ONE

Reefs in the Desert

The fact that the sea is in our blood is merely the most intimate evidence that life began in the ocean. There are many others, including the fact that most life is still there. The evidence doesn't explain how or why life began there. Origin theories are legion, and perhaps as unverifiable as Steller's sea ape. The idea that the first organisms evolved from complex molecules in the highly energetic environment of seafloor volcanic vents is popular now. It will be hard to test paleontologically because such environments don't fossilize well. It seems likely, anyway, that life occupied the sea very early.

J. William Schopf, an authority on early life, thinks an Australian rock formation called the Apex Chert contains fossils of filamentous bacteria and other prokaryotes, cells without nuclei, that may be more than 3.465 million years old. He thinks the organisms formed mats in the shallows surrounding early continents, which were like large islands in the vast primal oceans. "The scene was dominated by broad shallow seaways into which volcanic lavas erupted," Schopf writes of that environment. "Scattered volcanic islands were fringed by river gravels, sandy inlets, mudflats, and occasional evaporitic lagoons."

It is hard to tell if such unimaginably ancient structures are really the remains of life, but similar organisms definitely inhabited such environments very long ago, and for a very long time. Fossils from Montana's 1,300-million-year-old Belt Supergroup are of filamentous cyanobacteria growing in clumps called stromatolites. They still live in them, on North America's west coast among other places. Salty lagoons in Baja California, where more recent algae-eaters like snails can't survive, support stromatolites that resemble fossil ones, although the constituent species are different.

Fossils suggest that life underwent much of its further evolution from prokaryotic to eukaryotic organisms, cells with nuclei, and then to multicellular organisms in the seas. Fossils of unicellular eukaryotes are known from 1,800-million-year-old marine rocks. In western North America, the 850-million-year-old Kwagunt Formation from Arizona has yielded a "vase-shaped" protozoan like something one might see in plankton today.

Charles D. Walcott, a paleontologist with the U.S. Geological Survey, discovered some of the first really ancient fossils in Arizona. Exploring the Grand Canyon in the 1880s, he found algal reef structures from Precambrian times, over 550 million years ago. In 1899, again in the Grand Canyon, Walcott found tiny blackish disks, which he named *Chuaria* after the rock formation. He interpreted them as fossils of shelled animals, but they later turned out to be giant eukaryotic algal cells.

It took longer for paleontologists to find very early multicellular organisms. In 1946, strange saucer-shaped fossils turned up in 560-million-year-old rocks in an abandoned mine named Ediacara (an aboriginal word for a spring or seep) in southern Australia. Although unimpressive, they were too large and complex to be unicellular. As more fossils of similar structure and age emerged from places like Namibia and northern Russia, paleontologists realized that a diverse array of small and soft-bodied, but many-celled, organisms quite unlike most living ones had evolved by at least 800 million years ago.

More recent discoveries have shown that this "Ediacaran" ecosystem also occupied the gradually forming western margin of North America. In 1996, Mark McMenamin, a geologist, reported the discovery of 600-million-year-old "body and trace fossils" of "sediment-dwelling animals" in Mexico's northwestern state of Sonora. The body fossils were "headless, tailless, and appendageless." One of the the fossils, named *Cyclomedusa,* was shaped somewhat like a fried egg and may have dwelt on the ocean bottom like a sea anemone. Another, conical one, *Sekwia,* may have been the "semi-rigid basal attachment structure" of another bottom-dwelling Ediacaran. The siltstones and sandstones in which the fossils were embedded suggested that they had lived in shallow waters, probably "on or near the continental shelves of the North American craton."

Ediacaran fossils similar in age to the Sonoran ones have been found in northwest Canada's MacKenzie Mountains, implying that, even then, coastal environments extended thousands of miles along the continent's edge. Somewhat younger Ediacaran fossils have since turned up in the deserts of southwest Nevada and southeast California, and in northern California's Klamath Mountains. The remains of disklike, tubular, or frondlike organisms, they have similarities to Brazilian and Namibian fossils, suggesting that this continent lay across a narrow, newly forming ocean from what are now parts of Africa and South America.

Nobody is sure what the Ediacaran organisms were or how they lived—whether they had mouths and guts, absorbed food directly from water, or had symbiotic relationships with photosynthetic organisms. Various living organisms feed in all these ways, and it is possible that the Ediacarans were the ancestors at least of some of them, but nobody is sure about that either. The fossil record, anyway, shows that the Ediacarans and ancient versions of living groups inhabited Precambrian and Cambrian seas together for many millions of years before the Ediacarans disappeared.

