
AUSTRALIAN
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EDUCATION
Banded Iron Formations
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Cover Slide

What are Banded Iron Formations (BIFs)?

- Large sedimentary structures

Kalmina gorge banded iron
(Gypsy Denise 2013, Creative Commons)

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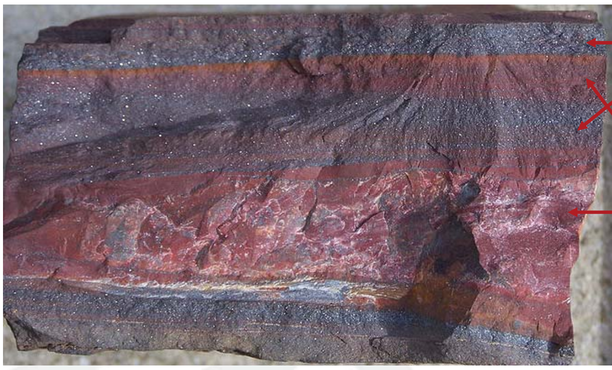
BIFs were deposited in shallow marine troughs or basins. Deposits are tens of km long, several km wide and 150 – 600 m thick.

Photo is of Kalmina gorge in the Pilbara (Karijini National Park, Hamersley Ranges)

What are Banded Iron Formations (BIFs)?

- Large sedimentary structures
- Bands of iron rich and iron poor rock



Iron rich bands: hematite (Fe_2O_3), magnetite (Fe_3O_4), siderite ($FeCO_3$) or pyrite (FeS_2).

Iron poor bands: chert (fine-grained quartz) and low iron oxide levels

Rock sample from a BIF (Woudloper 2009, Creative Commons 1.0)

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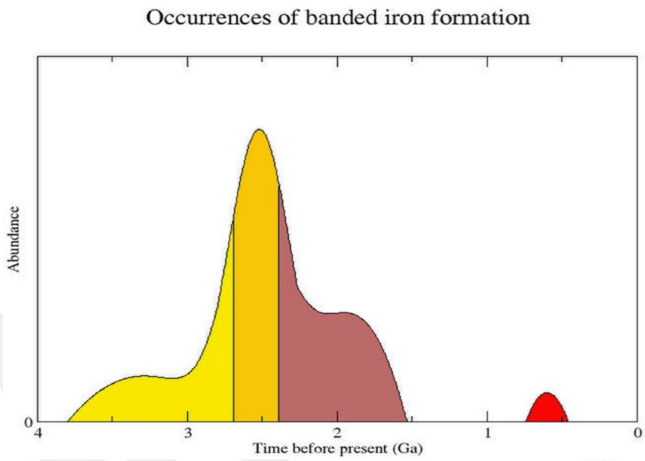
Iron rich bands are composed of hematitie (Fe_2O_3), magnetite (Fe_3O_4), siderite ($FeCO_3$) or pyrite (FeS_2). The iron poor bands contain chert (fine-grained quartz) with lesser amounts of iron oxide.

What are Banded Iron Formations (BIFs)?

- Large sedimentary structures
- Bands of iron rich and iron poor rock
- Archaean and Proterozoic in age



BIF formation through time (KG Budge 2020, public domain)

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BIFs were deposited for 2 billion years during the Archaean and Proterozoic. There was another short time of deposition during a Snowball Earth event.

Why are BIFs important?

- Iron ore exports are Australia's top earner, worth $61 billion in 2017-2018
- Iron ore comes from enriched BIF deposits

Rio Tinto iron ore shiploader in the Pilbara (C Hargrave, CSIRO Science Image)

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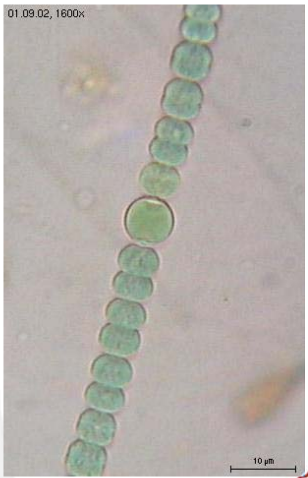
Australia is consistently the leading iron ore exporter in the world. We have large deposits where the iron-poor chert bands have been leached away, leaving 40%-60% iron.

