



Economic Geology: Lecture Notes

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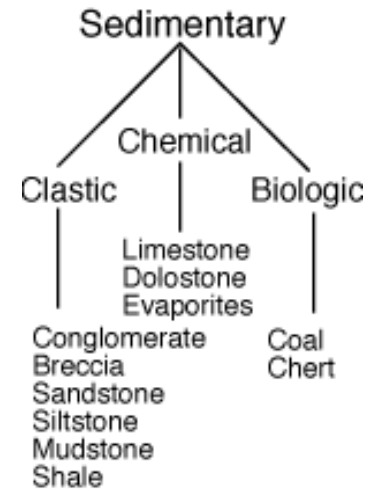
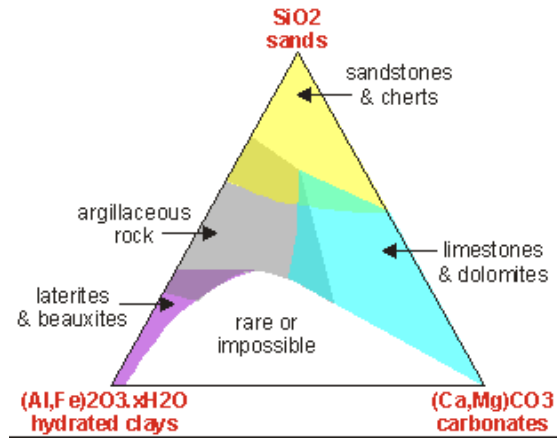
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Sedimentary Ore Deposits

The processes of **sedimentation** include **physical, chemical and biological components**. The prevailing regime lends its name to the major subgroups of sediments and sedimentary rocks: mechanical, chemical and biogenic sediments. Sediments are also classified according to the provenance of the material into **allochthonous** and **autochthonous**.



Allochthonous, are gravel, sand and certain clays. The source of the particles composing these rocks is distant from the deposits where the material was transported. **Metallic ore deposits of this genetic group are called placers. Placers** are mechanical enrichments of heavy and chemically resistant native metals and minerals by flowing or otherwise agitated water.

Rock Type	Rock Name	Method of Formation
Clastic Coarse-grained Medium-grained Fine-grained	Conglomerate or breccia Sandstone Shale	Lithification of clastic sediments
Chemical Calcite Halite Gypsum	Limestone Rock salt Rock gypsum	Precipitation of dissolved minerals from water
Organic Calcium carbonate—shells plant matter	Limestone Coal	Accumulation and lithification of remains of living things

Autochthonous raw material deposits were formed at the site of the deposit. This group includes **chemical precipitates** and **partially biogenic substances** such as:

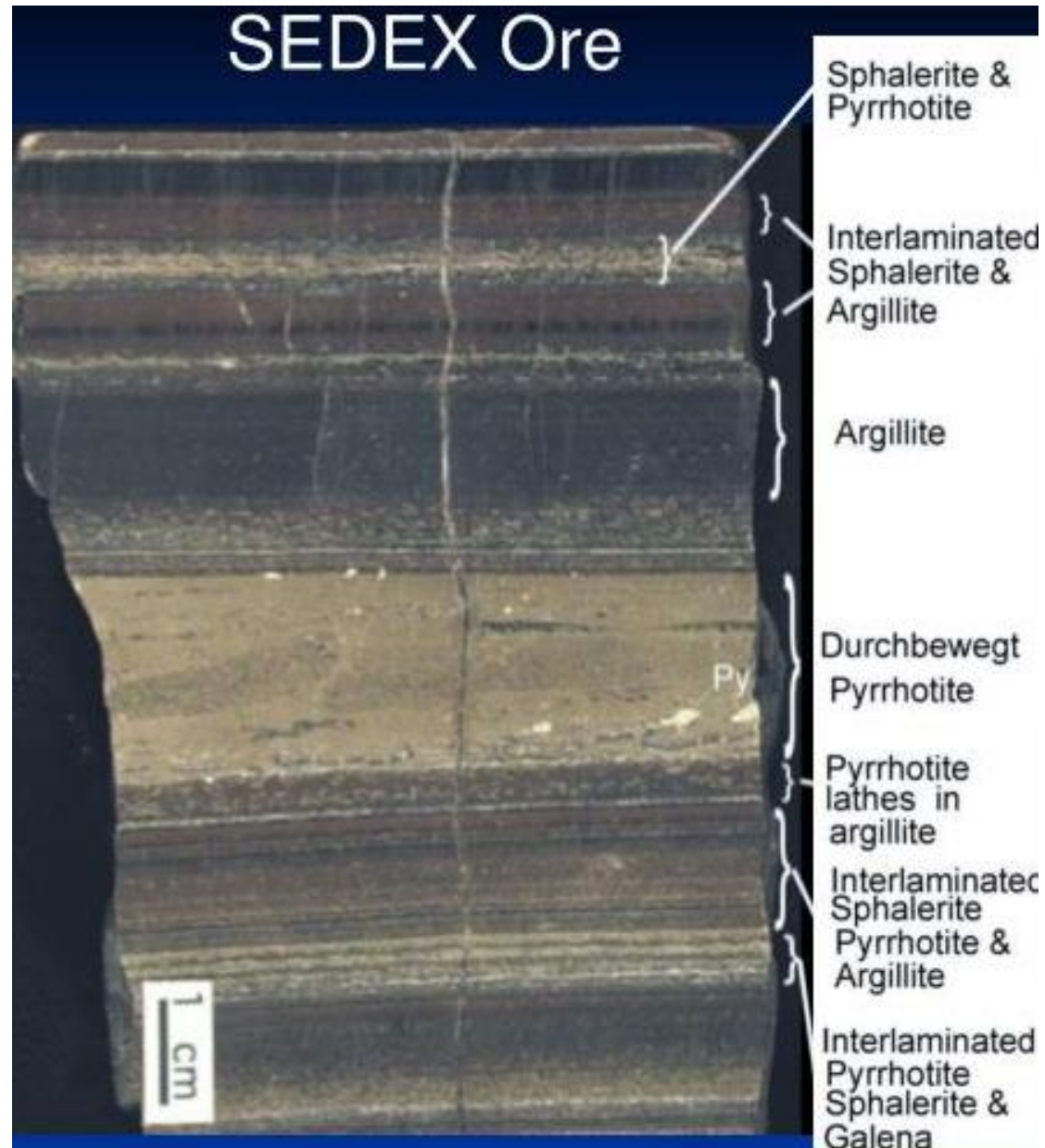
- i) **carbonates** (limestone, dolomite, magnesite);
- ii) **evaporites** (rock salt, potassium salt, gypsum),
- iii) **some massive and oolitic ironstones,**
- iv) **banded iron formations,**
- v) **marine phosphates,**
- vi) **sedimentary sulphide ores and manganese ore beds.**

Organic formation is the prevailing component for **coal, oil shale, diatomite** and for part of the limestones (e.g. chalk). In sedimentology, soils are also considered as autochthonous sediments. However, ore deposits related to soil formation processes were presented in the supergene enrichment.



Many metalliferous sulphide, oxide, carbonate and sulphate deposits originate by **autochthonous sedimentation** following **hydrothermal exhalation**, precipitation of solutes and deposition of ore particles on the seafloor. **Sensu stricto**, all ores with this origin are “sedimentary” (i.e., formed in a sedimentation-dominated environment and distal from contemporaneous volcanism. This is the class of **sedimentary-exhalative (Sedex deposits)**).

Sedimentary ore formation will almost always have a biogenic component. In some cases this is very obvious, for example in phosphate deposits made of bones and coprolites, or a lignite seam composed of fallen trees.



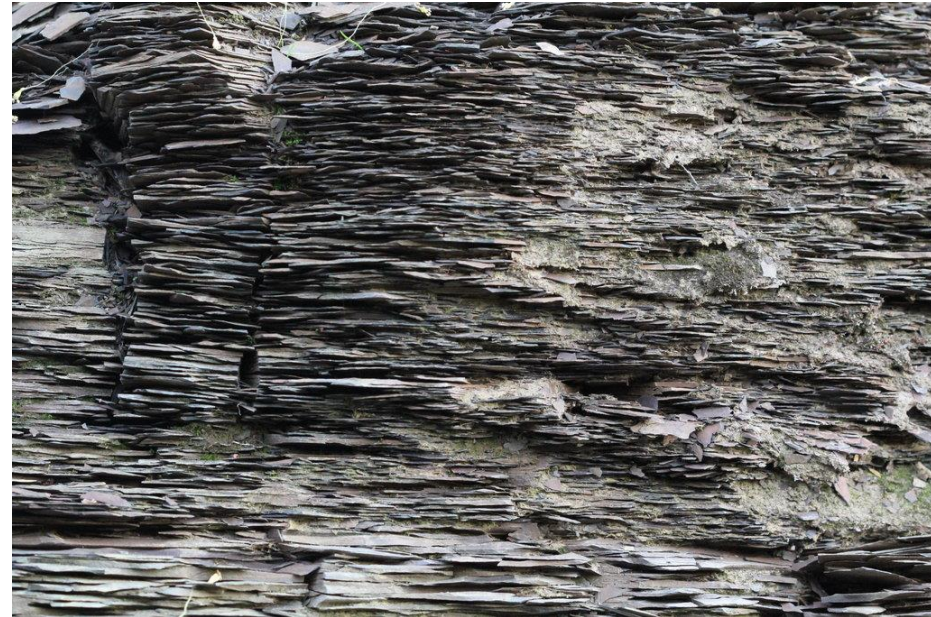
1- Black shales in metallogenesis

Carbonaceous shales are important host rocks of sedimentary ore deposits. They are fine grained laminated clastic sediments consisting variably of quartz, carbonate and clay with **more than 1% of organic matter**. The black shale sedimentary environment is characterized by **low energy, benthic anoxia and often, by euxinic conditions** (associated with stable reduced sulphur species in water above the seafloor).

The enrichment of metals in the **black shales** could be achieved by:

- I. the aid of **organic matter** which binds trace metals **such as Ni, Co, Cu and Zn**;
- II. **reduction**, such as **V, U, Mo and Cr**;
- III. **high biological productivity**, such as **Ba, P and Cd**.

Some black shale deposits are economically important such as the European copper shale and the Central African copper-cobalt shale. Other profitable use is the recovery of the energy inherent in organic matter, either by direct burning or by the production of synthetic oil.



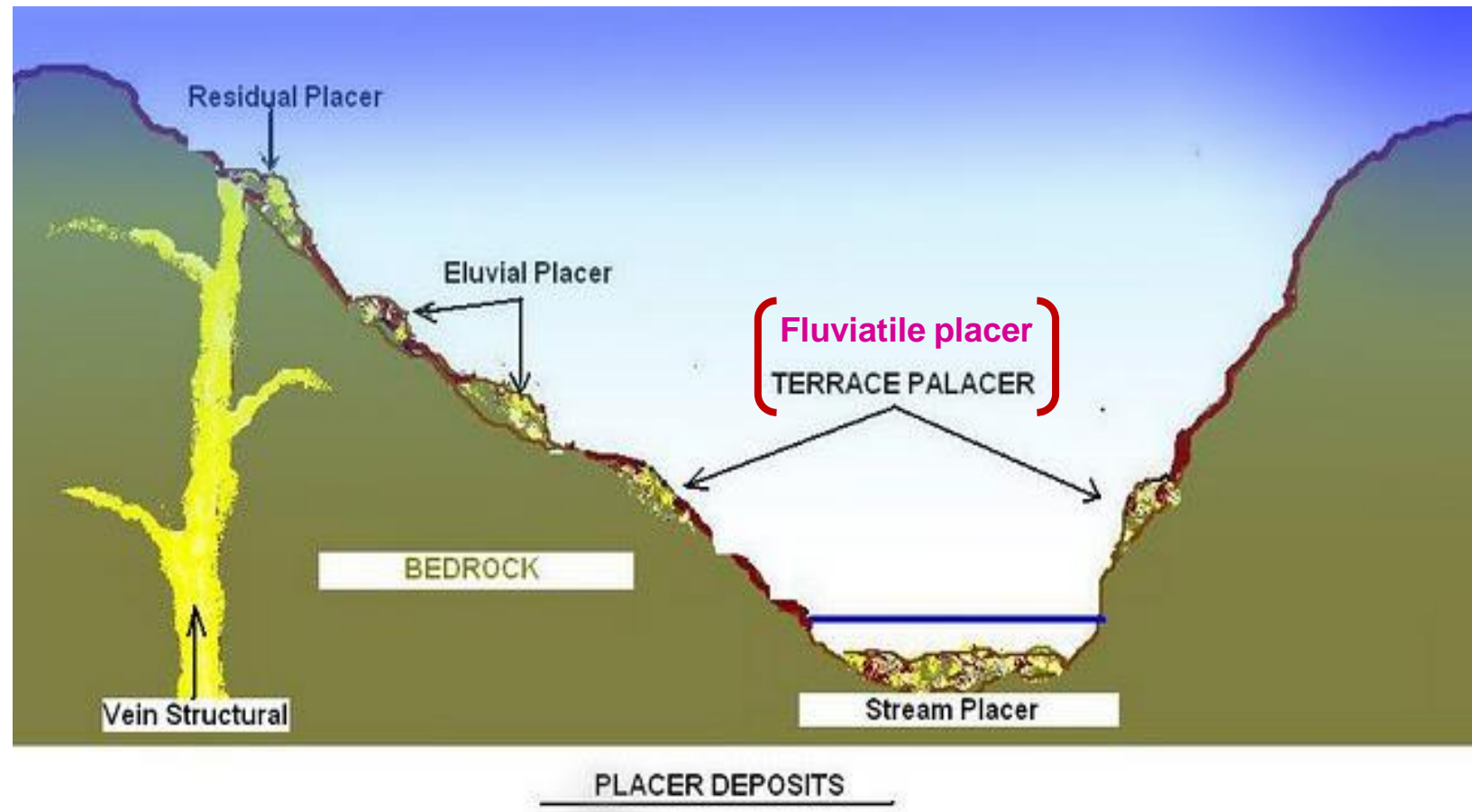
2- Placer deposits

Sedimentary placer deposits are mechanically formed concentrations of heavy, durable minerals that may occur in transported soil or regolith (colluvial), in fluvial and in coastal sediments.



