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1 **On the why's and how's of clay minerals' importance in life's emergence**

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22

23 **Abstract:**

24 A possibly prominent role for Green Rust minerals in life's emergence is inferred from a

25 comparison of their structural, mechano-dynamic and electrochemical properties and of the

26 layout of bioenergetic, i.e. free energy converting processes in extant organisms. From

27 fundamental thermodynamic considerations, the conversion of environmental free energy into

28 the decrease of entropy that defines life is an indispensable ingredient for life to emerge. A

29 specific scenario for life's emergence mediated by Green Rust minerals in the framework of

30 the alkaline hydrothermal vent hypothesis is proposed.

31

32 **Keywords:**

33 Emergence of life, Green Rust, double layered Fe-oxyhydroxides, alkaline vent hypothesis,

34 bioenergetics, foug  rite

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371.1. The focus on catalysis; betting on the wrong horse?

38 The potential relevance of clay minerals to origin of life research has been recognised
39 several decades ago (Bernal, 1951; Greenland et al. 1962; Cairns-Smith, 1966, 1982;
40 Solomon, 1968; Odom et al., 1979; Rao et al., 1980; Ponnampereuma et al., 1982). Due to their
41 extraordinary sorption properties, clays have been shown to accumulate monomers (mostly
42 organic molecules) from the solvent to local concentrations exceeding those of the bulk by
43 several orders of magnitude (Lailach et al., 1968; Ferris et al., 1996; Ferris, 2002; Aldersley et
44 al., 2011). The reduction in degree of orientational freedom of these monomers, brought about
45 by essentially restricting them to two dimensions, *i.e.* surfaces, adds a further intriguing
46 property to clay-type minerals. Of these, the anion-exchanging clays, hydrotalcites or layered
47 double hydroxides (LDH or DLH), are now a particular focus as organic anions (counter ions)
48 are readily absorbed as “guests” in their interior galleries (Kuma et al., 1989; Arrhenius, 2003;
49 Braterman et al., 2004). Due to such concentrating and structuring capabilities, clays in
50 general have been considered instrumental in facilitating and speeding-up fundamental
51 reactions and condensations at life’s origin. Several groups investigate their catalytic
52 properties and have already produced invaluable insights into the fine details, both with
53 respect to 3D-arrangement and to thermodynamic parameters, of clay-mediated reactions
54 (Pitsch et al., 1995; Ertem and Ferris, 1998; Hill et al., 1998; Krishnamurthy et al., 1999;
55 Meunier et al., 2010; Greenwell, 2010a; Coveney et al., 2012; Erastova et al., 2017;
56 Bernhardt, 2019; Barge et al., 2019). The fact that many clays can harbour in their interlayers
57 metal ions which mimic the catalytic sites of bioessential metalloenzymes makes them almost
58 irresistible candidates for the very earliest catalysts and promoters (Matrajt and Blanot, 2004;
59 Peretó, 2005; Rimola et al., 2009).

60 However, we suggest taking a step back and asking ourselves whether the exclusive
61 focus on catalysis is warranted. Catalysis is basically making exergonic reactions proceed
62 more readily by lowering their activation barriers and this is precisely what clays have been
63 shown to do. Catalysts thus facilitate reactions that would occur by themselves, just much
64 more slowly. This clearly is not what characterises living things. Life is all about processes
65 which would not happen spontaneously, but which are driven “uphill” by free energy –
66 (electro)chemical disequilibria as we will argue below – in the environment. The phenomenon
67 “Life” transforms rather randomly dispersed elements and molecules into highly ordered
68 structures and reaction networks. It only manages to effect this generation of order, as
69 imposed by the 2nd law of thermodynamics, by drawing upon environmental disequilibria and,
70 *in fine*, by decreasing the degree of order of the larger system encompassing both life and its

71environment (Endres, 2017; Branscomb et al. 2017; Branscomb and Russell, 2019). No
72ensemble of whatever catalysts can therefore ever bring forward life since they will only
73speed up exergonic reactions but cannot make endergonic ones proceed. What truly made life
74possible was the presence of converters of environmental disequilibria into the highly ordered
75machinery of metabolising cells. At first sight, these considerations may well appear
76appropriate but nevertheless too theoretical and utterly unhelpful when it comes to unravelling
77life's emergence. However, examining how these thermodynamic truisms play out in extant
78life on our planet turns them into extremely powerful criteria for constructing plausible
79scenarios in which emerging life actually resembles life as we know it today.

