



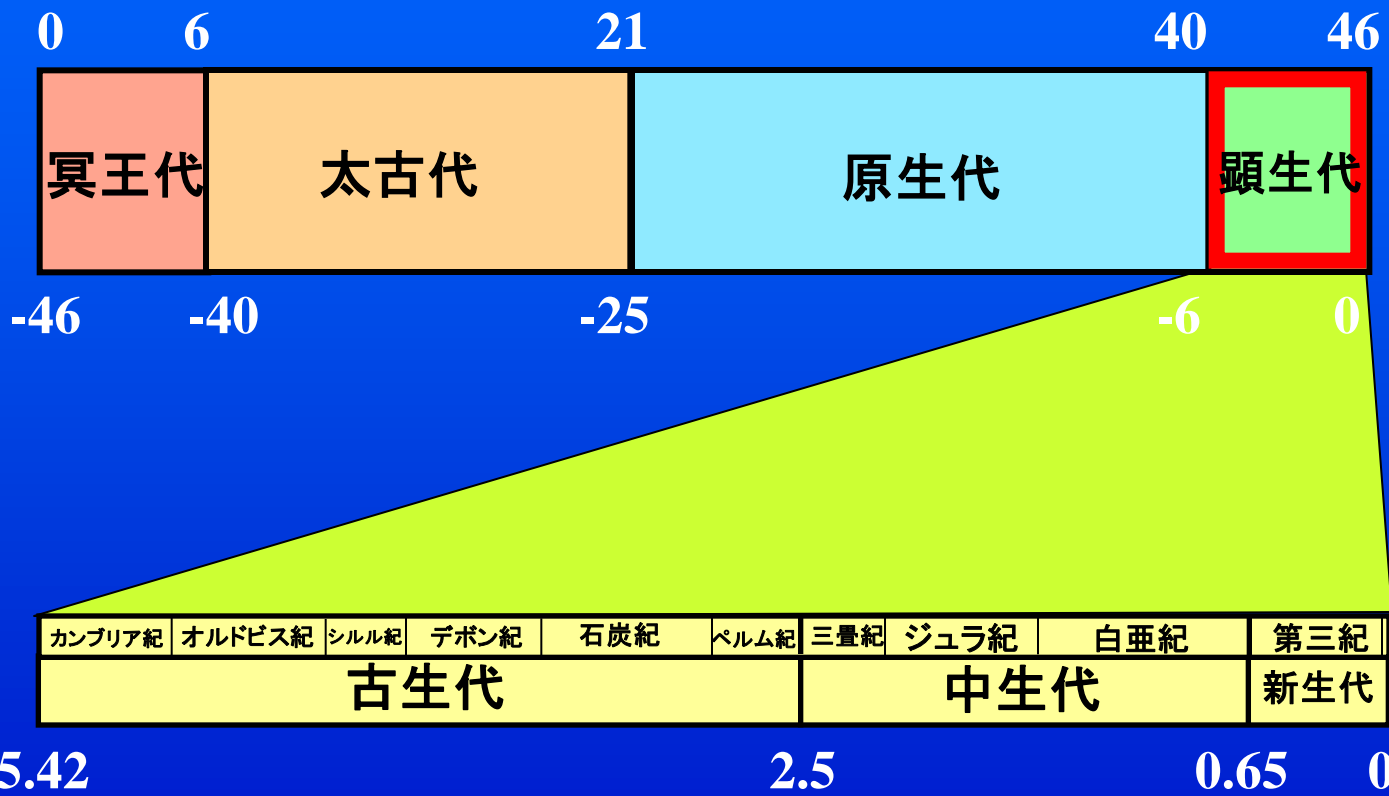
[5] 物質循環と生物

1. 顕生代における生物進化と気候変動

地球史年表

地球形成

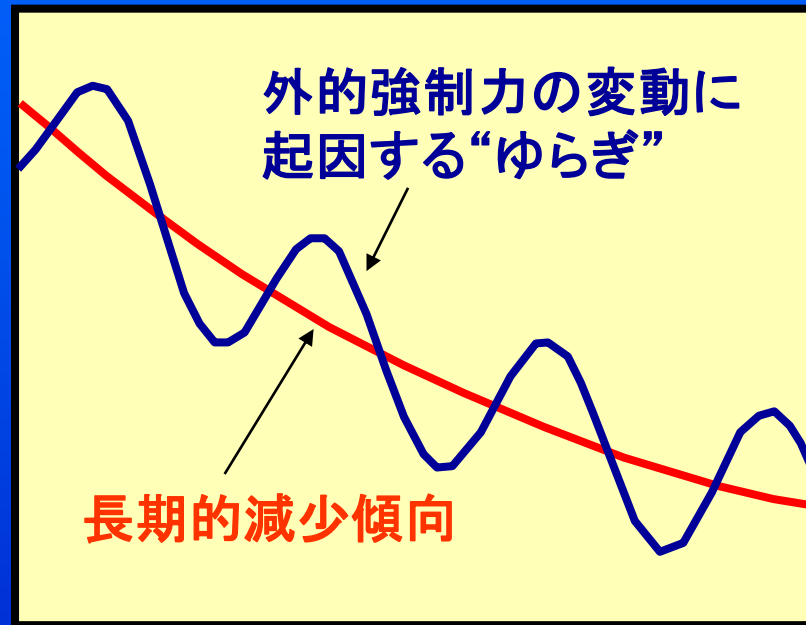
現在



(単位: 億年)

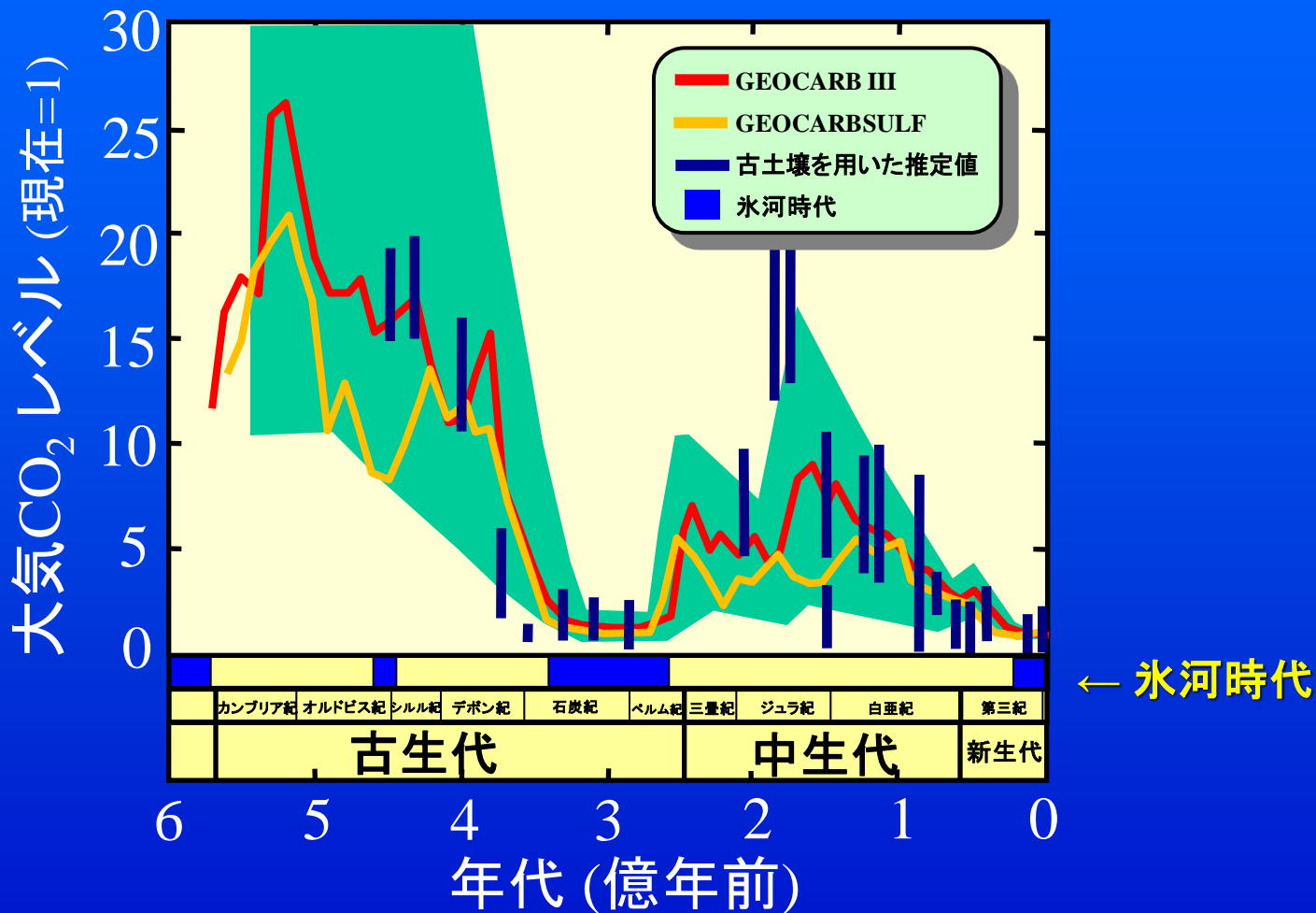
二酸化炭素のゆらぎと気候変動

二酸化炭素レベル



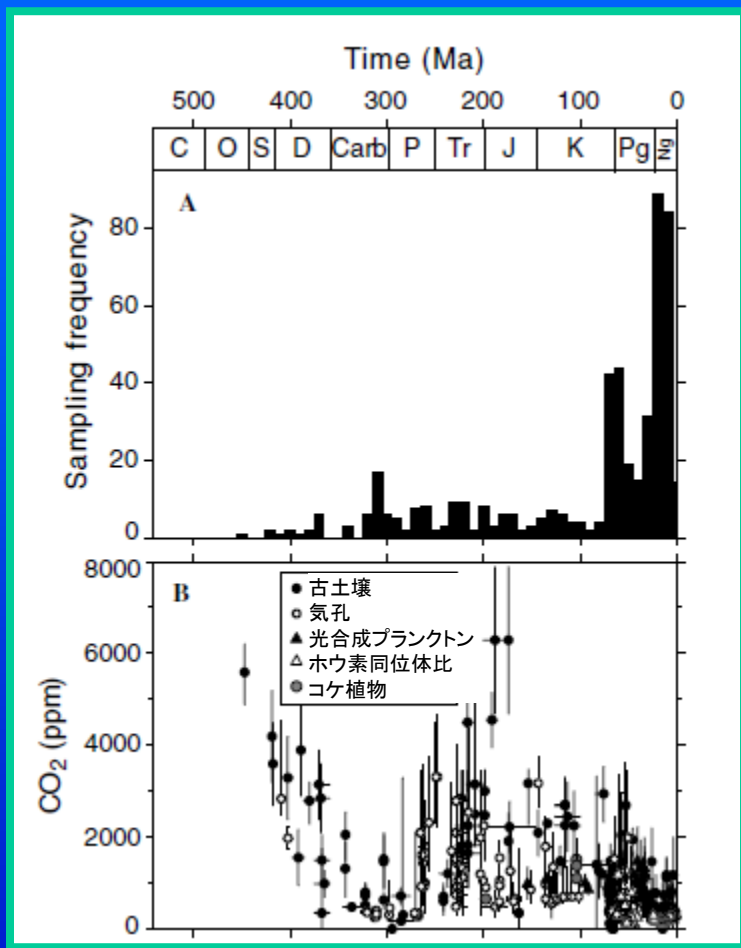
時間

過去約6億年間(顕生代)の気候変動

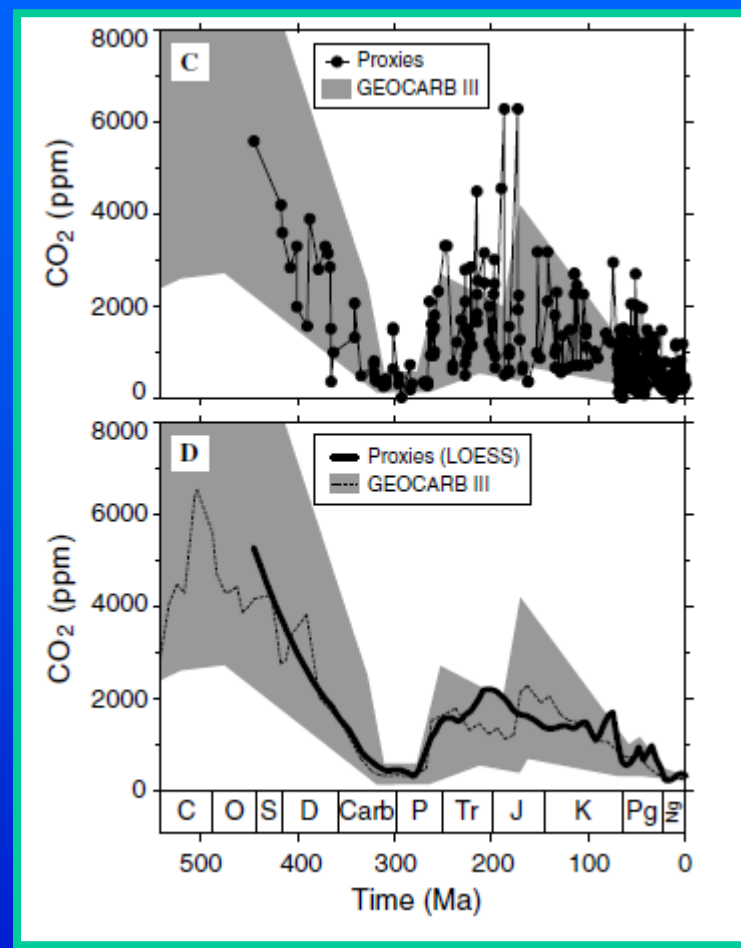


[Berner and Kothavala (2001), Berner (2006) に基づく]

