地球のマントル対流の特徴と物質分化・循環

１．地球のマントル対流の特徴

マントル対流の基礎方程式
マントル対流の性質
マントル対流の特徴
- リソスフェア（表層）とアセノスフェア（内部）
- アセノスフェア（内部）：遷移層
- アセノスフェア（内部）：CMB

マントル対流の基礎方程式

質量、運動量、エネルギーの保存

ブジネスク近似、浮力は温度→密度変化のみとし、無次元化

$$
\begin{aligned}
\nabla \cdot \vec{v} &= 0 \\
0 &= -\nabla P + \frac{\partial \tau_{ij}}{\partial x_j} + \mathrm{Ra} T \delta_{i3} \\
\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T &= \nabla^2 T + \epsilon
\end{aligned}
$$

ここで、Raはレイリー数　、ϵは無次元化された発熱量

Ra = 熱拡散の時間スケール／RT不安定成長の時間スケール

ε = 発熱量／熱伝導による熱流量

マントル対流の基礎方程式

状態方程式、構成則、相平衡

$$\rho \;=\; \rho_r\left[1-\alpha(T-T_r)+\frac{1}{K_T}(P-P_r)+\vec{\beta}\cdot(\vec{C}-\vec{C}_r)\right]$$

$$\sigma_{ij}=A^{-\frac{1}{n}}\dot{e}^{\frac{1-n}{n}}\exp\left(\frac{E+PV}{n\mathrm{R}T}\right)\dot{e_{ij}}$$

$$\sigma_{ij} \;=\; \left[-P+\left(\zeta-\frac{2}{3}\mu\right)e_{kk}\right]\delta_{ij}+2\mu e_{ij}$$

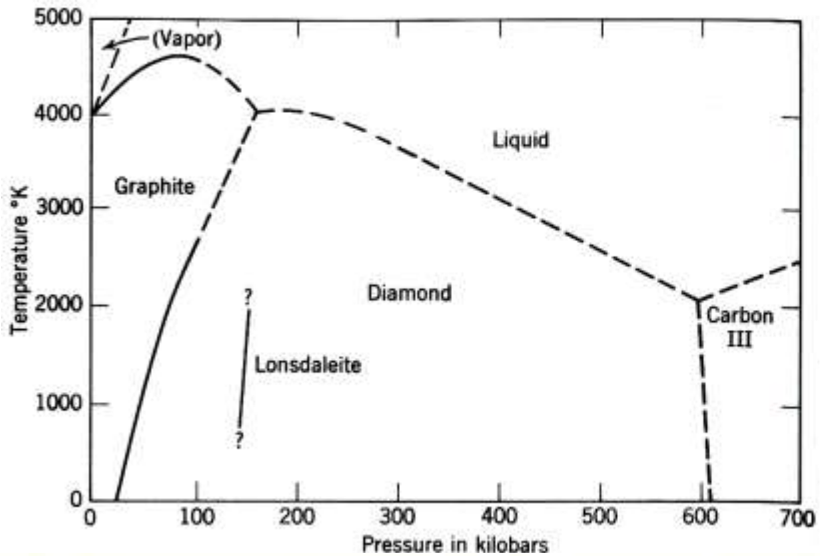
相平衡・化学反応 ($\mu^i_\alpha = \mu^i_\beta$)

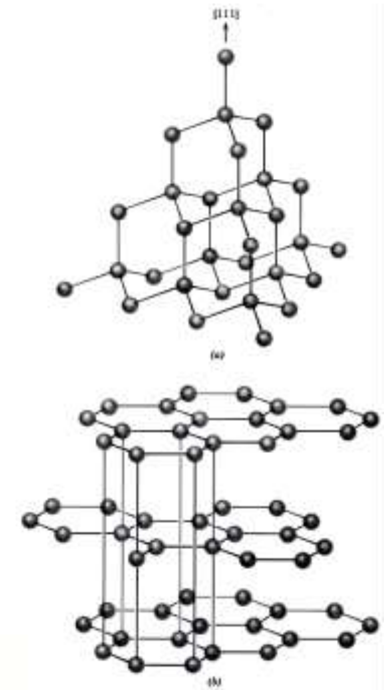
マントル対流の基礎方程式

相平衡・相変化

Klein et al, 1993

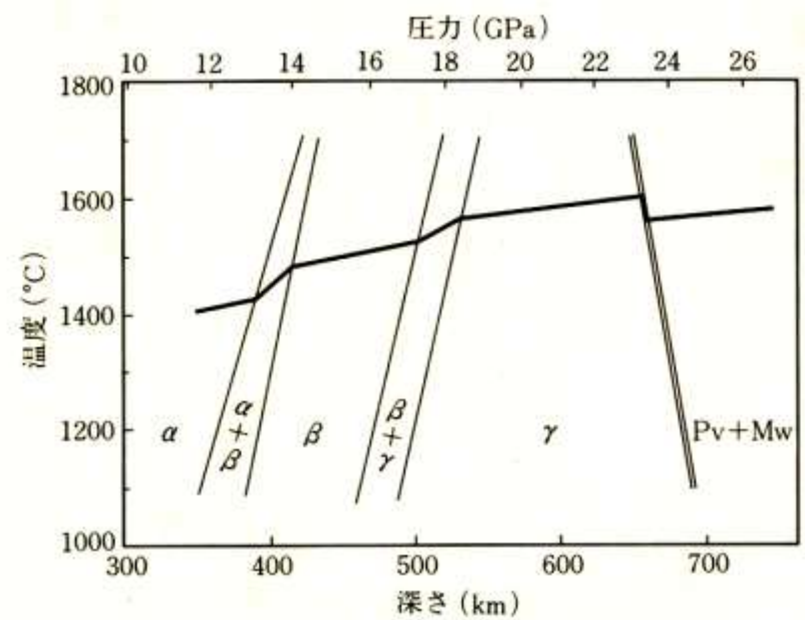
系の化学組成＝
C





Toriumi et al, 1997

系の化学組成＝
$(Mg,Fe)_2SiO_4$



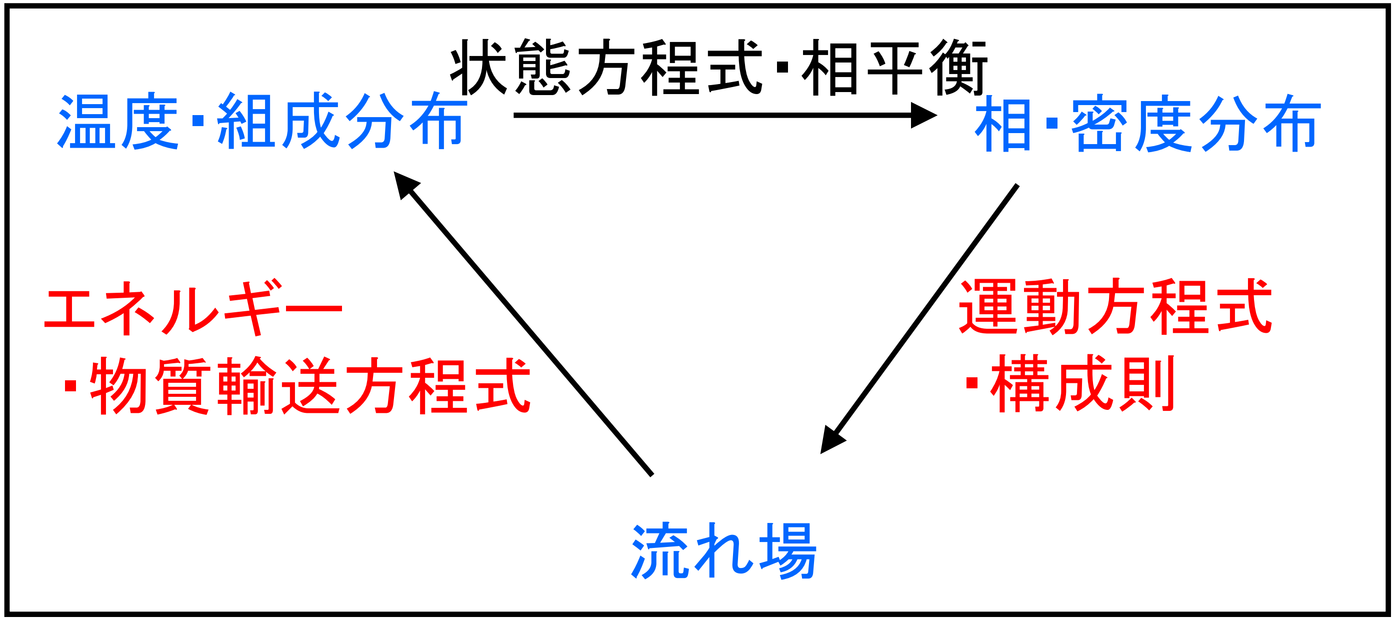
マントル対流の基礎方程式

重力が駆動：　地球内部の密度分布がパターンを決める

流れ場：粘性力が卓越するために、慣性項はおちるが解くのは大変
（定常解をもとめることに相当）

非線形性：　エネルギー輸送と非線形物性で生まれる

相変化や反応の化学も重要



マントル対流の性質
変数と無次元数

変数		単位/定義	上部マントル	下部マントル	全マントル
C_P	定圧比熱	$\mathrm{J\ kg^{-1}K^{-1}}$	1.2×10^3	1.2×10^3	1.2×10^3
D	対流層の厚さ	m	6.60×10^5	22.3×10^5	28.9×10^5
H	発熱量	$\mathrm{W\ kg^{-1}}$	$2.3\sim6.2\ \times10^{-12}$	$2.3\sim6.2\ \times10^{-12}$	$2.3\sim6.2\ \times10^{-12}$
k	熱伝導率	$\mathrm{W\ m^{-1}\ K^{-1}}$	4.2	11.8	8.1
κ	熱拡散率	$\mathrm{m^2\ s^{-1}}$	1×10^{-6}	2×10^{-6}	1.5×10^{-6}
ρ	密度	$\mathrm{kg\ m^{-3}}$	3.5×10^3	4.9×10^3	4.5×10^3
α	熱膨張率	$\mathrm{K^{-1}}$	3×10^{-5}	1×10^{-5}	2×10^{-5}
μ	粘性係数	Pa s	$0.1\sim1\times10^{21}$	$0.2\sim2\times10^{22}$	$1\sim3\times10^{21}$
ν	動粘性係数	$\mathrm{m^2\ s^{-1}}$	$0.3\sim3\times10^{17}$	$0.4\sim4\times10^{18}$	$2\sim7\times10^{17}$
ΔT	鉛直方向の温度差	K	$1.5\sim2.0\times10^3$	$1.0\sim2.0\times10^3$	$2.5\sim4.0\times10^3$
無次元数					
Ra	レイリー数	$\frac{g\alpha\Delta T D^3}{\kappa\nu}$	$0.5\sim6\times10^6$	$0.1\sim3\times10^6$	$1\sim6\times10^7$
ϵ	無次元発熱量	$\frac{Hd^2}{C_P\kappa\Delta T}$	$0.4\sim1.5$	$2.4\sim12.8$	$2.7\sim11.5$

マントル対流の性質

2次元定常状態での構造: 下面加熱、上面冷却、ε =0

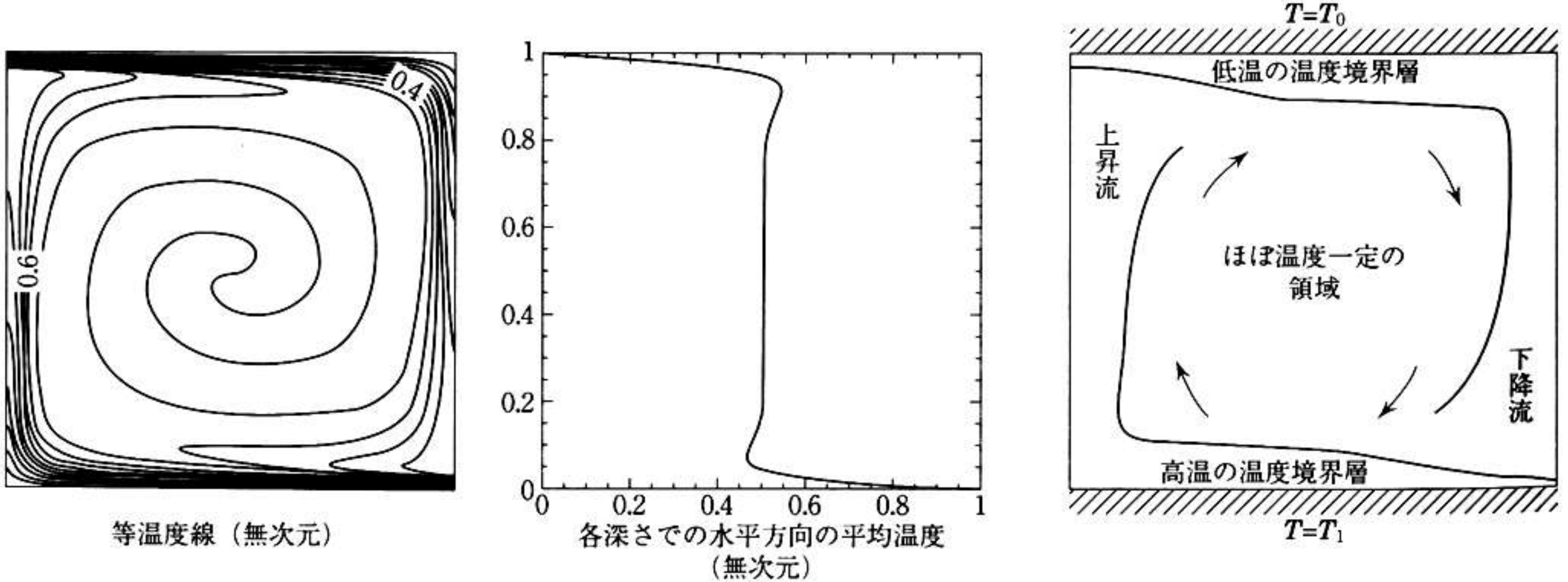


図 2　粘性が高く慣性力が無視できるような流体の箱の中での対流（岩波講座地球惑星科学10巻の図3.2および文献 3））。箱の上下面での温度が各々一定で側面からは熱の出入りはなく，いずれの面でも自由すべりが起こると仮定。レイリー数は10^6

野津憲治, 清水洋, 2003

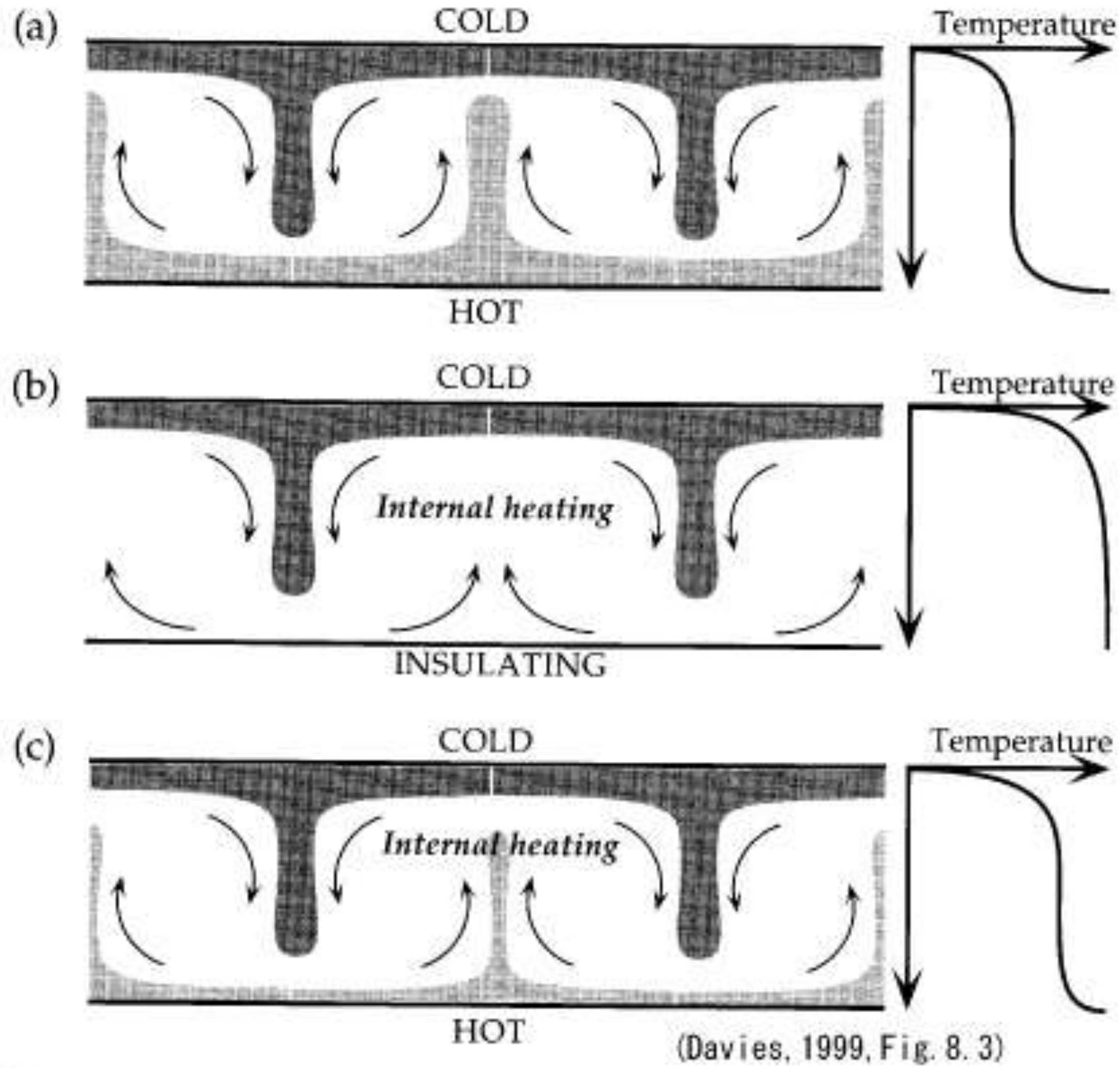
マントル対流の性質

ε の効果

ε= 0

Large ε

Intermediate ε



(Davies, 1999, Fig. 8. 3)

マントル対流の性質

スケーリング：境界層の厚さと速度

温度境界層における移流による熱流入量と熱伝導による排出熱量とのつりあい：

$$\rho C_P u \delta \Delta T \sim k \frac{\Delta T}{\delta} D$$

$\delta, D =$ 境界層の厚さと幅, $\Delta T = (T_1 - T_0)/2$、$u =$ 境界層内での水平流の速さ。

$$\delta \sim \sqrt{\frac{\kappa D}{u}} \quad \text{or} \quad u \sim \frac{\kappa D}{\delta^2}$$

境界層に働く浮力（$g\rho\alpha\Delta T D\delta$）と粘性抵抗（$\mu\frac{u}{D}D$）のつりあい:

$$u \sim g\rho\alpha\Delta T D\delta/\mu$$

$$\frac{\delta}{D} = \mathrm{Ra}^{-\frac{1}{3}} \quad \text{and} \quad \frac{u}{\kappa/D} = \mathrm{Ra}^{\frac{2}{3}}$$

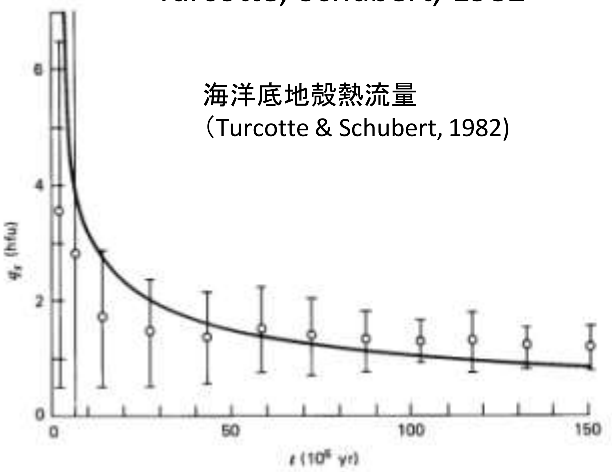
地球表層条件では

δ = 数 km ~ 数十 km
u = 数 cm/y ~ 数十cm/y

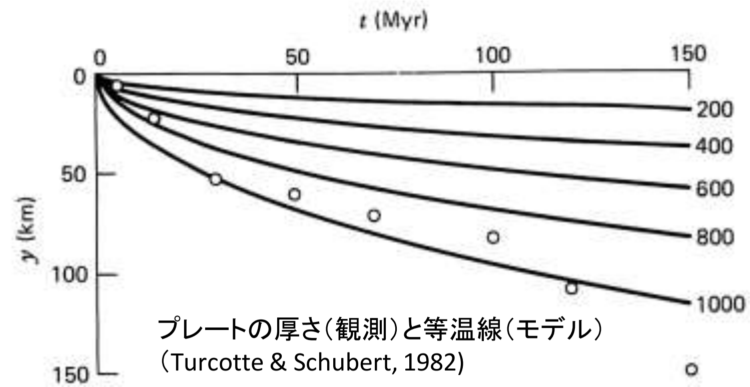
マントル対流の性質

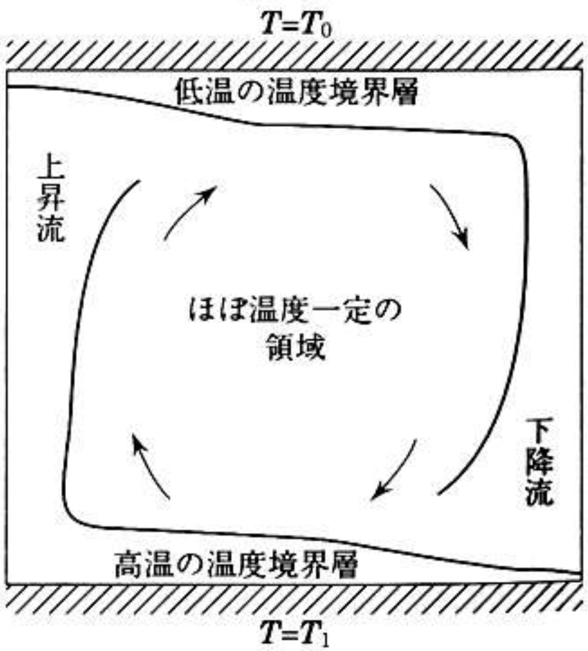
プレート運動＝マントル対流の地表表現：プレート～境界層

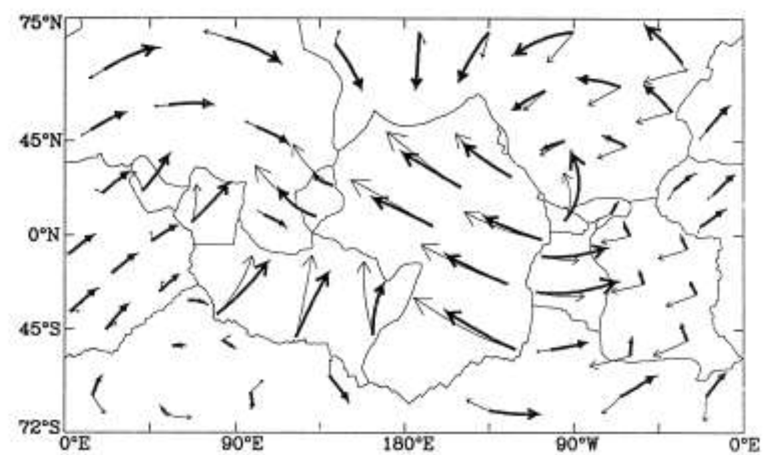
Turcotte, Schubert, 1982



Turcotte, Schubert, 1982







Argus and Gordon (1991) thick arrow: no-net rotation model
thin arrow: hotspot reference model

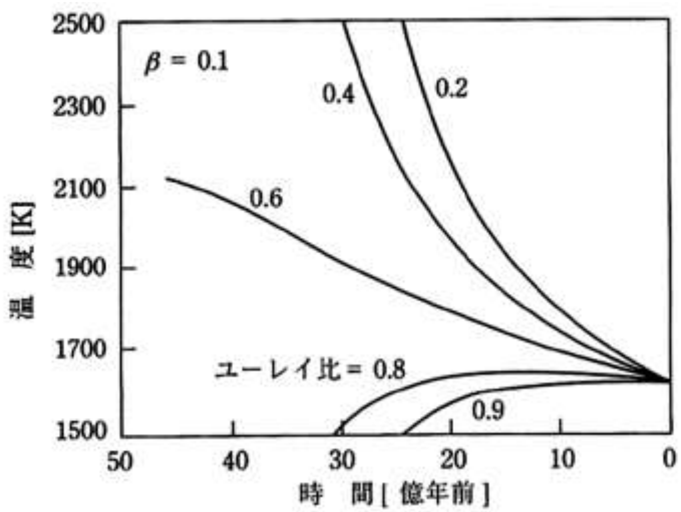
マントル対流の性質

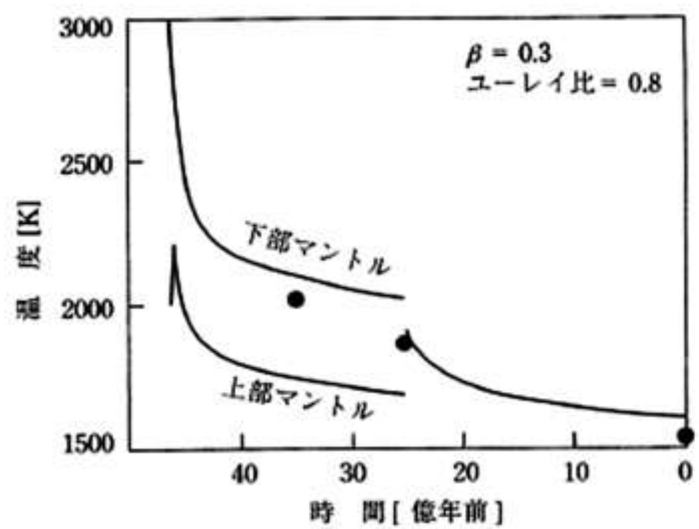
スケーリング：熱輸送とパラメター化対流モデル

$$Nu = aRa^{\beta}$$

$$MC_P \frac{dT(t)}{dt} = -Nu(Ra)\,K\,\frac{T(t)-T_s}{R}\,4\pi R^2 + \underline{H(t)}$$

発熱量→ユーレイ比





Honda (1995)

マントル対流の特徴

リソスフェア（表層）とアセノスフェア（内部）

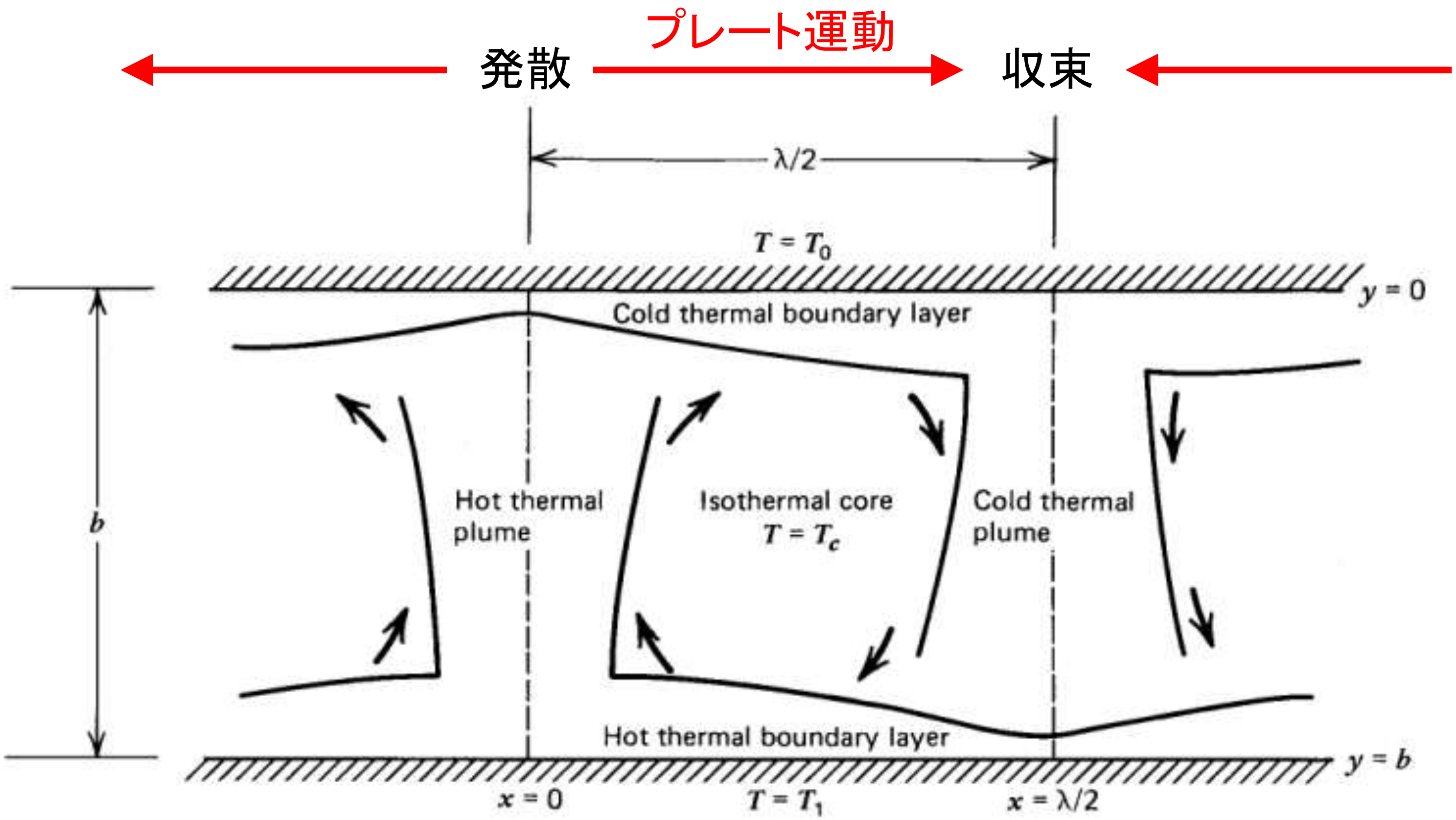


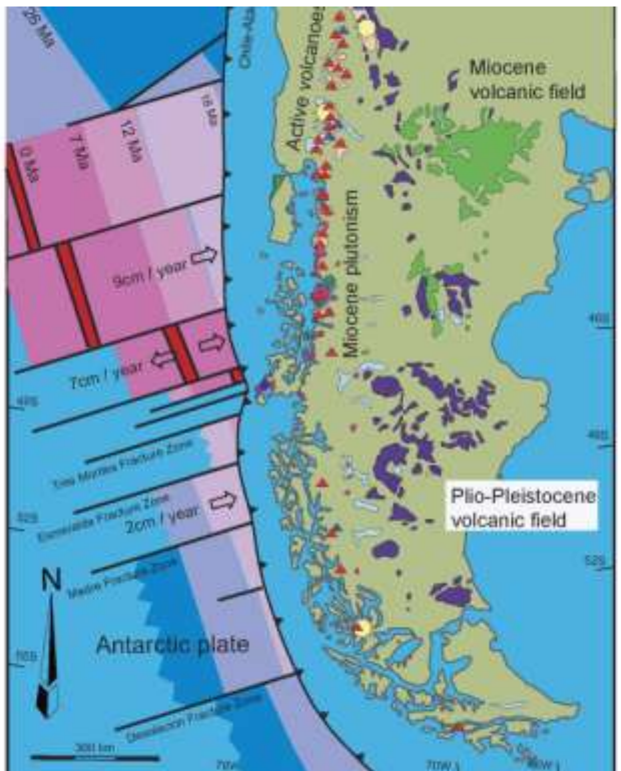
Figure 6-39 Boundary layer structure of two-dimensional thermal convection cells in a fluid layer heated from below.

Turcotte & Schubert（1982) に加筆

マントル対流の特徴

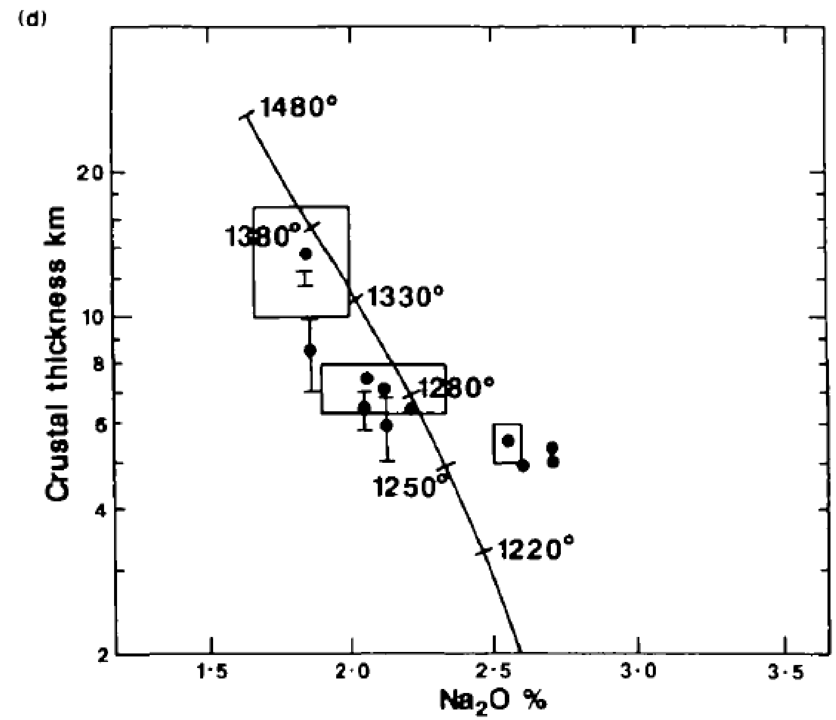
リソスフェア（表層）とアセノスフェア（内部）

海嶺（発散境界）の沈み込み（収束）



海嶺は熱くない
（平均的なマントルポテンシャル温度
~1300度Cにほぼ等しい)

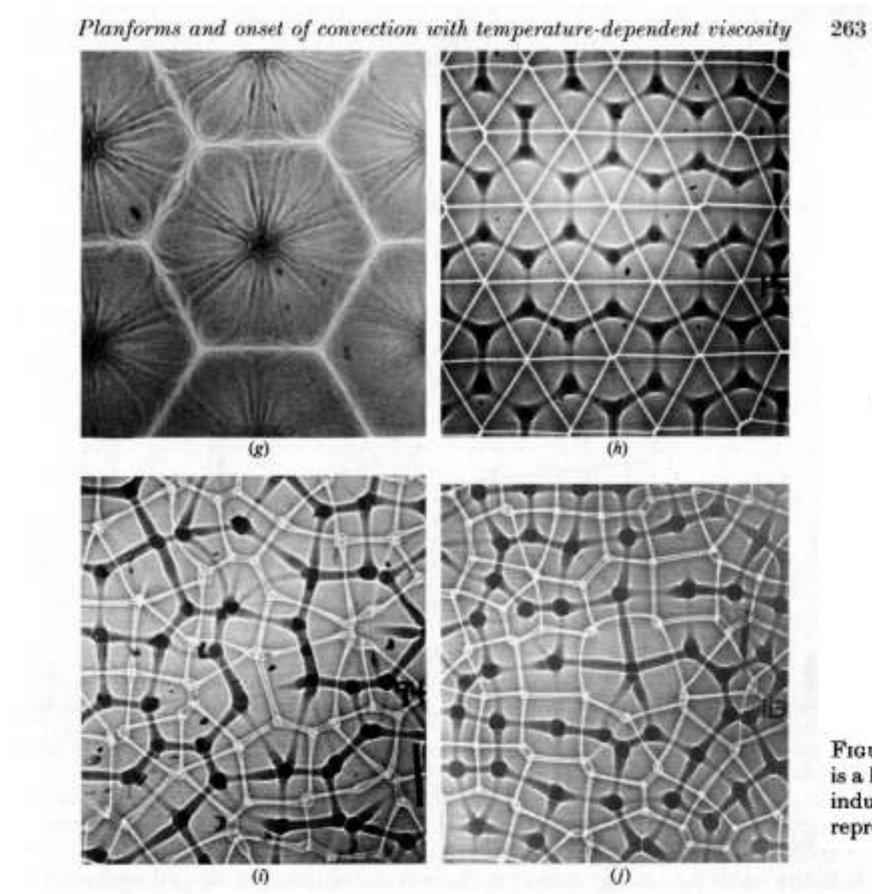
D McKENZIE AND M J. BICKLE (1988)



McKenzie, Bickle, 1988

マントル対流の特徴
リソスフェア（表層）とアセノスフェア（内部）

粘性の温度依存性⇒3次元対流中、上昇流はスポット的（≠線的構造）



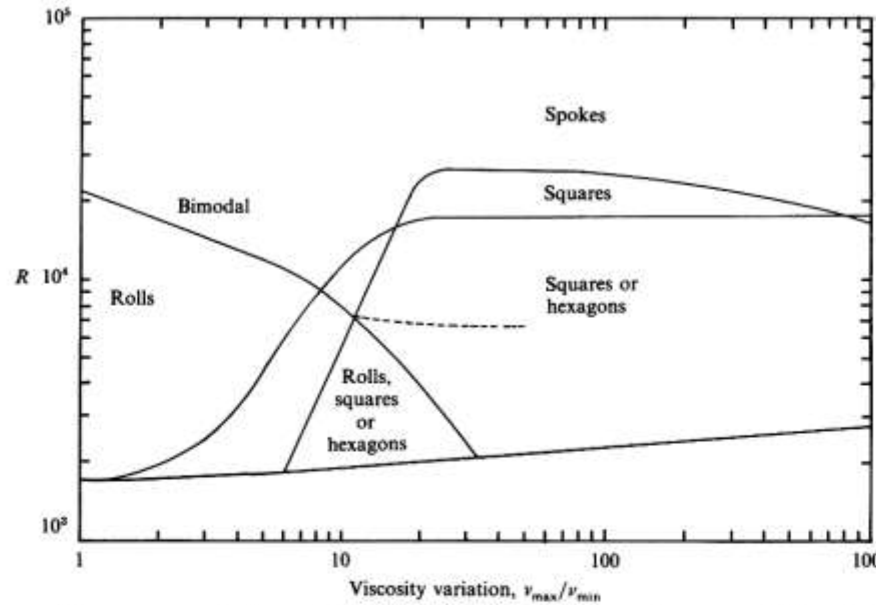


FIGURE 30. A summary of the stability maps for rolls, hexagons and squares with $k = 3.15$. There is a large amount of hysteresis where the realized planform depends on what pattern was originally induced. In one small area rolls, hexagons or squares are all possible planforms. The dashed line represents R_B.

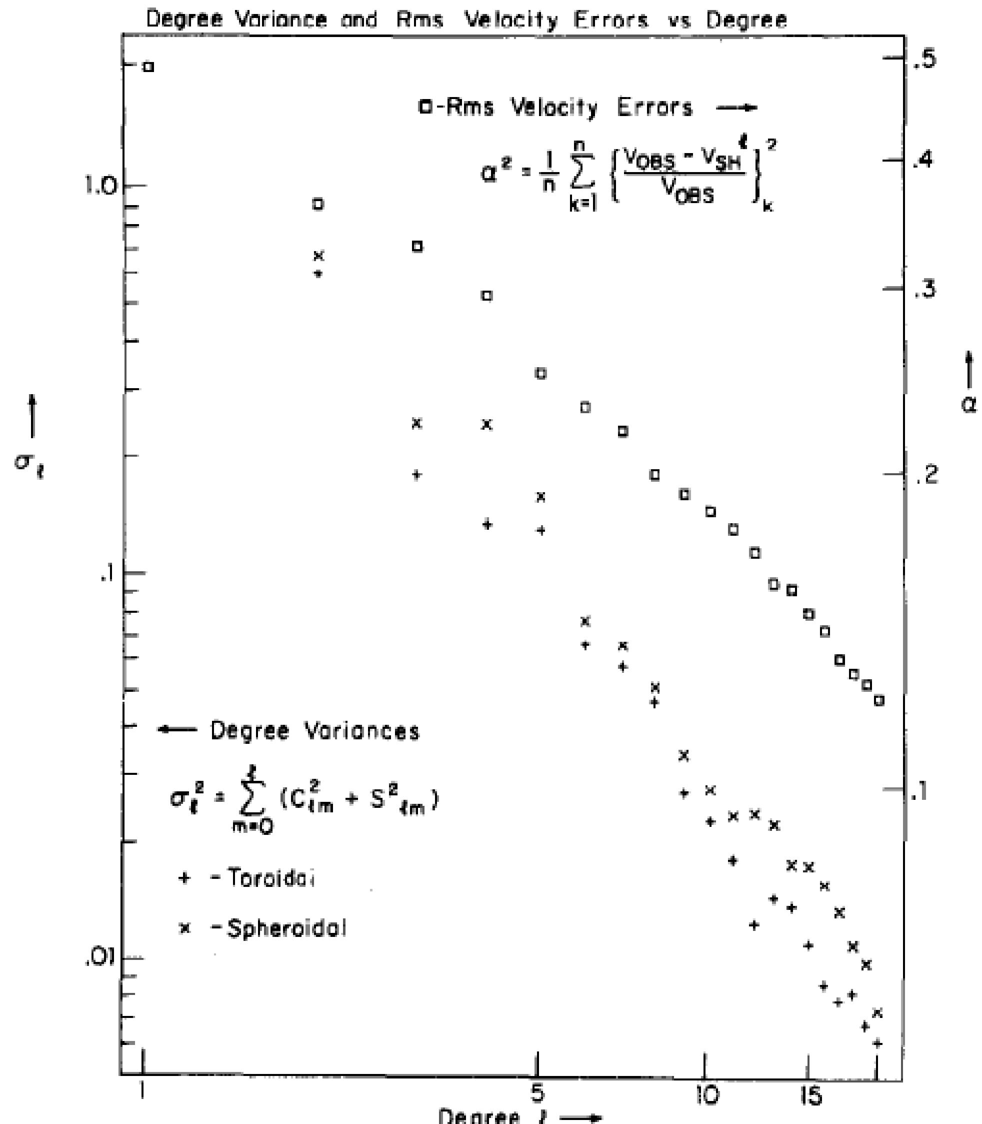
White（1988）

マントル対流の特徴

リソスフェア（表層）とアセノスフェア（内部）

プレート速度の
troidal成分～spheroidal成分

$$0 = \frac{\partial \sigma_{ij}}{\partial x_j} + \rho g \delta_{i3}$$



Hager & O’Connell（1978)

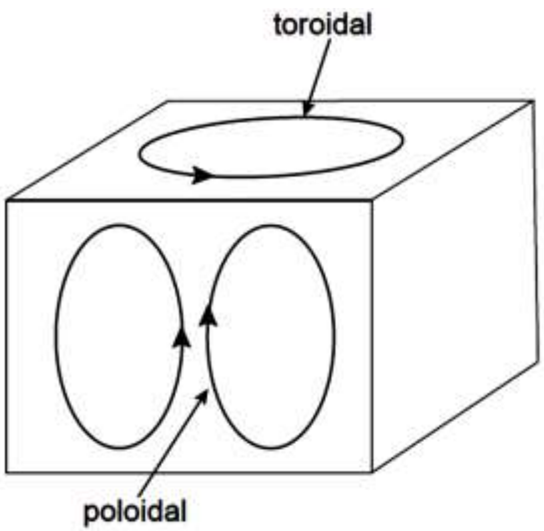
マントル対流の特徴

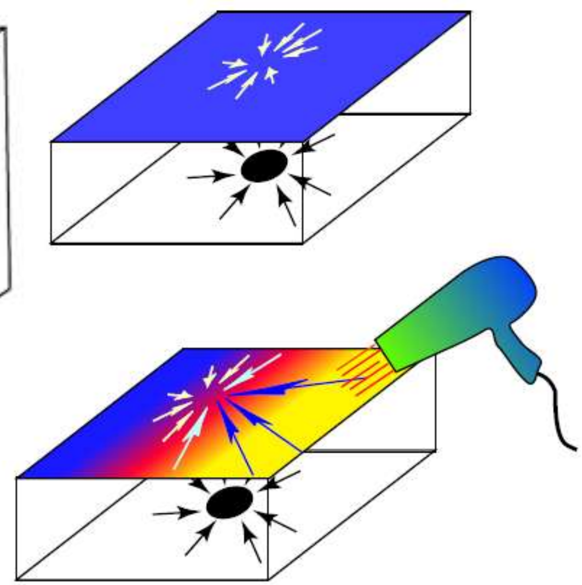
リソスフェア（表層）とアセノスフェア（内部）

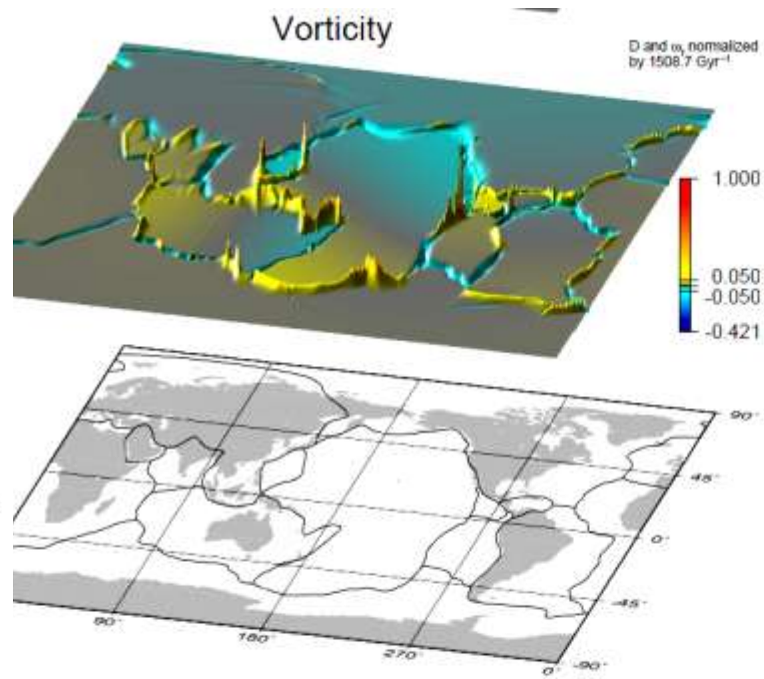
$$0 = \frac{\partial \sigma_{ij}}{\partial x_j} + \rho g \delta_{i3}$$

(松山、研究中) toroidal poloidal

$$-\rho g \delta_{i3} = \left(\frac{\partial \mu}{\partial x}\frac{\partial^2}{\partial z \partial y} - \frac{\partial \mu}{\partial y}\frac{\partial^2}{\partial z \partial x}\right)\Psi + \left[(\nabla \mu)\cdot\left(\frac{\partial^2}{\partial z^2}\nabla\right) - \left(\frac{\partial \mu}{\partial z}\right)\left(\frac{\partial \mu}{\partial z}\nabla^2\right) - \nabla\cdot(\mu\nabla)\nabla_H^2\right]\Phi$$



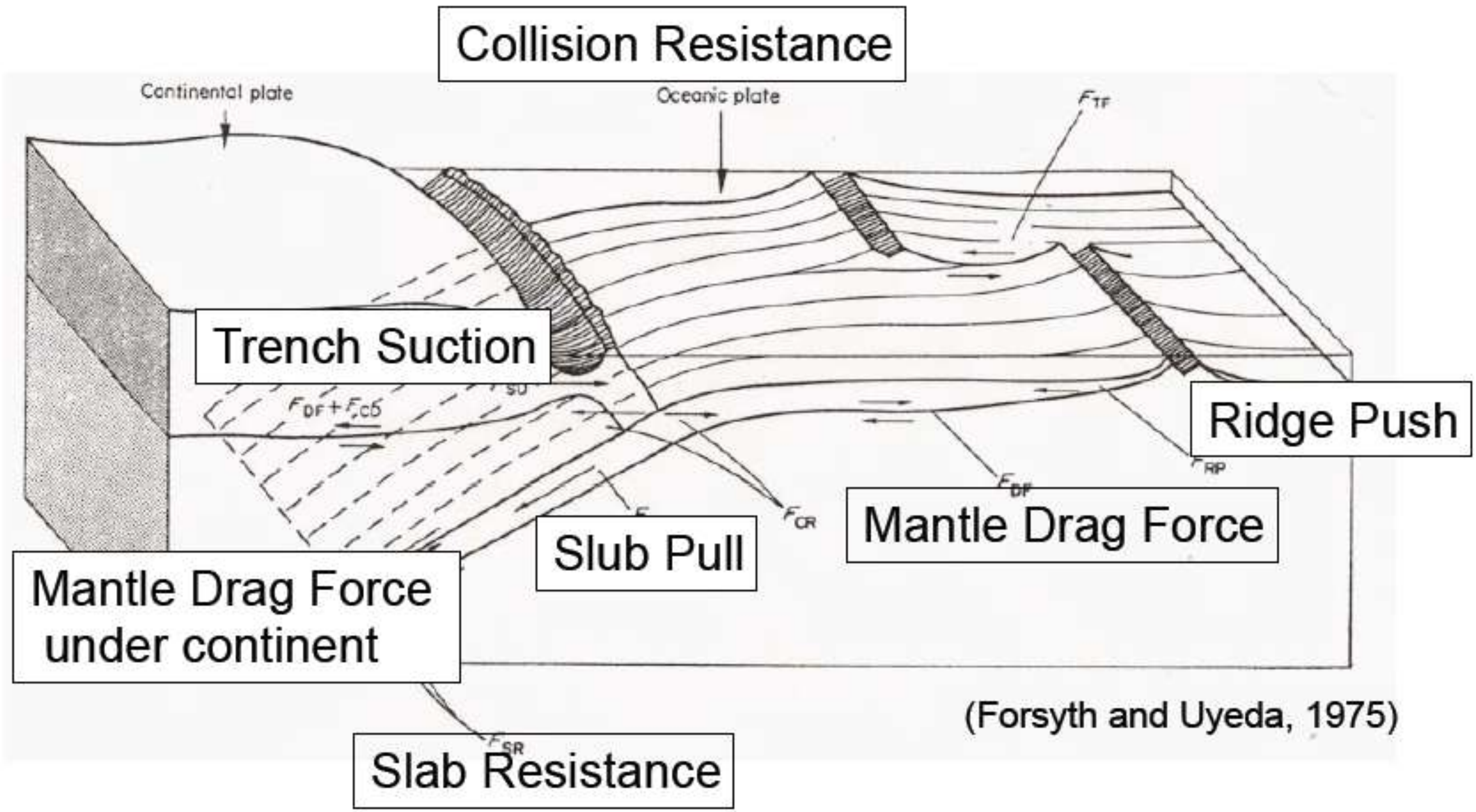




Bercovici et al. (2003)

マントル対流の特徴

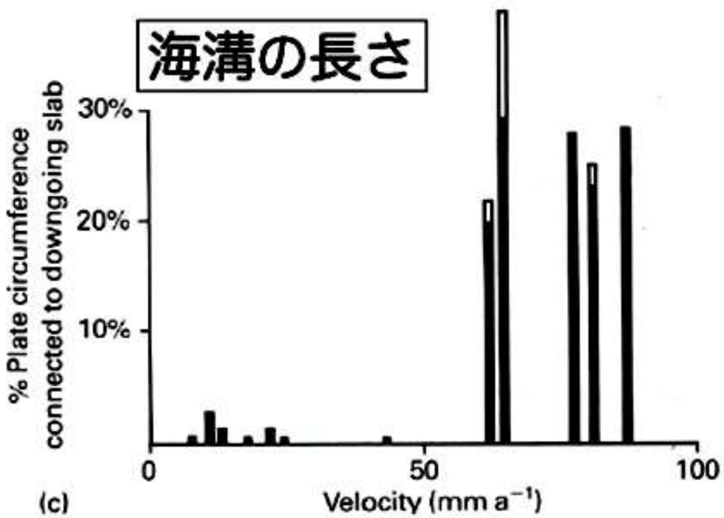
リソスフェア（表層）とアセノスフェア（内部）

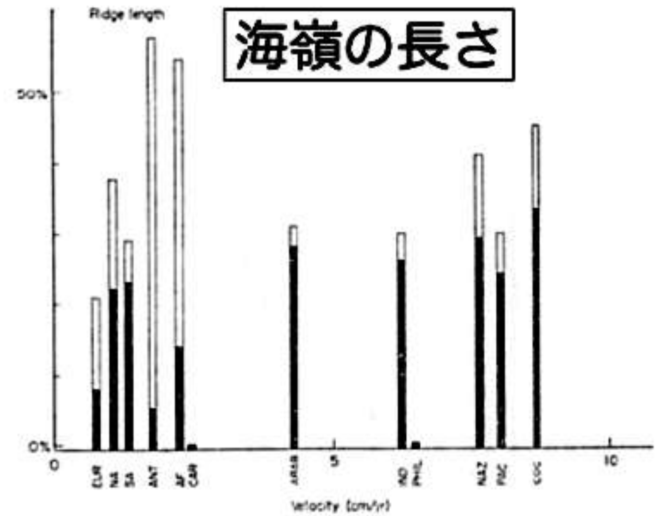


http://ofgs.ori.u-tokyo.ac.jp/~okino/lec_ofgd08/05lithosphere.pdf　より

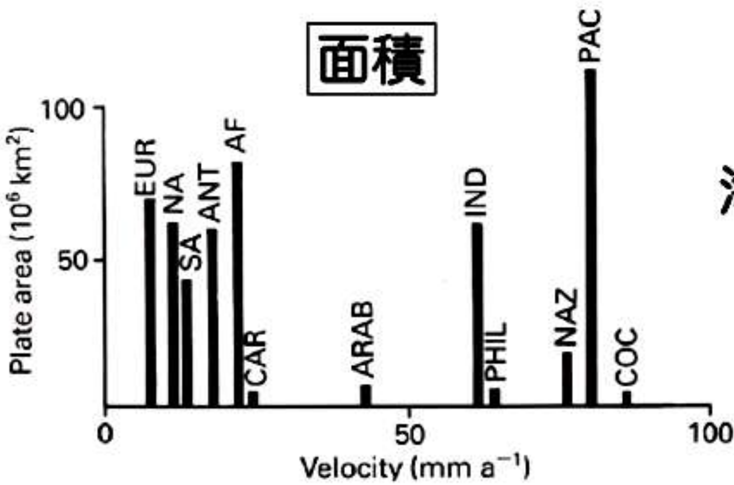
マントル対流の特徴

リソスフェア（表層）とアセノスフェア（内部）





(Forsyth and Uyeda, 1975)



海溝の長さのみが明らかな相関を示す
＝slab pull力の寄与大？

http://ofgs.ori.u-tokyo.ac.jp/~okino/lec_ofgd08/05lithosphere.pdf より

マントル対流の特徴

リソスフェア（表層）とアセノスフェア（内部）

表6.1.1　各種の力の大きさ（Forsyth & Uyeda, 1975）

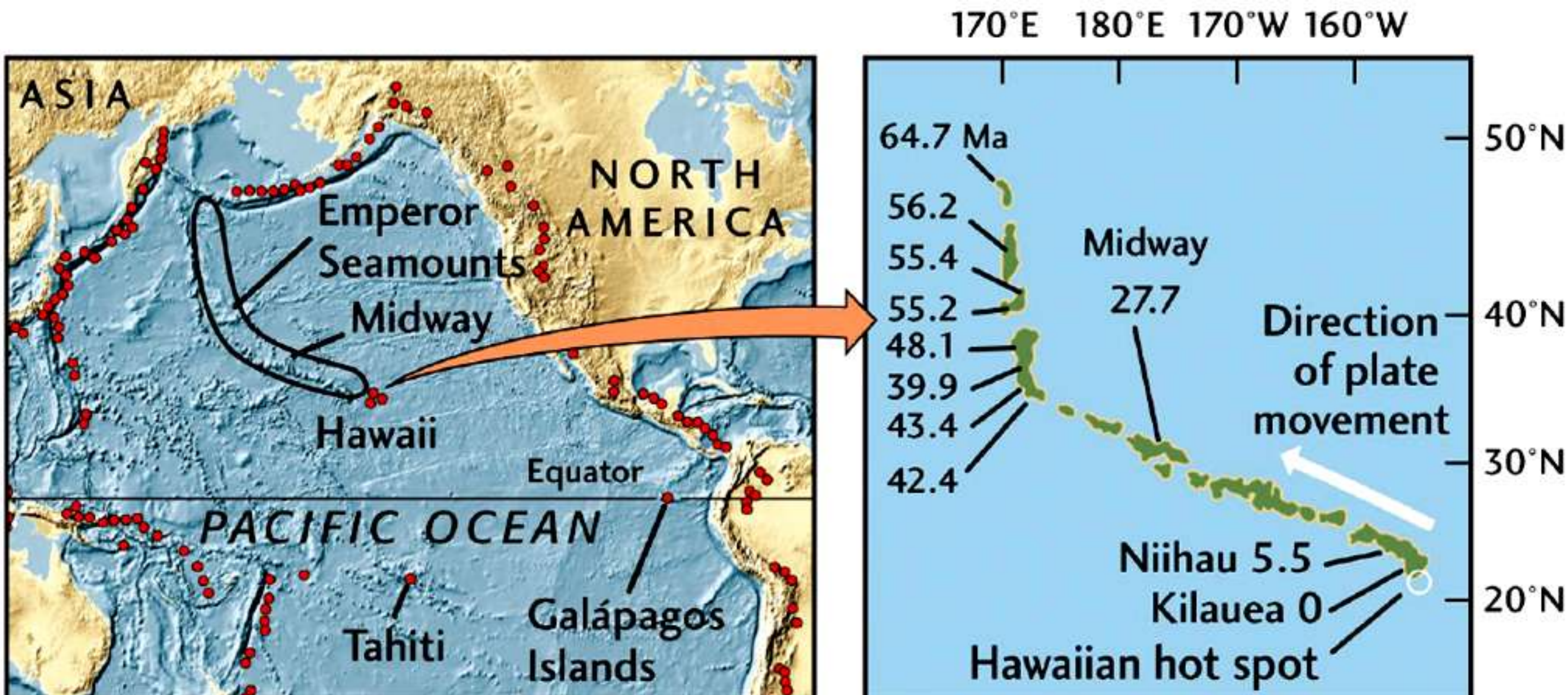
力	相対的重要度 y_m'	力の強さ y_m	（単位）
F_{RP}	0.075	0.36 ± 0.09	km^{-1}
F_{CR}	0.040	0.16 ± 0.09	km^{-1}
F_{TF}	0.063	0.36 ± 0.13	km^{-1}
F_{SP}	0.745	6.43 ± 0.19	km^{-1}
F_{SU}	0.044	0.50 ± 0.25	km^{-1}
F_{SR}	0.652	0.89 ± 0.03	$km^{-1} \cdot cm^{-1} \cdot yr$
F_{CD}	0.056	5.65 ± 2.22	$10^{-5} km^{-2} \cdot cm^{-1} \cdot yr$
F_{DF}	0.061	0.82 ± 0.30	$10^{-5} km^{-2} \cdot cm^{-1} \cdot yr$

F_{TF}：トランスフォーム断層抵抗力，F_{SU}：スラブ吸い込み力，F_{CD}：大陸プレート下ドラッグ力，F_{DF}：海洋プレート下ドラッグ力，その他は図 6.1.2 参照.

