is a <u>total</u> permeability, i.e. one due to both primary permeability of the rock material, and secondary permeability of the joints (and cleavages). Some typical results are presented on Table 5.

Strength and elasticity of the rock materials, at any one grade of weathering, are extremely variable. For example, uniaxial compressive strength of "shale" for Unit Ela shows the following ranges: Fresh (I) 19-58 MPa; SW (II) 18-22 MPa; MW (III) 11-17 MPa; HW (IV) 10-12 MPa. The average strength of CW (V) is 7 MPa. Similarly, the modulus of elasticity varies: Fresh (I) 2.5-4.5 GPa; SW (II) 1.4-1.5 GPa; MW (III) 0.8-1.55 GPa; HW (IV) 0.8-1.6 GPa and CW (V) 0.2-0.25 GPa.

If fresh rock is considered, quartzites have the highest uniaxial compressive strength (150 MPa) and elasticity (9 GPa) while the "shales" have the lowest strength (35 MPa) and elasticity (4 GPa) in the fresh condition. Limestones and dolomites have relatively high strength and elasticity. All rocks show strength and elasticity anisotropy: this is strongest in the "shales" where the ratio of UCS normal to foliation to that parallel to the foliation may be as high as 4.

Even in the weathered rocks, porosity is low. The highest value recorded was 18%, in CW "shale". In the fresh rock, porosity is usually considerably less than 5%, although it may be as high as 11%. Highest porosity values were obtained in weathered dolomite and limestone, where solution voids are numerous. Dry density of fresh "shale", and quartzite, is of the order of 2.7 Mg/m^3, and of the weathered rock 1.8 to 2.3 Mg/m^3. Limestones and dolomites have higher dry densities: in the fresh state an average of 2.8 Mg/m^3, and in the weathered state an average of 2.7 Mg/m^3.

TABLE 5

Permeability of Selected Rocks

Rock Type	Unit	Weathering	Coefficient of permeability cm/sec.
Dolomite	E1a	Surface hardened (IIiii)	2.6×10^{-8}
	E1a	Weathered (IIi)	8.5×10^{-8}
	E1a	Ferricrete (IIii)	1.5×10^{-7}
	E1a	Fresh (I)	2.3×10^{-7}
"Shale"	E1a	Fresh (I)	5.8×10^{-9}
		SW (II)	1.4×10^{-8}
		MW (III)	2.6×10^{-8}
		HW (IV)	1.3×10^{-8}
		CW (V)	2.9×10^{-8}
	E1b	Fresh (I)	6.4×10^{-9}
		SW (II)	1.9×10^{-8}
		MW (III)	1.2×10^{-8}
		HW (IV)	1.0×10^{-8}

IV. Engineering Soils

In general, by engineering soils is meant the C horizon of the pedologist. This does not imply that the upper soil horizons are ignored by the engineering geologist; they are not, since the total soil profile is of fundamental interest and importance in determining the engineering properties of the "engineering" soil. A detailed research programme into the engineering soils has been recently reported (Akpokodje, 1983). Here, a brief summary only of the results is presented. The soils at Fowlers Gap present a number of problems from an engineering point of view: high swelling capacity, thixotropy, high permeability, structural collapse and piping. The importance of these aspects in water storage and road construction is considerable.

Northcote (1971) recognized some 9 types of soil in the Australian arid zone: gravels, sands, loams, clays, calcareous earths, red and yellow earths, red friable loamy earths, crushy red duplex soils and hard red duplex soils. Chartres (1981) has commented on the importance of aeolian material in the soil profile at Fowlers Gap, while Akpokodje (1981), working on engineering soils on the Station, recognizes three major profiles as a basis for engineering studies. This statement by Akpokodje must be regarded as having a general, regional application, since fine differences in lithology and location can significantly influence the profile.

Donald (1971) has discussed some engineering properties of arid zone soils pointing to the importance of the partially saturated condition, with pore pressures less than atmospheric, in determining these properties. Although he discussed textural differences, no account was taken of soil fabric, nor of the influence of mineral composition. It is important in considering the engineering characteristics of arid zone soils to take into account all three of these factors, as well as such characteristics as deflocculation and salinity. Because of the unsaturated condition of arid zone soils, shrinkage cracks and other discontinuities are characteristic, and these fabric elements have a profound effect on engineering properties.

The collapse of partially saturated arid zone soils, on wetting, is common, while piping erosion is also common. Calcareous silts, clay coated dune silts and certain flood plain deposits seem to be particularly susceptible to collapse and piping.

Research by Aitchison (1956, 1957, 1961) and Donald (1971) has indicated that many aspects of shear strength and volume change characteristics of arid zone soils can be generalized by the use of a modified form of the effective stress law. The single most important parameter is the soil water stress, including its distribution, and its change with time. Unfortunately, this parameter is the most difficult to determine.

The three "regional" engineering soil types described by Akpokodje (1981, 1983) are: grey reddish brown silty soil of the hilly areas; reddish brown clayey colluvium; and sandy alluvium of the plains. Illite is the main clay mineral of the first type, randomly stratified illite-smectite in the second, while the alluvium contains a mixture of illite, montmorillonite, kaolinite and chlorite. All of these clay minerals occur in all of the soils, although in the first two soils, one specific clay mineral predominates. The clay mineralogy of the silty soils is inherited from the weathered bedrock - "shale" and siltstone. The degree of chemical weathering is limited (Beavis, 1980; Beavis et al, 1982) and this is reflected in the mineralogy of the soils.

Atterberg limits and potential expansiveness of the soils are influenced by the proportions of montmorillonite and expanding mixed layer clays in the soils. All soils contain one or more of lime, salt and gypsum in the profile. While a high gypsum content slightly increases the plasticity, high carbonate content decreases the plasticity and expansion potential of the soil (Akpokodje, 1981).

As previously noted, detailed studies of the engineering soils have been reported elsewhere. However, a summary of the results of some of the tests on the colluvium and on the grey-reddish brown silty soils are given in Table 6. Current studies are concerned with consolidation and shear characteristics of the unsaturated fine grained soils.

V. Siting of Water Storages

It must be emphasized that, in this paper, only the geological factors are considered. Bell et al (1973) suggested a number of potential sites. The present survey has not found any additional sites; however, since the earlier work merely listed the sites, here, each site is considered further in light of the additional work done since 1973. In terms of excavated tanks, Ela and E5 are the most satisfactory units; this is not to say that tanks could not be constructed elsewhere, but excavation could be difficult and costly. In relation to Unit E5a, caution must be stressed. High permeability lenses and layers exist in this Unit, so that any proposed site in this Unit should be thoroughly investigated.

