Outline of the geology and hydrogeology of Cape Range, Carnarvon Basin, Western Australia

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Abstract

Cape Range is composed of a sequence of predominantly calcareous sedimentary rocks of Palaeocene-Pliocene age, overlain by Pliocene-Holocene alluvial, littoral, and shallow water marine sediments on the coastal plain, which borders the range. It is a gentle anticline resulting from inversion of fault movement on an underlying fault. The uplift has occurred intermittently since the Late Cretaceous and has affected sedimentation. The range emerged as an island probably in the Pliocene and karstification is inferred to have rapidly extended down for about 100 m in karst-prone limestone and gradually extended laterally as the range emerged. During the lowstand of sea level in the Pleistocene the karstification is presumed to have extended further offshore and been accompanied by deep erosion and establishment of the present-day drainage system. The present regional water table occurs below the level of karstification in the central part of the range and within cavernous limestone around its margin. The groundwater is believed to occur as a lens of fresh groundwater overlying seawater as on some oceanic islands. The remnant cave system in the central part of the range is inferred to have provided a relatively stable habitat for a diverse subaerial cave fauna since the Pliocene, whereas water-filled cave system on the coastal plain, which is the habitat of aquatic troglobites, has probably extended and been subject to marked variation in the hydrogeological regime as the range has risen, and in response to changes in climate and sea level.

Introduction

Location

Cape Range is a prominent northerly trending peninsula north of the tropic of Capricorn, about midway along the Western Australia coastline. It is about 80 km long, 20 km wide and has a rugged topography reaching a maximum elevation of 314 m at Mt Hollister (Figure 1). The range is bordered on the west by the Indian Ocean and a narrow continental shelf about 12 km wide on which is developed the Ningaloo barrier reef; and to the east by the shallow Exmouth Gulf with local islands and reefs.

Cape Range National Park occupies the western part of the range and, subject to limitations imposed by a temporary reserve for limestone, the park may be extended to include most of the range (Figure 1). The population within the Shire of Exmouth in 1990 was 2 614, predominantly in the town of Exmouth towards the north-eastern end of the peninsula, and in small scattered pastoral, fishing and tourist communities.

Purpose and Scope

The purpose of this paper is to compile and interpret existing geological and hydrogeological data available for Cape Range, and to put the environment of a varied endemic cave fauna (Humphreys and Adams 1991; Humphreys 1993) into their hydrogeological context. Data for this paper was obtained from Geological Survey records, re-

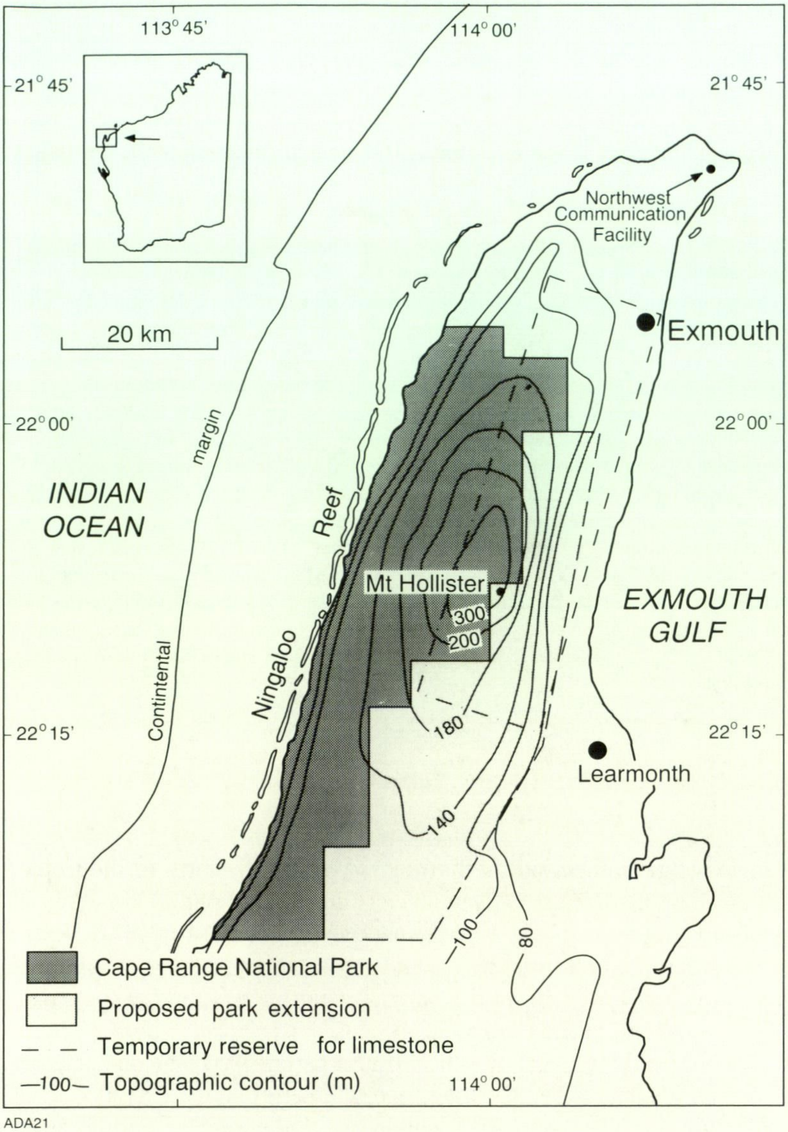

Figure 1. Locality map with generalised topographic contours.

interpretation of existing work and limited field work and observations by the writer since about 1975.