顕生代におけるCO₂変動の妥当性



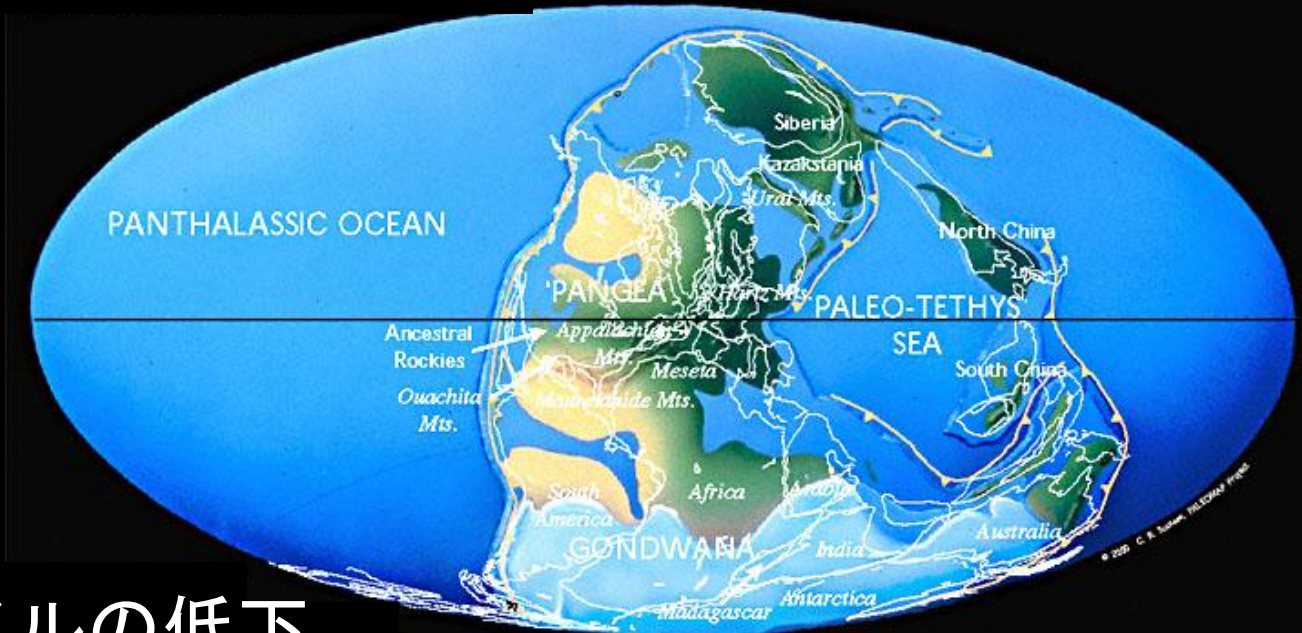
A 古環境指標の時代分布
B 手法別の推定データ



C 推定データの時系列分布
D 推定データの加重平均

石炭紀後期(ゴンドワナ)氷河時代

石炭紀後期 約3億年前



CO₂レベルの低下

■風化効率の増加

- ・大森林時代(風化効率の増加)

■大量の有機物が埋没

- ・パンゲア超大陸形成による低湿地帯の拡大
- ・維管束植物による難分解性有機物(リグニン, フミン等)の生産

[<http://www.scotese.com/>]

陸上植物進化による気候の寒冷化

■ 陸上生物進化による風化促進

1. 無生物状態 (4600Ma~)

$$f_E \sim 1/1000 \quad [\text{Schwartzman and Volk, 1989}]$$

2. 微生物/地衣類の進出 (3800Ma?~)

$$f_E \sim 1/7 \sim 1/3 \quad [\text{e.g., Drever and Zobrist, 1992}]$$

3. 維管束植物の出現と進出 (420~350Ma)

$$f_E \sim 2/5 \sim 3/4 \quad [\text{Volk, 1989}]$$

4. 被子植物の進出 (140~80Ma)

$$f_E = 1$$

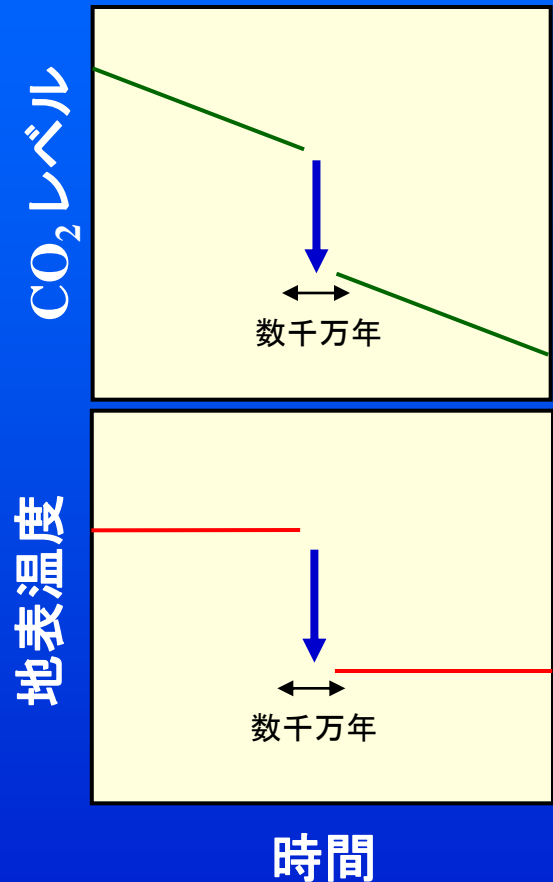
$$\text{風化率: } F_W^S = k_W^S \cdot f_E(t) \cdot f_A(t) \cdot f_B(P_{\text{CO}_2}, T_S)$$

陸上生物進化 → 全球的な風化率の増加

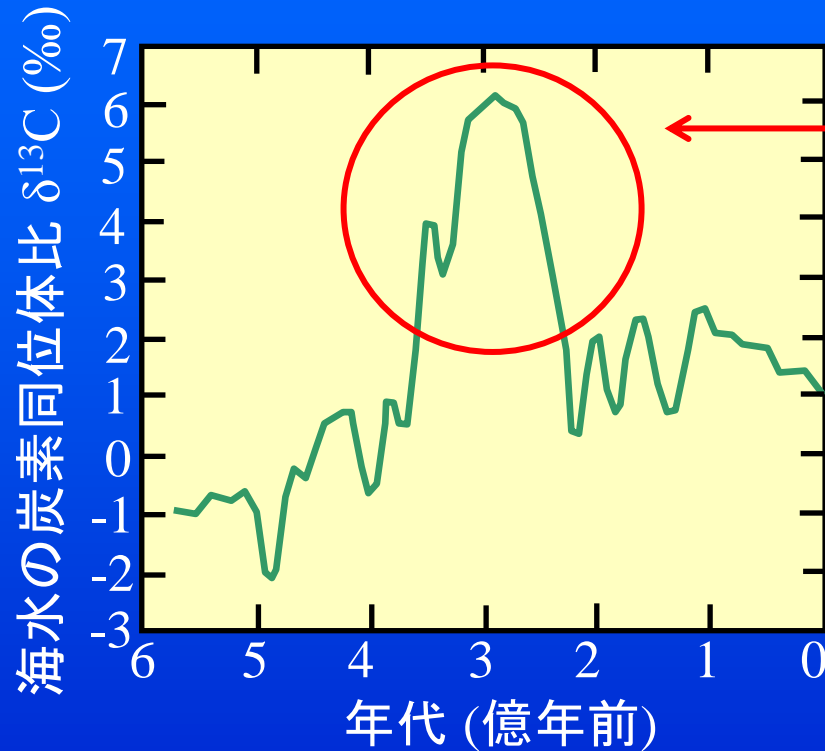
→ 平衡温度(定常状態におけるCO₂や温度)の低下

* 陸上植物の拡散時間: ~7千万年程度 [Stewart, 1983]

被子植物の拡散時間: ~6千万年程度 [Lidgard and Crane, 1988]



顕生代における海水の炭素同位体比



炭素同位体比の正異常



軽い炭素が取り除かれた



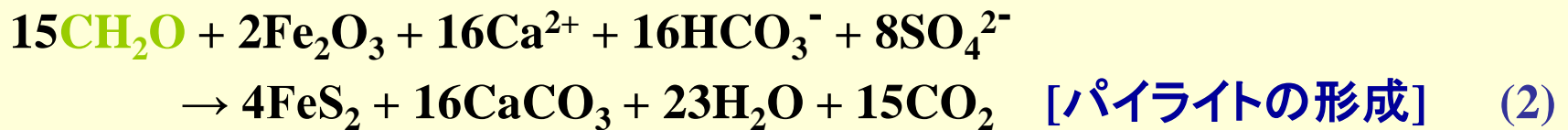
有機炭素の固定が増加

海水の炭素同位体比の変化 → 有機炭素の正味の固定(埋没率)

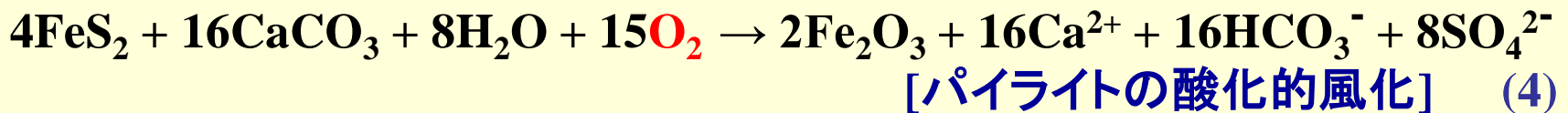
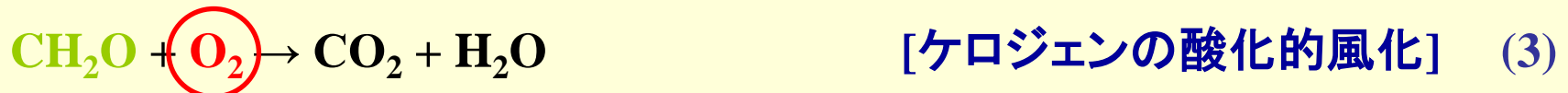
2. 顕生代における酸素濃度の変動