Placer deposits

Placer deposits of economic importance are classified as residual, eluvial, colluvial, fluvatile and coastal. Placers are important sources of gold, platinum metals, tin, titanium (rutile, ilmenite), zircon, rare earth elements (monazite) and gemstones (diamond, garnet, ruby). Precondition of the concentration of placer minerals is their mechanical and chemical durability during weathering and transport and their elevated density compared with the ordinary rock forming minerals.



Lateritic crusts

Laterite, soil



Eluvial sediments

Free gold



Colluvial sediments

Free gold

Gold-quartz-vein

Host rock

River valley; fluvatile sediments

Sterile overburden

Alluvial sediments



Free gold

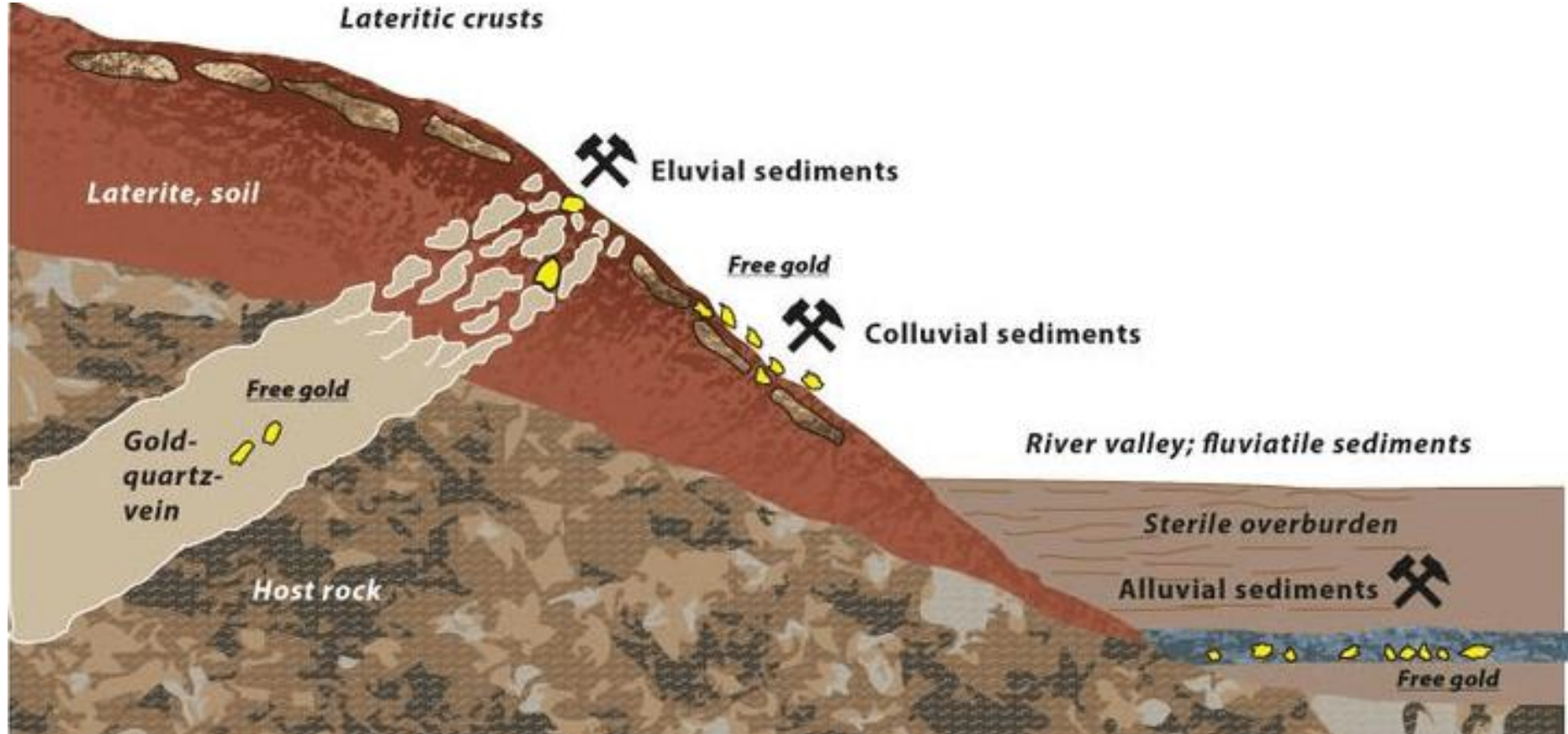
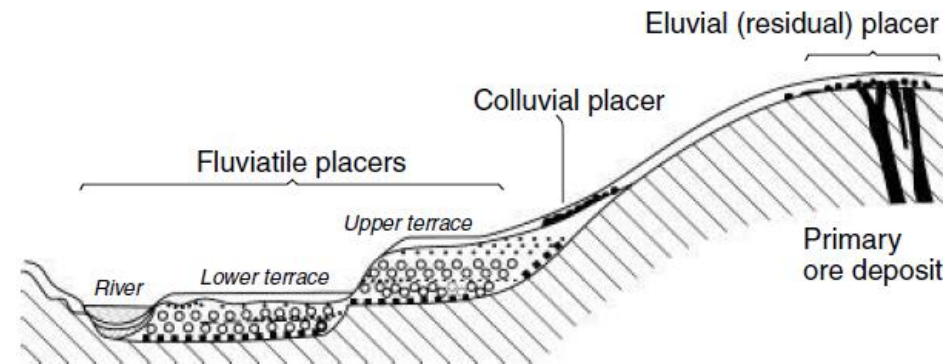


Table 1.4 Density of common placer and gangue minerals (g/cm^3)

Feldspar	2.5–2.8	Monazite	5.2–5.4
Quartz	2.65	Magnetite	5.2
Mafic silicates	ca. 3–4	Columbite	5.2–7.9
Diamond	3.5	Scheelite	5.9–6.1
Topaz	3.5–3.6	Cassiterite	6.8–7.1
Garnet	3.6–4.3	Wolframite	7.0–7.5
Corundum (ruby)	3.9–4.1	Cinnabarite	8.1
Rutile	4.2–4.3	Uraninite	7.5–9.7
Ilmenite	4.5–5.0	Platinum metals	12–21.5
Zircon	4.7	Gold	15–19.3

The density of many minerals varies considerably because of chemical variation. Alloys of native metals vary in composition.

Colluvial placers originate by downslope creep of soil from weathered primary deposits. Heavy minerals move to the base of the regolith, whereas lighter and fine grained fractions are displaced upwards. Orebodies are sheet- or channel-like bodies consisting of ore (e.g. cassiterite) and gangue (quartz) minerals, and of rock fragments. **Colluvial ore minerals** at the foot of a slope can be eroded by rivers and reconcentrated by alluvial processes.



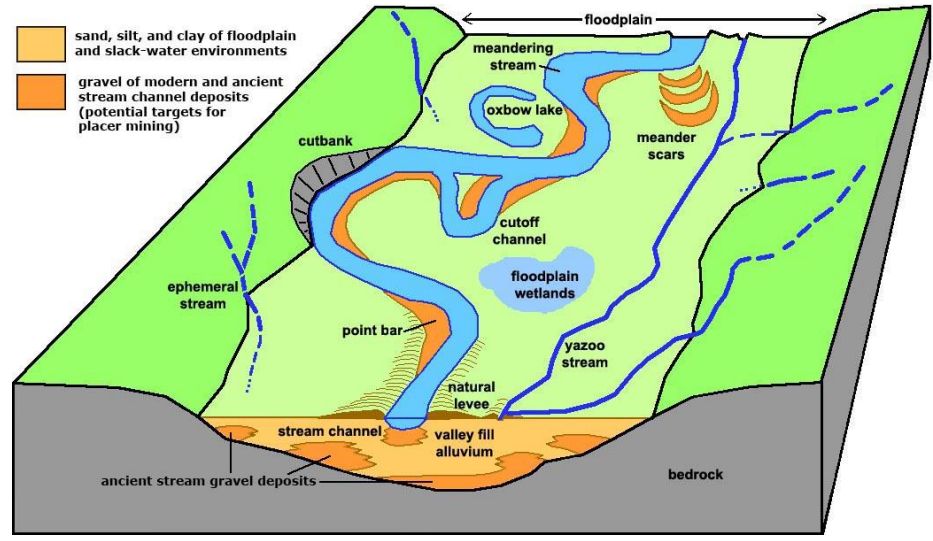
Cross-section of a river valley near an outcropping primary ore deposit, which is the source of residual (eluvial), colluvial and fluviatile placers (black dots).

Fluviatile, or alluvial placers

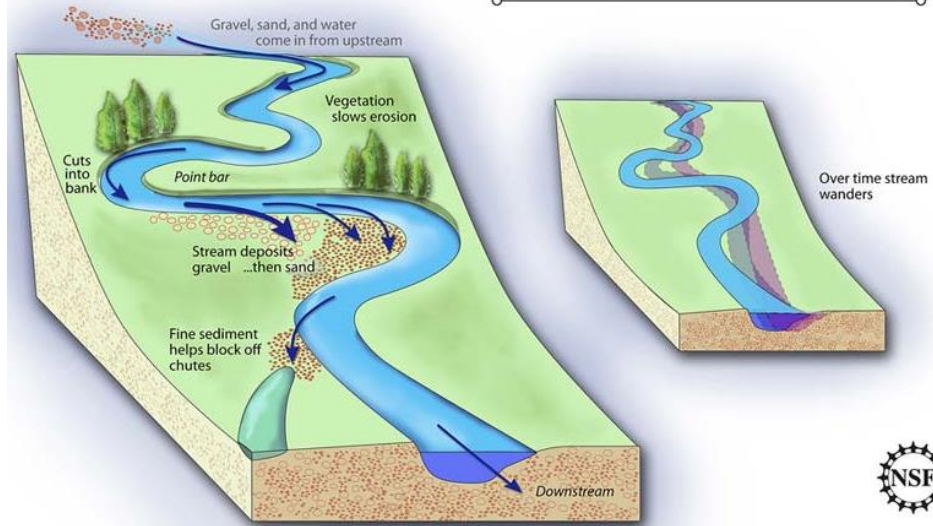
Fluviatile, or alluvial placers occur in active stream channels and in older river terraces. Heavy mineral concentrations form at morphologically well-defined sites, mainly characterized by changes of flow velocity. Such sites include large boulders, rock bars, gravel beds on the inside bank of river bends, the downstream end of gravel and sand islands (point bars), but also reed patches.

Hydraulic equivalence sensu stricto results in concurrent deposition of small high density grains with larger and lighter ones (e.g. fine-grained gold in coarse alluvial gravel).

Geologically young alluvial placers are mainly exploited for gold. Their economic role is feeble, however, compared to the time of the great gold rushes in California in the 19th century.



INGREDIENTS FOR A MEANDERING RIVER



Coastal placers

Coastal placers are mainly formed in surf zones. In contrast to typical alluvial placers, both light and heavy minerals occur roughly in the same grain size that is almost exclusively sand.

The hydraulic equivalence sensu stricto has no role in this environment and the critical factor is mainly entrainment equivalence.

When a wave runs out, sand grains settle for a moment. Return flow to the sea is laminar and only light minerals can be entrained. Heavy minerals are enriched in a narrow linear strip along the beach. Other coastal processes may enhance placer formation including tides, lateral currents, wind and especially storms that induce higher waves.



Many promising **coastal placer deposits** of coarse-grained (90–300 mm) quartz and the heavy minerals rutile, zircon, ilmenite and altered ilmenite (leucoxene) have been outlined.

Coastal placers can consist of up to 80 wt.% heavy minerals. Their contribution of **rutile and zircon** to world markets is of high economic importance. They are lesser sources of **diamond and cassiterite**. **Gold and platinum** are rare in coastal placers.



Autochthonous iron and manganese deposits

Autochthonous iron and manganese ores are chemical, partly biogenic marine sediments. They are marine banded iron and manganese formations and ooidal or massive iron and manganese ore beds.

3- Banded iron formations

Banded iron formations (BIF) are layered, banded (0.5–3 cm) and laminated (<1mm) rocks containing >15% iron. BIF consist of quartz and magnetite layers that form sedimentary units reaching lateral extensions of thousands of Km and a thickness of hundreds of meters.

BIF could be subdivided into three types:

1. Algoma type in submarine volcanic settings;
2. Superior type in marine shelf sediments; and
3. Rapitan type, which is closely related to glaciogenic marine sediments.



