The Aerobic Earth

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Co-Editor-in-Chief
Matter and Radiation at Extremes

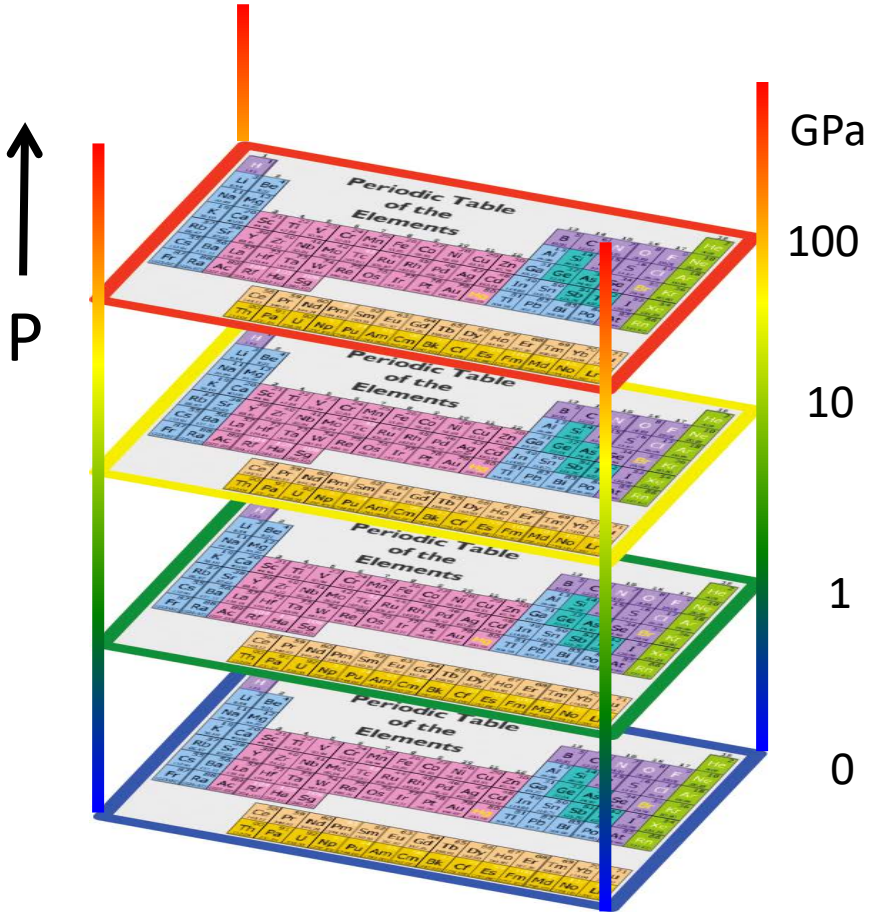
Center for High Pressure Science & Technology Advanced Research
HPSTAR

MRE Webinar on Matter at Extreme **Pressures**

January 14, 2021

The New Worlds in the Extreme Pressure Dimension

- Same elements; new physics, new chemistry, novel application, transformative planetary science
- Ten times more new materials to be discovered
- Requires interdisciplinary approach
- Relies on high-pressure technological advances



2020 MRE High-Pressure Special Volume

All you want to know about metallic hydrogen

Gregoryanz *et al*., *MRE* 5, 038101 (2020)

Ji *et al. MRE* 5, 038401 (2020)

Room-T superconductors

Lv *et al* 5, 068101 (2020).

Struzhkin *et al MRE* 5, 028201 (2020)

Xiao-Jia Chen *MRE* 5, 068102 (2020)

HP Chemistry

Choong-shik Yoo *MRE* 018202 (2020)

HP Technology

Hirao *et al. MRE* 5, 018403 (2020)

Walker and Li *MRE* 5, 018402 (2020)

Nanomaterials strength

Xu and Tian *MRE* 5, 068103 (2020)

Yang *et al. MRE* 5, 058401 (2020)

Bin Chen *MRE* 5, 068104 (2020)

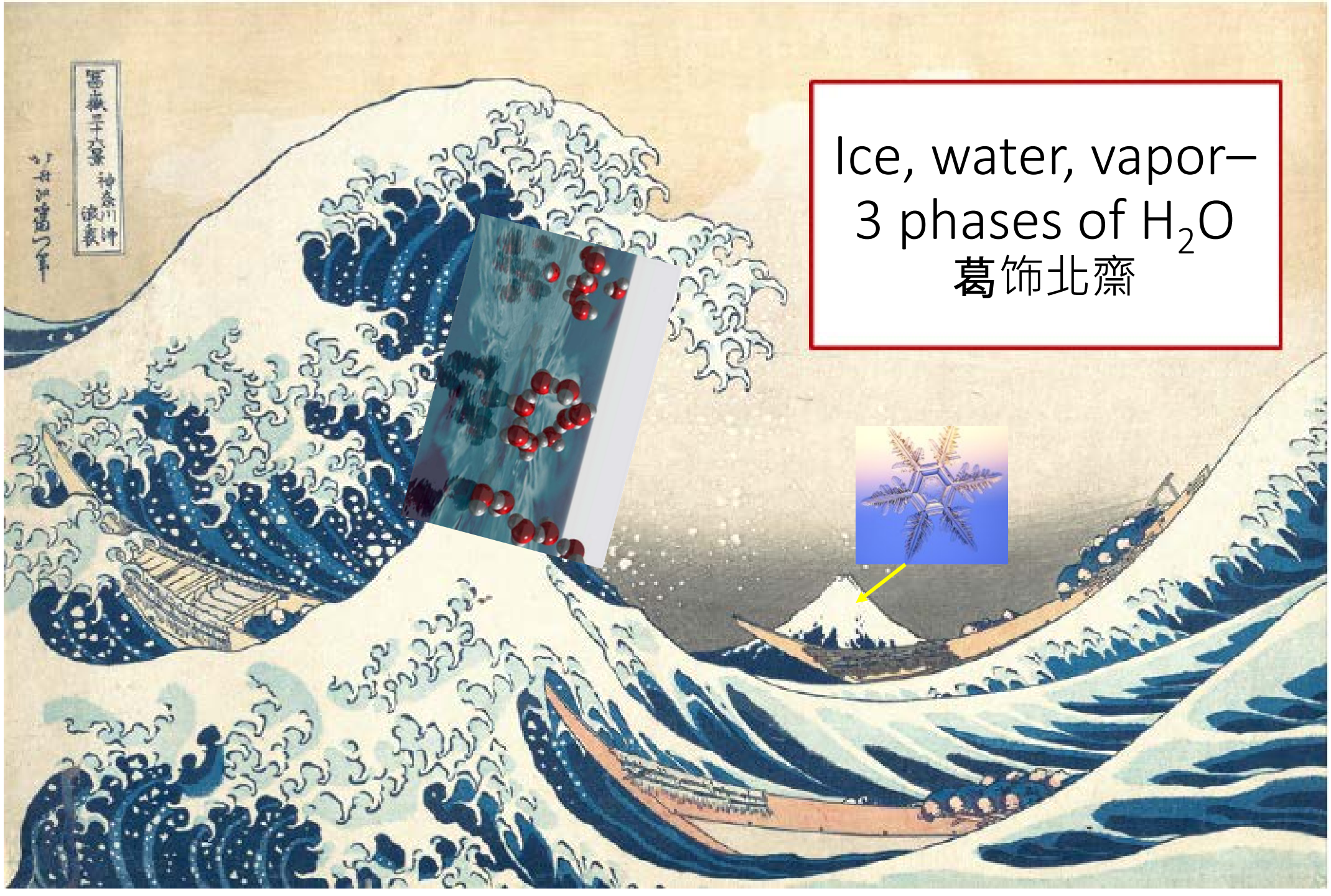
Functional Materals

Li *et al. MRE* 5, 018201 (2020)

The 4-Dimensional Earth

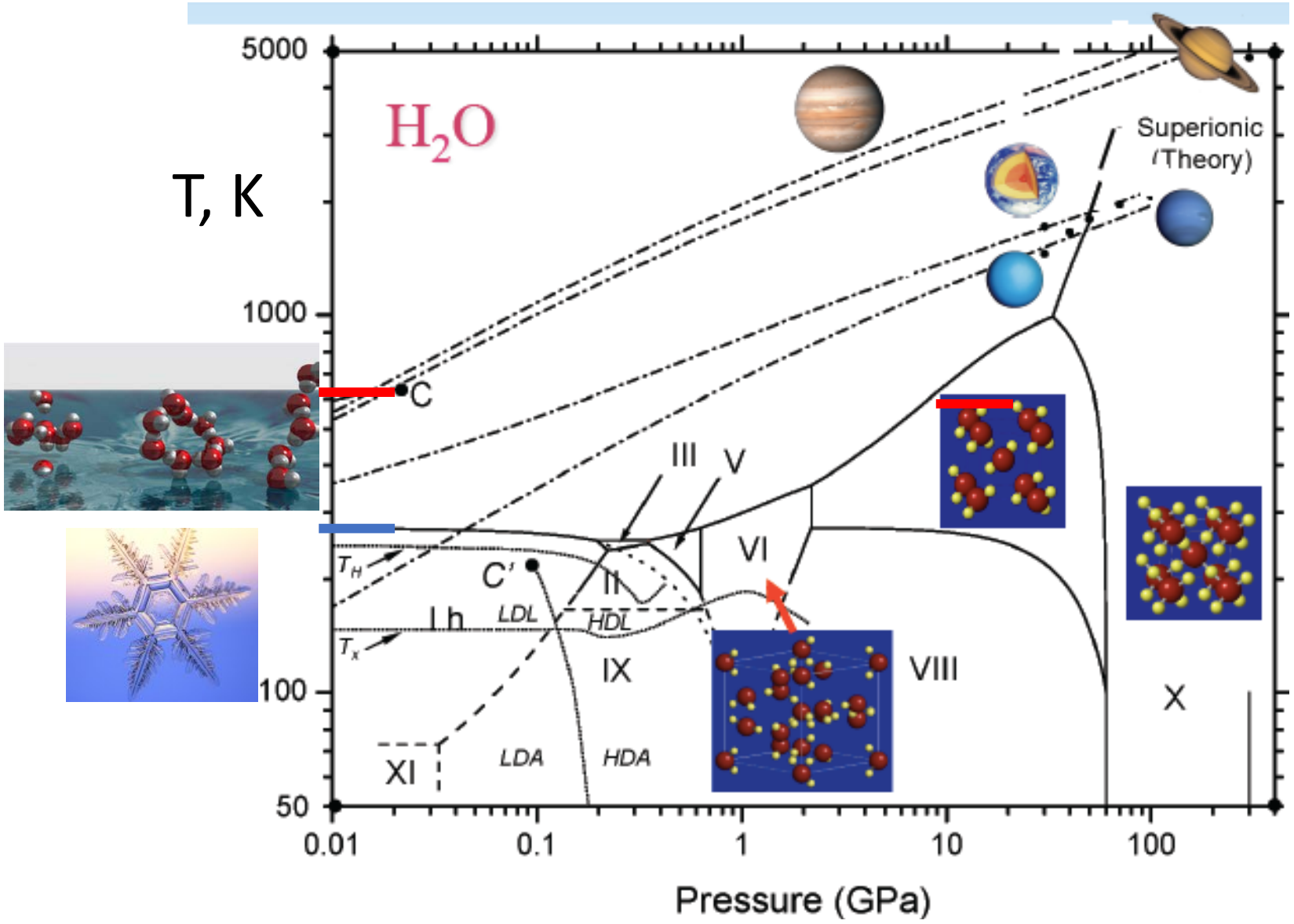
Mao and Mao *MRE* 5, 038102 (2020)

Good References to Cite



Ice, water, vapor–
3 phases of H_2O
葛饰北齋

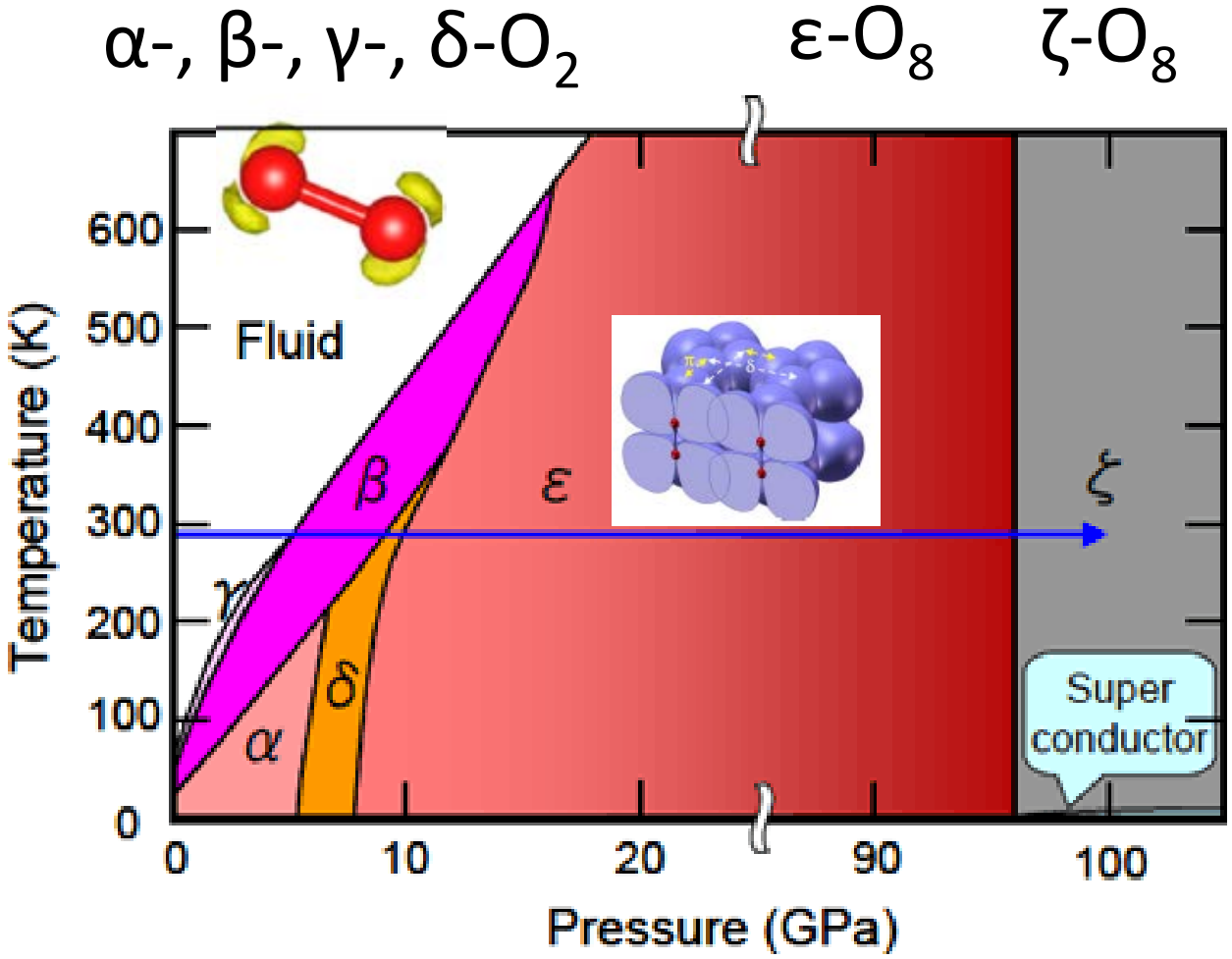
Thirty new phases of H_2O at extreme pressures

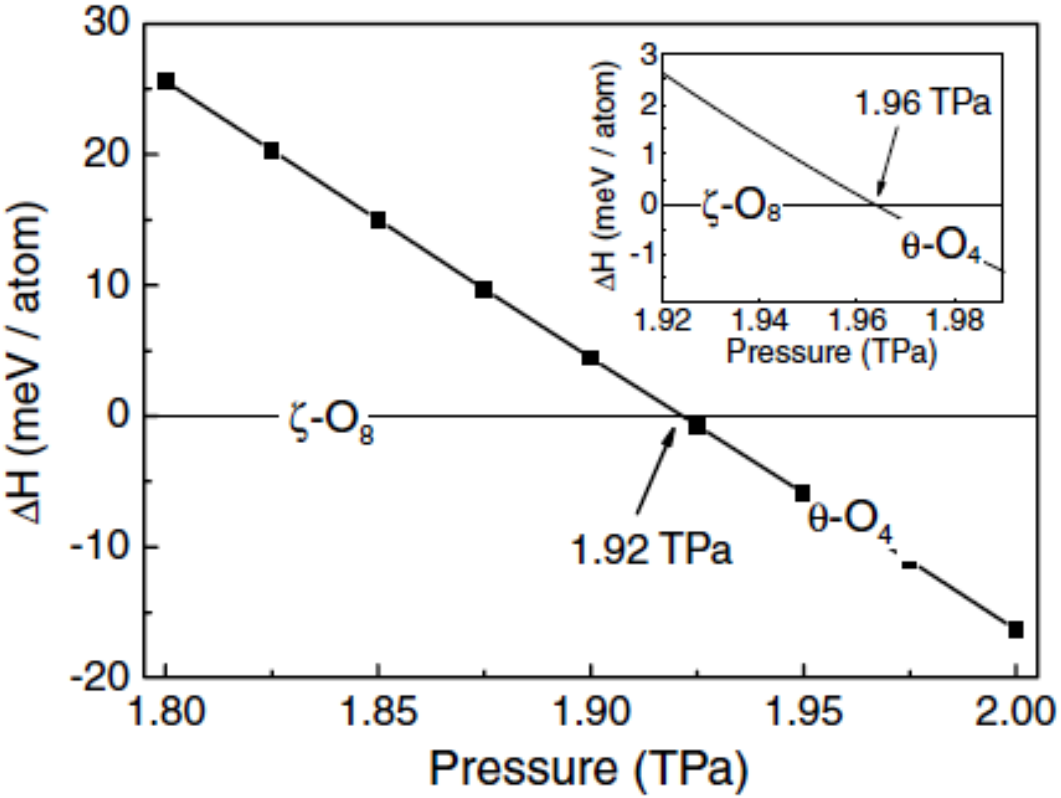


Novel Physics
- novel structures
- incommensurate
- amorphisation
- liquid-liquid
- metallization

