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EFFECTS OF SUBMARINE KARST DEVELOPMENT ON REEF SUCCESSION

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ABSTRACT

Many modern reefs are developed on submerged topographic highs composed of Pleistocene or older limestone. The geomorphic configuration of the limestone substrate commonly has been modified by one or more phases of subaerial karst development prior to submergence. Such reefs may be associated with submarine fresh water springs when the limestone substrate acts as a confined aquifer recharged from land.

Although such fresh water upwellings or "vruljes" are common in many parts of the world, their association with modern reef growth has received little attention. Examination of a lagoonal patch reef associated with submarine springs in Discovery Bay on the north coast of Jamaica, provides a basic understanding of the effects of these springs on reef biota, sedimentology, and reef geometry. Local reduction of salinity and water temperature and increasing development of collapse features have modified the reef biota toward a sponge-dominated rather than a coral-dominated fauna. In addition, reef bathymetry has been impressively altered during the 14-year study. This information may provide insight into the immediate and long-term impact of fresh water upwellings on reef development and may be used to recognize similar relationships throughout the geologic record.

REEF SUBSTRATES AND SUBMARINE SPRINGS

Research during the last three decades has resulted in recognition that most modern reefs form a relatively thin mantle upon submerged ancient reef surfaces (Davies 1983, Hopley 1983). In many cases these surfaces have been modified by solution and development of karst features during subaerial exposure prior to resubmergence. When the limestone is permeable enough to form a confined aquifer, it is possible for groundwater to move seaward from land and be discharged offshore from fractures or submarine collapse dolines (sinkholes). As fresh water moves out of the limestone, it flows upward forming a submarine spring or "vrulje."

The first submarine springs were reported by Greek, Roman, and Persian writers who described sailers drawing fresh water from offshore springs in the Mediterranean (Potie & Tardieu 1977). Submarine springs have also been found in the shallow waters of the United States (New York, Florida, and California), Cuba, Mexico, Chile, Jamaica, Hawaii, Australia, and Japan. The most frequent occurrences have been reported from the Mediterranean basin: Libya, Israel, Lebanon, Syria, Greece, France, Spain, Italy, and Yugoslavia. In Yugoslavia alone, more than 50 large "vruljes" have been mapped along the eastern coast of the Adriatic Sea (Bonacci 1987). Despite the large number of reported submarine springs, only a few references indicate their occurrence associated with modern reefs.

JAMAICA

The island of Jamaica is one of the Greater Antilles, lying in the Caribbean just south of Cuba. Structurally, Jamaica is located along the south side of the Cayman Trench and on the northeastern margin of the Nicaraguan Rise.

The island is composed primarily of Tertiary and Quaternary platform deposits overlying Cretaceous and Early Tertiary igneous rocks, volcaniclastic sediments, and reef limestones. The White Limestone, which includes shallow shelf to deep-water pelagic carbonates of Upper Eocene to Middle Miocene age, is exposed over approximately two-thirds of the surface of Jamaica. The limestones have been so extensively fractured and eroded by solution that permeable units form the major aquifers from which many springs emanate on land (Zans et al. 1962, Woodley & Robinson 1977).

Along the island margin, the White Limestone is overlain by the Coastal Group of deep-water marls (Robinson et al. 1970). These low permeability marls are in turn overlain by shallow-water reef limestones of the Hope Gate and Falmouth Formations along the north coast, which were deposited during Pleistocene interglacial high sea levels in environments similar to present reef conditions (Liddell et al. 1984, Mitchell et al. 1987). Following deposition, the Hope Gate and Falmouth reefs were exposed and fluctuating sea levels modified their surfaces into a series of wave-cut terraces and cliffs. Upward tilting of the island toward the north, which began in the Late Tertiary and continued through the Pleistocene to at least 15,000 y.b.p., has

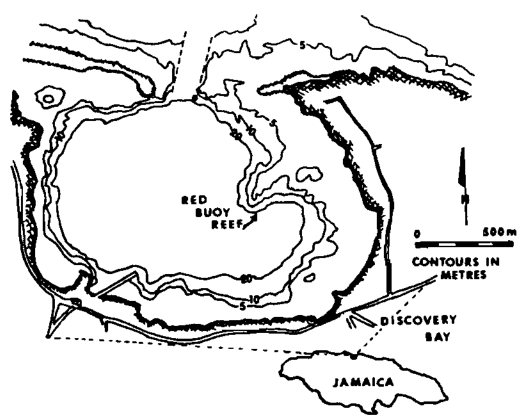

Figure 1. Bathymetric map of Discovery Bay (modified from Map No. 26122, U. S. Defense Mapping Agency. Note the position of Red Buoy Reef extending into the lagoon from the shore.