Algoma ore BIF is found within volcanogenic sediments such as greywackes, tuffaceous and magmatic volcanic rocks.

Algoma ore beds are less than 50m thick and display a transition from oxide through carbonate and silicate to sulphide facies. Oxide facies iron occurs as magnetite, haematite is rare. In several districts, numerous exhalative centres with sulphides and some larger VHMS deposits punctuate **Algoma BIF** horizons.

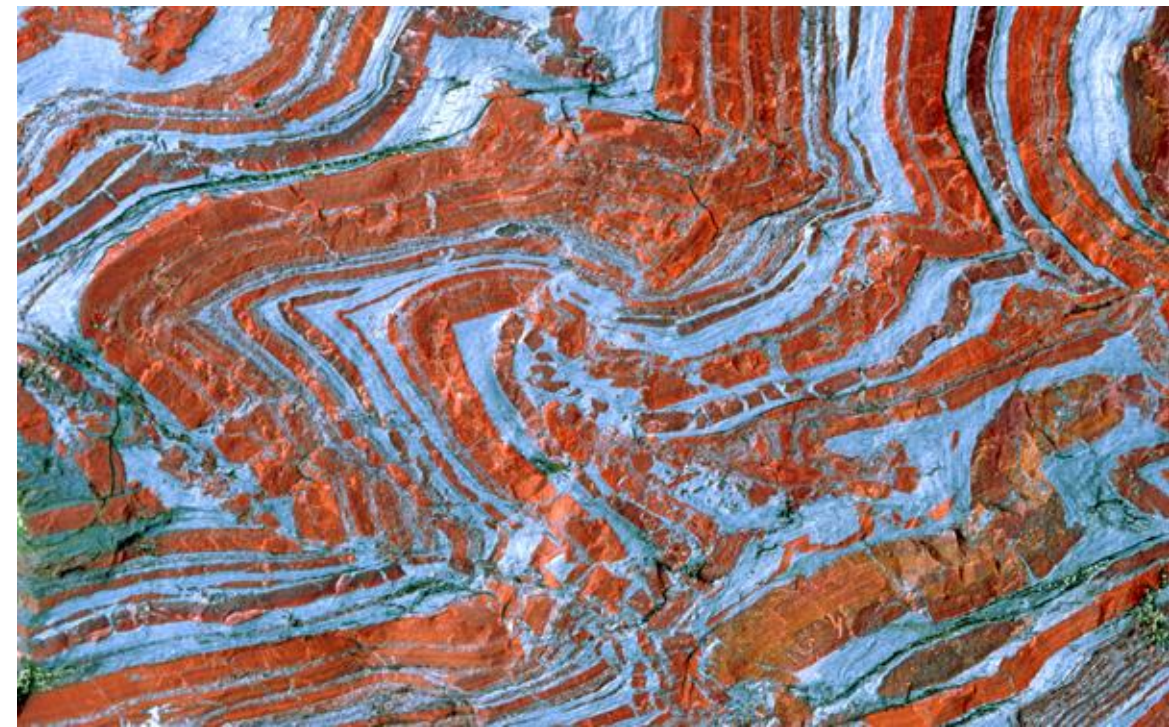
Algoma type BIF is formed on the seafloor by exhalative, hydrothermal-sedimentary processes driven by heat anomalies. Magmatic fluids may also participate in ore formation. Consequently, **Algoma type BIF** ore is essentially volcanogenic ore deposit.



Superior type BIF are hosted in sedimentary sequences that include **black, organic-rich and silicic shale, quartzite and dolomite**, and transgress older basement.

Bimodal volcanic rocks (rhyolite and basalt) may occasionally form part of the country rocks. This indicates **a sedimentary environment of stable continental shelves** covered by relatively shallow seas with some extensional tectonic strain and associated volcanism.

Superior type BIF are **marine sediments of global extension**. They are preserved in remnants of marine basins that reach tens of thousands of square kilometres.

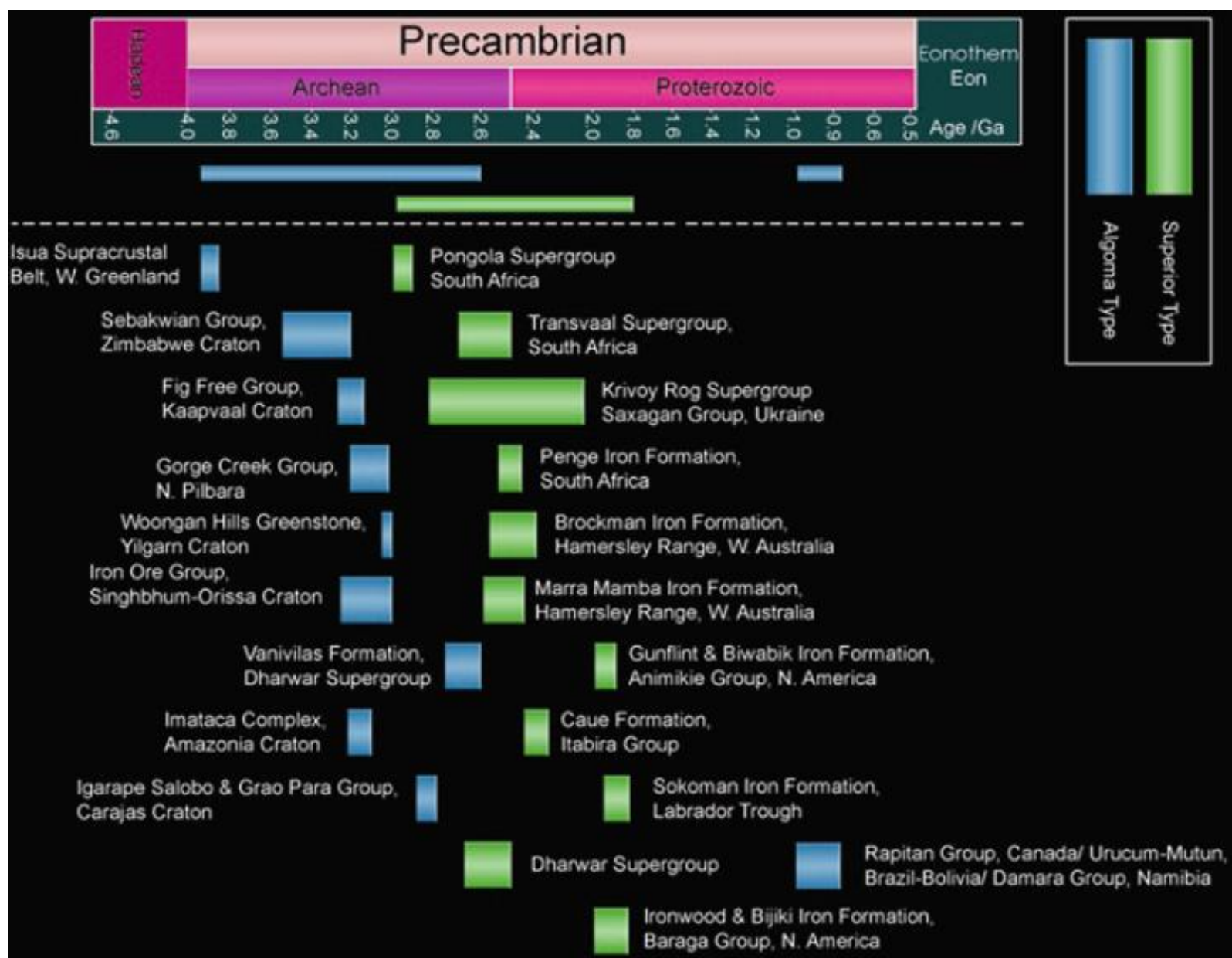


Superior type BIF contain iron in oxide, carbonate and silicate phases; **sulphides are rare**. Iron and SiO_2 were deposited as **fine-grained ooze** (or as a gel).

Primary precipitates were probably amorphous SiO_2 , **ferric hydroxide $\text{Fe}(\text{OH})_3$** and **nontronite** (iron(III) rich member of the smectite group of clay minerals) (near landmasses, **oxic conditions**), or precursors of magnetite, siderite and **greenalite** [$(\text{Fe})_{2-3}\text{Si}_2\text{O}_5(\text{OH})_4$] (far from land; in deeper, anoxic basins) (Origin of BIF comes later).

Superior type BIF have an **$\text{Fe}_2\text{O}_3/\text{SiO}_2$ ratio of 0.98 - 1.26** (which means high silica content), typically **25–45 wt.% Fe**, <3% each of Al_2O_3 , MgO and CaO , and small contents of Mn, Ti, P and S.



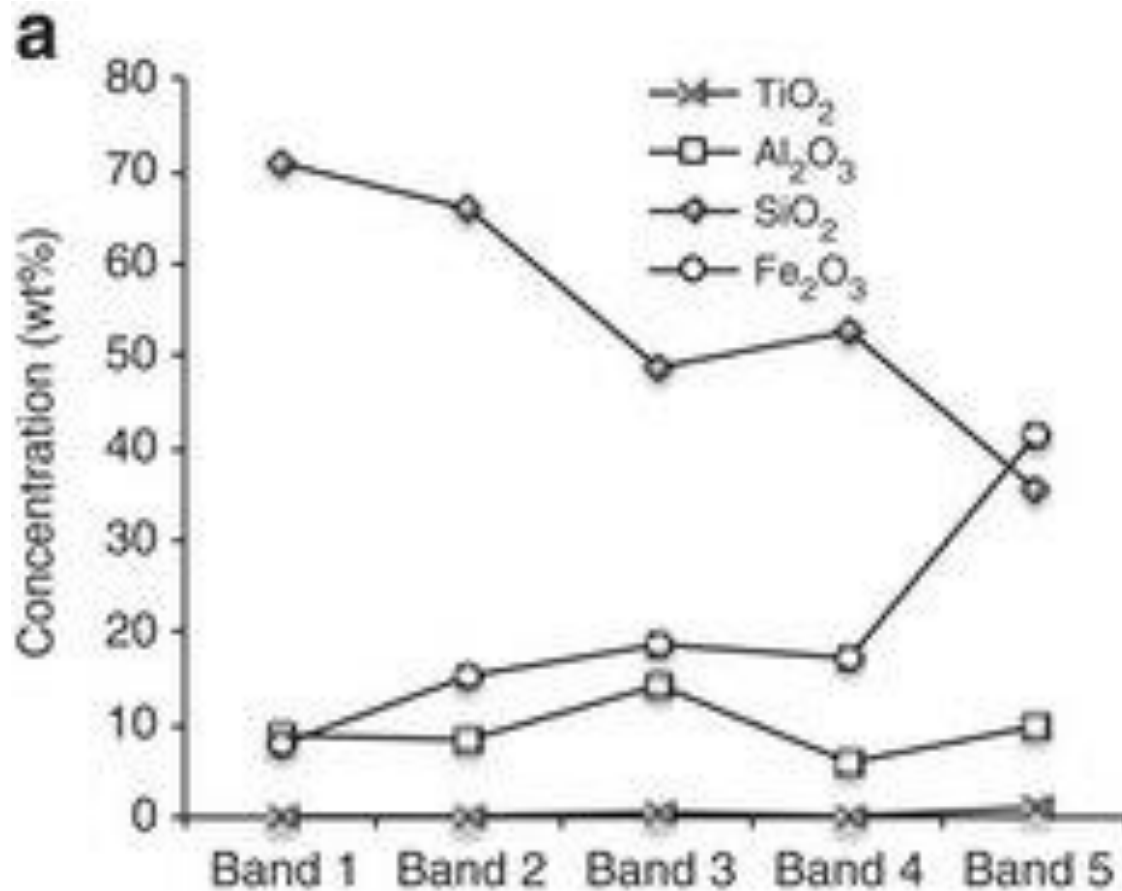


Temporal distribution of Algoma and Superior Type BIF. The Algoma type occur from 3.9 to 2.6 Ga and then again from 1.0 to 0.85 Ga. While the Superior type commonly occur between 1.7 and 3.0 Ga.

In most **BIF-based iron ore mines**, iron was enriched either by:

- i) **supergene enrichment processes** typically resulting in “**martite-goethite ore**” with **60–63 wt.% Fe**; or
- ii) by **hypogene hydrothermal processes** forming “**high-grade haematite ore**”, with **60–68 wt.% Fe**.

Martite is a term that denotes **haematite pseudomorphs replacing magnetite**.



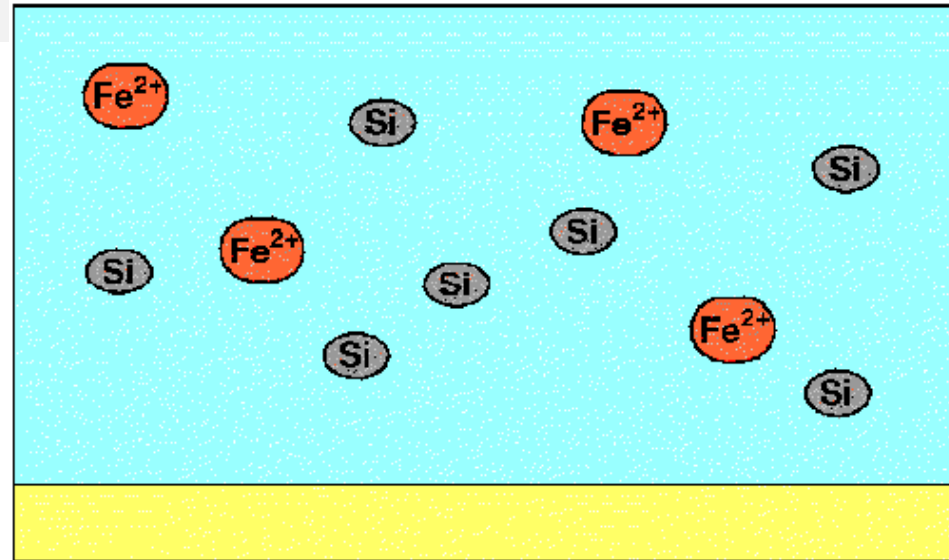
Behaviour of silica, haematite, Al₂O₃ and TiO₂.