Previous work

Intensive petroleum exploration on Cape Range and nearby Rough Range, since the early 1950s, has resulted in a considerable number of reports on aspects of the petroleum geology which are not reviewed here. In addition, there has been systematic geological mapping of Cape Range and the surrounding region by the Geological Survey of Western Australia. The geology of Cape Range is depicted on Onslow (van de Graaff *et al.* 1980), and Yanrey-

Ningaloo (van de Graaff *et al.* 1982) 1:250,000 geological sheets, and a review of the geology and geological description of the range, is given by Hocking *et al.* (1987). A detailed re-interpretation of the structure of the range, illustrating its geological complexity is given by Malcolm *et al.* (1991).

Hydrogeological data for Cape Range are available mainly for the coastal plain between Learmonth and Exmouth: from pastoral bores and wells; bores drilled for defence facilities; bores drilled during petroleum exploration, and particularly from bores drilled by the Water Authority (and predecessor the Public Works Department) for Exmouth town water supply. The latter bores have provided the best understanding of the factors controlling the present groundwater regime.

Various bores and wells were established for pastoral water supplies, for defence facilities and for the fishing industry prior to 1950. However, the first known observations on the availability of groundwater are by Sofoulis (1951) who had undertaken regional mapping for petroleum exploration in the area. Later when Exmouth was being established, O'Driscoll (1965) recommended the location of the Exmouth wellfield. He recognised that there was a thin layer of fresh groundwater overlying brackish groundwater and cautioned about overpumping. The performance of the wellfield was subsequently reviewed by Bestow (1966), and by Forth (1972, 1973) who estimated the available groundwater resources and considered that the fresh groundwater occurred in a wedge tapering seawards over brackish groundwater, resting on impermeable marl. Following further exploratory drilling by the Water Authority, Martin (1990), has provided the most detailed information on the groundwater occurrence adjacent to the wellfield. In particular, he showed that inland from the coastal plain fresh groundwater extended to more than 100 m below sea level in rocks previously considered to be impermeable.

The regional occurrence of groundwater and groundwater resources of the Carnarvon Basin including Cape Range have been briefly described by Allen (in Hocking *et al.* 1987). In this work, it was concluded that in the near surface, a regional water table rising to about 5 m above sea level and with groundwater less than 1,000 mg L^{-1} T.D.S. probably occurred beneath the central part of the range.

Topography and Drainage

Cape Range is the surface expression of an anticline (see Geology) and its topography and drainage pattern has developed in response to its geology and geological history. The generalised topography of the range is shown in Figure 1, and areas of different topographic style, and the drainage pattern are shown in Figure 2.

The crest of the range is gently undulating and rises from about 100 m above sea level at the northern end of the range to 314 m at Mt Hollister. It has gently sloping flanks steepening down to a bordering, relatively flat, coastal plain. Locally preserved along the crest of the range are remains of a pre-existing plateau on which sinkholes and areas of internal drainage are preserved (Figure 2). Elsewhere, the crest of the range has been stripped to expose gently arching strata with some discontinuous scarps formed by resistant beds of limestone.

Preserved along the southwestern side of the range are four well defined and partly dissected marine terraces (van de Graaff 1976; Kendrick *et al.* 1991; Wyrwoll *et al.* 1993). The terraces, and rest of the peninsula, are bordered by a coastal plain which is somewhat broader