Table 7 shows the tank and dam sites listed by Bell et al (1973). Two of the proposals, the Frieslich Dam and Frieslich Tank were put into effect in 1976. Of the remaining sites, more detailed examination has been made, with the following results:

Nundooka Creek Tank sites:

These two tank sites are located in Unit E3. Sandstone is exposed, and is in a MW to CW condition. Excavation would

TABLE 6

Some Engineering Properties of Soils

Preliminary Results

Property	Colluvium	Grey silty soils on shale	
		Depth 4 m	Depth 8 m
Linear Shrinkage (%)	10.5	1-8	1-2
Optimum moisture content (%)	14-17	16	16
Maximum density (Mg/m^3)	1.87-1.80	1.78	1.78
Permeability (cm/sec)	2×10^{-7}	2×10^{-7}	5×10^{-7}
Cohesion (kPa)	n.d.	25	25
tan ϕ	n.d.	0.92	0.92
Plastic Limit (%)	27	16-27	16-27
Liquid Limit (%)	45	29-45	29-45
Plasticity Index	18	13-18	13-18
Salt	Abundant	Present	Trace
Lime	Moderate	Present	Trace
Gypsum	Present	Abundant	Absent
Illite	15%	30%	35%
Degraded illite	-	10%	10%
Halloysite	-	20%	20%
Kaolinite	15%	-	-
Montmorillonite	15%	-	-

TABLE 7

Potential Tank and Dam Sites - Fowlers Gap

Name	Map No.	Grid Ref.	Catchment (ha)	Runoff Potential	Dam Site/Tank Potential	Remarks
Frieslich Dam	1	640626	1,000	Fair	Fair-Good	Dam constructed 1976.
Nundooka Ck.	2	661760	360	Good	Poor	Tank site.
	2a	667750	760	Good	Poor	Tank site.
Rocky Ck.	3	662613	900	Fair	Good	Dam. Faulted area.
Woolshed	4	672605	3,000	Fair	Good	Dam. Spillway available.
Picnic Ck.	5	685619	650	Fair	Good	Dam.
Airfield	6	657609	2,000	Fair	Poor	Airfield would be flooded by dam.
Frieslich Ck.	7	639626	1,000	Fair	Good	Tank constructed 1976.
Floods Ck.	8	642590	2,100	Fair	Good	Tank (Water quality? Dolomite).
Fowlers Ck.	9	635571	4,000+	Good	Good	Tank.
Telephone Ck.	10	(710660 (720658	460 730	Fair	Good	Tank alternative to Sandstone Bore.
Mulga	11	687742	140	Poor	Poor	Very poor prospects. Dam.
Hotel	12	703622	190	Fair	Fair	Tank. Old tank silted up.
Sandy Ck.	13	710705	4,000	Fair	Poor	Dam.

be difficult and costly, almost certainly requiring heavy ripping or even the use of explosives. The sandstone itself is highly permeable, with coefficient of permeability ranging from 10^{-4} to 10^{-7} cm/sec. Seepage losses would be unacceptably high. For all of these reasons, despite the anticipated moderately good runoff from the catchment, the site is not recommended.

Rocky Creek Dam site:

This site is located in Unit E2 on the Fowlers Gap Formation. Topographically the site is very good, while catchment runoff is estimated to be satisfactory. However, the area is faulted, with highly permeable brecciated zones, and one fault in particular could lead to serious leakage losses. Construction materials are not abundant. Suitable soils are thin; moreover they are of a type which collapse readily. Despite the qualifications, this site is satisfactory, but sealing faults, and providing construction material could be costly. In the event of serious proposals to construct a dam being made, the site should be investigated in detail.

Woolshed Dam site:

Bell et al (1973) regard this site as potentially good. Concern must be expressed, however, for the possibility of very rapid siltation of a storage here.

The bedrock is quartzite and "shale", overlain by highly permeable alluvials. The thickness of the alluvium is unknown, but is probably in the order of 2 to 5 m. If the site has been accurately defined by Bell et al, a number of problems are foreseen:

(i) the alluvium is an unsatisfactory foundation for a dam due to its high permeability. It would have to be stripped from the foundation area;

(ii) construction materials with satisfactory properties are not available in sufficient quantities;

(iii) considerable costly excavation would be required for a spillway, much of it in hard quartzite;

(iv) siltation of the storage.

It is submitted that this site is one of the least satisfactory on the Station.

Picnic Creek Dam site:

The site, and storage are excellent in geological terms. The geology is varied, the site lying in the Picnic Creek Metamorphics greenschists, limestones and amphibolites. Because of the varying responses of each of these rocks to weathering, detailed investigation of the site is essential. The carbonate rocks do not appear to be a cause for concern, since there is no evidence of extensive solution. The soils are thin, and of mixed origin. It is likely that large, shallow borrow areas would have to be developed to obtain adequate construction materials.

Airfield Dam site:

Topographically, this site is ideal. However, at full development, the storage would flood the airfield, which would have to be relocated. The site is in Unit E2 close to the boundary with Unit E1. The rocks are quartzites and quartz schists, all of which are highly fractured, so that some treatment of the foundation would be essential.

Construction materials would have to be transported. The soils of Unit E1b are thin, while the soils developed on the quartzitic rocks are highly expansive, and thixotropic, and are unsatisfactory for dam construction.

Floods Creek Tank site:

From a geological point of view, this general site is satisfactory, provided the tank were located in "shale" of Unit E1a. Bell et al have given co-ordinates which would place the tank in dolomite - this would be an impossible location. The characteristics of the "shale" are well known from experience with the Frieslich Tank.

Fowlers Creek Tank site:

Two possible sites are available, both in thin alluvium overlying shale of Unit Ela. Both sites warrant further investigation.

Telephone Creek Tank sites:

Again, two possible sites are available, one in the uppermost exposed bed of the Nundooka Sandstone, the other, the more easterly, in the plains alluvium. The easterly site would be the more easily excavated, but the high permeabilities at both sites suggest unacceptable seepage losses.

Mulga Dam site:

This site has very little to recommend it, except the topography, and even this does not favour the siting of an adequate spillway. The catchment and storage areas are small, while the rock is very permeable. The site is not recommended.

Hotel Tank site:

Located in coarse textured, piedmont type deposits, the permeability of which is unacceptably high, this site has little to commend it.

Sandy Creek Dam site:

Topographically, the site is favourable, although a very high dam would be required to achieve adequate storage. The foundation rock is highly fractured and would require treatment. Problems relating to an adequate supply of construction material exist, so that it is very doubtful if the site could be developed economically.

VI. Road Geology

This aspect of the engineering geology is not of direct importance to the Station; nonetheless, geological problems exist in relation to roads in arid zones and some research is being undertaken in an attempt to determine the road-construction characteristics of soils on the Station, and the effects on these of the addition of stabilizing additives. This research is still in progress; when completed, the results will be published elsewhere.

The major road problem in the Station area concerns the instability of the bulldust soils both as a subgrade and as a pavement material, under both wet and dry conditions. The bulldust soils are very fine textured, with up to 70% silt and clay size particles. Additionally, the soils tend to be rich in chlorite and montmorillonite so that in addition to being thixotropic, they have high swelling capacity. In the wet conditions, the soils are highly plastic, and fail under quite low traffic loads, and, after rainfall, unsealed roads require immediate grading.

The soils fail readily, also, in the dry condition, producing deep, but obscured ruts and potholes, and hazardous dust conditions. Lime or portland cement additives appear to ameliorate the condition, at least on the laboratory scale. Field trials have yet to be carried out.