Genesis of Banded iron formations

BIFs are sedimentary rocks dating back 3.8 to 1.8 billion years and have alternating layers of iron-rich minerals and a fine-grained silica rock called **chert**. About 3000 million years ago, there was no or very little oxygen dissolved in the oceans, because plants that produce oxygen had not yet evolved. However, the oceans did contain a lot of dissolved silica, which came from the weathering of rocks.

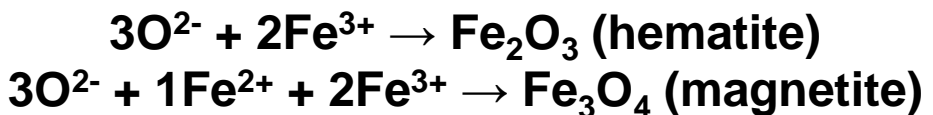
This silica precipitated out from the seawater as layers of silica gel, which slowly hardened to become the rock **chert**. Soluble iron oxide was also produced from the weathering of rocks and was washed into the sea by rivers.

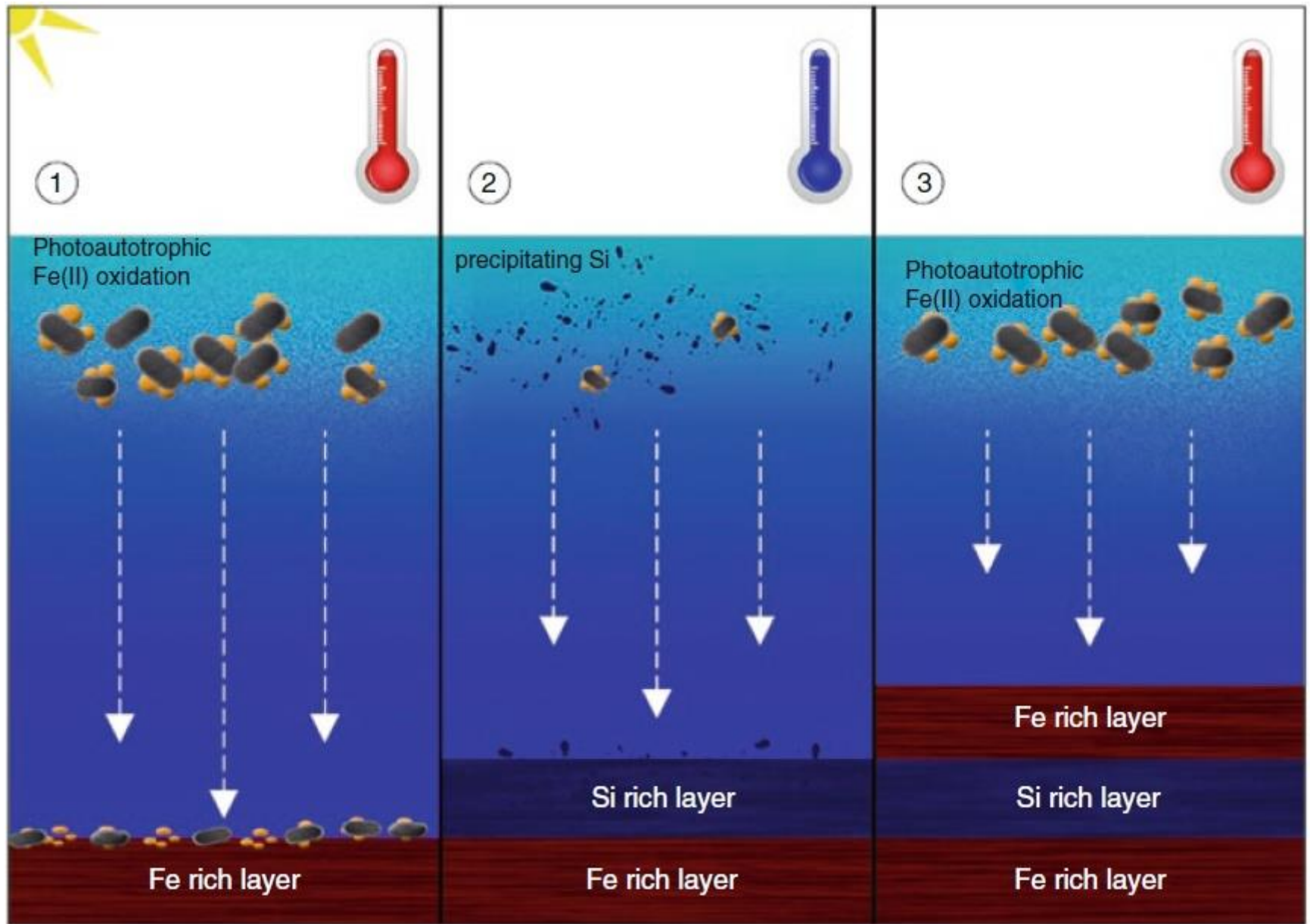
Some 2500 million years ago oxygen-producing life forms started to evolve and oxygen became part of the Earth's atmosphere. In time some oxygen also dissolved in the seawater where it reacted with the soluble iron oxide to form insoluble iron oxide. This precipitated out of solution on the ocean floor as the minerals magnetite (Fe_3O_4) and hematite (Fe_2O_3).



Ocean contains dissolved silica and Fe^{3+}

The deposition of alternating iron-rich and silica-rich mineral layers in the late Fe(II)-rich Archean to early Proterozoic periods



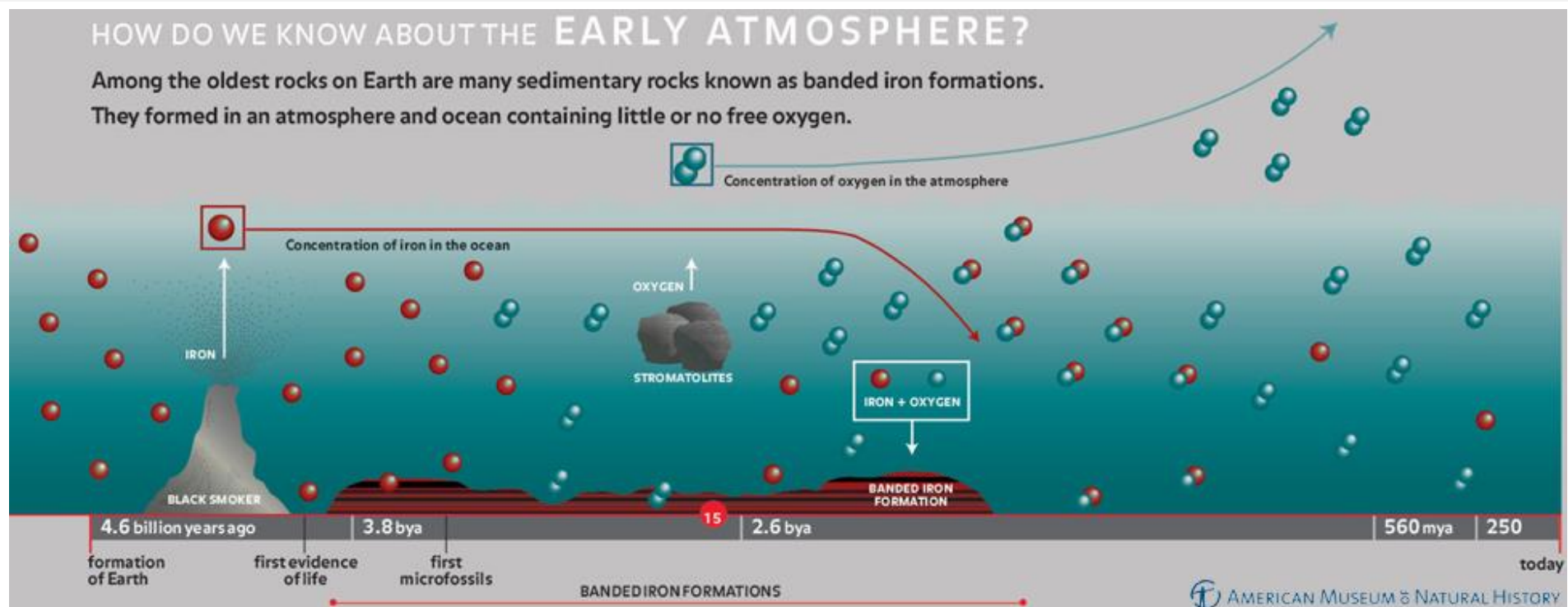


Possible deposition of alternating iron and silicate mineral layers triggered by temperature fluctuations in the ocean water: (1) and (3) Moderate/higher temperatures yield relatively high photoautotrophic bacteria oxidation rates and thus iron(III) mineral formation. Therefore, biomass and Fe(III) settle together to the seafloor. (2) With decreasing temperatures photoautotrophic oxidation rates slow down and at the same time lower temperatures initiate abiotic Si precipitation from Si oversaturated ocean water. Si minerals then settle to the seafloor.

The repeated precipitation of silica and iron oxide - due to seasonal variation - resulted in the deposition of alternating layers of chert (which is grey) (could be red jasper, a silica (SiO_2) with iron (Fe^{3+}) impurities), hematite (which is red) and magnetite (which is black). Thus, the name Banded Iron Formation BIF comes from the characteristic colour banding (Western Australia).

Source of Oxygen During deposition of BIFs

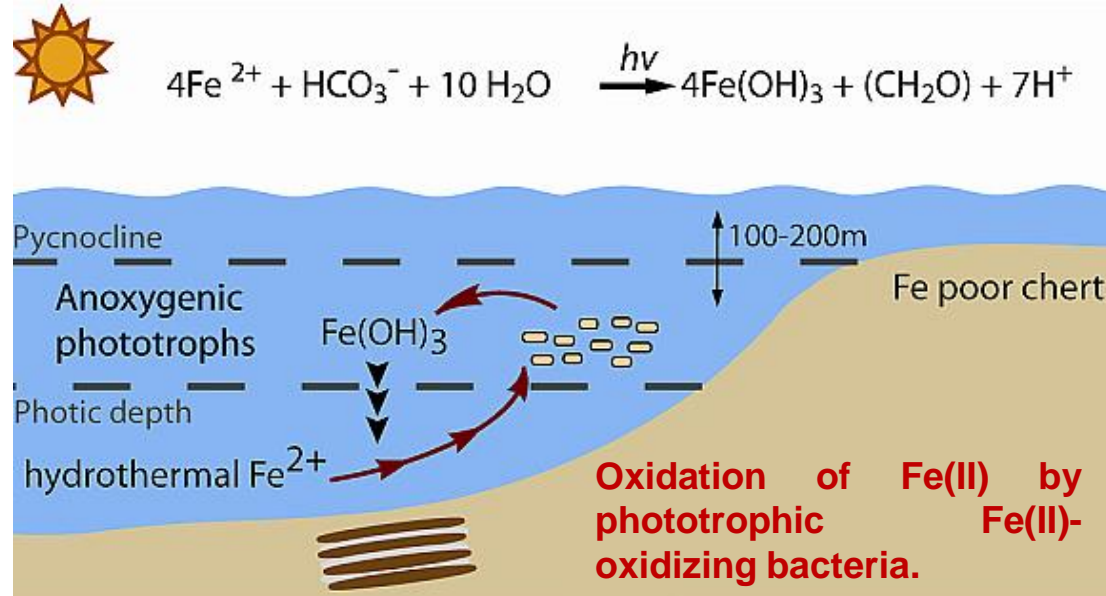
Stromatolites released free oxygen into seawater and immediately reacted with the iron which precipitated as iron oxide minerals. The stromatolites kept pumping oxygen, far outpacing the supply of iron. Today, the ocean is full of oxygen, causing iron that reaches the ocean to instantly precipitate; therefore, iron deposits tend to be localized around black smokers.



What happens during the absence of dissolved Oxygen in water?

It is likely that the earliest BIFs were deposited in the absence of significant amounts of atmospheric oxygen. **Anoxygenic phototrophic Fe(II)-oxidizing bacteria (photoferrotrophs and cyanobacteria)** have been suggested as the most plausible facilitators for the Fe(III) mineral deposition.

At the Archean and Paleoproterozoic time, the **UV radiation** and **iron concentrations** have made early marine environments inhospitable to life. The photosynthetic bacteria (photoferrotrophs and cyanobacteria) overcame these environmental conditions. **High silica abundances** in seawater was the initial survival of ancient photosynthetic bacteria, as well as to the early colonization of littoral marine environments, by forming **Fe(II)/Fe(III)-Silicate complexes and nanoparticles** in the ancient water column.