The southwestern Ediacaran fossils confirm an impression of dessicated marine antiquity that I got from the California desert when I first went there in the 1980s. Hiking in the eastern Mojave, I thought I saw evidence of an abundance of small carnivores—kit foxes, ringtails, and the like—assuming that black cylinders on most rocks were their scats. Then I realized that the cylinders were not mammal scats, but Paleozoic invertebrate fossils.

I also realized, looking at a mountain east of Death Valley, that what I was seeing was not just a pile of minerals but the petrified remains of an enormous reef formed by archaic organisms. To look closely at the mountain's strangely pillowed and fissured limestones was to see the reef's surface, faded and discolored by 500 million years above water, but still recognizably zoogenic. The organisms that built such reefs were not the corals of today. They are so long extinct that it is hard to tell what they were. One major reef-building group of porous, conical organisms called archeocyathids was thought to be related to sponges, animals that live by filtering detritus from the water. Now they seem as likely to be related to calcareous algae, which live by making food from sunlight. The creatures that lived in these reefs are equally distant in time, like helioplacoids, spindle-shaped, spirally scaled organisms that perhaps lived in the sea bottom, siphoning food out of the water. Their fossils are common in early Cambrian period western deposits but disappear thereafter.

Archeocyathids and helioplacoids were among the first organisms with hard parts, which appeared in the early Cambrian at the start of the Paleozoic some 550 million years ago. By the mid-Cambrian, such organisms had evolved a startling diversity, and western North America has the most famous example, discovered in 1909 by the same Charles D. Walcott who found the earlier Grand Canyon fossils. Exploring the mountains of eastern British Columbia on summer vacations, Walcott encountered a shale deposit at 8,000 feet on a steep mountainside that eventually, when its layers were split to reveal the fossils therein, yielded some 119 genera and 140 species of Cambrian animals. Because a sudden mudslide had covered the shallow reef where the animals lived, preventing aerobic decay, many of the fossils included soft structures that gave extraordinary insights into the biology of some of the earliest known animals. Stephen Jay Gould, the late twentieth century's paleontological superstar, called the deposit, now known as the Burgess Shale, "the world's most important" fossil fauna.

Despite (or because of) its exquisite preservation, however, the Burgess Shale fauna has caused almost as much confusion as enlightenment about early biodiversity. Walcott considered the Burgess animals ancestral to living phyla such as jellyfish, worms, and arthropods. But some paleontologists who studied the fossils in the 1960s and 1970s found them so strange that they decided many represented extinct phyla, groups as distinctive as living phyla such as mollusks or arthropods. This idea charmed Gould, who used it to construct an evolutionary scenario contravening the historically prevalent notion that life has become more diverse through time. Gould theorized that evolution originally experimented with a great diversity of basic body plans, but that most later died out, leaving the Earth populated by a relatively few lucky ones.

Then, however, new fossil discoveries in places like China and Greenland led some of the paleontologists who had studied the Burgess Shale in the 1970s to change their minds about many of the apparently extinct phyla and link strange fossils back to extant groups. For example, Walcott had classified an oval, scaly little fossil that he named *Wiwaxia* as an annelid worm, and thus a distant relative of the earthworm. Simon Conway Morris, a young English paleontologist who studied *Wiwaxia* in the 1970s, doubted its annelid nature because it lacked wormlike segmentation, and decided that it might have no living relatives. Gould accordingly claimed it as "another Burgess oddball," an extinct phylum. In 1990, however, a researcher Nick Butterfield, found that *Wiwaxia*'s scales had the same microstructure as an earthworm's chitinous bristles, leading Conway Morris to surmise that it was, after all, a very early version of an annelid worm.

Despite the confusion, some Burgess animals have clear affinities with living ones. The second most common animal in the shale, named *Canadapsis,* is a crustacean, a relative of crabs and lobsters, and of the little wood lice common in my garden. Another, a horseshoe crab-like creature named *Sanctacaris,* is considered a chelicerate, a relative of spiders and mites, although it lacked chelicerae, specialized claws that spiders use to manipulate prey. The Burgess fauna also included a few shelled mollusks, although they seem to have been uncommon, unlike the snails in my garden.

Two of the strangest Burgess animals, *Aysheia* and *Hallucigenia,* seem to be onychophorans, an extant group of segmented, wormlike animals, which, however, have multiple legs and may be related to the arthropod group that includes millipedes, centipedes, and insects. *Hallucigenia* is such a bizarre fossil—an apparently headless, segmented cylinder ornamented with bumps, tentacles, and spikes—that Conway Morris at first thought it belonged to an extinct phylum. The spikes are so long that he mistook them for legs and turned the creature upside down. But then new discoveries from China changed his mind. In fact, the Burgess onychophorans were not that much more bizarre than living ones, albeit spikier.

