CHAPTER 19

THE CONQUEST OF LAND—EVERY CRITERION FOR THE CLASSIFICATION OF THE MAJOR GROUPS OF ANIMALS AND PLANTS REFERS TO ADAPTATIONS FOR LIFE ON LAND

If the land held such potential for the evolution of all forms of life, why did it take so long (approximately 9/10 of the earth's history) for organisms to conquer the land? There are many hypotheses, but most of them in one way or another relate to the presence of oxygen in the atmosphere. We have many means of estimating how much oxygen was in the atmosphere at various ages of the earth, and we can interpret the appearance and physical characteristics of the land in the presence or absence of oxygen. The principle for estimating oxygen in the atmosphere is very straightforward. If you leave a piece of iron in the air, particularly in humid conditions, it will rust. Rust is the combination of iron with oxygen. If you keep the iron in an atmosphere of pure nitrogen, or prevent oxygen from reaching it by means of paint or oil, it will not rust. Iron rust, frequently seen as red earth, means that iron was exposed to oxygen. Other metals can also rust, turning different colors. For instance, one For instance, one equivalent of rust equivalent of rust for aluminum is a black powder. Also, crystals of stones form differently in the presence of different amounts of oxygen. Each of these reactions occurs at a different threshold, meaning that below a certain level of oxygen the reaction will not occur. By reading these various chemical reactions, we can establish the approximate levels of oxygen in the atmosphere at any given time. For instance, today the amount of oxygen in the atmosphere is a bit above 20%. It began to accumulate quite slowly and then increased rapidly.

Oxygen began to build in the atmosphere approximately 2.5 billion years ago and reached approximately 50% of current levels about 500 million years ago (Fig. 19.1).

What is particularly interesting is what is called banded iron formations. In various ancient sedimentary rocks, ranging from 3 billion years to a bit less than 2 billion years old, there is a peculiar fine striping, black or red rust between lines of sedimentary rock containing unrusted iron (Fig. 18.4). What must have happened is that the amount of oxygen varied during the time that the sediment

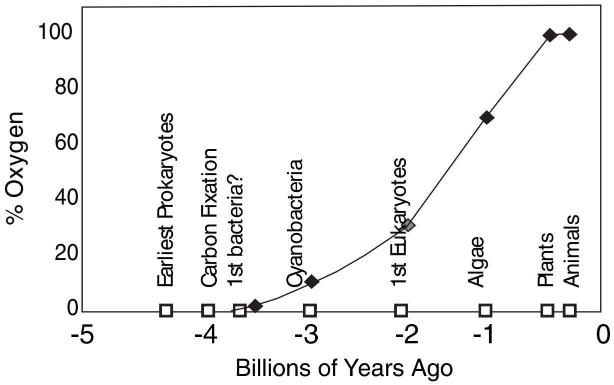

Figure 19.1. O_2 in the atmosphere. Chemical indicators suggest that oxygen first appeared in the atmosphere over 3.5 billion years ago. Large organisms did not proliferate on earth until atmospheric oxygen levels had increased to levels nearly equivalent to those seen today (21% of the atmosphere)

was deposited. One can speculate on the mechanisms producing this effect, but the most logical and consistent one is the following: Oxygen would get into the atmosphere only via photosynthesis, meaning that photosynthesis was functioning at that time. The banding pattern represents a seasonal (or most likely other) cyclical variation in photosynthesis. During alternate seasons or periods, photosynthesis was lower, and the available oxygen was used up or diluted further into the atmosphere. Finally, approximately 1.8 billion years ago, oxygen was definitively in the atmosphere but the raw iron available in the sea water and sediment was essentially fully oxidized and the banding ceased. Whether or not this interpretation is correct, the banding is remarkable and indicates that there was an active photosynthesis three billion years ago. In other words, there were living photosynthetic bacteria.

Photosynthesis offers a further advantage, in that both alcohol and lactic acid are soluble in water and will eventually make the water toxic to life—beer and wine stop fermenting when the alcohol level poisons the yeast that produced it—whereas carbon dioxide can escape into the atmosphere. Therefore, if organisms can use oxygen, they have the potential to do more, producing far more energy with lower requirements for food and less risk of poisoning themselves, than organisms that cannot use oxygen (Chapter 18). There is a cost, since oxygen is still a very reactive molecule and can react with (or burn) other molecules in the body. Antioxidants are used in paints, to protect the metal underneath, and in many manufactured foods, to prevent the food from developing a “stale” taste. The argument that oxidation creates damage is the primary argument on which the manufacture and sale of nutritional antioxidants is based. (As a practical matter, ingested antioxidants rarely reach the sites in the body where they might do some good.) If organisms can manage to avoid the damage produced by oxygen, they have the potential of living far more efficiently than organisms that cannot use oxygen.

