A study of geochemistry and hydrodynamics in Hutt Lagoon (Western Australia)

Geochemistry
Hydrodynamics
Diagenesis
Evaporitic basin
Western Australia

Géochimie
Hydrodynamique
Diagenèse
Bassin évaporitique
Australie occidentale

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ABSTRACT

Hutt Lagoon, in the Perth Basin, Western Australia is a shallow (< 11 m) evaporitic basin, developed as a result of ponding in a Pleistocene calcreted dune terrain. Holocene sequence in the lagoon reflects a history of evaporite sedimentation through successive stages ranging from open marine to pond and playa environments. The contemporary lagoon is a playa surface in which sedimentation is related to distribution and interaction of hydrologic units (groundwaters, seawaters and lagoonal brines). Precipitation is restricted to ephemeral halite in ponded waters, and diagenetic emplacement of $CaCO_3$ and $CaSO_4$ minerals in lagoonal sediments. Playa surfaces, predominantly below sea-level, fundamentally control the lagoonal circulation system ; hence, a net influx of seawater, impelled by a hydrostatic head of up to 4 m, is seasonally balanced by evaporative reflux.

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RÉSUMÉ

Étude géochimique et hydrodynamique de la lagune Hutt (Australie occidentale)

La lagune Hutt, située dans le Bassin de Perth (Australie occidentale) est un bassin évaporitique peu profond (< 11 m) formé dans une dépression dunaire du Pléistocène. L'évolution sédimentaire de la lagune depuis l'Holocène est caractérisée par la formation d'évaporites au cours de plusieurs étapes allant de conditions purement marines jusqu'à la constitution d'un « playa ». La lagune actuelle peut être assimilée à un playa dans lequel la sédimentation dépend de la distribution et de l'interaction des eaux souterraines, marines et saumâtres lagunaires. La précipitation chimique des évaporites est restreinte à des halites éphémères dans les réservoirs fermés, et à des formations diagéniques de $CaCO_3$ et de $CaSO_4$ dans les sédiments lagunaires. Les surfaces de playa, situées en grande partie sous le niveau de la mer, contrôlent fondamentalement la circulation des eaux dans la lagune ; ainsi, un flux net d'eau marine, induit par une pression hydrostatique élevée (atteignant la pression d'une colonne de 4 m), est saisonnièrement contrebalancée par l'évaporation.

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INTRODUCTION

Reconstruction of depositional environments of the shallow lagoons and basinal depressions developed in arid to semi-arid coastal areas of Western Australia demonstrates that progressive restrictions in circulation (due to increasing depth) and development of high salinities by seawater influx and high evaporative reflux has generally resulted in development of evaporitic deposits in these basins. However, in terms of sedimentological and geochemical evolution, contemporary conditions in most of these lagoons are seen as stages in a historical sequence of diminishing sedimentation because at present evaporite precipitation is restricted to diagenetic products which post-date earlier deposits and these in turn are mainly related to distribution and interaction of hydrologic units in playa settings.

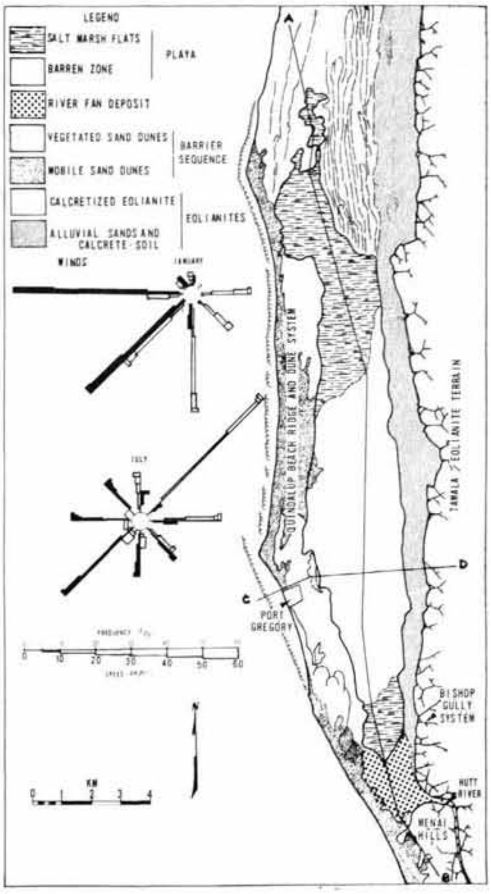

Figure 1

Map of Hutt Lagoon, showing main geomorphic divisions and winds.

Hutt Lagoon (Fig. 1) located in the northern part of the Perth Basin, Western Australia, is a part of a chain of coastal lagoons developed during the past 6,000 years as a result of the ponding of Holocene seas in Pleistocene depressions. The lagoon is elongated for almost 24 km in a north-south direction parallel to the coast and is characterised by playa surfaces dominantly below mean sea level (up to — 4 m).

The climate in the study area is Mediterranean (Table 1), characterised by high evaporation in summer and moderate precipitation in winter. An annual moisture deficiency (evaporation-precipitation) of 1.500-1.800 mm has been recorded at Hutt Lagoon.

Table 1

Summary of hydrologic and climatic data, Hutt Lagoon.

	Hutt Lagoon
Regional climate	Mediterranean (dry and warm summers, cold winters)
Winter season duration (months)	6
Average max. temperature (°C)	38
Average min. temperature (°C)	29
Temperature on Eolian rock surface (°C)	40.5
Average rainfall (mm)	478
Summer contribution (mm)	< 50
Annual evaporation (mm)	2.150-2.400
Prevailing winds (knots)	9
Average relative humidity (%)	46
Temperature of groundwater in summer (°C)	32
Sea-salt fallout (kgha^{-1})	140.3
Others	Occasional frost

Sedimentological and geochemical studies of the Hutt Lagoon indicate that since the Holocene, the sequence of sedimentary events, and hence the range of environments of lagoonal sedimentation has been diverse. The evidence for this is not only due to a marked contrast in mineralogy and vertical associations between different depositional units but also occurrence and peculiar distribution of the lagoonal hydrologic elements in terms of : 1) the source of solutions ; 2) the influx/reflux budget ; and 3) the physical setting in which precipitation takes places.

MATERIALS AND METHODS

Lagoonal brines were sampled from boreholes, shallow drillholes and trenches dug on the basis of systematic sampling patterns. Detailed levelling surveys were carried out using an infrared Wild Distomat (D13) surveying unit. The titration method of Strickland and Parsons (1965) was adopted for anion concentration analysis of brines ; cation concentration were determined by atomic absorption techniques. The precision of analytical methods used is as follows :

Na ± 2 %	Ca ± 2 %	Cl ± 1.5 %
K ± 1.5 %	Mg ± 0.5 %	SO_4 ± 0.75 %

Ion concentration in brines are calculated in parts per million (ppm) but for graphic correlation on log-semi log plots they are expressed in moles per thousand moles water (moles/1.000 moles H_2O). Additionally, on the assumption that the majority of brines collected from Hutt Lagoon result from concentration of Indian Ocean water, and that Mg ion concentration is approximately constant throughout the evaporitic concentration ranges encountered; the « concentration ratio » parameter, *E* (Levy, 1977) is used in data analysis. The concentration parameter *E* is defined as :

$$E = \frac{\text{Mg concentration in brine (moles/1,000 H}_2\text{O)}}{\text{Mg concentration is standard seawater (moles/1,000 moles H}_2\text{O)}}$$

The standard seawater used is a seawater collected from the Indian Ocean at Port Gregory which has an Mg concentration equal to 1,356 ppm (i. e. 1.005 moles/1.000 moles H_2O).