As though to uphold its "world's most important" status, the Burgess Shale also may feature the phylum that includes human beings—chordates. When Walcott named a two-inch-long animal *Pikaia,* he assumed it was a worm because of its flattened and segmented structure. Conway Morris, however, interpreted the segments as bands of muscle called myomeres, a chordate characteristic, and also found that *Pikaia* had a notochord, the stiffened dorsal rod for which chordates were named, and which evolved into the vertebrate spine. *Pikaia* was the same size and general shape as *Amphioxus,* a living chordate of warm coastal sediments, although, unlike *Amphioxus,* it lacked a tail fin.

A mere 20 million years after the Cambrian began, the Burgess Shale seems to have featured all the animal groups that would move onto land, along with many that wouldn't, such as sponges, jellyfish, echinoderms, brachiopods, and trilobites. Similar fossil deposits from a variety of locations, including California and Utah as well as Greenland and China, show that the groups were widely distributed. Given their apparently "explosive" evolution in the sea, a landward movement of these creatures might have been expected to be similarly brisk.

According to evolutionary tradition, however, life didn't colonize the land until the Devonian period, 100 million years after the Burgess Shale. "From the dawn of the Cambrian period, through the Ordovician, to the end of the Silurian . . . the quickening life of the planet remained in the warm primeval oceans," proclaims *The World We Live In,* a classic picture book that awakened my evolutionary imagination fifty years ago. "The dry lands stretched stark and desolate from sea to sea," it goes on, "their drab rocks naked save for a few green films of algae along the shores." In 2000, a PBS *Nova* program about the first tetrapods gave a similar impression of the Ordovician and Silurian periods, showing landscapes of cracked mud and blowing sand. In fact, most land phyla did not leave fossils until later. Land crustacean fossils first appear in Devonian rocks; land mollusks even later, in Carboniferous ones.

There apparently is good reason for the traditional view of life's movement to land as a slow, painful thing. Any walk along a beach, particularly on the west coast, will dramatize this. The actual meeting of land and sea is an abrasive, shifty place of sun, rock, surf, sand, and tides. The animals that live in it—mollusks like mussels and clams, crustaceans like barnacles and amphipods—hide in shells or burrows. They may be incredibly abundant. The rocks below Point Resistance bristle with mussels and barnacles, and the beach seethes with thumbnail-sized amphipods and mole crabs. But there is little landward momentum in their ways of life, which probably have existed since the Cambrian. They are not, in fact, adaptations to land, but to the physical stresses of the littoral zone itself, which reduce predation and competition but require high specialization.

There is a problem with blaming life's slow emergence on littoral zone stresses, however. The traditional view of evolution *doesn't* say that life colonized land across the littoral zone. According to *The World We Live In,* for example, life invaded land not by crossing beaches, but by moving up estuaries and rivers, then into ponds and swamps, before stepping out on *terra firma.* The book contains a two-page panorama by artist James Lewicki of a Devonian estuary teeming with land plants and animals. So the apparent impracticality of a littoral zone route doesn't explain eons of Ordovician and Silurian barrenness.

Moving up rivers and estuaries certainly does sound like an easier route to land than through the surf. But then why did *it* take so long? Moving from seawater into freshwater does pose metabolic obstacles. Freshwater is deficient in the salts that metabolism requires, and animals with permeable tissues would lose body fluids through osmosis without adaptations to prevent this. Indeed, one theory of the origin of hard parts like bones and shells is that they were a way of storing calcium and phosphates in chemically deficient brackish waters. And then, rivers and lakes are less reliable environments than seas, subject to droughts and floods, which could have terminated many promising experiments.

The freshwater route to land may not have been as slow as once thought, however. Recent evidence suggests that some animals began to take it much earlier than the Devonian. Freshwater is a poor preserver of fossils, particularly of very old ones, since its sedimentary deposits are shallow and sparse compared to marine ones. Land is an even poorer fossil preserver. Still, in the 1980s, eastern North American fossil soils from the Ordovician, 440 million years ago, yielded abundant burrows possibly made by millipedes. In the 1990s, British paleontologists found millipede-like tracks in what apparently was the mud of drying Ordovician ponds. Fragments of millipede-like arthropods have turned up from the Silurian period, and other tiny Silurian arthropods left evidence of their existence in the form of fecal pellets containing fungal remains.

Despite the scarcity of this evidence, it is suggestive, since the millipede-like creatures would not have lived in isolation. They would have needed food, plants as well as fungi, and if plants existed, there probably were other plant-eating animals as well, ones that wouldn't fossilize as well as the hard-shelled arthropods.