酸素収支とC-S-O-Fe サイクル

● 酸素の放出過程

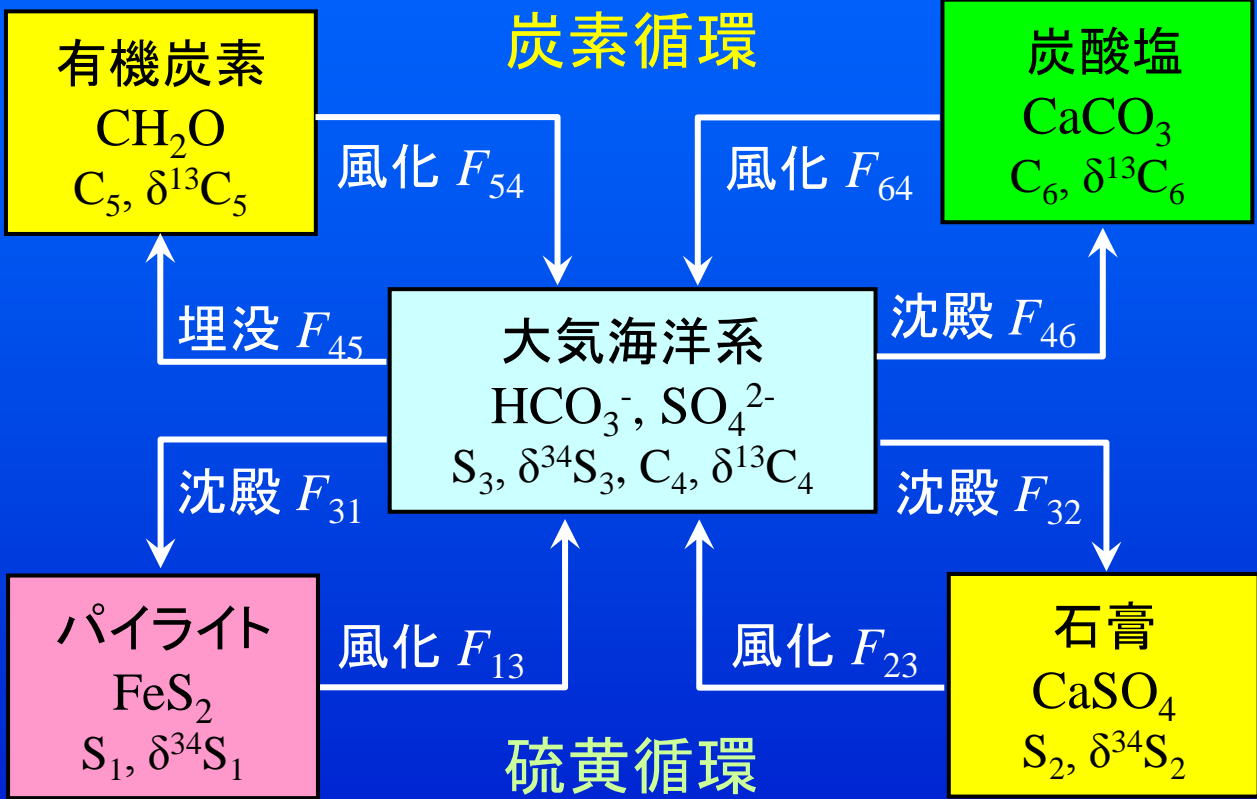


● 酸素の消費過程



酸素の生成は生命の光合成反応によるが、正味の酸素放出は有機炭素(もしくはパイライト)の埋没によるもの

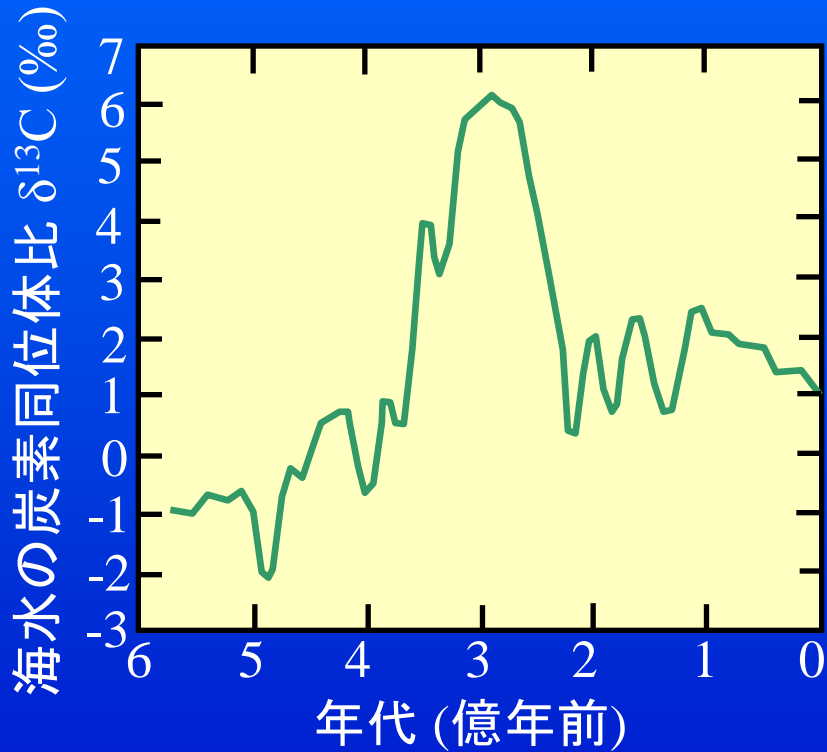
同位体質量収支モデル



[Garrels and Lerman, 1984; Berner, 1987; Lasaga, 1989]

顕生代における海水の同位体比変動

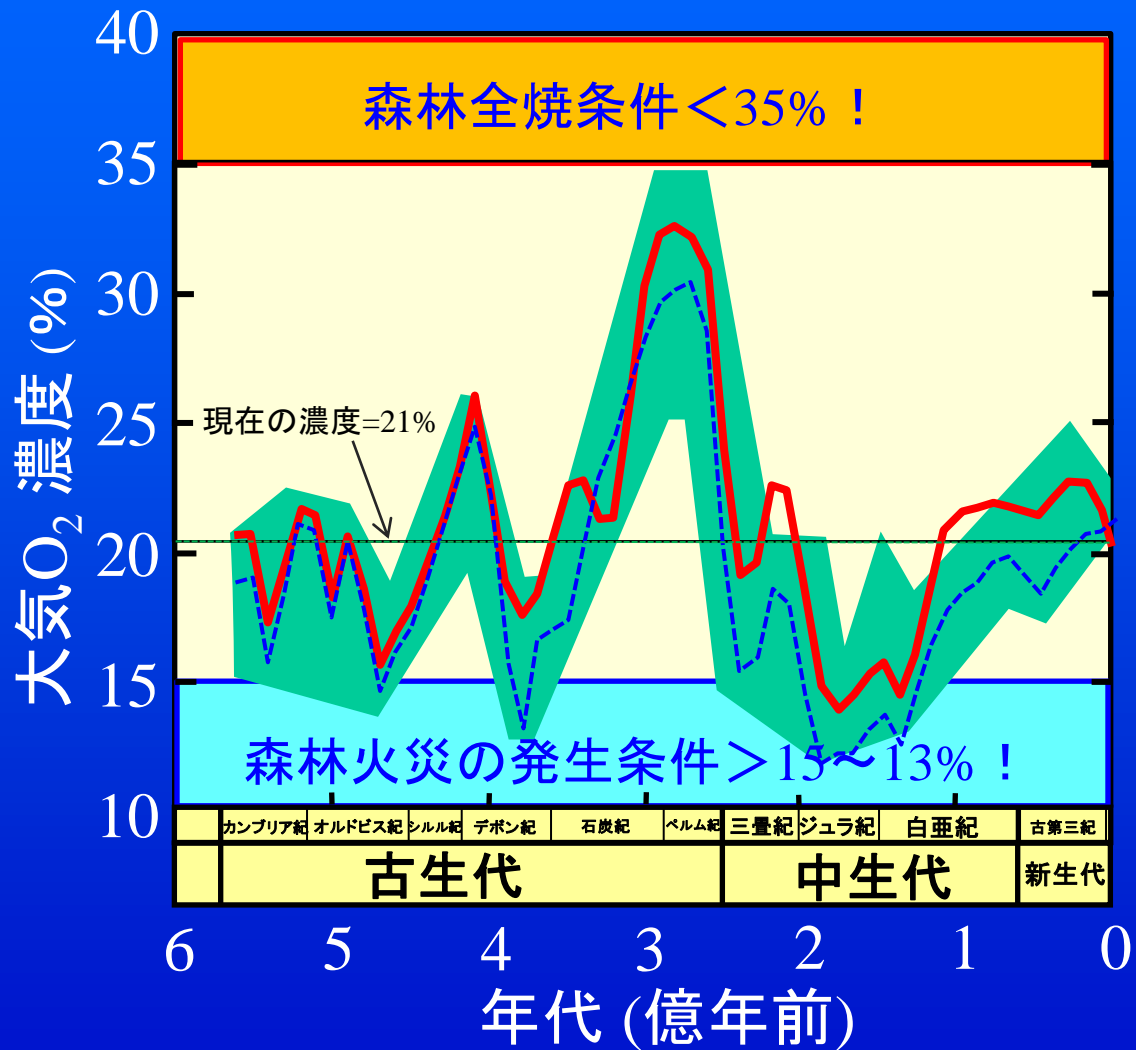
■ 炭素同位体比



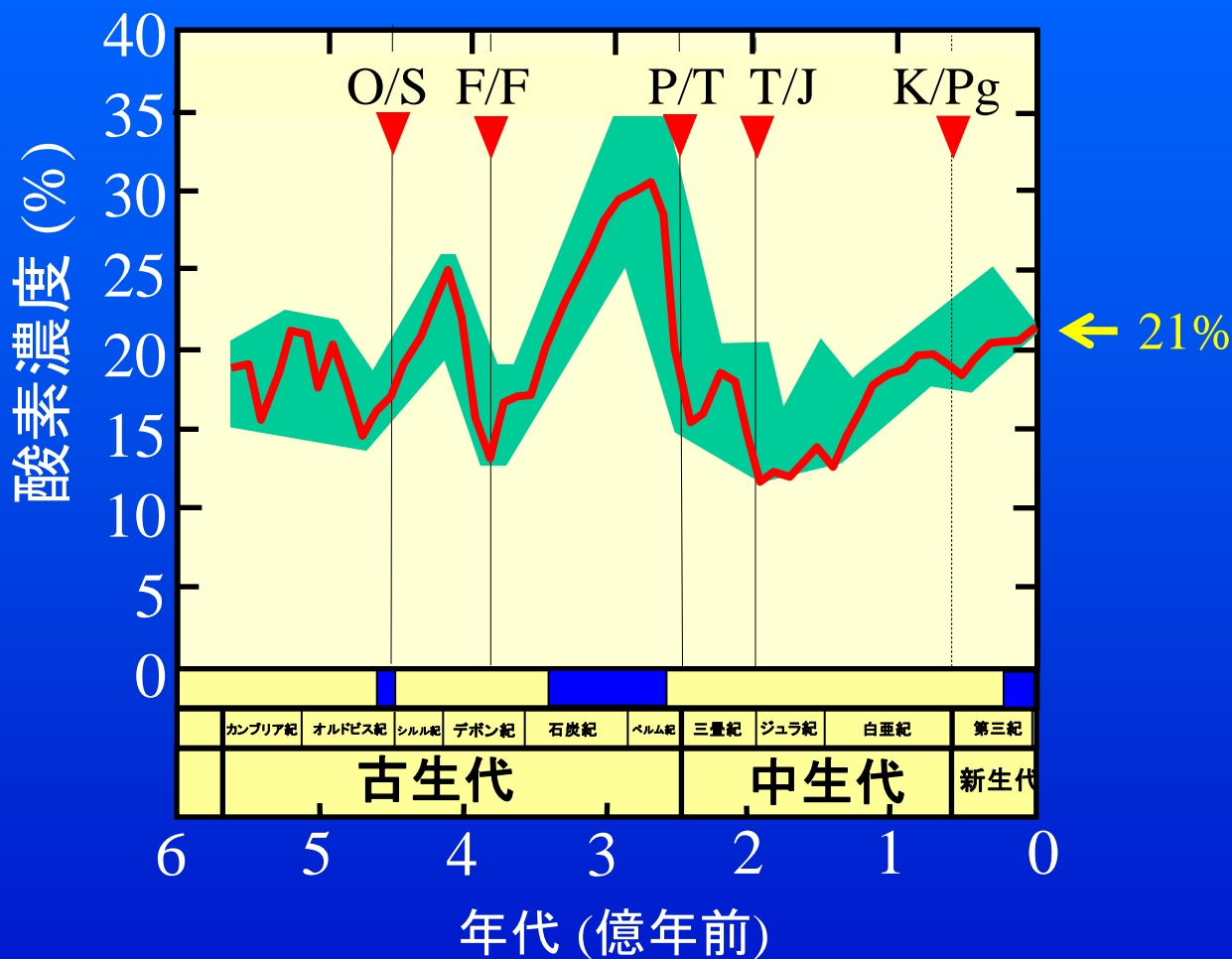
■ 硫黄同位体比



顕生代の酸素濃度変動

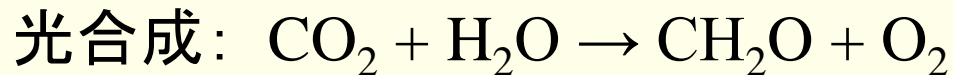
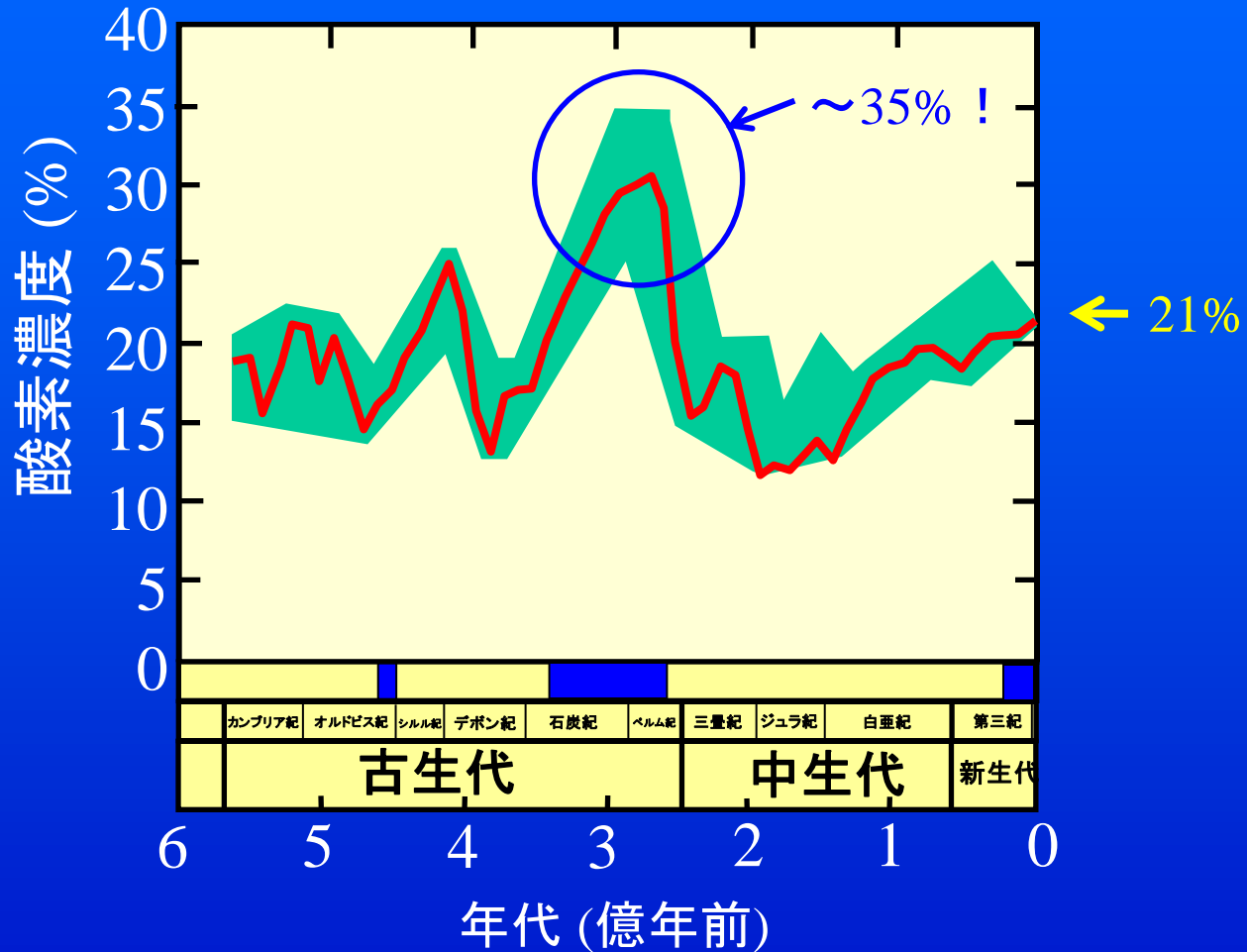


