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THE HYDROLOGY OF THE INLAND BLUE HOLES, ANDROS ISLAND

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ABSTRACT

Andros Island in the Bahamas contains numerous small lakes some of which are over 100 m in depth. A short programme of temperature and salinity profiling in these lakes suggests the presence of an extensive freshwater lens, thinning towards the coast and estuaries. A lake deeper than the thickness of the freshwater lens is defined as a "Blue Hole". These lakes are anoxic at depth and mixing is confined to the upper freshwater component. The interface between fresh and salt water may be a zone of intense solution, although geomorphic evidence suggests biologically enhanced erosion beneath photosynthetic mats. The blue holes probably developed by collapse of cavernous openings during times of low sea level when buoyant support was removed. There is little evidence for integrated conduit systems beneath much of the island, although long submarine caves have been explored, and some blue holes are tidal and exhibit conduits at depth. This suggests that tidal "pumping" may be the dominant driving force in developing the horizontal conduits explored by cave divers.

INTRODUCTION AND METHODS

The inland blue holes of Andros Island, Bahamas, are deep lakes of very small surface area. From the air, their deep blue colour makes them stand out clearly from the numerous shallow lakes and marshes of the island. The blue holes are broadly distributed on Andros, but concentrated towards the eastern edge of the Island (Fig. 1) Brackish water estuaries such as Stafford Creek run deep into the interior.

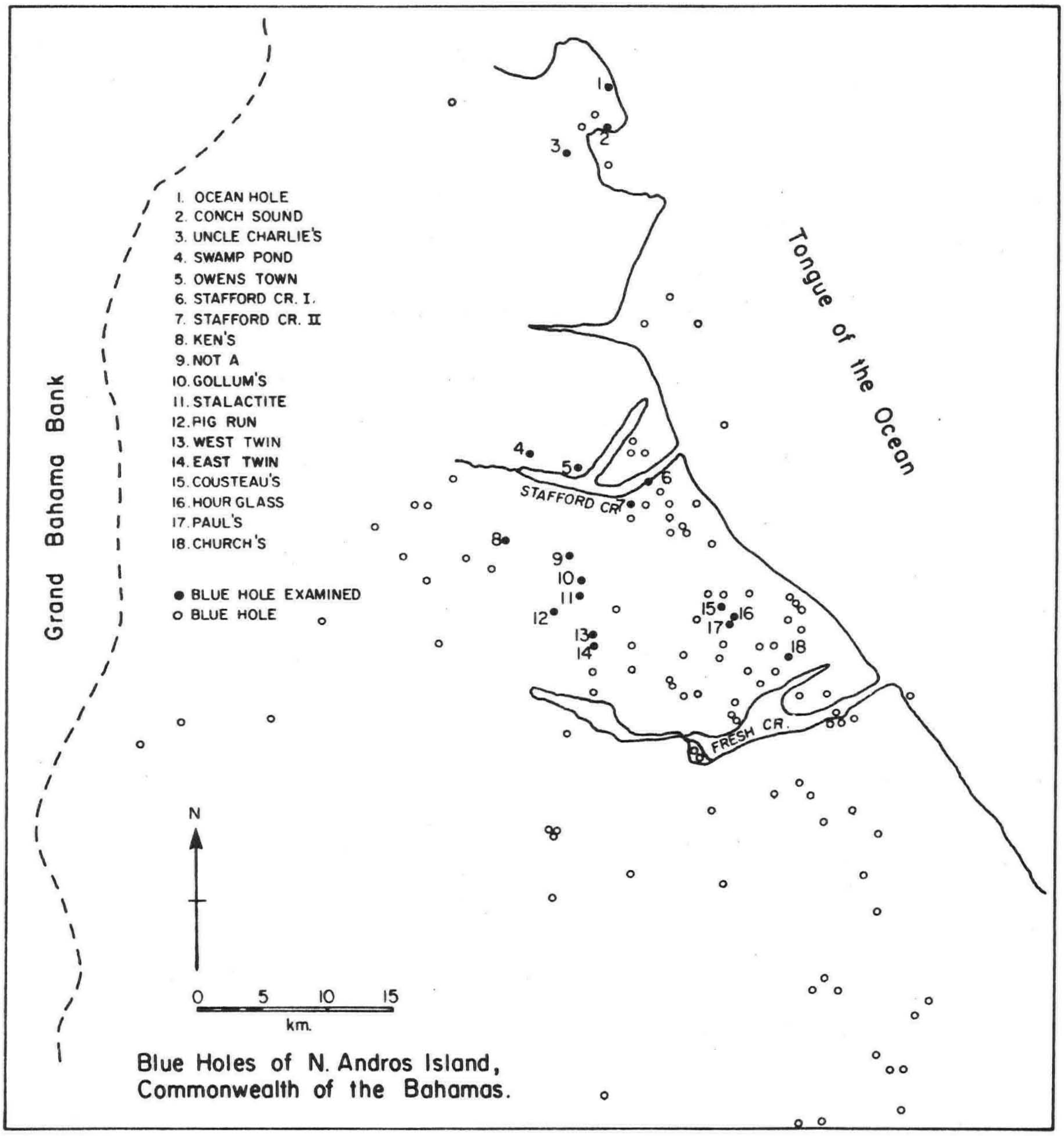

Fig.1. The distribution of Blue Holes on Andros Island compiled from 1:25000 topographic maps. Many of these may not be true Blue Holes and others offshore may not be shown.

