

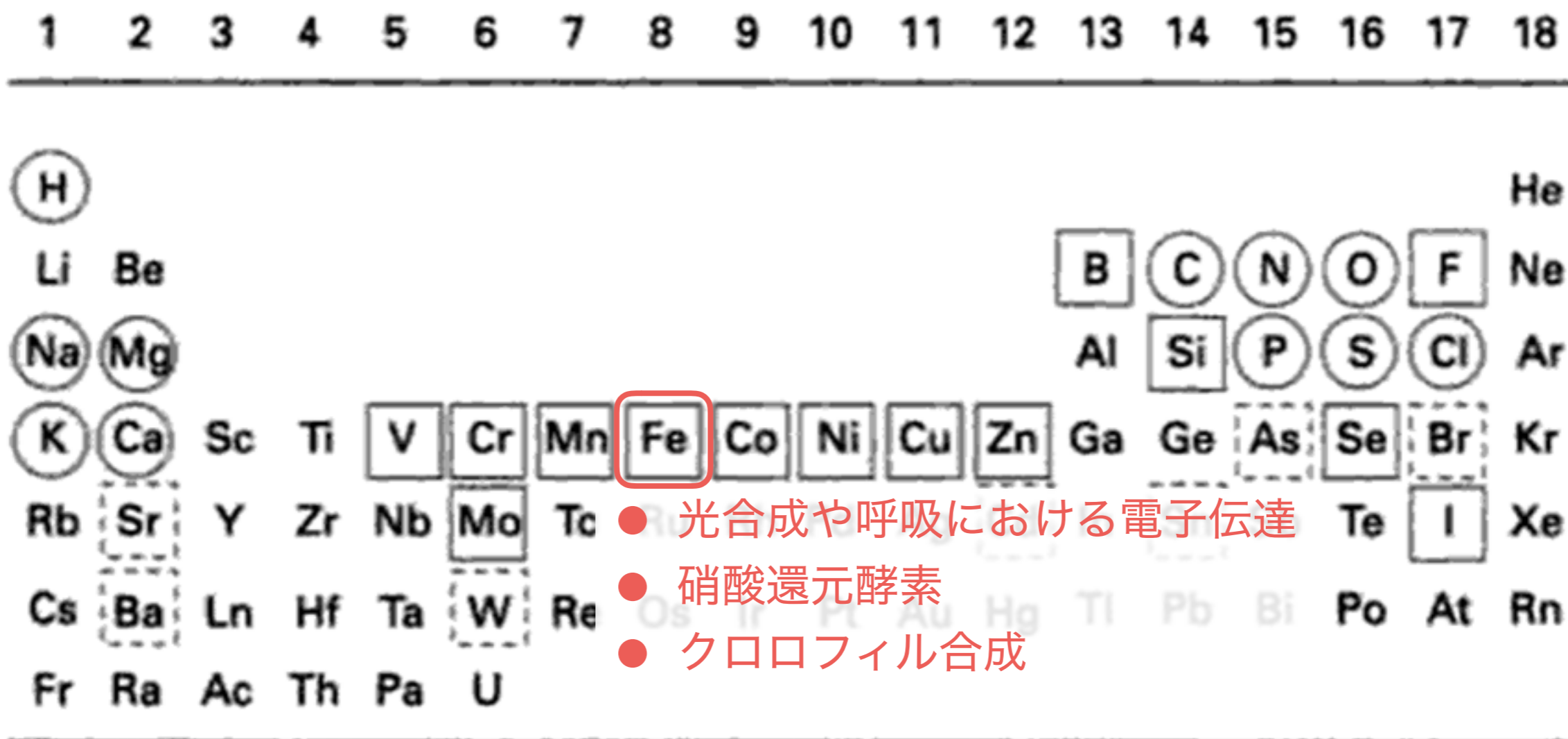
# 海洋鉄循環モデルの現状と課題

三角 和弘 / 電力中央研究所

# 目次

1. 海洋の鉄の基礎知識
2. 溶存鉄濃度の観測データの蓄積と  
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3. 海洋鉄循環モデルの国際相互比較  
FeMIP

# 1. 海洋の鉄の基礎知識

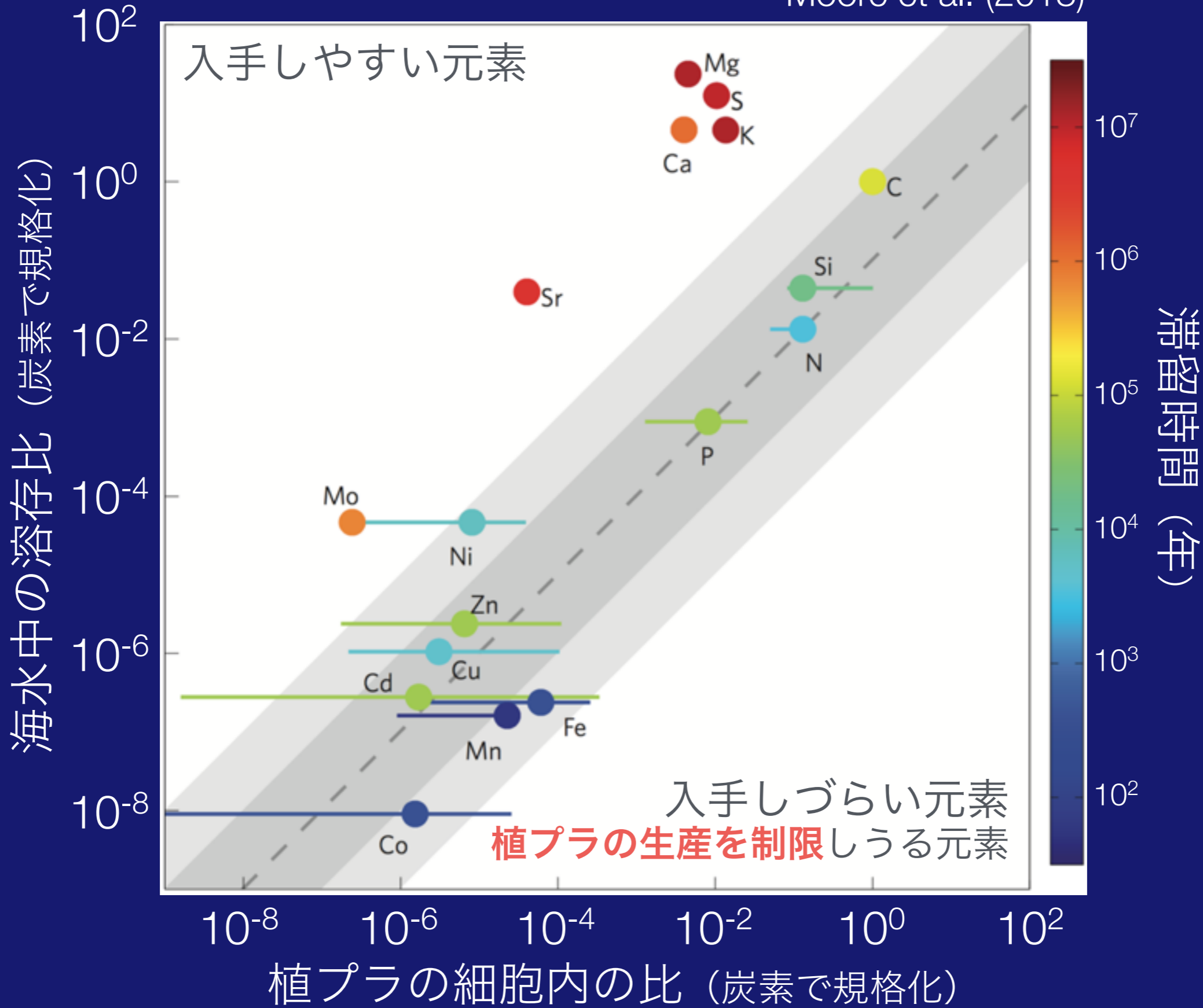


- 光合成や呼吸における電子伝達
- 硝酸還元酵素
- クロロフィル合成

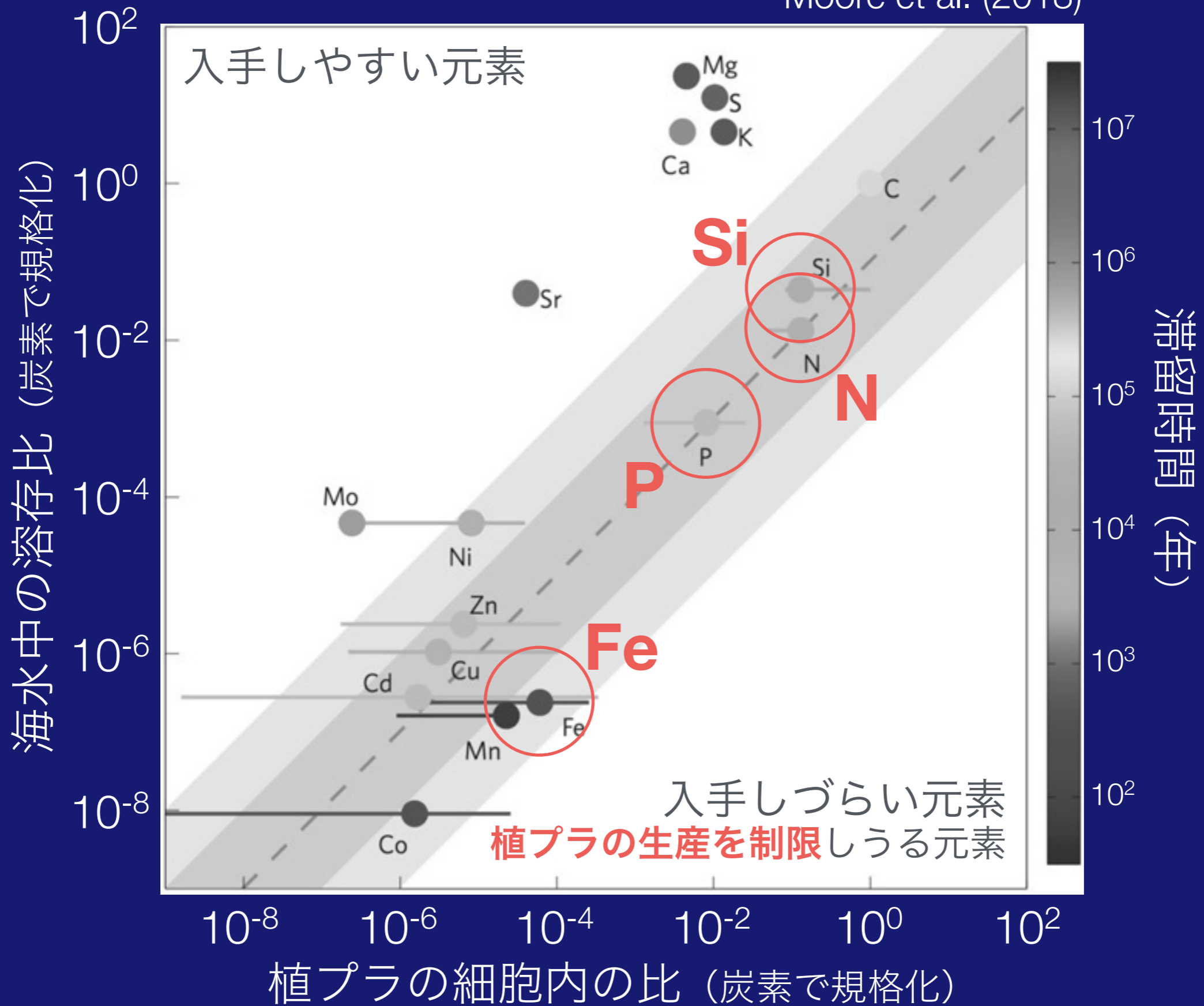
○ Bulk biological elements      □ Trace elements believed to be essential for bacteria, plants or animals      ▭ Possibly essential trace elements for some species

Frusta and Williams (2001)



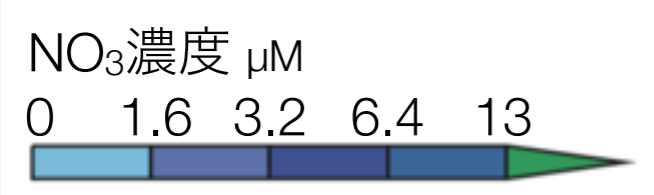
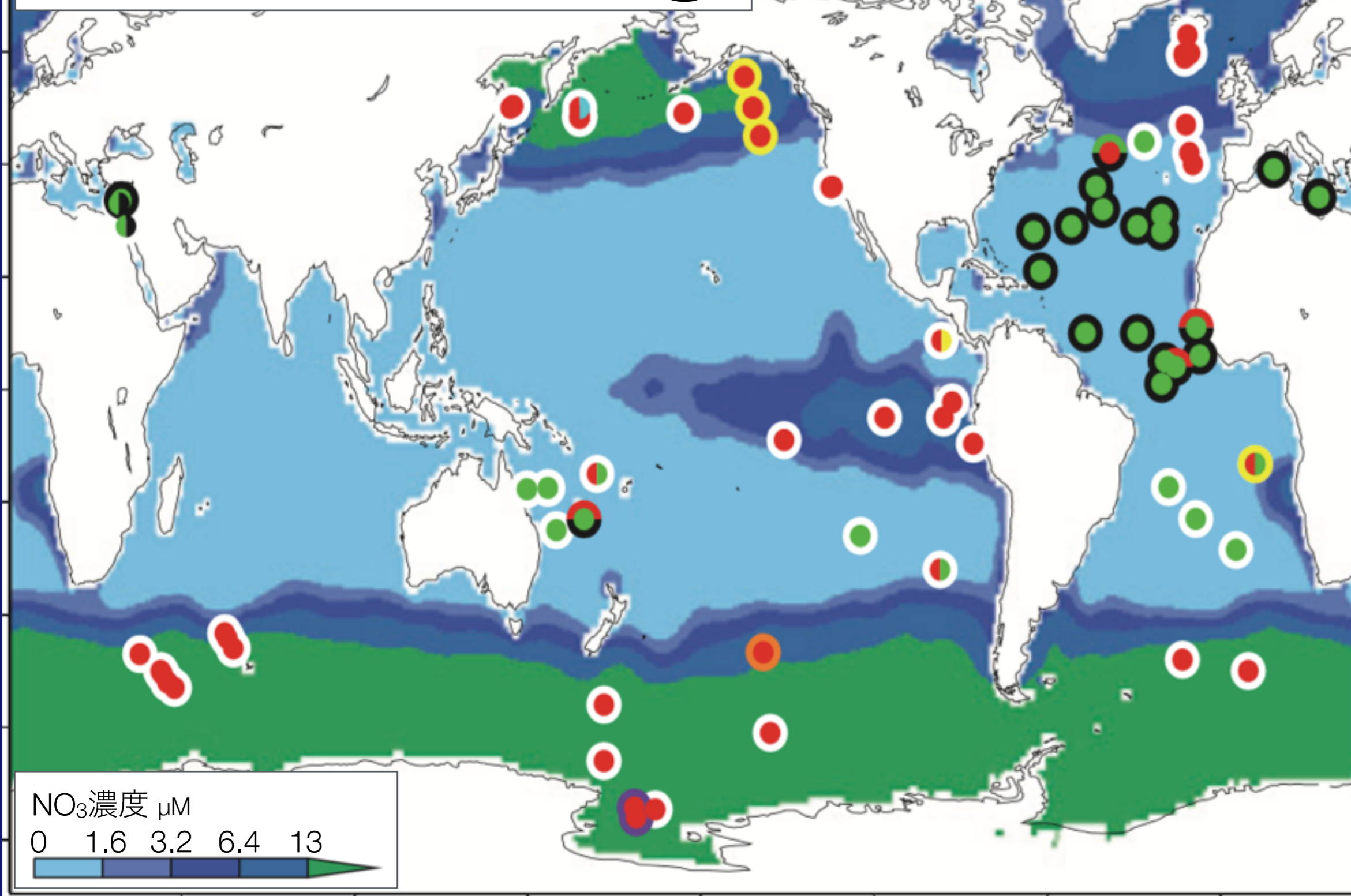
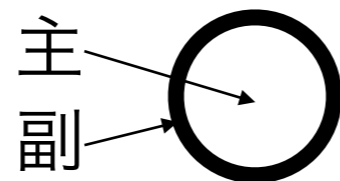


Moore et al. (2013)



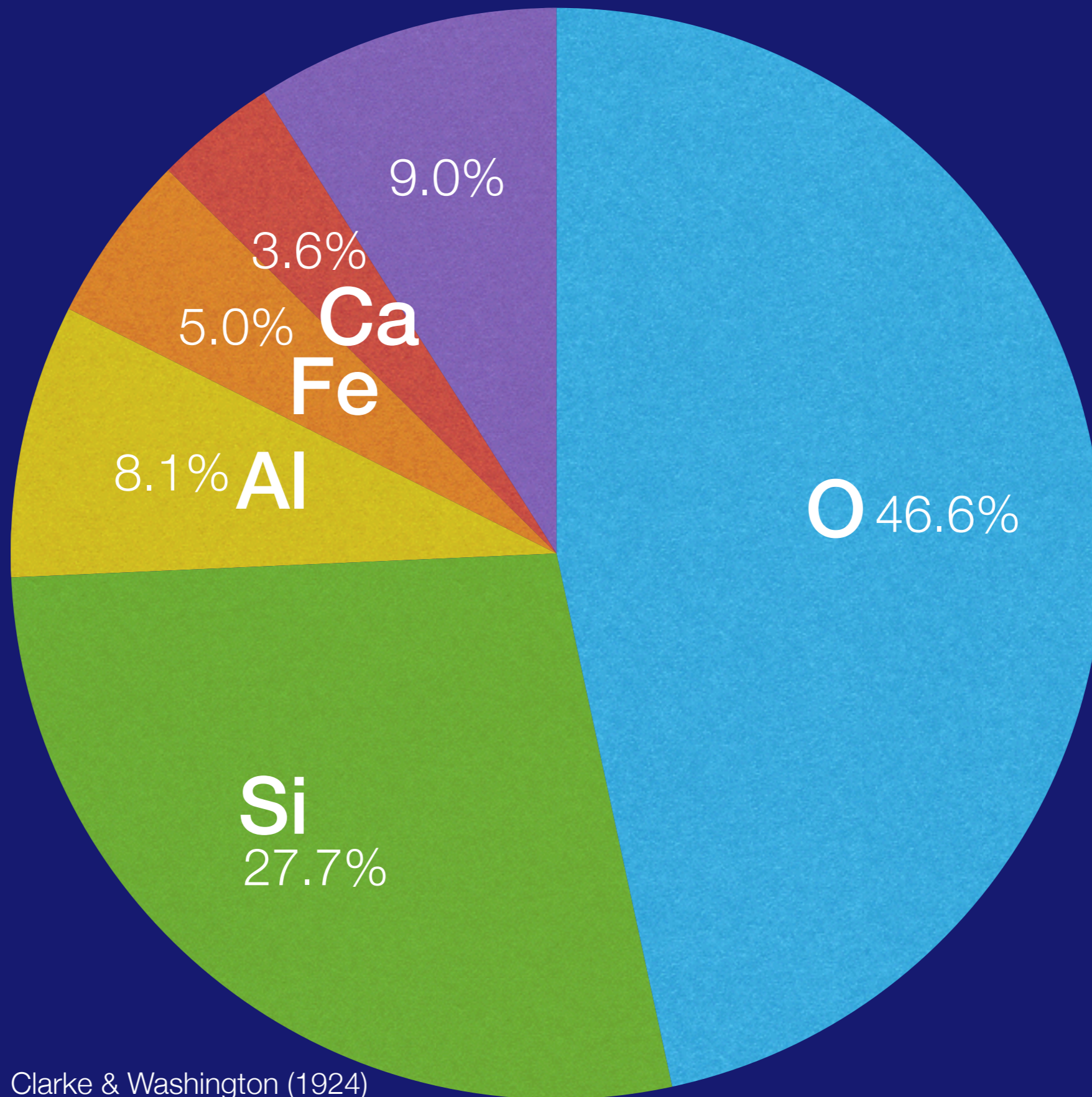
# 植プラの生産の制限要因

Fe N P Si Co Zn VB12

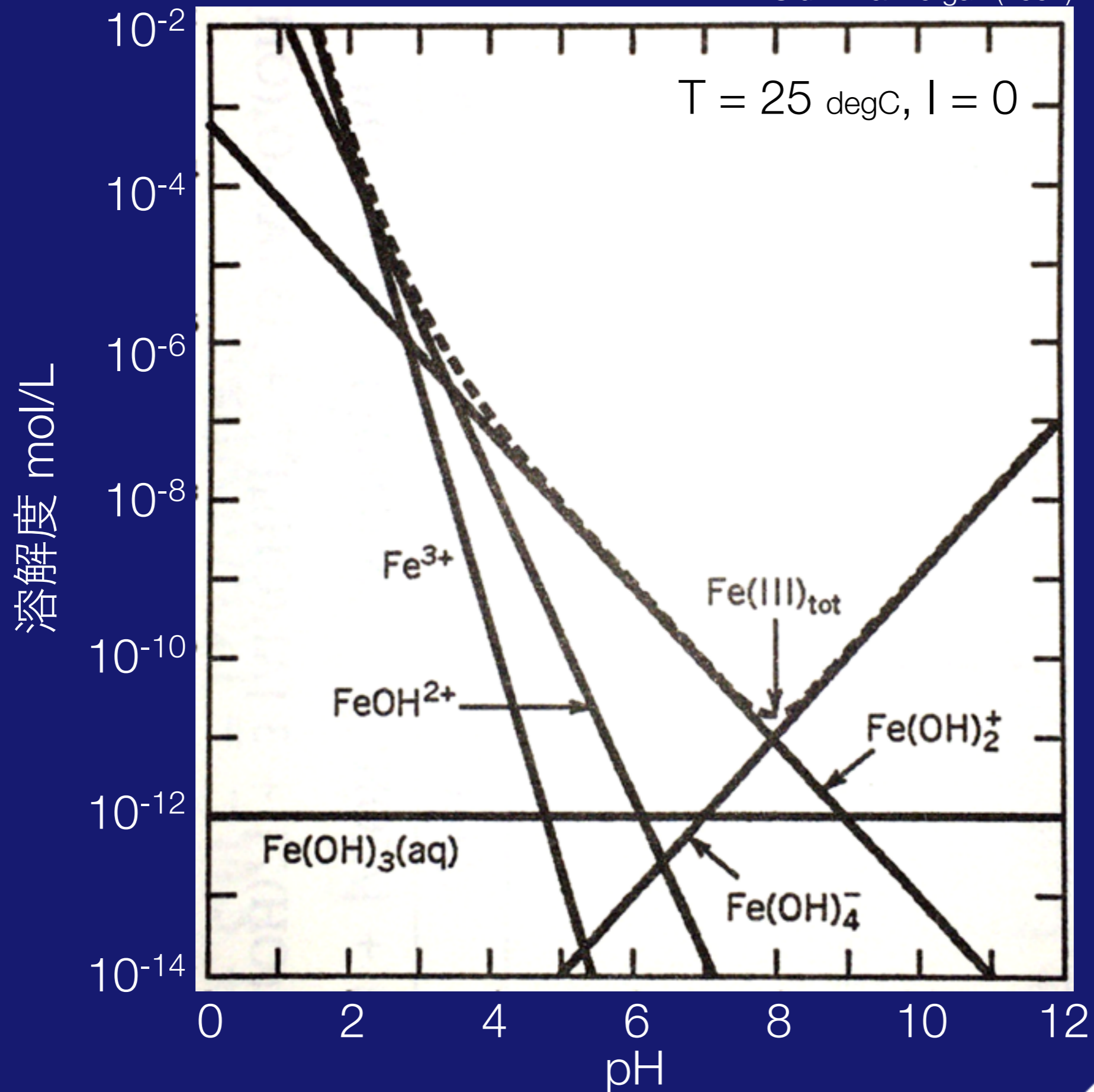


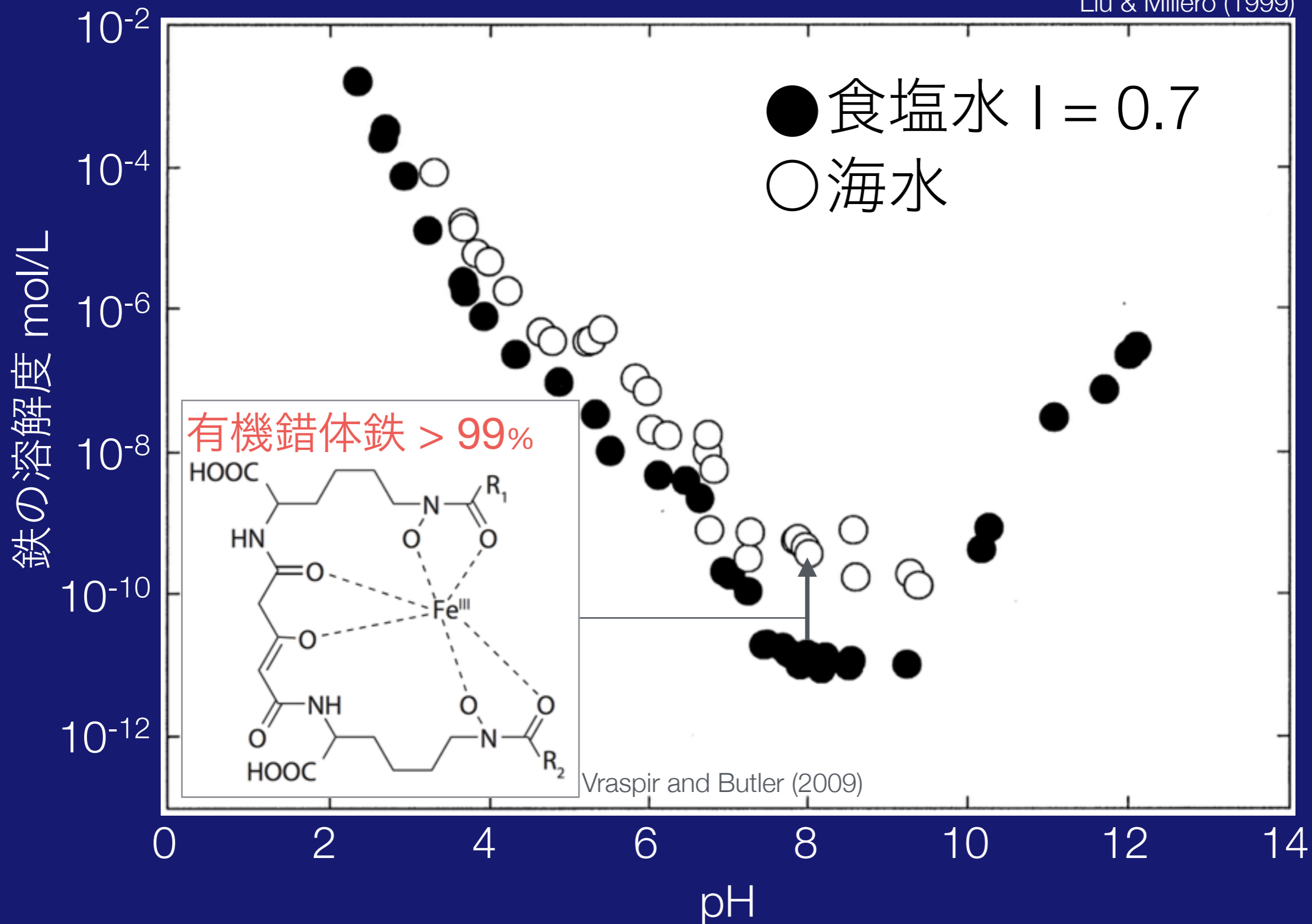
Moore et al. (2013)





Clarke & Washington (1924)







# まとめ

- 鉄は生元素の一つ，地殻中に豊富に存在
- 海水における無機態の鉄の溶解度は極めて低く  $\sim 10^{-11}$  M，除去されやすい
- 一部の溶存有機物と錯体を形成することで安定化し，海水中の溶存鉄濃度は  $\sim 10^{-9}$  M