GEOMORPHIC DIVISIONS AND STRATIGRAPHIC SETTING

The detailed descriptions of the depositional environments, including stratigraphy and sedimentology and hydrogeology of the Hutt Lagoon have been provided elsewhere (Arakel, 1979 ; 1980 ; 1981 ; 1982). In brief playas, ephemeral ponds, river fan, barrier ridges and eolianite ridges are physiographic divisions in the lagoon with playa and ephemeral ponds being major divisions (Fig. 1). The area referred to as playa is a flat surface above the local water table, which may fluctuate up to 65 cm, in response to total influxes and evaporative reflux. The Hutt playa, forming up to 90 % (about 70 km^2) of the lagoon floor in summer, is comprised of salt marsh flats and a barren zone, and ranges in elevation between + 3.1 m and − 4.5 m (in relation to mean sea level). The salt marsh flats are characterised by algal mats and sparse salt-bush and samphire vegetative cover, whereas the barren zone is a salt-crusted (< 50 cm thick) hummocky surface.

Ephemeral ponds and creeks, occupying less than 5 % of the lagoon floor, develop during and immediately after a wet season when groundwater and seawater seepages temporarily exceed the evaporation rate. The lobate river fan, located at the mouth of the Hutt River, occupies approximately 1.7 km^2 of the lagoon floor at the southern end of the lagoon. The fan has an average gradient of 0.8 m/km lagoonward. The present Hutt River channel is cut 4.5 m deep through the fan apex, but flow is mainly directed

Table 2
Holocene stratigraphy of the Hutt Lagoon.

	Sequence	Units	Geometry and thickness (m)	Lithologies
Holocene - Recent	Barrier	Beach ridge and dune	Hutt Lagoon Sheet 25	Quartz skeletal grainstone
	Lagoonal	Intraclast veneer	Sheet 1	Pellet-intraclast grainstone, diagenetic gypsite
		Ephemeral halite	Sheet 0.5	Bedded halite
		Gypsite	Lens 2.25	Detrital gyps- arenite/rudite, laminated clastic gypsite, laminated prismatic gypsite
		Gypsum - mud	Lens 1.75	Laminar gypsum and mud
	Alluvial	River fan	Wedge 6	Alluvial sand, silt, and clay
		Sand sheet	Sheet 3.5	Mud-intercalated silt and sand
	Basal	Basal sheet	Sheet 0.55	Lithoskel skeletal grainstone, lithoskel skeletal packstone
			Unconformity	
			Pleistocene formations (Tamala eolianite)	

towards the Indian Ocean through a narrow beach-ridge system.

The barrier ridges, up to 1.6 km wide, are composed of lobate, transverse and longitudinal dune forms. Lobate and transverse dunes attain heights of up to 17 m, and occupy southerly facing parts of the barrier system. These dunes have an open-scrub vegetative cover dominated by *Acacia lingulata.*

The eolianite ridges form an escarpment, about 35 m high, on the landward margins of the lagoon. The eolianite belt is deeply gullied (Bishop Gully System) and calcrete deposits, up to 3 m thick, are exposed along the gully channels.

The Holocene sediments of the Hutt Lagoon can be grouped into 4 stratigraphic categories (Table 2). These are : Basel Sheet Unit, Alluvial Sequence, Lagoonal Sequence and Barrier Sequence. The Basal Sheet (Fig. 2), which is a marine unit and characterised by lithoskeletal-skeletal packstone and grainstone association uncomformably overlies the Pleistocene eolianites and calcrete soils. The Alluvial Sequence (Fig. 2), consisting of the River Fan and Sand Sheet Units, represents bulk of the sedimentary fill in the lagoon. The River Fan Unit with a maximum thickness of about 6 m is a wedge-to mound-shaped body of alluvial material developed at the mouth of the Hutt River. The Sand sheet Unit (Fig. 2) is a sheet-like body of alluvial material that has a measured thickness of 3.5 m at the centre of the lagoon. Within the lagoon, the unit is composed of medium to well sorted quartzose silty sand and/or sandy silt, with minor amounts of skeletal material and thin beds of clay ; whereas landward, this unit forms elongated foredune heavy-mineral sand deposits at the foot of the Bishop Gullies, directly overlying the Pleistocene eolianites. Overlying the Alluvial Sequence are lensoid evaporite bodies of the Lagoonal Sequence which consists of (Fig. 2) : Gypsum-Mud Unit, Gypsite Unit, Ephemeral Halite Unit and Intraclast Veneer Unit. The bulk of the Gypsum-Mud Unit consists of planar, wavy, wedged or crenulated laminae of gypsum interbedded with calcareous clay layers. These laminae, together with their alternating mud laminae, are traceable for several tens of metres.

The Gypsite Unit is a lensoid body of clastic gypsum packstone and grainstone, that conformably overlies the Gypsum-Mud Unit. The unit varies in thickness between 0 to 2.2 m and is capped by an algal mat which in turn is overlain by the Ephemeral Halite Unit in the centre of the lagoon and the Intraclast Veneer Unit at marginal areas.

The Ephemeral Halite Unit is a sheet-like body of bedded halite which during dry seasons temporarily occupies the playa surfaces of the Hutt Lagoon, covering an area of almost 22 km^2. At the times of maximum development of the Unit, thicknesses of up to 50 cm have been recorded from the lagoon centre, but it is much thinner in the marginal parts where it forms discontinuous encrustations on algal mats. In summer, thick algal mats, underlying the brine pools are cemented by gypsum, and act as an effective seal to isolate surface brines for precipitation of halite when concentration of these brines reach saturation.

The Intraclast Veneer is a sheet-like body of pellet grainstone, intraclast packstone and breccia which underlies the contemporary surface. The Veneer is restricted to the

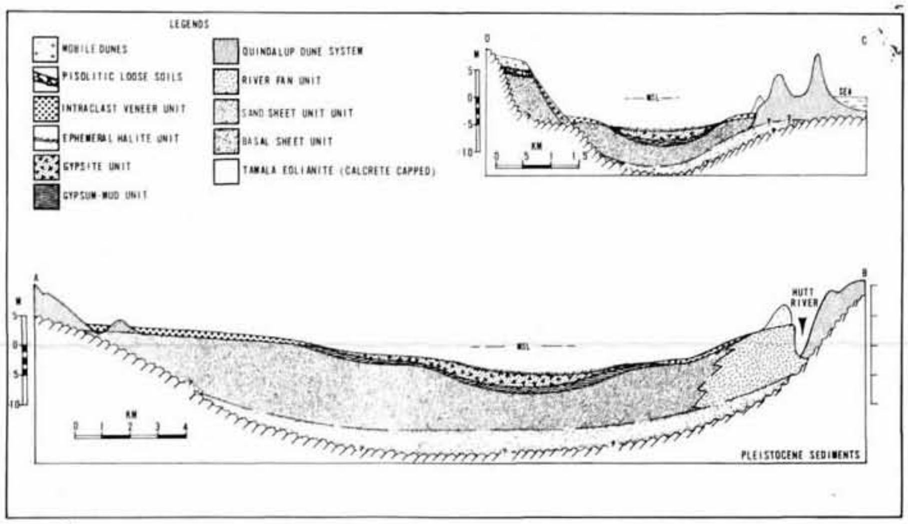

Figure 2
Stratigraphic cross sections, Hutt Lagoon. For lines of sections refer to Figure 1.

marginal parts where it attains thicknesses up to 1 m and thins basinward to a few centimetres, gradually merging into the Halite Unit.
Veneer sediments also include clasts of diagenetic hemipyramidal anhydrite crystals and gypsum nodules. The evaporites form less than 2.5 % of the sediment.
The barrier Sequence of beach-ridge and dune deposits is composed of sands with mud intercalations, and overlies the Basal Sheet and Pleistocene calcreted eolianites. Thickly vegetated dunes, located at the northern arm of the Hutt Lagoon, include several interdunal depressions in which gypsum sands have accumulated. The Barrier Sequence is the northern equivalent of the Quindalup Dune System, which is commonly recorded from most coastal areas of the Perth Basin (McArthur, Bettenay, 1960).

Table 3
Chemistry of Tamala groundwater (ppm).