Highly saline soils create problems, especially if these constitute the subgrade of roads with a bituminous seal. Salt tends to become concentrated beneath the pavement, and this results in early failure. No deleterious effects, due to saline soils, have been observed in the unsealed roads of the Station area.

VII. Engineering Geological Mapping

VII.1. General statement

For any undertaking in engineering geology, the basic tasks are the preparation of a sound geological map, and of maps which relate geology to the specific engineering project to be undertaken. The conventional geological map rarely meets the requirements of the engineer. Because of this, techniques for the preparation of engineering geological maps for various types of engineering project have been developed (Unesco, 1976). Such maps should "provide a generalized representation of all those components of a geological environment of significance in land use planning, and in design, construction and maintenance as applied to civil engineering" (Unesco, 1976, p. 11). To assist in the planning, design and construction of water storages, and of groundwater development on the Station, engineering geological (water storage) and hydrogeological maps have been prepared. These are, in a sense, pilot-type studies; on their success depends whether or not the techniques can be extended to larger areas in the Australian arid zone.

VII.2. Engineering geological (water storage) maps

In this Chapter, five engineering geological units, comprising seven sub-units, were defined in terms of water storage geology on the Station. Definitions were in terms of topography, runoff, rock weathering, and soil type and condition. These units are the map units of the engineering geological map (Figure 9), and the map should be read in conjunction with these definitions. This map provides a basis for water storage planning only; it does not eliminate the need for the closer inspection of any site area which might be under consideration.

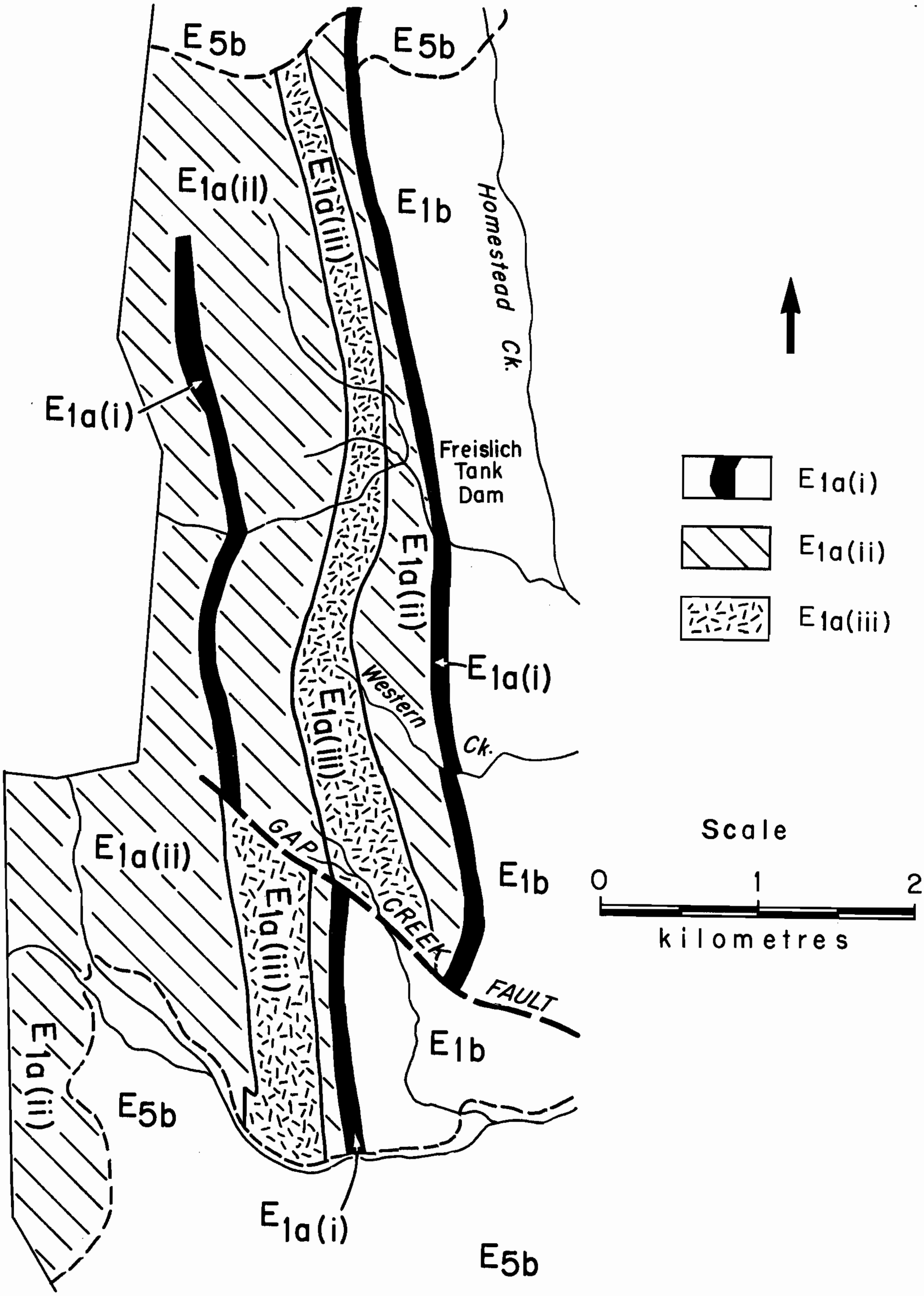


Fig. 10. Engineering Geological map: Unit E1a.

By increasing the scale of observation, and the amount of detail presented, the area of investigation can be narrowed. Because Unit Ela has the most promising potential for siting both dams and tanks, and E5a for tanks, these two units have been mapped in greater detail, at a larger scale (Figures 10 and 11). Selection of sites is possible using these maps; further investigation, for Unit Ela, should require merely on-site inspection. Because the subsurface conditions of Unit E5a are highly variable, any tank site selected, on the basis of the map, would require some subsurface investigation by boring.

The map units of Figure 10 are defined as:

Ela(i) Extremely high strength fine grained recrystallized quartzite. Fracture spacing index I_f = 0.05 m. Suitable for location of dams, after removal of loose rubble and soil. Weathering consists of physical disintegration only. Joints and other fractures open at surface.

Ela(ii) Dolomitic phyllite, low strength. Fracture spacing index I_f, in weathered zone, 0.10-0.25 m. Deeply weathered. CW to MW to depths of 15 m. Soils up to 2 m thick. Soils and weathered rock contain montmorillonite and are expansive. Readily excavated to 10-12 m by ripper or bulldozer. Suitable for excavated tanks.

Ela(iii) Dolomite, variable strength. Surface zone extremely high strength due to secondary silicification. Weathered to 40 m. Fracture spacing index I_f = 0.02-0.10 in weathered zone. Rock requires blasting for excavation. No satisfactory tank or dam sites.