瀬野（2001）

マントル対流の特徴

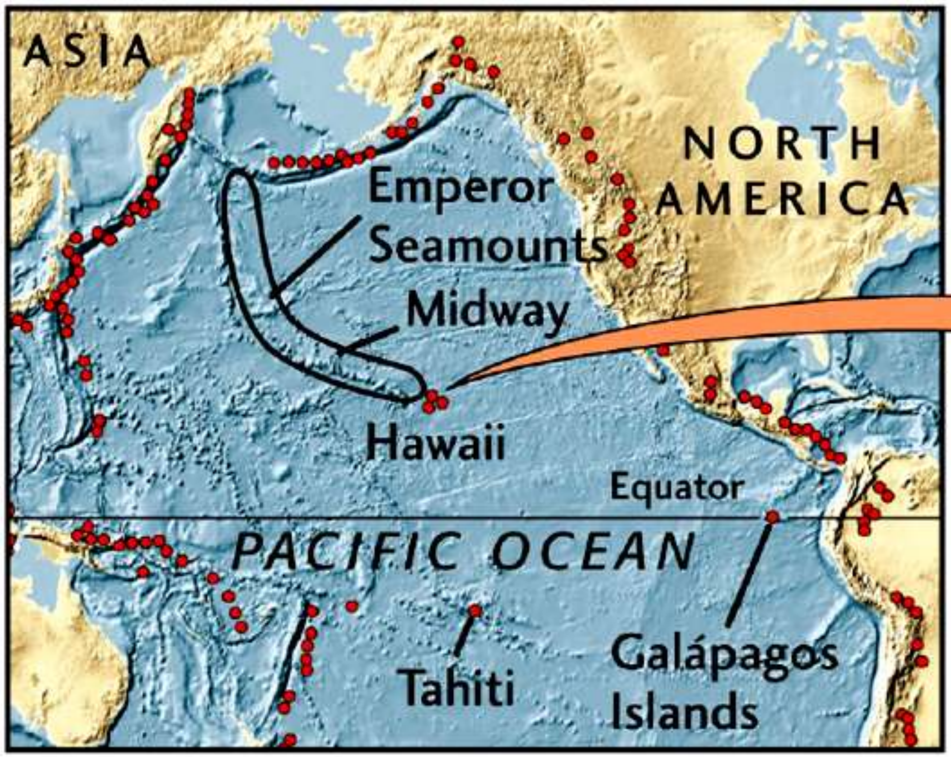
リソスフェア（表層）とアセノスフェア（内部）

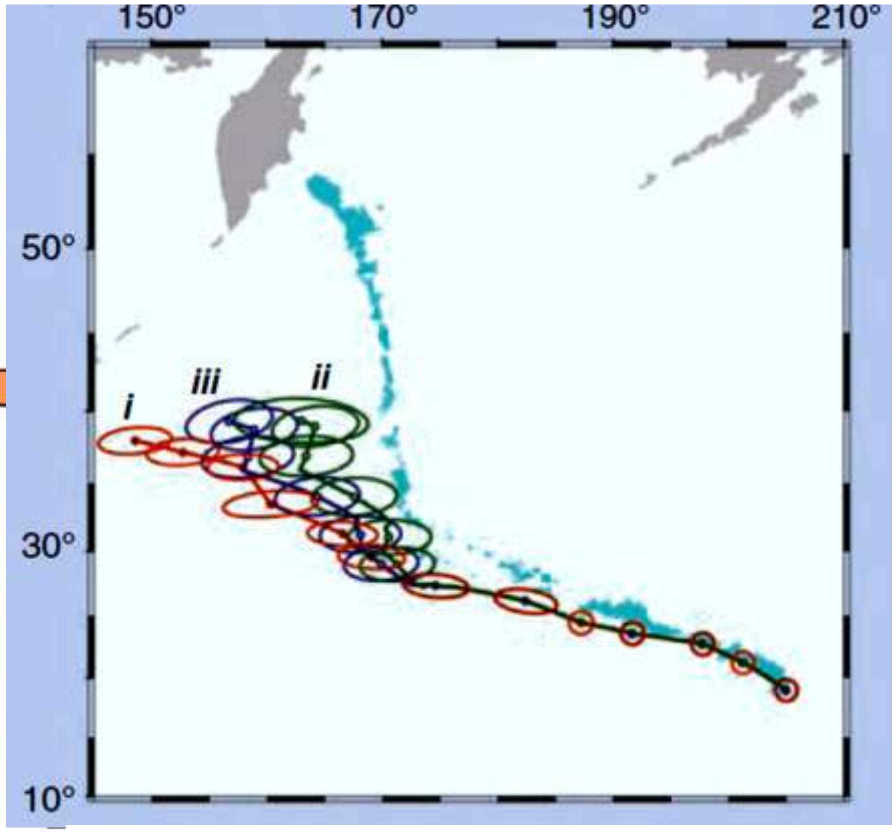


(Understanding Earth, Sliver&Jordan 2003)

マントル対流の特徴

リソスフェア（表層）とアセノスフェア（内部）





Tarduno et al. (2009)

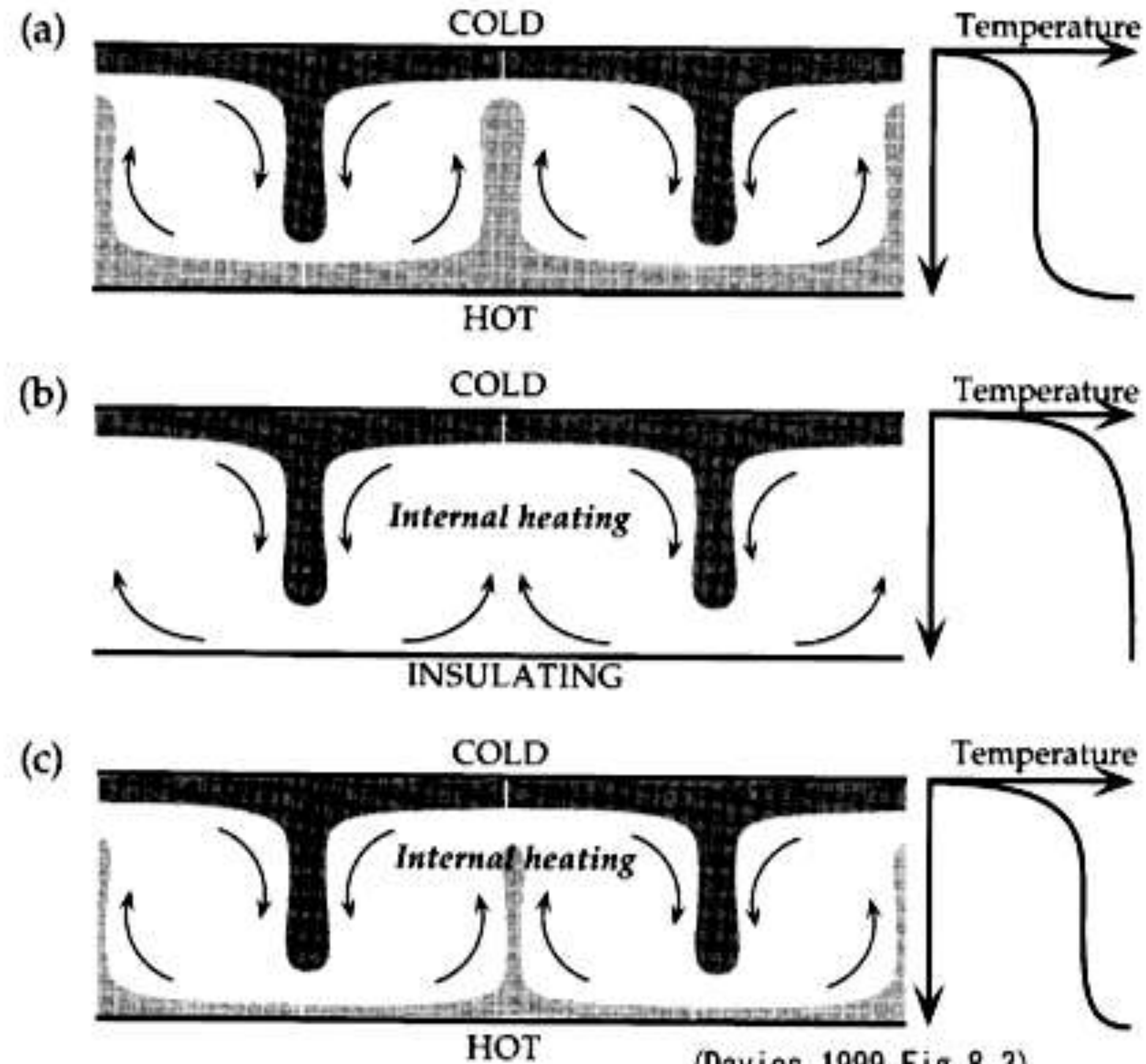
マントル対流の特徴

リソスフェア（表層）とアセノスフェア（内部）

ε= 0

Large ε

Intermediate ε

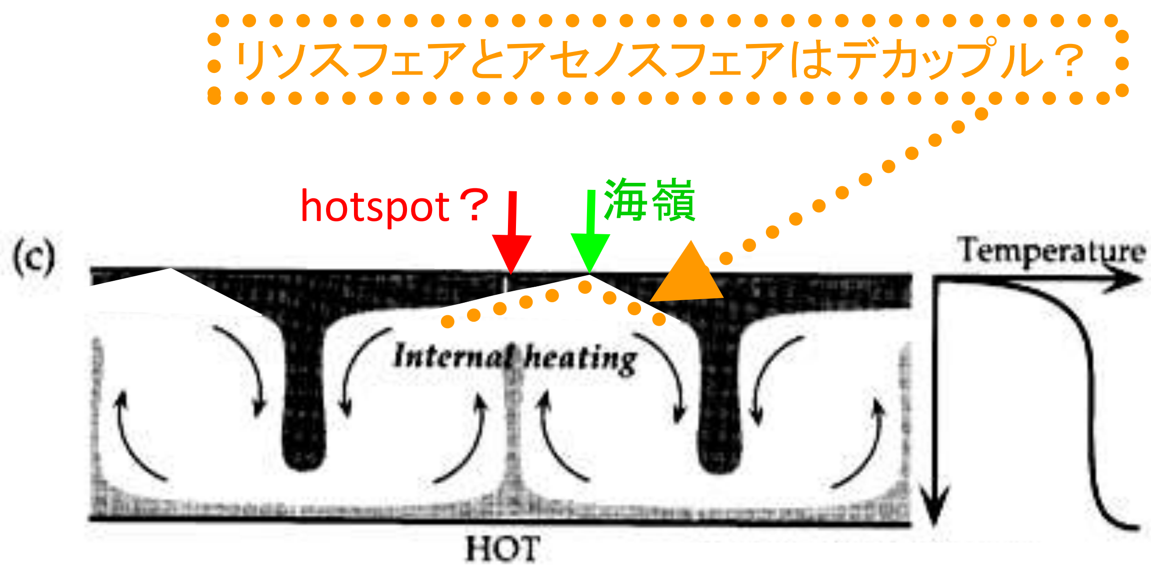


(Davies, 1999, Fig. 8. 3)

マントル対流の特徴

リソスフェア（表層）とアセノスフェア（内部）

Intermediate ε

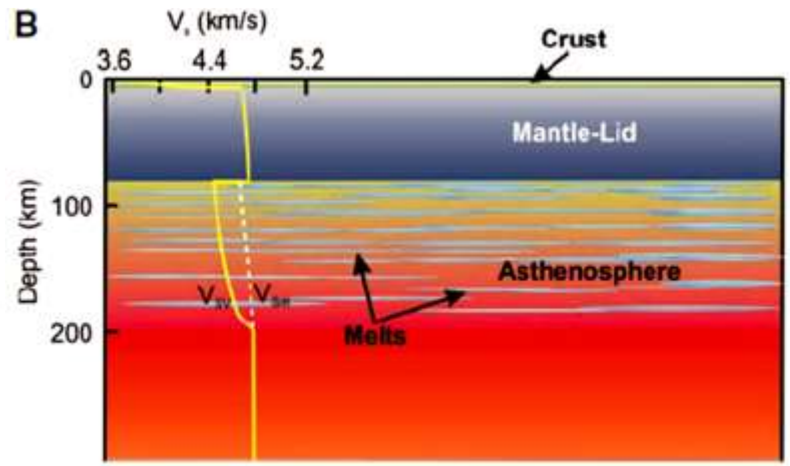


Davies, 1999 に加筆

マントル対流の特徴

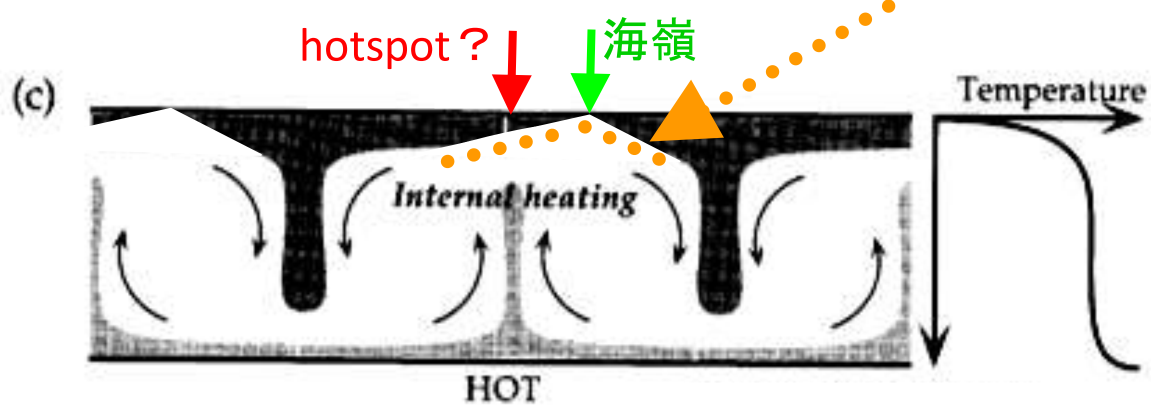
リソスフェア（表層）とアセノスフェア（内部）

Kawakatsu et al. (2009)
リソスフェア直下にS波の強いコントラストを発見



リソスフェアとアセノスフェアはデカップル？

Intermediate ε



Davies, 1999 に加筆

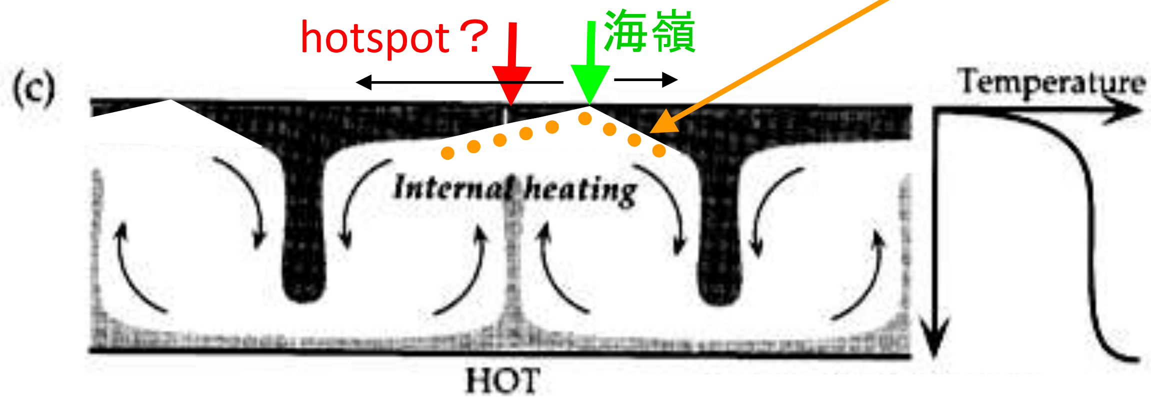
マントル対流の特徴

リソスフェア（表層）とアセノスフェア（内部）

プレート運動はマントル対流の地表表現に間違いない。
しかし内部の対流と、表面運動・テクトニクスの関係をきちんと（かなり大筋でも）理解していないように思われる。
レオロジーの複雑性、大陸地殻の存在、水などの組成の効果などが原因？

リソスフェアとアセノスフェアはデカップル？

Intermediate ε



Davies, 1999 に加筆

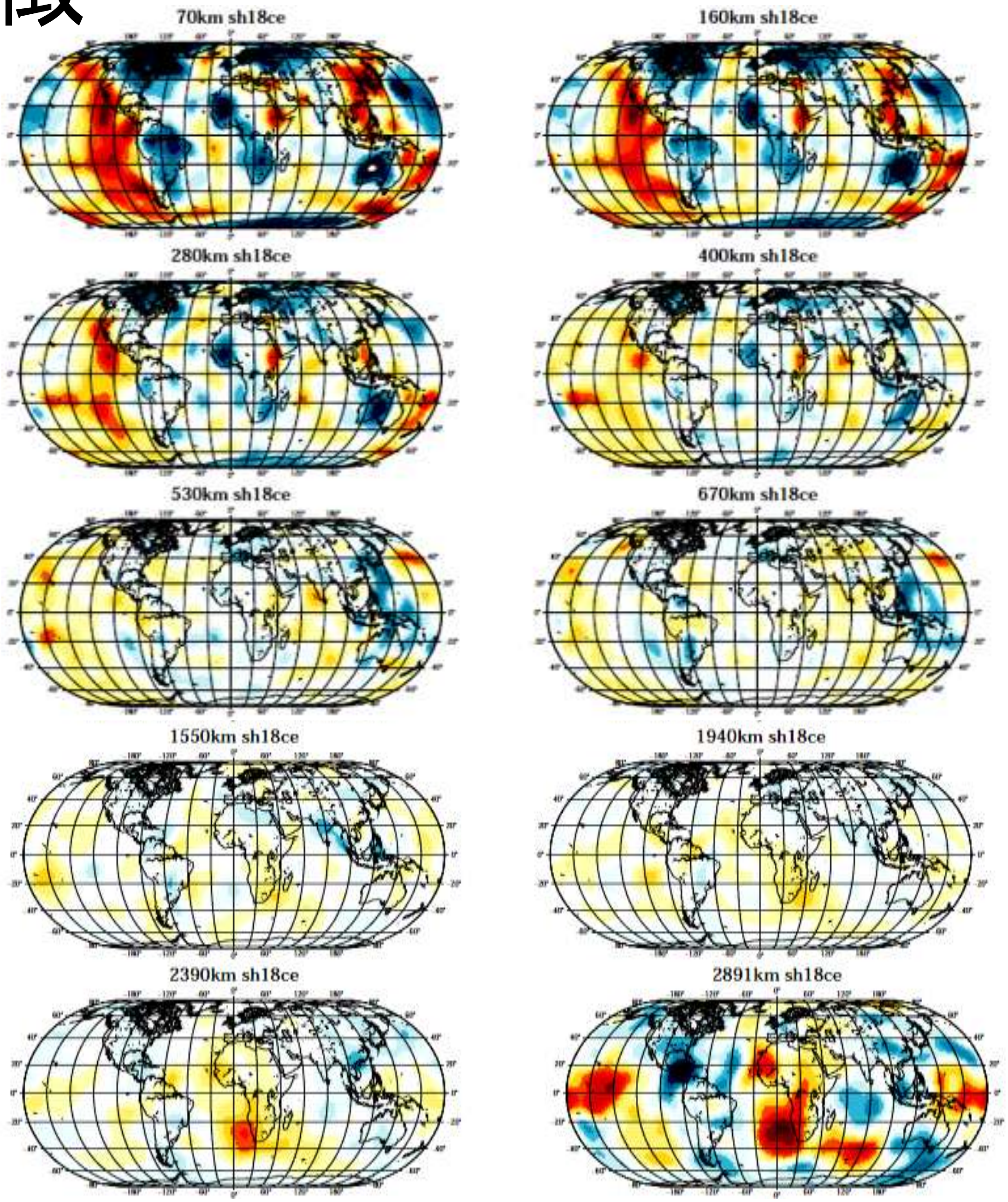
マントル対流の特徴

アセノスフェア（内部）の流れ

地震波（S波）トモグラフィーモデル
Takeuchi (2007)

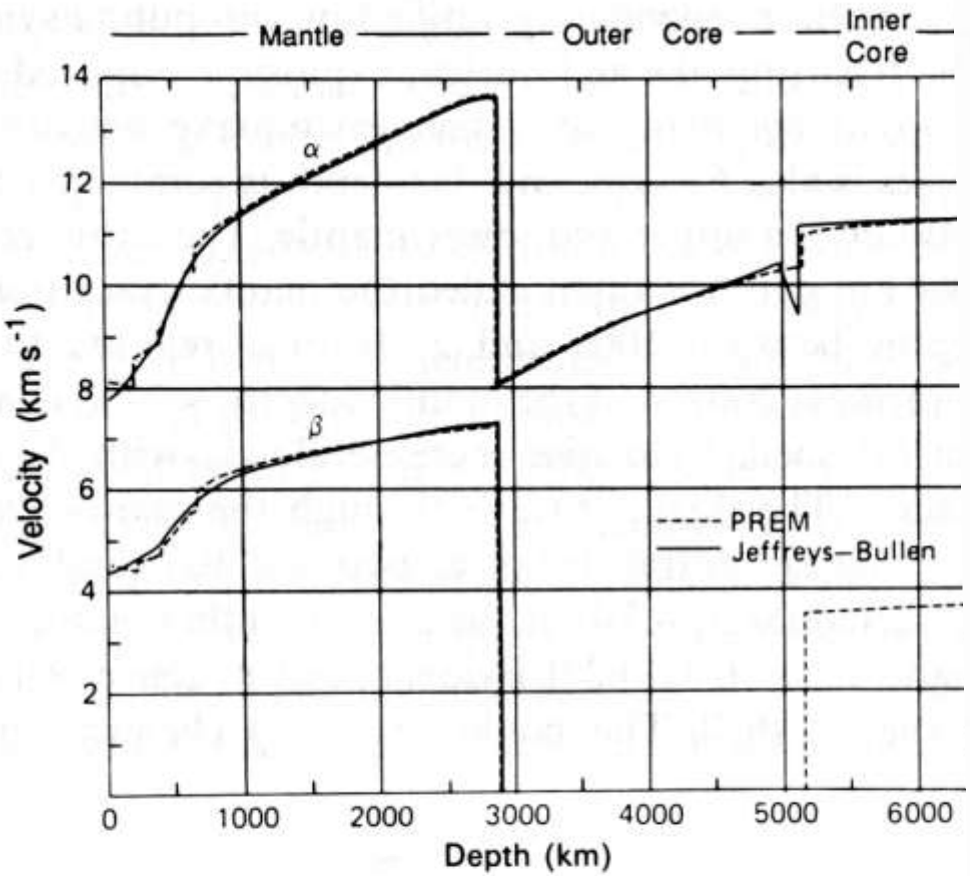
不均質性が大きい部分
リソスフェアー遷移層（660km）
コアーマントル境界付近（2891km）

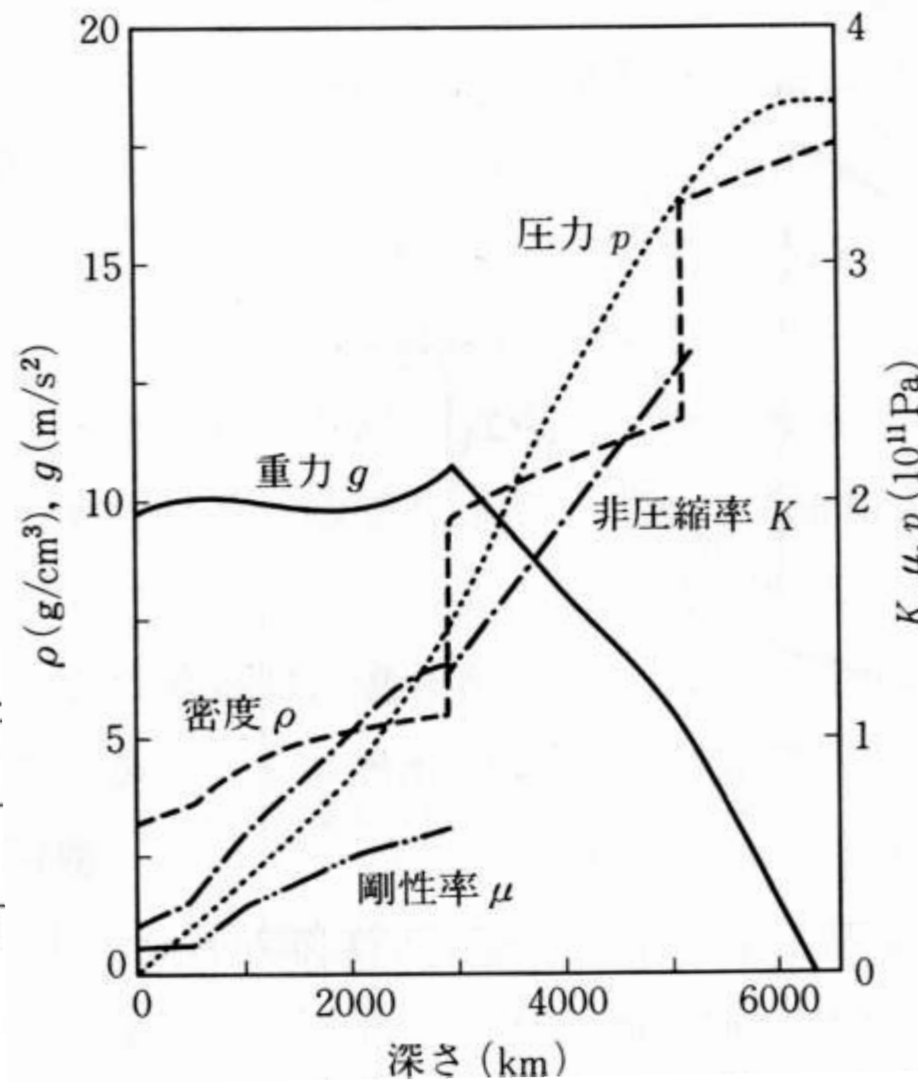
地球は表面から冷やされ、
不均質・不安定が発達
＋
下面から（表面よりは弱く？）
不安定が発達



マントル対流の特徴

アセノスフェア（内部）の流れ





地球内部構造

Toriumi et al, 1997

マントル対流の特徴

アセノスフェア（内部）の流れ

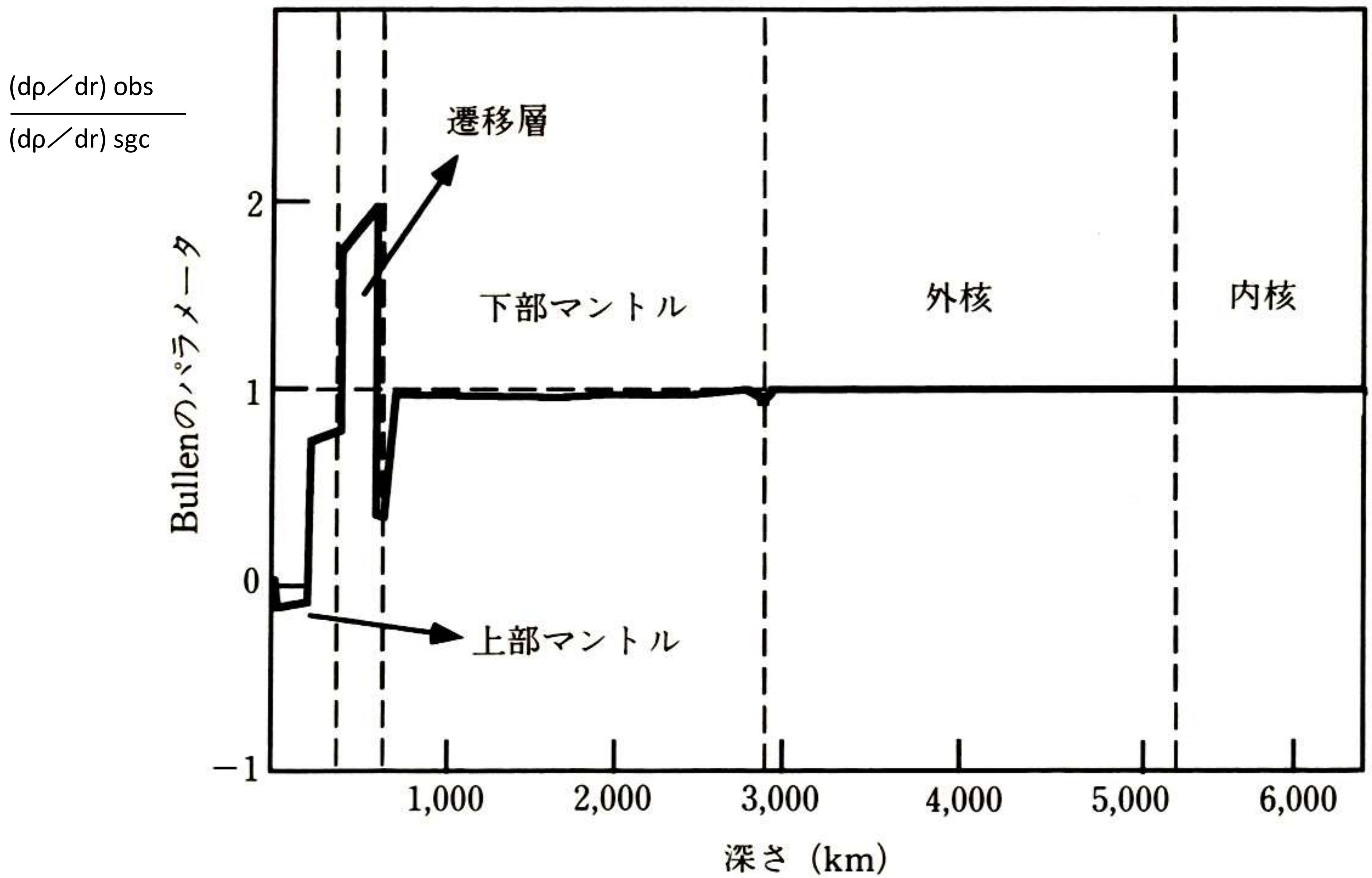


図 1-4 Bullen のパラメータの深さ分布（Dziewonski and Anderson, 1981 にもとづく）

唐戸（2000）

マントル対流の特徴

アセノスフェア（内部）の流れ

Akaogi et al,. 1989

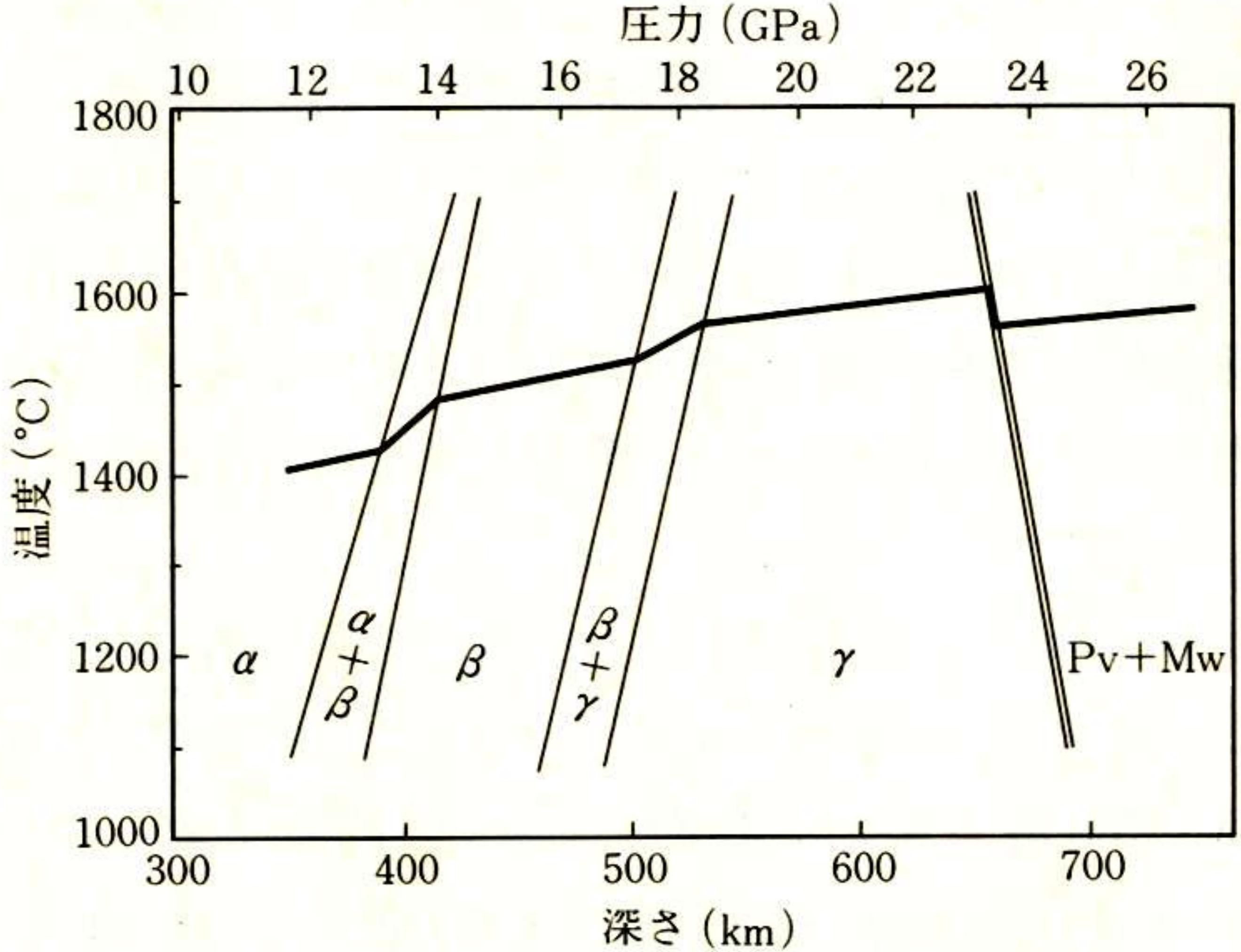


図 4.35 マントルオリビンの相転移境界線と温度分布（Akaogi et al., 1989 などによる）．

マントル対流の特徴

アセノスフェア（内部）の流れ

$$dG = -(S^\beta - S^\alpha)\,dT + (V^\beta - V^\alpha)\,dP$$
$$\equiv -\Delta S\,dT + \Delta V\,dP = 0$$

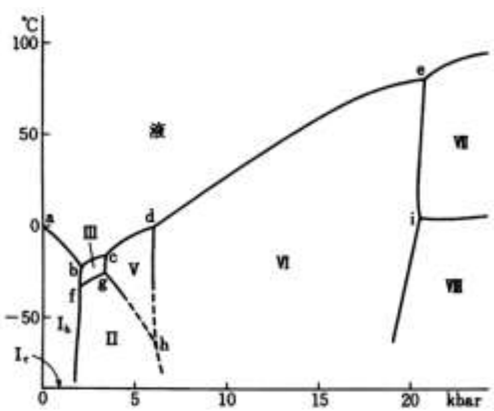
Clausius-Clapeyron Slope

$$\frac{dP}{dT} = \frac{\Delta S}{\Delta V} = \frac{\Delta H}{T\Delta V}$$

多くの場合、⊿Sと⊿Vは同符号
⇒　dP/dT＞0

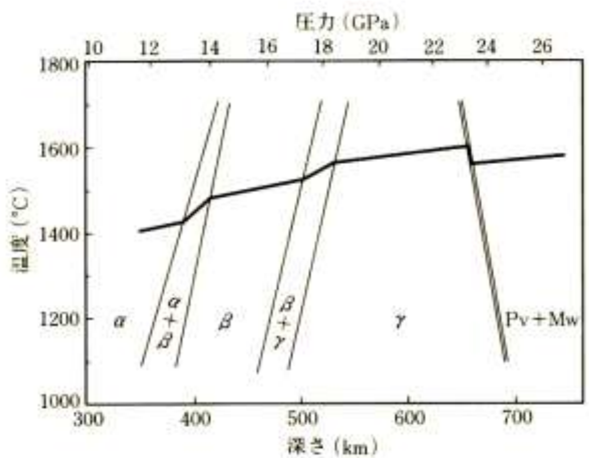
dP/dT＜0の例

H_2O（氷と水）



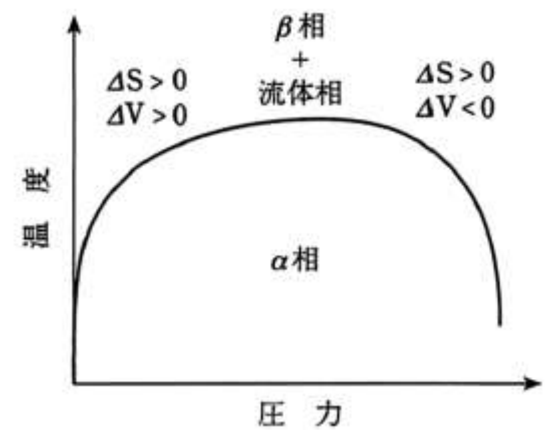
野津憲治, 清水洋, 2003

Mg_2SiO_4（660km相転移）



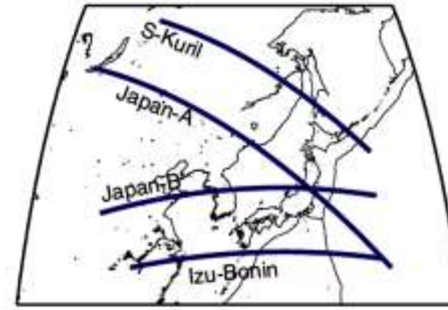
Akaogi et al,. 1989

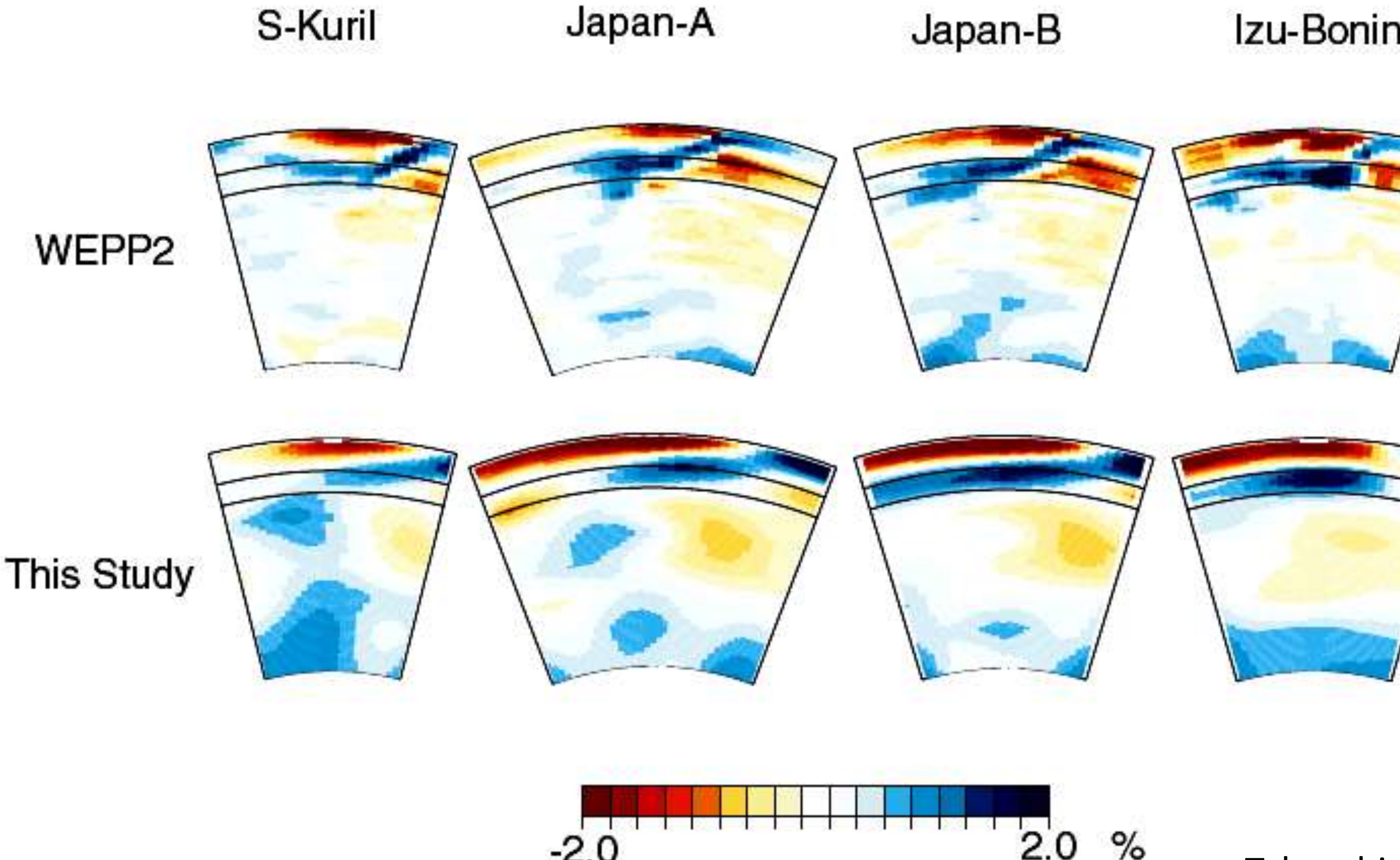
脱水・脱ガス反応



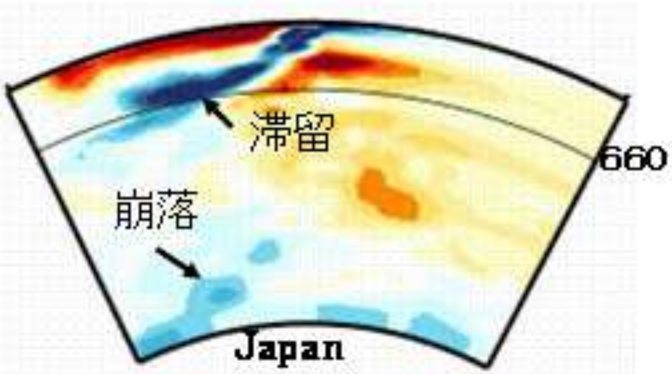
マントル対流の特徴

アセノスフェア（内部）の流れ

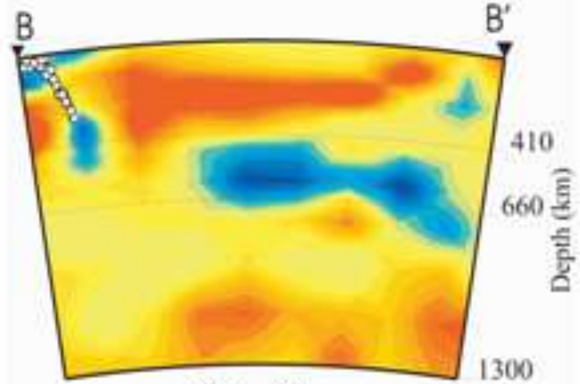




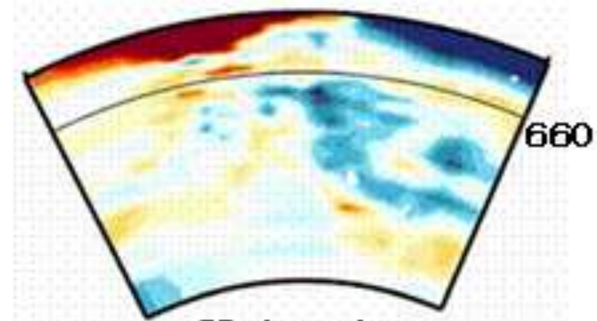
Takeuchi (2007)



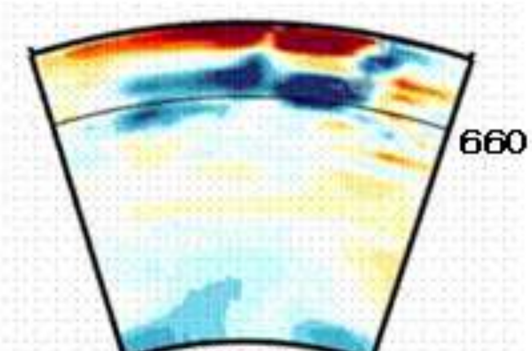
Japan



Aleutian



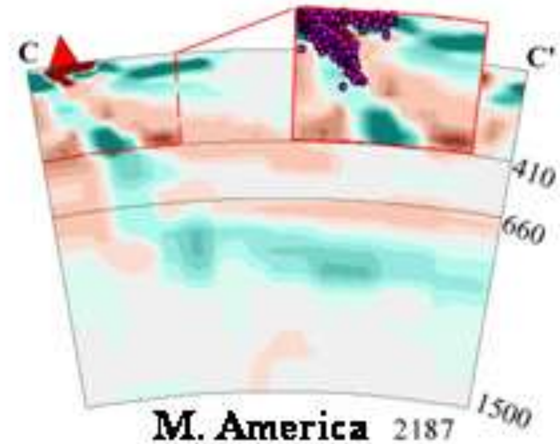
N. America



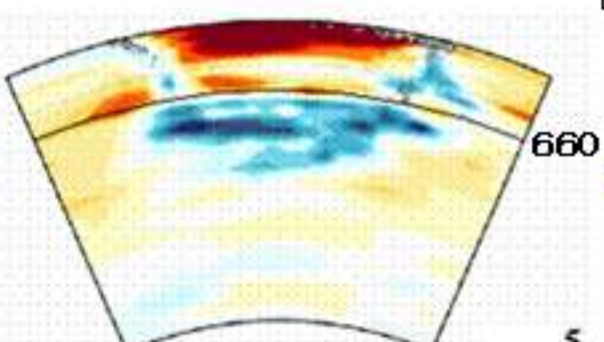
Bonin

海溝から沈み込んだプレートは上部・下部マントル遷移層に滞留し、やがて下部マントルに崩落 (Fukao et al., 1992)

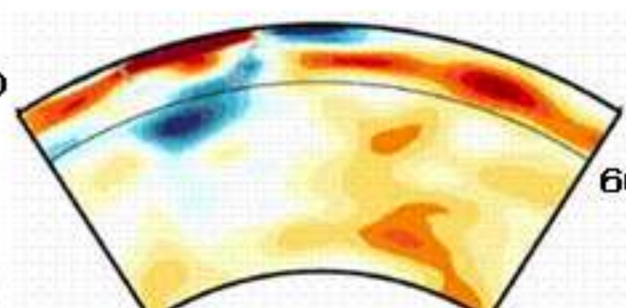
スタグナントスラブはグローバルな現象 (Fukao et al., 2001)



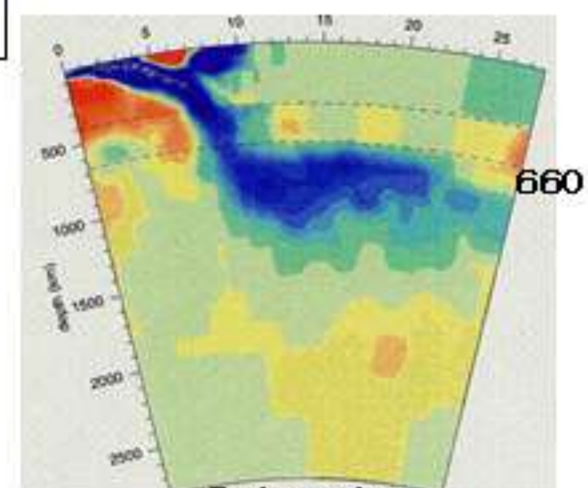
M. America



Indonesia



Tonga



S. America

http://ohp-ju.eri.u-tokyo.ac.jp/tokutei/

マントル対流の特徴

アセノスフェア（内部）の流れ

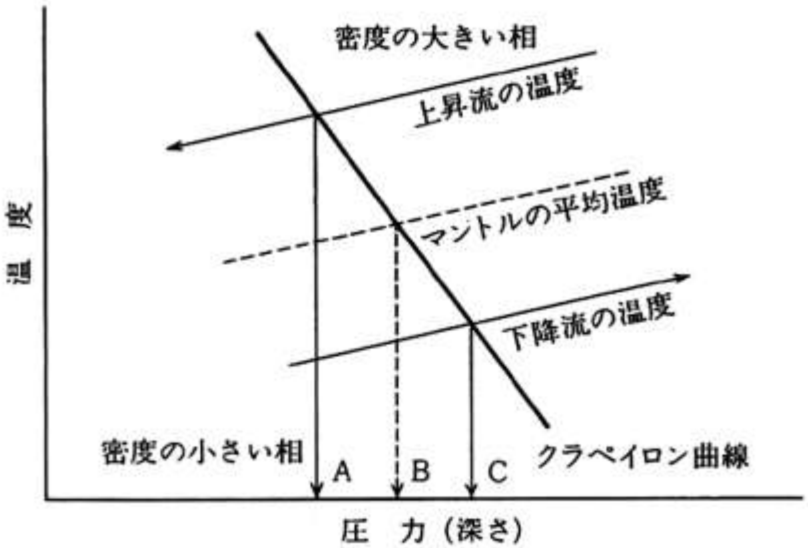


図 3.14　相変化がマントルに与える影響を示す図.

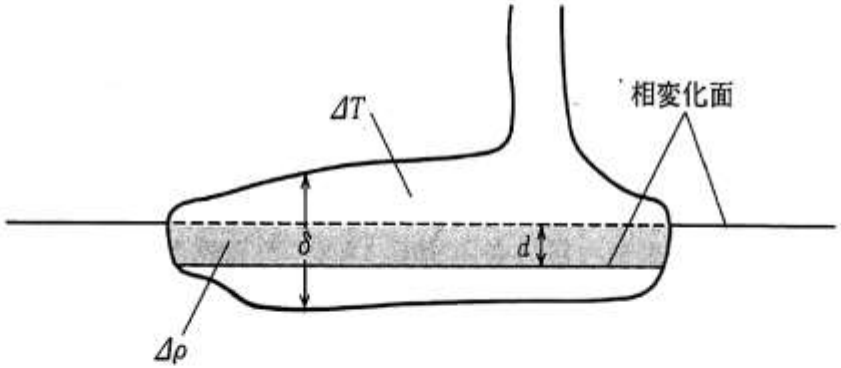


図 3.15　相変化面に冷却塊が停留している状態を示す図. 太い実線で囲まれた部分は, まわりより ΔT だけ温度が低い. アミをかけた部分は, 相変化面の位置の変化によって生じた密度の低い部分を示す.

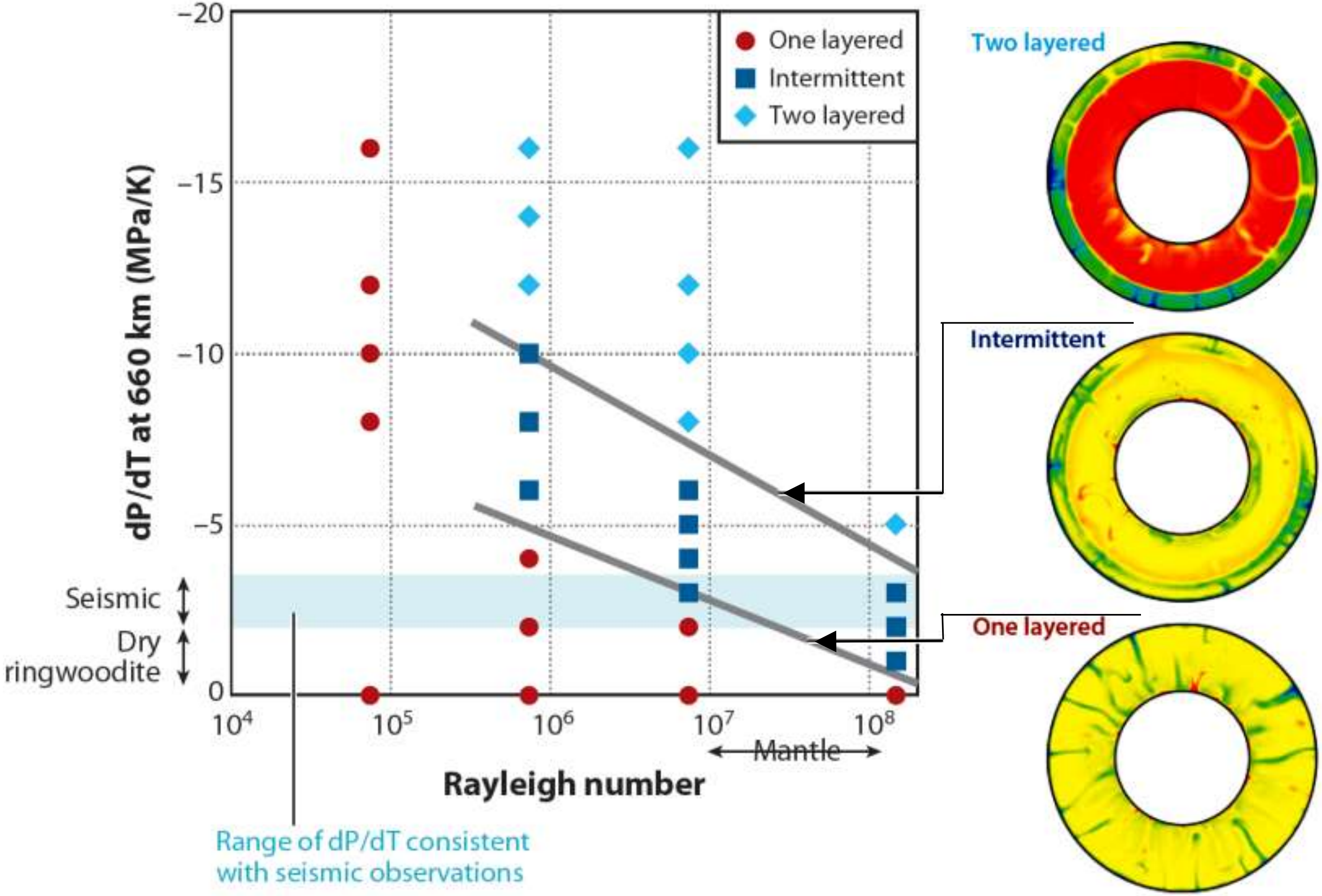
$$\left.\frac{\Delta\rho|\gamma|}{\rho^2 g\alpha D}\right|_{\mathrm{critical}} \equiv |P_{\mathrm{cr}}| = c_1\left(1-c_2\frac{\mu_{\mathrm{s}}}{\mu_{\mathrm{m}}}\right)Ra^{-1/3}$$

本多 (1997)

マントル対流の特徴

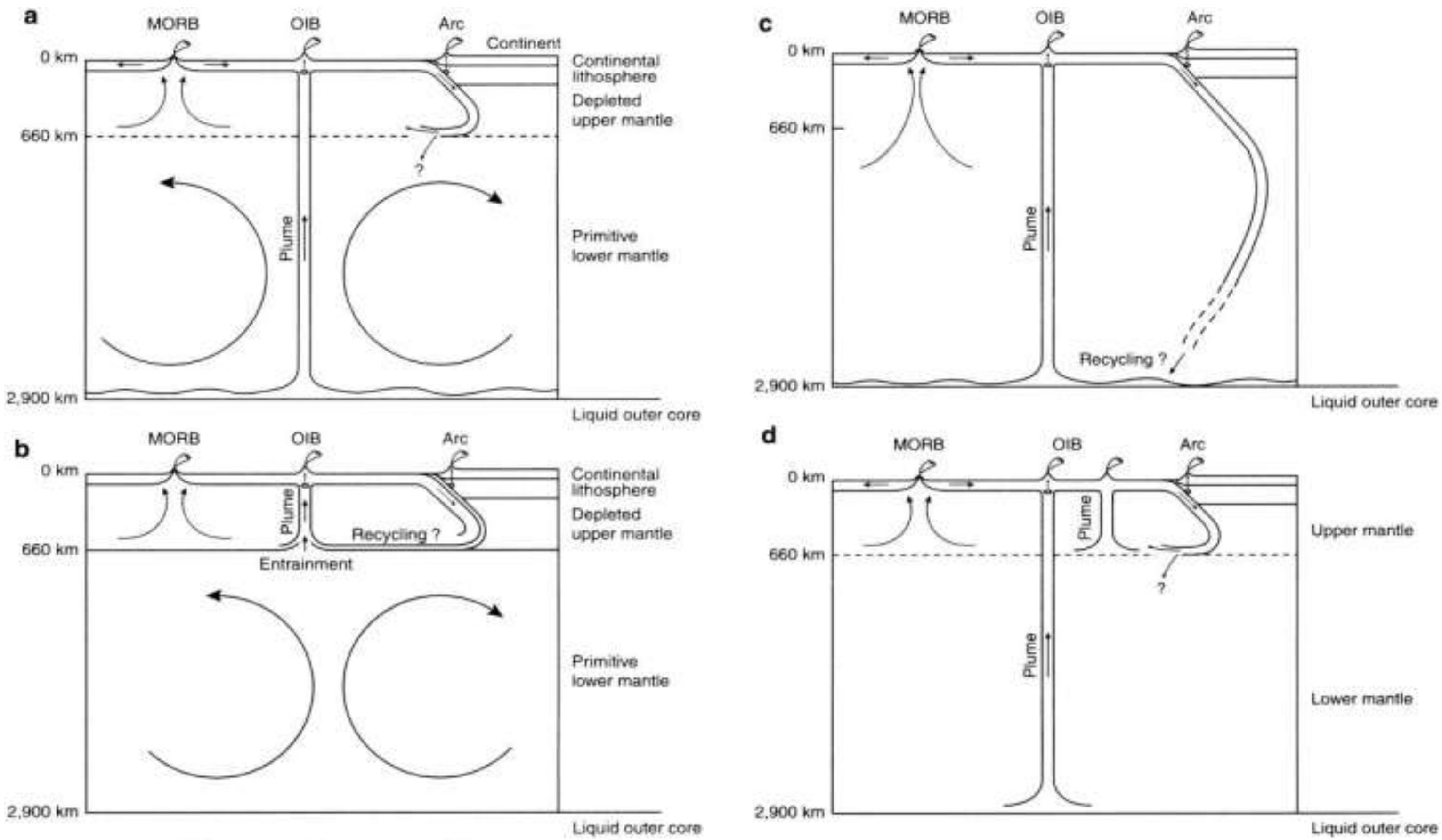
アセノスフェア（内部）の流れ

Fukao et al. (2009)

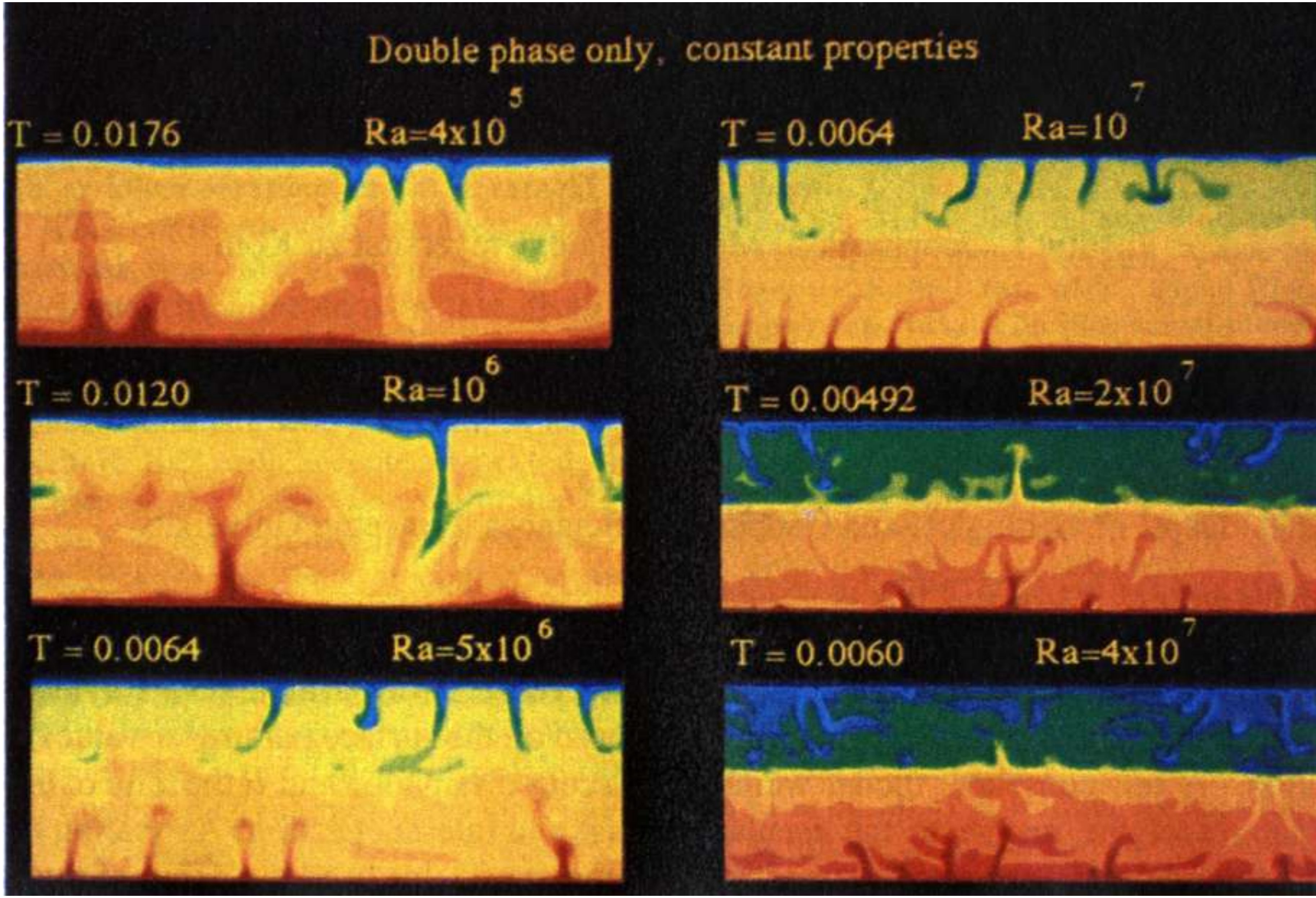


マントル対流の特徴

アセノスフェア（内部）の流れ



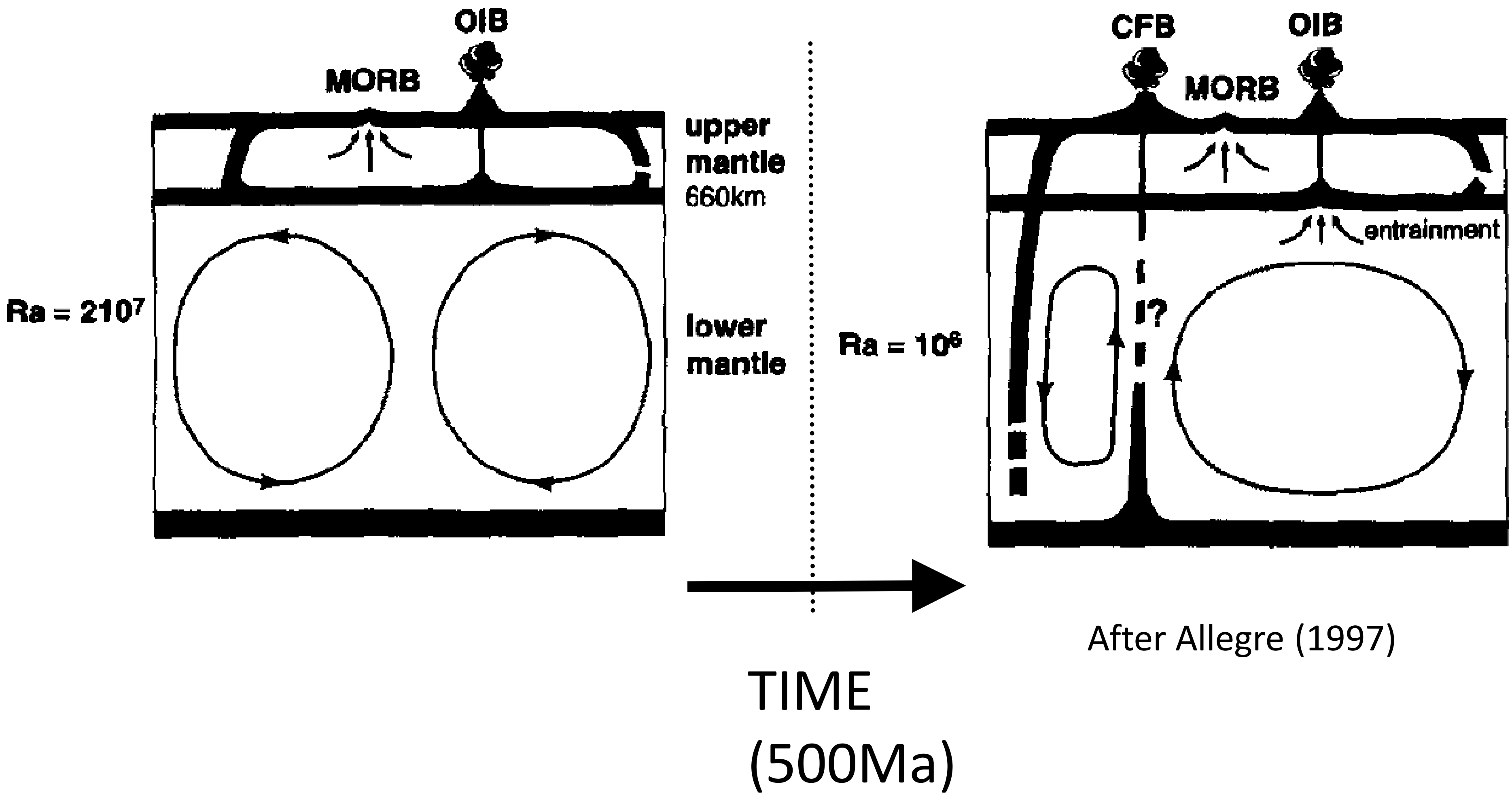
Hofmann (1997)



Steinbach et al. (1993)

マントル対流の特徴

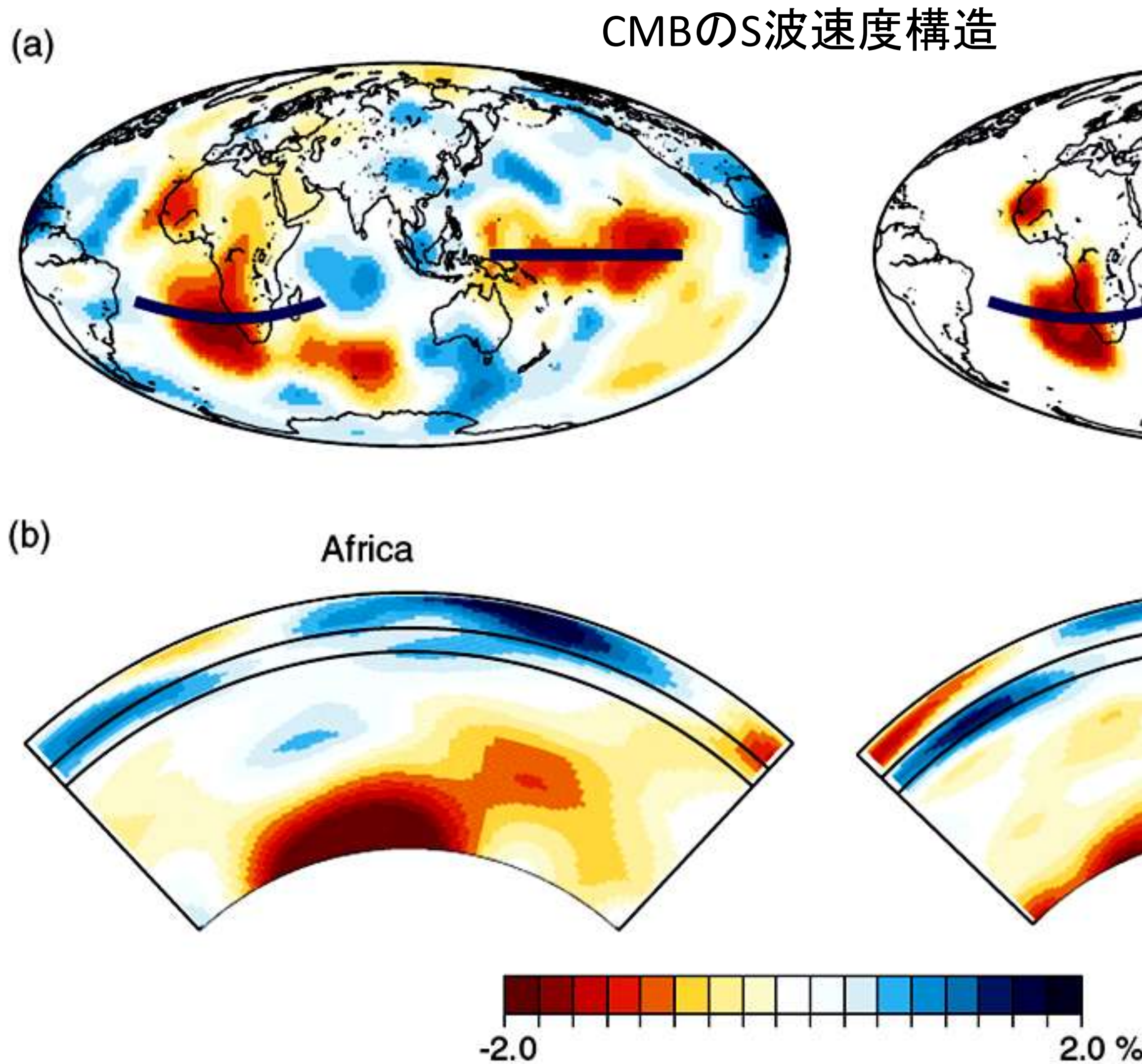
アセノスフェア（内部）の流れ



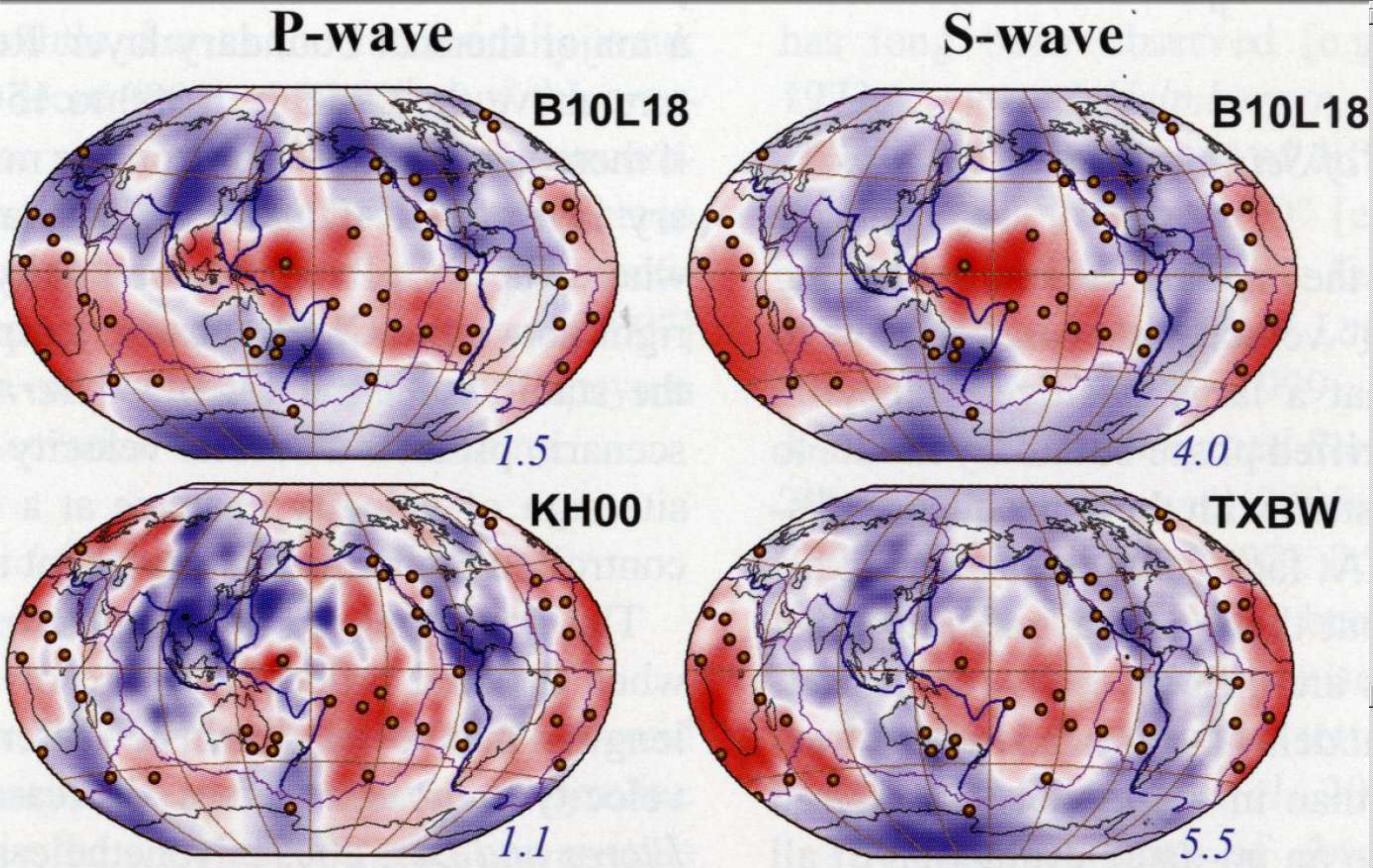
After Allegre (1997)

マントル対流の特徴

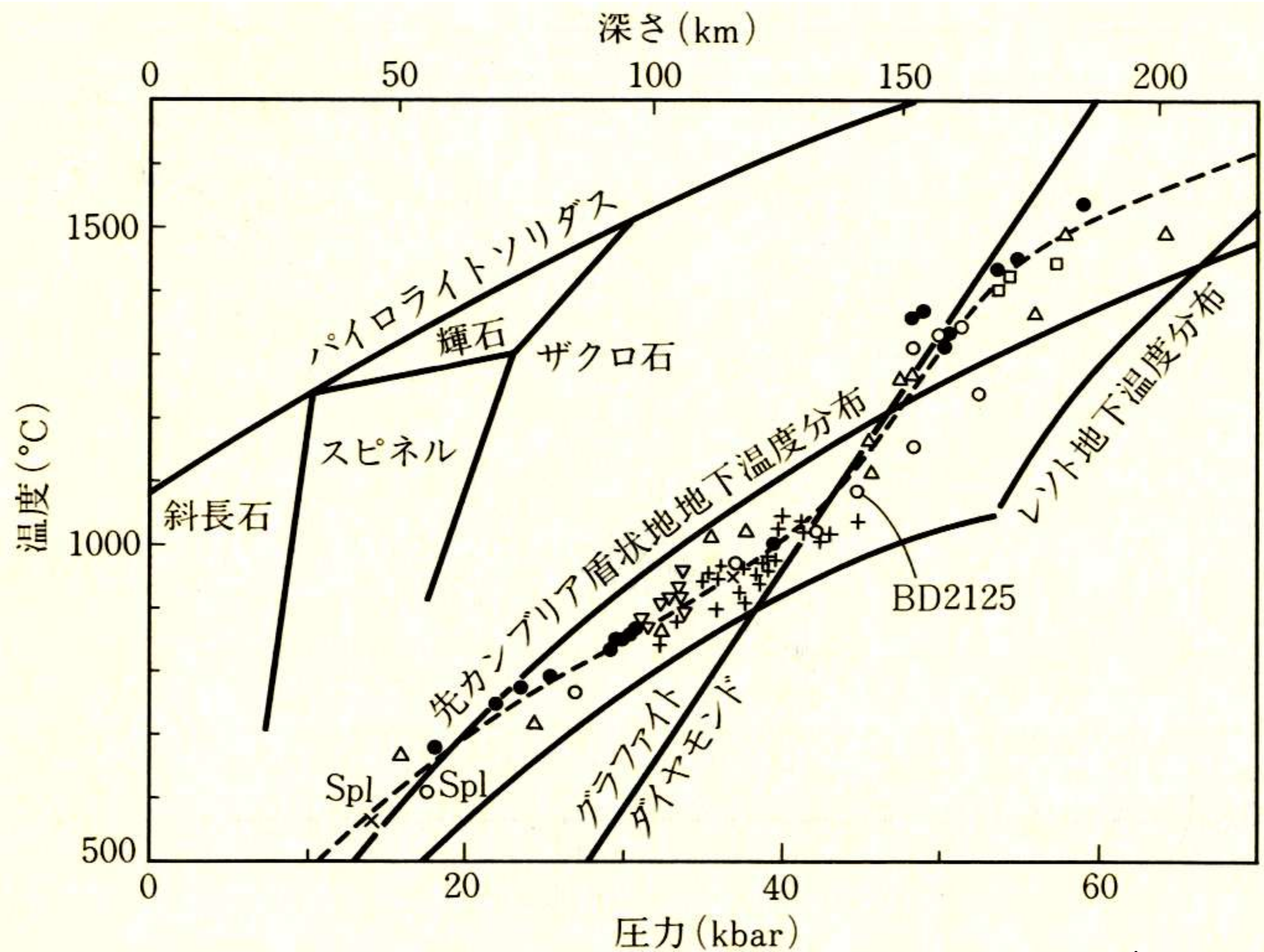
アセノスフェア（内部）の流れ: CMB



Takeuchi (2007)



Lay & Garnero (2007)



Toriumi et al, 1997

Akaogi et al,. 1989

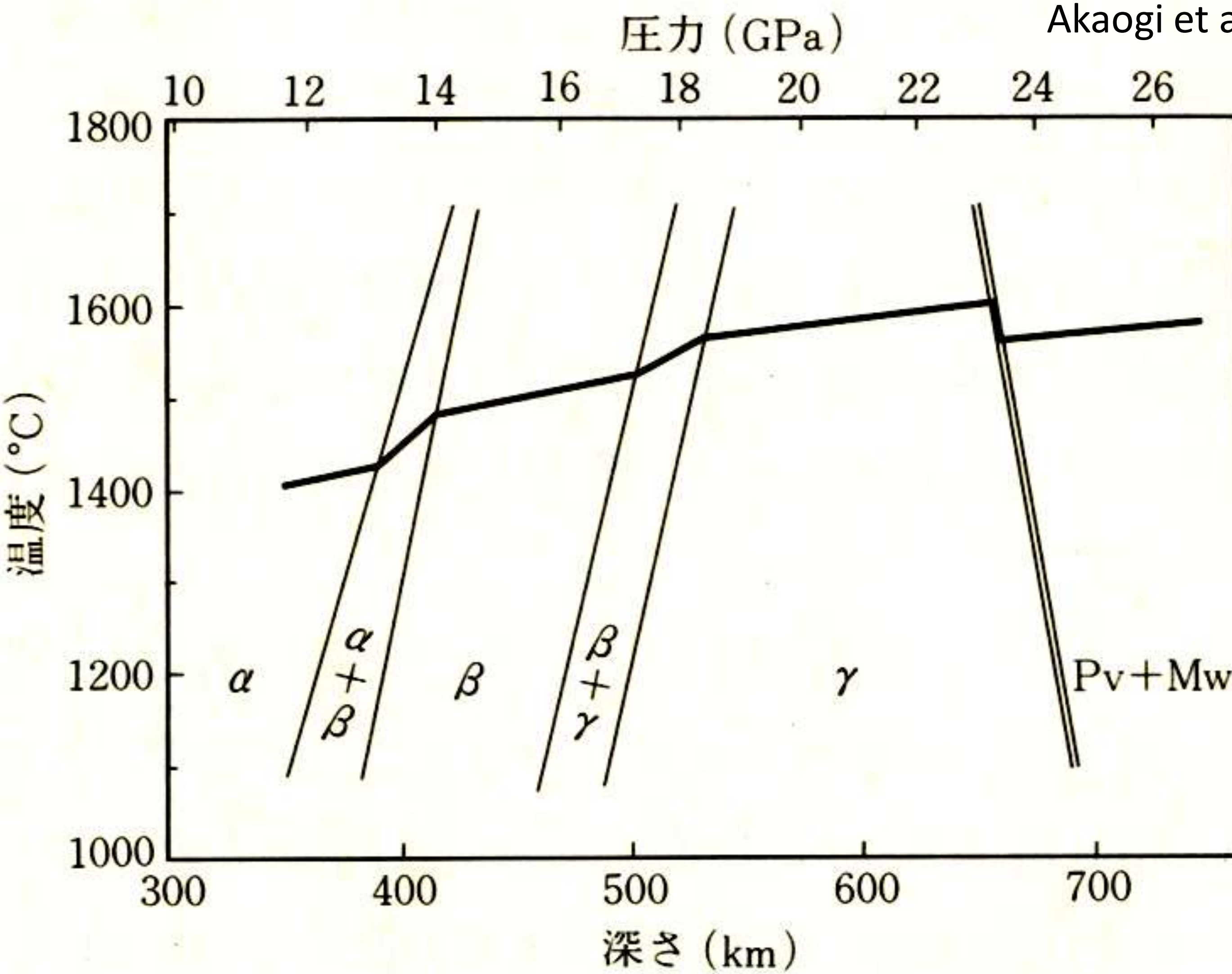


図 4.35 マントルオリビンの相転移境界線と温度分布（Akaogi et al., 1989 などによる）.

