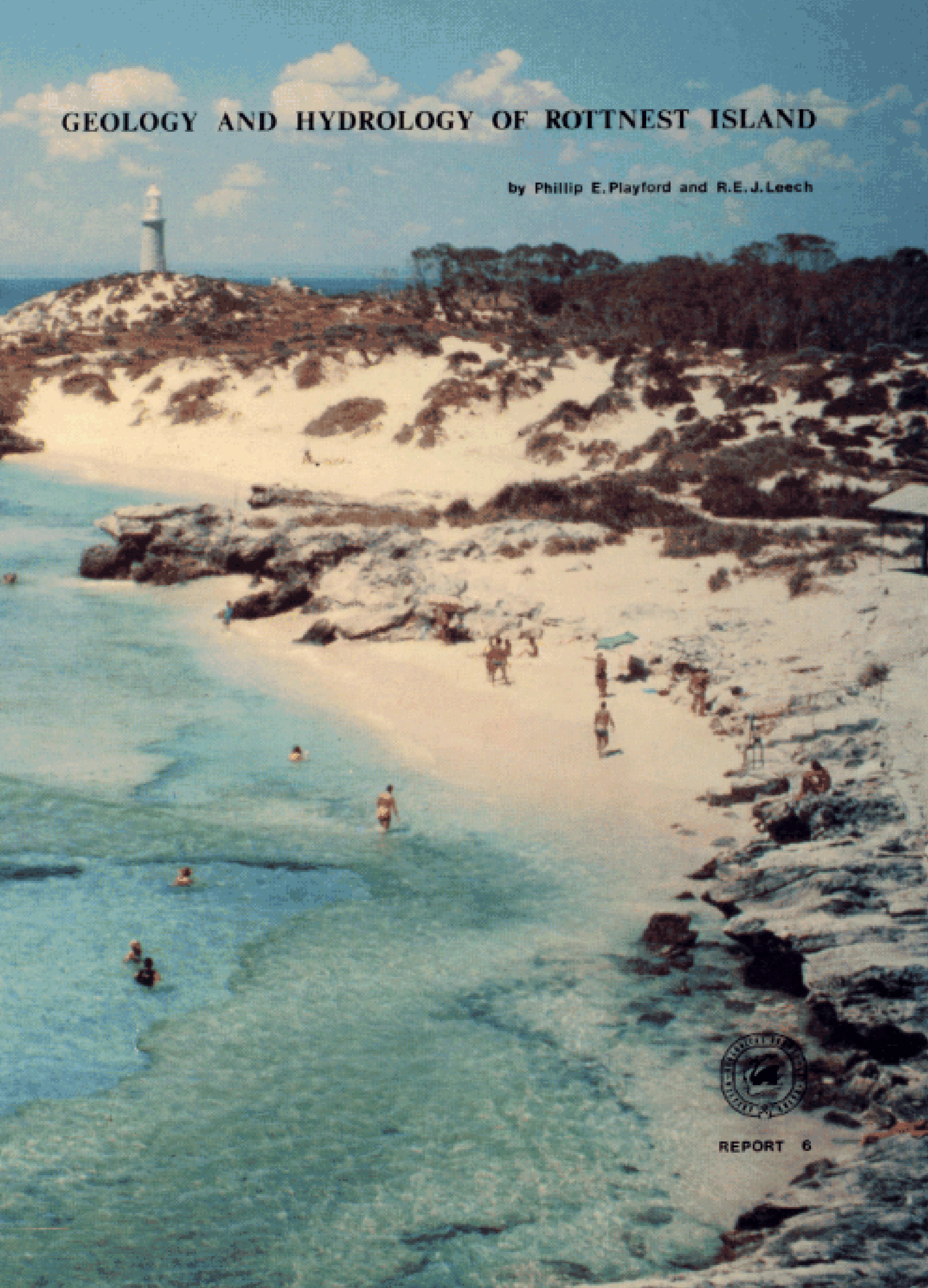
GEOLOGY AND HYDROLOGY OF ROTTNEST ISLAND

by Phillip E. Playford and R. E. J. Leech



REPORT 6

FOREWORD

In 1976, following a request from the Department of Public Works, the Geological Survey investigated in detail the possibility of obtaining adequate supplies of potable water on Rottnest Island. Over the years several minor investigations had been made without success. The 1976 investigation successfully sought shallow sources of groundwater and a fresh-water supply for the island now seems assured, providing it is properly managed.

The island's recent geological history was, to a large extent, conditioned by relative rises and falls of sea level, and these are evidenced by elevated marine deposits and erosional features, which are prominently displayed for all to see. These features may be of interest to some of the many tourists who visit the island, and they are certainly of more than passing geological interest.

This volume contains two separate papers, one dealing with the geology and groundwater potential, the other with the hydrogeology and investigation by drilling, plus an appendix which lists the fossils collected from the island and housed in the collection of the Western Australian Museum.

While this publication will be of value to the scientific workers it is thought also that holiday makers on the island may find it interesting for an understanding of the geological history of their playground.

J H LORD

14th June, 1977

GEOLOGICAL SURVEY

OF

WESTERN AUSTRALIA

REPORT 6

GEOLOGY AND HYDROLOGY OF ROTTNEST ISLAND

PART I

GEOLOGY AND GROUNDWATER POTENTIAL

by Phillip E. Playford

PART II

HYDROLOGY

by R.E.J. Leech

APPENDIX

FOSSILS FROM THE HERSCHELL LIMESTONE

IN THE COLLECTION OF THE WESTERN AUSTRALIAN MUSEUM

by George W. Kendrick

1977

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PART I

GEOLOGY AND GROUNDWATER POTENTIAL

GEOLOGY AND GROUNDWATER POTENTIAL

by

Phillip E. Playford

ABSTRACT

Rottnest Island is the largest island in a chain of small limestone islands and reefs on the continental shelf near Perth. It covers some 1 900 ha, including about 200 ha occupied by a chain of salt lakes in the northeastern part of the island.

Rottnest is composed of Quaternary limestone and dune sand, and is fringed by limestone reefs. Three named formations are recognized on the island - the Tamala Limestone (Pleistocene to Holocene), Rottnest Limestone (Late Pleistocene), and Herschell Limestone (Holocene). They are overlain by late Holocene dune sand, beach sand, swamp deposits, and salt-lake deposits.

The Tamala Limestone consists of dune limestone (eolianite), and is the most widespread unit on the island. The Rottnest Limestone is a fossil coral reef, which is believed to intertongue with the Tamala Limestone. It has been dated as 100 000 ± 20 000 years old. The mid-Holocene Herschell Limestone consists of shell beds and lime sand, mostly only weakly lithified. Much of the unit was deposited some 5 000 to 5 500 years ago. The fauna consists wholly of living species, dominantly bivalves and gastropods.

Holocene swamp deposits more than 1 m below the surface contain pollen of species indicative of tuart woodland, which is typical of the mainland coast opposite Rottnest today, but does not occur now on the island.

The most interesting feature of the geology of Rottnest Island is the clear evidence seen there of Quaternary sea-level changes. This is in the form of elevated marine deposits, elevated intertidal platforms and shoreline notches, and subaerial features which extend below modern sea level.

The elevated marine deposits are firstly the Late Pleistocene Rottnest Limestone coral reef, which grew during the Riss-Würm Interglacial when sea level at Rottnest was at least 3 m higher relative to the land than today, and secondly the Herschell Limestone, which was deposited in mid-Holocene times, when sea level was again as much as 3 m relatively higher than now. At that time the area of the present salt lakes formed arms of the sea, between numerous small islands.

Three levels of elevated intertidal platforms and notches are recognized on the island: an upper level at about 3 m above modern low-water mark, an intermediate level at about 1.5 m, and a lower level at about 0.7 m. The upper level coincides with the maximum mid-Holocene transgression of about 5 000 to 5 500 years ago, while the other levels are probably only a few hundred years older. The older notches were encrusted with serpulid worm tubes and other sessile marine invertebrates, and were bored by marine organisms, while the sea was at the 3 m level.

Lithified dunes of the Tamala Limestone extend below sea level at many localities on the coast of the island. These dunes are believed to have accumulated during periods when sea level was significantly lower than today, during phases of the Riss and Würm Glaciations and during the Flandrian Transgression. Solution pipes can be seen to extend below modern sea level at a number of places around the coast of the island in the Rottnest and Tamala Limestones, and they must have formed when sea level was significantly lower than at present. The salt lakes probably overlie major dolines which were formed by solution during the period of greatly lowered sea level (as much as -100 m) associated with the Würm Glaciation.

Previous authors have ascribed all Pleistocene and Holocene changes in the relative elevations of sea and land at Rottnest to world-wide eustatic fluctuations in sea level resulting from advance and retreat of the polar ice caps. However, there is increasing evidence in the southwest of Western Australia that tectonism associated with epeirogenic uplift of the Darling Plateau and/or movement along the Darling Fault has also played a significant role in the displacement of Quaternary shorelines. Thus, although Quaternary eustatism is an established fact, and it was of major importance in the Quaternary history of the Rottnest area, tectonic factors may also have contributed to the relative changes of sea level and land that are evidenced on the island. Of particular significance is the conclusion that although sea level must have been as much as 3 m higher relative to the land at Rottnest during the mid Holocene, the subsequent emergence about 5 000 years ago could have been tectonic rather than eustatic.

Water supply has been a major problem at Rottnest ever since the island was first developed as a holiday resort, more than 60 years ago. The Thomson Bay settlement is supplied by two water systems: a first-class system of fresh water and a second-class system of saline water (for ablution and sanitary purposes). Fresh water has been obtained on the island in recent years from bituminized catchment areas, and has been supplemented by water imported by barge from the mainland. A water-distillation plant was also used for a few years, but it proved to be uneconomic and unreliable. The second-class system is supplied by a number of saline wells in the settlement area, which have steadily deteriorated in water quality as demand has increased.

An attempt to obtain artesian water was made in 1911-13, when a bore was drilled near the settlement, but it recovered only small flows of salt water from the Early Cretaceous Leederville Formation. Recent drilling and seismic exploration for petroleum on the adjacent continental shelf confirm that the prospects of obtaining low-salinity artesian water below the island are very poor. Several faults cutting the Lower Cretaceous aquifers are present between Rottnest and the mainland, and these apparently act as hydrogeologic barriers preventing the fresh to brackish artesian water present below the Perth area from reaching the equivalent aquifers below Rottnest. It is therefore concluded that any further drilling for artesian water at Rottnest would have little chance of success.

Up to the time of the present investigation there had been a long-standing belief that significant quantities of shallow potable groundwater could not be obtained on Rottnest Island, and this was the basis for earlier decisions to extend catchment areas, install a water-distillation plant, and import water from the mainland. However, the present investigation showed that the shallow groundwater resources of the island had never been properly evaluated, and that the most prospective area remained untested. This area is the highest and broadest part of the island west and south of the salt lakes, where a significant fresh-water lens might be expected to occur. A programme of shallow drilling to investigate this hypothesis was therefore recommended. Drilling was carried out during 1976, and it demonstrated the presence of substantial reserves of potable water. Production of water from the area began in October, 1976.

INTRODUCTION

Rottnest Island is situated some 18 km west of the mainland coast of Western Australia opposite Perth. It is administered by the Rottnest Island Board as a holiday resort.

The supply of domestic water for the Thomson Bay settlement on Rottnest, in sufficient quantities and at reasonable cost, has been a major problem for more than 60 years (Somerville, 1949). When a decision was made in 1975 to build a new settlement beside Geordie and Longreach Bays it was expected that the water-supply situation could become even more acute. An earlier attempt to obtain artesian water below the island had been unsuccessful, but the Public Works Department suggested that further deep drilling might be warranted, and the Geological Survey was therefore asked to review the artesian-water prospects of the island. I was invited by the Director to examine the question because of my familiarity with the results of geophysical surveys and drilling for petroleum on the continental shelf around Rottnest, and my long-standing interest (based on holiday visits) in the surface geology of the island. Additional field work for this investigation occupied eight days in January and March 1976.

I wish to express thanks for the cooperation received during this study from staff of the Rottnest Island Board, especially the manager, D.J. Sullivan. The Director of Fisheries and Wildlife, B.K. Bowen, kindly made available his Department's Landrover on the island for my use. Special thanks are due to G.W. Kendrick, who made fossil collections from the Holocene Herschell Limestone, and prepared the appendix to this report dealing with this fauna. Important information relating to the geology and ecology was also provided by B.E. Balme, R.W. George, E.P. Hodgkin, and L.M. Marsh. The management of West Australian Petroleum Pty Ltd agreed to the release of some details of their seismic surveys around Rottnest. Useful advice on the old army water-supply system on the island was obtained from T. Boreham, G.E.M. Dean, and R. Wade. L.J. Hanley made available several army files in the Commonwealth Archives. The assistance and cooperation of all these people is gratefully acknowledged.

HISTORICAL REVIEW

Rottnest was discovered by the Dutch navigators of the 17th century, the first to record the island on a map being Samual Volkersen of the ship Waeckende Boeij in 1658. It was named "Rottenest" (meaning Rat's Nest) by Willem de Vlamingh in 1696, at the beginning of his voyage along the west coast between Swan River and North West Cape. Vlamingh's "rats" are the marsupial quokkas (wallabies) which still abound there.

Rottnest was first settled for agriculture in 1831, but the Government resumed all private holdings in 1839, following the establishment of an Aboriginal prison on the island in 1838. In 1903 it was decided to close the prison and to develop Rottnest as a holiday resort, although some prisoners continued to be held there until 1931 (Somerville, 1949).

The growth of holiday-resort facilities proceeded rather slowly in the years before and immediately after World War II. However, in recent years the Rottnest Island Board has embarked on a major programme of expansion in the accommodation available on the island, and construction of a second settlement, fronting Geordie and Longreach Bays, began in 1976.

The first detailed publication on the geology of Rottnest was by Teichert (1950). He dealt mainly with the eastern part of the island, and carefully described evidence displayed there for Quaternary sea-level changes. Earlier brief references to the geology had been made by Somerville (1921), Aurousseau and Budge (1921), and Clarke (1926).

Hassell and Kneebone (1960) studied the geology of Rottnest as a B.Sc. Honours project at the University of Western Australia. A summary of part of their work was published by Glenister, Hassell, and Kneebone (1959) in the volume on Rottnest scientific research edited by Hodgkin and Sheard (1959).

The regional geology of the Perth Basin, which includes Rottnest, is described by Playford and others (in press). A preliminary report on the present project was prepared by Playford (1976).

PHYSIOGRAPHY

Rottnest is the largest island in a chain of limestone islands and reefs on the continental shelf near Perth. This chain also includes Garden, Carnac, and Penguin Islands, Stragglers Reef, and Five Fathom Bank (Fig.1). Rottnest is about 10.5 km long (east-west), up to 4.5 km wide, and covers about 1 900 ha.

The island is composed wholly of Quaternary deposits - mainly Pleistocene limestone and Holocene dune sand. The coastline is characterized by alternating bays and limestone headlands, the bays generally having wide sandy beaches, backed by sand dunes (Plate 1, Figs 2, 3). The coast is fringed by limestone reefs and by several small islands.

Most of Rottnest consists of undulating limestone hills and sand dunes, reaching a maximum elevation of 45.2 m at Wadjemup Hill. About 43% of the island is more than 10 m above sea level, and 12% is above 20 m (Fig.4). The northeastern part of the island encloses a belt of salt lakes, which occupy some 200 ha, or about 10.5% of the area of the island. The lake levels range from close to mean sea level in winter to between 0.8 m and 0.4 m below mean sea level in summer. The average summer salinity of the lakes, about 155 000 mg/l, is more than four times that of the sea. Lake Timperley has the lowest salinity of the lakes (68 000 mg/l in March, 1976) as it is fed by several brackish-water seepages and is smaller than the others. Its summer water level is several centimetres higher than that of the adjoining Serpentine Lake, and a narrow stream of water flows from one to the other. Salinity measurements taken in 1976 on water samples from several lakes and swamps are shown on Table 1.

The lakes have elongate-ovoid to sub-circular shapes, the general direction of elongation being west-southwest. Government House Lake is the deepest, reaching a depth of 8.5 m in its centre (Hassell and Kneebone, 1960). Each lake is rimmed by a platform, up to several metres wide, which is dry in summer and covered in winter. Lake Negri, Lake Sirius, and both Pearse Lakes normally dry up completely by the end of summer.

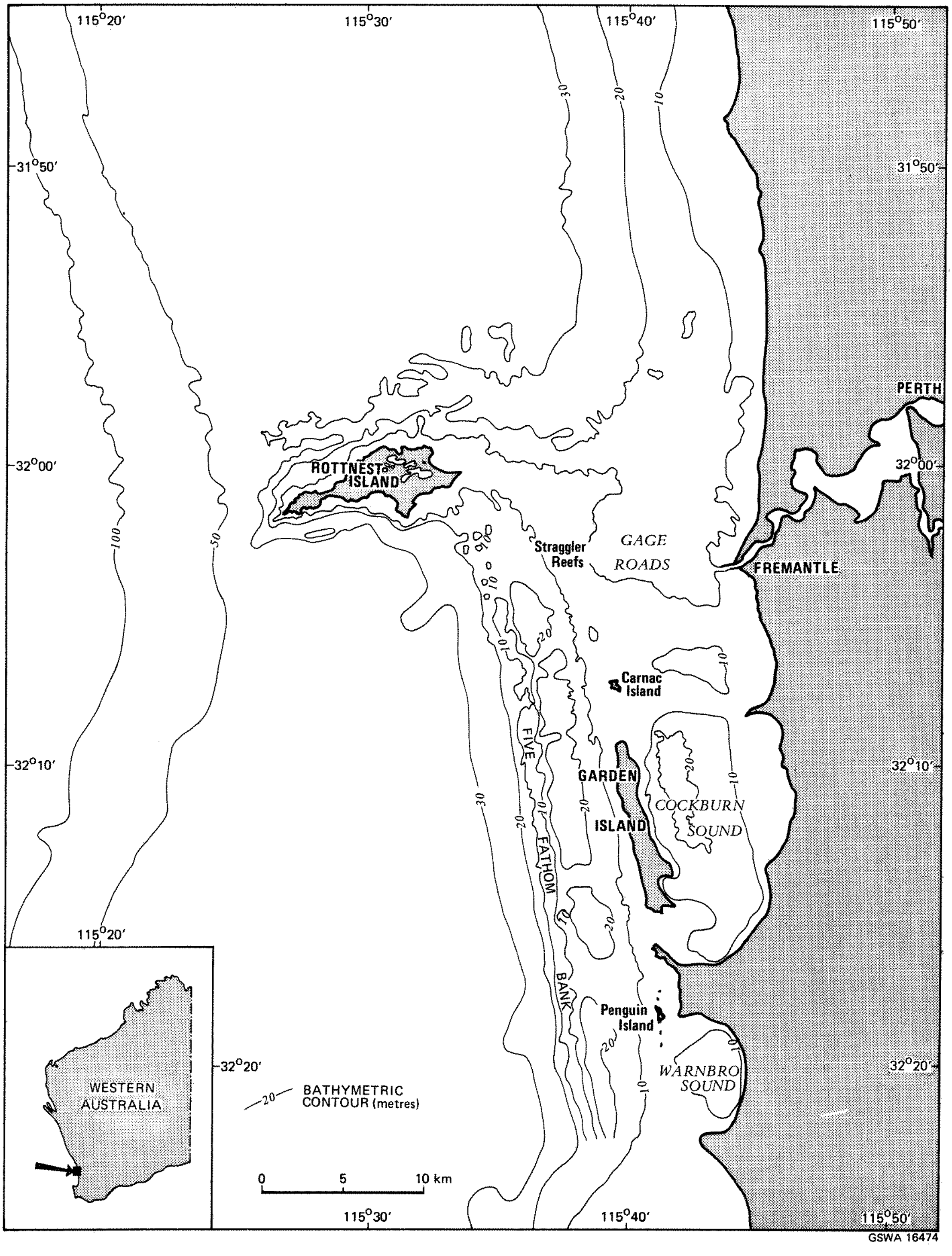

Figure 1 Locality map, Rottnest area, showing bathymetry.

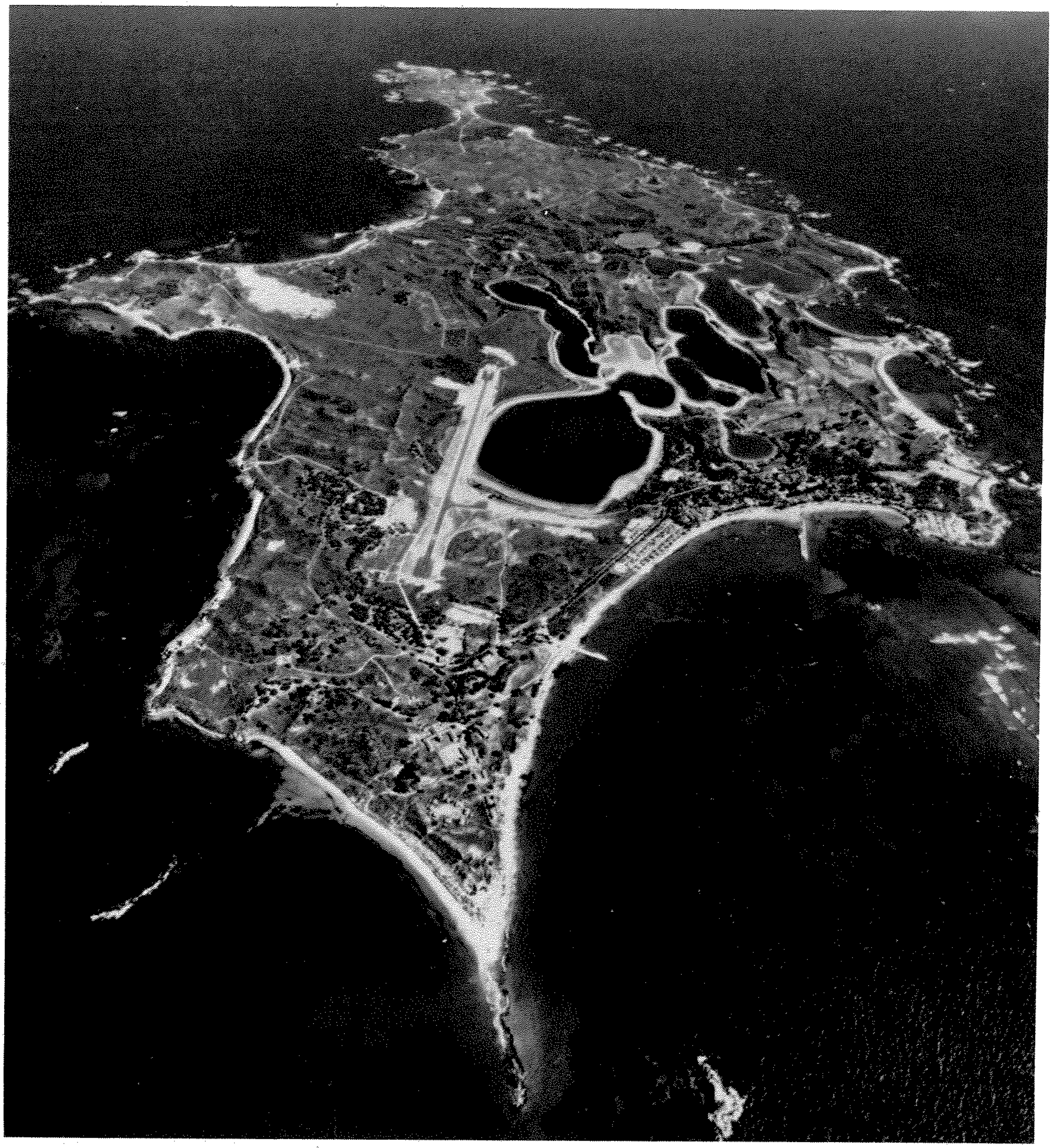

Figure 2 Oblique aerial view of Rottnest Island, looking west-southwest from near Phillip Point. Photo by courtesy of Department of Lands and Surveys, Perth.

Figure 3 The Basin, view looking east towards Bathurst Point Lighthouse. The sandy beaches, rocky headlands, and intertidal shoreline platforms (submerged in the photo) in this view are typical of those found on the island.

TABLE 1. Salinity measurements, salt lakes and swamps

Lake	Sample date	Salinity (mg/l)
Government House Lake	24-2-76	164 000
Serpentine Lake	25-2-76	160 000
Lake Timperley	14-3-76	68 000
Garden Lake	25-2-76	141 000
Lake Baghdad	25-2-76	144 000
Herschell Lake	25-2-76	158 000
Pink Lake	25-2-76	210 000
Bickley Swamp	24-2-76	157 000
Lighthouse Swamp	25-2-76	14 000
Salmon Swamp	24-2-76	282 000
Parakeet Swamp	24-2-76	56 000
Bulldozer Swamp	24-2-76	66 000
Barker Swamp	24-2-76	2 500

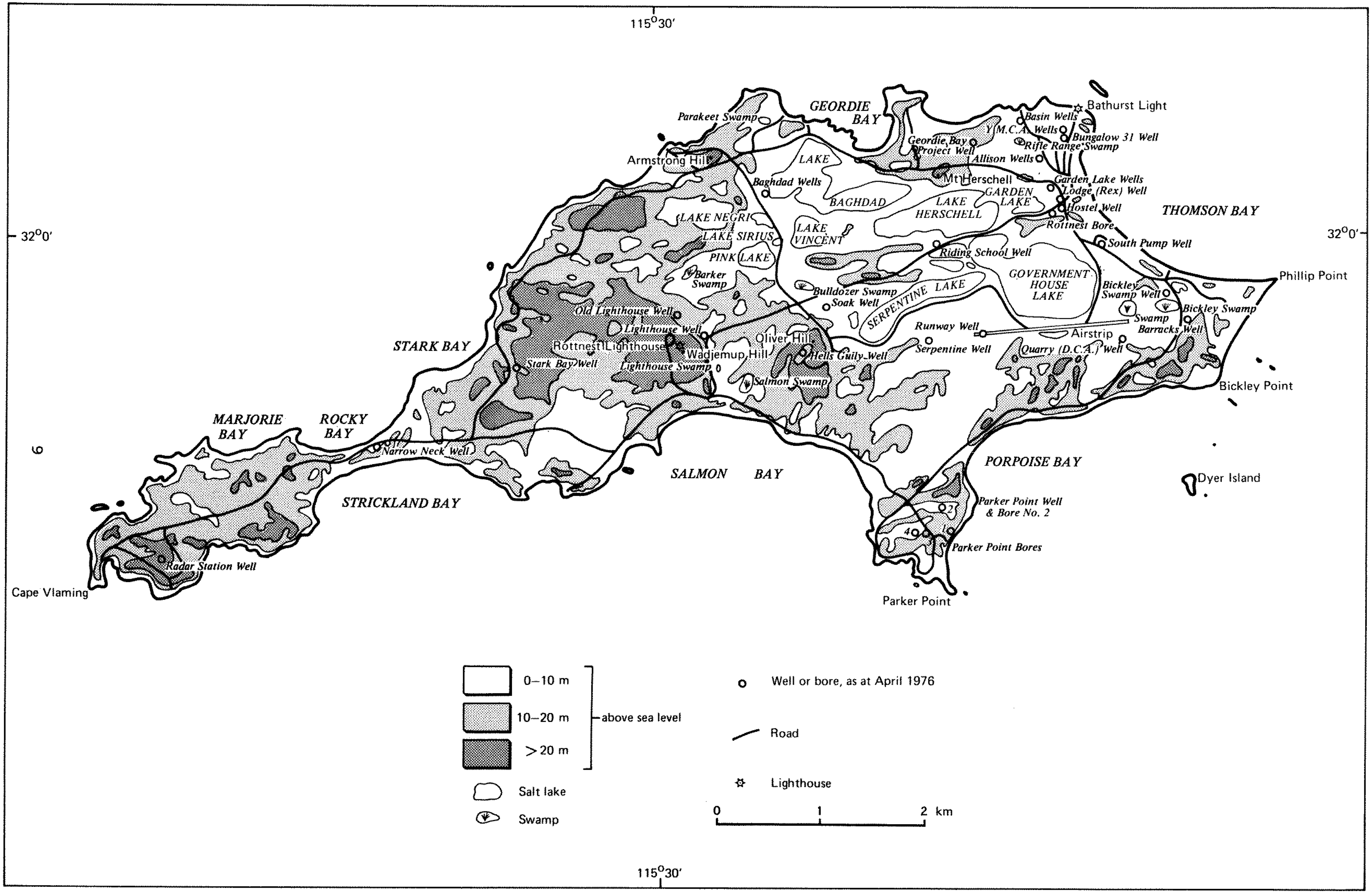

Figure 4 Rottnest Island, relief map.