resulted in north-south faulting and fracturing of the White Limestone, Coastal Group, Hope Gate and Falmouth Formations. Subaerial exposure has enhanced solution weathering of fractures and has resulted in development of karsted landforms (Robinson et al. 1970, Woodley & Robinson 1977, Liddell & Ohlhost 1981). Additional fracturing of the lithified upper layer of the Falmouth Formation was caused by collapse of caves in the older limestones (Land & Epstein 1970). After rapid rise in sea level between 15,000 and 5,000 y.b.p., the modern reef developed as a veneer over the lower part of this Pleistocene profile (Liddell & Ohlhorst 1981). Several authors, including Goreau & Land (1974), have recognized that present Jamaican reef morphology is derived from the morphology of the eroded Pleistocene reef surfaces.

DISCOVERY BAY

Discovery Bay, located on the north coast of Jamaica between Montego Bay and St. Ann's Bay (figure 1), has been a centre for reef studies since the late 1960's. According to Woodley & Robinson (1977, p. 18), Discovery Bay has been described as a "drowned river valley excavated by solution, which has been partly cut off from the sea by recent reef growth." The bay is a circular, saucer-like depression with a maximum depth of -53 metres. A submerged collapse doline (sinkhole) occurs in the northwest corner of the shallow shelf that restricts the bay. A fault, trending approximately N. 40° E., can be traced from land into the bay, cutting the shallow shelf and displacing the east forereef -10 metres relative to the west forereef (Liddell & Ohlhorst 1981).

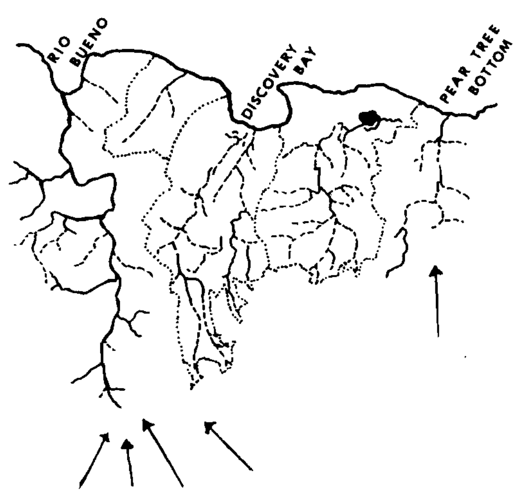

Figure 2. Surface drainage patterns along north-central Jamaican coast from Rio Bueno to Pear Tree Bottom (approximately 11 km). Dashed lines indicate ephemeral streams and dotted lines outline the drainage basins around Discovery Bay. Note that no perennial streams now flow into Discovery Bay. Arrows show underground water flow directions proposed by Sweeting (1973).

As shown in figure 2, no perennial surface streams currently flow into Discovery Bay, although an extensive drainage basin is easily identified from the St. Ann's Bay - Moneague 1:50,000 topographic sheet. In a map of "swallow holes and springs of north-central Jamaica," Sweeting (1973, p. 128) suggests that the 21-km^2 drainage basin into Discovery Bay illustrated in figure 2, is only a small portion of the actual drainage basin. If Sweeting (1973) is correct in suggesting probable lines of underground water flow northward from the Cave River, then the actual drainage basin may be almost three times the area shown.

Along the coast, the limestone formations are extensively fractured and caves and sinkholes are common features. Within Discovery Bay submerged fractures can be traced along hard ground surfaces and numerous submarine springs can be identified. The map published by Sweeting (1973, p. 128) is one of the earliest records of submarine springs at Discovery Bay.

RED BUOY REEF

The Red Buoy Patch Reef caps a limestone bank that extends southwestward into Discovery Bay from the northwestern shore (figure 1). From 1974 to 1988, I examined the bottom bathymetry, reef biota, and sedimentologic history of the reef. Maps of bathymetry and reef biota were compiled using underwater compass, depth gauge, and lines during 1974, 1978, 1980, 1981, and 1982. Soft sediment cores were taken in 1980, 1981, 1982, 1984, 1986, and 1987 using a pneumatic drill and modified core barrel. Preliminary reports of the data collected may be found in Bonem & Stanley (1977) and Bonem (1984, 1985).