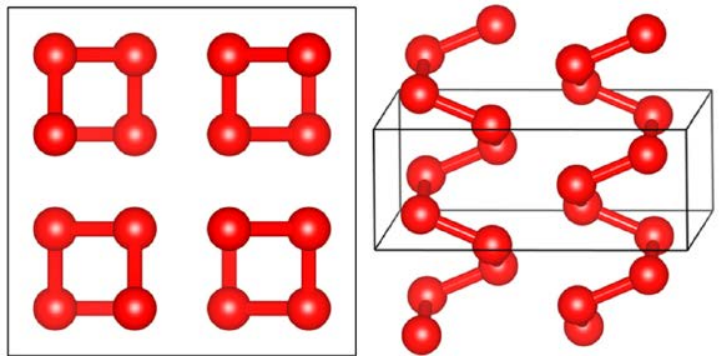
Novel Chemistry
- symmetric H bonding
- non-molecular
- superionic hydrogen
- strong oxidant
- dissociation into H & O

Oxygen at high pressures



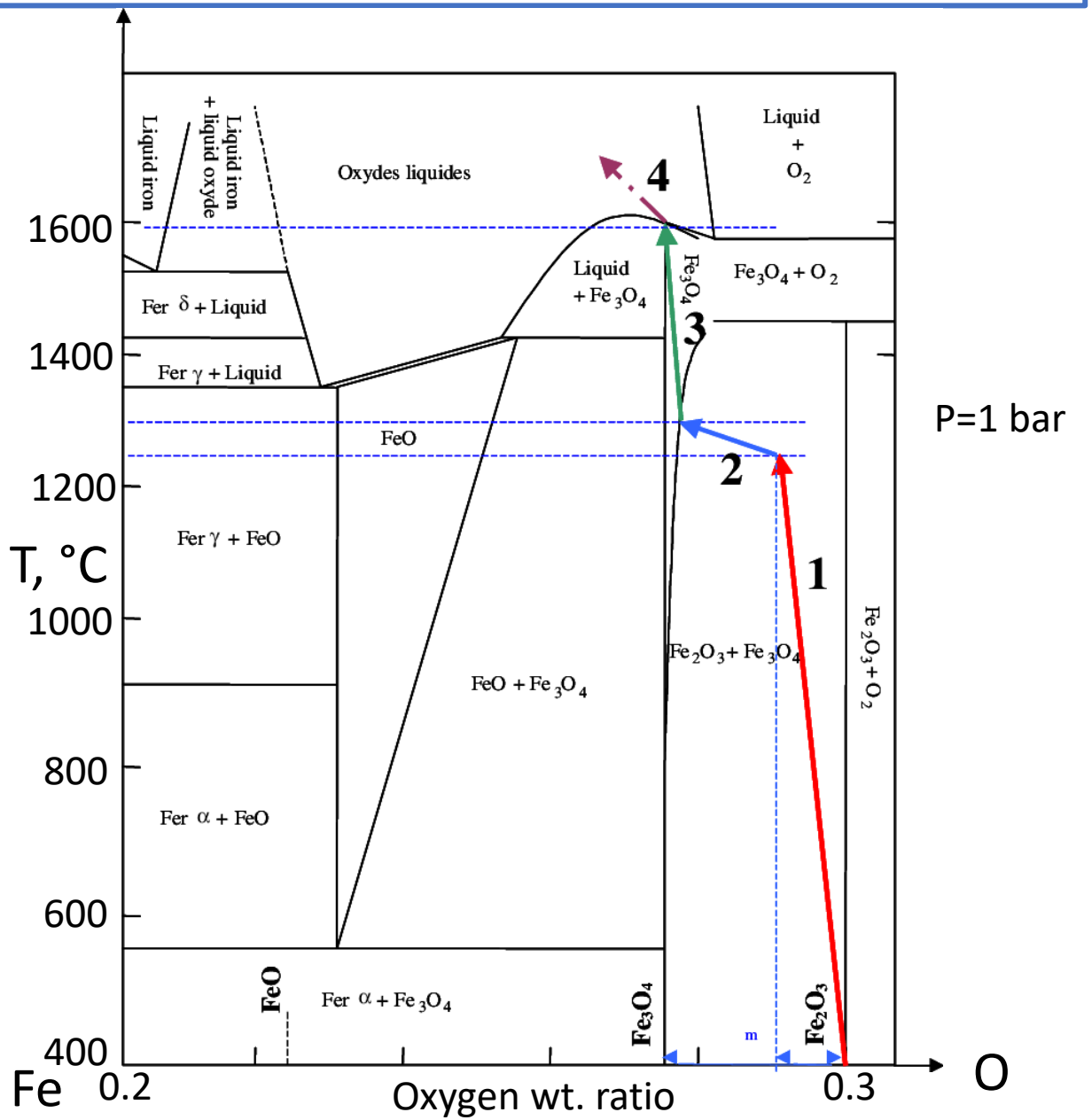


θ-O_4

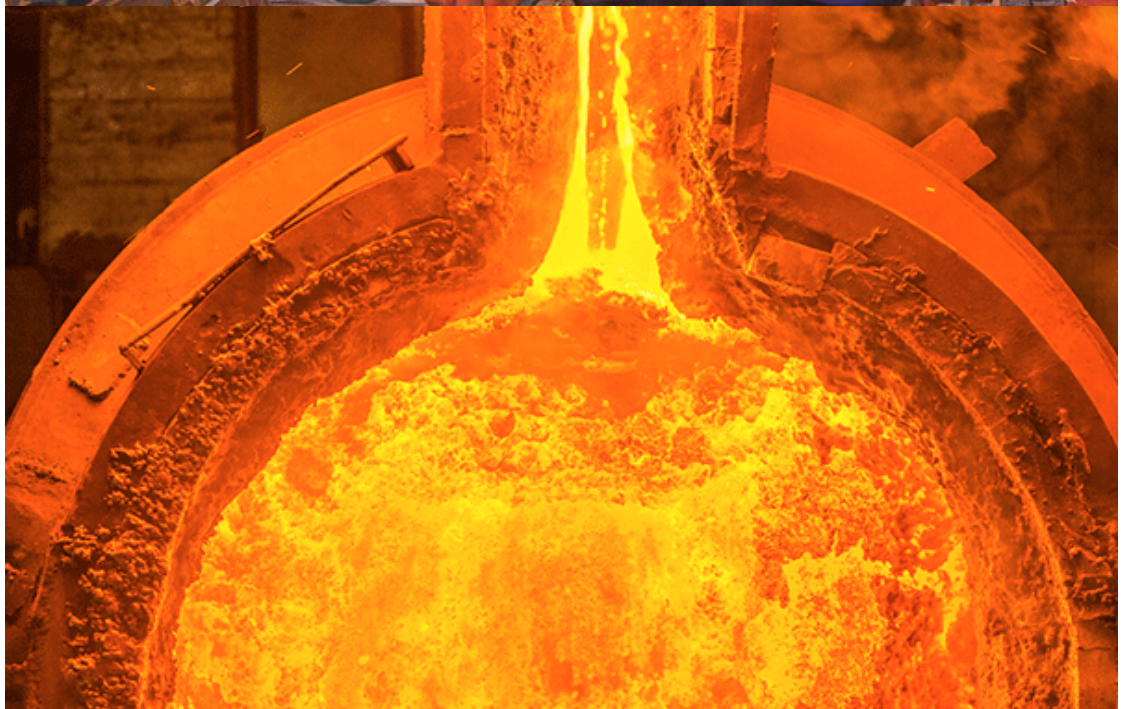


Zhu *et al, PNAS* 109, 751 (2012)

Steelmaker's Fe-O phase diagram



P=1 bar



O & Fe—the Most Abundant Elements by Atoms & Mass

The Conventional Wisdom
The mantle is uniformly reducing

Lower Mantle — Upper Mantle — Surface

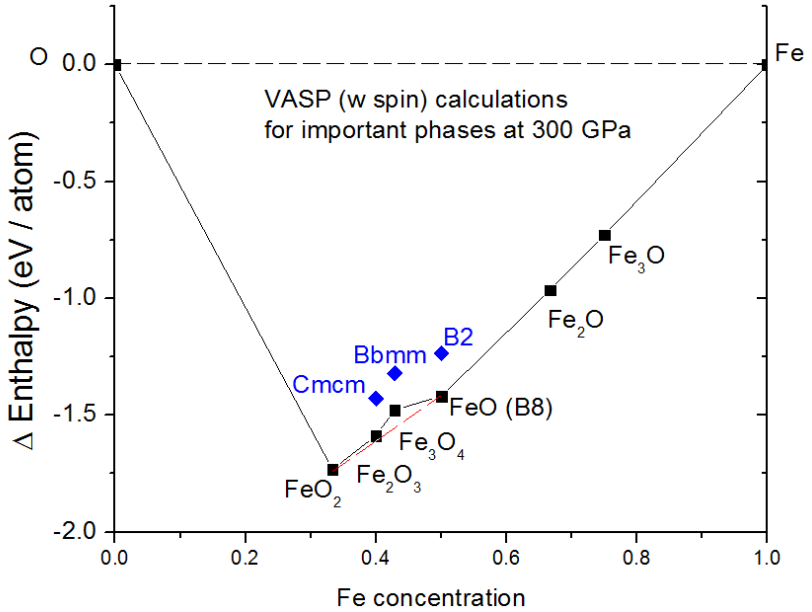
FMQ-5 — IW — FMQ — MH

$Fe \longleftrightarrow FeO \longleftrightarrow Fe_3O_4 \longleftrightarrow Fe_2O_3$ | $\longleftrightarrow O_2$

O/Fe>1.5 uninteresting and unrealistic?

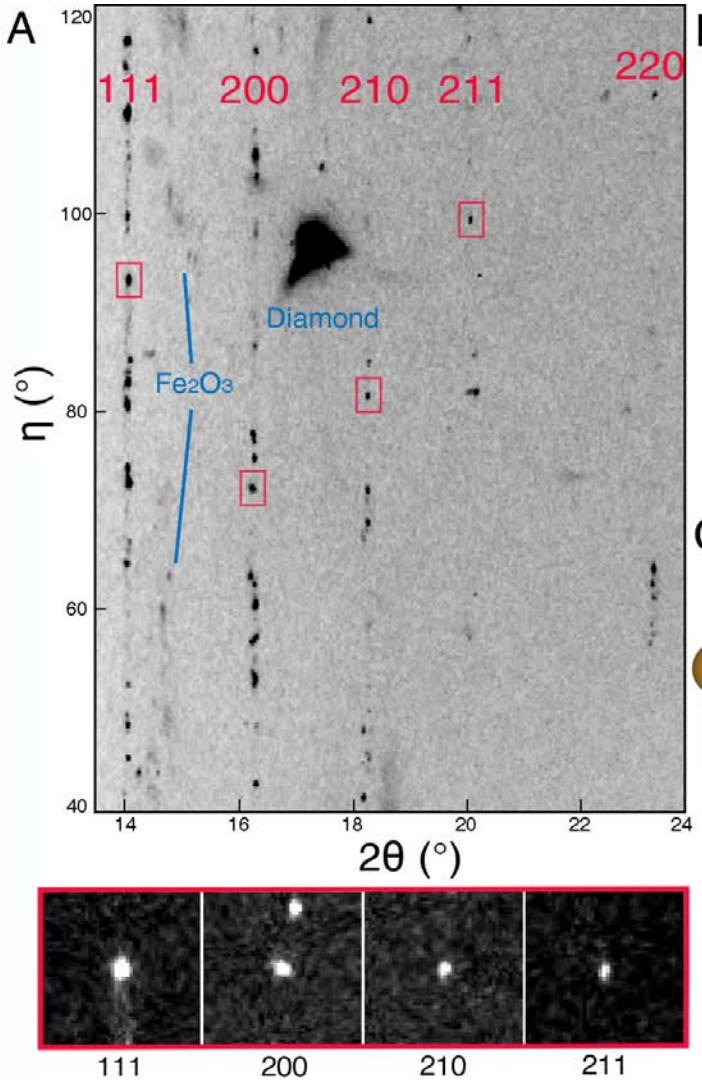
Theory predicts FeO_2 stable in the deep lower mantle conditions

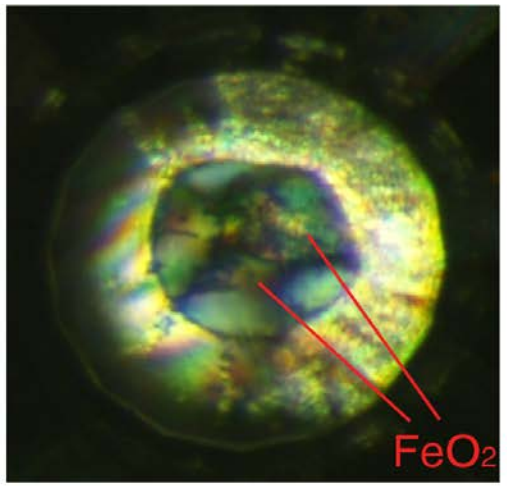
Duckyoung Kim



$2Fe_2O_3 + O_2 = 4FeO_2$

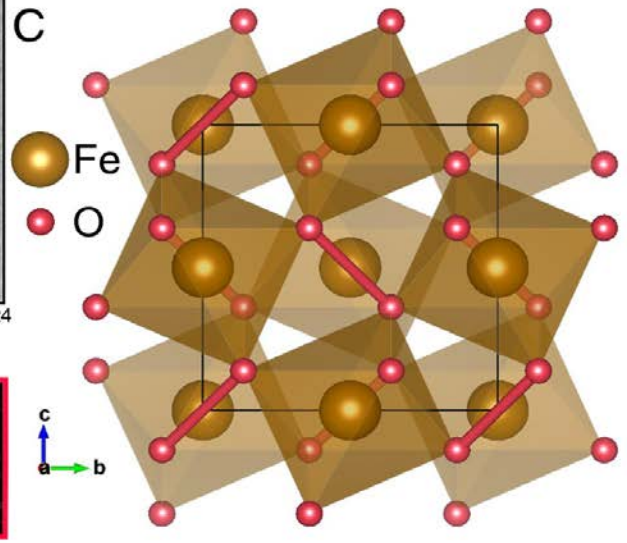
$Fe_2O_3 + H_2O = 2FeO_2 + H_2$





$Fe_2O_3 + O_2$
to 2000 K, 76 GPa

Produced FeO_2 with FeS_2 pyrite structure



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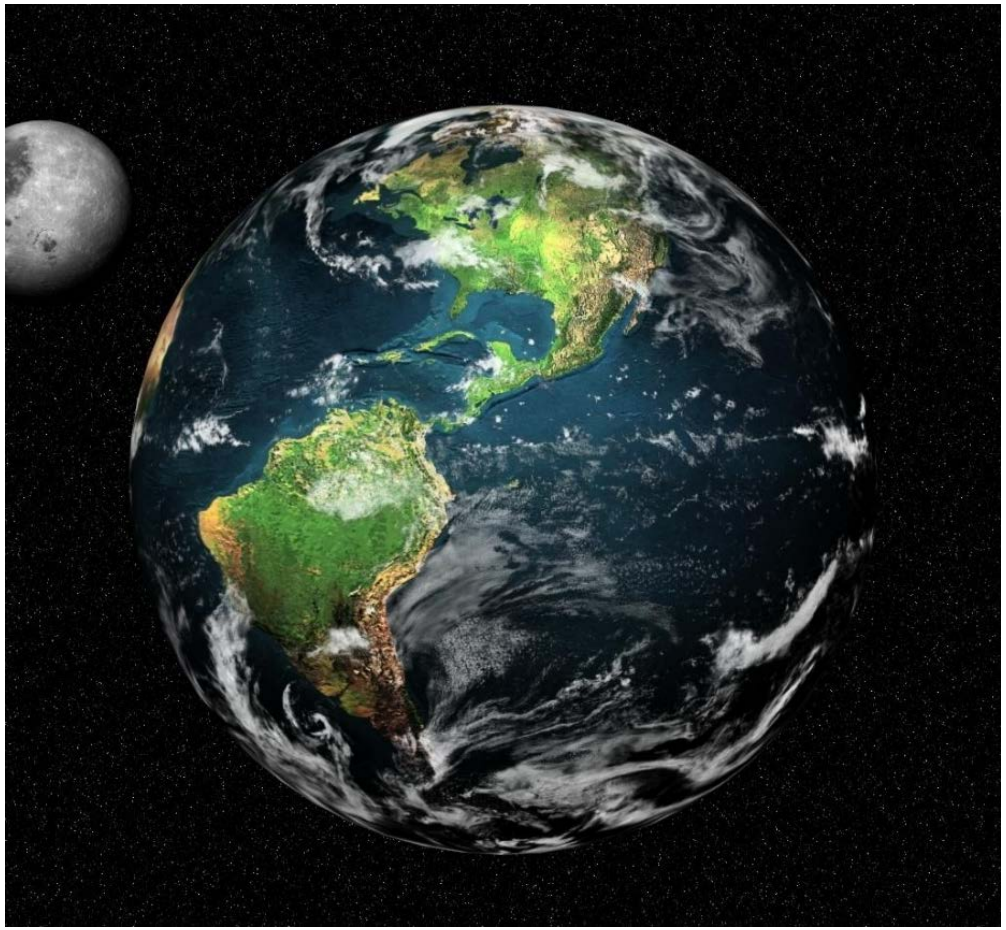
Qingyang Hu