There are also a number of small swamps on the island, most of which once contained fresh to brackish water in winter and dried up in summer. However, all but one of these swamps (Barker Swamp) have now been excavated for marl (used for road building), and as a result most of them permanently contain salt water (Table 1).

Rottnest has an extreme mediterranean climate, characterized by wet winters and extremely dry summers (Fig.5). The mean annual rainfall is 736 mm, and the annual evaporation is about 1 500 mm. Nearly 75% of the rain falls in four months, from May to August, whereas only 5% falls from November to February. The island has no significant watercourses, and nearly all the rain is absorbed into the surface sand and limestone. Part of this water is lost to the atmosphere by evaporation from the soil, and part of the transpiration of plants. The rest moves laterally below the water table to the ocean and salt lakes. Numerous small fresh- to brackish-water seepages occur around the lake margins.

The original vegetation of the island consisted of forests of tea tree (*Melaleuca pubescens*), wattle (*Acacia rostellifera*), and Rottnest Island pine (*Callitris preisii*), interspersed with open heath (Storr and others, 1959). The early explorers and settlers made frequent reference to the widespread forest cover, and Dr. N.G. Marchant of the W.A. Herbarium (personal communication, 1976) estimates that forest once covered about 65% of the island. Air photos show that by 1941 this had been reduced to 23%, while today native forest occupies only 5% of the island, and an additional 6% is occupied by reforested areas (containing both indigenous and exotic species). The rest of the island is now covered by open low heath, characterized by the prickly scrub *Acanthocarpus preissii* and the native grass *Stipa variabilis*. The native forest has been lost as a result of human activities - mainly fires and timber cutting. Regeneration of trees in many burnt areas has been prevented in recent years by a "population explosion" of quokkas, which has resulted in new growth being eaten out (Storr, 1963).

Deforestation of the island can be expected to have raised the water table over wide areas, as the amount of groundwater lost through plant transpiration must have been greatly reduced. However, there are no data available to quantify the amount of any such rise in the water table.

The maximum daily tidal range at Rottnest amounts to about 1 m, and the extreme range is about 1.5 m. Sea level is strongly influenced by air pressure, water temperature, and the prevailing winds (Hodgkin and others, 1959).

Intertidal shoreline platforms ("reefs") which fringe most of the island range from a few metres up to about 100 m in width (Fig.3). They are cut almost horizontally into eolianite of the Tamala Limestone, and range in elevation from just below low-water mark to almost mean sea level. Most approximate low-water level. In some places "paddy-field" terraces are conspicuous on the platforms, the stepped terraces extending through a maximum vertical range of about 1 m above the surrounding platform level (Fig.6).

The platforms normally meet limestone headlands and cliffs at undercut shoreline notches, each of which extends back some 1 to 2 m below an overhanging visor, or at sloping shoreline ramps. The intertidal platforms themselves are commonly deeply undercut below sea level, and in some areas parts of the platforms have consequently collapsed. The limestone of each notch, visor, ramp, and platform is strongly indurated, whereas most of the rest of the Tamala Limestone is only weakly cemented.

The outer rim of each platform commonly has a raised rim, protected by the coralline alga *Lithothamnium*. Limestone crusts precipitated by this alga are also common on some other parts of the platforms, and *Lithothamnium* nodules occur in certain areas (for example near Green Island). Brown algal polygons are conspicuous in a few areas on the platforms; the reason for their distinctive growth form is unknown (Fig.6). Hermatypic corals occur in some places, generally only as scattered colonies in holes and on the outer edges of platforms, but in a few areas they are more extensive, forming coral reefs (such as Pocillopora Reef beside Salmon Point). Details of some other aspects of the fauna and flora of the intertidal platforms at Rottnest are given by Hodgkin and others (1959).

The processes of erosion which form the intertidal platforms and their associated notches and ramps are not fully understood, but these features probably result from a combination of mechanical abrasion and chemical and biochemical corrosion (Hodgkin, 1964, 1970). Hodgkin (1964) has shown that the intertidal platforms and associated notches in Western Australia are being eroded at rates of about 1 mm per year.

GEOLOGY

SURFACE GEOLOGY

Rottnest is composed of Pleistocene to middle Holocene dune limestone

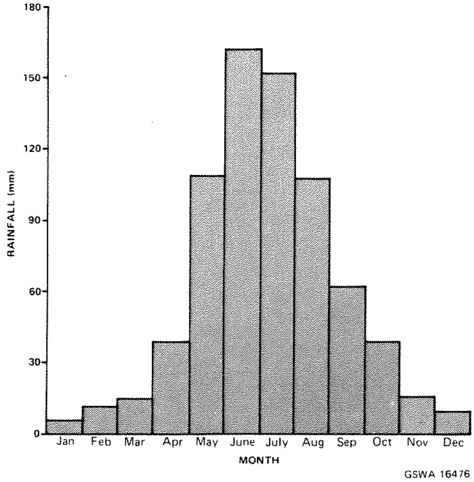

Figure 5 Rottnest Island, annual rainfall.

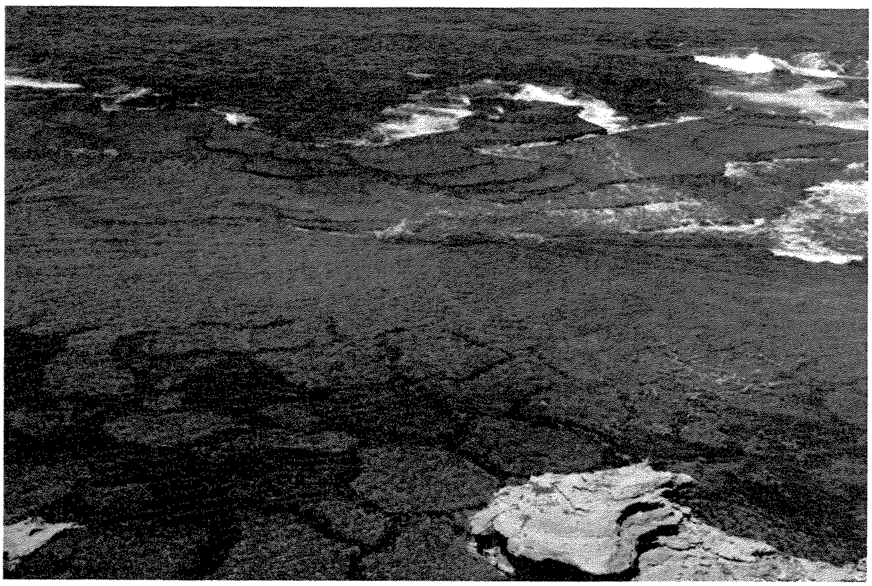

Figure 6 View looking south over the intertidal shoreline platform at Wilson Bay, showing algal polygons in the foreground and "paddy-field" terraces near the platform margin.

(Tamala Limestone) with a thin intercalation of Late Pleistocene marine limestone (Rottnest Limestone), overlain by Holocene shell beds (Herschell Limestone), dune sand, beach sand, swamp deposits, and lake deposits. The surface geology of the island is illustrated on Plate 1.

Tamala Limestone

The Tamala Limestone is a unit of dune limestone (calcareous eolianite) which crops out along much of the coast of Rottnest Island and along the margins of the salt lakes. It also occupies much of the interior, but is largely obscured there by thin soil cover.

The Tamala Limestone was originally named "Tamala Eolianite" in the Shark Bay area of the Carnarvon Basin, and the name was amended by Playford and others (in press) who extended the unit to include Pleistocene eolian calcarenites in the Perth Basin. The type locality is at Womerangee Hill on Tamala Station, south of Shark Bay.

The formation is composed of white to pale-yellow, grey-weathering, fine- to coarse-grained skeletal-fragment calcarenite with variable amounts of quartz sand. It commonly shows large-scale eolian cross bedding (Fig.7). Depositional foreset dips of up to 35° have been measured in the unit at Rottnest.

The limestone varies from strongly lithified to friable. Hard calcrete horizons occur in places, and these are commonly overlain by grey to brown fossil soils (marking old land surfaces), and underlain by softer limestone with abundant fossil-root structures (Fig.8). However, a calcrete layer is not always present between a fossil soil and the underlying fossil-root horizon. The old soils often contain fossil land snails (*Bothriembryon*) and weevil pupal cases (*Leptops*). The fossil-root structures have formed by lime precipitation around roots of trees and shrubs which grew in the original dunes. The fossil soils, calcretes, and root horizons mark periods of local still-stand in dune development which allowed time for soil to develop and vegetation to become established, before being overwhelmed again by advancing dune sand.

The thickness of the Tamala Limestone in the Rottnest area is probably up to about 115 m (including some 70 m of section below sea level). Most of the exposed formation is believed to be younger than the Rottnest Limestone coral

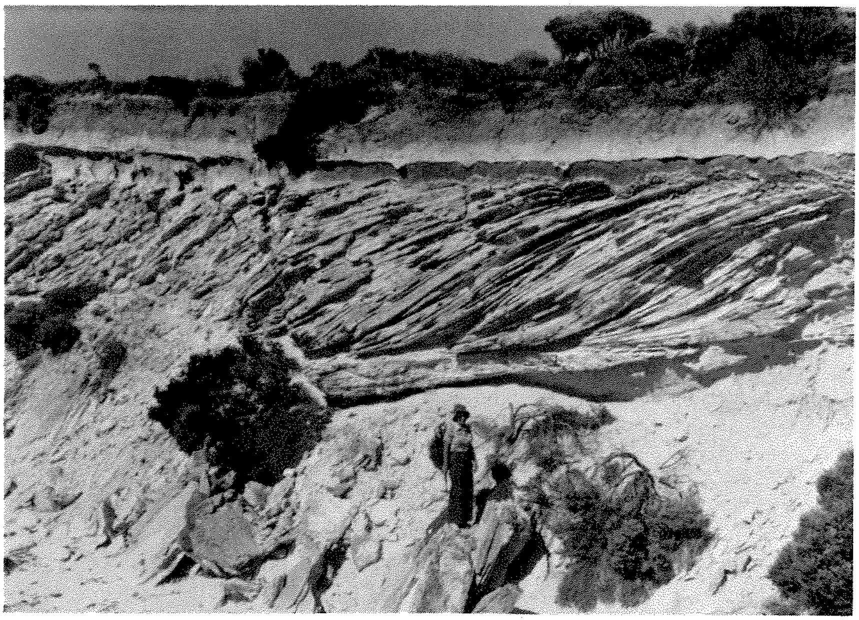

Figure 7 Tamala Limestone exposed on the west side of Strickland Bay, showing well-developed eolian foreset and bottomset bedding. Also note the well-developed soil horizons at the cliff top.

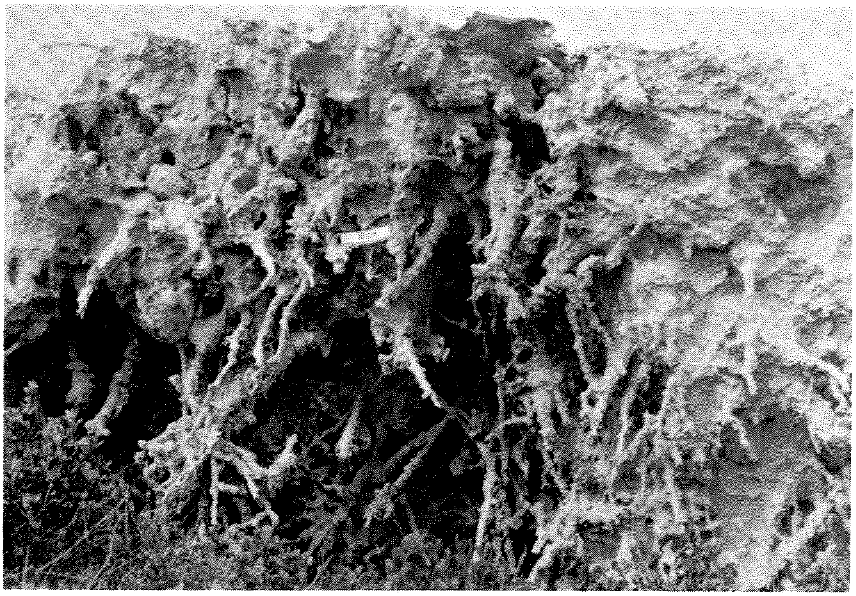

Figure 8 Typical fossil-root structures in Tamala Limestone at Salmon Point.

reef, which is dated as 100 000 ± 20 000 years B.P. However, part of the Tamala Limestone is older than the reef, and at least some of this was probably deposited during the Riss Glaciation and the following transgression. The youngest Tamala Limestone is believed to be of Holocene age, laid down during the Flandrian Transgression. The contact with the overlying Holocene dune sands is transitional, as lithification of these sands is taking place gradually below the surface.

The Tamala Limestone forms the main shallow aquifer at Rottnest. Its reservoir characteristics are variable in any one area, depending on the degree of cementation and sorting of the lime sand in the rock. No evidence has been found of any significant cavernous porosity in the subsurface.

Rottnest Limestone

The Rottnest Limestone (Fairbridge, 1953) is a unit of coral-reef and shelly limestone exposed at Fairbridge Bluff (named here in honour of Rhodes W. Fairbridge) in Salmon Bay (Figs 9, 10). It is overlain and underlain by Tamala Limestone at this locality, but elsewhere it is believed to interfinger with that formation. The total exposed thickness of the Rottnest Limestone is nearly 3 m, but the lowest part is not exposed as it extends below sea level on the erosional contact with the underlying Tamala Limestone. The formation crops out for about 150 m along the low sea cliff forming Fairbridge Bluff. It does not crop out elsewhere on the island.

The coral reef and associated deposits are described by Teichert (1950) and Hassell and Kneebone (1960). Teichert states that branching species of *Acropora* predominate in the reef, mixed with some foliose types, and that large colonies of *Platygyra lamellina* and *Favites favosus* occur in some places. Coralline algae (*Lithothamnium?*) encrust many of the corals and have contributed significantly to the reef frame. Shelly limestone containing the gastropods *Turbo (Marmarostoma) pulcher*, *Coralliophila costularis*, *Pyrene bidentata*, and *Conus* sp. cf. *C. lividus* is associated with the reef (identified by G.W. Kendrick, written communication, 1977).

The Rottnest Limestone has been dated by uranium/thorium methods as being 100 000 ± 20 000 years old (Veeh, 1966, Teichert, 1967). At that time sea level must have been at least 3 m higher relative to Rottnest Island than at present. However, it is quite possible that the top of the exposed reef

Figure 9 Branching corals (*Acropora* sp.) in growth position in the Rottnest Limestone at Fairbridge Bluff.

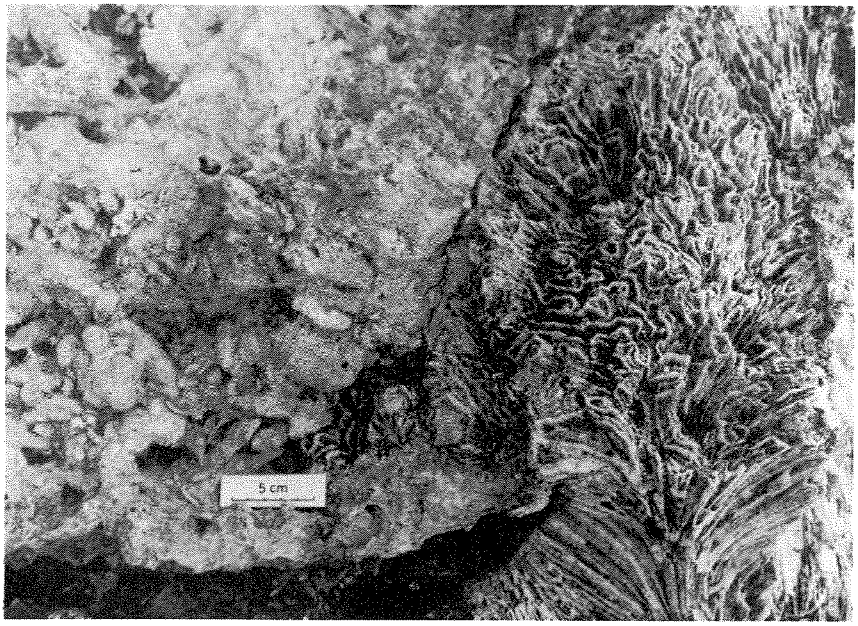

Figure 10 Colony of brain coral (*Platygyra* sp.) in growth position in the Rottnest Limestone at Fairbridge Bluff.

at Fairbridge Bluff could have grown in water a few metres deep. Shell beds at Minim Cove on the Swan River estuary, that are thought to be of the same age as the Rottnest Limestone, were deposited when sea level was relatively about 7 m higher than today (Fairbridge, 1953).

The coral fauna of the Rottnest Limestone indicates warmer water conditions than at present. *Acropora* is the main genus in the Rottnest Limestone, but it is not now found living south of the Abrolhos Islands reefs, 350 km north of Rottnest, where it is the dominant genus. Seven species of hermatypic corals are recorded from modern reefs around Rottnest (L.M. Marsh, written communication, 1976), but none of these are known to occur in the fossil coral reef.

The Rottnest Limestone does not form a significant aquifer on the island.

Herschell Limestone

The name Herschell Limestone is proposed for the unit of Holocene shell beds with intercalated lime sand and marl which is exposed around the margins of the Rottnest salt lakes, disconformably overlying and abutting the Tamala Limestone, and overlain by Holocene dune, swamp, and lake deposits. It is named after Mount Herschell, and the type section is in the small quarry 300 m southwest of the summit ($31^{\circ}59'45''$S, $115^{\circ}31'30''$E). This section is 3 m thick, but only the upper 1.5 m is well exposed. It consists of weakly lithified bivalve-gastropod coquina interbedded with cross-bedded lime sand containing scattered shells, and is overlain by weakly lithified dune sand containing shell fragments and *Leptops* pupal cases.

The Rottnest Island Board has previously worked the Mount Herschell quarry for road-building material, but owing to its geological importance the Board has now agreed to preserve the site without further excavation.

The Herschell Limestone is weakly lithified to unlithified in most areas, but it is well cemented on the lake platforms that are alternately exposed in summer and submerged in winter. These platforms are cut in Tamala Limestone, and are partly covered by a thin veneer of Herschell Limestone. They have been mapped as Herschell Limestone without attempting to differentiate areas where the veneer of this formation is absent.

Figure 11 Herschell Limestone exposed at the type section in Mt. Herschell quarry showing abundant bivalves (mainly *Katelysia scalarina*) and gastropods (mainly *Batillaria estuarina*). Shell orientations indicate current deposition in the upper part of the photo and quiet-water deposition in the lower part.

The Herschell Limestone consists of shallow-marine and beach deposits laid down when the present salt-lake area formed arms of the sea between numerous small islands, and sea level was relatively as much as 3 m higher than at present. Some beds have abundant bivalves with well-developed convex-upward orientation, indicating strong current action, but in other beds the orientation is random, and closed valves occur, indicating quiet-water deposition (Fig.11).

The fossil fauna of the Herschell Limestone is varied and abundant; it includes many species of bivalves, gastropods, and foraminifers, several species of echinoids, hermatypic corals, arthropods, and bryozoans. A detailed faunal list and a discussion of the fauna are given in the appendix, by G.W. Kendrick.

The fauna is dominated by molluscs, the most common species among the larger forms being the bivalves *Katelysia scalarina, K. rhytiphora, Fragum (Afrocardium) erugatum,* and *Brachidontes* sp.; and the gastropods *Monodonta*

(Austrocochlea) constricta, Batillaria (Batillariella) estuarina, and *Cominella (Josepha) tasmanica.* The tiny gastropods *Hydrococcus graniformis* and *Diala lirulata* are extremely abundant. Many shells still show their original colouration.

All fossils recorded from the Herschell Limestone are living species, and most of them still occur in the Rottnest-Fremantle area. G.W. Kendrick (in the appendix) states that six of the mollusc species are now restricted to waters north of Rottnest, whereas another six occur only to the south. There is no positive evidence that the water temperatures around Rottnest at that time were significantly different from those in the area today.

Bivalves from the Mount Herschell quarry have been dated by C14 methods with the following results:

3 810 ± 90 years B.P. (top of unit, Deevey and others, 1959)
4 950 ± 160 years B.P. (lower part of unit, Tamers and others, 1964)
5 660 ± 220 years B.P. (upper part of unit, Tamers and others, 1964)

Bivalves from another locality in the formation (a "pocket" of shells in Tamala Limestone beside Government House Lake) were dated as:

5 180 ± 100 years B.P. (Deevey and others, 1959).

Radiocarbon results thus suggest an age range from about 3 800 to 5 700 years B.P. for the dated parts of the Herschell Limestone. However, the youngest dating (3 810 ± 90 years) seems anomalous beside the others, and it is probably incorrect. It is unlikely that the deposits of two separate transgressions could be represented in exposures at the top of the Mount Herschell quarry. It therefore seems probable that the peak of the transgression responsible for deposition of the Herschell Limestone occurred about 5 000 years ago.

The Herschell Limestone is the aquifer in the Baghdad wells and in a few old abandoned wells (not shown on the map) near the salt lakes. Because of its proximity to the salt lakes and its low elevation, this formation can contain only a thin layer of fresh water, and as a result wells in it rapidly become salty when pumped.

Dune sand

Late Holocene and modern dune sand occurs in various parts of the island, the main developments being in the vicinity of Salmon Bay, Porpoise Bay, Paterson Beach, Thomson Bay, Stark Bay, and Narrow Neck. The dunes are composed of lime sand consisting of fragmentary skeletal material and small amounts of quartz sand. The dunes are up to 35 m high, and generally form only a thin layer over Tamala Limestone or (in a few areas) Herschell Limestone. The maximum thickness of dune sand is probably about 20 m, at Oliver Hill.

Most dunes are firmly fixed by low scrub, and they are being gradually lithified below the surface. Consequently there is a transitional contact with the underlying lithified dunes of the Tamala Limestone. Sand blowouts occur in some areas where the vegetation cover has been lost, the most notable example being Barnett Gully, north of Salmon Point.

Holocene dune sands at Rottnest do not generally extend below the water table over large areas, and therefore they do not form extensive aquifers. The only wells in current use which produce from Holocene dunes are the South Pump wells, south of the hotel. The dune sand in these wells is partly lithified. The disused well at Narrow Neck is also constructed in dune sand.

Beach sand

Modern beach sand at Rottnest has essentially the same composition as the dune sand. Most consists predominantly of skeletal-fragment lime sand, although quartz sand is dominant in a few areas.

Swamp deposits

Holocene swamp deposits on the island are of only minor extent, and consist of thin layers of lime sand, peat, and algal sediments. These are described by Hassell and Kneebone (1960), who also examined the palynology of the deposits. They state that the maximum thickness of swamp sediments ranges from 2.6 m in Salmon and Parakeet Swamps to 4.4 m in Barker Swamp.

Pollen from tuart, jarrah, marri, white gum, sheoak, peppermint, banksia, and zamia palm occur in the deposits at depths of more than a metre below the surface (Hassell and Kneebone, 1960). This shows that tuart woodland typical of the modern mainland coast opposite Rottnest was present on the island in the recent past. A blackboy (*Xanthorrhoea*) stump recovered in 1939 from a well (locality unknown) on Rottnest, at a depth of 5.8 m, was radiocarbon-dated as being 7 090 ± 115 years old (Grant-Taylor and Raffer, 1963). This shows the tuart woodland association (which includes *Xanthorrhoea*) occurred on the island at that time, but it is not known just when this vegetation disappeared. It may have become extinct during the transgression represented by the mid-Holocene Herschell Limestone (probably some 5000 to 5 500 years ago) when the land area was smaller than today and the increased effect of salt spray could have been sufficient to kill this vegetation. It also seems that the climate then was significantly drier than at present, and this factor may also have contributed to the extinction (Kendrick, in press).

Lake deposits

Modern salt-lake deposits, consisting of algal and evaporitic sediments, occur as thin veneers on the floors of the salt lakes and around their margins. They overlie Herschell Limestone. Common salt was gathered commercially for more than 100 years from Pearse Lakes, two small salt pans adjoining Government House Lake, which normally dried out completely by the end of summer. The last recorded production was in 1952.

Hassell and Kneebone (1960) describe algal gyttja in the lake deposits. It consists of gel-like material from the alga *Botryococcus* mixed with gypsum and lime mud. They also record edgewise conglomerate at localities along the shores of the lakes, formed by brecciation of lithified algal-mat deposits.

Stromatolites also occur in the salt lakes, the best examples being at the old bathing groyne on the north side of Government House Lake. On the shallow shelf immediately east of the groyne stromatolites occur at depths (relative to summer water level) from about 0.2 m to 3 m. Nodular, branching columns and smooth, rounded, linked columns occur. Most are only about 5-10 cm high, but some nodular forms are up to 20 cm high. The stromatolites become sparser moving into deeper water. Some grew on water-logged tree branches and other debris. From the height of stromatolites growing on old bottles it is deduced that they grow at rates of up to 1.5 mm per year. Bubbles of oxygen are visible in the living algal mat, which is greenish to yellow-grey and black in colour.

SUBSURFACE GEOLOGY

Our knowledge of the subsurface geology of Rottnest Island is based on the old Rottnest Bore (788 m deep), and on geophysical and well data obtained from petroleum exploration on the continental shelf by West Australian Petroleum Pty Ltd (Wapet). This company has conducted extensive seismic surveys and has drilled seven offshore wells in the vicinity of the island. Most details of the geophysical work have not yet been made public, but the company has released the interpretive fault data shown on Figure 12.

The total sedimentary section below Rottnest is believed to be about 10 000 to 12 000 m thick, and is Tertiary, Cretaceous, Jurassic, Triassic, Permian, and possibly older Palaeozoic in age. This is the normal Perth Basin sequence as described by Playford and others (in press). Rottnest overlies the eastern edge of the Vlaming Sub-basin, which is characterized by its thick Tertiary and Cretaceous sequence.

The section penetrated in the Rottnest Bore is shown on Figure 13. The Leederville Formation (the upper formation of the Warnbro Group) was penetrated in the lower part of the hole, but the underlying South Perth Shale (the lower formation of the group) was not reached.

Seismic surveys have shown that the early Neocomian and older rocks in the subsurface of the area around Rottnest are extensively faulted. Movement is believed to have been normal, and most fault activity ceased during the Neocomian, following the main break-up of the Gondwanaland super-continent (Playford and others, in press). However, some faults in the area cut the Neocomian unconformity between the Yarragadee Formation below and the Warnbro Group above (Fig.12). Faults passing below and to the east of Rottnest Island have west-block-down displacements, whereas those to the west of the island are downthrown to the east.

Rottnest Island is elongated approximately west-southwest, nearly at right angles to the usual north-south coastal trends in this part of the Perth Basin. This suggests the possibility of underlying structural control, but there is nothing in the known subsurface structure of the area to confirm this.