During that period, submarine springs associated with the Red Buoy Reef were mapped and their associated biota were described. Crude measurements of water chemistry, temperature, and water flow rates were recorded for many of the springs. During the investigation, it became apparent that springs were modifying reef geometry and biota due to enlargement, filling, and collapse of surrounding areas.

DISTRIBUTION OF SPRINGS

Thirty-two submarine springs have been mapped at the Red Buoy Reef since 1978. Figure 3 shows the 1982 reef bathymetry and distribution of collapse structures in solid contours. Although some variation occurs, the distribution of the springs closely parallels the fracture/joint systems mapped in the Falmouth Formation on the north-central coast of Jamaica by Hill (1980). Hill determined three dominant fracture orientations in the Falmouth Formation: N. 36-40° E. (parallel to the fault that cuts Discovery Bay), N. 61-65° W., and N. 5° E. to N. 10° W. The first two of these directions appear to correspond to the orientation of springs and collapse features as indicated in figure 3.

It should be noted that the number and position of springs has changed little since 1974, although a few additional springs have opened along fracture

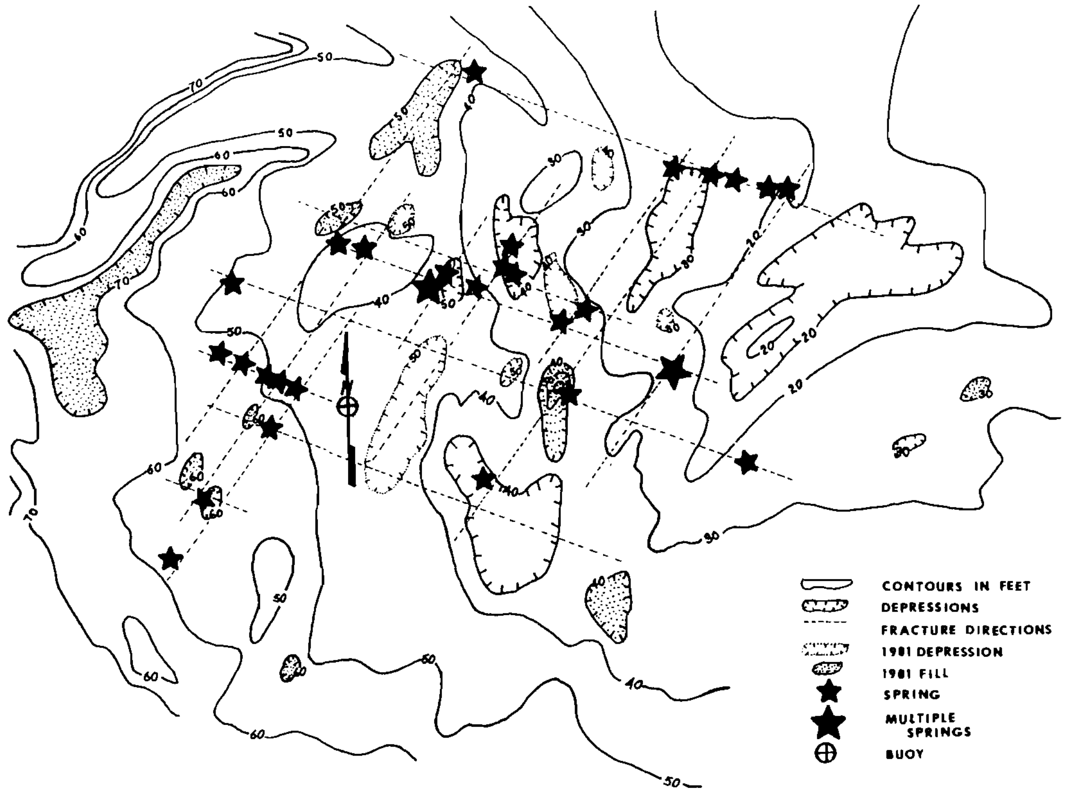

Figure 3. Map of Red Buoy Reef using 1982 contour base. Depth contours are in feet (1 foot = 0.305 metre) and map area is 100 metres across. Collapse features (sinkholes) are shown by hatchures and freshwater upwellings are indicated by stars. Note the apparent relationship of upwellings and collapse features to the fracture orientations represented by dashed lines.

lines. However, the development of collapse features has been dramatic. Only two broad depressions were present in 1974: a 28-foot-deep depression at the site of the present 60-foot-deep hole and a small hole along the fracture line to the southwest. Approximately two to three new collapse holes have appeared each year since 1980. However, Hurricane Allen in August of 1980, caused several changes that are reflected in the 1981 survey. Several collapse features were filled with sediment (indicated in figure 3 by stippling inside the contours) and new collapse structures appeared (dotted features in figure 3). However, by the following year, these structures had filled with sediment and the collapse features that had been filled by the hurricane were reopened. This suggests that storm-induced modification of the reef may be ephemeral when compared with the development of collapse features.