These minerals acted as a **'sunscreen'** against the high levels in incident UV radiation. By complexing with iron, **silica would have lowered the level of soluble iron to more manageable levels**, thus enabling the survival and evolution of early bacteria under high iron conditions.



Cyanobacteria in the ocean was significant by 3.8 by ago, and this started the oxidation of iron there and raised the Eh. This led to the formation of banded iron formations. Later, oxygen built up in earth's atmosphere.

In recent years, microbial reductive and oxidative respiratory metabolisms have been implicated in the deposition of iron-bearing minerals in the iron-rich laminae of BIFs. **Microaerophilic Fe(II) oxidizers**, such as *Gallionella ferruginea*, might have **metabolically oxidized Fe(II) coupled to the oxygen generated by oxygenic photosynthesis**. However, it is that **oxygenic photosynthesis evolved enough oxygen to account for the precipitation of Fe(III)-rich minerals**.

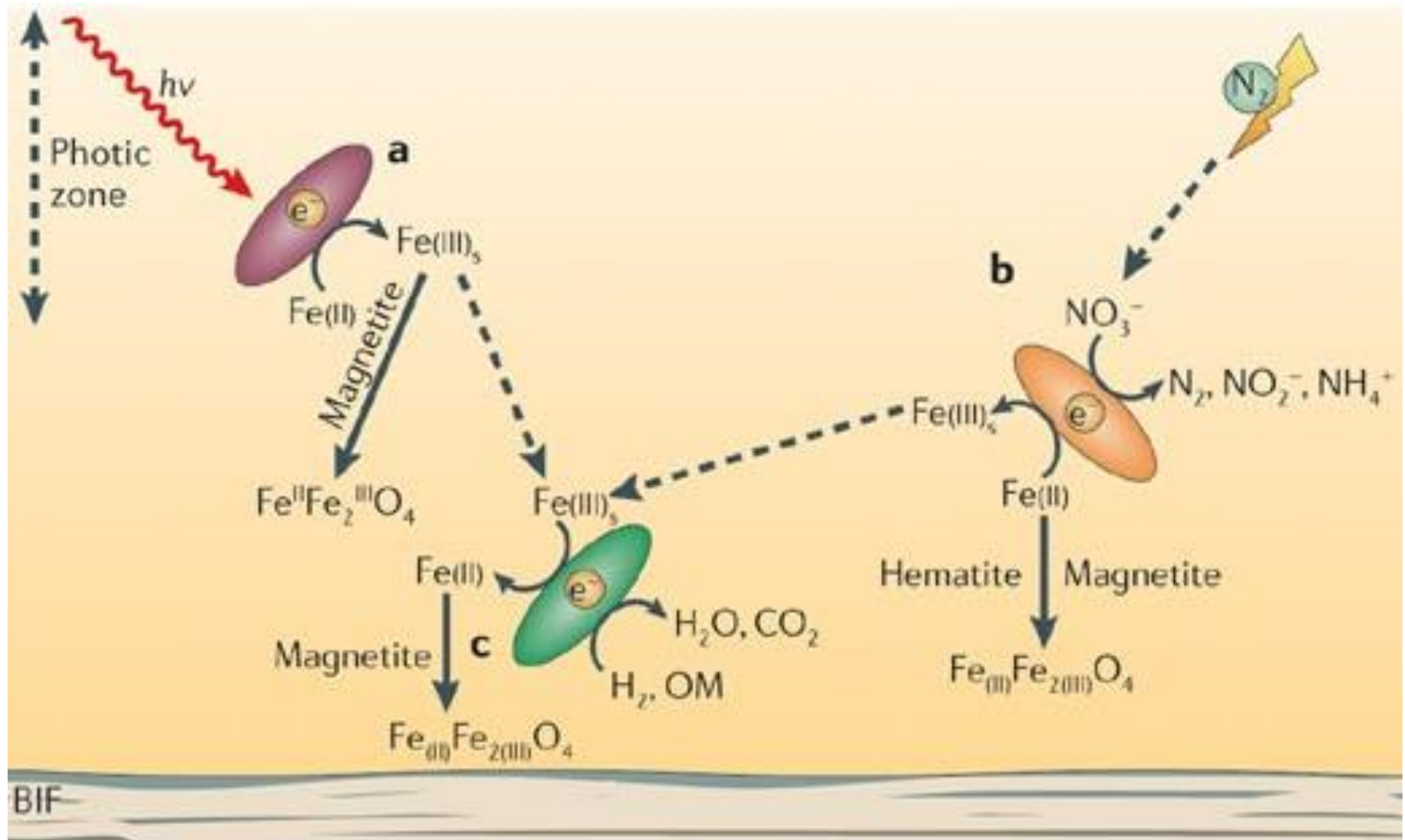
Other microbially mediated mechanisms influencing the precipitation of Fe(II)- and Fe(III)-rich minerals in anoxic environments have been proposed as plausible alternatives (to the oxygenic photosynthesis), **including:**

- 1. phototrophic Fe(II) oxidation by micro-organisms,**
- 2. nitrate-dependent Fe(II) oxidation by micro-organisms; and**
- 3. Fe(III) reduction by micro-organisms.**

However, the bio-oxidation (by the effect of bacteria) of Fe(II) not only results in the precipitation of Fe(III) oxides but also results in the direct precipitation of magnetite and hematite as well.

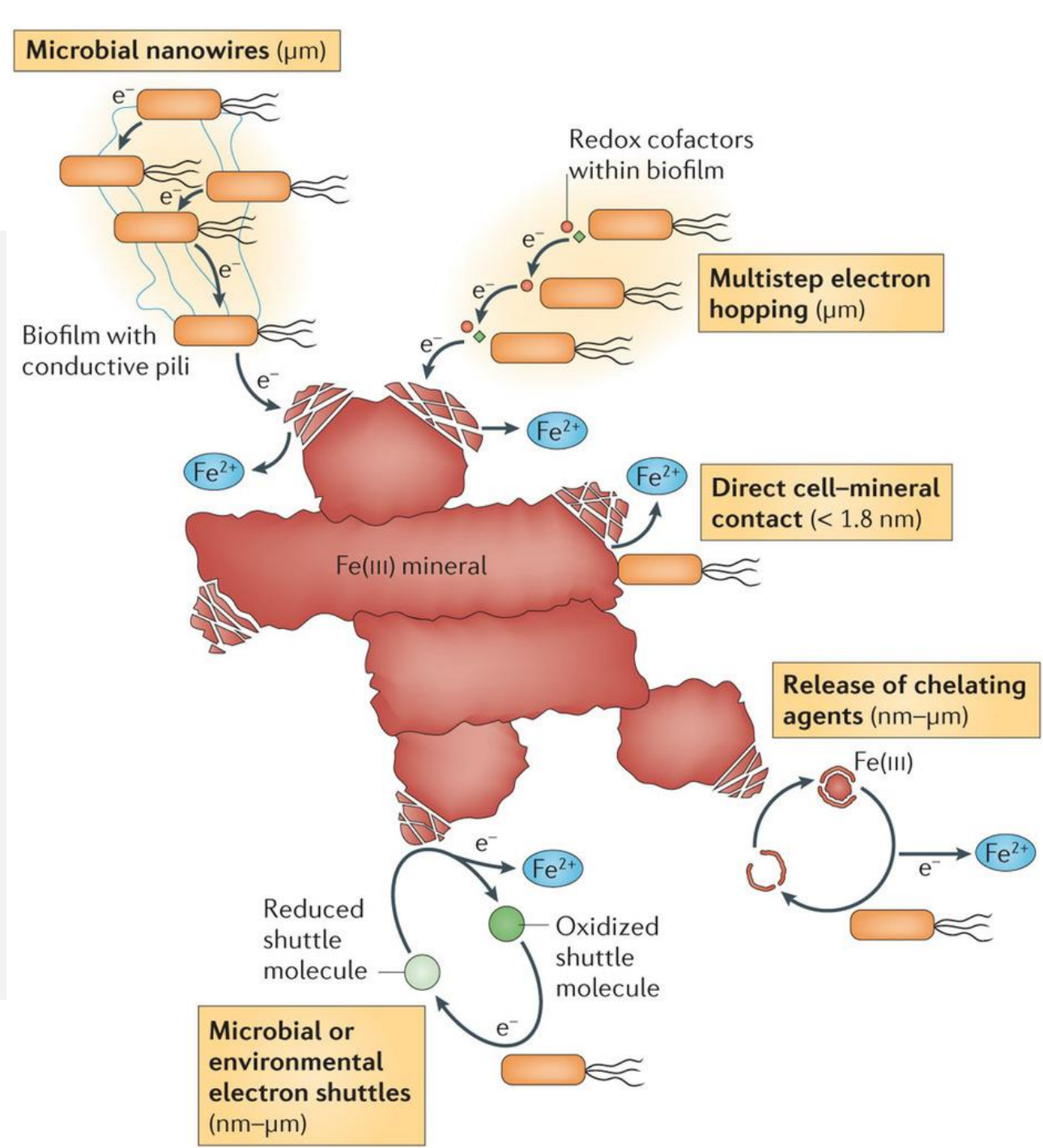
Microbial communities contribute to a dynamic **anoxic iron redox cycle**. The figure shows the models proposed for the **microbial mediation of anoxic deposition of BIF**. The **direct oxidation of Fe(II) by photoautotrophic bacteria (a)** and **nitrate-dependent Fe(II) oxidizing bacteria (b)** results in the formation of magnetite and hematite, and solid-phase Fe(III) oxides. **The biogenic Fe(III) oxides are subsequently reduced by Fe(II)-reducing microorganisms (c)** forming magnetite.

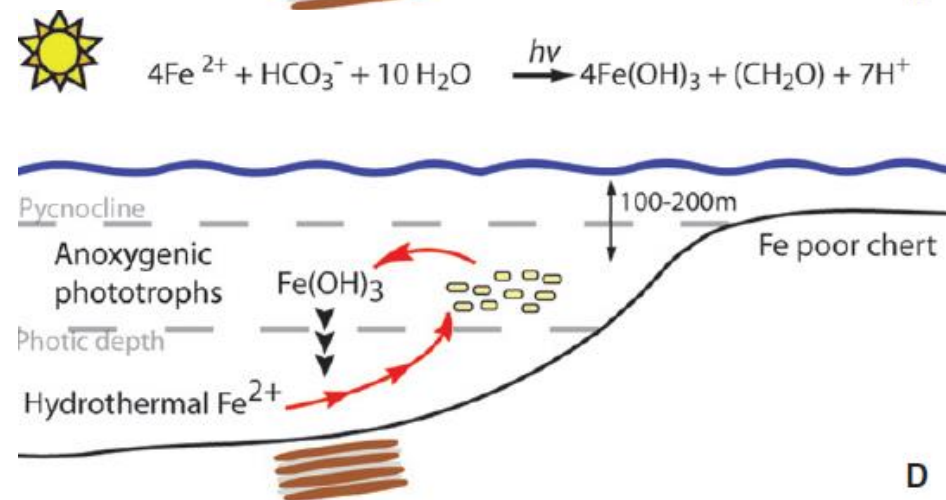
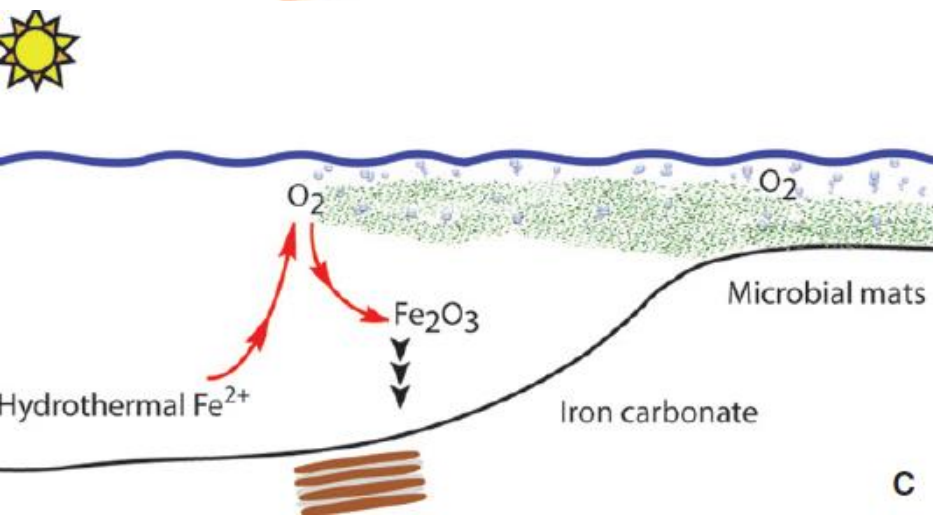
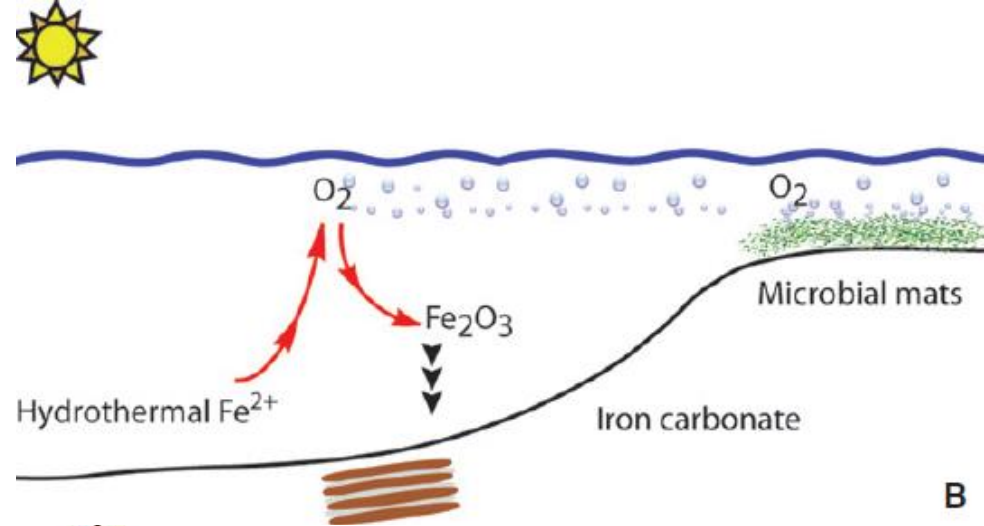
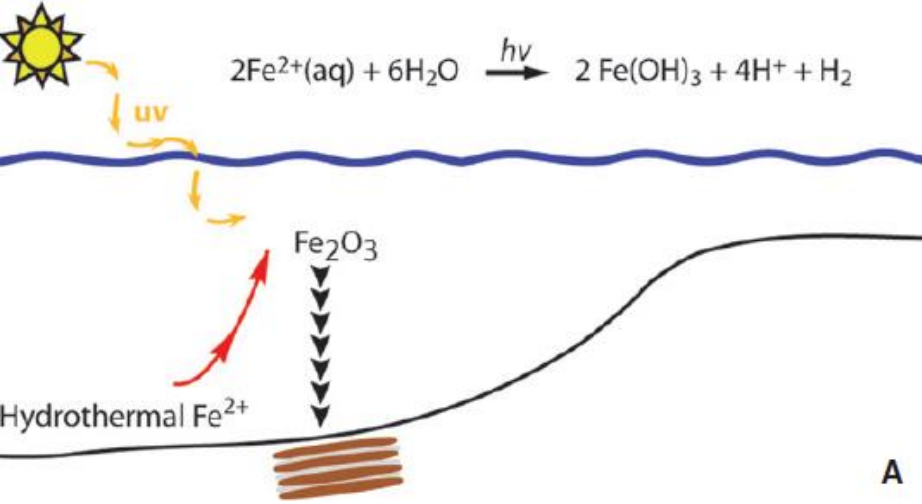
Nitrate reduction has received much less attention as a model; however, it does provide an additional mechanism leading to BIF formation in the Precambrian to produce significant quantities of magnetite and hematite. **Lightning discharge contributed to the fixation of nitrogen (N_2)** into nitric (NO); nitrous (N_2O) oxides and the nitrite (NO_2^-) and the nitrate ion (NO_3^-). Such oxidized nitrogen species could have functioned **as an electron acceptor (reducing agent)** supporting the mixed-valence phase Fe(II)–Fe(III)-bearing mineral magnetite (Fe_3O_4).



