Evidence for Photosynthesis
Teacher Notes

What is photosynthesis?

Photosynthesis uses a light-harvesting pigment to absorb light and convert this into chemical energy. Light energy is used to remove an electron from the pigment. This electron is picked up by other molecules and used to power cellular metabolism. The electron lost from the pigment must be replaced.

Different types of photosynthesis

Oxygenic photosynthesis replaces the pigment electron with an electron produced by splitting a water molecule (Figure 1). This produces oxygen as a byproduct. Oxygenic photosynthesis is used by plants, eukaryotic algae and cyanobacteria.

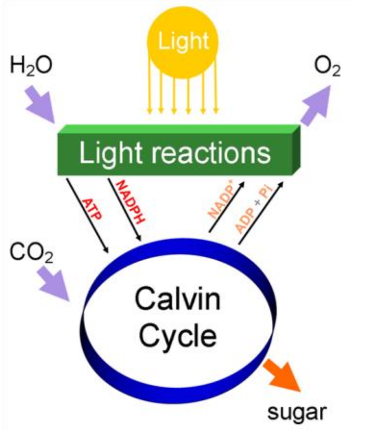

Figure 1: Simplified diagram of oxygenic photosynthesis (D Mayer 2007, Creative Commons)

The most ancient forms of photosynthesis did not produce oxygen. This is known as anoxygenic photosynthesis. Oxygen is not produced as a byproduct because water is not the electron donor. Electron donors for anoxygenic photosynthesis include:

- Hydrogen sulfide (H_2S)
- Elemental sulfur
- Hydrogen (H_2)
- Ferrous iron (Fe^{2+})
- Nitrite (NO_2^-)

Hydrothermal vents and volcanoes would have directly or indirectly supplied these substances. Canfield et al (2006) calculated that an iron-based ecosystem would be the most productive of the anaerobic photosynthetic options (Figure 2). The estimates for iron-based primary production are the best match with observed carbon isotope ratios used to estimate primary production in the Early Archaean.

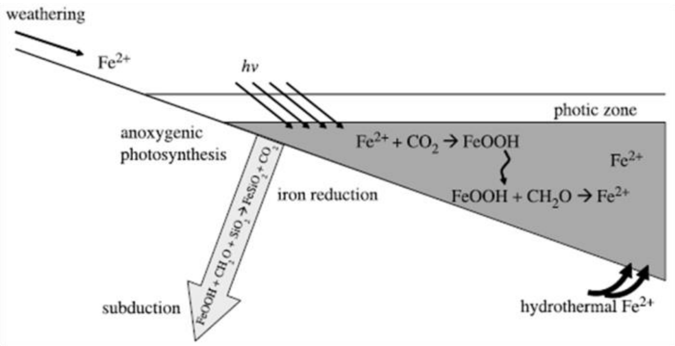

Figure 2: Early Earth iron cycle incorporating anoxygenic photosynthesis from Canfield et al. 2006.

Ecosystems based on oxygenic photosynthesis are 10 times more productive than those using other forms of photosynthesis. Anoxygenic photosynthetic organisms use one of two different photosystems, but oxygenic photosynthesis combines both photosystems. This is evidence of the relatively recent evolution of oxygenic photosynthesis.

Cyanobacteria and oxygenic photosynthesis

It is widely accepted that oxygenic photosynthesis originated in cyanobacteria. Genetic evidence suggests that oxygenic photosynthesis arose at approximately 2.35 Ga (billion years ago). This is consistent with geological evidence for atmospheric oxygen after 2.4 Ga. The oldest definite fossils of cyanobacteria are from 1.9 Ga strata in Canada.

Stromatolites as evidence for photosynthesis

Modern stromatolites

Modern stromatolites are formed by a multi-layered microbial ecosystem that both traps sediment and precipitates carbonate to form distinctive domed structures. Not all microbial mats form stromatolites. Stromatolites are dependent on both the microbial community and local geochemical conditions. The best studied modern stromatolites occur in a variety of habitats: hypersaline Shark Bay, Australia (Figure 3); open ocean Highborne Cay, Bahamas; and freshwater Ruidera Pool, Spain.

Figure 3: Stromatolites in the hypersaline environment of Shark Bay, Western Australia. Oxygen bubbles are visible on the upper surface of the stromatolite.

All modern stromatolites contain cyanobacteria.
However, the most abundant bacteria are in the sub-Phylum *Alphaproteobacteria*. Microbial mats include purple non-sulfur phototrophic bacteria and anaerobic bacteria in deep layers. The hypersaline stromatolites contain at least 17 different types of bacteria, versus ten types in the freshwater stromatolites.