80

811.2. **Deducing the ancestral disequilibria and their converters from extant biology**

82 Let us first emphasize that modern life, no matter whether prokaryotic or eukaryotic,
83unicellular or multicellular, features an extraordinary unicity with respect to its free energy
84converting processes (Schoepp-Cothenet et al., 2013). In brief, an electrochemical gradient
85between reductants and oxidants (in photosynthetic organisms produced by photon energy) is
86collapsed by electron transfer events mediated by protein complexes which are integrated
87into, or are peripherally associated with, the cytoplasmic membrane (Fig. 1). These redox
88reactions are coupled to the transfer of protons (and occasionally sodium ions) generating an
89electrostatic (and sometimes an additional ion-concentration) disequilibrium (a "gradient")
90over the membrane which topologically insulates the compartment from the outside world
91(Fig. 1). The simplest and most widespread strategy in extant life to achieve this coupling
92relies on combining reducing equivalents and protons into uncharged entities which readily
93diffuse through the barrier. In bioenergetic systems this task is performed by quinones and
94their functional analogs (*e.g.* methanophenazines) which take up and release 2 electrons and
95two protons and hence formally transfer a hydrogen molecule over the membrane. The
96outcome of the ensemble of these mechanisms is a (hydrogen- or sodium-) ion-motive force
97(imf) which is converted by membrane-integral systems into the first of the following two
98predominant sources of free energy that in turn drive the entropy-lowering processes of living
99cells.

100 (1) A phosphate-group transfer disequilibrium which in the majority of cases consists in
101extremely far-from-equilibrium ATP/ADP ratios but frequently also takes the simpler form of
102pyrophosphate (PP_i) to orthophosphate (P_i) disequilibria (PP_i/P_i) (Stucki, 1980; Baltscheffsky
103et al. 1999; Oster and Wang, 2000; Drozdowicz and Rea, 2001). The paramount importance
104to life of maintaining high ATP/ADP disequilibria (of approximately 10¹⁰) is for example

105illustrated by the fact that humans transform roughly the equivalent of their own body weight
106in ATP per day to ADP in order to maintain low entropy states, that is, to avoid decay. The
107vast majority of biochemical reactions making up metabolic networks are indeed intrinsically
108endergonic and are only rendered exergonic by strict coupling to ATP hydrolysis. For the case
109of the ATP/ADP disequilibrium, the quintessential converter is the multi-subunit enzyme
110ATP-synthase (Fig. 1, 1st from right). ATP-synthase is an intricate molecular motor which,
111due to its very high molecular complexity, is extremely unlikely to have played a role while
112life emerged. The protein machine which converts imf into PP_i/P_i disequilibria, by contrast, is
113a single polypeptide membrane-transporter (Fig. 1, 2nd from right) with a comparatively
114simple functional mechanism (Tsai et al., 2014). PP_i/P_i disequilibria are therefore often
115stipulated as the ancestral phosphate-transfer potential (Russell et al., 2013).

116 (2) The second major source of free energy for driving metabolic reactions arises from the
117maintenance of a cytoplasmic pool of strong reductants mainly in the form of NAD(P)H and
118reduced ferredoxins (Nicholls and Ferguson, 2013). The electrochemical potentials of these
119cytoplasmic reductants are in most organisms substantially more negative (Fig. 2) than those
120of available environmental reducing substrates. A further type of disequilibrium converter
121therefore increases the reducing power of environmental substrates to the level required for
122the respective metabolic reactions to occur. Several processes (Fig. 2) have been found to
123achieve this goal:

124 (i) So-called reverse electron transfer (Ferguson and Ingledew, 2008) taps into the free
125energy stored in the imf to augment the reducing power of environmental substrates (Fig. 2,
126i).

127 (ii) Certain types of photosynthesis (Schoepp-Cothenet, et al., 2013) produce reducing
128equivalents with sufficiently low redox potentials to directly reduce ferredoxins (Fig. 2, ii).

129 (iii) The phenomenon of electron bifurcation (Fig. 2, iii) allows two-electron compounds
130to generate a very low potential electron at the expense of the reducing power of the other one
131(Mitchell, 1975; Nitschke and Russell, 2011; Crofts et al., 2013; Lubner et al., 2017; Buckel
132and Thauer, 2018; Baymann et al., 2018).