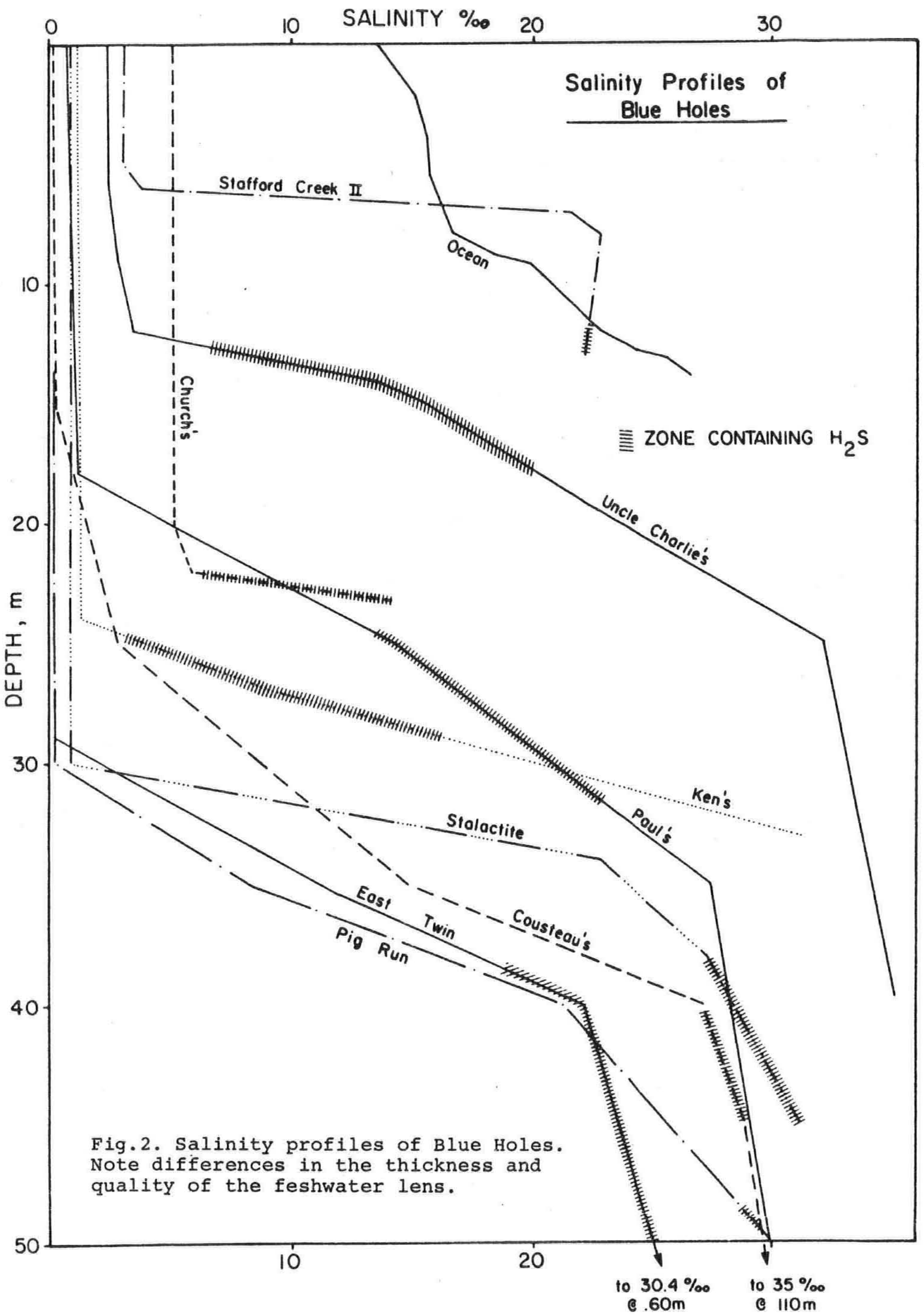

Fig.2. Salinity profiles of Blue Holes. Note differences in the thickness and quality of the feshwater lens.