In any event, oxygen is accumulating in the atmosphere, and all organisms must evolve means of dealing with it. A few organisms do not. The bacteria that cause food poisoning, tetanus, and gangrene depend on living in the complete absence of oxygen and are rapidly killed by exposure to it. Thus oxygen in the air provides the possibility of life capable of producing far more energy and thus living at a more energetic pace.

PROTECTION FROM UV

The other effect of oxygen is readily seen by extrapolating from other situations that most of us have seen. We are generally familiar with the fact that human skin can be burned by excess exposure to the sun, and most people are aware that it is the UV part of the spectrum that does the most damage. (Fig. 19.2). We also know that a risk of sunburn is a type of cancer known as melanoma. Melanomas are produced by mutations of DNA, from which we learn that UV can damage DNA. We deliberately exploit this possibility when we use UV lights to sterilize surgical suites or surfaces that we need to keep sterile. The UV kills bacteria by destroying their DNA.

The extrapolation is that the amount of UV reaching the earth at present is 1% or less of the UV that could reach the earth, and our UV lamps produce miniscule amounts of UV compared to the sun. The UV coming from the sun is substantially blocked by oxygen, which is excited (activated) in the upper atmosphere to form a version of oxygen called ozone. The ozone absorbs UV light and prevents it from reaching earth. This subject is commonly in the news, since human-produced chemicals can also react with and destroy the ozone. You can imagine what the surface of the earth would have been in an oxygen-free atmosphere. It would have

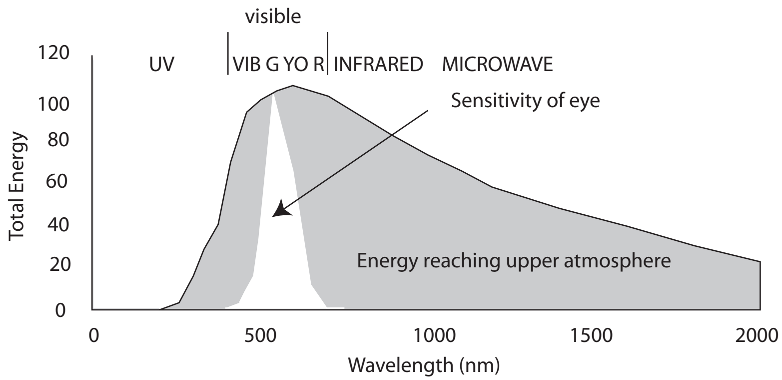

Figure 19.2. Light reaching the earth. The sun emits a wide spectrum of energy. Primarily because of the ozone in the upper atmosphere, most of the destructive high energy emission (short wavelengths, to the left) that reaches the upper atmosphere is blocked. Approximately 99% of the gray area to the left of the white area, which indicates what we can see, does not reach the surface of the earth

been one vast sterilization chamber, bombarded every day by intense ultraviolet radiation. Anything that ventured onto land would have been, quite literally, fried. Life on land, based on DNA, was impossible until sufficient oxygen built up in the atmosphere to block the UV. Although the amount of UV, particularly the most damaging form of UV, UV-B, that is absorbed varies with time of day, elevation, latitude, and cloud cover, today approximately 99% of it is blocked by the ozone, and an even more damaging form, UV-C, does not reach the surface of the earth. Life on land was not possible before photosynthesis.