The Aerobic Earth

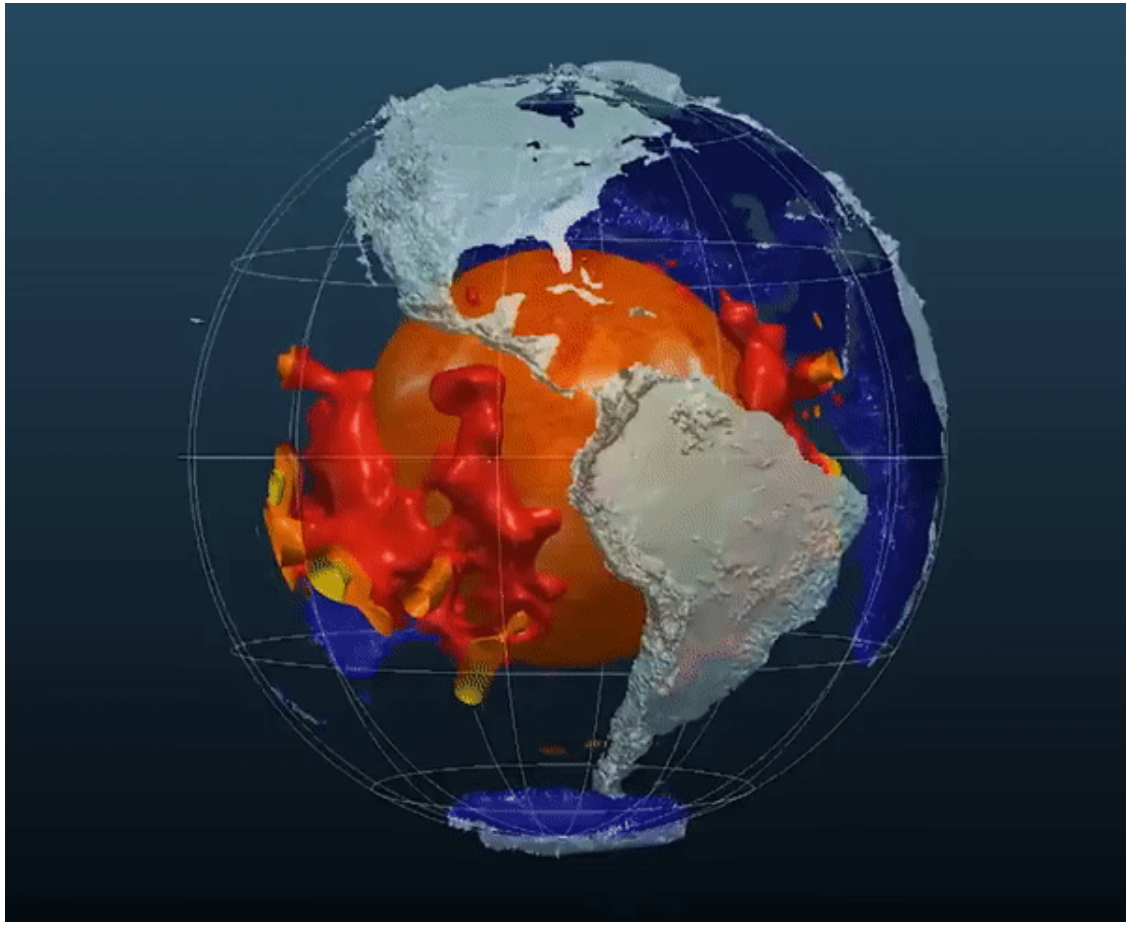
The living planet—Sir Attenborough



$CO_2 + H_2O \leftrightarrows C H_2O + O_2$

plant⇒ ⇐animal

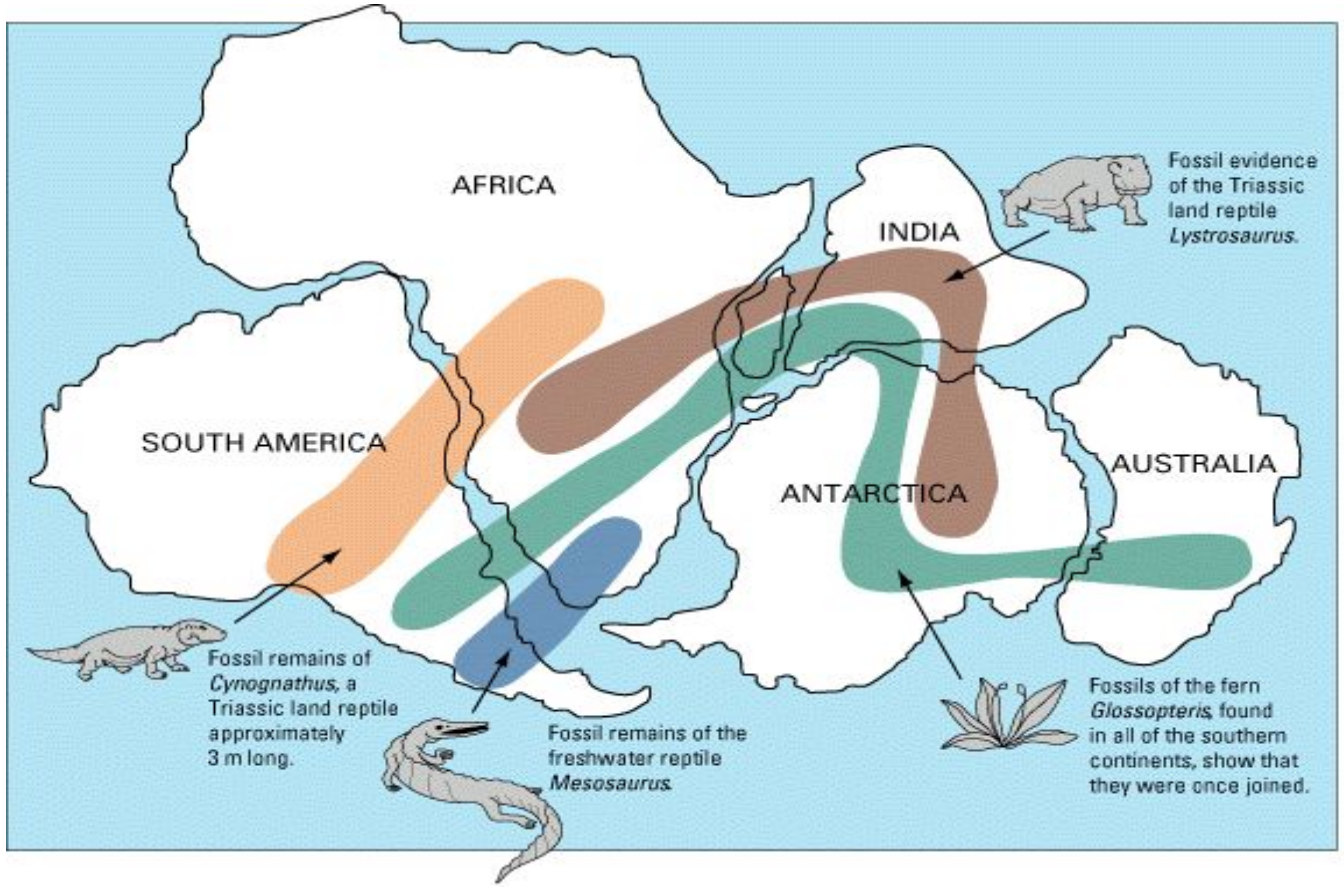
The dynamic Earth



$MO + H_2O \leftrightarrows MO_2 + H_2$

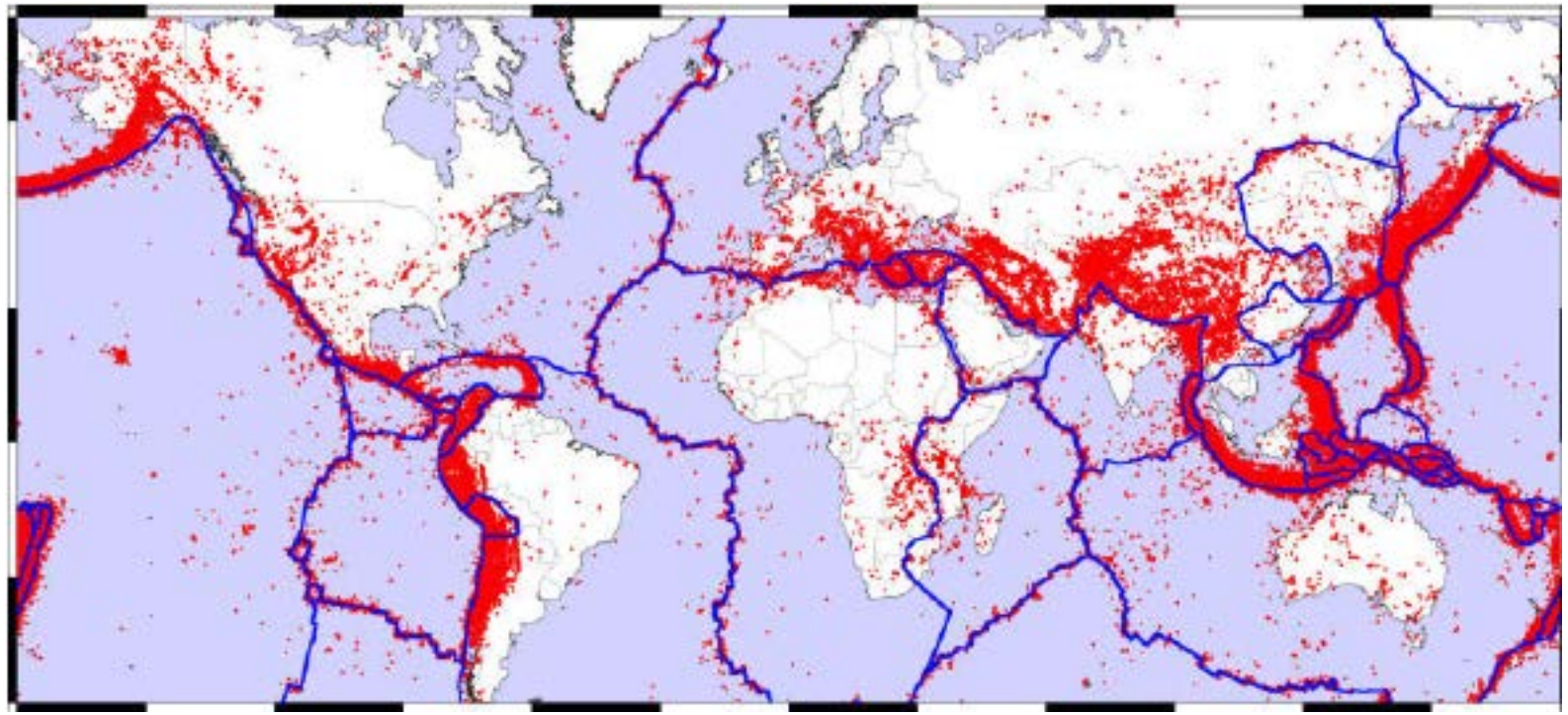
shallow⇒ ⇐ deep

Alfred Wegener's Recognition of Continental Drift --the foundation of the 20th Century Earth science



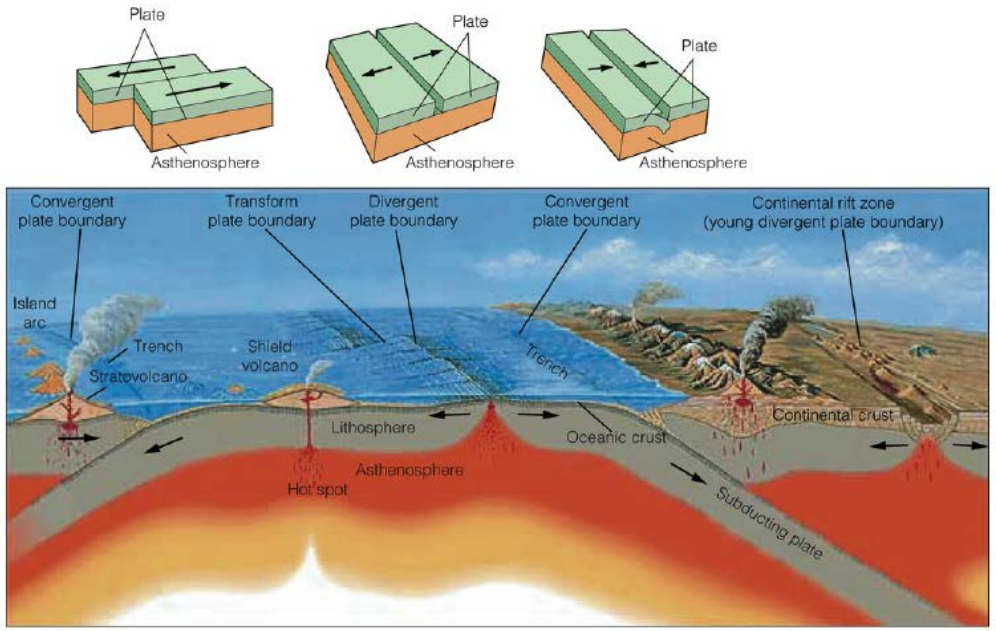
Adapted from Wegener's discussion of floral and faunal distributions across continents of Gondwanaland

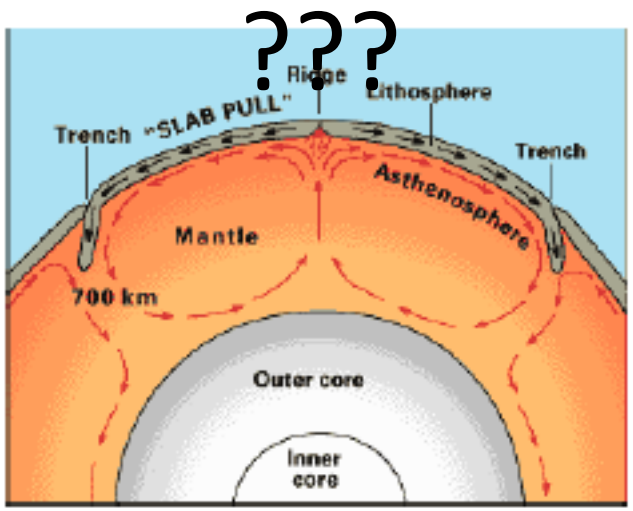
Plate tectonics—the transformative recognition



But our understanding is only skin deep

Plate tectonics—the transformative recognition





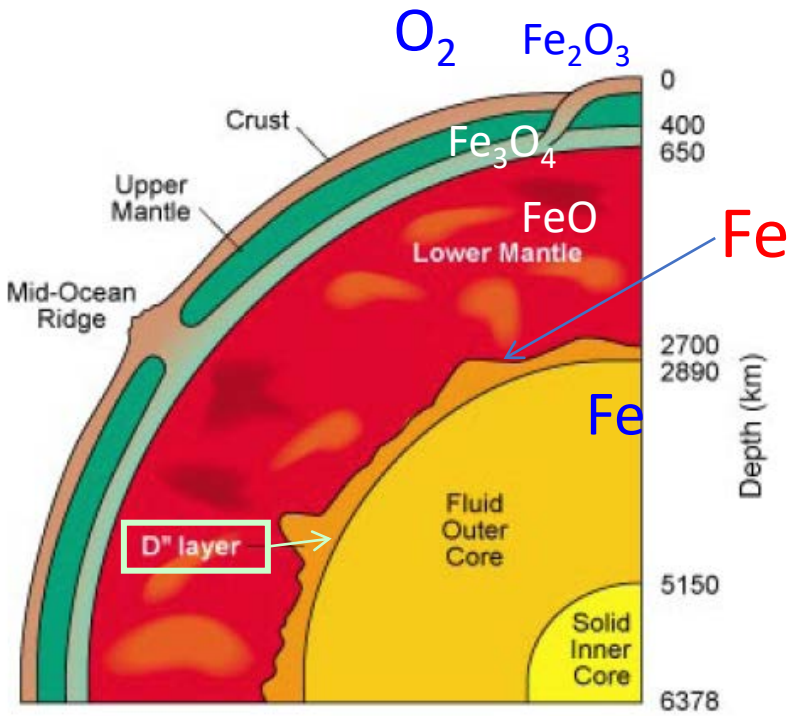
But our understanding is only skin deep

Steady thermal convection cannot explain the rifting of supercontinent; needs additional mechanism

Experimental Discovery of superoxides FeO_2 & FeO_2H

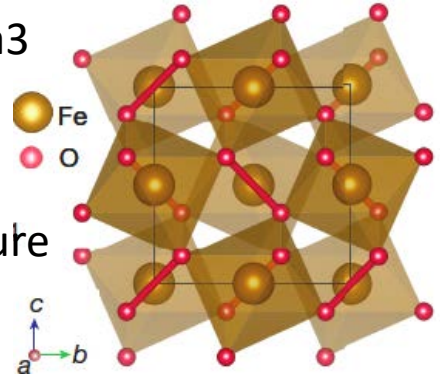
FeO_2 and FeOOH under deep lower-mantle conditions and Earth's oxygen-hydrogen cycles

9 JUNE 2016 | VOL 534 | NATURE | 241



S.G. Pa3

Pyrite structure



Qingyang Hu[1,2*], Duck Young Kim[1,2*], Wenge Yang[1,3*], Liuxiang Yang[1,3], Yue Meng[4], Li Zhang[1,2] & Ho-Kwang Mao[1,2]

胡清揚

金德荣

杨文革

杨留响

張莉

孟悦

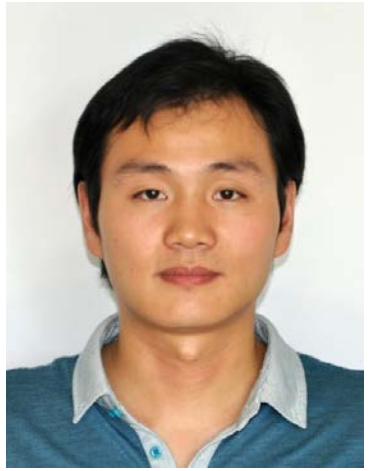
Confirmed FeO_2 stable under DLM conditions

Novel oxygen chemistry in Deep Lower Mantle

Altered chemistry of oxygen and iron under deep Earth conditions

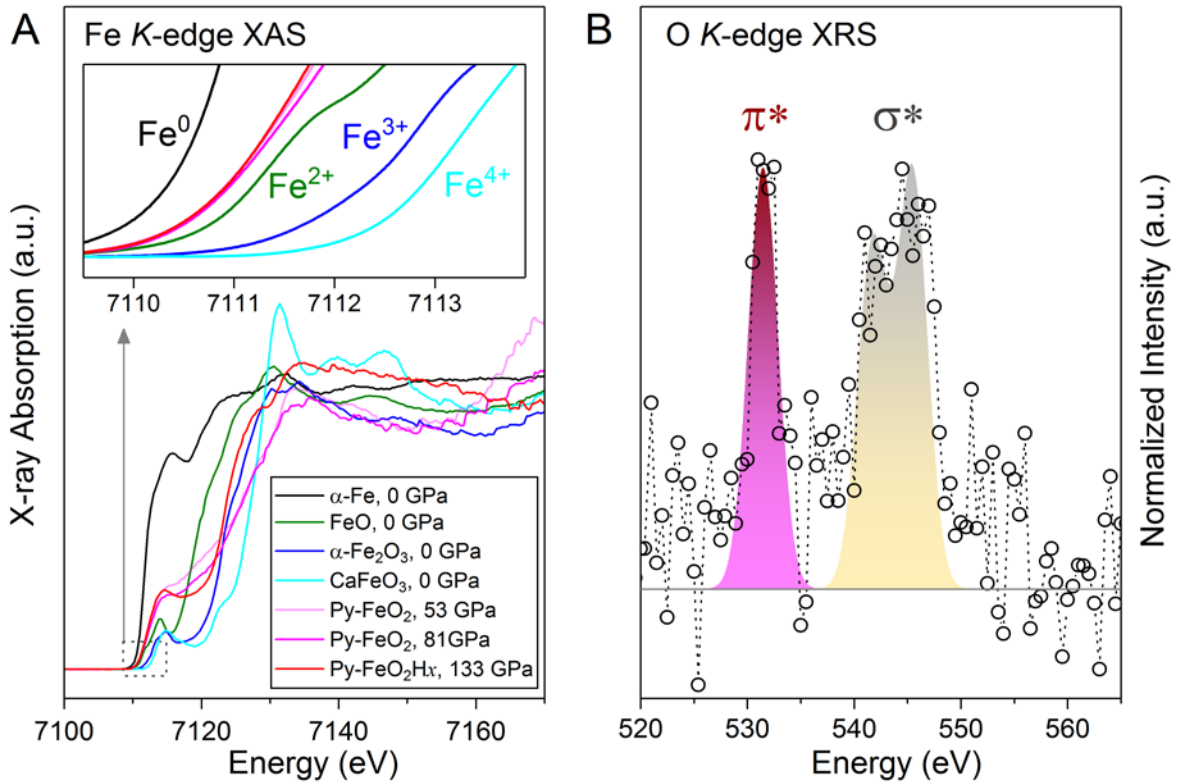
Nature Communication, 2019

Jin Liu[1,2], Qingyang Hu[1], Wenli Bi[3,4], Liuxiang Yang[1,5], Yuming Xiao[6], Paul Chow[6], Yue Meng[6]
Vitali B. Prakapenka[7], Ho-Kwang Mao[1,5] & Wendy L. Mao[2,8]