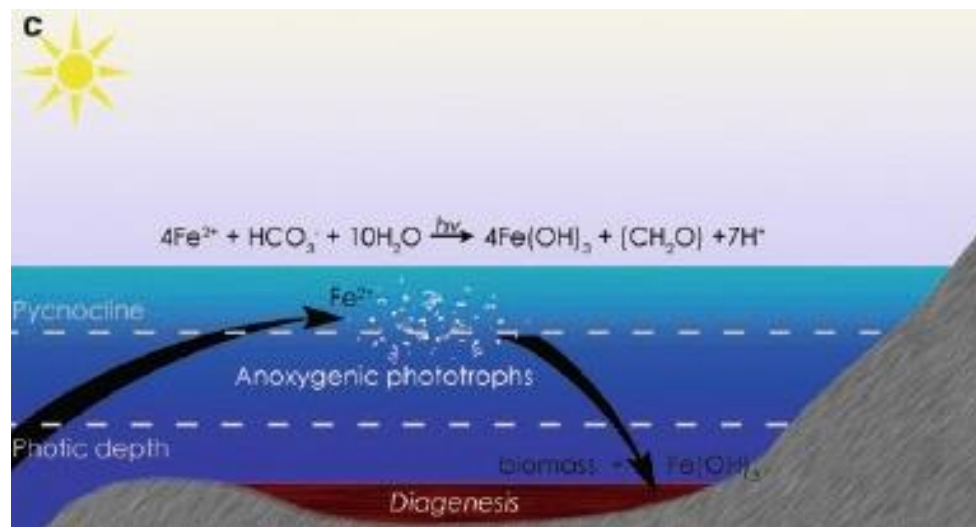
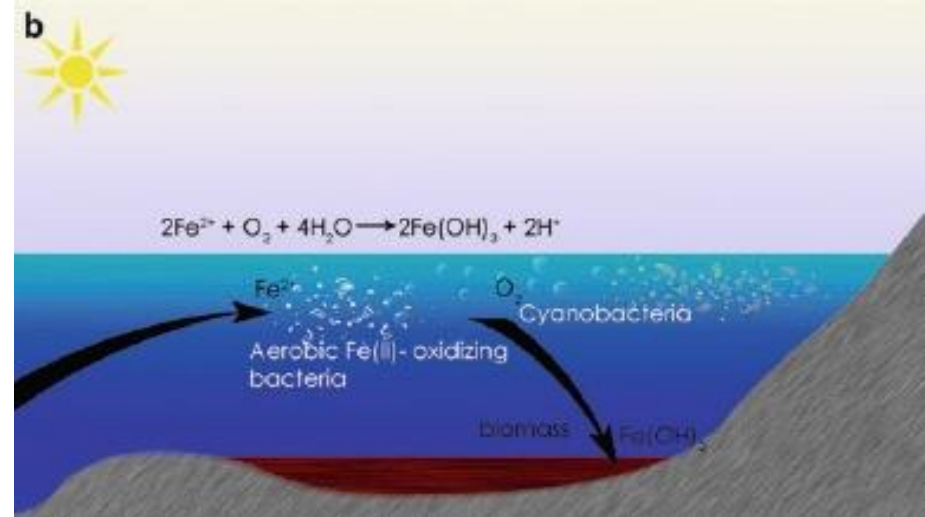
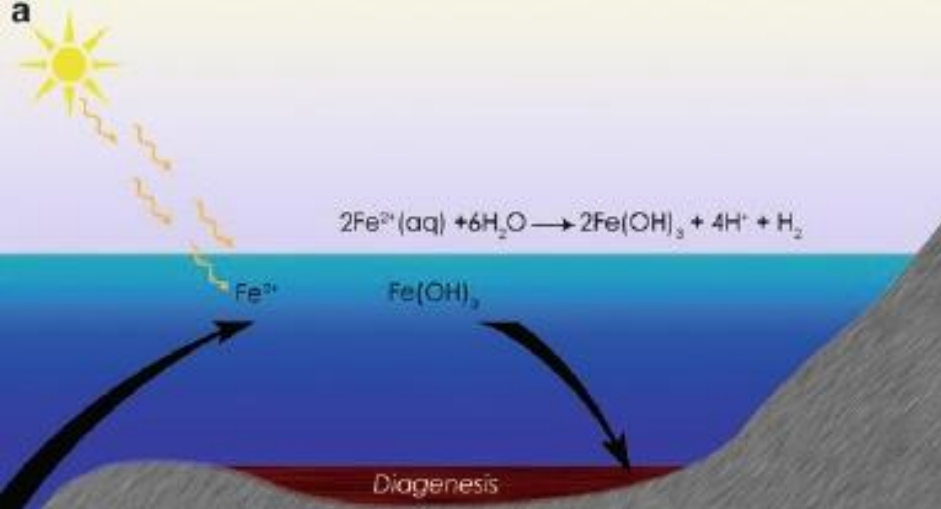
Mechanisms of electron transfer from microorganisms to Fe(III) minerals (reduction)

Schematic representation of metabolic strategies by microbial Fe(III) reducers to reduce Fe(III) minerals. Direct contact between the bacterial cell and Fe(III) minerals facilitates Fe(III) reduction over short distances. Bacteria secrete chelating agents to facilitate electron transfer over short (nm) and/or long (μm) distances (dependant on type and quantity).



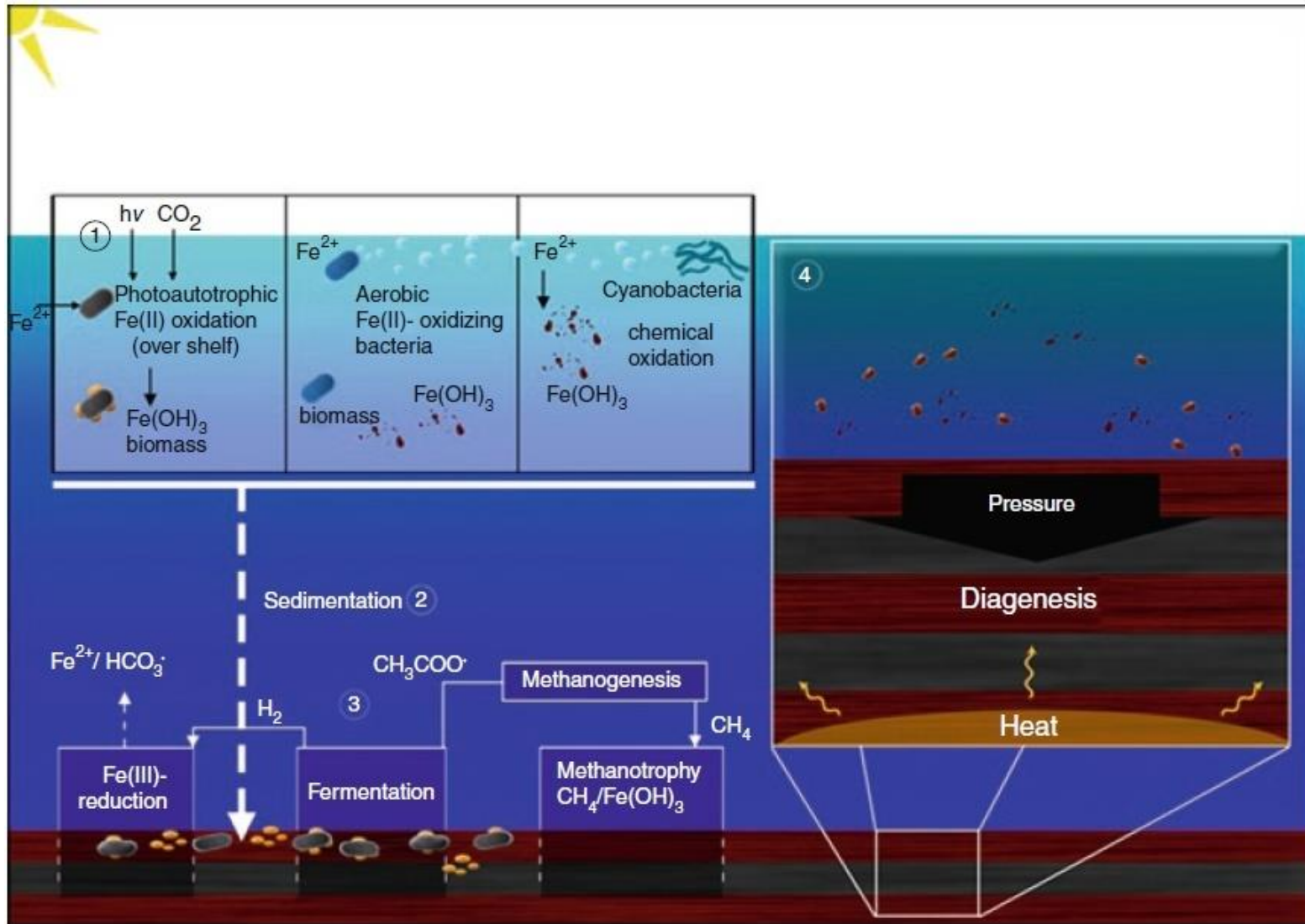


Models of BIF deposition: For an anoxic water column, the proposed abiotic mechanism of Fe(II) photooxidation by UV light (A). The traditional model of BIF deposition involves production of oxygen by cyanobacteria, which then chemically reacts with hydrothermal dissolved Fe(II). The restriction of cyanobacterial mats to the near-shore would physically separate Fe(III) oxyhydroxides from organic carbon precipitates (B), which would not be the case in a system where cyanobacteria also populated off-shore regions (C). A biotic mechanism of deposition proposed for an anoxic setting is the direct microbial oxidation of Fe(II) via anoxygenic Fe(II) oxidizing phototrophy (D).