One of the most interesting arguments that we can make is that we can almost always group the animals and plants that were first defined by the Cambrian explosion (page 277) into categories that we know today, such as arthropods (jointed-footed animals such as crabs, lobsters, and insects), vertebrates and, among vertebrates, fish, amphibians, reptiles, birds, and mammals. In plants, we recognize such groupings as algae, mosses, ferns, evergreens, and flowering or broad-leafed plants. Many of the finer distinctions arose much later, but they represented continuation of trends established by the earliest groupings of animals and plants. What you may not appreciate is that essentially all of the criteria that we use to distinguish among these categories describe one or another adaptation to life on land. Compare a large alga such as a kelp—the large-leafed seaweed—to a spruce tree. The kelp's life is relatively easy. Though one end may attach to a rock, it floats in the water. It needs no serious support structure. Since the leaf is thin, everything that it needs can diffuse into each cell and all of its wastes can diffuse out. To reproduce, it releases its gametes (a type of egg or sperm) directly into the water, where the different gametes will hopefully find each other. Since it exists in a solution of unchanging salinity (the ocean) it does not have to worry about having too much salt or too much or too little water. Contrast this with the situation for a spruce tree. To reach the sunlight, it must have a rigid structure to support itself against gravity. This will require a fairly bulky structure, which means that nutrients and waste products will not diffuse easily but must be transported in a specialized circulatory system. It will gather its water through its root system, which is also structured to support the tree in wind, but it may encounter flooding or drought. Therefore its needles and parts exposed to air must be sealed against too much water loss, and it must have means of adjusting its intake of water; it can easily drown or wilt. The water must be transported up to 60 feet into the air to be delivered to the uppermost needles, and the sugars produced by photosynthesis must be sent to the roots, which receive no light and cannot photosynthesize. The female part of its reproduction can hold the fat, nutrient-containing gamete (seed) to await fertilization by a smaller, mobile gamete (pollen) but the pollen must be capable of being transported by wind over great distances, and survive potentially drying out. Each problem that it faces must be dealt with by a different adaptation. One can carry out the same logic of reasoning for invertebrates (earthworms, mollusks, sea-dwelling arthropods such as lobsters or land-dwelling arthropods such as insects, and many lesser-known creatures) or for vertebrates (fish, amphibians,

Table 19.1. The major phyla of plants and animals

Phylum or family	Circulation	Respiration	Renal	Reproduction	Skin	Skeleton
Fish	2-chambered heart	Gills	Pronephros; excrete ammonia	Usually external; eggs –> fry –> fish	Scales, permeable	No true limbs
Amphibia	3-chambered heart; nearly complete separation into 4-chambered	Small lungs, skin	Mesonephros; excrete urea	External, unprotected eggs –> tadpoles –> adults	Moist, permeable or dry, semipermeable	4 limbs out to sides; some hop
Reptiles	3-chambered heart	Lungs	Mesonephros; excrete uric acid	Internal, hard shelled egg	Dry, impermeable, scales	4 limbs out to sides
Birds	4-chambered heart	Lungs; air sacs	Mesonephros; excrete uric acid	Internal, hard shelled egg	Dry, impermeable, feathers	4 limbs; wings and aligned legs
Mammals	4-chambered heart	Lungs	Metanephros; excrete urea	Internal, placental, no yolk	Dry, impermeable, hair or fur	4 limbs, aligned with body axis
Algae	Diffusion	Diffusion	Aquatic	Permeable	No skeleton	
Mosses	Diffusion	Diffusion, circulation	Wet areas, mobile gametes	Permeable	Modest vertical support	
Ferns	Tracheal system	Tracheal system	Minor semi-aquatic haploid phase, mobile gametes	Semipermeable	Tracheae, support structures	
Pines	Tracheal system, phloem & xylem	Tracheal system	Pollen and hidden seeds	Impermeable	Tracheae, support structures	
Flowering plants	Tracheal system, phloem & xylem	Tracheal system	Tube pollen and flowers	Impermeable	Tracheae, support structures	

reptiles, birds, mammals). These groups and their solutions are described in Table 19.1.

The fact that the major means that we have for grouping animals and plants relates to surviving on land might be an artificial intellectual construct. For instance, we might have classified animals according to whether they swam (fish, sharks, penguins, dolphins, and squid), flew (birds, insects, bats) or walked (frogs, lizards, and most mammals). However, these classifications do not explain many features of each animal and, today, we can show by DNA analysis that, for instance, penguins are birds and are not related to dolphins. Thus our groupings appear to have some validity. What this suggests is that access to land was an important step in the evolution of the organisms that we see on earth today. There were several independent solutions to each of the problems (an insect has Malpighian tubules, which are very different from vertebrate kidneys, while reptilian, bird, and mammalian kidneys each differ from each other in very pronounced ways) and those solutions that worked provided the ancestors of the animals and plants that we know today. Those animals and plants that got a foothold on the land found a vast and highly varied new territory in which to evolve, and each of those successful ancestors underwent an adaptive radiation into the land (see Chapter 24, page 335). We conclude that the new accessibility of land provided an outstanding opportunity to those animals and plants with the ingenuity to find ways to handle the difficulties of support, internal circulation, water retention and removal, and reproduction; that several solutions worked very well; and that we see today the descendents of those creatures that found the original solutions.