WATER PROPERTIES

Submarine springs are easily recognized because of their relatively low salinities and temperatures. Temperatures measured near the orifices of the springs ranged from 78-82°F during May and June. In contrast, water temperatures in other parts of the bay and on the shallow forereef ranged from 86-88°F during the same period.

When salinity was measured by titration using samples taken near the spring orifices, values of 33.8 to 29.1 ppt were obtained. The lowest value recorded was 18.0 ppt from a sample obtained by inserting a syringe into a narrow opening. These values are consistent with those obtained by D'Elia et al. (1981) who speculate that the values are higher than expected because of "a great deal of subterranean mixing" of salt water with the fresh water prior to water discharge into the bay. Vertical mixing occurs relatively rapidly and normal salinities are commonly measured within a few feet of the inverted conical discharge pattern.

Dissolved oxygen levels were near saturation for samples obtained from springs and from the shallow forereef terrace. The spring water had slightly higher values, but these values were not significantly higher when water temperature was considered. These results support values obtained by D'Elia et al. (1981) who also reported elevated nitrate levels for spring waters.

BIOTIC RELATIONSHIPS

Observations of organisms associated with the submarine springs at the Red Buoy Reef indicate that the areas immediately surrounding the springs are usually barren of sessile organisms except for sponges (including Gelloides, Haliclona, Neofibularia, and Mycale and the pencil coral Madracis mirabilis. Laboratory studies by Shelvey (1980) demonstrated that Madracis mirabilis, unlike many other hermatypic corals, is able to survive salinities as low as 29 ppt for extended periods of time. However, the coral died when subjected to salinities of 16 ppt for periods as short as 4 days. This helps explain the presence of the coral only around springs where the salinity is approximately 30 ppt or higher.

Springs that have relatively high flow rates commonly lack living sessile organisms. This is also true of springs that are surrounded by active collapse features. Recent collapse structures commonly show evidence of the destruction of the previously existing biota. The central area of the patch reef (where many collapse structures have developed) appears to have been modified from a coral to a dominantly sponge biota as suggested by the sedimentary history of the reef (Bonem 1984).

INTERPRETATION AND IMPLICATIONS OF SOLUTION AND COLLAPSE HISTORY

Observations at the Red Buoy Patch Reef suggest that collapse is occurring along two sets of fractures that are parallel to the major fracture and fault orientations measured in the Late Pleistocene Falmouth Formation along the north-central coast of Jamaica. Two possible explanations for the formation of collapse features exist.

Collapse could be the result of submarine springs removing sediment that had accumulated in a karst system that formed during a former low stand of sea level. As the sediment is removed, lack of support for the relict karst features would result in collapse. This explanation is supported by classical karst theory which states that once the karst landform is submerged, the rate of deposition will exceed the rate of erosion by biological or physical processes (James & Choquette 1988).

Theoretically, it may also be possible that the movement of fresh water through the submarine karst system may cause solution of the fractured limestone platform upon which the Red Buoy Reef is developed. Lower pH and undersaturation relative to calcium carbonate can occur when two carbonate waters with different temperatures and salinities are mixed (Wigley 1976). Back (1979, 1986) describes a situation in Mexico where fresh water and Caribbean sea water are mixed, resulting in an unusually reactive geochemical zone in which enhanced calcite and aragonite dissolution takes place. However, this example differs from the Red Buoy Reef in that the reactive zone forms where salt water has invaded the ground water system on land, not underwater.

The ultimate effect of collapse on the reef is the same, regardless of the cause. Collapse is effectively reducing the size of the reef and modifying the biota by increasing the percentage of sponges relative to scleractinian corals. However, if active dissolution of limestone is currently occurring, it might indicate that Discovery Bay has been enlarged by a series of collapse dolines. The morphology of the bay would support such a history. The relationship between submarine springs and modern reefs also may have important implications for the study of ancient reef systems developed on submerged karst landforms.

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REFERENCES

Back, W., Henshaw, B.B., Herman, J.S. & van Driel, J.N. 1986. Differential dissolution of a Pleistocene reef in the groundwater mixing zone of coastal Yucatan, Mexico. **Geology** 14:137-40.