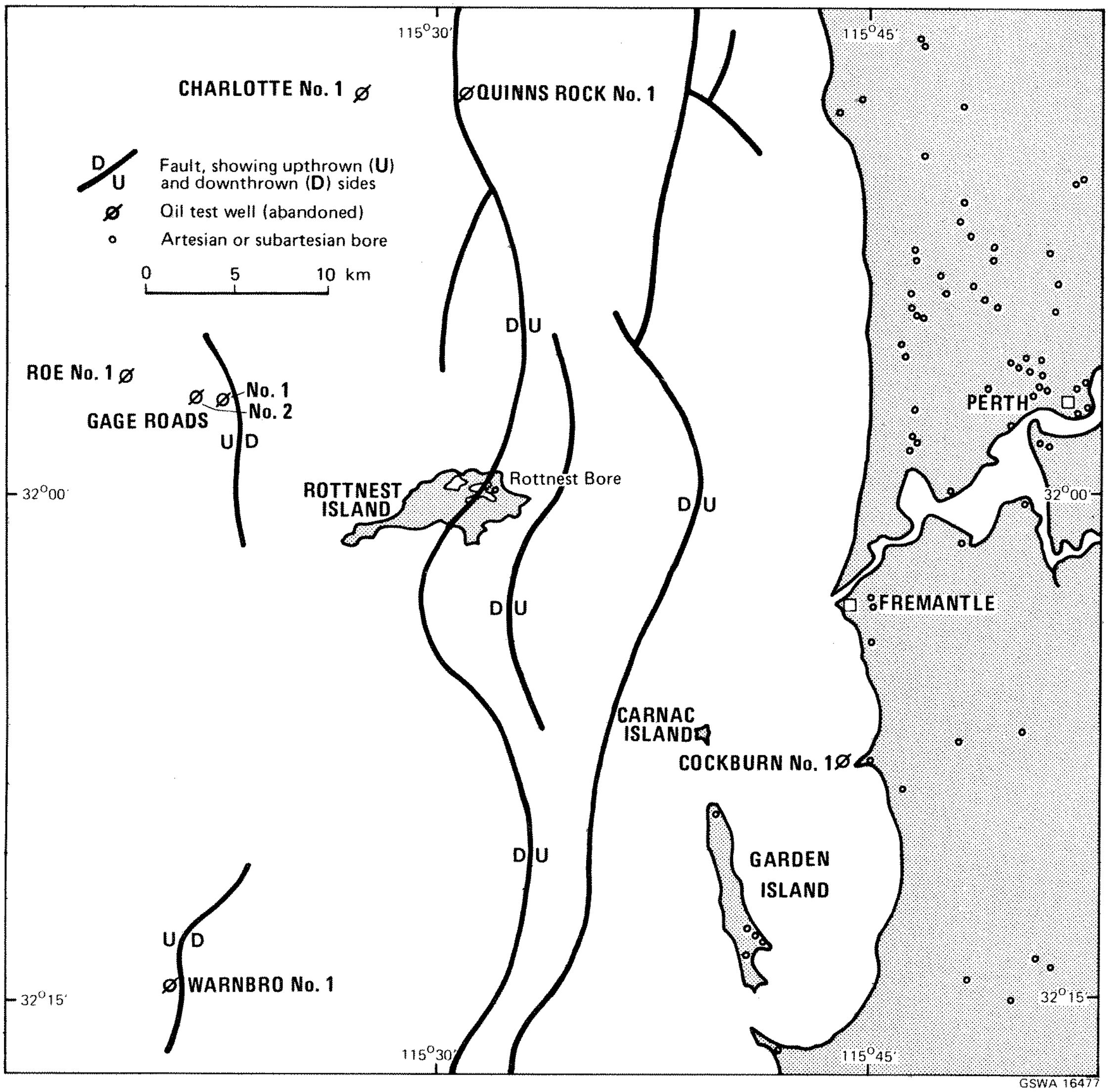

Figure 12 Rottnest Island-Perth area, showing bore locations and faults cutting the Early Cretaceous unconformity.

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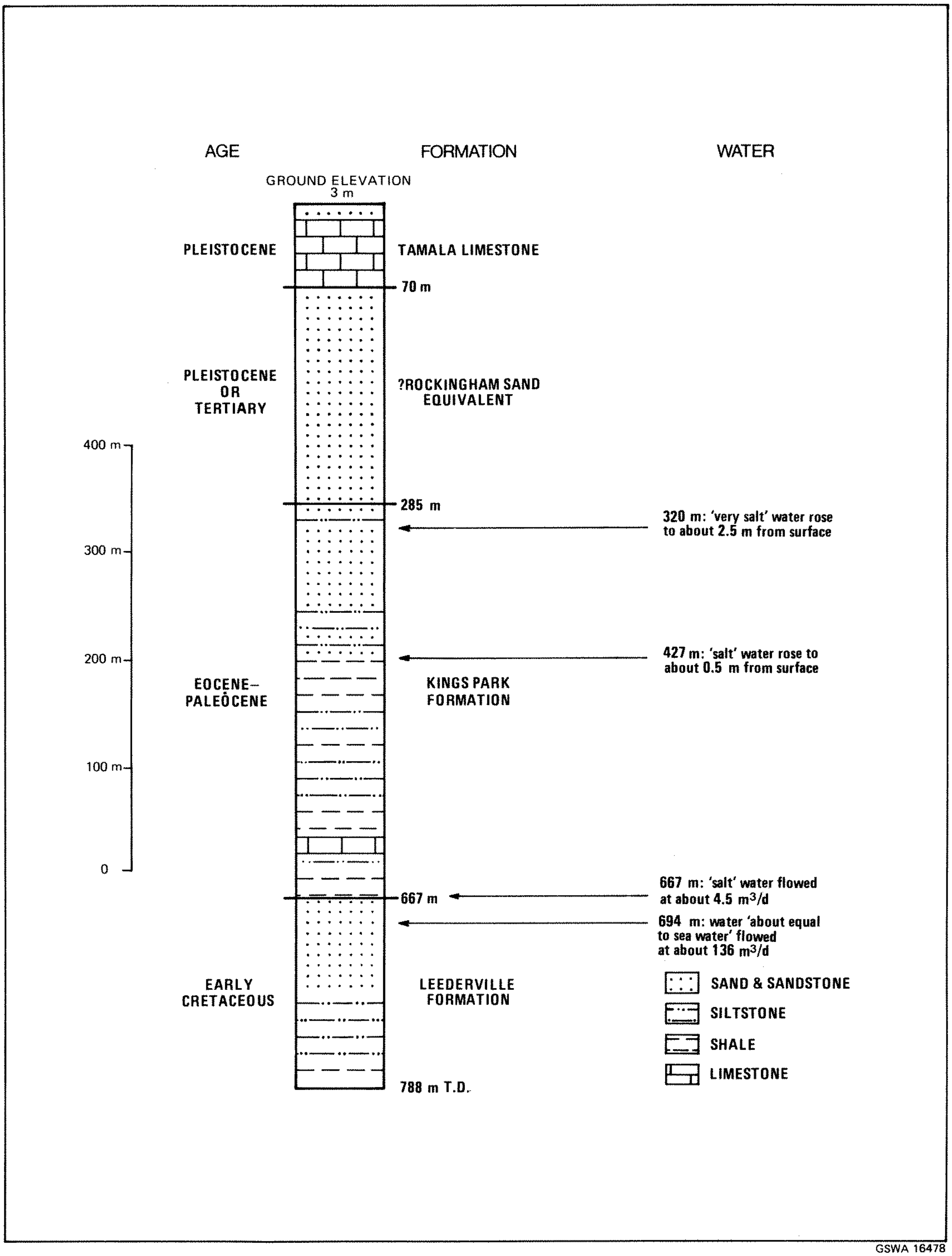

Figure 13 Rottnest Bore, showing stratigraphy and water encountered.

SEA-LEVEL CHANGES

The most interesting feature of the surface geology of Rottnest Island is the evidence displayed there of Quaternary sea-level changes (Teichert, 1950; Churchill, 1959; Fairbridge, 1958, 1961; Hassell and Kneebone, 1960). The main positive evidence is in the form of: (a) elevated marine deposits, (b) elevated intertidal platforms and shoreline notches, and (c) features which formed subaerially, but now extend below sea level.

Elevated marine deposits

The fossil coral reef represented by the Rottnest Limestone extends to about 3 m above low-water-springs tide level, and this indicates a relative change in sea level equal to at least this amount since the reef grew, as already discussed. The reef is about 100 000 years old, which means that it developed during the Riss-Würm Interglacial when sea level is believed to have reached a few metres higher than today's level, because of the smaller extent of the polar ice caps at that time (Fig.23). Confirmation of warmer water conditions is provided by the presence of abundant *Acropora* in the reef, as today this genus is not found south of the Houtman Abrolhos reefs, 350 km north of Rottnest. Similar elevated Pleistocene reefs from the Abrolhos, Dongara, and the mouth of the Greenough River have not been dated, but it seems likely that they too grew during the Riss-Würm Interglacial.

Marine shell beds in the Holocene Herschell Limestone extend to elevations of about 3 m above present sea level. As previously discussed, it seems likely that the maximum transgression associated with deposition of the Herschell Limestone occurred some 5 000 years ago, and that a younger dating (3 810 ± 90 years) obtained from high in the Mount Herschell quarry may be incorrect. This younger dating appears to have been a principal reason for the recognition of a "Younger" Peron Submergence (Fig.25) by Fairbridge (1961). Previously he had recognized only a single Peron Submergence, based on his earlier work at Point Peron (Fairbridge, 1950). However, the more recently published older datings of the Herschell Limestone by Tamers and others (1964) suggest that the Herschell Limestone actually belongs to the "Older" Peron Submergence, and there no longer seems to be any good evidence for the "Younger" submergence. More radiocarbon datings are required to fully resolve this question.

Elevated platforms and notches

The elevated intertidal platforms and shoreline notches on Rottnest have been described by Teichert (1950) and Hassell and Kneebone (1960). They are also referred to by Fairbridge (1958, 1961) in his analysis of eustatic sea-level changes.

Three levels are recognized; an upper level at about 3 m, an intermediate level at about 1.5 m, and a lower level at about 0.7 m above modern low-water mark.

The upper level is represented by remnants of emerged intertidal platforms and notches about 3 m above the modern platforms. These remnants occur at many places along the coast, for example north of Cape Vlaming (Fig.14) and especially around the salt lakes (Figs 15, 16, 17). They probably formed from about 5 500 to 5 000 years ago, when the highest shell beds of the Herschell Limestone were being deposited.

The intermediate-level and lower-level notches are best preserved around the salt lakes, associated in a few places with weakly developed narrow platforms. They are largely destroyed around the coast of the island, as there they are subject to modern wave erosion, in contrast to the lake area, where there is no significant wave erosion.

Conspicuous "double notches" occur below the 3 m platform at many localities beside the lakes (Figs 16, 17). The 0.7 m notch is more deeply incised than the 1.5 m notch, and this, no doubt, indicates that it formed over a longer period. All three levels are very well displayed at the south-eastern end of the causeway between Government House and Herschell Lakes in the form of a narrow 3 m platform and typical 1.5 m and 0.7 m notches (Figs 15, 16).

These emergent platforms and notches formed when sea level was relatively about 3 m, 1.5 m, and 0.7 m higher than today. Previous authors believed that the intermediate and lower-level platforms formed after the upper-level platform, marking either relatively brief periods of still-stand as sea level fell eustatically from the upper (3 m) level to its modern level (Teichert, 1950, Hassell and Kneebone, 1960), or separate pulses of high sea level post-dating the "Younger Peron Submergence" (Fairbridge, 1958, 1961). However, new evidence indicates that the intermediate and lower-level features must have formed before the upper-level features, during periods of still-stand in sea level during the transgression which culminated at the 3 m level.

Figure 14 View looking north from Cape Vlaming showing remnants of the upper-level (3 m) platform at the foot of the cliffs, adjoining a wide modern intertidal platform.

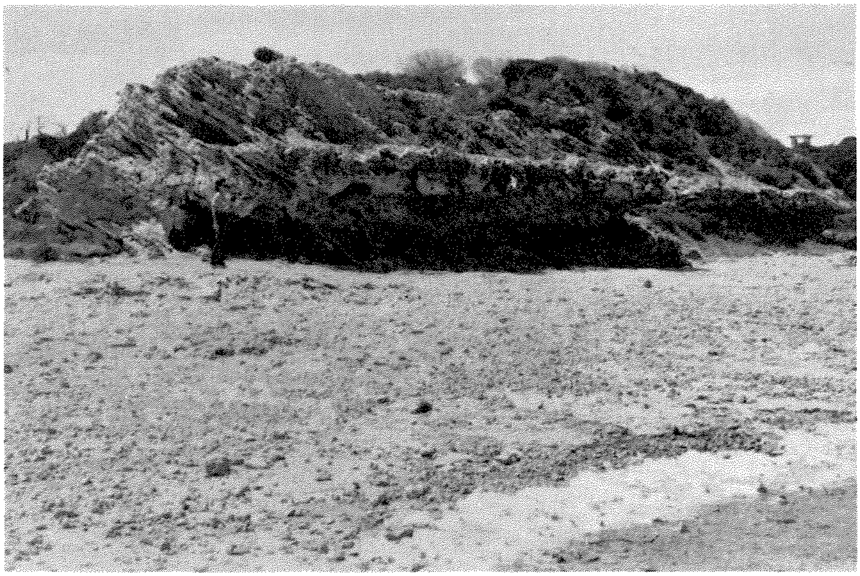

Figure 15 View looking east beside the eastern end of the causeway between Government House and Herschell Lakes, showing the upper-level (3 m) platform and the intermediate-level (1.5 m) and lower-level (0.7 m) notches. The platform and notches are cut in Tamala Limestone showing prominent foreset bedding. The summer shoreline of Government House Lake is shown in the right foreground.

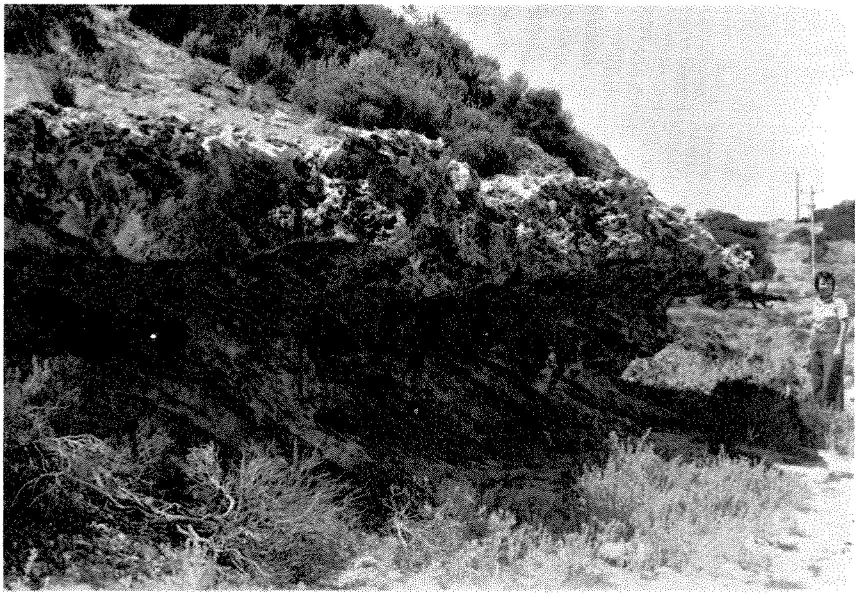

Figure 16 Closer view of the upper-level platform and intermediate-level and lower-level notches at the same locality as figure 15.

Figure 17 View looking southwest on the northwest side of Serpentine Lake, showing well-developed lower-level and intermediate-level notches and eroded lower-level and upper-level platforms. Note that the lower-level notch is deeper than the intermediate-level notch.

This evidence is in the form of an eroded crust of entwined calcareous worm tubes (serpulids), up to 5 cm thick, which once formed an essentially continuous layer over the intermediate and lower-level notches and visors and extended up to within a few centimetres of the 3 m level (Figs 18, 19, 20). It indicates that the notches (and their associated platforms) were already in existence when the transgression reached the 3 m level.

Associated with the serpulid tubes are pockets of bivalves (species which also occur in the Herschell Limestone), and, at one locality on the north margin of Herschell Lake, encrustations of bryozoans and small corals. The serpulids commonly encrust an intensely bored surface. Fine borings (Fig.20) were probably formed by sponges and algae, whereas large tubes have resulted from boring bivalves (Fig.21).

The regression which followed the 3 m still-stand must have been rapid; otherwise marine erosion would have completely destroyed the fragile serpulid crust and the bored rock on the lower and intermediate-level notches and visors. Although some erosion of the serpulid layer has occurred, it is remarkably well preserved at many localities, such as the eastern end of the causeway, the northwest margin of Herschell Lake, and the north margin of Pearse Lakes.

There are a number of localities around the coast where near-horizontal elevated benches occur in Tamala Limestone that are not elevated shoreline platforms. These benches follow indurated horizons which formed below old land surfaces. They are commonly overlain by soft fossil soils and friable limestone, which are readily eroded away. An example occurs east of Cape Hayward.

Subaerial features extending below sea level

Lithified sand dunes of the Tamala Limestone can be seen to extend below sea level at many localities around the coast of Rottnest Island. They may reach a depth of 70 m in the Rottnest Bore. Most of the formation is thought to have accumulated as dunes during the Pleistocene Riss and Würm Glaciations and the Holocene Flandrian transgression, when sea level was lower than today.

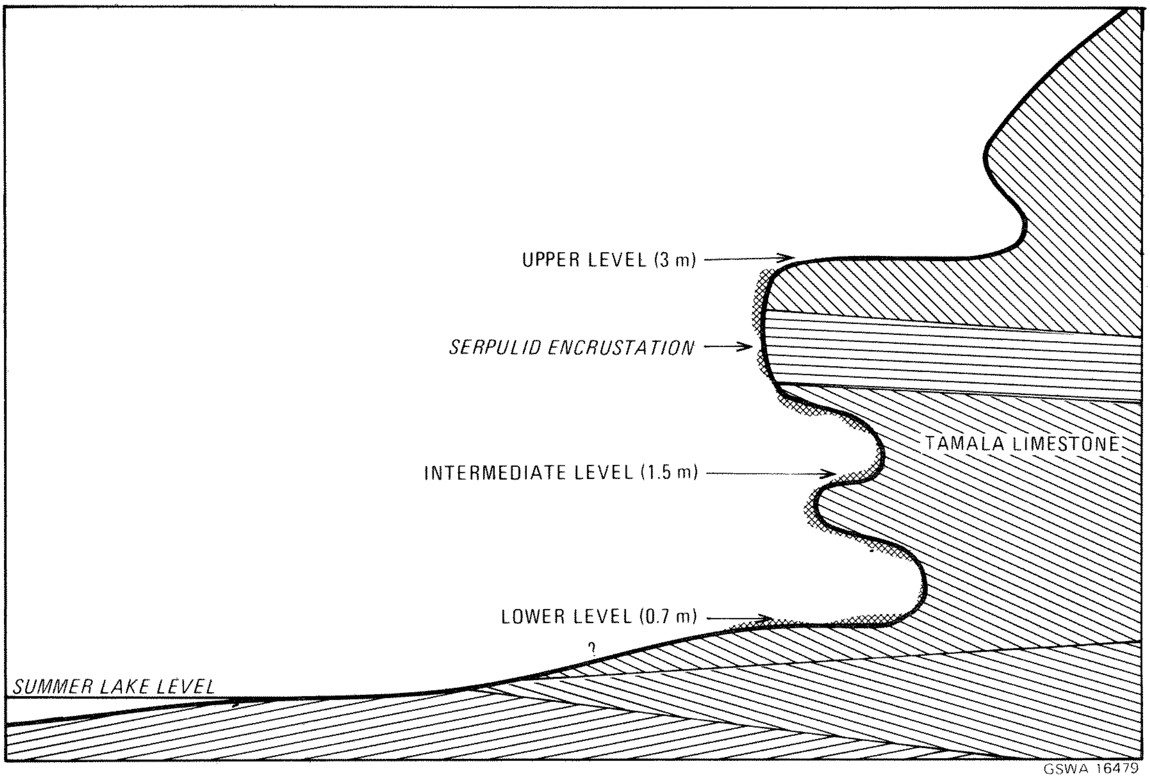

Figure 18 Diagram illustrating elevated platforms and notches around the Rottnest salt lakes. A thin discontinuous layer of serpulid worm tubes is encrusted on the surface almost up to the 3 m level.

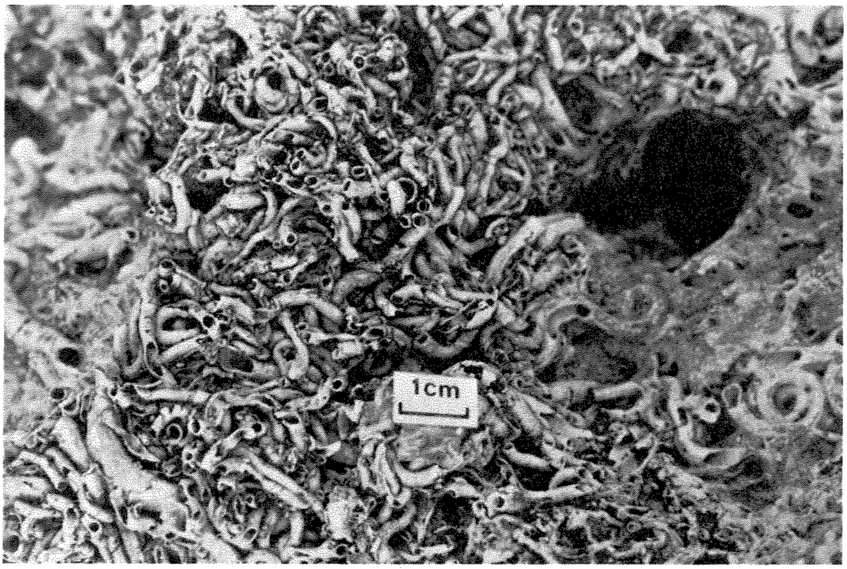

Figure 19 Serpulid worm tubes encrusted on the visor above the intermediate-level (1.5 m) notch north of Pearse Lakes.

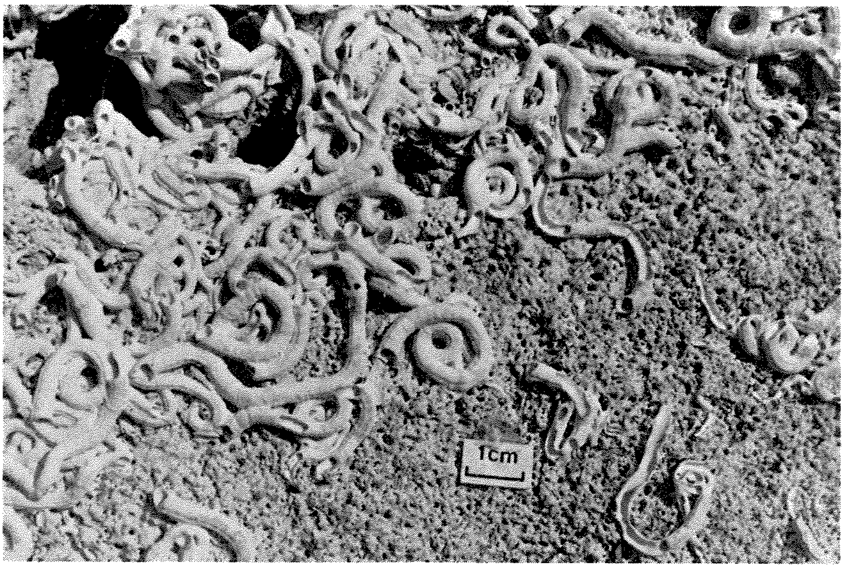

Figure 20 Serpulid worm tubes encrusted on Tamala Limestone that has been finely bored by marine organisms. Photo taken on a bulldozed block from the intermediate-level notch 100 m southwest of Mt. Herschell Quarry.

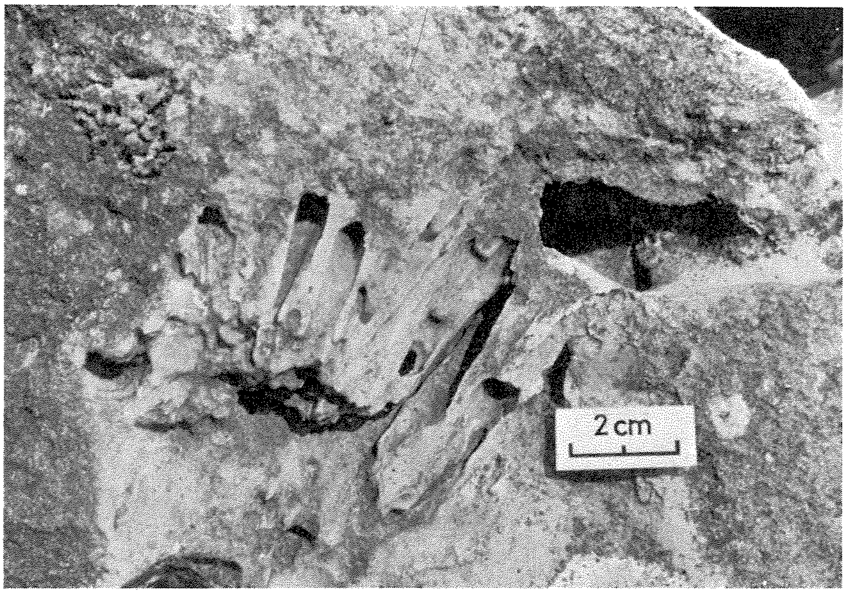

Figure 21 Bivalve borings in Tamala Limestone about 0.5 m below the upper-level platform, 75 m southwest of Mt. Herschell Quarry.

At several localities around the coast, such as the west end of the island and at Fairbridge Bluff, solution pipes (possibly originally localized by tap roots of trees) can be seen to extend below sea level in the Tamala and Rottnest Limestones. They must have formed when sea level was lower than at present.

The salt lakes (Fig.22) probably overlie major dolines formed by solution during the period of greatly lowered sea level (to about -100 m) associated with the peak of the Würm Glaciation. Deep circular to ovoid "blue holes" having similar shapes and dimensions to the Rottnest lakes occur on the Pleistocene reef platforms of the Houtman Abrolhos. Where these have been enclosed in islands by the accumulation of sand and coral rubble they closely resemble the Rottnest lakes. Fairbridge (1948) has ascribed the deep holes on the Abrolhos platforms to solution during the Würm Glaciation, and similar features are recorded from many coral reefs in other parts of the world (Purdy, 1974).

Semi-circular bays on Rottnest such as Eagle Bay and Mabel Cove probably represent parts of similar large dolines that have been breached by modern marine erosion and are now largely filled with sediment.

The modern intertidal platforms around Rottnest are commonly undercut, and Fairbridge (1961) has ascribed this to a period of eustatic lowered sea level, about 2 m below present sea level, during the last few hundred years. However, these undercuts are commonly much deeper than modern shoreline notches, and it seems more likely that they are products of contemporary submarine erosion of the softer limestone below the indurated surfaces of the modern platforms.

Carrigy and Fairbridge (1954) have also described a series of terraces on the continental shelf of the Perth Basin which are considered to represent successive periods of still-stand during Quaternary eustatic sea-level changes.

Origin of sea-level changes

Teichert (1950), Hassell and Kneebone (1960), and Fairbridge (1958, 1961) have ascribed changes in the positions of sea level relative to land at Rottnest to eustatism resulting from waxing and waning of the continental ice caps during the Pleistocene and Holocene. They point to similar evidence in other parts of the southwest of Western Australia, and Fairbridge (1961)

Figure 22 Oblique aerial view looking southwest from near Bathurst Point over Thomson Bay Settlement (left foreground) and the salt lakes. The Mt. Herschell catchment areas and storage tanks are visible in the right foreground. Photo by courtesy of the Department of Lands and Surveys, Perth.

has correlated Quaternary sea-level changes on a world-wide basis. Figure 23 shows the eustatic oscillations deduced by Fairbridge for the past 400 000 years, while Figure 24 compares his curve for the past 6 000 years with that of Mörner (1976), and with the relative sea-level change now deduced to have occurred at Rottnest. Mörner and several other authorities have disputed Fairbridge's evidence for several high eustatic sea-levels during the past 6 000 years (Jelgersma, 1966; Thom and others, 1969, 1972; Mörner, 1971, 1976; Cook and Polach, 1973). These authorities claim that sea level has shown only minor eustatic oscillations over the past 5 000 to 6 000 years, and that it is now close to its highest level since the last glaciation. However, other authorities have published evidence which supports the concept of Holocene sea levels higher than at present (Schofield, 1964, 1973; Gill and Hopley, 1972).

Thus, while there can be no doubt regarding the validity of the major eustatic changes in Quaternary sea level, controlled by advance and retreat of polar ice caps, there is considerable disagreement as to the magnitude of oscillations during the past 6 000 years and as to whether or not sea level has been significantly higher during this period than at present.