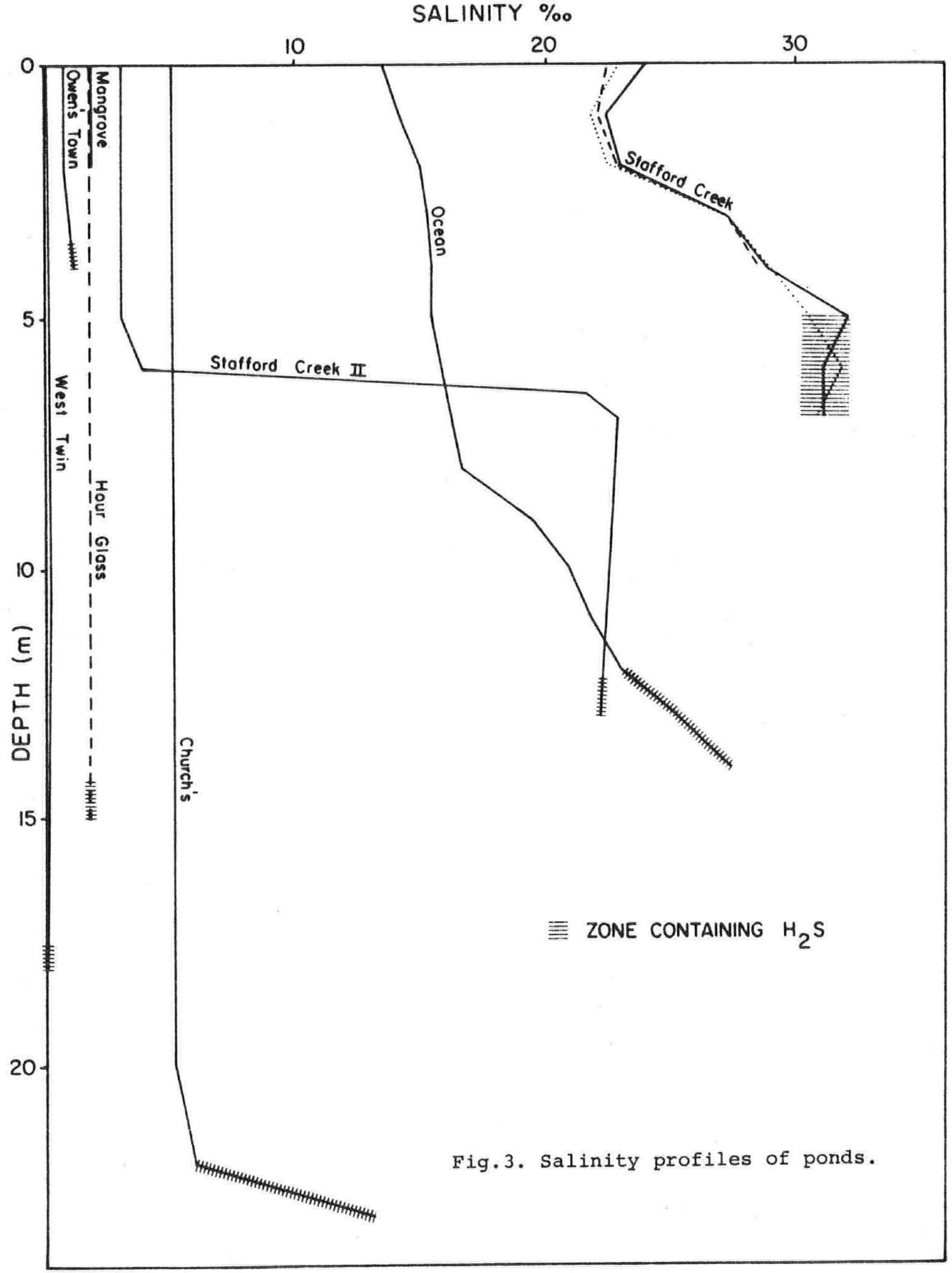

Fig.3. Salinity profiles of ponds.

The blue holes occur in all types of environment on Andros: pine barrens, swash, mangrove swamp and within lakes and estuaries. The logistic difficulties of travelling in many areas meant that only the more accessible sites were visited such as those near logging roads in the pine barrens.

At each site visited the depth was recorded along with descriptive information. The profile of temperature and conductivity was usually determined with a 15 m probe and a YSI-33 Salinity, Conductivity, Temperature meter. Samples below 15 m were obtained by a water sampler or direct sampling by diver.

A temperature/salinity profile of the Stafford Creek Estuary was conducted up to the limits of navigation.

RESULTS

The blue holes investigated are circular in plan and range from 30 to 250 m in diameter and varied from 2 m to 110 m in depth. There are no surface streams associated with the blue holes. The walls are usually vertical, but sloping sides occasionally lead down from the surface. Overhanging walls are reported at depth. The sides are irregular and pitted, except where angle of repose slopes occur. These are covered in coarse calcareous mud. Subaerial cliffs are rare, but are 15 m high at Ocean Hole. Surface relief on Andros is seldom more than 2 m a.s.l.

The water quality varies from clear to cloudy, but at great depth is very clear. Algal/bacterial mats occupy much of the sloping walls except in the more saline holes. The limestone beneath the mats is extremely weak and friable. In places spontaneous collapse of walls is occurring. Beneath overhangs and at great depth the limestone is hard and sharply etched. Stalactite Blue Hole contains "speleothems" at approximately 30 m depth.

