THE DISCOVERY OF HYDROTHERMAL VENTS
25th Anniversary CD-ROM

Chemosynthetic Production of Biomass: An Idea from a Recent Oceanographic Discovery

by

Holger W. Jannasch

Reprinted from *Oceanus*, Vol. 41, No. 2, 1998

Printed from "The Discovery of Hydrothermal Vents - 25th Anniversary CD-ROM"

Chemosynthetic Production of Biomass:

an idea from a recent oceanographic discovery

by Holger W. Jannasch

The generation of biomass from carbon dioxide (CO_2) is called "primary production" because it is the first, fundamental step in turning inorganic material into organic compounds and cell constituents. This "photosynthetic" reduction of CO_2 is carried out by plants that use light as the source of energy. All life depends on this primary production and is thus maintained by solar energy. In turn, the formation of animal biomass from plant materials is termed "secondary production." It is, however, rather a conversion, whereby some of the organic matter is oxidized back to CO_2 to provide the necessary energy. Chemosynthesis is another type of primary production of organic matter.

Photosynthesis and Chemosynthesis

It is not only the energy that is important. Using the analogy of the water wheel, it is not only the elevation of water that is needed to turn the wheel, but also the water itself. The flow of water compares to the flow of electrons. Hydrogen sulfide was used as a source of electrons by the earliest primary producers, the photosynthetic purple bacteria, in the anoxic primordial biosphere of the globe. During the course of evolution, light-absorbing pigments and the mode of electron transfer developed further, and, at a critical point, blue-green bacteria converted to using H_2O (water) instead of H_2S (hydrogen sulfide) as the source of electrons. As a waste product of the oxidation of water, free oxygen emerged in the atmosphere. Since free oxygen reacts spontaneously with many potential electron sources, thereby competing with life processes, it acts like a poison for anaerobic organisms and might have been the first instance of a deadly pollutant. As a result of the subsequent evolution of green plants, our present atmosphere contains about 21 percent free oxygen. A complex system of enzymes allows the aerobic organisms, including humans, to cope through an intricate electron transfer system with the high reactivity of free oxygen.

Where does chemosynthesis fit into the picture? Instead of using light for the reduction of carbon dioxide, some bacteria used the energy liberated by the oxidation of certain electron