But were there land plants for Ordovician herbivores to eat? "For perhaps a billion years, the marine plants had drifted virtually unchanged in the primeval seas," says *The World We Live In.* "Then astonishingly, in the space 50 million years . . . during the Devonian Period . . . they evolved from simple seaweeds into great cone-bearing trees, carpeting the lowlands with ferns and leafy plants, transfiguring the naked hills." A problem with this traditional view, however, is that genetic analysis shows that "seaweeds" such as brown algae are only distantly related to land plants, suggesting that they may not have been their forebears.

Biologists still believe that land plants evolved from algae, but recent opinion has favored not marine ones, but multicellular, freshwater green algae that may have resembled a living group called the Coleochaetales. Presumably, spreading into increasingly dry habitats, these freshwater algae would gradually have evolved features necessary for land life—spores for reproduction out of water, stems for support and transfer of fluids, roots for support and absorption of water and nutrients from soil. Or land plants may even have evolved from land organisms. Moist soils contain single-celled green algae that resemble land plants in chemistry and genetics, and these soil algae probably are as ancient as freshwater algae. A botanist, G. Ledyard Stebbins, thought that "some of these populations of cells evolved directly into flat, tissuelike, multicellular land plants."

Whatever the details, it seems likely that the Coleochaetales-like multicellular algae evolved from a unicellular green algae in either freshwater or soil. Thus, instead of invading from the sea, land plants seem to have been on shore from their green algal beginnings. If this is so, the photosynthetic basis for both land and freshwater ecosystems probably evolved even before the Cambrian.

Indeed, there is no reason to assume that prokaryotes and eukaryotes were confined to the oceans during their first three billion years. By the Cambrian period, they probably pervaded the planet, as they do today, when green algae live inside desert boulders, and prokaryotes inhabit the boiling water of hot springs. At least a rudimentary soil would have covered much of the Precambrian land, barren appearances notwithstanding, and small multicellular organisms—fungi, plants, and animals—could have thronged its moist interstices as they do today. Freshwater habitats also would have teemed with mini-organisms. I once found myriads of tiny jellyfish relatives, hydras, feeding on even tinier crustaceans in a desert rivulet that flows perhaps two weeks of the year. Derek Briggs, who studied the Ordovician animals, observes: "Smaller arthropods may have come ashore at even earlier times, but the smaller the animal, the more difficult it is to find its traces."

Whenever they came ashore, invertebrates definitely were the pioneers and dominated the land long before vertebrates. As herbivores diversified, predators would have proliferated. Devonian sites in Scotland, Germany, and Illinois have yielded fossils of spiders, other arachnids, scorpions, pseudoscorpions, centipedes, and primitive insects as well as millipedes and mites. Other likely early predators were the onychophorans, which, despite their Cambrian marine abundance, live only on land now. Nobody knows how they accomplished this transition, but it suggests great antiquity, although their first probable land fossils are from Carboniferous sites in Illinois and France. I've found onychophorans very like the Burgess fossil *Aysheia* under logs in Costa Rican forest, reddish, velvety creatures that, alarmed at my intrusion, spat a gluelike substance. They use it to catch prey and may have done so since the Ordovician.

Invertebrates still dominate land, particularly insects, which apparently evolved terrestrially from some millipede-like ancestor, since very few are marine. Yet this dominance has a strange adjunct from a coastal viewpoint.

With few exceptions, land invertebrates have failed to reverse evolutionary direction and return to marine life, thus missing opportunities, since there is nothing like the seas for food and living space. Of course, many land invertebrates inhabit coasts, like the kelp flies that can make touring a marine bird or mammal rookery less enjoyable than anticipated. But the ones that actually have returned to salt water are an unimpressive lot. Perhaps this is related to the factors—gravity, gas exchange—that limit their size on land, although sea life might be expected to ameliorate those factors.

Whatever the reasons, invertebrates seem to drop out of the main thrust of coastal evolution after their original land conquests. Not only have land invertebrates shown limited ability to return to the sea, marine ones have seemed little inclined to new land conquest. Despite science fiction's many octopus-like villains, the crafty cephalopods, which appeared in Ordovician oceans, have never even invaded freshwater, much less land. The most octopi do is squirm over rocks from one tide pool to another. Echinoderms and corals have been equally conservative.

Other marine groups—sponges, jellyfish, worms, mollusks—do a lot of slipping in and out of streams. At Limantour Estuary a few miles north of Point Resistance, closed sea anemones stud the sand like pebbles during low tide, a kind of coelenterate pavement. Some mainly marine arthropods may have designs on permanent terrestriality. When I turned over logs on a cloud-forested mountain overlooking Costa Rica's Pacific, I found little brown crabs very like those that scuttle beside Limantour Estuary. Still, invertebrates since the Paleozoic seem to have neglected both sea-to-land transitions and land-to-sea ones, as though having permanent global dominance in animal diversity and abundance is enough. As perhaps it is.