The salinity profiles of the blue holes are low and uniform for a depth of from 5 to 31 metres. Below this there is a transition to saline water called the halocline. A blue hole was defined as a lake exhibiting a marked halocline. The salinity profiles for blue holes are shown in Fig. 2, those for ponds in Fig. 3. Stafford Creek II and Church's Blue Holes are intermediate features and are shown on both Figures.

The depth of freshwater was taken for the blue holes studied in central Andros and mapped to determine whether there was sufficient continuity between sites to define a freshwater lens (Fig. 4). The thickness of the freshwater lens at Church's Blue Hole was calculated assuming a complete mixing of two end-member types of salinity: 1.0‰ and 15‰ (see Discussion). Lens thickness was estimated as 15.4 m.

Maximum thickness of freshwater is 31 m. The data support the existence of a freshwater lens, although the thickness contours are very tentative.

The sampling locations in Stafford Creek estuary are shown on Fig. 4. The salinity profiles are shown in Fig. 5. The freshwater lens exists only in the narrow channel at the head of Stafford Creek. The remainder of the estuary was well-mixed because of strong wave and tide activity. However, there appears to be fresher water at the mouth of Riley Creek (Profile 8) than in the centre of the estuary (Profile 9). The very saline water of Stafford Creek Blue Hole (Profile C) is discharging into the estuary at profile 10.

Selected temperature profiles are shown in Fig. 6. East Twin Lake Blue Hole shows the typical double thermocline. The shallow one being daily, the deeper being seasonal. Slight increases with temperature occur occasionally at depth. This temperature inversion is most marked in Stafford Creek Blue Hole (Fig. 7). There is no fresh water here, it is the high salinity of the "hot layer" which maintains internal stability.

Water sampled from ponds and blue holes occasionally stank of H_2S (rotten eggs). The layers from which such samples came are marked in Figs. 2 and 3. Odorous samples come from the bottom of ponds, but from distinct levels in blue holes. Divers also reported marked one-two metre thick opaque maroon layers in blue holes. A similar phenomenon was observed at 6 m depth in Stafford Creek Blue Hole. These layers are bacterial plates probably of the purple sulphur bacteria (Thiorhodaceae). The optimal conditions for these bacteria are strictly defined (Wetzel 1975) which is why they occupy such narrow zones within the blue holes.

DISCUSSION

The salinity profiles of the blue holes create highly stable conditions. All chemical and physical exchange between fresh and salt water is then by diffusion and conduction, or by inclusion in strong overturning events in the freshwater "mixolimnion". Within chemically homogeneous zones, however, conditions are less stable, and the density changes caused by temperature differences may cause overturning. Overturning will allow surface and deep water to exchange. This exchange will decrease in frequency with depth. The surface zone will exchange perhaps every day, in response to diurnal temperature fluctuations. This "epilimnion" is also mixed by winds. The zone of annual or less frequent overturning is the "mixolimnion". Both zones are usually able to support conventional aquatic fauna and flora.

The perennial stability of the underlying saline water induces the condition of "meromixis". The lower "monimolimnion" is anoxic and abiotic which accounts for the clarity reported by divers. Very little oxygen diffuses down to the top of the monimolimnion, but energy is available to those bacteria which convert sulphate to sulphide. The dense bacterial plates found here demonstrate the sharp transition between oxygenated and anoxic water, where sulphate reduction is occurring.

The salinity profiles (Fig. 2 and 3) are probably correct to the halocline, some contamination occurring at lower levels due to sampling problems. However, most blue holes fit the pattern of meromixis, the H_2S zone occurring within the halocline and below the thermocline.