## 2. 溶存鉄濃度の観測データの蓄積 と海洋鉄循環モデルの発展



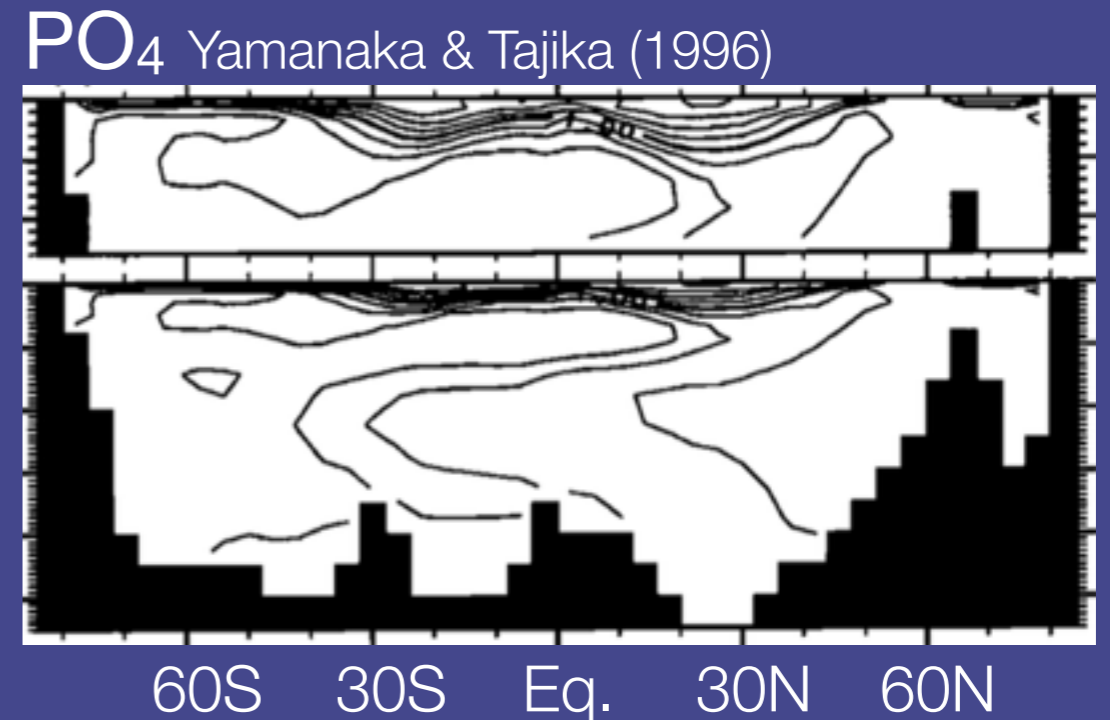
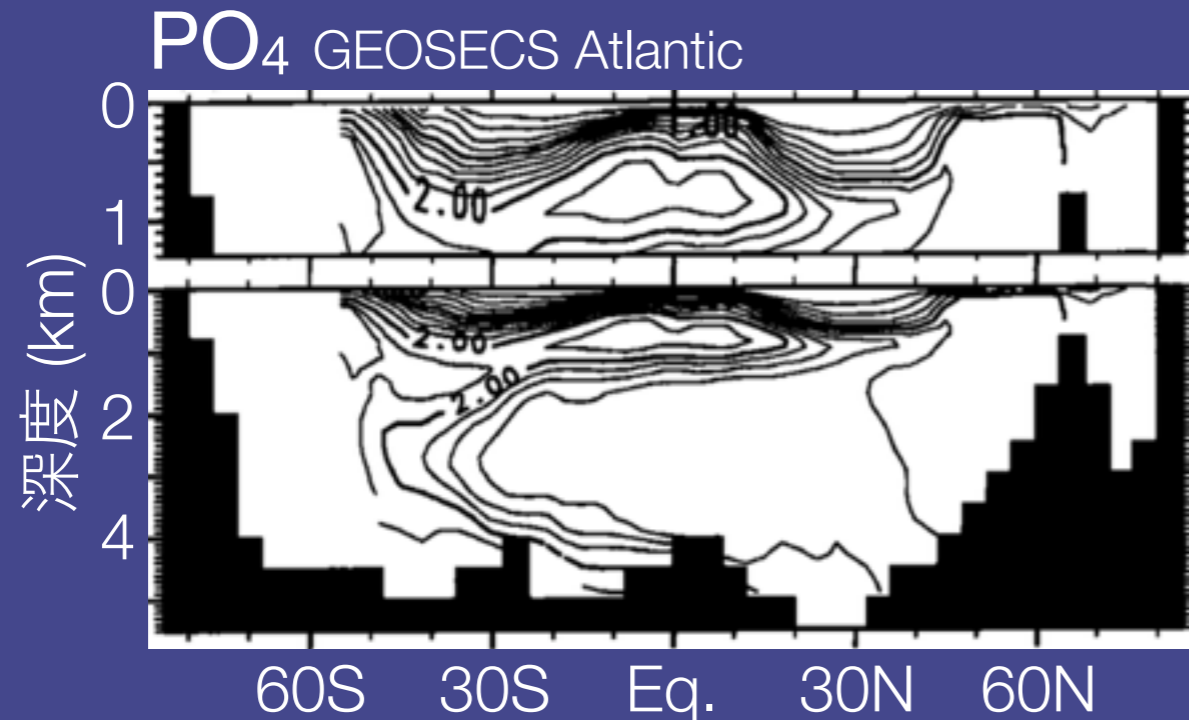
# 海水中の物質の濃度の計算方法

$$\frac{\partial C}{\partial t} = \underbrace{\text{PHY}(C)}_{\text{物理過程による変化}} + \underbrace{\text{BGC}(C)}_{\text{生物化学過程による変化}}$$

ある物質の濃度Cの時間変化

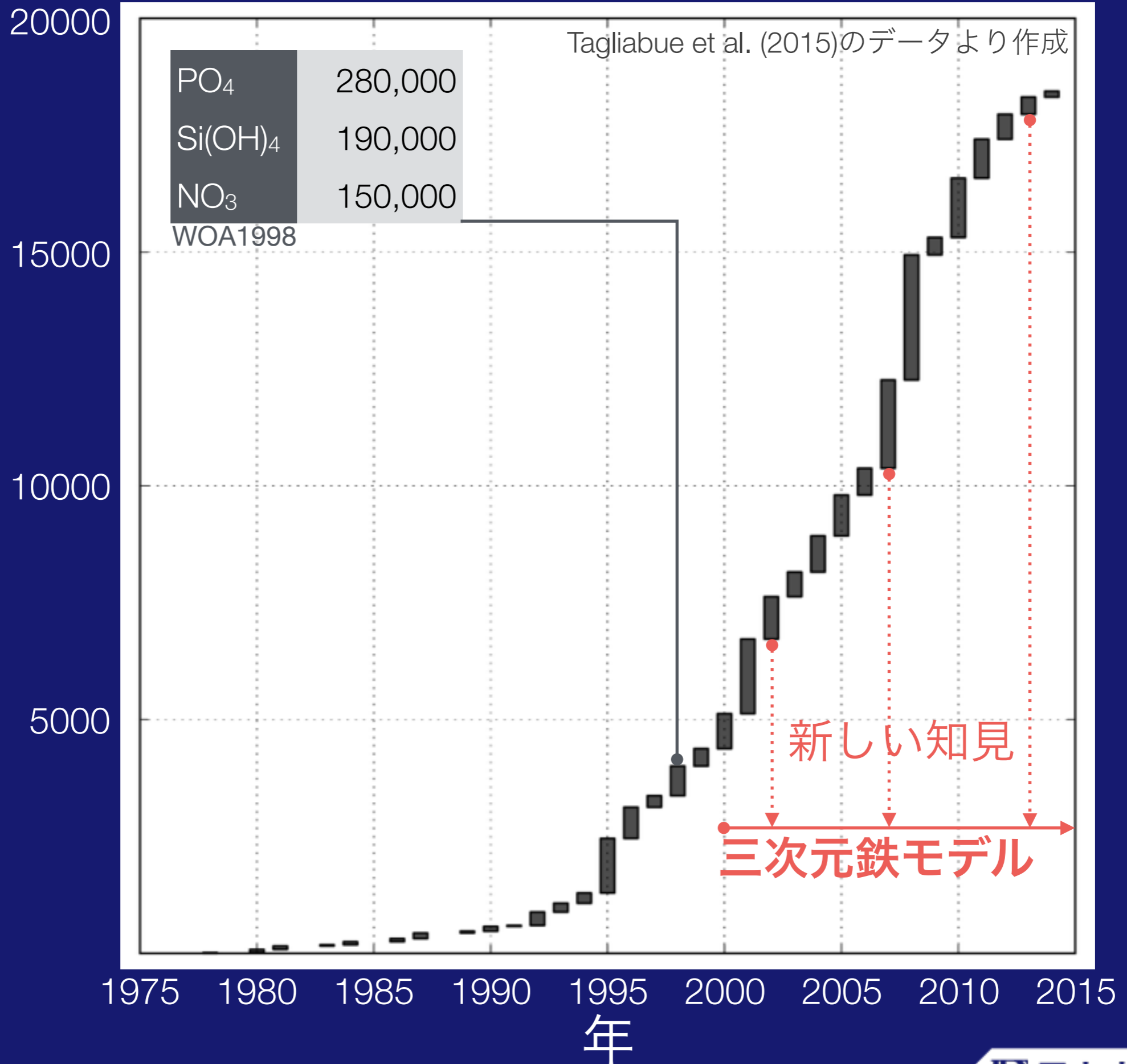
物質循環モデルの開発は  
この項をどのような式で  
表すか考える

# 観測データからBGC項を考える



$$\text{BGC}_{\text{surf}} = -rL [\text{PO}_4], \quad \text{BGC}_{\text{deep}} = -EP \frac{d}{dz} \left( \frac{z}{100m} \right)^a$$

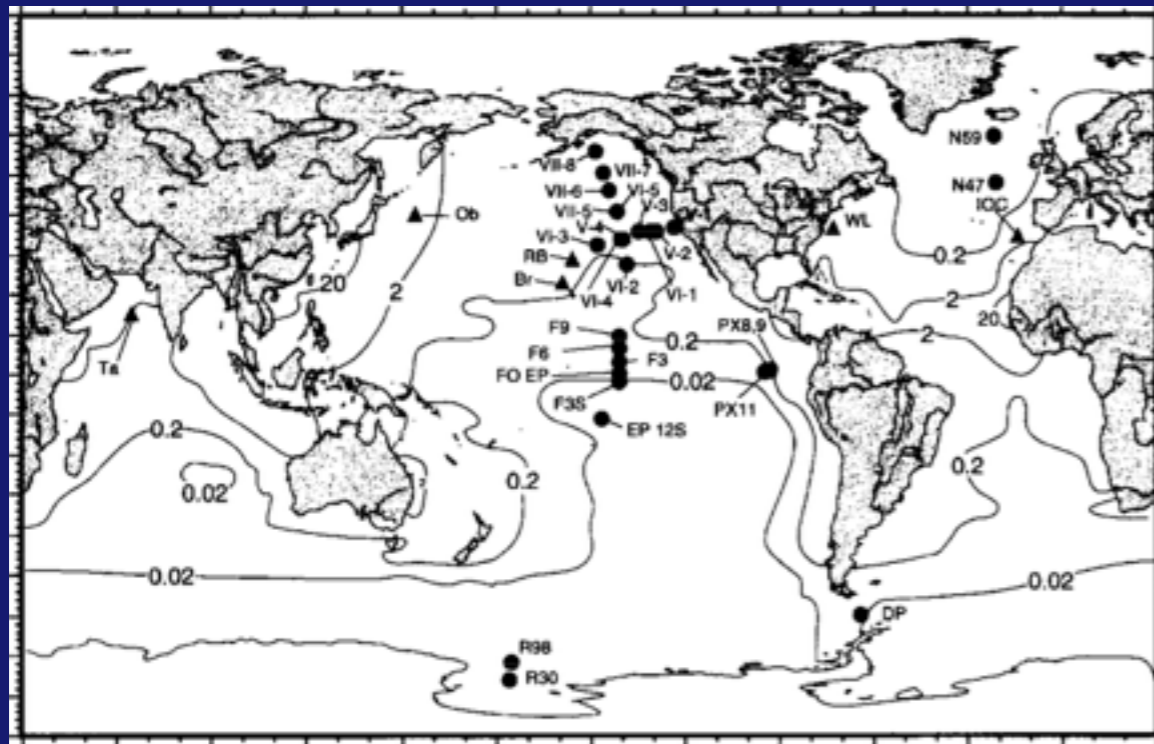
観測データ数



# 第1世代のモデル

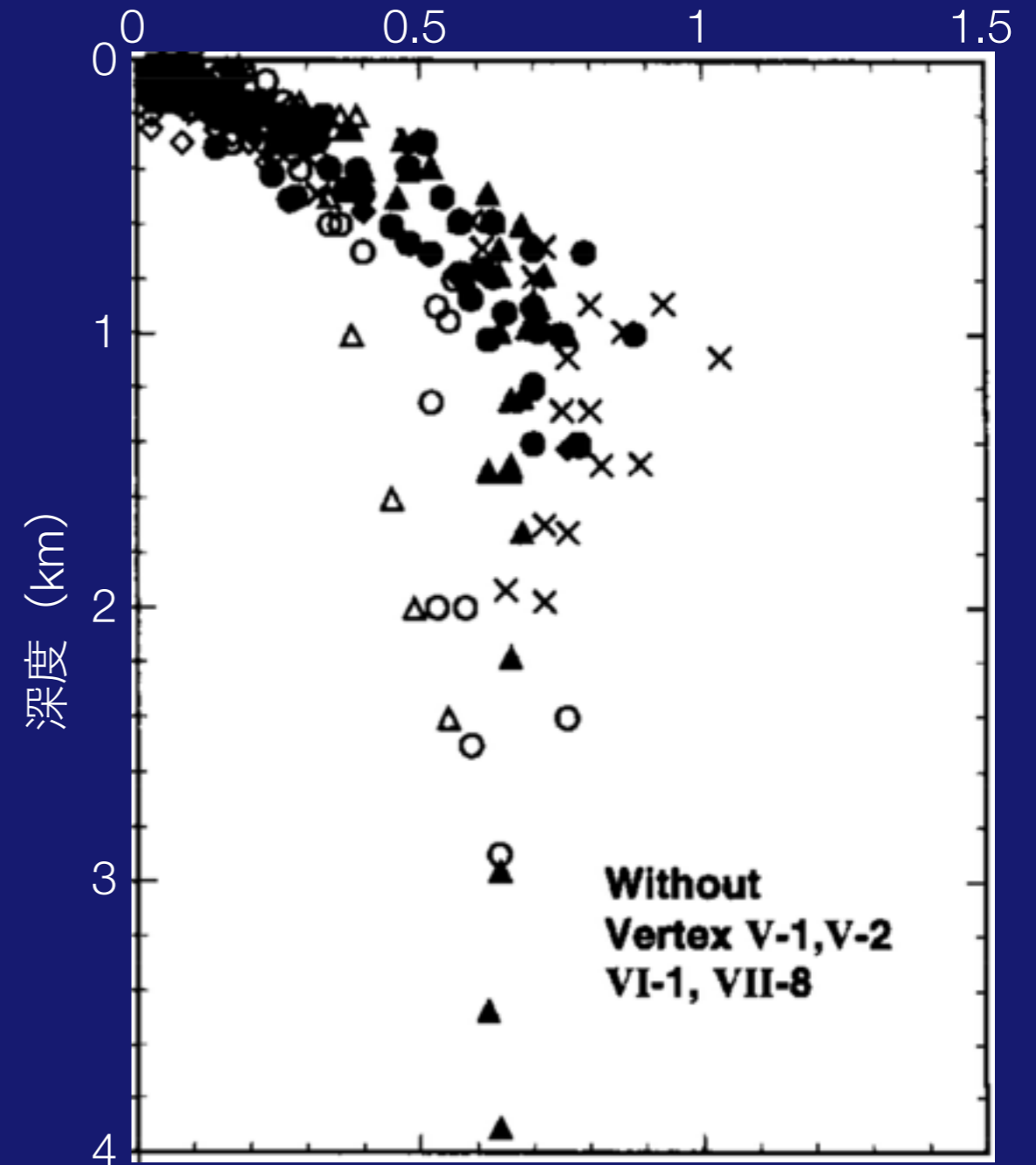
Archer & Johnson (2000)

溶存鉄濃度 (nmol kg<sup>-1</sup>)



Johnson et al. (1997)

- Data from Moss landing lab.
  - ▲ Data from other groups
- 等値線：風成塵フラックス  
(Duce & Tindale, 1991)



- |   |            |   |                |
|---|------------|---|----------------|
| x | Vertex V   | ◇ | EqPac          |
| ● | Vertex VI  | ○ | North Atlantic |
| ▲ | Vertex VII | ◆ | Drake Passage  |
| □ | Ross Sea   | ■ | PlumEx         |
| △ | FeLine     |   |                |

溶存鉄 (Fe<sub>T</sub>)

風成塵  
↓

有機錯体鉄  
Fe<sub>L</sub>

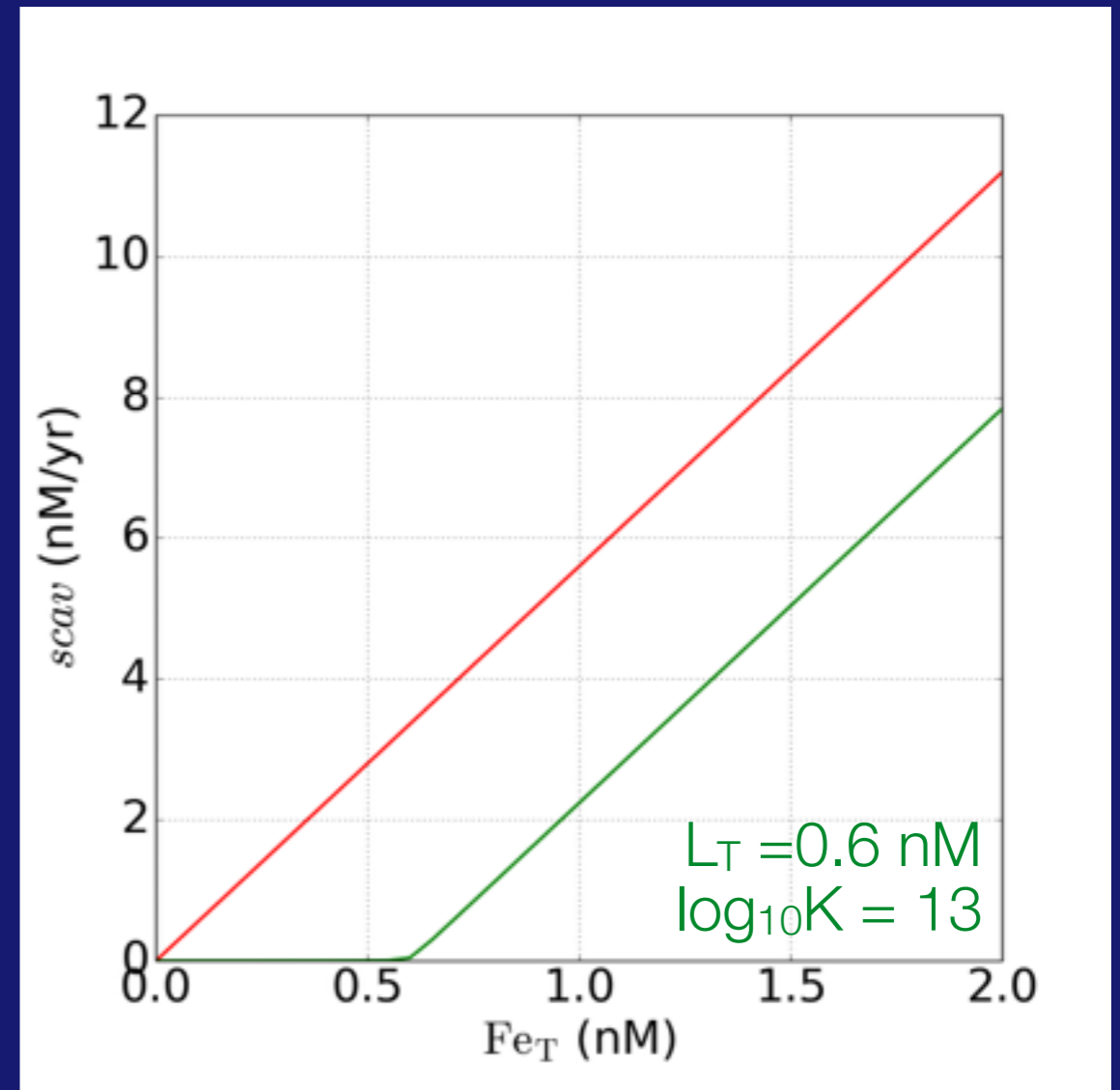
フリー鉄  
Fe'

鉄の除去項

$$scav = -kFe_T$$

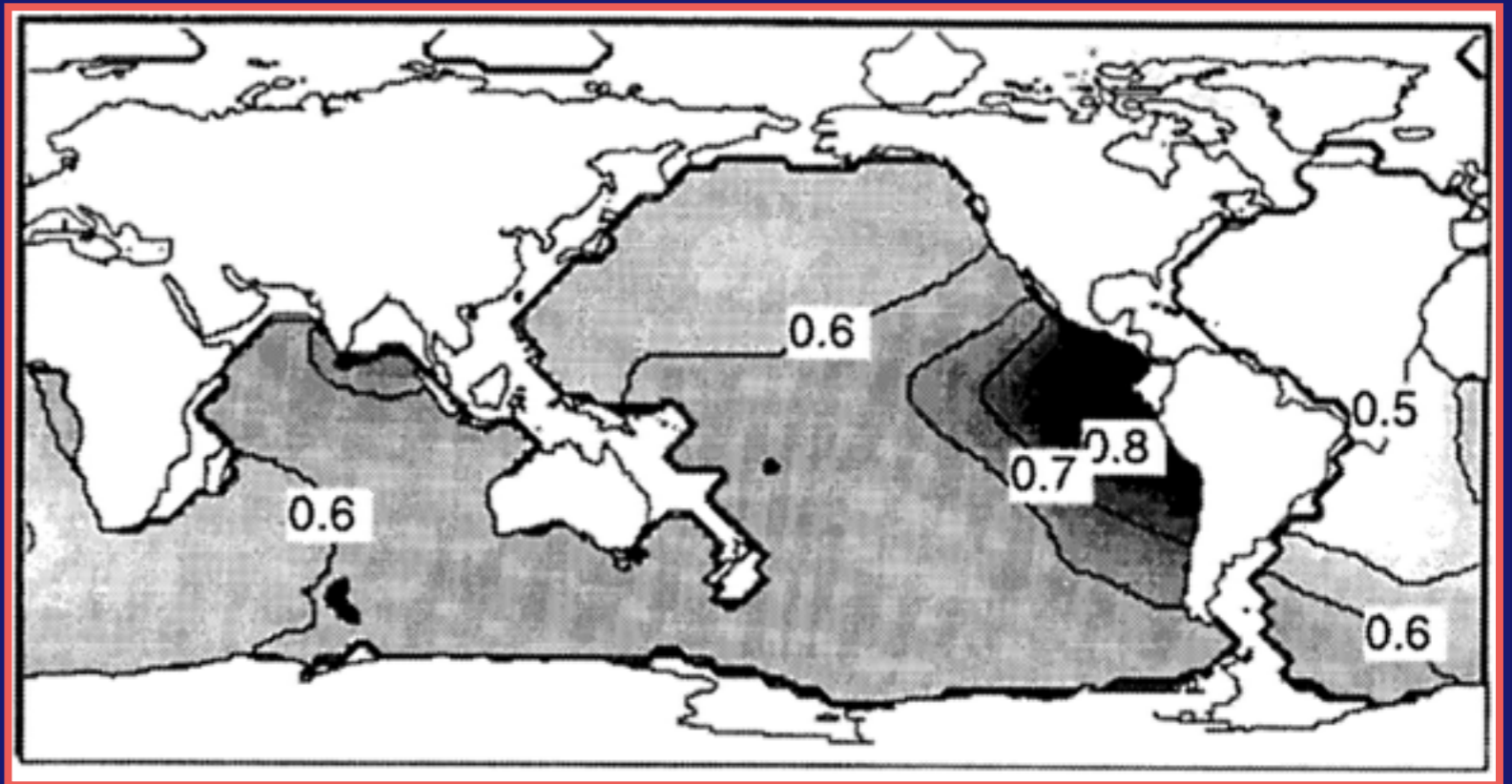
$$scav = -kFe'$$

Archer and Johnson (2000)

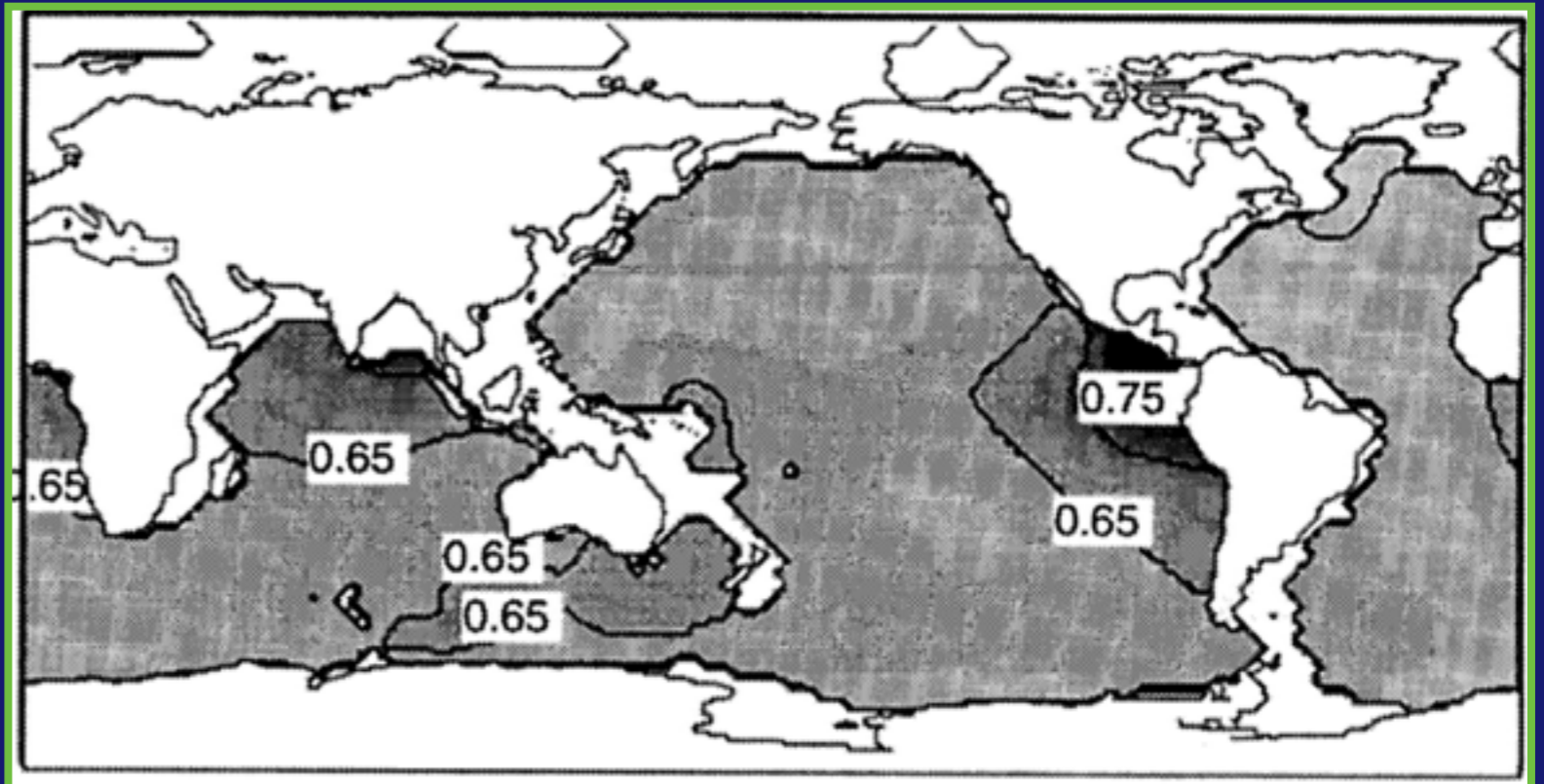




$$scav = -kFe_T$$



$$scav = -kFe'$$



Archer & Johnson (2000)