	Bishop Gullies H.L.	Homestead Bore H.L.
Ca	36	61
Mg	50	200
K	10	32
Na	1,000	1,215
SO_4	69	85
Cl	646	1,804
HCO_3	180	325
pH	6.9	6.6
TDS	2,815	3,885

GEOCHEMISTRY

Chemical sedimentation

The significance of chemical sedimentation in arid coastal basins of Western Australia can be appreciated when the extent of evaporite sedimentation in the Hutt Lagoon is considered. The evaporite varieties represented by bedded gypsum, clastic gypsum, bedded halite and aragonitic pellet grainstone/intraclast packstone which includes hemipyramidal gypsum and anhydrite constitute between 2.5 and 99.5 wt% of the bulk of the sediments in the Lagoonal Sequence. These sediments were formed in a variety of lagoonal sub-environments where the hydrological zones vary between aragonite and halite precipitation fields. However, as it will be discussed herein, contemporary sedimentation is mainly related to interaction of lagoonal brines with influxing solutions, and hence, the recorded sediment assemblages are those diagenetic products which overprint the precursor deposits.

Hydrologic elements

Based on results of the chemical analysis of Ca^{2+}, K^+, Mg^{2+}, Na^+, Cl^-, SO_4^{2-}, and HCO_3^- in solutions from different areas of the Hutt Lagoon, three main hydrologic elements are identified : 1) local brackish groundwaters, moderate-salinity waters occurring in the eolianites (Tamala aquifer), and barrier sand dunes (Quindalup aquifer) which border the lagoon ; 2) oceanic water mass, Indian Ocean water enters the lagoons by seepage through coastal barriers, replenishing lagoonal solutions ; and 3) lagoonal brines, evaporitic brines, possessing concentration ratios (E) between 1 and 25 are sub-divided into : *a*) concentrated seawater brines, and *b*) enriched brines. Lagoonal brines recorded from Holocene sequences of Hutt Lagoon are saturated with respect to early-stage evaporitic mineral phases. However, concentration ratios of these solutions as well as associated solid products are initially controlled by seasonal climatic conditions.

Tamala aquifer water

The Tamala aquifer is a major groundwater source in coastal areas of the Perth Basin (Harley, 1974 ; Milbourne, 1967) and contains brackish waters, ranging from 600 to 7,000 total dissolved solids (Table 3).
The groundwater of the Tamala Eolianite is unconfined, and has a standing water level of around 7 m, which gently slopes lagoonward ; the saturated thickness is about 3.5 m. Recharge of Tamala groundwater is from the east. At Hutt, a low dune belt, located east of Bishop Gully is the intake area, from where a subsurface flow is directed down in an approximate westerly direction towards the lagoon. Groundwater undergoes constant chemical change from the recharge areas, where rainwater replenishes the system, to the lagoon margins, where it breaks out in springs.
The evolutionary trend of coastal groundwaters is presented in Figure 3 which depicts changes in ionic strengths and salinity as Tamala groundwater (samples E and F) proceeds to discharge at springs (samples C and D).

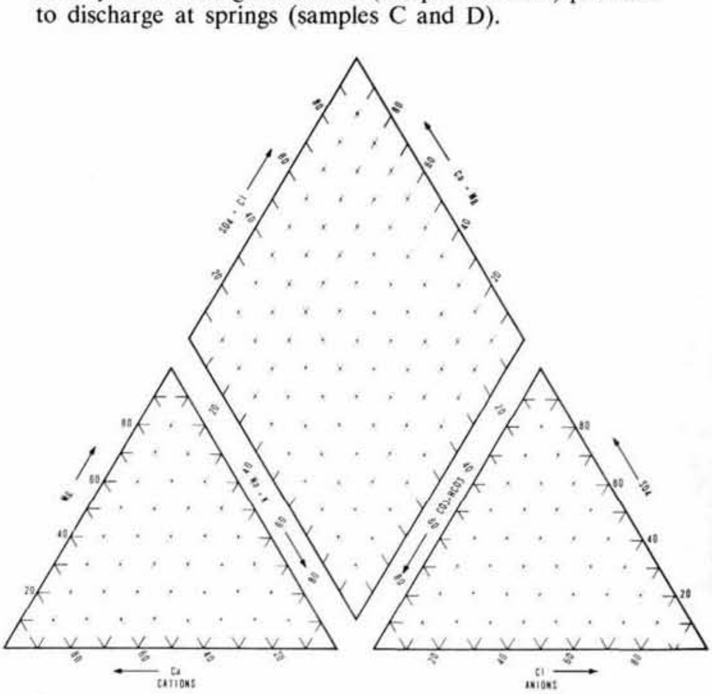

Figure 3
Trilinear diagram showing groundwater component variation in Tamala Aquifer.

Quindalup aquifer water

The Quindalup dunes which form the lagoonal barriers are unconfined aquifers. The groundwaters collected from interdunal pools, bores, and trenches dug into these sands exhibit a wide range of ionic strengths varying between 13.6 moles/1,000 moles H_2O (6,000 ppm total dissolved solids), and 26.4 moles/1,000 moles H_2O (35,000 ppm total dissolved solids), denoting variable admixing between brackish waters and seawater. Salinity in the aquifer is seasonally variable with minimum and maximum values being 17 % and 110 % of the annual mean.
The groundwater lens attains a maximum recorded thickness of about 6.7 m, in barrier dunes north of the Hutt Lagoon. In general, the water table forms an elongate mound at around mean sea level.
Data presented in Figure 4 show that the ionic strength distribution patterns of the Quindalup dune waters vary between those of standard seawater and groundwater. The cation population (Ca + K + Mg + Na) of these solutions closely follows the distribution of cations in seawater, whereas anion population shows regular variations in response to Cl-ion concentrations, indicating an admixing of seawater and brackish water.

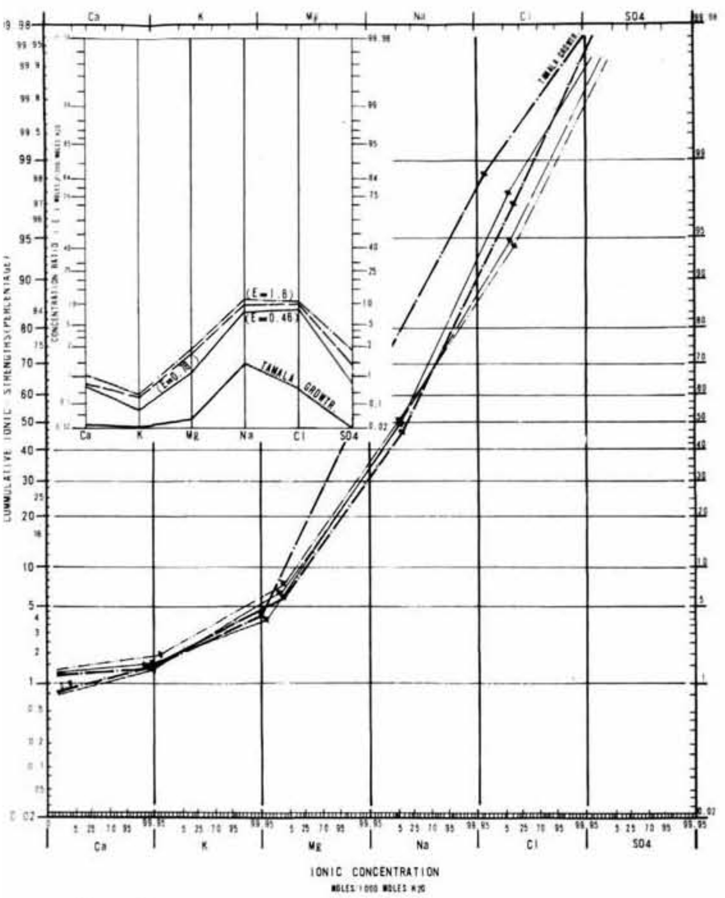

Figure 4

Ionic strength distribution patterns of the Quindalup aquifer waters ; insert shows the concentration of individual ions in the same brines. Seawater is from Port Gregory.

The trilinear diagram of these waters (Fig. 5) shows two distinct evolutionary trends :

1) contamination by seawater (trend A), which is usually accompanied by substantial segregation of solutes due to evaporation at surface ; and

2) replenishment of solutes due to recycling (trend B).

