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HOW TO BUILD A BARRIER REEF

Forget the familiar portrait of Charles Darwin as an aged legend, with his fringe of white hair, his bushy eyebrows and his full beard reaching several inches below the top V of his waistcoat; and imagine instead a man in his late 20s, his body fit, his eyes alight with curiosity.

Darwin was a competent draftsman (a skill common to scientists, as well as engineers and military officers, of his day) and a meticulous observer. Examining Keeling Atoll, now better known as the Cocos Islands, in the Indian Ocean due south of Sumatra, he noted that the sections of coral subjected to the constant sunlight at the surface died. Deciding that this phenomenon deserved a closer look than that afforded from the deck of the *Beagle,* he pole-vaulted onto this jagged reef top, risking painful scrapes to stand within a few yards of the crashing breakers. His account reads like a nineteenth-century adventure story:

> [I]t is possible only under the most favorable circumstances, afforded by an unusually low tide and smooth water, to reach the outer margin [of the reef], where the coral is alive. I succeeded only twice in gaining this part, and found it almost entirely composed of a living Porites [stony finger coral], which forms great irregularly rounded masses . . . from four to eight feet broad, and little less in thickness. These mounds are separated from each other by narrow crooked channels, about six feet deep; most of which intersect the line of reef at right angles. *On the furthest reef, which I was able to reach by the aid of a leaping-pole, and over which the sea broke with some violence* [italics mine], although the day was quite calm and the tide low, the polypifers in the uppermost cells were all dead, but between three and four inches lower down on its side, they were living, and formed a projecting border around the upper and dead surface.[1]

Then, as the breakers crashed at his feet, the young Darwin took soundings off the far edge of the reef using a bell-shaped lead sinker about four inches wide at its concave bottom, to which he attached a wad of tallow to retrieve impressions of the coral. Beginning near the surface, he dropped the lead successively deeper, noting that the tallow almost always came up smooth above 72 feet.[2] Below that, the bottom consisted of sand or water-worn rock.

Noticing that coral larvae only attached themselves to rocks or other hard structures in the relative shallows, Darwin concluded that after a volcano burst through the surface, forming an island, the larvae, spawned by corals far away and hitching a ride on ocean currents, would settle into the sunlit water next to the land. There they would build what he called a fringe reef. Eventually, the island would erode or subside, creating a placid lagoon between itself and what would now be a barrier reef. In time, the island would disappear beneath the surface, and the roughly circular reef that had surrounded it would become an atoll.

Based on these observations, in 1842 Darwin published what was for its time the definitive work on coral reefs. Appearing 17 years before *On the Origin of Species, The Structure and Distribution of Coral Reefs* was the iconic naturalist's first publication. The scientific community of the day received it enthusiastically, and the major findings it brought forth remain unchallenged to this day,[3] which is especially remarkable given that Darwin conducted all his observations from the surface. He lacked scuba or even snorkeling gear. Pearl- and sponge-divers had been plunging into the depths since ancient Greece, divers unaided by anything but a heavy rock to help them descend had salvaged valuables from wrecks since seafaring began, and the diving bell had been in use at least since 1531, when Italian inventor Guglielmo de Lorena utilized one to recover treasure from submerged Roman ships. A rudimentary version, perhaps an inverted cauldron, was probably used well before that, perhaps as early as the fourth century BCE. Legends and epic poems describe Alexander the Great employing a glass barrel to allow him to breathe underwater during the Siege of Tyre.[4] In 1775 Scottish candy-maker Charles Spalding improved on the concept with a sort of submersible elevator.[5] However, these methods didn't allow the luxury of scientific exploration. It wasn't until 1943, more than a century after Darwin's breakthrough book, that Jacques-Yves Cousteau and Émile Gagnan patented a functional self-contained underwater breathing apparatus, giving the world the acronym "SCUBA."[6] Able to maneuver untethered beneath the surface, researchers henceforth could study coral reefs up close and at varying depths.

Darwin made his observations in the Pacific and Indian Oceans, during his voyage on the HMS *Beagle* from 1831 to 1836.[7] The closest he got to Central America was Brazil on the Atlantic side and the Galapagos Islands, off Ecuador, on the Pacific, so he missed the Mesoamerican Barrier Reef.[8] Darwin freely admitted that his descriptions of the coral reefs of the West Indies were drawn from the maps and charts of other maritime explorers.[9] Nonetheless, he did examine the Great Barrier Reef off Australia (then known as New Holland) and the smaller one in New Caledonia, and his basic conclusions apply to coral barrier reefs in tropical waters everywhere.

I knew of Darwin as the author of *On the Origin of Species,* the naturalist aboard the HMS *Beagle,* and the father of the theory of evolution. I had read *To the Edge of the World,* Harry Thompson's riveting account of Darwin's voyage around South America. But I had never heard about his pioneering work on coral reefs until Thomas M. Iliffe, Professor of Marine Biology at Texas A&M University at Galveston, told me about it in 2016. Iliffe was a middle-aged man with a receding hairline and a neatly trimmed beard and moustache. We were sitting in his modest office, the two visitors' chairs wedged between his desk and the back wall. The single window looked out at the narrow dock where several of the university's research boats lay in wait for the students, called "Sea Aggies," who would return the following week for the start of the spring semester.