Rottnest has long been regarded as being one of the most important localities in Australia for the study of Quaternary eustatic sea-level changes, as there is clear evidence on the island for emergence and submergence at intervals since the Riss-Würm Interglacial, and Western Australia has commonly been considered to be one of the most stable parts of the earth's crust. Earlier authors (Teichert, 1950; Fairbridge, 1959, 1961, and Hassell and Kneebone, 1960) studying the record of changing sea level at Rottnest have accordingly concluded that the changes must have been eustatic.

However, Playford and others (in press) point out that although eustatism must have been of major importance in controlling Quaternary shorelines in the Perth Basin, the picture is likely to be further complication by tectonism. The Darling Fault may have been active in Cainozoic time in the Perth area. Moreover, the Darling Plateau has been uplifted at least 300 m since the Eocene. If this uplift was not accompanied by concomitant down-to-the-west movement along the Darling Fault, the Perth Basin must also have been uplifted, although possibly to a lesser extent than the plateau owing to peripheral sagging of the continental margin. The 1968 Meckering earthquake (magnitude 6.9), centred on the Darling Plateau 100 km east of Perth, suggests that uplift of the plateau may still be occurring, but no movement has been recorded along the Darling Fault in historic times. There is good evidence of the warping of Pleistocene or late Tertiary deposits in the Perth

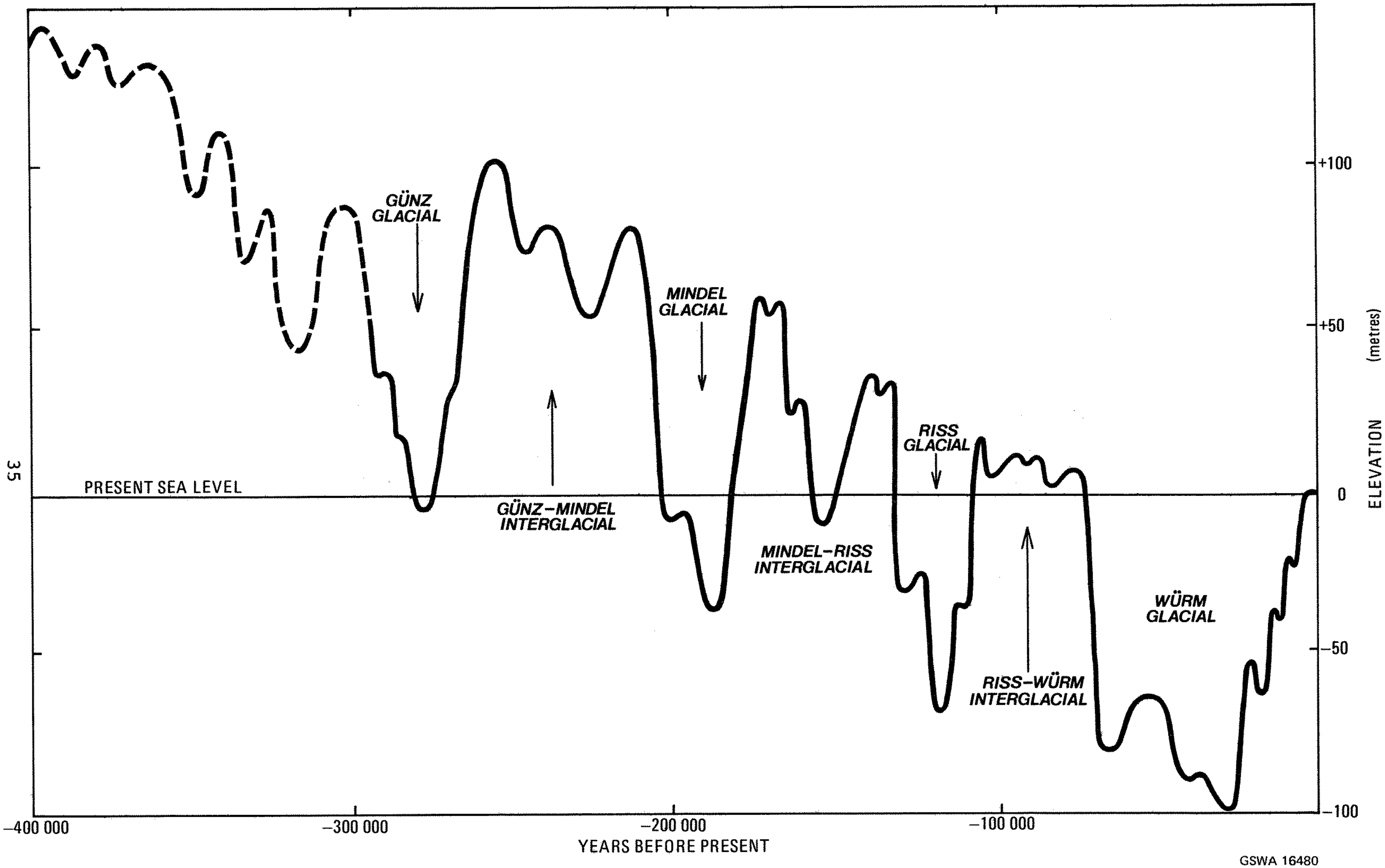

Figure 23 Late Quaternary eustatic changes in sea level according to Fairbridge (1961).

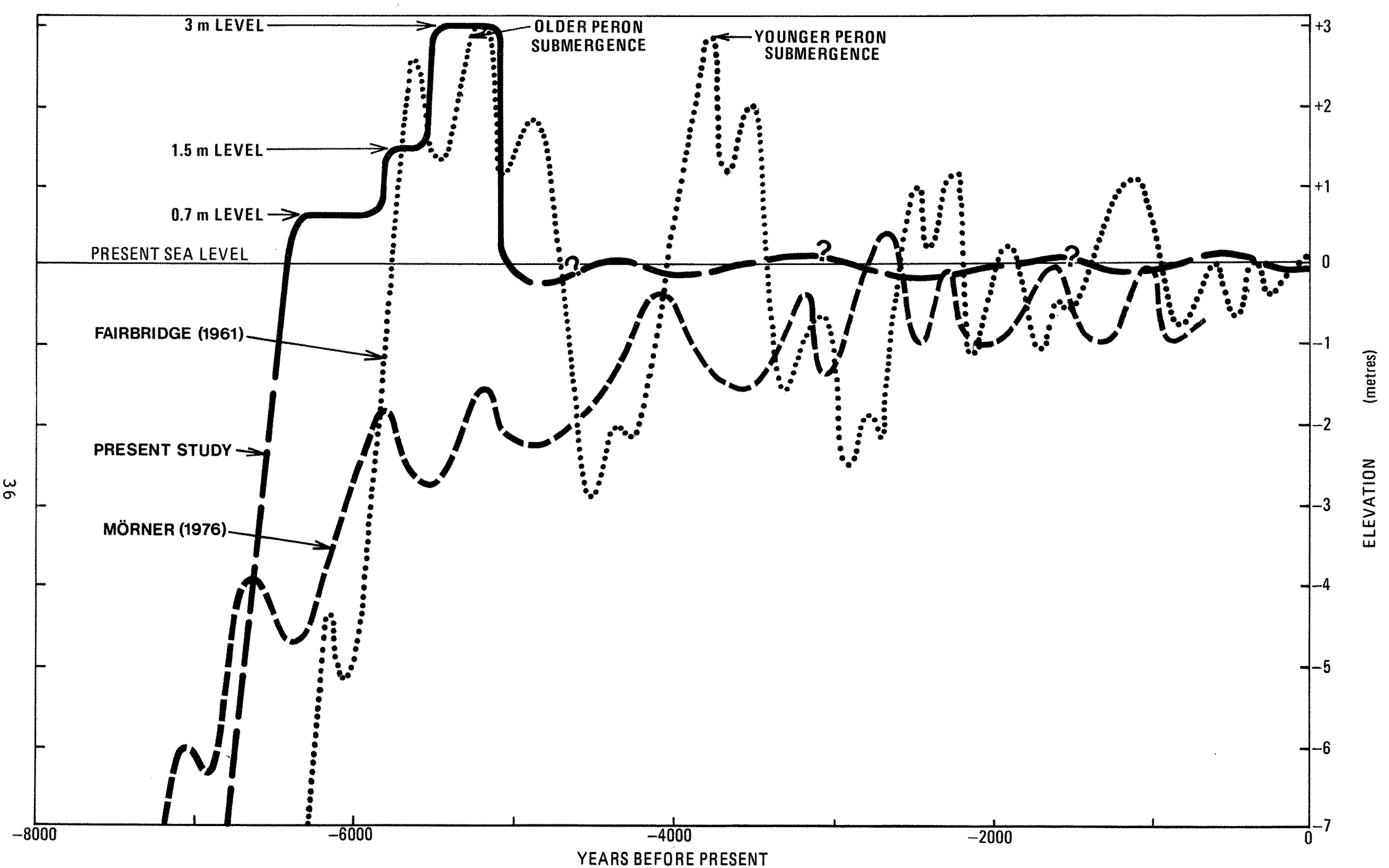

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Figure 24 Diagram illustrating approximate changes in sea level relative to land at Rottnest Island from middle Holocene times to the present, compared with eustatic sea-level curves of Fairbridge (1961) and Mörner (1976).

Basin (Cope, 1975; Playford and others, in press) and of Quaternary deposits in the Carnarvon Basin at Cape Range (van de Graaff and others, 1976), Shark Bay (Playford and Cockbain, 1976) and Cape Cuvier (Denman and van de Graaff, in press).

It is therefore concluded that if pulses of epeirogenic uplift and/or movement along the Darling Fault persisted into the Holocene, this tectonism could have been partly responsible for the Holocene sea-level changes relative to land that are evidenced at Rottnest Island.

QUATERNARY GEOLOGICAL HISTORY

The early Pleistocene history of the Rottnest Island area is uncertain. The island may have been localized by some form of structural uplift in the underlying Tertiary rocks which acted as a foundation for the accumulation of the dunes of the Tamala Limestone. Alternatively the foundation may have been a sand shoal. The oldest dunes may have formed during a period of lowered sea level associated with the Riss Glaciation, and during the following transgression.

The dune ridge in turn localized a coral-reef platform as sea level reached its highest level during the Riss-Würm Interglacial, some 100 000 years ago. During the following Würm Glaciation sea level fell abruptly, reaching its lowest level (about -100 m) some 20 000 years ago. The coastline was then some 10 km west of Rottnest (Fig.25, Churchill, 1959), and the old reef platform stood high above the surrounding plain. Although the annual rainfall during this glacial period was probably considerably lower in the area than it is today, it was apparently sufficient to form a strong karst topography of major dolines on top of the platform. These were later to localize the modern salt lakes.

Sea level rose rapidly during the Holocene Flandrian transgression. Dune sands accumulated on the Rottnest platform, but did not fill all dolines of the earlier karst surface. The Rottnest dunes formed part of a belt which also extended through the present Carnac, Garden, and Penguin Islands. As sea level rose towards its present level, Rottnest remained in connection with the mainland along this belt of dunes (Fig.25). The island finally separated some 6 500 years ago. Major changes in the land flora and fauna of the island occurred as a result of this separation, so that only a few species of trees and grasses and a sole marsupial species (the quokka) survived.

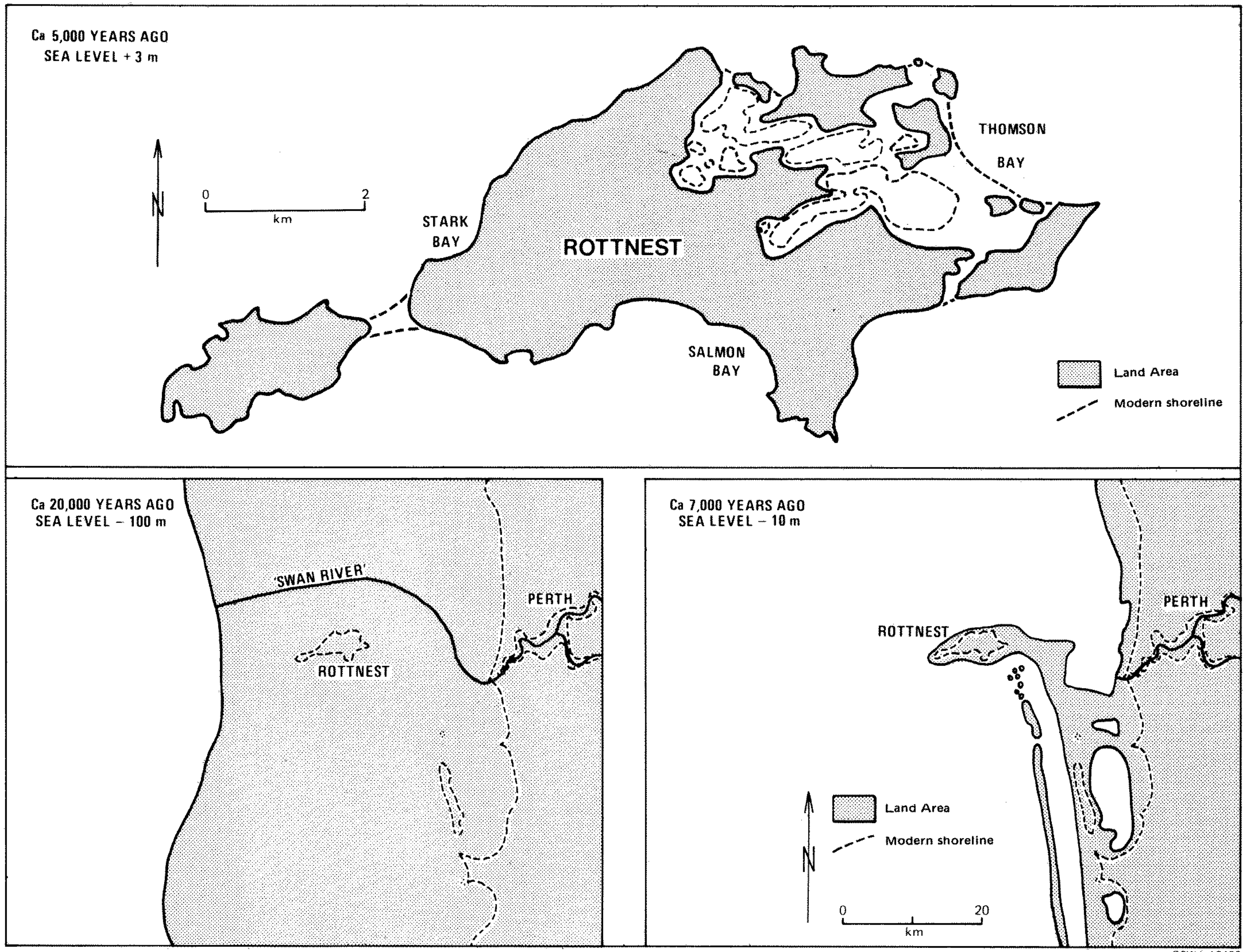

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Figure 25 Palaeogeographic maps of the Rottnest-Perth area illustrating shorelines approximately 20 000, 7 000, and 5 000 years ago.

The maximum transgression at Rottnest, to about 3 m above present sea level, probably occurred about 5 500 to 5 000 years ago. The area of the present salt lakes then formed inlets of the sea between more than 10 separate islands (Fig.25). The shallow warm waters along the margins of these inlets supported a prolific fauna of bivalves and gastropods, which accumulated with lime sand and mud to form the Herschell Limestone. As sea level rose to the 3 m level, there were two intervals of still-stand amounting to a few hundred years at about 0.7 m and 1.5 m above present sea level. Notches and narrow shoreline platforms were eroded at those levels, those at the 0.7 m level having been formed over a longer time interval than those at the succeeding 1.5 m level (Fig.24). Similar platforms and notches were cut soon afterwards at the 3 m level, and at that time the two older submerged notches and platforms and visors were encrusted with serpulid worm tubes and other marine invertebrates, and were extensively bored by organisms.

Sea level fell or the Rottnest area was uplifted abruptly some 5 000 years ago. The area of the present salt lakes remained in connection with the sea through one or more channels for some time, but they were eventually closed off by the accumulation of beach ridges and sand dunes. Dune, beach, swamp, and lake deposits have continued to accumulate since then, but it seems unlikely that there have been any major changes in the overall configuration of the island during the past 2 000 to 3 000 years.

WATER SUPPLY

INTRODUCTION

During Rottnest's 70-year history as a prison for Aborigines, the relatively small amounts of water required were readily obtained from roof catchments and shallow wells near Thomson Bay. However, when a decision was made in 1903 to establish a tourist resort on the island it was realized that larger supplies of water would be required, and that these might be obtained from artesian aquifers equivalent to those yielding large flows of potable or brackish water on the mainland. As a result, the Geological Survey recommended that a deep bore should be drilled on the island, and approval for the drilling was finally granted in 1911.

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The Rottnest Bore was put down in 1911-1913 to a depth of 788 m using calyx (rotary) equipment. However, only small flows of salt water were encountered, and the well was therefore abandoned.

Up to World War II, the main source of water on the island continued to be roof catchments, supplemented by wells yielding brackish water for washing purposes, the salinity of which increased steadily during the summer months. Rationing of drinking water was necessary during the summer, and there was also some blending of rainwater with brackish well-water to extend the potable supplies.

In 1939, an army report was prepared on Rottnest water supply, in which it was concluded that the most satisfactory way of providing large quantities of water for troops based on the island would be to seal an area of ground to provide runoff of rainwater into storage tanks (Dean, 1939). Shortly afterwards the army bituminized 1.6 ha of land beside Mount Herschell, feeding the runoff into a 9 100 m^3 tank. This provided the source of drinking water for troops on the island during the war. Second-class water was obtained from a system of wells and pipelines.

Army files on the wartime water supply on Rottnest have unfortunately been destroyed, but a map dated August 1945 showing the army wells, catchment areas, pipelines, and tanks that were then in use is preserved in the Commonwealth Archives. The main second-class water system was served by three wells south of the salt lakes. These were Serpentine well (south of Serpentine Lake), Quarry well (now known as D.C.A. well) near the eastern end of the airport, and another well that is now covered by the western end of the airport runway (referred to here as Runway well). The positions of these wells are shown on Plate 1 and Figure 4.

The army facilities around the Oliver Hill gun emplacements were supplied separately by Hells Gully well, situated in the interdune valley between the two guns. Several other wells in various parts of the island were used for small camps, radar installations, etc., but it has not been possible to locate all of these today.

The only army facility now remaining on the island, Kingstown Barracks, is supplied entirely with first-class water from the Mount Herschell storage and from roof catchments at the barracks. In 1965 the army made an attempt to obtain water for gardening purposes by drilling near the barracks, but the equipment used had a maximum drilling capacity of only 3 m, and no water was found.

After the war the Rottnest Island Board was able to make use of water in excess of the army's requirements from the Mount Herschell catchment. However, this soon proved inadequate for the fresh-water needs of the Thomson Bay settlement, and in 1960 the Geological Survey was asked to report on the groundwater potential of the island. Berliat (1961) recommended that the best way of improving the supply of potable water would be to extend the sealed surface catchments. He stated that the prospects of obtaining usable artesian water were poor in view of the results of the earlier bore, but that if a further deep bore were to be drilled it should be located on Phillip Point, at the eastern extremity of the island.

The catchment at Mount Herschell has since been expanded by the Board to 7.3 ha, and the storage to 27 000 m^3. However, in dry years the runoff is insufficient to fill the tanks, and in any case for many years it has been inadequate for the needs of the settlement. Bituminized catchments are aethetically displeasing, and the Board therefore decided against further extensions of these areas. As a result it has been necessary to bring fresh water from the mainland by barge during every summer since 1960/61, except for 1964/65 and 1967/68. In 1974/75 a total of 6 360 m^3 of water was taken to the island in this way.

Over the period 1963-66 fresh water was produced intermittently on the island by a distillation plant, at rates of up to 1.6 m^3 per hour. However, the equipment proved to be both unreliable and costly to operate, and its use was therefore discontinued.

Shallow wells between Thomson Bay and the salt lakes have been used since the earliest years of settlement on Rottnest, and several of those now in use were dug during the last century. The wells around the Thomson Bay settlement now supply only very saline water, and this is reticulated in the second-class water system, for sanitary and ablution purposes. The 1975/76 consumption of this water amounted to about 120 m^3 per day during the summer months, falling to about 95 m^3 per day in winter.

Most of the second-class water supply is from the Allison, Y.M.C.A., and South Pump wells, with minor amounts from the Hostel and Garden Lake wells. The Lodge has its own well, which yields small volumes of brackish water for lawn watering, and other shallow wells near the Basin supply water for an ablution block.

At one time the settlement also obtained water from the "Bungalow 31" wells, but these were abandoned when the water table fell. A major factor contributing to this fall appears to have been that a grove of fast-growing eucalypts was planted around the wells.

The only other groundwater source in use when the present investigation was carried out was a well supplying the main Rottnest Lighthouse and the nearby University Research Station. This well yields brackish water for ablution, sanitary, and lawn-watering purposes.

In February 1976 the Public Works Department drilled four shallow bores to locate water suitable for an ablution block at Parker Point. One bore (no.2) found at least 5 m of potable water, but the others were brackish to very salt.

WATER REQUIREMENTS

The number of visitors to Rottnest each year is increasing rapidly. Between 1970 and 1975 there was a 225% increase in total visitors (including "day-trippers") from 93 640 in 1970 to 212 968 in 1975. The numbers of visitors actually accommodated on the island on a weekly basis, compared with the consumption of fresh water over the period 1961/62 to 1974/75, are shown on Figure 26. With the projected increase in accommodation on the island, including development of another settlement at Geordie and Longreach Bays, the annual requirement for potable water will probably reach at least 60 000 m^3 during the next 5 to 10 years (compared with the 1975/76 requirement of about 36 000 m^3).

The annual consumption of second-class water (now about 38 000 m^3) would be at least doubled if better-quality water were available (below 4 000 mg/l), especially if areas of lawn or gardens were to be established around the settlement. In 10 years the annual demand for such water could exceed 150 000 m^3.

SHALLOW GROUNDWATER

This section will outline what was known about the occurrence of shallow groundwater of Rottnest Island prior to the 1976 drilling programme.

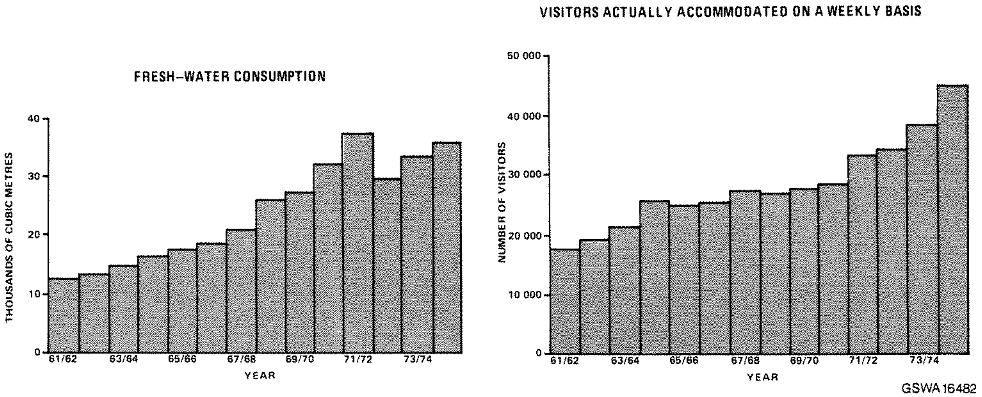

Figure 26 Histograms illustrating annual fresh-water consumption and visitors accommodated on Rottnest Island.

Figure 27 Oblique aerial view looking east from near Stark Bay (right foreground) over the highest and broadest part of the island, which is also the most prospective area for groundwater. Photo by courtesy of Department of Lands and Surveys, Perth.

Most wells on the island were dug in low-lying areas, generally less than 5 m above sea level, and fairly close to the sea and salt lakes. In such areas a thin layer of fresh water is commonly present, overlying salt water. Most wells originally produced fresh or brackish water when pumped at low rates from the fresh-water layer. However when such a well is pumped too rapidly a cone of salt water rises from below the fresh-water layer, and the well becomes salty. Almost all of the settlement wells are consequently very salty, as they have been over-pumped for many years. Salinity changes that have occurred as a result of over-pumping are well illustrated by the Y.M.C.A. wells (Table 2).

Well water being produced for the settlement's second-class water system in February 1976 ranged in salinity from 11 500 to 16 400 mg/l (compared with the uppermost limit of 4 000 mg/l that is normally accepted for ablution water). The most saline water is that obtained from the South Pump wells, which are also the most recent of the wells dug to supply the Thomson Bay settlement.

The settlement wells currently having the lowest summer salinities are the Lodge and Garden Lake wells, but they are produced at rates of not more than a few cubic metres per day. High pumping of the Lodge well in 1963 resulted in the salinity rising to 22 300 mg/l (Table 2).

The Geordie Bay Project well, put down for the new settlement beside Geordie Bay, contains slightly brackish water (1 150 mg/l on 25 February 1976), but it has never been produced for prolonged periods. Geologically it is better situated than the Thomson Bay wells, but it is unlikely to be able to yield large volumes of low-salinity water, owing to the relatively small intake area.

On hydrogeological grounds the Thomson Bay settlement wells are situated in one of the worst parts of the island for underground water. The elevation is low, the intake area is small, and the area is close to both the sea and salt lakes. Furthermore, there are groves of large trees near some of the wells, and these can be expected to transpire much of the available fresh water.

Each of the four main army wells used during the war (Serpentine, Runway, Quarry, and Hells Gully wells) apparently produced fresh to brackish water when first developed, and the Serpentine and Quarry (D.C.A.) wells still contained fresh water when sampled in February 1976 (Table 2). However,

TABLE 2. Rottnest Island well and shallow-bore data

Well or shallow bore	Approx. depth (m)	Approx. elev. (m)	Aquifer	Salinity (mg/l)	Sample date	Remarks
Allison wells	2.5	3	Tamala Limestone	6 700 12 700 11 500	9- 8-63 6- 3-69 25- 2-76	Main sources of second-class water for the settlement area
YMCA wells	2.5	3	Tamala Limestone	530 500 785 842 571 14 600	19-11-34 16- 1-35 11- 2-48 21- 6-48 21- 3-51 25- 2-76	
South Pump wells	2.5	3	Dune sand or Tamala Limestone	16 400	25- 2-76	
Garden Lake wells	2.5	3	Tamala Limestone	10 500 10 400 6 650	9- 8-63 5- 3-69 23- 2-76	Smaller sources of second-class water for the settlement area
Hostel (engine house) well	4.5	5	Tamala Limestone	3 100 3 370 13 200	18- 2-32 21- 3-51 25- 2-76	
Lodge (Rex) well	6	7	Tamala Limestone	1 745 2 445 1 115 4 255 22 300 3 540	18- 2-32 14- 2-34 11- 2-48 21- 3-51 9- 8-63 25- 2-76	Now only used as minor source of water for Lodge (lawn watering)
Basin wells	2.5	3	Tamala Limestone	1 970 7 400	5- 3-69 25- 2-76	Used for ablution block at The Basin
Bungalow 31 wells	?	3	Tamala Limestone	1 185 6 185	10- 8-48 21- 3-51	Now abandoned, filled
Geordie Bay Project well	10	13	Tamala Limestone	1 150	25- 2-76	For Longreach-Geordie Bay settlement
Quarry well (D.C.A.)	4	5	Tamala Limestone	745 670 645 785 680	7-10-37 15-11-37 11-10-39 16-11-39 25- 2-76	Main sources of second-class water for the Army facilities during World War II. Runway Well is now covered by the air-strip
Serpentine well	4.5	5	Tamala Limestone	550	25- 2-76	
Runway well	?	4	Tamala Limestone	"Fresh to brackish"		
Hells Gully well	9?	13	Tamala Limestone	1 328 714 860	7-10-37 11-10-39 1-11-39	Now abandoned, filled. Was used by Army as source of good-quality water

Table 2 - continued

Stark Bay well	?	15	Tamala Limestone	"Fresh"		Now abandoned. Supplied WRAAF camp in war
Bickley Swamp well	3.7	4	Herschell Limestone	2 470 1 770	16-10-39 16-11-39	Army well, now abandoned
Barracks well	7	8	Tamala Limestone	1 790	25- 2-76	May be Deacons Well of Army records
Deacons well	?	?	?	960 7 145	7-10-37 15-11-37	See above note. Salinity rose rapidly with heavy pumping
Old Lighthouse well	?	14	Tamala Limestone	660	18- 8-51	Now abandoned. Sample is probably from this well
Lighthouse well (new)	8.5	9	Tamala Limestone	1 035 4 250 3 480	1967 1967 26- 2-76	1967 samples taken on the same day, before and after pumping
Radar Station well	25	28	Tamala Limestone	"Brackish"		Army supply for Radar Station during war
Narrow Neck well	1.5	1.5	Dune sand	6 870	25- 2-76	
Soak well	1	1.5	Tamala Limestone	3 850	26- 2-76	
Baghdad wells	0.6	0.6	Herschell Limestone	826 1 690	Jan. 65 26- 2-76	
Riding School well	3	4	Tamala Limestone	2 120	25- 2-76	
Parker Point well	3.3	7	Tamala Limestone	1 460	25- 2-76	Sample from top of water table. Note lower salinity from below water table in Bore 2
Parker Point bore 1	9.75 11.25	11	Tamala Limestone	2 582 9 932	25- 2-76 "	
Parker Point bore 2	5.30 6.30 6.80 8.30	7	Tamala Limestone	880 800 770 825	26- 2-76 " " "	Drilled beside Parker Point well. Water table at 3.3 m. Note salinity change with depth
Parker Point bore 3	9.80 11.30	10	Tamala Limestone	8 576 9 776	26- 2-76 "	Water table at 9.1 m. Drilled in teatree copse
Parker Point bore 4	5.30 6.80 8.30	7	Tamala Limestone	16 524 19 760 20 388	27- 2-76 " "	Drilled in teatree copse

verbal reports indicate that when these wells were serving large numbers of troops on the island, all except Hells Gully well (which supplied small camps at the Oliver Hill guns) became salty. The Hells Gully well was certainly the best situated of these wells, as it was dug in a high area of the island, where the fresh-water lens should be relatively thick. It apparently produced low-salinity water throughout the war years.