Replenishment of brackish water in the Quindalup aquifer occurs by infiltration of rainfall through porous dune sands. Field measurement of ground water levels has indicated that the vertical position of the water table, and hence the extent of groundwater/seawater mixing is largely determined by rates of precipitation, and to a much lesser degree, by seasonal sea level fluctuations.

Discharge from the Quindalup aquifer occurs by infiltration

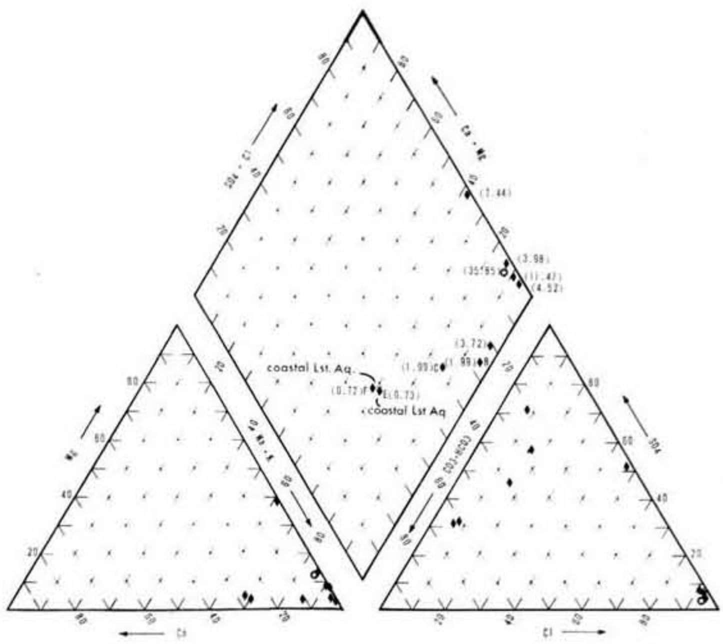

Figure 5

Trilinear diagram showing groundwater component variation in Quindalup aquifer. For legends see Figure 10.

through porous sands of the lagoonal barriers feeding springs and seeps at lagoon margins.

Concentrated seawater brines

Concentrated seawater brines have a marine origin but possess concentration ratios (E) ranging from $E = 1$ to $E = 25$. In general, concentration ratios (and therefore total salinities) are higher for solution collected in summer than those collected in winter.

Concentrated seawater brines are confined to Holocene sequences above the impermeable calcreted eolianites which act as a seal. These brines also are excluded from the Gypsum-Mud and Gypsite Units because of the presence of low porosity-permeability zones at Unit boundaries. The seawater brine also lies in the Veneer at the marginal parts of the lagoon and towards the centre (where the Veneer has piched out) it forms a brine pool directly above the algal mats. As a result, layered halite deposits form in brine pools.

Seawater intrudes the lagoon through the coastal barriers. Plots of E versus the concentration of major seawater ions and total salinity (expressed as the sum of anion and cation concentrations) of brines obtained from lagoon-marginal sediments (Fig. 6) indicate that : 1) concentration trends of

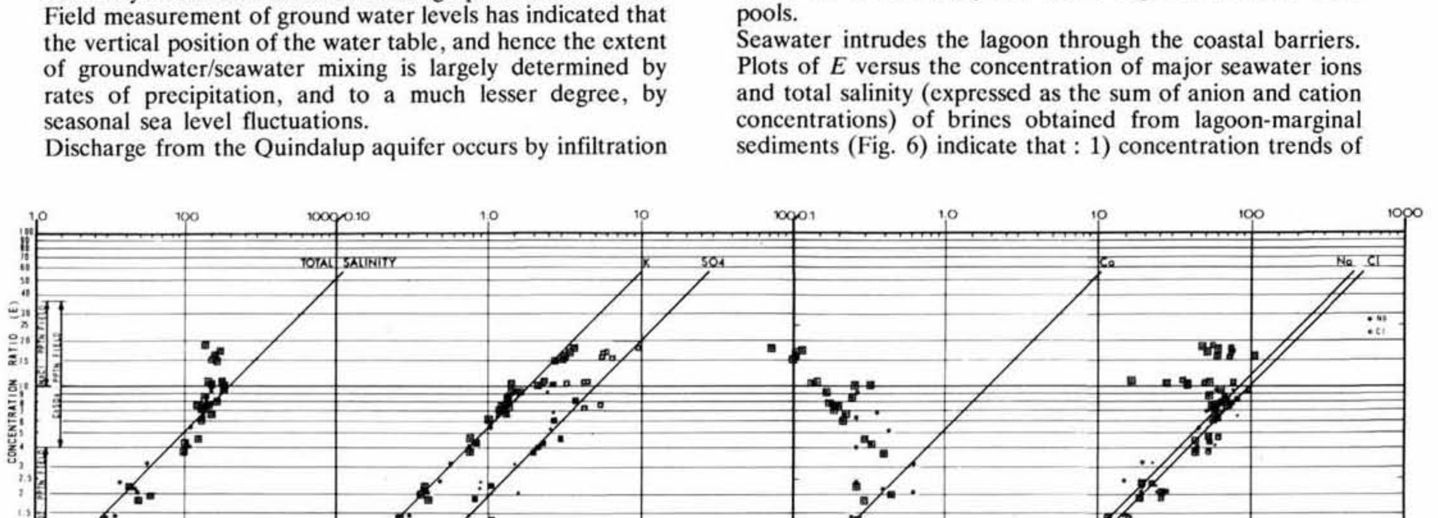

Figure 6

Plot of concentration ratio (E) *against total salinity, potassium, sulfate, calcium, sodium and chloride for concentrated seawater brines collected from Hutt Lagoon. Filled symbols represent samples from Basal Sheet Unit ; unfilled symbols represent samples from Intraclast Veneer and Ephemeral Halite Units. Boxed symbols represent samples collected in dry seasons, and unboxed ones represent those collected in wet seasons. The solid lines (equimolar reference lines) represent simple evaporative concentration.*

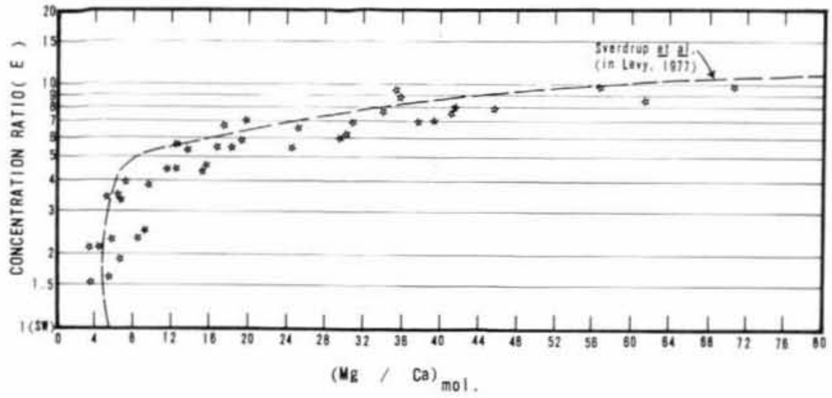

Figure 7
Plot of concentration ratio (E) *against Mg : Ca mol. ratio ; concentrated seawater brines.*

these solutions are similar to those of concentrated seawaters, and hence predictable (cf. Sverdrup, *in :* Levy, 1977 ; Herrmann, Knake, 1973 ; Miller, 1961) ; and 2) concentration ratios progressively increase upward into the halite precipitation field, reflecting evaporative concentration. With increased concentrations, seawater solutes are successively precipitated, as solutions reach saturation. Major precipitation occurs in the early stages of concentration at $1 < E < 4$ when Ca, HCO_3, and CO_3 are depleted from the solutions as aragonitic muds. The significance of early-stage depletion is seen by examining the molar ionic ratios. Figure 7 shows that at concentration ratios below the gypsum precipitation field ($E < 4$), the Mg : Ca mol. ratios of the Hutt concentrated seawater brines increase 3-4 times. In Figure 13, the minor variations in sulphate concentration are attributed to the reducing nature of the brine body as indicated by the strong H_2S smell of these brines. The K ion of the seawater solutions does not participate in any precipitational phase, and hence, has a concentration trend similar to that of seawater brine. Similarily, a minor Na-Cl enrichment at low ($E < 6$) concentration ratios and depletion at higher concentrations has resulted in the marked deviation of the concentration trends from that of seawater. The plot of E against the Na : Cl mol. ratios of these solutions (Fig. 8) shows that the low-concentration brines generally have a narrow (0.7-0.9) range of Na : Cl mol. ratios, similar to concentrated seawaters. However those highly concentrated seawater brined ($E > 6$) collected from sediments of the Intraclast Veneer, at the eastern margins of the lagoon (circled samples in Fig. 15) have higher Na : Cl mol. ratios which vary between 0.9 and 1.0. Abnormally high Na : Cl mol. ratios of the lagoon marginal waters are attributed to the effcets of mixing with inflowing groundwaters which are characterised by Na : Cl mol. ratios grater than 1.0.