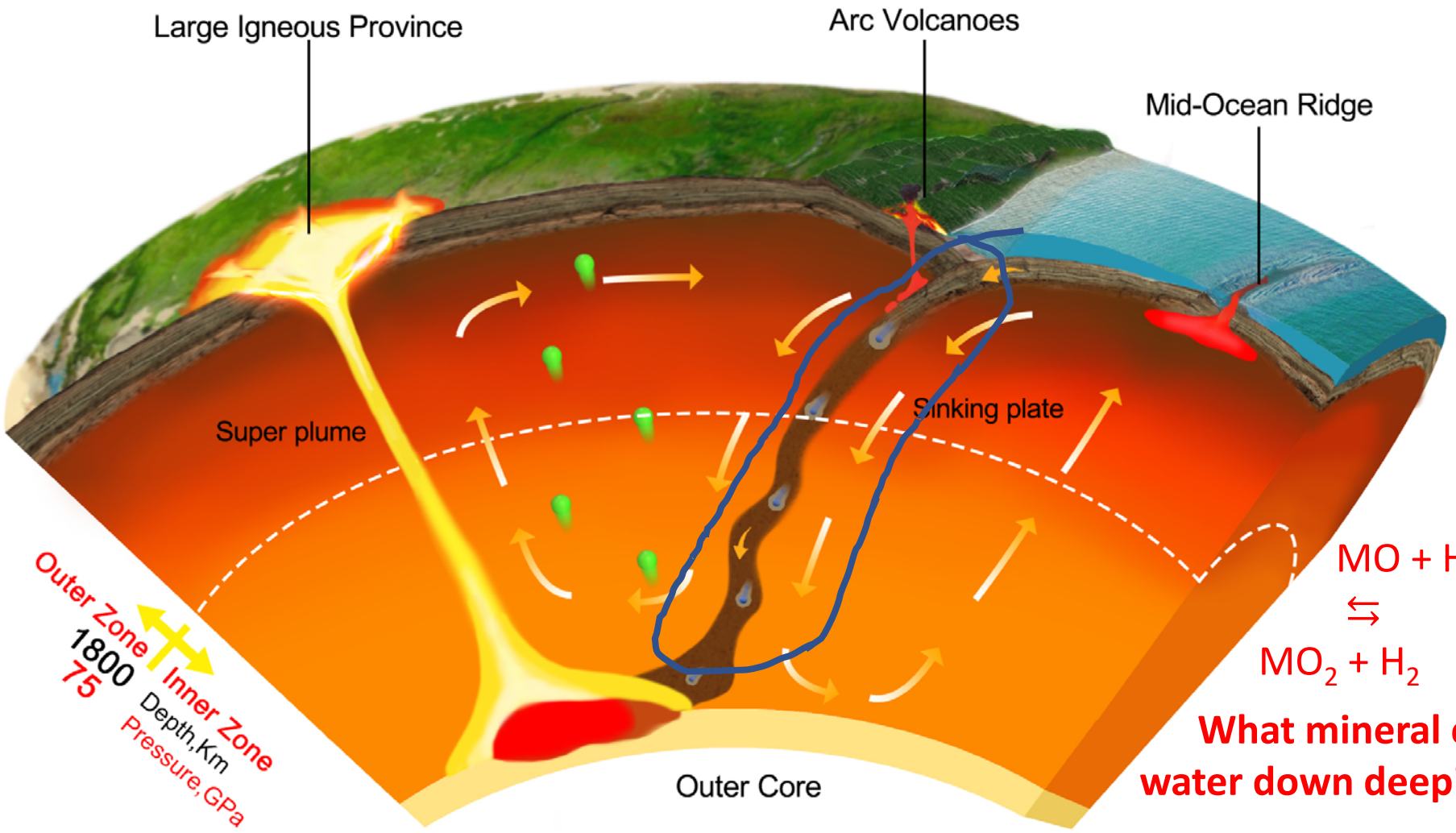
Jin Liu

Qingyang Hu



Fe is still 2+, but O become 1-

The Aerobic Reaction needs H_2O



$MO + H_2O$

$\leftrightarrows$

$MO_2 + H_2$

What mineral can carry water down deep?

Mao, H. K., and W. L. Mao (2020), Key problems of the four-dimensional Earth system, ***Matter & Radiation at Extremes***, *5*, 038102.

Hydrogen generation by metal in H_2O at HP

$Ca+2H_2O = Ca(OH)_2+H_2$

$Mg+2H_2O = Mg(OH)_2+H_2$

$2Na+2H_2O = 2NaOH+H_2$

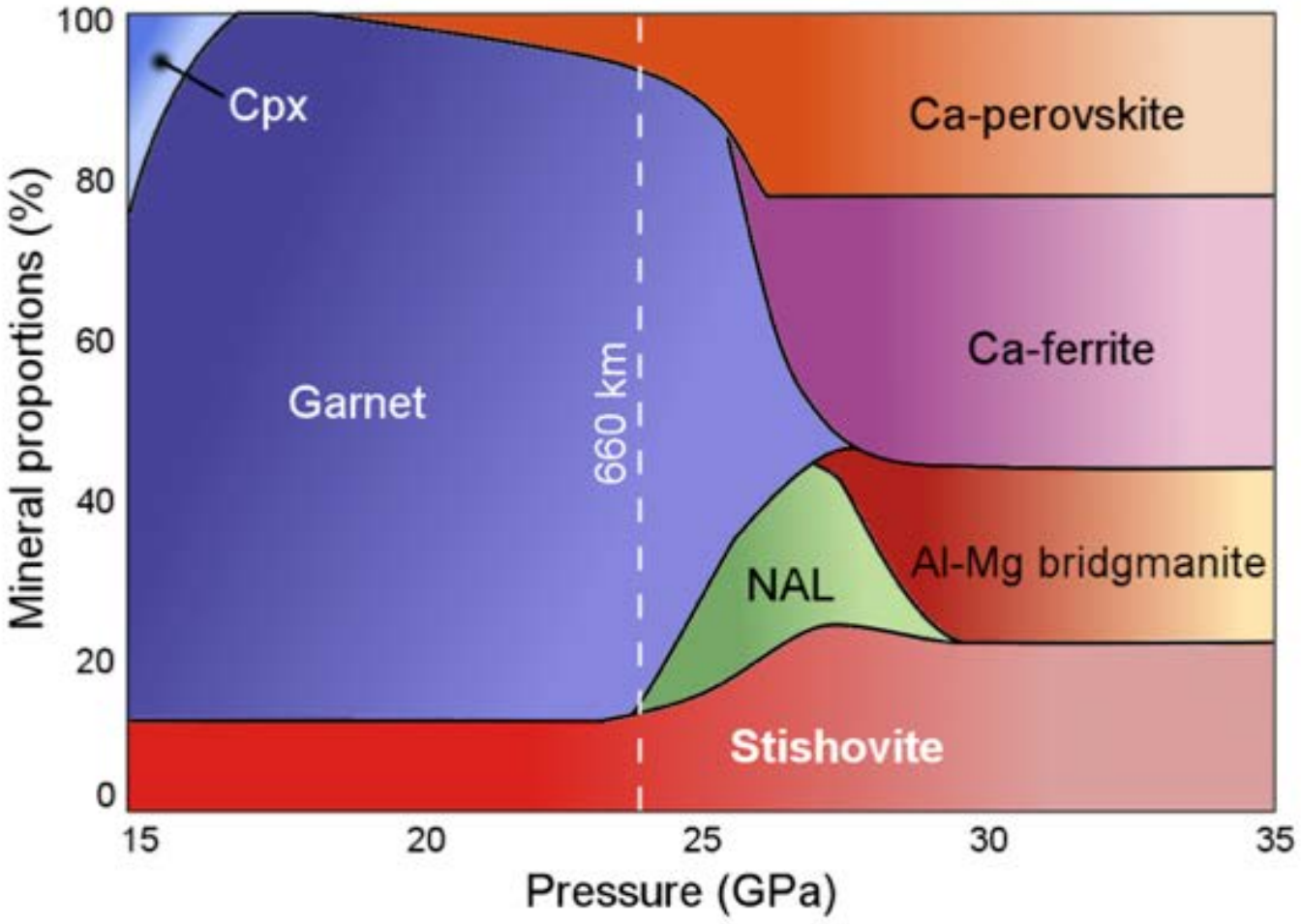
Mao, *et al*, *National Sci. Rev*. (2017)

$3Fe + H_2O = FeO + 2FeH$

$FeO + H_2O = FeO_2 + H_2$ Enrichment of O

Stishovite SiO_2 can be an important water carrier

Basaltic Slab



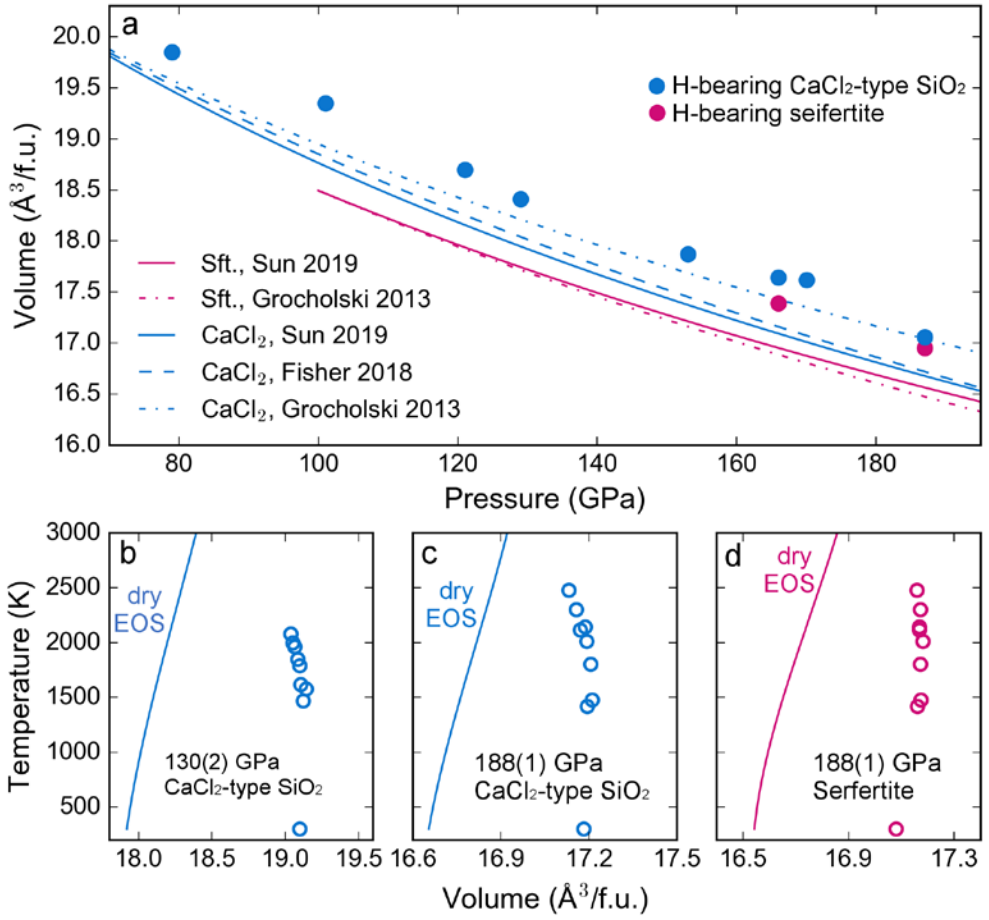
Stishovite SiO_2 as an important water carrier

Hydrogen-bearing silica up to 188 GPa

Yanhao Lin[1,2], Qingyang Hu[1], Yue Meng[3], Michael Walter[2], Ho-Kwang Mao[1]

Yanhao Lin

CARNEGIE SCIENCE



2-4% H_2O in stishovite and seifertite up to 188 GPa

Lin, Y., *et al.* Evidence for the stability of ultrahydrous stishovite in Earth's lower mantle. *Proc. Natl Acad. Sci. USA* **117**, 184–189 (2020).

Nisr, C. *et al.* Large H_2O solubility in dense silica and its implications for the interiors of water-rich planets. *Proc. Natl Acad. Sci. USA* **117**, 9747–9754 (2020).

Ferropericlase (Fe,Mg)O, in the deep lower mantle with H_2O

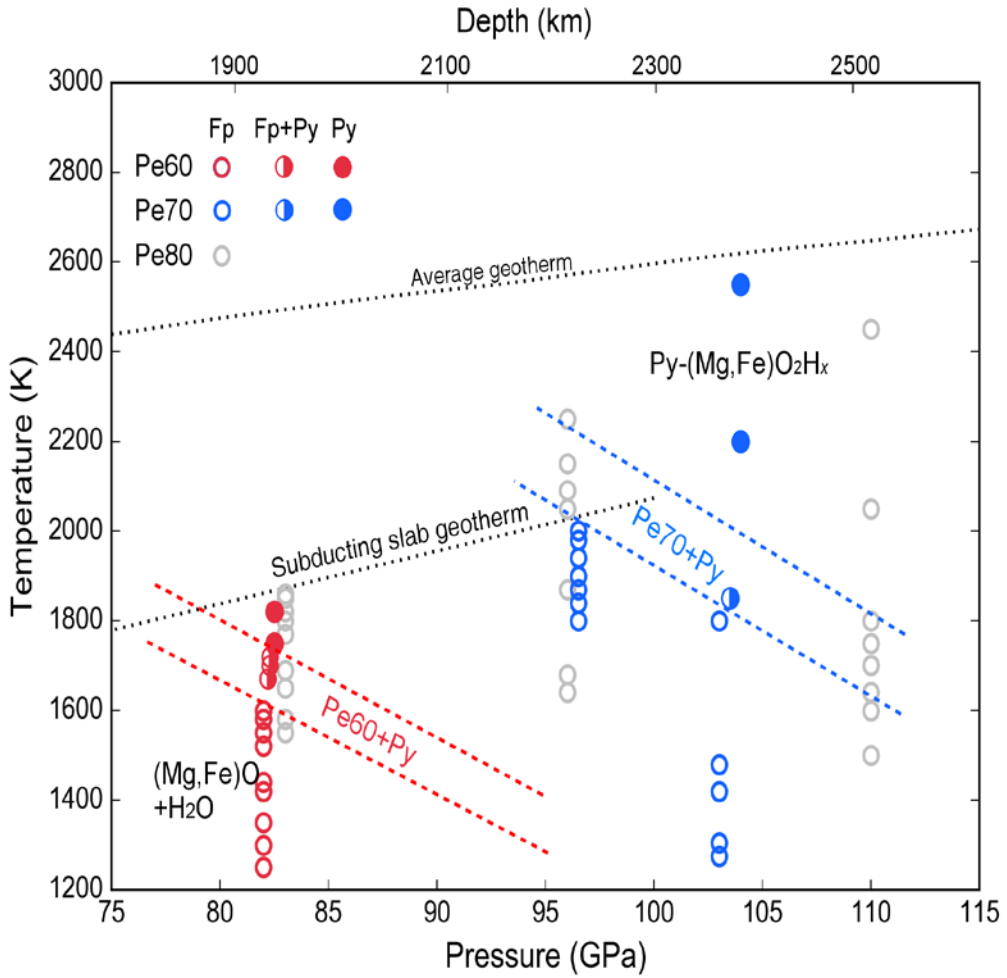
Mineralogy of the deep lower mantle in the presence of H_2O

Qingyang Hu, Jin Liu, Jiuhua Chen, Bingmin Yan, Yue Meng, Vitali B. Prakapenka, Wendy L. Mao and Ho-kwang Mao

National Science Review (2020)
10.1093/nsr/nwaa098

$(Fe,Mg)O + H_2O =$
$(Fe,Mg)O_2Hx$ (Py) + $(1\text{-}0.5x)H_2$

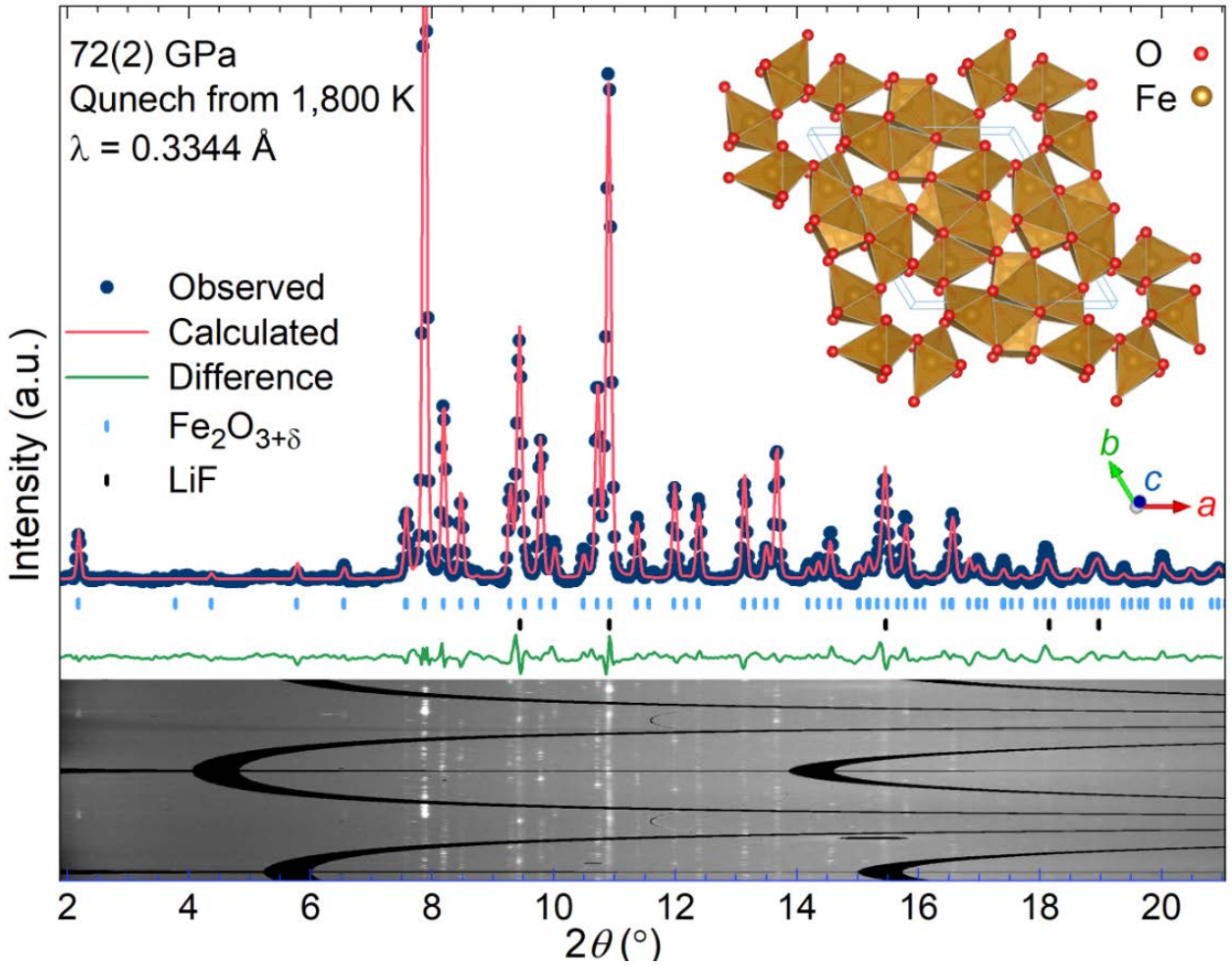
$$MO + H_2O = MO_2 + H_2$$



Ferropericlase (Fe,Mg)O, at intermediate *P* or with less H_2O

$$2(Fe,Mg)O + H_2O = (Fe,Mg)_2O_3 + H_2$$

$$MO + H_2O = MO_2 + H_2$$



Jin Liu et al (2020)

$(Fe,Mg)_2O_{3+\delta}$

National Science Review

10.1093/nsr/nwaa1096.