酸素濃度の低下と大量絶滅



酸素濃度低下と大量絶滅が関係？

顕生代の酸素濃度変動



酸素濃度の増加と昆虫の巨大化



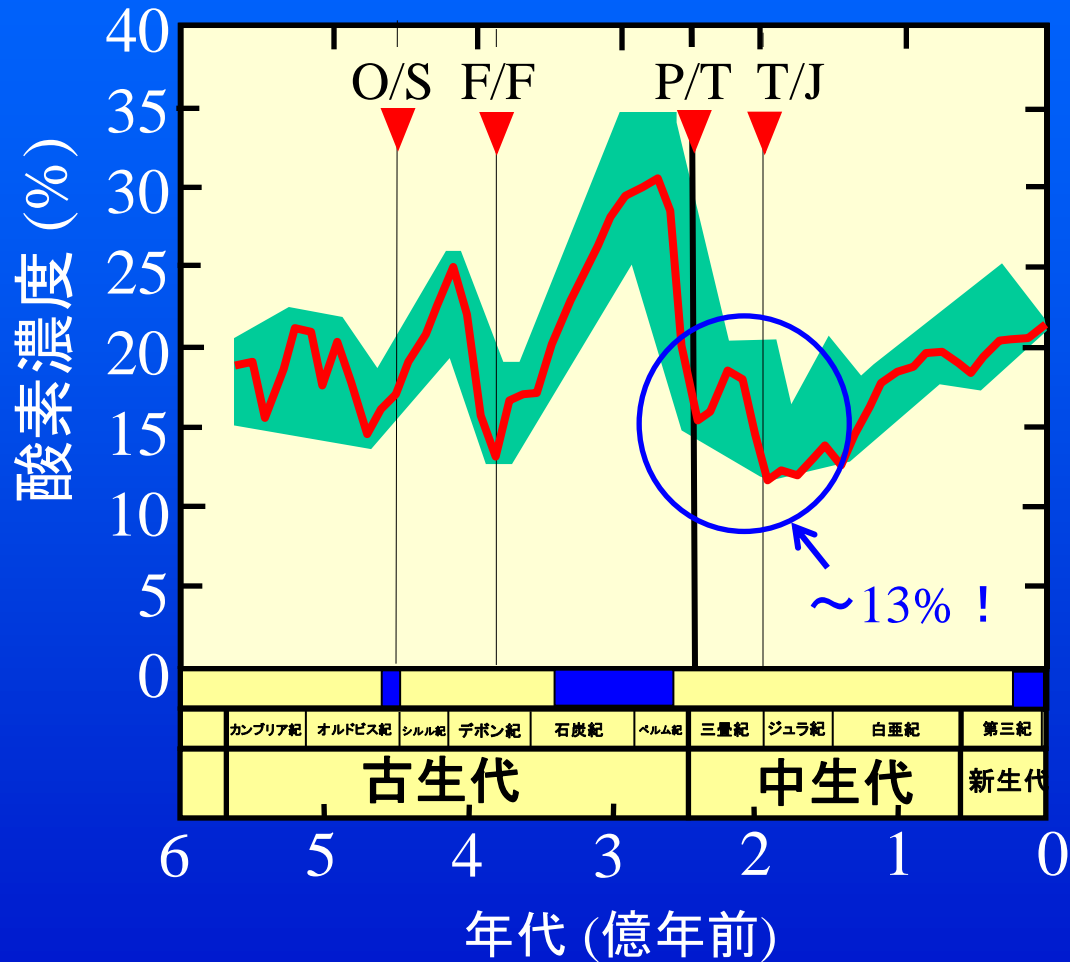
石炭紀の巨大トンボ(*Meganeura monyi*)の模型(国立科学博物館)

* 石炭紀にみられる昆虫の多様化と巨大化

酸素代謝は酸素濃度が高い方が有利 (拡散浸透によって律速)

飛行力学的には大気密度が高い方が有利

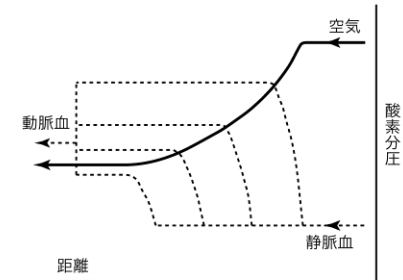
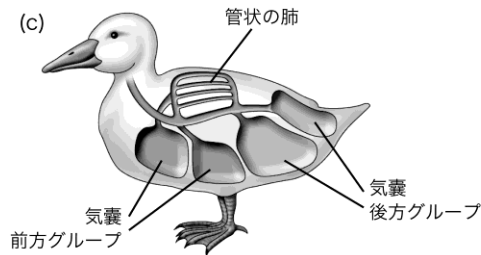
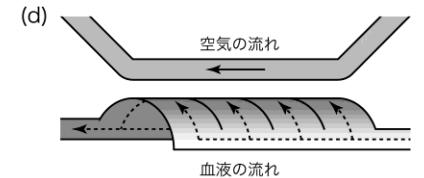
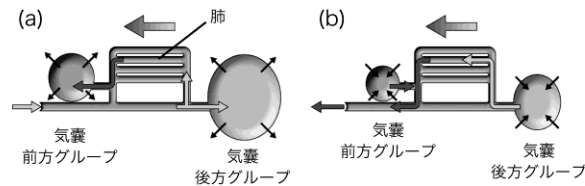
顕生代の酸素濃度変動



鳥類の気嚢システム

■ 気嚢システム

効率的な酸素呼吸 ← 低い酸素濃度への適応？



<http://uc-itsumokamisama.seesaa.net/article/169217859.html>

[平沢 (2010) 岩波科学]

- * 肺は何本かの管を束ねたような形状
- * 前後の開口部は「気嚢」につながっている。
- * 肺への吸気・排気は、「気嚢」の拡大・縮小により、空気は一方向に流れる

恐竜は鳥類と同じ気嚢システムを持っていた

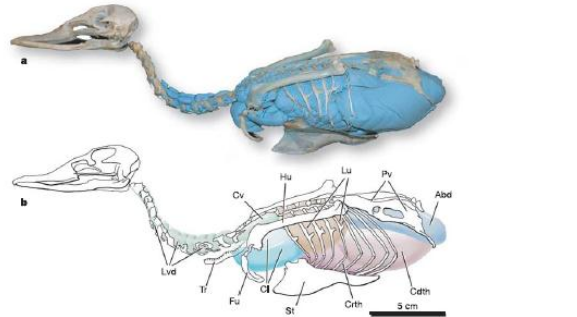


Figure 1 | Pulmonary air-sac system in a bird. a, Latex injection (blue) of the pulmonary system in a duck (*Anas crecca*), highlighting the extent of air sacs throughout the body. b, Main components of the avian flow-through system (ribs have been illustrated in their proper anatomical positions).
Abd, abdominal air sac; Cdth, caudal thoracic air sac; Cl, clavicular air sac; Crth, cranial thoracic air sac; Cv, cervical air sac; Fu, furcula; Hu, humerus; Lu, lung; Lvd, lateral vertebral diverticula; Pv, pelvis; Tr, trachea.

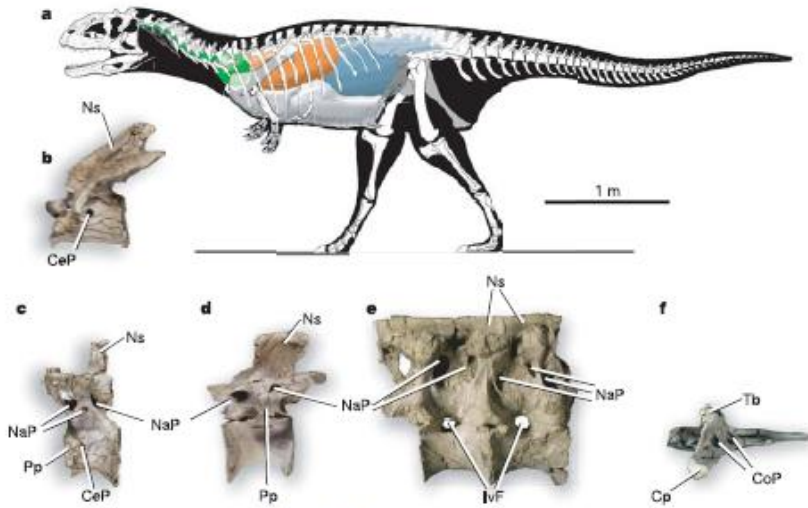


Figure 4 | Reconstruction of pulmonary air-sac system in *Majungatholus atopus* (based on UA 8678/FMNH PR 2278/2100 (ref. 21)). a, Pulmonary components based directly on vertebral morphology in UA 8678 include the following: cervical system (green), lung (orange) and abdominal system (blue). In modern birds, clavicular and thoracic air sacs are also present (see Fig. 1); their placement here (indicated in light grey), combined with the overlapping nature of other components, represents tertiary-level inferences emphasizing the uncertainty surrounding the reconstruction of soft tissues

not constrained by osteological evidence. Unknown skeletal elements are indicated by dark grey shading. b-f, Vertebrae (b-e) and rib (f) of UA 8678 illustrating pneumatic features. b, Second cervical; c, first thoracic; d, ninth thoracic (reversed); e, sacral complex, left lateral view; f, left ninth cervical rib, medial view (reversed). CeP, central pneumatic foramen; Cp, capitulum; IvF, intervertebral foramen; NaP, neural arch pneumatic foramen; Ns, neural spine; Pp, parapophysis; Tb, tuberculum.

“含気孔”

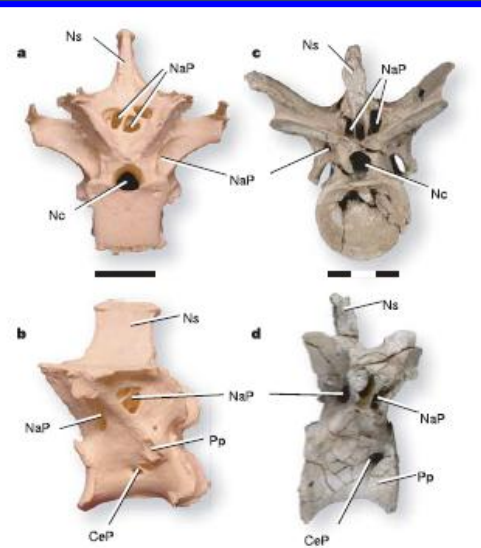


Figure 3 | Vertebral pneumaticity in avian and non-avian theropods. Comparisons between a bird (a, b) and theropod dinosaur (c, d) in caudal (a, c) and right lateral (b, d) views, illustrating the topological similarity of pneumatic features. a, b, Cranial thoracic vertebra of a sarus crane (*Grus antigone*, SBU AV104063). c, d, Mid-cervical (c) and cervicothoracic (d) vertebra of an abelisauroid theropod (*Majungatholus atopus*, UA 8678). Scale bar, 1 cm (a, b) and 3 cm in (c, d). CeP, central pneumatic foramen; NaP, neural arch pneumatic foramen; Nc, neural canal; Ns, neural spine; Pp, parapophysis.