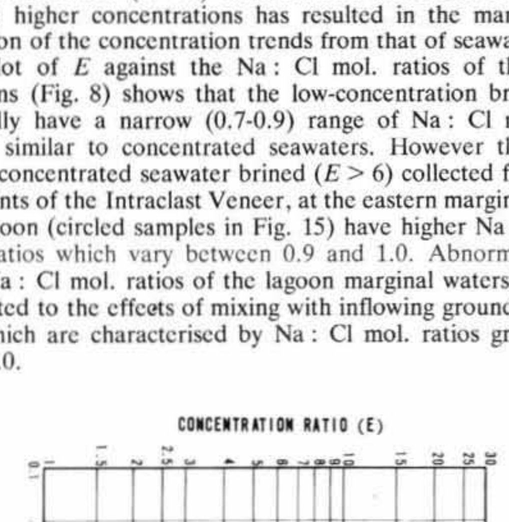

Figure 8
Plot of concentration ratio (E) *against Na : Cl mol. ratio ; concentrated seawater brines. Circled samples represent brines collected from the eastern margins of the lagoon.*

When the ionic-strength distribution patterns of those brines which are interstitial to bedded halites are compared with the patterns of concentrated seawaters (Fig. 9), variations of ionic cumulative percentages of the halite brines are seen to match the variations of similar ions in concentrated seawaters. For example, after concentration due to evaporation, K, Mg, Cl, and SO_4 ions exhibit *progressive* distribution trends, whereas Ca and Na have *regressive* distribution trends. In general, a strong upward increase in brine concentration indicates that solvent loss from the concentrated-seawater brines is due to surface evaporation and capillarity in nearsurface sediments.

Enriched brines

Gypsum-Mud and Gypsite Units contain intrastratal brines that are enriched by the dissolution of soluble phases from the host sediment bodies. These brines (Fig. 10) have total salinities between 30 and 180 moles/1,000 moles H_2O and are characterised by excessive enrichment of major ions at low concentration ratios.

The enriched brines are characteristic of the Gypsum-Mud and Gypsite Units in the Hutt Lagoon where they form lensoid bodies, up to 4 m thick. Mud laminae act as low-permeability seals preventing mixing of these brines with concentrated seawater brines in underlying strata. Exchange with overlying concentrated seawater brines, interstitial to sediments of the Intraclast Veneer and Ephemeral Halite Units, also is restricted by the algal mats which have generally low permeability. Due to the presence of cracks, the algal mat does not however, form a complete seal, and some downward percolation of highly concentrated seawater brines, and evaporative loss of solvents is possible.

Deviation in concentrative trends of brines interstitial to sediments of the Gypsum-Mud and Gypsite Units is more marked in solutions collected during dry seasons (Fig. 10). The data represented in Figure 11 show the density is best correlated with the chloride content of the enriched solutions, indicating that their densities are chloride-controlled (cf. Sonnenfeld, Hudec, 1978). It shows also that a relatively poor correlation ($r = 0.54$) exists between the density and total salinity of the brines collected in a wet season from the Hutt Lagoon. Their regression line has a high slope, suggesting an early contribution of ions to the density of processes other than evaporative concentration. Such excessive enrichment can possibly be attributed to replenishment by the downward percolation of brines characterised by high Na and Cl values due to the dissolution of surficial halite. Whereas concentration variations occur the net volume of solutions which make up the enriched brines, shows little, if any, seasonal fluctuations because the water table (for the concentrated seawater brines) is always above the enriched brine body.

The admixing of evaporite-interstitial brines with influxing solutions results in diagenesis of the lagoonal deposits, until equilibrium is attained with host solid phases. The correlation between density and total salinity of brines collected

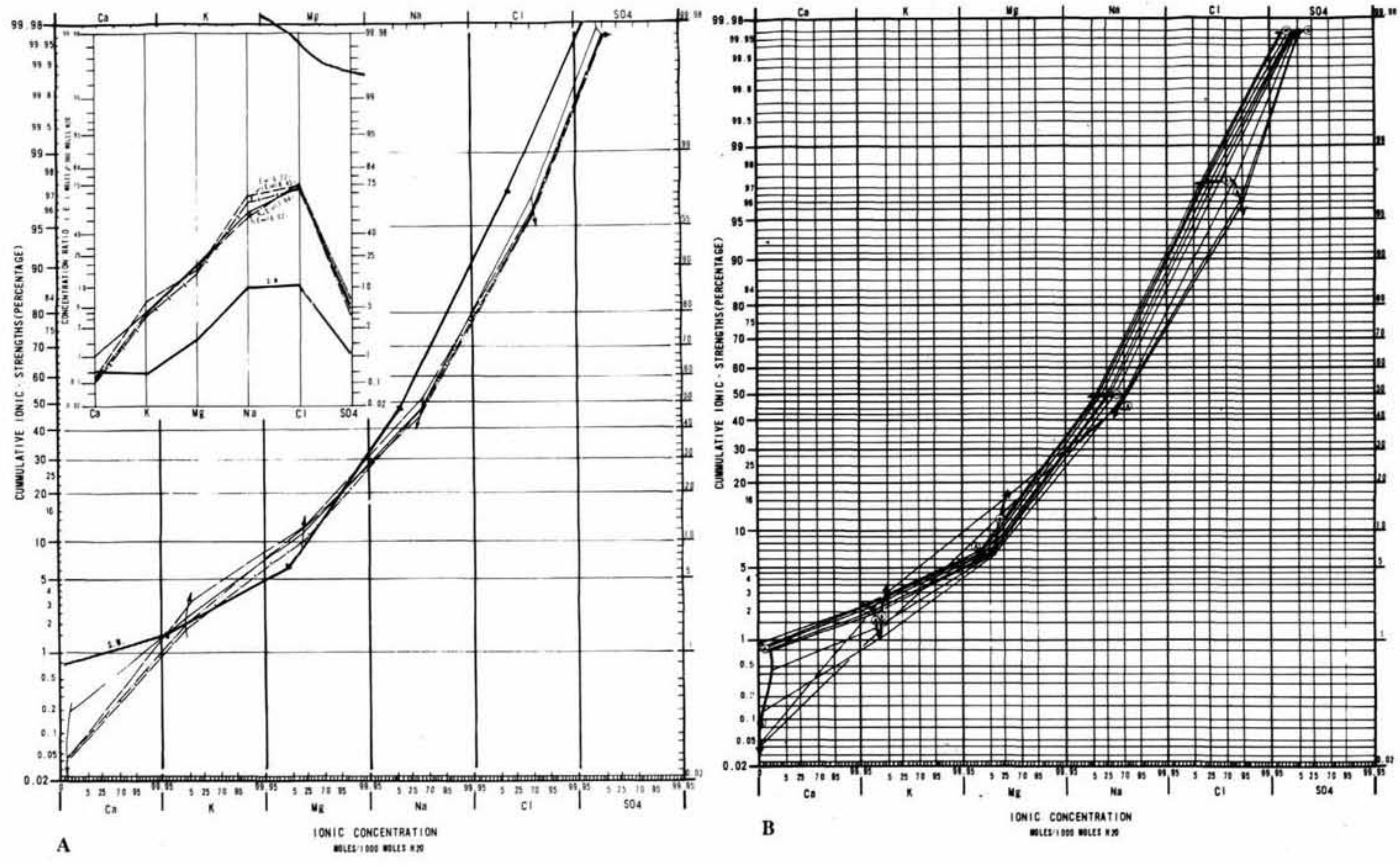

Figure 9

Ionic strength distribution patterns of : A) *concentrated seawater brines interstitial to bedded halites ; and* B) *the standard concentrated seawater brines. Insert in* A *shows the concentration of individual ions in the same brines. Data for standard concentrated seawater brines are from Herrmann and Knake, 1973.*