133 (iv) Two specific redox cascades of substrates abundant in many environments stand out
134by their intriguing electrochemical properties: the reduction of nitrogen oxides and oxyanions
135as well as the oxidation of alkanes and in particular methane (Fig. 2, iv). The reduction of
136NO₂⁻ to NO (occurring at a standard potential of about +400 mV with respect to the standard
137hydrogen electrode) enables a further reduction reaction to N₂O (at +1200 mV). The product
138of nitrite reduction is thus by about 800 mV more oxidising than nitrite itself. Nitrite is

139formed via two-electron redox conversion of nitrate at an ambient potential almost equal to
140that of the nitrite/NO transition. On the other end of the redox scale, the oxidation of methane
141to methanol and on through formaldehyde to eventually CO₂ (as observed in certain
142methanotrophic bacteria) generates ever more reducing products (Nitschke and Russell, 2013)
143which eventually are able to reduce NAD(P)⁺ and ferredoxin (Fig 2, iv). Coupling the
144reduction of nitrogen oxides to the oxidation of methane (as occurring in the methanotroph
145*Methylobacterium oxyfera*) thus produces a network of redox reactions (Fig. 2, iv) which, very
146much like electron bifurcation, augments the intracellular electrochemical disequilibrium
147substantially over that prevailing in the environment.

148 To comply with the 2nd law, life throughout its existence had to rely on environmental
149disequilibria to fuel its order-generating processes. Applying Occam's razor (that is, avoiding
150scenarios more complicated than necessary), we have previously stipulated that the types of
151environmental disequilibria have likely remained constant from life's emergence to the
152present day. On the background of this hypothesis and given the intriguing and well-
153established catalytic properties of clay-type minerals, it is tempting to envisage that such
154minerals be able to perform processes similar to the above described free-energy-converting
155reaction schemes. The redox reactions of scheme (iv) (Fig. 2) and the make-up of involved
156metal centres directly lead from extant biology to double layered Fe-oxyhydroxide minerals,
157that is, Green Rusts, as we will elaborate upon below.

158

1592.1. Green Rust, an intriguing candidate for the ancestral disequilibrium converters

160 Structural affinities between catalytic centres in bioenergetic enzymes and certain
161minerals have been pointed out in the past (Nitschke et al., 2013). One of the presented cases
162of metalloenzyme/mineral is particularly interesting since the respective enzyme performs the
163key step in the redox-upconverting methanotrophic pathway mentioned above (Russell and
164Nitschke, 2017). Fig. 3 juxtaposes the catalytic site of soluble methane monooxygenase
165(sMMO) to the iron-containing sheet of double layered Fe-hydroxides, Green Rusts.
166Stimulated by this structural resemblance, we looked more deeply into the properties of Green
167Rusts and their naturally occurring form, fougérite (Trolard et al., 1997; Trolard and Bourrié,
1682006, 2012; Génin et al., 2006, 2008; O'Loughlin et al., 2015). The following remarkable
169properties indicate a potential role of Green Rusts in life's emergence.

170 - Mineralogists have shown that Green Rusts are able of performing the reduction of
171nitrate to ammonia (Hansen et al., 1996, 2001) as well as several of the partial reduction steps
172(Etique et al., 2014; Guerbois et al., 2014). These are precisely the redox reactions driving the

173generation of strongly reducing compounds *via* the energetic pull from the reductive arm of
174the anaerobic methanotrophic reaction network required for life to emerge (Schoepp-Cothenet
175et al., 2013; Nitschke and Russell, 2013). A potential ability to also perform the oxidation of
176methane to methanol (using intermediates of the nitrogen oxide arm as O-atom donors) has
177not been tested so far. We are presently addressing this question in our laboratories. In
178addition to this potential role in an ancestral methanotrophic reaction scheme, producing
179reduced nitrogen compounds from nitrate is certainly crucial for a plethora of synthesis
180reactions yielding organic compounds (amino acids, flavins, NAD, etc). We have recently
181summarized intriguing reaction pathways involving intermediates and end-products of the
182nitrate to ammonia reduction by Green Rusts (Duval et al., 2019; Duval et al. 2020).

183 - Green Rusts are redox-flexible over a very wide range of reduction levels (Poinsignon,
1841997; Génin et al., 2006; Ruby et al., 2010a, 2010b; Mills et al., 2012) allowing facile transfer
185of charges within the Fe-oxyhydroxide layers and likely even (much slower) electron
186tunnelling between layers. Interestingly, high oxidation levels (resulting in so-called
187metastable ferric Green Rust, Génin et al., 2014) have been shown to be associated with
188deprotonation of the μ -hydroxo bridges. Transfer of charges parallel to the Fe-oxyhydroxide
189layers therefore seem to be associated to protonation/deprotonation events reminiscent of the
190redox behaviour of quinones.