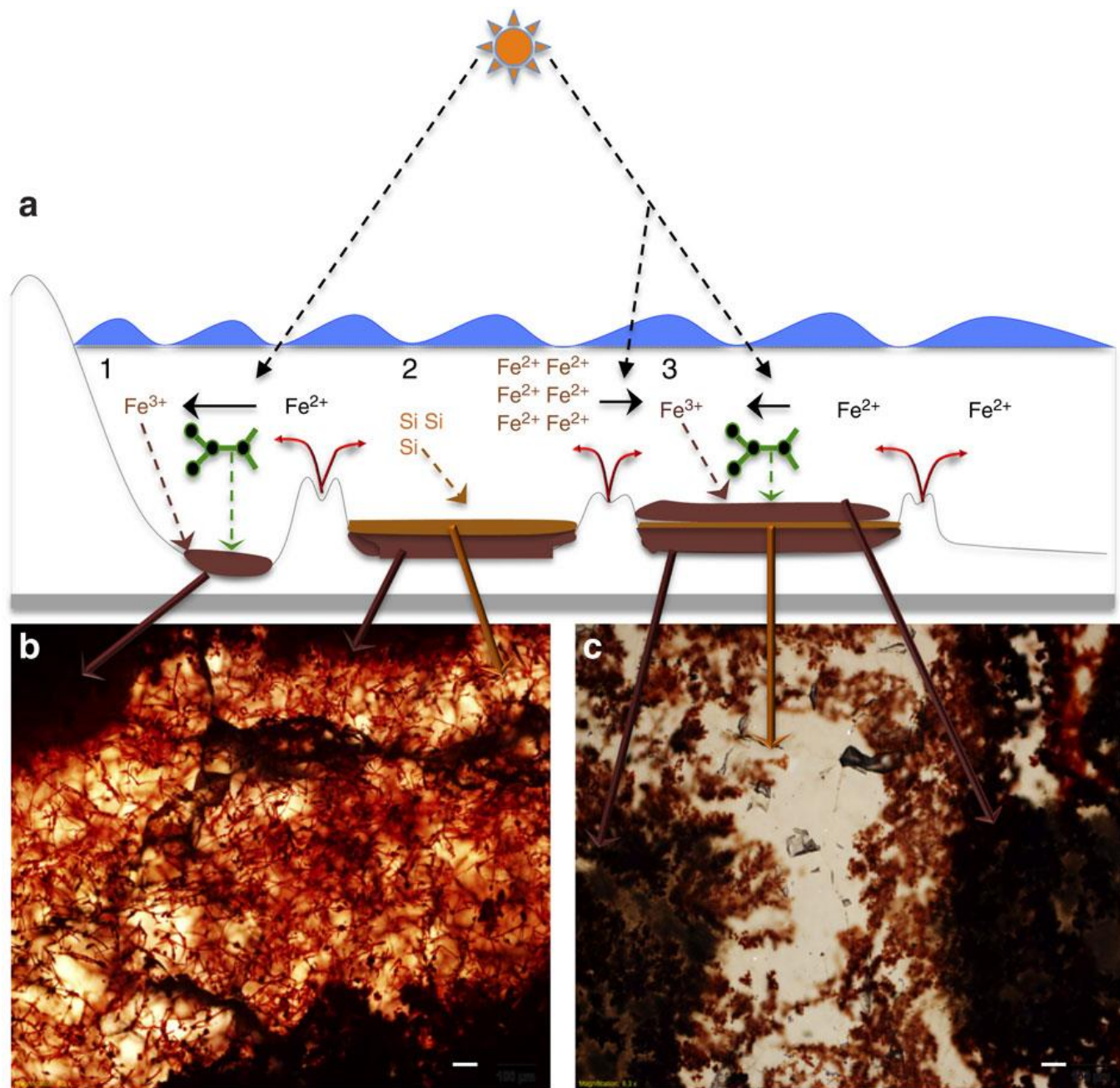
Summary of Fe(II) oxidation processes potentially involved in BIF deposition.

- Abiotic photooxidation of hydrothermal Fe(II) by UV light with sedimentation of iron minerals.
- Chemical oxidation of hydrothermal Fe(II) by cyanobacterial produced O₂ and Fe(II) oxidation by aerobic Fe(II)-oxidizing bacteria with sedimentation of either iron minerals only (chemical oxidation) or sedimentation of joint biomass (bacterial mats) and iron minerals (aerobic Fe(II)-oxidizing bacteria).
- Direct biological oxidation of Fe(II) by anoxygenic phototrophic Fe(II) oxidizing bacteria with joint sedimentation of biomass and iron minerals.



Model summarizing potential biological and chemical processes during BIF deposition. (1) Hydrothermal Fe(II) is oxidized by photoautotrophic anoxygenic Fe(II)-oxidizing bacteria, aerobic Fe(II)-oxidizing bacteria or via chemical oxidation by cyanobacterially produced O_2 . (2) Biomass and Fe(III) sediment to ocean floor as cell-mineral aggregates. (3) After sedimentation metabolically driven redox processes by fermenters and Fe(III) reducers take place (and magnetite formation), possibly also involving methanogens and methanotrophs. (4) Pressure and temperature alter the source sediment and cause induced diagenetic/metamorphic overprint

(a) Intense phototrophic oxidation of hydrothermal Fe^{2+} precipitates Fe^{3+} together with microbial cells and stalks following biofilm (green lines connected by black filled rings) encrustation and death (1). Negative feedback halts Fe^{2+} transformation to Fe^{3+} allowing for the precipitation of Si, as most of the highly soluble Fe^{2+} is retained in solution (2). Another episode of abundant photoferrotrophic biofilm growth and Fe^{3+} encrustation leads to the deposition of a new iron-rich band (3). (b,c) Light micrographs showing direct environmental evidence for the proposed model. The two panels show examples of photoferrotrophic bacterial fossilization patterns related to the alternating Fe^{3+} and silica precipitation in the Cape Vani rock deposits. Scale bar, 100 μm .



Most scientists relate the precipitation of the giant mass of iron contained in **BIF** to the transition of oceans and atmosphere from a **reduced** to an **oxidized state** (the “**Great Oxidation Event**” between 2.45 and 2.2 Ga). In the Archaean **before oxidation**, **concentration of O₂ of the atmosphere was <10⁻⁵ PAL (present atmospheric level)**.

Sources of iron in BIF may have been:

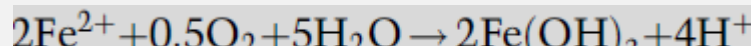
- 1. submarine-exhalative systems similar to today's mid-ocean ridges;**
- 2. submarine-exhalative systems associated with intraplate tensional tectonic structures and volcanoes; and**
- 3. continental weathering.**

Sources of SiO₂ in the chert bands were most probably weathering landmasses. It is assumed that the ancient oceans were saturated with **dissolved silica (as Si(OH)₄)**. **The modern oceans are markedly under saturated in silica and this may be the main reason for the changing character of iron ores, from ancient BIF to more recent ironstones.**

The banding in BIF can be explained by **diurnal to seasonal cycles of biological activity**, **to temperature fluctuations**, or to **episodic depletion of ferrous iron in the water column**.

Superior type BIF ores is chemical or biogenic precipitates by:

1- Oxidative precipitation of dissolved reduced iron (Fe²⁺) forming banded iron formations is possible:



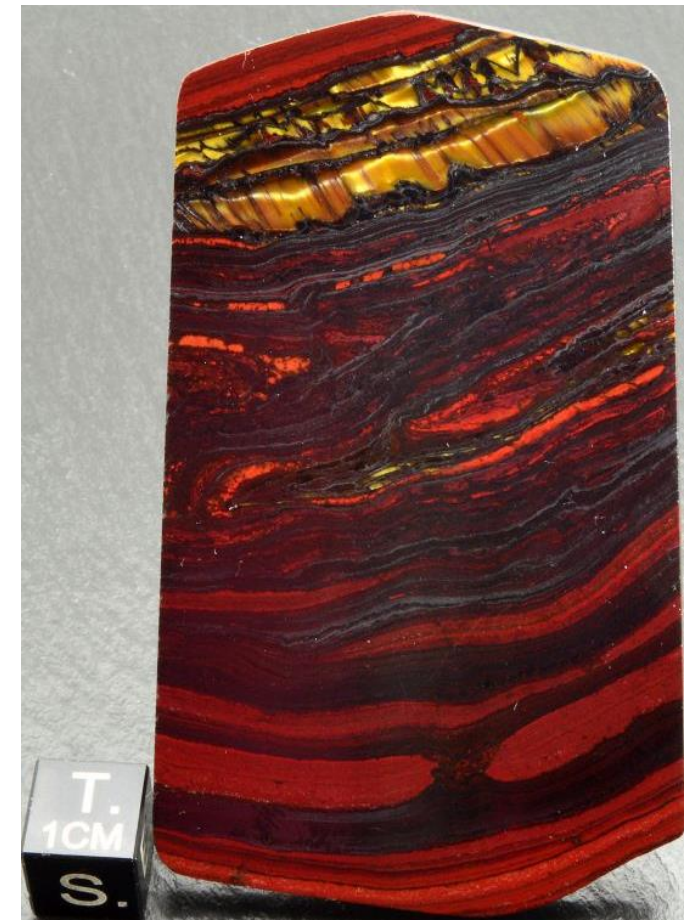
2- Under anoxic conditions (depletion of oxygen), BIF deposition may have been catalysed by anoxygenic photoautotrophic bacteria. An euxinic model, with precipitation of iron is achieved at the contact between reduced deep water and O₂-rich surface water.

3- A third possible precipitation mechanism is abiogenic UV-induced oxidation.

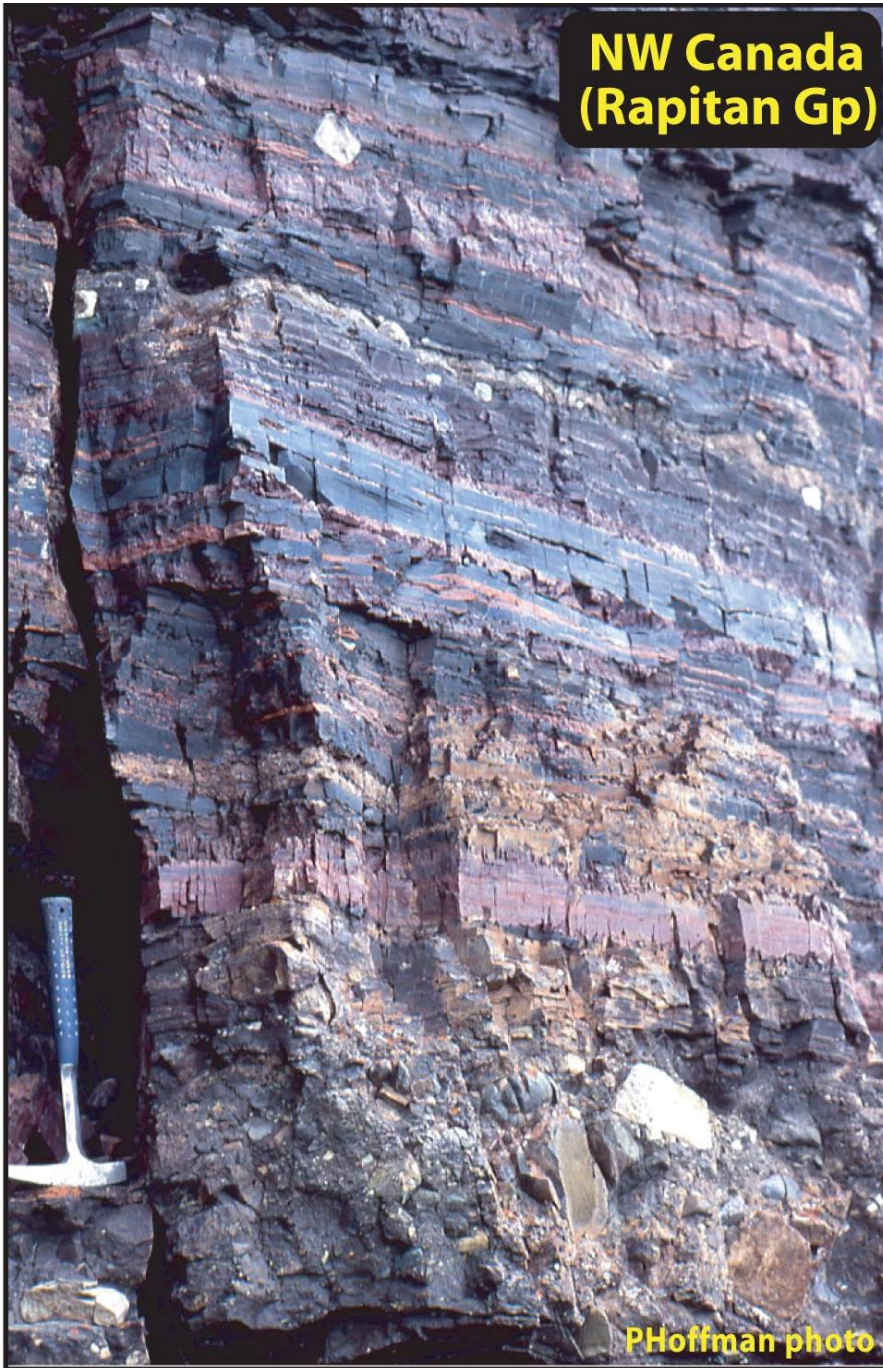
Many scientists support the following hypothesis: “The atmosphere may have been nearly free of oxygen, while the oxygen in the oceans started to increase. Seasonal blooms of the earliest photosynthetic micro-organisms (cyanobacteria) increased oxygen concentration in seawater that oxidized and precipitated dissolved Fe²⁺”.