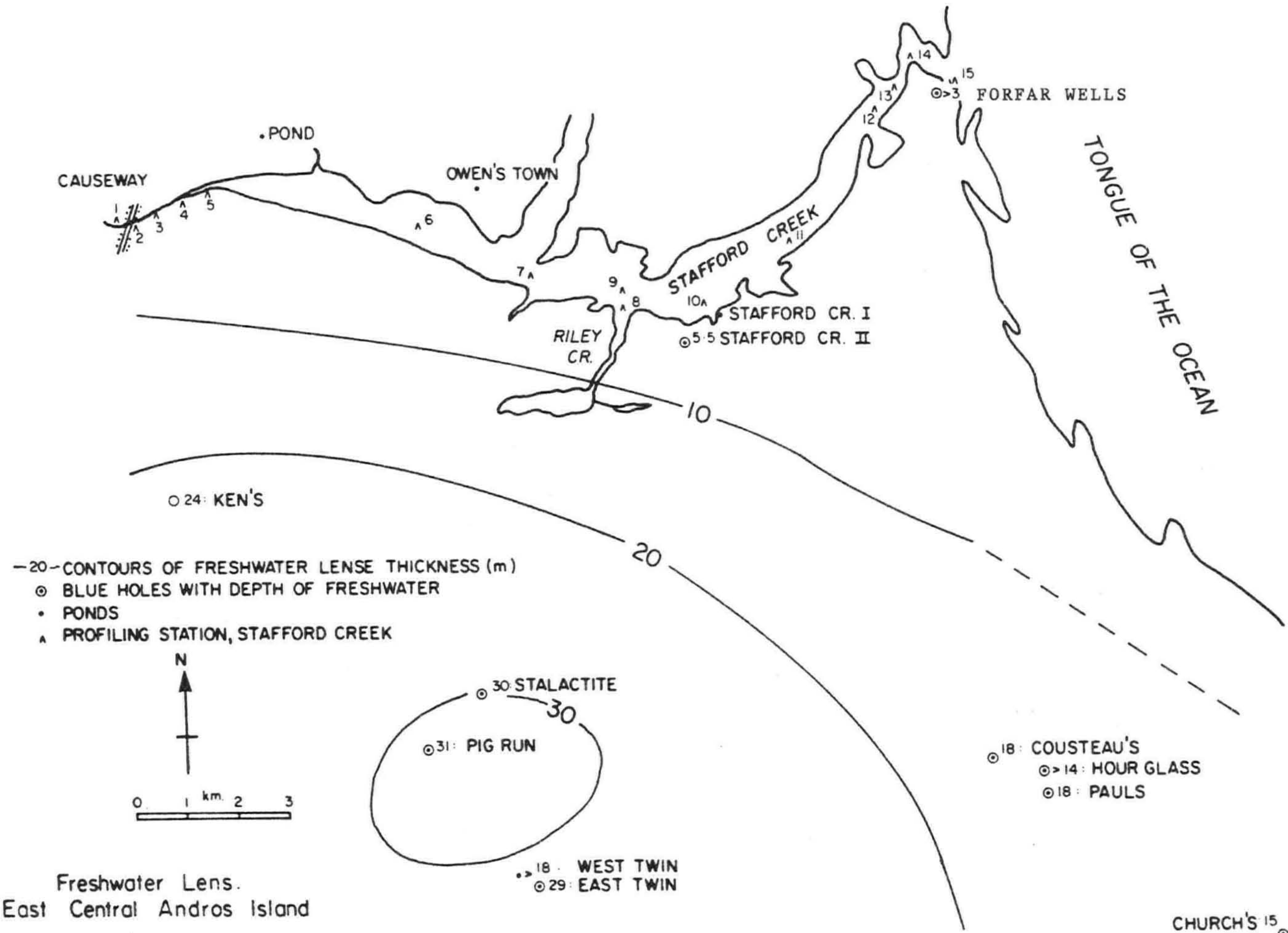

Fig.4. Approximate contours of freshwater lens thickness. Sites investigated in Stafford Creek estuary are also marked (see Fig.5 for results).