The engineering geology map units of Figure 11 are defined as:

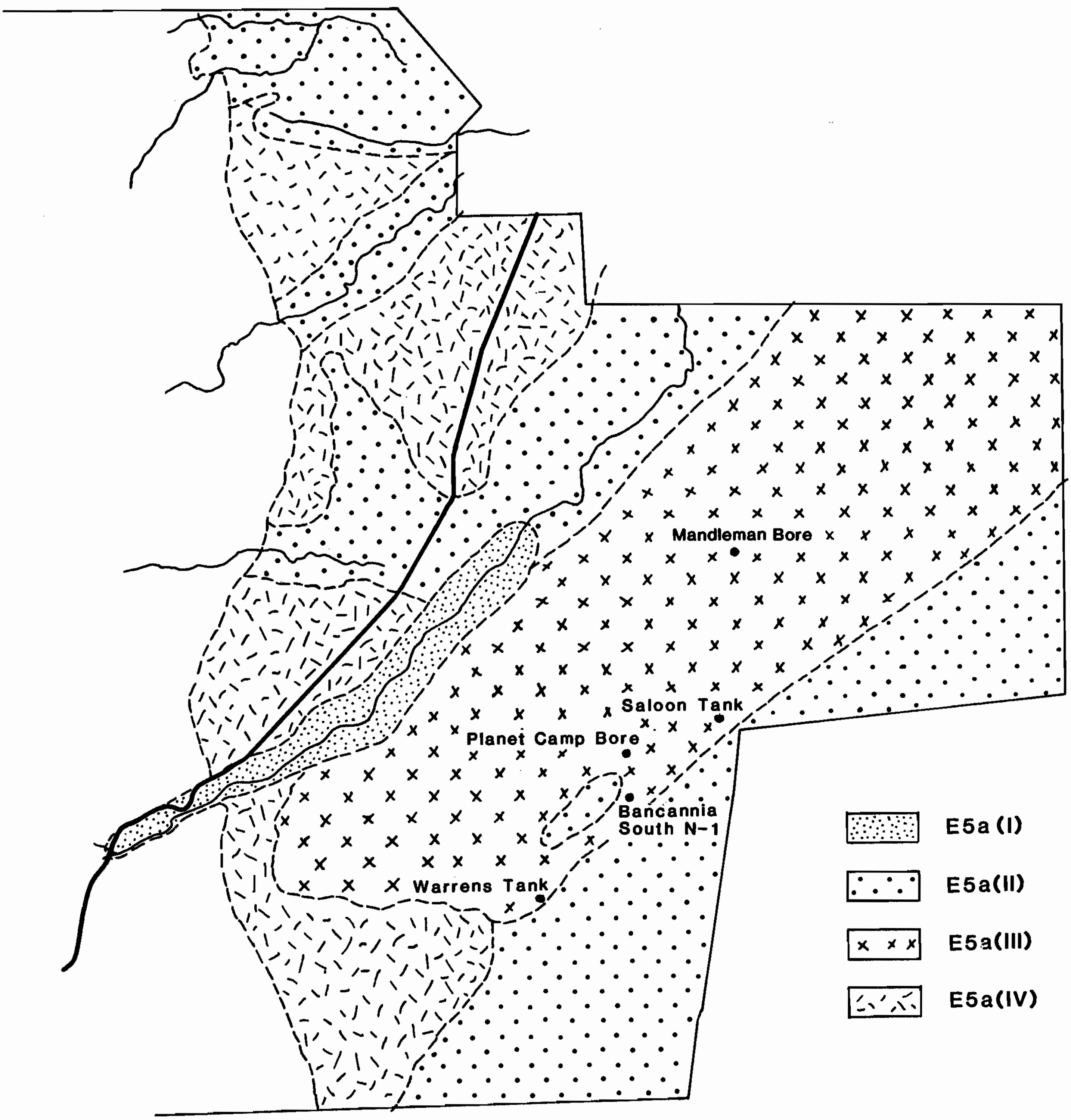


Fig. 11. Engineering Geological map: Unit E5a.

E5a(i) Mainly flood plain, with loamy sand type soils, highly permeable, and occasional levees of sand. Unsuitable for tanks due to high permeability.

E5a(ii) Thick red to reddish yellow loamy sands of terminal flood plains. Gilgai occur extensively. At eastern margins sometimes stony. With depth, silt and clay content increase, and the soil becomes calcareous. This unit is of doubtful suitability for excavated tanks, and requires boring at any site selected. Permeability of the upper soil, at least, is high.

E5a(iii) Alluvial plains with red to yellow sandy loams with moderate permeability. In places sand, up to 50 cm thick occurs. With depth the soils become more clayey and less permeable; the soils become calcareous at depth. The unit is suitable for excavated tanks, but any proposed site should be subjected to subsurface investigation.

E5a(iv) This unit, developed along the margin of the uplands, comprises relatively stony soils, usually dissected by stream courses with gullies 12 to 15 m deep. Soils are massive sandy loams with very high permeability. Downslope the soils are deep red calcareous sandy loams, often with gilgai; they are frequently expansive types. The high permeability renders them unsatisfactory for excavated tanks.

It is possible that, with more detailed subsurface investigation of Unit E5a, finer subdivision than that shown would be possible.

VII.3. Hydrogeological maps

The purpose of the hydrogeological map is to define possibly productive, and unproductive, groundwater units; to depict aquifers and aquicludes, and to delineate possible

