ABOVE AND FACING PAGE, FIGURE 1. *A SCUBA business at an abandoned west Kentucky limestone quarry that filled with clear water with a Secchi disk depth of 9.25 m (estimate for Kd = 0.184).*

An Abandoned Marine Quarry: A Unique Resource for Aquaculture

William A. Wurts

Limestone rock formations typically have many cracks and fissures. Water seeps into and percolates through the limestone and can eventually create larger channels. Mammoth Cave in Kentucky, USA was formed this way. Abandoned limestone quarries often fill with fresh water and the water is clear enough in some of these for SCUBA diving (Fig. 1).

Over the years, limestone has been mined in the Florida Keys for road construction. Some abandoned quarries in the area have filled with seawater through cracks, fissures and channels in the limestone formations. In July 2015, two individuals in Florida were seeking aquaculture information about producing live bait for the Florida Keys sport fishing industry. One owns an abandoned limestone quarry in the Florida Keys near Looe Key Reef that is filled with seawater. The quarry surface area is 4.9 ha and the average depth about 9 m.

Production of enough live bait to be profitable requires intensive production methods and technology. Considerable knowledge and training in aquaculture and water quality is needed to manage this business. The quarry owner and the business partner did not have any training or experience in aquatic biology, aquatic science or aquaculture. Furthermore, the partner wanted to retire to manage the live bait venture.

Potential use of the quarry for aquaculture poses challenges. Nutrients in effluents associated with intensive feeding could stimulate moderate to dense algal blooms in the quarry. Loss of water clarity could affect much of the marine life presently found in the quarry ecosystem. Additionally there are potential environmental protection issues associated with waste effluents. Some type of low management intensity, low-maintenance aquaculture would have better chances of success.

TABLE 1. Physical requirements of coral reefs (adapted from Wheaton et al. 1996).

FACTOR	REQUIREMENT
High light	Surface irradiance of 2,000 μE/m2 sec
High oxygen concentration	5-7 mg/L
Low turbidity	0.01-0.10 mg/L
Low nutrient concentration	0.10-1.0 μM (N or P)
Stable temperature	23-30 C
Stable salinity	33-36 ppt

The Quarry Resource

Native marine life is already present in the quarry. Live whelks and limpets were attached to the quarry wall. Other native marine species are present in the quarry including coral, trumpet fish and small grouper. This suggests the quarry has or had a direct connection with the Gulf of Mexico or Atlantic Ocean. Larval marine organisms may have been swept into the quarry with seawater entering and exiting through channels or fissures in the limestone. Alternatively the quarry was inundated by ocean water during hurricanes, leaving marine life impounded when storm surges receded.

This healthy community of marine organisms suggests that water quality is good for aquaculture. The quarry's limestone walls and bottom should provide an ample supply of calcium and carbonate to maintain suitable hardness, alkalinity and pH. Salinity was about 37 ppt. Quarry water was clear. Local SCUBA divers reported good visibility to an estimated depth of 10 to 12 m.

Rationale for Live Rock/Artificial Reef Culture

An article on live rock aquaculture was published in ***World Aquaculture*** in 2003 (Falls *et al*. 2003a). Pieces of limestone or artificial substrate were placed on the ocean floor in Florida coastal waters and native marine organisms colonized the substrate. Many species can be found on live rock including corals, coralline (calcareous) algae, anemones, octocorals, brittle stars, sea urchins and mollusks (Falls *et al*. 2003b). Cultivation of these rocks and creatures has become its own specialized tropical marine aquarium industry.

Growing live rock and coral for retail and wholesale markets represents a good low-management, low-technology aquaculture business option for a marine quarry. Small-scale ornamental marine fish production could integrate well with live-rock aquaculture. The potential impact of live rock culture on the pre-existing quarry environment and ecosystem could be minimal to non-existent.