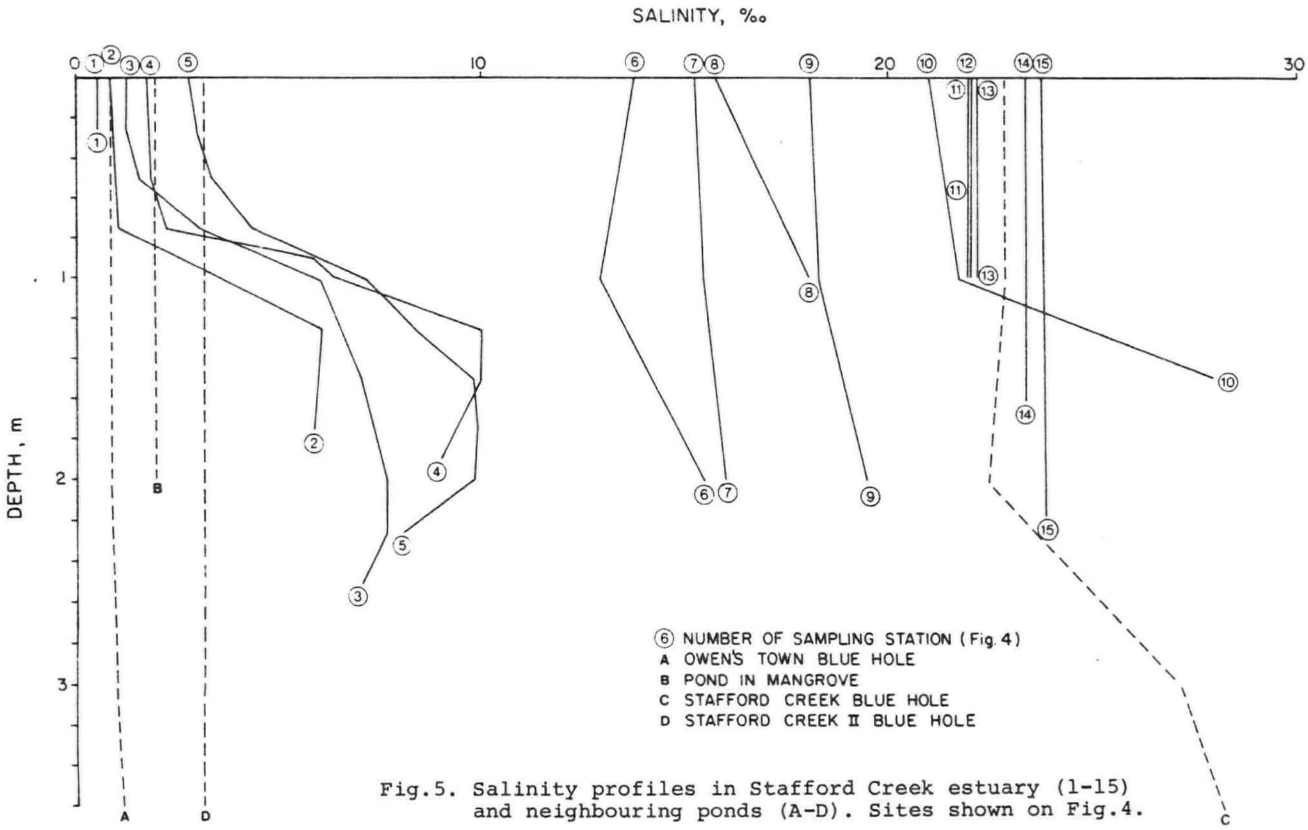

Fig.5. Salinity profiles in Stafford Creek estuary (1-15) and neighbouring ponds (A-D). Sites shown on Fig.4.

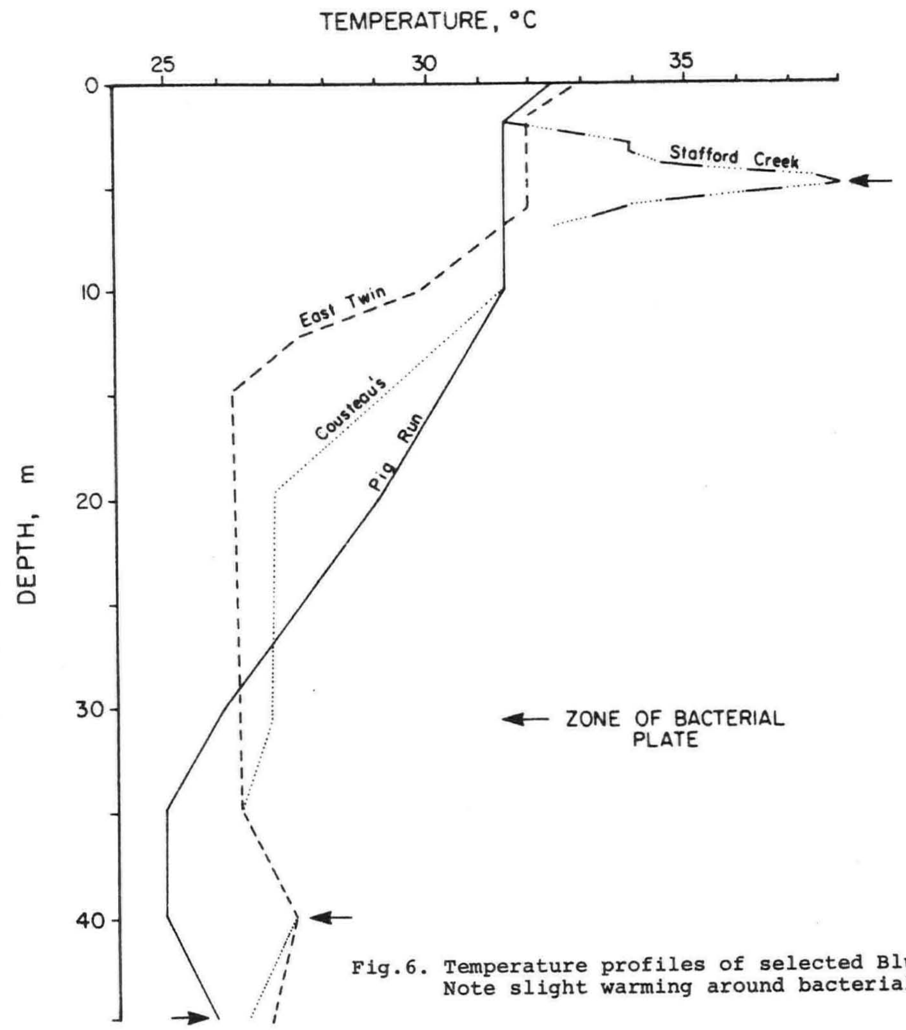

Fig.6. Temperature profiles of selected Blue Holes. Note slight warming around bacterial plates.