Koemats et al (2020)

$Fe_{2+\delta}O_3$

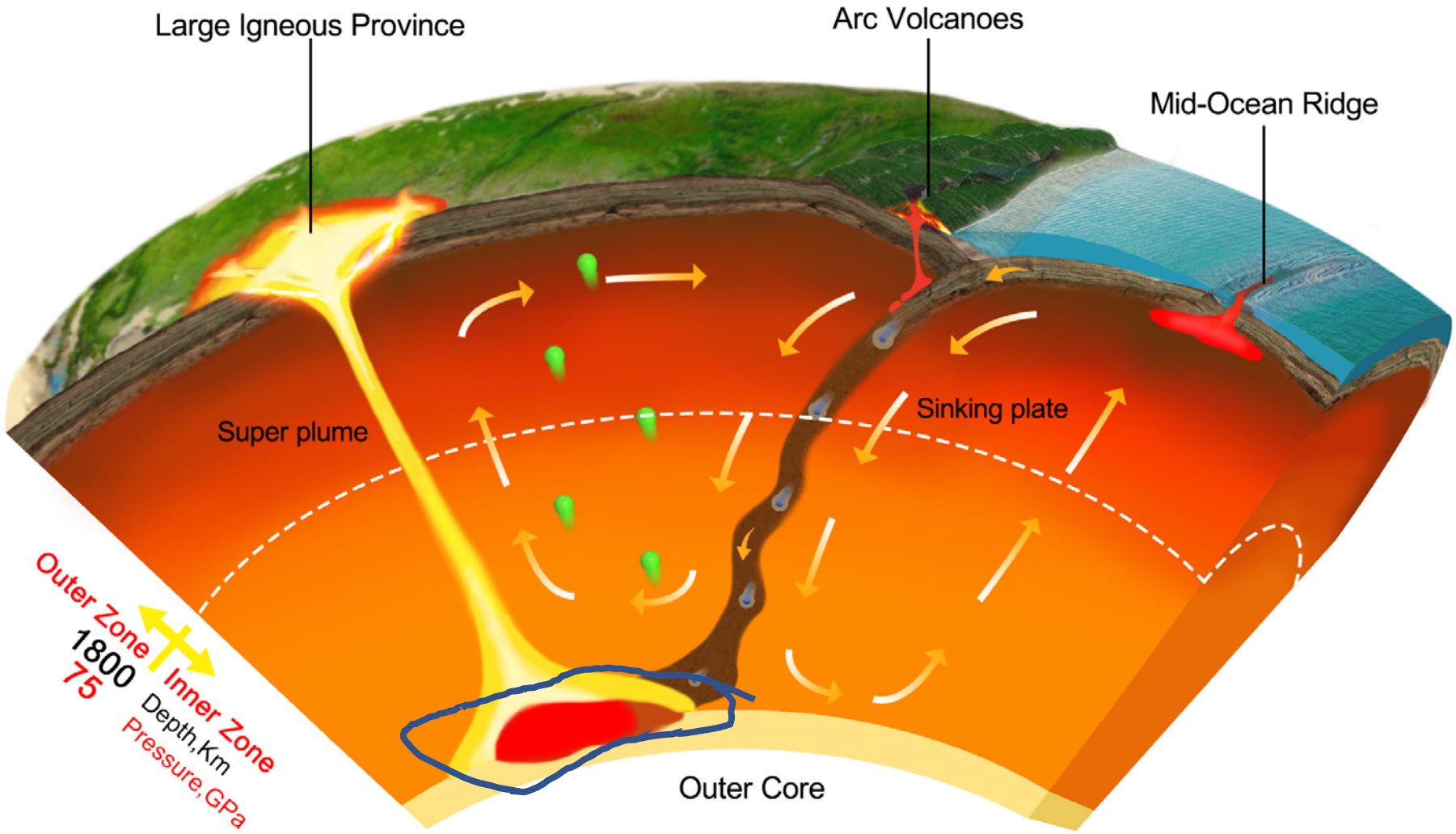
arXiv

Huawei Chen et al (2020)

$Fe_2O_{3+\delta}$

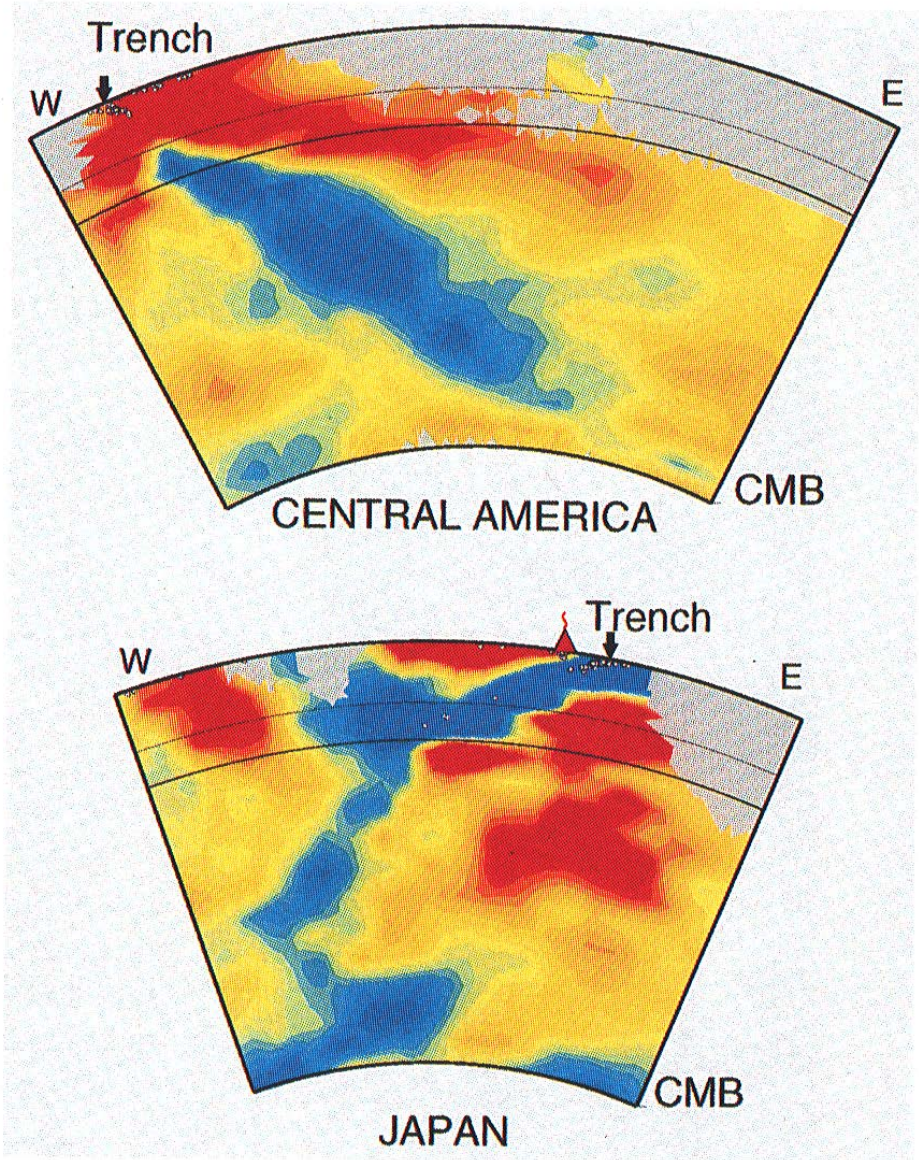
EPSL 550, 116551

Can we see the oxygen-rich materials in deep mantle?



Mao, H. K., and W. L. Mao (2020), Key problems of the four-dimensional Earth system, ***Matter & Radiation at Extremes***, *5*, 038102.

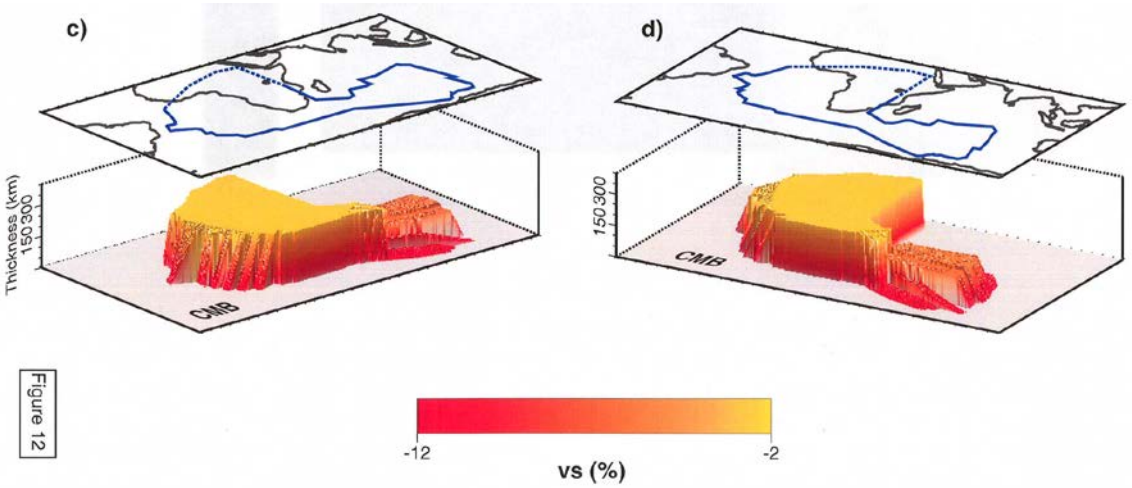
Using seismic tomography to see Earth's interior



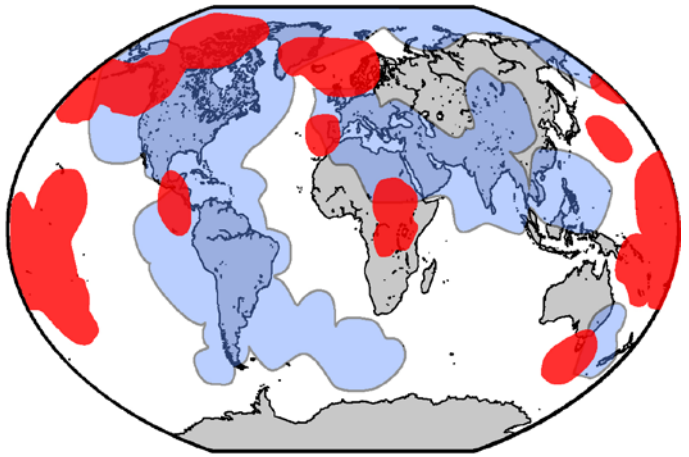
van der Hilst *et al.*, *Nature* 1997

Seismic evidence of FeO_2 above the core –mantle boundary?

- Sharp discontinuity at top of D”
- Lateral velocity variations
- Splitting of shear waves
- Anti-correlation of Vs and Vp
- Ultra-low velocity zones



Wang and Wen, JGR 2004



Lay *et al,* PEPI 2004

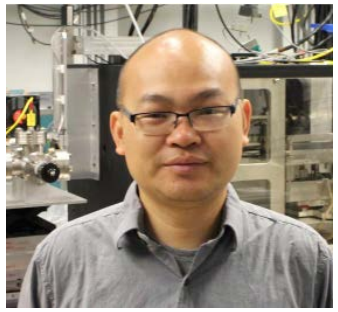
Elasticities of ULVZ at CMB match iron superoxides