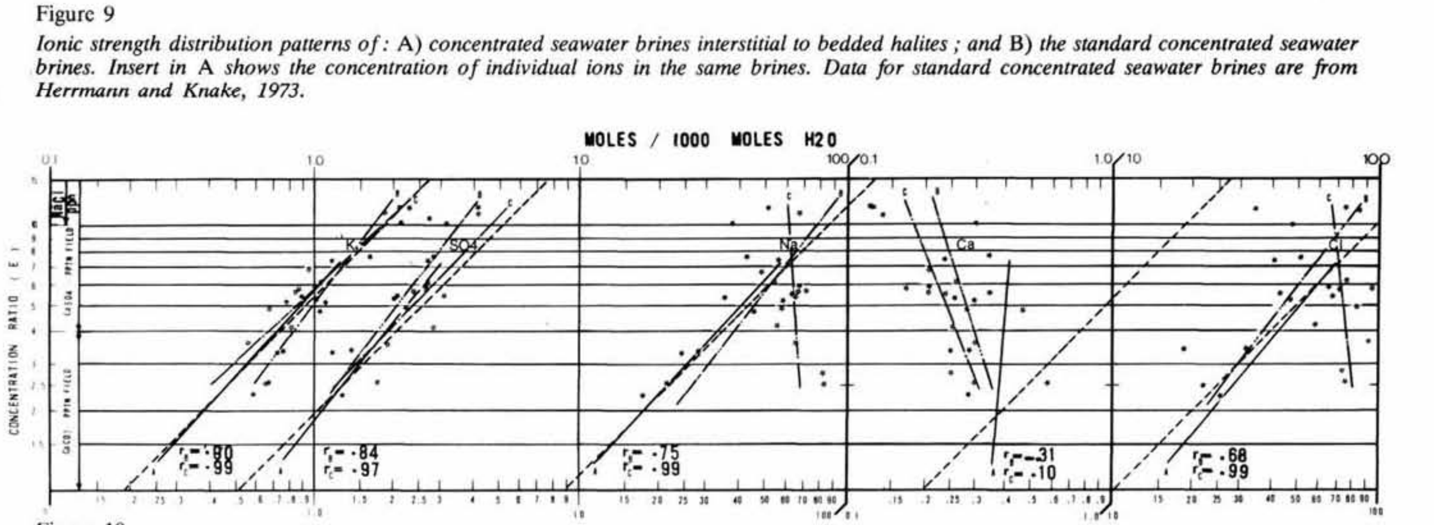

Figure 10

Plot of concentration ratio (E) *against potassium, sulfate, sodium, calcium and chloride for enriched brines collected from Hutt Lagoon. Filled symbols represent samples collected in dry seasons and their regression lines are shown as* B. *Unfilled symbols are for samples collected in wet seasons, and* C *represents their regression lines.* A *represents regression lines for concentrated seawater brines (data from Herrmann and Knake, 1973). The dashed lines, with 45° slope, represent simple evaporative concentration.*

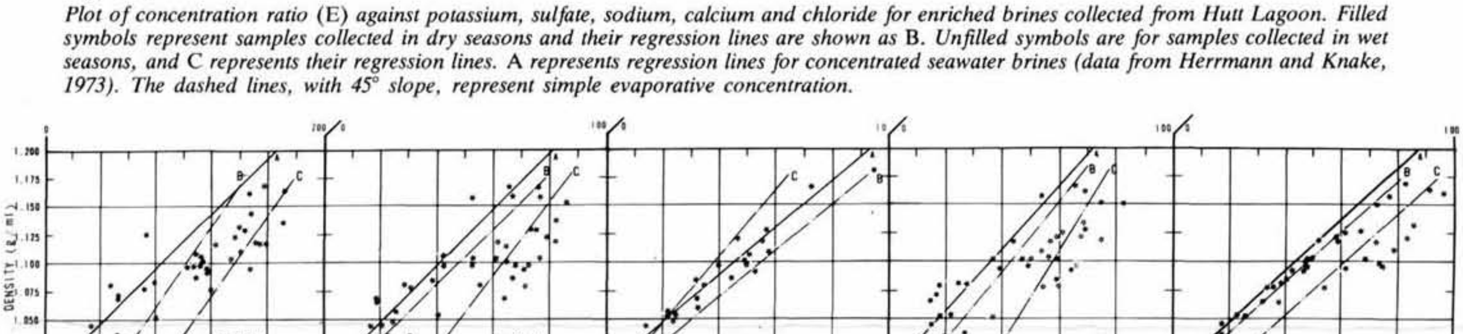

Figure 11

Plot of density versus total ions, total cations, magnesium, sodium and chloride for enriched brines collected from Hutt Lagoon. A *represents regression lines for concentrated seawater brines. Filled symbols represent samples collected in wet seasons, and unfilled symbols represent samples collected in dry seasons, and their regression lines are shown as* C.

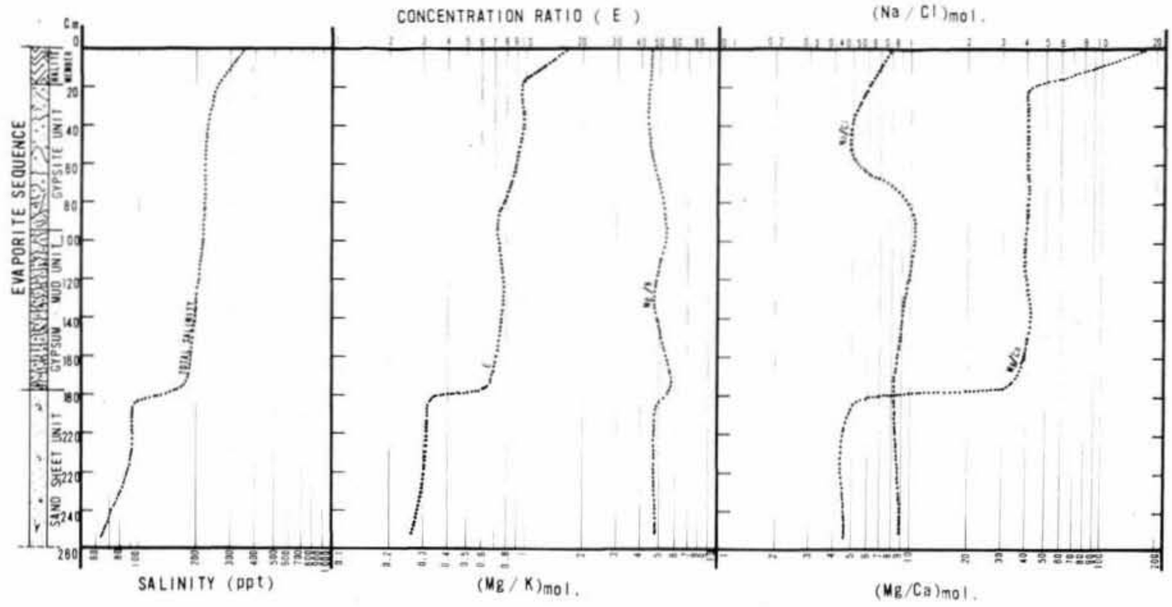

Figure 12

Plots of total salinity (ppt), concentration ratio (E), *Mg : K mol. ratio, and Mg : Ca mol. ratio of lagoonal brines as obtained from a core at different stratigraphic levels.*

during a dry season is significantly higher, whereas the slope of their regression line remains the same. This probably indicates the depletion of ions due to the effects of processes such as precipitation and/or common ion-effects, sorption and reduction have probably compensated for the excessive early-stage solute enrichment. In general, all correlations have significance levels over 85 %. This can be best explained by enrichment from a non-seawater source, followed by evaporative concentration, during which the initially high Na enrichment progressively offsets the chloride content of the enriched brines.