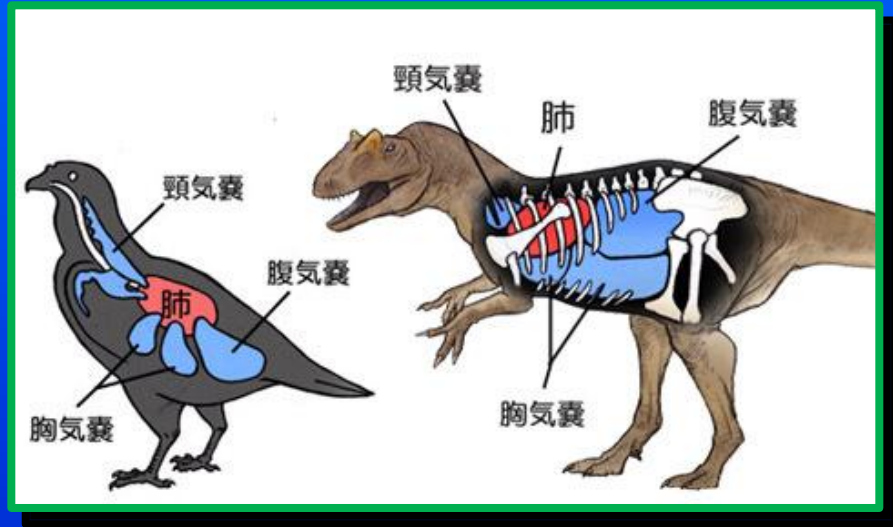
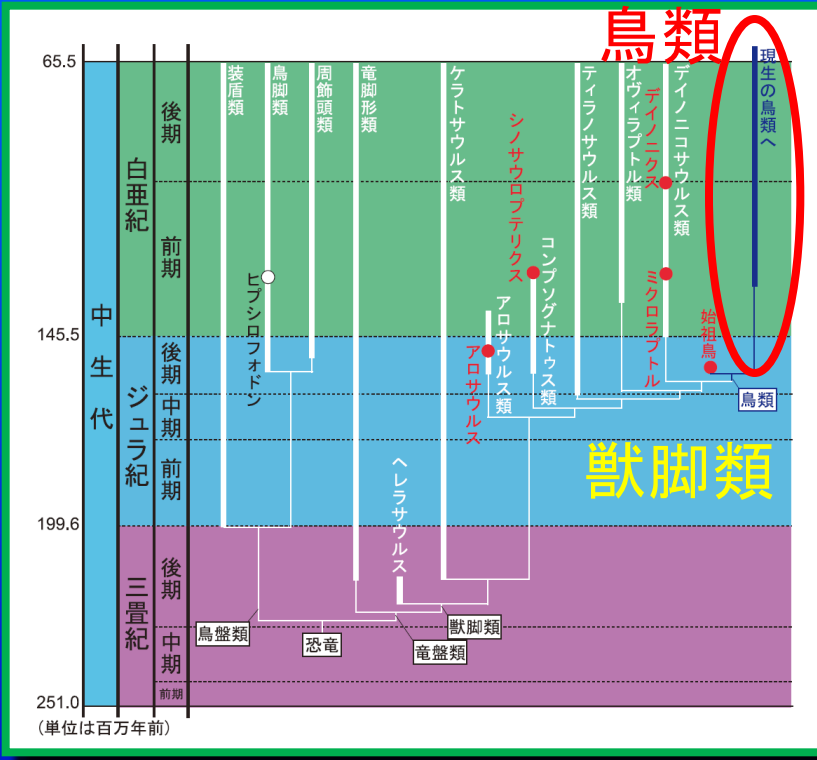
頸椎には前方グループの気嚢が入り込み、
 胴椎および仙椎は後方グループの気嚢が
 入り込むという対応関係が判明

[O'Connor and Claessens, 2005]

恐竜は気嚢システムを持っていた

■ 気嚢システム

効率的な酸素呼吸 ← 低い酸素濃度への適応？



[<http://ameblo.jp/oldworld/entry-10153482359.html>]

恐竜の系統図

[真鍋 (2009) JGL, 5(1), 10-12.]

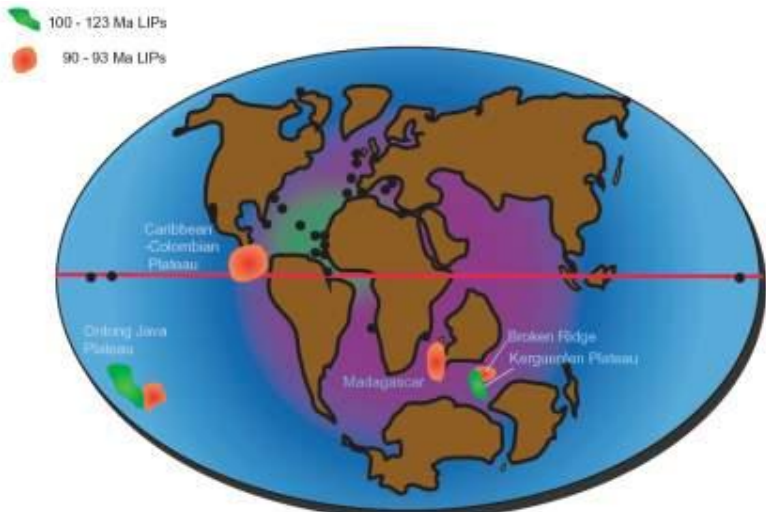
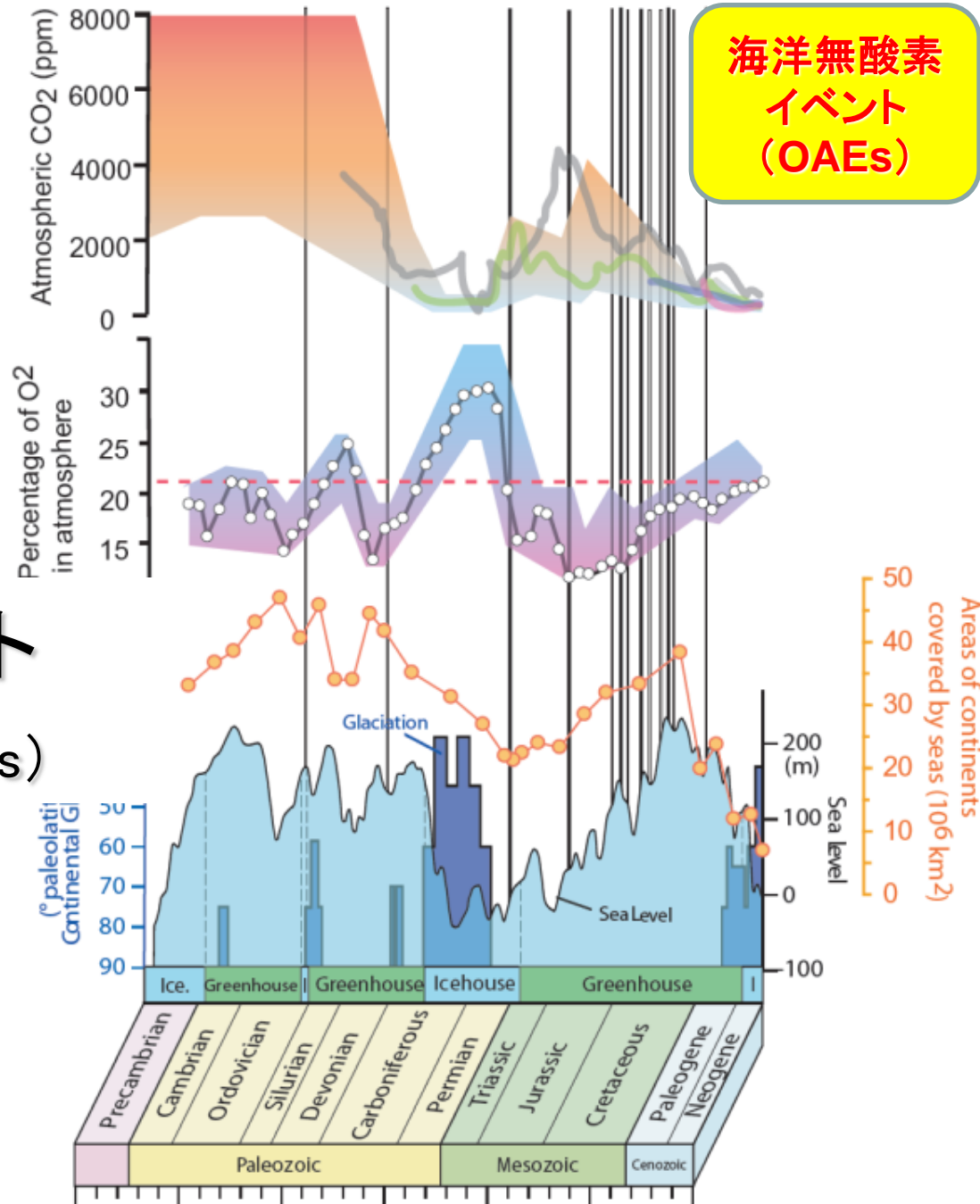
4. 海洋無酸素イベント



黒色頁岩

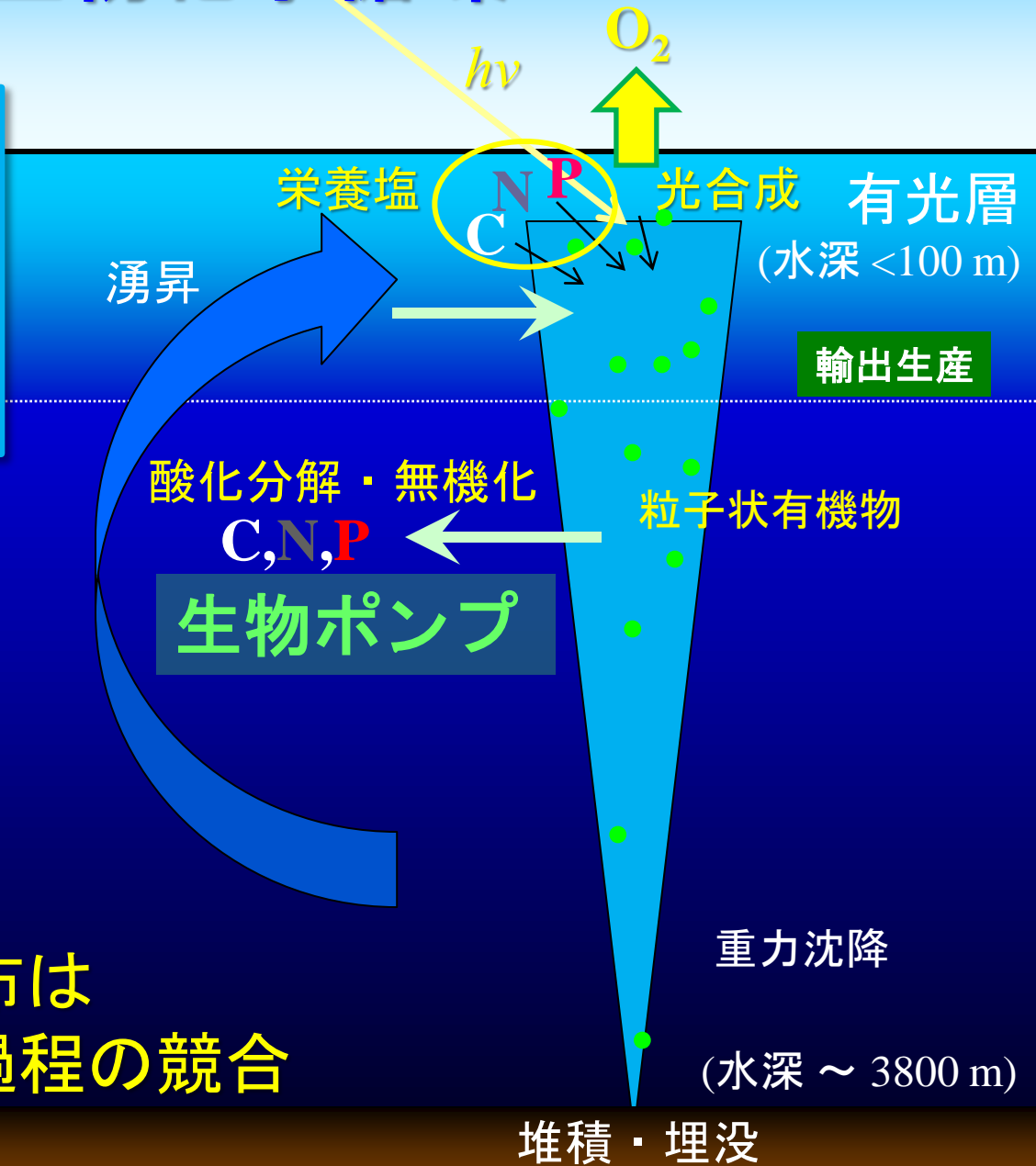
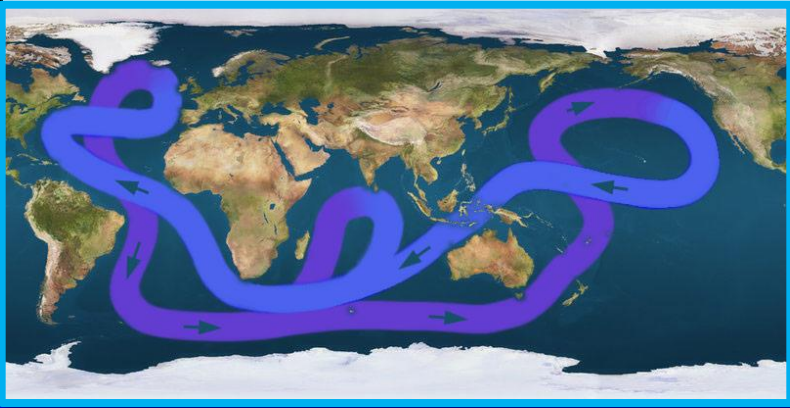
海洋無酸素イベント (Ocean Anoxic Events; OAEs)

海洋無酸素
イベント
(OAEs)