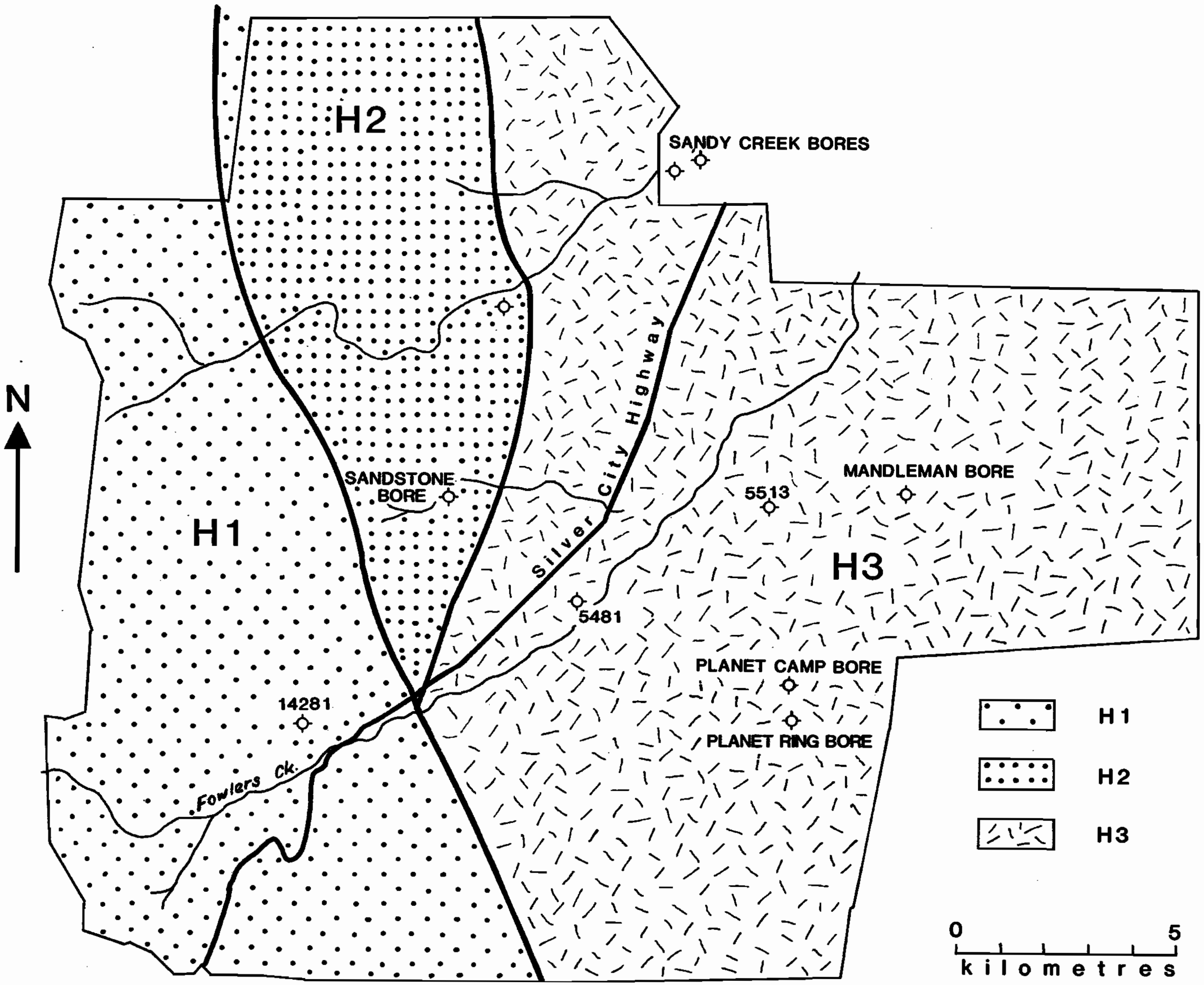


Fig. 12. Hydrogeological map: Fowlers Gap Station.

recharge and discharge areas. Figure 12 shows the main hydrogeological units, and Figure 13, detail of Unit H2, the Devonian Sandstone belt. Basically, three groundwater units have been recognized on the Station:

H1 The crystalline Precambrian metamorphic rocks which are, for practical purposes, unproductive.

H2 The Devonian Sandstone belt which has moderate groundwater potential, and in which two productive bores have been sunk.

H3 The Cainozoic sediments which have the highest groundwater potential on the Station, and in which there are two productive bores.

Most detailed work has been carried out on Unit H2: aquifers, aquicludes and possible recharge areas within this unit, are shown on Figure 13. The possibility exists, as indicated on the map, that the boundary between Units H2 and H3, generally an unconformity, is not impermeable, with water leaking from the Cainozoic aquifers into the Devonian.

The probability that recharge of the aquifers of Unit H2 occurs in outcrop has already been discussed in Chapter 7. On Figure 13, two possible recharge areas are outlined. These areas are marked by more intense jointing, and since, as Udofia (1980) pointed out, mass permeability in this unit is dependent on fracturing, it is in these two areas that recharge is most likely to occur.

To the west of the lower quartzite aquiclude, no separation of stratigraphic units is necessary on the hydrogeological map, since all appear to have similar hydrogeological characteristics. The uppermost stratigraphic unit (Unit G), a shaly sandstone, is distinguished, however, because of its much lower permeability. The map presented as Figure 13 should form the basis for any future hydrogeological research in the Devonian rocks on the Station.

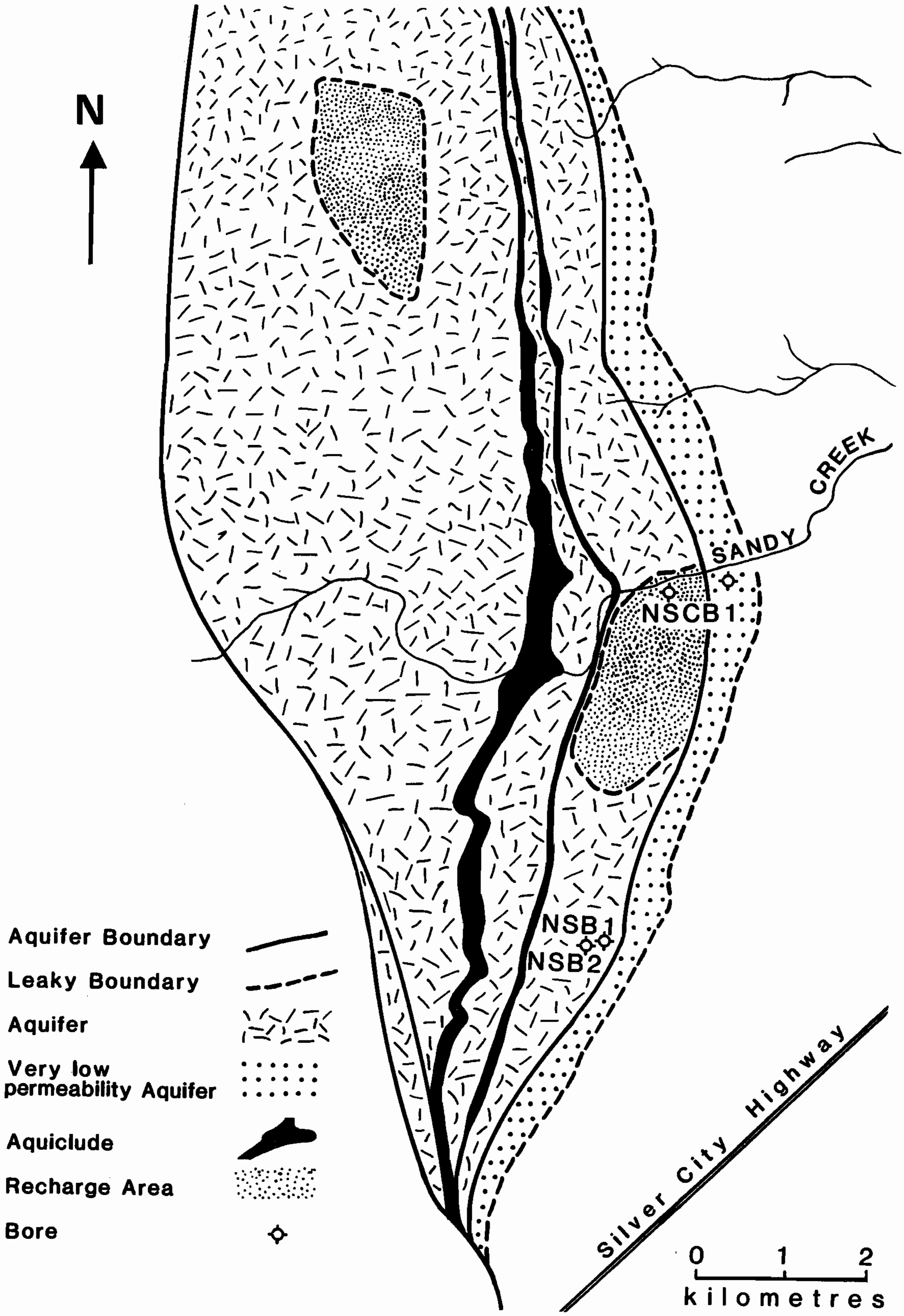


Fig. 13. Hydrogeological map of Unit H2.