Hydrologic changes

Vertical changes in solution chemistry

The plots of chemical parameters for interstitial solutions (concentrated seawater brines, and enriched brines), obtained from sediments of a core which penetrated different lithostratigraphic units in the central depression of Hutt Lagoon, is used in Figure 12 to demonstrate the vertical variations in the solution chemistry of the lagoonal brines. As indicated by concentration ratios and total salinities, seawater entering Hutt Lagoon is progressively concentrated. The upward increase in concentration is further reflected by changes in solution chemistry resulting from precipitation of aragonitic mud at Mg: Ca mol. ratios varying between 4 and 5 (cf. Bush, 1970 ; Levy, 1977).

An abrupt chemical boundary exists between the Sand Sheet Unit, and the overlying Gypsum-Mud Unit. Increases of E from around 3 in the Sand Sheet Unit, to more than 7 in the Gypsum-Mud Unit are significant. High concentrations and total salinities are constantly maintained throughout the Gypsum-Mud and Gypsite Units, indicating the limited nature of fluxes between enriched brines and adjacent reservoirs. The Ca depletion due to precipitation of both carbonates and gypsum, is a major solute segregation which is evidenced by a sharp rise of Mg : Ca mol. ratios at the same boundary. Uptake of K, and to a lesser degree Mg ions by clay minerals in the anaerobic muds is shown by a minor increase of Mg : K mol. ratios at the contact. This change appears to reflect K fixation by montmorillonitic clays (eg. Jones, 1965 : Friedman, Gavish, 1970 ; Levy, 1977) ; some exchangeable Na ions may be released during this process (eg. Grim, 1968).

The Na : Cl mol. ratios show a minor increase from 0.85, at the base of the Gypsum-Mud, to values around 1.0, at the base of the Gypsite Unit. In the Gypsite Unit the Na : Cl mol. ratio shows a marked decrease followed by a more gradual increase. The decrease in the mol. ratio appears to be due to the precipitation of halite as pendant cement, whereas the subsequent increase may be due to limited downward percolation of dense concentrated sea water brines.

Seasonal changes

To elucidate the chemical changes due to climatic variation during a seasonal cycle, ten compositional analyses representing duplicate solution samples of the lagoonal brines (concentrated seawater brines, enriched brines, and ephemeral pond waters), Tamala and Quindalup groundwaters, springwater, and Indian Ocean water are listed in Table 4. For comparison, analysis results of brines from Leeman Lagoon, located 250 km south of the Hutt Lagoon are also included.

The results from duplicate samples, collected during successive wet and dry seasons, indicated that : 1) lagoonal waters are brines with concentration ratios (E) within gypsum and/or halite precipitation fields ; and that 2) total quantity of dissolved solids in these brines is higher is a dry season than in a wet season, suggesting that concentration is largely by solar evaporation (cf. Friedman *et al.*, 1976).

The latter change is further exemplified by variations in ionic concentrations between the duplicate samples. In March, 1977, NaCl and $CaSO_4$ minerals were observed precipitating in Hutt Lagoon, from brines (No. 132) interstitial to sediments of the Intraclast Veneer Unit ; the concentration was within the gypsum-precipitation field (E = 6.36). By May, 1977, additional water influx to the lagoon margin resulted in the partial dissolution of the precipitates and dilution of the concentrated seawater brines. Sample No. 16, collected in June 1977, shows that the value of E has decreased, and that Ca concentration has increased due to dissolution of carbonates and sulphates. The extension of inflowing solution towards the lagoon centre resulted in the dissolution of the halite crust and the eventual formation of ephemeral brine ponds. The brines of wet-season ponds are represented by sample No. 142 which is less concentrated than its dry-season counterpart (Sample No. 36), and is characterised by Na : Cl mol. ratios greater than 1.

Seasonal variations in the chemistry of enriched brines are less pronounced, because of restricted fluxes between their

Table 4
Analyses of water from Indian Ocean, local groundwaters, and brines, Hutt and Leeman Lagoons.

Hydrologic environment		Water type	Date of sampling	Ca	K	Mg	Na	Cl	SO_4	HCO_3	Density (g/ml)	T.D.S. (1)	E
Sea		Indian Ocean water (2) (3)	3.76	0.194	0.187	1.005	8.652	10.09	0.516	0.038	1.019	20.684	1
Ground water		Tamala (3) (4) groundwater	3.77	0.016	0.004	0.037	0.784	0.328	0.012	0.053	1.003	1.234	NA
		Quindalup (3) groundwater	12.77	0.23	0.05	0.44	7.05	7.11	0.26	0.002	1.008	15.142	NA
		Spring water (3)	12.77	0.036	0.11	0.66	1.56	1.31	0.73	0.003	1.012	4.406	NA
Hutt Lagoon	Playa	Conc. sw	6.77	0.42	0.82	5.33	47.82	50.29	2.25	0.005	1.102	106.935	5.65
			3.77	0.20	0.83	6	58.80	58.92	2.62	0.001	1.115	127.371	6.36
		Enriched brine	6.77	0.47	1.07	4.46	46.25	49.25	2.27	0.009	1.103	104.309	4.73
			12.77	0.26	0.83	3.92	56.44	58.92	2.78	0.002	1.115	123.152	4.16
	Pond	Conc. sw	6.77	0.07	3.61	17.63	55.66	47.58	9.67	0.003	1.104	134.222	18.71
			12.77	0.06	0.95	20.42	50.17	72.13	10.05	0.003	1.254	153.783	21.67
Leeman Lagoon	Playa	Conc. sw	6.77	0.29	1.00	5.55	51.74	57.91	2.57	0.002	1.107	119.062	5.89
			12.77	0.22	0.98	5.4	56.89	59.58	1.62	0.002	1.104	124.692	5.73
		Enriched brine	6.77	0.22	1.28	6.15	40.31	45.28	3.14	0.001	1.102	96.381	6.52
			12.77	0.16	1.20	6.37	65.07	66.04	4.13	0.002	1.135	142.972	6.76
	Pond	Pondwater	7.77	0.47	0.39	1.87	19.60	24.25	0.61	0.002	1.037	47.192	2.03
			11.77	0.42	0.67	2.18	46.25	35.56	1.99	0.002	1.061	87.072	2.31

(1) Sum of anions and cations, expressed in moles/1000 moles H_2O.
(2) Collected at Port Gregory.
(3) Mean values.
(4) Collected from bores at Bishop Gullies, Hutt Lagoon.

reservoir and enclosing concentrated seawater/groundwater reservoirs. Minor changes in Na and Cl concentrations appear to relate to limited downward percolation of overlying denser Na-Cl brines, whereas variations in the concentrations of other ions appear to be related to their release from interstitial brines trapped between salt precipitates (Friedman *et al.*, 1976). In general sense, it can be concluded from the small seasonal variations in the concentration of major salt-forming ions that salts dissolved during a wet season are largely reprecipitated during the following dry season.

DYNAMICS SYSTEM : DISCUSSION

The dynamics system of the Hutt Lagoon is a function of physiographic setting of the lagoon, intralagoonal hydrologic units, and external hydrologic units.

The contemporary surfaces of the lagoon lie at elevations between + 2 m and − 4.5 m (in relation to MSL). That the lagoon surfaces are predominantly below sea level is the fundamental control on : 1) lagoonward seepage of both groundwater and Indian Ocean waters ; the latter impelled by a hydrostatic head of up to 4 m ; and 2) absence of seepage reflux, as evidenced by net accretion of halite on the playa surfaces.