Rapitan Type BIF were deposited immediately during glaciation. During glacial events, land and oceans were widely covered with ice (“Snowball Earth” hypothesis) causing a nearly **global anoxia** and **the presence of dissolved ferrous iron in seawater**.

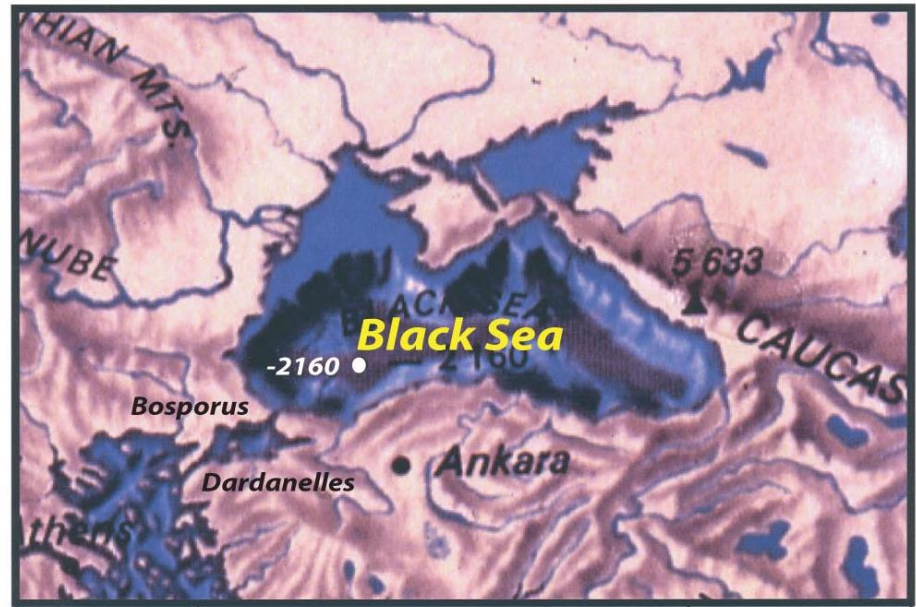
Interand **post-glacial melting of the ice caps resulted in formation of glacial sediments**, re-oxidation of the oceans, and precipitation of ferric iron and manganese oxides. **As marine sediments, Rapitan type iron formations are similar to Superior type BIF**, but have little economic significance.



**NW Canada
(Rapitan Gp)**



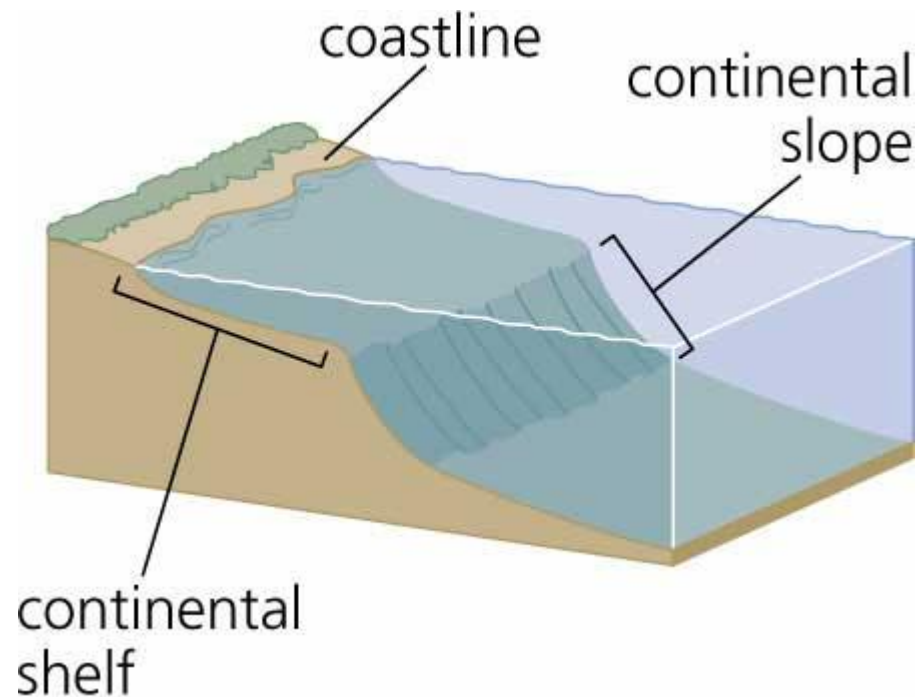
PHoffman photo



- Factors favoring glacial BIF:**
- (1) "oxygen deficiency in stagnating bottom waters caused by an ice cover" (Henno Martin, 1965)**
 - (2) attenuated continental runoff, causing a low rate of BSR (Canfield & Raiswell, 1999)**
 - (3) large sea level fall, causing high Fe:S ratio in MOR hydrothermal flux (Kump & Seyfried, 2005)**

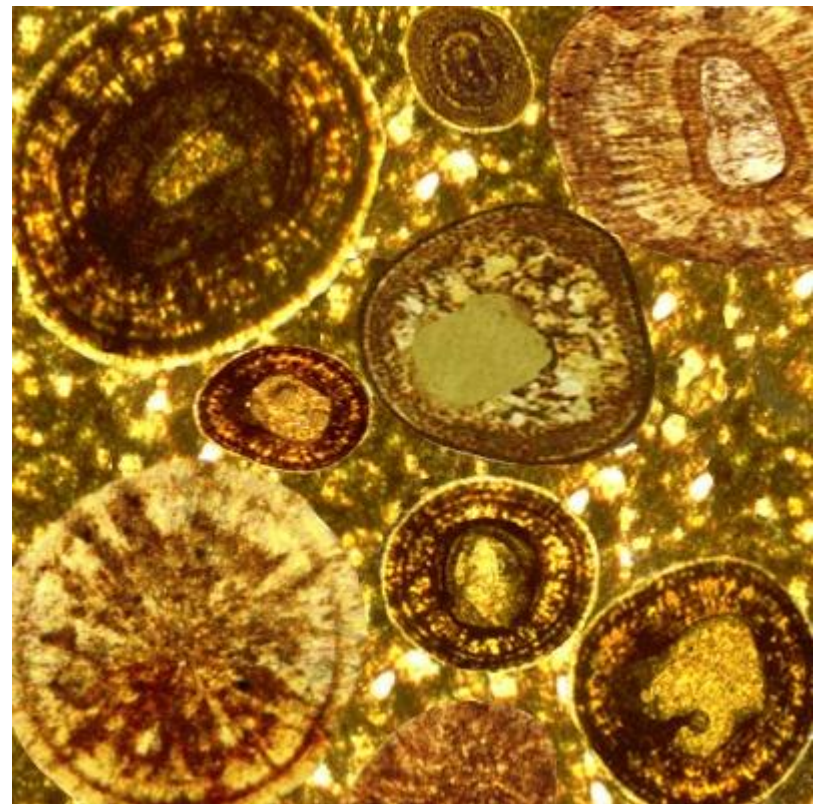
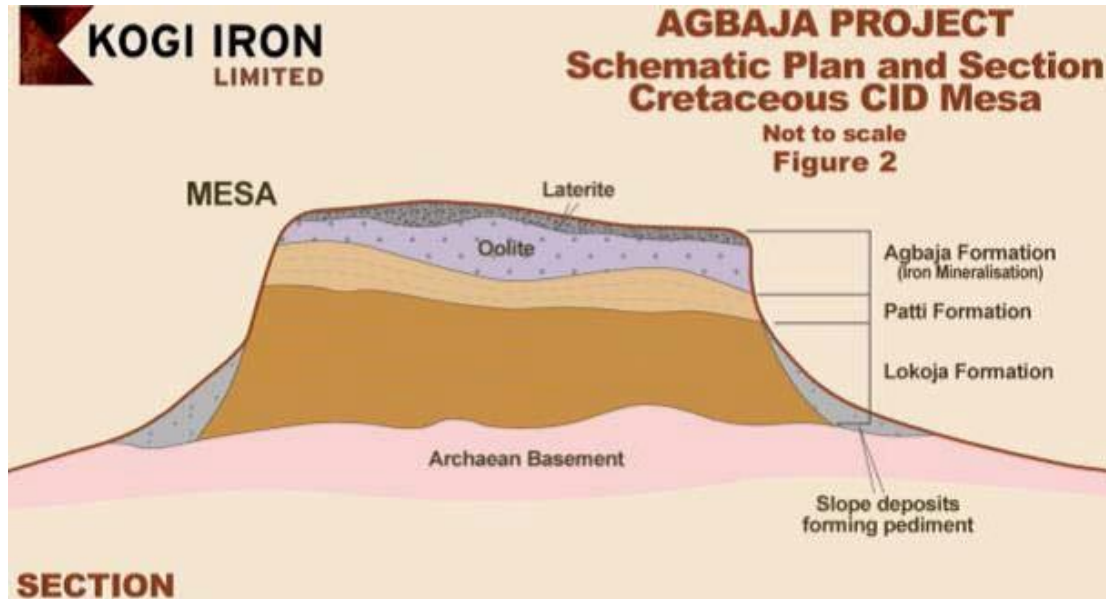
Oolitic iron ore

Formation of **oolitic iron ore** is restricted to Phanerozoic time. Economically outstanding mining led to the distinction of “**Minette type**” (limonitic) and “**Clinton type**” (haematitic). Always, these ores are sediments of **shallow epicontinental seas** (epicontinental sea is a shallow sea that covers central areas of continents during periods of high sea level that result in marine transgressions) or of **shelf regions** and are interbedded with clastic sediments. Ore beds reach a thickness of about 30m and lateral extensions up to 150 km.



Oolitic iron ore is not banded and contains no primary colloidal silica. Textural varieties include mainly **ooids and pisoids**, but also fine grained iron ore particles in between. Precipitation of **ooids in agitated water** is indicated by **intraclasts in ooidal matrix, fractured and freshly mantled ooids**, cores of ooids formed by quartz, phosphorite and fragments of fossils, **oblique and cross-bedding**.

Iron oolite beds are often connected with **rich fossil communities**. Fossils are typically replaced and cemented by iron ore minerals. **Single ooids** consist of **goethite, haematite, chamosite and siderite (with very little magnetite and pyrite)**. Iron and phosphorus are enriched Fe = 34% and P = 0.6%.



The coincidence of both sedimentary and diagenetic textures caused very different genetic interpretations. Originally **aragonitic oolitic rock had been replaced by iron ore after lithification**. However, many observations favour a **syndimentary supply of iron followed by chemical and biochemical precipitation**.



The unlithified sediments at the origin of oolitic iron ore consisted of ooids, pisoids and peloids **that originated by rolling on the seafloor**. The matrix between these larger grains consists of **detrital minerals, fossils, organic material and fine grained iron-bearing kaolinitic clay**.

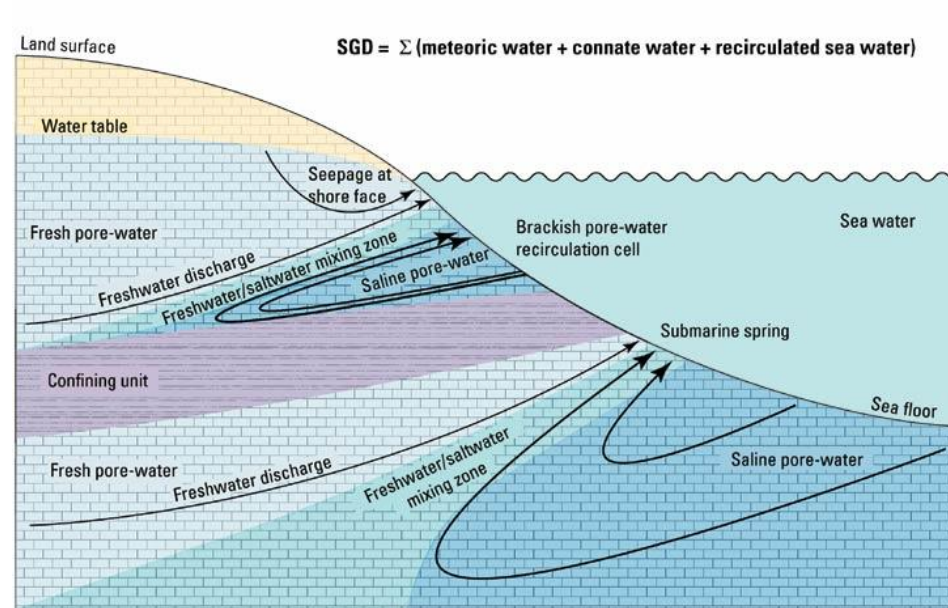
Subsequent diagenesis, mostly under reducing conditions, **caused by bacterial decomposition of organic matter, typically leads to transformation of kaolinite into chamosite (an iron-rich chlorite) and neoformation of pyrite and siderite**.



Finally, many deposits were upgraded by oxidation caused by **meteoric seepage waters**. The source of iron in marine oolitic iron ores were probably **lowlands experiencing intensive weathering in tropical climates**, where **humidity and profuse plant growth produced wetlands discharging river water rich in dissolved organic matter**.

Oxidized iron (Fe^{3+}) may be adsorbed to organic matter and clay (either in colloidal or particle size suspended in the water).

Mixing of **river water** with **seawater (pH >7)** provokes immediate precipitation of **iron oxy hydroxides**. Other possible iron sources that have been considered are **coastal submarine groundwater springs**.



End of Lecture