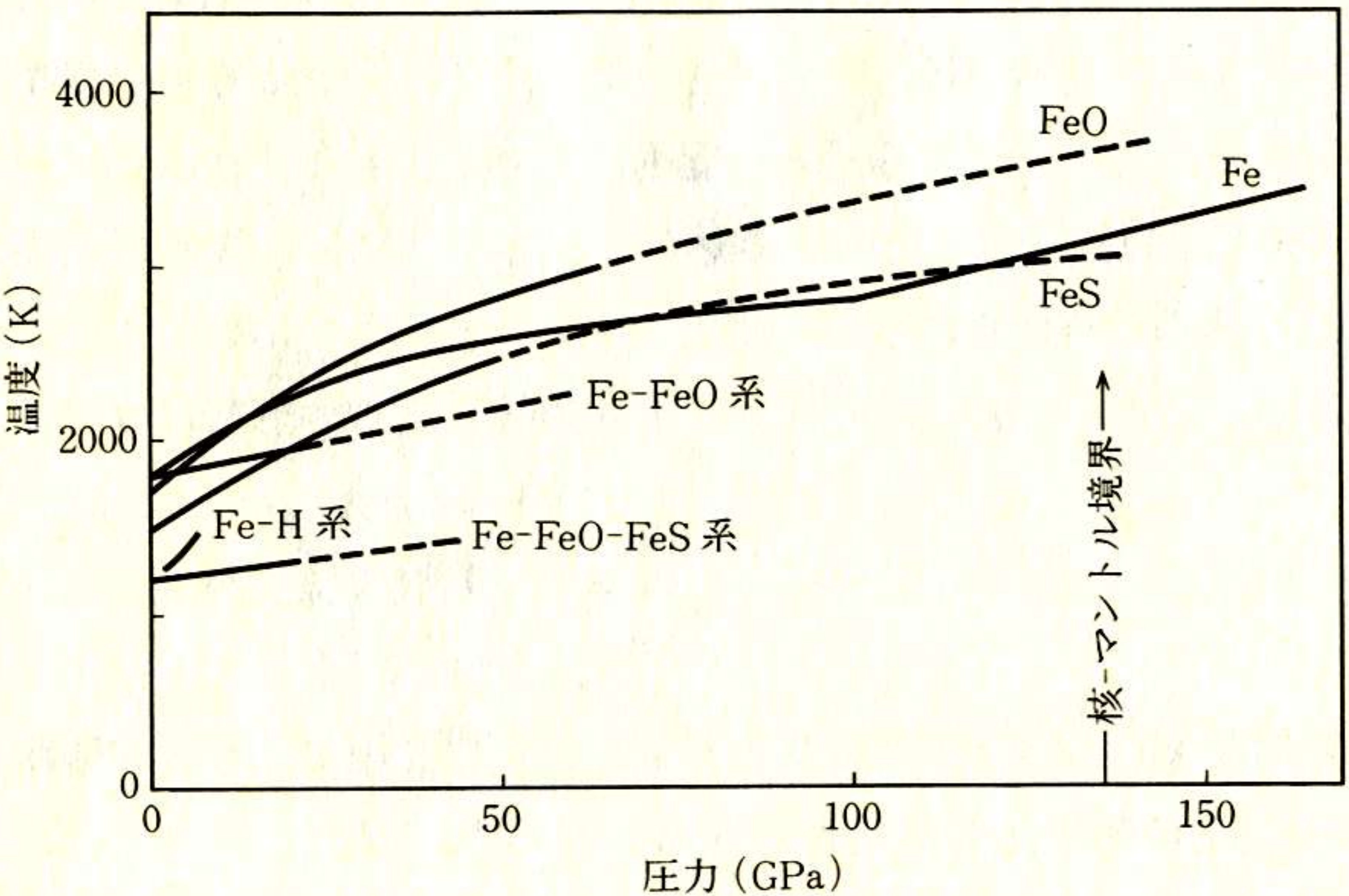
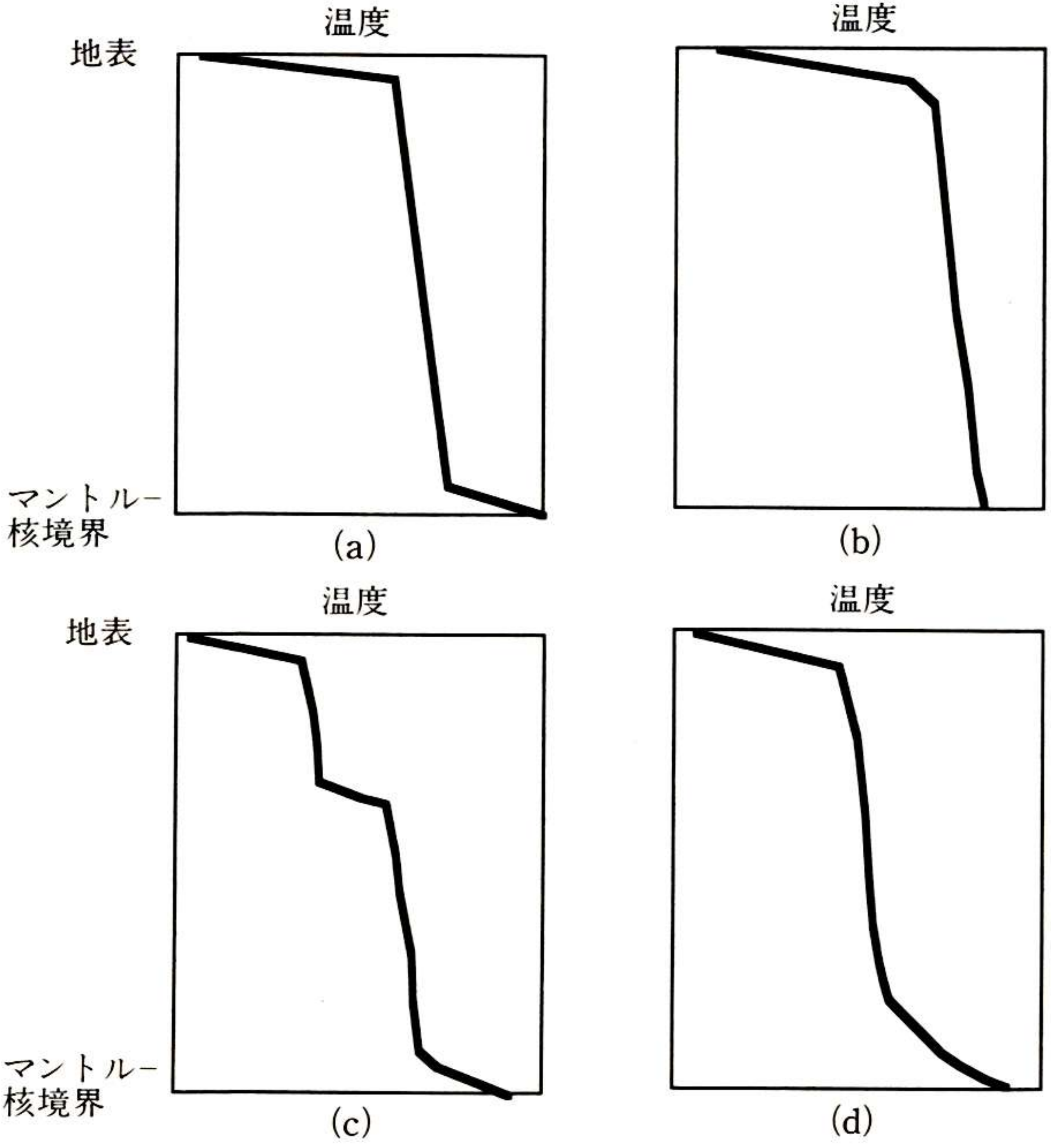
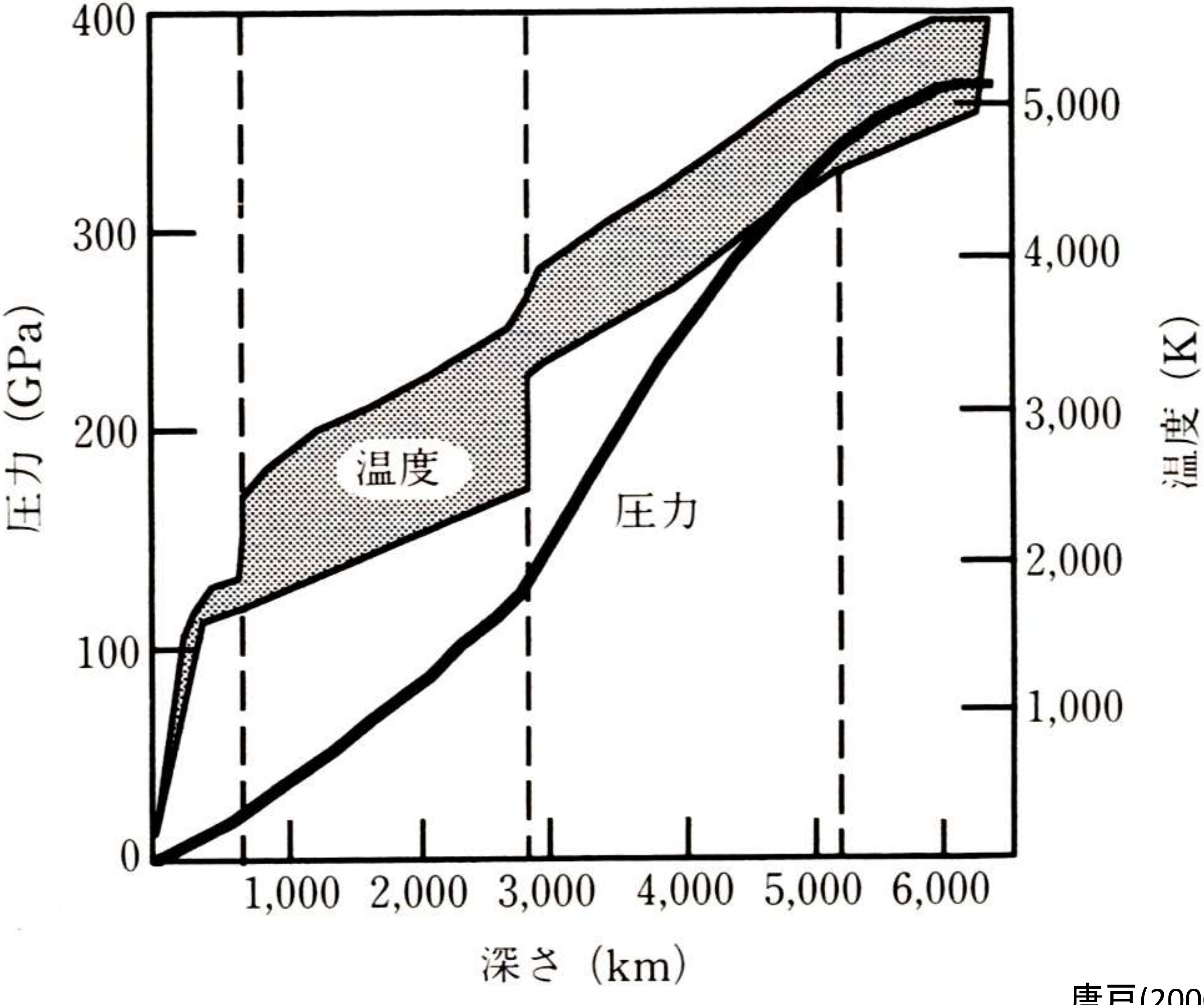


図 4. 38　鉄および鉄化合物の融解曲線.（Fe, FeO, FeS は Boehler, 1992, 1993 に, Fe–FeO は Ohtani et al., 1984 ; Ringwood and Hibberson, 1990 に, Fe–FeO–FeS は Urakawa et al., 1987 に, Fe–H は Yagi and Hishinuma, 1995 による）

Toriumi et al, 1997

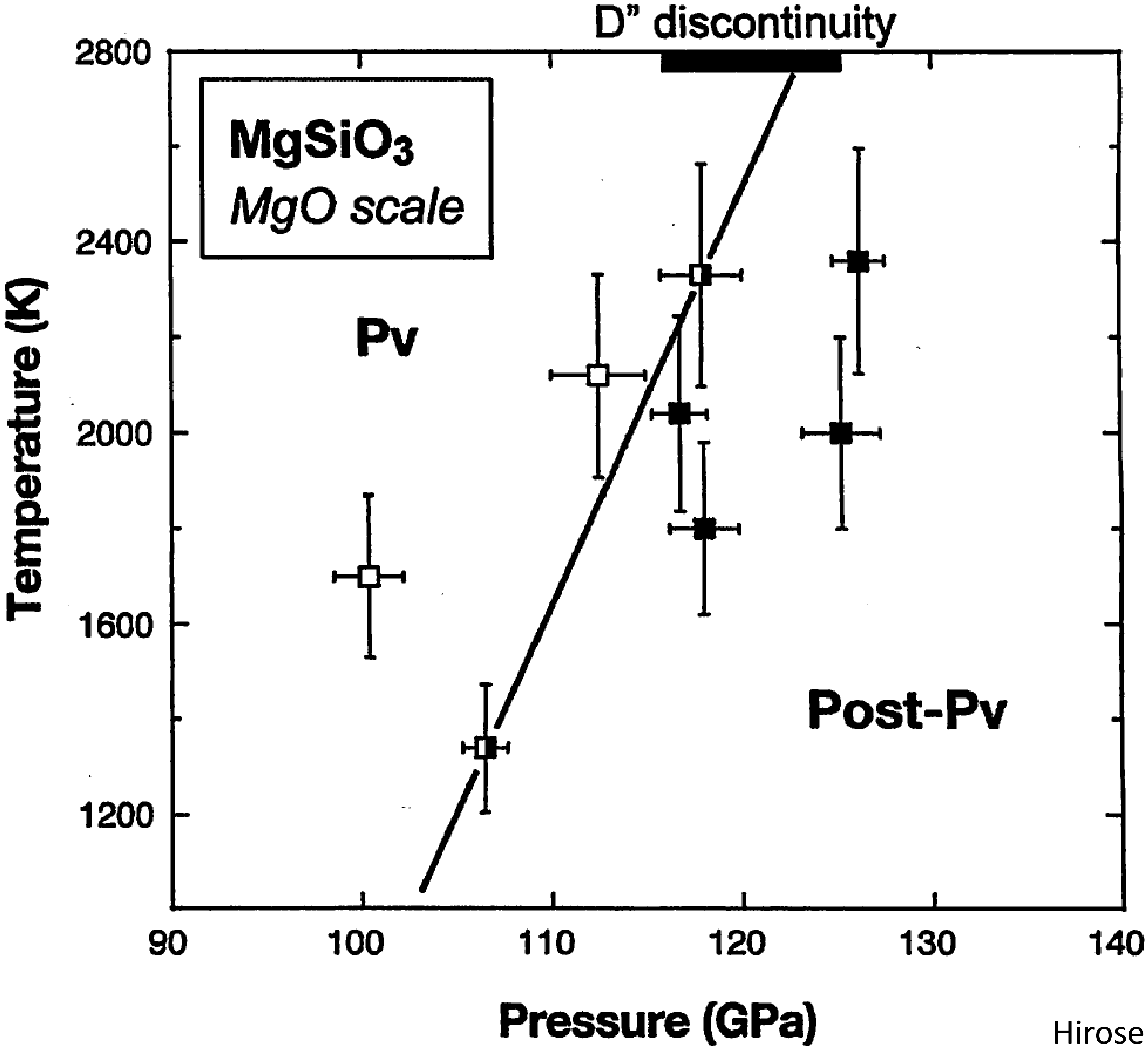


唐戸(2000)



400
300
200
100
0
圧力 (GPa)
5,000
4,000
3,000
2,000
1,000
温度 (K)
温度
圧力
1,000
2,000
3,000
4,000
5,000
6,000
深さ (km)

唐戸(2000)

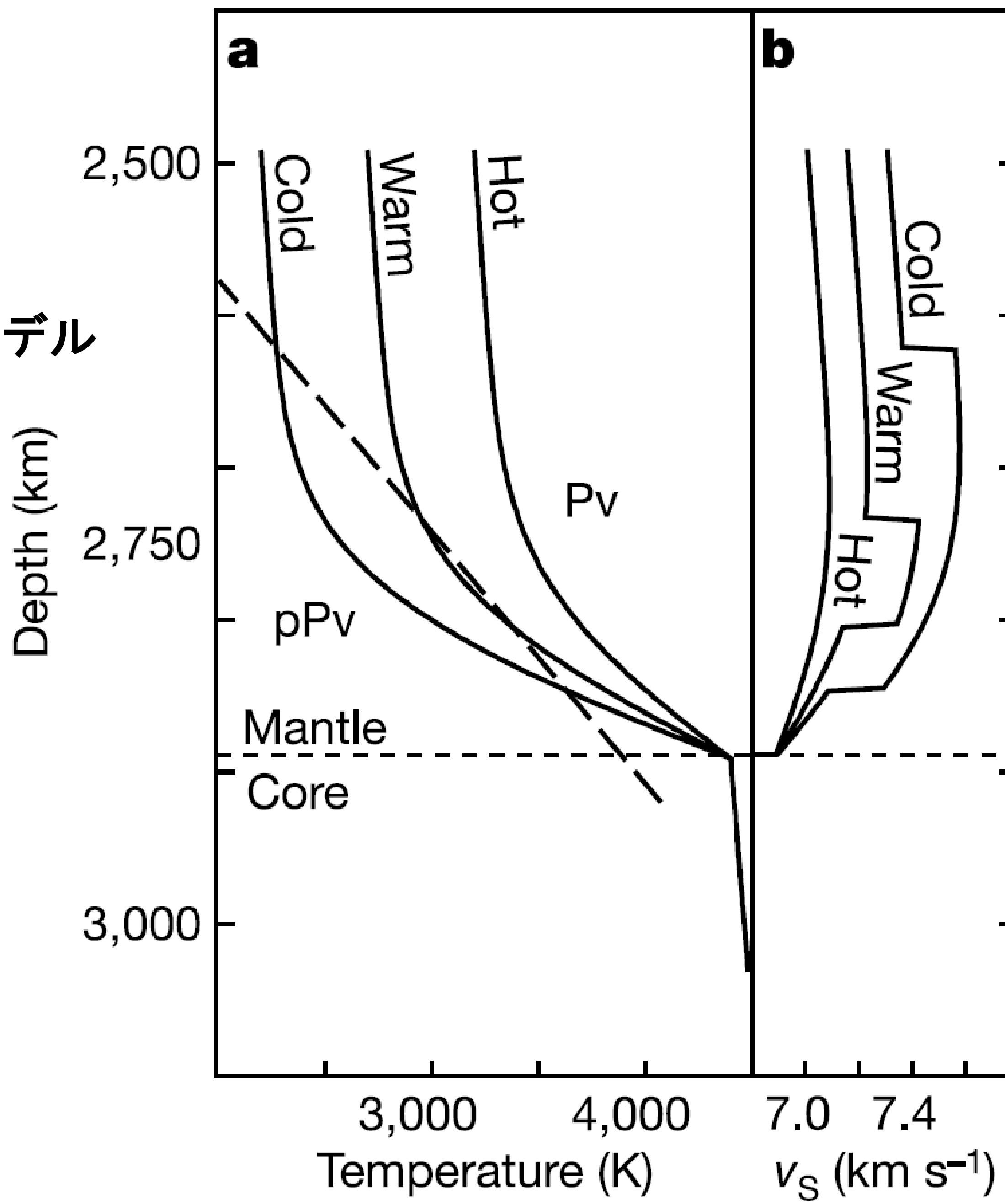


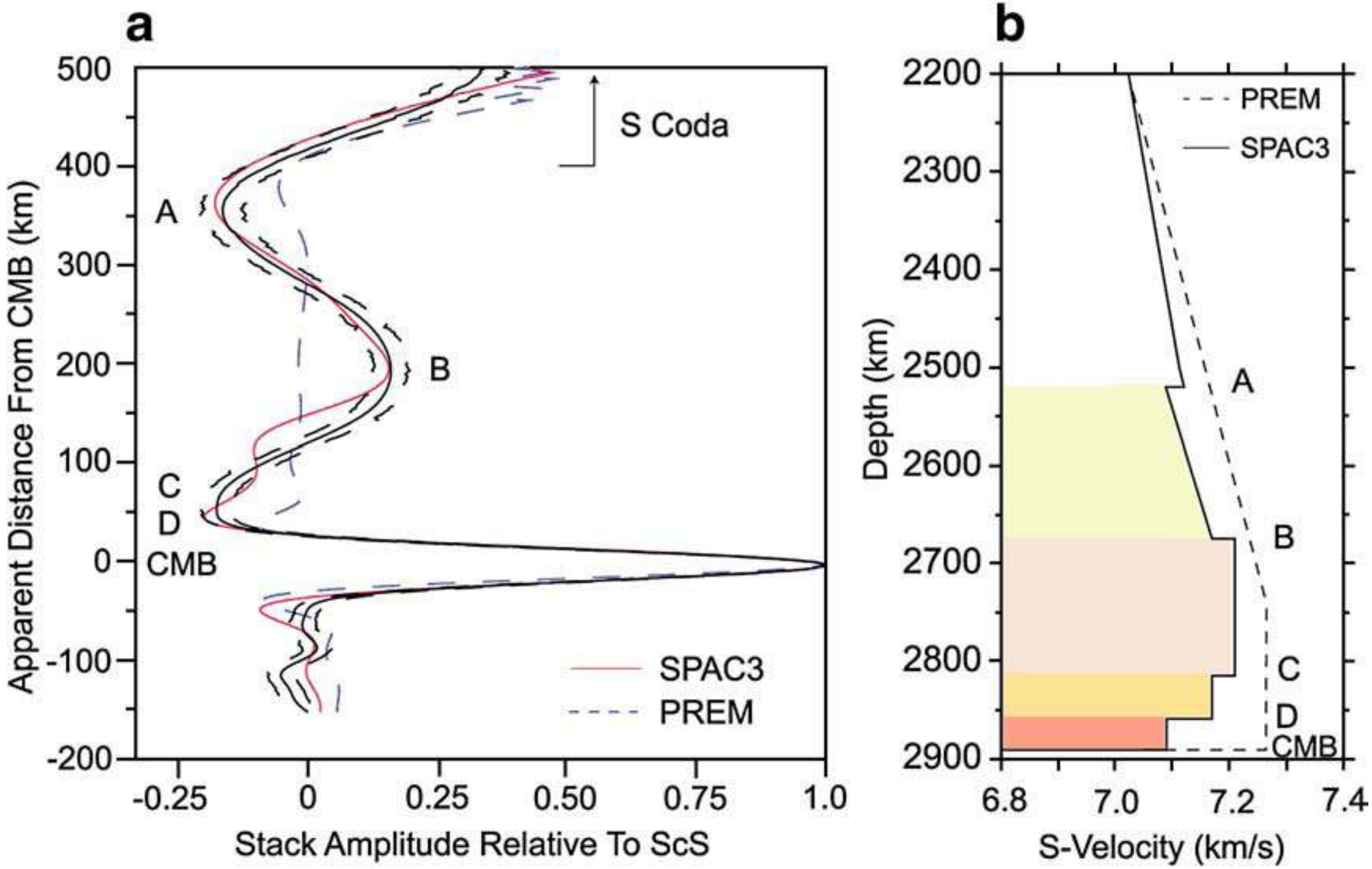
D" discontinuity
MgSiO3
MgO scale
Pv
Post-Pv
Temperature (K)
2800
2400
2000
1600
1200
90
100
110
120
130
140
Pressure (GPa)

Hirose (2007)

Double Crossing Model
「相変化境界を2度よぎる」モデル

Hernlund et al. (2005)





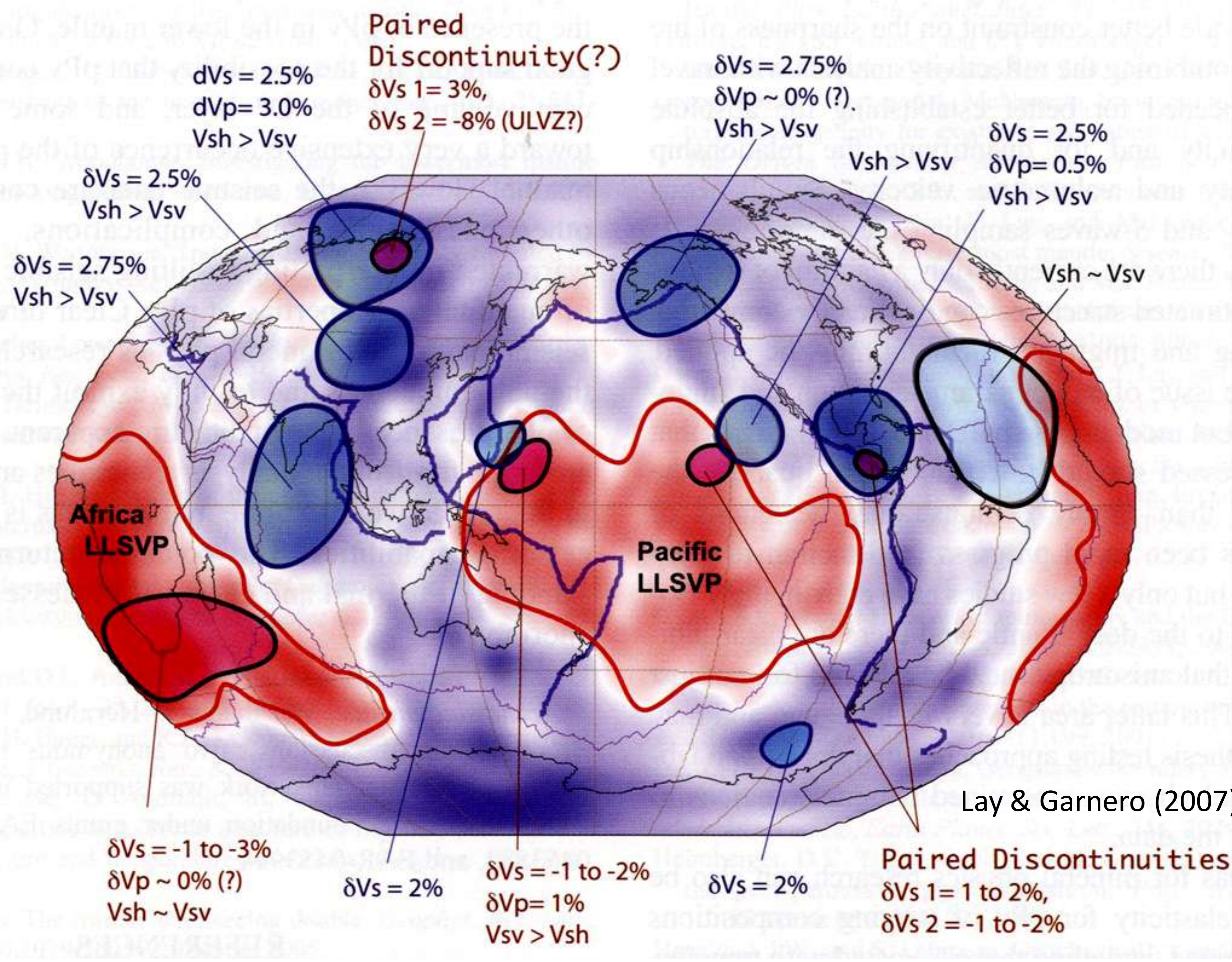
A results from post-perovskite and SiO2 phase transitions in the MORB component,

B from post-perovskite phase transition in the pyrolitic component,

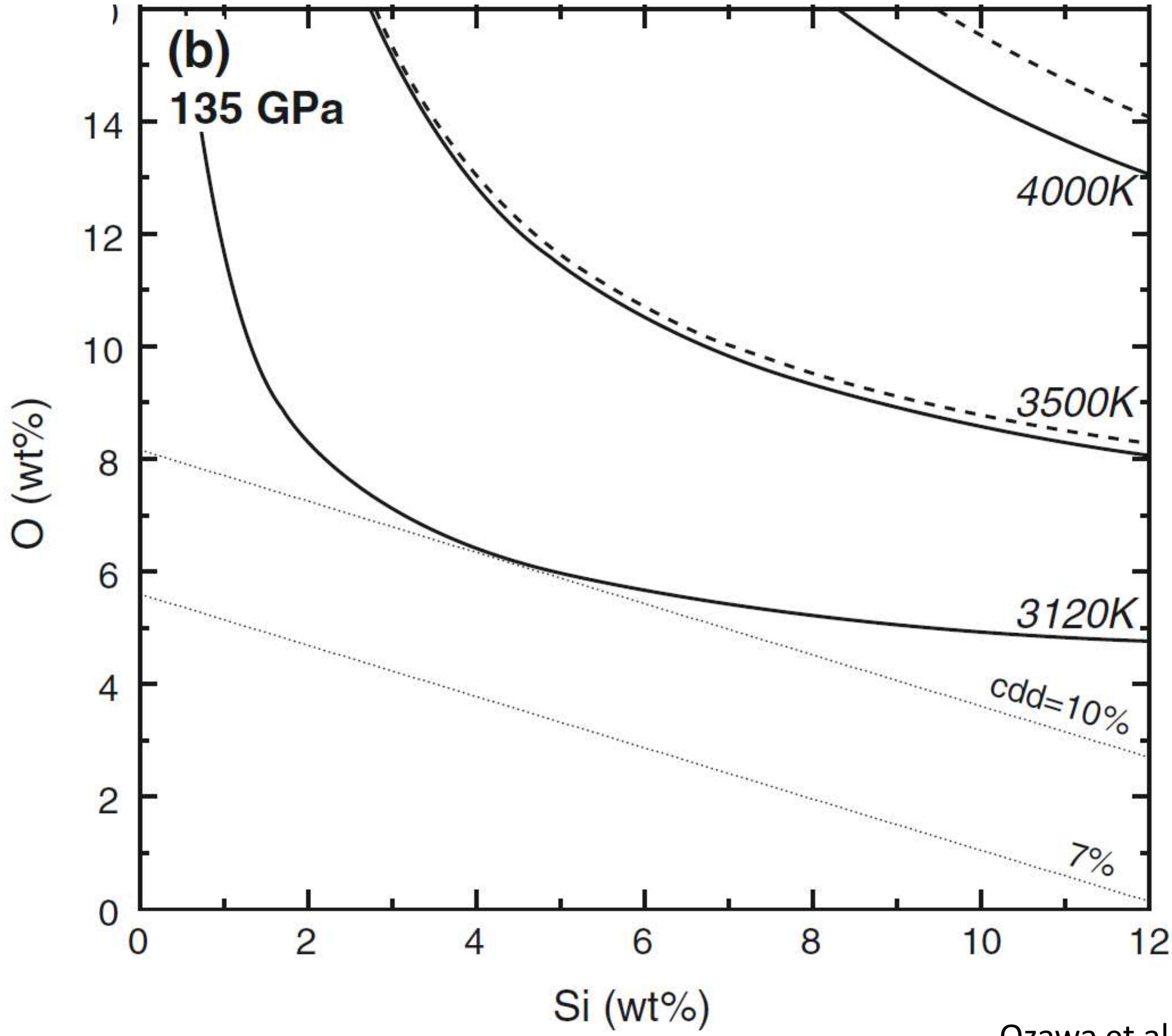
C from back transformation of the post-perovskite to perovskite in the pyrolitic material due to rapid temperature increase (Lay et al., 2006)

D from onset of partial melting just above the CMB.

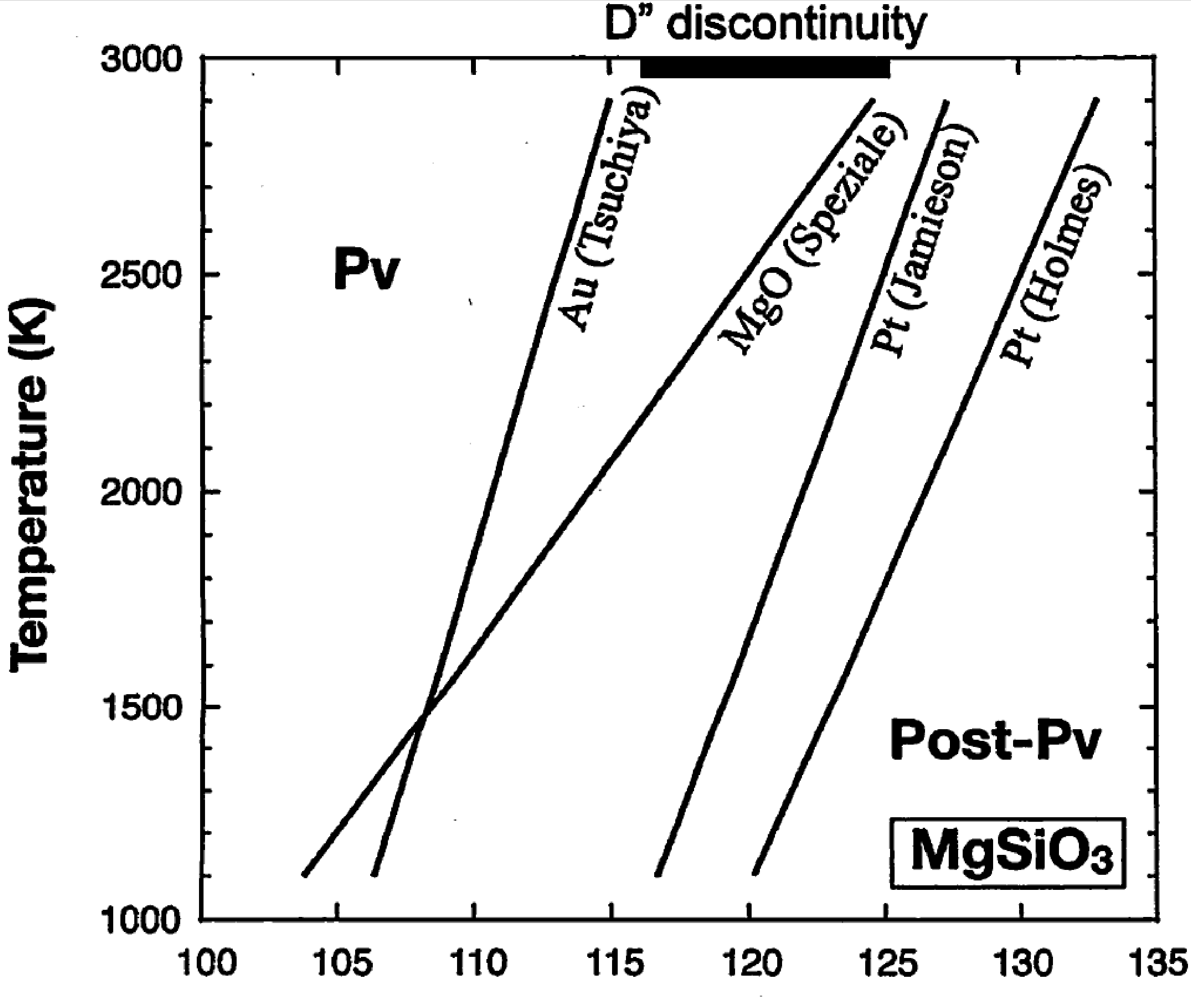
Ohta et al. (2008)



Lay & Garnero (2007)

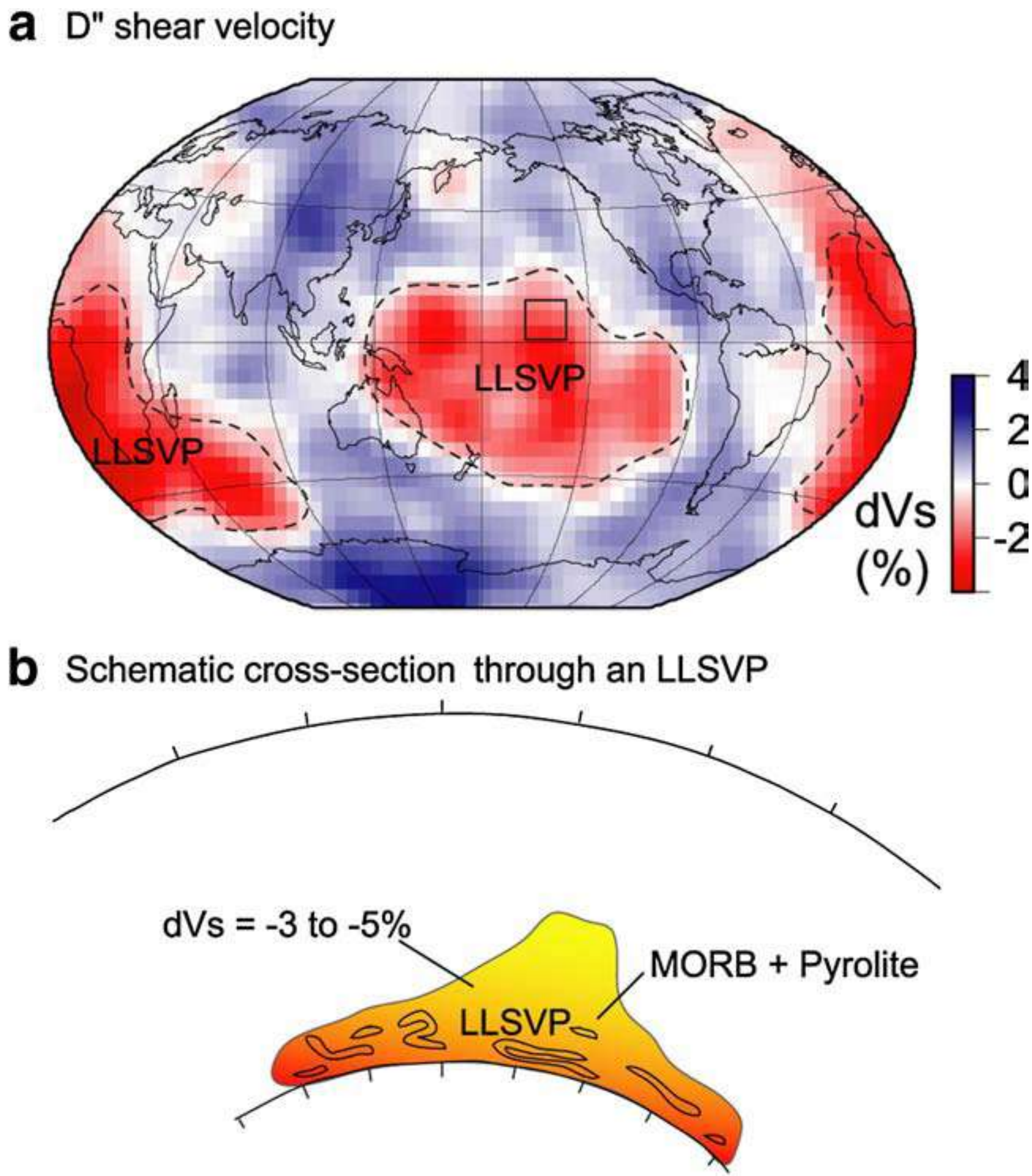


Ozawa et al. (2009)

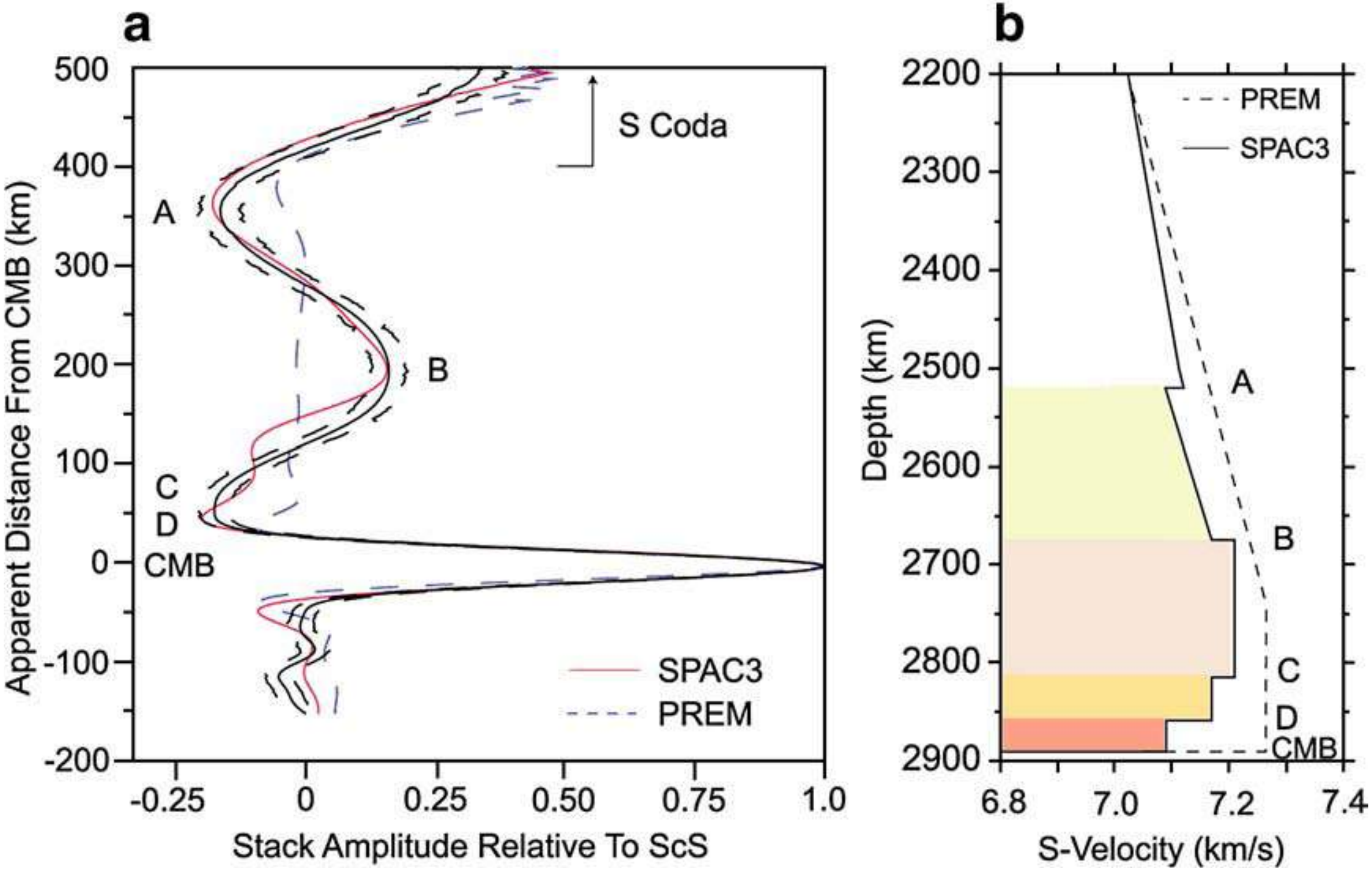


D" discontinuity
3000
2500
2000
1500
1000
Temperature (K)
100
105
110
115
120
125
130
135
Pressure (GPa)
Pv
Post-Pv
MgSiO3
Au (Tsuchiya)
MgO (Speziale)
Pt (Jamieson)
Pt (Holmes)

Hirose (2007)



Ohta et al. (2008)



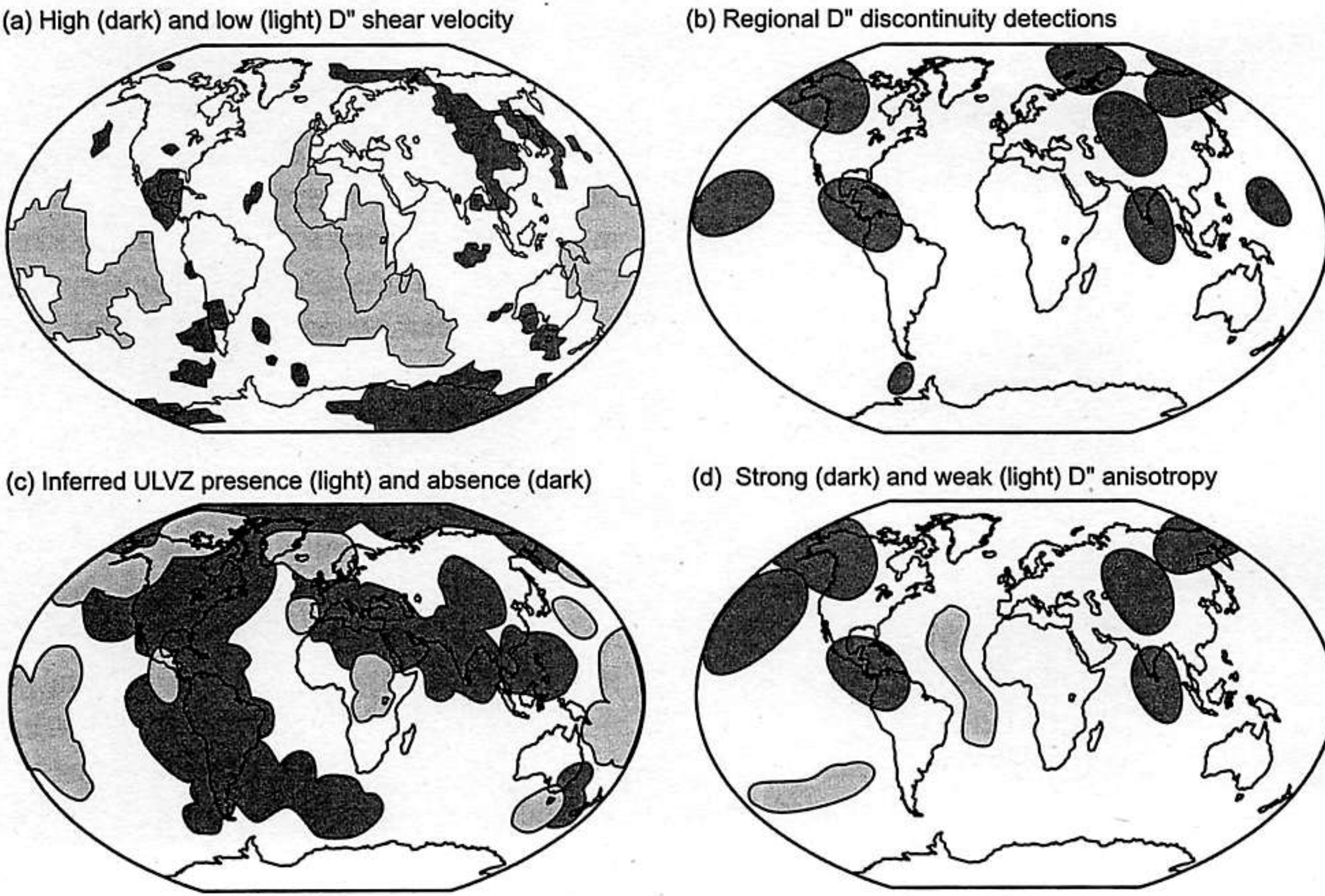
A results from post-perovskite and SiO2 phase transitions in the MORB component,

B from post-perovskite phase transition in the pyrolitic component,

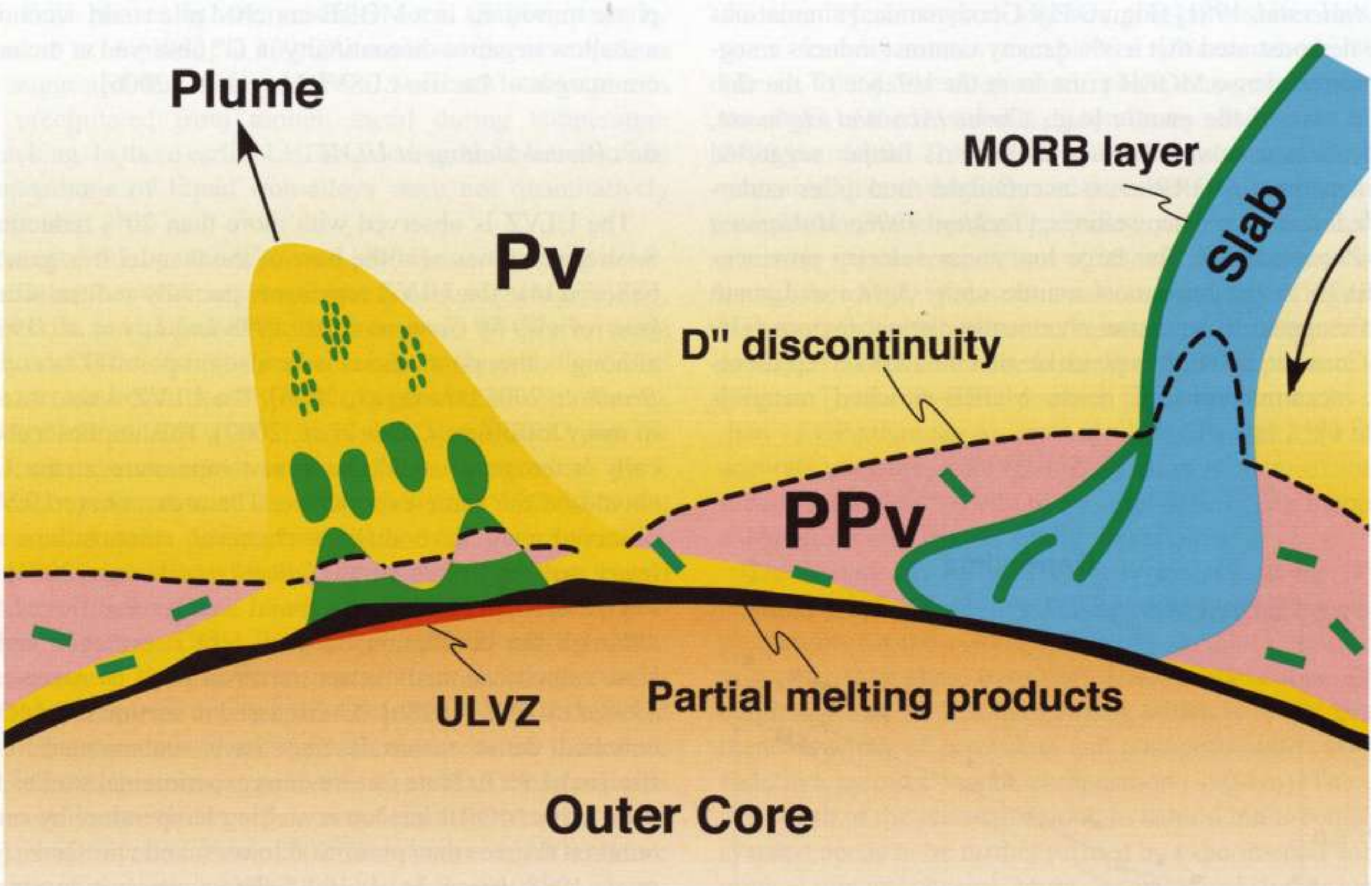
C from back transformation of the post-perovskite to perovskite in the pyrolitic material due to rapid temperature increase (Lay et al., 2006)

D from onset of partial melting just above the CMB.

Ohta et al. (2008)



Lay & Garnero (2004)


Plume
Pv
MORB layer
Slab
D'' discontinuity
PPv
ULVZ
Partial melting products
Outer Core

Hirose (2007)

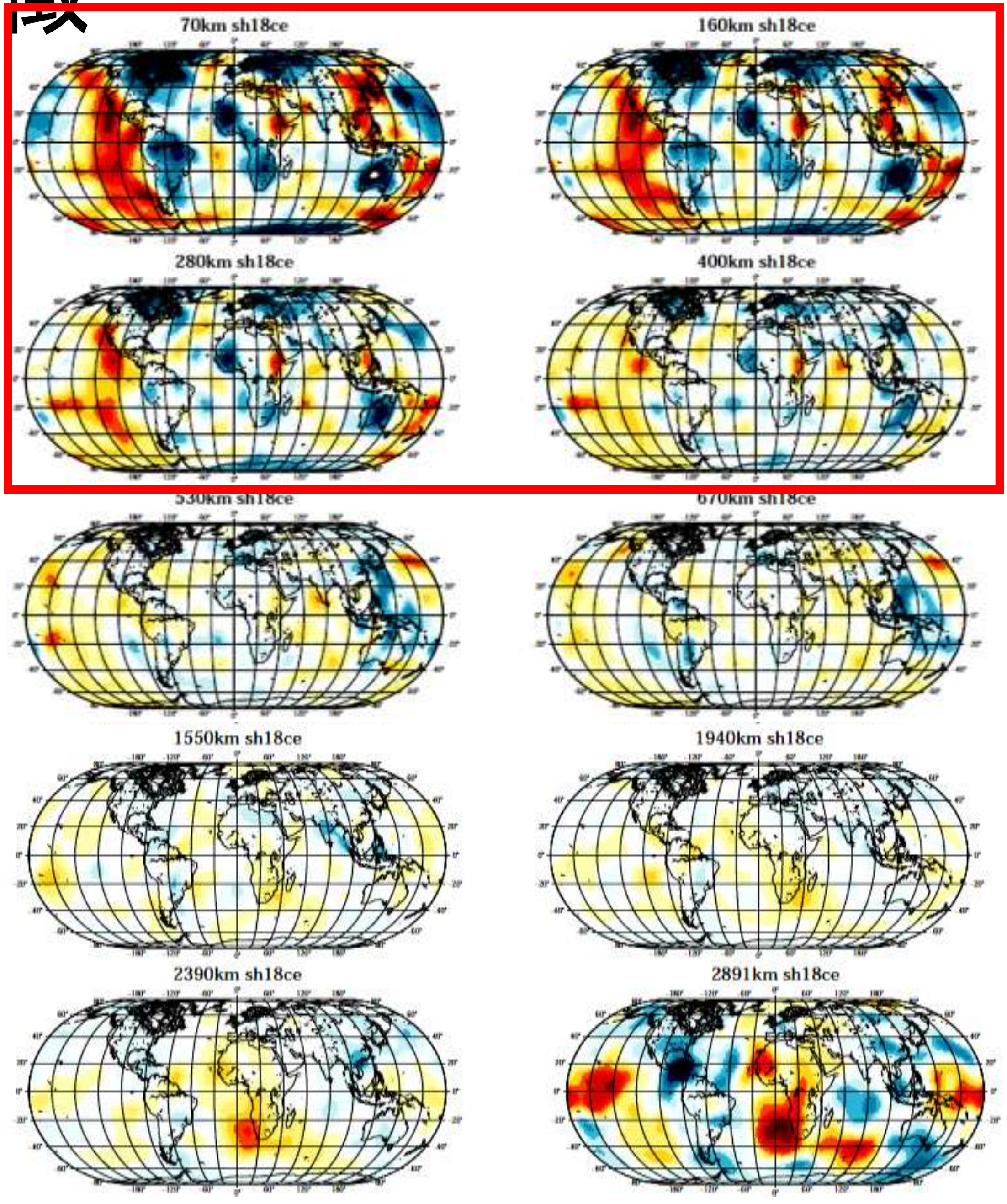
マントル対流の特徴

アセノスフェア（内部）の流れ

地震波（S波）トモグラフィーモデル
Takeuchi (2007)

不均質性が大きい部分
リソスフェア一遷移層（660km）
コアーマントル境界付近（2891km）

地球は表面から冷やされ、
不均質・不安定が発達
＋
下面から（表面よりは弱く？）
不安定が発達

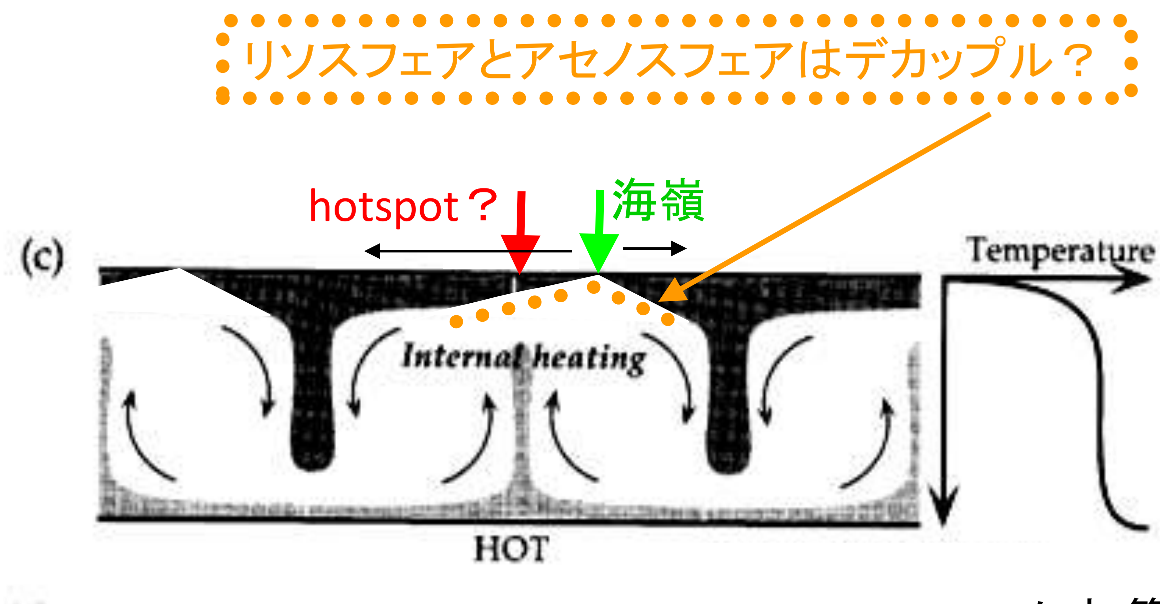


マントル対流の特徴

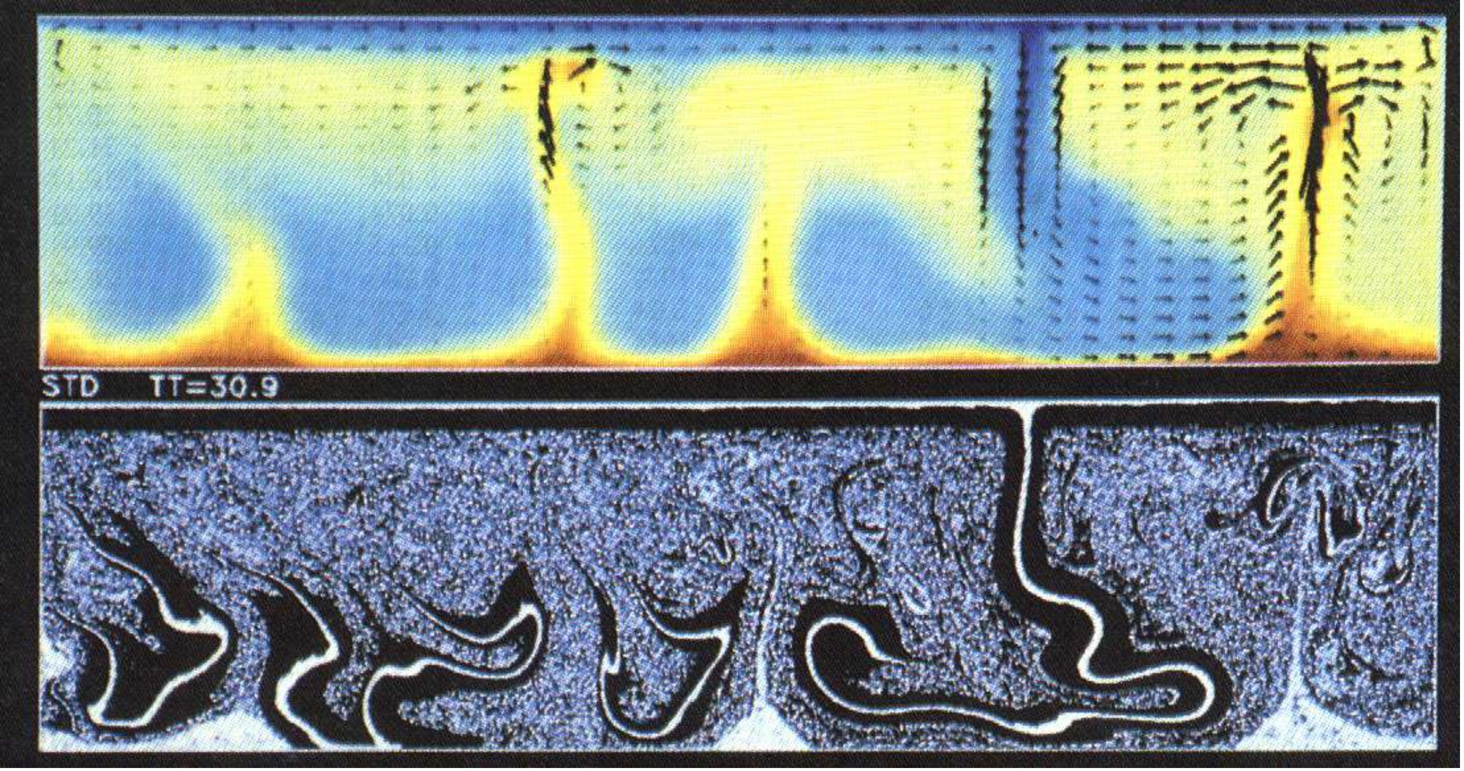
リソスフェア（表層）とアセノスフェア（内部）

εは小さくはなく、実際にトモグラフィーでは表面～遷移層の不均質性が大きい。
⇒　地球内部は「五右衛門風呂」ではなく、表面からの冷却が主要因となる対流？

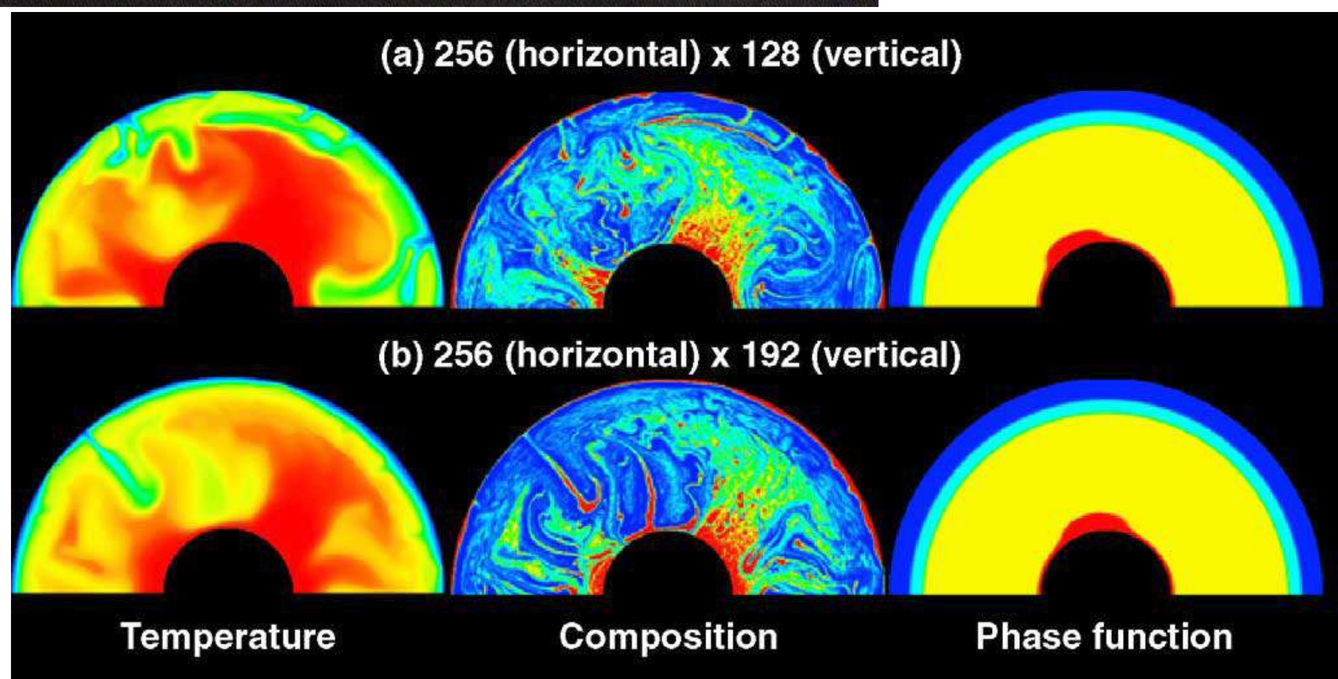
Intermediate ε



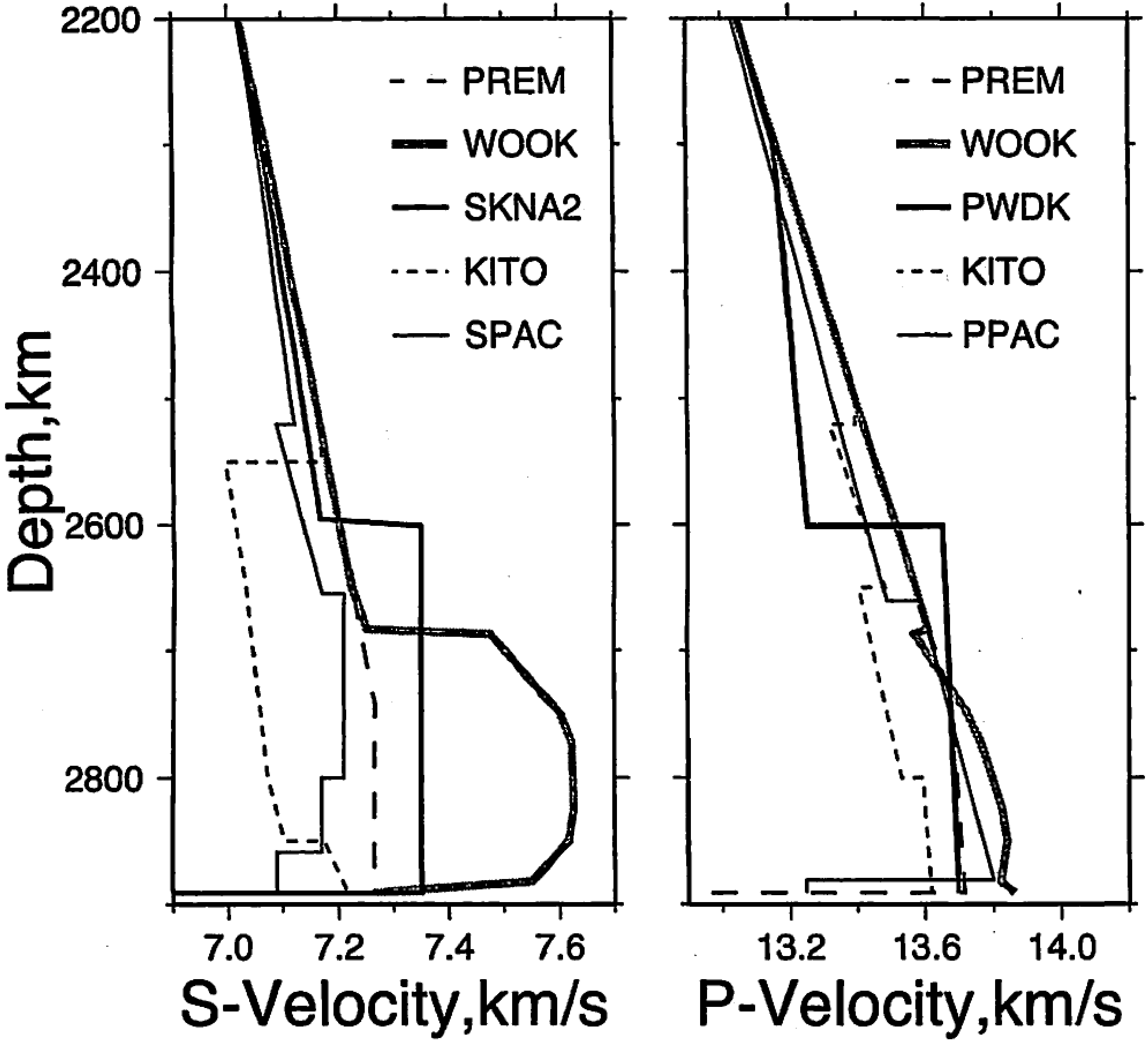
Davies, 1999 に加筆



Christensen & Hofmann (1994)