191 - In addition to their redox softness, Green Rusts also show an extraordinary structural
192flexibility due to their clay-like structure with interlayer spaces that can be occupied by a
193range of different counterions (anions for the case of Green Rusts while in most clays the
194interstitial ions are positively charged). The initial Cl^- interstitial ions have for example been
195replaced by carbonate, sulphate and many others (Usman et al., 2018). Such anion exchanges
196have been studied by mineralogists in the past and the heights of interstitial galleries have
197been determined by XRD. Two main types have been reported corresponding to Green Rust 1
198(GR1) with a monolayer of spherical or flat anions and interstitial height of about 7.5 Å and
199Green Rust 2 (GR2) with two distinct layers of tetrahedral anions (e.g. sulphate) resulting in
200interlayer spacings of about 11 Å (Usman et al., 2012; 2018). Swelling of interstitial spaces
201by long linear carboxylates and alkanes of up to ~40 Å have been reported (Braterman et al.,
2022004; Ayala-Luis et al., 2010; Usman et al., 2018).

203 As is obvious from the general outline of bioenergetic conversion of disequilibria
204which we have presented above, the anion most pertinent to emergence of life scenarios is
205phosphate (Arrhenius et al., 1997; Bocher et al., 2004; Barthélémy et al., 2012; O'Loughlin et
206al., 2015). Pyrophosphate/orthophosphate disequilibria are extremely likely candidates for

207having played the role of high ATP/ADP-ratios at life's emergence. Phosphate has a
 208tetragonal geometry and, in its fully deprotonated state, is isostructural to sulphate which has
 209been shown to be readily incorporated into GR's interstitial spaces and to form the di-
 210interlayer structures of GR2. The steric similarities between fully deprotonated phosphate and
 211sulphate render the possibility of phosphate intercalating GR's Fe-oxyhydroxide sheets in
 212ways resembling the sulphate interstitial di-layers tempting. However, the empirical data with
 213respect to intercalating phosphate are somewhat ambiguous so far. While Hansen and Poulson
 214(1995) reported that phosphate can replace about half of the sulphate anions in GR2, in most
 215other studies (Bocher et al., 2004; Ruby et al., 2006; Barthélémy et al., 2012) phosphate was
 216seen as adsorbing to the edges of GR nanocrystals without entering interlayer galleries.
 217Indeed, the perceived steric similarity between sulphate and phosphate may be misleading.
 218Firstly, the net charge of deprotonated phosphate is 3- rather than 2- for sulphate which may
 219render the charge-balancing act between Fe-oxyhydroxide layers and interlayer anions
 220trickier. Secondly, phosphate features 2 pK values in the relevant pH region (that is, slightly
 221acidic to strongly alkaline) in bulk water and will therefore occur in 3 distinct protonation
 222states (and hence with net negative charges varying between 3- and 1-) over this pH-interval.
 223This problem is likely exacerbated by the fact that water and proton activities in the interlayer
 224must be expected to differ substantially from those of bulk water. The inconsistencies of
 225published results therefore in our mind beg for more experimental work to arrive at a
 226comprehensive understanding of phosphate sorption to GR nanocrystals.

227 A superposition of phosphates in GR2-type interstitial di-layers comparable to that of
 228sulphates would obviously be particularly pertinent in the framework of emergence of life
 229hypotheses since the strongly lowered water activity in the interstitial spaces would
 230necessarily displace the PP_i/P_i equilibrium towards higher proportions of the condensed
 231pyrophosphates. Pyrophosphates, once formed, hydrolyse only sluggishly and take in the
 232range of a hundred hours to resume equilibrium proportions if transferred back into bulk
 233water (von Wazer et al., 1955; Huang, 2018, 2019). Of course, to be of use as a vector of free
 234energy, these pyrophosphate molecules would need to be transported to where the ancestral
 235entropy-lowering processes would have occurred. We have previously developed a scenario
 236in which GR nanocrystals are hypothesised as embedded in the amyloid-based walls of
 237vesicles (Fig. 4) which separate an electron-rich interior (resulting from mineral-catalysed
 238oxidation of reducing gases such as molecular hydrogen and/or methane) from an oxidising
 239(due to the presence of nitrogen oxides and nitrogen oxyanions, NO_3^- , NO_2^- and NO) outside
 240world (Duval et al., 2019). Due to this redox disequilibrium, electrons would flow through the