Live Reef Requirements

Publicly available information about commercial production of live rock, especially environmental requirements, is sparse. Many if not most of the organisms that colonize live rock inhabit coral reefs. Wheaton *et al*. (1996) listed 22 animal phyla can be found on coral reefs. It is likely that the physical requirements (Table 1) of living coral reefs would be suitable and desirable for live rock culture. Looe Key Reef data provided by Johns (2015) and Gramer (2015) for salinity and temperature are consistent with the requirements listed in Table 1.

Anemones and a broad variety of marine invertebrates host symbiotic algae (Bold and Wynne 1978). Corals contain symbiotic algae called zooxanthellae within their living tissue. The zooxanthellae help provide food and the calcium carbonate needed for the coral polyps to build exoskeletons and grow. The algae also

(CONTINUED ON PAGE 62)

help recycle nutrients in oligotrophic tropical waters where reefs typically are found. Zooxanthellae need light for photosynthesis and survival. Water clarity, which affects light penetration and intensity, is critical for corals as well as coralline algae. Therefore, a minimum water clarity (light intensity) is needed.

The amount of surface light reaching a given depth can be determined from the equation $I_Z = I_0 e^{-kz}$, where I_0 is surface light intensity; I_Z is the light intensity at depth z (in m); e is the natural logarithm; and k is the extinction coefficient. The extinction coefficient is related to light wavelength and the level of suspended particulate matter. In clear coastal waters, k is about 0.15, while in turbid coastal waters it is around 0.46. In highly turbid waters of many harbors and estuaries, values of k may be as high as 1.5 (Clark and Denton 1962). An extinction coefficient (or attenuation coefficient), K_d, can be estimated from Secchi disk depth measurements using the equation K_d = 1.7/ Secchi disk depth (in meters).

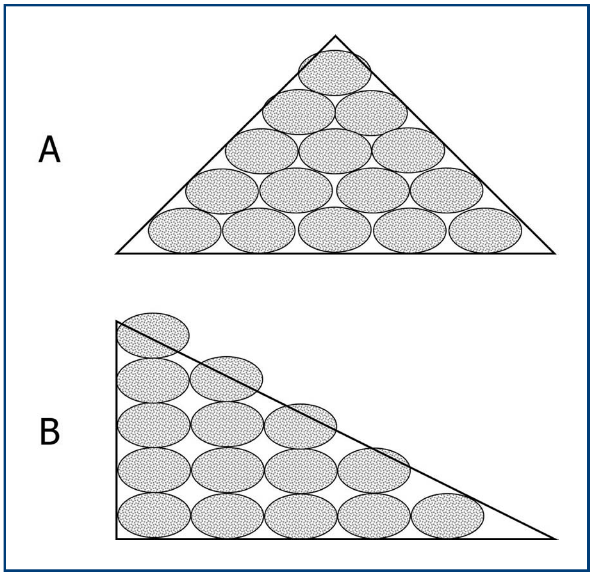

FIGURE 2. *Conceptual diagrams of triangular cross-section shapes for substrate ridges placed in north-south (A, isosceles triangle) and east-West (B, right triangle) directional orientations.*

A live rock culture study was conducted by Hillsboro Community College at five locations in Florida coastal waters (Falls *et al*. 2003b). Using the light transmittance data reported for the five culture sites, calculated K_d values ranged from 0.096 to 1.05. The overall average K_d value was 0.36.

Looe Key Reef is located in the Looe Key National Marine Sanctuary (LKNMS) just off the coast of the Florida Keys. The reef and sanctuary are close to the latitude of the marine quarry under consideration. Most of LKNMS lies in shallow water 0-7 m deep (Lidz *et al*. 1985). Removing outliers from K_d data collected at Looe Key Reef from 1995-2014 (Briceno 2015), the average (n=56) K_d was 0.116 ± 0.053 (± SD).

Approximately 1.21 ha of quarry bottom lies within the 0-7 m depth range of Looe Key Reef. The reef K_d value of 0.116 represents an approximate Secchi disk depth of 14.7 m. Local SCUBA divers report good visibility to an estimated depth of 10-12 m in the quarry. Quarry water appears to be sufficiently clear to allow adequate light penetration for live rock/coral survival and growth.