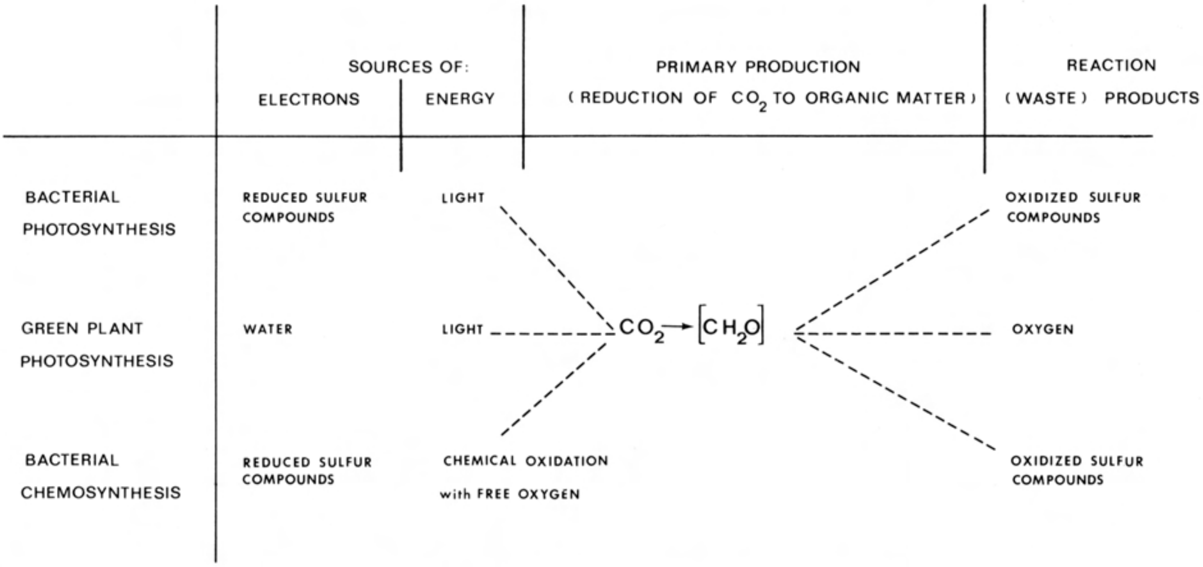

Figure 1. The three types of primary production. Bacterial chemosynthesis also can be based on the chemical oxidation of a number of other reduced inorganic compounds.

sources with free oxygen. Thus, in the course of evolution, these aerobic organisms emerged after the appearance of free oxygen. Since they use chemical energy instead of light, they produce organic matter chemosynthetically and not photosynthetically (Figure 1). For energy, they use hydrogen sulfide and other sulfur compounds, such as elemental sulfur (S°) and thiosulfate ($S_2O_3^{2-}$), in addition to hydrogen (H_2), ammonia (NH_3), nitrite (NO_2^-), reduced iron (Fe^{2+}), and probably other metals, such as manganese. Chemosynthesis is limited to special locations and situations where those reduced compounds meet with free oxygen.

These chemosynthetic or "chemolithotrophic" (lith-= stone, mineral; troph-= nourish) organisms have been known to microbiologists for some time. Their contribution to the primary production of organic matter in ecosystems, however, has never proved to be substantial. Since hydrogen sulfide is found predominantly in the oxic/anoxic interfaces of marine basins — such as observed in the Black Sea, the Cariaco Trench, or shallow estuarine waters — chemosynthetic production has been studied mainly in these environments. But even in such areas, it always has been found to be negligible in comparison with photosynthetic production.

The source of hydrogen sulfide in those marine environments is primarily a result of biogenic sulfate reduction, another microbial process. This process is driven by energy derived from the oxidation of organic matter originally produced by photosynthesis, that is, solar energy. In contrast, the sulfide content of volcanic fumaroles and hot springs found on the continents is of geothermic origin. At high temperatures and pressures, sulfur and other elements are leached from rocks and emerge at the surface dissolved in the spring water. Thus geothermic energy is converted into geochemical energy by "reducing" these elements — that is, combining them with hydrogen or electrons as in $S^\circ \rightarrow H_2S$ (sulfur→hydrogen sulfide). When these potential electron sources meet with free oxygen, the energy is recovered in the oxidation process. The chemosynthetic bacteria use sulfide, the origin of which can be traced back to the expenditure of either solar or geothermic energy.

The Galápagos Rift Thermal Springs

The notion that chemosynthetic production amounts to only a negligible or small fraction of an ecosystem was shattered when the first deep-sea thermal springs were discovered. The geological, geochemical, and biological aspects of this discovery were published in *Oceanus*, Vol. 20, No. 3 and Vol. 22, No. 2, and by Corliss and others, 1979. In essence, these submarine thermal vents found at a depth of 2,550 meters were surrounded by thick clusters of unusually large specimens of mussels (Figure 2), clams, vestimentiferan tube worms, and many other known and unknown invertebrates. It was hard to imagine that these dense populations, tightly concentrated around the vents almost two miles below the surface, could be directly or indirectly supported by photosynthetically produced organic matter.

Since the water emitted from the vents had a milky appearance and was found to contain hydrogen sulfide, it was readily suspected that chemosynthesis was the primary source of organic nutrients. Thus, it was hypothesized that the food chain began with the production of bacterial biomass, which led to the massive but highly localized animal communities. The preliminary microbiological work done during the January 1979 expedition to the Galápagos Rift area confirmed that there is, indeed, a high production of bacterial biomass in the water emitted from the vents (Jannasch and Wirsen, 1979). Up to a million bacterial cells (Figure 3) per cubic centimeter of water were found. The actual number is probably much higher since the sample was collected 1 meter above a vent where the emitted water is already diluted by ambient seawater.