No salinity measurements are available for the other wells sunk on Rottnest by the armed forces, but Stark Bay well, which served the Women's Royal Australian Air Force camp near Stark Bay, apparently produced potable water. This well (which is now covered) is geologically well situated, on high ground.

The main Rottnest Lighthouse, at Wadjemup Hill in the centre of the island, has been served by two wells. The reason for the abandonment of the older well is not recorded, but possibly the deterioration of its timber walls was responsible. This well was in use by the lighthouse establishment for many decades, and it was also used by the army during the war. A water sample taken in 1951 (presumably from the older well) had a salinity of 660 mg/l. The newer well is of poorer quality. In 1962 the lighthouse keeper reported that it could be emptied by pumping in 15 to 35 minutes (depending on the season). In 1967 a sample taken from the top of the water before it was pumped had a salinity of 1 035 mg/l, and after pumping until the well was nearly dry the salinity rose to 4 250 mg/l. The new lighthouse well has never been required to produce large volumes of water, and it is not known why the water yield and quality are poor at this locality.

The Parker Point bores have shown that in this area water quality improves away from the coast (from bore 1 to bore 2), but deteriorates where these is forest cover (bores 3 and 4). The water in bore 2 would be suitable for drinking purposes, bore 1 is brackish to salt, and the other two are very salty (Table 2).

Much of the shallow groundwater at Rottnest is contaminated with *Salmonella* bacteria, derived from the indigenous quokkas. The bacteria also occur in water from the Mount Herschell catchment, and therefore it must be chlorinated before being reticulated through the settlement.

There has long been the belief that significant quantities of potable underground water cannot be found at Rottnest, and this was the reason for previous decisions to extend bituminized catchments, install a water-distillation plant, and import water by barge from the mainland.

Consideration had also been given during 1975 to the construction of a pipe-line from the mainland. However, the present investigation showed that in fact the shallow groundwater potential had never been properly evaluated.

Shallow groundwater typically occurs on an island as a fresh-water lens "floating" on salt water, with a zone of brackish water between. This lens will normally be thickest where the island is highest and widest, and on this basis the most prospective part of Rottnest Island should be the high area west and south of the salt lakes (Fig. 27). There has been no previous attempt to thoroughly explore the groundwater resources of this part of the island. Playford (1976) concluded that there were good prospects for the discovery of domestic-quality water in this area, and recommended that a programme of auger drilling be undertaken there, to be followed by percussion drilling if encouraging results were obtained. This drilling was carried out, and it established the presence of sufficient reserves of potable water to meet the requirements of both the Thomson Bay and Geordie Bay settlements. The full results are described in the following paper, by R.E.J. Leech.

ARTESIAN WATER

Two main artesian aquifers have been developed in the Perth Basin: the Early Cretaceous Leederville Formation and the Middle Jurassic to Early Cretaceous Yarragadee Formation. These two units are separated by the Early Cretaceous South Perth Shale, the contact with the Yarragadee Formation being an unconformity. Another aquifer, the Gage Sandstone Member, is present at the base of the South Perth Shale in a number of offshore wells, and additional thin sandstone aquifers also occur in the formation in some onshore areas.

In the Perth Metropolitan area and on Garden Island, large volumes of fresh to brackish artesian water are obtained from the Leederville and Yarragadee Formations, whereas in the old Rottnest Bore only a small flow of salt water "equal to sea water" was obtained from the Leederville Formation (Fig. 13).

The reason for this difference in the hydrology of the Leederville Formation in the Rottnest Bore compared with that in bores on the mainland and Garden Island is now apparent: a hydrologic barrier is present to the east of Rottnest in the form of several faults cutting the Lower Cretaceous aquifers (Fig.12). Consequently the Leederville Formation below Rottnest is not in free hydraulic connection with the formation below the Perth Metropolitan Area and Garden Island. Connate salt water has not been flushed from the formation below Rottnest, and the hydraulic head is also low.

Calculations based on wireline logs show that water salinities are high in all the Cretaceous and Jurassic aquifers in offshore wells drilled near Rottnest (Table 3, by K.A. Crank). The only offshore well having low salinities in these aquifers is Cockburn 1, which is situated beside the mainland coast east of the zone of faulting.

The salinity determinations in the Wapet offshore wells indicate that artesian water below Rottnest is most unlikely to have salinities less than 7 500 mg/l, and indeed it is probable that the salinity of each aquifer will exceed 10 000 mg/l. It was therefore concluded that drilling of another deep bore to test the artesian-water prospects below Rottnest Island would be unwarranted (Playford,1976).

CONCLUSIONS

There is clear evidence on Rottnest Island of important changes in the relative positions of land and sea during the Pleistocene and Holocene. Although eustatism is believed to be responsible for the major changes in sea level during these intervals, tectonism may also be involved, associated with epeirogenic uplift of the southwestern part of Western Australia and/or movement along the Darling Fault. Rottnest was uplifted about 3 m, or sea-level fell abruptly, some 5 000 years ago. Since then the relative position of sea level to land in the area has been essentially stable.

The results of the artesian bore drilled on Rottnest in 1911-13 and of offshore drilling and seismic surveys give no grounds for optimism that water of domestic quality can be obtained from artesian aquifers below Rottnest. On the other hand, the present investigation showed that there were good prospects for the discovery of low-salinity shallow groundwater in the untested high area at the centre of the island, and this conclusion has since been validated by drilling.

TABLE 3. Salinities calculated from wire-line logs in WAPET offshore wells

WELL	UNIT	DEPTH (m)	SALINITY (mg/l)
Charlotte 1	Leederville Formation	644	9 500
	Gage Sandstone Member	1 495	20 000
	Yarragadee Formation	2 150	7 500
Quinns Rock 1	Leederville Formation	397	14 000
	Yarragadee Formation	1 287	24 000
	Yarragadee Formation	1 693	60 000
Roe 1	Leederville Formation	622	10 000
	Yarragadee Formation	1 647	42 000
	Yarragadee Formation	2 135	30 000
Gage Roads 1	Leederville Formation	625	25 000
	Gage Sandstone Member	1 601	45 000
	Yarragadee Formation	1 815	41 000
	Yarragadee Formation	2 660	22 000
Gage Roads 2	Leederville Formation	1 098	8 000
	Gage Sandstone Member	1 357	(a)45 000
	Yarragadee Formation	1 559	26 000
	Yarragadee Formation	1 896	24 000
	Yarragadee Formation	2 934	8 000
Warnbro 1	Leederville Formation	1 083	45 000
	Gage Sandstone Member	1 952	44 000
	Yarragadee Formation	2 278	40 000
Cockburn 1	South Perth Shale	107	(b) less than 400
	Yarragadee Formation	320	less than 700
	Yarragadee Formation	732	1 400

NOTE: Data provided by K.A. Crank.

(a) A drill-stem test in the Gage Sandstone Member from 1 781 to 1 783 m produced water of salinity 38 200 mg/l

(b) Water samples from the adjoining onshore artesian well, Woodman Point No.1, showed salinities of 1 100 mg/l in the South Perth Shale and 1 500 to 1 550 mg/l in the Yarragadee Formation.

REFERENCES

Arousseau, M., and Budge, E.A., 1921, The terraces of the Swan and Helena Rivers and their bearing on Recent displacements of the strand line: Royal Soc. West. Australia Jour., v.7, p.24-43.

Berliat, K., 1961, Report on subterranean water potentialities on Rottnest Island: West. Australia Geol. Survey Ann. Rept for 1960, p.9-10.

Carrigy, M.A., and Fairbridge, R.W., 1954, Recent sedimentation, physiography, and structure of the continental shelves of Western Australia: Royal Soc. West. Australia Jour., v.38, p.65-95.

Churchill, D.M., 1959, Late Quaternary eustatic changes in the Swan River district: Royal Soc. West. Australia Jour., v.42, p.53-55.

Clarke, E. de C., 1926, The geology and physiography of the neighbourhood of Perth, Western Australia: Austral. Assoc. Adv. Sci., Handbook, 18th meeting, Perth, p.23-30.

Cook, P.J., and Polach, H.A., 1973, A chenier sequence at Broad Sound, Queensland, and evidence against a Holocene high sea level: Marine Geology, v.14, p.253-268.

Cope, R.N., 1975, Tertiary epeirogeny in the southern part of Western Australia: West. Australia Geol. Survey Ann. Rept for 1974, p.40-46.

Dean, G.E.M., 1939, Rottnest Island water supply: Australian Infantry Forces, report to Military Headquarters, Fifth Military District, 24 April 1939 (manuscript).

Deevery, E.S., Gralenski, L.J., and Hoffren, V., 1959, Yale natural radiocarbon measurements IV: Radiocarbon, v.l, p.144-172.

Denman, P.D., and van de Graaff, W.J.E., in press, Emergent Quaternary marine deposits in the Lake MacLeod Area, W.A.: West. Australia Geol. Survey Ann. Rept for 1976.

Fairbridge, R.W., 1948, Notes on the geomorphology of the Pelsart Group of the Houtman's Abrolhos Islands: Royal Soc. West. Australia Jour., v.33, p.1-43.

______ 1950, The geology and geomorphology of Point Peron, Western Australia: Royal Soc. West. Australia Jour., v.34, p.35-72.

______ 1953, Australian Stratigraphy: Univ. West. Australia Text Books Board, Nedlands.

______ 1958, Dating the latest movements of the Quaternary sea level: New York Acad. Sci. Trans., Ser.2, v.20, p.471-482.

______ 1961, Eustatic changes in sea level, in Physics and chemistry of the earth, v.4: Pergamon, London, p.99-185.

Gill, E.D., and Hopley, D., 1972, Holocene sea levels in Eastern Australia - a discussion: Marine Geology, v.12, p.223-242.

Glenister, B.F., Hassell, C.W., and Kneebone, E.W.S., 1959, Geology of Rottnest Island: Royal Soc. West. Australia Jour., v.42, p.69-70.

Hassell, C.W., and Kneebone, E.W.S., 1960, The geology of Rottnest Island: Univ. West. Australia Dept Geology, B.Sc. Honours thesis (unpublished).

Grant-Taylor, T.L., and Raffer, T.A., 1963, New Zealand natural radiocarbon measurements I-V: Radiocarbon, v.5, p.118-162.

Hodgkin, E.P., 1964, Rate of erosion of intertidal limestone: Zeitschr. Geomorphologie, N.F. v.8, p.385-392.

______ 1970, Geomorphology and biological erosion of limestone coasts in Malaysia: Geol. Soc. Malaysia, Bull.3, p.27-51.

Hodgkin, E.P., Marsh, L., and Smith, G.G., 1970, The littoral environment of Rottnest Island: Royal Soc. West. Australia Jour., v.42, p.85-88.

Hodgkin, E.P., and Sheard, K., editors, 1959, Rottnest Island: The Rottnest Biological Station and recent scientific research: Royal Soc. West. Australia Jour., v.42, p.65-95.

Jelgersma, S., 1966, Sea-level changes during the last 10 000 years, in Sawyer, J.S., editor, World Climate from 8 000 to 0 B.C.: Proc. Internat. Symposium on world climate 8 000 to 0 B.C., p.54-70.

Kendrick, G.W., in press, Middle Holocene marine molluscs from near Guildford, Western Australia, and evidence for climatic change: Roy. Soc. West. Australia Jour.

Mörner, N.A., 1971, Eustatic changes during the last 20 000 years and a method of separating the isostatic and eustatic factors in an uplifted area. Palaeogeography, Palaeoclimatology, Palaeoecology, v.9, p.153-181.

______ 1976, Eustatic changes during the last 8 000 years in view of radiocarbon calibration and new information from the Kattegart region and other northwestern European coastal areas: Palaeogeography, Palaeoclimatology, Palaeoecology, v.19, p.63-85.

Playford, P.E., 1976, Rottnest Island: geology and groundwater potential: West. Australia Geol. Survey Record 1976/7.

Playford, P.E., and Cockbain, A.E., 1976, Modern algal stromatolites at Hamelin Pool, a hypersaline barred basin in Shark Bay, Western Australia, in Stromatolites M.R. Walter (Editor): Developments in Sedimentology, v.20, Elsevier, Amsterdam, p.389-411.

Playford, P.E., Cockbain, A.E., and Low, G.H , in press, Geology of the Perth Basin, Western Australia: West. Australia Geol. Survey Bull.124.

Purdy, E.G., 1974, Reef configurations: cause and effect, in Reefs in time and space, L.F. Laporte (ed.): Soc. Econ. Paleontologists and Mineralogists Spec. Publication 18, p.9-76.

Schofield, J.C., 1964, Postglacial sea levels and isostatic uplift: New Zealand Jour. Geology and Geophysics, v.7, p.359-370.

______ 1973, Post-glacial sea levels of Northland and Auckland: New Zealand Jour. Geology and Geophysics, v.16, p.359-366.

Somerville, J.L., 1921, Evidence of uplift in the neighbourhood of Perth: Royal Soc. West. Australia Jour., v.6, p.5-20.

Somerville, W., 1949, Rottnest Island: Rottnest Island Board of Control special publication.

Storr, G.M., 1963, Some factors inducing change in the vegetation of Rottnest Island: West. Australian Naturalist, v.9, p.15-22.

Storr, G.M., Green, J.W., and Churchill, D.M., 1959, The vegetation of Rottnest Island: Royal Soc. West. Australia Jour., v.42, p.70-71.

Tamers, M.A., Pearson, F.J., and Davis, E.M., 1964, University of Texas radiocarbon dates II: Radiocarbon, v.6, p.138-159.

Teichert, C., 1950, Late Quaternary changes of sea level at Rottnest Island, Western Australia: Royal Soc. Victoria Proc., v.59, p.63-79.

______ 1967, Age of Coastal Limestone, Western Australia: Australian Jour. Sci., v.30, p.71.

Thom, B.G., Hails, J.R., and Martin, A.R.H., 1969, Radiocarbon evidence against higher postglacial sea levels in eastern Australia: Marine Geology, v.7, p.161-168.

Thom, B.G., Hails, J.R., Martin, A.R.H., and Phipps, C.V.G., 1972, Post-glacial sea levels in eastern Australia - a reply: Marine Geology, v.12, p.223-242.

van de Graaff, W.J.E., Denman, P.D., and Hocking, R.M., 1976, Emerged Pleistocene marine terraces on Cape Range, Western Australia: West. Australia Geol. Survey Ann. Rept for 1975, p.62-70.

Veeh, H.H., 1966, Th^{230}/U^{238} and U^{234}/U^{238} ages of Pleistocene high sea level stand: Jour. Geophysical Research, v.71, p.3379-3386.

PART II

HYDROLOGY

HYDROLOGY

by

R.E.J. Leech

ABSTRACT

Sixteen bores drilled to appraise the unconfined-groundwater potential of Rottnest Island identified a fresh-water lens overlying brackish and salty water. The fresh-water lens is as much as 0.5 m above sea level, and extends to approximately 8.5 m below sea level. Seven pumping bores were constructed to test the unconfined aquifer and to evaluate its potential for a production bore field.

A supply of 1.82×10^4 m^3/year is needed to satisfy the deficit in the water supply from the bitumen catchments to the present settlement and the proposed Geordie Bay development. Calculations indicate that an average 736 mm of annual rainfall will contribute 3.80×10^5 m^3/year of recharge water to the fresh-water lens in the central part of the island, for an annual safe yield of 1.9×10^5 m^3, which is just in excess of ten times the requirement, and is one-twelfth of the volume of fresh water in storage. The problem is to extract the groundwater efficiently without causing salt-water encroachment into the fresh-water lens or the pumping bores. Long-term pumping rates have been predicted for pumping bores already constructed. Further, continuous pumping at low discharge rates is preferable to intermittent pumping at higher discharge rates. An area for a bore field is defined and sites are suggested for future production bores.

Groundwater salinity varies from place to place, but within the fresh-water lens it is low enough for drinking. As nitrate and fluoride concentrations are close to the maximum desirable limits for human consumption, regular monitoring of these anions is suggested.

INTRODUCTION

This investigation was made because the Public Works Department asked for advice as to whether a water supply could be obtained from a deep artesian bore. Playford (1976) concluded that confined aquifers below Rottnest Island were likely to yield saline water. However, as a result of his examination of the surface geology of the island and of the previous groundwater exploration and development, he suggested that an unconfined aquifer containing low-salinity water might exist in the previously untested high area towards the centre of the island. A program of auger drilling was therefore proposed to test this possibility.

At present, and for the immediate future, Rottnest Island is served by a two-class water system. First-class water is supplied by surface runoff from two bituminized catchments, and is used for domestic consumption. Second-class water is employed for washing, showering, and sanitary purposes, and is pumped from several wells close to the Thomson Bay settlement. This report describes an investigation into the groundwater potential of a shallow unconfined aquifer to supplement the first-class water system.

For several years the number of summer visitors to Rottnest Island has increased, causing an increased demand upon the limited water-supply system. Since 1961 this has necessitated supplementing the water supply each summer with water carted in barges from the mainland. Carting of water is expensive, and provision of an adequate supply of groundwater would save an estimated $60 000 each year in cartage costs.

EXPLORATION METHODS

During early 1976 Rottnest Island was geologically mapped (Playford, 1976), and drilling was started by the Public Works Department in June to determine the occurrence of fresh groundwater. Bore sites are shown on Figure 28.

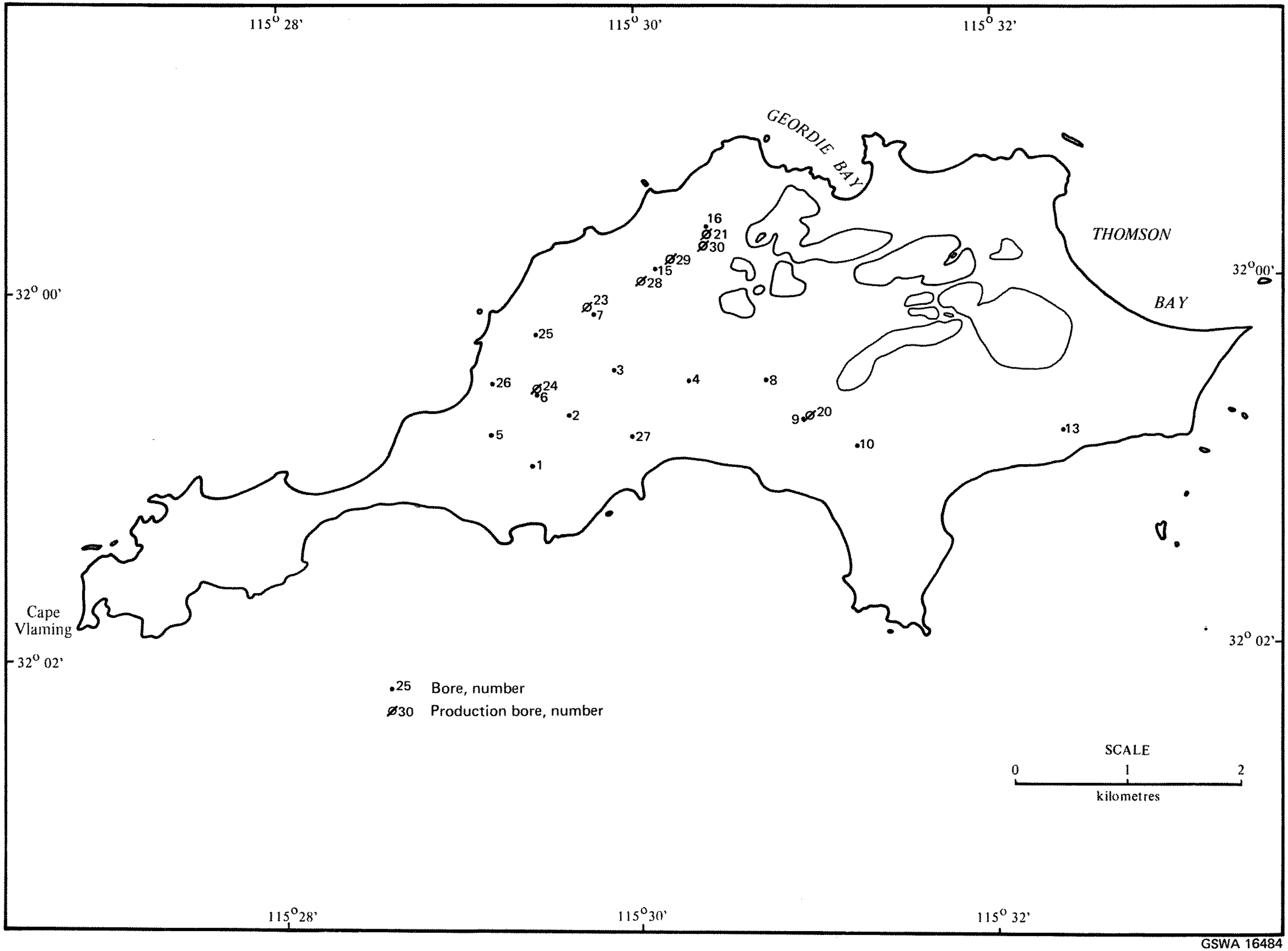

Figure 28 Bore locations.

DRILLING

The drilling was in two phases. Phase I using a Gemco auger rig was designed to delineate areas of potable water, and to define the extent of the freshwater lens. Phase II started seven weeks later, using a Hydromaster cable-tool rig to construct test-pumping bores.

Phase I drilling commenced on 1st June 1976 and was completed on 8th August; sixteen bores were drilled for an aggregate depth of 325 m (Table 4). Each bore was drilled to the water table, and a water sample taken; further water samples were taken every 0.5 m until the total soluble salt content (TSS) exceeded 4 000 mg/l (Table 5). Each bore was completed by running 38 mm PVC casing to total depth; the casing was slotted from the bottom upward to approximately 1 m above the water table.

Phase II drilling commenced on 14th July, 1976, and was completed on 29th September, 1976. A total of seven production bores was drilled and tested. The bores were drilled using a Hydromaster cable-tool rig; in each case, a 250 mm diameter hole was drilled to total depth, and then 152 mm diameter, gravel-packed screens and casing were set in a selected interval (Table 6). After completion, the bores were developed and test pumped; the results are discussed elsewhere in this report.

WATER SAMPLING

The water-sampling technique used during Phase I drilling was arrived at by trial and error during construction of the initial bores. Firstly, small holes were drilled in the auger bit, and a filter set inside the bit, but this method was unsuccessful because the holes and filter became blocked with formation material. Secondly, two 25 mm diameter holes were drilled in the lead auger just above the bit, and a metal screen was welded over them; this also failed because of blocking by formation material. Ultimately, a series of small slots, which allowed formation water to enter freely, but kept most of the formation material out, were cut in the lead auger. When a sampling depth was reached, the water level inside the auger was measured, and the water inside the augers bailed out, to allow formation water from the test interval to enter the auger string. Water samples obtained this way had their TSS content measured on site with a portable resistivity-bridge.

TABLE 4. Summary of Phase I bore data

Bore site	Natural surface reduced level (m AHD)	Total depth (m)	Water rest level (28-7-76) (m)	Thickness of freshwater (less than 1 000 mg/l) (m)	Slotted casing interval (m)	Aquifer
1/76	2.64	7.4	2.18	2.0	0.68- 7.38	Tamala Limestone
2/76	11.45	25.3	10.95	3.7	10.25-25.25	Tamala Limestone
3/76	17.20	28.3	16.68	8.0	15.28-28.28	Tamala Limestone
4/76	8.17	19.2	7.77	0.7	6.70-19.20	Tamala Limestone
5/76	14.52	23.8	14.15	4.3	13.23-23.73	Tamala Limestone
6/76	13.55	25.3	13.07	8.6	12.00-25.24	Tamala Limestone
7/76	6.47	17.6	6.02	6.7	5.09-17.59	Tamala Limestone
8/76	10.66	14.7	10.36	<0.5	9.70-14.70	Tamala Limestone
9/76	16.97	26.9	16.63	1.8	15.83-26.83	(Quartz sand (Tamala Limestone
10/76	9.22	16.3	8.87	<0.5	8.25-16.25	Tamala Limestone
13/76	2.36	7.8	2.12	1.0	1.05- 7.80	(Herschell Limestone (Tamala Limestone
15/76	8.09	16.2	7.74	4.0	6.17-16.17	Tamala Limestone
16/76	9.43	16.6	9.15	6.1	6.55-15.55	Tamala Limestone
25/76	21.36	30.4	21.08	6.7	18.40-30.40	Tamala Limestone
26/76	14.03	20.8	13.80	4.4	12.61-20.61	Tamala Limestone
27/76	17.61	28.4	17.15	8.5	16.40-28.40	Tamala Limestone

NOTE: AHD is Australian Height Datum. Depths measured below natural surface.

These drilling and sampling techniques proved successful for measuring the salinity profile, which was then used as a guide in selecting prospective areas for further exploration.

SALINITY LOGGING

A Tamam Salinity Probe was used to measure the salinity profile in completed bores. By November, 1976, most bores had been logged three times at monthly intervals, results confirming the fresh-water thickness defined by drilling. An example is shown in Figure 29. Monthly profile measurements were taken to observe the time needed for the bore to reach equilibrium with the surrounding formation, and also to record any seasonal variations; none have reached equilibrium with the surrounding formation water. Insufficient data have been collected to draw any firm conclusions from the salinity logging.