oxyhydroxide layers from the vesicle interior towards the outside electron acceptors. Such a current of electrons is equivalent to the hopping of positive charges, *i.e.* locations of Fe^{3+} sites, towards those edges of the nanocrystals which face the vesicle interior (Fig. 4). Since interstitial anions charge-compensate Fe^{3+} sites, the inward movement of these Fe^{3+} sites is expected to pull the interstitial anions in the same direction. For the case of phosphates/pyrophosphates as interstitial anions, the higher negative charge of pyrophosphate (4-) as compared to that of phosphate (~50% 1-, ~50% 2- at pH 7) (and possibly also their differing bulkiness) will strongly favour delivery of pyrophosphate to the vesicle interior and thus further augment the displacement of the PP_i/P_i ratio from its equilibrium value within the vesicles. The analogy to the processes occurring in living cells is obviously striking. The details of the proposed structural picture (that is, types of environmental substrates and nature of the dielectric barrier) are rationalized by the fact that we consider alkaline hydrothermal vents (Russell et al., 2013; Branscomb and Russell, 2018a; Duval et al., 2019) as the most promising sites for life's emergence. The reasons for this choice are manifold, ranging from the stunning analogies in pH and electrochemistry between these vents and extant cells (Lane, 2010; Schoepp-Cothenet et al., 2013) to fundamental thermodynamic considerations (Branscomb and Russell 2018b). We feel that spelling out these reasons exceeds the scope of this article and direct interested readers to the respective literature (Branscomb et al., 2017).

We emphasise that the mentioned experimental ambiguities with respect to phosphate sorption to GR don't necessarily impact our scenario for the role of GR as disequilibrium converter as described above. The envisaged processes do not require mass-replacement of for example sulphate by phosphate. Rather, a tiny fraction of interstitial anions substituted by phosphate would be enough for these mechanisms to proceed. The cited mineralogical studies, by contrast, measure bulk properties and almost certainly would fail to detect highly sub-stoichiometric anion replacements.

There are certainly still fundamental conceptual differences between the model we propose and the presumed functional mode of protein machines such as H^+ -translocating pyrophosphatases and cellular bioenergetics in general. To progress towards better defining the similarities and differences, we have formulated our scenario intentionally in a very specific manner which renders it amenable to experimental falsification of some of its parts or of its entirety. However, irrespective of your preferred hypothesis for life's emergence, most of the analogies in behaviour of Green Rust and bioenergetic systems are scenario-independent and suggest that an ancestral role of GRs in putting life on the road may have been overlooked for far too long.

2762.2. GRs' properties relevant to life's emergence; the path from speculation to 277knowledge

278 The scenarios we have developed here and previously (Nitschke and Russell, 2013;
279Russell et al., 2013, 2014; Russell, 2018; Duval et al., 2019), and which imply a crucial role
280of fougérite in life's emergence, invoke a number of redox processes and nano-structural
281properties of GR minerals. Some of these features have indeed already been found in GRs
282while others are still speculative although plausible given the ensemble of available data.
283Apart from the mentioned methane-to-methanol reaction scheme, most other speculative
284features discussed above are correlated to putative nano-structural properties of GR
285nanocrystals. To assess the validity of these features, a better understanding of these
286properties is required:

287 - The precise nanostructure of nanocrystals containing mixed populations of
288flat/spherical and tetragonal interstitial anions is unknown even if computational approaches
289on several clay-type materials are starting to provide glimpses into the range of possible
290geometries (Bernal et al., 1959; Génin et al., 2001, 2008; Braterman et al., 2004).

291 - Water activities in the interstitial galleries of diverse GRs are badly constrained.
292Again, computational methods are yielding first data.

293 - Charge conductivity parallel and normal to the layer sheets is badly defined (but see
294Poinssignon, 1997; Wander et al., 2007; Katz et al., 2012).

295 - Nanoscale redox inhomogeneities within single GR nanocrystals have not been studied
296so far.

297 - The possibility of motional coupling of layer/interlayer pairs of opposite charges
298represents an intriguing topic but has also not been studied so far.

299 - The interaction of single GR nanocrystals with barriers made up of organic molecules
300(polypeptides, lipids) as hypothesised in our scenario described above (Fig. 4) has never been
301studied.