The old story for the formation of BIFs

- Cloud (1973) explained BIFs as evidence of photosynthesis carried out by cyanobacteria



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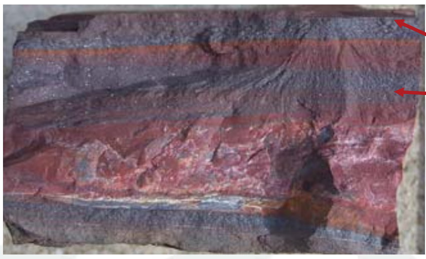
Scientists agree that cyanobacteria were the first organisms to carry out oxygenic photosynthesis. This is the type of photosynthesis where oxygen is a waste product. The oxygen is produced when a water molecule is split to provide an electron for the chemical reactions involved in photosynthesis.

Cloud P (1973). Paleoecological significance of the banded iron-formation. *Economic Geology* **68**(7):1135-1143.

The old story for the formation of BIFs

- Cloud (1973) explained BIFs as evidence of photosynthesis carried out by cyanobacteria
- The oxygen byproduct combined with dissolved iron ions (Fe^{2+}) to form the iron oxides (Fe_2O_3, Fe_3O_4) in iron rich bands

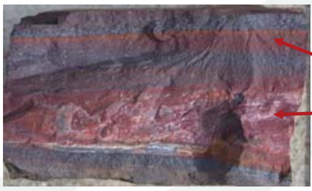


Iron rich bands: hematite (Fe_2O_3), magnetite (Fe_3O_4), siderite ($FeCO_3$) or pyrite (FeS_2).

Although often simplified as iron + oxygen → iron oxide, the true reactions are much more complex. Iron first forms iron hydroxide ($Fe(OH)_2$ and subsequent reactions lead to hematite and magnetite formation.

The old story for the formation of BIFs

- Cloud (1973) explained BIFs as evidence of photosynthesis carried out by cyanobacteria
- The oxygen byproduct combined with dissolved iron ions (Fe^{2+}) to form the iron oxides (Fe_2O_3, Fe_3O_4) in iron rich bands
- Local accumulations of oxygen would kill off cyanobacteria, leading to deposition of iron poor bands



Iron poor bands: chert (fine-grained quartz) and low iron oxide levels

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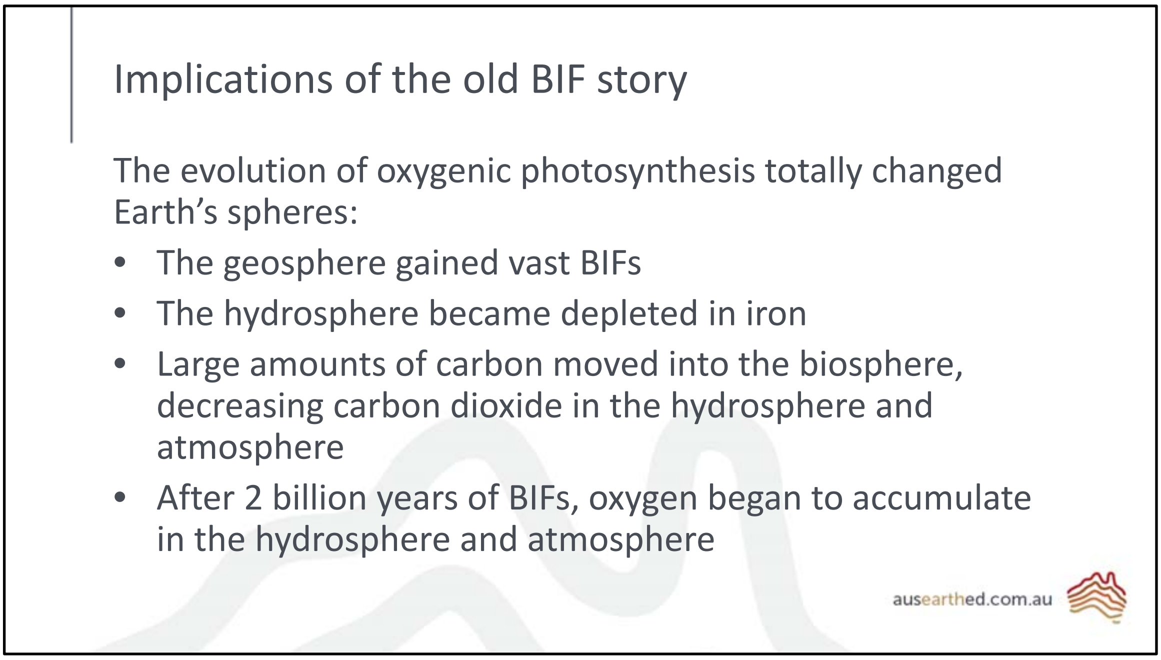
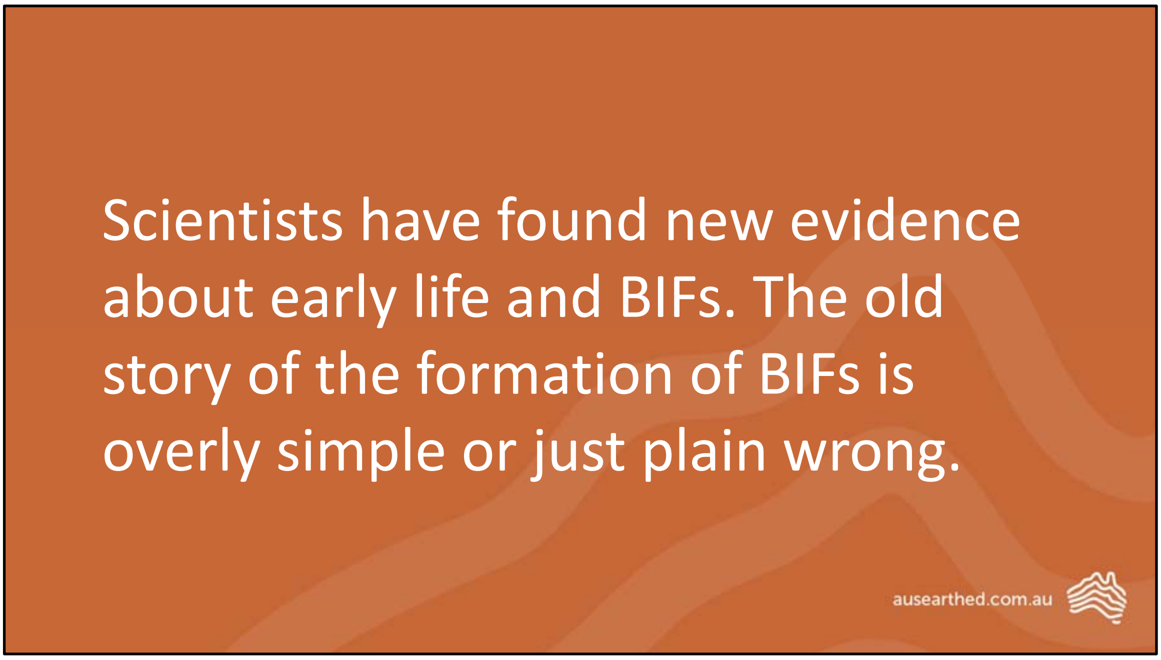
The presence of iron poor bands could be produced by