# 第1世代

## 観測

風成塵が主な鉄の起源

栄養塩型で深層が全球一様 0.6 nM

## モデル

風成塵が鉄の起源

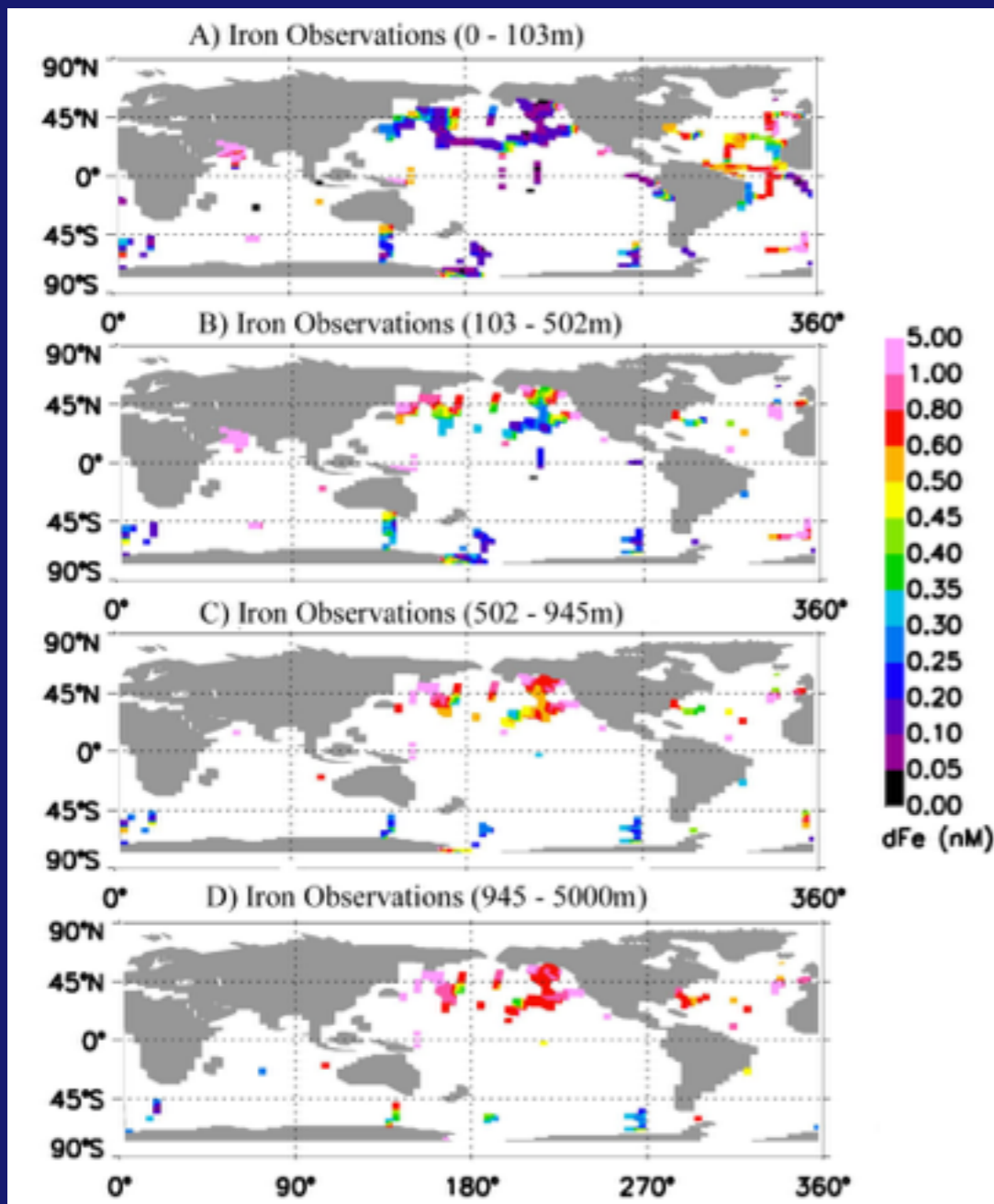
有機配位子の濃度は全球一様と分布

$L = 0.6 \text{ nM}$ ,  $\log_{10} K \sim 13$

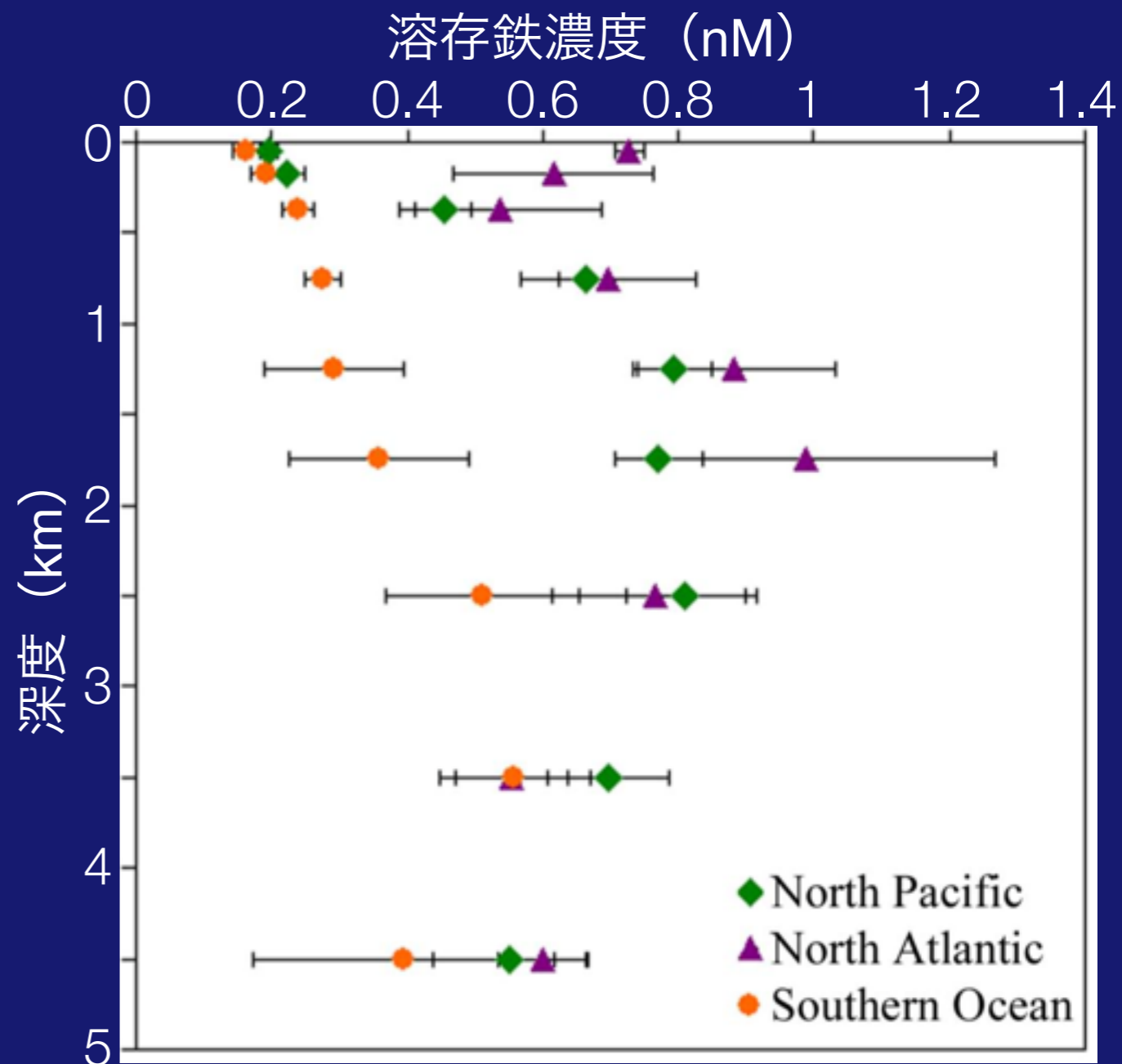


# 第2世代のモデル

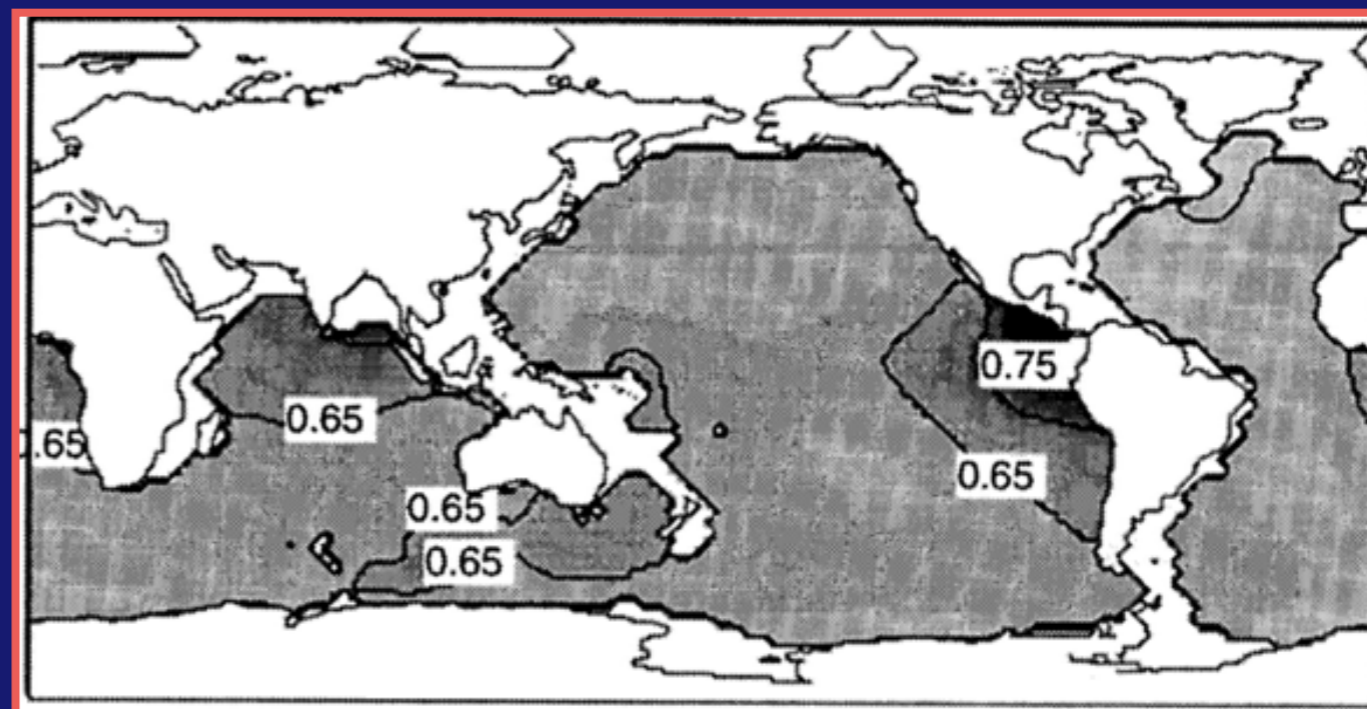
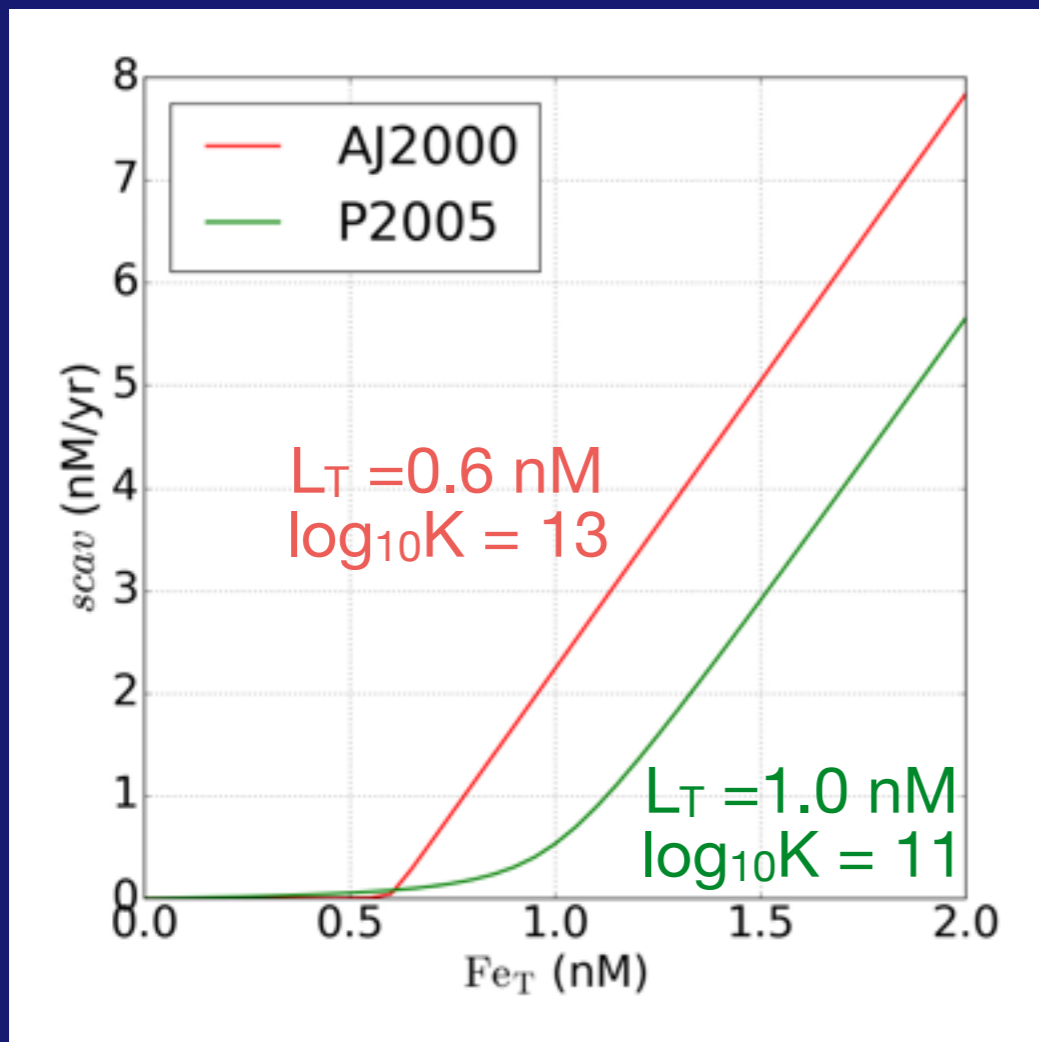
Moore et al. (2004), Parekh et al. (2005), Aumont et al. (2006),  
Moore et al. (2008), Misumi et al. (2011)



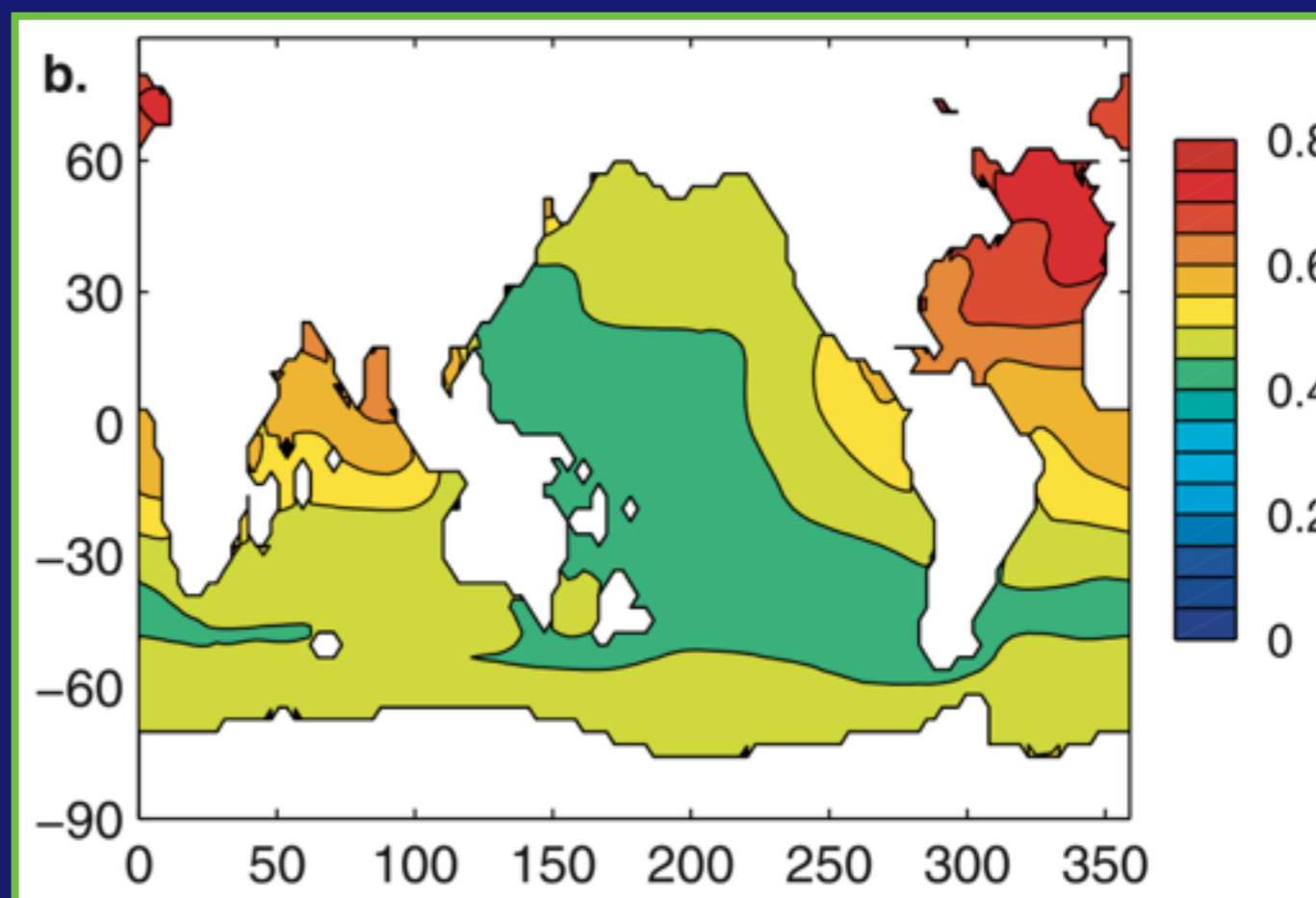
Moore & Braucher (2008)



Moore & Braucher (2008)

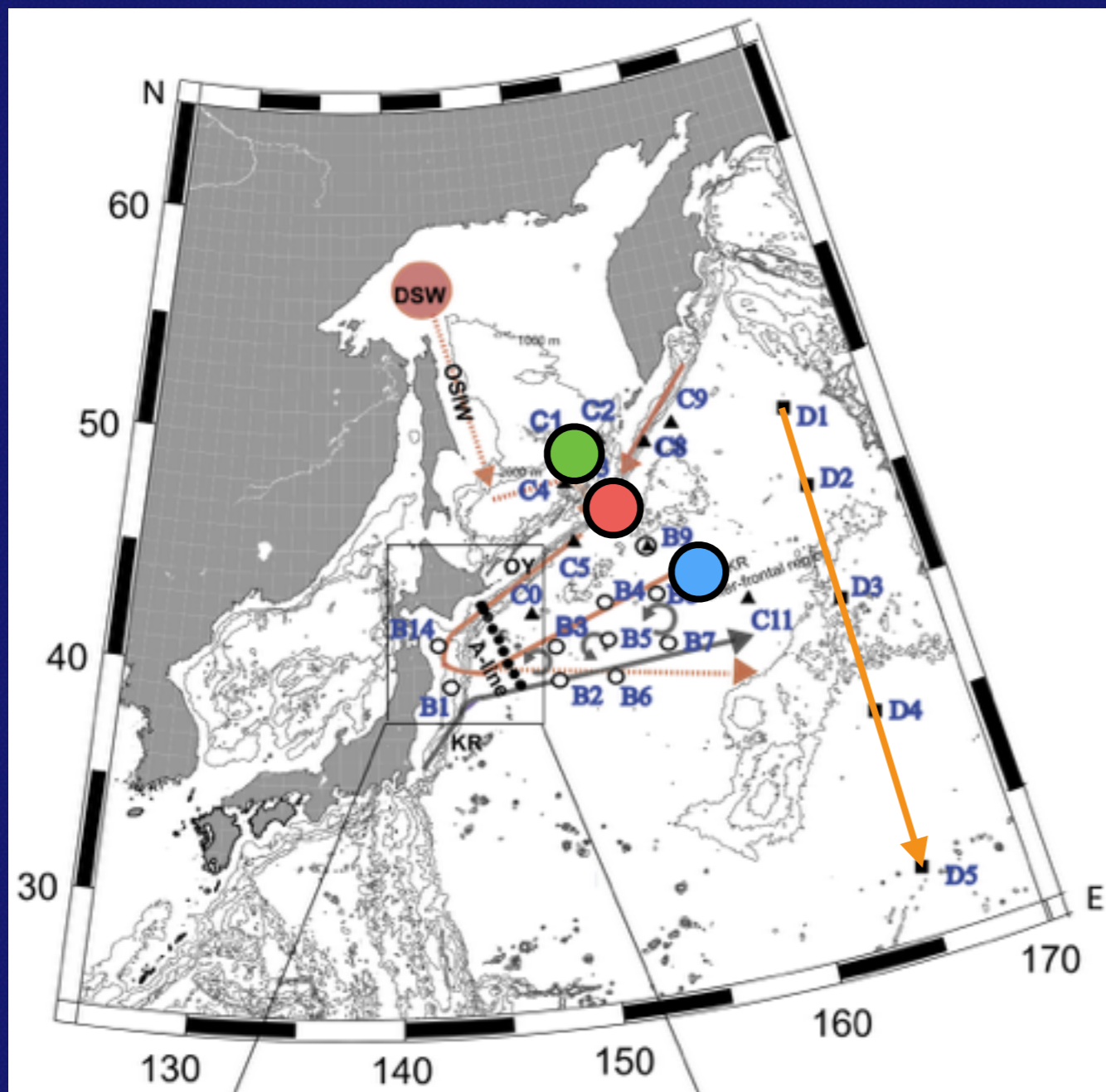


Archer & Johnson (2000)

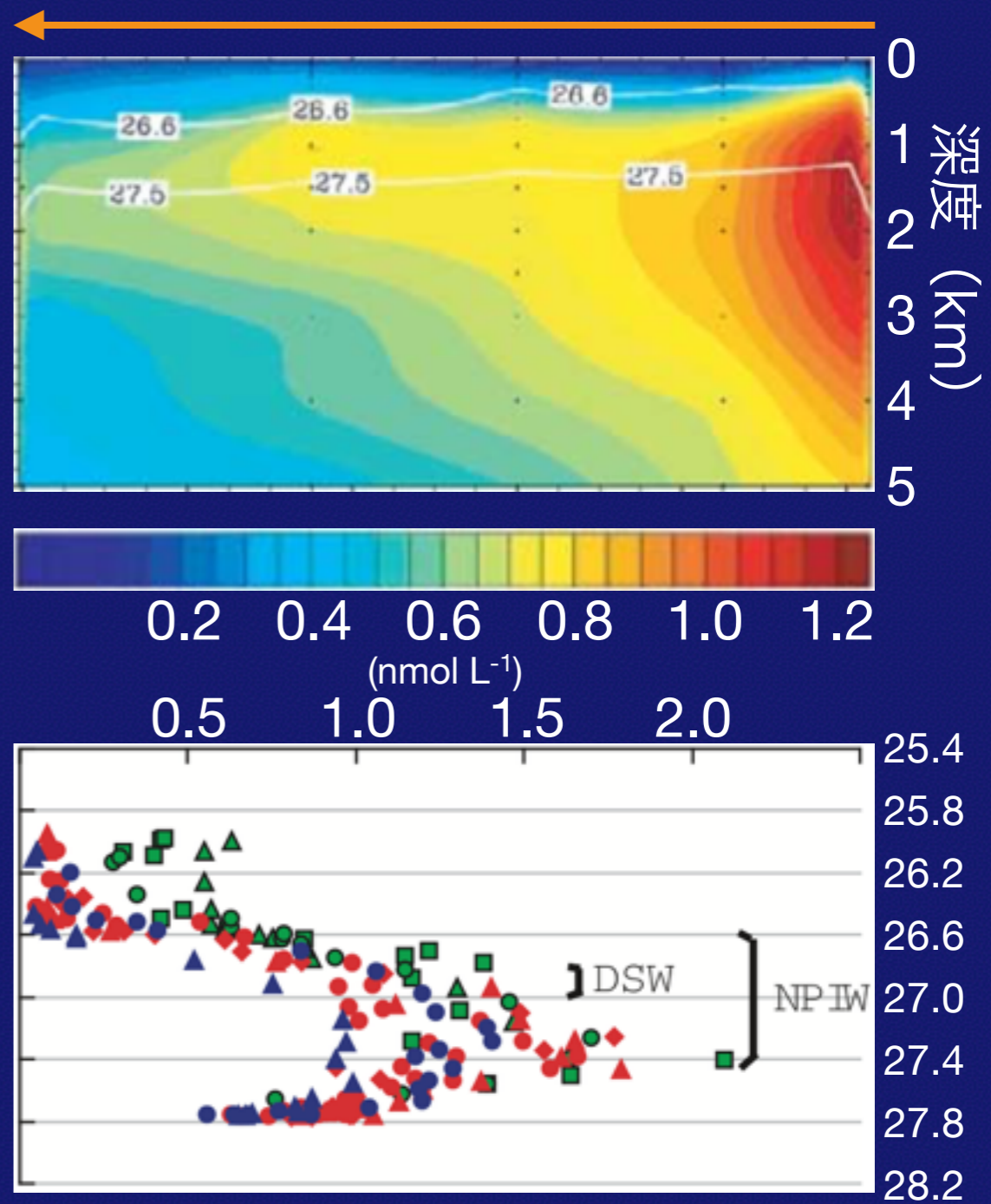


Parekh et al. (2005)





Nishioka et al. (2007)