302 The methods routinely applied to study clays and in particular transition-metal
303containing clay-related minerals such as GRs (e.g. XRD, Mössbauer spectroscopy) average
304over many atoms and many layers and therefore inform on bulk properties only. This lack of
305atomic scale information has over the last few years increasingly been remedied by
306computational approaches (Thyveetil et al., 2008; Greenwell, 2010b; Pérez-Villa et al., 2018;
307Martínez-Bachs and Rimola, 2019; Ugliengo, 2019). However, state-of-the-art
308nanotechnological approaches (e.g. nano-SIMS, nanoscale chemical analysis in TEM,

309Synchrotron beamlines) may well provide more solid grounds to notions obtained solely via
310computation (see Fracchia et al., 2018). The conductivity properties of nanocrystals may be
311addressed by growth on microelectrodes or incorporation into black membranes coupled to
312electrochemical techniques. Interaction of GR nanocrystals with micro-sized organic
313structures can be studied by biochemical methods in combination with SEM and TEM. We
314have recently initiated research on some of these questions in our laboratories.

315

3163. Conclusions

317 We fully share the clay community's conviction that clay-type minerals are extremely
318likely to have played a crucial role in life's emergence. In this contribution we have tried to
319raise awareness, based both on thermodynamic arguments and on the layout of extant life, that
320the common focus on clays' catalytic capacities may be too narrow. To make life emerge we
321first and foremost need processes which convert environmental disequilibria (think redox and
322possibly also pH gradients) into the entropy decrease that characterises life. The clay-type
323mineral Green Rust appears prone to perform processes which are intriguingly reminiscent of
324certain disequilibrium converters observed in life. The challenge of assaying the pertinence of
325these perceived similarities between Green Rusts (and fougérite) and pivotal processes in life
326will heavily rely on nanotechnological approaches to obtain atomic resolution information on
327the above-mentioned processes in the layered Fe-oxyhydroxide minerals. The scope of
328possible approaches seems virtually limitless and we partially conceived this contribution as
329an appeal to the community of mineralogists to join research on GRs' potential role in life's
330emergence.

331

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334

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Figure Captions

Figure 1: Schematic representation of cellular conversion of environmental free energy (electrochemical disequilibria) into phosphate-group-transfer disequilibria in the form of far-from-equilibrium ratios of ATP/ADP or PP_i/P_i . The plethora of different layouts of electron transfer chains (in response to varying types of environmental substrates) is represented by a dark gray box (for details, see Schoepp-Cothenet et al, 2013). The principal outcome of the collapse of environmental redox gradients by these chains is the buildup of an electrostatic field which, in certain cases in combination with a concentration gradient, translates into a “proton-motive-force” (which may in a few organisms be converted *via* antiporters into a “sodium-motive-force”). The proton-motive gradient is converted into far-from-equilibrium values of ATP/ADP and PP_i/P_i by rotor-stator-type ATP synthases (1st enzyme from the right, pdb-entry: 5DN6) and H^+ -translocating pyrophosphatases (2nd enzyme from the right, pdb-entry: 4A01), respectively.

351

Figure 2: Four predominant strategies exploited by extant life to maintain strongly reducing conditions in their cytoplasm, required for a wide range of metabolic processes. Low redox potential conditions are mediated by high reduction levels of the soluble redox compounds NAD and ferredoxins. As detailed in the main text, it is in particular scheme iv which points towards a potential role of Green Rust minerals as inorganic precursors of the enzymatic systems employed by extant life.

358

Figure 3: Structural juxtaposition of a diiron unit within an Fe-oxyhydroxide layer of Green Rust (top, left) and the catalytic site of the enzyme sMMO catalyzing the conversion of methane to methanol in many methanotrophic organisms (top, right). The bottom schemes represent two Green Rust layers (bottom, left) from which the diiron centre was extruded and the parent enzyme sMMO (bottom, right, pdb-entry: 1MTY).

364

Figure 4: Schematic representation of a part of the barrier of a hypothetical (dielectrically insulated) compartment in hydrothermal vent chimneys (Russell, 2018) spiked with a Green Rust nanocrystal protruding on both sides of the barrier. The envisaged redox reactions are shown in the left scheme while resulting electron transport (in the Fe-oxyhydroxy layers) and condensation as well as ion-transport phenomena (in the interlayers) are depicted in the blown-up representation of the right-side scheme. These processes are described in the main text and in more detail in Duval et al. (2019) as well as Duval et al. (2020).