Back, W., Henshaw, B.B., Pyle, T.E., Plummer, L.N. & Weidie, A.E. 1979. Geochemical significance of groundwater discharge and carbonate solution to the formation of Caleta Xel Ha, Quintana Roo, Mexico. **Water Resources Research** 15:1521-35.

Bonem, R.M. 1984. Sedimentologic development of lagoonal patch reefs. In: **Advances in reef sciences**, University of Miami, Florida, pp.12-13.

Bonem, R.M. 1985. Hurricane impact on lagoonal patch reefs - implications for recognition of ancient storm deposits. In: **Abstracts with programs for 1985** (Annual Meeting of the Geological Society of America) 17:527.

Bonem, R.M. & Stanley, G.D. 1977. Zonation of a lagoonal patch reef - analysis, comparison, and implications for fossil biohermal assemblages. In: **Proceedings, third international coral reef symposium**, University of Miami, Florida, 2:175-81.

Bonacci, O. 1987. **Karst hydrology - with special reference to dinaric karst.** Springer Verlag, New York, 184 pp.

Davies, P.J. 1983. Reef growth. In: **Perspectives on coral reefs**, Barnes, D.J. (ed.), Brian Clouston Publisher, Manuka, ACT, Australia, pp. 69-106.

D'Elia, C.F., Webb, K.L. & Porter, J.W. 1981. Nitrate-rich groundwater inputs to Discovery Bay, Jamaica - a significant source of N to local coral reefs? **Bulletin of Marine Science** 31:903-10.

Goreau, T.F. & Land, L.S. 1974. Fore-reef morphology and depositional processes, north Jamaica. In: **Reefs in time and space** Society of Economic Paleontologists and Mineralogists Special Publication 18:77-89.

Hill, W. 1980. Formation of buttress and groove morphology - Discovery Bay. In: **Studies in modern coral reef environments, May 1980,** Unpublished student papers, Discovery Bay Marine Laboratory, Jamaica, pp. 39-65.

Hopley, D. 1983. Morphological classifications of shelf reefs - a critique with special reference to the Great Barrier Reef. In: **Perspectives on coral reefs**, Barnes, D.J., (ed.), Brian Clouston Publisher, Manuka, ACT, Australia, pp.180-199.

James, N.P. & Choquette, P.W. 1988. **Paleokarst.** Springer Verlag, New York, 416 pp.

Land, L.S. & Epstein, S. 1970. Late Pleistocene diagenesis and dolomitization, north Jamaica. **Sedimentology** 14:187-200.

Liddell, W.D. & Ohlhorst, S.L. 1981. Geomorphology and community composition of two adjacent reef areas, Discovery Bay, Jamaica. **Journal of Marine Research** 39:791-804.

Liddell, W.D., Ohlhorst, S.L. & Coates, A.G. 1984. **Modern and ancient carbonate environments of Jamaica.** University of Miami Comparative Sedimentology Laboratory, Miami Beach, Florida, 93 pp.

Mitchell, J.T., Land, L.S. & Miser, D.E. 1987. Modern marine dolomite cement in a north Jamaican fringing reef. **Geology** 15:557-60.

Potie, L. & Tardieu, B. 1977. Development of submarine springs. In: **Karst hydrogeology,** Tolson, J.S. & Doyle, F.L. (ed.), University of Alabama at Huntsville Press, Huntsville, Alabama, pp. 39-48.

Robinson, E., Lewis, J.F. & Cant, R.V. 1970. Fieldguide to aspects of the geology of Jamaica. In: **International field institute guidebook to the Caribbean island-arc system,** American Geological Institute, Washington, D.C., 23:1-44.

Shelvey, S.A. 1980. An analysis of the effect of varying salinities on the coral Madracis mirabilis as compared to the salinity tolerances of some other selected corals. In: **Studies in modern coral reef environments, May 1980**, Unpublished student papers, Discovery Bay Marine Laboratory, Jamaica, pp. 110-21.

Sweeting, M.M. 1973. **Karst landforms.** Columbia University Press, New York, 362 pp.

Wigley, T.M.L. & Plummer, N.L. 1976. Mixing of carbonate waters. **Geochimica et Cosmochimica Acta** 40:985-89.

Woodley, J.D. & Robinson, E. 1977. **Field guidebook to the modern and ancient reefs of Jamaica - third international coral reef symposium,** University of Miami, Florida, 33 pp.

Zans, V.A., Chubb, L.J., Versey, H.R., Williams, J.B., Robinson, E. & Cooke, D.L. 1962. Synopsis of the geology of Jamaica. **Geological Survey Dept. of Jamaica Bulletin 4,** 72 pp.