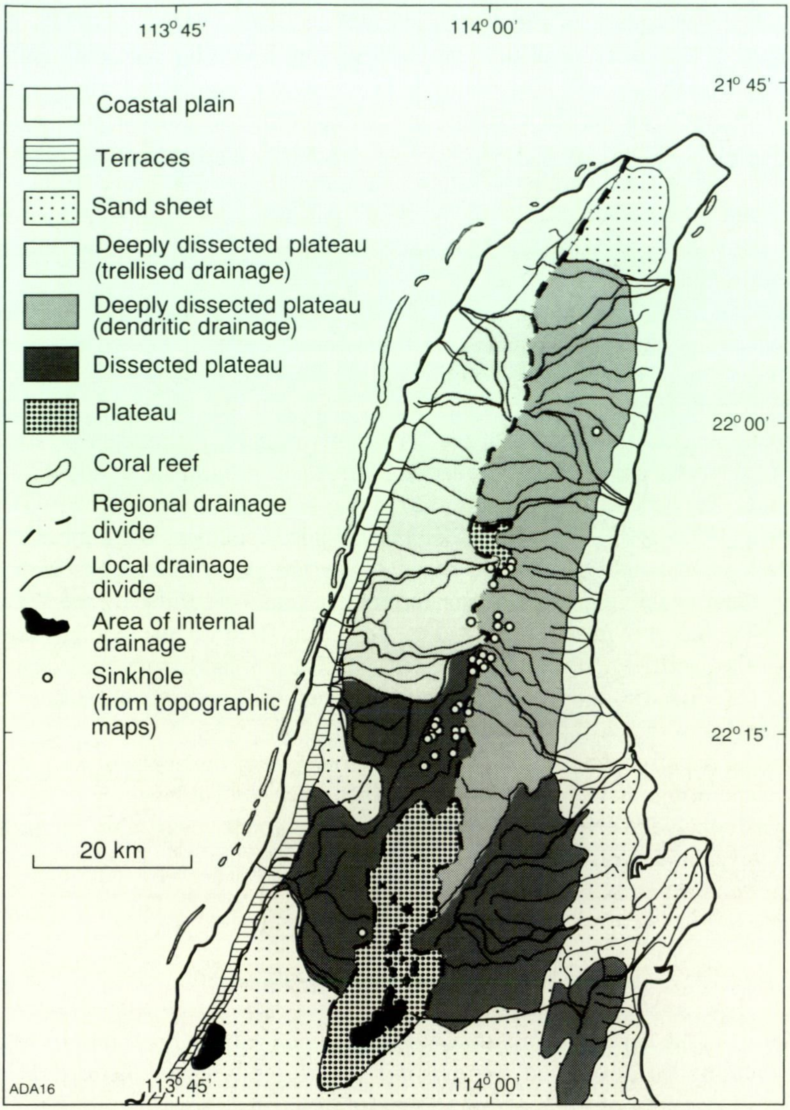

Figure 2. Topographic and drainage subdivisions.

on the eastern side of the range. Offshore along the western and northern sides of the range (Figure 2) a coral barrier reef is developed.

The crest of the range forms a regional drainage divide (Figure 2) with drainage systems to the east and west. In the northern two thirds of the range the drainage system is deeply incised whereas in the south it is less deeply incised and partly buried by a sand sheet. The drainage pattern on the north eastern side of the range is dendritic whereas in the northwest it is trellised. In the south the drainage pattern is mainly dendritic with some long, fault controlled reaches such as in Yardie Creek.

Geology

General

Cape Range is situated within the Exmouth Sub-Basin of the Carnarvon Basin (Hocking *et al.* 1987). It is underlain by about 10,000 m of Phanerozoic sedimentary rocks of which the upper 1,000 m is of interest in the context of this paper (Figure 4).

The rocks immediately underlying, and forming the core of the range are a sequence of predominantly carbonate rocks of Palaeocene-Miocene age about 500 m thick (Figures 4 and 5). Several different rock units which interfinger into each other are recognised and reflect the structural conditions controlling sedimentation. Superimposed and preserved on marine