1. a local depletion of iron due to lower activity of deep sea hydrothermal vents and/or terrestrial weathering, OR
2. die off of cyanobacteria due to excess oxygen production.



This story is a very neat explanation of how Earth's systems are interrelated and how an evolutionary innovation (oxygenic photosynthesis) can have a profound effect on all of them. This story features prominently in the NSW EES Syllabus (along with those of other states) and is frequently examined. Unfortunately, it is old and outdated.



New ideas are more complicated, but interesting!

Problems with the old story of BIFs

1. BIFs are very old and have been altered
2. Iron oxide can be produced without O_2
3. There are many types of photosynthesis

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BIF Outcrop (RM Coveney, Jr 2009, Creative Commons 3.0)

Content Slide

BIFs are very old and have been altered

- Physical and chemical changes to rock have occurred due to the processes of diagenesis (sedimentary rock formation), fluid flow and metamorphism

3.8 Ga graphitic banded iron from Greenland. The graphite was produced by metamorphic decomposition of iron carbonates and other minerals (J St John 2010, Creative Commons)

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During diagenesis, the sedimentary layers are compacted and dewatering begins to occur. Fluid flowing through layers may dissolve the silica, leaving behind iron compounds. The heat of metamorphism (>400°) can cause iron silicates and carbonates to become magnetite. Lower heat (200-300°) plus water will have the same effect. Many BIFS have folds, suggesting regional metamorphic events.

BIFs are very old and have been altered

- Physical and chemical changes to rock have occurred due to the processes of diagenesis (sedimentary rock formation), fluid flow and metamorphism
- Greenalite (iron silicate) is probably the original mineral of BIFs

Galena (silver-grey) crystals with siderite and greenalite (Bergminer 2020, Creative Commons 4.0)

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Rasmussen and colleagues carried out electron microscopy studies of chert nodules in BIFs from Australia and South Africa to determine what the original minerals were. Chert is resistant to fluid, so it is more likely to preserve the original minerals. They found that greenalite (iron silicate) was the most likely mineral. Magnetite cut across other grains and was clearly a replacement product.