TABLE 5. Salinity profiles for each bore (measured during drilling in mg/l)

Depth below water table (m)	Bore number															
	1/76	2/76	3/76	4/76	5/76	6/76	7/76	8/76	9/76	10/76	13/76	15/76	16/76	25/76	26/76	27/76
0.1	650	540	420		680	420	550		780	1260			580	580	650	
0.5	640	580	420	850	690	480	590		760	1300	1160	900	580	580	650	
1.0	600	640	430	1140	710	470	610	2200	840	1510	1000	1040	700	650	770	1040
1.5	650	700	430	1120	710	470	620	2850	950	1750	1410	1010	810	900	770	870
2.0	1080	725	440	1120	710	500	580	3300	1030	1760	1420	1020	770	720	770	880
2.5	2600	725	450	1400	710	500	570	4050	1200	1800	1560	960	700	620	770	940
3.0	4280	860	440	1600	710	500	600		1320	1940	2100	980	640	620	780	920
3.5	5980	960	440	1825	740	520	630		1380	2140	3200	1100	560	550	800	920
4.0		1070	420	2120	900	570	660		1370	2360	>6000	1150	500	550	900	930
4.5		1150	420	2500	1040	590	740		1500	2620		1180	540	560	1040	890
5.0		1240	420	3000	1240	600	800		1640	2870		1250	600	620	1570	870
5.5		1300	420	3340	1480	570	860		1750	3250		1360	750	650	2160	900
6.0		1350	420	3700	1800	540	850		1940	3620		1560	870	780	4050	910
6.5		1400	420	4350	2200	490	960		2240	3830		1920	2100	950	5650	925
7.0		1550	500	4660	3000	440	1070		2530	4000		2620	5000	1100		940
7.5		1700	700	4950	3530	450	1170		2550			3500	7900	1360		940
8.0		1900	1000	5250	4300	730	1200		2600			5000		1760		940
8.5		2100	1600			920	1320		2800					2400		1000
9.0		2300	1560			1350	1480		3200					3700		1100
9.5		2550	1250			1800	1750		3650							1240

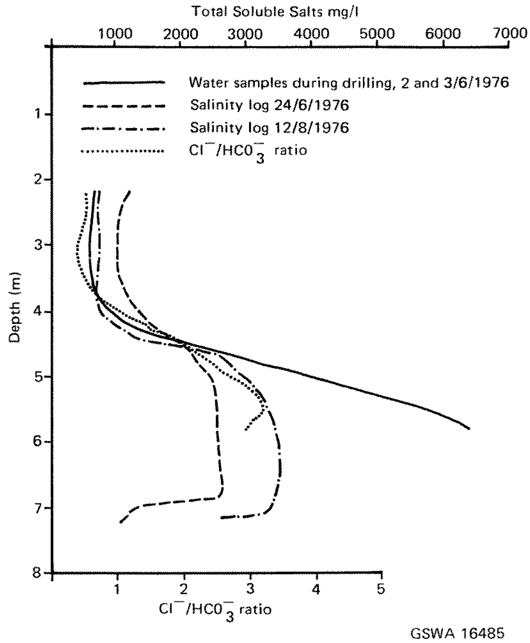

Figure 29 Salinity profiles from Rottnest bore.

GROUNDWATER SYSTEM

INTRODUCTION

Like other small oceanic islands, Rottnest has a shallow, fresh groundwater-mound resting upon salt water. The fresh-water lens is as much as 0.5 m above sea level and extends to approximately 8.5 m below sea level. Withdrawal of water from the freshwater lens, if not managed correctly, will induce salt-water intrusion from below the bore field, and sea-water intrusion from the coast. Therefore, very careful monitoring of any bore field should continue throughout its operation.

The gradation with depth from fresh to salt water is theoretically represented by a sharp interface, (Ghyben, 1888-1889; Herzberg, 1901) although in practice, a zone of mixing exists (Figure 30a). At Rottnest, the zone of mixing can be more than 10 m thick, or thicker than the fresh-water zone. Any calculation to predict the movement of the fresh-/salt-water interface must also take account of the motion of the zone of mixing. This zone includes water unsuitable for drinking, and if over-pumping occurs, the bore will be rendered useless for fresh-water supply long before the fresh-/salt-water interface intersects the bore, because of influx of water from the zone of mixing.

DEFINITIONS

The terms 'sea-water intrusion' and 'salt-water intrusion' used in this report should not be confused. Sea-water intrusion is the landward movement of saline water at the fresh-/salt-water interface; and salt-water intrusion is the upconing of the fresh-/salt-water interface below either a pumping bore or a bore field which is being overpumped.

FLOW SYSTEM

A theoretical flow system expected on an oceanic island with vertical recharge to the water table is shown in Figure 30b. In an ideal situation the depth to the underlying fresh/salt-water interface can be calculated from the Ghyben-Herzberg relation, which is based on the contrasting densities of fresh and salt water.

TABLE 6. Summary of Phase II bore data

Bore site	Natural surface reduced level (m AHD)	Total depth (m)	Water rest level (m)	Screened interval (m)	Test pumping discharge rate (m^3/day)	Aquifer
20/76	16.71	18.90	16.33	16.46-17.98	109	Quartz sand
21/76	9.75	12.50	9.49	10.04-11.59	56	Tamala Limestone
23/76	6.89	10.66	6.44	6.69- 9.74	218	Tamala Limestone
24/76		19.48	13.56	15.47-18.54	224	Tamala Limestone
28/76		9.88	5.86	5.83- 8.88	157	Tamala Limestone
29/76		15.95	11.51	11.92-14.95	157	Tamala Limestone
30/76		15.66	11.30	11.95-15.02	157	Tamala Limestone

NOTE: AHD is Australian Height Datum. Depths measured below natural surface.

The Ghyben-Herzberg relation has one major limitation; it assumes a hydrostatic equilibrium for the groundwater, such is not the case because groundwater is constantly in motion. A hydrodynamical approach was developed by Hubbert (1940), which predicts the discrepancy between the actual depth to the interface and the Ghyben-Herzberg calculated depth. This approach shows the actual depth to the interface to be below that calculated from the Ghyben-Herzberg relation. Further, the Ghyben-Herzberg relation neglects the vertical flow component when calculating induced movement of the interface caused by pumping.

TABLE 7. Predicted long-term pumping rates

Pumping bore	Hydraulic Conductivity (m^3/day/m^2)*	Discharge during test pumping (m^3/day)	Long - term pumping rate at which interface rises to base of bore screen (m^3/day)	Long-term pumping rate at which 1500 mg/l boundary rises to base of bore screen (m^3/day)
1	2	3	4	5
20/76	101	109	229	13.7
21/76	94.5	56	136	8.2
23/76	39.5	218	167	10.0
24/76	69.0	224	336	20.2
28/76	76.5**	157	250	15.0
29/76	86.0	157	208	12.5
30/76	49.0	157	83	5.0

* Hydraulic conductivity values used here are averages of the 'fair' results for individual bores shown in Table 6

** Average of hydraulic conductivity values from bores 21/76, 29/76 and 30/76, the three closest bores.

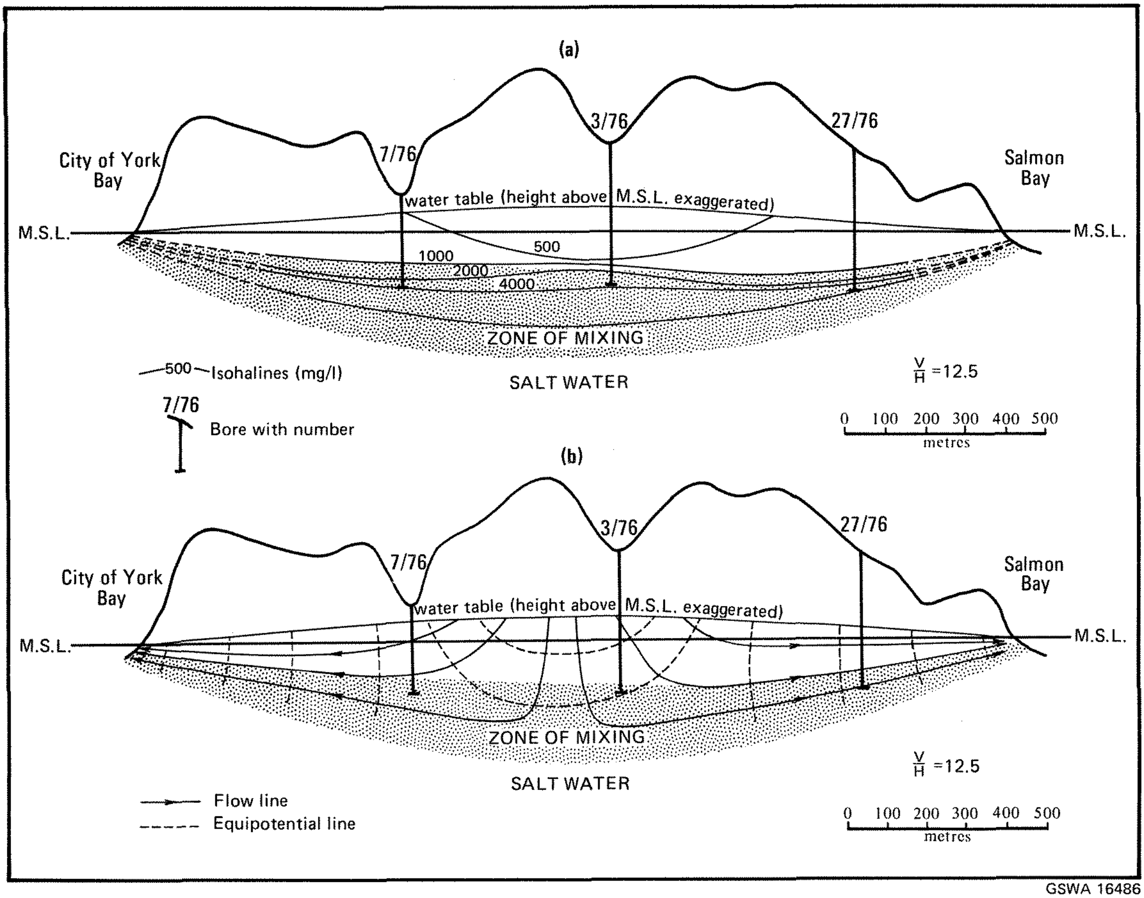

Figure 30 Cross sections of Rottnest Island.

(a) salinity profile of fresh-water lens.
(b) diagrammatic flow system within fresh-water lens.

Chandler and McWhorter (1975) developed relationships between critical discharge (the discharge at which the upconing of the interface reaches the bore screen) and bore penetration within the fresh-water zone. From their equations, long-term pumping rates (Table 7) have been estimated.

Abstraction rates in column 4 of Table 7 show the maximum pumping rates permissible if a sharp fresh/salt-water interface is assumed. However, the long-term pumping rates predicted in column 5 of Table 7 should be adopted for production, as these results allow for the upconing of the zone of mixing. Chandler and McWhorter suggest the optimum screen penetration into the fresh-water lens should be approximately one third of the lens thickness.

It has been found (Visher and Mink, 1964) that intermittent pumping from a fresh-water lens has a deleterious effect upon the zone of mixing. On-off pumping results in abrupt movements of the fresh-/salt-water interface, thus causing a thickening of the zone of mixing. Pumping continuously at low discharges is preferable to intermittent pumping at high discharges. It is, therefore, strongly recommended that any bore field constructed on Rottnest Island be pumped continuously during the summer season to meet peak demand, and then rested for several months during the low-demand winter period.

At the height of the summer tourist season in 1975 the demand for first-class water was 203 m^3/day. This means that if Rottnest were totally dependent on groundwater, at least four bores pumping continuously at 50 m^3/day, or seventeen bores pumping continuously at 12.1 m^3/day (average long-term pumping rate predicted in column 5 of Table 7) would be required to meet peak demand. The latter is preferable.

HYDROCHEMISTRY

The chemical character of the groundwater varies considerably, not only in total soluble salt content but also in its ionic constituents. Table 8 shows a total of 31 chemical analyses completed on samples collected during the project, and one of sea water from Davis and De Wiest (1966). The freshest groundwater occurs in areas where the water table is highest, as can be seen by comparing the isohalines (Fig.31) with the water-table contours (Fig. 32), for the central part of the island. Other areas of fresh groundwater are found mainly in high dunal regions.

Water salinity within the proposed bore field is (Fig.33) low enough for human consumption, and has a TSS range of 420-730 mg/l. However, certain ion concentrations must be monitored occasionally, as they approach the upper limit for human consumption. Eleven analyses report nitrate levels in excess of 45 mg/l (upper recommended limit for domestic purposes); although fortunately most of these analyses come from bores or wells outside the proposed bore-field. Figure 34 indicates the areas in which nitrate ion is likely to occur. High concentrations of nitrate can cause methaemoglobineamia, a disease which afflicts infants, and regular analyses should therefore be conducted to monitor any fluctuations in nitrate concentration, as seasonal variations may occur. The origin of the nitrate is uncertain, but the most likely sources are nitrogen-fixing vegetation, and waste products from the

TABLE 8. Chemical Analyses

Bore/well	TDS EVAP.	TSS COND. x0.64	HARD-NESS ($CaCO_3$)	ALKAL-INITY ($CaCO_3$)	pH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	SiO_2	B	F	Mn	$\frac{Cl}{HCO_3}$
1/76	600	640	320	253	7.6	90	23	88	6	NIL	308	140	43	28	11	0.38	1.7	<0.02	0.45
2/76	640	700	373	255	8.1	44	64	90	8	NIL	311	158	71	32	15	0.42	2.1	<0.02	0.51
3/76	420	480	240	190	7.9	58	23	60	3	NIL	232	100	30	13	5	0.15	0.8	-	0.43
4/76	1480	1620	508	315	7.7	70	81	345	20	NIL	384	540	161	53	10	0.25	0.8	<0.02	1.41
5/76	650	730	362	273	7.6	56	54	99	7	NIL	332	155	79	16	7	0.28	1.5	-	0.47
6/76	470	520	244	167	8.0	50	29	74	2	NIL	240	129	44	14	4	-	1.4	-	0.54
8/76	3140	3350	884	391	7.8	112	137	821	21	NIL	476	1440	207	37	7	-	1.1	-	3.03
9/76	720	790	359	243	8.0	58	52	123	11	NIL	296	187	79	64	7	-	1.4	-	0.63
10/76	3290	3680	799	331	8.0	81	145	927	45	NIL	403	1530	328	55	4	-	1.1	-	3.80
13/76	1180	1340	519	305	7.7	119	54	225	12	NIL	372	407	138	1	10	0.71	0.6	-	1.09
15/76	730	840	331	213	7.9	50	50	145	7	NIL	259	267	49	19	7	-	0.8	-	1.03
20/76	650	760	351	233	7.8	58	50	111	8	NIL	284	170	78	59	7	-	1.2	-	0.60
21/76	560	660	305	208	8.0	63	36	92	5	NIL	253	155	46	46	9	0.25	1.5	-	0.61
23/76	690	770	374	236	7.7	54	58	100	14	NIL	287	148	107	67	9	0.21	1.3	-	0.52
24/76	490	580	291	217	7.8	41	46	74	4	NIL	264	118	55	21	1	0.60	1.6	-	0.45
25/76	520	610	310	215	7.7	45	46	78	4	NIL	262	124	64	26	7	-	1.8	-	0.47
26/76	680	790	318	226	7.6	50	47	135	6	NIL	275	203	89	18	7	-	1.6	-	0.74
27/76	770	920	404	303	7.5	58	63	145	5	NIL	369	252	49	21	5	-	1.7	-	0.68
28/76	680	770	280	200	7.8	53	36	135	9	NIL	244	211	75	13	8	0.32	1.0	-	0.86
29/76	520	600	310	226	7.6	58	40	73	8	NIL	275	118	59	30	9	-	0.9	-	0.43
30/76	670	770	325	215	7.6	64	40	121	5	NIL	262	214	61	18	<1	-	0.6	-	0.82
Baghdad W	1490	1590	509	303	7.9	105	60	334	10	NIL	369	595	95	4	12	0.29	1.0	<0.02	1.61
Serpentine W	640	720	303	215	7.8	85	22	110	5	NIL	262	199	42	12	7	0.23	1.2	<0.02	0.76
Lighthouse W	1010	1130	411	228	7.7	74	55	212	11	NIL	278	364	102	46	15	0.47	0.4	<0.02	1.31
Geordie Bay Project W	1360	1430	485	338	8.1	54	85	288	26	NIL	412	437	136	61	14	0.86	1.2	<0.02	1.06

TABLE 8 - continued

Riding School W	4 300	4350	931	326	7.6	182	116	1 100	99	NIL	397	1 850	318	225	16	0.84	0.6	<0.02	4.66
Groundwater Seepage - Serpentine Lake	2 720	3040	711	298	7.5	79	125	708	35	NIL	363	1 200	248	63	7	-	0.7	-	3.31
South Pump W1	7 920	8510	1564	293	8.2	214	250	2 260	107	NIL	357	4 040	515	114	10	-	0.4	-	11.32
Rainwater	110	130	37	28	6.4	10	3	26	2	NIL	34	39	12	<1	4	<0.05	0.1	-	1.15
Seawater	32 545	-	-	-	-	400	1350	10 500	380	-	28	19 000	885	-	1	-	-	0.002	678

NOTE: All results given in mg/l except pH and Cl/HCO_3. TDS is total dissolved solids as determined by evaporation. TSS is total soluble salts as determined by conductivity

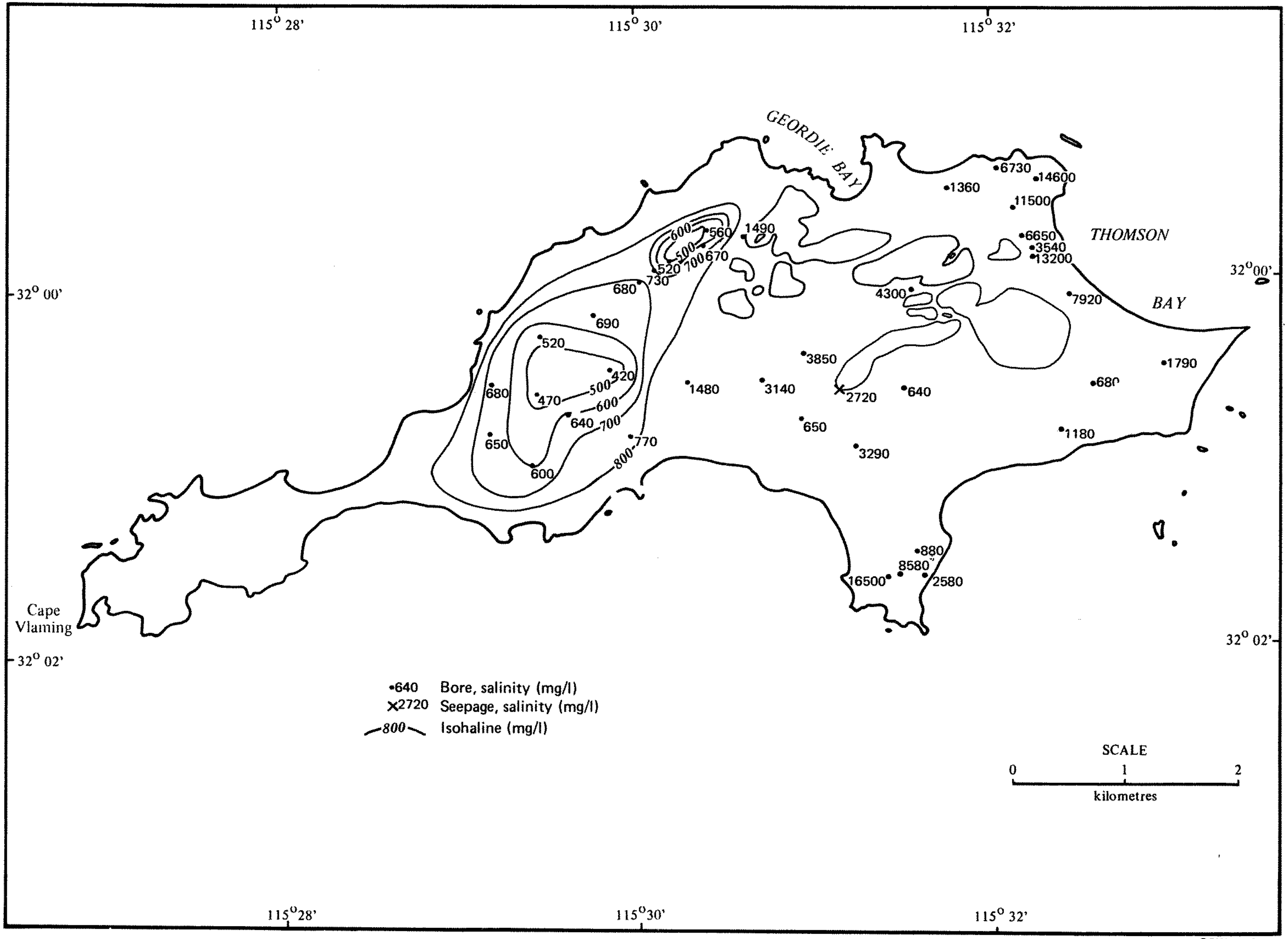

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Figure 31 Isohalines.

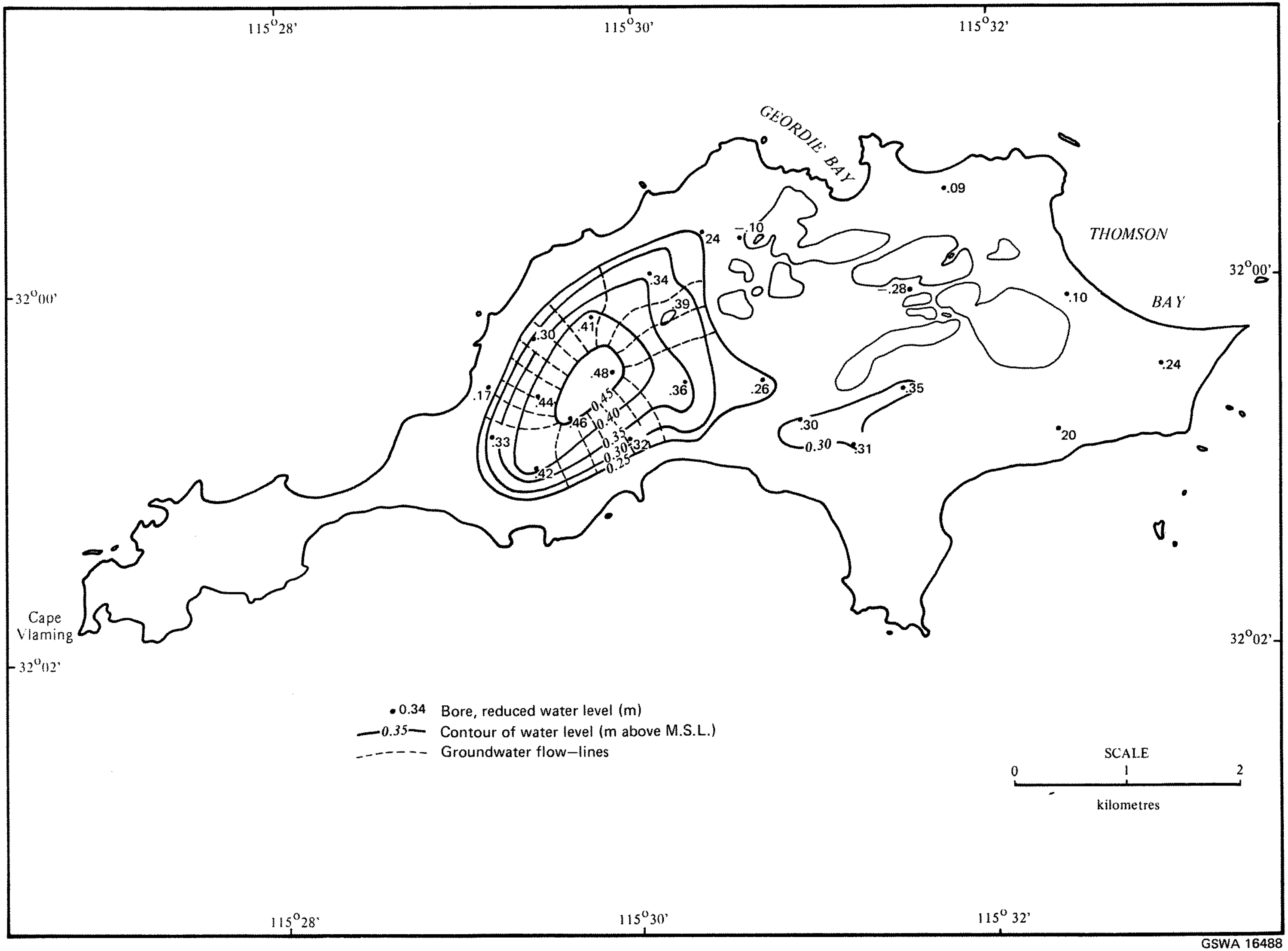


Figure 32 Water-table contours and flow net.

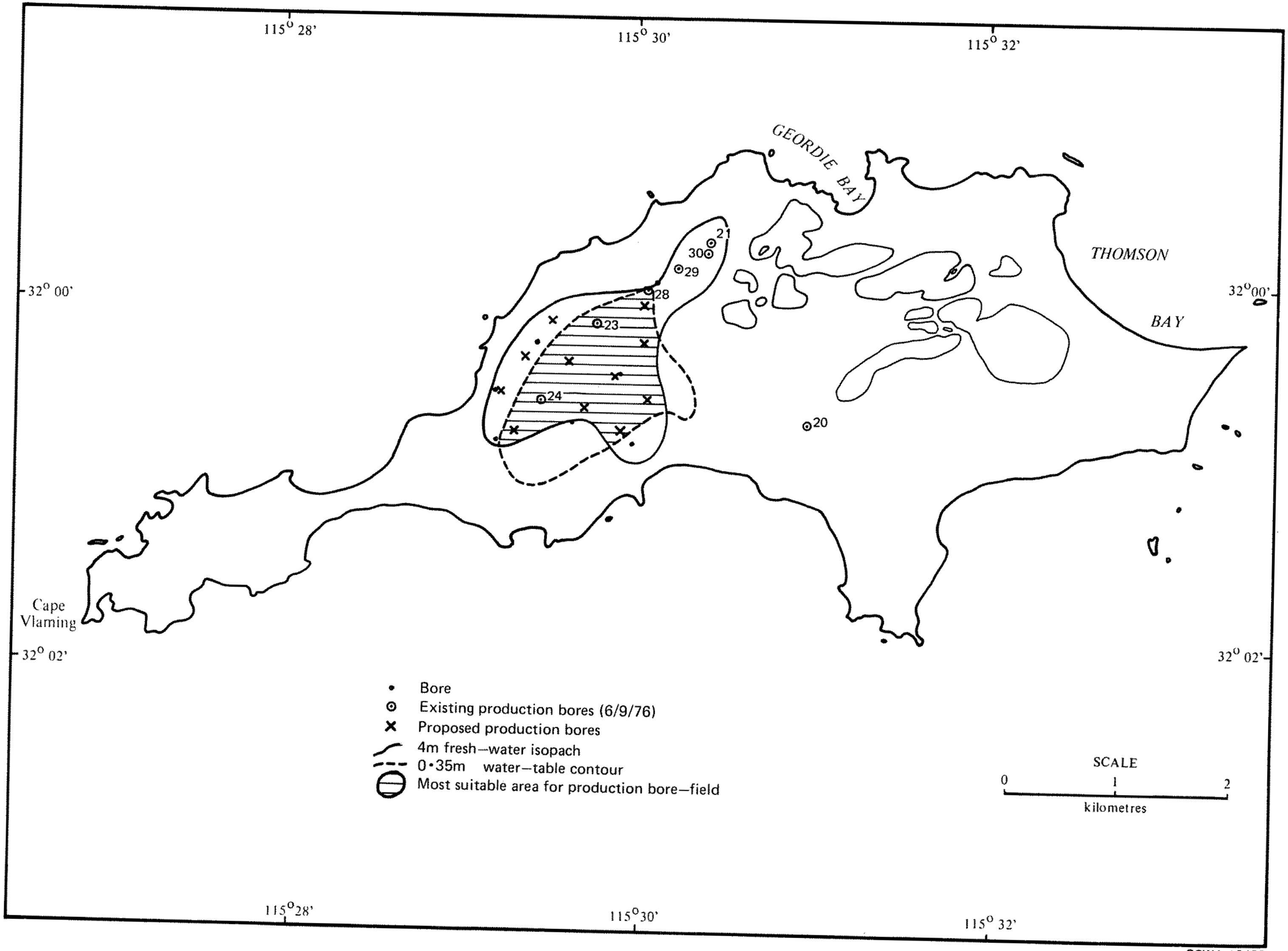


Figure 33 Proposed bore-field location.

indigenous quokkas. Nitrate pollution is leached downward from these sources by rainfall and infiltrates the water table.

The World Health Organization recommends a fluoride content of between 0.7 and 1.0 mg/l for a climate similar to that of Rottnest Island. Eight analyses exceed the 1.0 mg/l limit and could possibly be harmful to the health of children by causing dental fluorosis if ingested over a long period.