While light is critical for living reefs, water movement is equally important. Beyond wave action and strong currents created by storms, there is a continuous movement of water over coral reefs. Many of the organisms that colonize reefs are sessile. A constant flow of water is needed to distribute food and nutrients, enable oxygen and carbon dioxide exchange for respiration and photosynthesis, and facilitate reproduction and dispersal of larvae.

Ocean surface current speeds can be estimated as a percentage of the wind speed 10 m above the water. For wind speeds from 5 to 30 m/sec, total surface current speed would be 3.1 percent to 3.4 percent of wind speed (Weber 1983). Based on 36 years of data, the annual average prevailing wind speeds for Miami and Key West, Florida are 4.0 and 4.9 m/sec (NCDC 1998), respectively. Looe Key Reef is only a few miles from shore. It is reasonable to assume that the average prevailing wind speed at Looe Key Reef is within this range. Estimated total ocean surface current velocity for those wind speeds would be between 12.4 to 16.6 cm/sec.

Water current velocities were recorded at a Looe Key Reef moored monitoring station from 2005-2010 (Gramer 2015). The current had an average velocity of 20.5 ± 14.4 (± SD) cm/sec in water with an average depth of 23.1 ± 0.9 (± SD) m.

It is reasonable to assume that a live-rock reef in a quarry must have continuous water flow over its surface. A current of 12.4 to 20.5 cm/sec would be a reasonable target velocity for live rock and coral culture in a large closed system. Research in this area could be instructive. Solar-powered airlift technology using regenerative blowers represents a viable method for water circulation

Construction

As with environmental requirements, there is limited information about commercial live rock culture sites regarding substrate size, type, shape, quantity, structure and its placement. The Hillsboro Community College live-rock research project placed substrate pieces of unspecified size in circular piles on the sea bottom in Florida coastal waters (Falls *et al*. 2003a, 2003b). These piles were 1.5-15.2 m in diameter and 0.9-1.5 m high. Substrate piles were placed at depths of 2-15 m. Various types of limestone and artificial substrate were used. Commercial live rock culture businesses have used 45.5 to 272.7 t of limestone/substrate to create individual reef sites in Florida's public offshore waters (Falls *et al*. 2003a).

Circular piles would not be an efficient use of horizontal space. Long rectangular ridges, triangular in cross section, would provide more surface area for live rock growth. The size, spacing, lengthwise orientation (north-south vs. east-west), and triangular cross-section shape (Fig. 2) of ridges will affect the amount of substrate surface receiving light and the duration of light exposure.

Basically the quarry is a large closed system. A 4.86-ha surface area with an average depth 9.1 m would hold 444,200 m^3 of water. The estimated bottom area suitable for live rock/reef culture in the quarry is 1.2 ha. Assuming limestone density is 2,300 kg/m^3 and the open spaces within the ridges of limestone riprap account for 25 percent of ridge volume, it should be possible to place 5,178 t of limestone in rectangular ridges with triangular cross sections (1 m high with bases 2 m wide) in a culture area of 1.2 ha.

Harvests could begin 3 to 5 years after substrate placement (Falls *et al*. 2003a). Assuming a 10 percent annual harvest of live rock from the 5,178 t of limestone riprap placed, 518 t of live rock could be harvested and sold each year. Harvested rock would be replaced annually. If native marine ornamental fish are stocked as an added species to create a more diverse reef community, a sustainable percentage of those fish could also be harvested for sales. A sufficiently large number/biomass of live rock organisms and fish must remain to reproduce and maintain a harvestable population.

Biomass

The objective is to create a large self-sustaining ecosystem to culture the desired native species. Water clarity and quality must be maintained as closely as possible to that found in the seawater of a healthy live reef environment. Limestone rocks of suitable size and shape for the aquarium trade are placed over the culture area. Natural benthic organisms and other marine life are allowed to colonize these rocks over a several year period. Some seeding of native Florida marine life from cultured and/or other legal sources may be needed to improve the variety of species found on the live rock. Marine ornamental fish and other valuable seawater animals/plants could be stocked to enhance maintain a sustainable balance.