Jin Liu

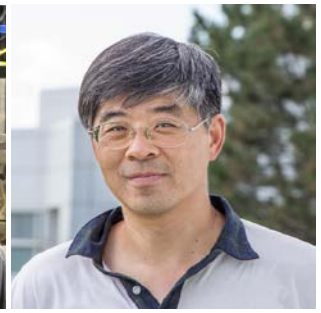
Wendy Mao

Stanford Univ
Dept. Earth,
Energy &
Environmental
Sciences

HPCAT
staff
scientists

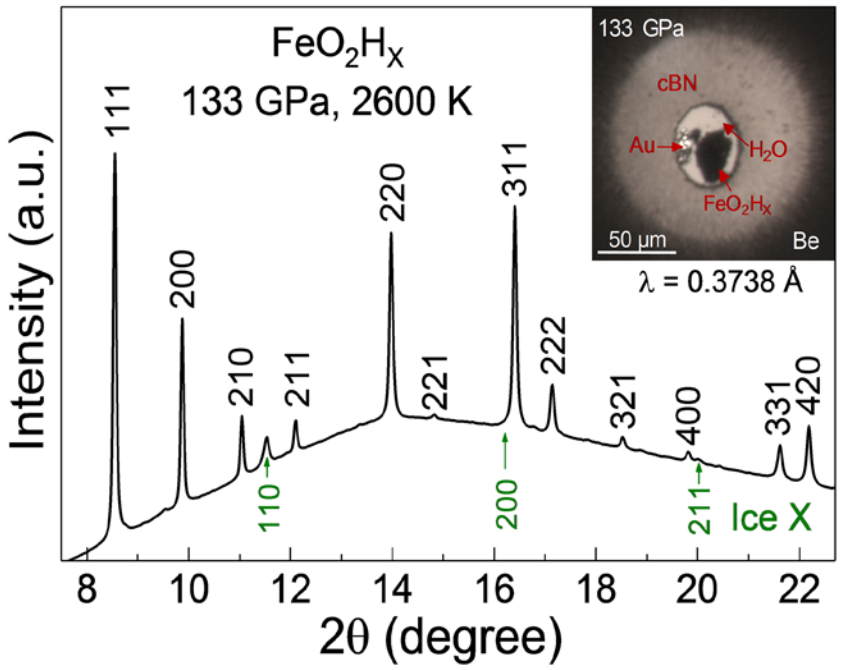


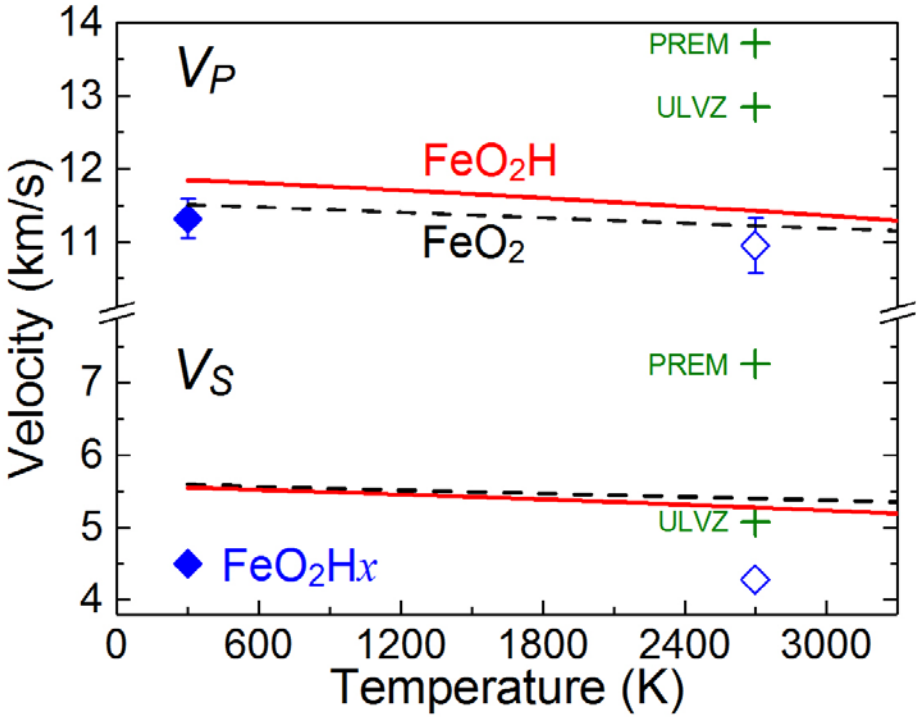
Yuming Xiao



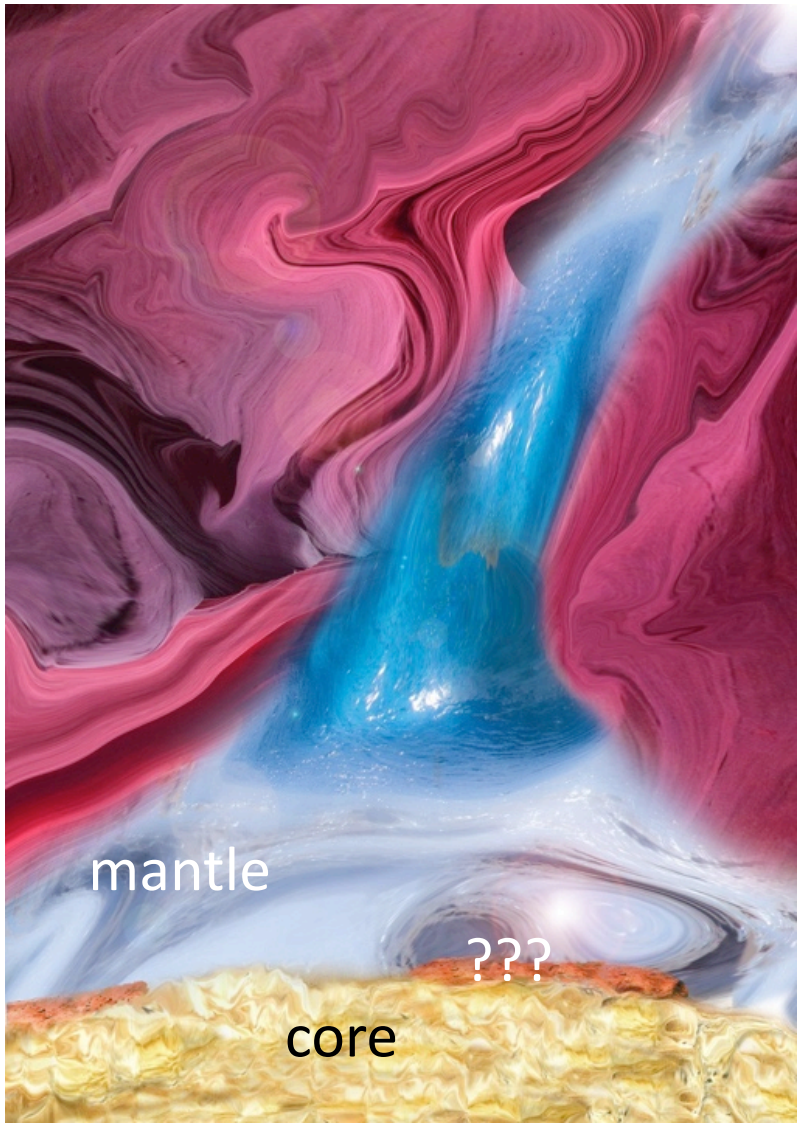
Paul Chow

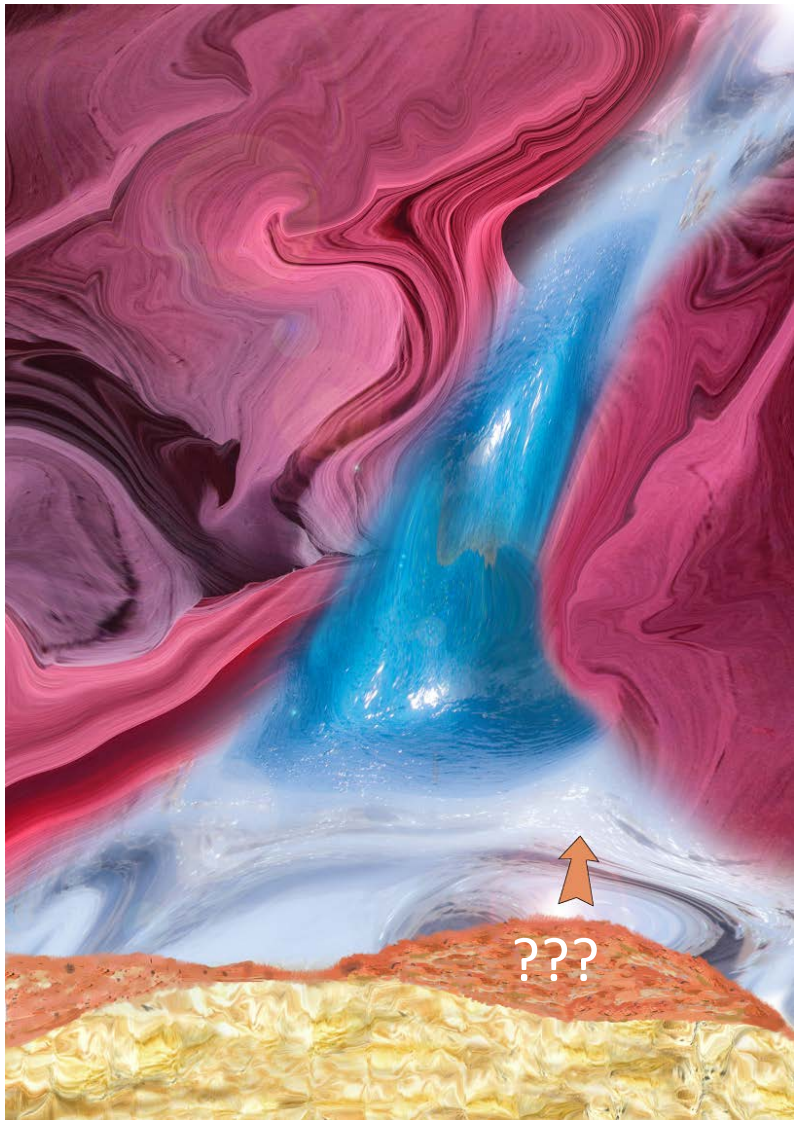
Liu *et al, Nature* ***551,*** 494 (2017)



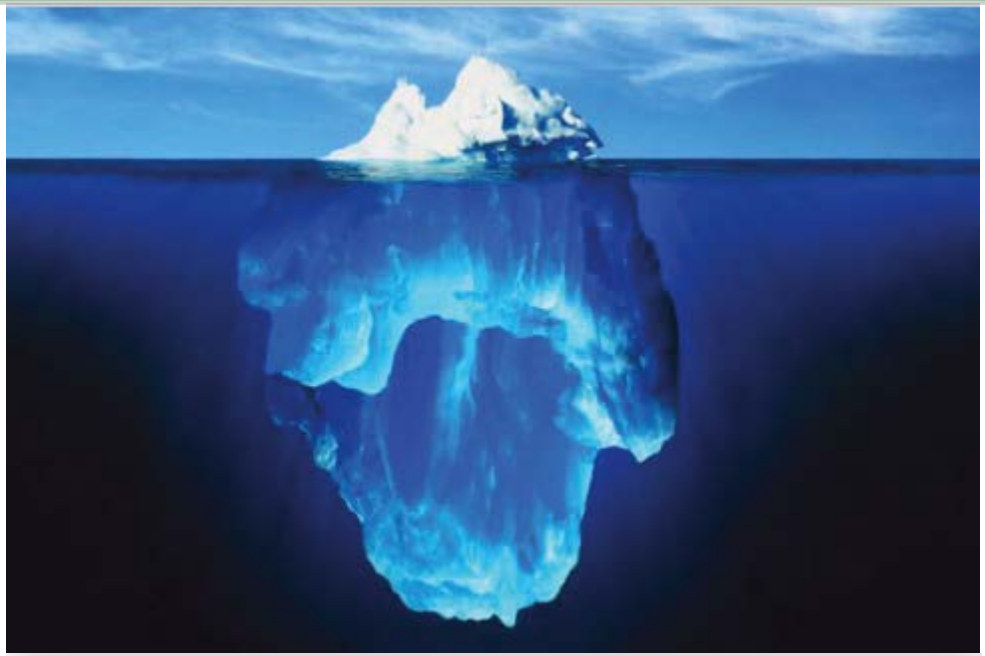


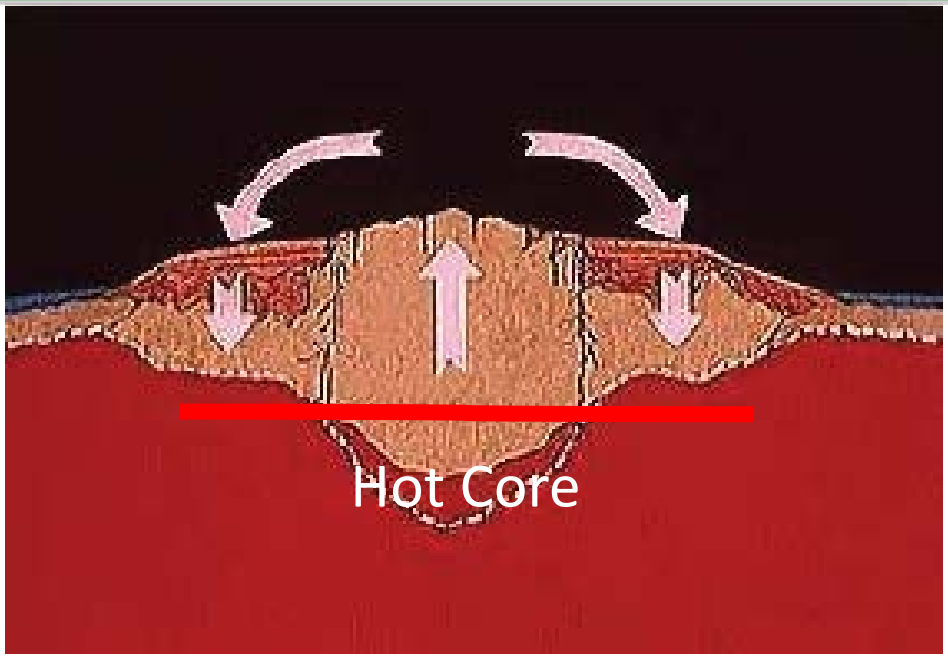
What will happen if the oxygen-rich materials keep piling up?

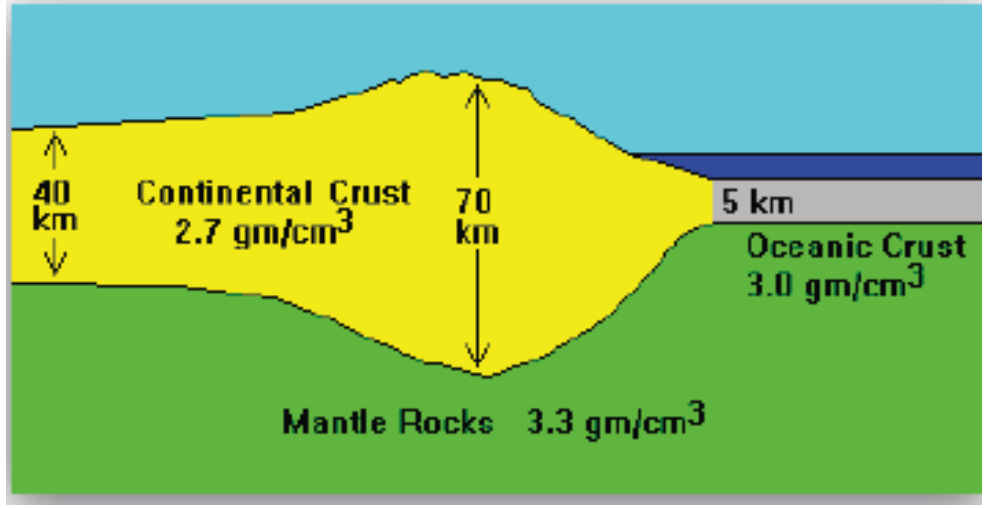




Isostasy and the Great Time Bomb--Catasophism

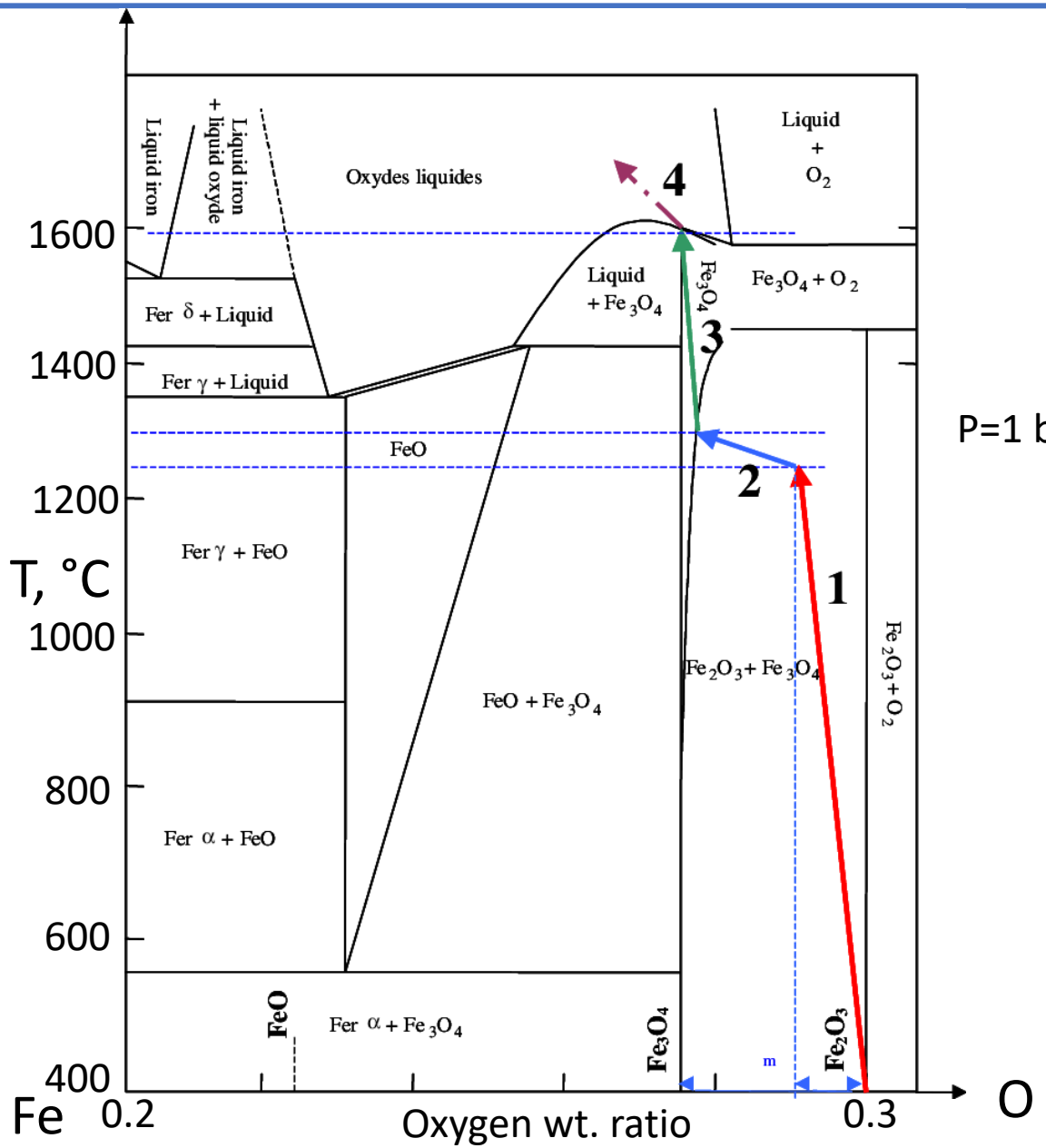






What happens when the oxygen reservoirs get thick ?

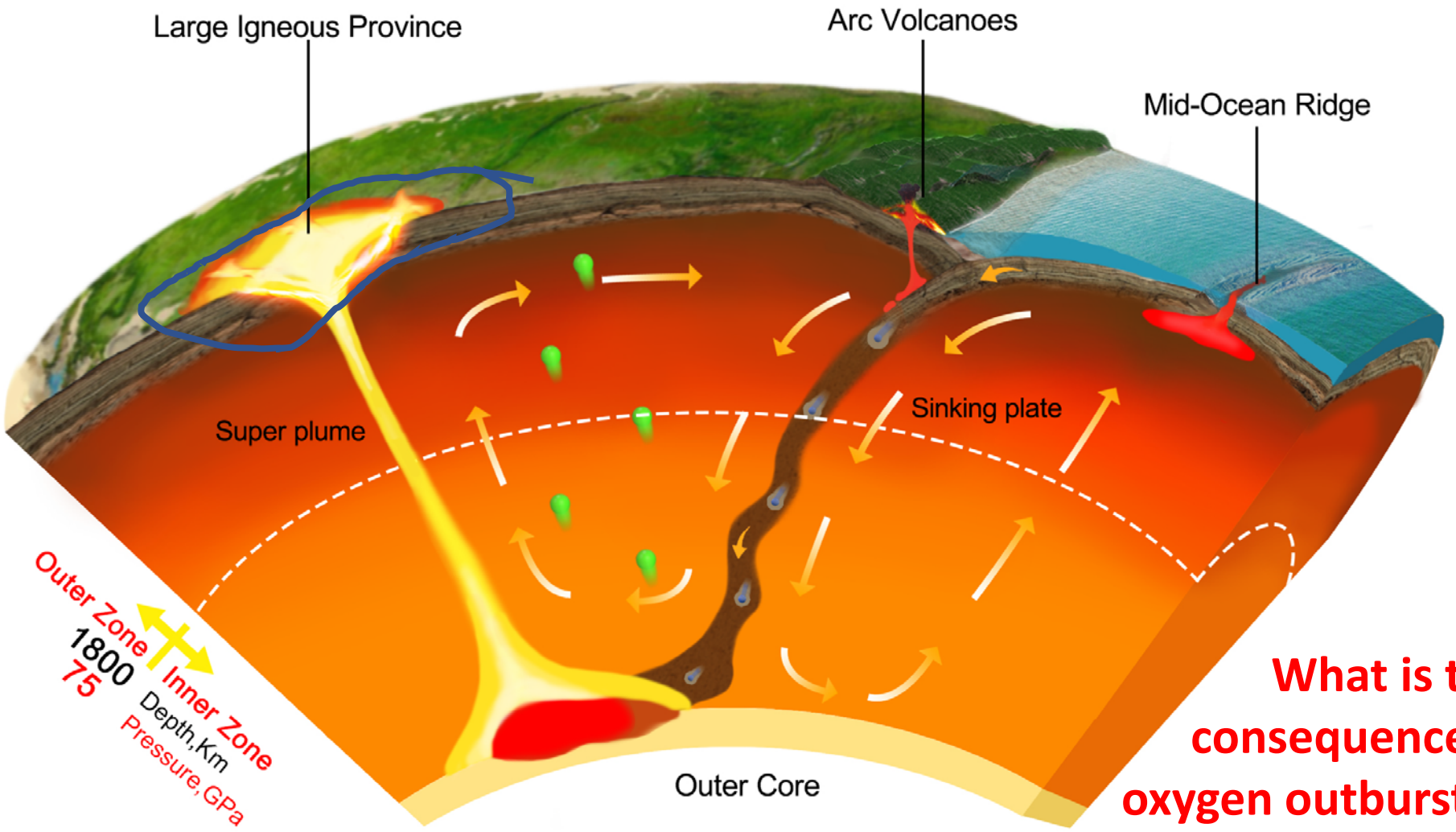
Steelmaker's Fe-O phase diagram



P=1 bar

At the core-mantle boundary at high-*T*, the oxygen-rich compounds also dissociate into liquid Fe going into the core and solid oxygen trapping at the CMB waiting for uprising.