In addition, the concentration of ATP (adenosine triphosphate), used as an indirect measure of living microbial biomass, was found to be two to four times higher than in the surface waters inhabited by phytoplankton of the same region, and two to three orders of magnitude higher than in deep water sampled some distance away from the vents (Karl and others, 1979). Some 200 strains of bacteria were isolated and are now under study, all of them capable of oxidizing sulfur compounds. Some of the other chemosynthetically oxidizable compounds mentioned previously are also found in the vent waters. The mere abundance of sulfur compounds leads us to conclude that the major portion of chemosynthesis is carried out by sulfur-oxidizing bacteria.

The mussels and clams (and, in one vent, the

Figure 2. The turbidity in the water emitted from the Galápagos Rift vents is primarily caused by oxidation of hydrogen sulfide to colloidal and particulate sulfur and by the chemosynthetic production of bacterial cells. Large mussels of up to 20 centimeters in length cluster around the vents. (Photo by J. F. Grassle)

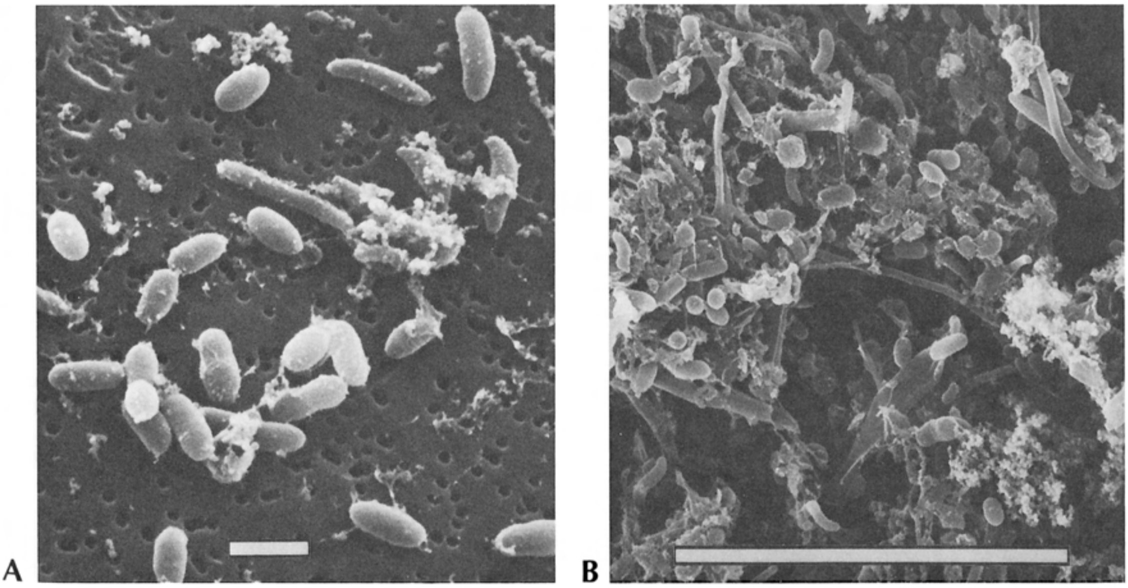

Figure 3. Scanning electron micrographs of the suspended matter in the turbid water collected from one of the Galápagos Rift vents on a Nucleopore filter. A: freely suspended bacterial cells (bar=1 micron); B: surface section of a large clump, containing bacterial cells and amorphous material, primarily sulfur (bar=10 microns). (From Jannasch and Wirsen, 1979; photo by E. Seling)