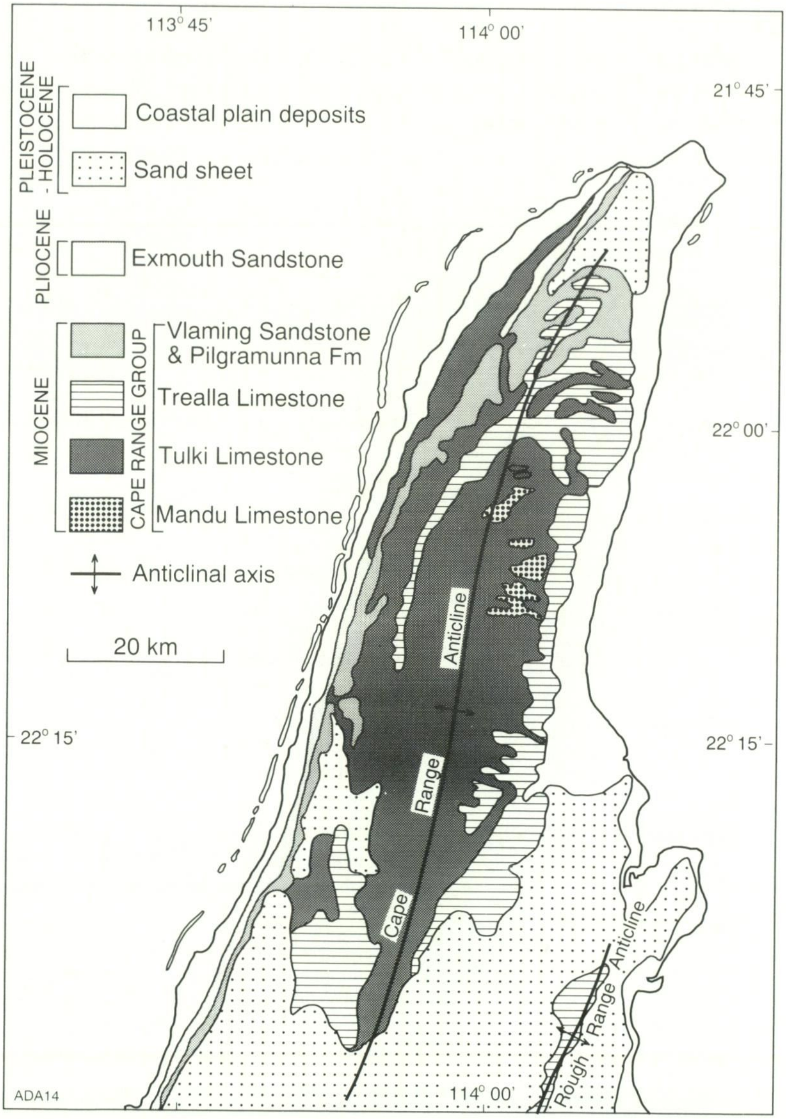

Figure 3. Generalised geology.

terraces on the south western side of the range, and on the coastal plain are Pliocene-Recent littoral, shallow water marine, alluvial and eolian sediments (van de Graaff *et al.* 1976; Kendrick *et al.* 1991; Wyrwoll *et al.* 1993). The sediments on the coastal plain range from about 5 m in thickness on the western side of the range to 10 m in the east. On the southern end of the range and locally at the northern end are parts of an extensive Pleistocene sand sheet widely developed in the Carnarvon Basin. This is composed of red-brown silty sand with fixed northwest trending seif dunes (Wyrwoll *et al.* 1993).

The generalised geology of Cape Range is given in Figure 3 and the geological structure of the range is shown in Figure 4. The near-surface structure and relationship of some of the stratigraphic units are illustrated in the hydrogeological section (Figure 5).

Stratigraphy

The stratigraphic sequence underlying Cape Range has been established from detailed field mapping and from subsurface data from oil exploration wells and water bores. In this paper only the uppermost rock units forming the range are considered. They are listed in Table 1 with a brief description, and their stratigraphic relationships are illustrated in Figure 5. For a

Table 1. Generalised near-surface stratigraphic sequence.

Age	Formation	Thickness (m)	Lithology	Comments
Holocene	Various minor units	<20	Eolian deposits, alluvium, colluvium, littoral deposits.	Sediments preserved on marine terraces and coastal plain.
Pleistocene	Bundera Calcarenite		Calcarenite and calcirudite.	
Pliocene	Exmouth Sandstone		Quartzose calcarenite.	
		UNCONFORMITY		
M-L Miocene	Vlaming Sandstone	65	Calcarenite: well sorted, medium, quartzose, eolian	Restricted to western side of Cape Range.
M. Miocene Cape Range Group	Pilgramunna Formation	25	Calcarenite: well sorted, quartzose, fine-very coarse with interbedded beds of packstone and boundstone.	Lateral equivalent of the upper Trealla Limestone; mainly restricted to western side of Cape Range.
	Trealla Limestone	20	Packstone/grainstone: bioclastic fossiliferous, high carbonate content.	Lateral equivalent of the Pilgramunna Formation; exposed in western and northern part of Cape Range.
E. Miocene - L. Oligocene	Tulki Limestone	90	Packstone/grainstone: foraminiferal marly packstone, and grainstone	Lateral equivalent of upper Mandu Limestone, caves mainly developed in this unit.
	Mandu Limestone	280	Calcarenite/calcilutite/ calcisiltite: chalky to marly fossiliferous, notable large Lepidocyclinid foraminifera.	Locally exposed in valleys on range between Exmouth and Learmonth
		UNCONFORMITY		
M. Eocene - Palaeocene	Cardabia Calcarenite	<200	Calcarenite/calcisiltite and greensand	Not exposed.

detailed discussion of the stratigraphic nomenclature and lithological descriptions reference should be made to Hocking *et al.* (1987).

Structure

The most recent interpretation of the geological structure, based on seismic and oil well data, and incorporating current tectonic concepts is by Malcolm *et al.* (1991). They show that the area is tectonically complex and that the Cape Range Anticline has resulted from inversion of fault movement, (from normal to reverse) along the Learmonth Fault (Figure 4). The movement along this fault (and others) since the Late Cretaceous has controlled the Cainozoic sedimentation and resulted in the present geological structure.

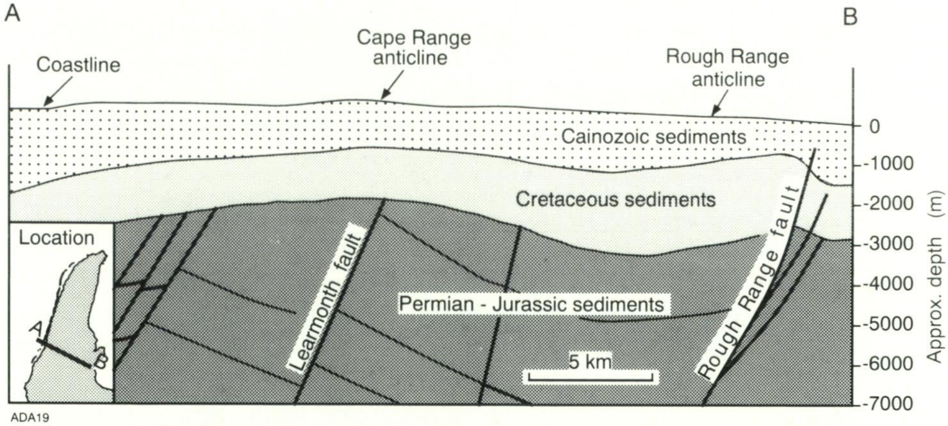

Figure 4. Geological cross-section (redrawn after Malcolm et al. 1991).