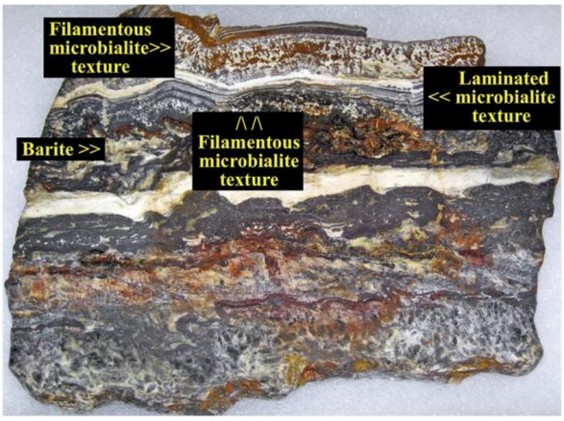

Figure 4: Stromatolite from the 3.48 Ga Dresser Formation of North Pole Dome, Pilbara. This stromatolite formed in a hot spring near a volcanic caldera. (J St John 2019, Creative Commons)

Ancient stromatolites

The Shark Bay stromatolites were described in 1954 and helped scientists interpret the formation of fossil stromatolites. Because of the prominence of cyanobacteria in modern stromatolites, researchers assumed that cyanobacteria were key in the formation of ancient stromatolites. Closer examination of Archean stromatolite fossils does not provide clear evidence of cyanobacteria.

Ancient stromatolites have been recrystallised, destroying possible microfossils. Stromatolites occur in shallow marine areas, suggesting that they hosted photosynthetic bacteria, probably those using anoxygenic photosynthesis. Like their modern counterparts, ancient stromatolites appear to have formed layers by both trapping sediments and depositing carbonates.

Geological evidence of photosynthesis

Ratios of carbon isotopes preserved in marine rock can be used to estimate primary production, e.g. the amount of life in ecosystems. The amount of organic carbon rose significantly at 3.5 Ga. This increase suggests the evolution of photosynthesis and the ability to use abundant carbon dioxide for metabolism. The estimated rates of primary production based on observed carbon ratios fit best with models of anaerobic photosynthesis using iron (photoferrotrophism) as the first mode of photosynthesis.

Remains of microbial mats found in 3.4 Ga cherts are restricted to areas that would have received light. Isotopic analysis of these layers is consistent with photosynthesis or chemosynthesis. The location in shallow water provides indirect evidence that these mats were mainly composed of photosynthetic microbes. Evidence from stromatolites provides similar support for photosynthesis at that time.

Banded Iron Formations (BIFs) were once considered evidence of the rise of oxygenic photosynthesis. However, more recent research suggests that photoferrotrophy and/or chemical processes may have led to the initial phases of BIF deposition.

References:

Allwood AC, Grotzinger JP, Knoll AH, Burch IW, Anderson MS, Coleman ML, Kanik I (2009). Controls on development and diversity of Early Archean stromatolites. *PNAS* **106**(24): 9548-9555.

Camacho A, Walter XA, Picazo A, Zopfi J (2017). Photoferrotrophy: remains of an ancient photosynthesis in modern environments. *Frontiers in Microbiology* **8**: 323. doi: 10.3389/fmicb.2017.00323 (Open Access)

Canfield DE, Rosing MT, Bjerrum C (2006). Early anaerobic metabolisms. *Philosophical Transactions of the Royal Society B* **361**: 1819-1836. doi: 10.1098/rstb.2006.1906 (Open Access)

Fischer WW, Hemp J, Johnson JE (2016). Evolution of oxygenic photosynthesis. *Annual Review of Earth and Planetary Sciences*. **44**: 647-683.

Foster JS, Green SJ (2011). Microbial diversity in modern stromatolites. From VC Tewari & J Seckbach (eds.) *Stromatolites: Interaction of Microbes with Sediments*, Cellular Origin, Life in Extreme Habitats and Astrobiology **18**: 383-405. doi: 10.1007/978-94-007-0397-1_17 (Open Access)

Hanada S (2016). Anoxygenic photosynthesis – a photochemical reaction that does not contribute to oxygen reproduction. *Microbes and Environments* **31**(1): 1-3. doi: 10.1264/jsme2.ME33101rh (Open Access)

Lumen Learning (n.d.). Photosynthesis. Accessed 19/6/20 from https://courses.lumenlearning.com/microbiology/chapter/photosynthesis/#:~:text=In%20oxygenic%20photosynthesis%2C%20H2O%20serves%20as%20the%20electron,is%20formed%20as%20a%20byproduct.

Soo RM, Hemp J, Parks DH, Fischer WW, Hugenholtz P (2017). On the origins of oxygenic photosynthesis and aerobic respiration in Cyanobacteria. *Science* **355**: 1436-1440.

Tice MM, Lowe DR (2004). Photosynthetic microbial mats in the 3,416-Myr-old ocean. *Nature* **431**: 549-552.