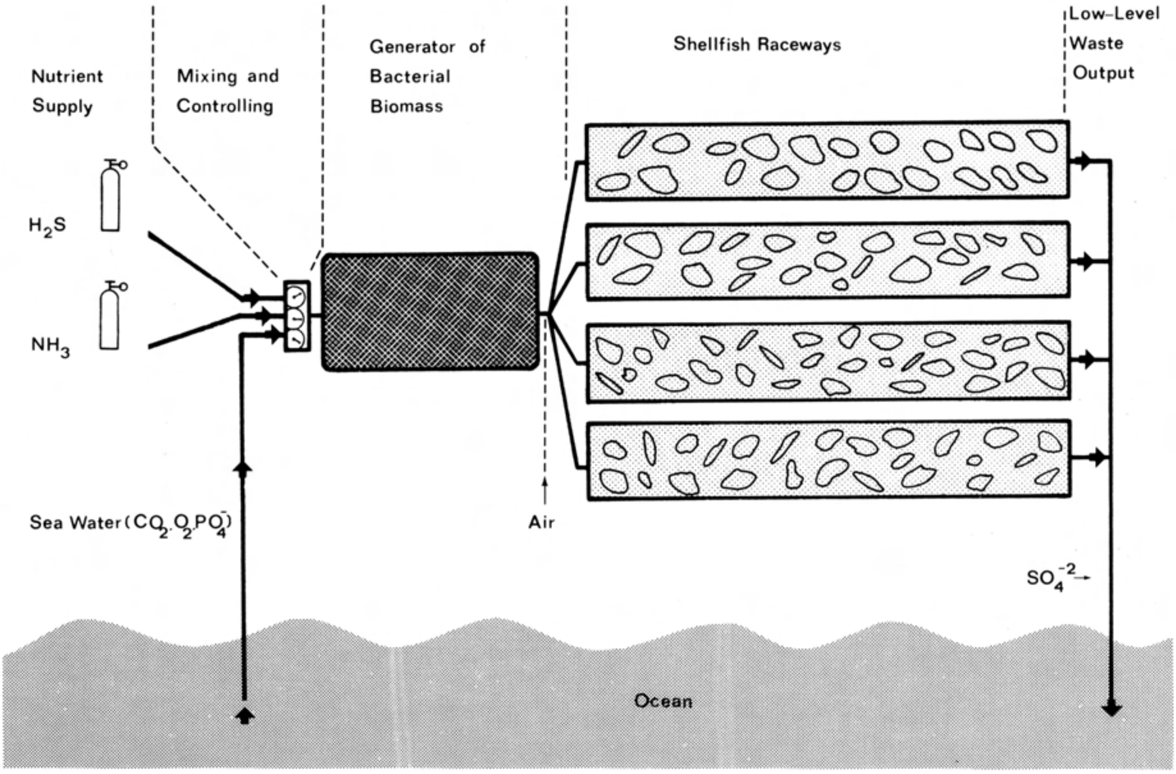

Figure 4. Plan of aquaculture system based on the oxidation of hydrogen sulfide by chemosynthetic bacteria.

vestimentiferan tube worms) are by far the most conspicuous and massive of the animal populations surrounding the vents. They appear to constitute the largest portion of biomass originated by secondary production. All our observations, including those on gut materials and a comparative study of carbon isotope ratios in chemosynthetic bacteria and mussel tissue (Rau and Hedges, 1979), indicate that the bivalves are able to feed on bacteria directly. Karl K. Turekian and his colleagues at Yale University have estimated (1979) the age of a clam 22 centimeters long at 6½ years, indicating a substantial growth rate.

Chemosynthesis for Aquaculture

From here it is not very far to the idea of using a similar chemosynthetic system for aquaculture. An experimental pilot plant is being built at the Environmental Systems Laboratory of the Woods Hole Oceanographic Institution, under the direction of C.D. Taylor, C.L. Winget, and the author.

The first task, after extensive experimentation, is to design an efficient and trouble-free generator of bacterial biomass. The technical requirements of mixing and controlling the proportions of the liquid and gaseous constituents pose no problem. Figure 4 schematically presents the major parts of such a system.