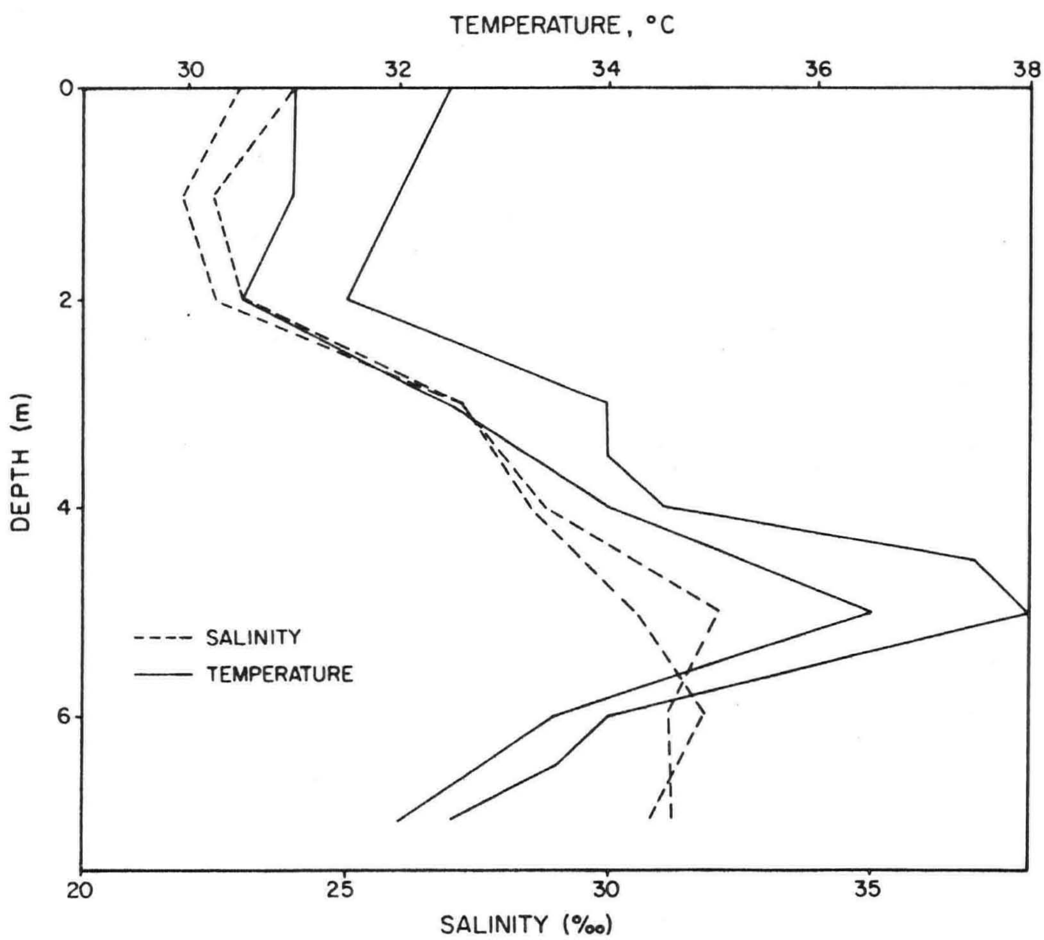

Fig.7. Temperature and salinity profiles of Stafford Creek Blue Hole.

There is a possible association between the bacterial plate and slight temperature inversions. This clearly occurs in Stafford Creek Blue Hole (Fig. 7). Here the strong stability of the water has allowed a bacterial plate to develop at 6 m depth. The origin of the stability is unclear; it may have been capture of estuarine saline water, purely biogenic, or caused by a saline spring. A combination of the former two processes is probably responsible. The high temperature at depth is caused by the absorbtion of solar radiation without subsequent heat dispersion by overturning (Wetzel, 1975).

Fig. 3 shows that even for entirely fresh blue holes some H_2S generation occurs in contact with the basal sediments.

Ocean, Uncle Charlie's, Stafford Creek II and Church's Blue Holes are all somewhat anomalous, having relatively high surface salinities. Both Ocean and Uncle Charlie's Blue Holes are tidal. The enhanced mixing is probably associated with tidal fluctuations. In addition, like Stafford Creek II, the halocline is very shallow which means it may be mixed by shallow instability. Church's Blue Hole is exceptionally well mixed. It also has the largest area of the blue holes studied (about 3 ha). This means that it will be more influenced by winds which may induce overturning and mixing. The basal salinity increase has possibly developed since the last overturning. The chemical homogeneity of the profile also means that the lake is susceptible to thermal instability, which will ensure continued homogeneity.

The sparse data obtained from the Stafford Creek Estuary (Fig. 4 and 5) suggest a double zonation. The lower, broad estuary is vertically mixed because it is shallow and strongly influenced by tides and waves. The profile up the narrow channel is increasingly strongly stratified, which can only occur where freshwater inflow occurs and mixing proceeds. A significant enhancement of the fresh groundwater resources of Andros Island could be gained if Stafford Creek were controlled at its mouth.