It will be noted that the hydrogeological maps do not show any representation of the level of the water table. This is due to the fact that data on this aspect of the hydrogeology is almost completely lacking, only a few spot levels being available. The maps, then, indicate not only the information which is available, and its interpretation, but indirectly data which are not available, and which are essential for proper hydrogeological appraisal.

VII.4. General application

The engineering geological and hydrogeological studies carried out on Fowlers Gap Station provide a basis for application to other properties in the district. The clear recognition of specific units, e.g. for tank construction, enables a more rational approach to be made to the siting of these structures, and promises an increased chance of success, both in terms of economic construction, and in-service performance.

Although the pilot study at Fowlers Gap was based on quite detailed geological mapping, experience with this project suggests that such mapping is not in general essential. The availability of regional geological maps and aerial photographs, combined with some field checks are quite adequate, and, provided complex areas are avoided, detailed on-site investigation may be dispensed with completely. Specifically, for tank sites, units of relatively deep weathering are ideal; Tertiary-Quaternary units are highly variable and may present percolation problems. Units suitable for dam construction require a suitable site: a narrowing of the valley behind which there is an open storage area, and of equal importance, highly weathered rock; or other material suitable for dam-construction. So called dam-site units require recognition on the basis of engineering soil properties, especially compaction characteristics and susceptibility to piping.

The location of Frieslich Tank and Dam on Fowlers Gap Station was determined on the basis of the principles established during the research programme. The economics of construction, and the successful performance of the tank (due to prolonged drought the dam has not been fully tested) point to the utility of this methodology.

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CHAPTER 7 HYDROGEOLOGY

I. Introduction

With the low rainfall in the area, and with the high probability of frequent long term droughts, the Station is very dependent on groundwater as a supply for both stock and domestic purposes. At times, as for example in the recent drought, the Station depends entirely on groundwater. It is therefore surprising that only sporadic studies of groundwater potential have been undertaken in the past. Systematic studies are now under way, and this Chapter summarizes the results achieved to date.

In hydrogeological terms, the Station area can be divided into three units (Figure 12):

(i) H1: the area of Precambrian metamorphic rocks, the hydrogeological characteristics of which are a function of fracturing, since the rock materials themselves are, for practical purposes, impermeable.

(ii) H2: the area of Devonian sediments which are fractured, and, with the exception of the thin shales and quartzites, which have relatively high material permeability.

(iii) H3: the thick sequence of unconsolidated Tertiary sediments forming the eastern half of the Station, and which contain highly permeable sands and gravels confined between less permeable clays.

The basic hydrogeological problems of the Station area involve:

(i) the determination of groundwater level;

(ii) recognition of aquifers and the determination of aquifer parameters;

(iii) determination of groundwater quality; any variation in quality with time, and the causes of any variation;

(iv) the direction of groundwater flow;

(v) the degree of hydraulic interconnection between Units H2 and H3;

(vi) intake areas; and

(vii) sources of the present groundwater.

At the present time (January, 1983) the following wells are in production, or are capable of being put into production:

New Sandstone Bore
Gorge Bore (New Sandy Creek Bore)
Mandleman Bore
Planet Camp Bore

The first two of these are in the Devonian Sandstones, the two latter are in the Tertiary deposits. Figure 12 shows the location of all water bores drilled on the Station.

In 1980, two water bores were sunk at Sandstone Bore for both research and production, and one at The Gorge for research and production. Pump tests were carried out on these wells to determine aquifer characteristics. Logs and tests have been reported by Udofia (1980). Apart from these, no record seems to exist of logs, or tests, for other bores drilled on the Station. Hussein (1975) made a study of the Precambrian rocks.

Table 8 lists all of the water bores drilled on the Station. Much of this data is contained in Bell et al (1973), but it has been supplemented with more recent data.

The data provide only 12 spot levels for the water table over the whole area (28,889 ha), of which 3, for bores

TABLE 8

Water Wells on Fowlers Gap Station

Bore	Year	Depth (m)	Cased to (m)	Static W.L. (m)	Drawdown Level (m)	Supply (cmh)	Quality Soils (ppm)	Depth to Aquifers	Aquifer
Sandy Creek 1*	1893	207	?207	36.6	49/55	4.5	1,350	90 111 137	Upper Sand, Tertiary Lower Sand, Cretaceous
Sandy Creek 2*	1943	113	108	56.1	-	4.1	"Fresh"	85 94.5 104	Upper Sand
Sandy Creek 3	1952	101	99	61	?61	2.3	2,544	89 101	Upper Sand
No. 5481*	1914	90	90	-	-	3.4	?"Stock"	84 89	Upper Sand
No. 5513*	1914	104	?90	6.4	67	4.1	"Good Stock"	73 99	Upper Sand
Mandelman	1954	94	?94.5	5.7	57	2.0	2,300	66 78 93	Upper Sand
Planet Camp	1967	110?	?	-	-	4.5+	1,640	-	Upper Sand
Planet Rig*	1967	110?	?	-	-	9.1?	"Fresh"	-	Upper Sand
Sandstone (Old)	-	116	?116	97.5	?97.5	?1.4	3,600	99 to 113	Devonian Sandstone
Sandstone 1 (New)	1980	125	125	96.8	104.5	2.0	3,350	101.5 to 125	Devonian Sandstone
Sandstone 2 (New)	1980	120	120	97.5	100.5	1.1	4,090	103 to 120+	Devonian Sandstone
Sandy Creek 1 (New) (New Gorge 1)	1980	125	125	79.3	-	2.7	2,150	80 to 125+	Devonian Sandstone
No. 14280*	-	26.5	?27	12	20.5	0.5	?	19 26.5	Precambrian
No. 14281*	-	54	24.7	18	34	0.8	3,050	24.4 42 54	Precambrian
Fowlers Gap*	pre 1934	32	-	17	-	2.0	9,000	-	Precambrian

14280, 14281 and Fowlers Gap, are suspect. The high levels on these bores suggest a very wet season, but, since the date of drilling is unknown, this cannot be checked. If the admittedly dubious assumption is made that groundwater level at any point is fixed, there are still too few data for a reliable estimate of general groundwater level over the Station. The data provided, however, do confirm that the Unit H1, the Precambrian rock belt, is an unlikely source of groundwater, and that future investigation should be restricted to the Units H2 and H3.

II. The Hydrogeology of the Devonian Sediments

Bell et al (1973) identified several beds within the Unit H2 as aquifers, aquicludes, and intake areas. Since their work was published, detailed geological and hydrogeological mapping of the Unit has been completed (Udofia, 1980), and in general, the earlier findings have been confirmed; additionally, the lowermost bed of the Nundooka Sandstone has been postulated as an aquifer, but this has not yet been tested. In this section of the paper, the various hydrogeological aspects of the Devonian rocks will be examined.