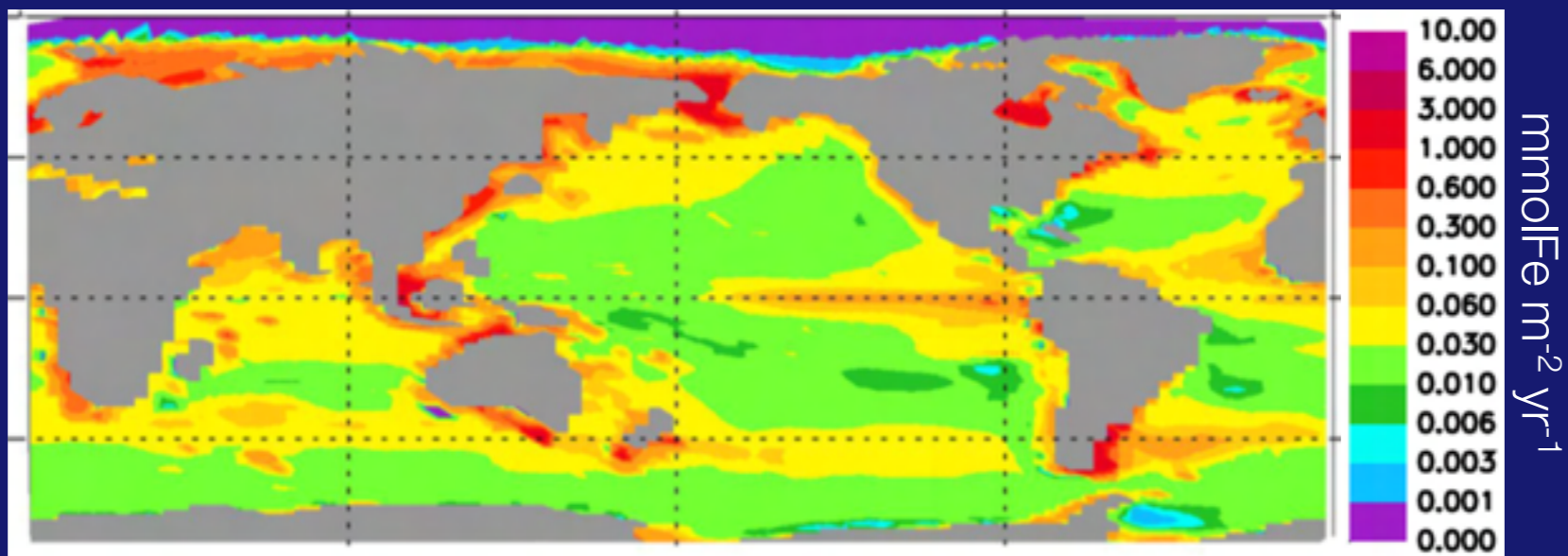
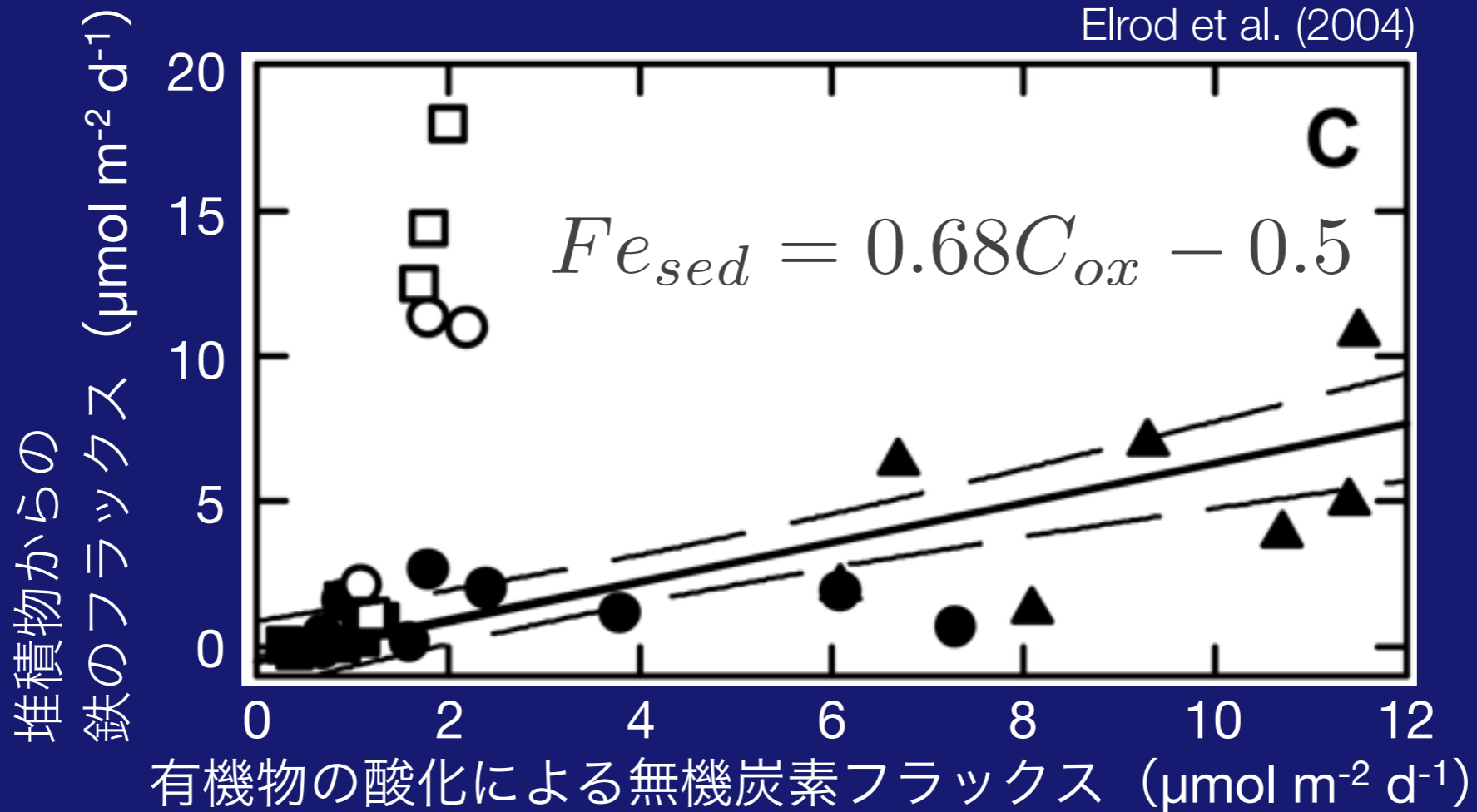
# 海洋環境における有機物の段階的酸化分解

|   | $\Delta \text{Alk}/\Delta \text{C}$<br>(eq/mol) | $\Delta G^\circ$<br>(kJ/mol C) |
|---|---|--------------------------------|
| 1 酸素還元<br>$(\text{CH}_2\text{O})_{106} (\text{NH}_3)_{16} (\text{H}_3\text{PO}_4) + 138\text{O}_2$<br>$\rightarrow 106\text{CO}_2 + 16\text{HNO}_3 + \text{H}_3\text{PO}_4 + 122\text{H}_2\text{O}$                                   | -17/106   | -480                           |
| 2 硝酸還元<br>$(\text{CH}_2\text{O})_{106} (\text{NH}_3)_{16} (\text{H}_3\text{PO}_4) + 94.4\text{HNO}_3$<br>$\rightarrow 106\text{CO}_2 + 55.2\text{N}_2 + \text{H}_3\text{PO}_4 + 177.2\text{H}_2\text{O}$                              | 93.4/106  | -450                           |
| 3 マンガン (IV) 還元<br>$(\text{CH}_2\text{O})_{106} (\text{NH}_3)_{16} (\text{H}_3\text{PO}_4) + 212\text{MnO}_2$<br>$\rightarrow 212\text{Mn}^{2+} + 106\text{CO}_3^{2-} + 212\text{OH}^- + 16\text{NH}_3 + \text{H}_3\text{PO}_4$        | 439/106   | -241                           |
| 4 鉄 (III) 還元<br>$(\text{CH}_2\text{O})_{106} (\text{NH}_3)_{16} (\text{H}_3\text{PO}_4) + 212\text{Fe}_2\text{O}_3$<br>$\rightarrow 424\text{Fe}^{2+} + 106\text{CO}_3^{2-} + 636\text{OH}^- + 16\text{NH}_3 + \text{H}_3\text{PO}_4$ | 863/106   | -150                           |
| 5 硫酸還元<br>$(\text{CH}_2\text{O})_{106} (\text{NH}_3)_{16} (\text{H}_3\text{PO}_4) + 53\text{SO}_4^{2-}$<br>$\rightarrow 53\text{H}_2\text{S} + 106\text{HCO}_3^- + 16\text{NH}_3 + \text{H}_3\text{PO}_4$                             | 121/106   | -77                            |
| 6 メタン発酵<br>$(\text{CH}_2\text{O})_{106} (\text{NH}_3)_{16} (\text{H}_3\text{PO}_4)$<br>$\rightarrow 53\text{CO}_2 + 53\text{CH}_4 + 16\text{NH}_3 + \text{H}_3\text{PO}_4$  | 15/106  | -62                            |

海と湖の化学, 宗林 & 一色 (2005)

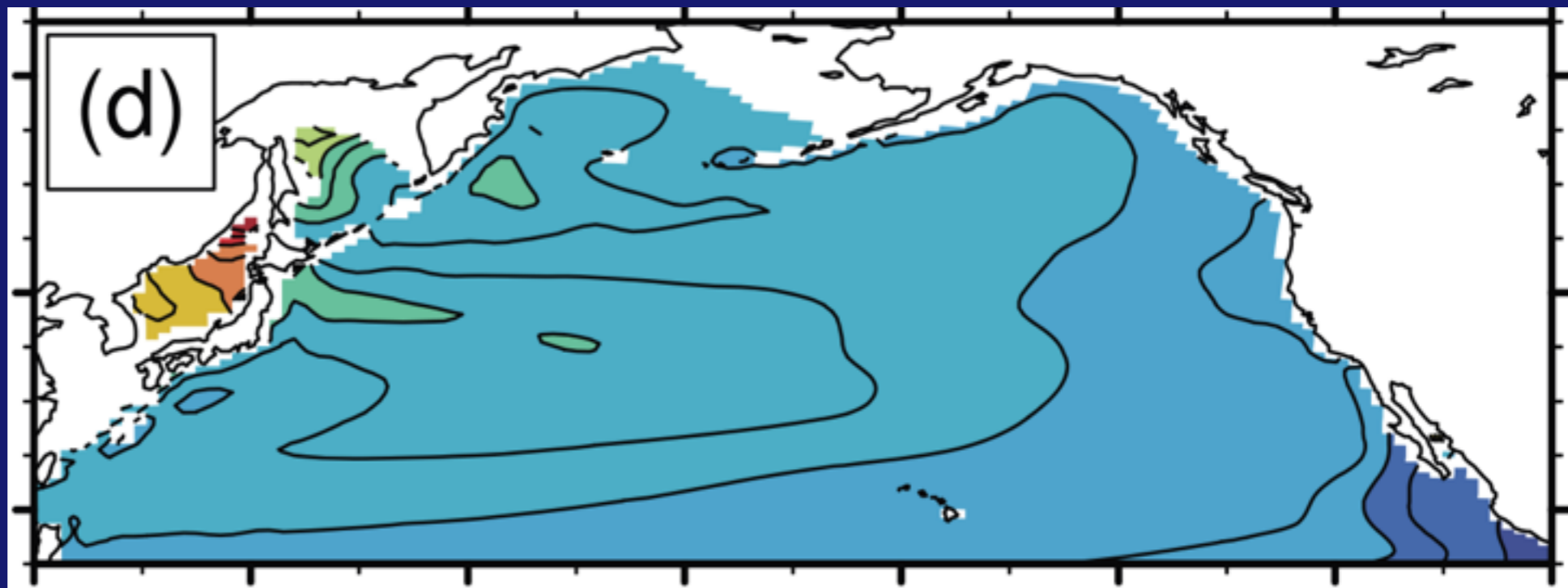


Elrod et al. (2004)

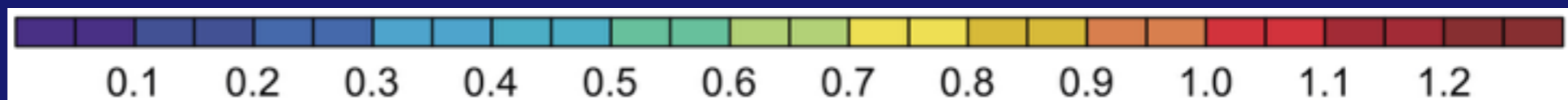
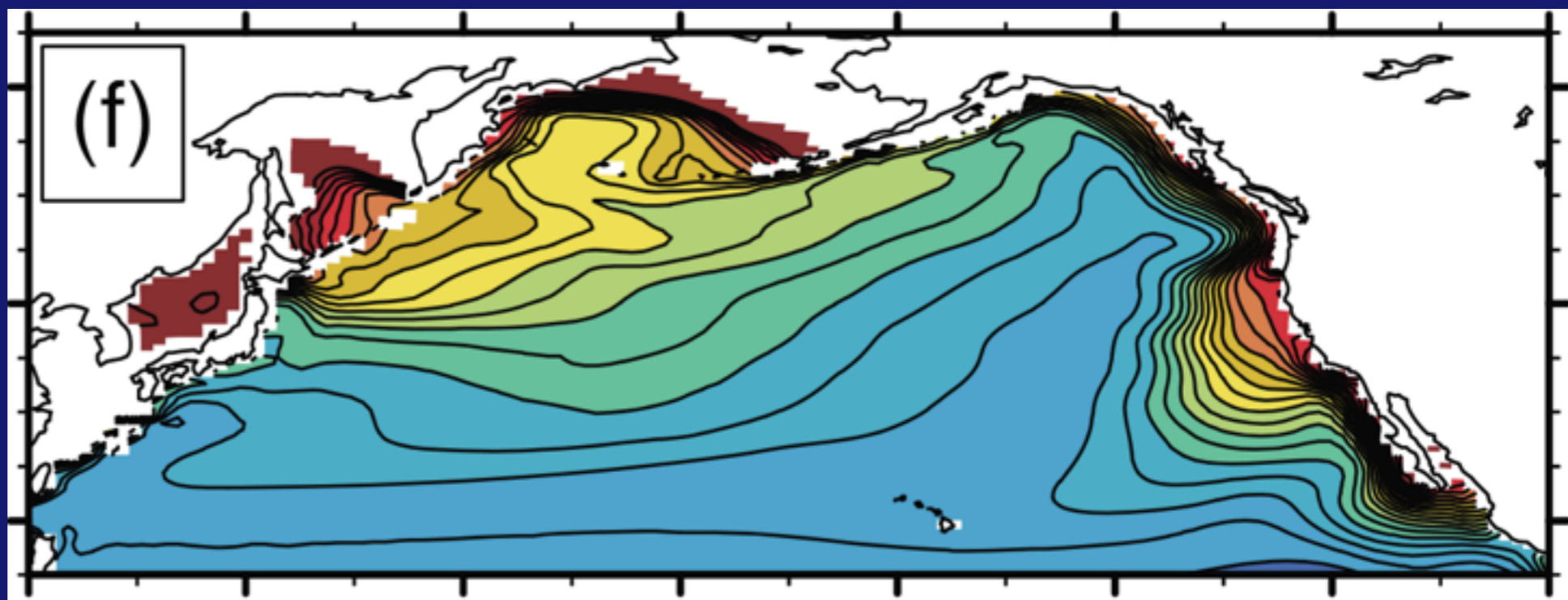


Moore & Braucher (2008)

# 風成塵のみ



# 堆積物のみ



nM

Misumi et al (2011)

# 第2世代

## 観測

風成塵+堆積物が主な鉄の起源  
海盆間の濃度勾配  
大西洋/インド洋 > 太平洋 > 南大洋

## モデル

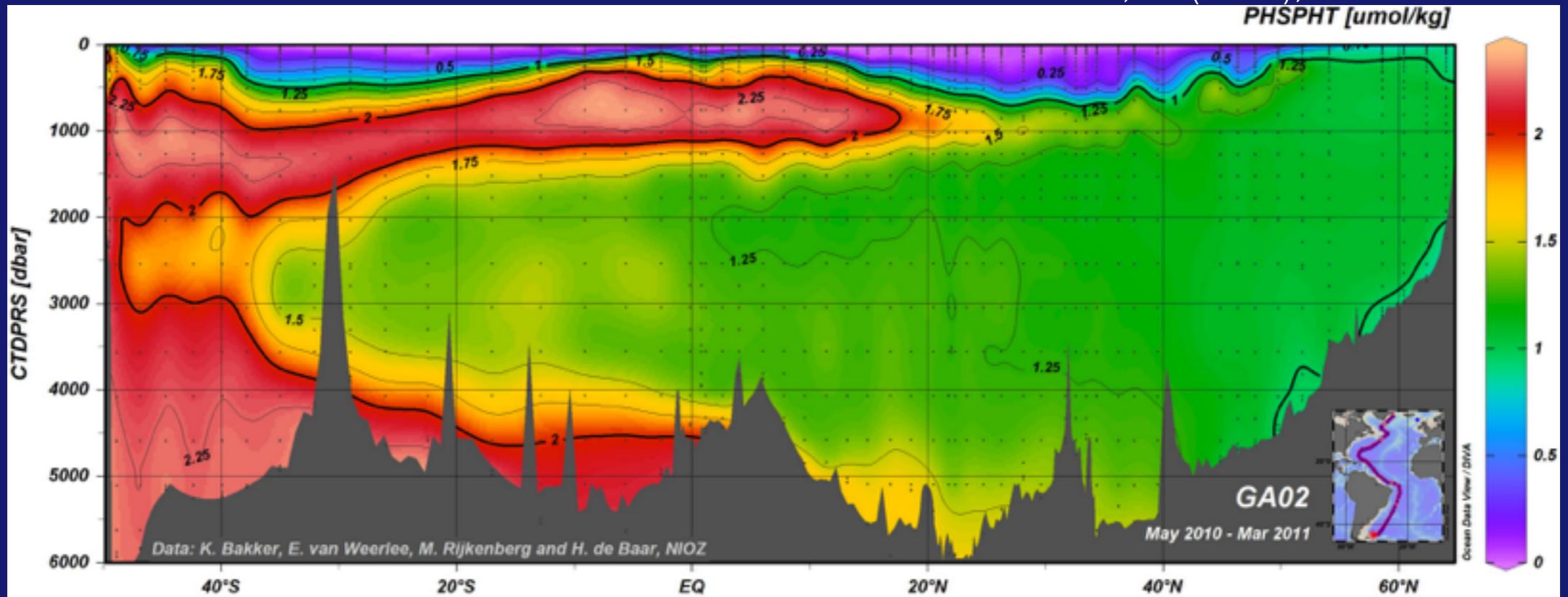
風成塵+堆積物が鉄の起源  
有機配位子の濃度は全球一様と分布  
 $L > 0.6 \text{ nM}$ ,  $\log_{10} K \sim 11$



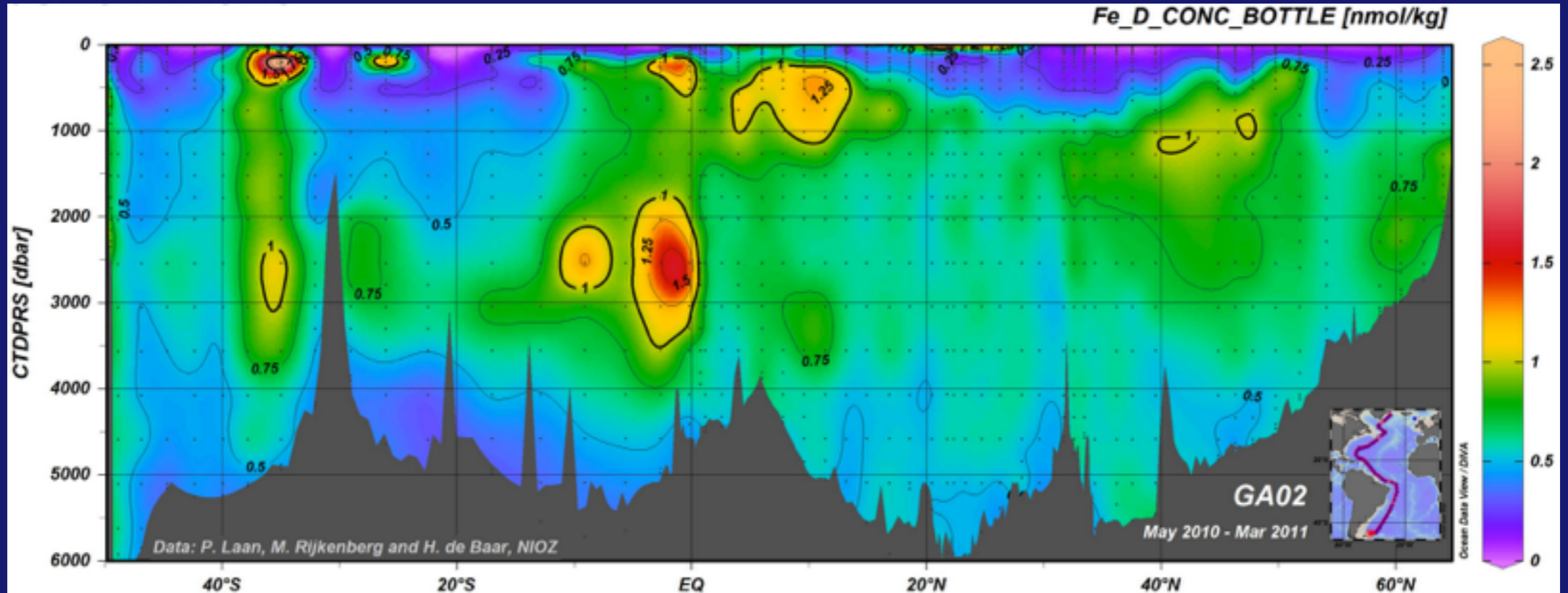
# 第2.x世代のモデル / 第3世代の観測

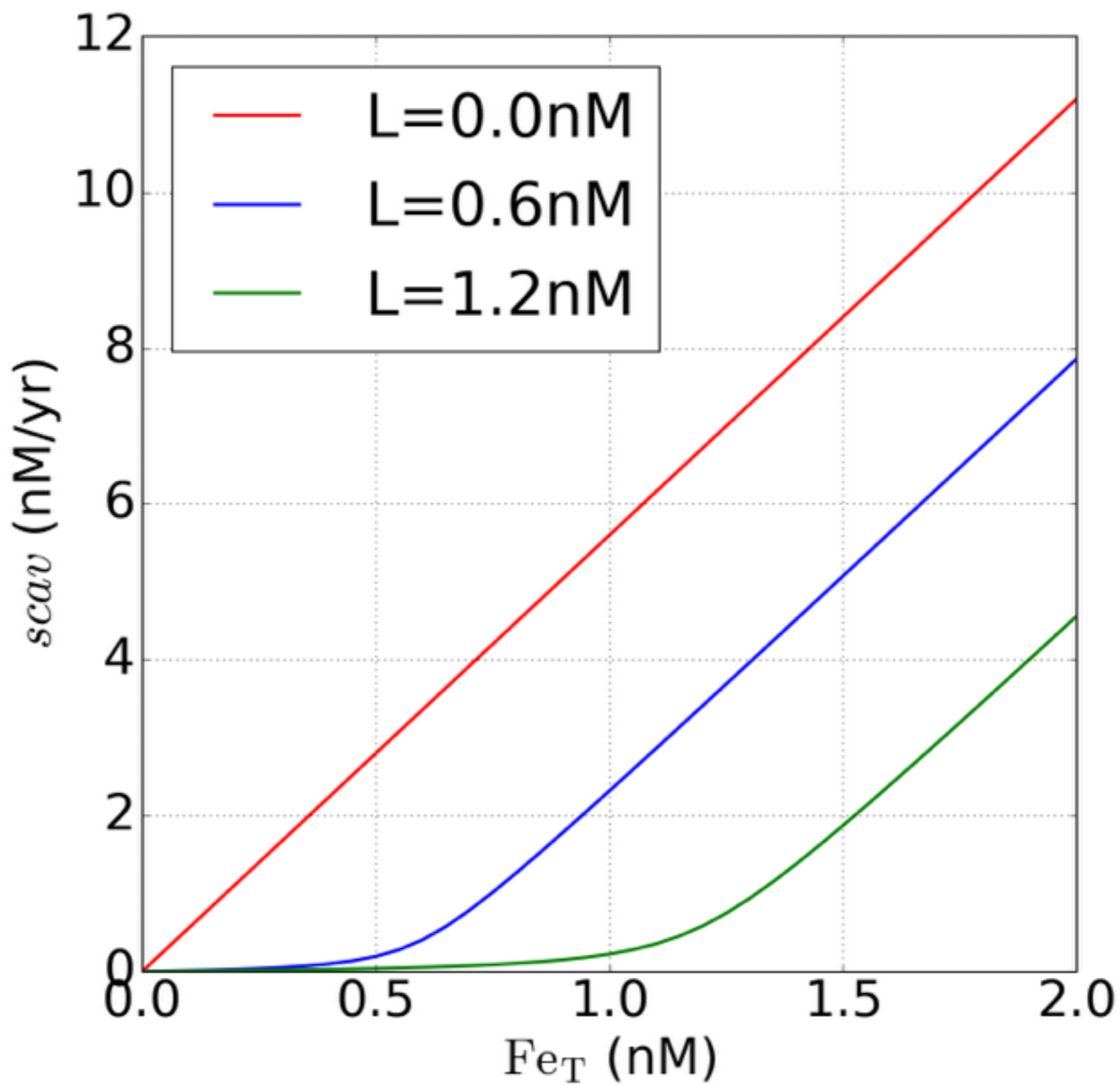
Tagliabue et al. (2010, 2014), Misumi et al. (2013),  
Völker & Tagliabue (2015)

**PO<sub>4</sub>**  
μM

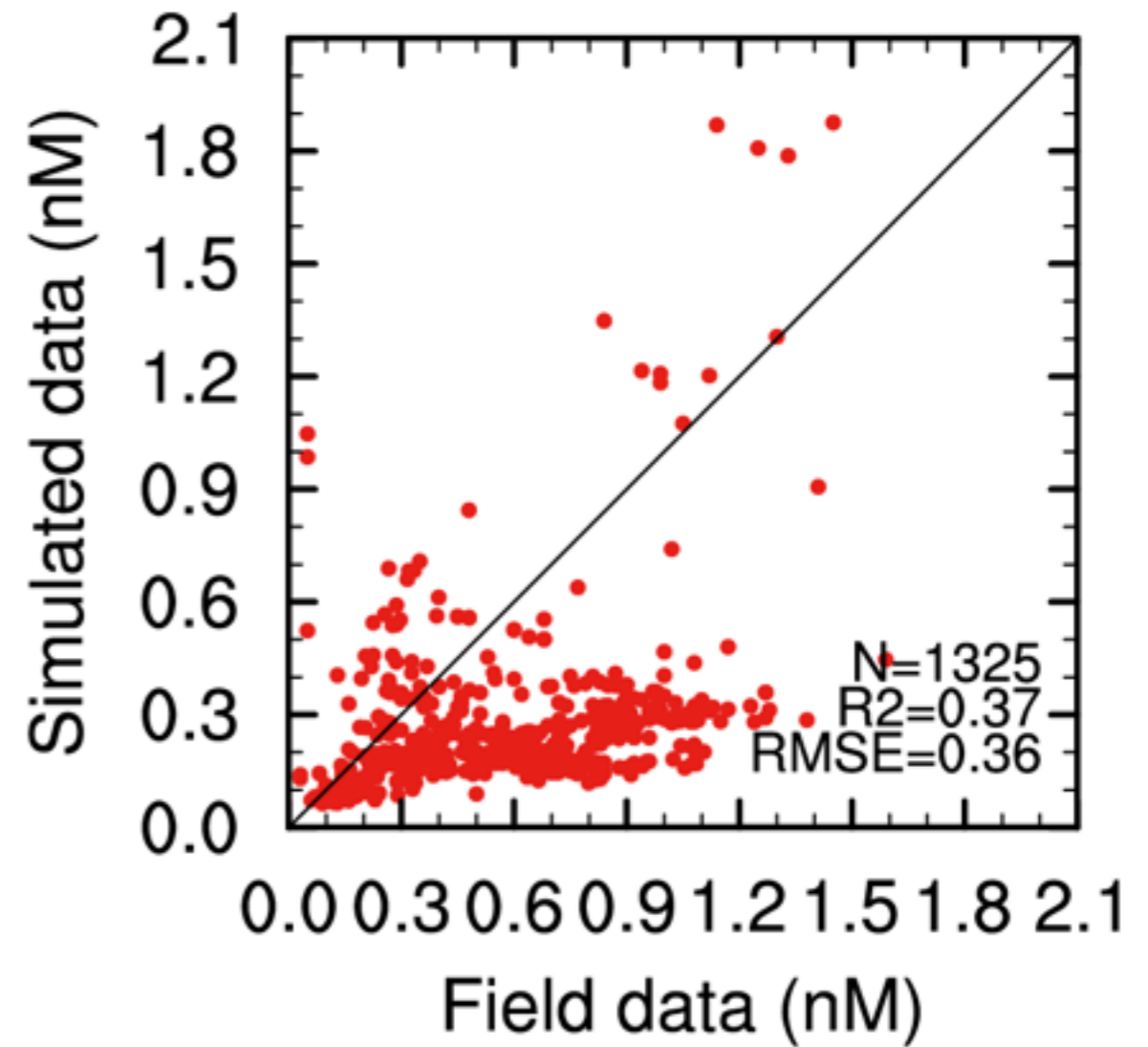
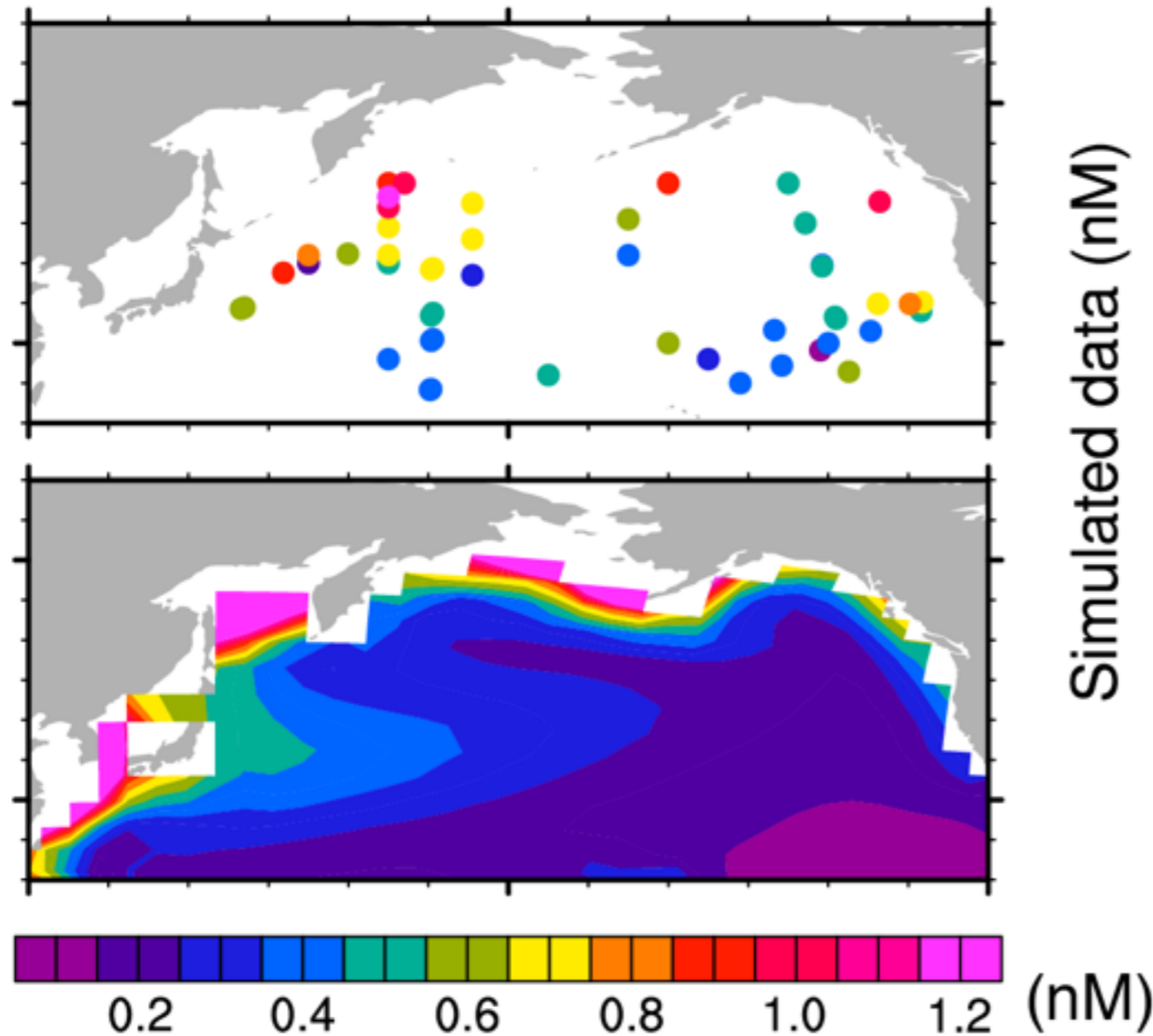