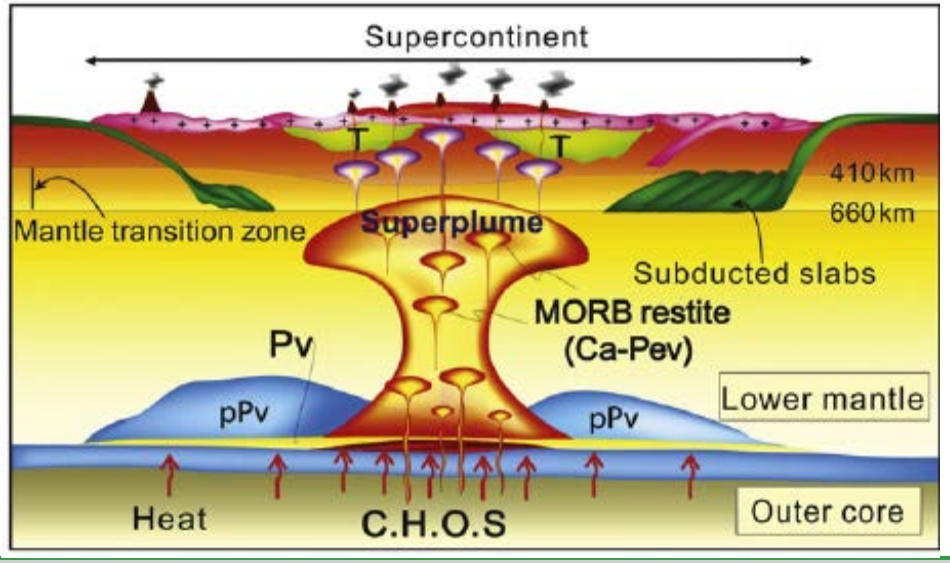
The Aerobic Earth



What is the consequences of oxygen outburst?

Mao, H. K., and W. L. Mao (2020), Key problems of the four-dimensional Earth system, ***Matter & Radiation at Extremes***, *5*, 038102.

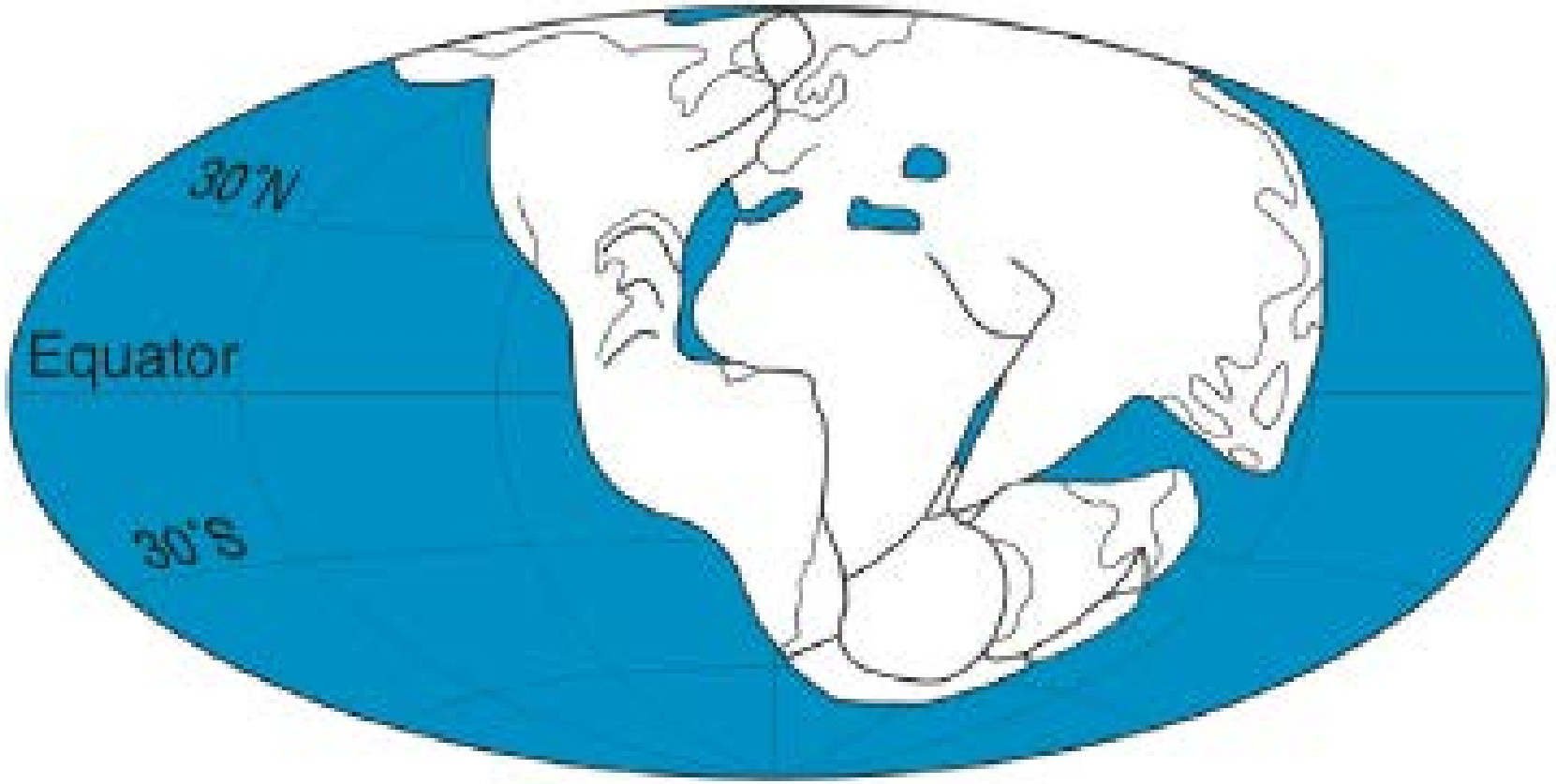
Large Igneous Province and Flood Basalts

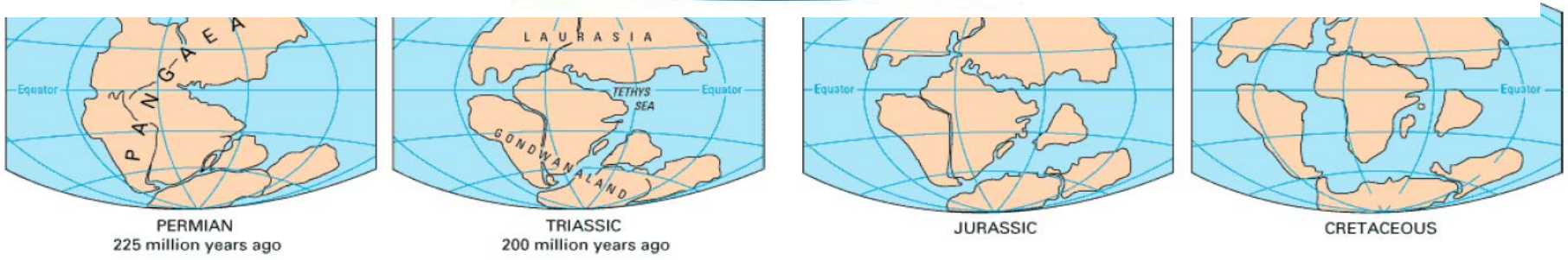


Flood basalt resulted from oxygen outburst

Supertectonics & Supercontinents

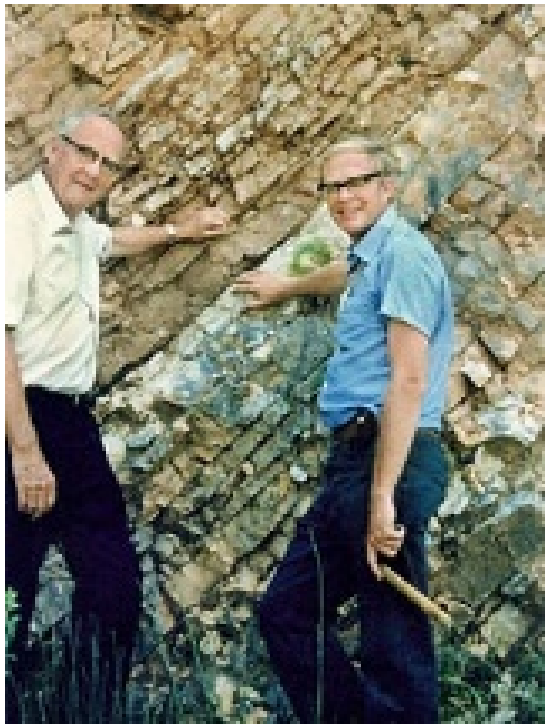
Chemical convection led to super plate tectonics

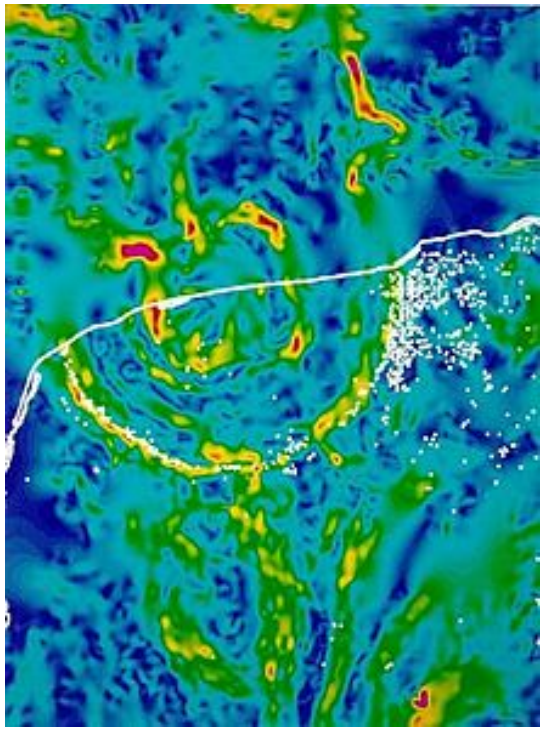


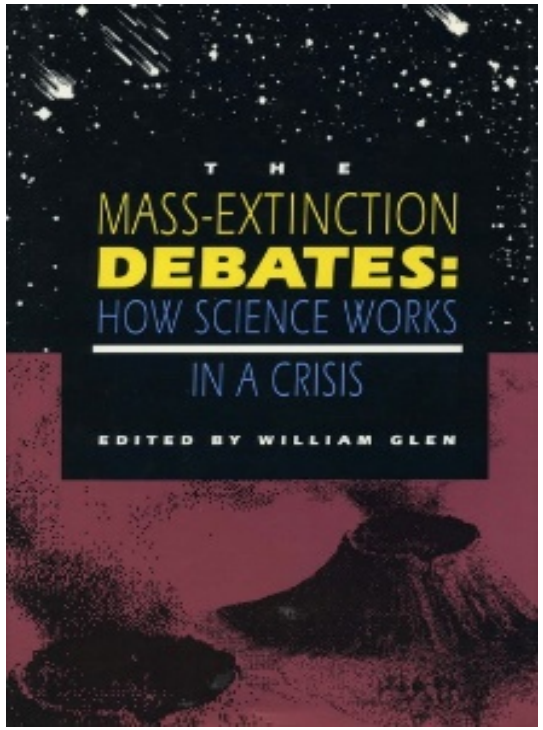


Mass extinction caused by asteroid impact

Luis Alvarez (1911-1988) & Walter Alvarez (1940-) at the K-T boundary Iridium layer (Gubbio, Italy)





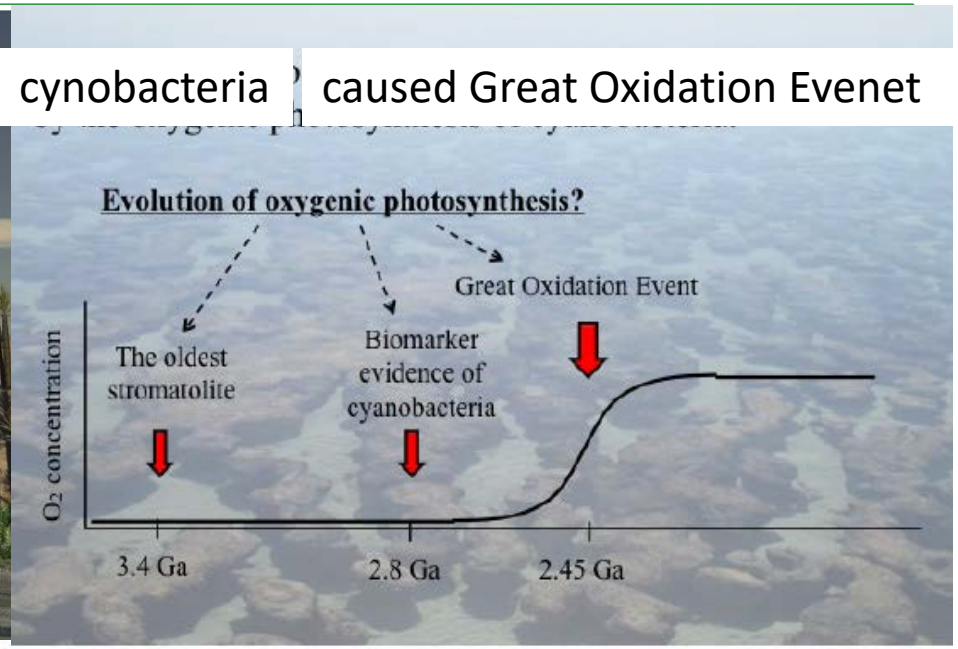


External causes? Surficial activities? Dynamic engine?