The Holocene evaporite lagoons of the Western Australian coast are mainly formed in depressions in calcreted Pleistocene eolianites, which are characterised by low porosity-permeability (Arakel, 1979 ; 1980 ; 1981 ; 1982). These calcretes form a near-perfect seal, capable of retaining brines within the lagoon sequences, as well as preventing the influx of seawater and groundwater through the base of these lagoons. The calcrete surface is continuous from the Hutt Lagoon to the sea, but nowhere does it rise above sea level. Therefore, although the calcrete is a basal aquiclude, it does not prevent seawater influx to the lagoon through the barrier system which overlies these calcretes.

The barrier dunes constitute an aquifer connecting the ocean reservoir to the lagoons. The barriers also accommodate lensoid-shaped bodies of brackish water (Quindalup aquifer) which seasonally modify the rate of seawater influx, as the extent and thickness of the lenses vary. However, volumetrically the concentrated seawater brine reservoir comprises the largest hydrologic unit in the lagoon system, extending from the Basal Sheet and Sand Sheet Units upwards into the Intraclast Veneer Unit and the modern Ephemeral Halite Unit (excluding the Gypsum-Mud and Gypsite Units).

The exchange of solutions between enriched brine reservoirs, which are confined to the Gypsum-Mud and Gypsite Units, and the enclosing concentrated seawater brine reservoirs is very limited because of textural barriers at the contacts.

Atmosphere and ocean are two external hydrologic units which have major control on the maintenance of brine balances. Rainfall has the greatest impact during the wet season, when the inflow of groundwater effectively recycles the lagoonal brines. Field evidence indicates that in surficial brines when the relative humidities exceed the equilibrium pressure of the concentrated brines, leading to influx of water to the brines (cf. Kinsman, 1976). The addition of salts from sea aerosols to the lagoonal solutions has been reported as being a significant process in coastal environments of the Perth Basin (Hingston, Gailitis, 1976). However, apart from NaCl as the major salt component, the distribution of the other salts in the aerosols approximates the distribution of solutes in seawater. Hence, the addition

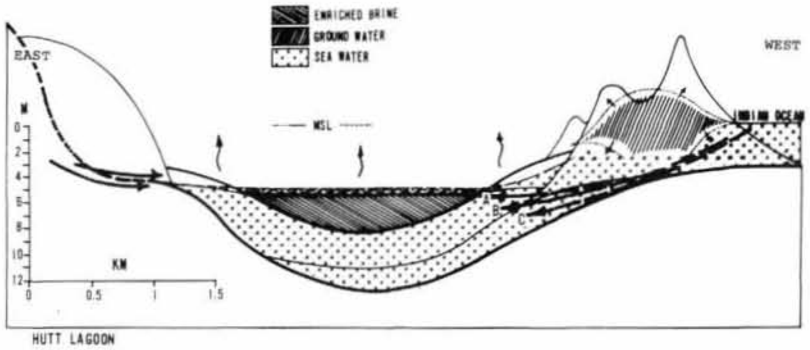

Figure 13

A schematic section across the Hutt Lagoon, demonstrating the vertical arrangement of the main hydrologic elements.

of dry sea salts to lagoonal brines would result in partial concentration of the brines, without any significant change in distribution of major sea water ions.

Circulation system

Analysis of the data presented earlier indicates that the hydrologic circulation system within the Hutt Lagoon is a function of the topographic relief of the lagoon, and the net balance between evaporative reflux and influx.

Influx to the lagoon is from the ocean, dune sand aquifers, direct precipitation, and in very rare cases, cyclonic and river floods.

A hydrostatic head of several metres exists between the lagoon and the Indian Ocean because the contemporary lagoon surfaces ranges up to 4 m below mean sealevel. As a result of this hydrostatic head, Indian Ocean waters influx to the lagoon through porous sands of the barrier dunes. However, the hydraulic gradient of seawater influx shows cyclic shifts which can be directly related, by field observations to changes in the aerial and vertical extent of the brackish dune-water pockets during consecutive wet and dry seasons (Fig. 13). During the wet season the dune-water lenses expand and tend to press down the influxing seawater inflow, compared with similar inflow during a dry season.

Apart from seawater influx down a hydraulic gradient, recharge to lagoon waters is seasonally boosted by springwater inflow under a local gravity head (Fig. 14). Note that there is no surface runoff into the lagoon.

Although the inflowing solutions are initially concentrated by the partial dissolution of existing solid phases (dominantly gypsum and halite), discharge from the lagoons is through evaporative reflux (direct evaporation and capillarity) as evidenced by the presence of salt-crusted playas which comprise the ephemeral environmental units in these lagoons. Evaporative concentration affects both concentrated seawater brine and enriched brine reservoirs. However, discharge from enriched brine reservoirs is limited because : 1) concentration solely by capillary is less efficient than direct evaporative concentration ; and 2) a textural barrier exists at the top of the enriched brine reservoir. Note that seasonal discharge from the enriched brine body may probably be replaced by the downward percolation of overlying highly concentrated (and hence denser) seawaters. The downward percolation is assumed to be driven by a density head which develops because the concentration of overlying brines by direct evaporation is more efficient than concentration of the underlying enriched brines by capillarity. The flux volumes to and from the enriched brines are minimised by textural barriers, as discussed earlier.

In summary, the configuration of the major hydrologic units in Hutt Lagoon indicates that the circulation system in the evaporite lagoon system is driven by recharge under a hydrostatic head, and discharge by evaporative reflux.

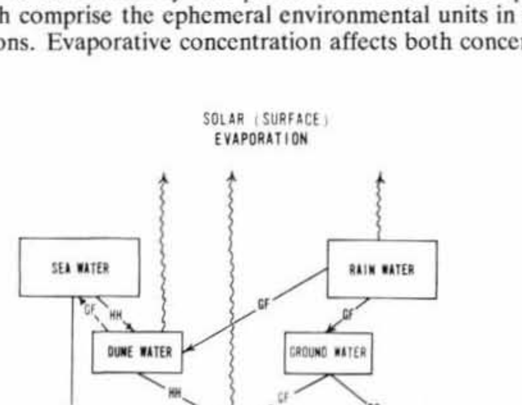

Figure 14

Circulation pattern of evaporite lagoonal system and major controlling forces in Hutt Lagoon.

CONCLUSIONS

Whereas the Hutt Lagoon, similar to most of the other lagoons developed along the arid - to semi-arid Western Australian coast, is essentially the Holocene product of coastal submergence, followed by development of enclosing barriers, the marked contrast observed in geochemistry and mineralogy of the vertical sediment associations between lagoonal units, indicate that the lagoon has evolved into the present day environments through the following successive stages of sedimentation :

1) Open marine embayment stage, which is represented by a sheet of lithoskel grainstone incorporating skeletal remains and sea grass leaf-sheaths.

2) Marine lagoonal stage, when accretion of coastal barrier beach and dune complexes progressively restricted open marine circulation. This resulted in changes in the faunal and floral assemblages, and an upward fining of the marine sediment sequences. Also, concurrent with barrier formation, the embayment was encroached by prograding alluvial suites due to Hutt River discharge.

3) Evaporitic pond stage, in which lagoon was isolated from the sea, followed by the development of gypsum and mud layers as a result of alternative brine concentrations in the ponds. Rapid shoaling produced playas where lagoonal brines were confined below the sediment surface ; locally subaerial exposure resulted in the reworking of earlier evaporites towards the lagoon centre. Subsequent winnowing of surface eolian sediments facilitated the development of a veneer of pellet intraclast grainstone which has since prograded basinward, forming extensive barren zones and salt marsh flats.

4) Contemporary pond-playa stage — contemporary conditions are seen as stages in a historical sequence of diminishing evaporite sedimentation due to increasing restriction. The basinward progradation of the onlapping sequences is continued, and the evaporite lagoons have substantially evolved through major readjustments in the distribution of hydrologic units, as the interface of mixing between local

groundwaters and lagoonal brines has migrated. The contemporary hydrologic circulation system within Hutt Lagoon remains a function of : *a*) topographic relief ; and *b*) the net balance between evaporitic reflux and total influx. The location of the lagoon surfaces, predominantly below mean sea level, fundamentally controls the influx of sea water (impelled by a hydrostatic head of up to 4 m) with net influx being seasonally balanced by evaporative reflux.

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