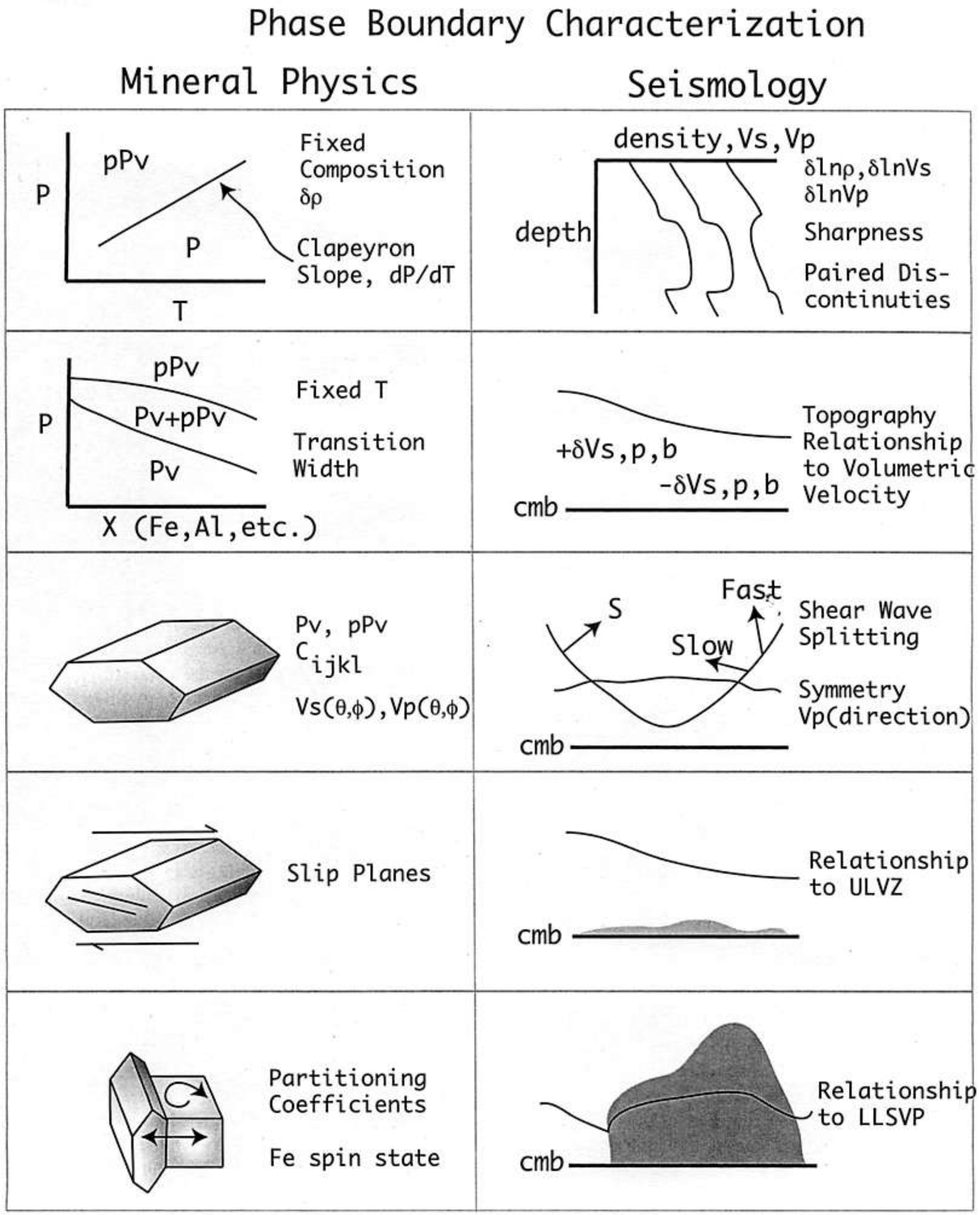


Nakagawa & Tackley (2005)



Lay & Garnero (2007)

Lay & Garnero (2007)



* Multiple reflectors

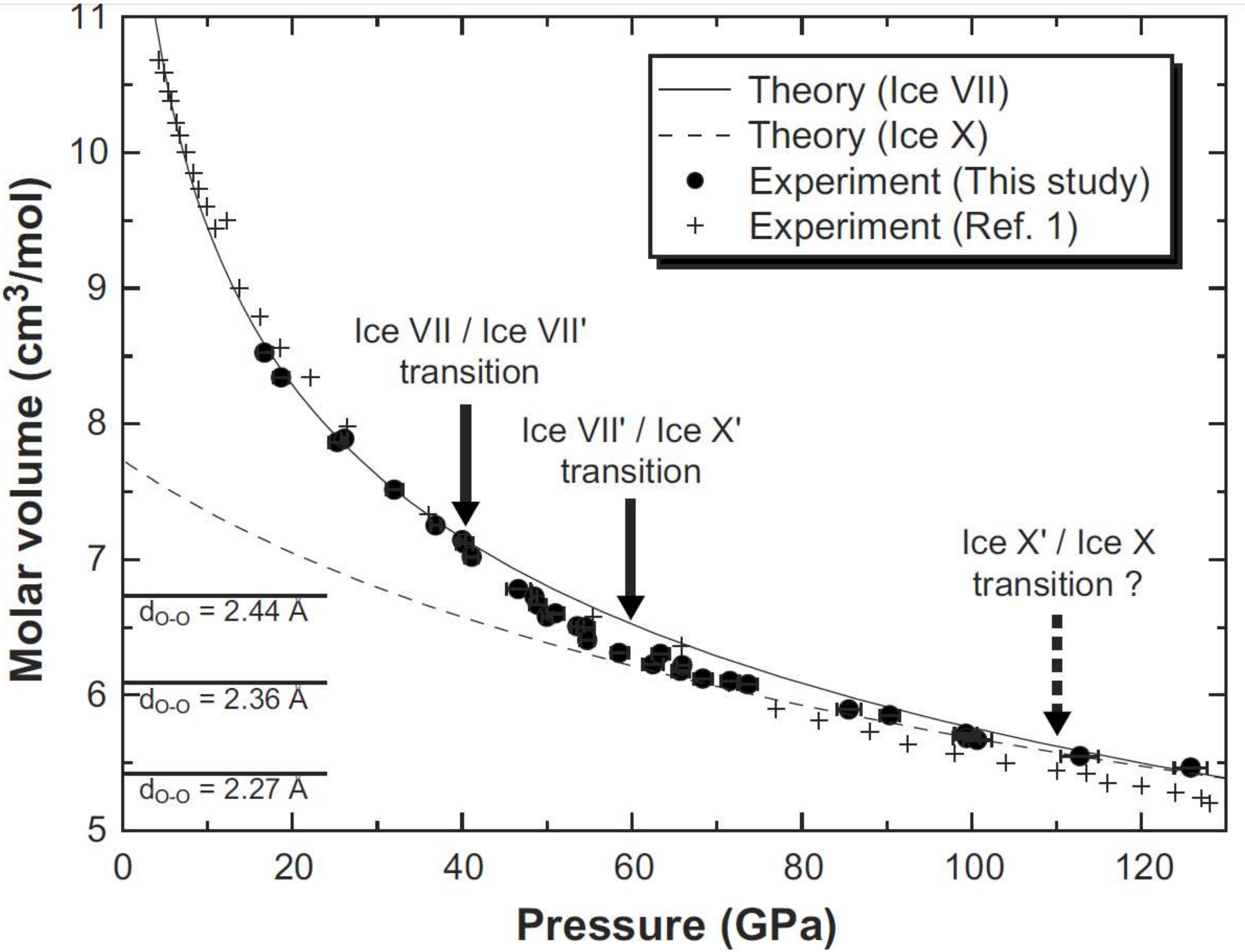
* Vs, Vp, bulk sound V

* Double crossing & dT/dP

* Undulated topography

* Anisotropy

* ULVZ



Sugimura et al. (2008)

地球のマントル対流の特徴と物質分化・循環

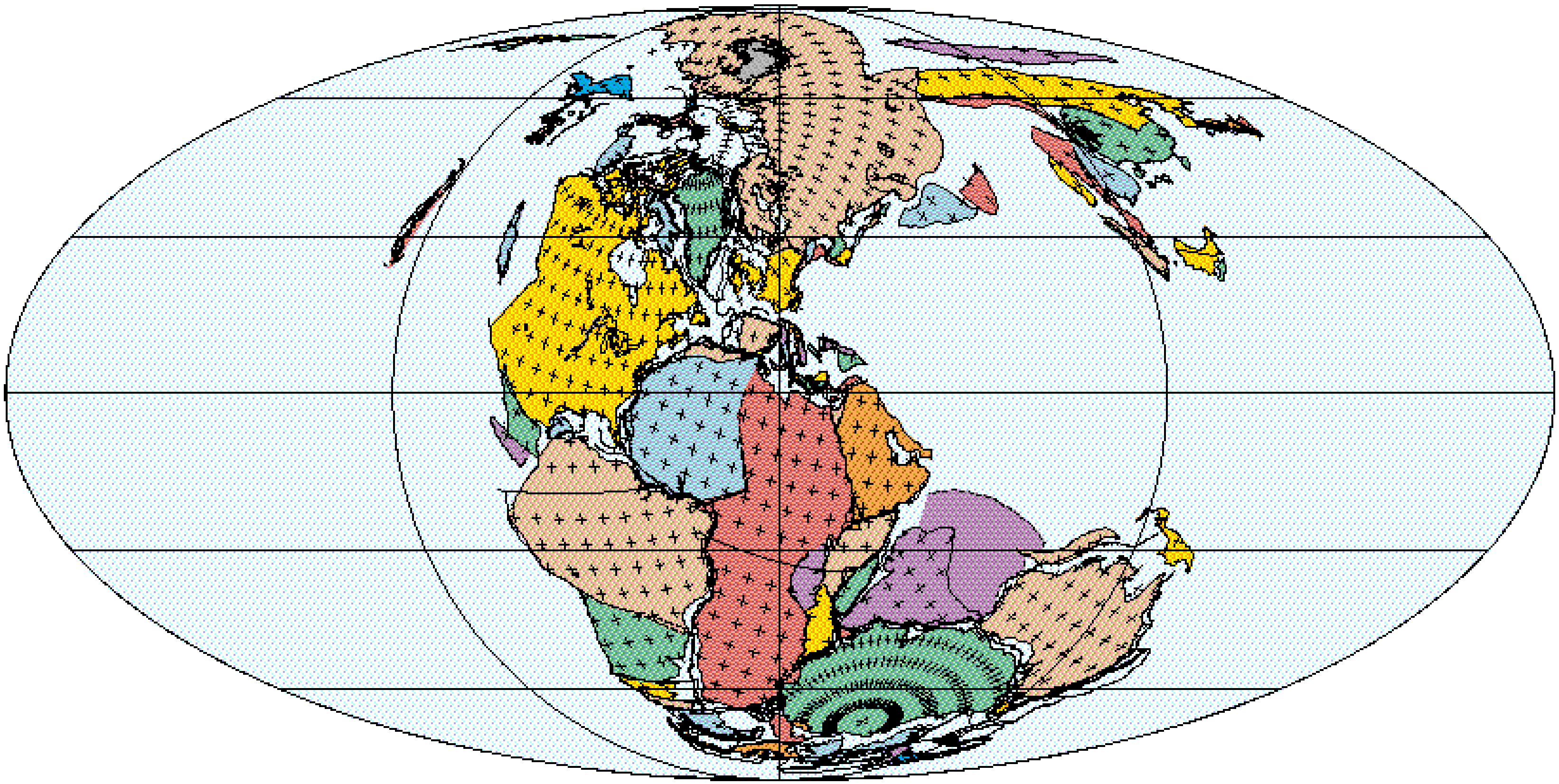
2. 地球内部の物質分化・循環

地殻と分化過程

沈み込み帯の物質循環

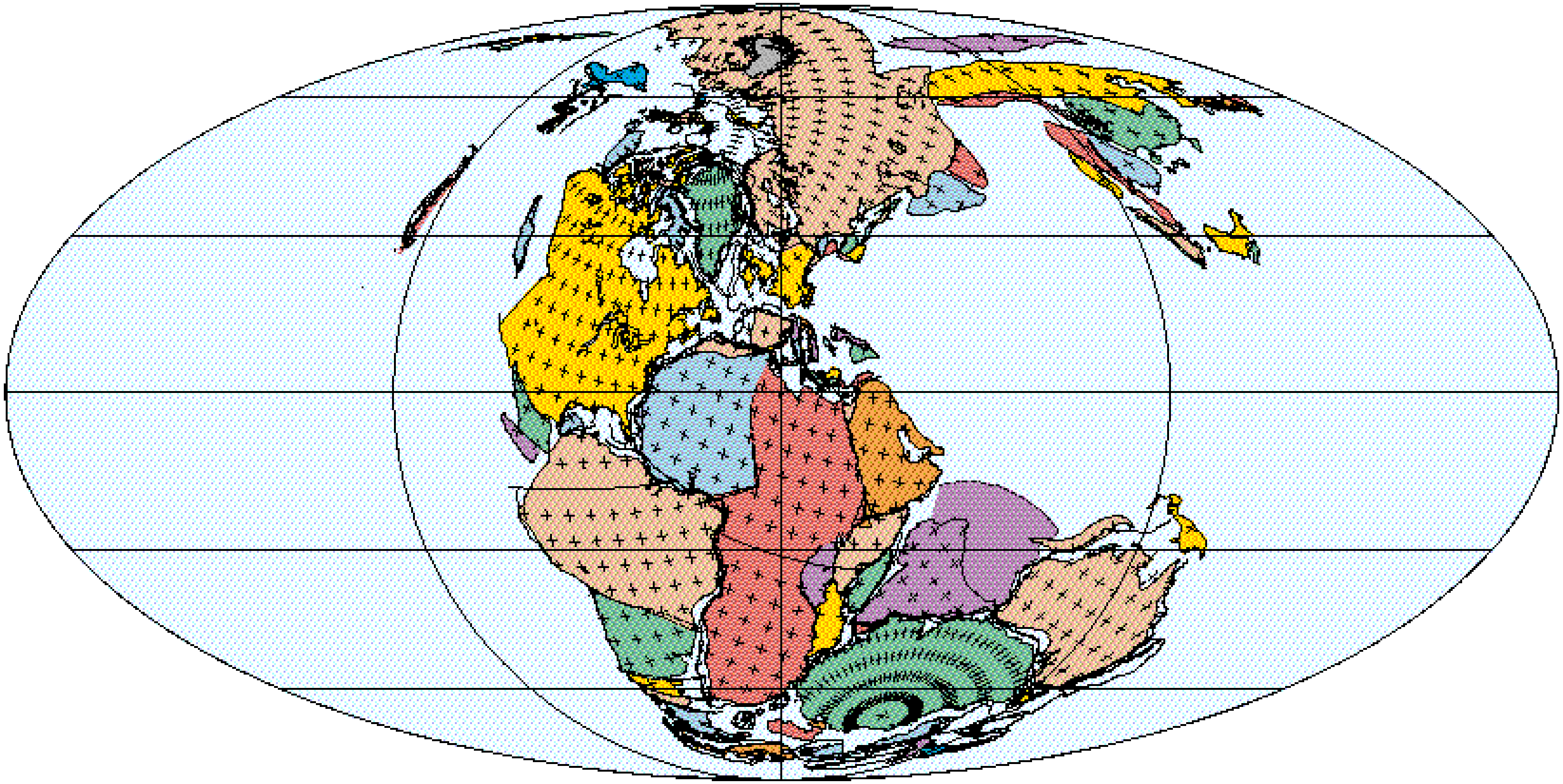
地殻物質と水のグローバルな循環

マントルの同位体不均質と対流構造



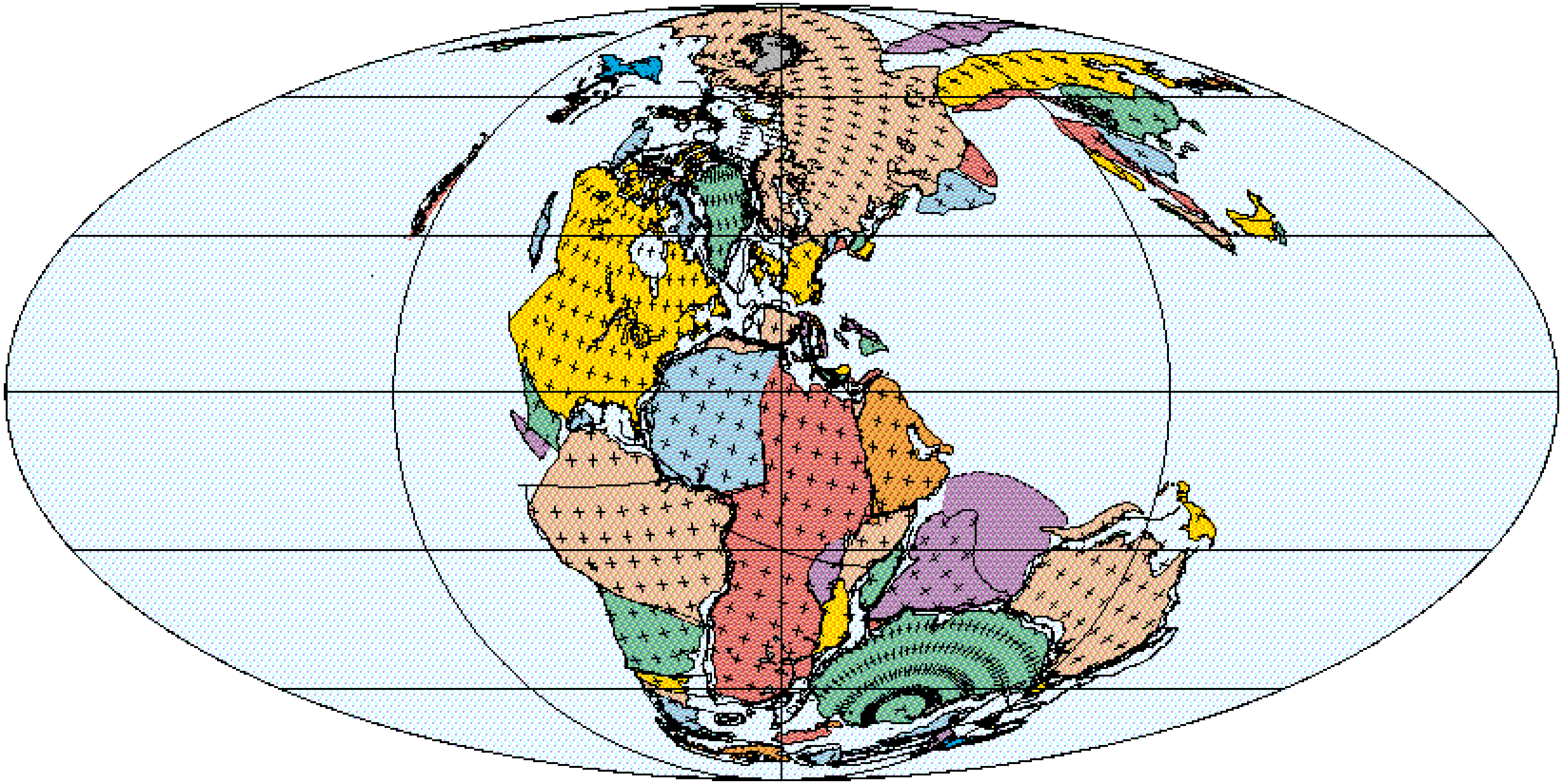
200 Ma
Sinemurian (Early Jurassic)

PLATES/UTIG
July 1999



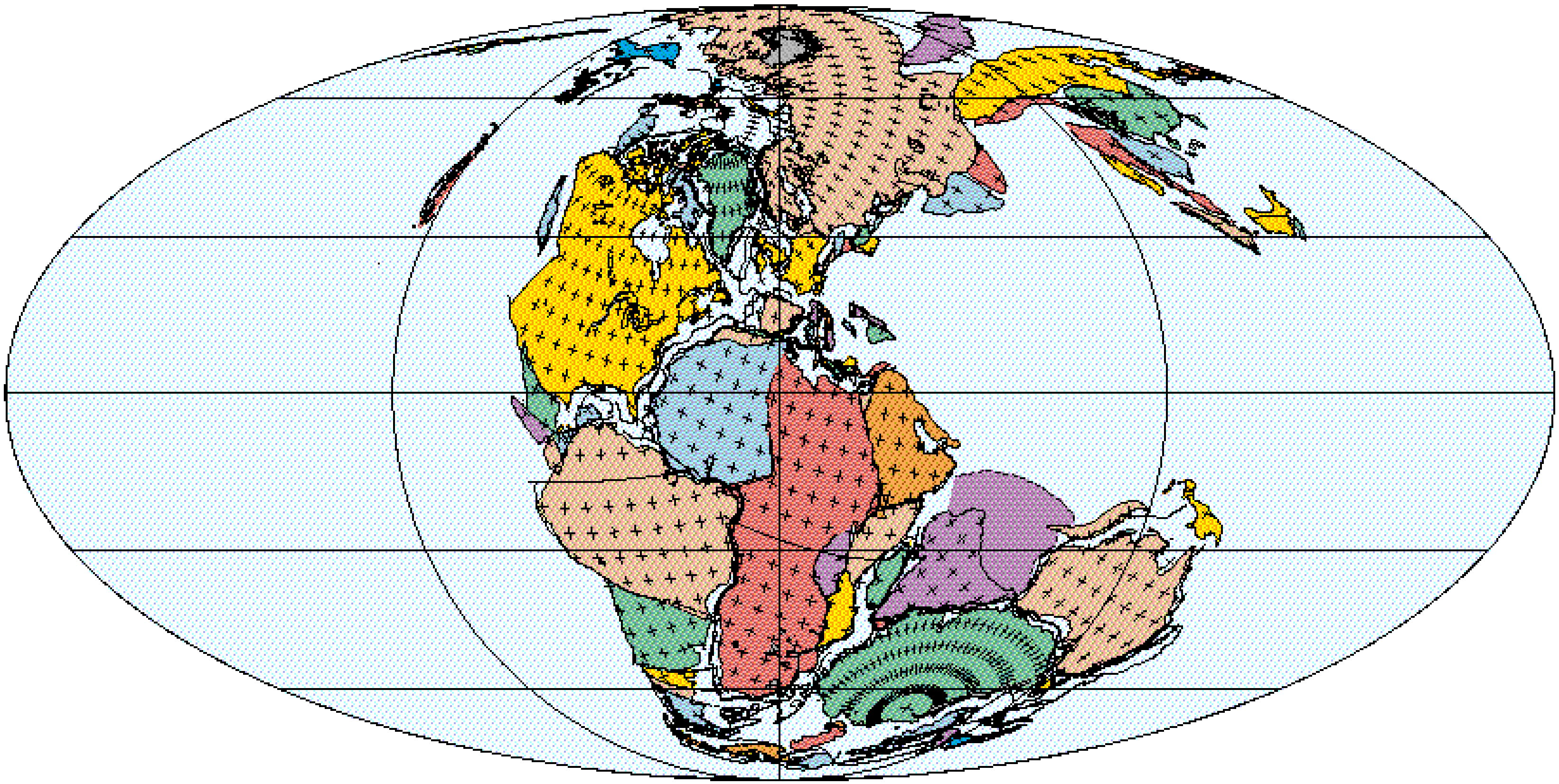
190 Ma
Pliensbachian (Early Jurassic)

PLATES/UTIG
July 1999



180 Ma
Aalenian (Middle Jurassic)

PLATES/UTIG
July 1999

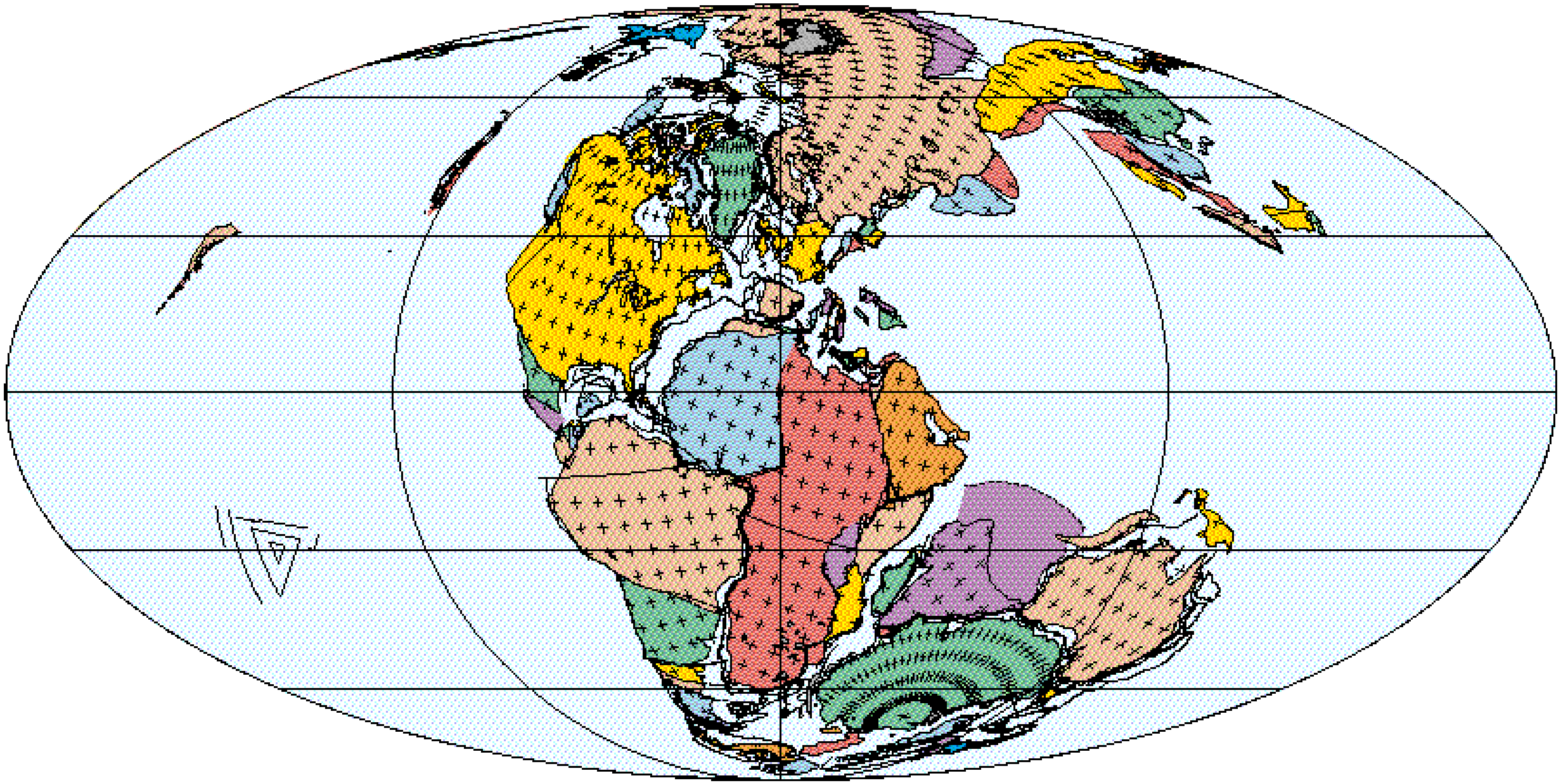


170 Ma

Bajocian (Middle Jurassic)

PLATES/UTIG

July 1999

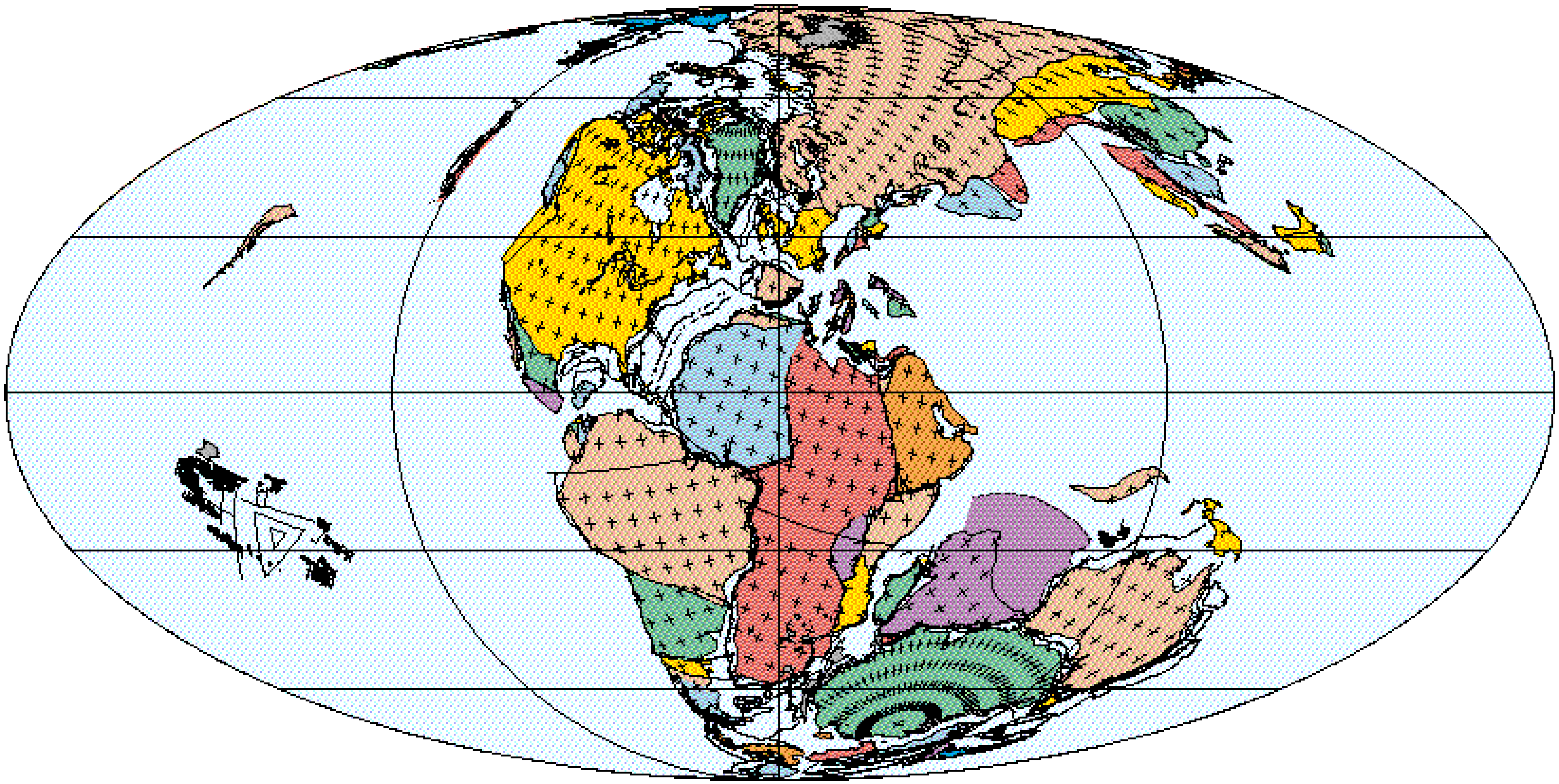


160 Ma

Callovian (Middle Jurassic)

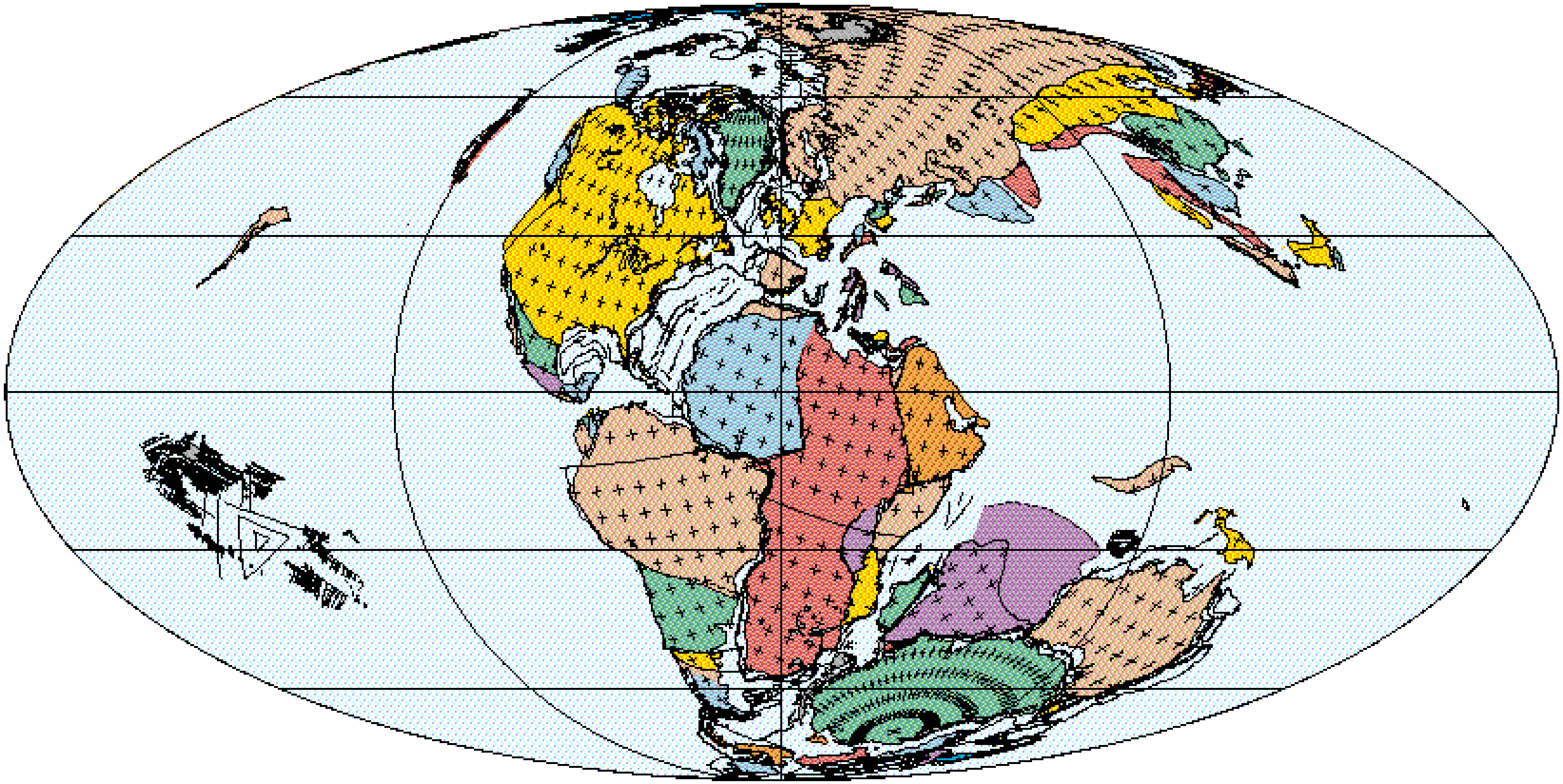
PLATES/UTIG

July 1999



150 Ma
Volgian (Late Jurassic)

PLATES/UTIG
July 1999

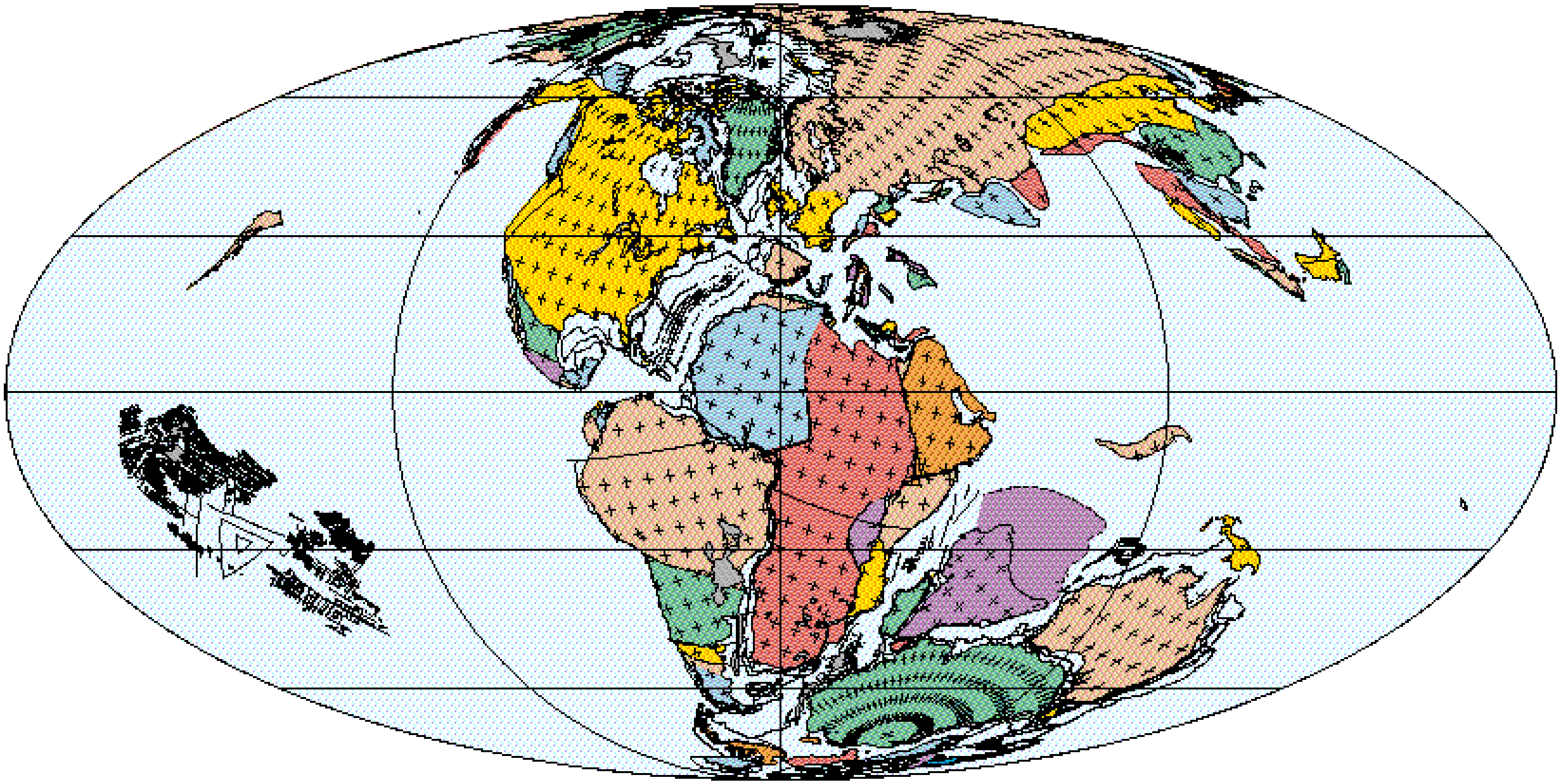


140 Ma

Ryazanian (Early Cretaceous)

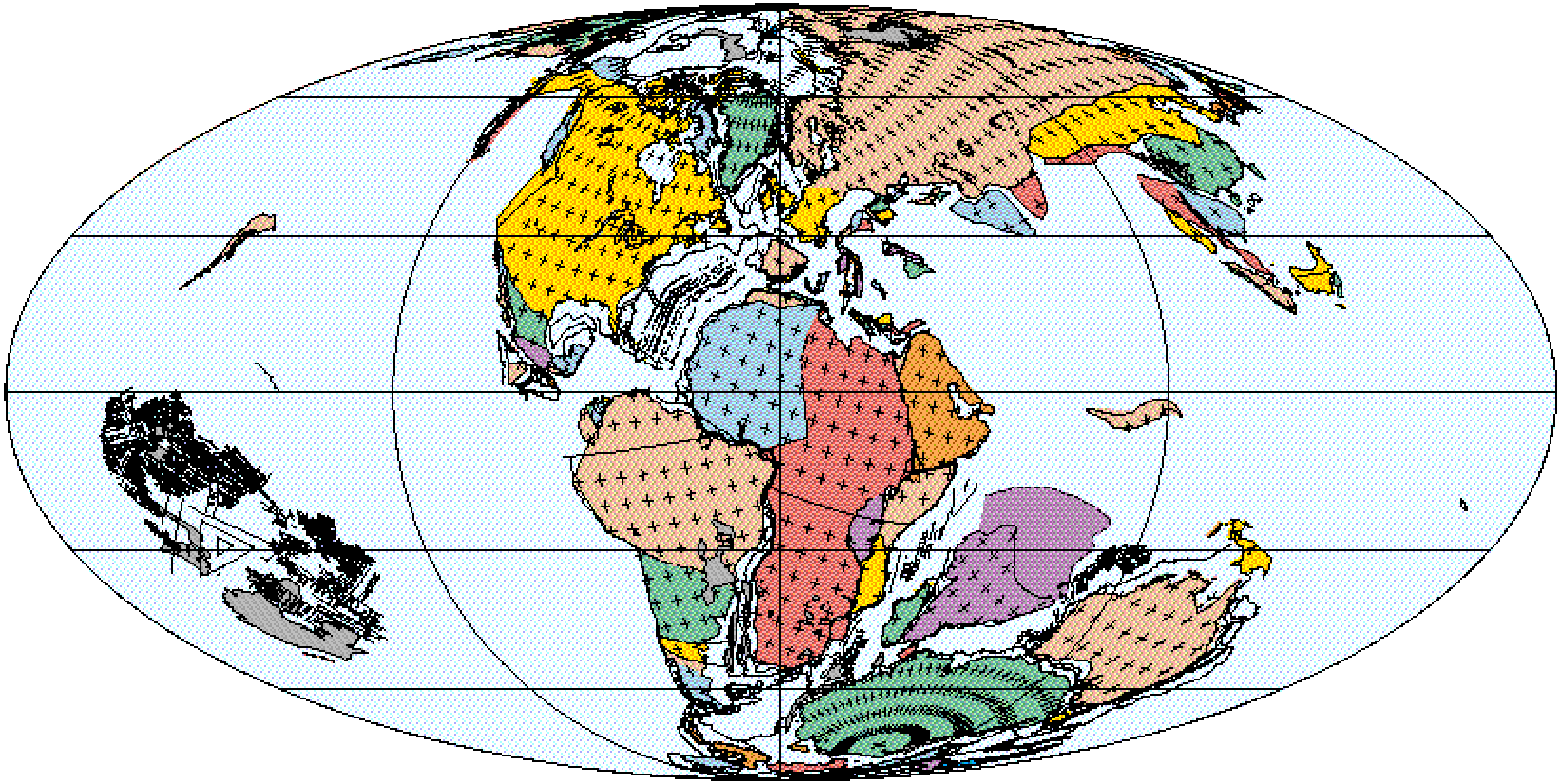
PLATES/UTIG

July 1999



130 Ma
Hauterivian (Early Cretaceous)

PLATES/UTIG
July 1999

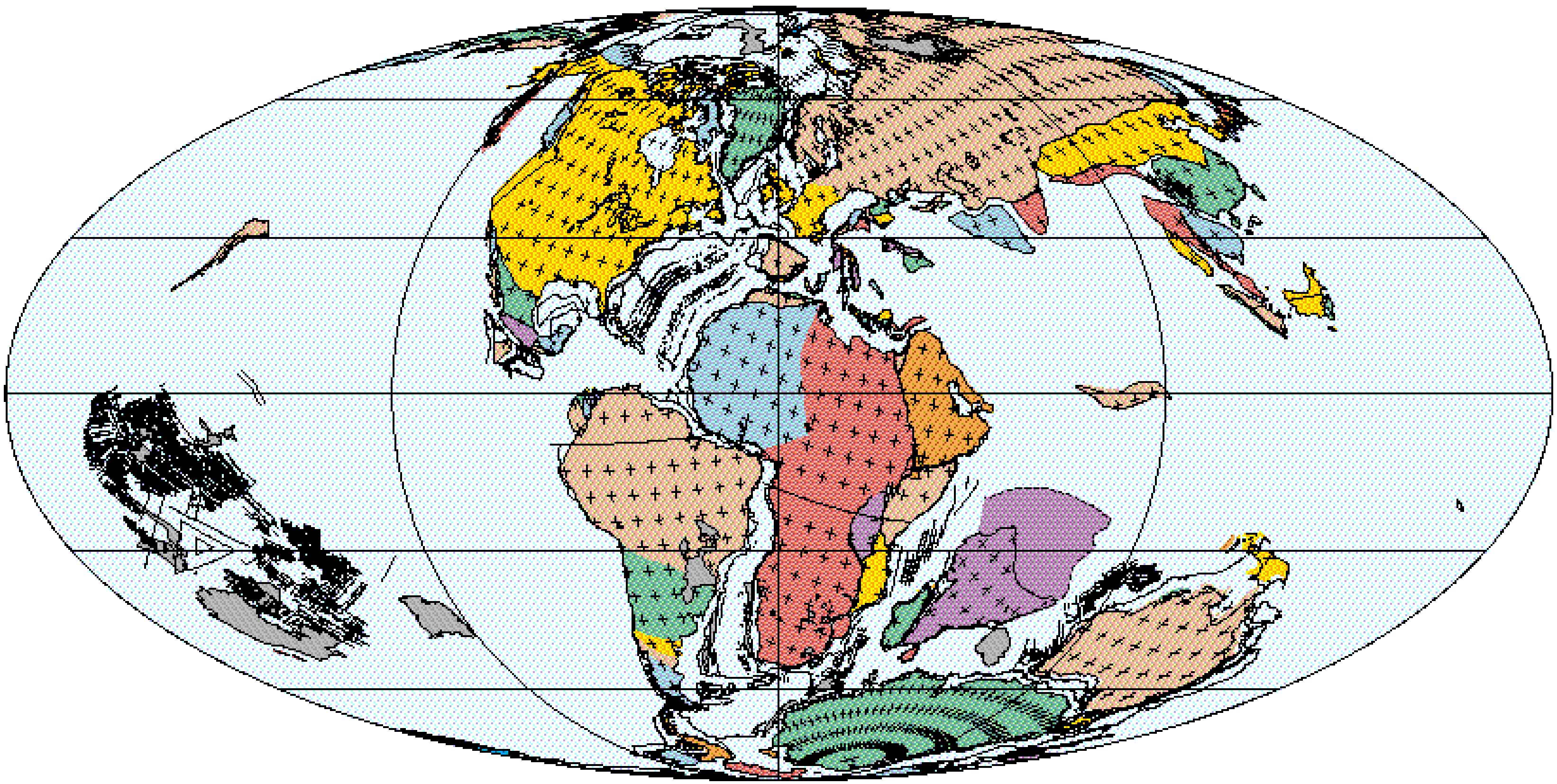


120 Ma

Aptian (Early Cretaceous)

PLATES/UTIG

July 1999

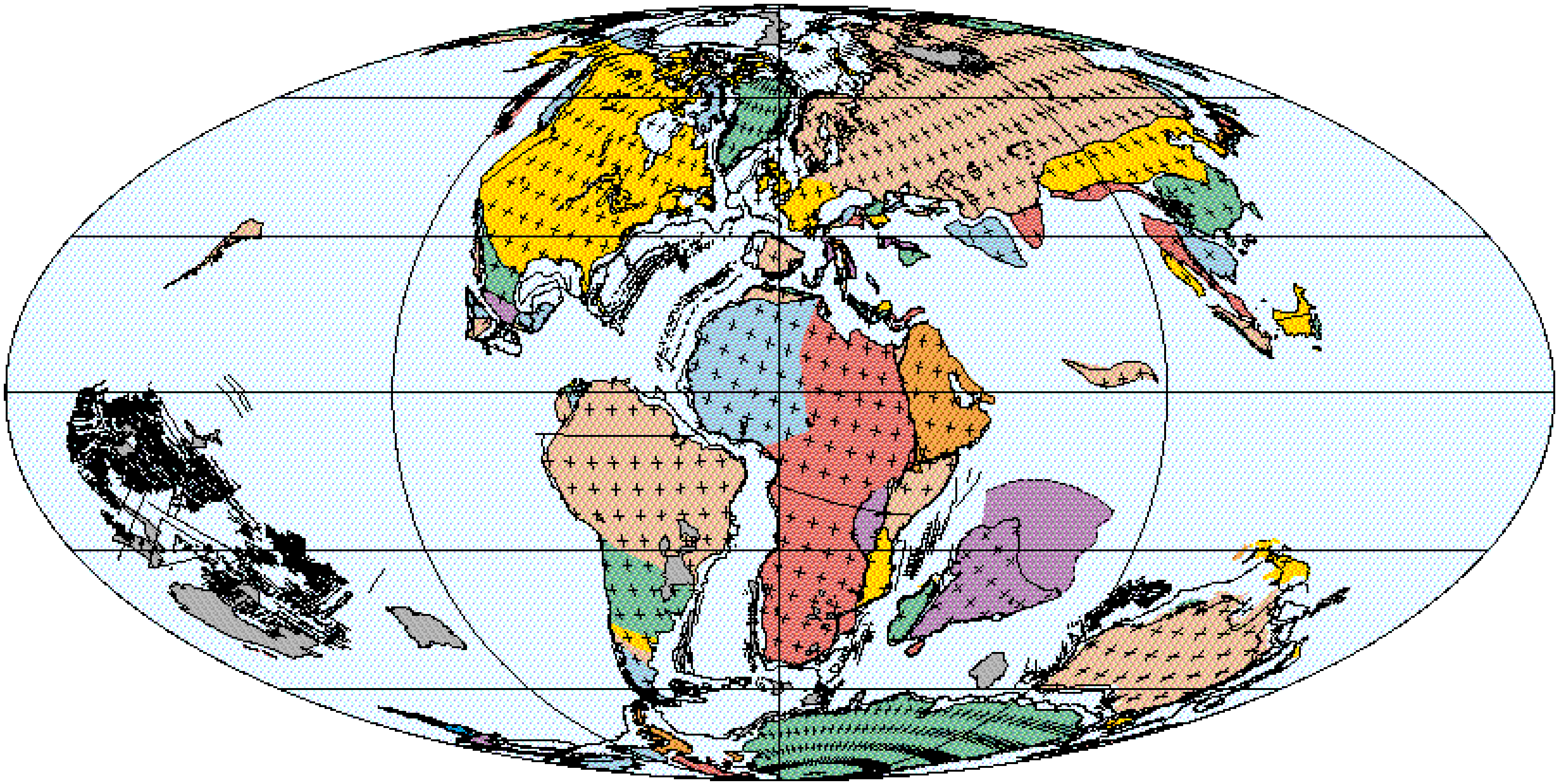


110 Ma

Early Albian (Early Cretaceous)

PLATES/UTIG

July 1999

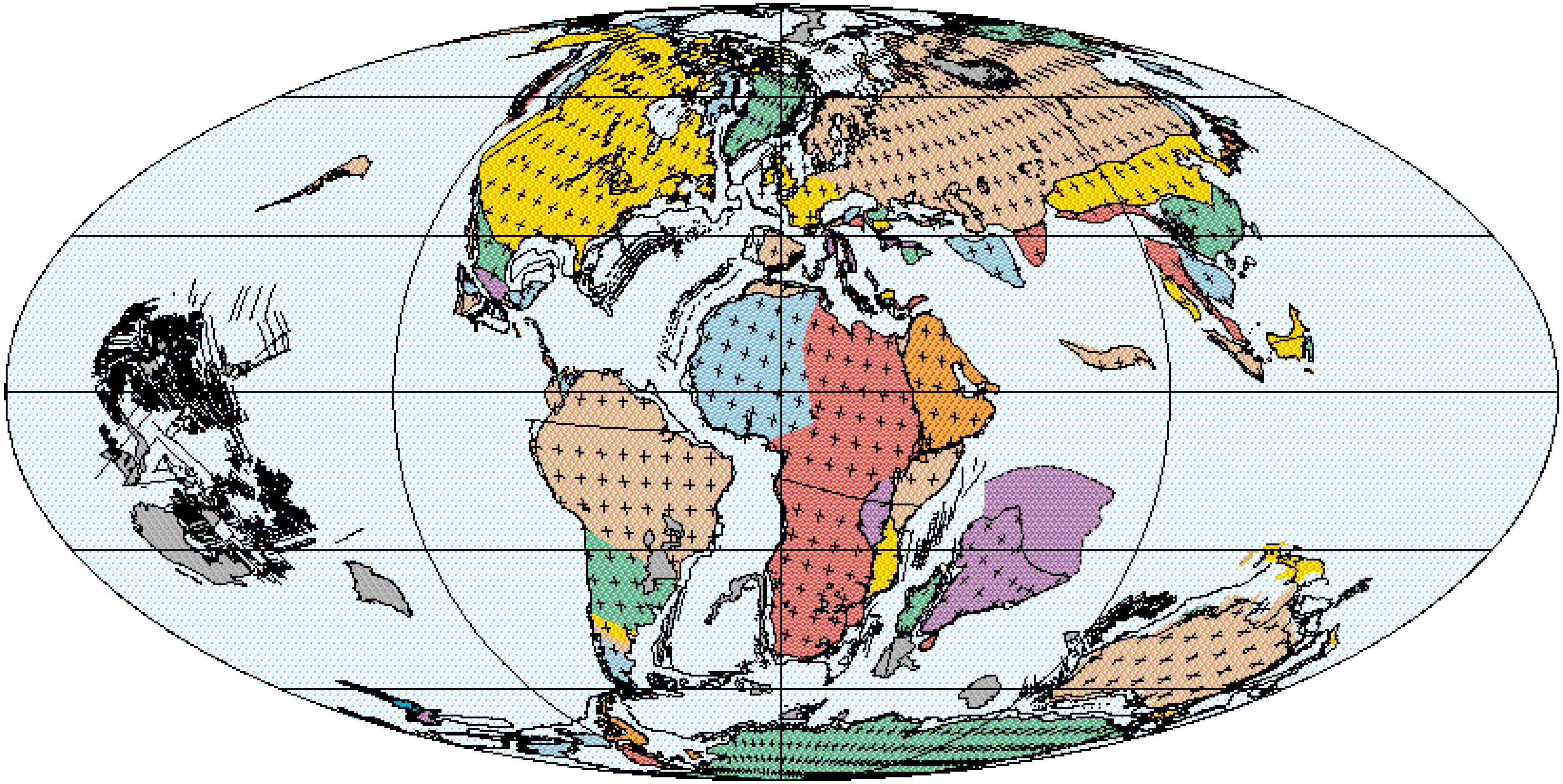


100 Ma

Late Albian (Early Cretaceous)

PLATES/UTIG

July 1999

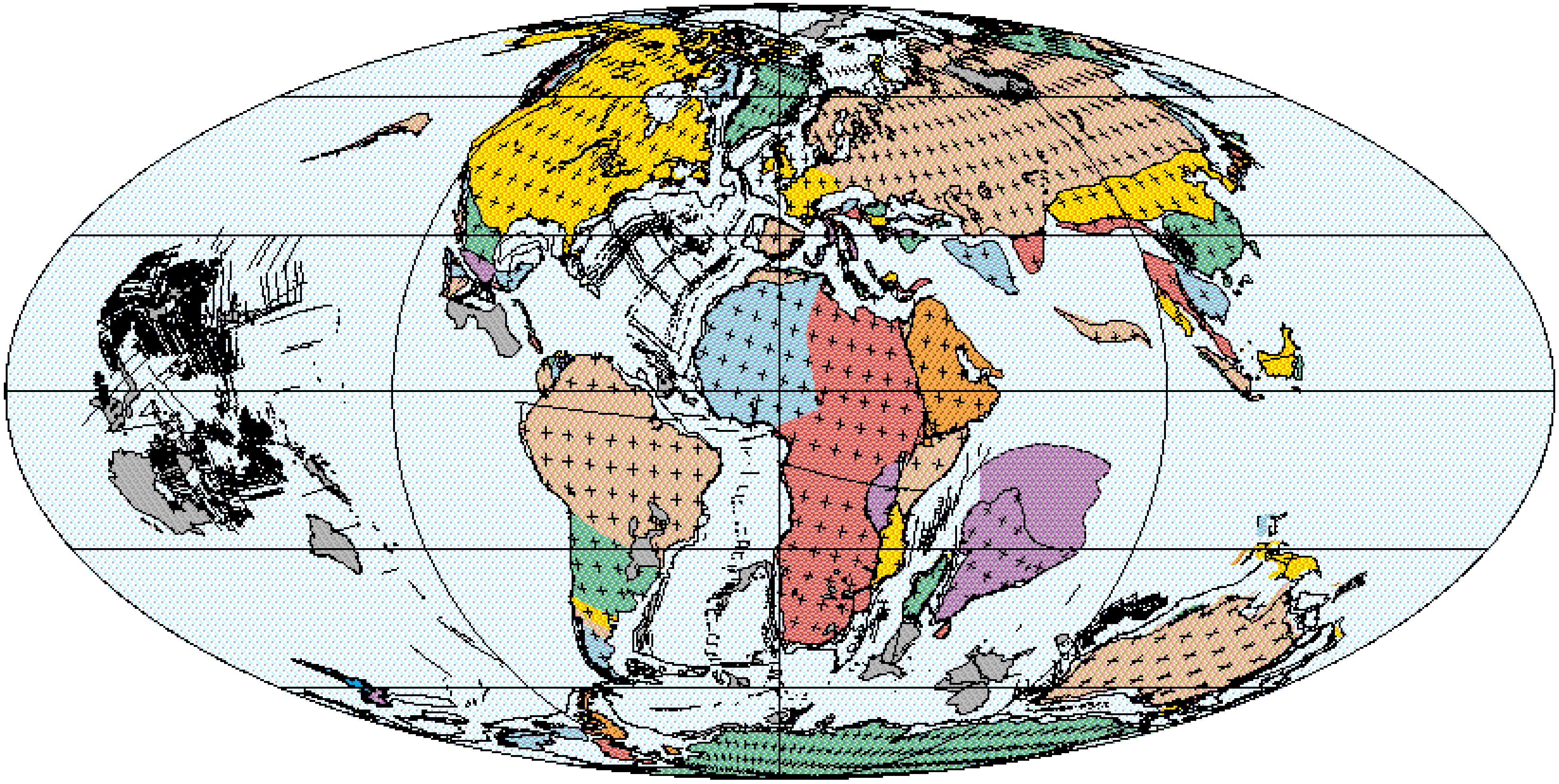


90 Ma

Turonian (Late Cretaceous)