**Fe**  
nM





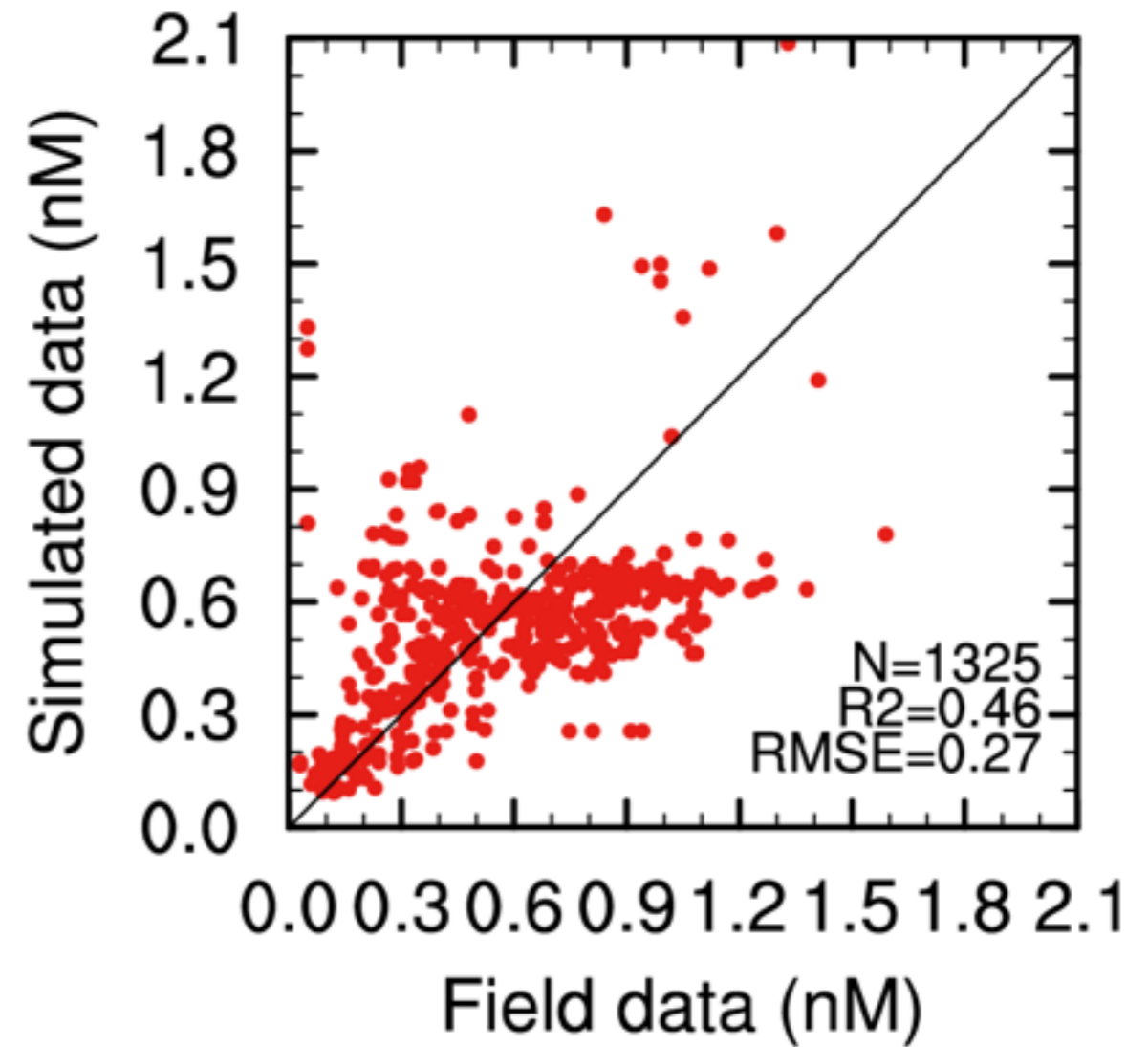
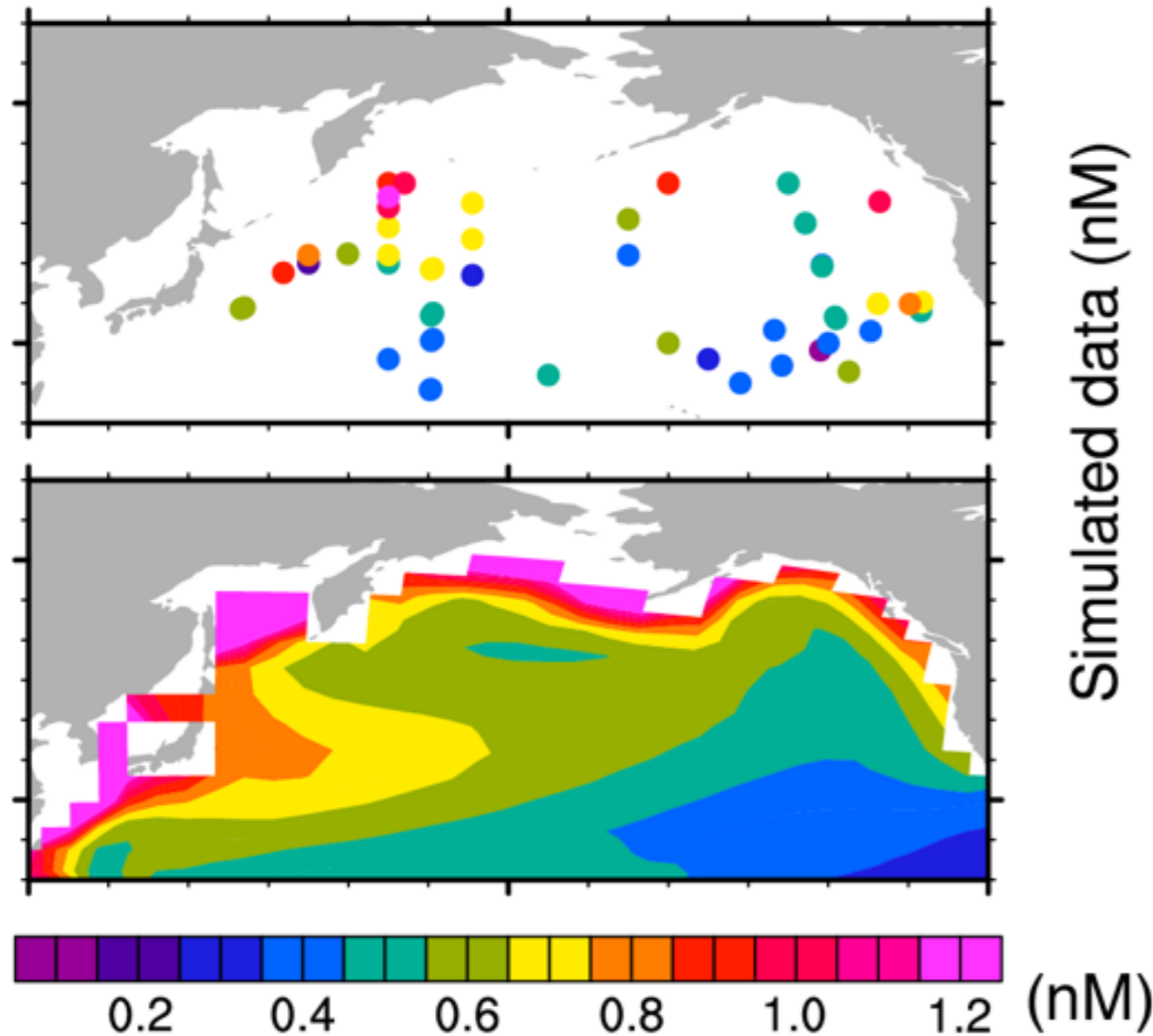
# 有機配位子の濃度 $L = 0.0$ nM



after Misumi et al. (2013)

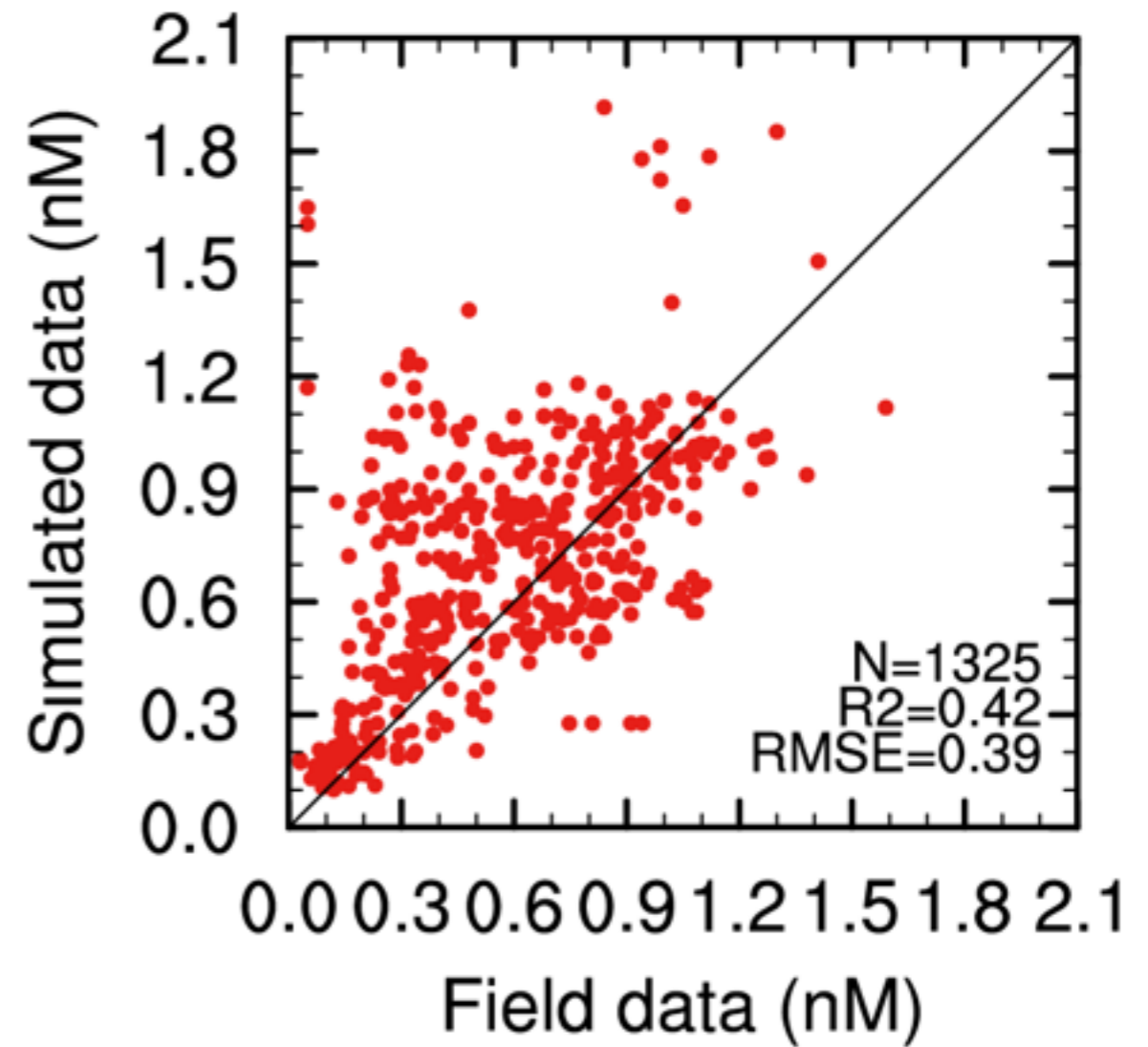
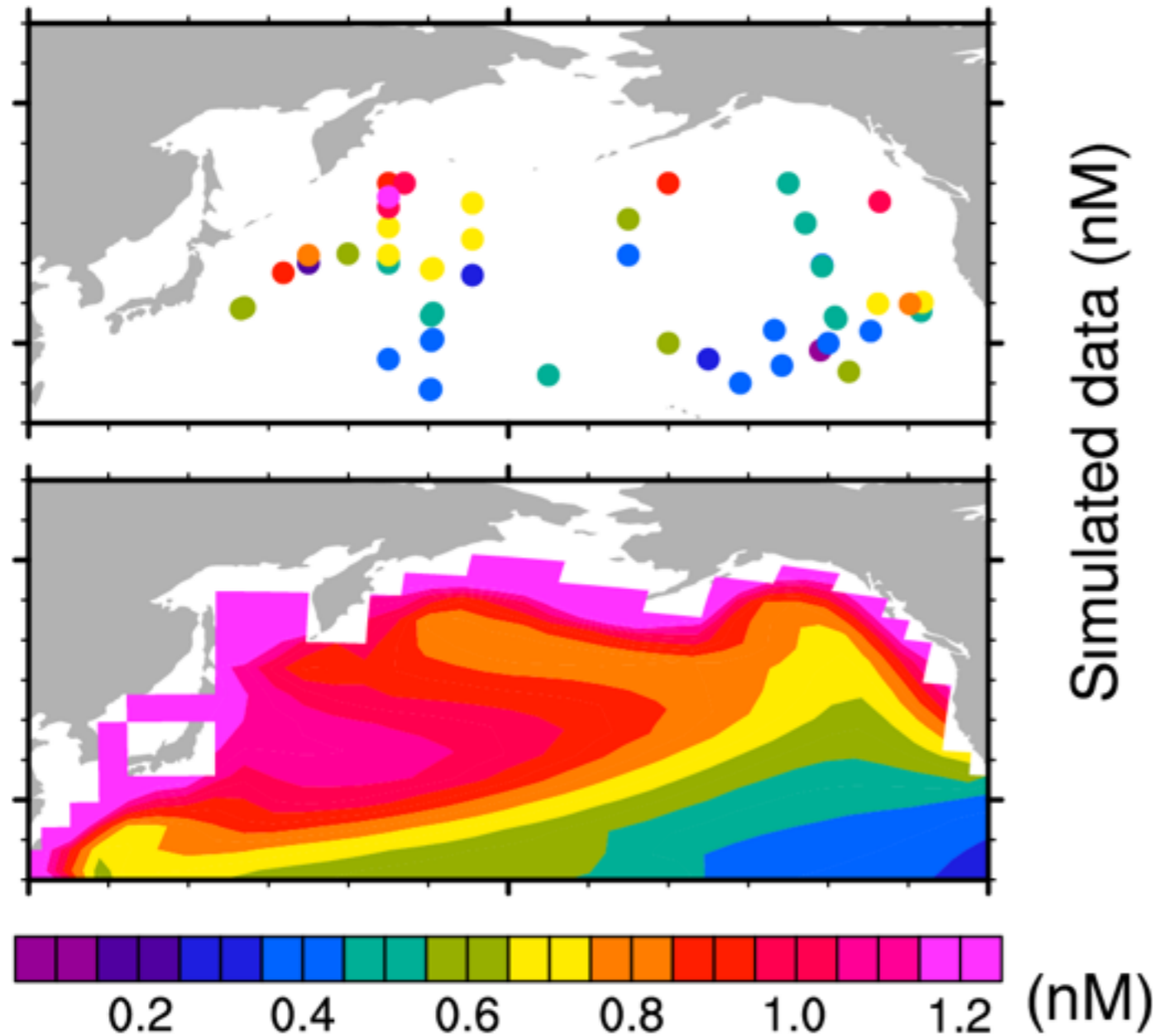


# 有機配位子の濃度 $L = 0.6$ nM



after Misumi et al. (2013)

# 有機配位子の濃度 $L = 1.2$ nM



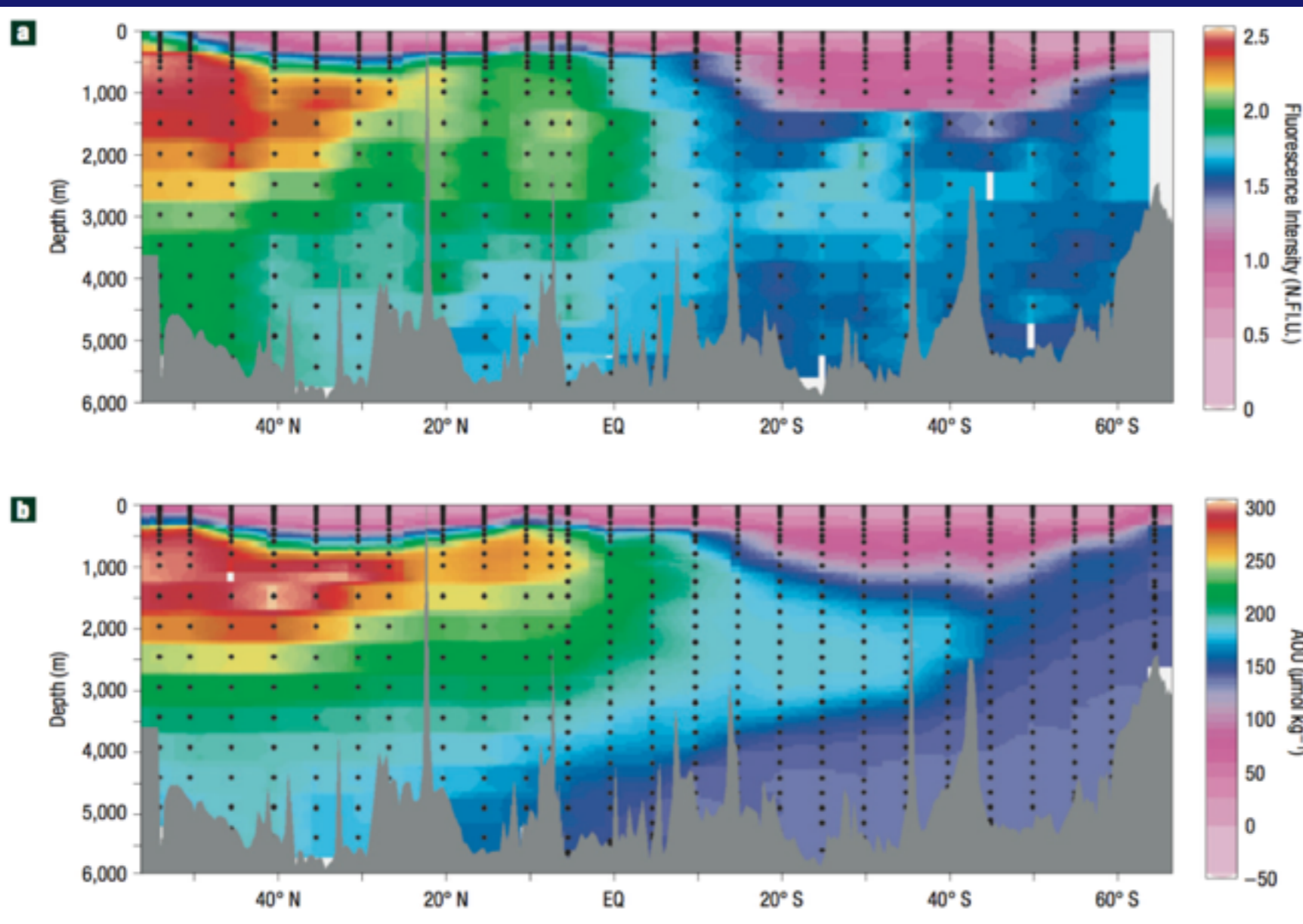
after Misumi et al. (2013)

## Evidence for geochemical control of iron by humic substances in seawater

*Luis M. Laglera*<sup>1</sup> and *Constant M. G. van den Berg*<sup>2</sup>

Department of Earth and Ocean Sciences, University of Liverpool, Liverpool L69 3GP, United Kingdom

Laglera et al. (2009)



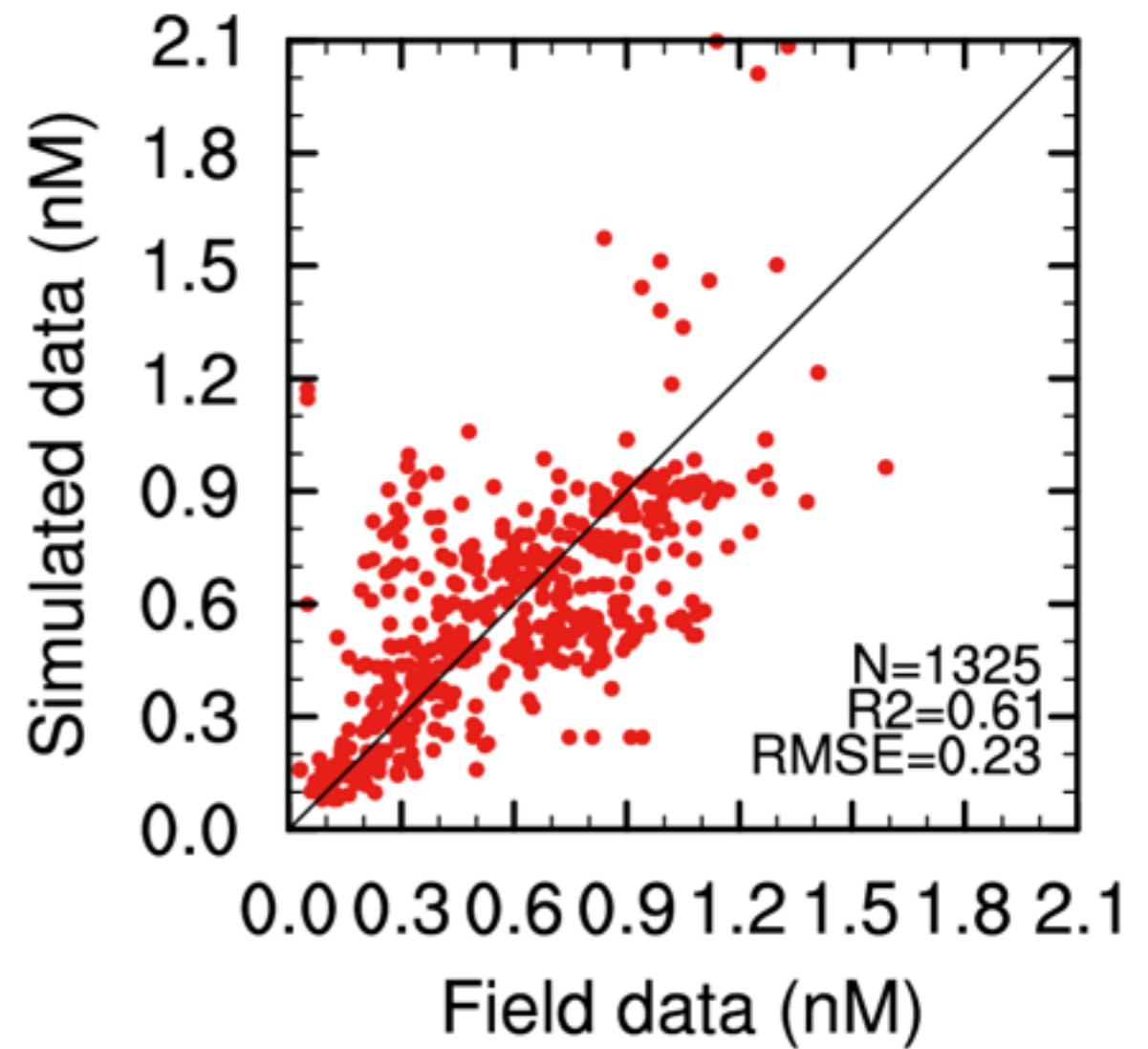
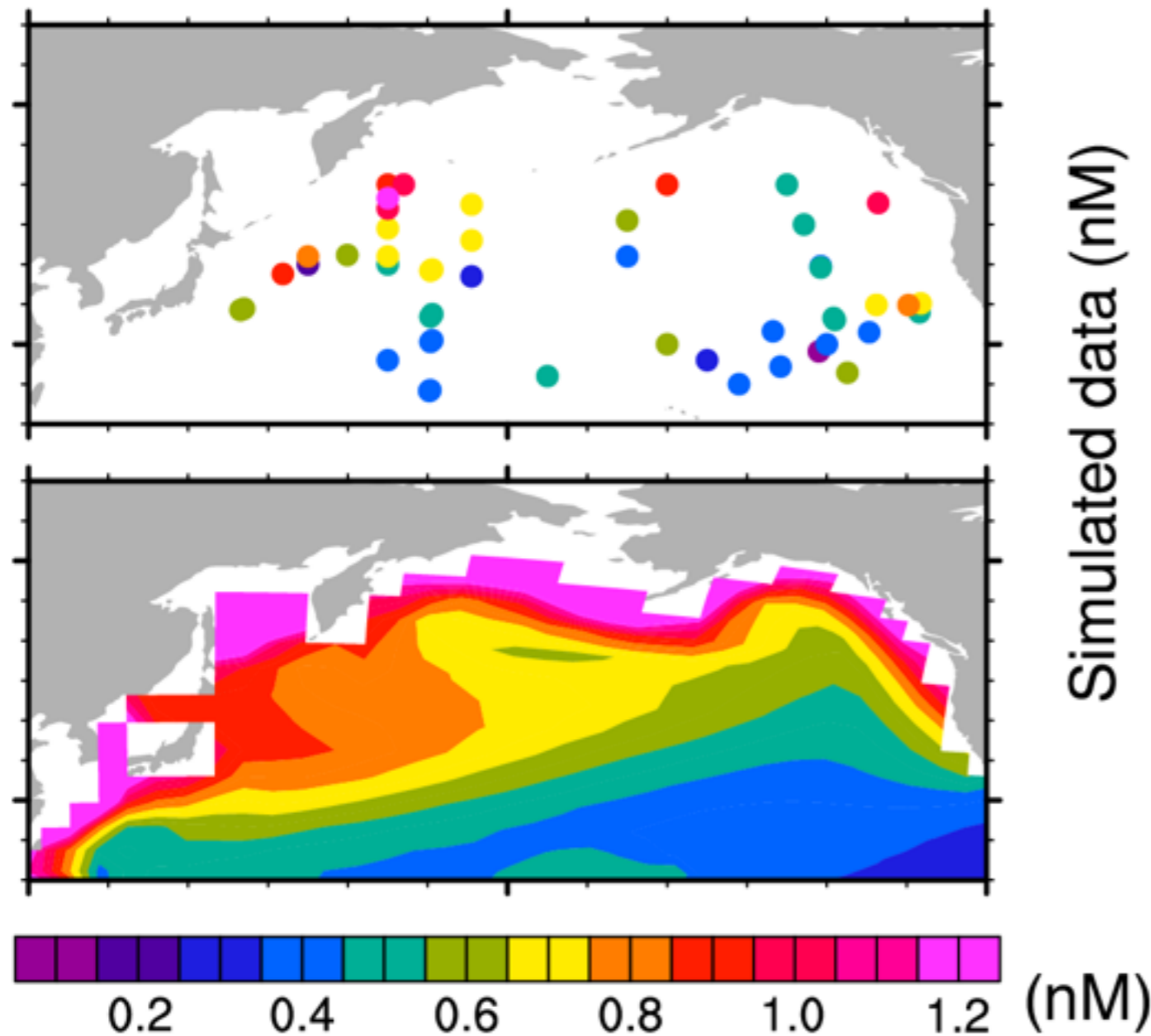
Yamashita & Tanoue (2008)