The apparent continuity across the aquifer of central Andros suggests a disperse rather than karst groundwater flow. In contrast, Uncle Charlie's, Ocean, and Conch Sound are tidal and have major karst conduits at depth. Karst development implies an organisation of water discharge along fractures, which develop into conduits. The present discharge of Conch Sound is brackish, becoming less saline further in at 1.15 km. A net mean efflux of 1.57 $m^3 s^{-1}$ was recorded in 1981. Conch Sound is therefore draining a reasonably large part of the freshwater lens.

Although flow data are not available from Stafford Creek, there is clearly a significant freshwater discharge from the estuary. The salinity of "Ocean Water" at Forfar Pier is 24-27‰, less than the global average of 35‰. Salinities of up to 46‰ occur on the west edge of Andros (Cloud, 1962). There may be a net west-east flow of saline water at depth beneath the island. At 100 m depth in Cousteau's Blue Hole salinity is 35‰. The low salinity of east coast water suggests that an aureole of brackish water exists on the narrow shelf of eastern Andros.

Back et al (1979) and Hanshaw and Back (1980) have described karst estuarine discharge on the Yucatan Peninsula, Mexico. They attribute the growth of estuarine features to the mixing of fresh and salt water. Back et al (1981) have demonstrated that this is most likely to occur underground where loss of CO_2 to the atmosphere is prevented. It is possible to develop phreatic caves at points of groundwater discharge. Thus the caves associated with blue holes may be presently developing.

The Yucatan peninsula is characterised by "cenotes" which are essentially sub-aerial blue holes. These are interpreted as collapse features formed in response to active solution at the water table. If the Andros blue holes are analogous, then sea level must have been considerably lower for their formation. If solution is occurring at depth in the aquifer, this need not be the case. The apparent lack of karstic continuity between blue holes suggests the blocking of any pre-existing karst by sedimentation. This is believed to have occurred in Florida (Back and Hanshaw, 1970).

The chemistry of the blue holes is complex because of the mixture of water types, and biological activity. The role of bacterial mats and plates is unclear. The contrast in the chemistry of recharge through a vadose zone and marshes has been demonstrated by Plummer et al (1976) for Bermuda. Fish (pers.comm.) has reported chlorinities higher than sea water at depth in the blue holes. The intense erosion beneath photosynthetic mats suggests locally very high PCO_2.

There appear to be no processes presently active at depths sufficient to develop the deeper blue holes. They must have formed in periods of lower sea level. A possible model of their origin is:

1. Development of cavernous porosity at both water table and halocline.
2. Fluctuating sea level enlarges the vertical extent of these features and reduces buoyant support favouring collapse.
3. Marine-fresh water sedimentation fills interconnecting karst conduits.
4. Solution continues at the approximate water table ($\pm$ land surface) and at the halocline. Flow is disperse because of poorly developed karst system.

CONCLUSION

The blue holes of Andros Island are meromictic lakes of complex biology and chemistry. They provide cross-sections through a fresh water lens of up to 30 m thickness which thins towards estuaries and the sea. Discharge of fresh water occurs through caves and by diffuse seepage. The blue holes appear to reflect deep solution and collapse of limestone enhanced by sea-level fluctuations. At present they are generally non-karstic although karst horizons may be developing.

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REFERENCES

Back, W. and Hanshaw, B.B., 1970. Comparison of chemical hydrogeology of the carbonate peninsulas of Florida and Yucatan. *Jour. Hydrology,* vol. 10, pp330-368.

Back, W., Hanshaw, B.B., Pyle, T.E., Plummer, L.N. and Weidie, A.E. 1979. Geochemical significance of groundwater discharge and carbonate solution to the formation of Caleta Xel Ha, Qintana Roo, Mexico. *Water Resources Research,* vol. 15, no. 6, pp1521-1535.

Back, W., Hanshaw, B.B., Van Driel, J.N., Ward, W. and Wexler, E.J. 1981. Chemical characterisation of cave, cove, caleta and karst creation in Qinta Roo. *Abstract with Programs, Annual Meeting Geol. Soc. Amer.,* Cincinnati, p400.

Cloud, P.E. 1962. *Environment of calcium carbonate deposition west of Andros Island, Bahamas.* U.S. Geol. Surv. Prof. Paper 350.

Hanshaw, B.B. and Back, W. 1980. Chemical mass-wasting of the northern Yucatan Peninsula by groundwater dissolution. *Geology,* vol. 8, pp222-224.

Klein, H. and Hull, J.E. 1975. *Biscayne Aquifer, south-east Florida.* U.S. Geol. Surv. Water Resource Investigation 78-107.

Plummer, L.N., Vacher, H.L., Mackenzie, F.T., Bricher, O.P. and Land, L.S. 1976. Hydrogeochemistry of Bermuda: a case history of groundwater diagenesis of biocalcarenites. *Geol. Soc. Am. Bull.,* vol. 87, pp1301-1316.

Wetzel, R.G. 1975. *Limnology.* W.B. Saunders, Philadelphia, 743pp.

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