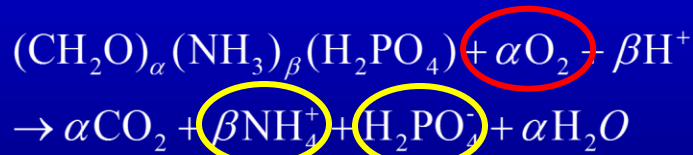


海洋生物化学循環

海洋大循環

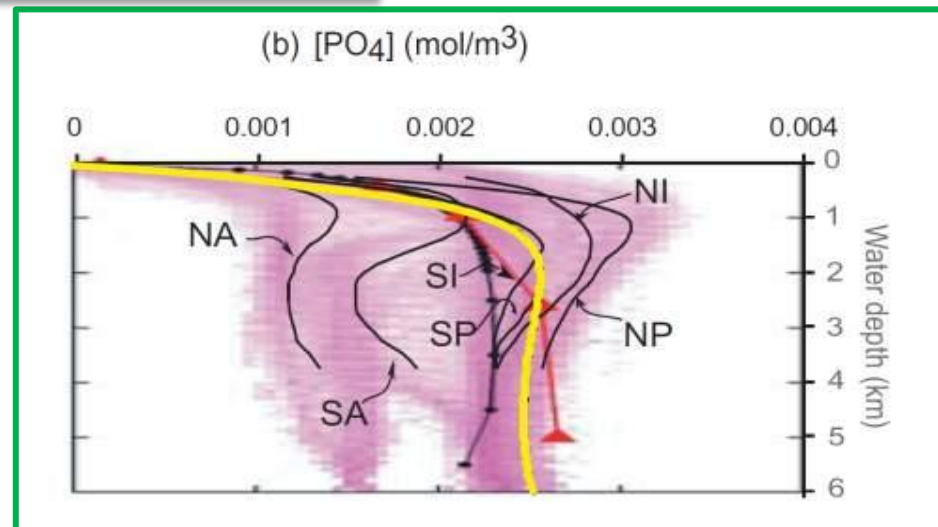
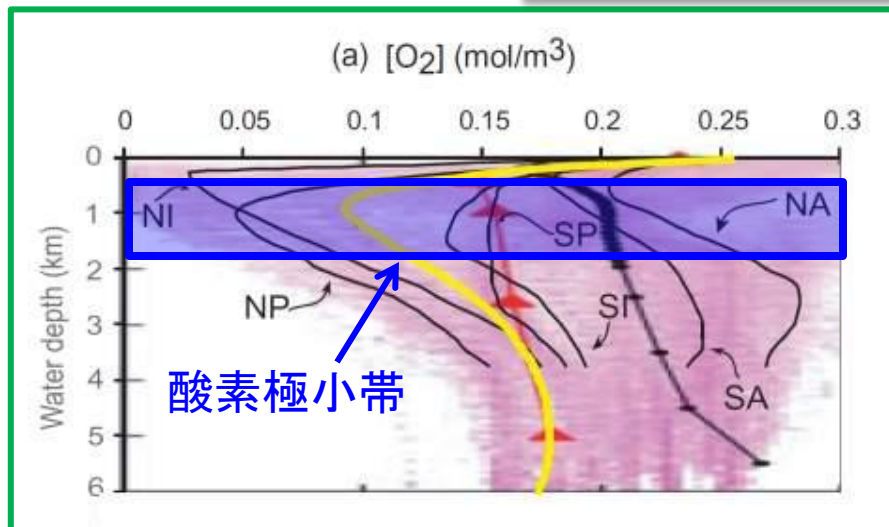
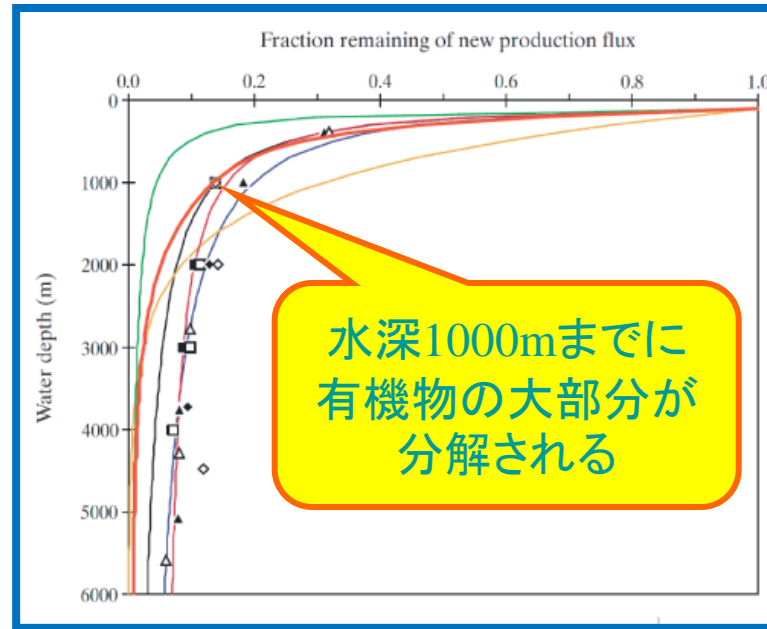


好氣的分解



物質の鉛直分布は
生物化学過程と物理過程の競合

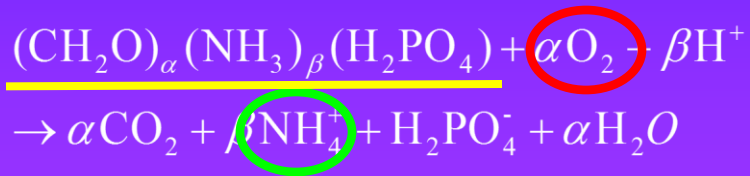
海洋の鉛直構造



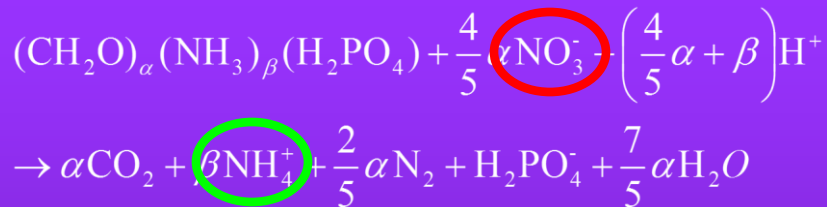
海洋における酸化還元反応

● 粒子状有機物の分解

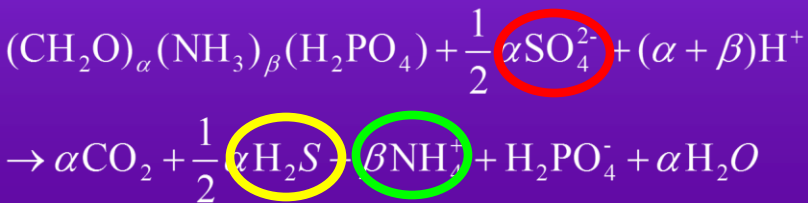
好氣的分解



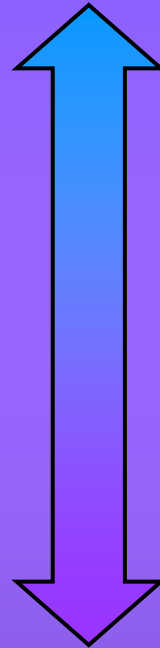
脱窒



硫酸還元



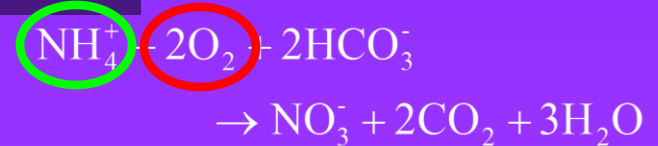
富酸素



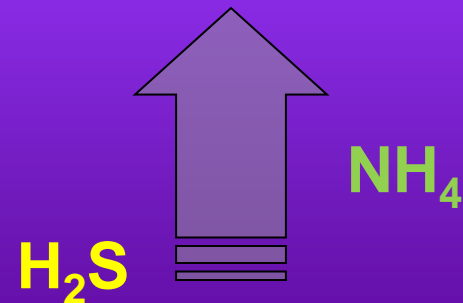
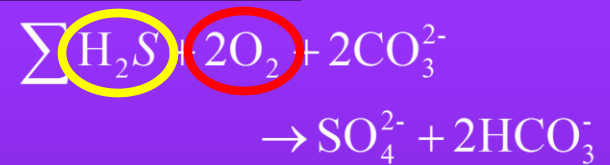
貧酸素