According to Iliffe, what Charles Darwin had concluded in the 1840s was still the best model of coral reef formation around islands and held, with one important difference, for coastal barrier reefs.[10] Describing the probable genesis of the Mesoamerican Barrier Reef, Iliffe explained that unlike barrier reefs that ring islands in the Pacific and Indian Oceans, but like its larger cousin off Australia, it didn't form around a volcano.[11] It probably began as a coastal fringing reef during the last interglacial period (about 127,000 to 116,000 years ago), when the surface of the Caribbean Sea was 20 to 30 feet higher than it is today.[12] Iliffe described finding an underwater cliff indicating that the shoreline of the Yucatán was 413 feet below its present level during the Last Ice Age about 20,000 years ago.[13]

Human beings inhabited caves in that limestone and the passages that connected the inland sinkholes called cenotes. Well-developed stalactites hang from the ceilings and stalagmites rise from the floors of these labyrinths, clear evidence that they once were dry.[14] According to findings by Mexican underwater archeologist Arturo González González and his German colleague Wolfgang Stinnesbeck, the first wave of settlers to make these chambers their homes arrived in the Yucatán as early as 13,000 years ago, probably crossing from Asia via the Bering Strait land bridge, then over the course of thousands of years making their way south and east.[15]

Beginning in the first part of the present century, underwater archeologists have discovered in now-flooded caves the remains of species, such as the American horse and a New World elephant, wiped out during the massive extinction at the end of the Last Ice Age. A bone of one, a camelid related to the present-day llama, was charred and left next to a pile of ashes, indicating that the animal had been cooked and eaten.[16]

And underwater archeologists have found human remains, as well. The DNA of the oldest proved to be closer to samples retrieved from burial sites hundreds of miles away in the state of Puebla and even to those from China than to the DNA of present-day Mayas—or to that of pre-Columbian Maya remains recovered from cenotes.[17] Before these more recent discoveries, which included a skeleton 11,600 years old discovered by González and Stinnesbeck,[18] scientists had thought that humans first arrived at the peninsula between 4,000 and 2,000 years ago.[19] The jungle had degraded any evidence older than the start of the Common Era, but the fresh water and fine silt of the sinkholes and caves had preserved far more ancient artifacts.[20]

As to those Mayan remains, underwater archeologists have also turned previous wisdom on its head. Initially convinced that the Mayan monumental structures in the Yucatán jungle were the remains of the legendary lost civilization of Atlantis,[21] early twentieth-century Massachusetts Mayanist Edward Herbert Thompson bought the plantation that included Chichén Itzá, a 1,500-year-old site that surrounded a sinkhole dubbed the Sacred Cenote. Between 1904 and 1909, Thompson dredged the cenote, bringing up ceramics, gold and jade jewelry, and human remains bearing evidence of wounds that indicated that they had been sacrificed. Because sixteenth-century Spanish missionaries had documented such rituals, and banned them, this was a logical interpretation; and it was at least partially correct.[22] Neither Thompson's crude methods nor his habit of shipping relics of Mexico's past to Harvard's Peabody Museum would pass muster today. But although he lacked the underwater technology to examine human remains and artifacts in situ, he went about his research seriously, seeking to understand the civilization that had once inhabited the Yucatán and had disappeared so mysteriously. (Thompson eventually concluded that Chichén Itzá was not Atlantis.[23])

Nine decades later, recreational cave divers exploring the cenotes began reporting encountering human remains and artifacts. Some of these dated from the Spanish colonial period, but the oldest were prehistoric.[24] In 1999 Mexico's Instituto Nacional de Antropología e Historia began efforts to protect and recover them. One of the cenotes in the state of Quintana Roo contained the remains of 118 individuals—so many that it was called Las Calaveras (The Skeletons).[25] In the 25 prehistoric sites and the dozens of Mayan sites discovered in the first six years of the program, many of the skeletons were 80 to 90 percent intact, indicating that the individuals had been laid out in funerary fashion, not tossed into the water to drown, their remains carried along underwater passages and eventually broken apart.[26] Some of the skulls displayed the distinctive sloping forehead resulting from the pre-Columbian Maya practice of binding young children's heads, suggesting that the Mayas had utilized the caves as burial sites at a time when they were dry.[27] Given that the Mayas considered cenotes and caves as occupying a boundary between the inhabited surface and the underworld, it would have made sense for them to use them as burial, as well as sacrificial, sites.