The biomass of organisms encrusting the substrate might not be determined by available surface area. In addition to light, zooxanthellae and other reef algae need phosphorus, nitrogen and other nutrients. The total biomass of organisms found on live rock will depend on quarry productivity – the natural aquatic food supported by quarry water – determined by nutrient availability. It is not known how much live rock/coral the quarry can support without adding nutrients.

The marine quarry has clear water, a good indicator that an aquatic environment has low nutrient concentration. Nutrient availability limits the amount of life the quarry can support. At low nutrient concentrations, biomass is determined by a self-sustaining (balanced) ecosystem. Carrying capacity will likely be controlled by nutrient availability and not oxygen demand. Too much nutrient input creates too much biomass. As the amount of available nutrient increases, the biomass increase is eventually limited by oxygen availability and respiration.

To increase the biomass of live rock organisms and harvest yields beyond carrying capacity, nutrients would have to be added to the system. This could conceivably be done with some form of integrated multi-trophic aquaculture, but this could be a delicate and difficult balancing act. Quarry water nutrients should not exceed those found in a healthy reef environment. Nutrient levels above natural concentrations could be detrimental to live rock and coral production by decreasing water clarity.

Opportunity

The quarry represents an opportunity for commercial aquaculture. Compared to open coastal waters, the quarry may provide a relatively stable environment that is potentially more sheltered from the impacts of storms. Marine limestone quarries can be used to create live reef/coral preserves. Placed substrate would be used to create artificial reefs for corals and other reef organisms that are or may become threatened or endangered. With the global decline of living coral reefs, the value of live rock aquaculture in quarries for preservation may be greater than that for profit.

Notes

William A. Wurts, Aquaculture Specialist, 201 Apache Drive, Princeton, KY 42445-1165
wawurts@gmail.com

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References

Briceno, H.O. 2015. Looe Key attenuation coefficient data, 1995-2014, provided by the SERC-FIU Water Quality Monitoring Network which is supported by EPA Agreement #US EPA Agreement #X7 00D0241

Bold, H.C. and M.J. Wynne. 1978. Introduction to the Algae: Structure and Reproduction. Prentice Hall Prentice-Hall, Inc., Englewood Cliffs, NJ, 706 pp.

Clark, G.L. and E.J. Denton. 1962. Light and animal life. Pages 456-468 *In:* M.N. Hill, editor. The Sea, Vol. 1. John Wiley and Sons, New York, NY. USA

Falls, W.W., J.N. Ehringer, R. Herndon, T. Herndon, M.S. Nichols, S. Nettles, C. Armstrong and D. Haverkamp. 2003a. Aquaculture of live rock: and eco-friendly alternative. World Aquaculture 34(2):39-44.

Falls, W.W., J.N. Ehringer and P. Stinnette. 2003b. Live rock aquaculture. Final report prepared for the National Science Foundation.

Gramer, L.J. 2015. Moored current velocity and temperature data provided by NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL.

Johns, E.M. 2015. Moored salinity data provided by NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL.

Lidz, B. H., D. M . Robbin and E.A. Shinn. 1985. Holocene carbonate sedimentary petrology and facies accumulation, Looe Key National Marine Sanctuary, Florida. Bulletin of Marine Science 36(3):672-700.

NCDC (National Climatic Data Center). 1998. Climatic wind data for the United States. National Climatic Data Center (NCDC)/NOAA.

Weber, J. E. 1983. Steady wind- and wave-induced currents in the open ocean. Journal of Physical Oceanography 13:524–530.

Wheaton, J.L., W.C. Jaap, P. Dustan, J. Porter and O. Meier. 1996. Florida Keys National Marine Sanctuary water quality protection plan coral reef and hard bottom monitoring project annual report (10/1/95-9/30/96).