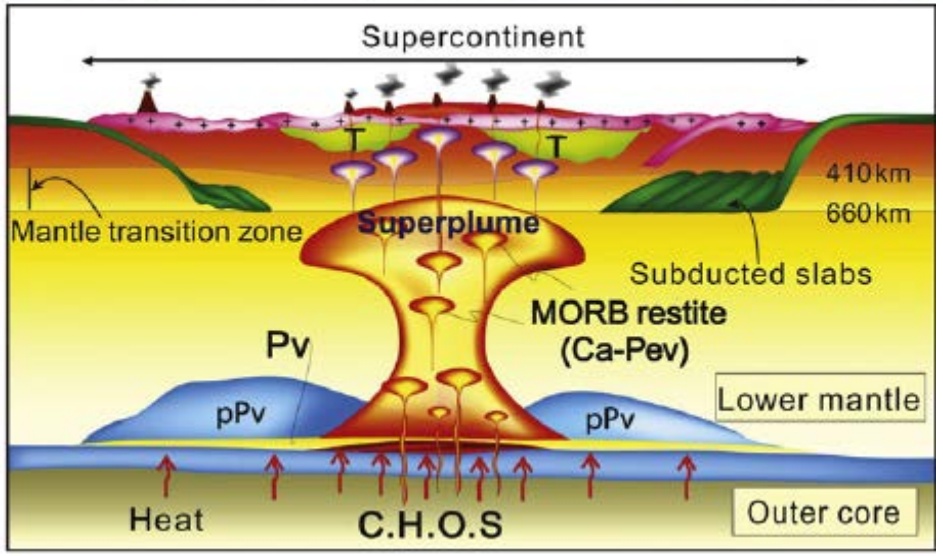
Asteroid impacts

Caused extinctions

cynobacteria caused Great Oxidation Evenet

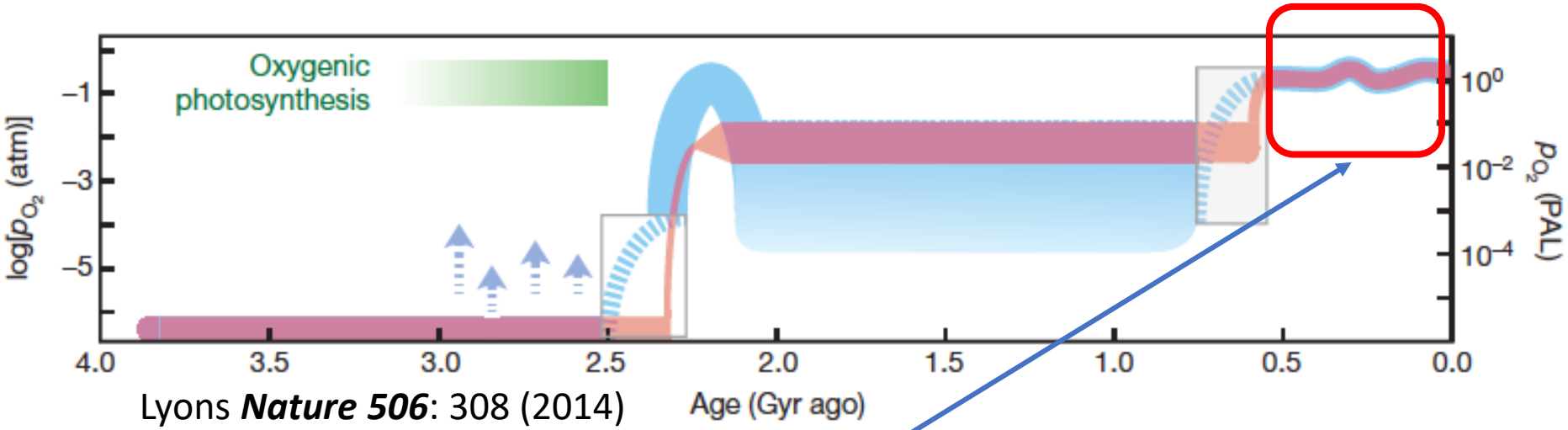


Caused snowball Earth



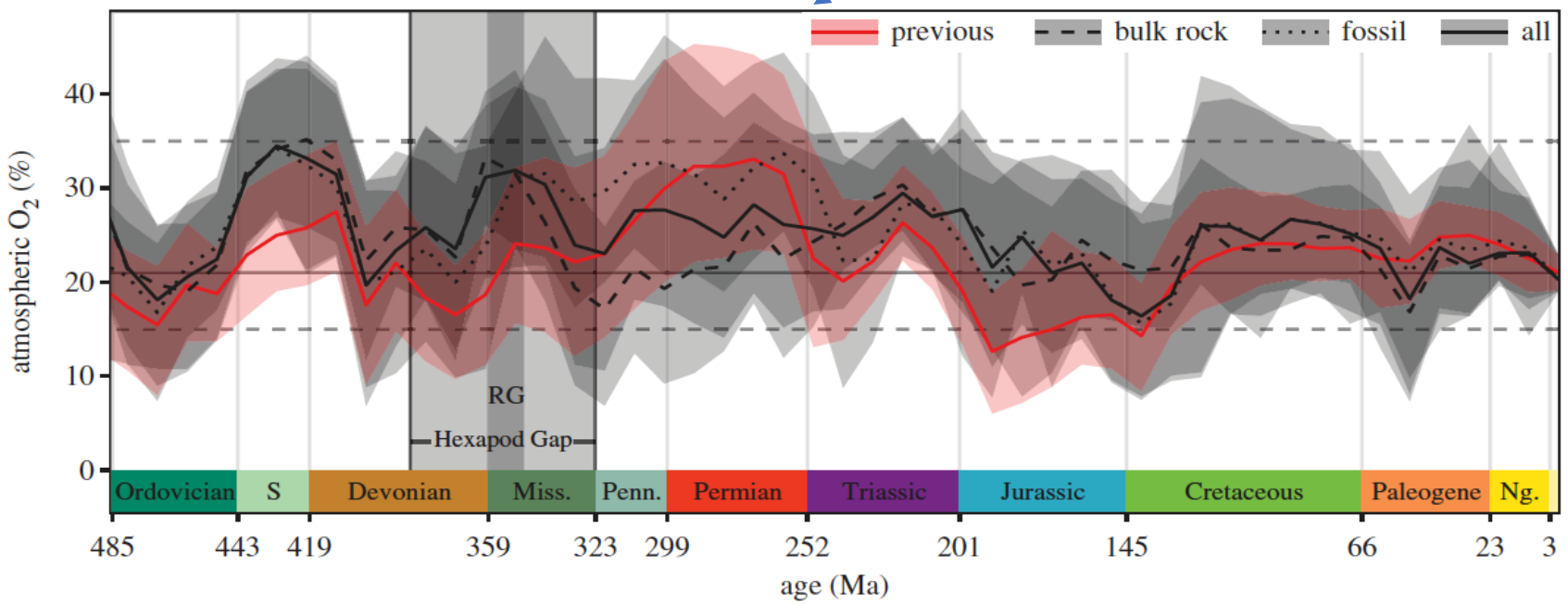
Dozen explanations mean no explanation

GOE, The Great Oxidation Event — Caused by cynobacteria



Lyons ***Nature 506***: 308 (2014)

Oxygen Fluctuation— many causes

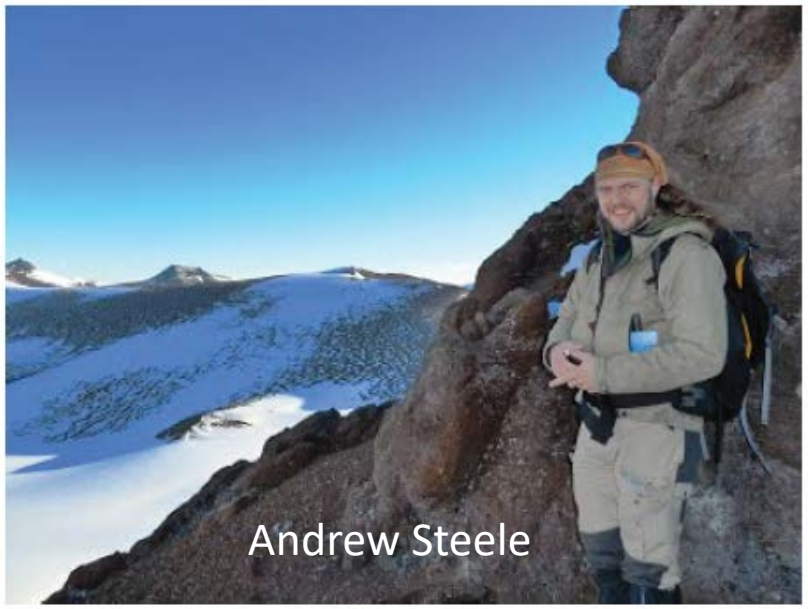


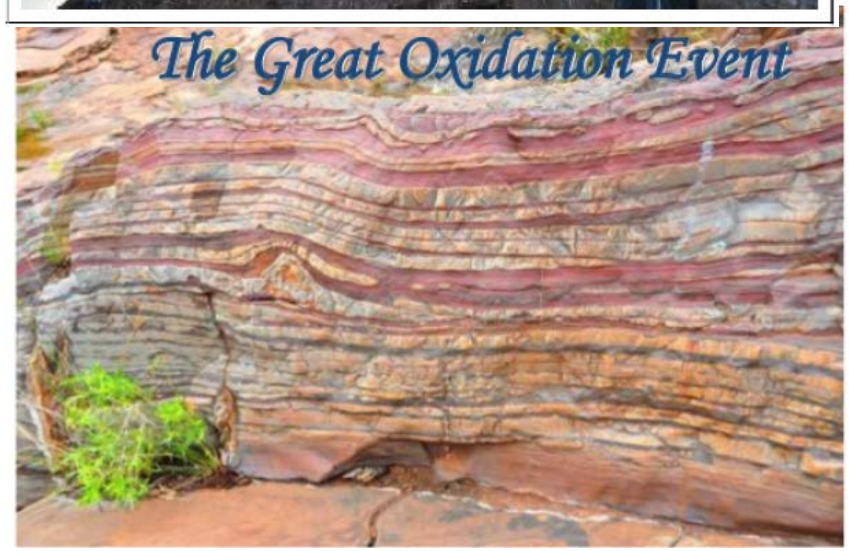
Schachat ***Proc. R. Soc. B 285***: 20172631 (2018)

Oxygen Toxicity and Flammability

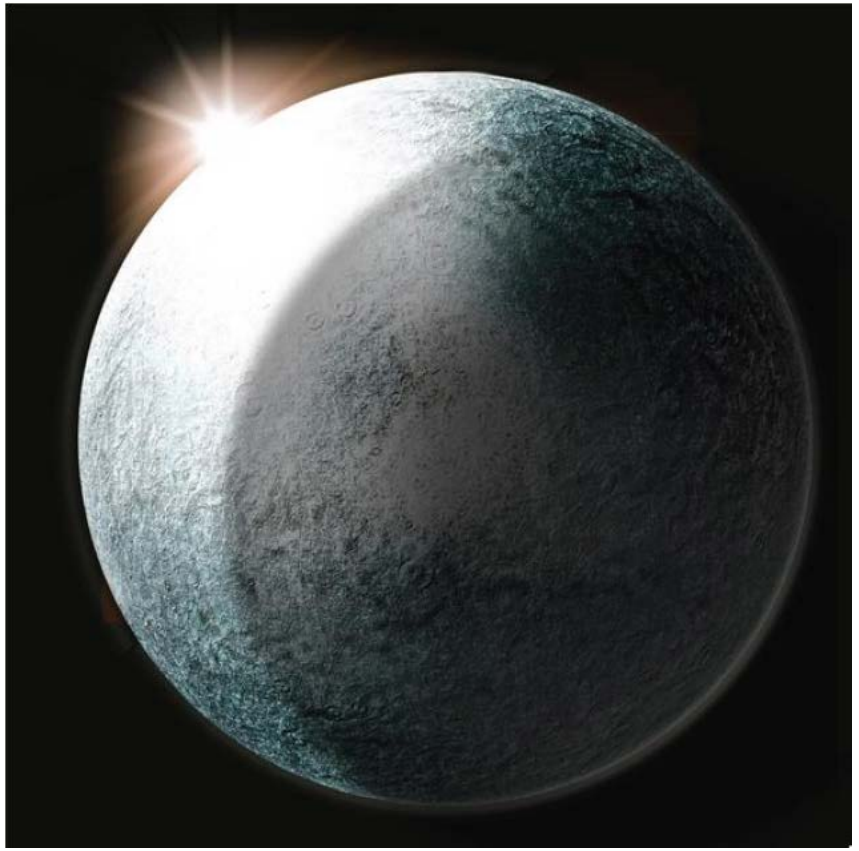
Environmental catastrophe resulted from oxygen outburst

Ice Ages & Snowball Earth



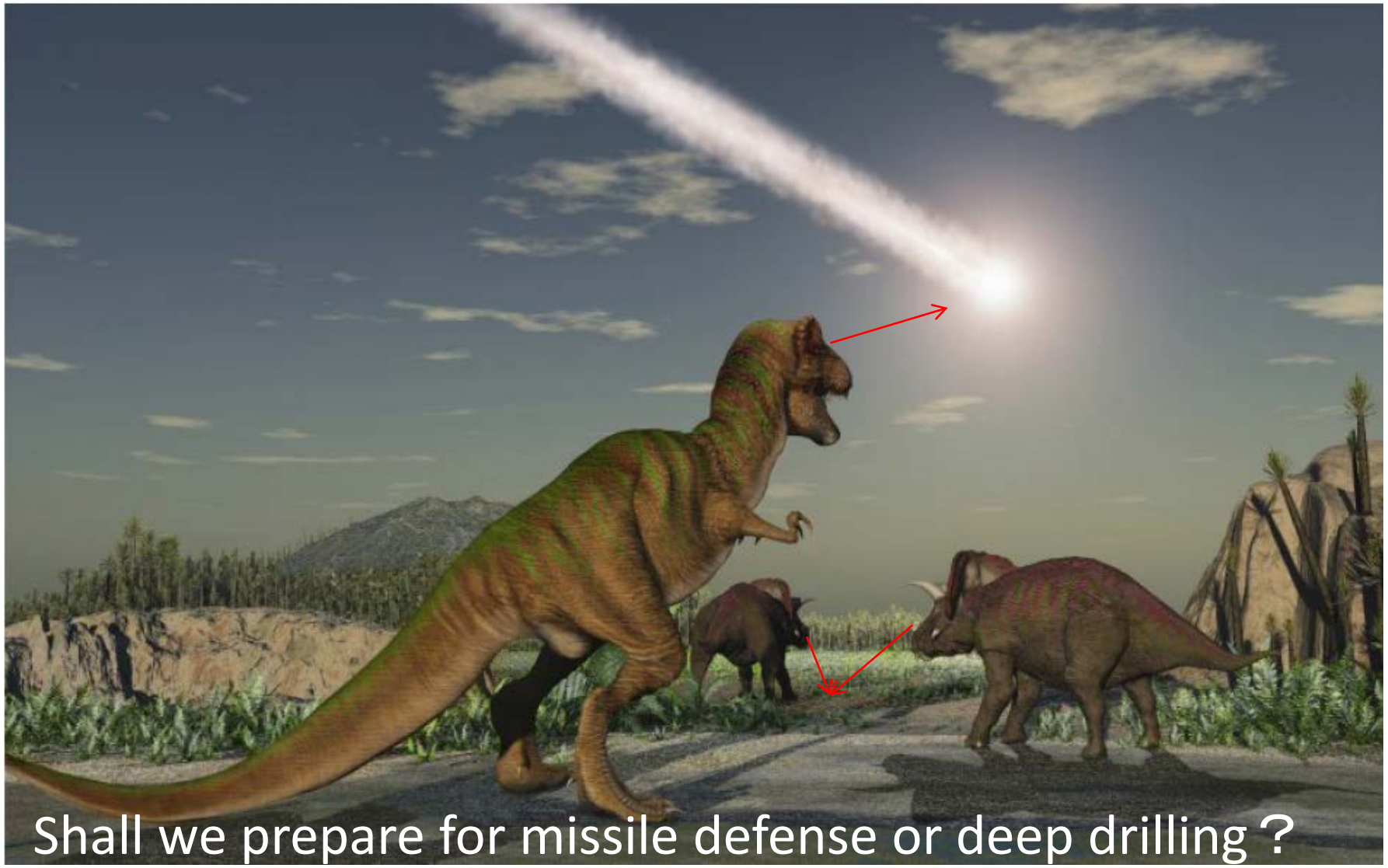


Banded-Iron Formation, Great Oxidation Event, Snowball Earth, all indications of great increase in oxygen which was previously attributed to cynobacteria.

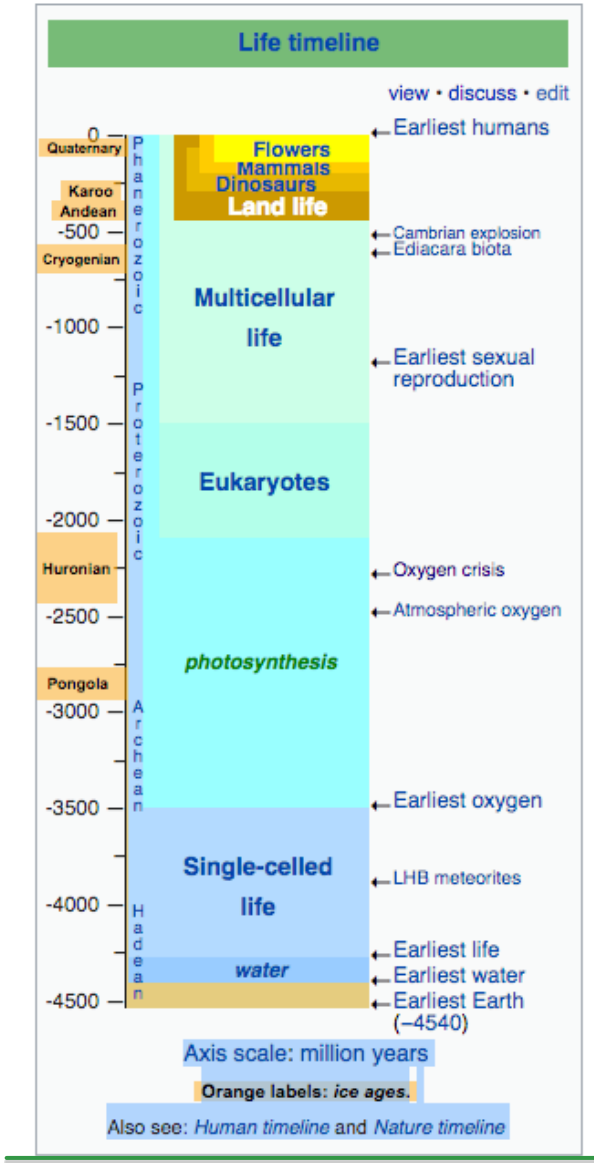


resulted from oxygen outburst

Did the Apocalypse come from heaven or Earth?

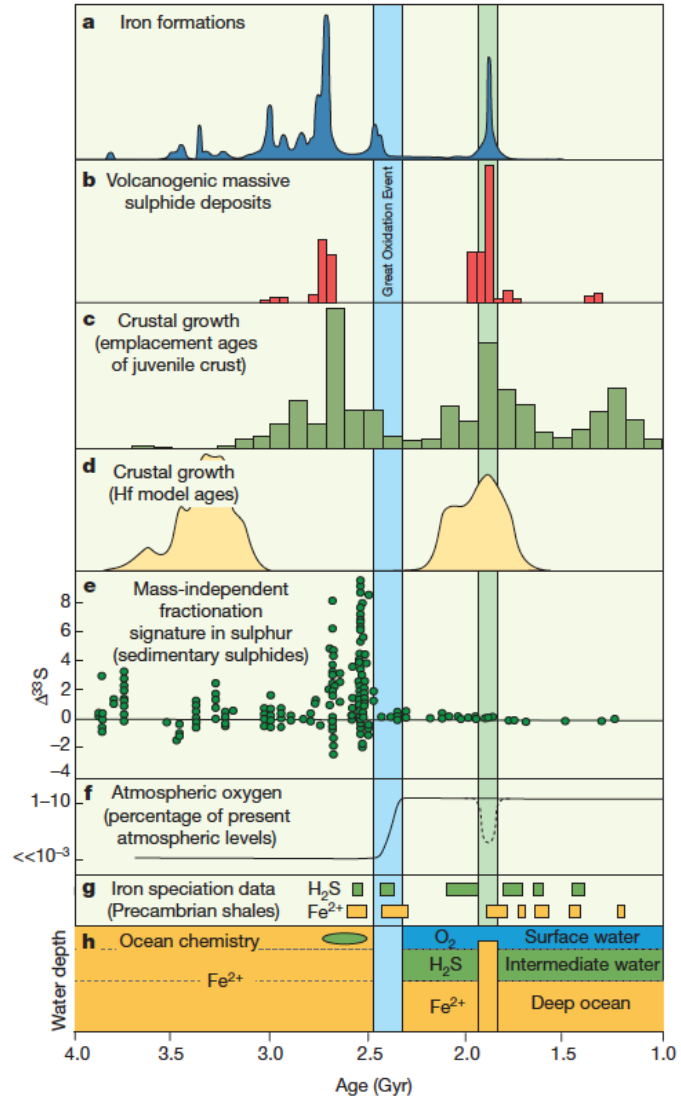


Aerobic activity can cause all major events of the Earth



All major environmental catastrophes can be used as evidences for deep aerobic activities

- Great Oxidation Event
- Mass Extinctions
- Ice Age & Snowball Earth
- Banded iron formation
- Super tectonics
- Flood Basalt



(Rasmussen *et al, Nature* 2012)

Aerobic activity--a single theory to unify all major events of the Earth

2020 MRE High-Pressure Special Volume

All you want to know about metallic hydrogen

Gregoryanz *et al*., *MRE* 5, 038101 (2020)

Ji *et al., MRE* 5, 038401 (2020)

Room-T superconductors

Lv *et al., MRE* 5, 068101 (2020).

Struzhkin *et al., MRE* 5, 028201 (2020)

Xiao-Jia Chen, *MRE* 5, 068102 (2020)

HP Chemistry

Choong-shik Yoo, *MRE* 018202 (2020)

HP Technology

Hirao *et al., MRE* 5, 018403 (2020)

Walker and Li, *MRE* 5, 018402 (2020)

Nanomaterials strength

Xu and Tian, *MRE* 5, 068103 (2020)

Yang *et al., MRE* 5, 058401 (2020)

Bin Chen, *MRE* 5, 068104 (2020)

Functional Mat

Li *et al., MRE* 5, 018201 (2020)

The 4-Dimensional Earth

Mao and Mao, *MRE* 5, 038102 (2020)

Answers on key problems of the Earth are hidden in the depth