Oxygen Upheaval

The crashing of continents may have shaped the atmosphere

By Richard Monastersky

That breath you just inhaled — hold it for a second. Think about the gases diffusing into your bloodstream and providing cells with the component they so desperately need: oxygen.

While oxygen currently makes up 21 percent of the atmosphere, there was none in the air when life first appeared on this planet, according to standard theories about the early Earth. At that time, the most advanced organism was a single-celled bacterium dwelling in the sea that didn't need oxygen to live. Then somewhere along the way, oxygen molecules began accumulating in the oceans and atmosphere, a development that eventually allowed large, multicellular animals to evolve. Without that critical addition to the atmosphere, life might never have grown bigger than a pinpoint.

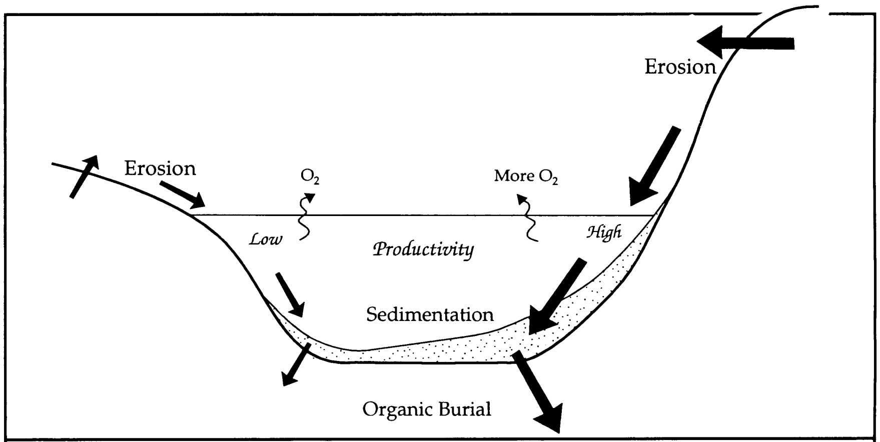
According to the textbook story, minute quantities of oxygen first appeared in the environment when early bacteria developed the ability to split water molecules apart by harnessing the energy in sunlight — a key part of photosynthesis. Yet, the next chapter in the oxygen tale remains a cryptic one. Researchers believe that photosynthesizing organisms produced the oxygen that eventually accumulated in the atmosphere, but they do not know how quickly oxygen filled the environment or why.

New work, published in the Oct. 15 NATURE, points to Earth's own geological metabolism as a leading character in the oxygen story. Major plate tectonic cataclysms have caused oxygen surges into the atmosphere during two separate pulses, say David J. Des Marais of NASA's Ames Research Center in Mountain View, Calif., and his colleagues, Harald Strauss of Ruhr University in Bochum, Germany, Roger E. Summons of the Bureau of Mineral Resources in Canberra, Australia, and John M. Hayes of Indiana University in Bloomington.

The researchers arrived at these conclusions about oxygen by way of studying carbon in rocks from Earth's Proterozoic eon, which ran from 2.6 billion years to 600 million years ago. That roundabout technique works because carbon shares an intimate connection with atmospheric oxygen. When photosynthesizing organisms liberate oxygen by splitting water, they also create organic carbon molecules in the form of carbohydrates. For every mole of oxygen molecules set free, a mole of carbohydrates is produced.

The liberated oxygen doesn't remain unfettered for long. Almost all of the photosynthetically-produced oxygen eventually gets recaptured when bacteria and other organisms digest the available organic carbon through an oxygen-requiring process called respiration. A tiny fraction of the oxygen, however, does manage to escape the recapturing when bits of organic matter find their way to the sea-floor, where they get covered over by sediments washing in from the continents. That burial of organic carbon leaves behind an equivalent amount of photosynthetically produced oxygen in the oceans and atmosphere. So the amount of carbon being locked away beneath the sea relates directly to the amount of oxygen that can accumulate in the air.

Des Marais and his colleagues investigated the oxygen story by trying to estimate the global amount of organic carbon buried in seafloor sediments throughout the Proterozoic. To do this, they compared data on the carbon isotopes within two types of rocks: shales, which record the isotopic value of carbon in organic matter, and carbonate rocks, which record the isotopic value of inorganic carbon in seawater. Using this isotope data, Des Marais' group could estimate what fraction of ocean carbon was being stored in organic form.



When continents collide, they create high mountains; when they split apart, deep ocean basins form. In either case, such tectonic rearrangements create relief between the highest and lowest points on Earth's surface. During periods of enhanced tectonic activity (shown on the right side of the diagram), the forces of erosion carry more sediments into the ocean than during tectonically quiet times (shown on the left). When eroded sediments bury organic matter in the deep ocean, oxygen can accumulate in the ocean and air. This process picks up during tectonically active times, when the flow of sediments increases.