● 酸化反応

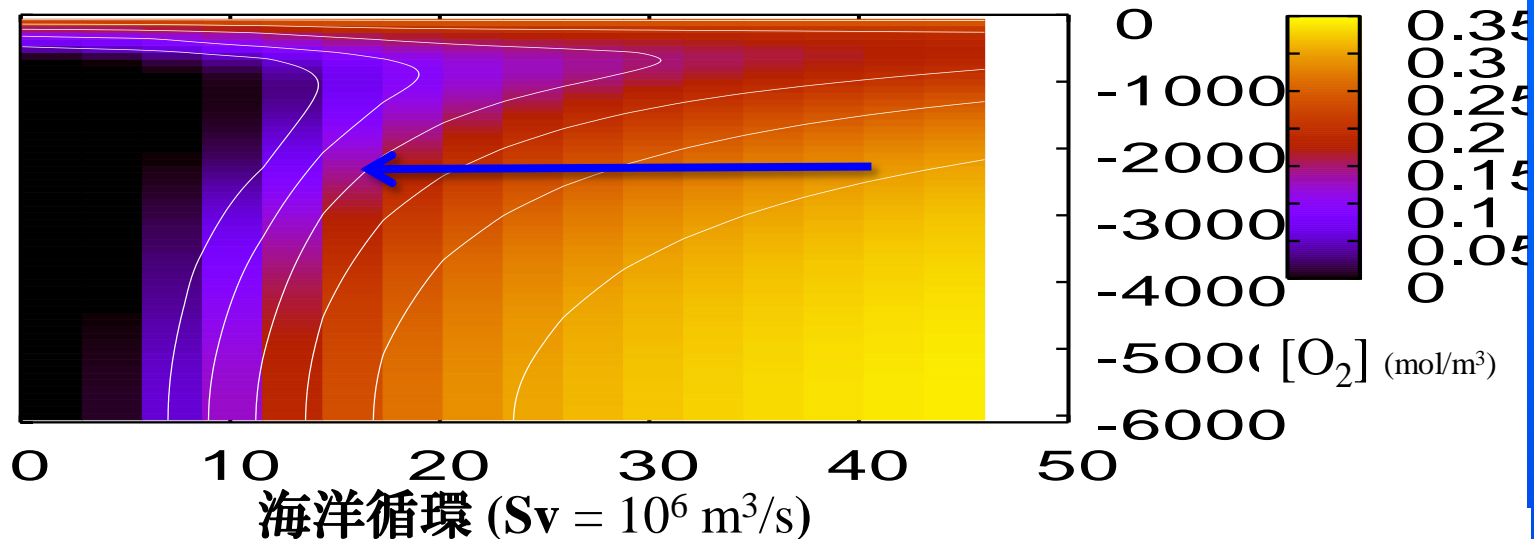
硝化



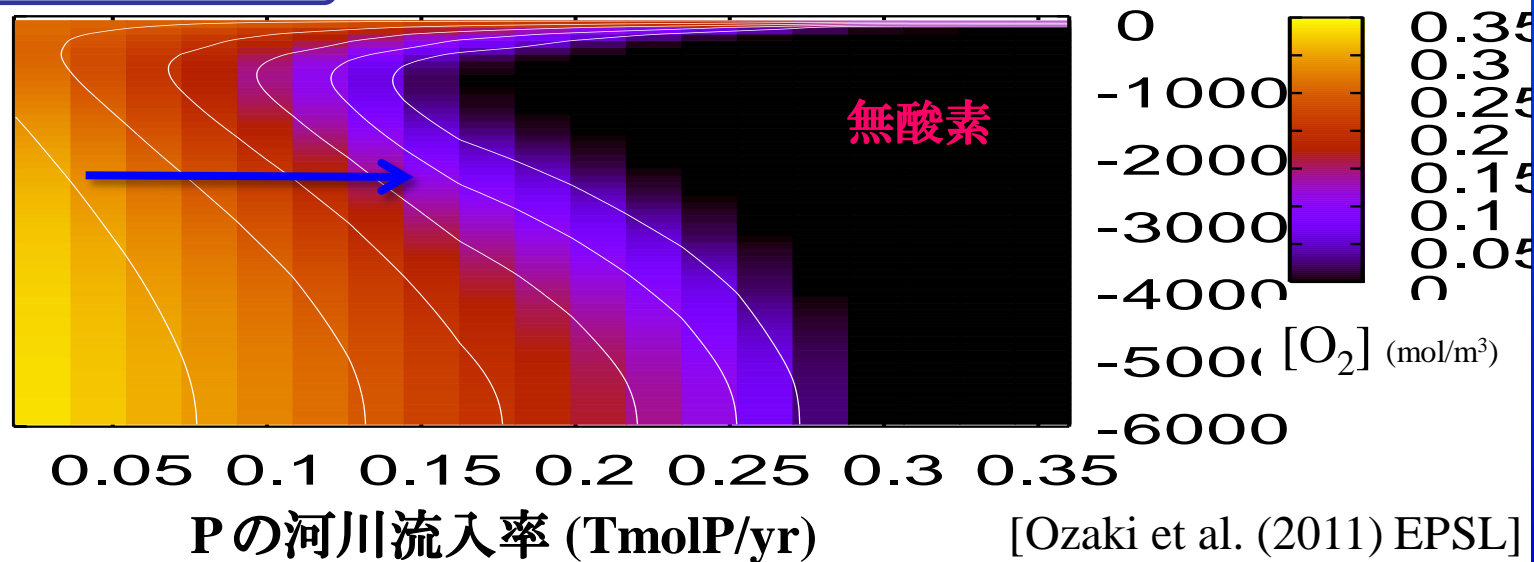
硫化物の酸化



Pの河川流入率は一定 0.126 TmolP/yr、海洋循環は変化



Pの河川流入率を変化、
海洋循環は一定 17 Sv



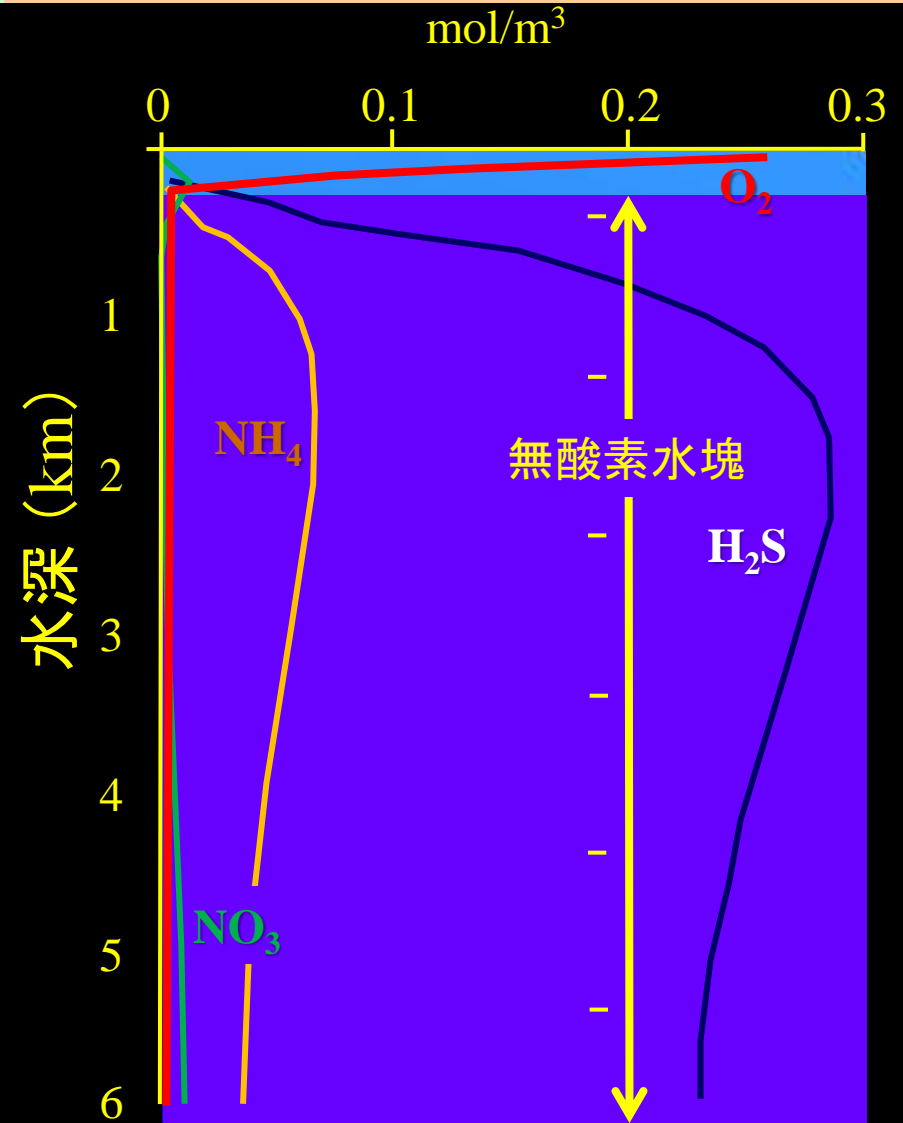
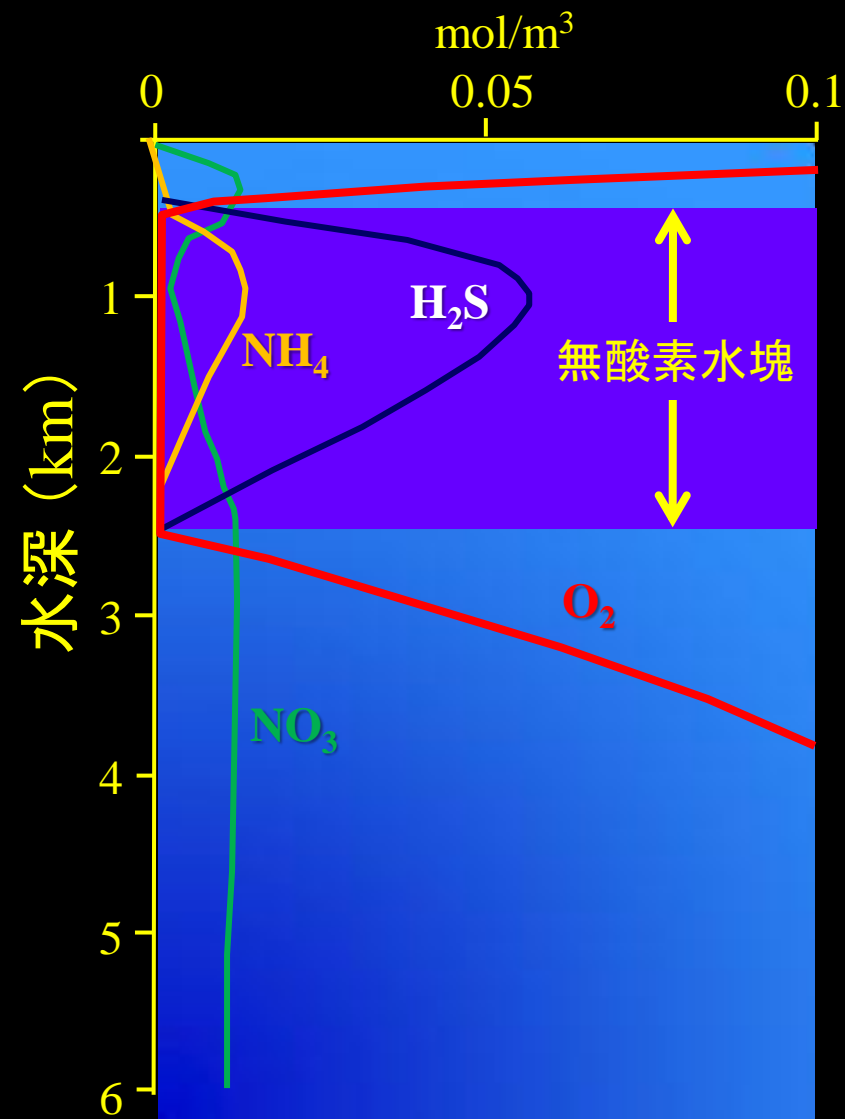
無酸素海洋の2つのタイプ

中層水アノキシア

Intermediate Water Anoxia (IWA)

深層水アノキシア

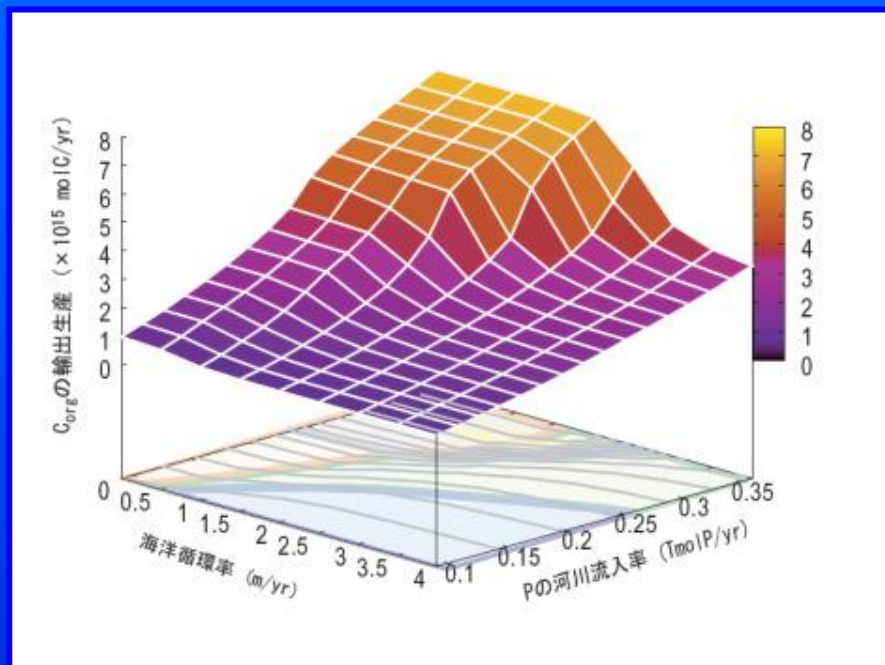
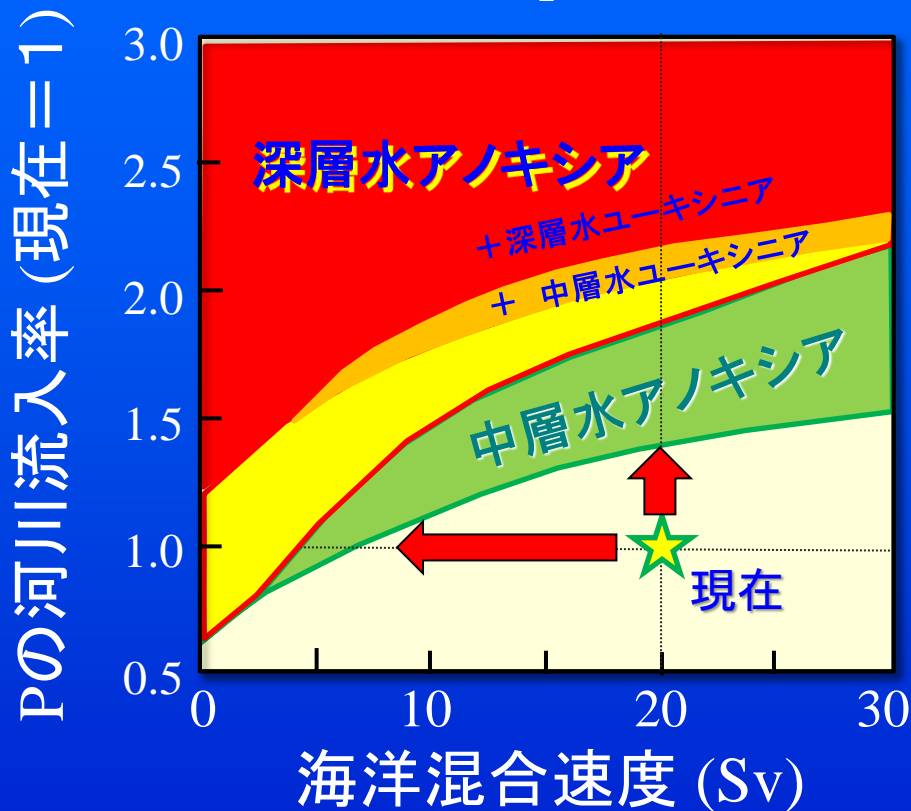
Deep Water Anoxia (DWA)



海洋無酸素イベント(アノキシア)の発生条件

“アノキシア” : $[O_2] < 10^{-3} \text{ mol/m}^3$

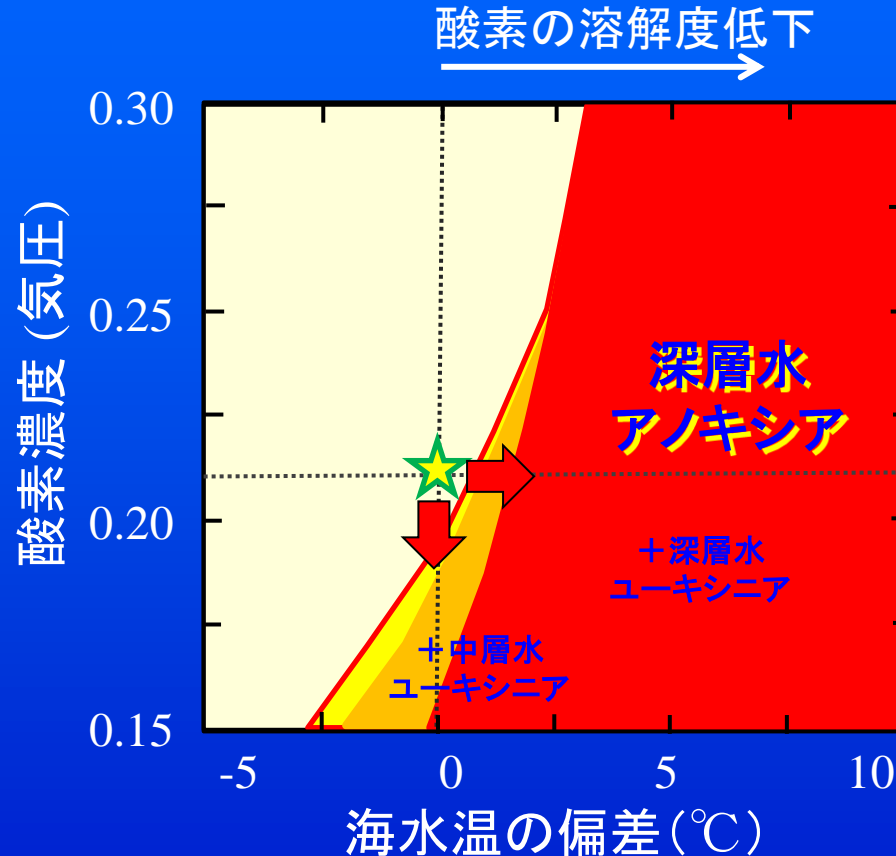
“ユーキシニア” : $[H_2S] > 0.1 \text{ mol/m}^3$



リン流入増加(化学風化増加)で容易に無酸素海洋に
→ 温暖化が原因!?