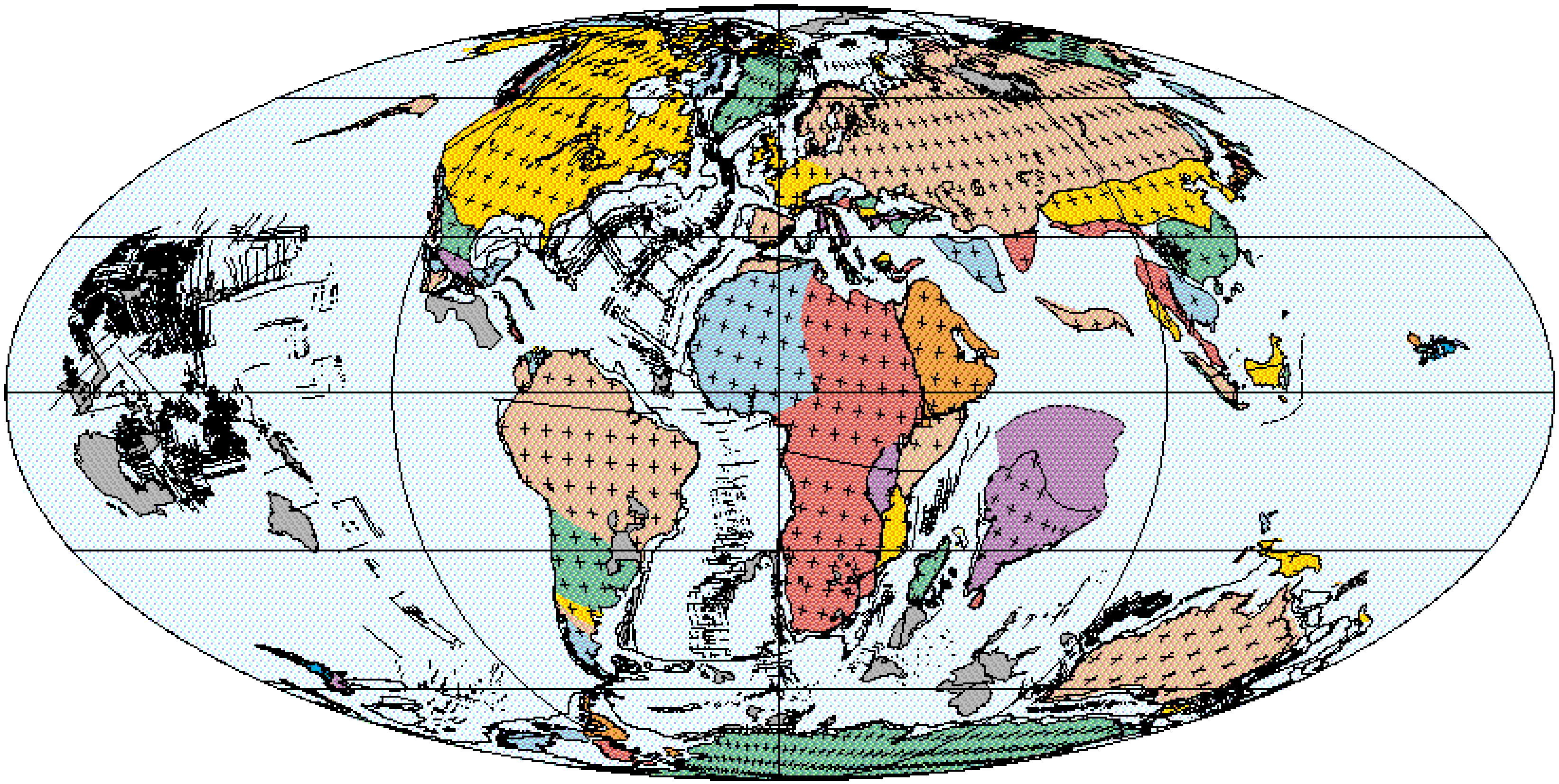
PLATES/UTIG

July 1999



80 Ma
Campanian (Late Cretaceous)

PLATES/UTIG
July 1999

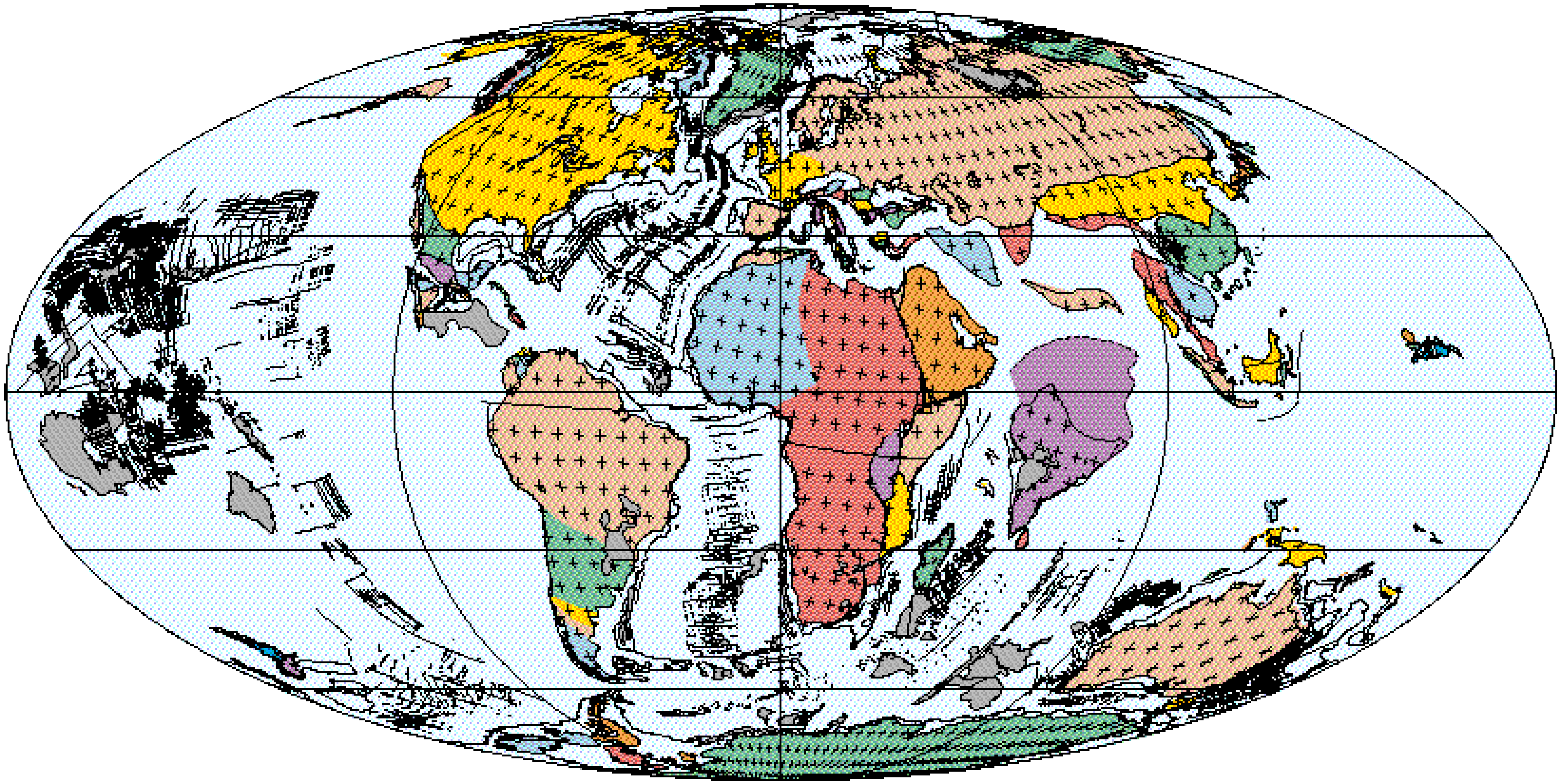


70 Ma

Maastrichtian (Late Cretaceous)

PLATES/UTIG

July 1999

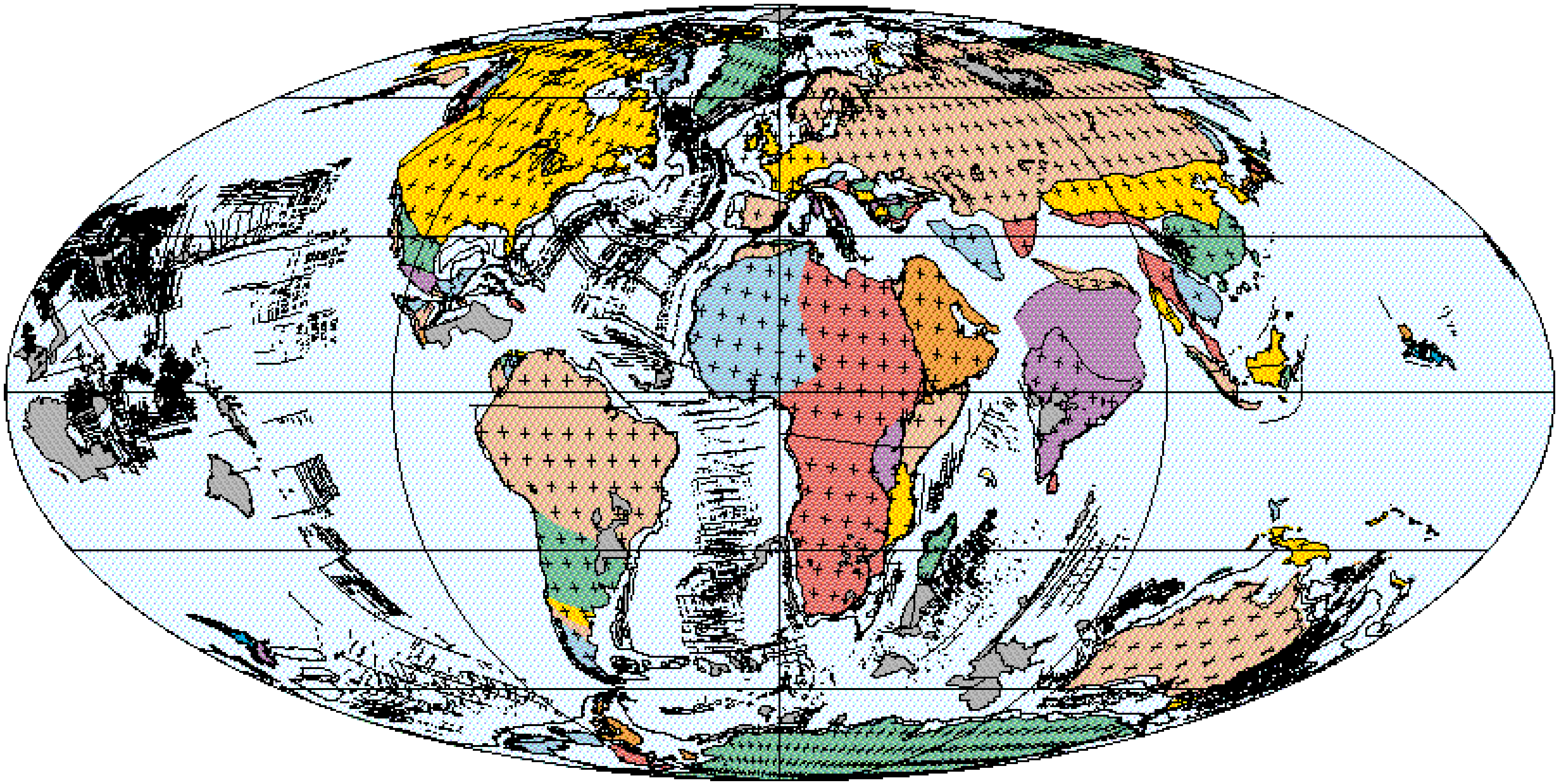


60 Ma

Late Paleocene

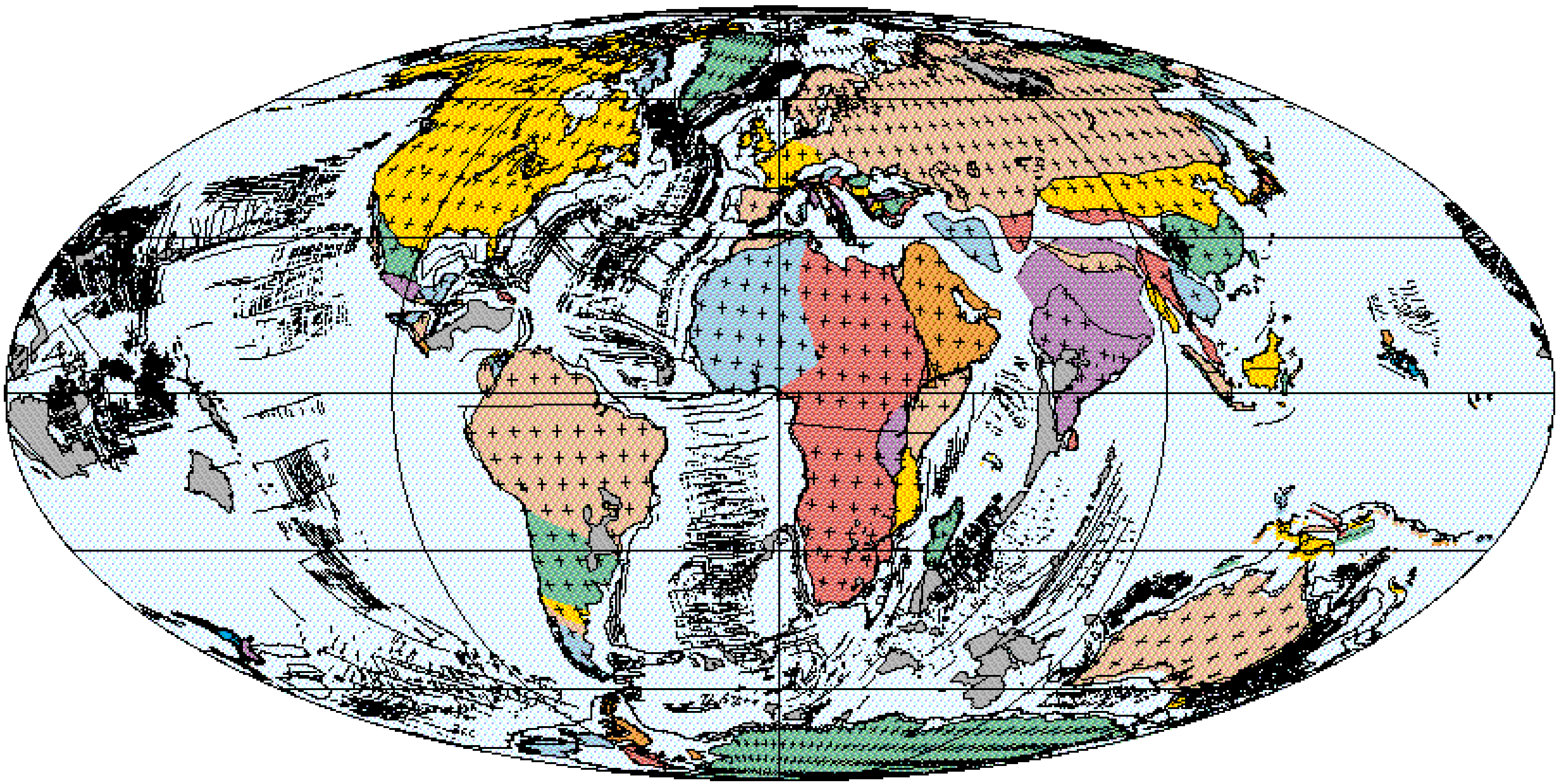
PLATES/UTIG

July 1999



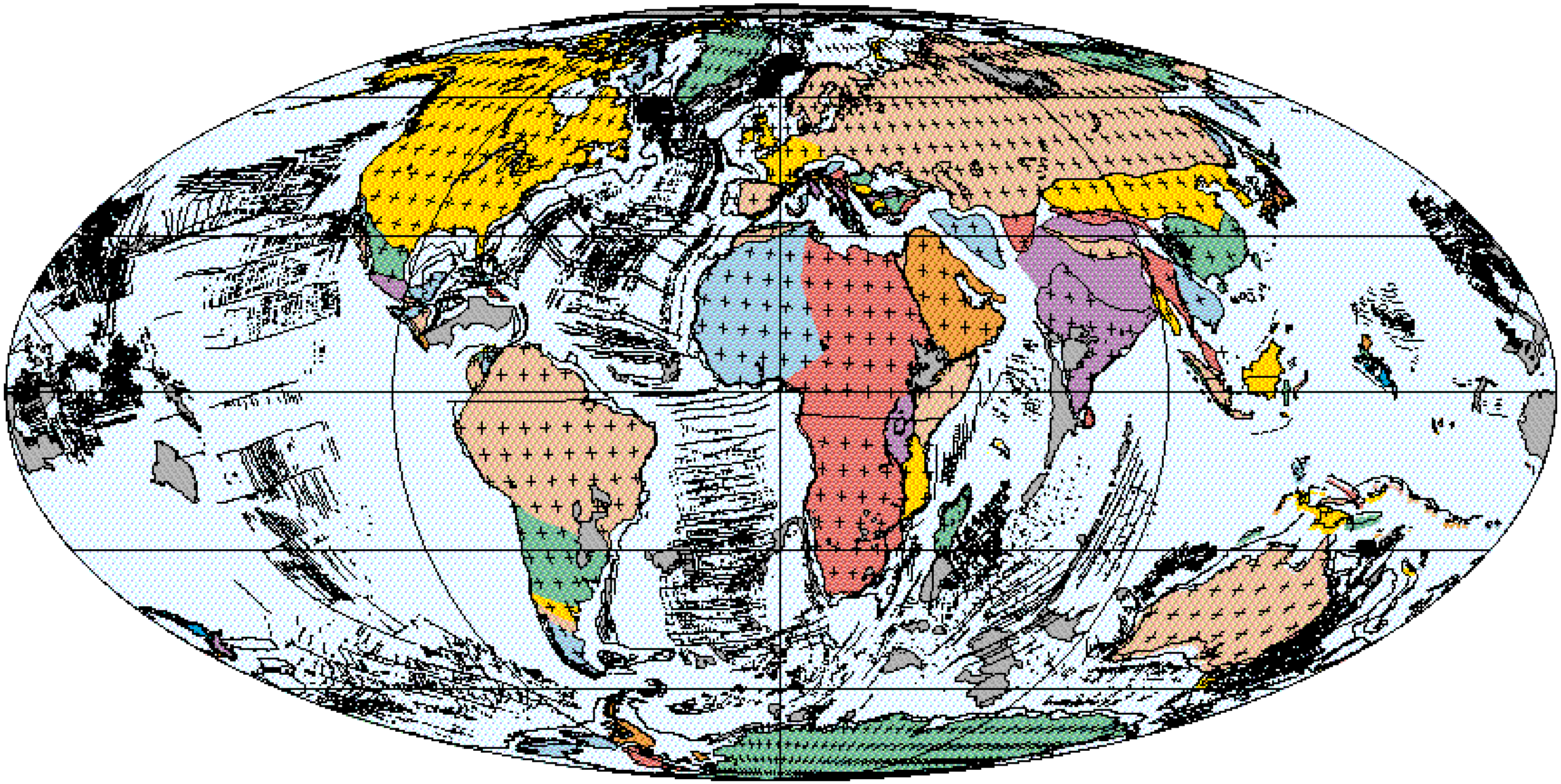
50 Ma
Early Eocene

PLATES/UTIG
July 1999



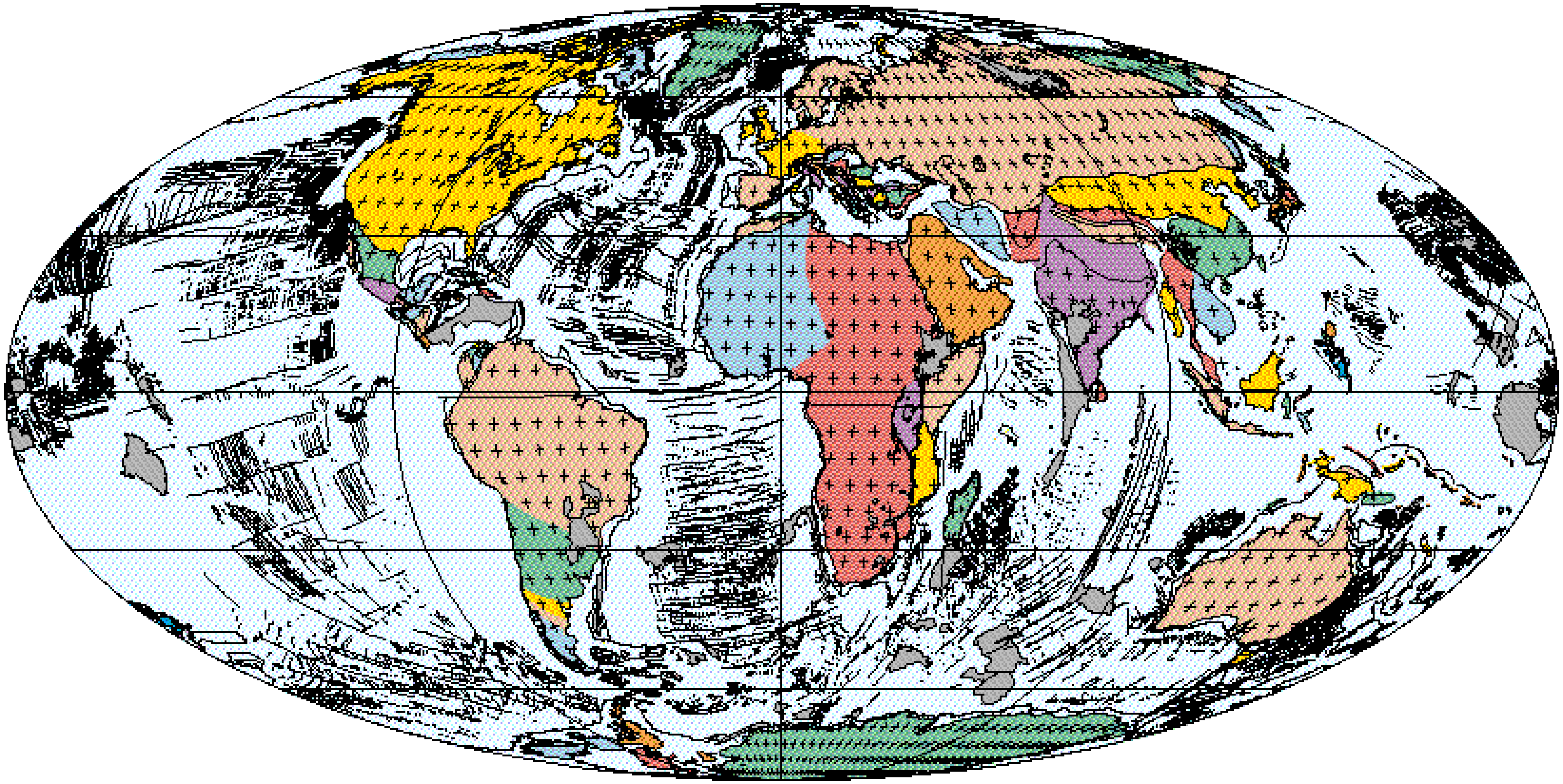
40 Ma
Middle Eocene

PLATES/UTIG
July 1999



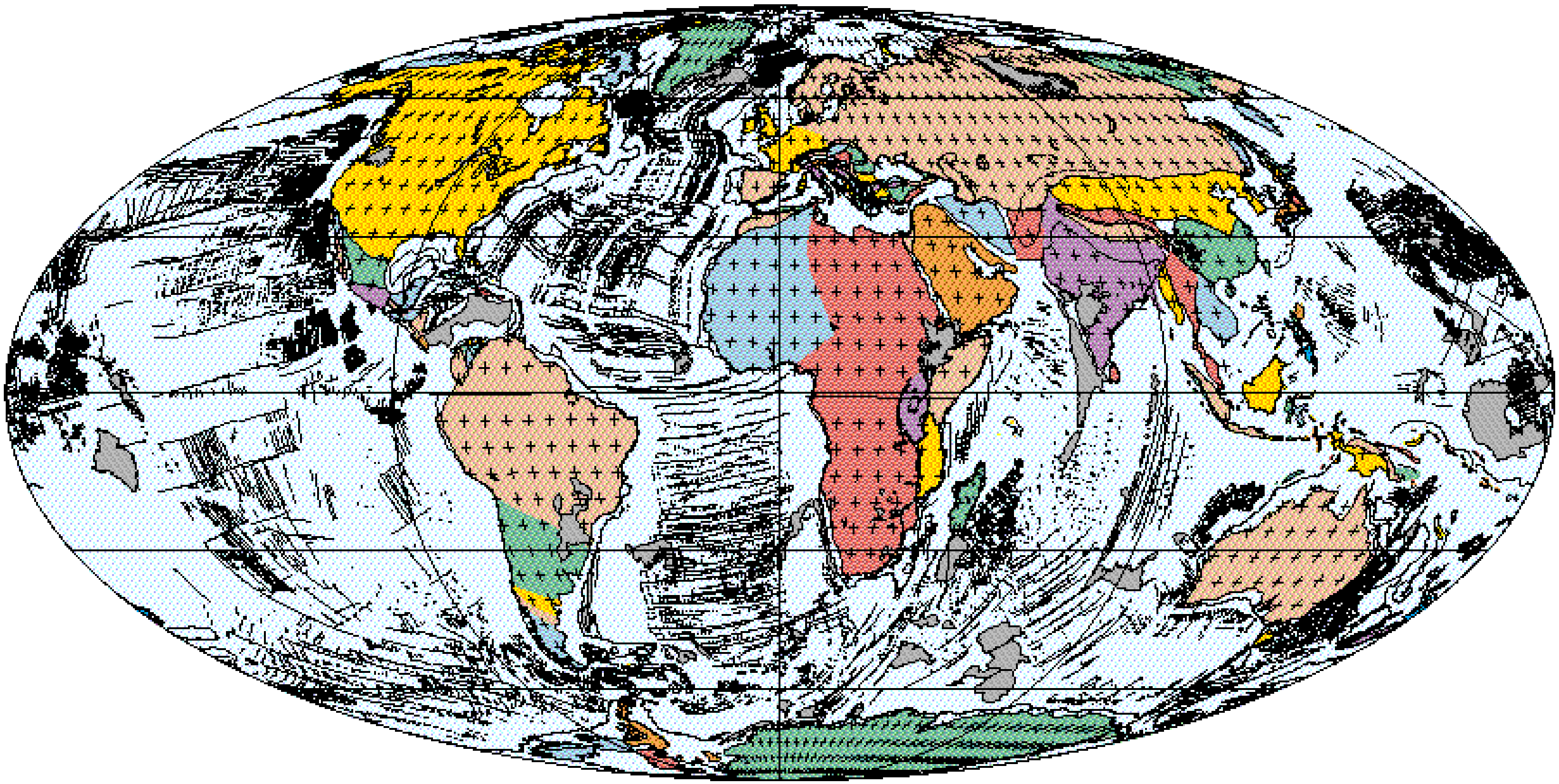
30 Ma
Early Oligocene

PLATES/UTIG
July 1999



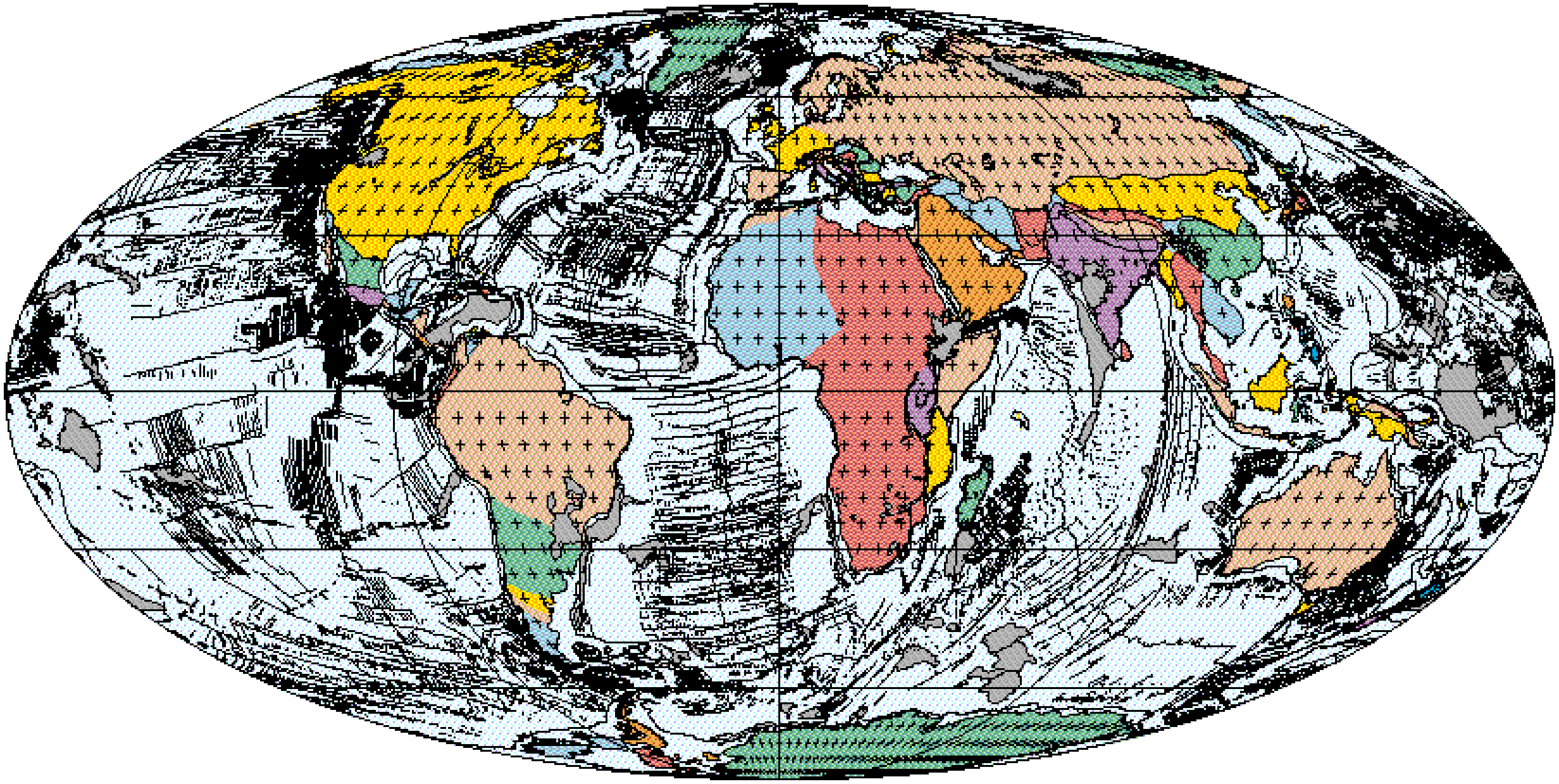
20 Ma
Early Miocene

PLATES/UTIG
July 1999



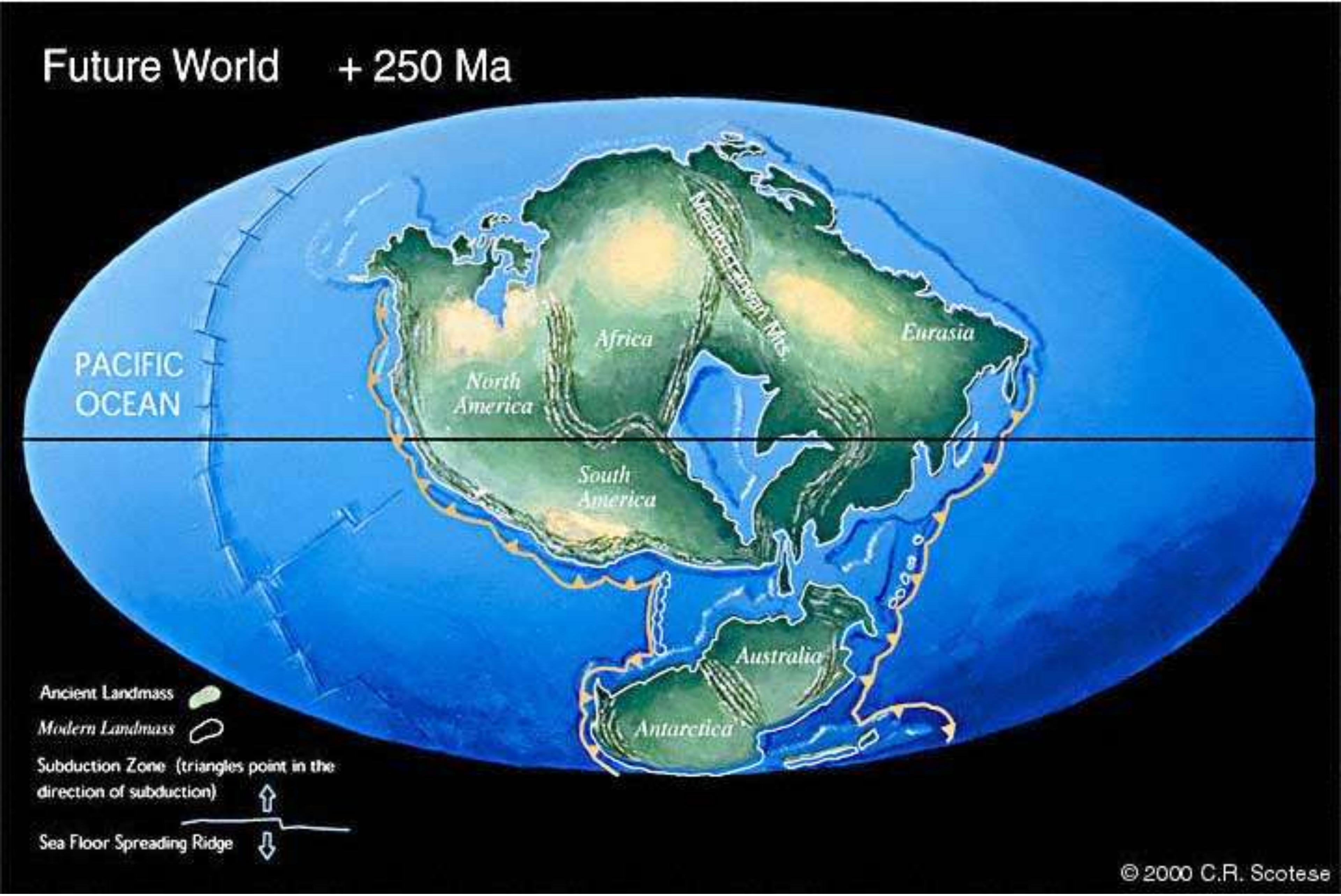
10 Ma
Late Miocene

PLATES/UTIG
July 1999



0 Ma
Present Day

PLATES/UTIG
July 1999



"Pangea Ultima" will form 250 million years in the Future

http://www.scotese.com/precambr.htm

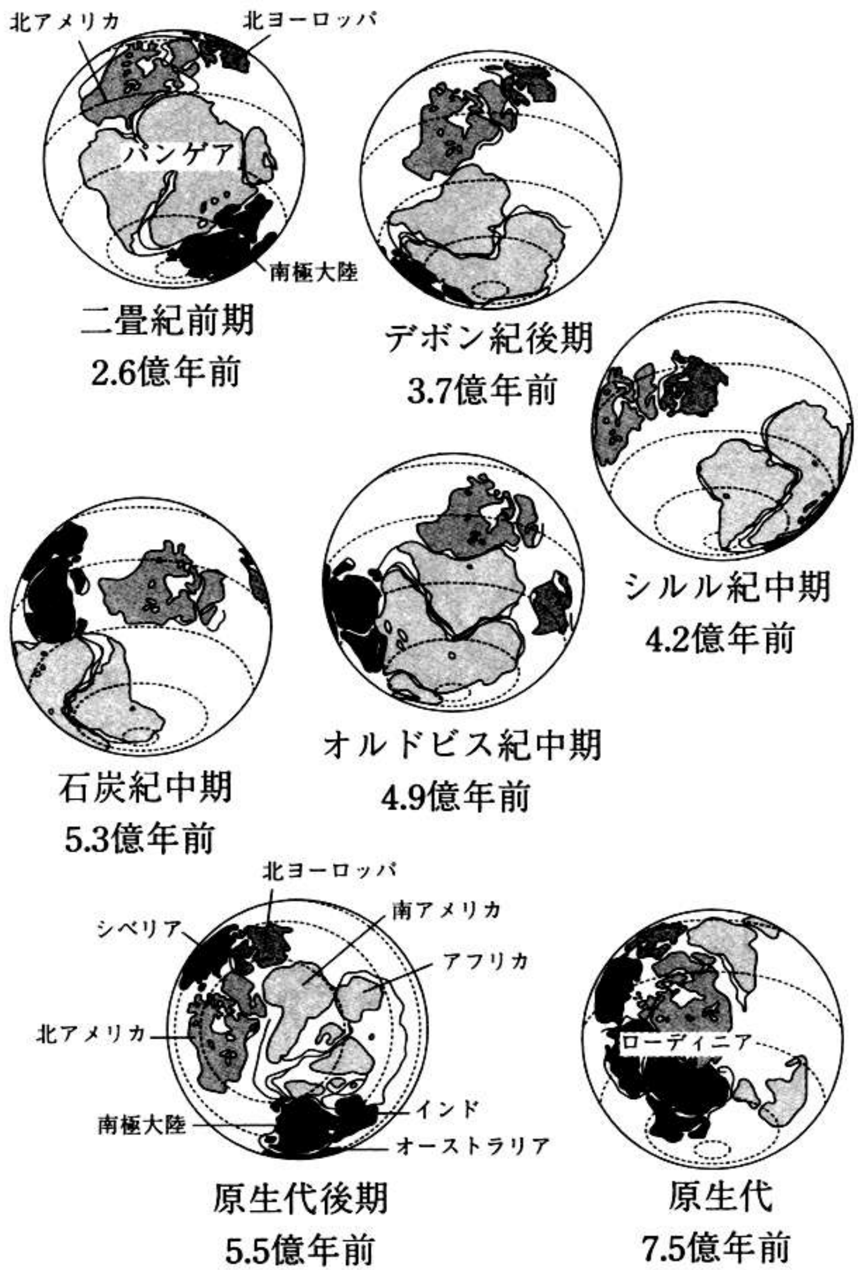


図 3.3.15　2 億 6000 万年前から 7 億 5000 万年前までの大陸の復元図の一例．Daliziel（1995）を改変して引用．

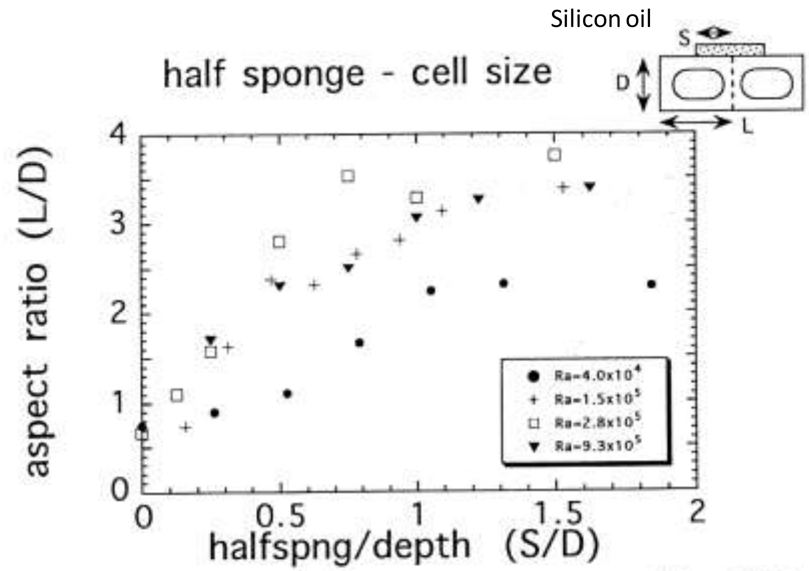


図１　断熱材の長さと対流セルのアスペクト比の関係

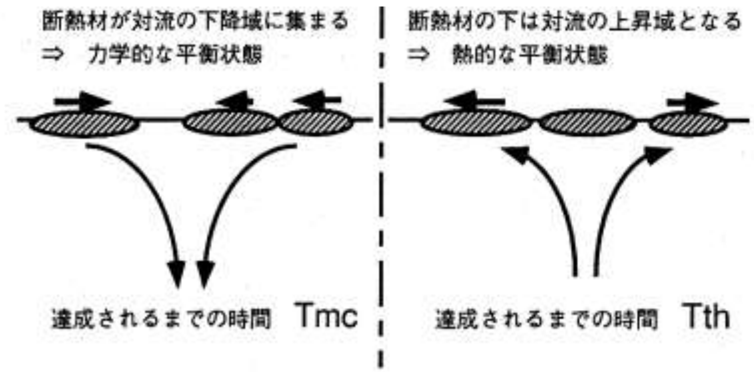


図２　対流パターンと断熱材の関係。

（左）力学的平衡状態、（右）熱的平衡状態。

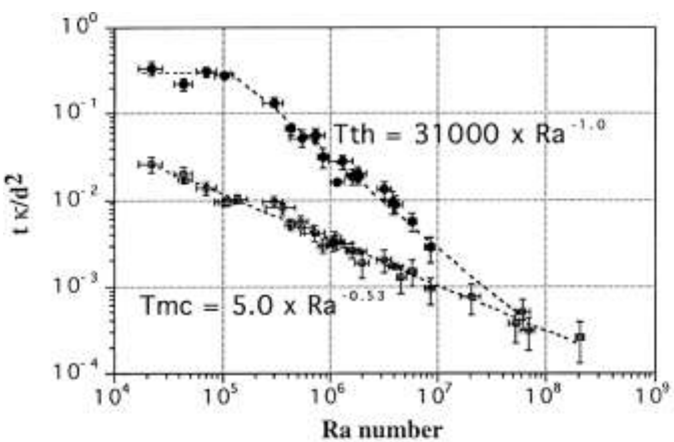


図３　平衡状態の達成までに要する時間の測定結果。

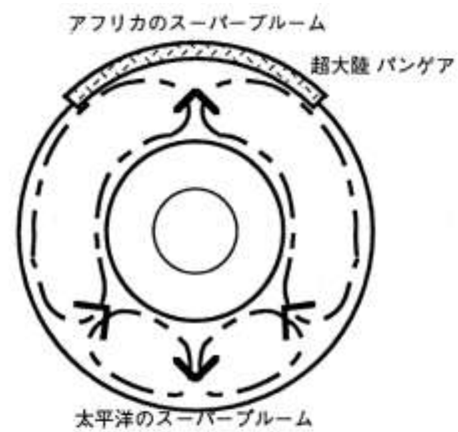
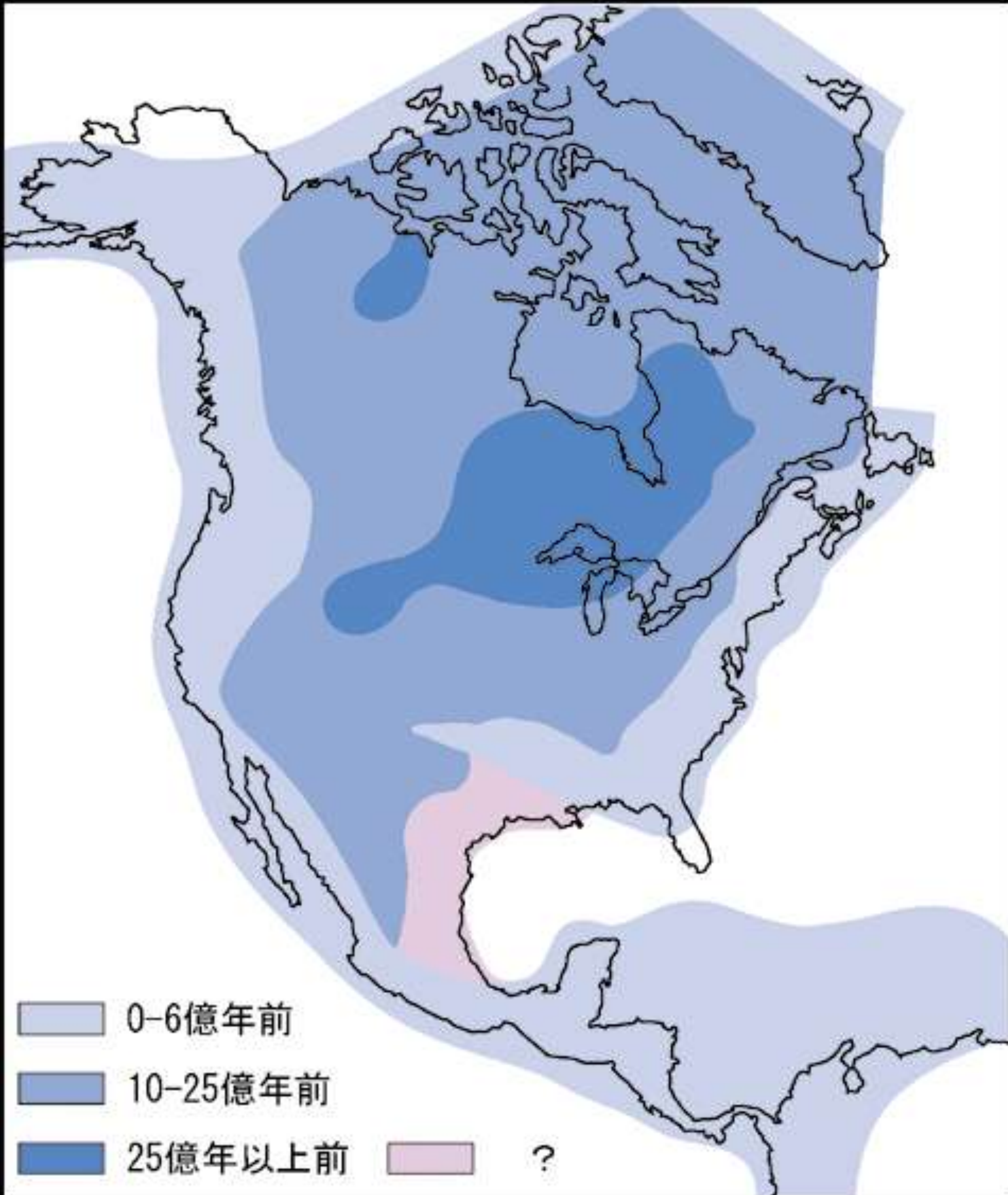


図４　地球の断面図。超大陸の分裂直前のマントル対流のパターン。

柳澤（1996）



http://chigaku.ed.gifu-u.ac.jp/
chigakuhp/rika-b/
htmls/supconti/nameri.html

「全地球史解読（熊澤ほか編）」丸山より

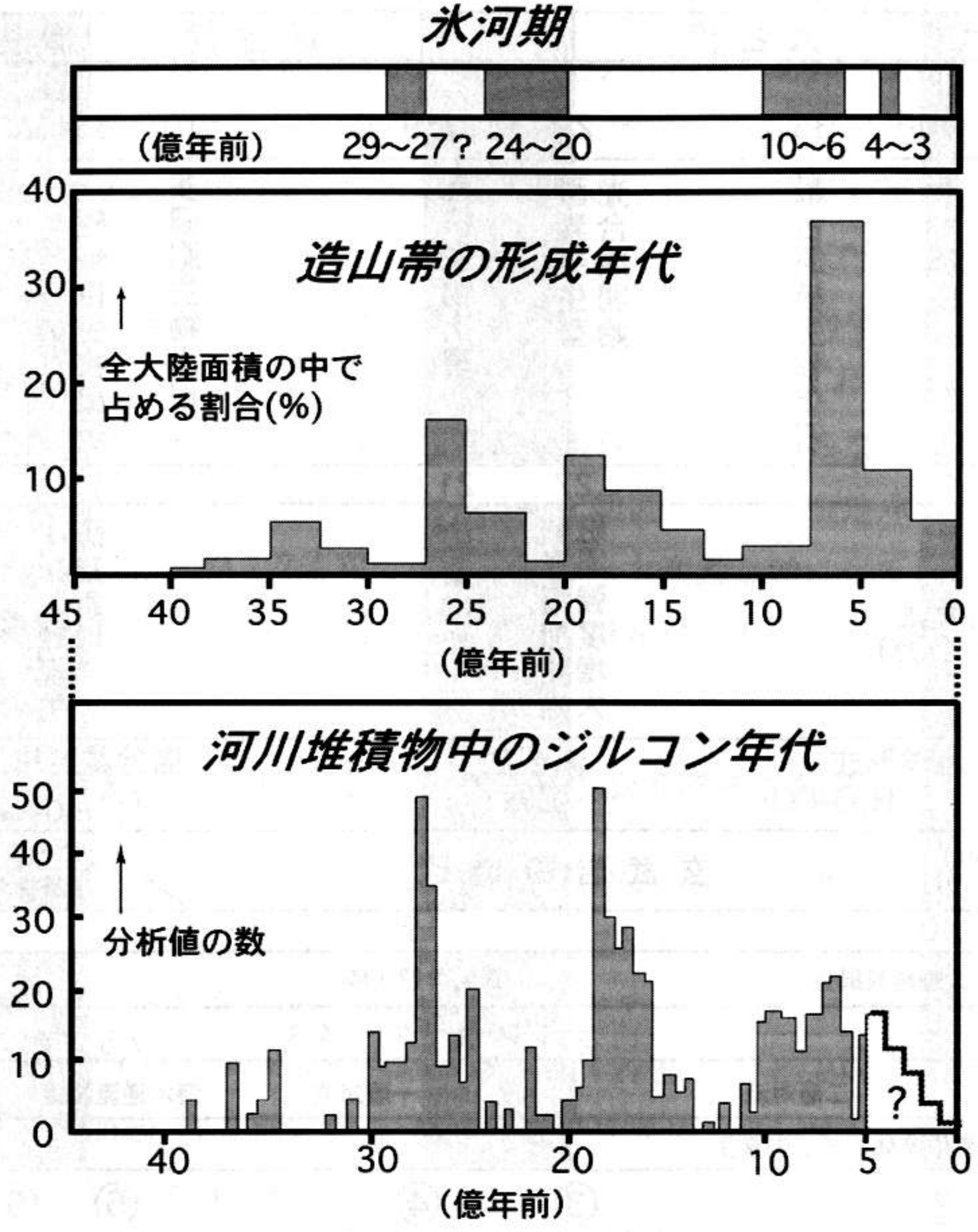


図 1.2.5 （上）氷河期，（中）太平洋型造山帯の形成年代頻度分布（面積比），（下）河川堆積物のジルコン年代頻度分布（丸山，1998）．

半径	10cm	6400km
皮の厚さ	0．05cm	30km
全質量	300g	6．0x10^{24}kg
皮質量	?	2．4x10^{22}kg

	地球の岩石部分（始原マントル）		海洋地殻（MORB)		大陸地殻
SiO_2 (wt%)	45.0	<	49.93	<	59.1
MgO	37.8	>	7.56	>	4.4
K_2O (ppm)	0.029	<<	0.17	<<	1.9
Th	0.0795	<<	0.20	<<	5.6
U	0.0203	<<	0.10	<<	1.42

X 10　　X 10

地殻は全地球の～０．４ 重量%に過ぎないが、
全地球放射性元素の半分近くを含む。

大陸地殻の形成：2桁の元素濃縮メカニズム

ある圧力Pにおいて:

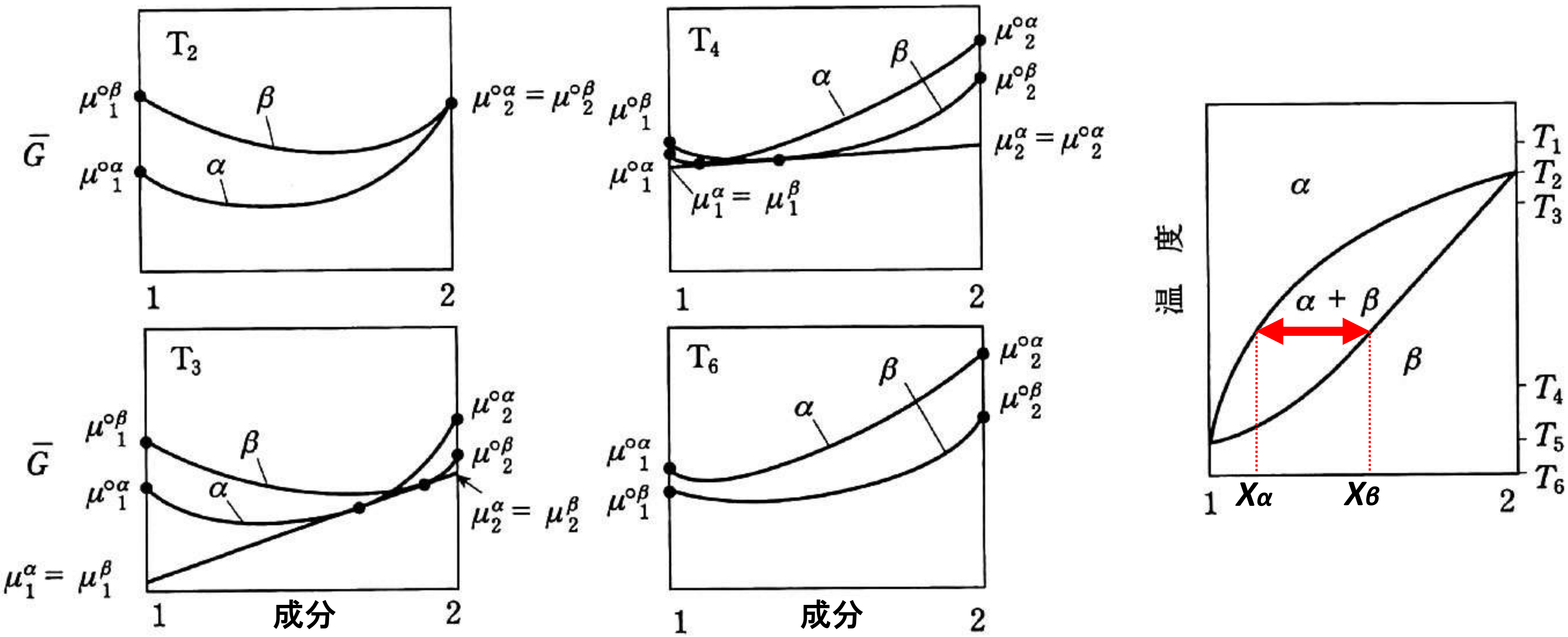


図 7-8 2成分系(二つの溶液(固溶体)相)の X-$\bar{G}$ 図および X-T 図

$$\ln \frac{X_1^\alpha}{X_1^\beta} = \frac{-\Delta G_1}{RT}$$

$$\ln \frac{X_2^\alpha}{X_2^\beta} = \frac{-\Delta G_2}{RT}$$

$$X_2^\alpha = 1 - X_1^\alpha, X_2^\beta = 1 - X_1^\beta$$

＊２相間での元素濃度比（分配係数）＝エネルギー差
＊元素は、居心地の良い相により多く分配される
＊２相の構造が異なるほど、分配の偏りが大きくなる

培風館 地球化学講座3巻

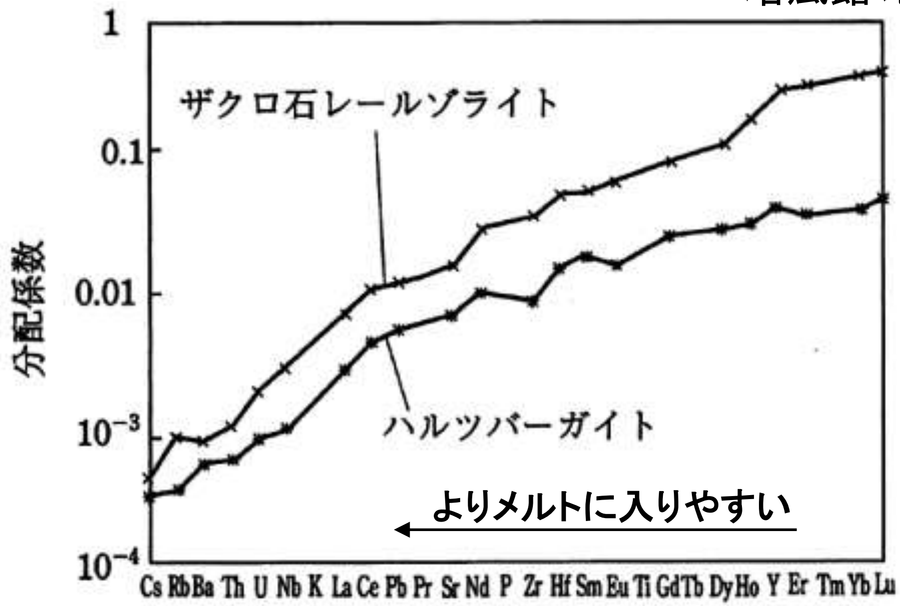
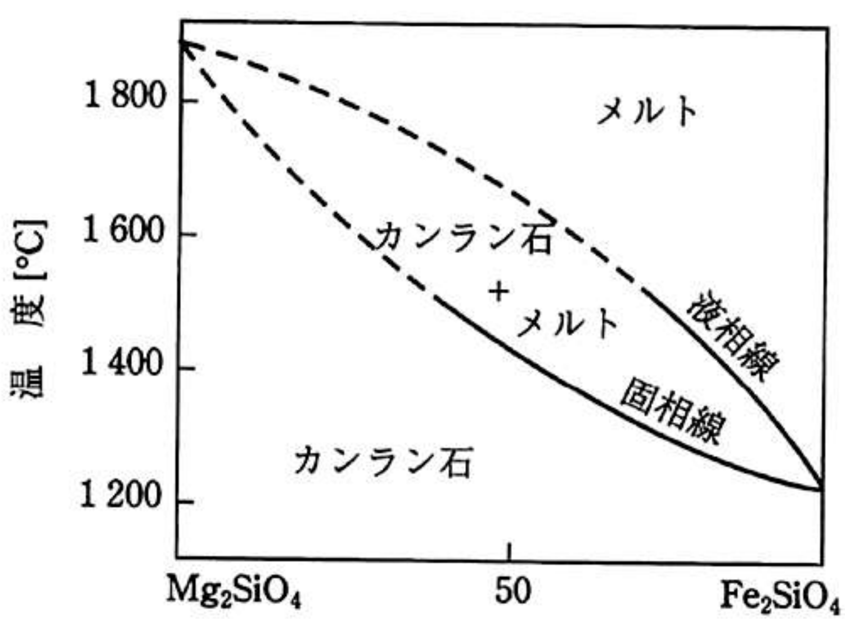
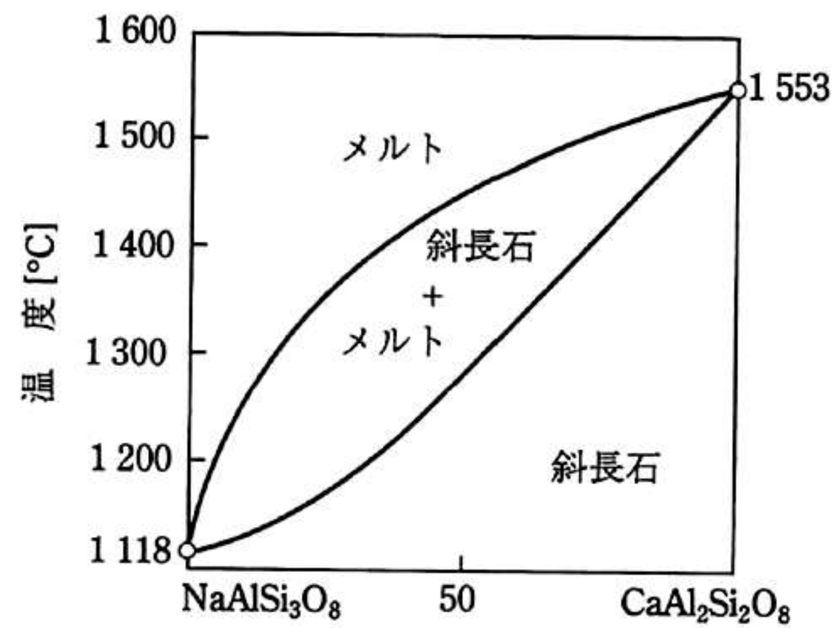


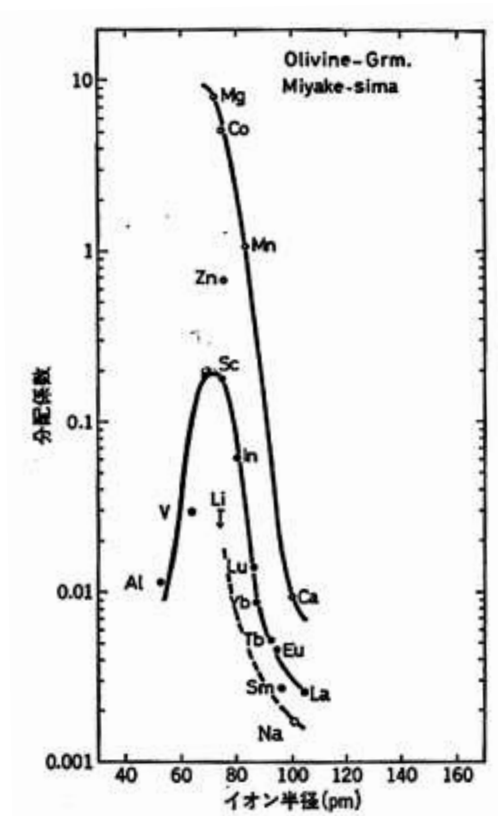
図 7-21　カンラン岩とケイ酸塩メルトの間の微量元素の分配係数



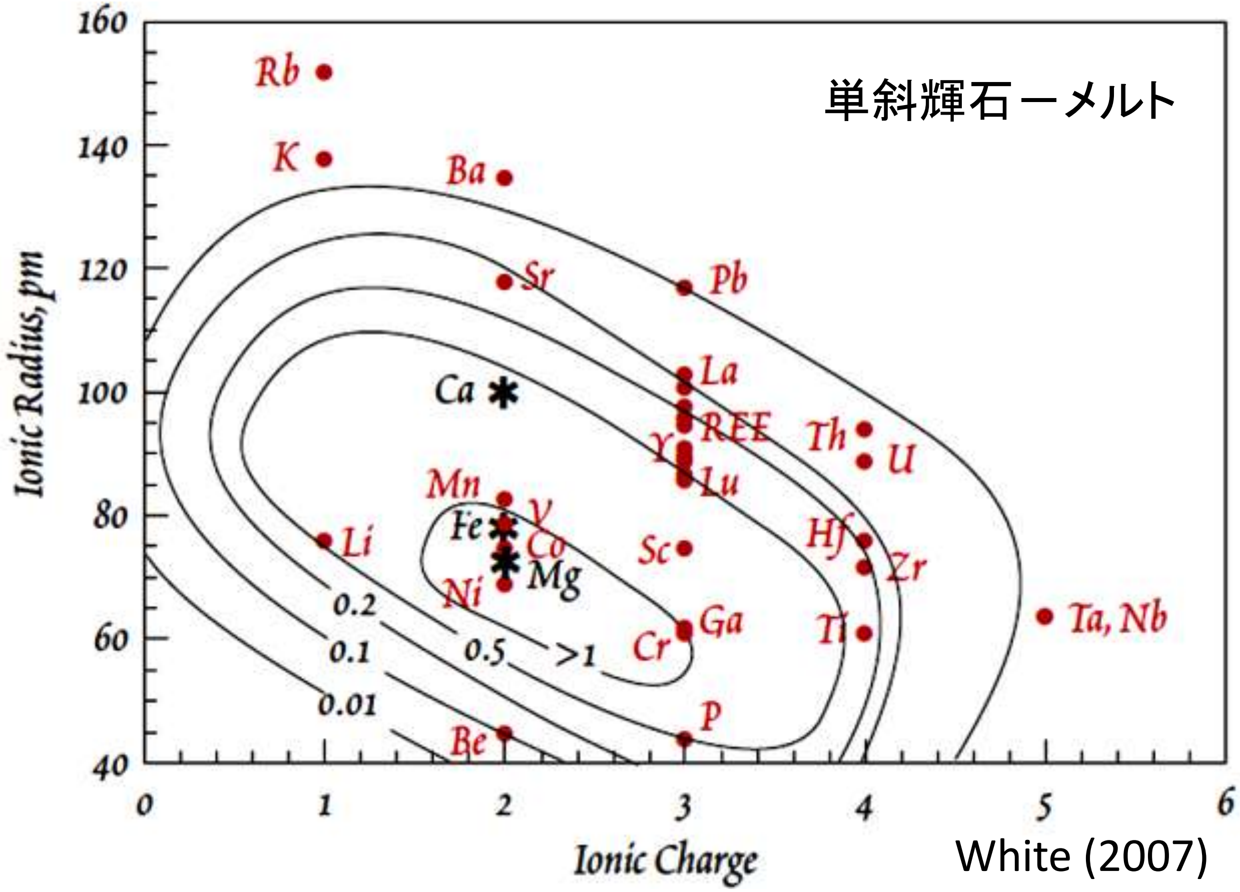


イオン半径、電荷(⇒固体中のポテンシャルエネルギー)固体とメルトの間の分配を整理・定量化可能:

(ー)ポテンシャルエネルギー



岩波地球科学講座4巻



White (2007)

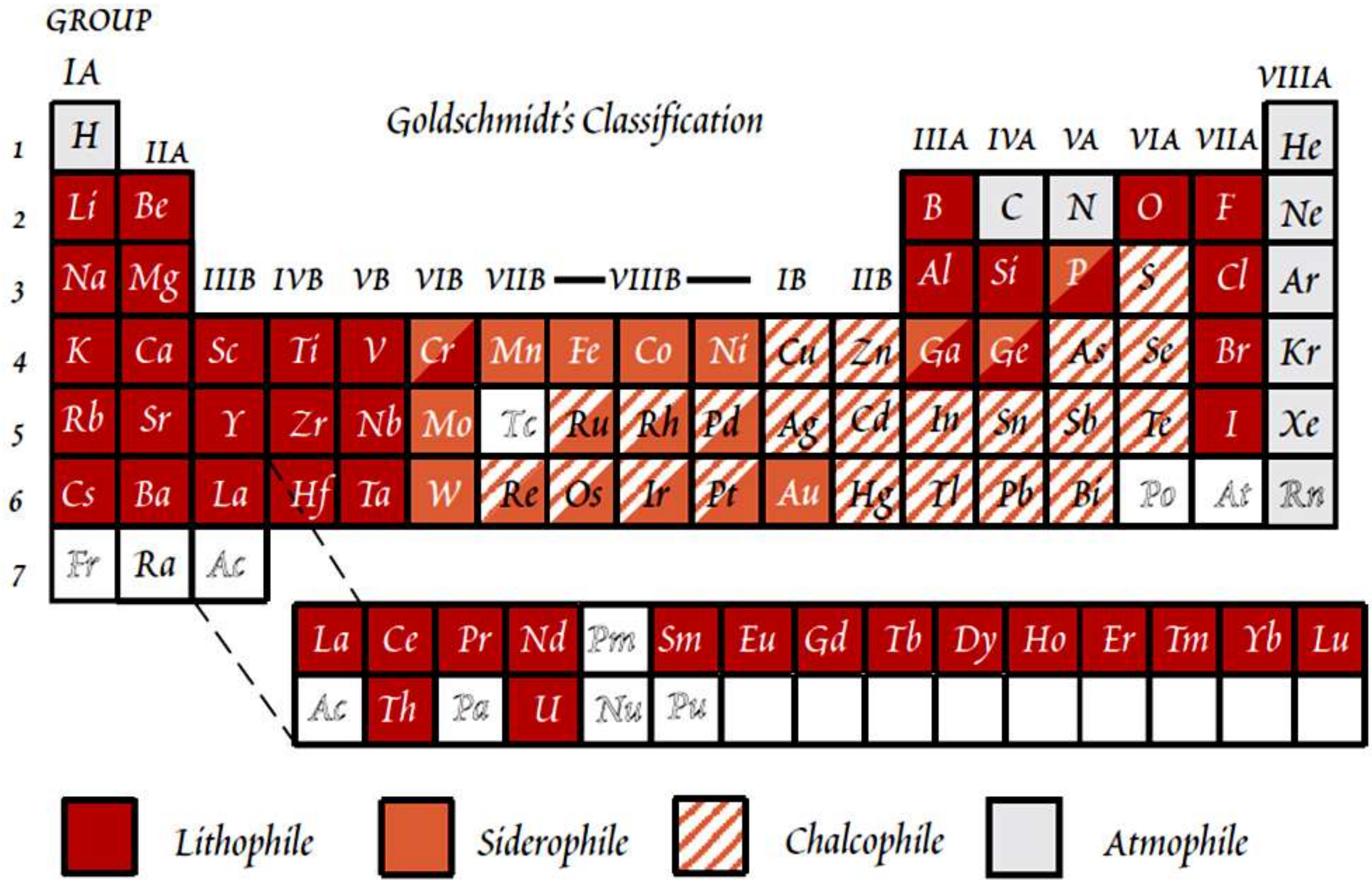


Figure 7.2. Goldschmidt's classification of the elements.