In broad terms Cape Range is a gentle, slightly asymmetric anticline (upwarp) with the steepest flank in the east. The crest of the anticline is gently undulating with the culmination of the anticline occurring near the highest part of the range. The anticline has been intermittently rising since the Late Cretaceous and uplift is probably still continuing.

Superimposed on the tectonic movements have been changes in sea level during the Pleistocene. These, together with the tectonic uplift have resulted in raised, slightly warped, marine terraces preserved on the south west side of the range (van de Graaff *et al.* 1976; Kendrick *et al.* 1991) and in the formation and deposition of the sedimentary sequence on the coastal plain (Wyrwoll *et al.* 1993).

Geological history

The main events leading to the formation, and current physiography of Cape Range are summarised in Table 2.

Hydrogeology

Regional water table

Based on very limited water level data from existing bores and wells; the groundwater occurrence illustrated by Martin (1990) and the regional topography, water table formlines have been drawn which are believed to approximate the configuration of the water table beneath Cape Range (Figure 6). The interpretation indicates that a subdued groundwater

Table 2. Outline of the geological history of Cape Range.

Period	Events
Holocene	Variation in sea level; continuing emergence of range.
Pleistocene	Variation in sea level; formation of marine terraces along south western side of range; accelerated erosion during low stand of sea level; continued emergence of range and warping of marine terraces.
Pliocene	Emergence of range as an island; inception of drainage system; commencement of karstification.
Miocene	Cape Range Anticline begins to develop and sedimentation controlled by rising anticline.
Oligocene	Commencement of predominantly carbonate deposition of Cape Range Group.
Eocene - Palaeocene	Deposition of predominantly carbonate sediments (Cardabia Calcarenite); inversion of fault movement on Learmonth Fault.
E-L Cretaceous	Deposition of clastic and carbonate sediments.
E Cretaceous - L Carboniferous	Various phases of faulting and sedimentation commencing with onset of rifting and culminating in break-up and separation of Australian and Indian Plates.

mound about 10 m above sea level (Cape Range Mound) and separated from the regional water table of the Carnarvon Basin by a groundwater col in the vicinity of Yardie Creek, occurs beneath the highest part of Cape Range. The water table formlines indicate that relatively steep groundwater gradients occur near the crest of the range but gradients are virtually flat on the coastal plain.

Local perched groundwater is also believed to occur in pools in some caves. However, these are likely to be only small and transient.

Aquifer system

The regional water table occurs within a non-homogeneous karstic aquifer system formed by the Mandu Limestone on the crest of the range, the Tulki Limestone on the flanks of the range, and the Pliocene-Recent sediments and/or Tulki Limestone on the coastal plain, all of which are in hydraulic continuity. The groundwater in the Mandu Limestone is inferred to occur in joints and some minor permeable interbeds, whereas the groundwater occurs in permeable beds and karst-developed solution openings and cave systems in the Tulki Limestone and Pliocene-Recent sediments.

Recharge

Recharge to the groundwater system is inferred to occur after heavy rainfall events by direct surface infiltration through permeable beds, bedding plain partings and joints; by direct run-off into areas of internal drainage and cave openings (Figure 2) along the crest of the range; and by infiltration of run-off along drainage lines.

There are unconfirmed reports of surface flows in some drainage lines being completely lost to infiltration. There are also anecdotal accounts of turbid water seen flowing in some wells on the coastal plain and of ephemeral streams in some cave systems. Such observations, if correct, indicate rapid and effective recharge to the aquifer system.

The average annual rainfall at Exmouth is 250 mm (1967-1992) and the actual annual