The green and brown crystals of greenalite and siderite shown in the photo are typical of the original minerals found in banded iron formations.

Rasmussen B, Muhling JR (2018). Making magnetite late again: evidence for widespread magnetite growth by thermal decomposition of siderite in Hamersley banded iron formations. *Precambrian Research* **306**: 64-93.
Rasmussen B, Muhling JR, Suvorova S, Krapež B (2017). Greenalite precipitation linked to the deposition of banded iron formations downslope from a late Archean carbonate platform. *Precambrian Research* **290**: 49-62.

Iron oxide can be produced without oxygen gas (O_2)

- Oxygen compounds can be formed without the presence of oxygen molecules (O_2)
- Iron silicates ($Fe_3Si_2O_5OH_4$) and carbonates ($FeCO_3$) lose silicon or carbon atoms during metamorphism and heat flow, producing iron oxides (Fe_2O_3, Fe_3O_4)

Magnetite crystals (S Sepp 2007, Creative Commons 2.5)

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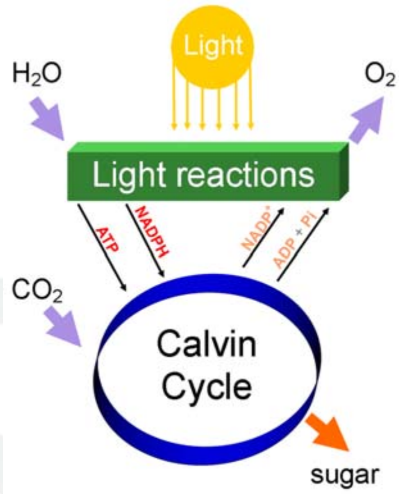
Oxidation is a chemical process that involves the loss of electrons. This can occur without the involvement of O_2. As noted in the previous slide, silicate and carbonate minerals may be altered to form hematite and magnetite.

There are many types of photosynthesis

- Oxygenic photosynthesis uses water as an electron donor and produces oxygen as a waste product



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

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Oxygenic photosynthesis uses energy from light to remove an electron from a light-harvesting pigment. The electron powers the light reactions and must be replaced. A water molecule is split to replace the electron and oxygen is produced as a byproduct. Cyanobacteria are the only bacteria that use this process.

There are many types of photosynthesis

- Oxygenic photosynthesis uses water as an electron donor and produces oxygen as a waste product
- Anoxygenic photosynthesis may use
  - Hydrogen sulfide
  - Sulfur
  - Hydrogen
  - Ferrous iron
  - Nitrite

Sulfur bacteria live in extreme modern environments such as Morning Glory Pool at Yellowstone National Park (daveynin 2010, Creative Commons)

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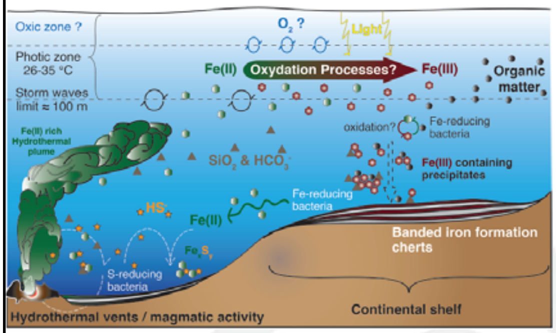
Anoxygenic photosynthesis is the most ancient type of photosynthesis. It is still used by a diverse range of Bacteria and Archaea living in lakes, hot springs and soil. None of the electron donors produce oxygen as a byproduct.

Ferrous iron (Fe^{2+}) is the most efficient of these systems and probably dominated in the early Archaean. Oxidation of ferrous iron causes precipitation of ferric iron (Fe^{3+}) compounds. This type of photosynthesis is observed in some deep lakes and called photoferrotrophy.

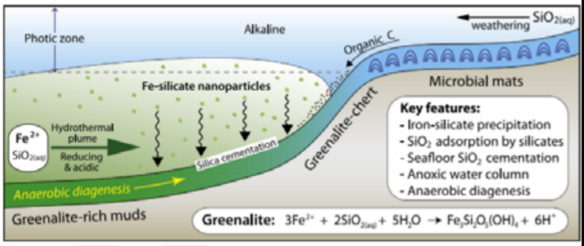
Camacho A, Walter XA, Picazo A, Zopfi J (2017). Photoferrotrophy: remains of an ancient photosynthesis in modern environments. *Frontiers in Microbiology* **8**: 323. doi: 10.3389/fmicb.2017.00323 (Open Access)
Canfield DE, Rosing MT, Bjerrum C (2006). Early anaerobic metabolisms. *Philosophical Transactions of the Royal Society B* **361**: 1819-1836. doi: 10.1098/rstb.2006.1906 (Open Access)

What is the new explanation of BIF formation?