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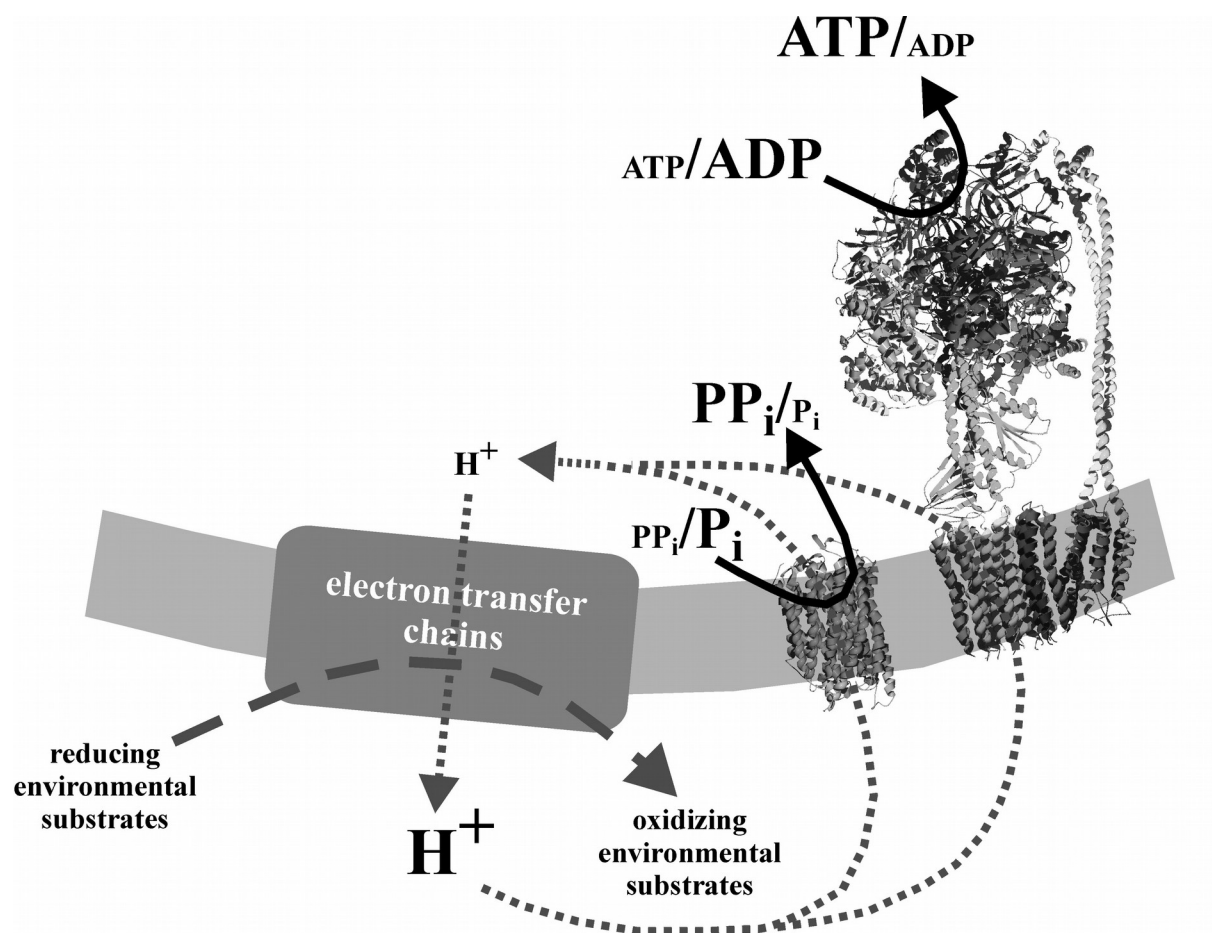