As many may have expected, the researchers found that the fraction of organic carbon being buried has increased through time, indicating an overall increase in the amount of oxygen left in the atmosphere after photosynthesis. "But the real breakthrough discovery is that the increase seems to be focused in two key intervals," says Des Marais.

Instead of increasing steadily, carbon burial appears to have jumped between 2.1 and 1.7 billion years ago and then again between 1.1 billion and 700 million years ago. By inference, then, oxygen levels must have increased dramatically in those intervals, according to the researchers.

Des Marais finds the timing of these jumps particularly intriguing because they coincide with moments when plate tectonics went into overdrive. At both times, geological evidence suggests that Earth's continents were splitting apart to form new ocean basins and then crashing together to form large landmasses. Between these two active spans, the geological drama quieted down.

Des Marais thinks there is more to the correlation than just coincidence. "It's really the timing of these global events that has a lot to do with the accumulation of oxygen in the atmosphere," he says.

Geological upheaval can have such a dramatic effect because, whether rifting or crashing, continents generate vast amounts of sediments that pour into the oceans. As an example, Des Marais points to India, which is currently ramming into Asia and raising the Himalaya mountain range. As it grows, the range continually sheds its outer skin, turning the rivers of India turbid with sediment. The collision creates so much erosion that the Ganges River carries four times more sediment than the Amazon, even though the South

American river is three times the size of the one in India.

Now just imagine a time far back in history when several continents were slamming into each other, creating Himalaya-size mountains that ran the length of North and South America, says Des Marais. With so much erosion from these peaks, the flood of sediments would bury vast amounts of organic matter on the ocean floor, ultimately allowing oxygen to accumulate in the atmosphere, he suggests.

This view of tectonics and oxygen conflicts directly with some long-standing theories about the atmosphere. Although scientists recognized previously that volcanic activity may have played a part in the oxygen story, traditional theories have held that biological evolution controlled the pace and scale of oxygen's accumulation in the atmosphere, says Des Marais. According to this view, as new organisms appeared, they developed more efficient photosynthetic machinery and pumped more oxygen into the air.

Des Marais doesn't deny the importance of photosynthesis; after all, this process ultimately produces the oxygen in the atmosphere. But he maintains that geological events have triggered the changes by burying organic matter and allowing more oxygen to accumulate in the air.

Other scientists who study the early Earth admit the carbon burial theory makes a good story, but Des Marais has yet to convince many it really happened that way. "What he suggests as an interpretation is reasonable. But it is not the only possible interpretation," says Heinrich D. Holland of Harvard University.

James C.G. Walker of the University of Michigan comments, "They describe a very plausible scenario. It makes a lot of sense and could well be correct. But it is in no way demonstrated by the data."

Both Holland and Walker question how Des Marais and his co-workers have derived their story from changes in the ratio of carbon isotopes in rocks, which are supposed to record shifts in the amount of organic carbon being buried. Holland and Walker point out that the data are scattered over a wide range of isotopic values, making it difficult to track the global changes from 2 billion years ago. Des Marais and his colleagues have drawn one curve with its own peculiar wiggles to represent the data, but the scatter in the isotopic values makes that line look somewhat suspect, several researchers say.

"The real question is, What is the true history of carbon isotopic changes and how well are we arriving at it?" argues Walker. He also says that the Des Marais paper has a number of assumptions that, though reasonable, may not be correct.

"This is a tough field, and it's difficult to get concrete, convincing information for the Proterozoic Earth. I think these guys have done a good job and they could well be right, but there are simply more uncertainties. The whole situation is not perhaps as clear-cut as they have suggested, which is a pity, because I'd like to believe the conclusion," Walker says.

Holland, as well, would like to believe the results, or at least some of them. In his own research, Holland has found evidence of a major increase in oxygen levels between 2.2 and 2.0 billion years ago — a time that agrees with Des Marais' team. But Holland thinks the change may relate more to the pace of volcanic activity than to continental collisions.

Since the birth of the planet, volcanic activity above and below the sea has dwindled as the inside of the Earth has cooled. Because erupted gases react with oxygen, the slowdown in volcanic activity has left more oxygen to accumulate in the atmosphere, suggests Holland.

He readily admits, however, that this theory is speculative. "At this point, I don't think anybody knows for sure."

In any case, earth scientists have grown convinced that some geological factor had a starring role in the oxygen story. In their view, life certainly acted in the same drama, but it did not control how the oxygen tale evolved. ☐