- The story is no longer simple.



Model of BIF formation based on anoxygenic photosynthesis using iron from Camacho et al. 2017.



Model of abiotic deposition of greenalite from Rasmussen et al. 2017.

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At present, there are groups of scientists arguing for both a biological and abiotic origin of BIFs. However, neither group thinks cyanobacteria and oxygen were important – particularly in the early and middle phases of BIF deposition.

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)

Rasmussen B, Muhling JR, Suvorova S, Krapež B (2017). Greenalite precipitation linked to the deposition of banded iron formations downslope from a late Archean carbonate platform. *Precambrian Research* **290**: 49-62.

What is the new explanation of BIF formation?

- The story is no longer simple.
- Ocean chemistry changed radically over 2 billion years, favouring different types of iron deposition at different times.

Artist's impression of the Archean Earth (NASA/Goddard Space Flight Center/ Francis Reddy 2017, public domain)

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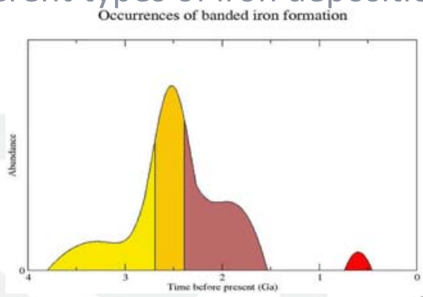
Oceans in the Archaean were high in iron and low in sulfur, favouring the evolution of photoferrotrophy (photosynthesis using iron). Over time, sulfur levels rose and bacteria with sulfur metabolisms would have been favoured. It is very likely that multiple factors were active at different times.

Abiotic precipitation offers the simplest explanation for deposition of BIFs (Occam's Razor). The proponents of this theory state that it is dependent on pH, which would have varied on a variety of timescales.

What is the new explanation of BIF formation?

- The story is no longer simple.
- Ocean chemistry changed radically over 2 billion years, favouring different types of iron deposition at different times.
- Cyanobacteria and oxygen were late factors in BIF deposition.



BIF formation through time (KG Budge 2020, public domain)

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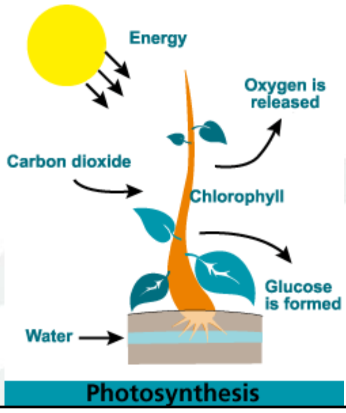
Genetic studies of a range of cyanobacteria have suggested that oxygenic photosynthesis arose very close to the time of the Great Oxygenation Event (2.3 billion years ago). This corresponds with the last phase of BIF deposition (brown on graph). These BIFs have a granular composition, quite different from earlier deposits.

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.

Did the evolution of photosynthesis cause massive change?

- Yes! Just in a different way than was originally taught.



(Riyasachdeva250 2016, Creative Commons)

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Although the simple story of BIFs is now replaced, the evolution of oxygenic photosynthesis changed Earth profoundly.

Did the evolution of photosynthesis cause massive change?

- Yes! Just in a different way than was originally taught.
- Oxygenic photosynthesis is the most efficient form of primary production (10x more than other methods).

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Oxygenic photosynthesis is a very efficient form of primary production that dramatically increased the amount of carbon in the biosphere.

Did the evolution of photosynthesis cause massive change?

- Yes! Just in a different way than was originally taught.
- Oxygenic photosynthesis is the most efficient form of primary production (10x more than other methods).
- The release of oxygen changed minerals on land, created the ozone layer and caused a mass extinction.

Grand Canyon redbeds (T Hisgett 2014, Creative Commons)

Minerals formed by reactions with oxygen were formed on land (continental redbeds) due to the release of oxygen in the atmosphere. The ozone layer began to form as oxygen levels increased. Oxygen was toxic to most organisms, so they died as a result of increasing oxygenation of the oceans and atmosphere. Those that developed aerobic respiration were able to outcompete anaerobic organisms because of increased metabolic efficiency.


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