II.1. Geology and aquifers

All of the sandstones are to be regarded as potential aquifers, although, as shown by Udofia, certain areas, or sections, tend to be more favourable than others, due to localized fracturing which results in an increase of mass permeability. The quartzite units are to be regarded as aquicludes, while the uppermost exposed unit of interbedded shaly sandstones and shales is also to be regarded as an aquiclude with thin internal aquifers, although somewhat less efficient than the quartzites.

Even when lithology is taken into account, structures exert the dominant hydrogeological control. The control exercised by the Nundooka Fault is uncertain, but it has been demonstrated by Udofia that joints are the most important structures from a hydrogeological point of view. Meinzer (1923) argued that joint intersection is important in determining the mode of groundwater circulation. He showed that this is greatest where joints of the principal sections intersect and in particular at the intersection of steeply dipping and flat dipping joints. Opening of joints due to such processes as weathering also aids circulation of groundwater, and, in the three bores sunk in 1980 in the Devonian sandstones, joint weathering was observed to depths of over 65 m.

In the Devonian sandstones, the dominant joints are east-west structures with dips 70^{o} to 90^{o}. Some horizontal joints are present, at least in surface exposures. Again, in surface exposures at least, the joints have a spacing of 10 to 40 cm with continuity of 10 to 15 m, and have openings of 2 to 5 cm. The near horizontal joints have the appearance of erosional sheeting structures, an observation confirmed by the diminution of frequency of these structures at depth in bores.

At least two areas of more intense surface fracturing were observed (Figure 13). These were regarded by Udofia as having the greatest potential for groundwater development. This assessment was made on the basis of the role of joints in achieving satisfactory mass permeabilities. One of the areas was tested by boring; the bore produced satisfactory, but not good, flows.

II.2. Properties of aquifers

From the three bores drilled in 1980, NSB1, NSB2, and NGB3, samples were taken to determine effective size, coefficient of uniformity, and permeability, while pump tests on NSB1 were made to determine transmissivity, storage coefficient, and specific capacity of the aquifer. In terms of grading, the aquifer intersected in NSB1 is a uniform fine sand; all of the other materials intersected in the bores were well graded, poorly sorted silty fine sand, the porosity of which was much lower than that of the uniform fine sand. The results of grading, porosity and permeability tests are shown on Table 9.

No clear relationship exists between porosity and permeability; however, Hazen (1893) indicated that permeability should vary as the square of the effective size. Despite this, he also noted that higher values of the coefficient of uniformity have the result of reducing the influence of effective size on permeability, and the relationship is not necessarily valid in such a case.

Characteristics of the aquifer in NSB1 were determined by a pumping test, using NSB2 as an observation well. Four methods were used: Theis; Copper-Jacob; Chaw, and the Theis Recovery. The results are shown on Table 10. Q was determined using Bowuer's (1978) method.

If average values for T of 4^2m /day, and S of 3.75 x 10^{-4} are adopted for the sandstone aquifers in the Devonian rocks, it is obvious that these aquifers cannot yield large quantities of water to a given well. Nonetheless, provided pumping is periodical and not continuous, at a rate of about 2 m^3/hr, supply sufficient for stock watering can be obtained. Assuming 8 hours pumping per day, adequate water could be extracted from each bore to supply the daily needs of about 300 sheep.

II.3. The hydrogeological system

In order to define the hydrogeological system, identification of the water table, intake areas, discharge areas and direction(s) of flow is necessary. Insufficient data exists

TABLE 9

Porosity, Effective Size, Coefficient of Uniformity and Permeability of Nundooka Sandstone

Bore No.	Sample Depth (m)	Porosity	Effective Size D_{10} (mm)	Coefficient of Uniformity (Cu)	Coefficient of Permeability cm/sec (Average)
NSB1	0-1	0.32	-	-	2×10^{-6}
	44-45	0.35	0.04	4.21	3×10^{-5}
	97-98	0.35	0.04	4.14	1.5×10^{-4}
	101-102	0.32	0.04	3.75	1.5×10^{-4}
	110-112	0.32	0.09	1.88	9.0×10^{-4}
	123-125	0.29	0.03	5.33	7.2×10^{-6}
NSB2	0-0.5	0.37	0.006	30.8	8.5×10^{-5}
	43-44	0.33	0.03	4.69	4×10^{-4}
	98-99	0.34	-	-	1×10^{-4}
	103-104	0.32	-	-	2×10^{-4}
	110-111	0.28	0.01	10.7	2×10^{-4}
	119-120	0.32	0.05	3.54	3×10^{-4}
NGB1	0-1	0.34	0.004	62.5	5×10^{-5}
	84-85	0.38	0.003	61.5	2×10^{-4}
	85-86	0.34	0.02	9.2	2.5×10^{-5}
	101-102	0.35	0.02	8.6	7.5×10^{-6}
	114-115	0.37	-	-	7×10^{-5}
	124-125	0.38	-	-	9×10^{-5}

TABLE 10

Aquifer Characteristics - Bore NSB1

1980 Tests

Method	Transmissivity T (m^2/day)	Storage Coefficient S	Specific Capacity Q (m^3/day/m)
Theis	4.1	6.83×10^{-4}	
Cooper-Jacob	4.2	1.75×10^{-4}	
Chaw	3.6	2.65×10^{-4}	
Theis Recovery	4.2	- *	
Bowuer			5.99

* Indeterminate by this method.

1981 Tests

Method	Transmissivity T (m^2/day)	Storage Coefficient S
Theis	2.7	3.03×10^{-4}
	3.4	2.00×10^{-4}
Cooper-Jacob	3.9	1.64×10^{-4}

to determine the first of these: e.g. only 7 readings exist (see Table 8), and these were taken at varying times. Depth to the water table increases from north to south; since no accurate levels are available for most sites, the level of the water table cannot be determined accurately. Data are available for NSB1: Surface 185 m, gwl 88.5 m; NSB2: 185 m, and 87.91 m respectively, and NGB: 170 m and 90.25 m respectively. This does appear that gwl increases from north to south. Since data are both inadequate and inaccurate it is impossible to construct a flow net, and the direction of groundwater flow to be determined.

Because of the nature of the geology, it has to be assumed that the main intake area is within the known outcrop area, on the Station; any contribution from the Precambrian belt would be negligible, if it occurs at all. There is no doubt that the Nundooka Fault, and the Precambrian-Devonian unconformity constitute together and separately, a groundwater boundary.

It has to be asked, then, where recharge occurs? Two possibilities have been considered, but these are merely working hypotheses which require rigorous testing:

(i) by infiltration, through the Quaternary beds, into the Devonian. This would require an east-west flow. Intake would be from water discharged onto and into the Quaternary and Tertiary sediments from rainfall on the plains (where runoff is effectively zero) and stream flow onto the plains from the hills. However, the Bancannia South No. 1 well cut the upper sandstones between 820 and 1,200 m, immediately below the shaly silty sandstone, which, as noted, is an aquiclude. For this reason, any significant recharge to the Devonian must be in the outcrop area.