Both the nitrate and fluoride concentrations are not so high as to cause serious concern, and in any case, will be diluted to acceptable levels when the bore water is blended with catchment water before reticulation to the settlement. A further water-quality problem is caused by the presence of the bacteria *Salmonella*, introduced into the groundwater from waste products of quokkas. *Salmonella* can be eliminated by chlorination, as is already done with water from the bitumen catchments.

Pumping tests have shown the groundwater to be clean, clear and odourless; therefore, no treatment will be necessary except for chlorination. If bore development takes place due to pumping, suspended material may occur in the groundwater.

HYDROGRAPHIC MEASUREMENTS

Two water-level recorders have been installed to record groundwater fluctuations. The first recorder installed was on Baghdad Well, adjacent to Baghdad Lake; this well is in Herschell Limestone. Two distinct water-level responses occur; the first is due to recharge from rainfall; the second is a diurnal fluctuation due to evapotranspiration. On 28th August 1976, 18 mm of rain caused the water table to rise 90 mm; from this a porosity of 0.2 may be estimated for the Herschell Limestone, assuming 100% recharge.

The diurnal fluctuations in Baghdad Well are interesting, as they cannot be attributed to ocean or earth tides, to barometric pressure, or to temperature. The diurnal fluctuations almost by definition occur regularly each day. The highest water level occurs between 04.00 and 06.00 hours and the lowest, between 16.00 and 18.00 hours. The water table in Baghdad Well is approximately 0.3 m below ground surface, and it seems likely that direct evaporation takes place from the capillary fringe above the water table.

Also, the well is surrounded by moss and reeds which transpire the shallow groundwater. The water table falls during daylight hours, which correspond to times of maximum evaporation and transpiration. Water-balance calculations on diurnal fluctuations for 17 days, which were unaffected by rainfall, showed an average daily loss of 2.26 mm of water in the vicinity of Baghdad Well. The average daily gain due to lateral flow from higher up the groundwater mound was 1.06 mm. Therefore, the net daily loss due to evapotranspiration close to Baghdad Well is 1.20 mm. When unaffected by rainfall the hydrograph shows an overall decline, and a water-balance on the 'smoothed' hydrograph also shows a net daily loss of 1.2 mm. The mean daily loss from groundwater is 40% of the open-pan evaporation measured at the Perth Meteorological Observatory.

The second water-level recorder is sited on bore 20/76, some 350 m south of Oliver Hill. The hydrograph from this location only shows responses due to rainfall. No calculation of porosity has been made, as no large storms have occurred since recording began.

Monthly measurements of water levels in the Phase I bores show a steady decline in the water table from mid-August to the end of December, 1976. This decline in the water table was due to the lack of recharging rainfall, 1976 having been one of the driest years on record with a total precipitation of 462 mm.

GROUNDWATER RESOURCES

AREAS OF INTEREST

Hydrologically, the Thomson Bay settlement is situated in one of the worst parts of the island for obtaining fresh groundwater supplies. The settlement is close to salt lakes, and the surrounding area has a low elevation. Early wells in this area intersected a thin layer of fresh water which turned brackish on pumping. Further, the water table falls during summer, thus decreasing the thickness of the fresh-water layer. The most prospective areas for obtaining unconfined groundwater are the high areas in the central part of the island (Playford, 1976), and it was in this region that most bores were located.

The main study-area for the drilling project was north and west from the central lighthouse. It is to this area that the quantitative analyses discussed in this report apply. Contours of different parameters are only drawn for the central area as, in other areas, there is insufficient information. However, point values have been recorded. Three other areas are worth mentioning, as they may contain small supplies of potable water.

A narrow strip, south and southeast from Oliver Hill, may extend under high dune country to Parker Point, where an earlier bore intersected 5 m of fresh water. A small lens of fresh water may also be expected between Porpoise Bay and the aerodrome. Groundwater from these two areas could be used to increase the supply of first-class water or to upgrade the second-class reticulation system. The third area likely to hold a small fresh-water lens is the west end of the island, west of Narrow Neck. The water could possibly be used for drinking fountains or ablution blocks for Marjorie and Wilson Bays.

Assessments for supplies of confined water from deep Mesozoic aquifers on Rottnest Island have been made by Berliat (1961) and Playford (1976). Both concluded that the prospects were poor, because the water would almost certainly be too saline for domestic use.

RATE OF REPLENISHMENT

Recharge to the unconfined aquifer is totally dependent upon winter rainfall. A diagrammatic recharge flow system is shown in Figure 30. Most of the recharging rainfall falls during June, July and August. The percentage of rainfall which infiltrates the water table can be estimated by comparing groundwater chlorinity to that of rainwater. An analysis of rainwater collected from the settlement area in June, 1976 showed a chloride content of 39 mg/l. An average groundwater chloride-content for the area of interest (above the 4 m isopach - Fig.35) was determined by drawing isochlors and superimposing the 4 m isopach upon them. Eleven equidistant points were taken along the 4 m isopach, and point chloride contents were determined by extrapolating from the isochlors. These gave an average chloride content of 195 mg/l.

Therefore, the amount of recharge from rainfall

$$= \frac{\text{chloride content in rainfall} \times 100}{\text{chloride content in groundwater}} = 20\%$$

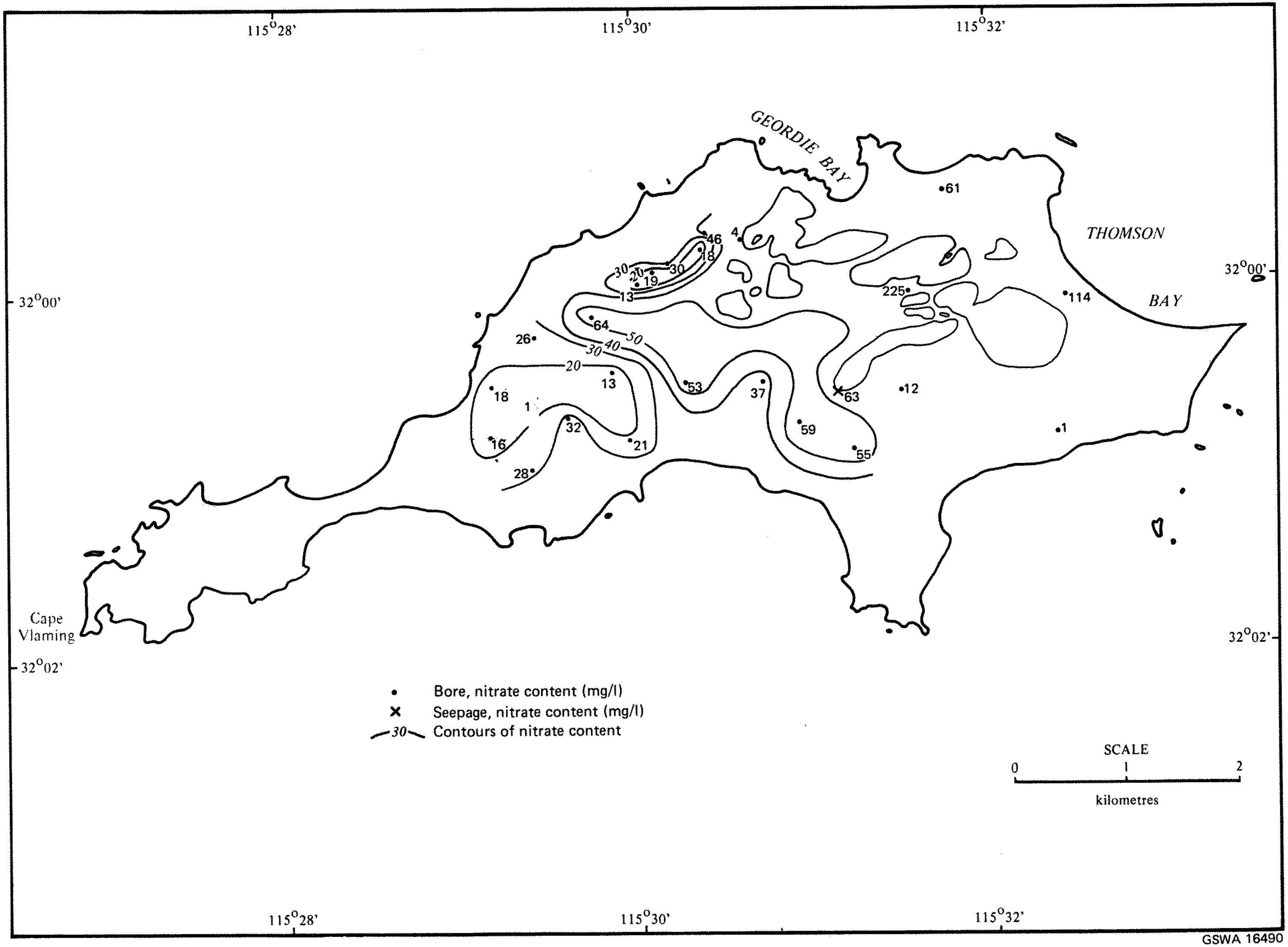
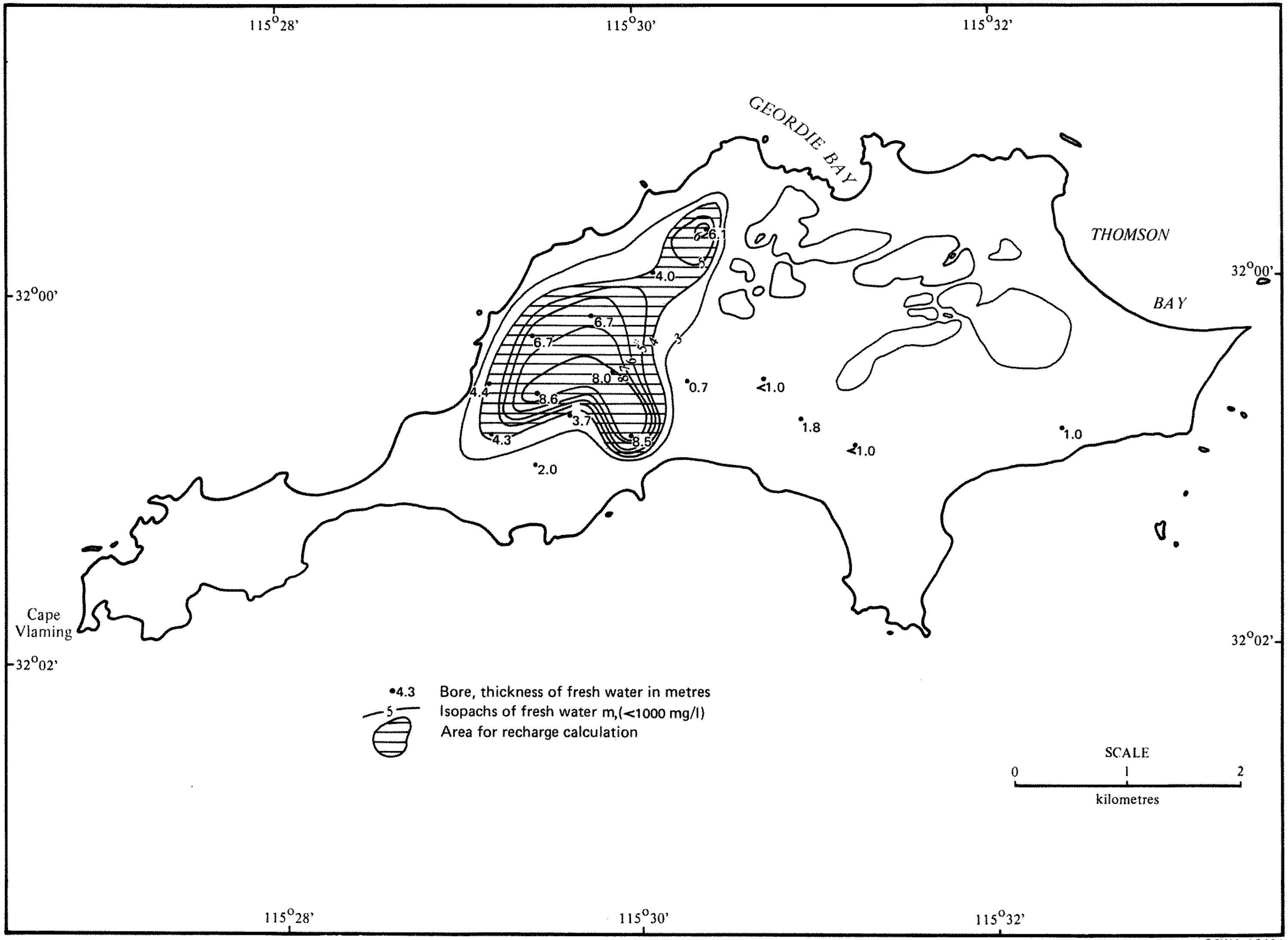


Figure 34 Contours of nitrate content.



GSWA 16491

Figure 35 Isopachs of fresh water.

The remainder of the rainfall is lost by evaporation, and transpiration. There are no water courses on the island, so that virtually no surface runoff flows directly into the ocean.

The mean annual rainfall is 736 mm. Using a recharge coefficient of 0.20 (i.e. per cent recharge divided by 100), the volume of effective recharge infiltrating through the area of 2.58 km^2 above the 4 m isopach (shown shaded on Fig.35) is obtained by:

Annual volume of recharge = Area x Annual rainfall x Recharge coefficient
= 3.80×10^5 m^3/year

Abstraction of groundwater induces sea-water intrusion by flattening the groundwater gradient. In a dynamic situation, it is commonly accepted that at least 25% and preferably 50% of annual recharge should be retained in the aquifer to preserve hydraulic gradients. On this basis, a maximum of 2.85×10^5 m^3 of groundwater could be withdrawn annually from the study area, provided efficient abstraction methods are adopted. However, this figure is not to be taken as the annual safe yield, as it is based on an ideal aquifer with no zone of mixing. An annual safe yield figure is calculated later in this report.

Further samples of rainwater should be collected from the centre of the island and analysed for their chloride content, because the 39 mg/l figure used above seems too high.

TEST PUMPING

The unconfined aquifer is part of the Tamala Limestone, a poorly cemented calcarenite composed of fragmental shell material. There is no evidence to suggest this rock unit is cavernous below the water table, and hydraulic parameters are determined on the assumption that the aquifer is homogeneous and isotropic. Variations in horizontal and vertical hydraulic conductivity occur, but no clear trends are evident.

Seven test-pumping bores have been constructed, four on Phase I sites (6/76, 7/76, 9/76, and 16/76) and three others (28/76, 29/76, and 30/76). Qualitatively, these results have been most promising except for the pumped bores at sites 16/76 and 30/76 which gave large drawdowns for low yields; at other sites pumping rates of 100 m^3/day produce drawdowns in the order of

0.3 m. Data collected from pump tests have been difficult to analyse because each pumping bore reached maximum drawdown within a few minutes after pumping commenced. The most reliable results were obtained from observation bores, although in some cases the drawdowns measured in these bores were less than 0.04 m. From the usable data, values for transmissivity, hydraulic conductivity and storage coefficient were determined, the results being summarized in Table 9.

The reliability rating of each test is based upon the quality of data obtained during testing. Averaging results which have a 'fair' reliability rating gives the following figures for the hydraulic aquifer parameters: transmissivity 1 000 m^3/day/m, hydraulic conductivity 77 $m^3/day/m^2$ and storage coefficient 0.09. These results are probably of the correct order, although the storage coefficient is based on short-term tests and could be low by a factor of about two.

FLOW-NET ANALYSIS

Figure 32 shows the water-table contours and flow net for the central part of Rottnest Island. The fresh-water lens forms a mound which discharges towards the ocean and salt lakes. Discharge from the groundwater mound is represented by small seepages along the fringes of salt lakes; and samples of seepage water had a total-soluble-salt (TSS) content of 3 000 mg/l compared to 155 000 mg/l from the salt lakes. A flow net was drawn to determine a regional estimate for transmissivity.

As no intermediate losses have been detected, the mound is assumed to be in a steady-state condition, in which the discharge volume is equal to the recharge volume. The volume of water moving between the 0.45 and 0.25 m potentiometric contours is calculated using the formulae given by Walton (1962).

The area bounded by the 0.45 and 0.25 m potentiometric contours is 3.87×10^6 m^2 and the aquifer front is 5 900 m. The area above the 0.25 m contour is 4.16×10^6 m^2. The recharge coefficient is different in this calculation because the area being dealt with has changed. The recharge coefficient was calculated by the same method previously used, and is 0.18. From this:

TABLE 9. Summary of pump testing results.

Bore Pumping	Bore Observation	Type of test	Analytical method	Transmissivity. m^3/day/m	Hydraulic conductivity* m^3/day/m^2	Storage Coefficient	Reliability rating
20/76		Drawdown	Theis	90	7.5	-	Poor
20/76		Drawdown	Cooper-Jacob	998	83	-	Poor
20/76		Recovery	unusable				
	9/76	Drawdown	Theis **	1 250	104	0.06	Fair
	9/76	Drawdown	Cooper-Jacob	1 173	98	0.06	Fair
	9/76	Recovery	unusable				
21/76		Drawdown	unusable				
21/76		Recovery	unusable				
	16/76	Drawdown	Cooper-Jacob	1 025	107	0.002	Fair
	16/76	Recovery	Cooper-Jacob	790	82	0.008	Fair
23/76		Drawdown	unusable				
23/76		Recovery	Cooper-Jacob	1 140	70	-	Poor
	7/76	Drawdown (early data)	Theis	550	34	0.013	Fair
	7/76	Drawdown (late data)	Theis	490	30	0.79	Poor
	7/76	Drawdown (early data)	Cooper-Jacob	2 500	152	0.008	Poor
	7/76	Drawdown (late data)	Cooper-Jacob	740	45	0.3	Fair
	7/76	Recovery	unusable				
24/76		Drawdown	unusable				
24/76		Recovery	unusable				
	6/76	Drawdown (early data)	Theis	5 230	297	0.003	Poor
	6/76	Drawdown (late data)	Theis	1 112	63	0.14	Fair
	6/76	Drawdown (early data)	Cooper-Jacob	5 385	306	0.003	Poor
	6/76	Drawdown (late data)	Cooper-Jacob	1 320	75	0.12	Fair
	6/76	Recovery	Cooper-Jacob	3 030	172	0.003	Poor
28/76		Drawdown	unusable				
28/76		Recovery	unusable				
29/76		Drawdown	Cooper-Jacob	1 065	86	-	Fair
29/76		Recovery	unusable				
30/76		Drawdown	Cooper-Jacob	513	49	-	Poor
30/76		Recovery	unusable				

* Hydraulic conductivity is determined using an aquifer thickness equal to the thickness of fresh water at each bore site calculated by the Ghyben-Herzberg Relation

** Average of two matches.

Average daily discharge = Recharge

= Area x Mean annual rainfall x Recharge coefficient / 365

= 1 510 m^3/day.

The groundwater hydraulic gradient was determined to be 3.05×10^{-4}. Transmissivity is then calculated by:

Transmissivity = Average daily discharge / Hydraulic gradient x Aquifer front

= 839 m^3/day/m.

The hydraulic conductivity can be determined by dividing the transmissivity by the aquifer thickness.

The aquifer thickness over the region is estimated as the depth of water above the fresh-/salt-water interface. Using an average water-table elevation of 0.35 m above mean sea level, and applying the Ghyben-Herzberg relation this indicates an aquifer thickness of 14.35 m. Hence:

Hydraulic conductivity = 58.5 $m^3/day/m^2$

The values for transmissivity and hydraulic conductivity calculated by flow-net analysis are reasonably close to those determined from pumping tests. More reliance should be placed on the flow-net values, as pump-test results are point solutions within the mound and are also subject to bore efficiency and interpretive effects.

STORAGE

The volume of fresh water held in storage above the 4 m fresh-water isopach (Fig.35) can be calculated:

Volume in storage = Aquifer volume x Storage coefficient

The aquifer volume is calculated as the sum of the incremental volumes between each isopach above 4 m, and gives an aquifer volume of 1.58×10^7 m^3. The storage coefficient derived from short-term pump-test solutions was 0.09, but, for calculating aquifer storage, a more realistic value would be 0.15.

Therefore ,

Volume of water in storage = 2.37×10^6 m^3

The recharge: storage ratio is in excess of 1:6, therefore, only a prolonged drought would seriously deplete the thickness of the fresh-water lens.

SAFE YIELD

The safe yield of an aquifer is the amount of water which can be withdrawn annually without producing an undesired result. Safe yield is influenced by many factors including recharge, losses, water salinity and legal considerations. The first three of these criteria apply to the Rottnest unconfined aquifer. In an ideal aquifer, withdrawal can equal recharge without any undesirable results. However, on Rottnest the ever-present problem of sea-water or salt-water intrusion exists. This in turn leads to the second consideration, groundwater losses. In order to prevent sea-water intrusion, a percentage of recharge must be retained within the aquifer to preserve underflow and eventual discharge of fresh water into the ocean and salt lakes. Evapotranspiration losses from the water table appear to be negligible in the study area as very few phreatophytes are present. The overriding constraint on safe yield in this aquifer is water salinity due to the delicate balance between the fresh water and the more salty water in the zone of mixing.

It is estimated that the safe yield from the Rottnest groundwater lens amounts to approximately 50 percent of the annual recharge, allowing the other 50 per cent to preserve adequate underflow. On this basis the safe yield would be 50 percent of $3.8 \times 10^5/m^3$/year, or 1.9×10^5 m^3/year.

This safe yield represents slightly more than ten times the present annual requirement of 1.82×10^4 m^3, and one-twelfth of the volume of fresh water in storage.

MANAGEMENT OF PUMPING SYSTEM

GENERAL

This section of the report indicates an area for a bore field, and describes the management procedures necessary for effective groundwater development. Any pumping system designed to abstract water from an aquifer must be governed by the limitations imposed by the geology, hydrology, and hydraulics of the aquifer. Previous sections of this report have emphasized that the most important constraint on groundwater production is water salinity, and a method is described for the recognition of salt-water intrusion into the bore field. Water-table response to pumping is considered, and a monitoring scheme is designed to observe the behaviour of the groundwater under the influence of pumping.

PROPOSED BORE FIELD

Figure 33 shows a proposed bore-field layout, which incorporates pumping bores already constructed and a further eleven sites for future production bores. It should be noted that the largest number of proposed bores is in an area where the 4 m fresh-water isopach coincides with an area bounded by the 0.35 m potentiometric contour. In this area a given rate of abstraction should cause the least sea-water intrusion. The bores are selected on an approximate 400 m grid spacing to ensure that abstraction and hence drawdown is evenly distributed over the bore-field area. This is important.

RECOGNITION OF SALT-WATER INTRUSION

An aquifer that is subject to salt-water intrusion needs an early-warning system which can be used to predict movements of saline water. Fresh groundwater on Rottnest Island is mainly of the bicarbonate (HCO_3^-) type, whereas the brackish water and sea water is a chloride (Cl^-) type. Revelle (1941) suggested an increase in the Cl^-/HCO_3^- ratio as an indication of salt-water intrusion. For this reason the Cl^-/HCO_3^- ratios for all analyses including sea water, are shown in Table 8. As the HCO_3^- content in groundwater is relatively stable, increases in Cl^- should indicate any detrimental trends in groundwater salinity caused by pumping. Therefore, measurement of chloride concentration should be done on a regular basis.

Analyses indicate that fresh groundwater within the proposed bore field has a Cl^-/HCO_3^- ratio less than unity, but wells outside this area, with one exception, have a Cl^-/HCO_3^- ratio greater than unity (Fig.36). A study of water samples taken during drilling showed that the Cl^-/HCO_3^- ratio increased with depth into the zone of mixing (Fig.29). Therefore, when a bore is pumped, an initial increase in the ratio will result from the upward movement of the zone of mixing. If the Cl^-/HCO_3^- ratio continues to increase then salt-water intrusion is taking place, and remedial measures should be taken, such as reducing the rate of pumping.

EFFECT OF PUMPING ON WATER TABLE

The annual requirement from groundwater in the immediate future at Rottnest is $1.82 \times 10^4\ m^3$, needed from November to April to supplement catchment water. If the bore field is pumped continuously for six months each year (180 days), for a total discharge of $1.82 \times 10^4\ m^3$, and no recharge occurs, the dewatered thickness of the fresh-water lens can be estimated. The area used in the following calculation is that bounded by the 4 m isopach, though depletion of the aquifer will spread beyond that limit, so that the dewatered thickness calculated will be a maximum. A storage coefficient of 0.15 is used for this calculation.

$$\text{Dewatered aquifer volume} = \text{Discharge/Storage coefficient} = 1.21 \times 10^5\ m^3$$

$$\text{Dewatered thickness} = \text{Dewatered aquifer volume/Aquifer area} = 0.05\ m$$

A dewatered thickness of 0.05 m will have negligible effect upon the hydraulic gradient, as only 2.5 per cent of this thickness is represented by lowering the water table, the rest being contributed by an upward movement of the fresh/salt-water interface. This small upward movement of the interface will not adversely affect the fresh-water lens, as movements of this magnitude are commonly caused by seasonal variations.

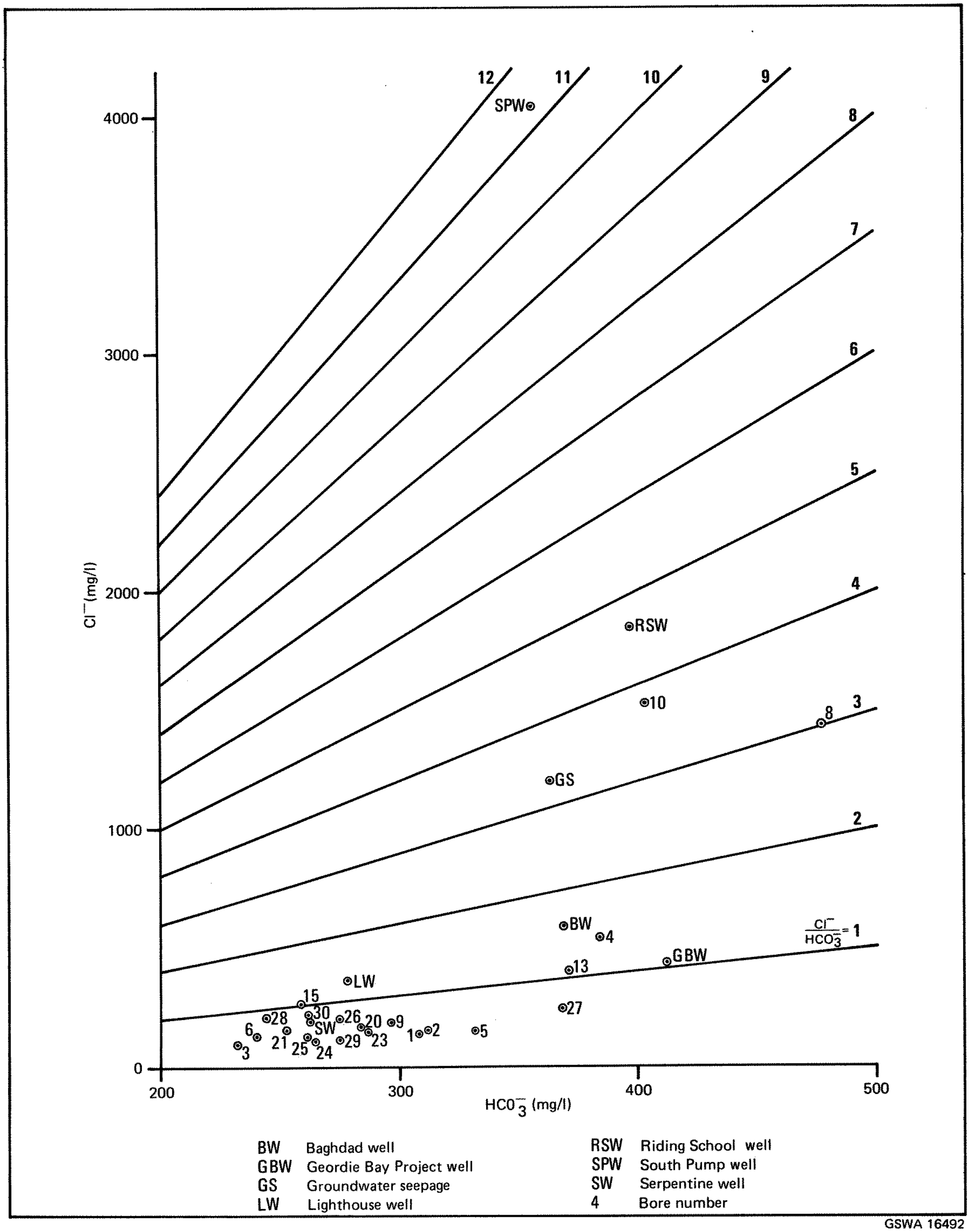


Figure 36 Relationship between chloride- and bicarbonate-ion concentrations.