- 深層の有機配位子のほとんどは腐植様物質
- 北太平洋の腐植様物質の濃度は AOU と相関がある

$$L = \alpha AOU + \beta$$

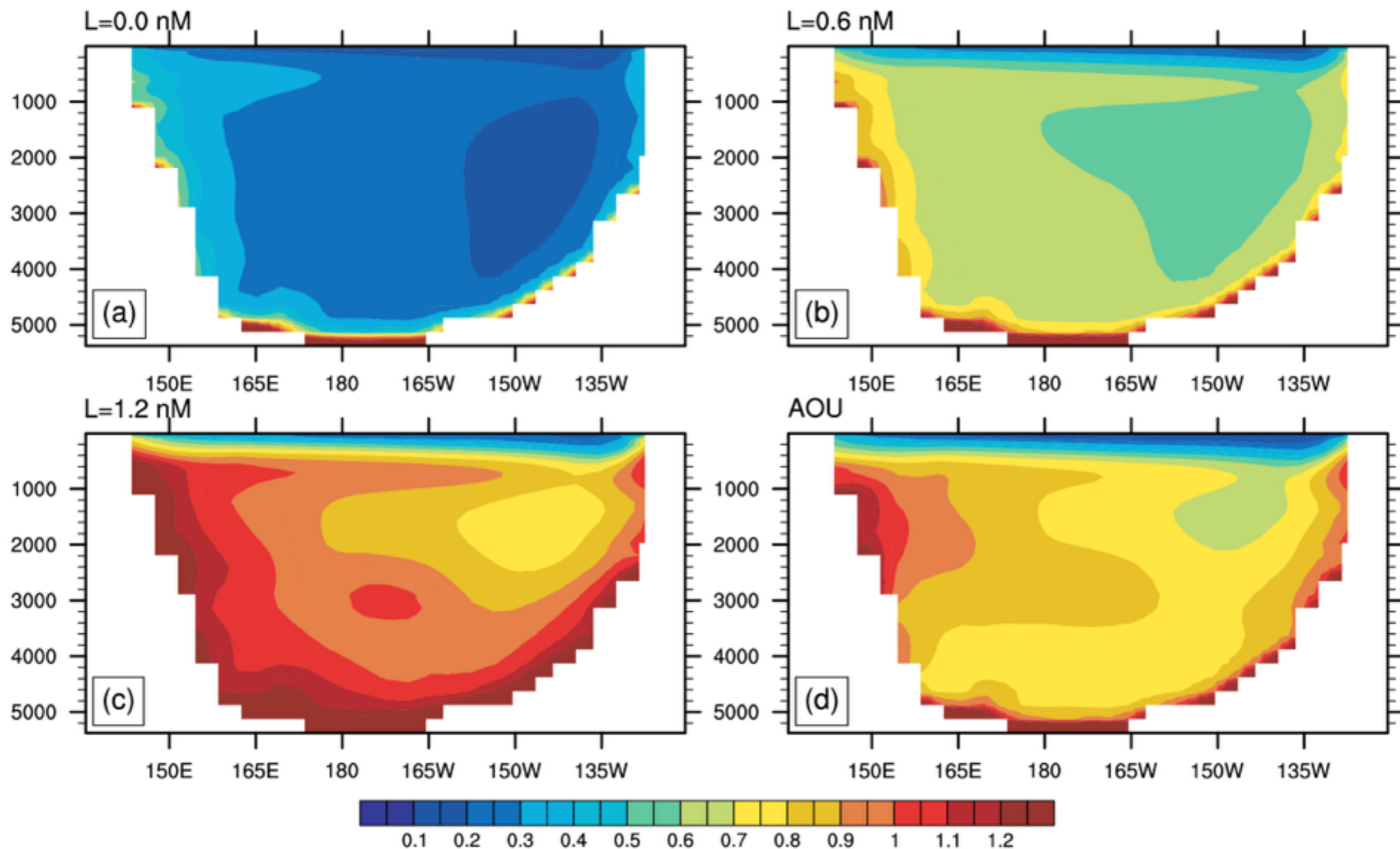


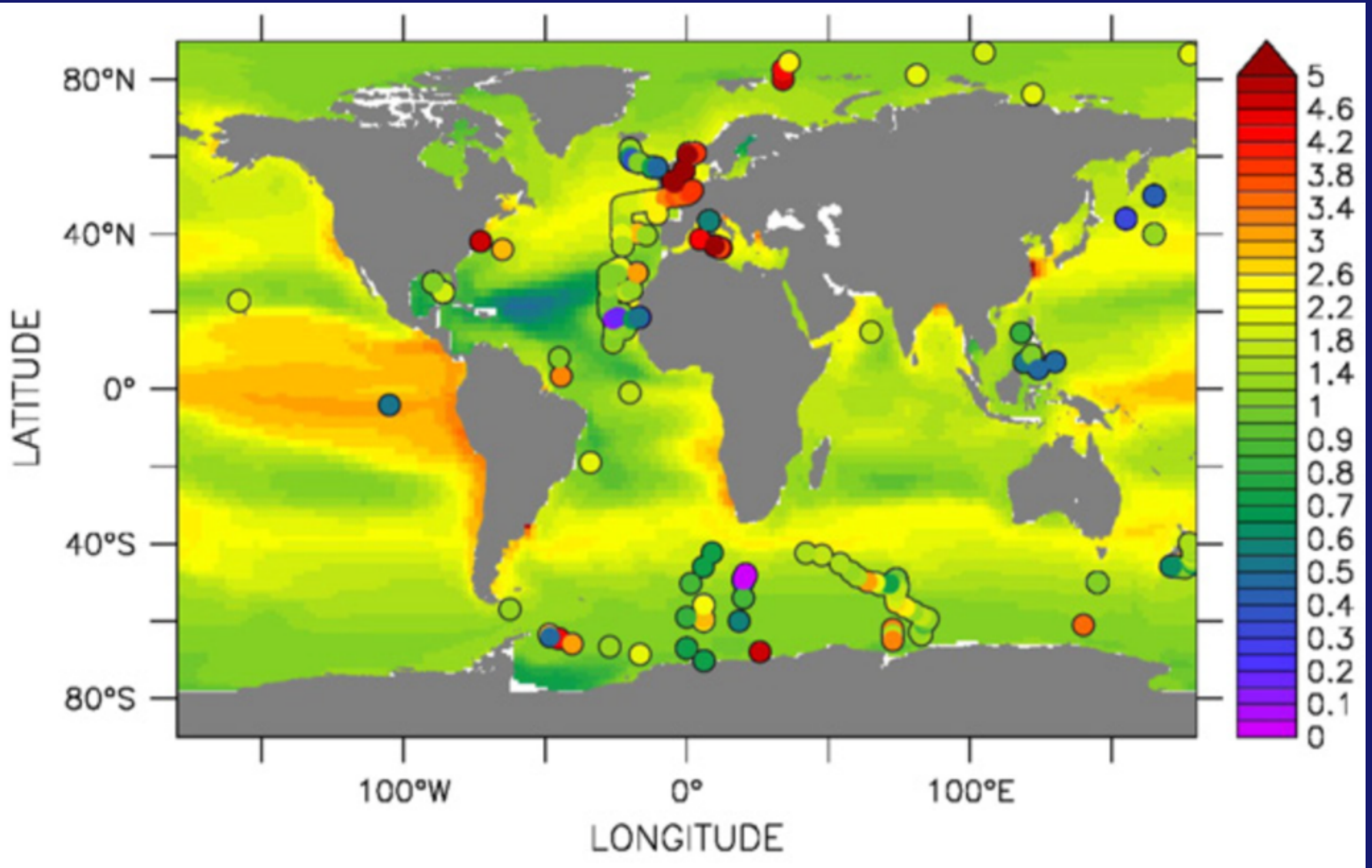
# 有機配位子の濃度 $L = \text{AOU}$ に比例



after Misumi et al. (2013)

# 北緯45度の断面





Völker & Tagliabue (2015)



熱水起源<sup>3</sup>Heフラックス

$$F_{3\text{He}} = 1000 \text{ mol yr}^{-1}$$

Craig et al. (1975)

海洋底拡大速度

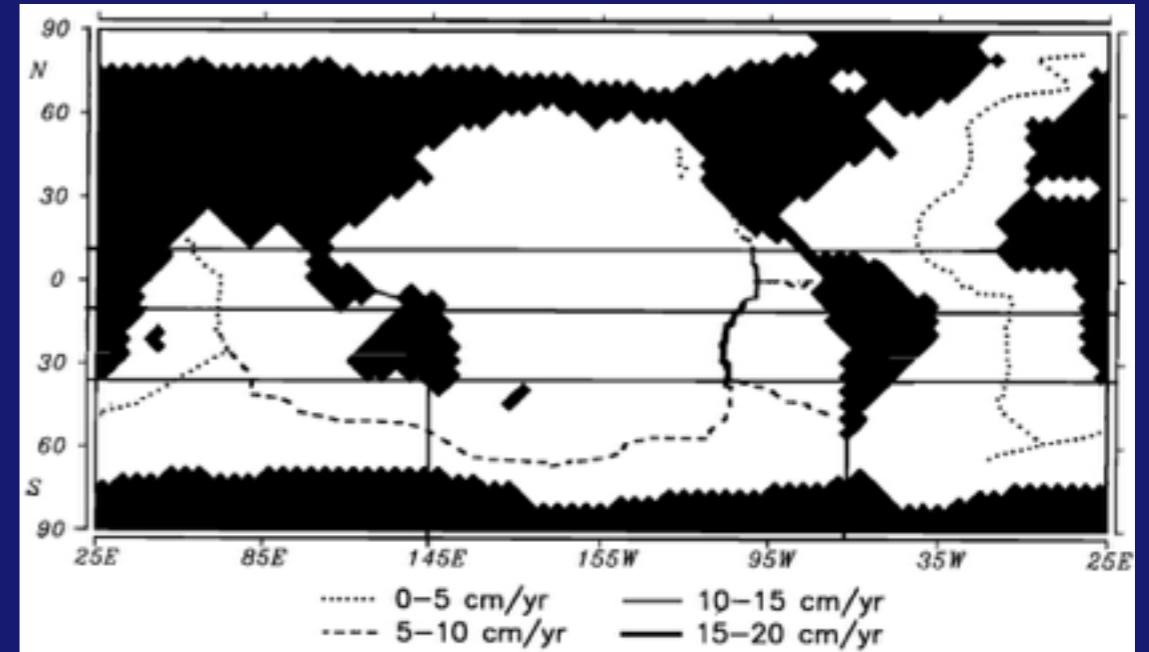
$$S = 3.0 \times 10^{10} \text{ cm}^2 \text{ yr}^{-1}$$

Parsons (1981)

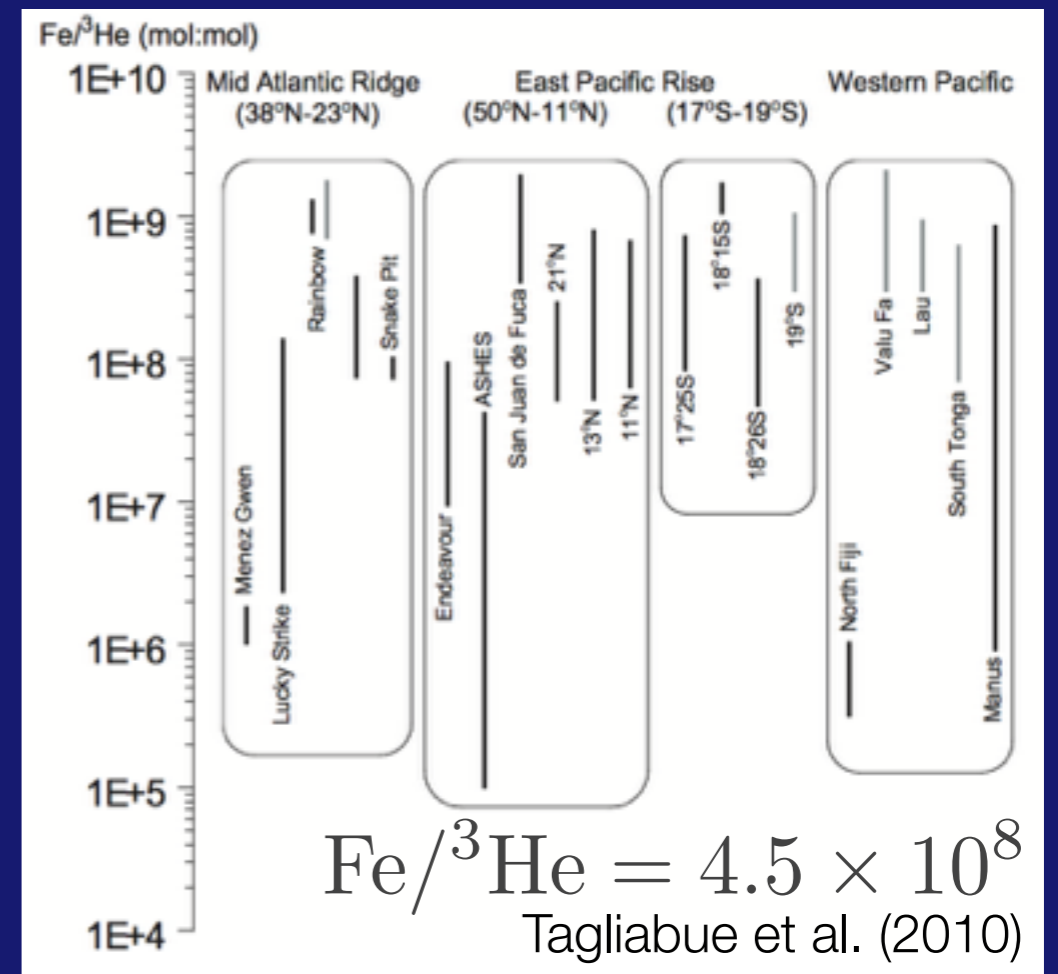
単位面積当たりの<sup>3</sup>Heの放出量

$$\alpha = \frac{F_{3\text{He}}}{S} = 3.3 \times 10^{-8} \text{ mol cm}^{-2}$$

Farley et al. (1995)



Farley et al. (1995)

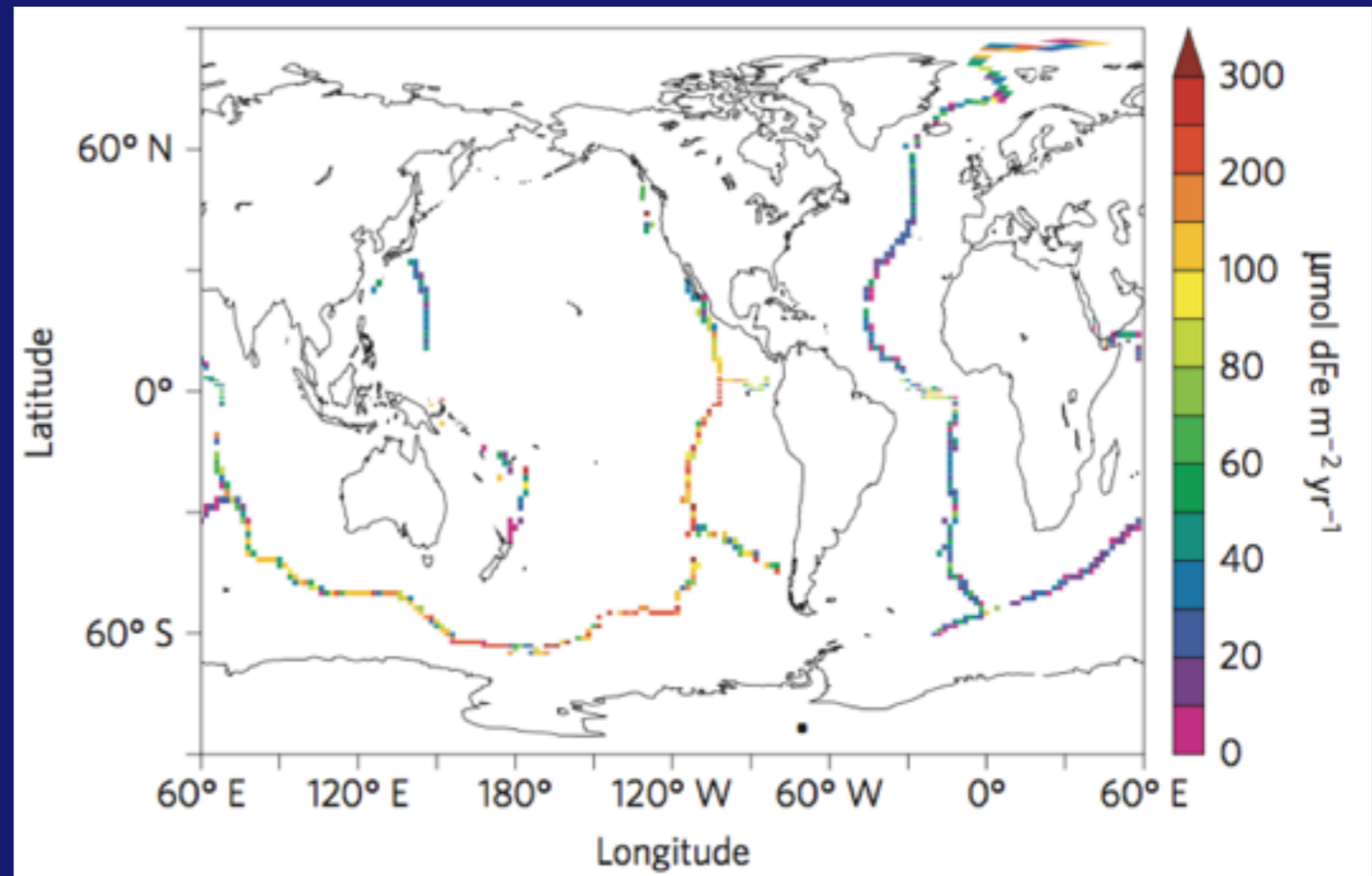


$$\text{Fe}/^3\text{He} = 4.5 \times 10^8$$

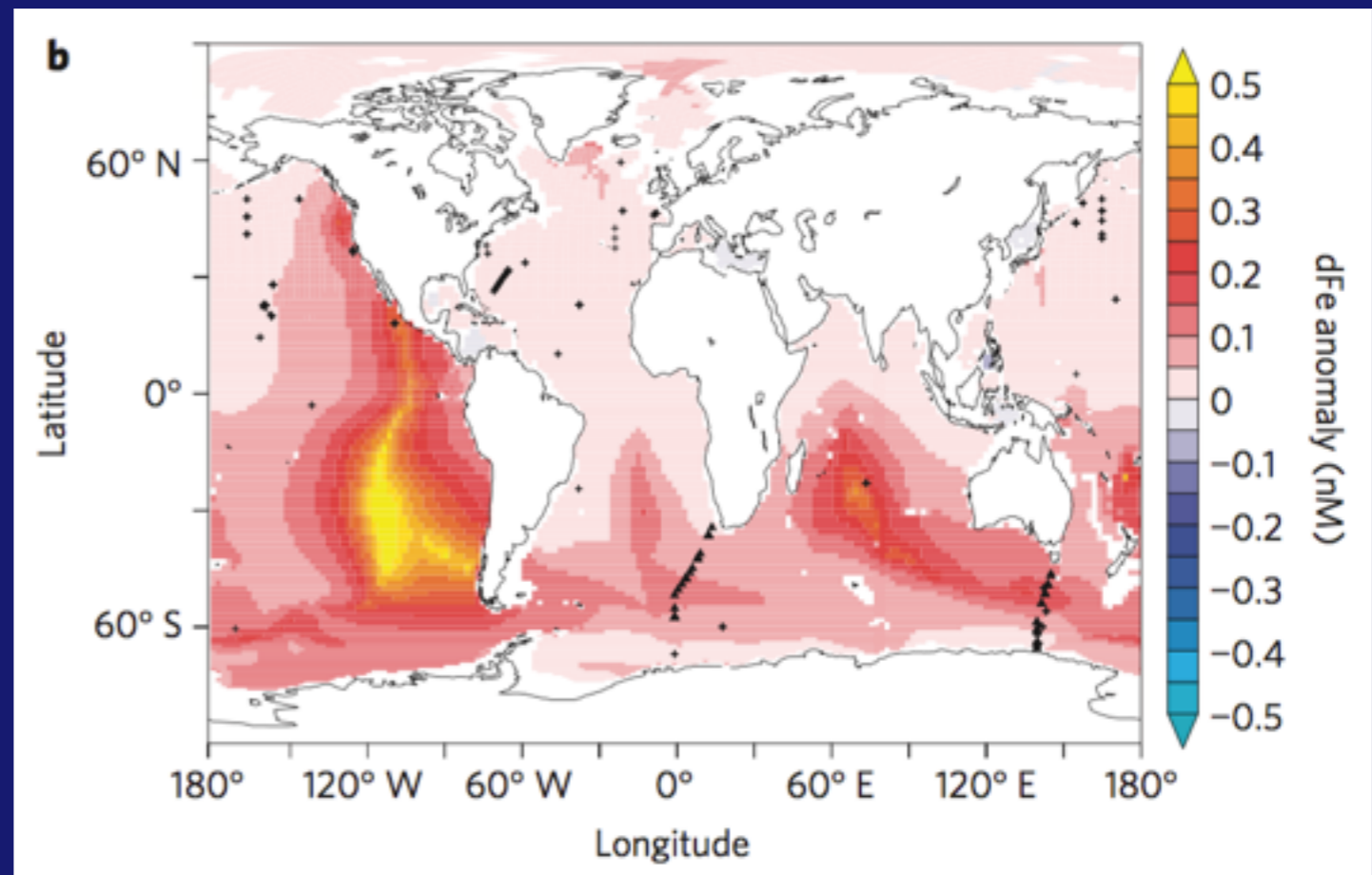
Tagliabue et al. (2010)



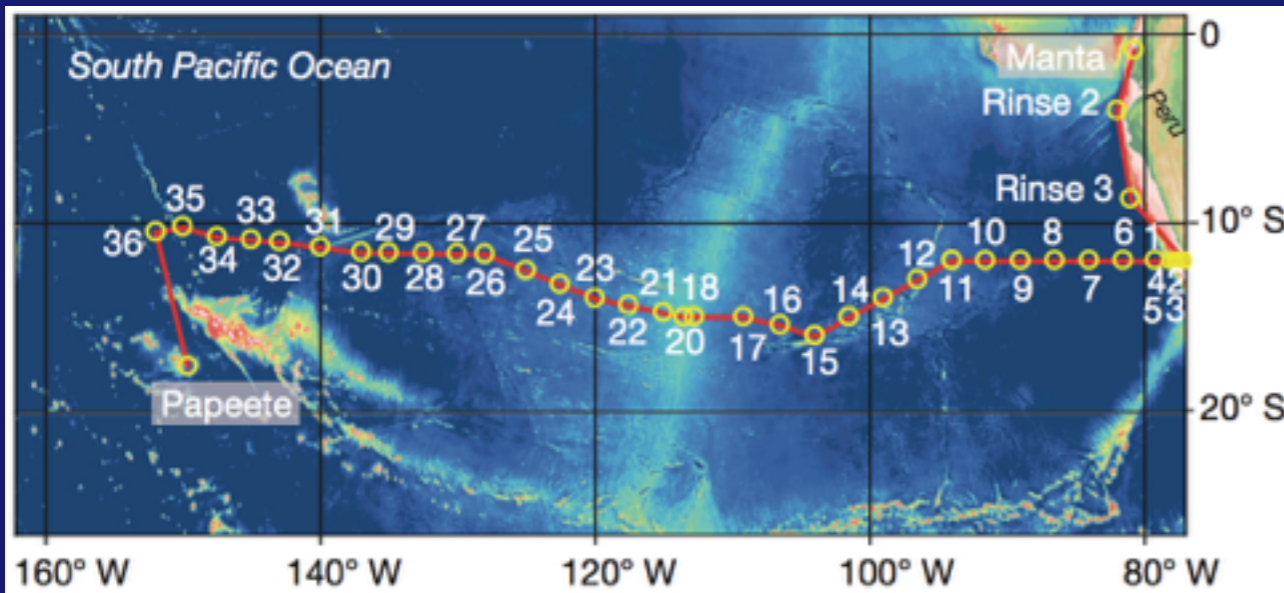
# 熱水起源の 鉄フラックス



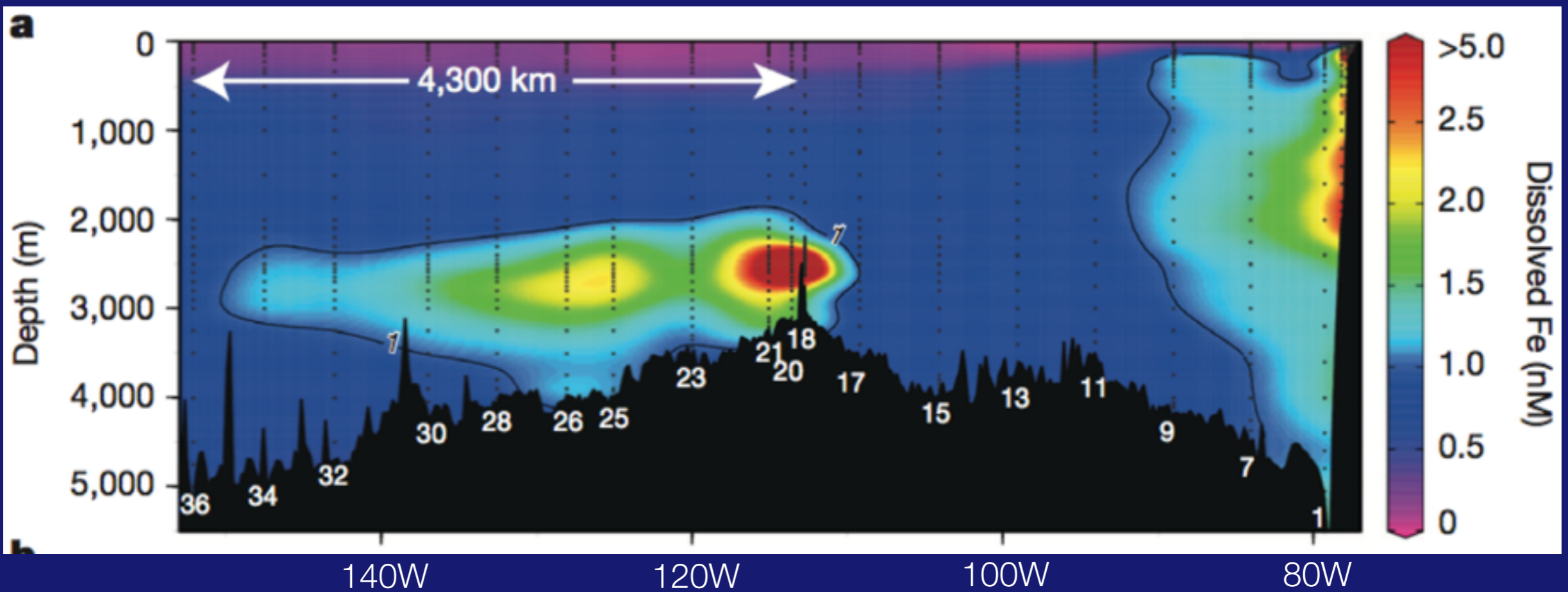
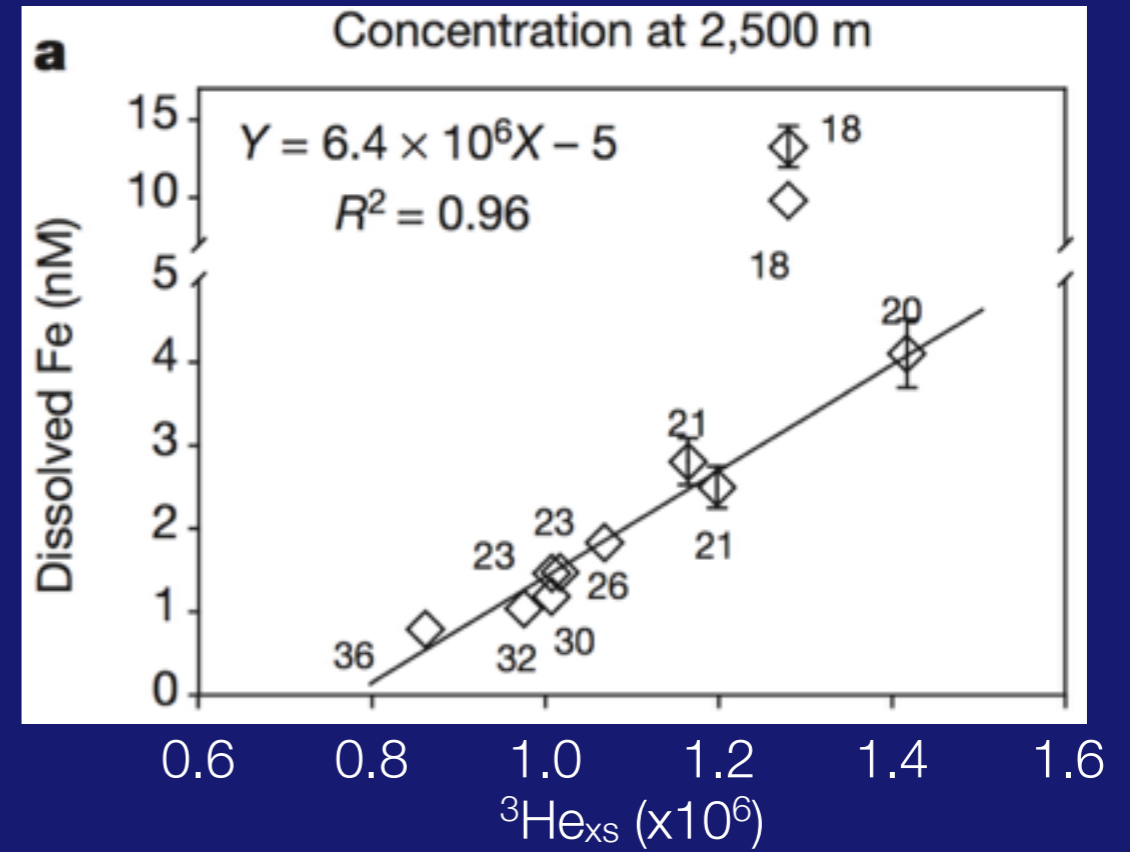
# 溶存鉄濃度の変化 @ 2000-3000 m