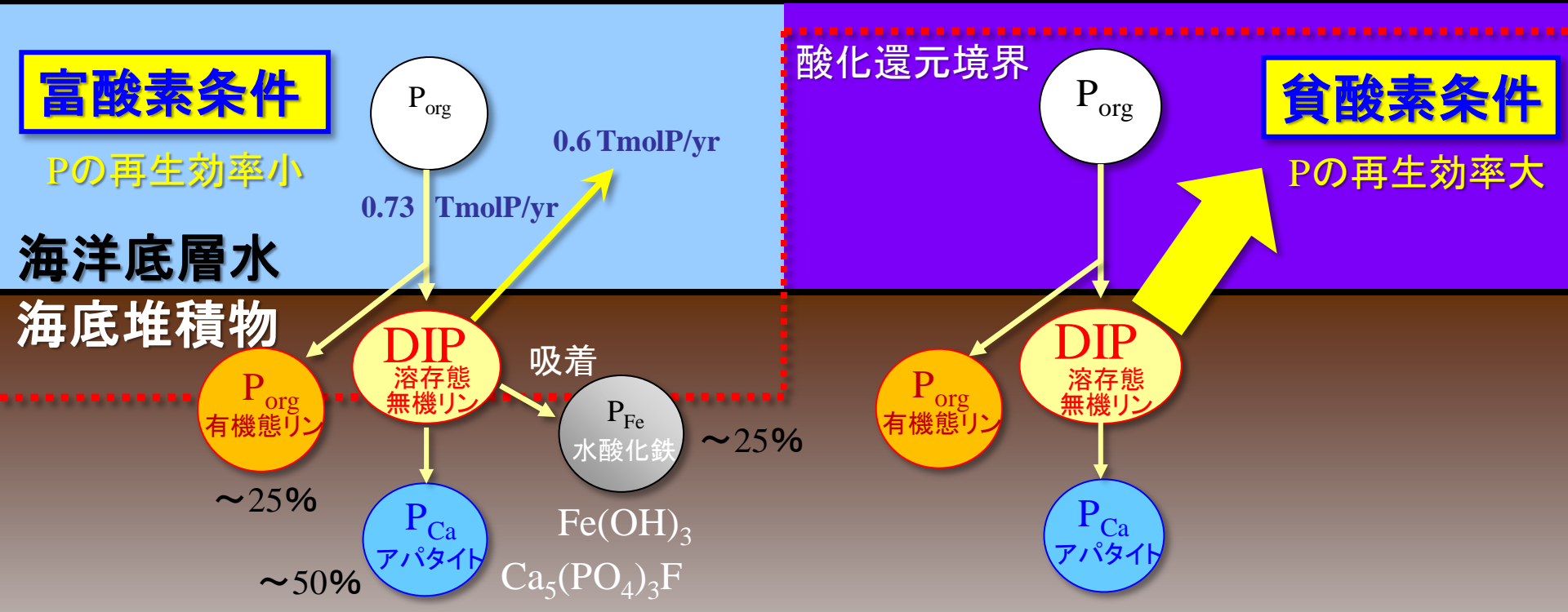
海洋無酸素イベント(アノキシア)の発生条件

“アノキシア” : $[O_2] < 10^{-3} \text{ mol/m}^3$ “ユーキシニア” : $[H_2S] > 0.1 \text{ mol/m}^3$



* 温暖化・酸素濃度の低下はアノキシアを引き起こす

リンの挙動

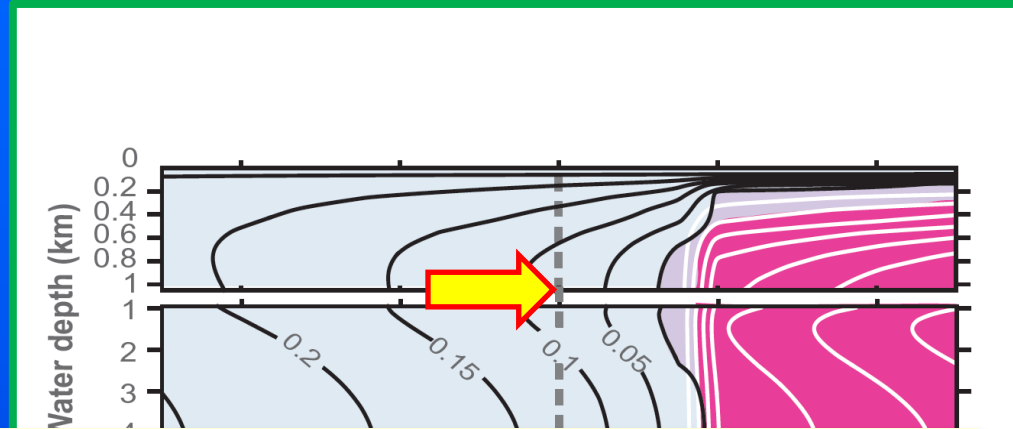


貧酸素的条件: Pの埋没効率低下 → 海洋のP濃度上昇
 → 生物生産増大 → 貧酸素水塊の拡大
 正のフィードバック過程!

“アノキシア-生物生産フィードバック”(A-P feedback)

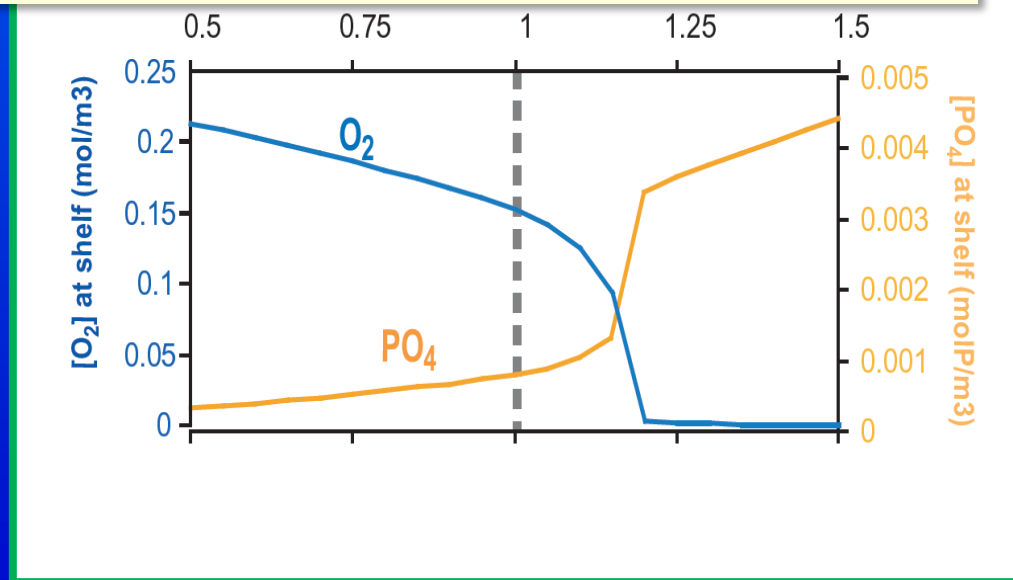
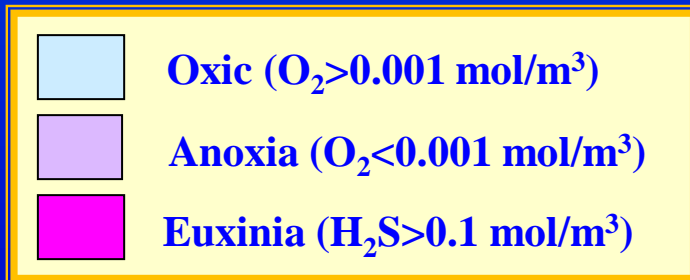
リンの流入率増加が海洋無酸素イベントをもたらす

- Pの供給率増加
- 富栄養化(P濃度上昇)
- 生物生産の増加
- 無酸素水塊の拡大



海洋無酸素イベントは酸素濃度の増大をもたらす？

- 生物生産の増加
- <正のフィードバック!>



地球温暖化と海洋無酸素イベント



火山活動の活発化

温室効果気体の供給

温暖化

化学風化促進

酸素の溶解度減少

栄養塩供給率の増大

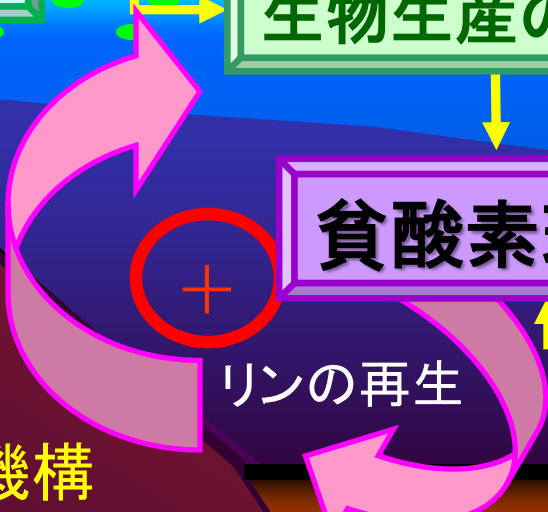
生物生産の増大

貧酸素環境

海洋循環の停滞

貧酸素環境では
Pの再生効率増加
→正のフィードバック機構

リンの再生



海洋無酸素イベントと生態系

* 海洋無酸素イベントの地層からバイオマーカーが検出

- ・イソレニアレテン (緑色硫黄細菌に由来)
- ・ジメチルホパノール (シアノバクテリアに由来)

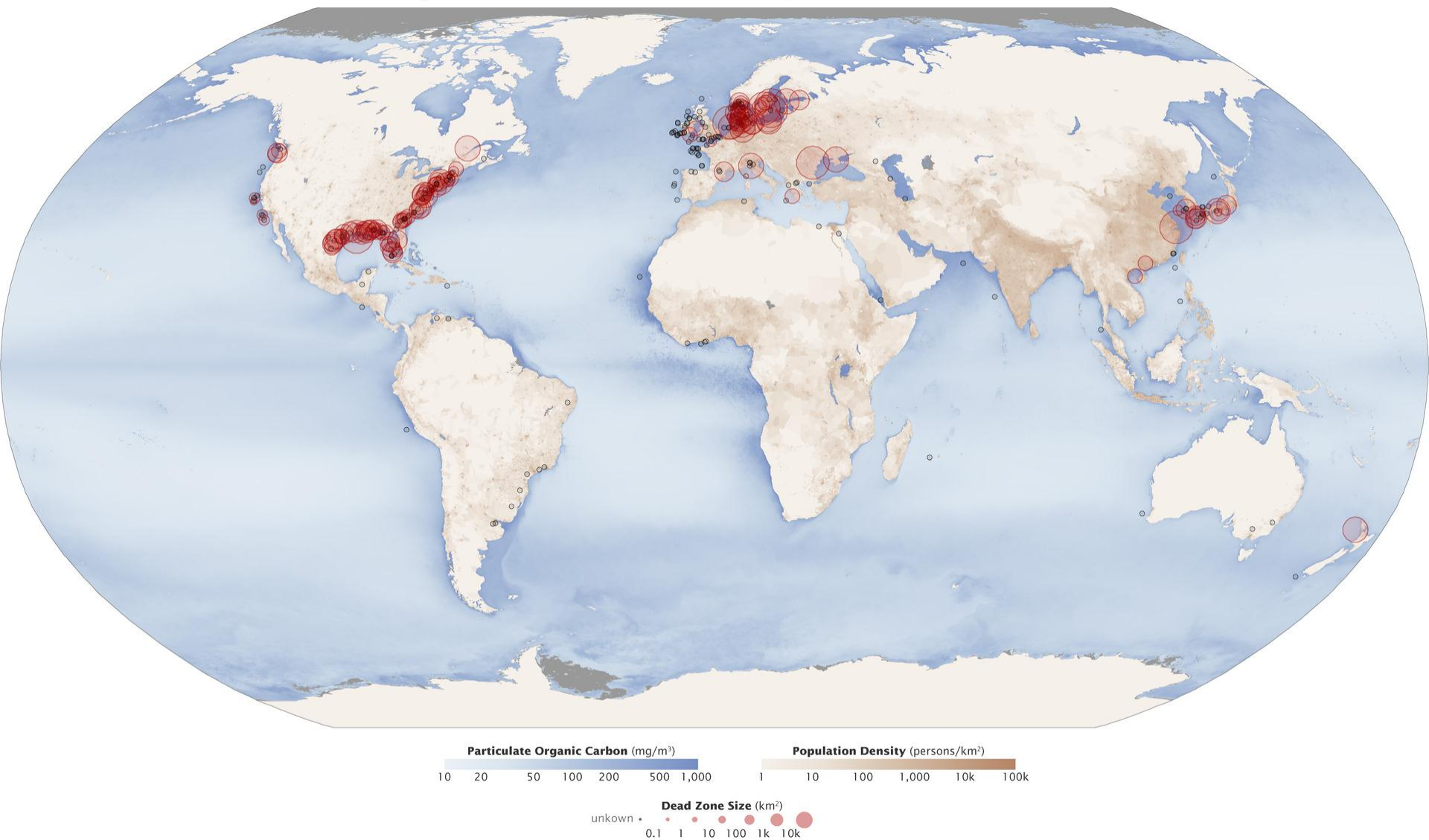
有光層において硫化水素が存在するような海洋環境

還元的水塊での脱窒反応(&アナモックス)により
硝酸に枯渇した海洋表層環境

* 海洋有光層にまで酸化還元境界が上昇!?
(有光層アノキシア / 有光層ユーキシニア)

* 硫化水素が大気中に漏れ出す!?
→ 陸上生物の大量絶滅 (P/T境界イベント?)

オーシャン・デッドゾーン



* 地球温暖化予測でも重要な研究課題

http://news.mongabay.com/2010/0722-hance_deadzones_nasa.html

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