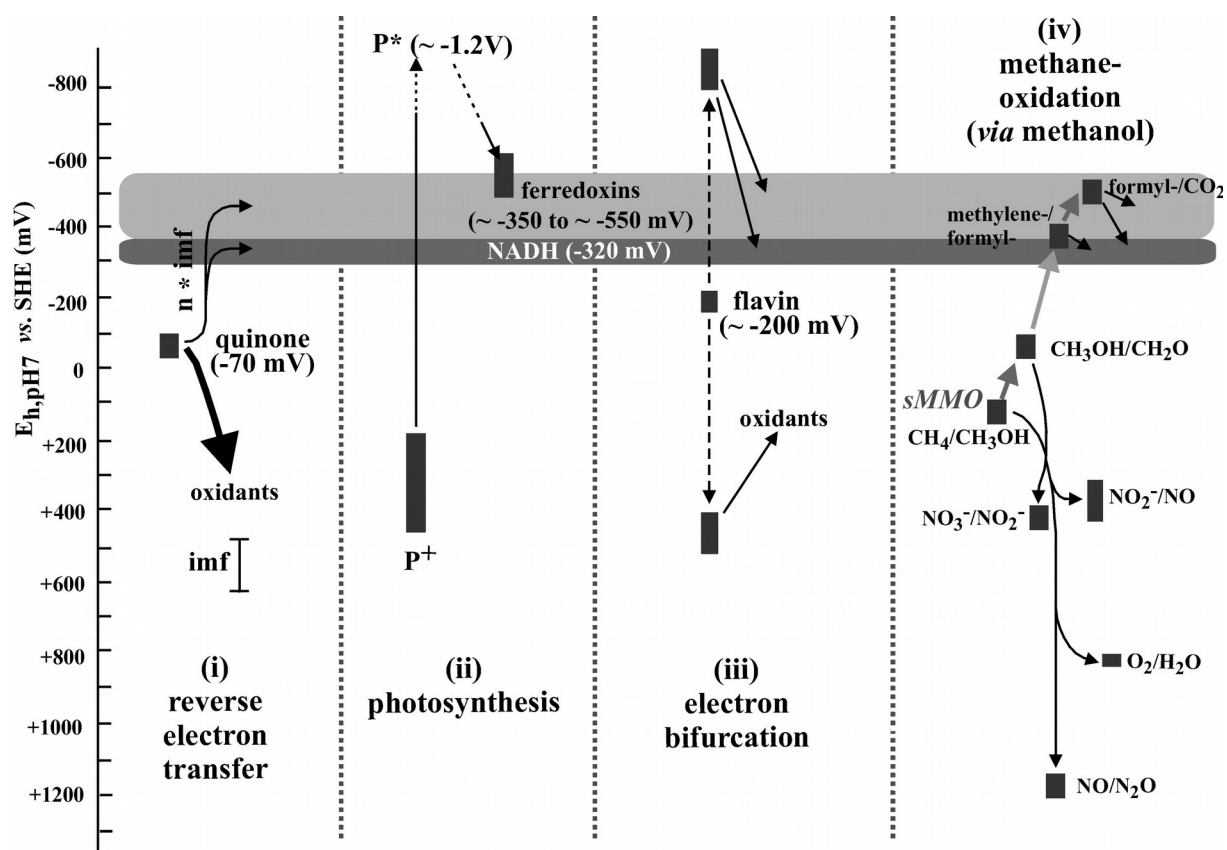
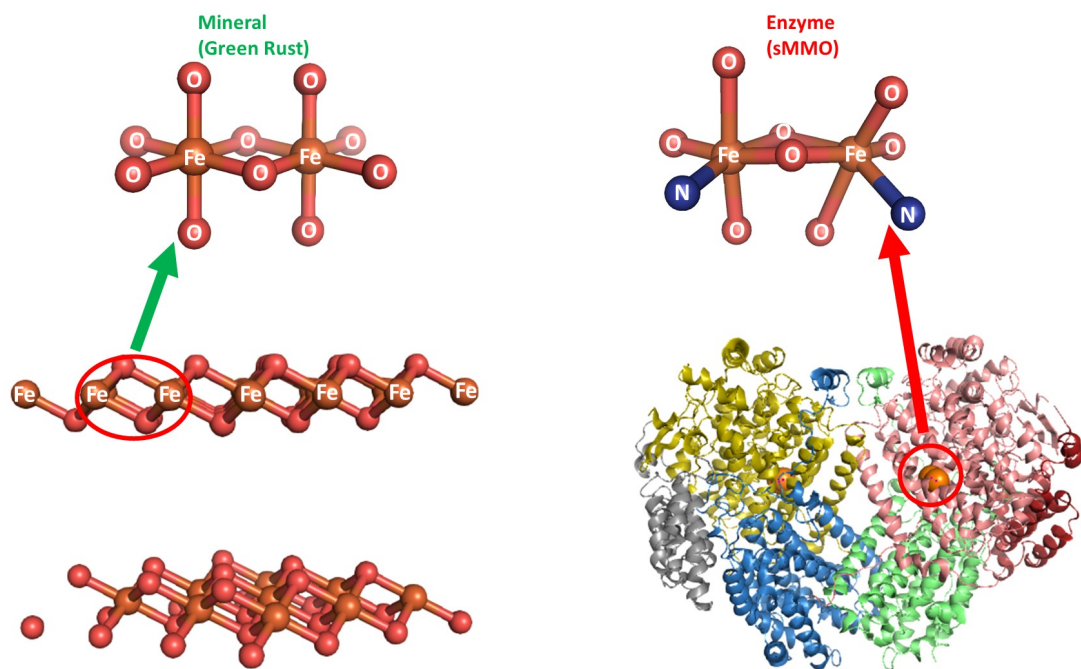


Figure 1



612 **Figure 2**



614 **Figure 3**