As Paleolithic people settled the slab of Yucatán limestone (which, after all, included layers of ancient seabeds), just offshore a fringe reef was forming. The first corals to colonize what is now the Mesoamerican Barrier Reef attached themselves to rock now 7,000 years old.[28] Because the seas were lower, that rock was close to the surface. As the seas rose, the original coral colonists died; new ones built on their exoskeletons—very, very gradually. In this part of the Caribbean, the rate of reef growth upward is only about one to six yards per thousand years.[29]

The Mesoamerican Barrier Reef began as a fringe reef, its crest close enough to the surface to provide the sunlight that the corals' symbiotic algae required to survive. As the sea rose and the mainland subsided, the hard corals continued to grow upward toward the light. The lagoon between the barrier reef and the coast developed, along with the peculiar geology of the Yucatán. The northern two-thirds of the Yucatán Peninsula is very old karst—limestone that began as coral reef. Lying near the coast, the youngest limestone is 120,000 years old.[30] Except for wetlands at the northeast end, not until well south of a line running from Campeche on the peninsula's west coast to Punta Soliman on the east do streams begin to emerge on the jungle floor; and those that do surface run south, to inland lakes and to the Bay of Chetumal on the Mexico-Belize border, not east to the sea. Throughout most of the peninsula, rainwater percolates vertically through the limestone, eventually finding an underground river that takes it to the Caribbean.[31]

Off the Belize sector of the Mesoamerican Barrier Reef, five submarine ridges parallel Belize's major rivers. The best-developed ridge extends north, forming the foundation for two atolls, Glover's Reef and Lighthouse Reef.[32] The shelf in Belize extends to the east, sloping gradually to 200 yards in depth, then dropping off at a 40-degree angle into the abyss.[33] The depth on the east side reaches 9,000 feet.[34]

"Why the reef is where it is is a good question," Gilbert Rowe, Texas A&M University at Galveston regents professor of marine biology, explained as we sat in his office down the hall from Iliffe's. "The ocean is full of larvae, whether it's a fish or a small worm. Wherever they find habitat, they stay."[35]

Oceanographers have a good idea why the Mesoamerican Barrier Reef ends so abruptly at Isla Contoy: the ocean currents that roil past the northern tip of the Yucatán Peninsula.

"Isla Contoy is very interesting," observed Nuno Simoes, a marine biologist at the Yucatán campus of the Universidad Nacional Autónoma de México. "In the south part, you find corals. In the north part, you have very cold, murky waters and almost no coral. You go just 500 meters or a kilometer, and it's a completely different environment."[36]

The reason? A huge upwelling of cold water in the north.[37]

Why so many larvae chose the particular stretch of marine outcrop running south from Isla Contoy to the Bay Islands of Honduras may be a mystery, but the conditions that made growth possible were present at the time—and may not be in the near future. The Mesoamerican Barrier Reef was able to develop where it did because of water temperature, and thus latitude.[38]

"If there's water temperature below 20 degrees centigrade (around 70 degrees Fahrenheit) for prolonged periods, you aren't going to find reef-building corals," Rowe clarified. "You don't find coral reefs farther from the equator than the 20 centigrade isotherm."[39]

Noting that temperatures about 30°C, such as those in the Persian Gulf, may kill corals, he continued: "The main reason that the Caribbean doesn't get hotter than 28 centigrade is *evaporation*. There's a lot of circulation in the Caribbean, which is an extension of the North Atlantic, and a lot of water turnover; so it doesn't get too salty, despite evaporation."[40]

Coral reefs rank as the world's most diverse ecosystems. Scientists estimate that they are home to as many as nine million species,[41] and thanks to DNA sequencing that number is increasing constantly. As Darwin noted, "The almost universal law of 'consume and be consumed'" applies to all tropical coral reefs.[42] But so do the rules of symbiosis and natural cooperation.

Each class of creatures and plants native to the reef helps maintain it. Colloquially known as Zooxanthellae, Symbiodiniaceae, the diverse family of algae that live symbiotically with hard corals and give them their color, utilize photosynthesis to provide energy-giving sugars to their hosts. Moray eels share hunting duties with Nassau groupers, flushing prey from niches in the reef, enabling their partners to grab it swimming. Using their sucker-equipped mouths, remoras clean parasites from sharks.

On the Mesoamerican Barrier Reef, as in seas around the world, each species depends on others. Microscopic organisms, marine plants, and algae use chlorophyll, carbon dioxide, and water to convert sunlight to oxygen, which enriches not just the seas but also the air we terrestrial beings breathe, and simple sugars, which pass to the animals that consume the ingredients of the diverse floating soup collectively known as plankton. Most of these plankton eaters are tiny, often larvae and juveniles of fish and invertebrates; but some, such as whale sharks, rank among the earth's giants. By eating the larvae and juveniles, as well as members of small species, or by grazing on aquatic plants or coral polyps, adults concentrate the energy and transfer it to whatever eats *them.*[43]

Thus, when one kind of creature goes missing from the reef, whether from disease, overfishing or a change in the water chemistry, the entire ecosystem can buckle.

Animals high on the food chain are especially vulnerable to increases in salinity. Jellyfish, for example, may easily accommodate a rise in salinity; but sea turtles, which eat jellyfish, concentrate their prey's salt in their own bodies.[44] Although turtles possess the means to expel the excess, even through what look like tears, these organs can become overwhelmed if lower-salinity water doesn't enter the system. Think of the landlocked Great Salt Lake, lifeless except for brine shrimp and certain saline-loving species of algae.