Oxygen in the atmosphere changes the earth in two major fashions: it provides a new, rich source of energy, and it makes the land habitable. Once the land is habitable, the first life on land transforms the earth in even more remarkable ways.

Once oxygen made the land habitable, the land was further transformed in another very important fashion. You have noticed, when the sun comes out after a summer rain, that earthworms that happened to be venturing onto a sidewalk or driveway when the sun reappeared often dry out and die. Or you may have tried to cross a driveway, street, or beach in your bare feet on a hot summer day. The ground is extremely hot, hot enough to burn you. You may have leaped off the driveway to the grass alongside. The grass is much cooler and refreshing. Even a thin layer of grass or moss is far cooler (Fig. 19.3)That is because living things contain water, and water can control heat and heat transfer far more comfortably than dry surfaces. Likewise, the first life that could establish itself on land, even a slimy coat of bacteria, would have made the surface of the earth far more tolerable than a dry, rocky surface. These creatures would have lived and died, and their remains would have accumulated and made the layer of water-containing organic material deeper and capable of supporting a more varied life. We see this kind of progression today, when life comes back to a burned-off land, or, more cogently, when living organisms begin to populate new land such as the lava from a recent volcanic eruption. At first the lava is very inhospitable to life, but once small plants such as mosses and lichens take hold, enough water is retained to sustain

Figure 19.3. If you were walking barefoot across a rocky terrain in full sun on a hot day, on what would you rather step? Even a very thin layer of moss can make a substantial difference in the surface temperature and in the ability of the substratum to transfer heat. Thus smaller organisms can survive on the moss where they cannot on the rock surface, and when they die they will contribute to the growing mass of soil building on the surface

slightly larger plants through the hottest and driest moments. Small animals can now live among these plants, and soon (over the course of a few years or a few tens of years) this previously harsh terrain is softened by an extensive assortment of life.

WHAT CAUSED THE CAMBRIAN EXPLOSION?

This is one interpretation of what it took for what is described as the Cambrian explosion—the apparently sudden proliferation of a wide variety of life, including most of the broad classifications of animals and plants that we know today, after a very long period in which life existed, but in very modest form. To recapitulate: in the approximately 4.5 billion year existence of the earth, we can detect evidence of life beginning approximately 3 billion years ago, or almost as soon as the earth was cool enough to tolerate organic molecules. Nevertheless, living organisms apparently did not become much more complex than photosynthetic bacteria and simple algae until less than 500 million years ago, and then by 350 million years ago, life had generated large numbers and multiple forms of plants and animals culminating, approximately 150 million years ago, in the early appearance of modern forms such as flowering plants and mammals. In terms of the history of the planet, the bursting forth of life occurred in a relative instant, and the question is, was life really relatively somnolent until this time, and what happened to kick evolution into high gear? One possible explanation is that land became accessible for life at this time. There are other possible explanations, including the development of specific types of genes (see page 283). There are no “correct” explanations for the Cambrian explosion; interpretations that we have are speculations based on the evidence that we have and logical interpretations of the evidence, but there is no criterion of falsifiability to solidify the hypothesis into a theory.

REFERENCES

Campbell, Neil A. and Reece, Jane B.(2004) Biology (7th Edition), Benjamin Cummings, Boston, MA

STUDY QUESTIONS

1. Why do we worry about ultraviolet light reaching the earth? What stops it?
2. Look at any plant or animal within your range. Can you identify how it resolves its problems of water gain and retention, support, and reproduction?
3. If you can find a rock that has a bit of moss on it, place it in the sun on a summer day. After about half an hour, measure the temperature at the surface where the rock is exposed and at the surface of the moss. What do you find?
4. On a sunny summer day, moisten a bit of peat moss and sprinkle it in a thin but complete layer on an asphalt driveway. Before the moss dries out, try to walk across the driveway where it is exposed, crossing onto the moss. What do you find?
5. If you live in an area where you can see lichens, look at them very closely and see how many other types of organisms live among the lichens.
6. Was there really a Cambrian explosion? Defend your argument.
7. If you feel that there was a Cambrian explosion, what do you think caused it? Defend your argument.