The fact that shellfish are able to grow on a bacterial diet appears to be amply demonstrated by the populations found around the Galápagos vents. A critical point in our endeavor will arise when it is determined whether or not the system can be run with organisms (bacteria as well as shellfish) occurring in surface waters. Strains of microorganisms from the Galápagos Rift vents are readily available, but whether spat from the deep-sea shellfish will be able to develop at normal pressure is unknown at this time. Small temperature changes may not be detrimental since those measured in the immediate vicinity of the vents ranged from 2.1 (ambient) to 12 degrees Celsius.

Since light is a free source of energy and water a convenient source of electrons, what would be the advantage of a chemosynthetic aquaculture system over one run by photosynthesis? Light is a variable source of energy, and the response of a mixed population to variable growth conditions is complex and often irreproducible. In a chemosynthetic system, all environmental factors could be kept constant. The temperature could be maintained at an optimal level by insulation or installing the plant underground.

Experiments with the regulation of flow rates of the individual ingredients concern the control of spontaneous oxidation of hydrogen sulfide, the removal of bacterial mats growing on surfaces, and other features of the system. The ability to control conditions could enable us to limit the complexity of the microbial population to such a degree that a very efficient application of a suitable nitrogen source would be possible. In our present experimental project, ammonia is used, which does not preclude the use of other nitrogen sources in later modifications of the system.

What is the advantage of using hydrogen sulfide? It is relatively inexpensive and easily available, and it has never been considered as a possible resource. It is a troublesome waste product of most mining industries. According to a recent book (1979) by John Hunt of the Woods Hole Oceanographic Institution, deeper drilling for natural gas has resulted in higher quantities of hydrogen sulfide — in some cases up to 90 percent. Too expensive as a source for commercial sulfur products, it is most often incinerated and blown into the atmosphere as sulfur dioxide. As such, it is adding considerably to the acid rain pollution. Under these circumstances, any potential use of hydrogen sulfide is of interest. If a use is established, its procurement could be simplified.

Since hydrogen sulfide has a bad odor, a logical question is whether the shellfish in our experiment are edible. The bacterial biomass will not contain any hydrogen sulfide because it will be completely oxidized from the water before it enters the shellfish raceways. In order to replenish the oxygen needed for shellfish respiration, the raceways will be aerated. This will further guarantee that possible traces of hydrogen sulfide will be completely removed and that the major end product of sulfur oxidation will be primarily sulfate (SO_4^{2-}), which will not be harmful to shellfish or the receiving waters.

At this stage, however, the main concern is whether a chemosynthetic generation of bacterial biomass would be feasible and efficient. Only then will it pay to study its application as food for aquaculture.

Holger W. Jannasch is a Senior Scientist in the Biology Department of the Woods Hole Oceanographic Institution.

References

Ballard, R. D. 1977. Notes on a major oceanographic find. *Oceanus* 20(3): 35-40.

Corliss, J. B., J. Dymond, L. I. Gordon, J.M. Edmont, R. P. von Herzen, R. D. Ballard, K. Green, D. Williams, A. Bainbridge, K. Crane, and T. H. van Andel. 1979. Submarine thermal springs on the Galápagos Rift. *Science* 203: 1073-83.

Galápagos Expedition Biology Participants. 1979. Galápagos '79: initial findings of a biology quest. *Oceanus* 22(2): 2-10

Hunt, J. 1979. *Petroleum geochemistry and geology.* San Francisco, CA: Freeman Co.

Jannasch, H. W., and C. O. Wirsen. 1979. Chemosynthetic primary production at East Pacific sea floor spreading centers. *BioScience* 29: 592-98.

Karl, D. M., C. O. Wirsen, and H. W. Jannasch. 1979. Deep sea primary production at the Galápagos Rift vents. *Science.* In press.

Rau, G. H., and J. I. Hedges. 1979. Carbon-13 depletion in a hydrothermal vent mussel: suggestion of a chemosynthetic food source. *Science* 203: 648-49.

Turekian, K. K., J. K. Cochran, and Y. Nozaki. 1979. Growth rate of a clam from the Galápagos Rise hot spring field using natural radionuclide ratios. *Nature* 280: 385-87.