CONJUNCTIVE USE

Rottnest Island has two bitumen catchments for the collection of rainfall runoff; the storage capacity of the catchment tanks is 2.73×10^4 m^3. After an average winter's rainfall, the storage tanks are full, and the supply would last the settlements for approximately 150 days, so that it is only in late summer and autumn that additional water is required. The proposed bore field will not have to operate for 12 months each year to meet the first-class water demand, but can be pumped continuously for several months at a rate which ensures water is available until the next winter rains.

Replenishment of storage tanks has two important factors; firstly, less than 203 m^3/day will be required from the bore field, and, secondly, any undesirable salinity constraints within the groundwater are overcome by mixing the two types of water.

BORE-FIELD MONITORING

Because of the likelihood of salt-water encroachment into pumping bores, a stringent monitoring procedure is necessary to ensure that the groundwater supply remains potable. Listed below are the measurements which should be taken during bore-field operation:

(i) Drawdown and discharge rate from pumping bores should be measured daily for the first week of operation, and then weekly throughout the production period;

(ii) total-soluble-salt (TSS) content from each pumping bore should be recorded daily for the first week of operation, then twice per week for the next month, and then once weekly if no deterioration is evident;

(iii) chloride content should be measured whenever a TSS measurement is recorded, because an increase in chloride-ion concentration is an indication that salt-water intrusion may be occurring;

(iv) full chemical analyses must be carried out on each bore every 3 months to safeguard against increases in nitrate and fluoride-ion concentrations, and to observe if any seasonal variations occur;

(v) the Public Health Department should conduct microbiological analyses at regular intervals;

(vi) monthly down-hole salinity profiles and water levels should be monitored in all bores constructed during the Phase I drilling, for a period of not less than one year.

If a pumping bore shows deterioration in water quality, the bore should be shut down until its salinity profile is consistent with that of the freshwater lens. This may mean the bore will be non-operational for as much as a year.

ENVIRONMENTAL CONSIDERATIONS

Long term pumping from an unconfined aquifer will lead to a lowering of the water table. This condition can result in the decrease or cessation of spring discharges, lowering of adjacent surface waters, and killing of deep-rooting trees. On Rottnest Island all three conditions must be considered.

Several springs or seepages occur around the margins of the salt lakes. These seepages reflect the groundwater gradient in that area, discharging from the groundwater mound into the salt lakes. The salinity of the seepages is approximately 3 000 mg/l, whereas the salinity of the salt lakes is about 155 000 mg/l. Pumping from a groundwater mound adjacent to salt lakes could cause a hydraulic-gradient reversal; thus, stopping springs and inducing very saline water into the aquifer, and resulting in a lowering of the lake level. However, on Rottnest Island the fresh water is already sitting on top of saline water within the aquifer, and over-pumping would result in brackish water being discharged long before any gradient reversal would take place in the vicinity of the lakes. Hence an inbuilt control exists to prevent spring discharges terminating and the lowering of lake levels. These springs are a water source for quokkas and birds.

Over the last sixteen years reforestation projects have commenced outside the settlement area. Several plantations (including deep-rooting eucalypts) are inside the proposed bore field, and dewatering and salinity increases within the mound could have some effect upon reforested areas. The deep-rooting trees (phreatophytes) tap water from the capillary zone above the water table, as well as from below the water table. Lowering of the water table could ultimately result in the killing of some trees. However, the water table should not be lowered by more than a few centimetres over the mound area over several months, which would allow tree root systems to adjust to this small decline in the water table. From a hydrological viewpoint the presence of trees in the mound area will reduce infiltration to the water table, and also increase the salt concentration of the groundwater. If because of over-pumping the fresh-water mound turns brackish, consideration will need to be given to the tree species and their salt tolerances. Indigenous trees to Rottnest Island are shallow rooting (xerophytes), and are probably unaffected by water-table movement and groundwater salinity. Introduced trees are less tolerant, and several species may die if salt-water intrusion takes place in their vicinity. However, constant salinity monitoring of the groundwater mound should take place when a production bore field is operational, thus safeguarding against the possibility of salt-water intrusion killing the phreatophytes. The Rottnest Island Board is reported to have wisely decided against further reforestation within the proposed bore field area, in order to limit evapotranspiration by phreatophytes.

Further development will result in an increased demand on water from the proposed bore field. A few further small areas are prospective for fresh groundwater, and further test drilling should be undertaken to evaluate these areas. However, development of these areas may prove too costly for the small yield expected. Therefore to become self-sufficient for water in the decades ahead, the island may again have to use more surface bitumen catchments to collect runoff water. Environmental objections to bitumen catchments are aesthetic. A bitumen catchment of several hectares cannot be hidden, but it can be surrounded by trees, or it could be placed in less populated areas.

CONCLUSIONS

1) A significant lens of fresh water exists in the area bounded by Armstrong Hill, White Hill, and the central lighthouse. Abstraction should be from the thickest part of the lens, above the 4 m isopach. Withdrawal of groundwater should be evenly distributed over the mound to avoid local upconing of the fresh-/salt-water interface.

2) A supply of 1.82×10^4 m^3/year is sought, which is slightly less than one-tenth of the calculated annual safe yield of 1.9×10^5 m^3. This

requirement can be met without any detrimental effect upon the fresh-water lens, as long as provision is made for bores to be properly designed and constructed and precautions are taken to avoid over-pumping. For optimum efficiency production bores should be:

(i) fully screened into the upper third of the fresh water lens;

(ii) of maximum diameter economically possible, and,

(iii) gravel packed.

3) An area is delineated for the development of a bore field, and production sites selected are approximately on a 400-m grid. Long-term pumping rates have been calculated for the production bores, and the production bore-field will have no deleterious effect upon the environment.

4) Production bores should be pumped continuously at low discharges rather than pumping intermittently at high discharges.

5) Drawdown and discharge measurements from each bore should be taken regularly, and daily discharge from the bore field monitored.

6) The aquifer parameters, transmissivity and hydraulic conductivity, which are determined by both flow-net analysis and pump tests, are reasonably close.

7) Water quality in the proposed bore-field area is suitable for domestic consumption. Nitrate and fluoride concentrations in certain bores may reach unacceptable levels with continuous pumping, so that regular monitoring of these anions is necessary. The abstracted groundwater is to be mixed with the catchment water, which will dilute to acceptable levels any excessive ionic concentrations.

8) When production commences, monitoring of groundwater quality should be done regularly to safeguard against salt-water encroachment into the production bores.

9) Salinity logging of bores should be continued on a monthly basis for at least twelve months.

10) Annual reassessments of the bore field should be done until the behaviour of the fresh-water lens under pumping conditions is fully understood.

11) The area above the 4-m fresh-water isopach should produce the island's additional water requirements for several years to come. Two or three other areas are likely to produce some fresh groundwater if required, or these could be used to upgrade the second-class water system. One of these is an area south and southeast from Oliver Hill, and this may extend in a narrow strip under high dune country to Parker Point. A small lens of fresh water may also be expected between Porpoise Bay and the aerodrome. A third area likely to yield a small fresh-water lens is the west end of the island, west of Narrow Neck Well.

REFERENCES

Badon Ghyben, W., 1888-1889, Nota in verband met de voorgenomen putboring nabij Amsterdam: Tijdschrift van het Koninklijk Instituut van Ingenieurs, The Hague, p.21.

Berliat, K., 1961, Report on subterranean water potentialities on Rottnest Island: West. Australia Geol. Survey Ann. Rept for 1960, p.9-10.

Chandler, R.L., and McWhorter, D.B., 1975, Upconing of the salt water-fresh water interface beneath a pumping well: Groundwater v.13, no.4, p.354-359.

Davis, S.N., and De Wiest, R.J.M., 1966, Hydrogeology: published by John Wiley and Sons, Inc.

Herzberg, B., 1901, Die Wasserversorgung einiger Nordseebäder: Jour. Gasbeleuchtung und Wasserversorgung, v.4, p.815-819, 842-844, Munich.

Hubbert, M.K., 1940, The theory of groundwater motion: Jour. Geol. v.48, no.8, p.785-944.

Playford, P.E., 1976, Rottnest Island: Geology and groundwater potential: West. Australia Geol. Survey Record 1976/7 (unpublished).

Revelle, R., 1941, Criteria for recognition of sea water in groundwaters: Am. Geophys. Union Trans. pt 3, 22nd Ann. Meeting 1941, p.593-597.

Visher, F.N., and Mink, J.F., 1964, Groundwater Resources in Southern Oahu, Hawaii: U.S.G.S. Water Supply Paper 1778.

Walton, W.C., 1962, Selected analytical methods for well and aquifer evaluation: Illinois State Water Survey Bull.49.

World Health Organization, 1971, International Standards for drinking water: third edition.

APPENDIX

FOSSILS FROM THE HERSCHELL LIMESTONE, IN THE COLLECTION OF THE WESTERN AUSTRALIAN MUSEUM

APPENDIX

FOSSILS FROM THE HERSCHELL LIMESTONE, IN THE COLLECTION OF THE WESTERN AUSTRALIAN MUSEUM

by
George W. Kendrick

INTRODUCTION

Fossil material from five sites around the Rottnest lake system was collected during January 1977 by G.W. Kendrick and P.E. Playford. The sites are:

1. Mount Herschell Quarry, at the east end of Lake Baghdad, the type section of the Herschell Limestone;

2. Quarry at the east side of Government House Lake; a shallow pit close to the road exposing an *in situ* shell bed;

3. Small island at the eastern end of Herschell Lake; a plaster of shelly material overlying eolianite;

4. Quarry, at the southwestern corner of Lake Baghdad, exposing an undisturbed shell bed with some surface induration; and

5. Small quarry on the spit at the junction between Serpentine and Government House Lakes.

Supplementing the above are small but useful collections of fossils made by L. Glauert between 1930 and 1938 from the shores of Herschell and Government House Lakes and from the island at the eastern end of Herschell Lake. Other material was collected by E.P. Hodgkin and G.W. Kendrick during 1958. An echinoid collected in 1959 by C.W. Hassell and E.W.S. Kneebone was also examined.

Molluscs predominate among the macrofossils, but echinoderms, annelids and arthropods are frequently observed and bryozoans and coelenterates are also present. Foraminifers and ostracods are abundant in sediment screenings but, together with the bryozoans, have been excluded from this examination.

Material in the Kendrick-Playford collections was initially washed over a 0.71 mm sieve, dried and sorted, and selected specimens were cleaned ultrasonically to remove adherent micrite.

Identifications comprise 1 coelenterate, 1 annelid, and 5 echinoderm species (L.M. Marsh), 8 arthropods (R.W. George) and 134 mollusc species (G.W. Kendrick); advice with opisthobranchs from R. Burn is gratefully acknowledged.

SYSTEMATIC PALAEONTOLOGY

Phylum COELENTERATA
Class ANTHOZOA
Family FAVIIDAE
Platygyra magna (Gardiner)

Phylum MOLLUSCA
Class BIVALVIA
Family NUCULIDAE
Pronucula (Pronucula) spp.
Pronucula (Austronucula) sp.

Family ARCIDAE
Barbatia (Barbatia) pistachia (Lamarck)
Barbatia (Acar) plicata (Dillwyn)

Family MYTILIDAE
Brachidontes sp.
Musculus sp. cf. *M. nanulus* Thiele
"Amygdalum" glaberrimum (Dunker)

Family PTERIIDAE
Electroma georgiana (Quoy and Gaimard)

Family PECTINIDAE

Chlamys (Chlamys) asperrimus (Lamarck)

Family OSTREIDAE

Ostrea angasi Sowerby

Saccostrea cucullata (Born)

Family LUCINIDAE

Wallucina sp.

Epicodakia sp.

Family UNGULINIDAE

Felaniella sp.

Family CHAMIDAE

Chama ruderalis Lamarck

Family LEPTONIDAE

leptonids, genera and species undetermined

Mylitta sp. cf. *M. gemmata* (Tate)

Melliteryx sp. cf. *M. acupunctum* (Hedley)

Family LASAEIDAE

Mysella spp.

Kellia australis (Lamarck)

Bornia trigonale (Tate)

Family CARDITIDAE

Cardita sp. cf. *C. calyculata* (Linnaeus)

Family CONDYLOCARDIIDAE

genus and species undetermined

Family CARDIIDAE

Fulvia aperta (Bruguière)

Fragum (Afrocardium) erugatum (Tate)

Family MESODESMATIDAE

Taria cuneata (Lamarck)

Family CULTELLIDAE

Phaxas (Ensiculus) cultellus (Linnaeus)

Family TELLINIDAE

Tellina (Pharaonella) perna Spengler

Tellina (Tellinangulus) sp.

Tellina (Pinguitellina) robusta Hanley

Family PSAMMOBIIDAE

Sanguinolaria (Psammotellina) biradiata (Wood)

Family VENERIDAE

Circe scripta (Linnaeus)

Circe sulcata Gray

Tapes dorsatus (Lamarck)

Katelysia scalarina (Lamarck)

Katelysia rhytiphora Lamy

Irus (Irus) irus (Linnaeus)

Timoclea (Chioneryx) cardioides (Lamarck)

Class SCAPHOPODA

Family SIPHONODENTALIIDAE

Cadulus (Gadila) sp.

Class AMPHINEURA

Family, genus and species undetermined

Class GASTROPODA

Family FISSURELLIDAE

Notomella candida (A. Adams)

Family ACMAEIDAE

Acmaea (Notoacmea) scabrilirata Angas
Acmaea (Notoacmea) onychitis (Menke)
Acmaea (Chiazacmea) sp.
Acmaea (Asteracmea) sp.

Family TROCHIDAE

Euchelus (Herpetopoma) sp.
Cantharidus sp.
Thalotia (Thalotia) conica (Gray)
Thalotia (Prothalotia) sp.
Monodonta (Austrocochlea) constricta Lamarck
Mondonta (Austrocochlea) rudis Gray
Clanculus (Clanculus) atropurpureus Gould
Clanculus (Microclanculus) sp. cf. *C. (M) gatliffi* Tomlin
Monilea (Monilea) callifera (Lamarck)
Ethminolia vitiliginea (Menke)

Family STOMATELLIDAE

Stomatella auricula Lamarck

Family TURBINIDAE

Astraea (Astralium) tentorium Thiele
Turbo (Marmarostoma) pulcher Reeve
Charisma sp.

Family CYCLOSTREMATIDAE

Elachorbis tatei (Angas)

Family LITTORINIDAE

Bembicium auratum (Quoy and Gaimard)

Family HYDROBIIDAE

Hydrococcus graniformis Thiele

Family TORNIDAE

Pseudoliotia angasi (Crosse)
Teinostoma sp.
Vitrinella sp.

Family RISSOIDAE

Ovirissoa sp.

Merelina sp.

Family VERMETIDAE

Serpulorbis sipho (Lamarck)

Family POTAMIDIDAE

Batillaria (Batillariella) estuarina (Tate)

Family DIASTOMATIDAE

Obtortio sp.

Scaliola sp.

Family CERITHIIDAE

Diala lauta (A. Adams)
Diala lirulata Thiele
Alaba fragilis (Thiele)
Alaba pusilla (Thiele)
Bittium (Eubittium) lawleyanum Crosse
Bittium (Semibittium) granarium (Kiener)
Bittium (Semibittium) icarus (Boyle)
Clypeomorus sp.
Hypotrochus monachus (Crosse and Fischer)
cerithiid, genus and species undetermined

Family TRIPHORIDAE

Triphora (Notosinister) sp.

Family EPITONIIDAE

Epitonium imperiale (Sowerby)
Epitonium sp. cf. *E. imperiale* (Sowerby)

Family HIPPONICIDAE

Hipponyx (Sabia) conicus (Schumacher)
Hipponyx (Antisabia) foliacea Quoy and Gaimard

Family EULIMIDAE

genus and species undetermined

Family NATICIDAE

Polinices (Conuber) conicus (Lamarck)

Family MURICIDAE

Nucella (Dicathais) orbita (Gmelin)

Family PYRENIDAE

Pyrene bidentata (Menke)
Zafra vercoi (Thiele)

Family BUCCINIDAE

Cantharus sp.
Cominella (Josepha) tasmanica (Tenison Woods)

Family NASSARIIDAE

Nassarius rufulus (Kiener)
Nassarius pyrrhus (Menke)
Nassarius pauperatus (Lamarck)
Nassarius pauperus (Gould)

Family MARGINELLIDAE

Kogomea sp.
marginellid, genus and species undetermined

Family TURRIDAE

Pseudoraphitoma sp.

Family PYRAMIDELLIDAE

Cossmannica? sp.
Syrnola spp.
Odostomia spp.
Paradostomia sp.
Hinemoa sp.
Egila sp.
Cingulina spina (Crosse and Fischer)
Turbonilla (Chemnitzia) spp.
Turbonilla (Pyrgiscus) spp.
Turbonilla (Pyrgiscilla) spp.
Kooloonella sp.

Family RINGICULIDAE

Ringicula sp.

Family BULLIDAE

Bulla tenuissima

Family SCAPHANDRIDAE

Cylichnatys sp.

Acteocina sp.

Family ATYSIDAE

Liloa brevis (Quoy and Gaimard)

Family RETUSIDAE

Retusa spp.

Volvulella sp.

Family AKERATIDAE

Akera soluta (Gmelin)

Family ELLOBIIDAE

Ophicardelus spp.

Family SIPHONARIIDAE

Siphonaria luzonica Reeve

Siphonaria baconi Reeve

Family SUCCINEIDAE

Austrosuccinea sp.

Family PUNCTIDAE

Paralaoma sp.

Family BULIMULIDAE

Bothriembyron bulla (Menke)

Phylum ANNELIDA

Class POLYCHAETA

Galeolaria caespitosa (Lamarck)

Phylum ARTHROPODA

Class MALACOSTRACA

Family CALLIANASSIDAE

Callianassa spp.

Family LEUCOSIIDAE

Leucosia pubescens Miers

Family PORTUNIDAE

Thalamita sima (M. Edwards)

Family XANTHIDAE

Megametope sp.

Ozius truncatus (M. Edwards)

Actaea sp.

Family GRAPSIDAE

Leptograpsus variegatus (Fabricius)

Phylum ECHINODERMATA

Class STELLEROIDEA

Family ASTROPECTINIDAE

Astropecten preissi Müller and Troschel

Class ECHINOIDEA

Family TEMNOPLEURIDAE

Amblypneustes leucoglobus Döderlein

Family TOXOPNEUSTIDAE

Nudechinus scotiopremnus H.L. Clark

Family ARACHNOIDIDAE

Ammotrophus crassus (H.L. Clark)

Family LAGANIDAE

Peronella lesueuri (Agassiz)

REMARKS

A diverse invertebrate assemblage has been identified in collections from exposures of the Herschell Limestone. With 134 species out of the 149 listed, molluscs constitute the dominant element among the macrofossils. More species of all of these groups - molluscs, annelids, coelenterates, arthropods and echinoderms - are likely to be found through further collecting.

The gastropod species *Thalotia* sp., *Clanculus atropurpureus* and *Clypeomorus* sp. are not known to occur in the central Perth Basin in deposits older than the Holocene. Their presence in the Herschell Limestone, viewed with the absence of any locally restricted Pleistocene species, is consistent with the middle Holocene age for the formation determined by C^{14} analysis.

The faunal assemblage inhabited the littoral and shallow sublittoral margins of a system of temporary marine lagoons, with adequate circulation of sea water, and having areas of sand sills, seagrass banks and rocky shores. Generally low-energy conditions are indicated by the abundance of articulated bivalve shells in the position of life, and the good preservation of a wide range of fragile specimens. A degree of bioturbation is evident in some of the deposits.

The fossil faunas were found to be essentially similar at all sites, with the partial exception of that from the quarry at the eastern end of Government House Lake. Only molluscs (25 species) were collected from this locality, compared with (for example), 118 species of molluscs, 6 arthropods, 4 echinoderms and an undetermined number of bryozoans from the small island at the eastern end of Herschell Lake. Such localized differences in fauna may have been due, wholly or in part, to uneven patterns of water circulation through the lagoon system. Faunal restriction could also be expected to have resulted from the progressive severance of the lagoon system from the sea, but this possibility has not been examined in the present study.

It may be noted that three of the gastropods listed, *Austrosuccinea* sp. *Paralaoma* sp. and *Bothriembryon bulla* are land snails. All are known to live in close proximity to the littoral, and their occasional presence in the shell beds is not unexpected.

Knowledge of the distributions of living molluscs along the western coast of Australia is incomplete for many groups, particularly among the smaller species (such as are prominent in the Herschell Limestone fauna), so that it is not possible to provide a comprehensive comparison of all of the fossil and modern distributions. However, available data from the modern mollusc collection of the Western Australian Museum suggest that not less than 12 of the species listed above are not at present living in the Rottnest-Fremantle area. The geographic ranges of six of these (*Ostrea angasi, Taria cuneata, Katelysia scalarina, K. rhytiphora, Batillaria estuarina* and *Bittium lawleyanum*) appear to have moved south since the middle Holocene, but six others (*Fragum erugatum, Tapes dorsatus, Thalotia* sp., *Clanculus atropurpureus, Diala lirulata* and *Clypeomorus* sp.) appear to have moved north. The annelid *Galeolaria caespitosa* has not been found north of about Cape Naturaliste (L.M. Marsh, pers. comm., Feb.1977). The presence of these species within a single community creates a distinctive faunal assemblage, which, as such, is no longer extant anywhere along the Australian coast. Similar fossil faunas, containing these and other locally restricted species, are known to occur in Holocene deposits on the adjacent mainland, notably in the Swan Estuary.

An explanation for these apparent distribution changes is not readily apparent, but their discrepant nature suggests that more than one factor is involved. Apart from some records of habitat preferences from field observations, the biology of each species, particularly its environmental tolerance, is unknown. Without this evidence, it cannot be assumed that distributions, modern and fossil, are (or have been) determined by sea temperature alone. The only coral in our collections from the Herschell Limestone, *Platygyra magna*, now lives as far south as Geographe Bay, and could also be expected to occur living around Rottnest (L.M. Marsh, pers. comm., Feb.1977).

The present study confirms my observations on mainland mollusc faunas, which indicate that there have been quite extensive alterations of geographic ranges by a number of species along the coast between about 28° and 34°S latitude since the middle Holocene.

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WILLIAM C. BROWN, Government Printer, Western Australia

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

GEOLOGICAL MAP
OF

ROTTNEST ISLAND

P.E. PLAYFORD 1976

SCALE 1:25 000

KILOMETRES

REFERENCE

HOLOCENE

- Qhb — BEACH SAND : lime sand, with variable amounts of quartz sand
- Qhd — DUNE SAND : unlithified to weakly lithified lime sand dunes, mainly fixed by vegetation
- Qhs — SWAMP DEPOSITS : marl, peat and algal sediments
- Qhh — *HERSCHELL LIMESTONE : shelly limestone and weakly lithified shell beds and lime sand

PLEISTOCENE TO EARLY HOLOCENE

- Qt — *TAMALA LIMESTONE : dune limestone, largely soil covered, with some patches of modern dune sand

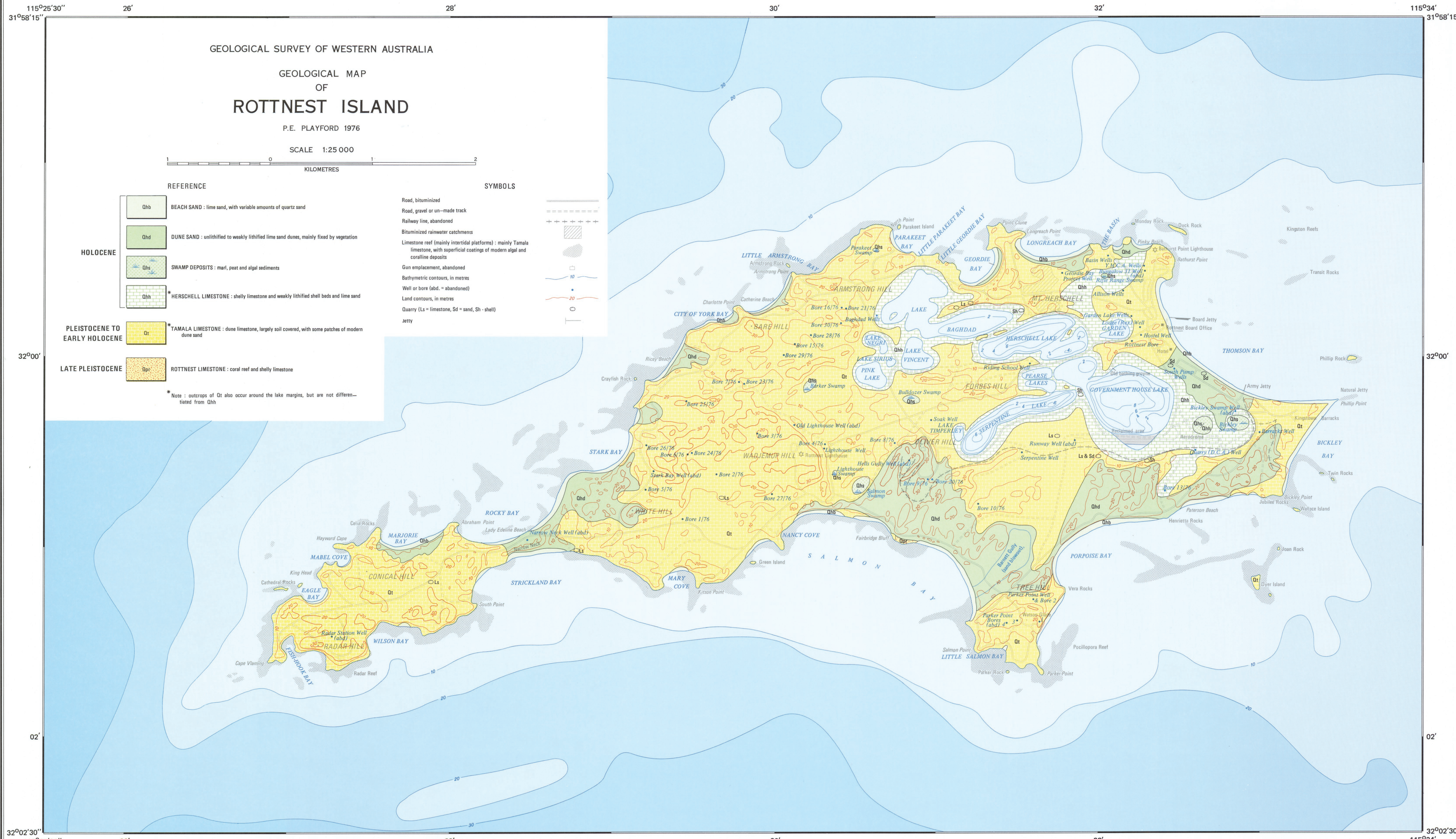
LATE PLEISTOCENE

- Qpr — ROTTNEST LIMESTONE : coral reef and shelly limestone

*Note : outcrops of Qt also occur around the lake margins, but are not differen– tiated from Qhh

SYMBOLS

- Road, bituminized
- Road, gravel or un–made track
- Railway line, abandoned
- Bituminized rainwater catchments
- Limestone reef (mainly intertidal platforms) : mainly Tamala limestone, with superficial coatings of modern algal and coralline deposits
- Gun emplacement, abandoned
- Bathymetric contours, in metres
- Well or bore (abd. = abandoned)
- Land contours, in metres
- Quarry (Ls = limestone, Sd = sand, Sh - shell)
- Jetty



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