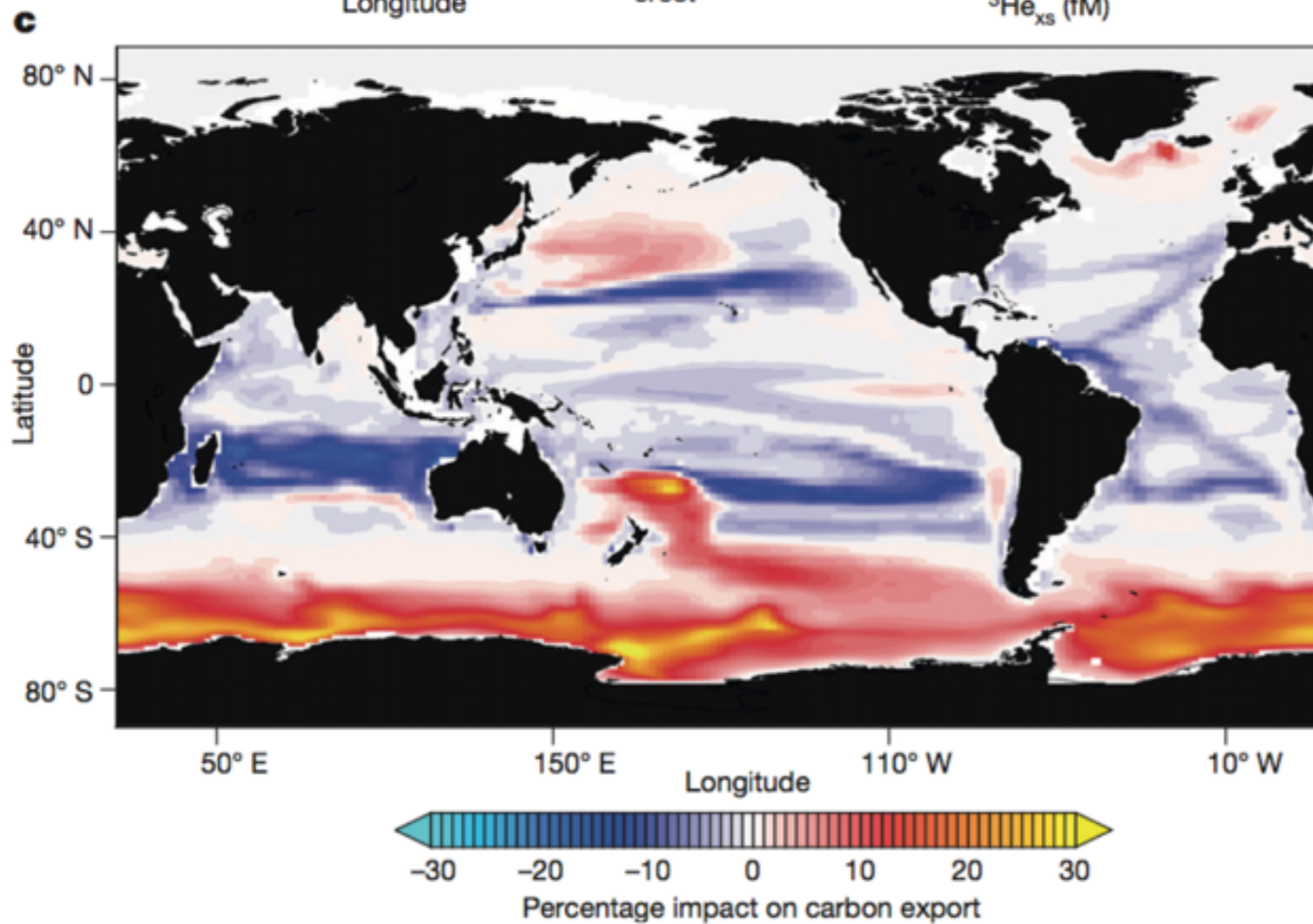
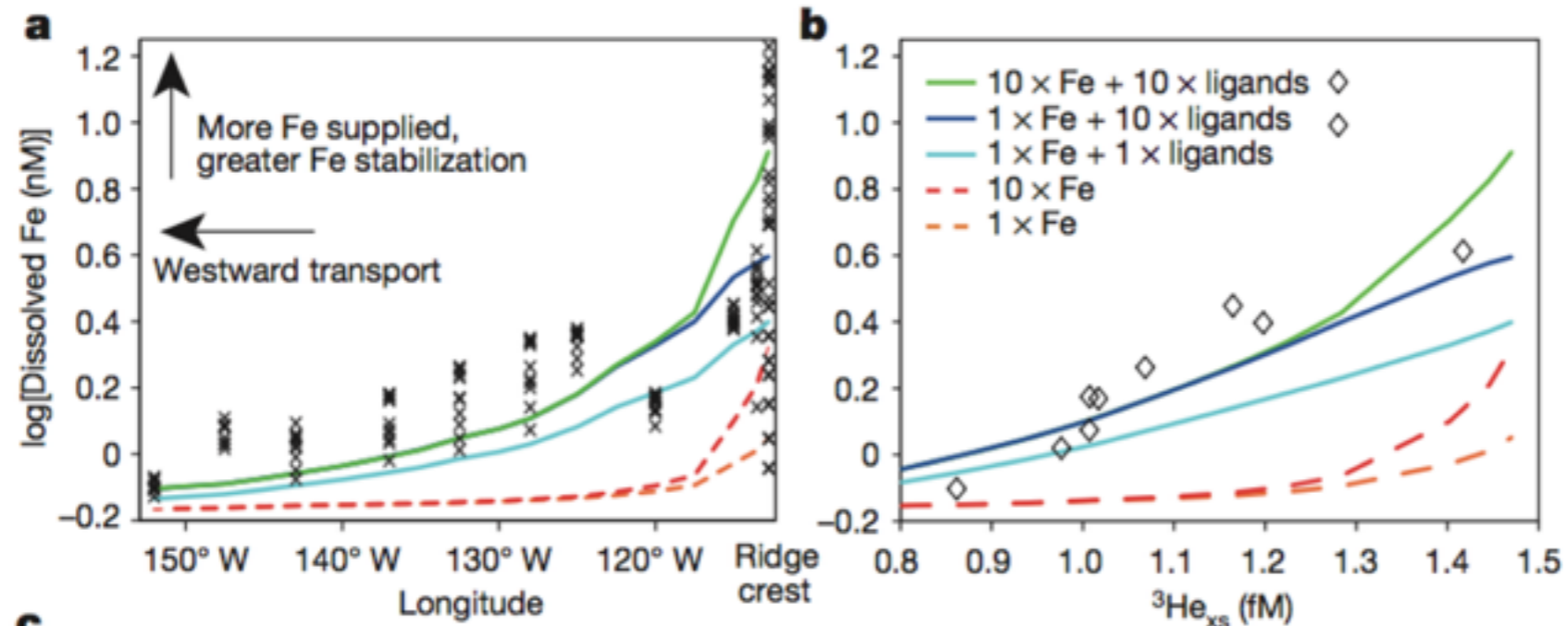
Tagliabue et al. (2010)



Resing et al. (2015)

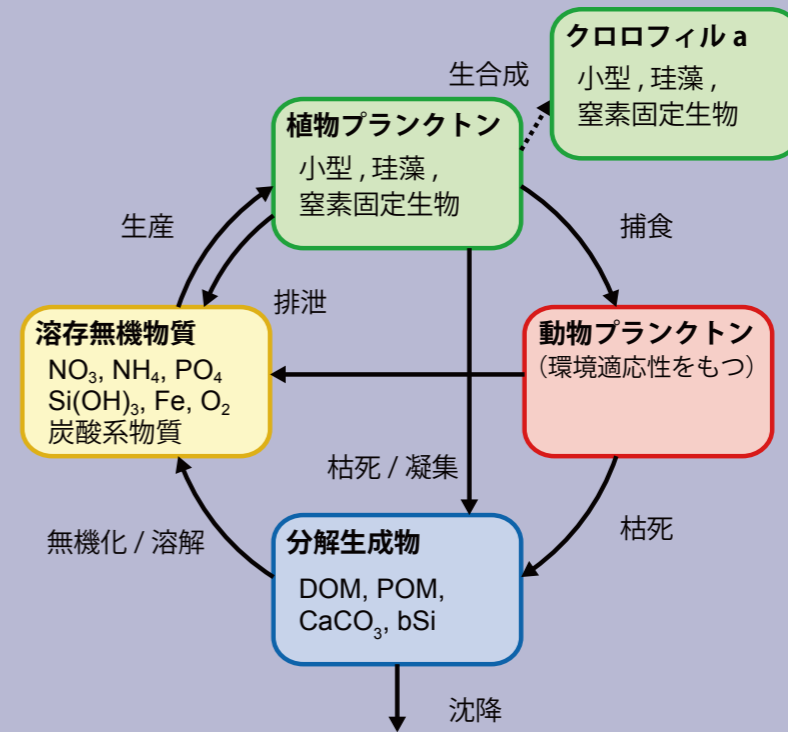
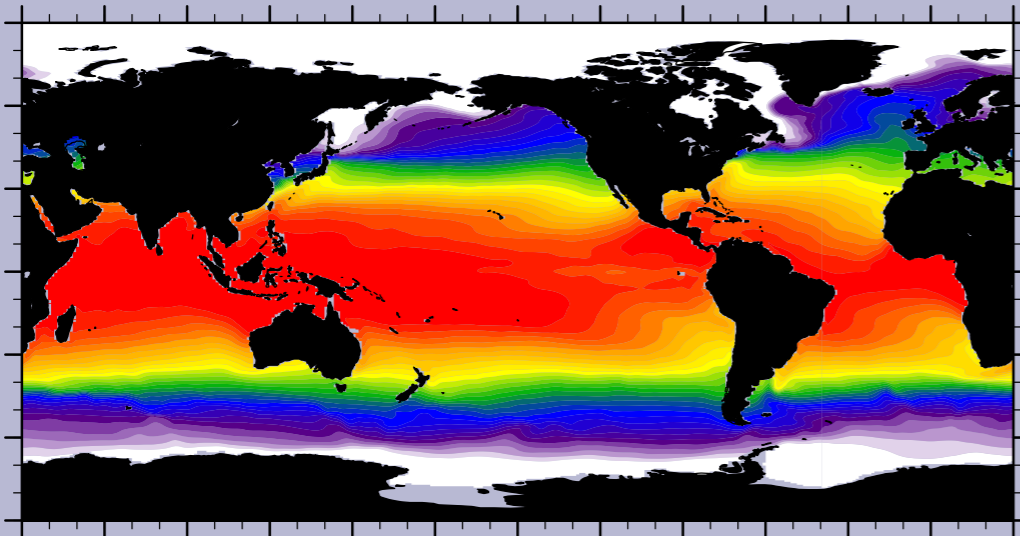




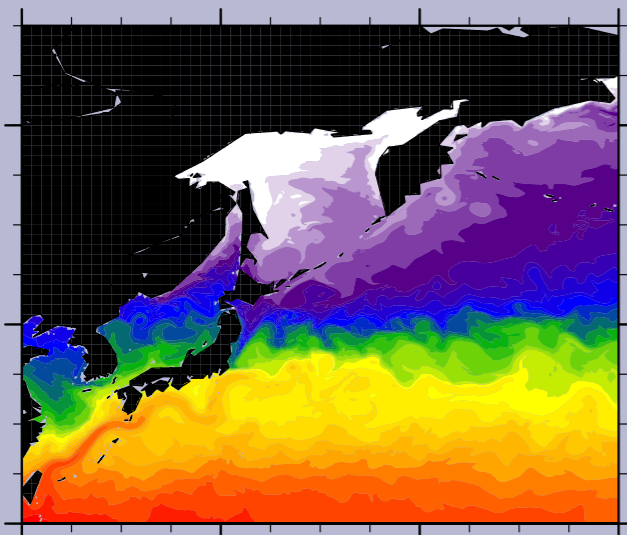


Resing et al. (2015)