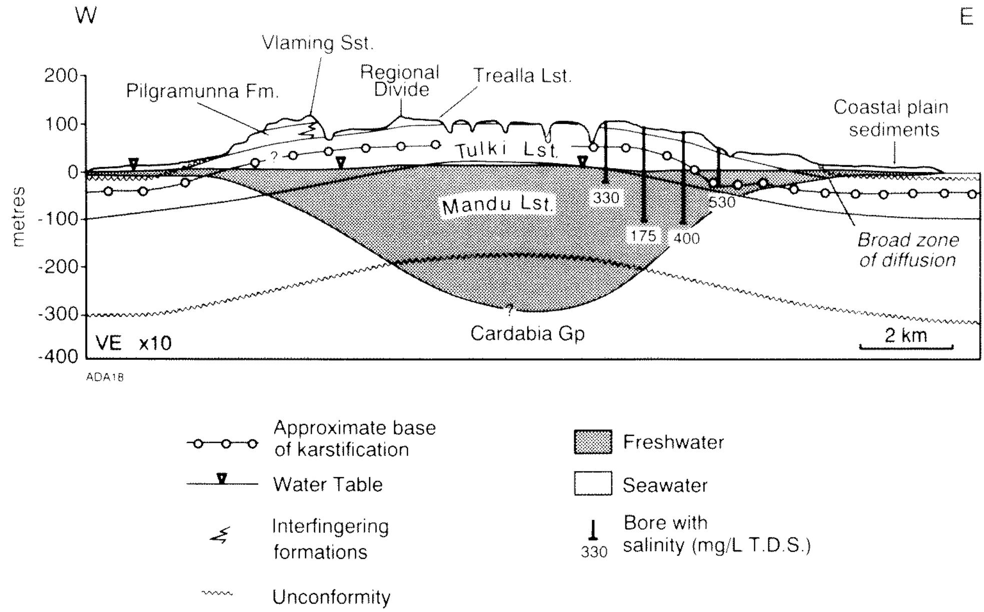

Figure 5. Hydrogeological cross-section (partly redrawn after Martin 1990).

rainfall is known to have varied from 84-569 mm (Bureau of Meterology). The rainfall originates from a variety of meteorological sources but the highest rainfall is usually associated with irregular cyclonic activity (Wyrwoll 1993). Recharge from rainfall probably only occurs after intense or long-duration rainfall events and it is inferred that in some years recharge may not occur, while in others recharge may occur on several occasions throughout the year (Humphreys 1991).

Movement and discharge

Based on the water table formlines radial groundwater flow takes place from the Cape Range Groundwater Mound and from the lobe of the regional water table (Figure 6). Rates of groundwater flow are unknown but judged from the gradient of the water table are relatively much more rapid beneath the coastal plain than in the range reflecting the difference in permeability between the Mandu Limestone, and the cavernous Tulki Limestone and coastal plain sediments.

Considering the karstic nature of the aquifer system beneath the coastal plain, it is likely that the groundwater may discharge from discrete sub-sea springs, but none are known although there are anecdotal descriptions of offshore springs on both the east and west coasts. Some groundwater is reported to be discharged by evapotranspiration from coastal vegetation near Exmouth (Forth 1973) and local groundwater discharge is inferred to occur in pools along the lower reaches of Yardie Creek and Qualing Pool. Rare ephemeral springs are reputed to occur, and Forth (1973) recorded the presence of a large perennial freshwater spring at the contact of the Tulki and Mandu Limestones in a tributary of Shothole Canyon.

Salinity

Non-synoptic measurements of groundwater salinity (mg L^{-1} T.D.S.) from Geological

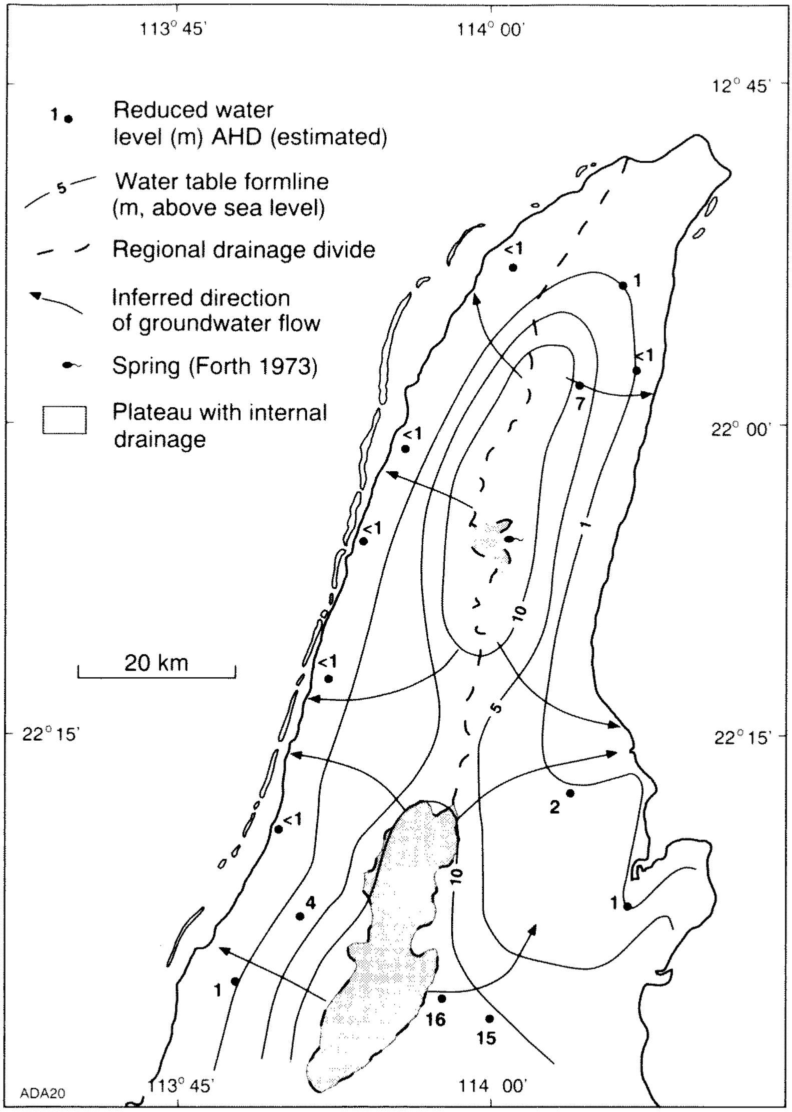

Figure 6. Regional water table formlines.