White (2007)

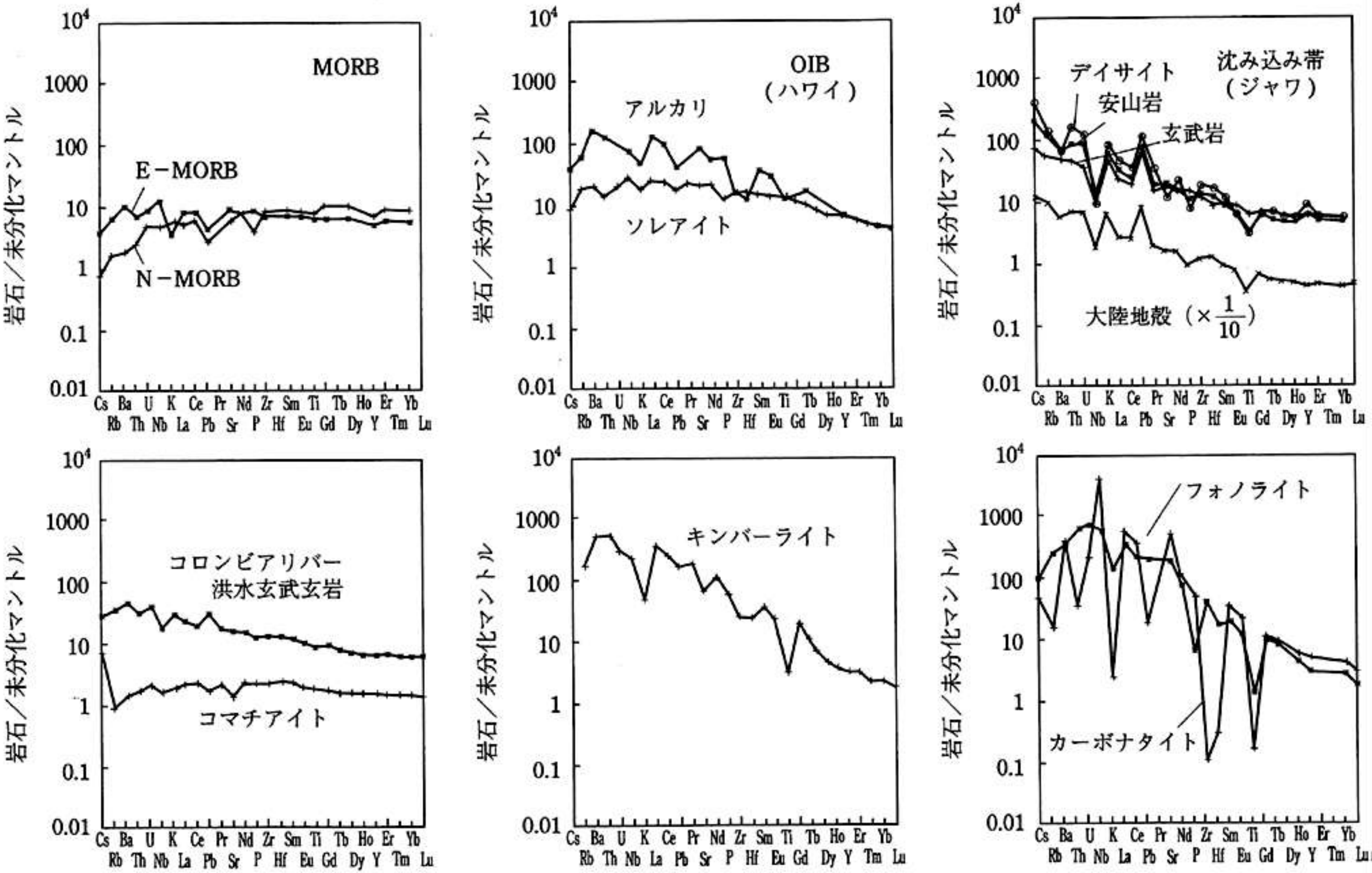
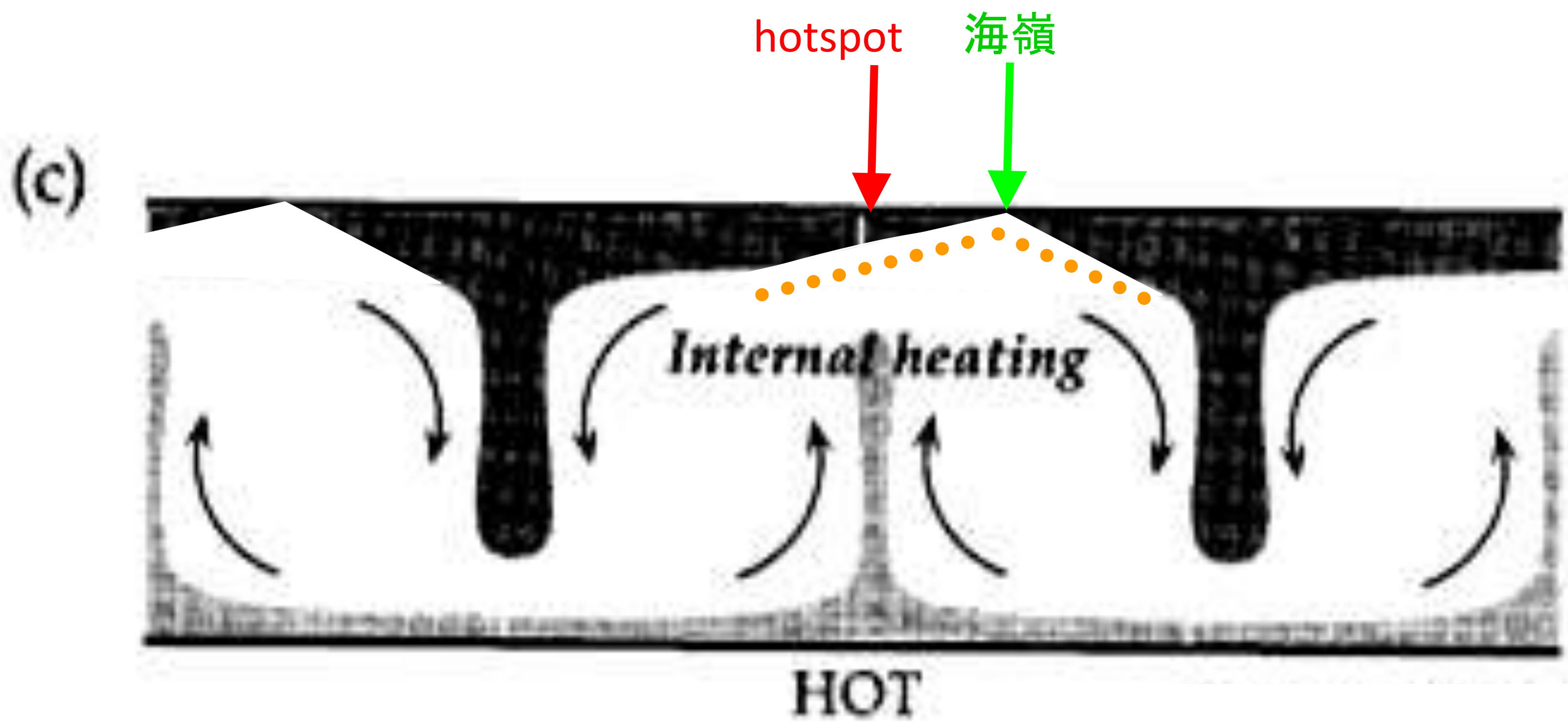
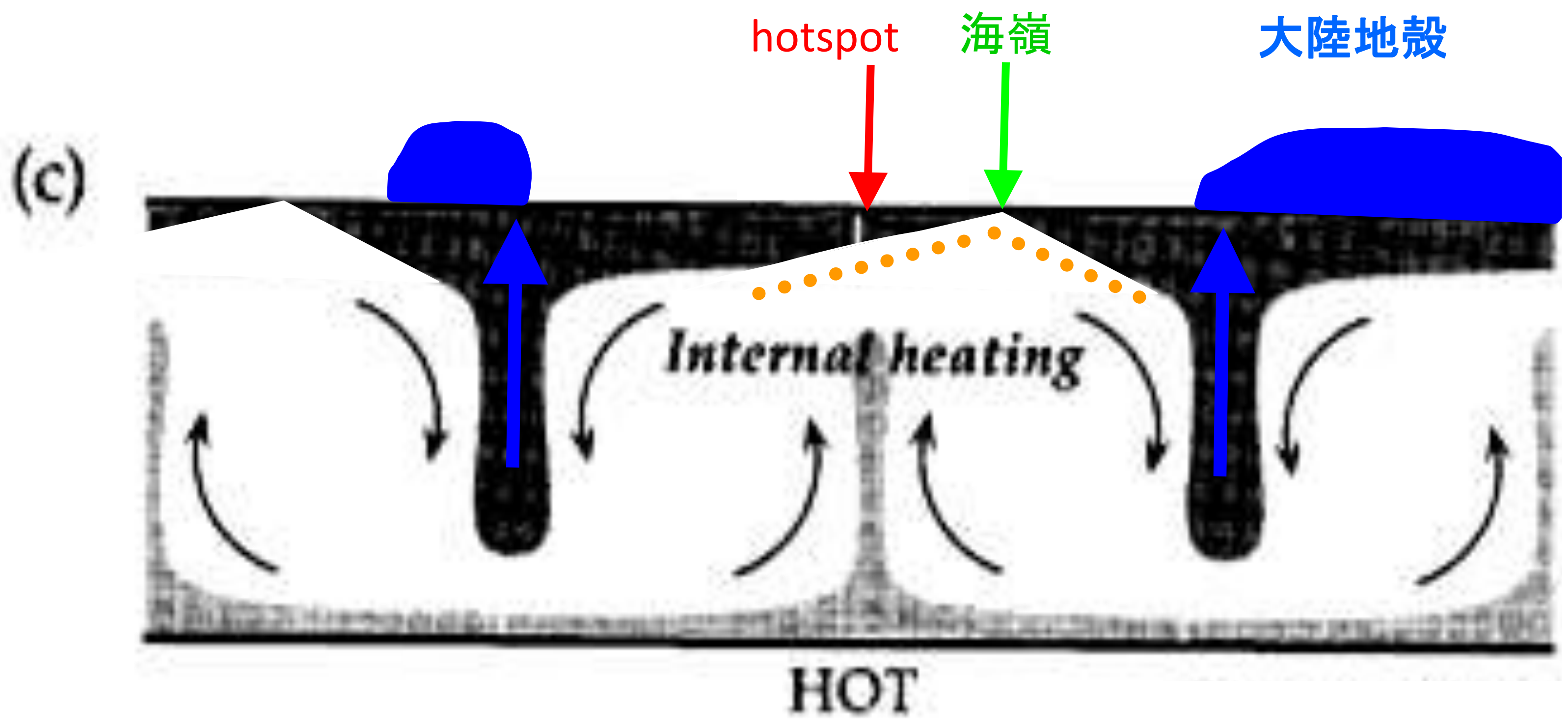


図 7-22 さまざまな火成岩の微量元素濃度のスパイダー図

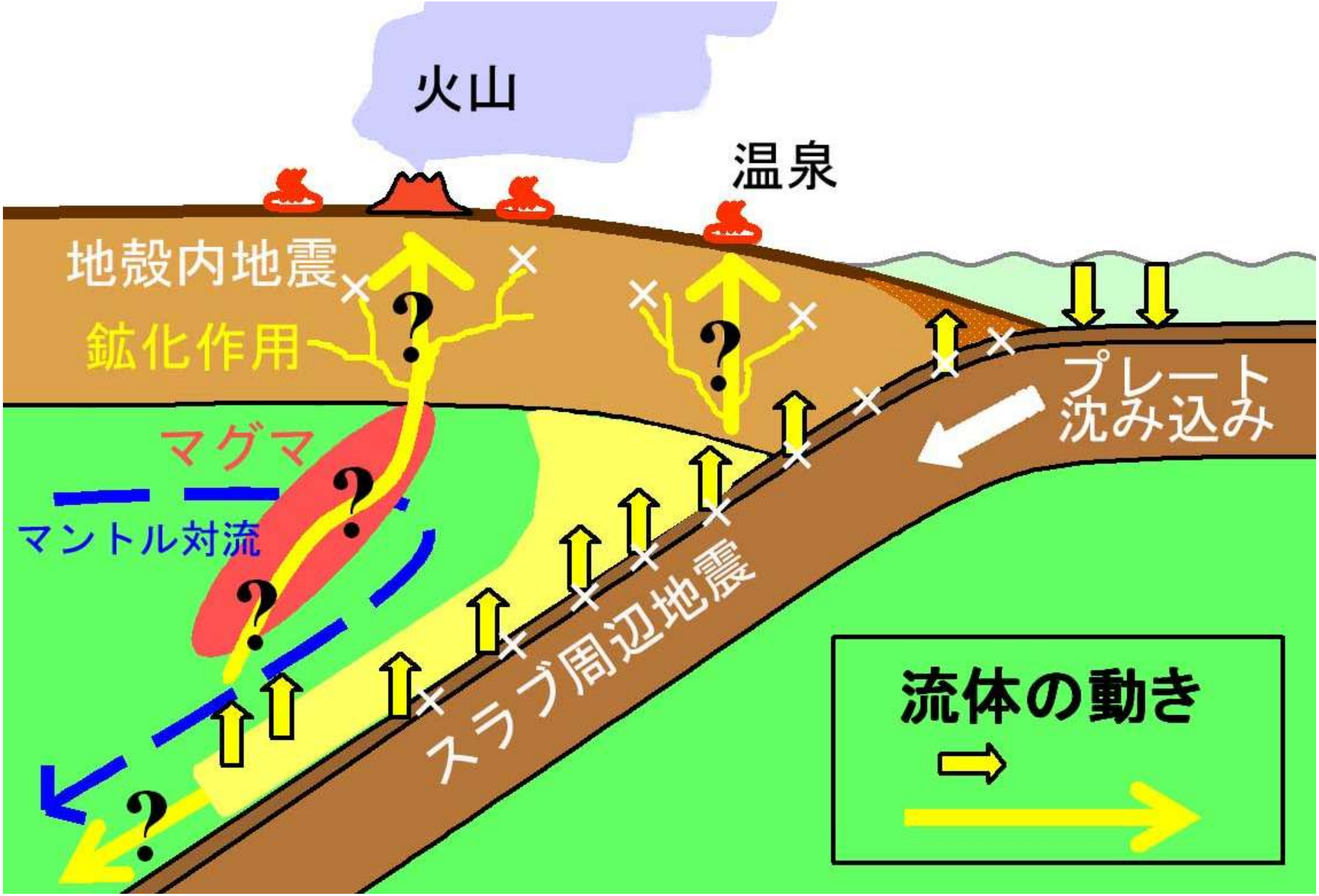
培風館 地球化学講座3巻

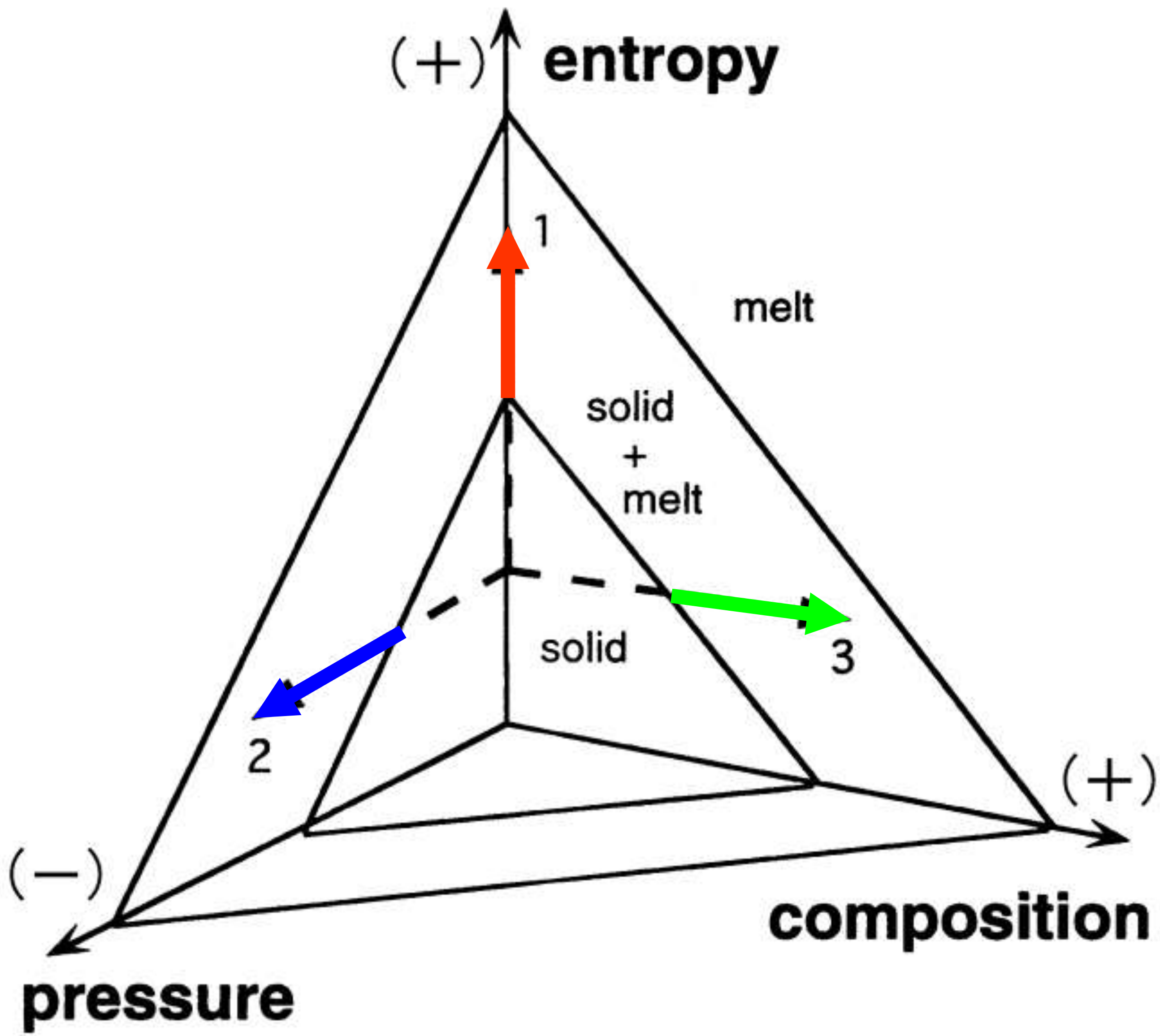


hotspot
海嶺
(c)
Internal heating
HOT



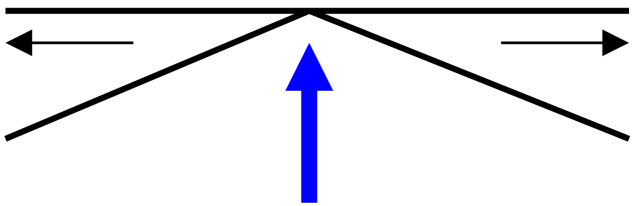
Davies (1999) に加筆


火山
温泉
地殻内地震
鉱化作用
プレート
沈み込み
マグマ
マントル対流
スラブ周辺地震
流体の動き

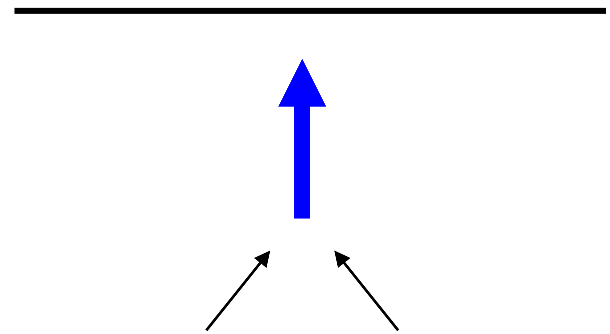


(+)
entropy
1
melt
solid
+
melt
solid
3
2
(+)
(−)
composition
pressure

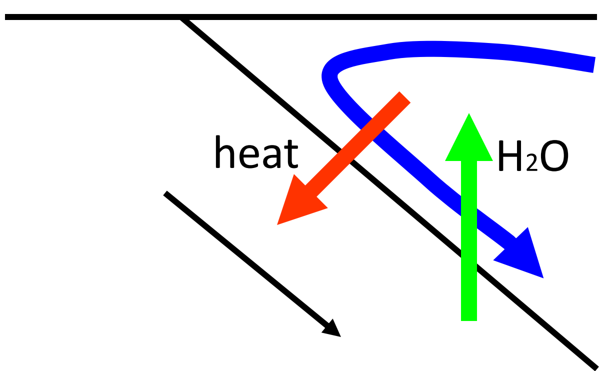
ridge

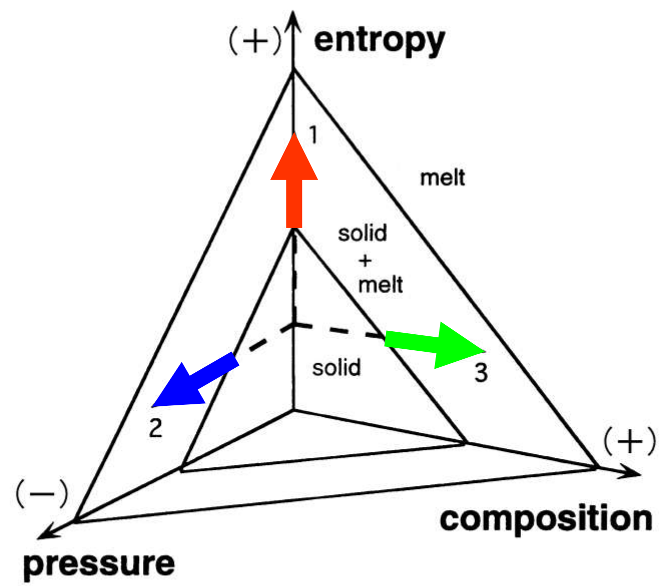


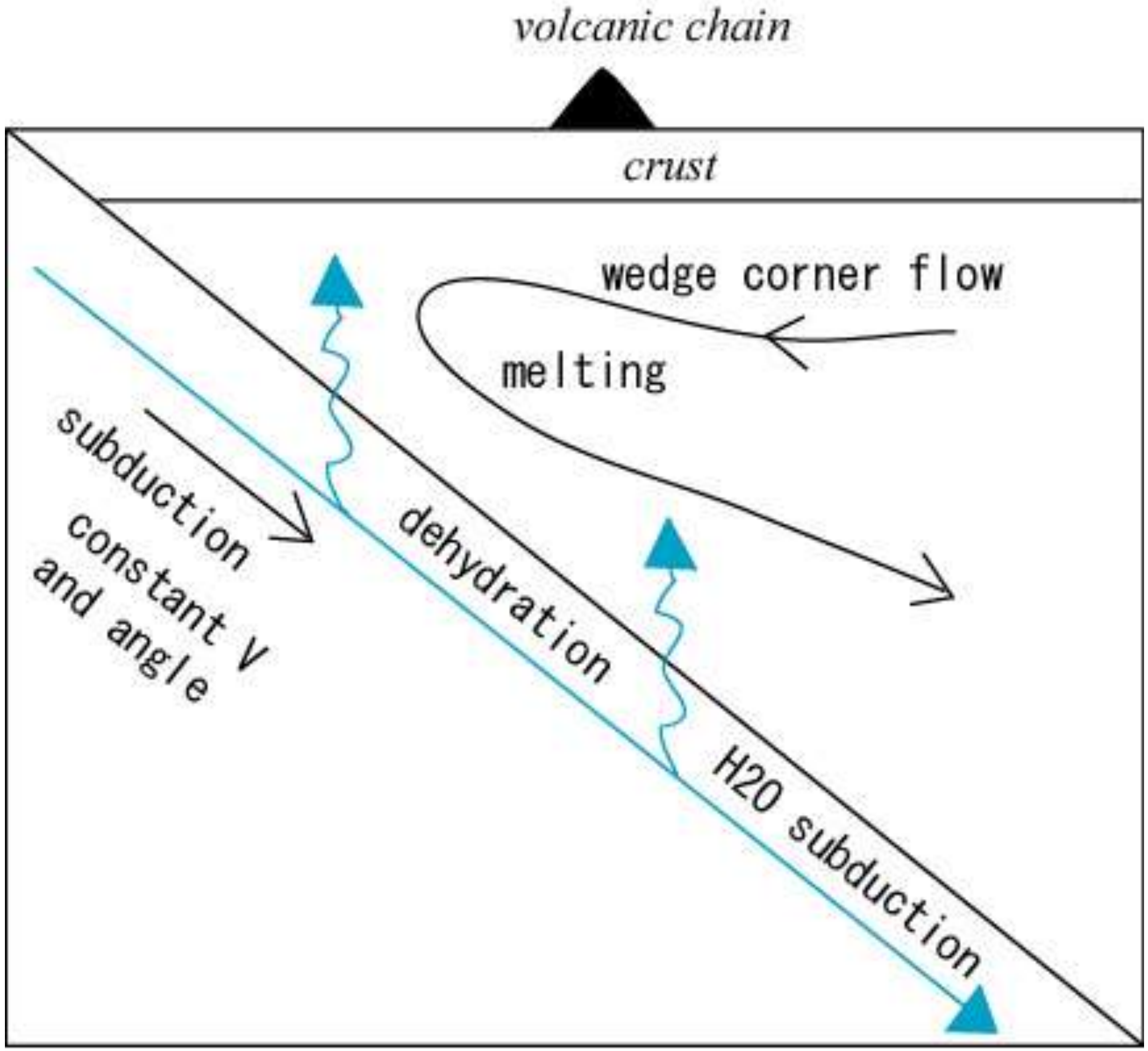
plume



subduction zone







viscous flow
mass & energy flux <---> phase equilibria

Iwamori(1998)

Mass (+ Chemical Reaction)

$$\frac{\partial(\rho_i\phi_i)}{\partial t} + \nabla\cdot(\rho_i\phi_i \boldsymbol{V}_i) = \sum_{j\neq i} \Gamma_{j\to i}$$

$$\text{and} \quad \sum_i \sum_{j\neq i} \Gamma_{j\to i} = 0 \quad (i, j = \text{m, s, a})$$

$$\frac{\partial(\rho_b C_b^{H_2O})}{\partial t} + \sum_i^{\text{m,s,a}} \nabla\cdot\left[\rho_i\phi_i C_i^{H_2O}\boldsymbol{V}_i\right] = 0$$

Momentum (Modified Darcy's Law)

$$\boldsymbol{V}_a = \boldsymbol{V}_s - \frac{k_{\phi_a}}{\phi_a\eta_a}\left[\eta_s\nabla^2\boldsymbol{V}_s + (1-\phi_a)\Delta\rho_a g\boldsymbol{z}\right]$$

$$\text{and} \quad k_{\phi_a} = \frac{R^2\phi_a^n}{B}$$

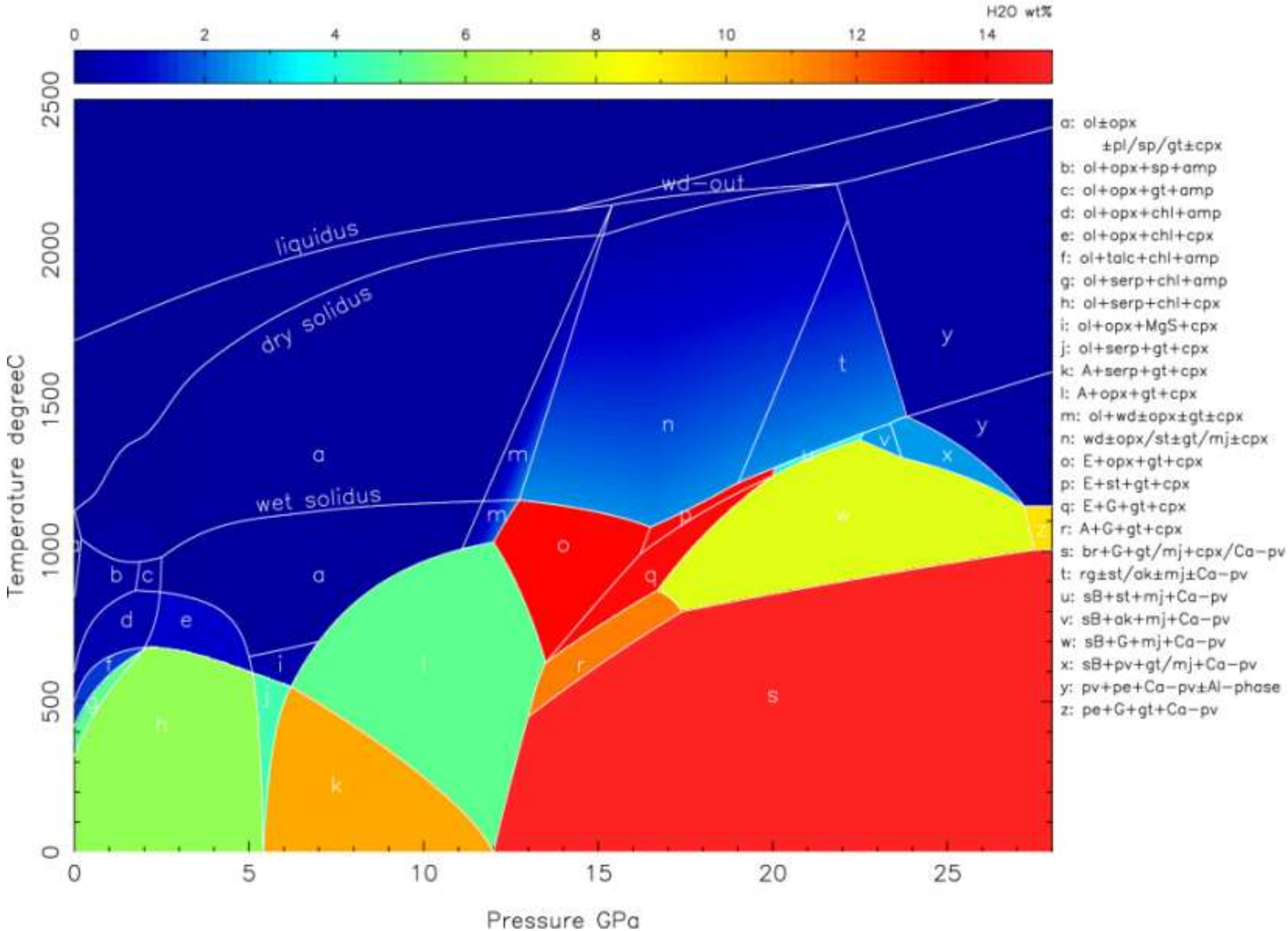
Energy (+ Phase Diagram)

$$\left[\sum_i^{\text{m,s}}(\phi_i\rho_i C_P^i) + T\Delta S\frac{(\partial\phi_m\rho_m)}{\partial T}\right]\frac{\partial T}{\partial t}$$

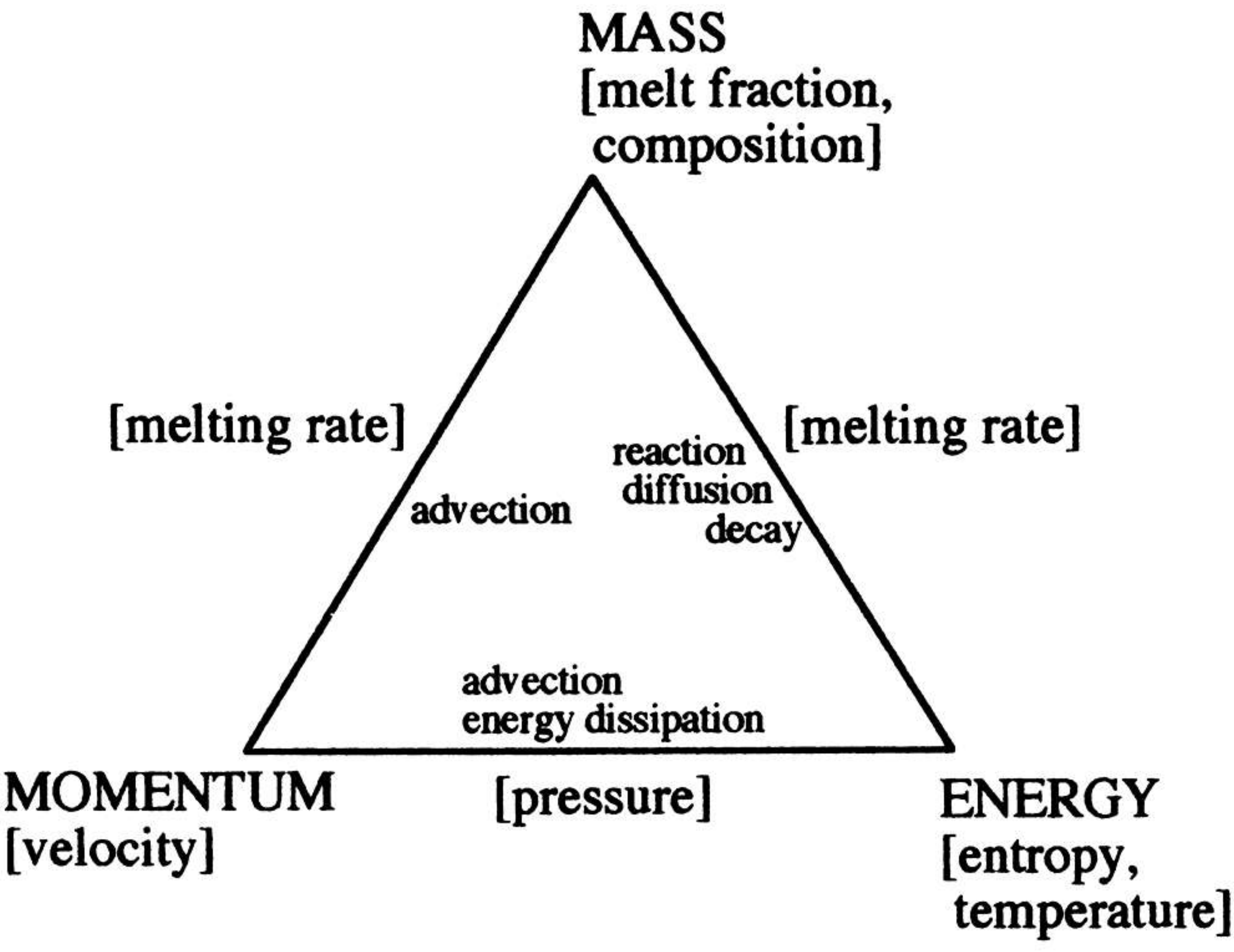
$$= K\nabla^2 T - \sum_i^{\text{m,s}}(\phi_i\rho_i C_P^i \boldsymbol{V}_i\cdot\nabla T - T\phi_i\alpha_i\boldsymbol{V}_i\cdot\nabla P)$$

$$- T\Delta S\frac{\partial(\phi_m\rho_m)}{\partial(C_b^{H_2O})}\frac{\partial(C_b^{H_2O})}{\partial t} - T\Delta S\nabla\cdot(\phi_m\rho_m\boldsymbol{V}_m)$$

Iwamori (1998)



Iwamori (2004)



Iwamori(1999)

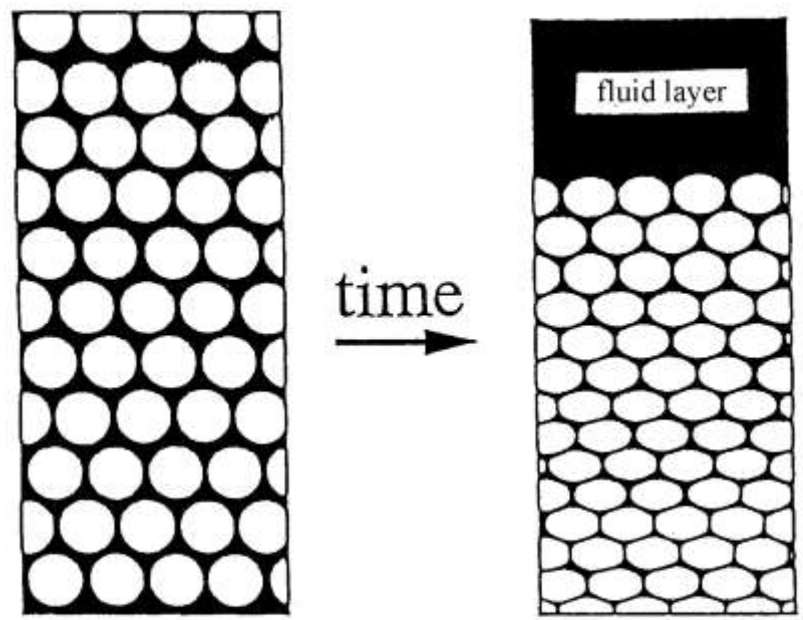
2相流の運動方程式： 圧密項（右辺第一項）の重要性

$$-\nabla\cdot\mathbf{V}_s+\Gamma\left(\frac{1}{\rho_m}-\frac{1}{\rho_s}\right)$$
$$=-\nabla\cdot\frac{k_\phi}{\mu}\left\{\nabla\left[\left(\zeta+\frac{4}{3}\eta\right)\nabla\cdot\mathbf{V}_s\right]-\nabla\times(\eta\nabla\times\mathbf{V}_s)-(1-\phi)\Delta\rho g\hat{\mathbf{z}}\right\}$$

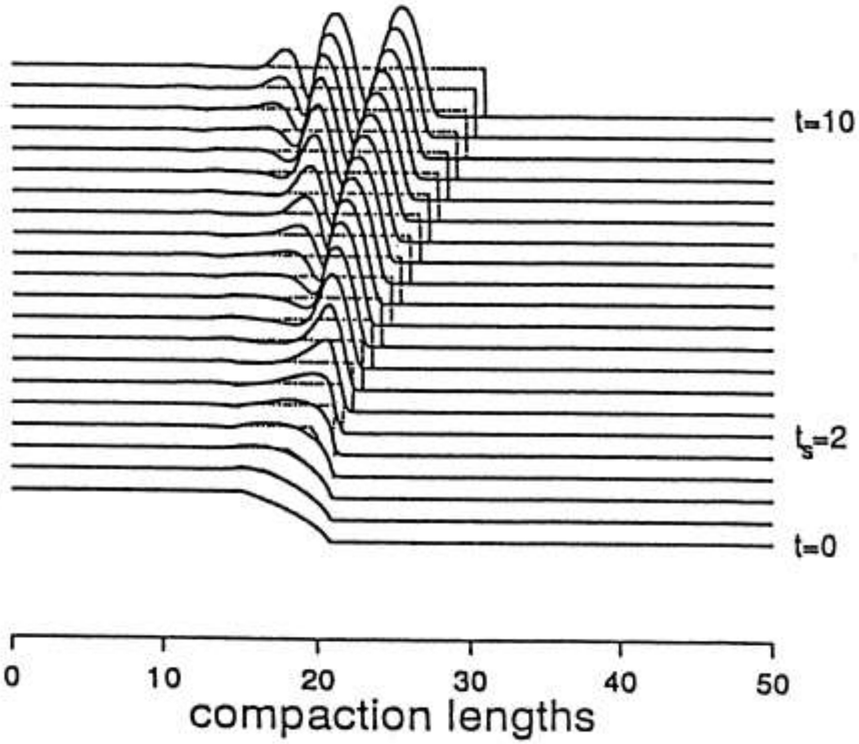
圧密長
（compaction length）

$$\delta_c = \sqrt{\frac{k_\phi^0\left(\zeta+\frac{4}{3}\eta\right)}{\mu}}$$

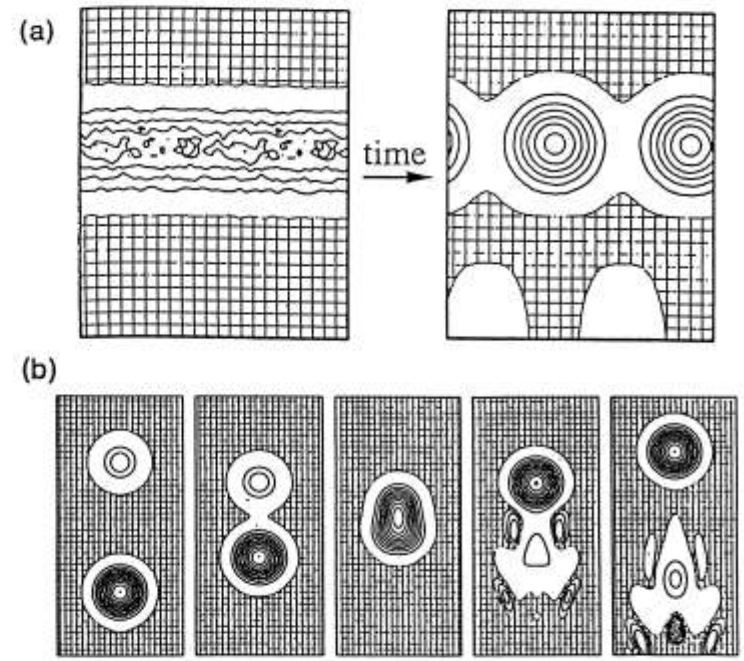
McKenzie (1984)



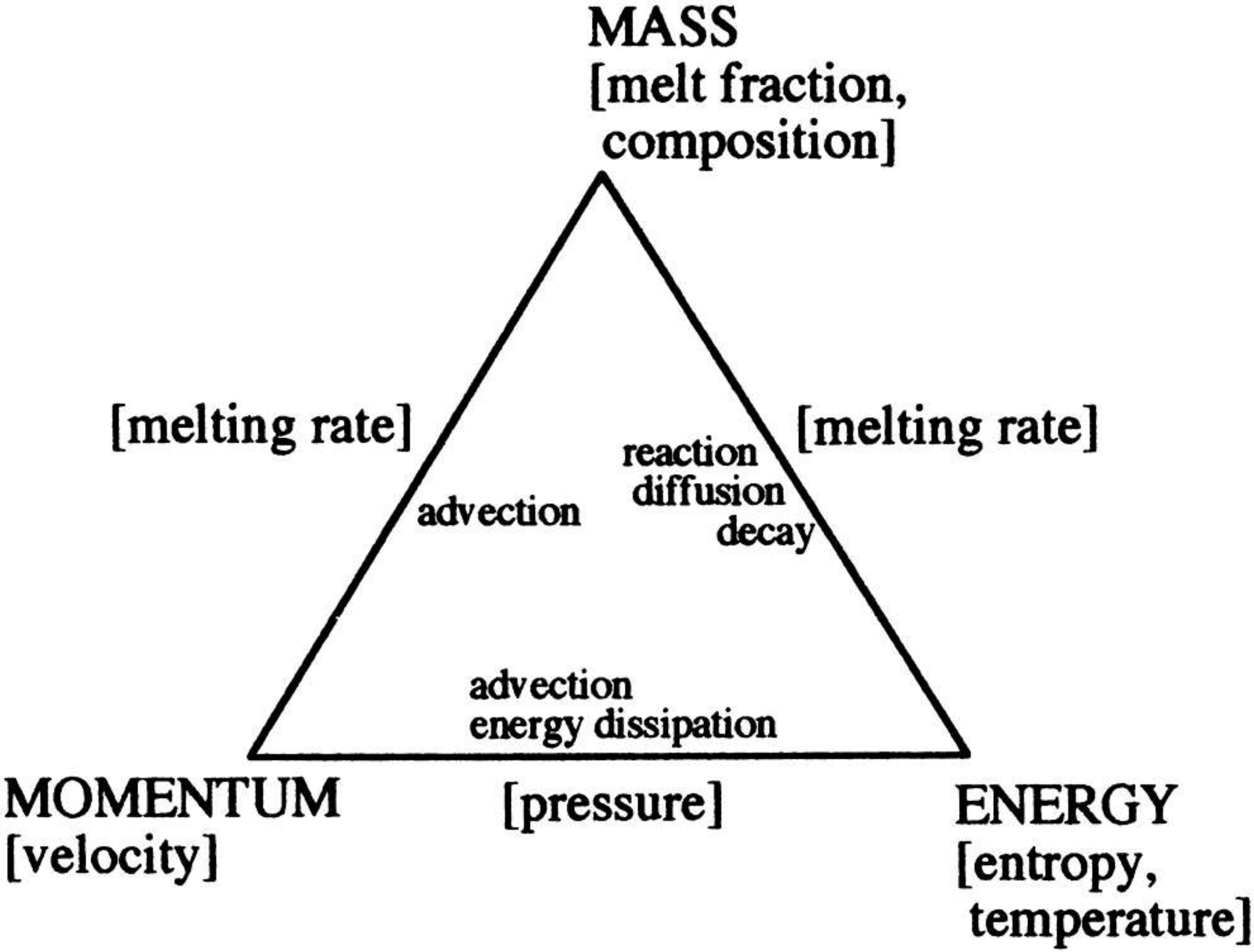
圧密を伴う2相流の数値シミュレーション



Spiegelman (1993)



Scott & Stevenson (1986)

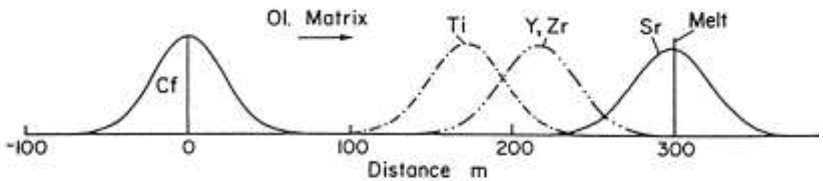


Iwamori(1999)

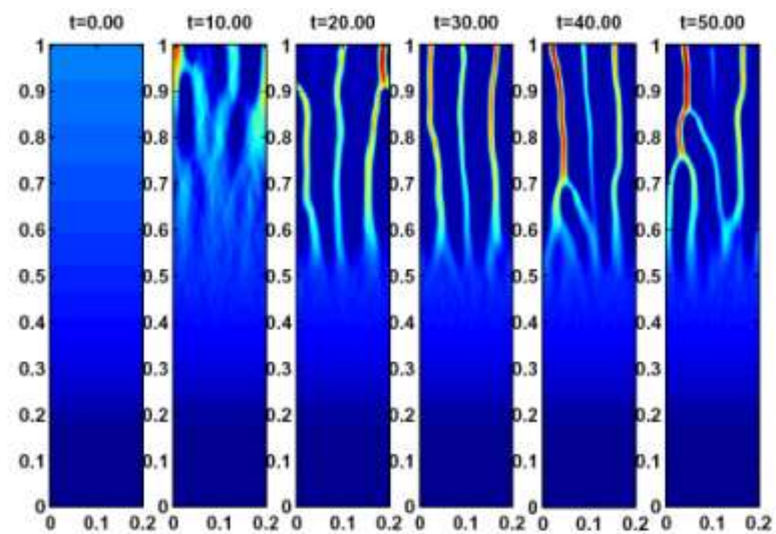
化学反応を伴う2相流

Chromatographic effect

$$v_e^j = \frac{V_m}{\frac{\rho_s}{\rho_m}\frac{1-\phi}{\phi}K^j + 1}$$



Kinetic effect and Channelling

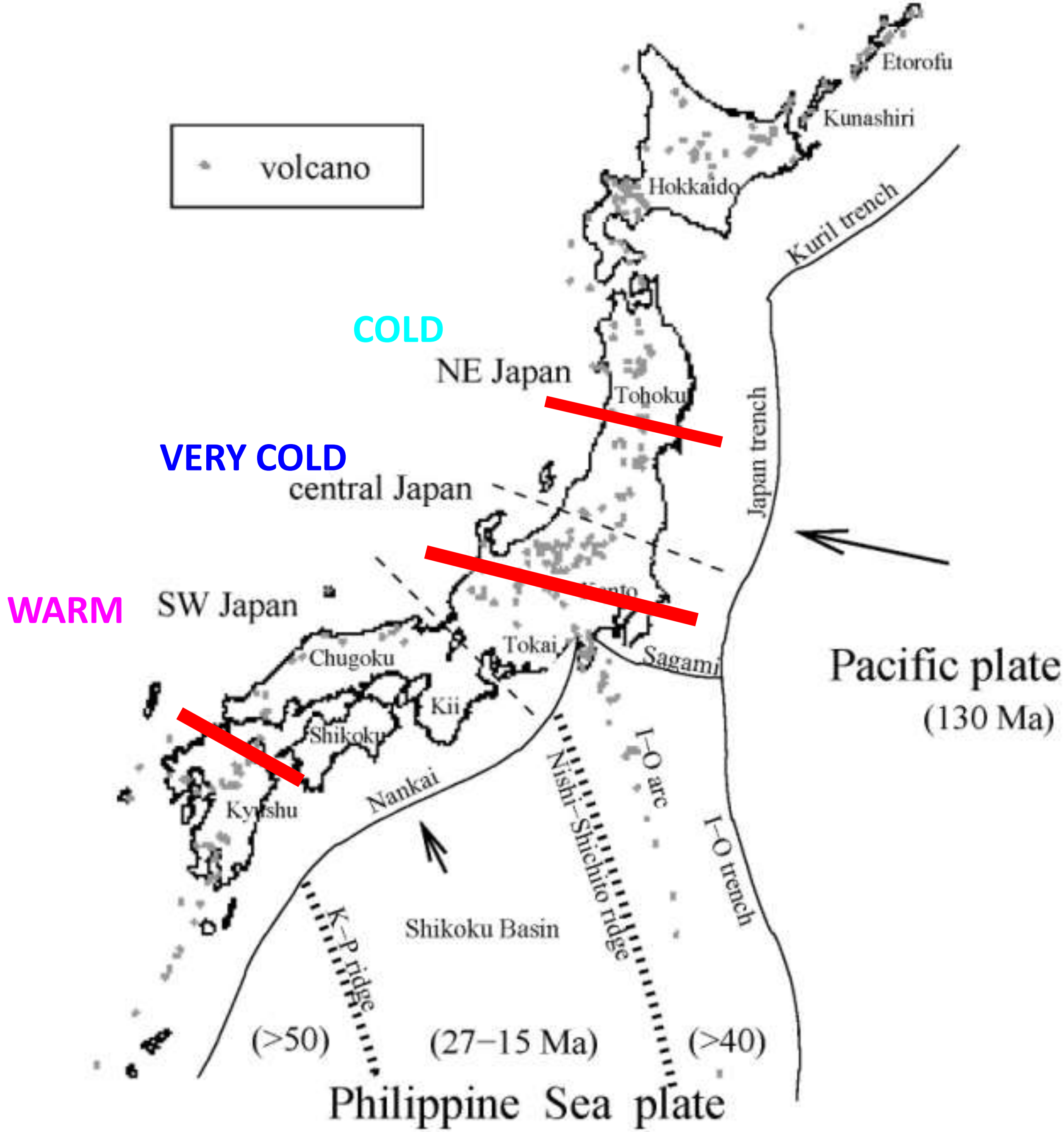


Damköhler numbers

$$Da = \frac{R_{\text{eff}} L}{\phi_0 w_0 \rho_f}$$

$$= \frac{\text{reaction rate}}{\text{convective mass transport rate}}$$

Spiegelman et al (2001)



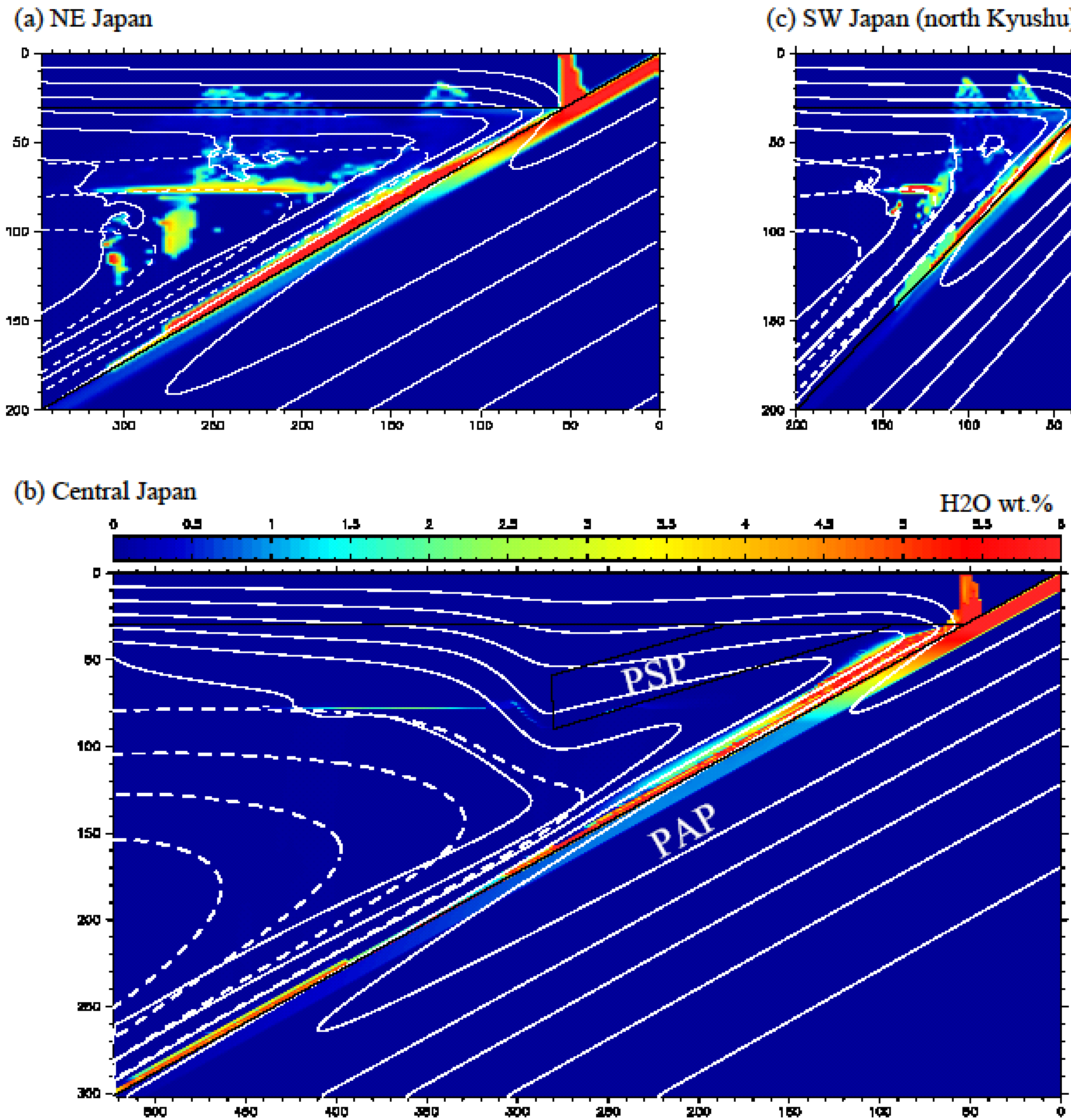
Iwamori(2007)

Model results of H2O distribution beneath Japan

COLD

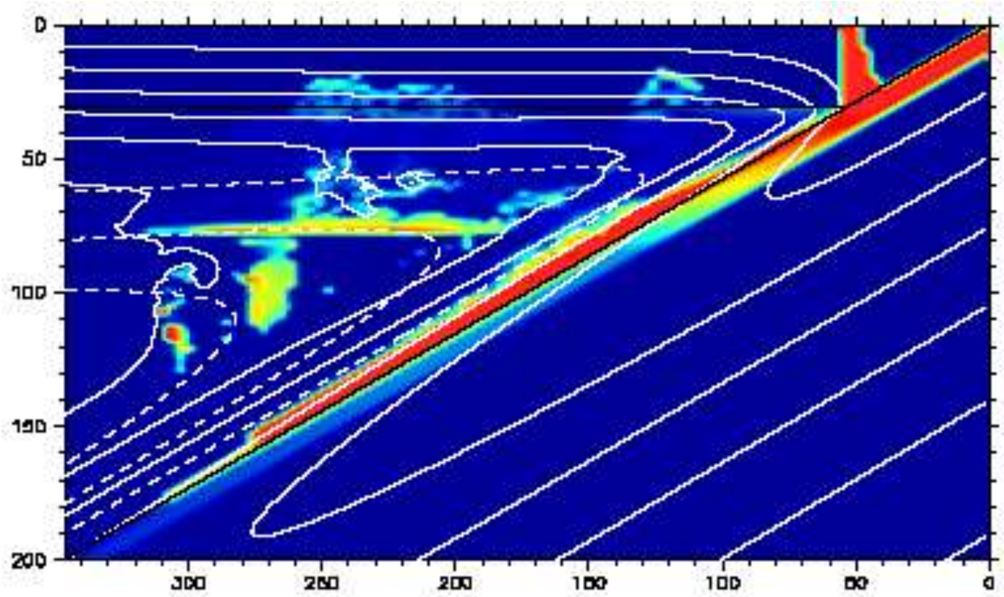
WARM

VERY COLD



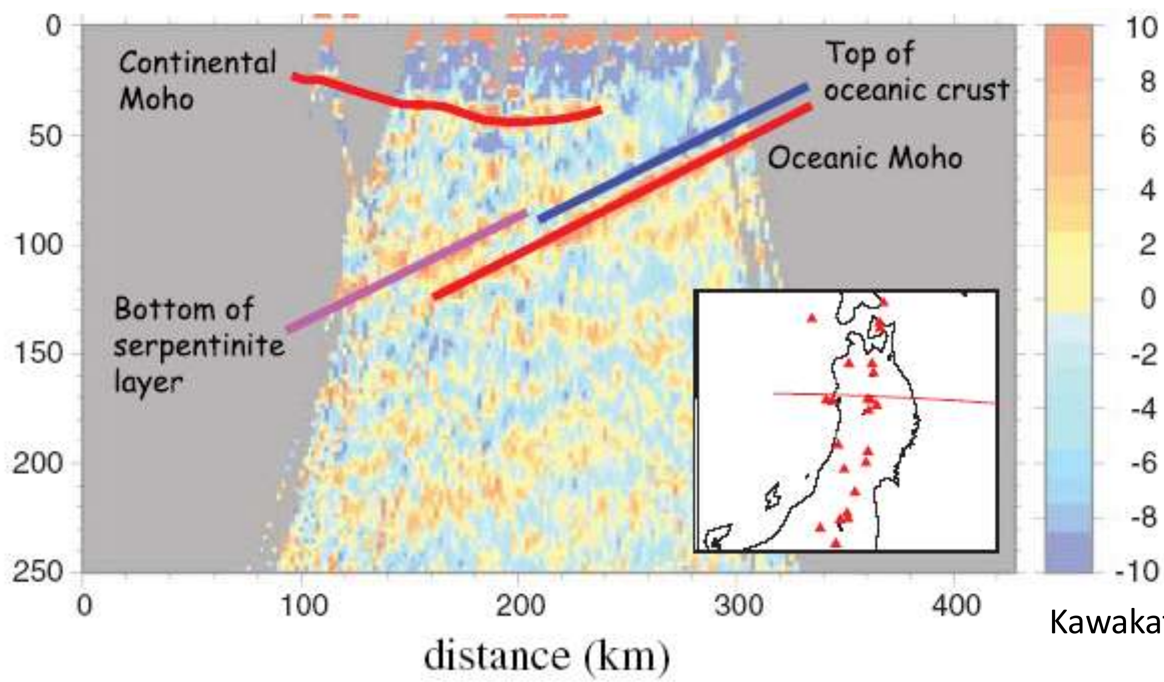
Modified from Iwamori (2006)

Numerical Simulation



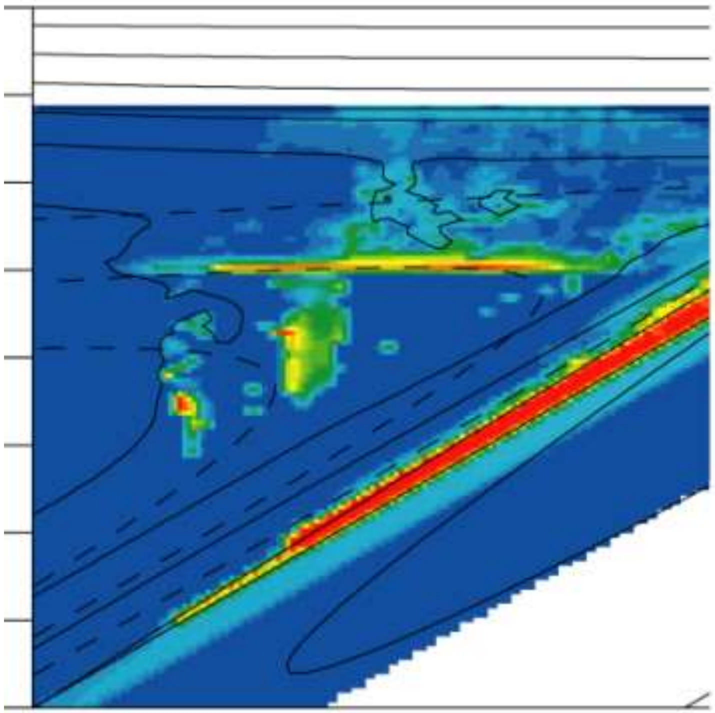
Iwamori (2007)

Seismic Structure

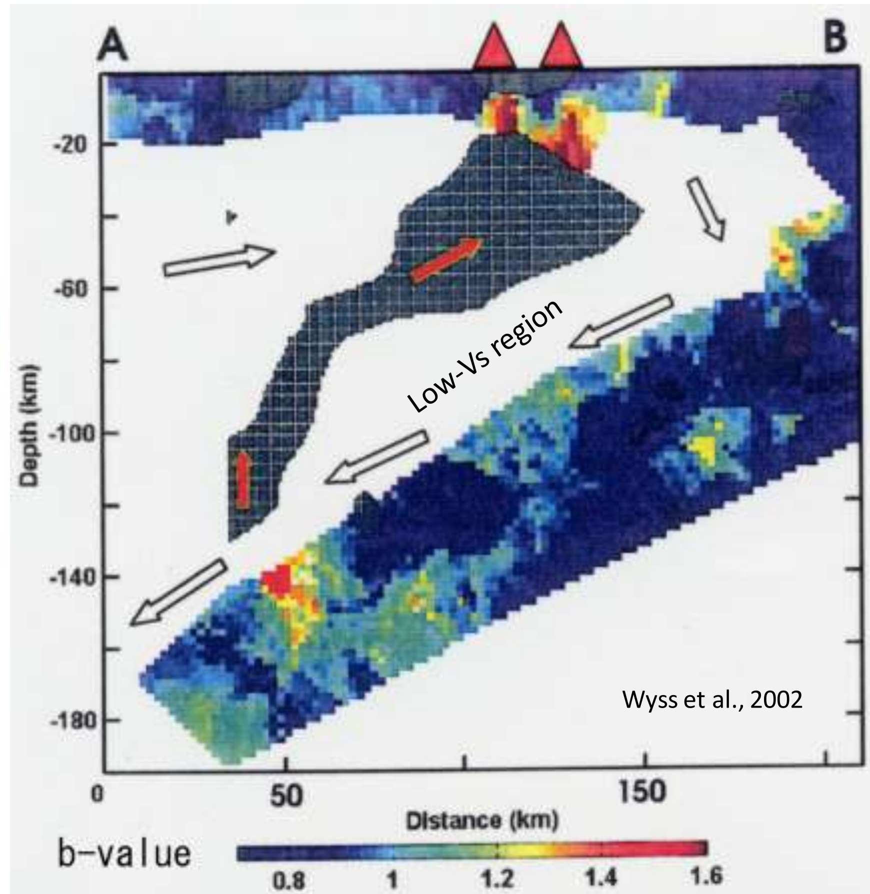


Kawakatsu and Watada (2007)

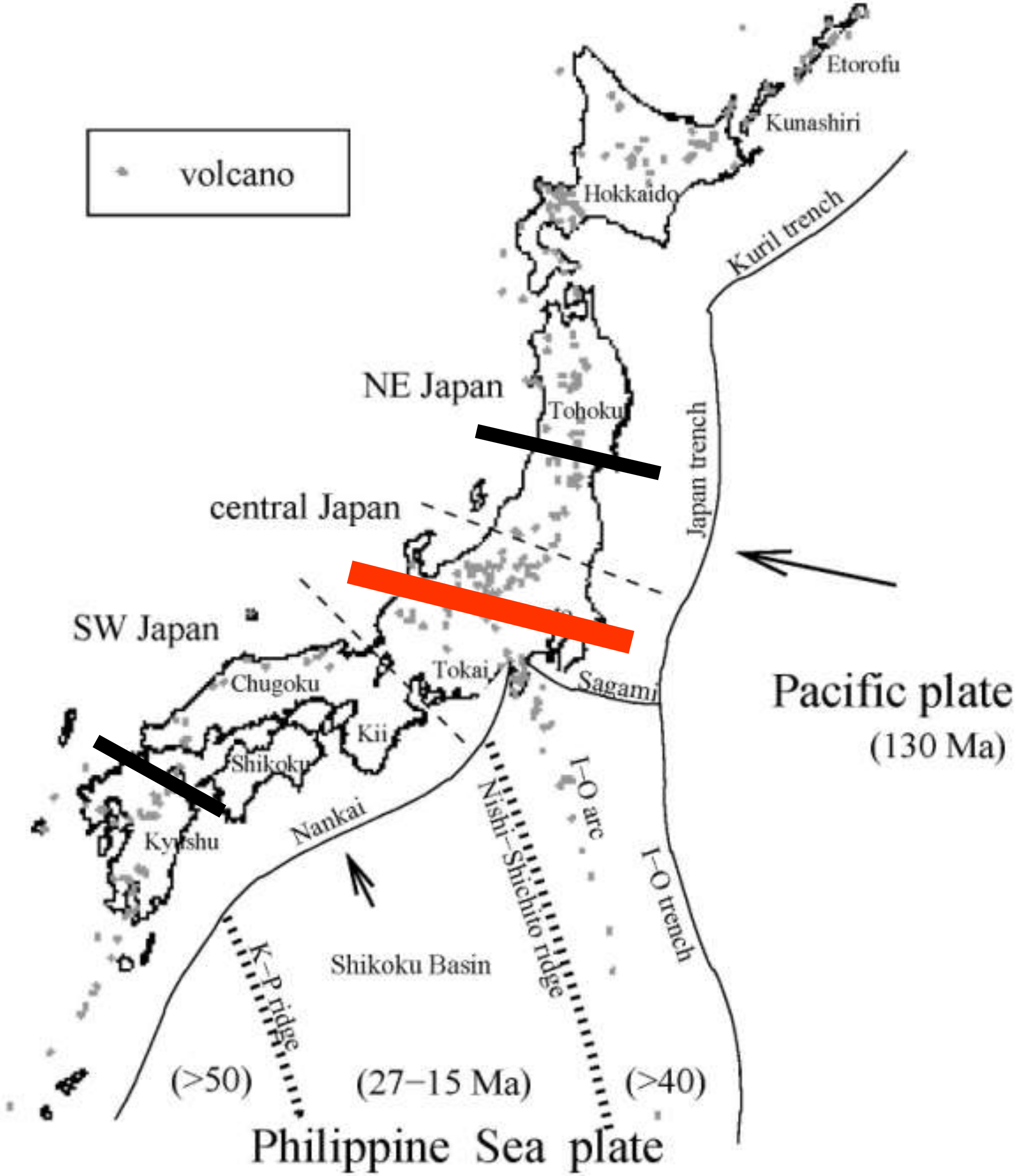
Model result



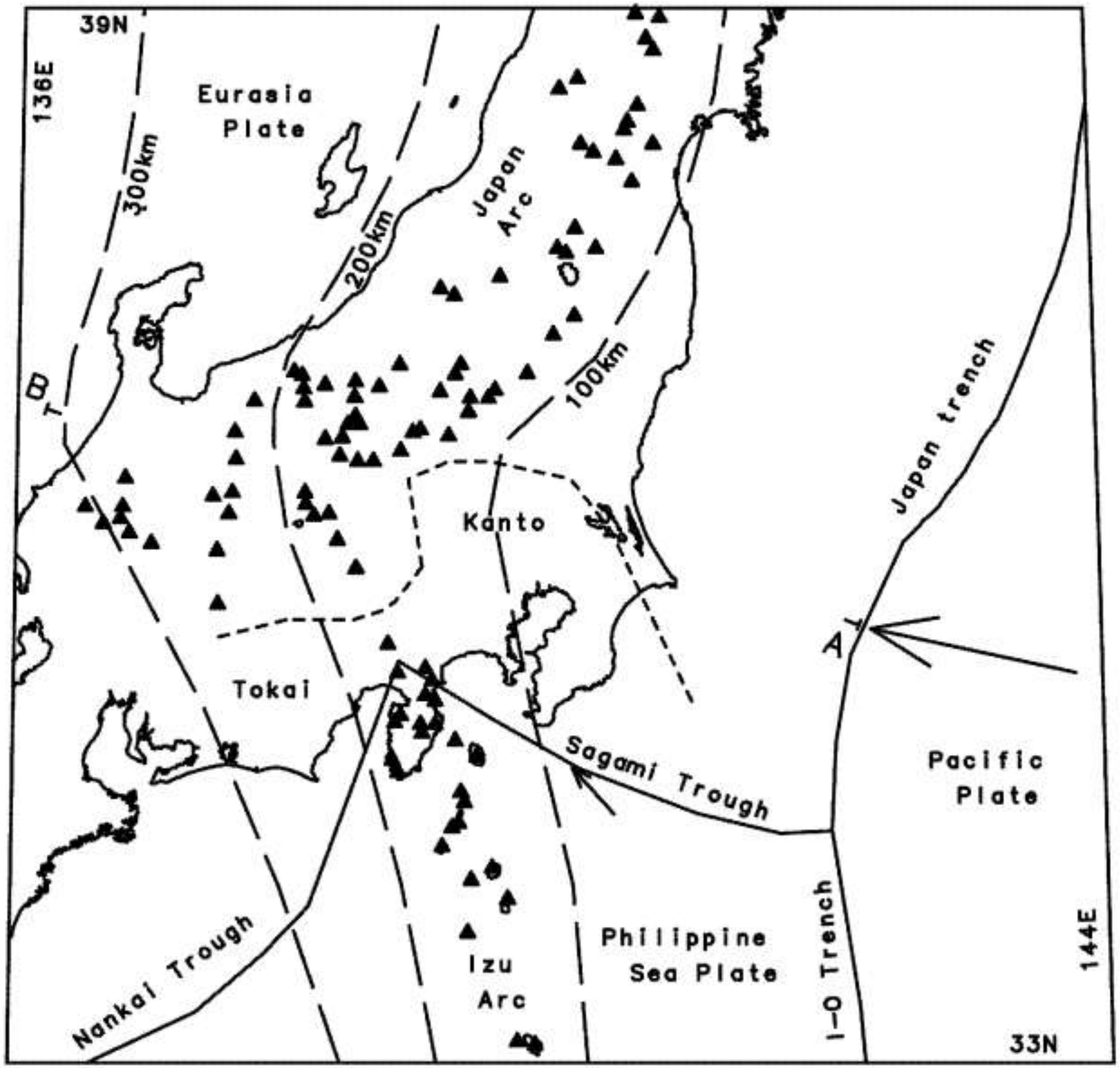
Observation



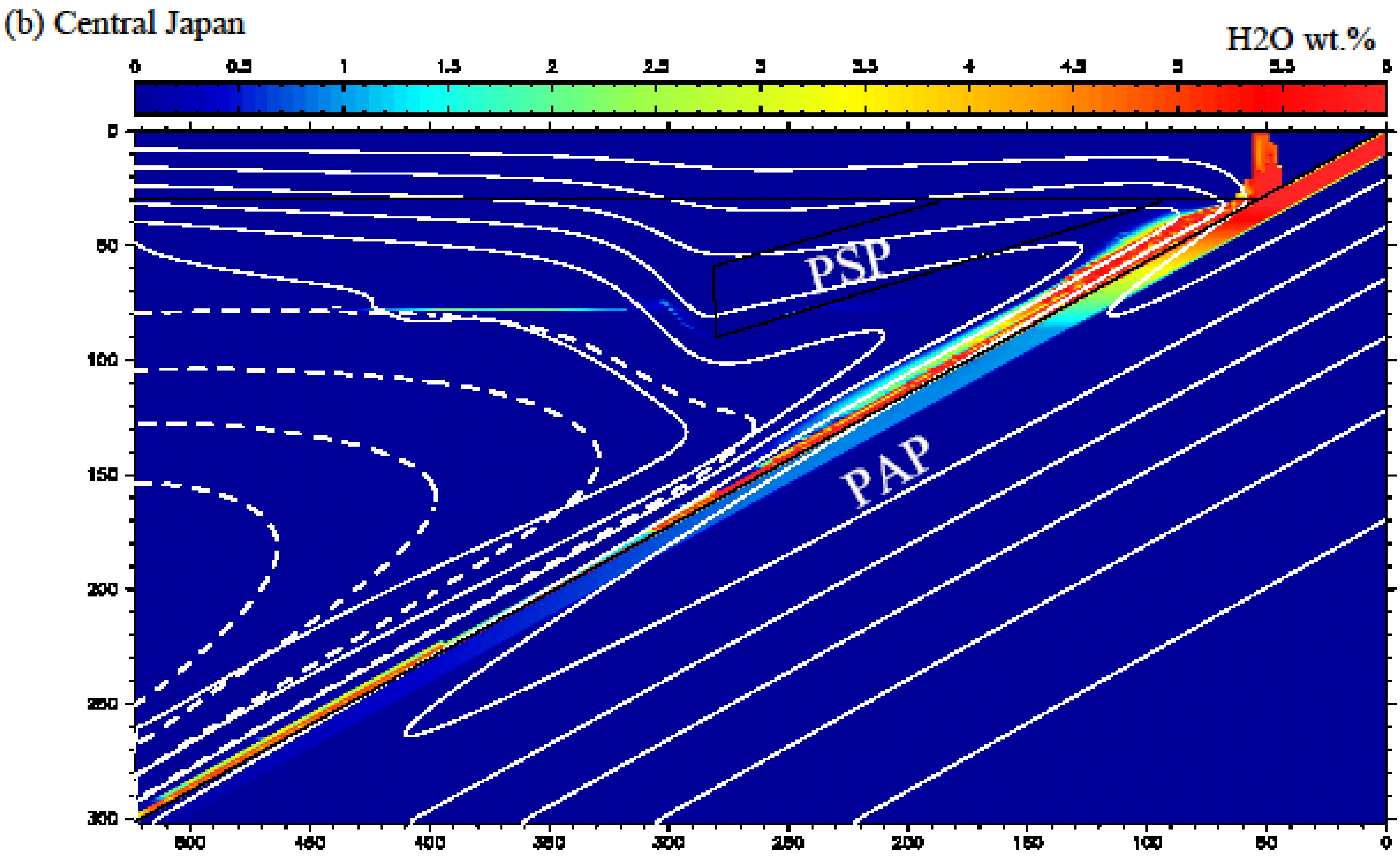
Iwamori(2007)