(ii) by infiltration directly into the sandstones on the flatter, low runoff areas of outcrop, and from streams traversing the sandstones.

TABLE 11

Analysis of Bore Waters - Devonian Sandstones

	SCB3*	NGB1		NSB1		NSB2	
		1980	1981	1980	1981	1980	1981
EC_{25}	3960	3930	6930**	6290	6740	6800	6930
Na^+	673	610	684	980	905	1120	958
K^+	12	5	19	15	21	25	22
Ca^{++}	222	120	112	210	152	340	177
Mg^{++}	-	15	83	60	128	65	157
HCO_3^-	236	95	nd	320	nd	490	nd
$CO_3^=$	nd	nd	nd	nd	nd	nd	nd
Cl^-	1003	925	923	1500	1306	1700	1346
$SO_4^=$	398	60	501	180	789	60	1061
NO_3^-	nd	10	-	40	-	20	4
T.D.S.		2150	2470	3350	3510	4090	3900
pH	nd	6.74	7.57	6.64	7.14	6.04	7.13

*SCB3 was drilled in Cainozoic sediments.

It is included here for comparison with NGB1.

**Result questionable.

In either (or both) case, recharge could not be expected to be great; in very wet years, such as were experienced in the mid-seventies it could be considerable, but in the long term it is considered that recharge would be dangerously low.

It is known that the Devonian beds in the Bancannia Basin, which are a subsurface continuation of those outcropping on the Station, contain groundwater. Where discharge occurs, if it does occur, is unknown. If the main intake is in the outcrop area, does this suggest a west-east flow? These are some of the problems which require further research.

II.4. Water quality

Analyses of bore water from Sandy Creek No. 3 (Bell et al, 1973) were carried out in 1967 and from NGB1, NSB1 and NSB2 in 1980. The analyses are shown in Table 11. According to the Hem classification, the water is moderately saline, or, according to the Davis and De Wiest system, it is brackish.

Some problems may be noted: e.g. bores NSB1 and NSB2 are contiguous; the water comes from the same aquifer, with the bores less than 100 m apart; yet the analyses show marked differences. The possibility exists that the aquifer near NSB1 has been "flushed" due to years of pumping of the old Sandstone Bore, located within a couple of metres of NSB1. This is not a likely explanation, it is admitted, but no other presents itself.

The water is suitable for stock use, within certain limits. While stock can tolerate higher levels of salt when on green pastures, lactating ewes and young lambs have a reduced tolerance, while during periods of high intake (e.g. hot weather or high salt intake) it is necessary for the salt content of water to be lower. In the case of the water under investigation, salt levels are tolerable for all conditions. However, in periods of high evaporation, water troughs should be flushed to guard against increased salt concentration.

III. Hydrogeology of the Cainozoic Sediments

Apart from checks on groundwater quality, little work has been done since that of Bell et al (1973); nonetheless, some further analyses of the hydrogeological data have been completed. Here, the whole Cainozoic sequence of the Bancannia Basin is regarded as a single hydrogeological unit rather than as two units, Tertiary and Quaternary, as treated by Bell et al. These earlier writers noted the occurrence of a (?) Mesozoic aquifer below the Cainozoic deposits, recorded in Bancannia South No. 1, and imply a correlation with the aquifer in Sandy Creek No. 1. The outcrop of Mesozoic rock about the Devonian silty sandstone probably is equivalent to part of this unit.

Cainozoic alluvial deposits are about 130 m thick in both Sandy Creek No. 1 and Bancannia South No. 1 wells, where they consist of clay and sand, with thin beds of dolomite and lignitic clay. It is more than probable that the sequence is highly variable, but, on the basis of two bores, Bell et al (op. cit.) recognized two units:

2. "The Upper Unit" 75 m thick

1. "The Lower Unit" 60 m thick

The upper unit consists of a stiff brown clay, with all the attributes of an aquiclude, included in which are layers or lenses of sandy and gravelly material. At the base are thin, light coloured and black, swelling clays. Seeps of water were recorded from the sands and gravels. The lower unit consists of white, light grey and black clay with layers or lenses of coarse, poorly graded sand, although some layers, up to 7 m thick, are well graded. The dark bands contain pyrite and lignite, and thin bands of dolomite. The sand beds, which are potential aquifers, are located between 70 and 110 m depth. At present, Mandelman and Planet Camp bores are producing from the sands of the lower unit. Elsewhere, outside of the Station area, these aquifers appear to be good producers.

TABLE 12

Analyses of Bore Water - Cainozoic Sands

	Planet Camp Bore 1967	Planet Camp Bore 1975	Planet Camp Bore 1981	Mandelman 1967	Mandelman 1981	Sandy Ck No. 3 1967
EC_{25}	2520	5239*	2820	3492	4300	3960
Na^{+}	409	380	402	667	505	673
K^{+}	8	7	7	8	12	12
Ca^{++}	} 133	66	20	} 140	62	} 222
Mg^{++}		57	33		43	
Fe^{++}	<0.02	nd	nd	0.13	nd	<0.02
HCO_3^{-}	282	254	nd	210	nd	236
$CO_3^{=}$	nd	nd	nd	19	nd	nd
Cl^{-}	558	{40}*	426	829	780	1003
$SO_4^{=}$	250	{62}*	262	401	400	398
NO_3^{-}	<0.5	0.59	-	nd	-	nd
TDS	1640	{867}*	1160	2274	2020	2544

{*} These results appear to be erroneous.

The water is of reasonable quality (Table 12).

The comparison of the analyses of water from Planet Camp bore carried out in 1967 and 1975 was made to assess any change in composition with more or less continuous pumping. If $SO_4^{=}$, Cl^{-} and TDS are excluded (the 1975 figures for these - Hussein, 1975 - are obviously erroneous), then it can be seen that no significant change has occurred over the 8-year interval.

From the little data available, the water from the Cainozoic aquifers being pumped is of slightly better quality than that from the Devonian aquifers. Udofia (1960) reported the analysis of New Sandy Creek bore (NGB1), drilled in the Devonian; this is shown on Table 10. If this analysis is compared with analyses from the Cainozoic aquifers, and from the Devonian aquifers, it will be seen that it is comparable to the former, and differs distinctly from the latter. Since the cuttings from the bore are Devonian sandstone (Udofia, 1980), the question is raised as to whether or not leakage is occurring from Cainozoic, into Devonian, aquifers. NGB1 is located very close to the Devonian-(?)Mesozoic-Cainozoic unconformities, this possibility cannot be excluded, and is a matter for future research.

Recharge of the Cainozoic aquifers obviously occurs on the plains of the Bancannia basin. Runoff on these plains is virtually zero, and while evaporation is high, infiltration, especially in wet years, would also be high. This, too, is a subject for further investigation, together with a study of the aquifers' characteristics and parameters. There seems to be no question that the Cainozoic area has the most promising potential for groundwater resources on the Station: it is the unit about which least is known. Further research and investigation is essential.

IV. References

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