Survey records are shown plotted in Figure 7. The data suggest a large area with salinity less than 1000 mg L^{-1} T.D.S. occurring on the crest of the groundwater mound and brackish groundwater on the coastal plain. However, the extent of brackish groundwater on the coastal plain may be misleading. O'Driscoll (1963), Forth (1972, 1973) and Martin (1990) all recognised that fresh groundwater on the coastal plain occurred as a thin wedge overlying seawater with a broad zone of diffusion 10-20 m thick, probably resulting from tidal oscillations noted as far as 1.3 km inland on the south western side of the range (W.F. Humphreys, pers. comm.). Consequently, the thin layer of fresh groundwater may not be detected if the well has been operating or if the sample is taken too far below the water table.

The apparent more brackish groundwater occurring on the coastal plain on the western side of the range has been attributed to high concentrations of marine salt being deposited by the prevailing wind and being dissolved in the rainfall recharge. However, in the writer's opinion, the effects of this salt accumulation are probably not significant compared to the volume of recharge which may occur during major recharge events. The higher salinity of the wells is probably attributable to the high permeability of the cavernous aquifer, and resultant very thin layer of fresh groundwater.

On the eastern flank of the range, the work of Martin (1990) showed that fresh groundwater inland of the existing wellfield (Figure 7) extended to more than 100 m below sea level. This is interpreted to indicate that Cape Range is underlain by a lens of fresh groundwater,

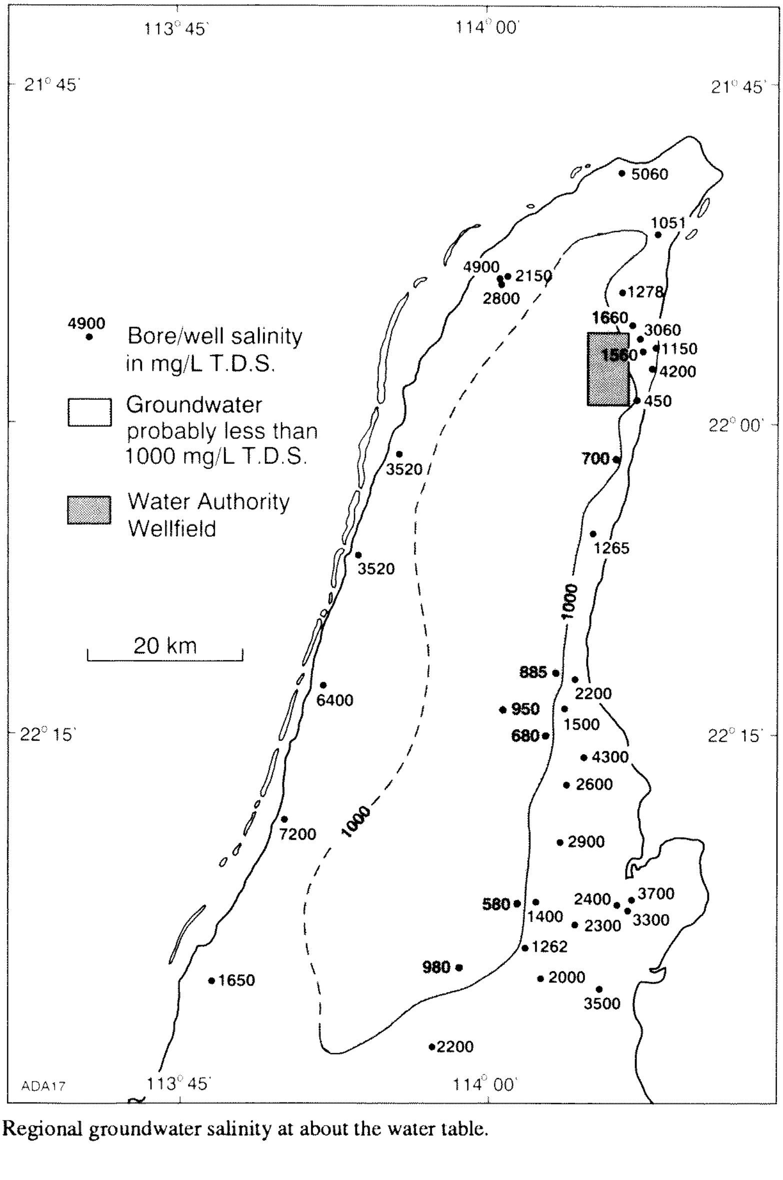

Figure 7. Regional groundwater salinity at about the water table.

overlying seawater (Figure 5), analagous to groundwater occurrence on oceanic islands (Ghyben-Herzberg relation).