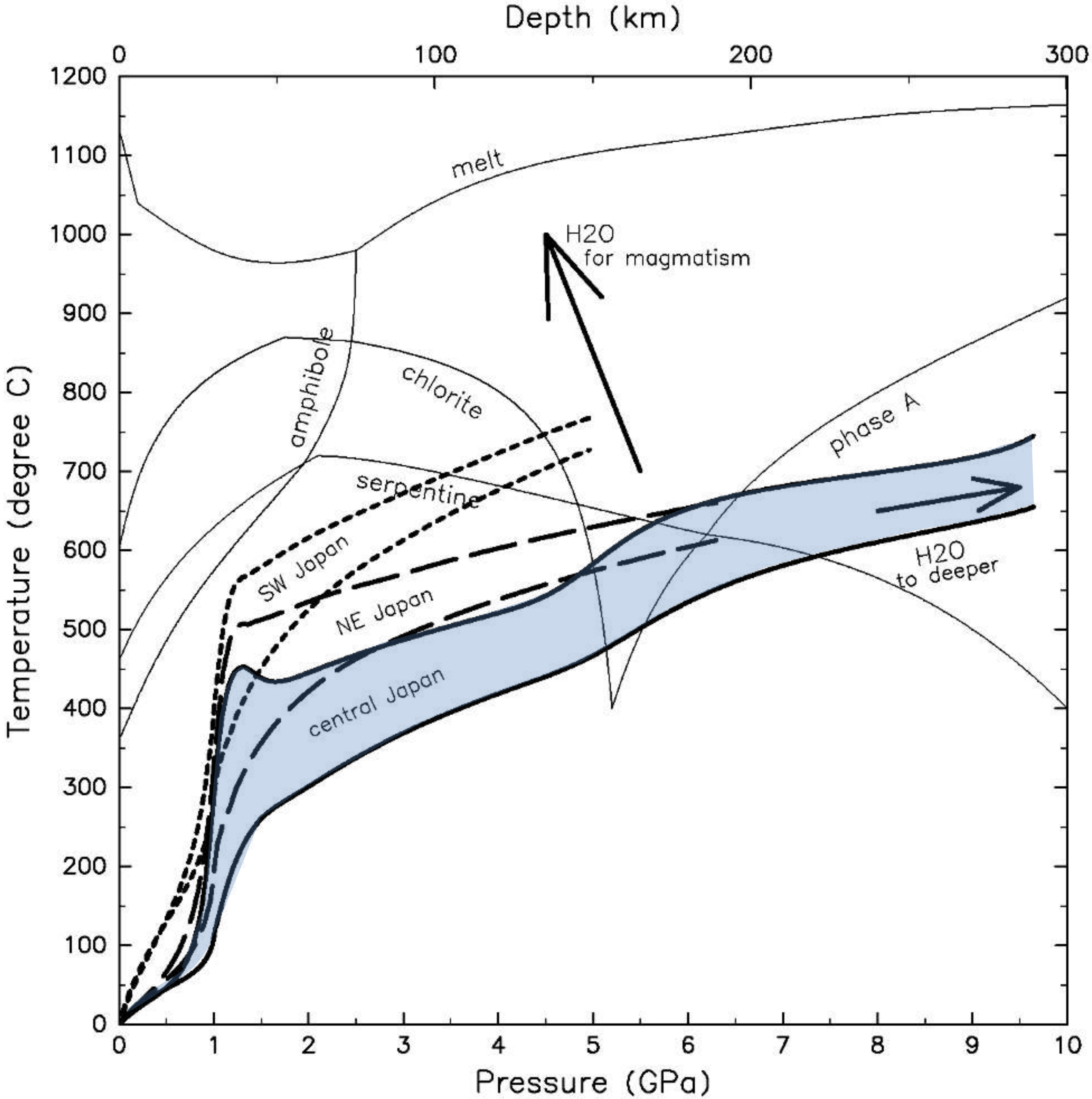
Iwamori(2007)



Iwamori (2000)

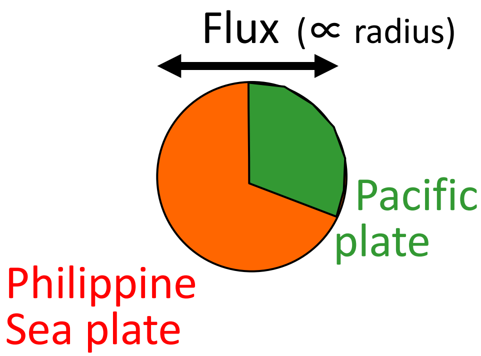


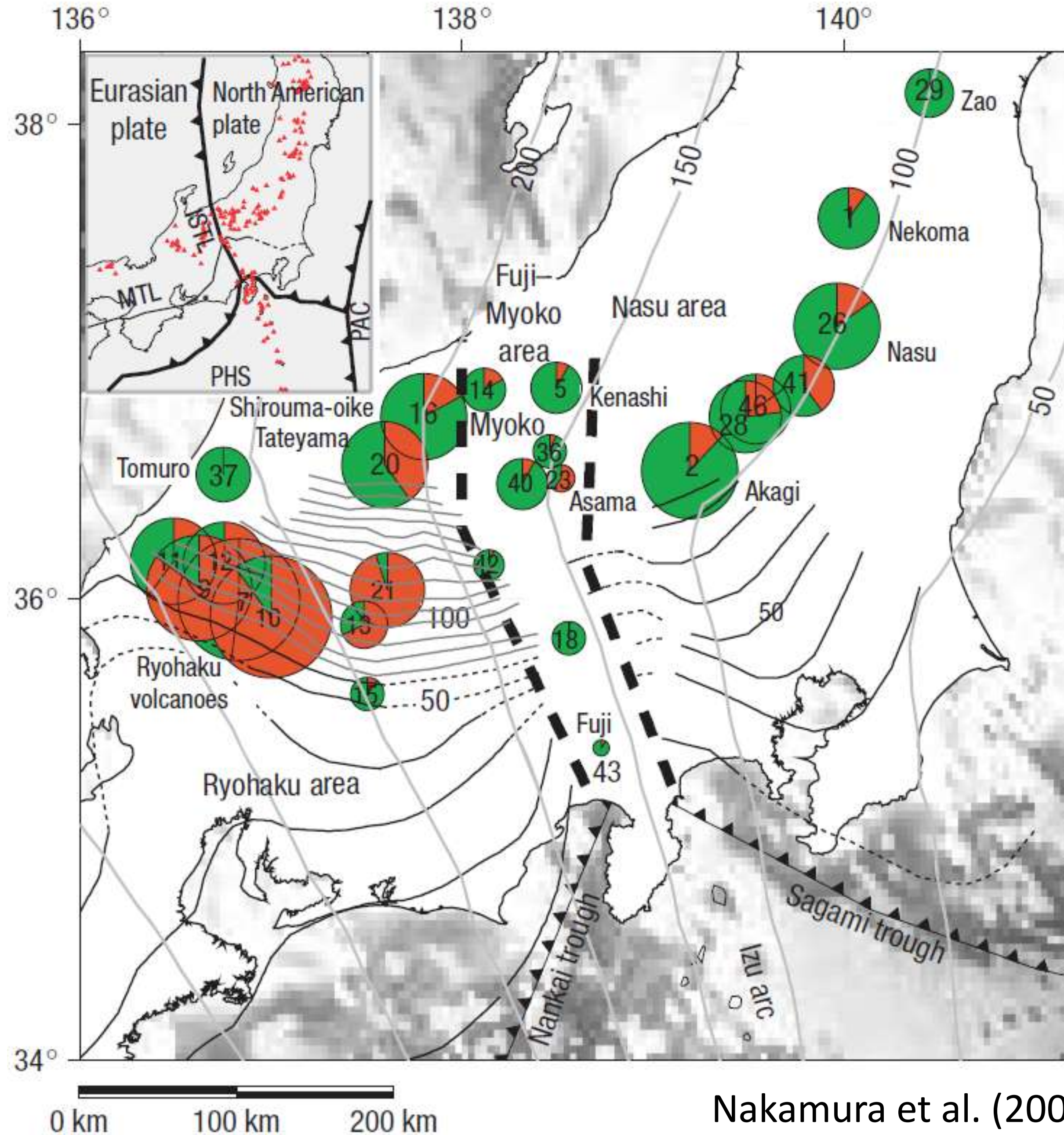
Iwamori (2007)



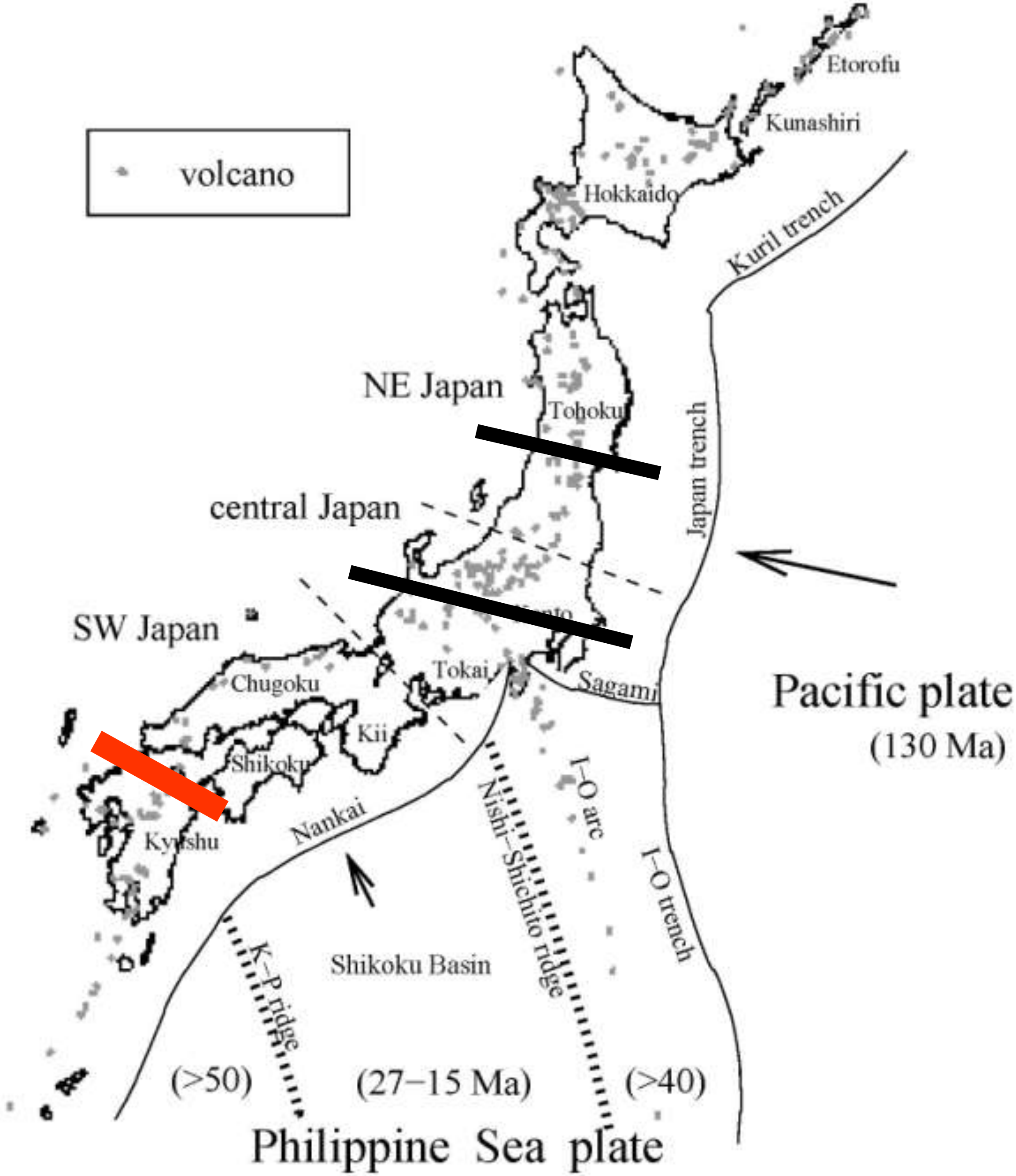
Iwamori (2007)

Slab-fluid



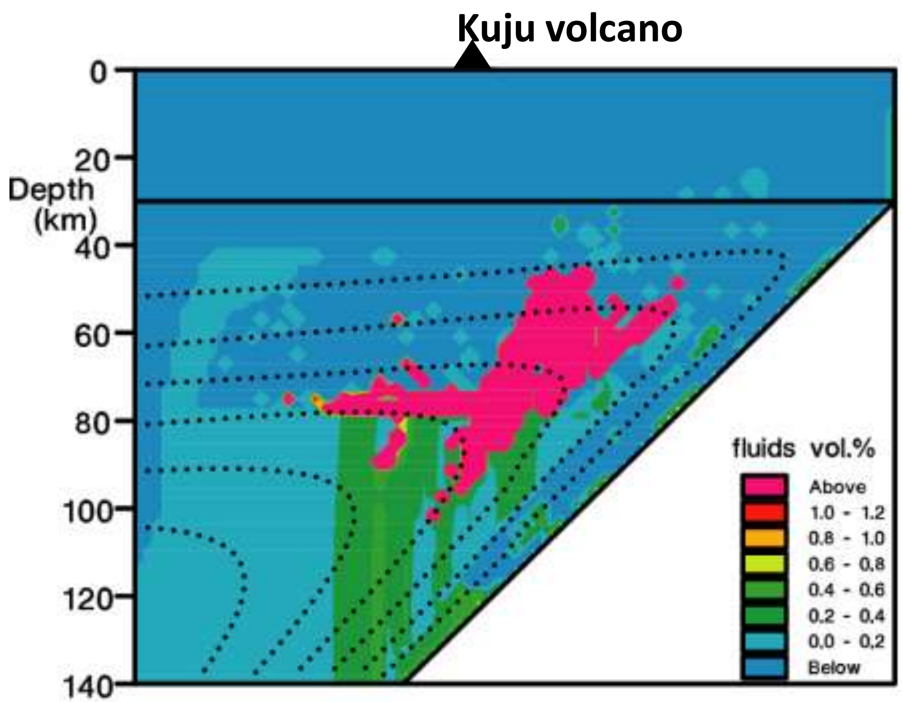


Nakamura et al. (2008)

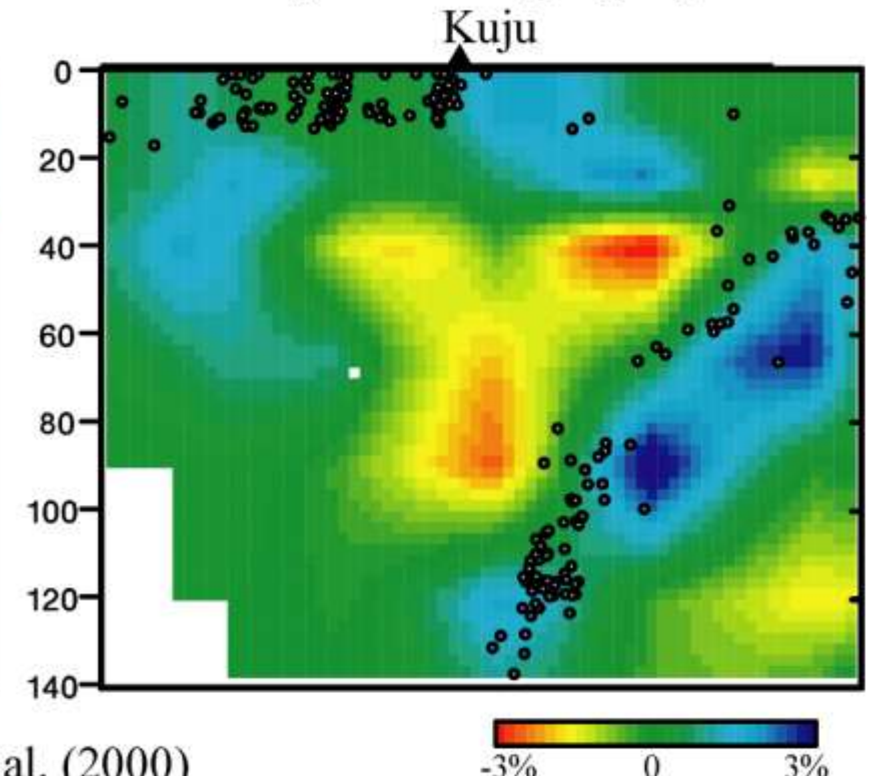


Iwamori(2007)

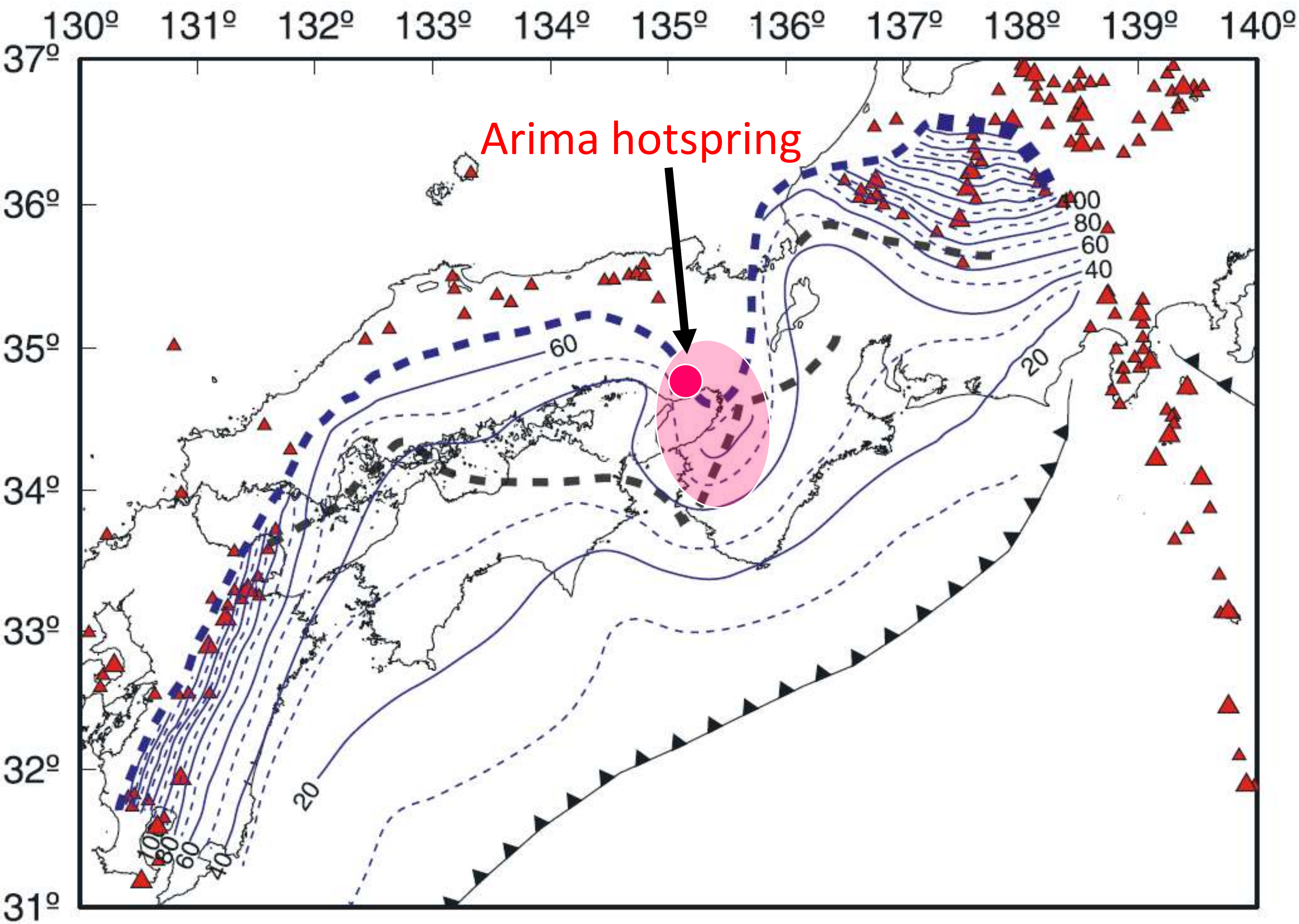
Model



Vp - tomography

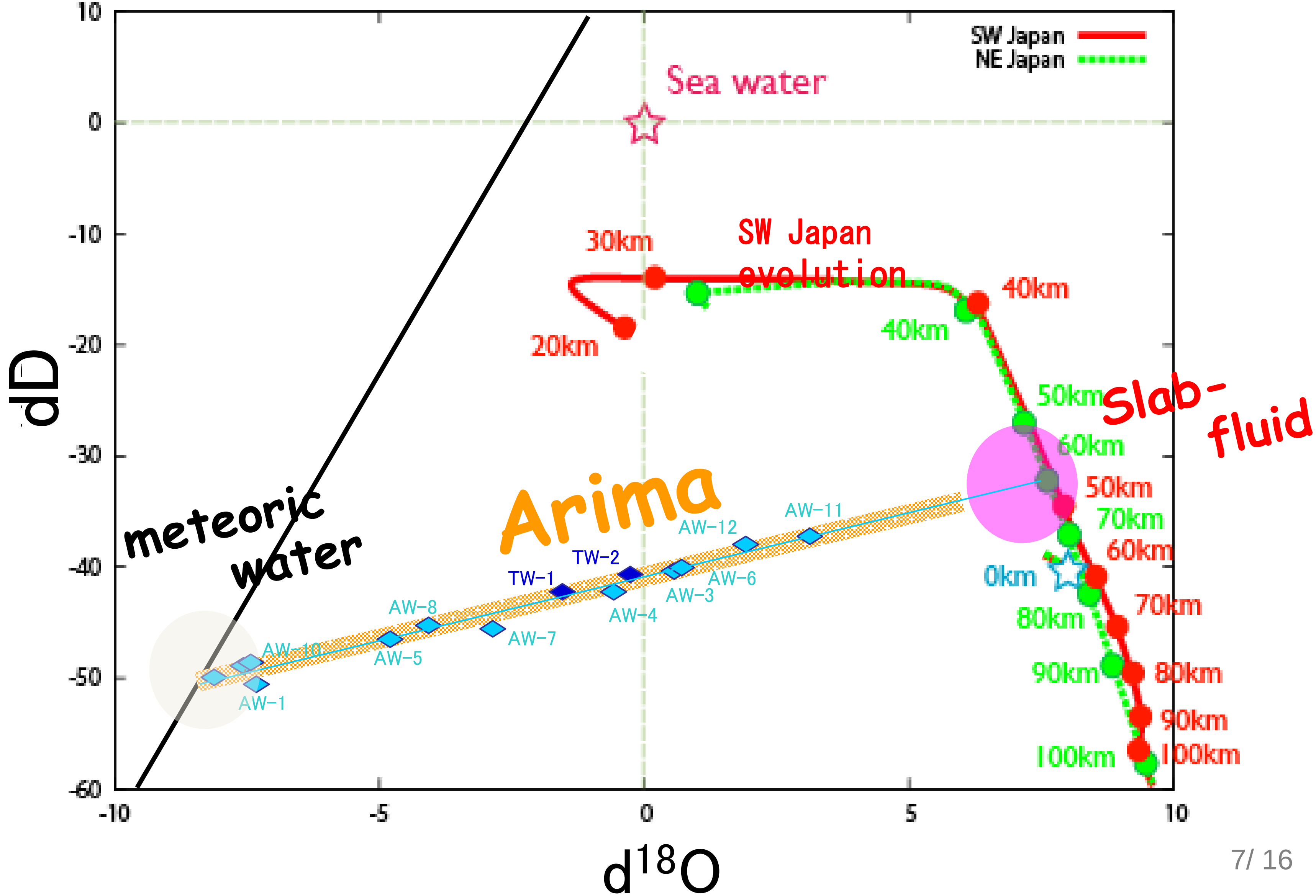


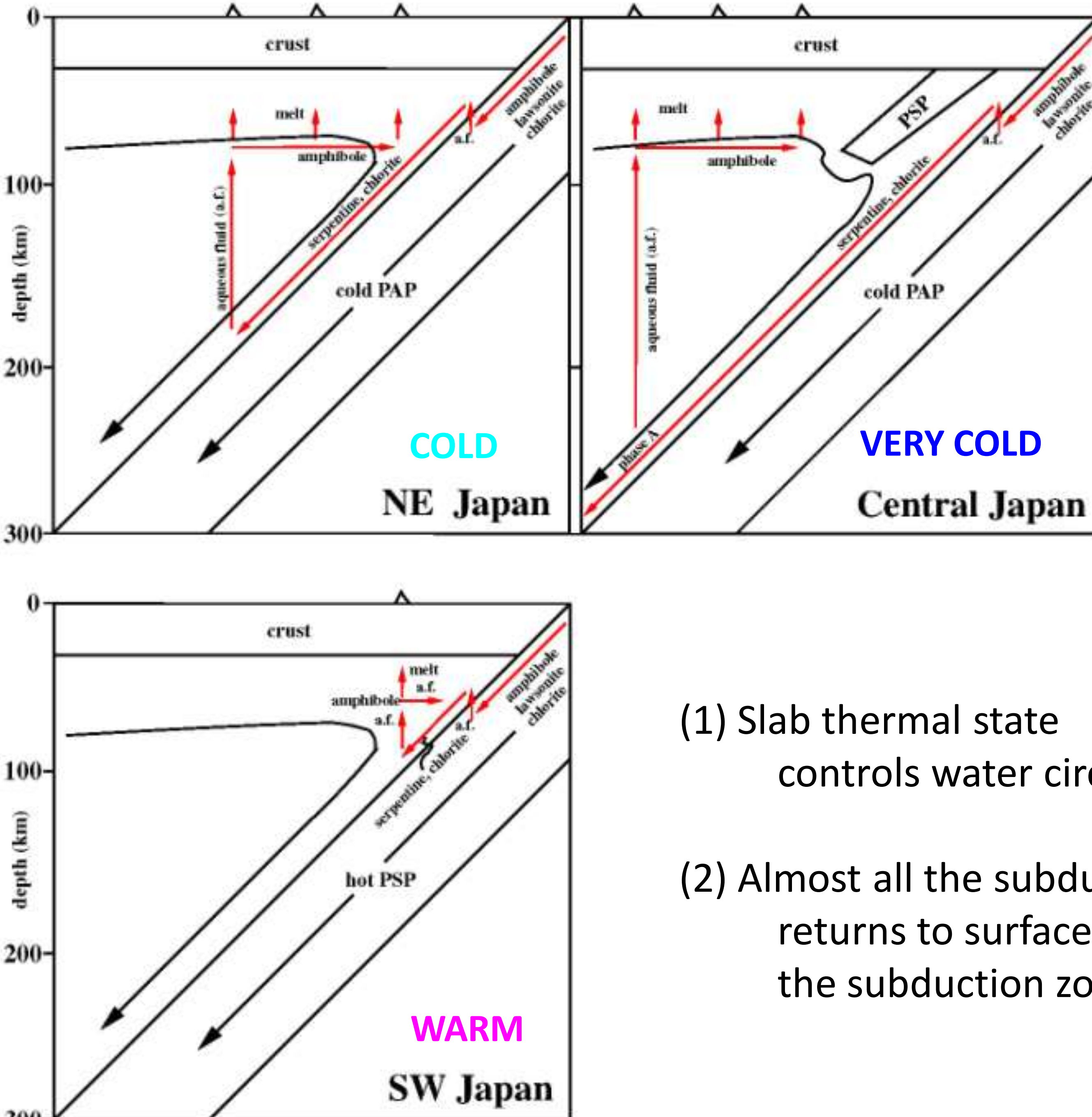
Zhao et al. (2000)



(modified from Nakajima and Hasegawa, 2007)

Oxygen & Hydrogen Isotopic Ratios of Slab-derived fluids (Kusuda, 2009)

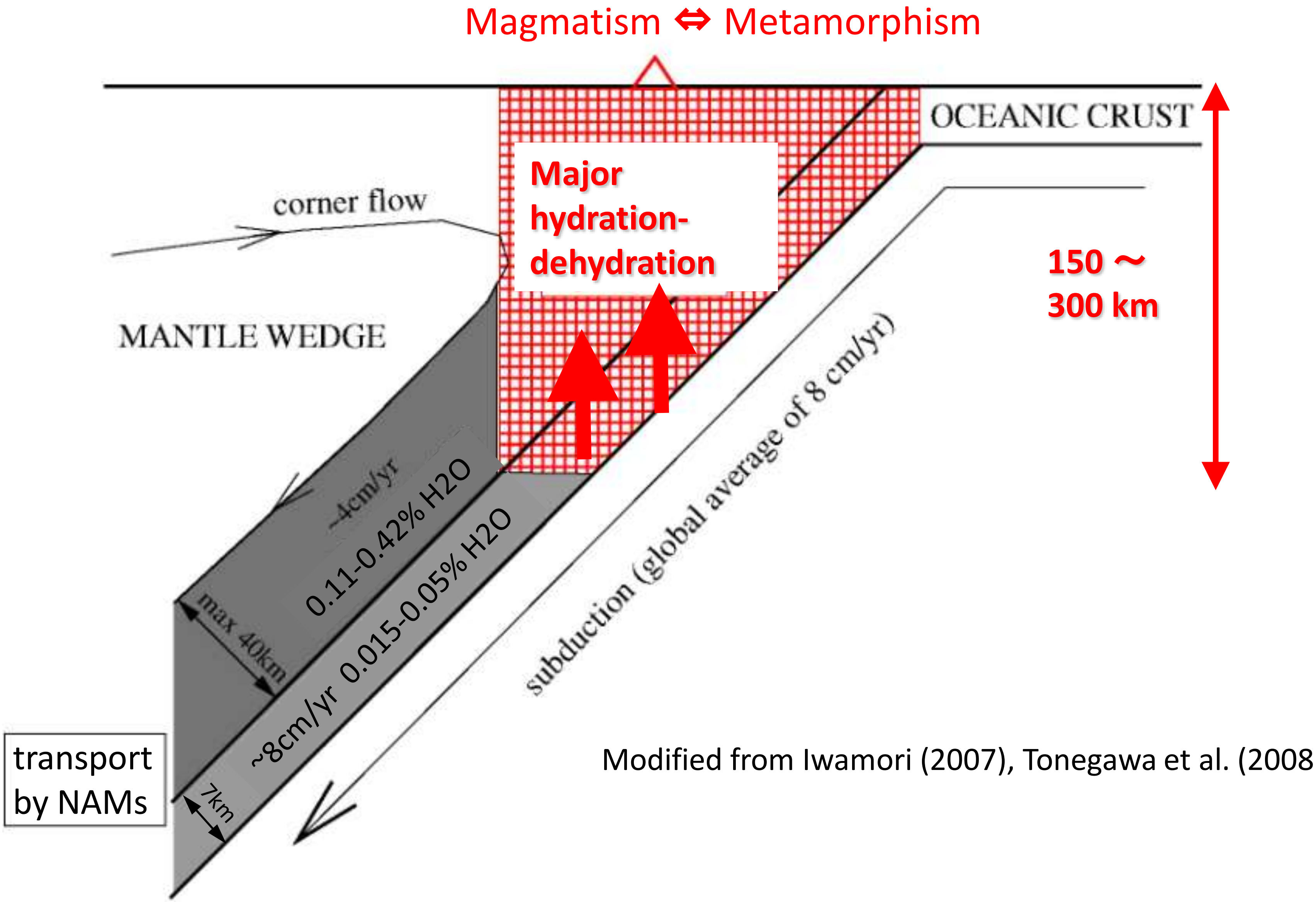




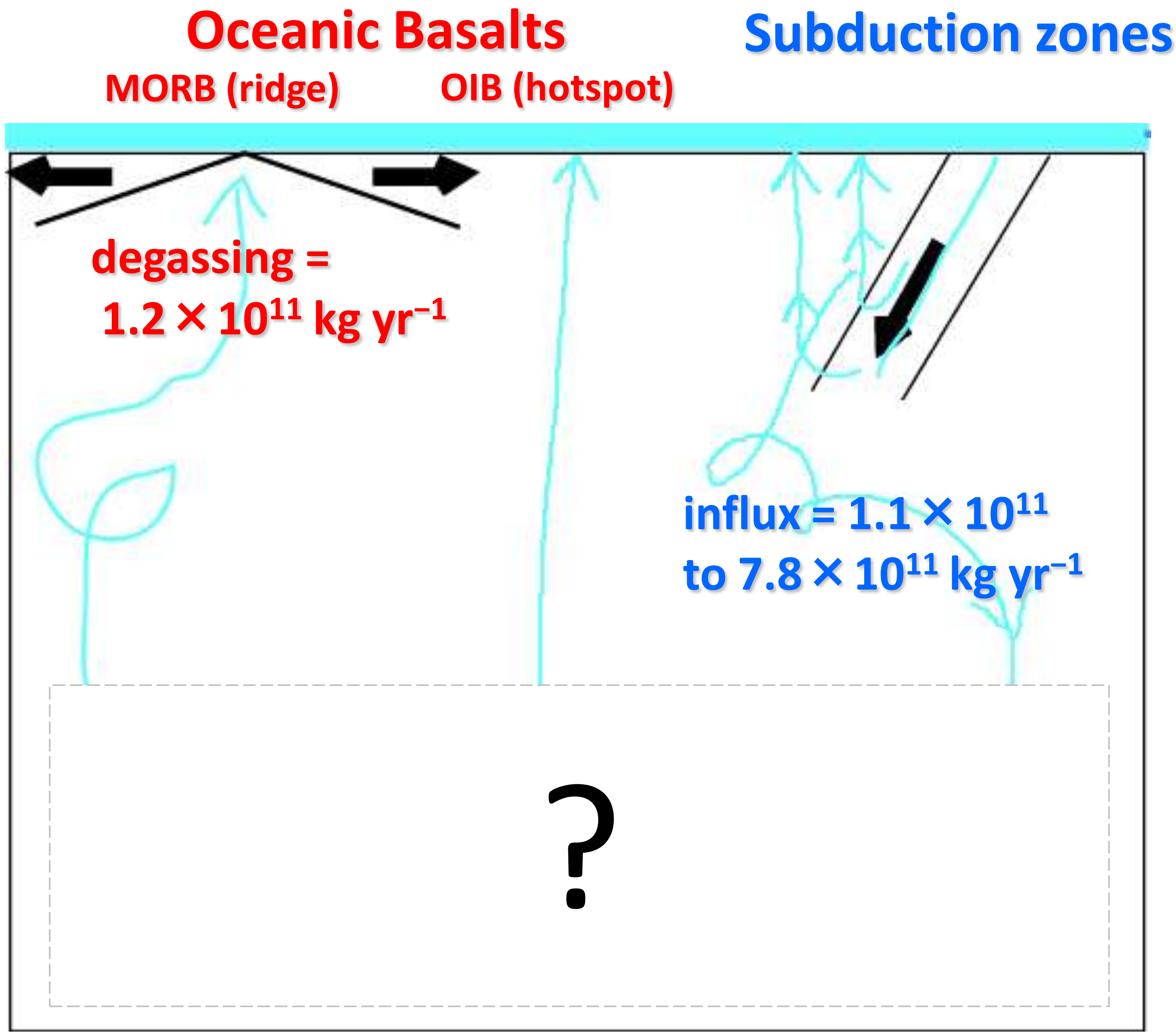
(1) Slab thermal state
controls water circulation

(2) Almost all the subducted water
returns to surface in most of
the subduction zones

Iwamori(2007)



Modified from Iwamori (2007), Tonegawa et al. (2008)



Oceanic Basalts
Subduction zones
MORB (ridge)
OIB (hotspot)
degassing =
1.2 × 10^11 kg yr^-1
influx = 1.1 × 10^11
to 7.8 × 10^11 kg yr^-1
?

Maximum H_2O in peridotite along standard geotherm

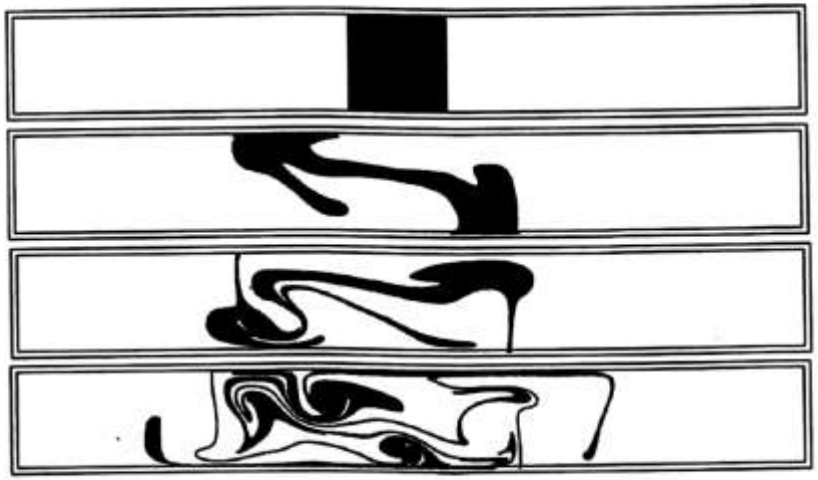
(unit)	Mass (10^{21} kg)	Max H_2O (10^{21} kg)	Max H_2O (wt.%)	Max H_2O (ocean mass)
Ocean	1.4	1.4	100	1.0
Upper mantle	615	4.2–5.8	0.68–0.95	3.0–4.2
Upper mantle*	615	1.1–2.8	0.18–0.45	0.79–2.0
Transition zone	415	5.4	1.3	3.8
Lower mantle	2955	0.03–6.2	0.001–0.21	0.02–4.4
Whole mantle	3985	9.6–17.5	0.24–0.44	6.9–12.5
Whole mantle*	3985	6.5–14.4	0.16–0.36	4.6–10.3

Iwamori (2007)

中生代ー現在までの平均海洋地殻生産率25 km3 per year (Reymer and Schubert, 1984)。
過去にはより対流が激しく、生産率が大きかったはずだが、この率で40億年間継続したとするとマントルの１１%が海洋地殻となる(Ohta et al., 2008)。

沈み込んださまざまな成分:
どこかに溜る　？　⇔　良く stirring を受ける　？

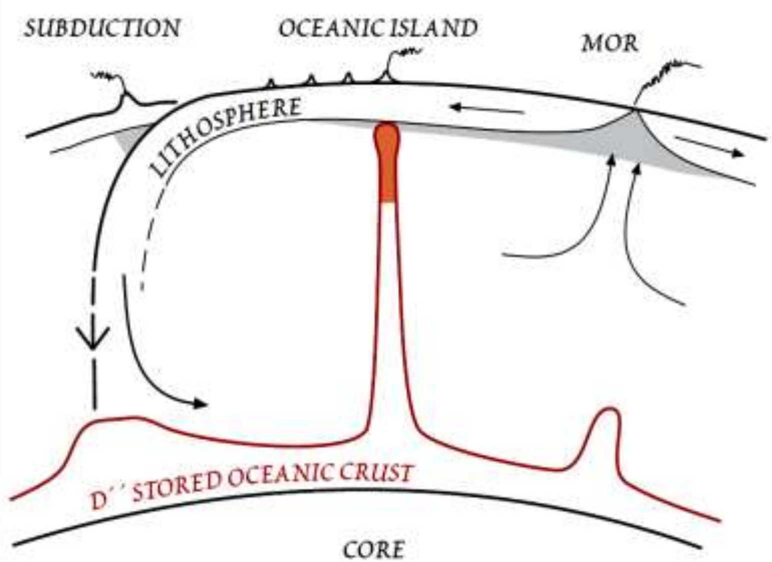
Christensen & Hofmann (1994)



Hoffman & McKenzie (1985)

沈み込んだ地殻物質の沈積

Hofmann and White (1982)
（広義の plum-pudding mantle）



Marble-cake mantle

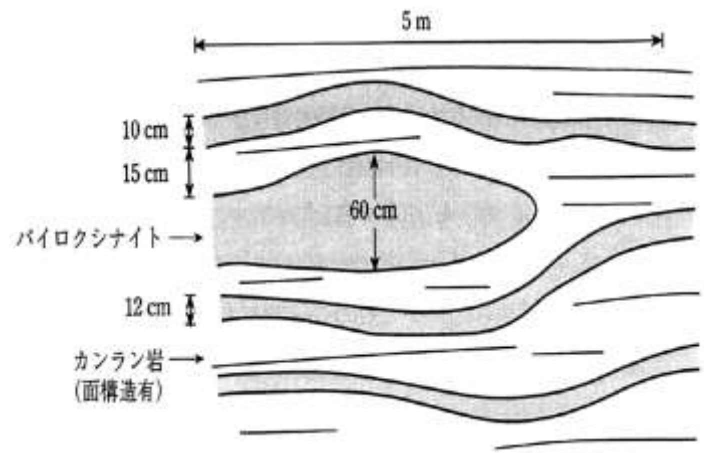


図 7-38 カンラン岩岩体中にみられるパイロクシナイトの薄層[75)]

培風館 地球化学講座3
(図の出典はAllegre and Turcotte (1986))

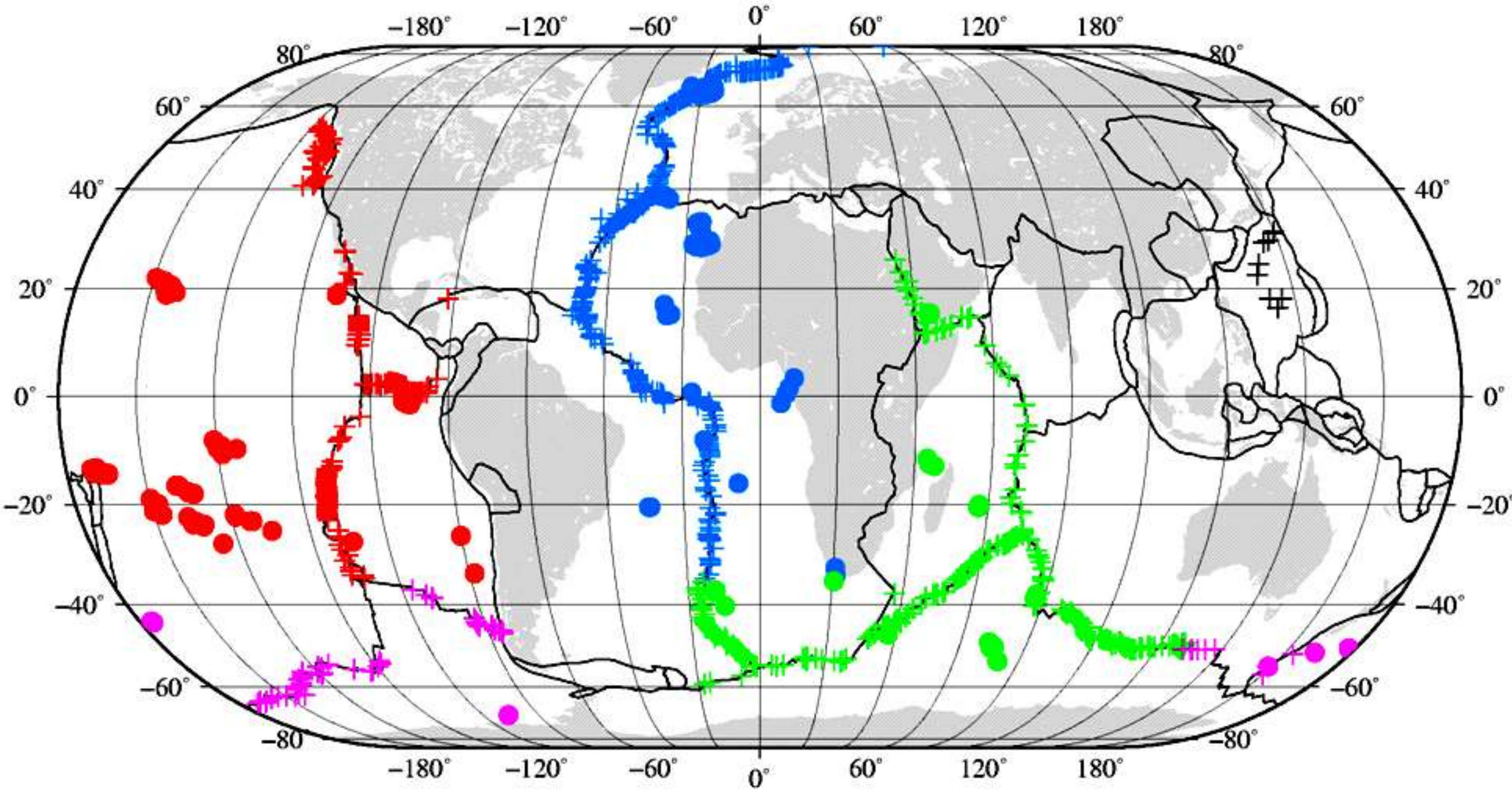
	地球の岩石部分（始原マントル）		海洋地殻（MORB)		大陸地殻
SiO_2 (wt%)	45.0	<	49.93	<	59.1
MgO	37.8	>	7.56	>	4.4
K_2O (ppm)	0.029	<<	0.17	<<	1.9
Th	0.0795	<<	0.20	<<	5.6
U	0.0203	<<	0.10	<<	1.42

X 10　　X 10

地殻は全地球の～0．４ 重量%に過ぎないが、
全地球放射性元素の半分近くを含む。

Oceanic Basalts

2769 MORB & 1514 OIB with 5 isotopic ratios



同位体分別:

＊ 軽い、重い

（H, He, Li ...Rb,Sr,Nd,Sm,Pb,Th,U）

＊ 安定、放射性

＊ 化学的性質（揮発性、親石、親鉄）

同位体分別：

＊ 軽い、重い

（H, He, Li …Rb,Sr,Nd,Sm,Pb,Th,U）

＊ 安定、放射性

＊ 化学的性質（揮発性、親石、親鉄）

温度・圧力分別を起こし難い

循環のタイムスケール

親娘元素の化学的分別

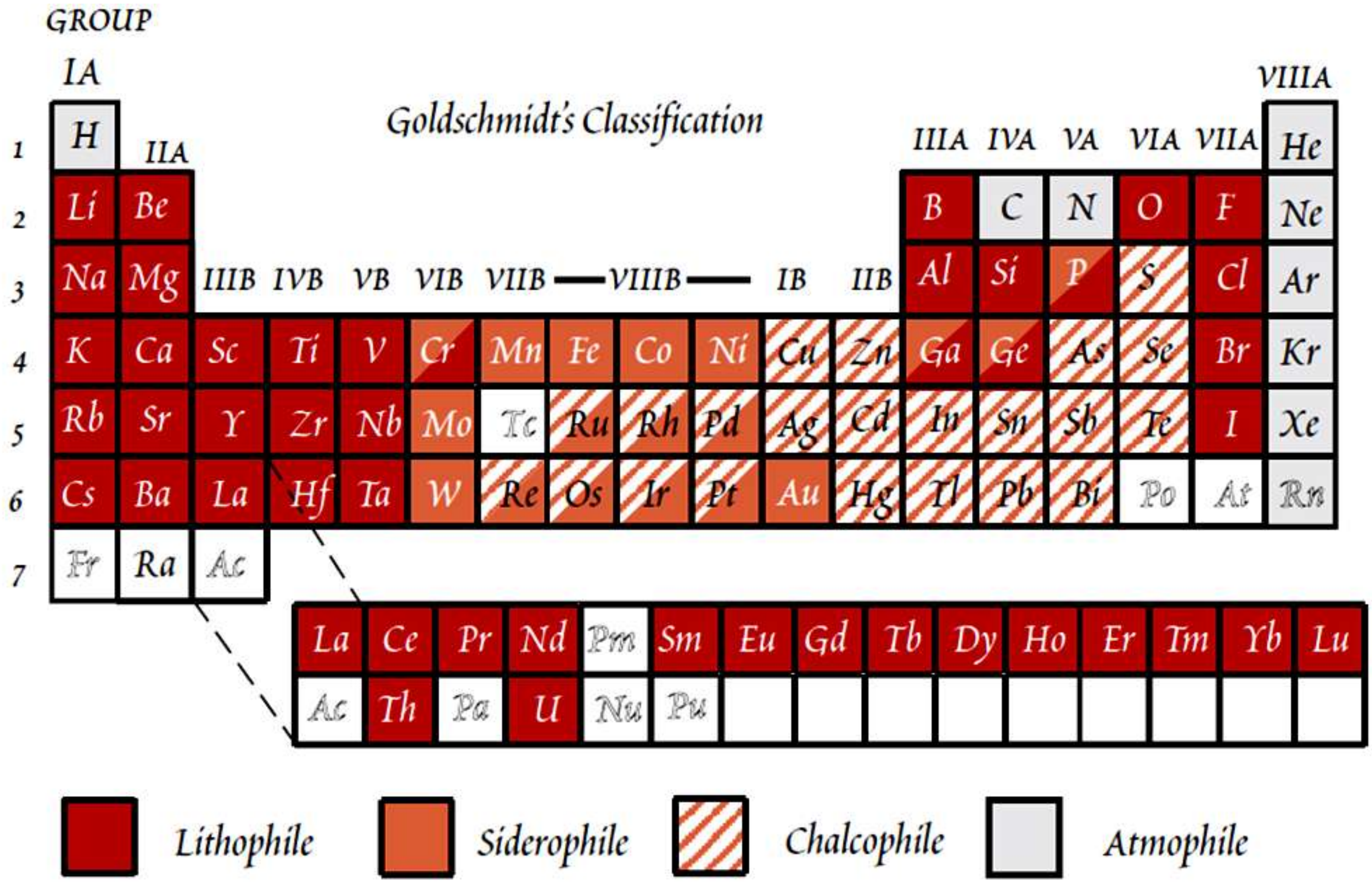


Figure 7.2. Goldschmidt's classification of the elements.

White (2007)

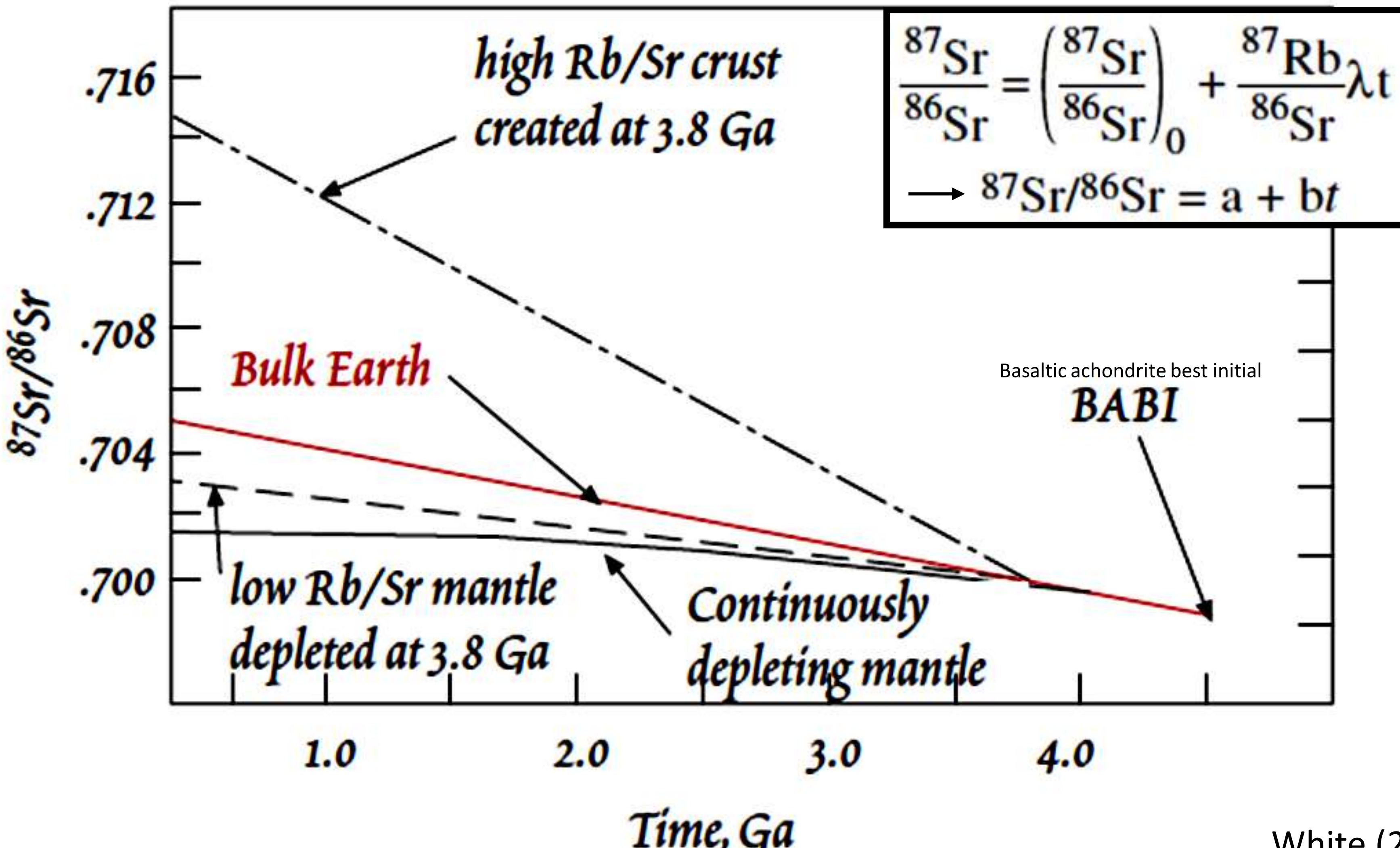
Table 1 Long-lived radioactive decay series used as tracers

Parent nuclide	Daughter nuclide	Half-life (yr)	Tracer ratio (radiogenic/ nonradiogenic)
^{147}Sm	^{143}Nd	106×10^9	$^{143}Nd/^{144}Nd$
^{87}Rb	^{87}Sr	48.8×10^9	$^{87}Sr/^{86}Sr$
^{176}Lu	^{176}Hf	35.7×10^9	$^{176}Hf/^{177}Hf$
^{187}Re	^{187}Os	45.6×10^9	$^{187}Os/^{188}Os$
^{40}K	^{40}Ar	1.25×10^9	$^{40}Ar/^{36}Ar$
^{232}Th	^{208}Pb	14.01×10^9	$^{208}Pb/^{204}Pb$
^{238}U	^{206}Pb	4.468×10^9	$^{206}Pb/^{204}Pb$
^{235}U	^{207}Pb	0.738×10^9	$^{207}Pb/^{204}Pb$

$$\frac{dN}{dt} = -\lambda N$$

Hofmann (1997)に加筆

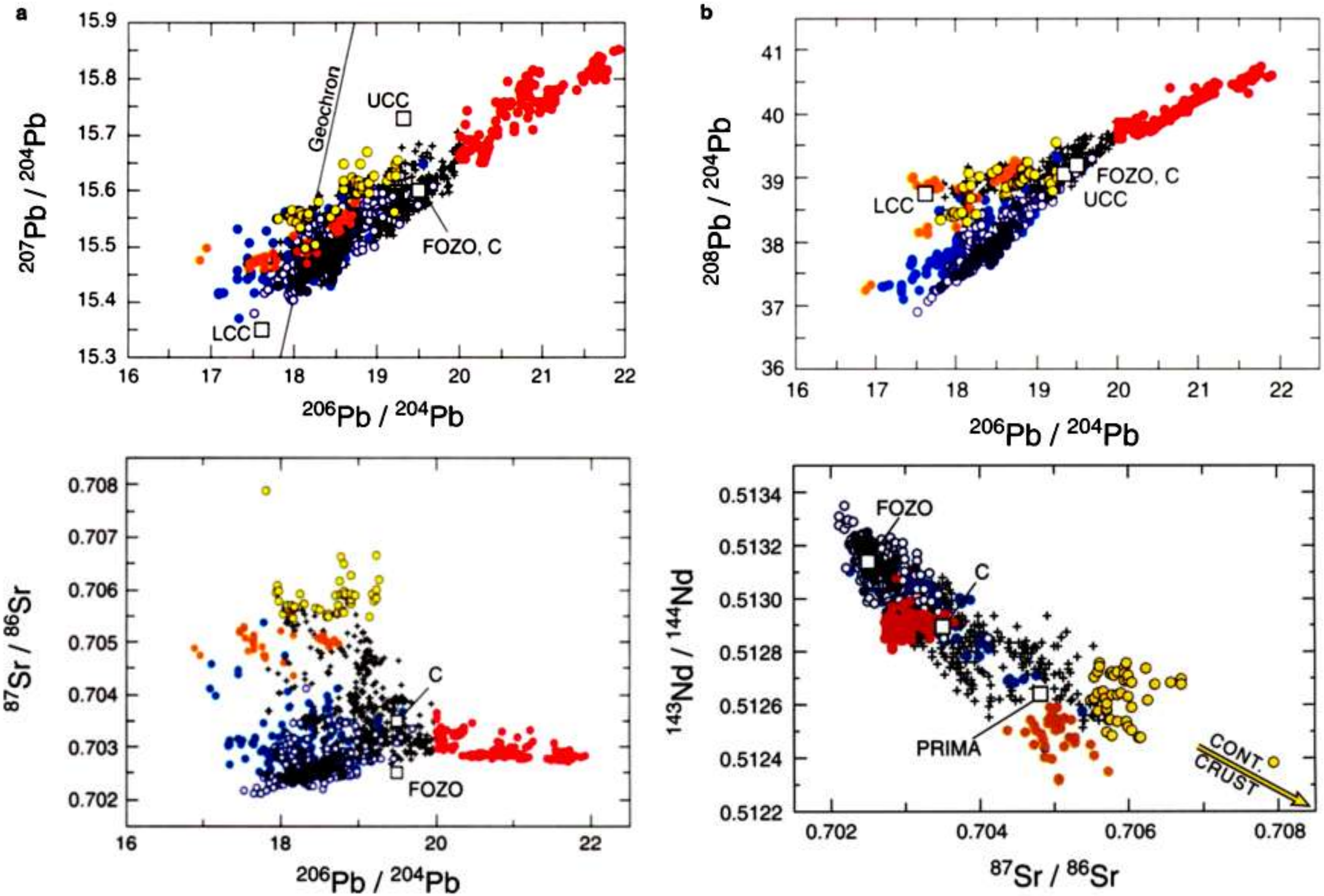
さまざまな元素の同位体比　⇒　さまざまな親娘核種の分別 （程度[傾き]x時間）
⇒ （先験的情報とあわせて）初期物質、分別プロセス・年代が推定可能



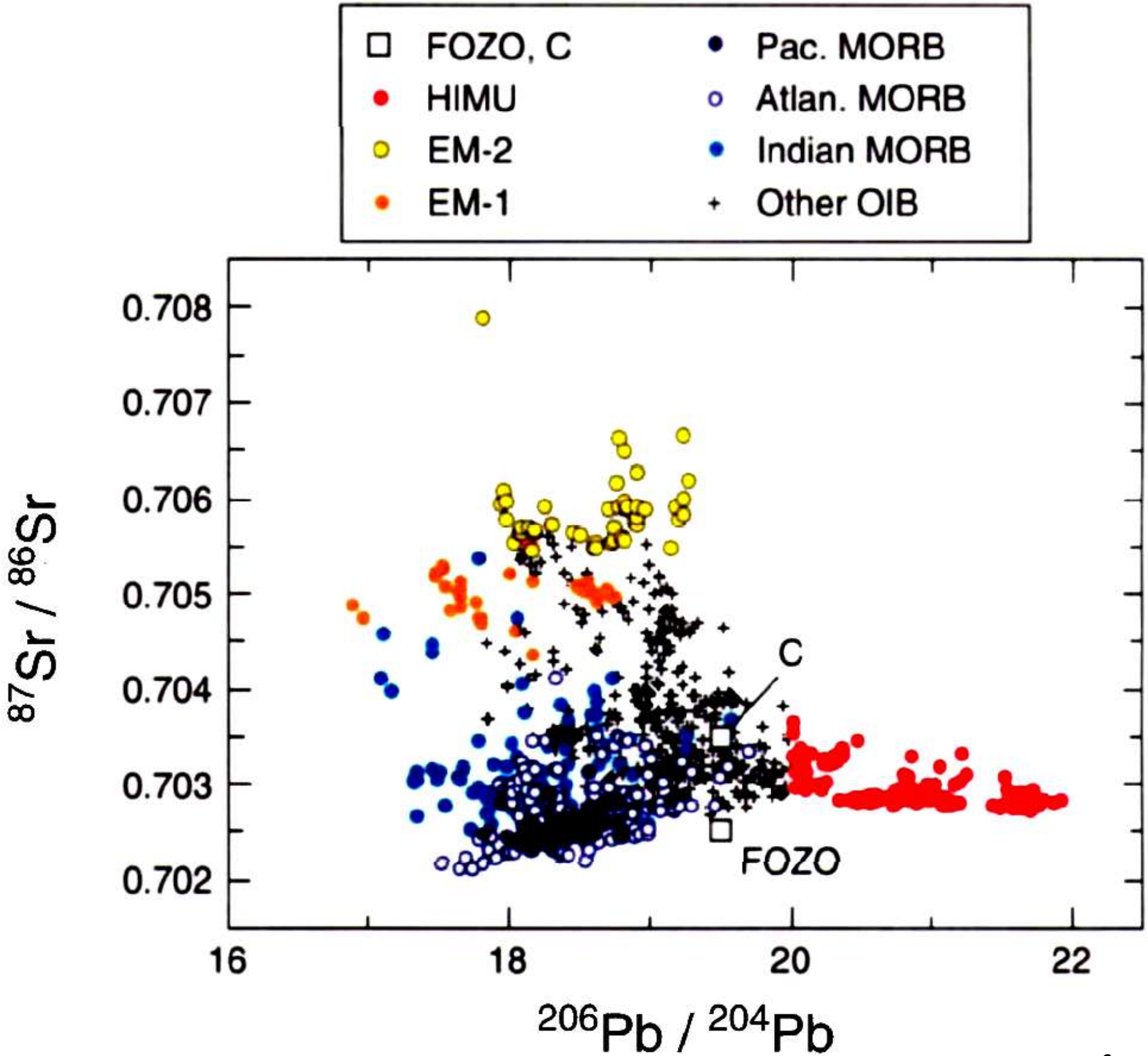
$$\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}} = \left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_0 + \frac{^{87}\mathrm{Rb}}{^{86}\mathrm{Sr}}\lambda t$$

$$\longrightarrow\ ^{87}\mathrm{Sr}/^{86}\mathrm{Sr} = a + bt$$

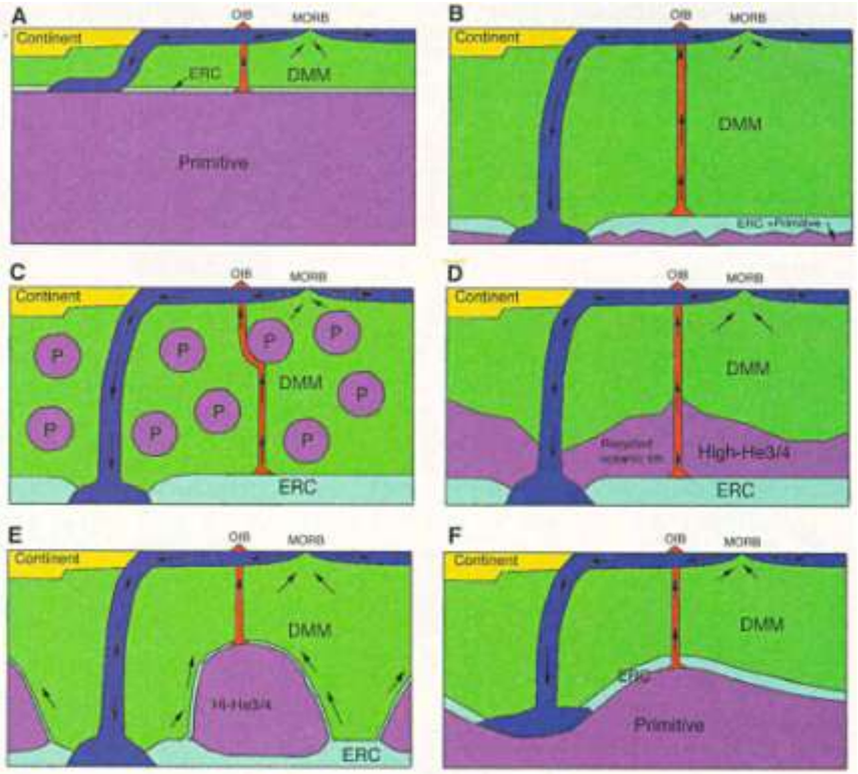
White (2007)