# POP Global / z-coordinate

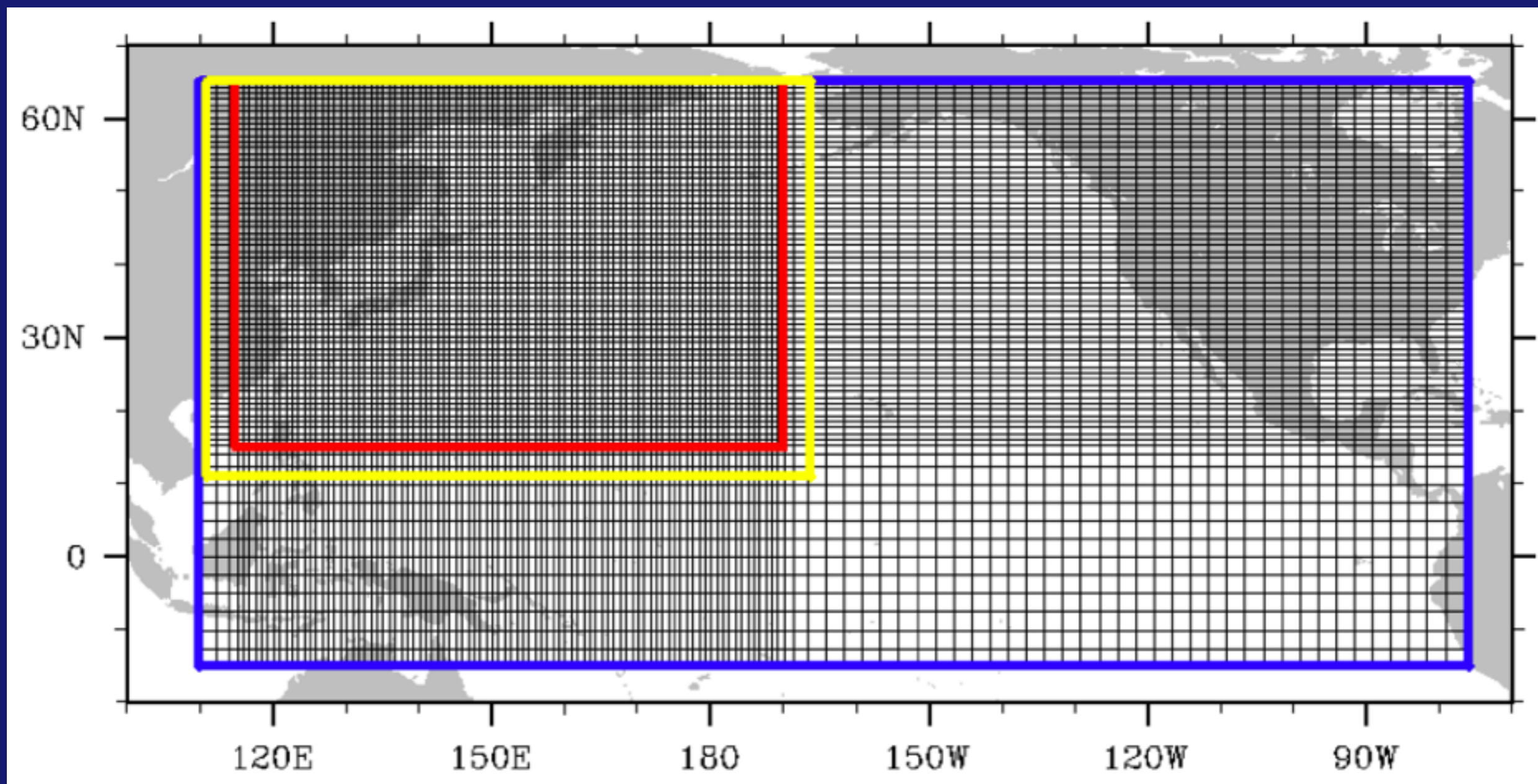


# ROMS Regional / s-coordinate



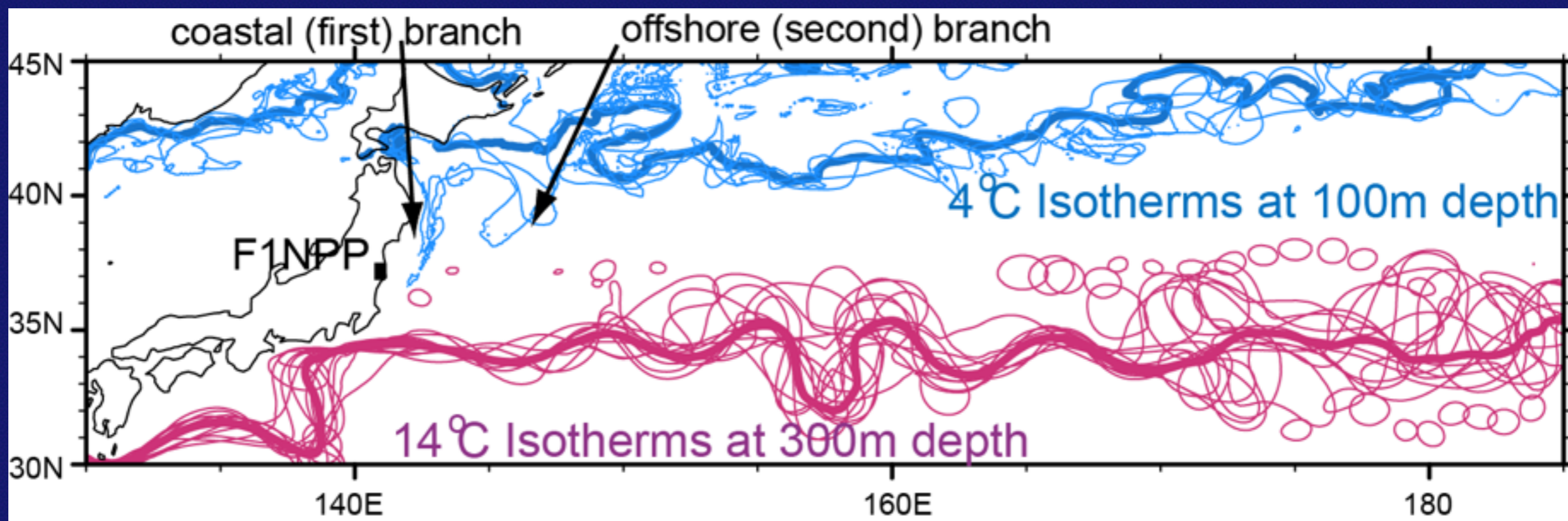
**BEC driver for ROMS**



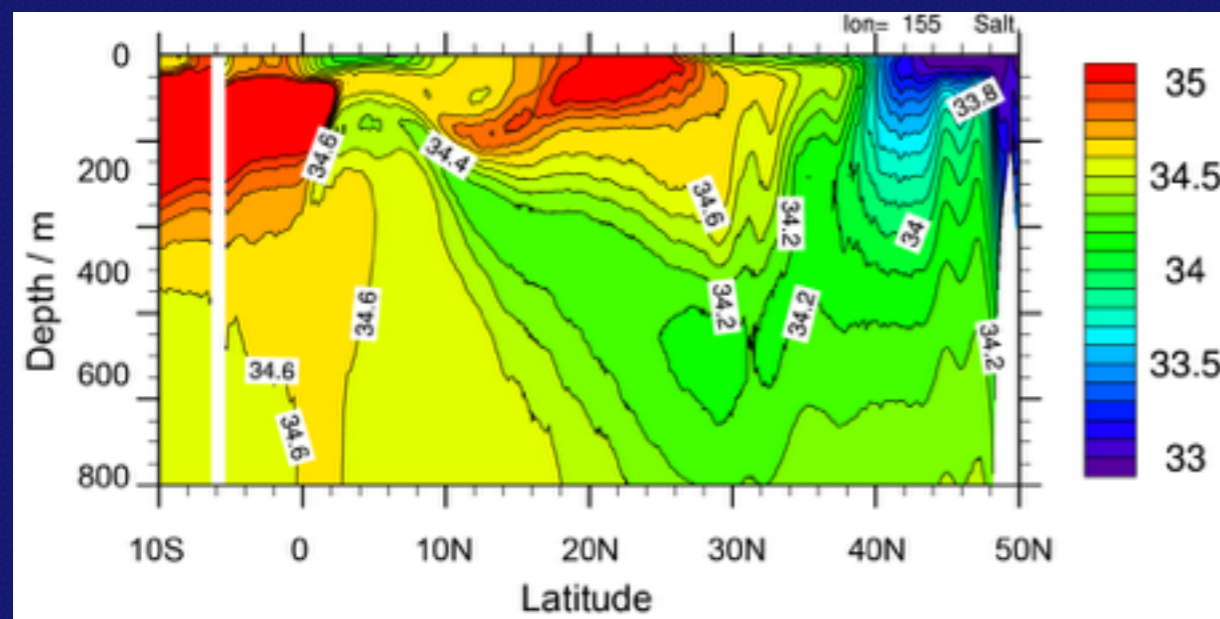




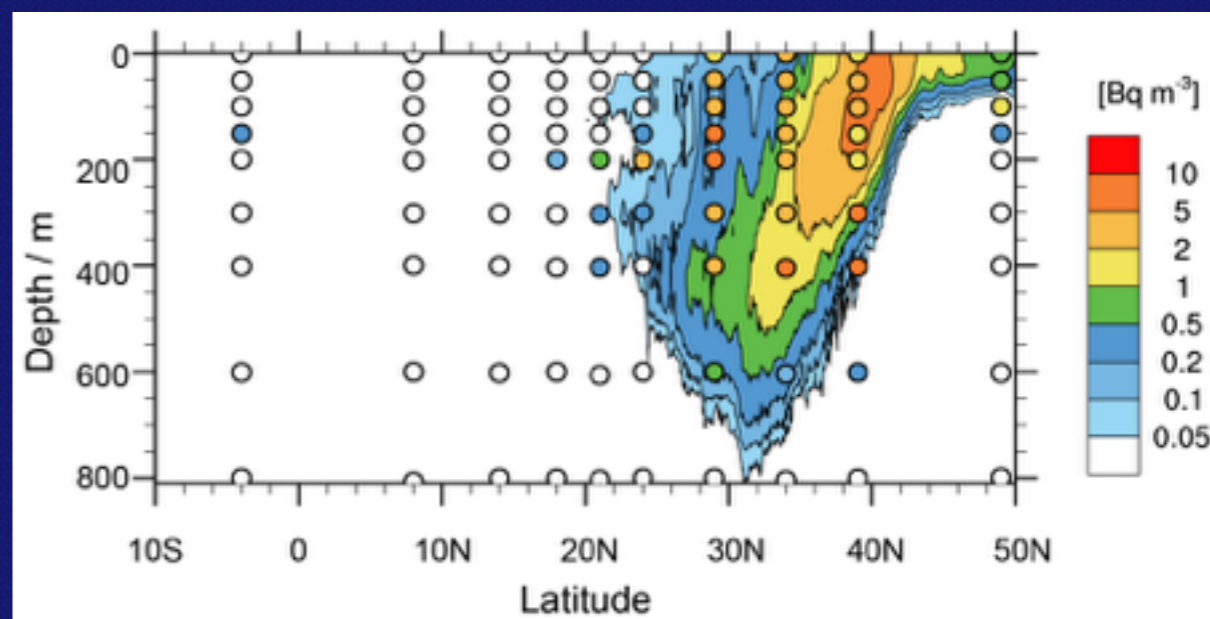
# 黒潮の離岸 / 亜寒帯前線



# 北太平洋中層水



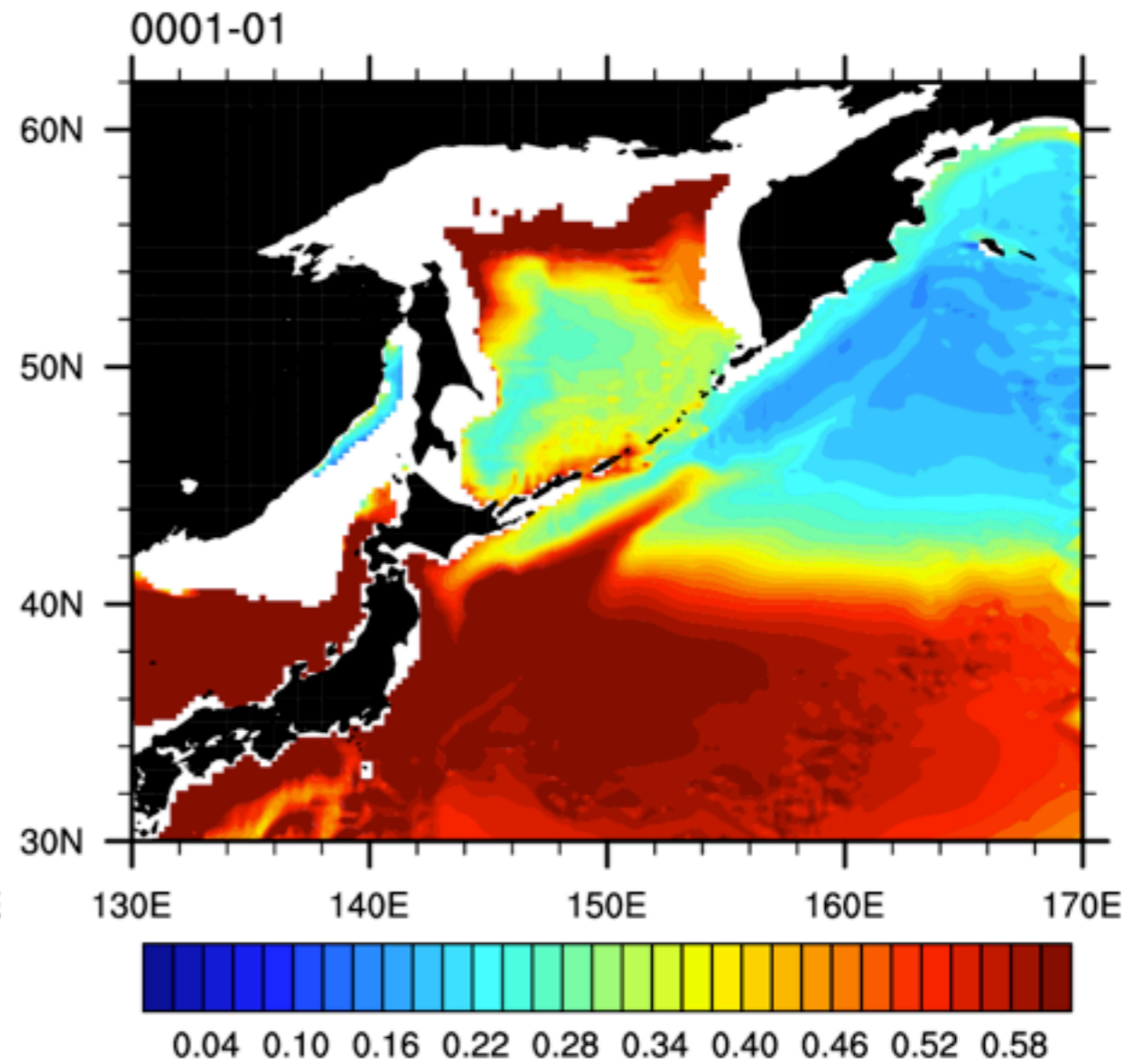
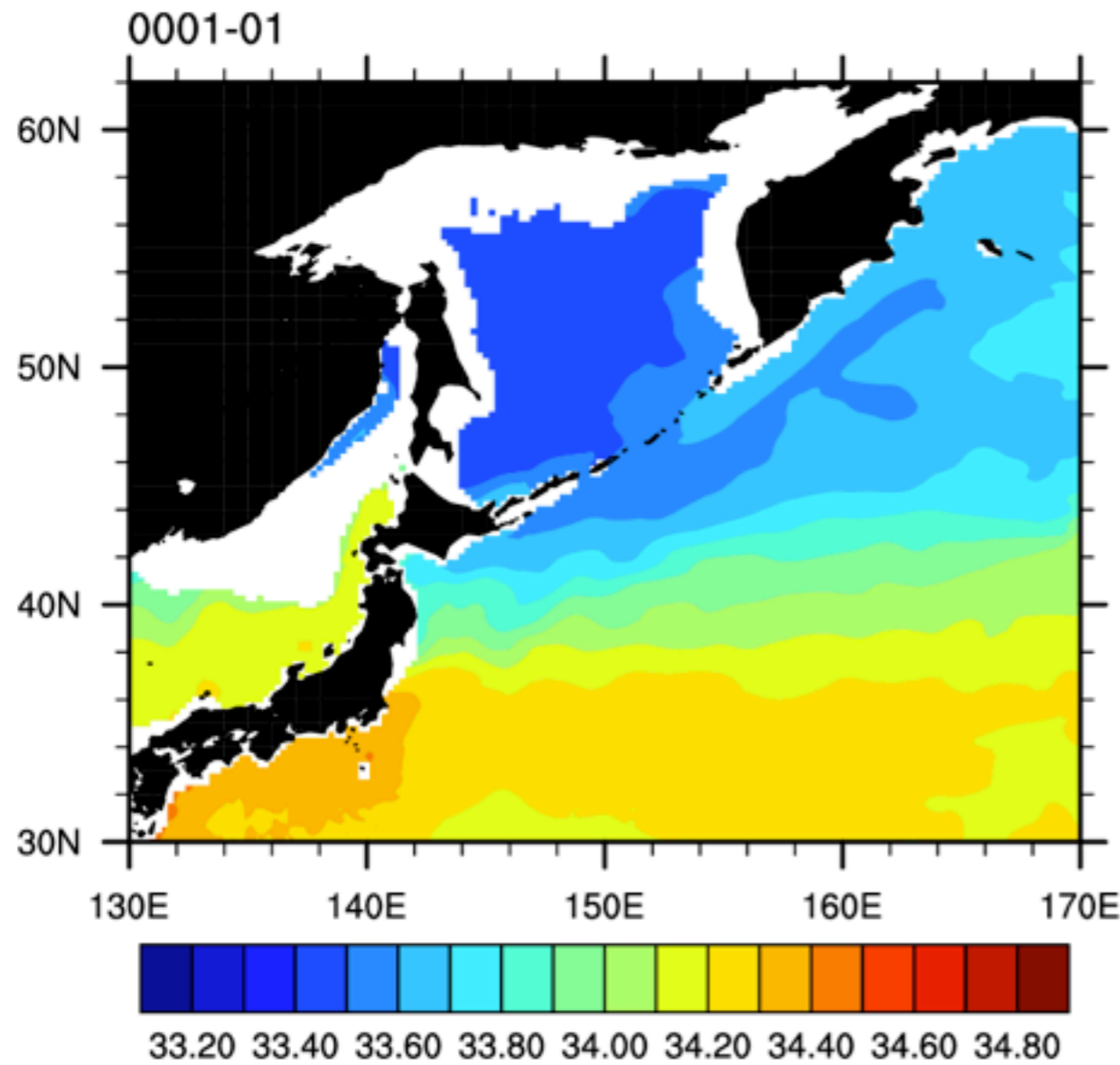
# $^{134}\text{Cs}$ のサブダクション



Tsubono et al. (2016)

# 塩分@26.8

# 溶存鉄@26.8



# 第2.x世代

## 観測

風成塵+堆積物+熱水が主な鉄の起源  
海盆内の複雑な構造

## モデル

風成塵+堆積物+熱水が鉄の起源  
有機配位子の濃度分布/予報変数化  
コロイドによる除去過程  
モデルの高解像度化



# 3. 海洋鉄循環モデルの 国際相互比較 (FeMIP)

# 参加したモデル / 5カ国 13のモデル

**BEC** (US, NCAR), **BLING** (US, Princeton), **COBALT, TOPAZ** (US, GFDL),  
**MITecco, MITigsm** (US, MIT), **BFM** (IT, CMCC), **GENIE** (UK, Bristol),  
**MEDUSA1,2** (UK, Southampton), **PISCES1,2** (FR, IPSL), **REcoM** (DE, AWI)

# 参加したモデル / 5カ国 13のモデル

**BEC** (US, NCAR), **BLING** (US, Princeton), **COBALT, TOPAZ** (US, GFDL),  
**MITecco, MITigsm** (US, MIT), **BFM** (IT, CMCC), **GENIE** (UK, Bristol),  
**MEDUSA1,2** (UK, Southampton), **PISCES1,2** (FR, IPSL), **REcoM** (DE, AWI)

## ルール

- 最良と思われる鉄の分布を月平均データで提出
- 計算している他の栄養塩も月平均データで提出
- 初期条件, 境界条件, 計算期間は自由

## 解析

- $1^\circ \times 1^\circ$ , 33層のグリッドに整形
- 観測データ (Tagliabue et al., 2012 +  $\alpha$ , 20,000点) と比較 (測定地点/月を合わせて)

| モデル     | 外部からの鉄供給 |     |     |     | 除去過程    |      | 生物過程     |          |
|---------|----------|-----|-----|-----|---------|------|----------|----------|
|         | 風成塵      | 堆積物 | 熱水  | 河川  | 配位子     | コロイド | 取込       | 再循環      |
| BEC     | Yes      | Yes | Yes | Yes | Fixed   | No   | Variable | Fixed    |
| BFM     | Yes      | No  | No  | No  | Fixed   | No   | Variable | Variable |
| BLING   | Yes      | Yes | No  | No  | Fixed   | No   | Variable | Fixed    |
| COBALT  | Yes      | Yes | No  | No  | Fixed   | No   | Variable | Variable |
| GENIE   | Yes      | No  | No  | No  | Fixed   | No   | Variable | Variable |
| MEDUSA1 | Yes      | No  | No  | No  | Fixed   | No   | Fixed    | Fixed    |
| MEDUSA2 | Yes      | Yes | No  | No  | Fixed   | No   | Fixed    | Fixed    |
| MITecco | Yes      | Yes | No  | No  | Fixed   | No   | Fixed    | Variable |
| MITigsm | Yes      | Yes | No  | No  | Fixed   | No   | Fixed    | Variable |
| PISCES1 | Yes      | Yes | Yes | Yes | Fixed   | Yes  | Variable | Variable |
| PISCES2 | Yes      | Yes | Yes | Yes | Dynamic | Yes  | Variable | Variable |
| REcoM   | Yes      | Yes | No  | No  | Fixed   | No   | Both     | Fixed    |
| TOPAZ   | Yes      | Yes | No  | No  | Fixed   | No   | Variable | Variable |



| モデル     | 外部からの鉄供給量 (Gmol yr <sup>-1</sup> ) |      |      |      |       | 鉄のシミュレーション結果 |         |
|---------|------------------------------------|------|------|------|-------|--------------|---------|
|         | 風成塵                                | 堆積物  | 熱水   | 河川   | 総量    | 平均濃度 nM      | 滞留時間 yr |
| BEC     | 21.9                               | 84.6 | 17.7 | 0.34 | 124.5 | 0.74         | 8.1     |
| BFM     | 1.4                                |      |      |      | 1.4   | 0.65         | 626.3   |
| BLING   | 3.3                                | 9.1  |      |      | 12.4  | 0.37         | 42.4    |
| COBALT  | 32.5                               | 155  |      |      | 182.5 | 0.50         | 3.7     |
| GENIE   | 1.8                                |      |      |      | 1.8   | 0.48         | 560.0   |
| MEDUSA1 | 2.7                                |      |      |      | 2.7   | 0.46         | 232.0   |
| MEDUSA2 | 3.4                                | 2.9  |      |      | 6.8   | 0.35         | 69.9    |
| MITecco | 3.5                                | 104  |      |      | 107.5 | 0.65         | 8.2     |
| MITigsm | 1.4                                | 194  |      |      | 195.4 | 0.66         | 4.6     |
| PISCES1 | 32.7                               | 26.6 | 11.3 | 2.5  | 71.0  | 0.59         | 11.5    |
| PISCES2 | 32.7                               | 26.6 | 11.3 | 2.5  | 71.0  | 0.81         | 15.7    |
| REcoM   | 3.7                                | 0.6  |      |      | 4.3   | 0.73         | 291.6   |
| TOPAZ   | 13.8                               | 74.8 |      |      | 88.6  | 0.58         | 7.6     |

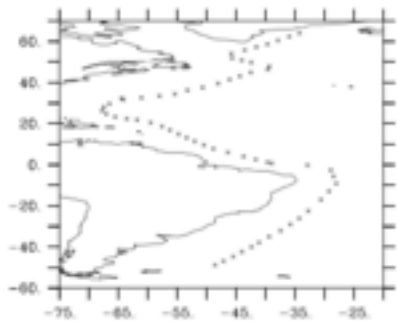
| モデル     | 相関係数  |         |         | 平均バイアス nM |         |         |
|---------|-------|---------|---------|-----------|---------|---------|
|         | 全深度   | 0-100 m | 2000- m | 全深度       | 0-100 m | 2000- m |
| BEC     | 0.51  | 0.48    | 0.31    | -0.02     | 0.23    | 0.01    |
| BFM     | 0.39  | 0.34    | -0.03   | -0.48     | -0.29   | -0.48   |
| BLING   | 0.37  | 0.37    | 0.01    | -0.33     | -0.13   | -0.44   |
| COBALT  | 0.45  | 0.38    | -0.11   | -0.25     | -0.19   | -0.25   |
| GENIE   | 0.25  | 0.43    | -0.14   | -0.28     | -0.02   | -0.40   |
| MEDUSA1 | -0.01 | 0.37    | 0.07    | -0.24     | 0.23    | -0.37   |
| MEDUSA2 | -0.14 | 0.35    | -0.10   | -0.32     | 0.29    | -0.51   |
| MITecco | 0.39  | 0.34    | -0.03   | -0.12     | -0.10   | -0.11   |
| MITigsm | 0.37  | 0.04    | -0.13   | -0.14     | -0.22   | -0.04   |
| PISCES1 | 0.47  | 0.36    | 0.21    | -0.23     | -0.06   | -0.27   |
| PISCES2 | 0.51  | 0.37    | 0.35    | -0.04     | 0.03    | -0.05   |
| REcoM   | 0.39  | 0.33    | -0.04   | -0.05     | 0.25    | -0.12   |
| TOPAZ   | 0.10  | 0.42    | 0.01    | -0.13     | 0.67    | -0.34   |

| モデル     | 相関係数  |         |         | 平均バイアス nM |         |         |
|---------|-------|---------|---------|-----------|---------|---------|
|         | 全深度   | 0-100 m | 2000- m | 全深度       | 0-100 m | 2000- m |
| BEC     | 0.51  | 0.48    | 0.31    | -0.02     | 0.23    | 0.01    |
| BFM     | 0.39  | 0.34    | -0.03   | -0.48     | -0.29   | -0.48   |
| BLING   | 0.37  | 0.37    | 0.01    | -0.33     | -0.13   | -0.44   |
| COBALT  | 0.45  | 0.38    | -0.11   | -0.25     | -0.19   | -0.25   |
| GENIE   | 0.25  | 0.43    | -0.14   | -0.28     | -0.02   | -0.40   |
| MEDUSA1 | -0.01 | 0.37    | 0.07    | -0.24     | 0.23    | -0.37   |
| MEDUSA2 | -0.14 | 0.35    | -0.10   | -0.32     | 0.29    | -0.51   |
| MITecco | 0.39  | 0.34    | -0.03   | -0.12     | -0.10   | -0.11   |
| MITigsm | 0.37  | 0.04    | -0.13   | -0.14     | -0.22   | -0.04   |
| PISCES1 | 0.47  | 0.36    | 0.21    | -0.23     | -0.06   | -0.27   |
| PISCES2 | 0.51  | 0.37    | 0.35    | -0.04     | 0.03    | -0.05   |
| REcoM   | 0.39  | 0.33    | -0.04   | -0.05     | 0.25    | -0.12   |
| TOPAZ   | 0.10  | 0.42    | 0.01    | -0.13     | 0.67    | -0.34   |

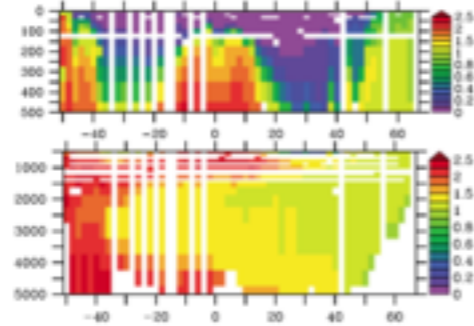
上位3モデル  
下位3モデル

# GEOTRACES GA-02 リン酸塩

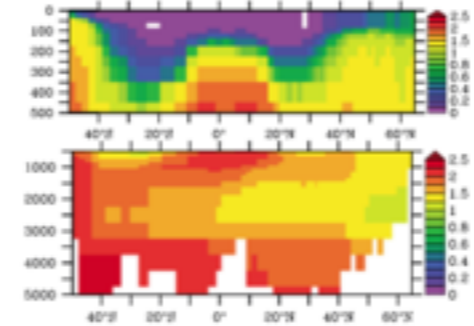
GA-02, Cruise



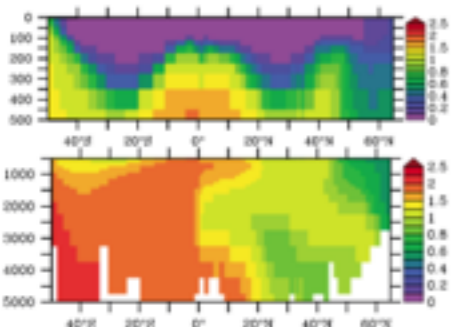
BEC, GA-02



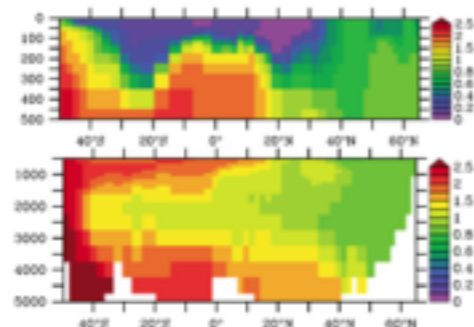
BEC, GA-02



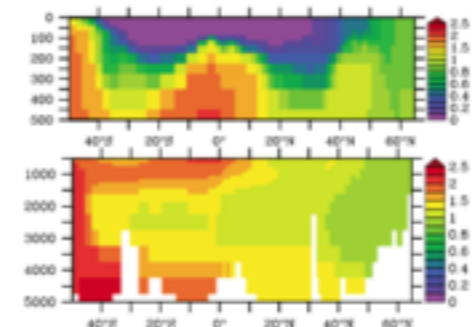
BFM, GA-02



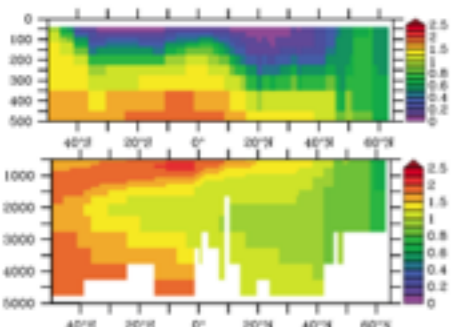
BLING, GA-02



COBALT, GA-02



GENIE, GA-02



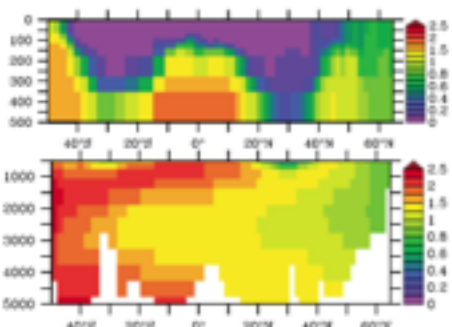
MEDUSA 1, GA-02



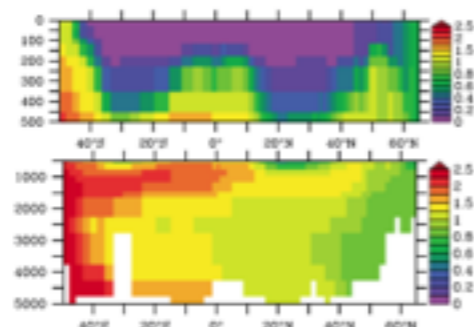
MEDUSA 2, GA-02



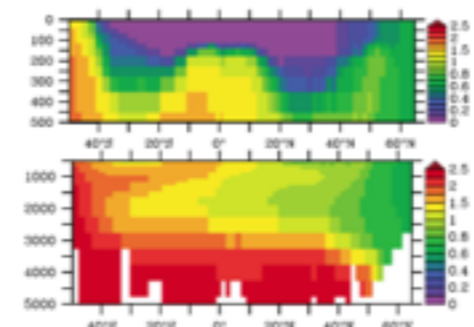
MITecco, GA-02



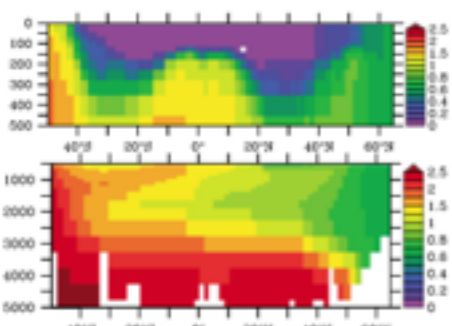
MITigsm, GA-02



PISCES 1, GA-02



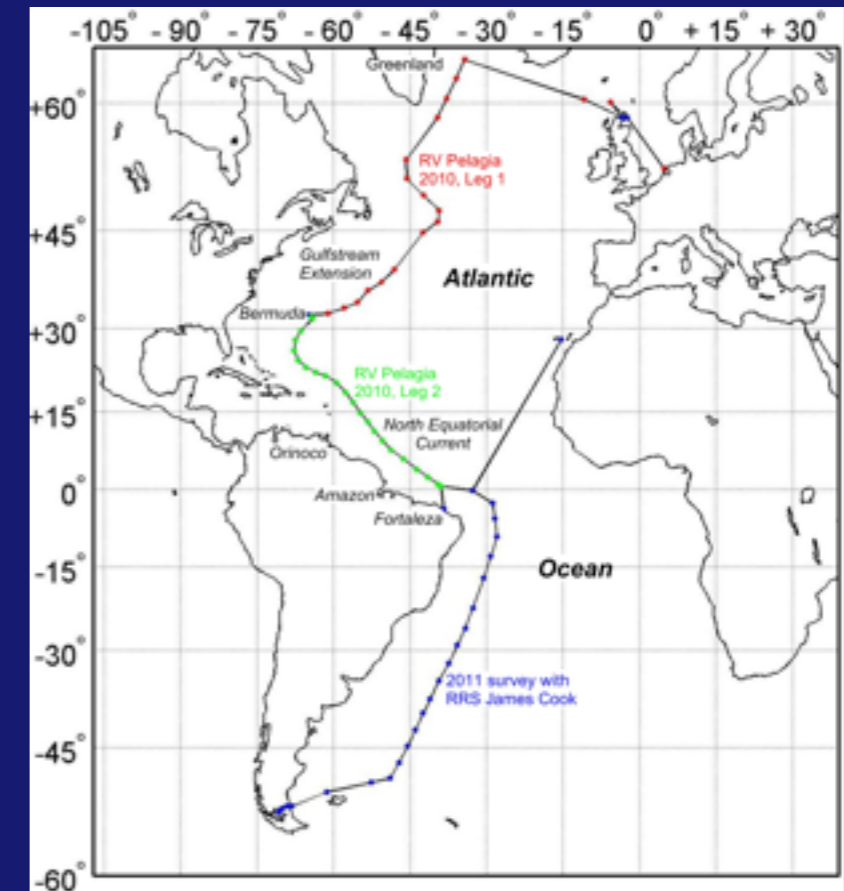
PISCES 2, GA-02



RECOM, GA-02

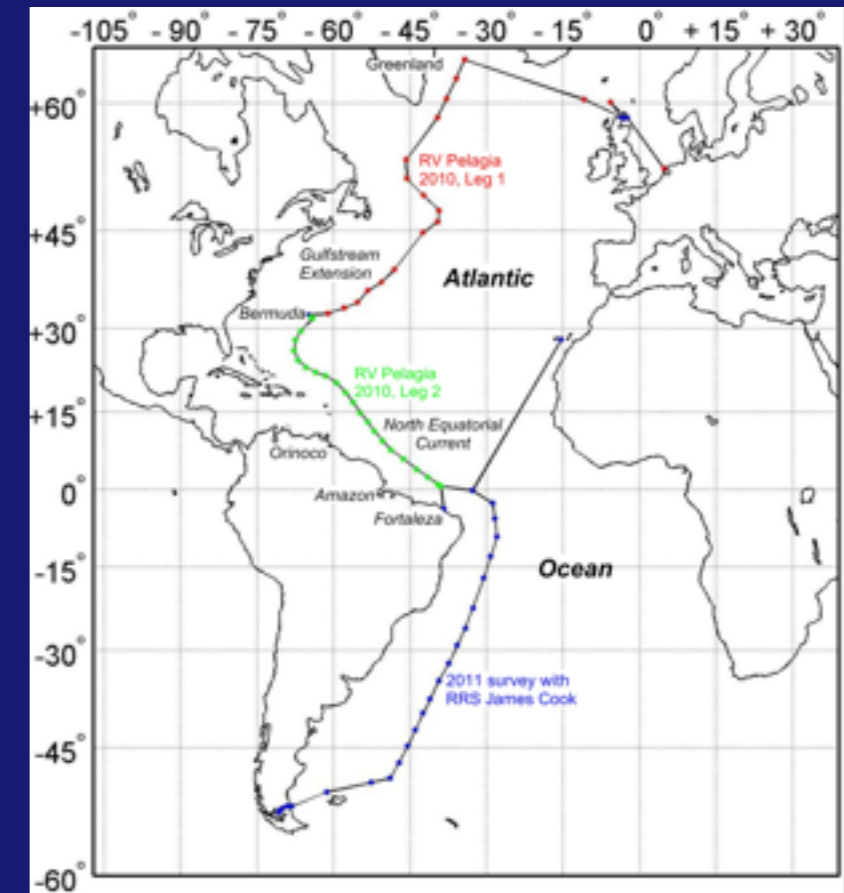
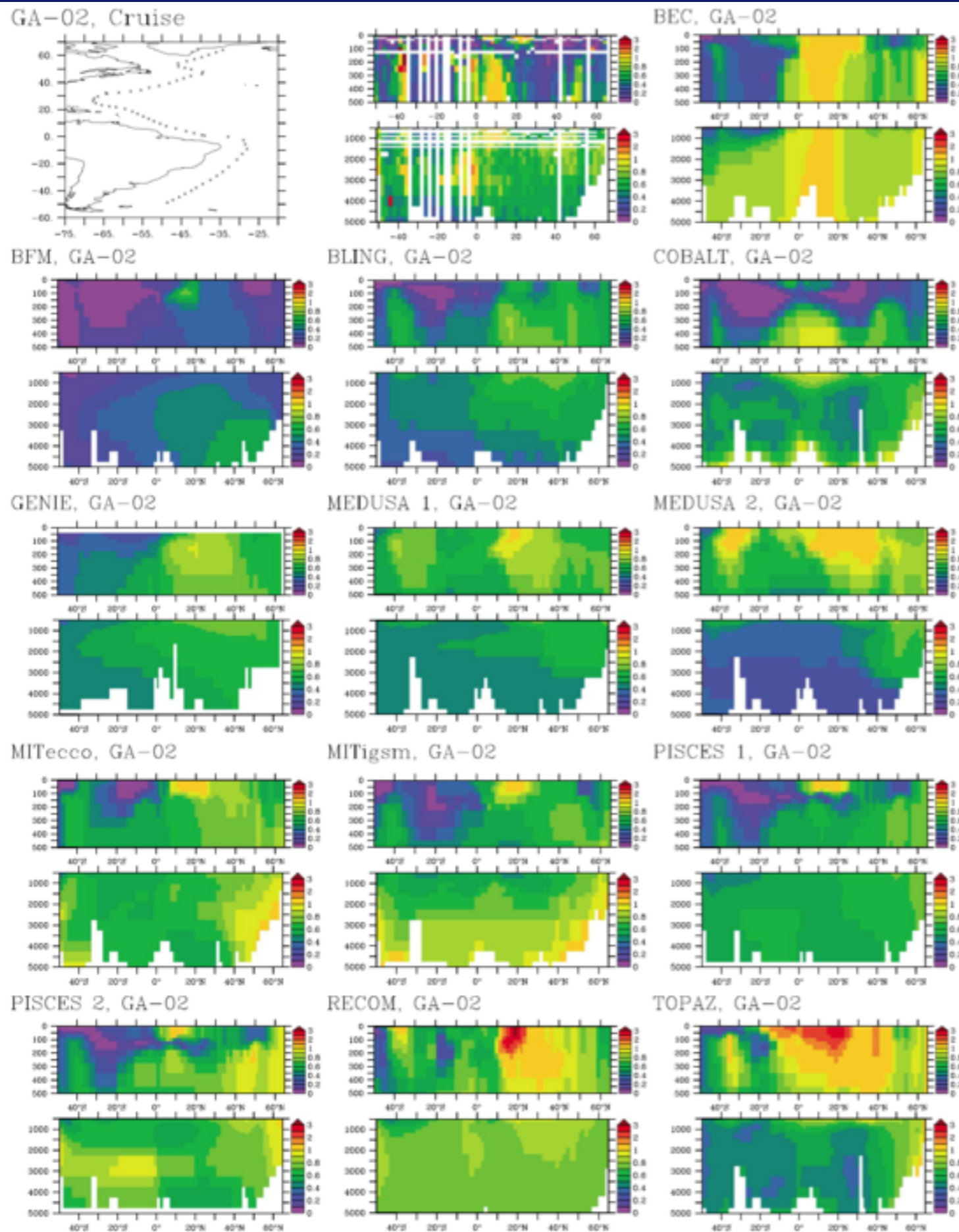


TOPAZ, GA-02





# GEOTRACES GA-02 溶存鉄



## **Iron Model Intercomparison Project (FeMIP)**

Working Group proposal submitted to SCOR April 2016

Prepared by co-chairs:

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# 主な実施項目

1. 必要最低限の鉄モデルの定式化を提案,  
オプションとしてより高度な定式化を提案
2. 鉄のデータセットを整備し,  
モデルのスキルを評価するツールを提供
3. モデル間相互比較により外部からの鉄供給  
量の評価や海洋内の鉄の滞留時間を評価
4. 鉄循環と生物過程の相互作用について検討