Cave system

Description

Over 300 caves are known on Cape Range and there are likely to be many others which are undiscovered. The entrances of some caves are shown on existing topographic maps (Figure 2), while the sites of many other known caves are recorded (W.F. Humphreys, pers. comm.). Along the crest of the range caves are developed on the regional divide and on the interfluves between the main drainage lines. The most extensive cave systems are inferred to exist in the areas mapped as undissected upland (Figure 2). Entrances to many of the known caves are marked by fig trees which have sub-aerial roots extending vertically for a considerable distance into the caves.

According to speleologists who have explored some of the caves, most are vertical solution pipes extending to a maximum depth of about 90 m with only limited development of galleries or tunnels which are mainly low and inaccessible. Caves that have been explored are usually dry and cave ornamentation is for the most part poorly developed. A slow flowing stream and minor seepages of water which fluctuate after heavy rainfall have been observed in the largest known cave system (Wanderers Delight).

In the deeply incised major drainages some small cave entrances associated with particular beds of limestone in the Tulki Limestone have been observed and are often used as animal shelters. However, none are known to discharge water.

On the coastal plain the cave system in the coastal plain sediments and underlying Tulki Limestone is partially or totally filled with water and the size and extent of the system is not known but may extend for some distance below sea level and offshore (see Origin). Various pastoral wells on the coastal plain (e.g. Milyering, Pilgramunna) are sites of former aboriginal water supplies, apparently on sinkholes and it is from these wells that the troglobitic fish have been recorded.

Origin

The cave system preserved on Cape Range has developed in response to geological, climate and eustatic factors. The main geological factors predisposing the area to karst development are the presence of the relatively pure and permeable Trealla and Tulki Limestones; the presence of the underlying relatively impermeable Mandu Limestone, and local jointing and faulting enabling solution and development of piping and flow paths within the limestone.

Karstification and initiation of the cave system probably commenced in the Late Miocene-Early Pliocene when the range emerged as an island. At that time, a Ghyben-Herzberg type groundwater flow system would have become established and is likely to have readily extended downward through the relatively pure and permeable Tulki and Trealla Limestones (about 100 m) to near the top of the Mandu Limestone. Subsequently, as the range continued to rise in response to intermittent fault movement, a cave system developed and extended laterally toward the coast and offshore during the low stand of sea level in the Late Pleistocene. Also about this time, and coinciding with onset of climatic conditions similar to the present (Wyrwoll 1993) when the water table was as low or lower than at present deep headward erosion to about the top of the Mandu Limestone established the present drainage system. This resulted in the destruction of the integrated cave system on the crest of the range, except beneath the plateau remnants (Figure 2), and the preservation of the system beneath the coastal plain, and presumably offshore. Subsequently, a cave system has also developed in some of the coarse alluvial sediments on the coastal plain this may relate to collapse features in the underlying cave system or be a new cave system developed in response to the changed hydrogeological conditions. The inferred sequence of events leading to the formation of the cave system are summarised in Table 3.

Table 3. Inferred history of cave development.

Timing	Event
Holocene	Return of sea level to present position; continued erosion of karst system and drowning of cave system around coastline; formation of cave system in coastal plain sediments.
L Pleistocene	Continued emergence of Cape Range; fall of sea level by about 130 m in response to glacial maxima; accelerated deep erosion; possible extension of cave system offshore.
E Pleistocene	Continued emergence of Cape Range; onset of arid condition; probably only limited extension of cave system.
Pliocene - L Miocene	Emergence of Cape Range as an island; development of a groundwater flow system; commencement of karstification and main development of cave system under tropical conditions.

Conclusions

Cape Range, is in part of the Carnarvon Basin which has had a complex geological history. The present physiography of the range results from the intermittent uplift of the range on an underlying fault and exposure of predominantly calcareous sedimentary rocks of Tertiary age, of which the uppermost units have been karstified and extensively eroded during emergence of the range and changes in sea level.

Limited data indicate the regional water table in the form of a groundwater mound, with fresh groundwater overlying seawater in a Ghyben-Herzberg relationship, underlies the range. The shape and extent of the groundwater system has probably changed through time as the range emerged and in response to variation in climate and sea level.

A karst system has developed in the Tulki and Trealla Limestones. These formations are about 100 m thick and their thickness has limited the depth of karstification. Consequently on the crest of the range, a cave system in the limestone has been deeply eroded and is mainly inactive (except for recharge), but is still active on the flanks of the range and beneath the coastal plain.

The habitat of the sub-aerial troglobitic cave fauna on the crest of the range has probably existed and been relatively unaltered since the range emerged above sea lavel in the Late Miocene - Early Pliocene. In contrast, the habitat of the aquatic troglobites on the coastal plain has probably varied significantly in response to the rise of Cape Range and especially sea level changes in the Pleistocene.

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