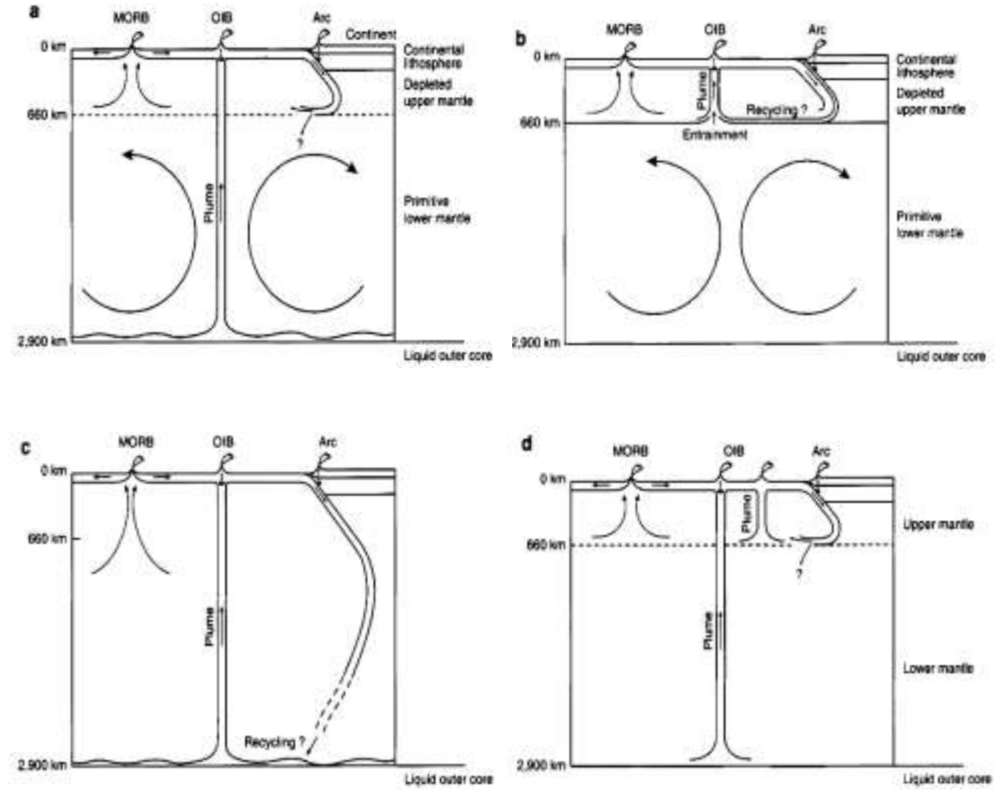
Hofmann (1997)



Hofmann (1997)



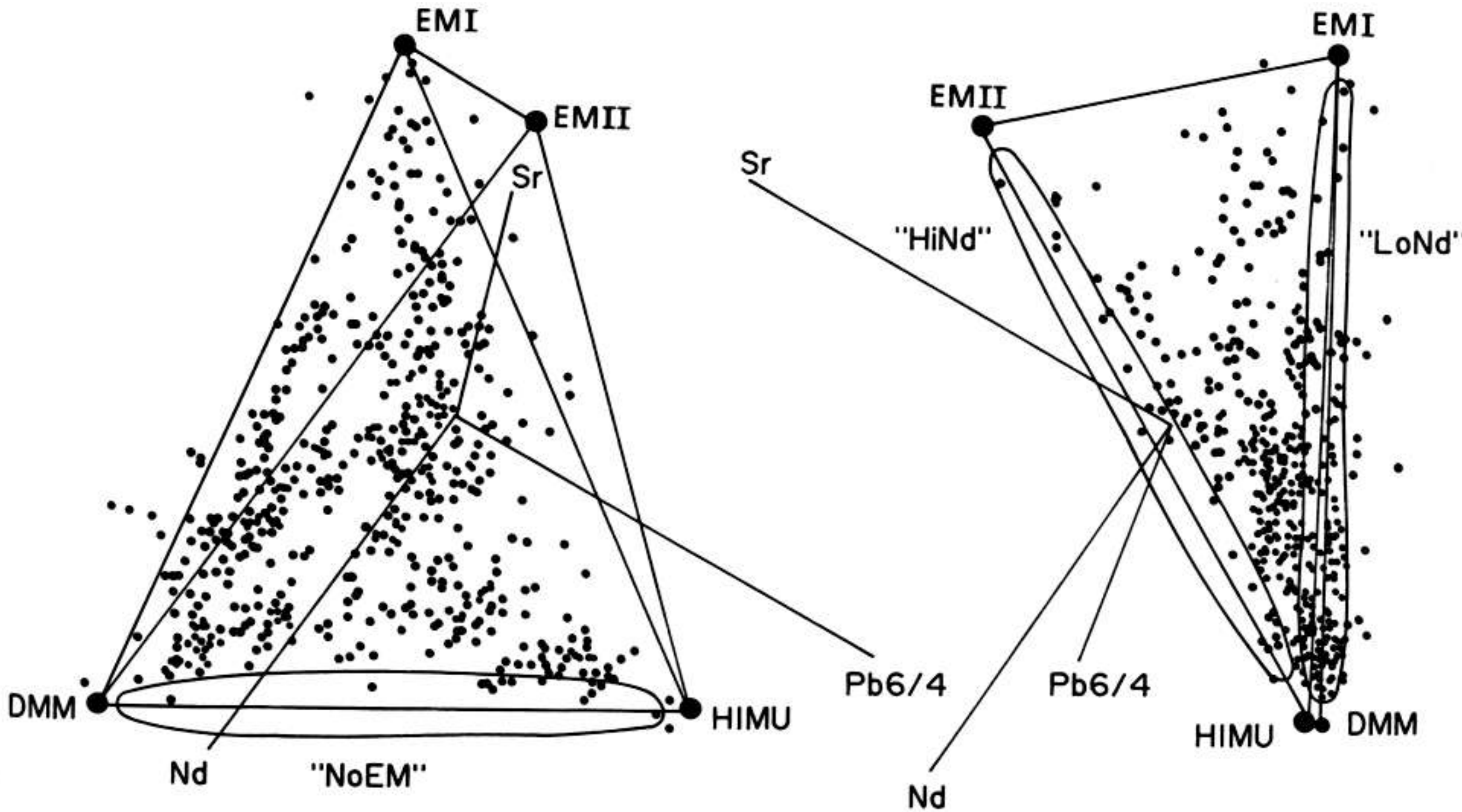
Tackley (2000)



Hofmann (1997)

定説:「地表付近、地球内部でのさまざまな元素分別 ⇒ 多様な同位体不均質:
不均質が対流攪拌によって marble-cakeとなるか、
不均質が大きく残って plum-pudding となるかは議論が分かれる」

FOZO, HIMU, and the rest of the mantle zoo (Stracke et al., 2005)



smaller data set. The percentage of variance accounted for by the five eigenvectors is 56.6, 37.2, 3.7, 1.8, and 0.7% (*11*). Thus, the planar aspect of the data in Fig. 1 is confirmed, because the first two eigenvectors account for 93.8% of the population

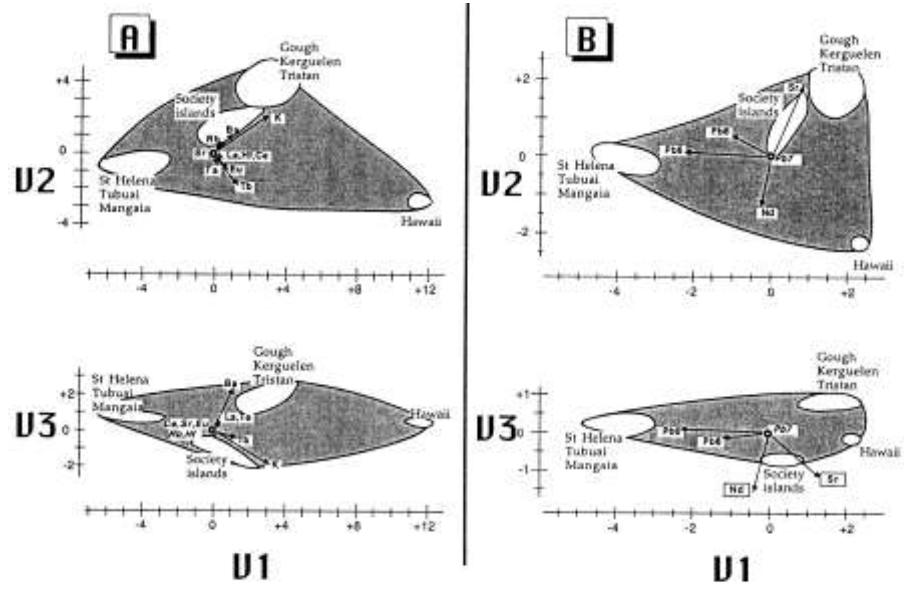
Hart et al. (1992)

Principal Component Analysis

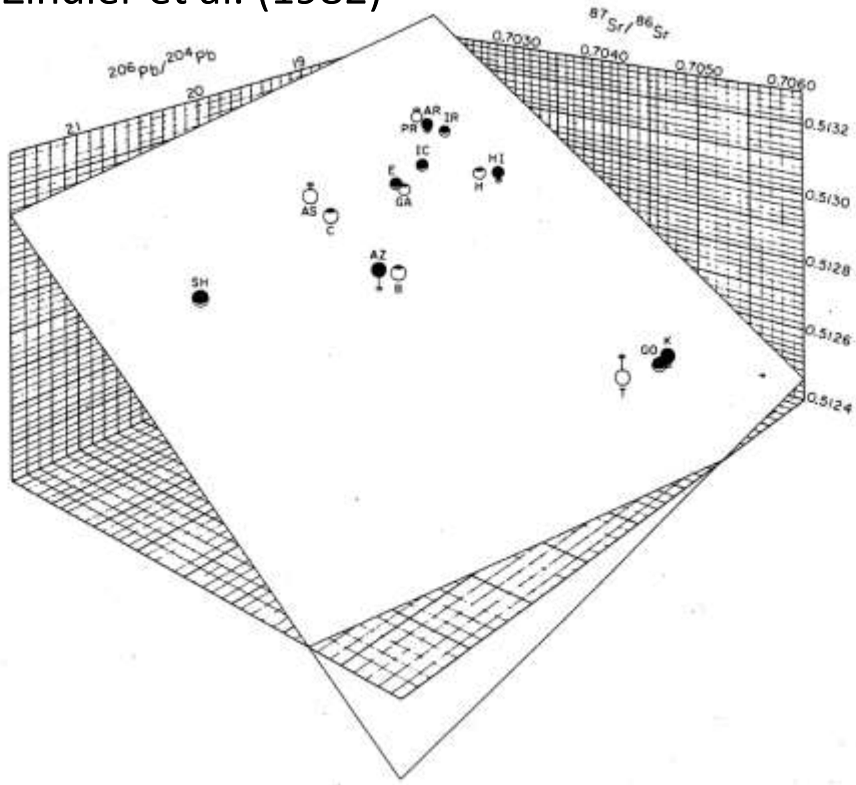
for

geochemical mantle components

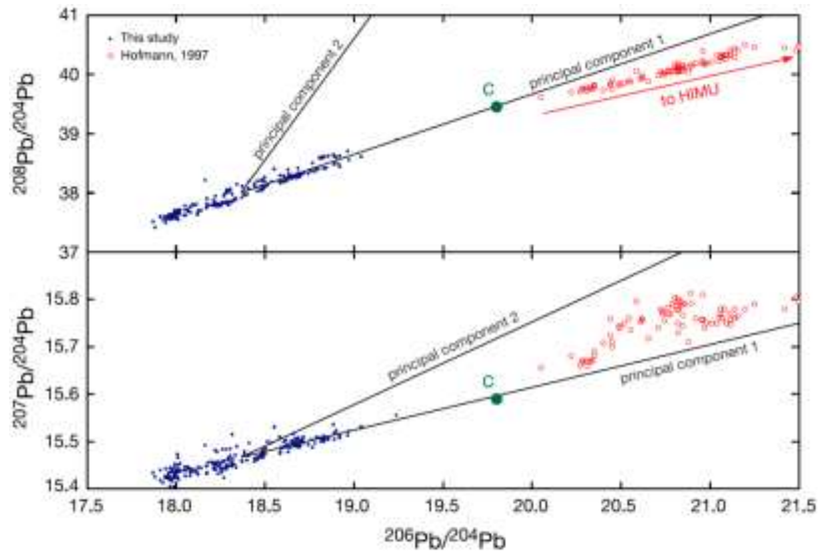
Allegre and Lewin (1995)

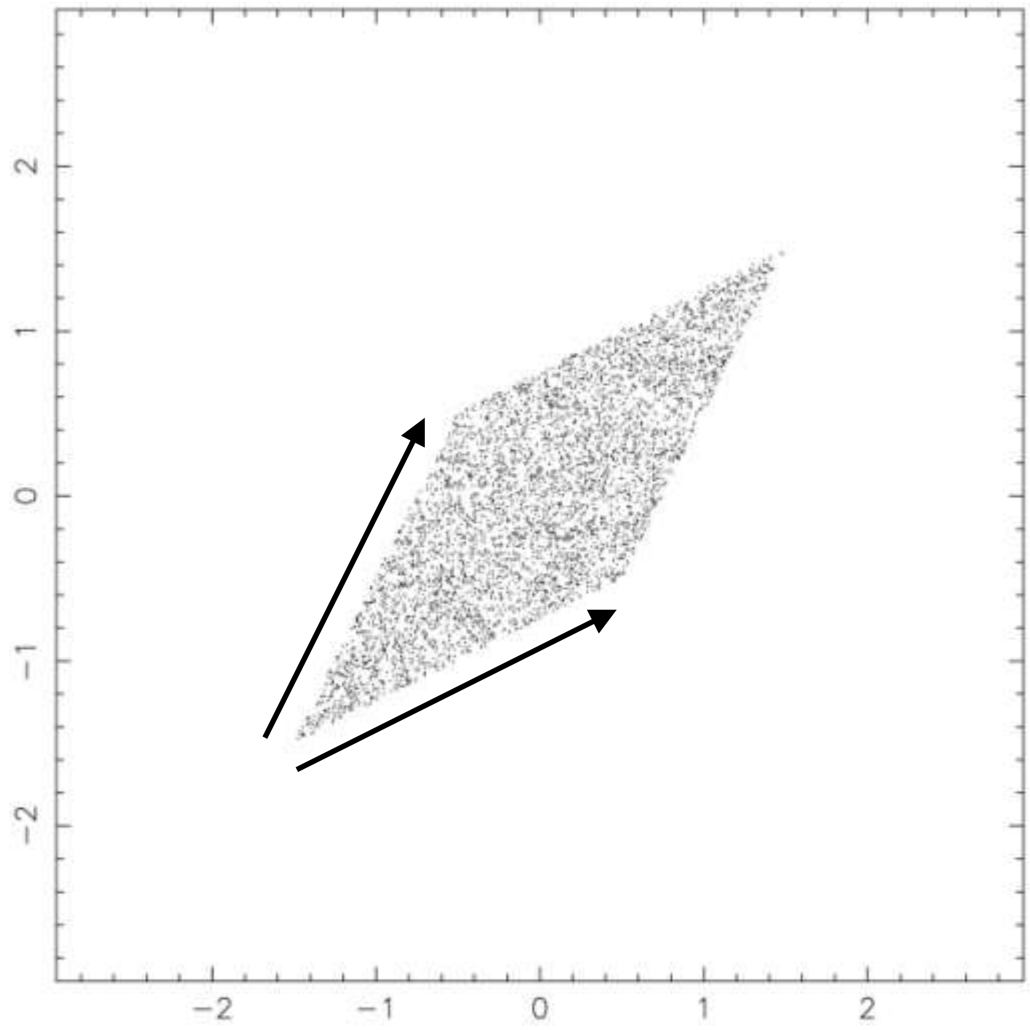


Zindler et al. (1982)

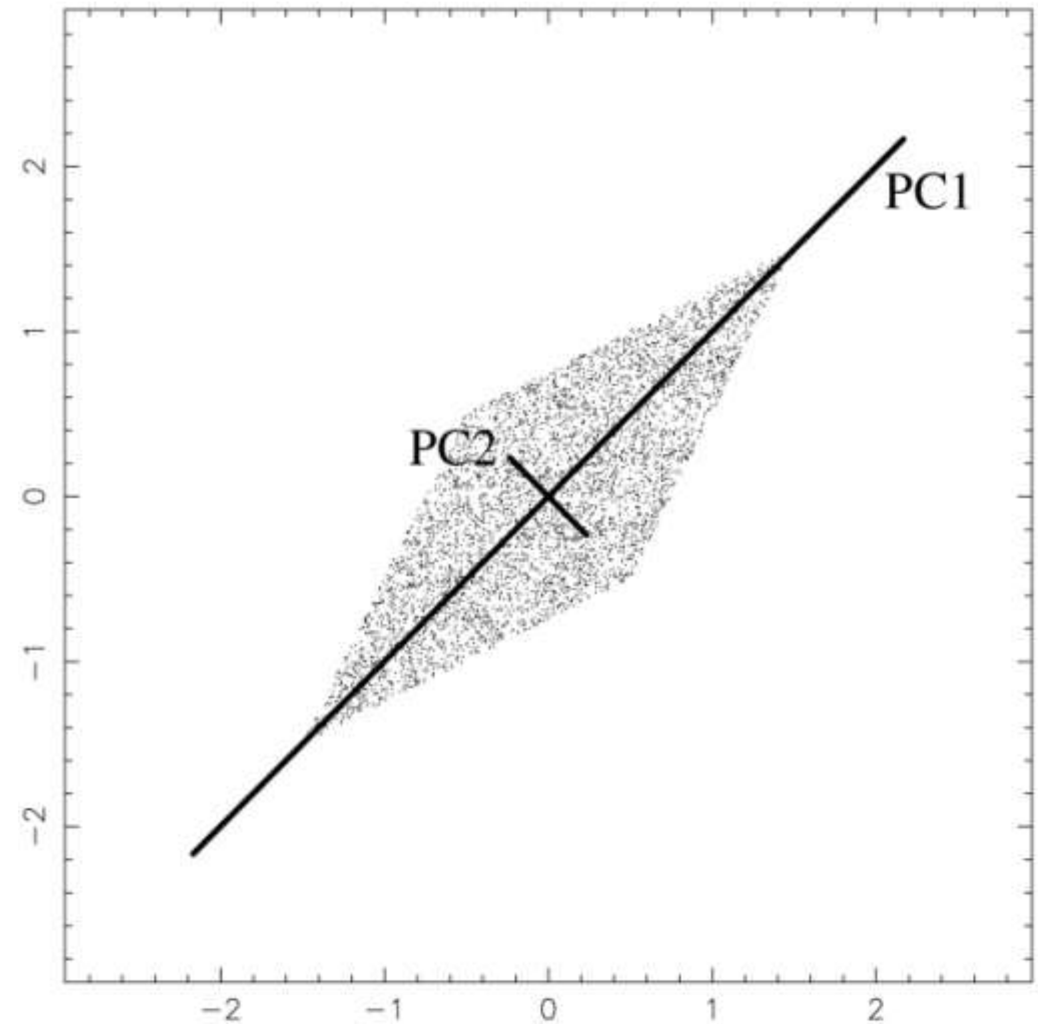


Blichert-Toft et al. (2005)



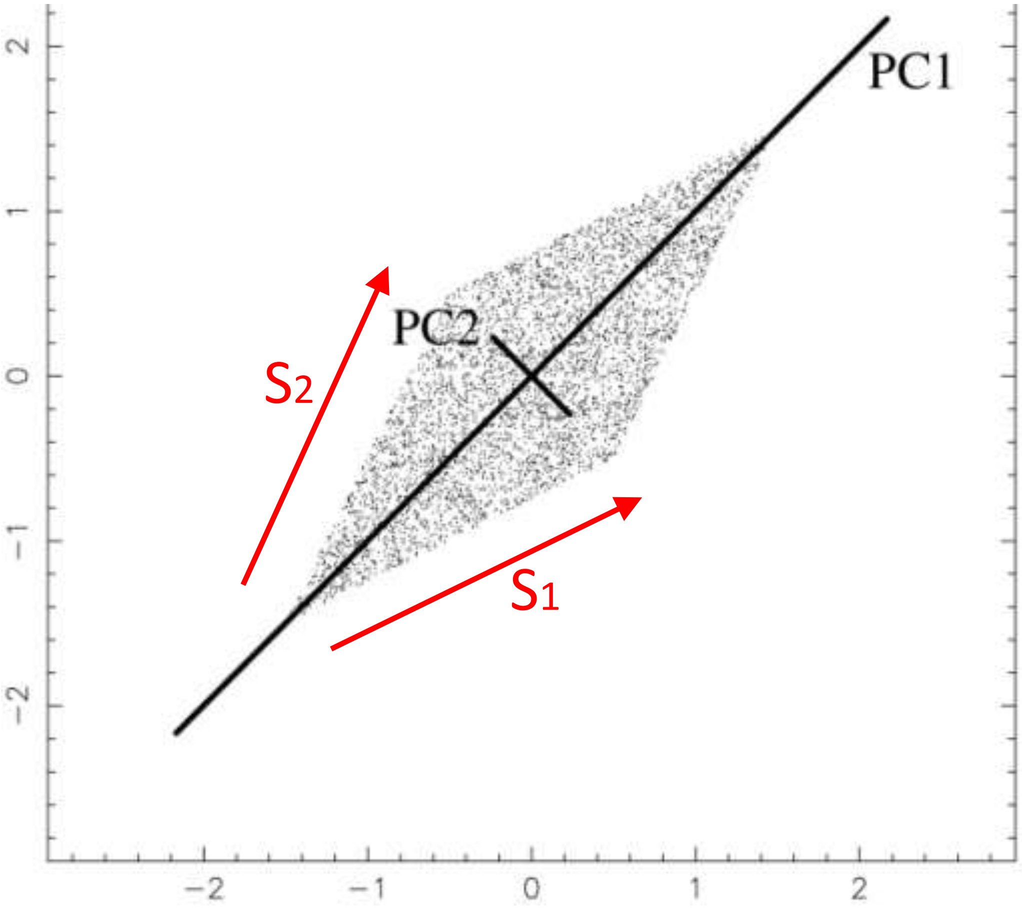


−2
−1
0
1
2

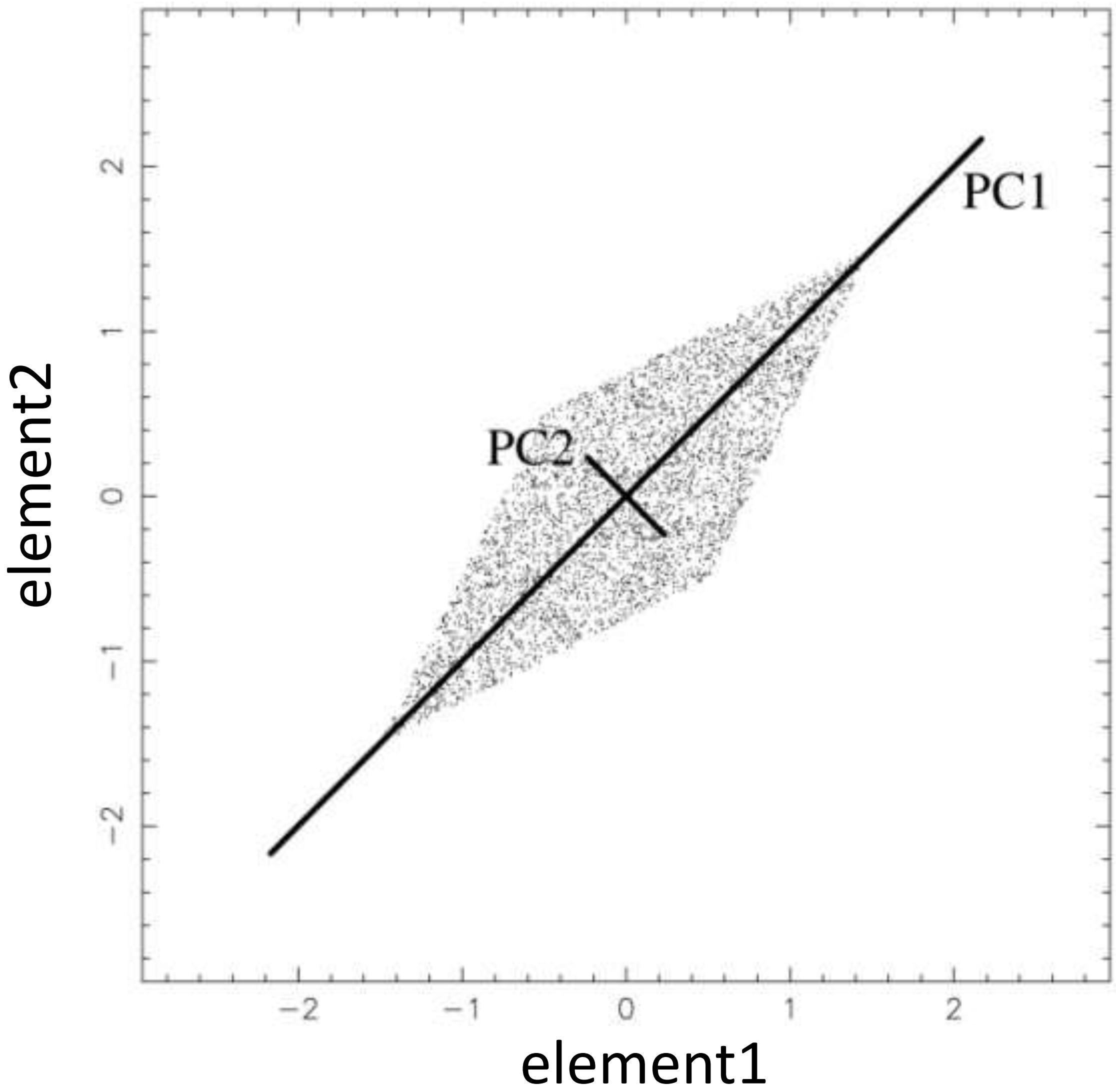

PC1
PC2
2
1
0
−1
−2
−2
−1
0
1
2

Non-Gaussian distribution

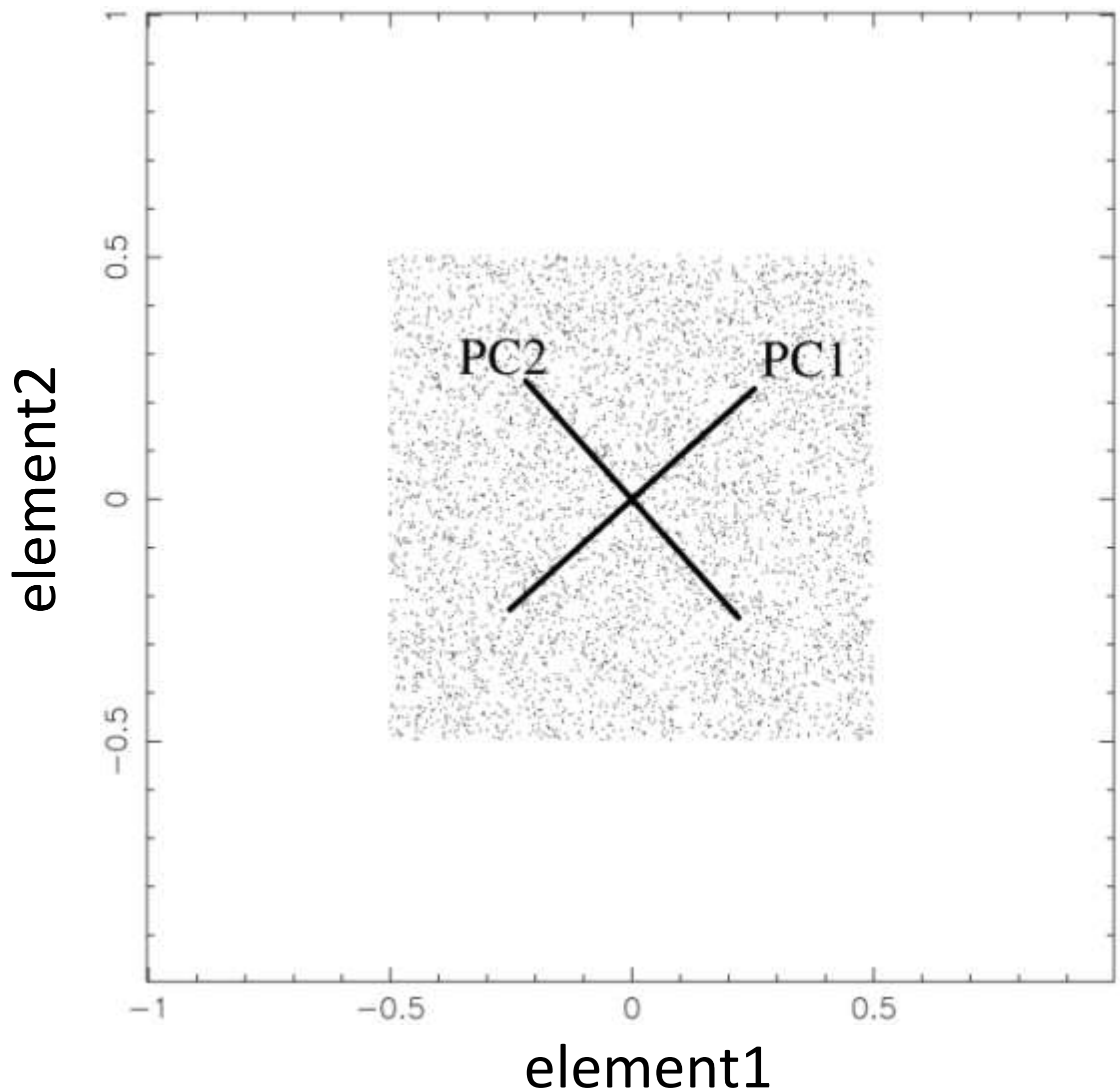
PCs are uncorrelated but NOT independent



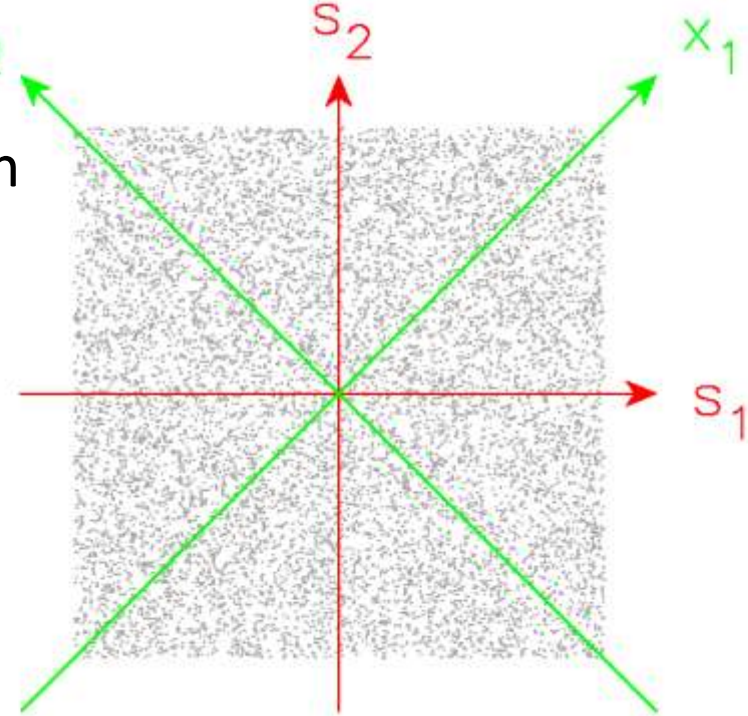
PCA for Geochemical Data



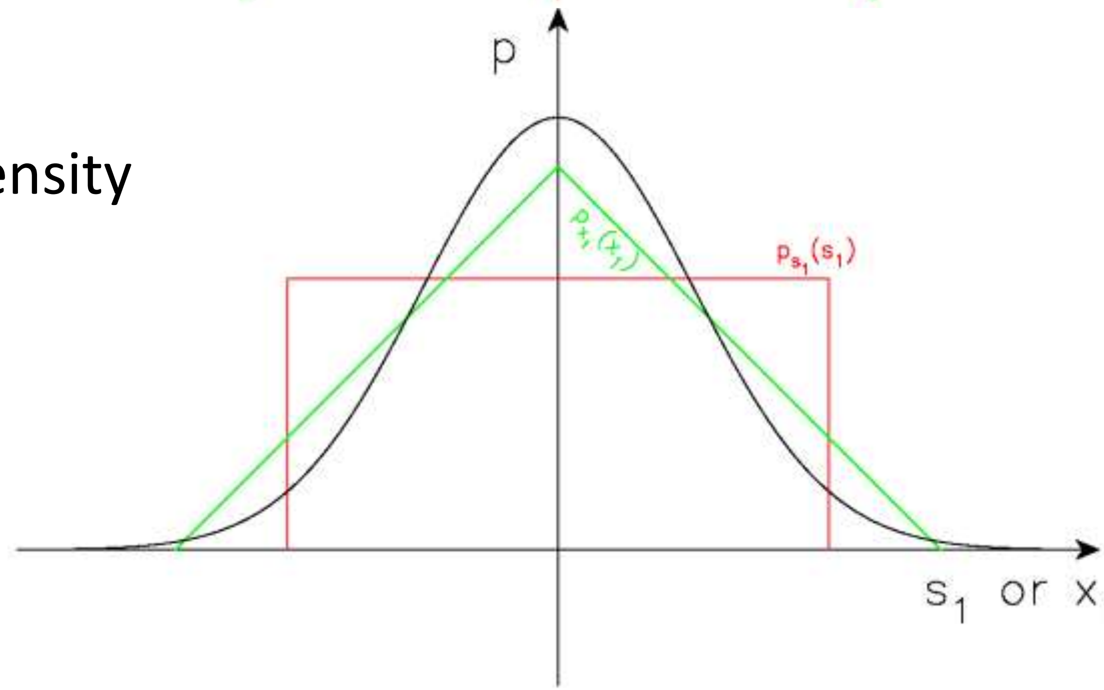
PCA for Geochemical Data



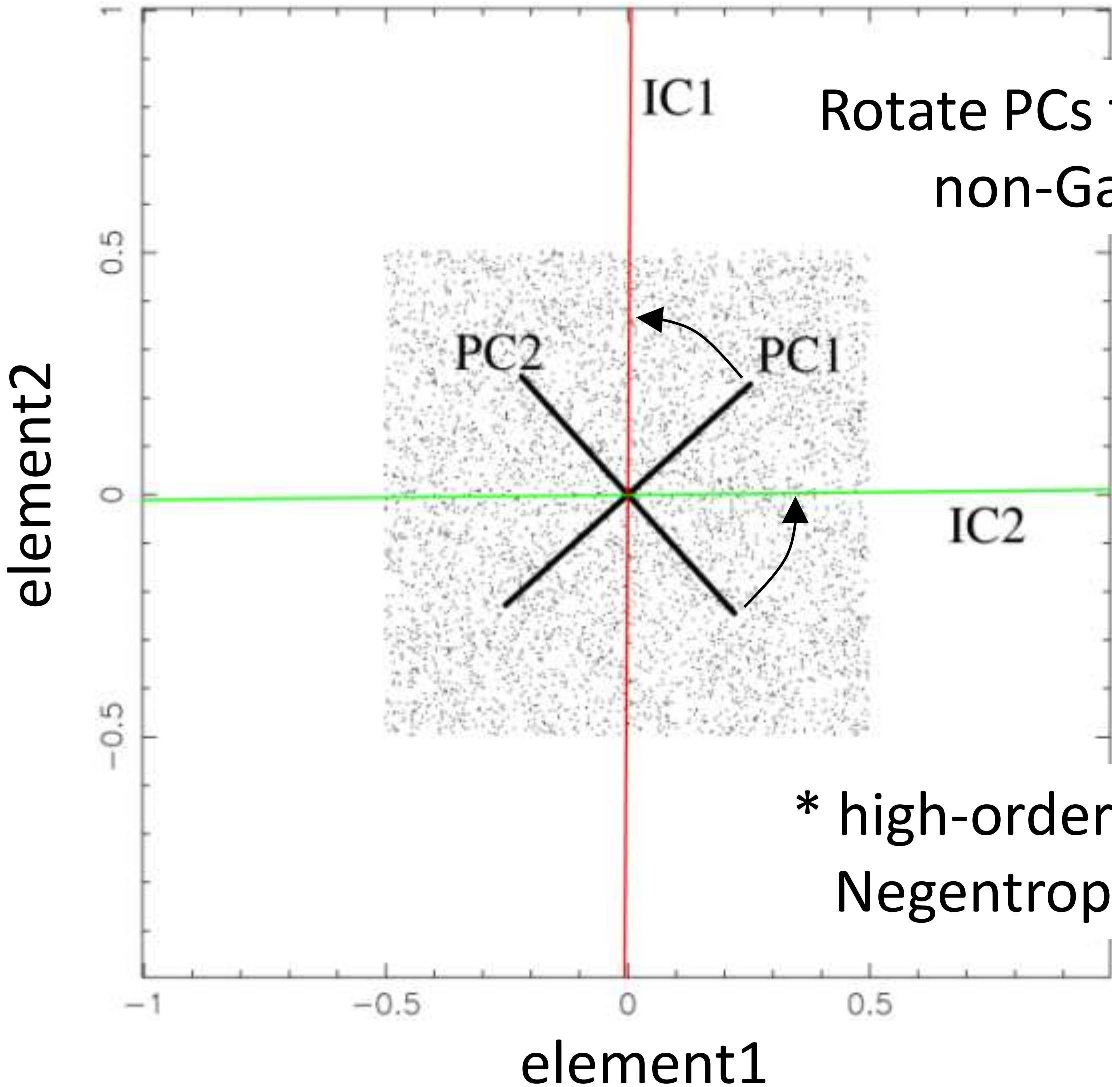
(a) Homogeneous joint distribution of S_1 and S_2



(b) Marginal probability density



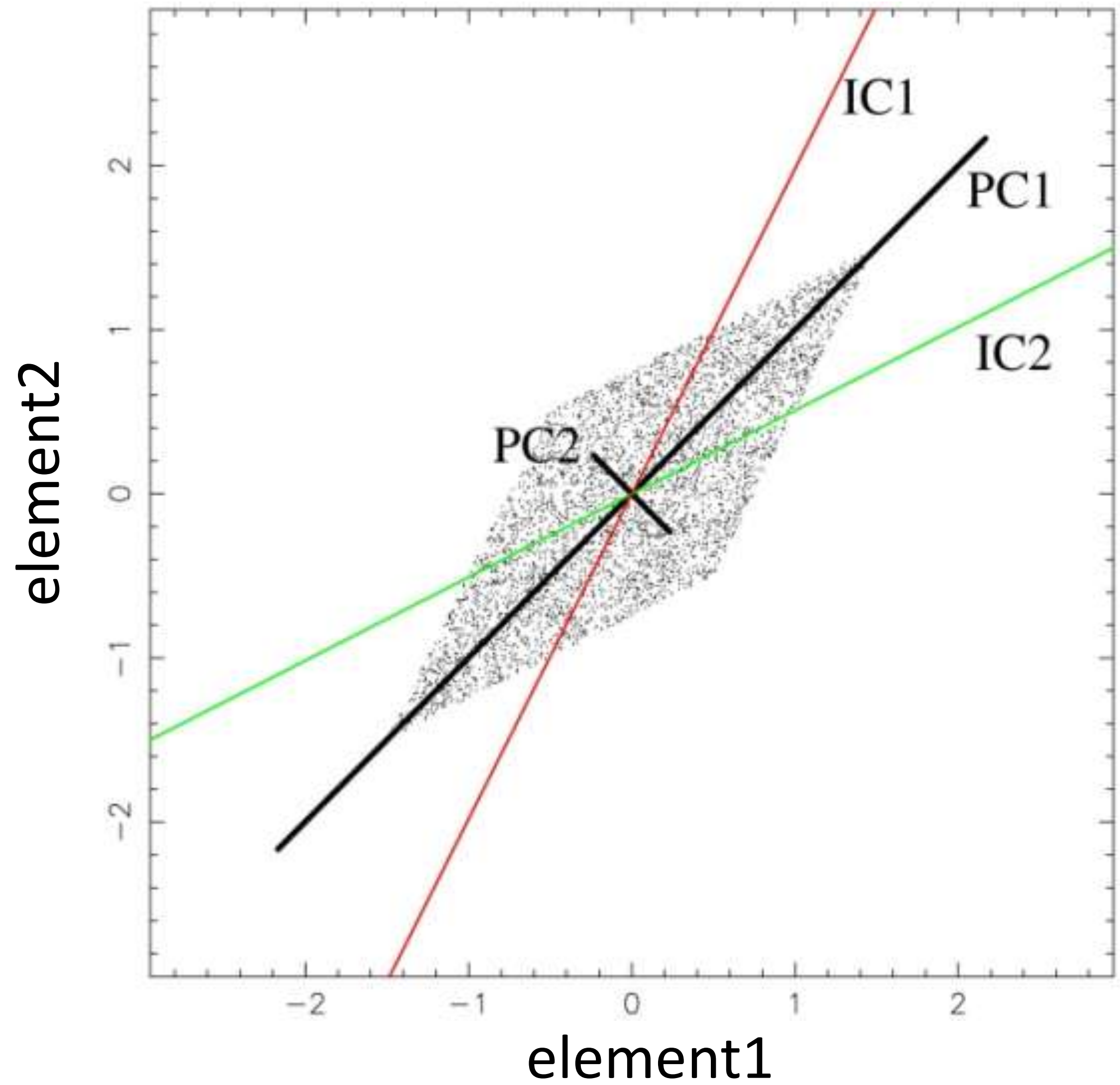
ICA for Geochemical Data



Rotate PCs to maximize
non-Gaussianity*

* high-order moment (> 2)
Negentropy, etc.

ICA for Geochemical Data



Procedure of Independent Component Analysis

[1]: Sphering (Whitening) data matrix ($\mathbf{X}$) using r-eigen values ($\mathbf{S_r}$: diagonal matrix that contains square root of the eigen values) and the eigen vectors ($\mathbf{V_r}$) to obtain the shpered data matrix ($\mathbf{U r}$):

$$\mathrm{U_r} = \mathbf{X V_r S_r^{-1}} \tag{1}$$

[2]: Searching an axis $\mathbf{w_i}$ to maximize non-Gaussianity J_G:

$$J_G(\mathbf{y}) = [E\{G(\mathbf{y})\} - E\{G(\nu)\}]^2 \tag{2}$$

$$G(a) = -\exp\left(\frac{-a^2}{2}\right) \tag{3}$$

$$\mathbf{y} = \mathbf{U_r w_i} \tag{4}$$

where E represents expectation, ν returns a standarized Gaussian distribution.

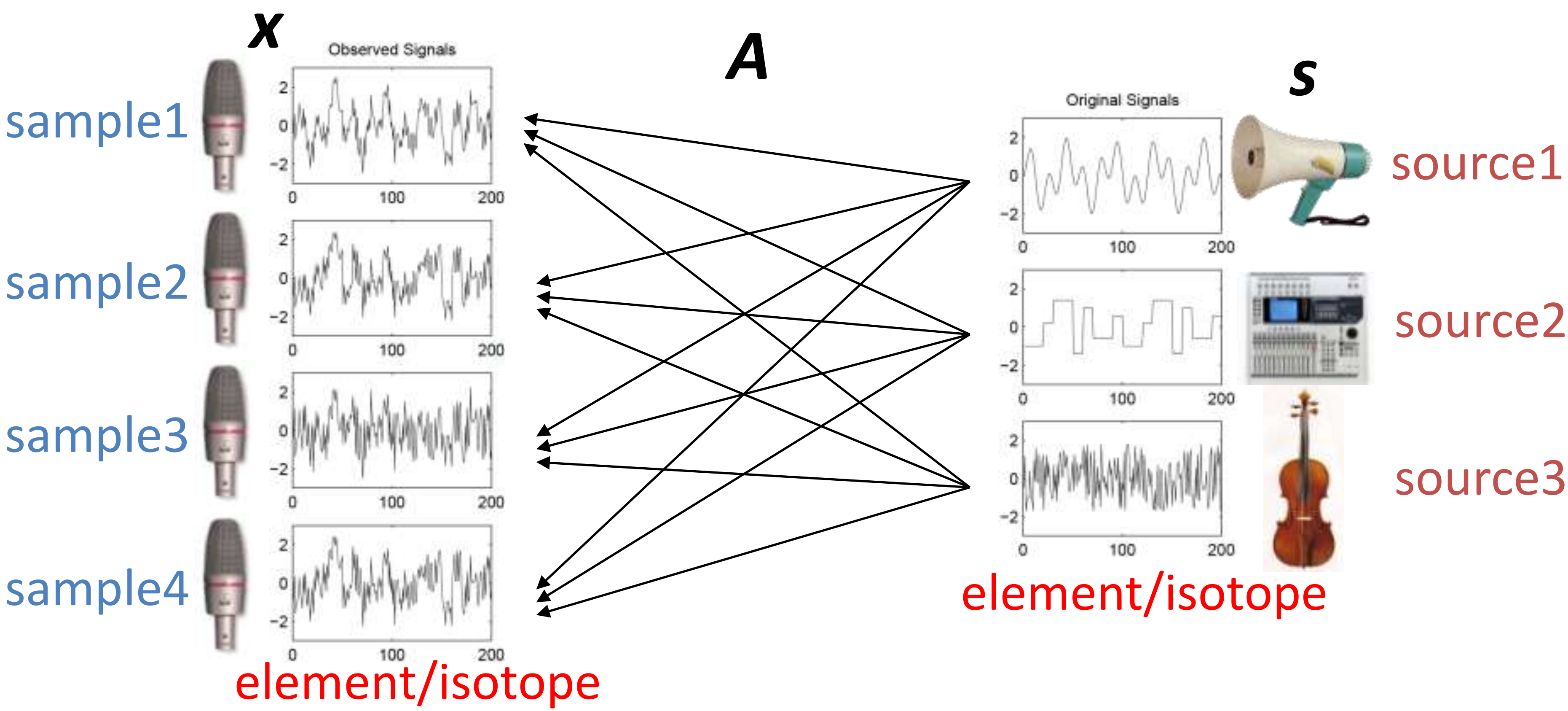
[3]: Finding another $\mathbf{w_{i+1}}$ in the space orthogonal to $\mathbf{w_{1,2,\ldots,i}}$.

$$x = A s$$

x : observed signal vectors

A : mixing matrix

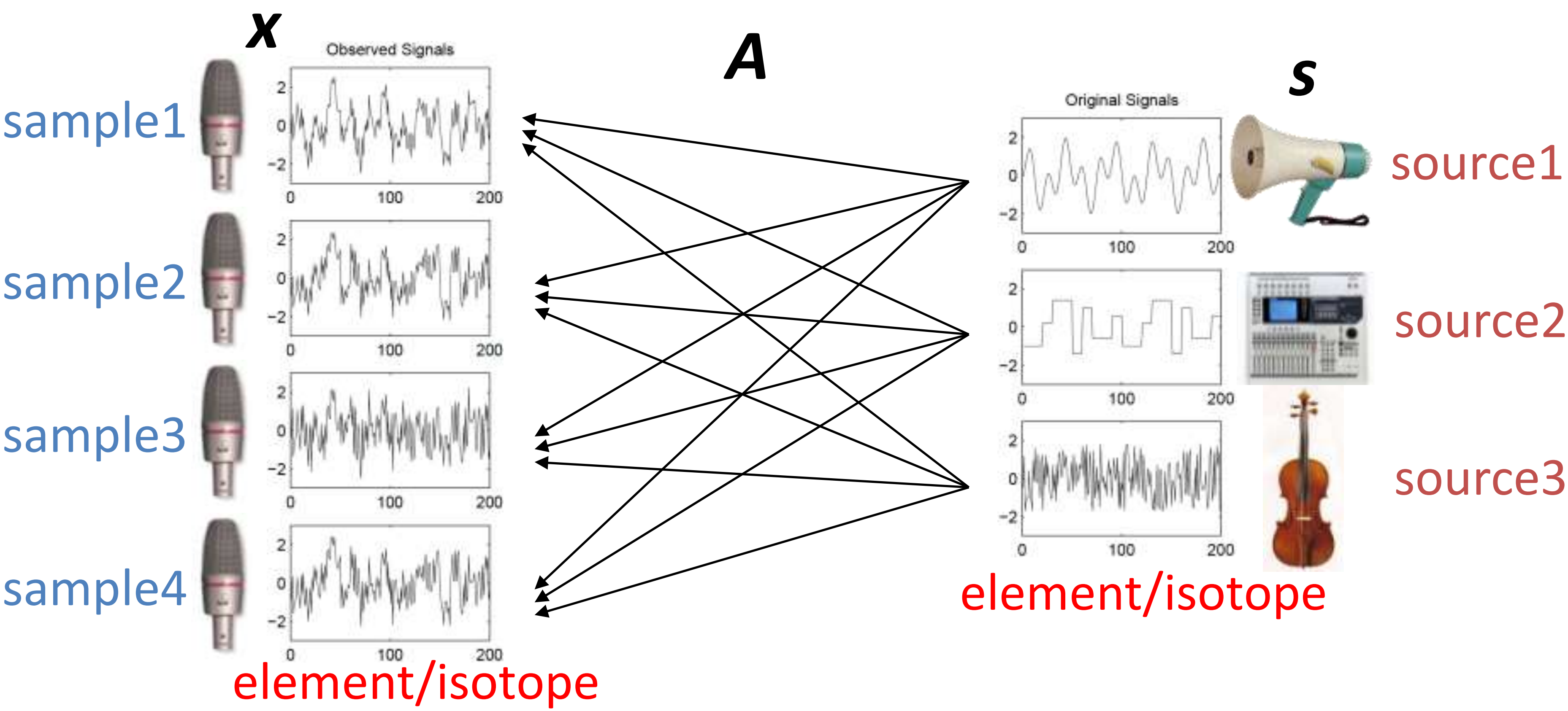
s : source signal vectors

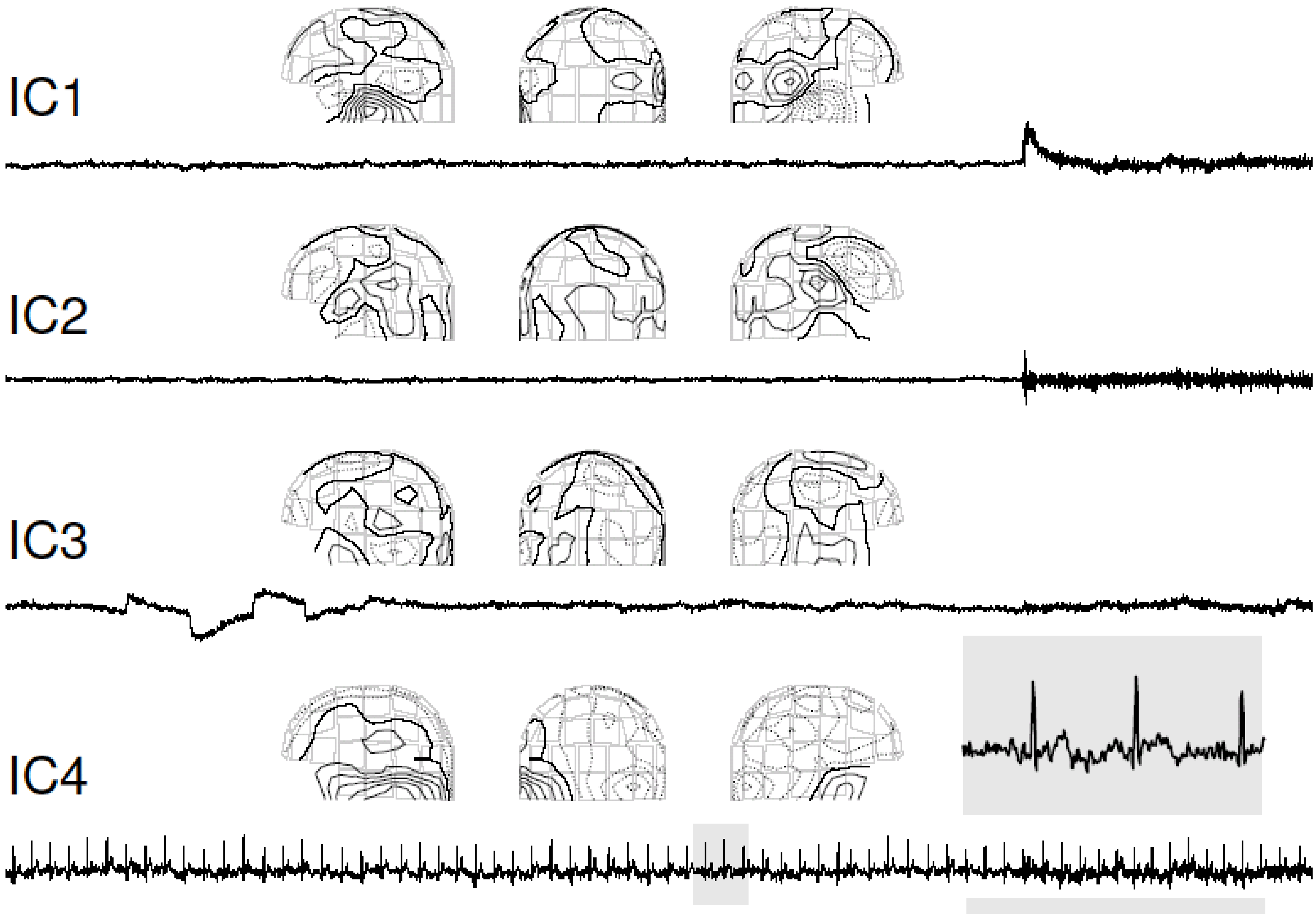


Independent Component Analysis

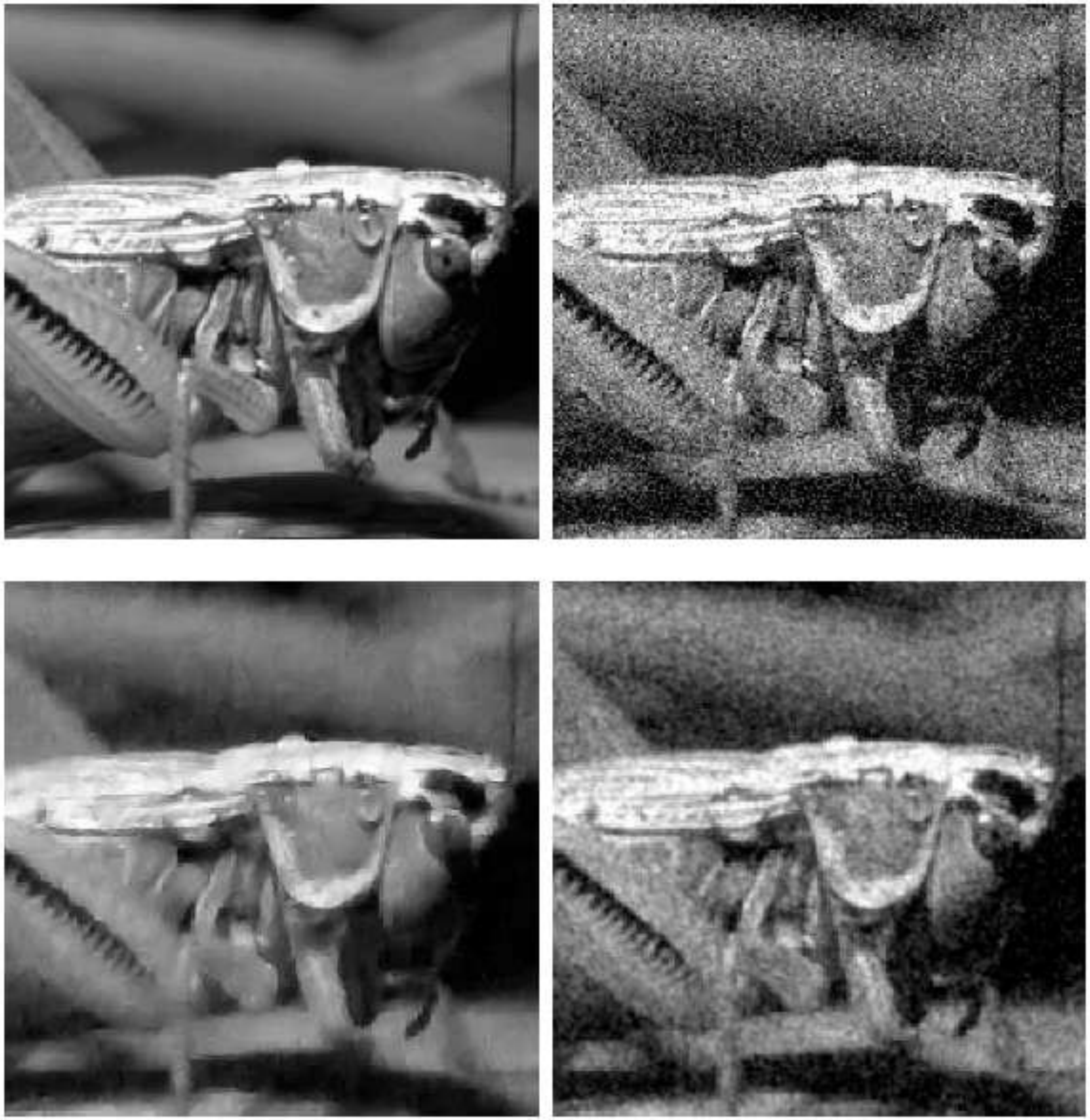
$\boldsymbol{x} \longrightarrow \boldsymbol{A}$ and $\boldsymbol{s}$

(blind source separation, cocktail party problem)





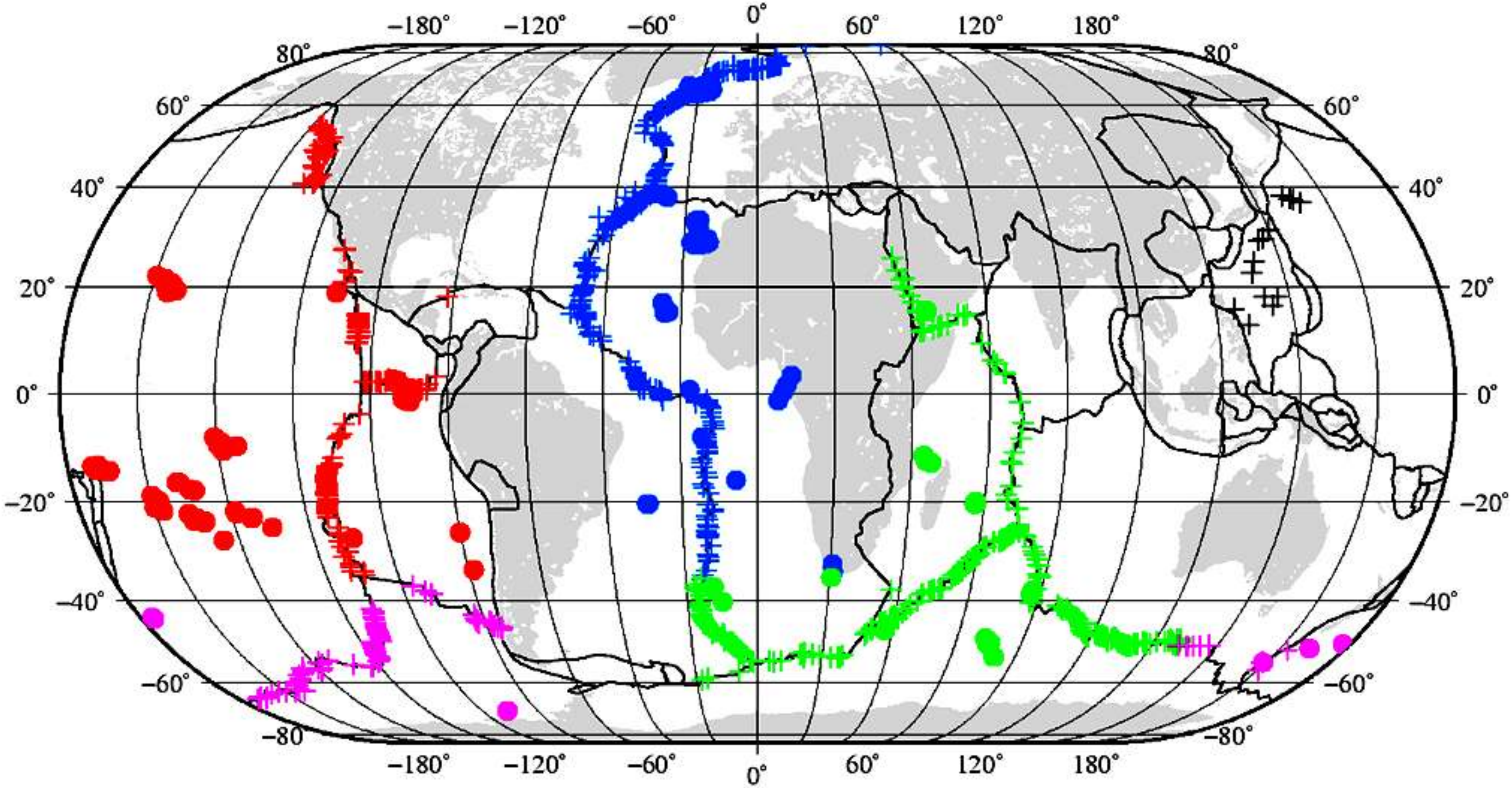
Vigario et al. (1998)



Hyvarinen (1999)

Oceanic Basalts 4308 data

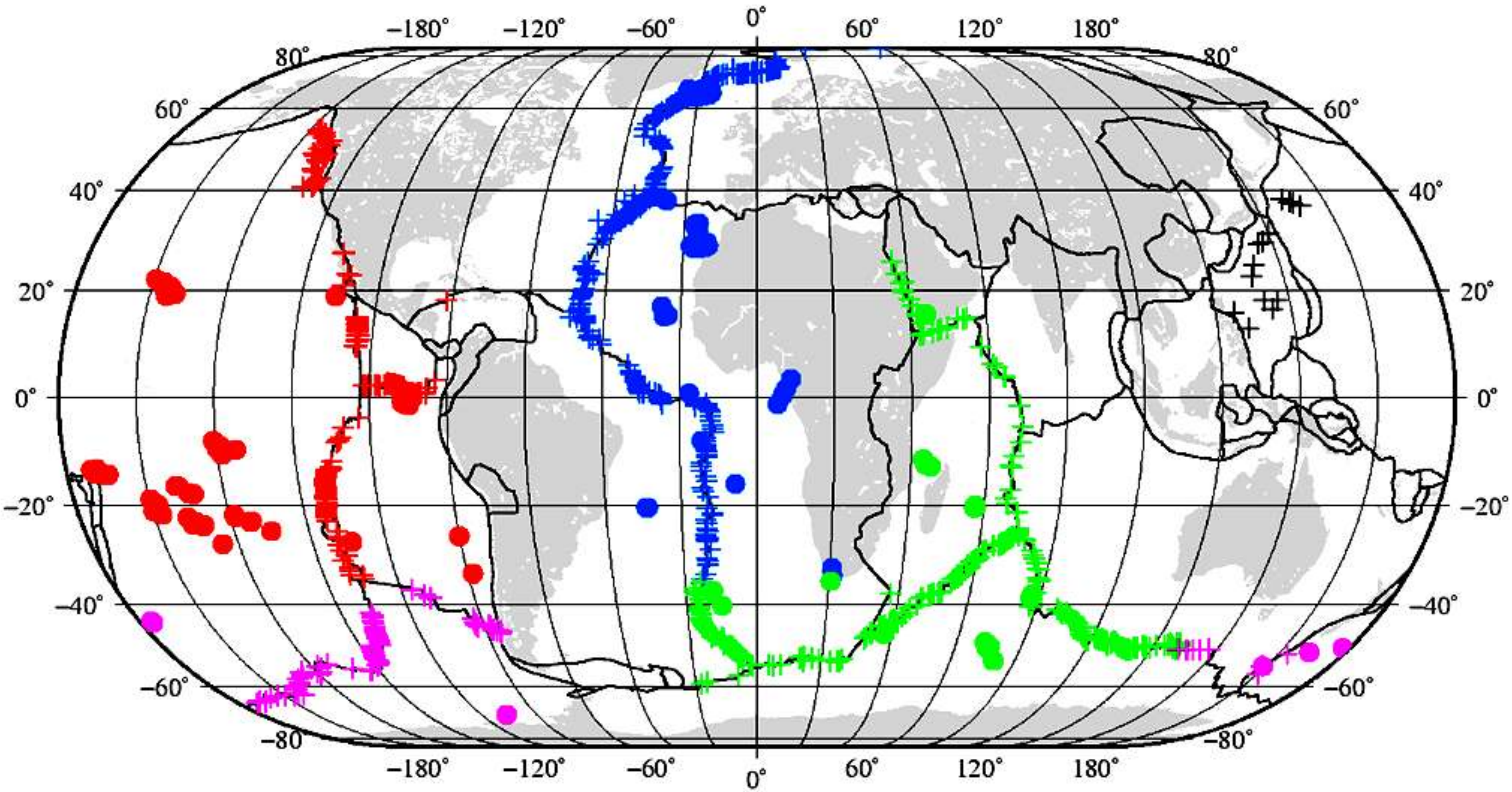
Sr(-Rb), Nd(-Sm), Pb(-U-Th) 5 isotopic ratios

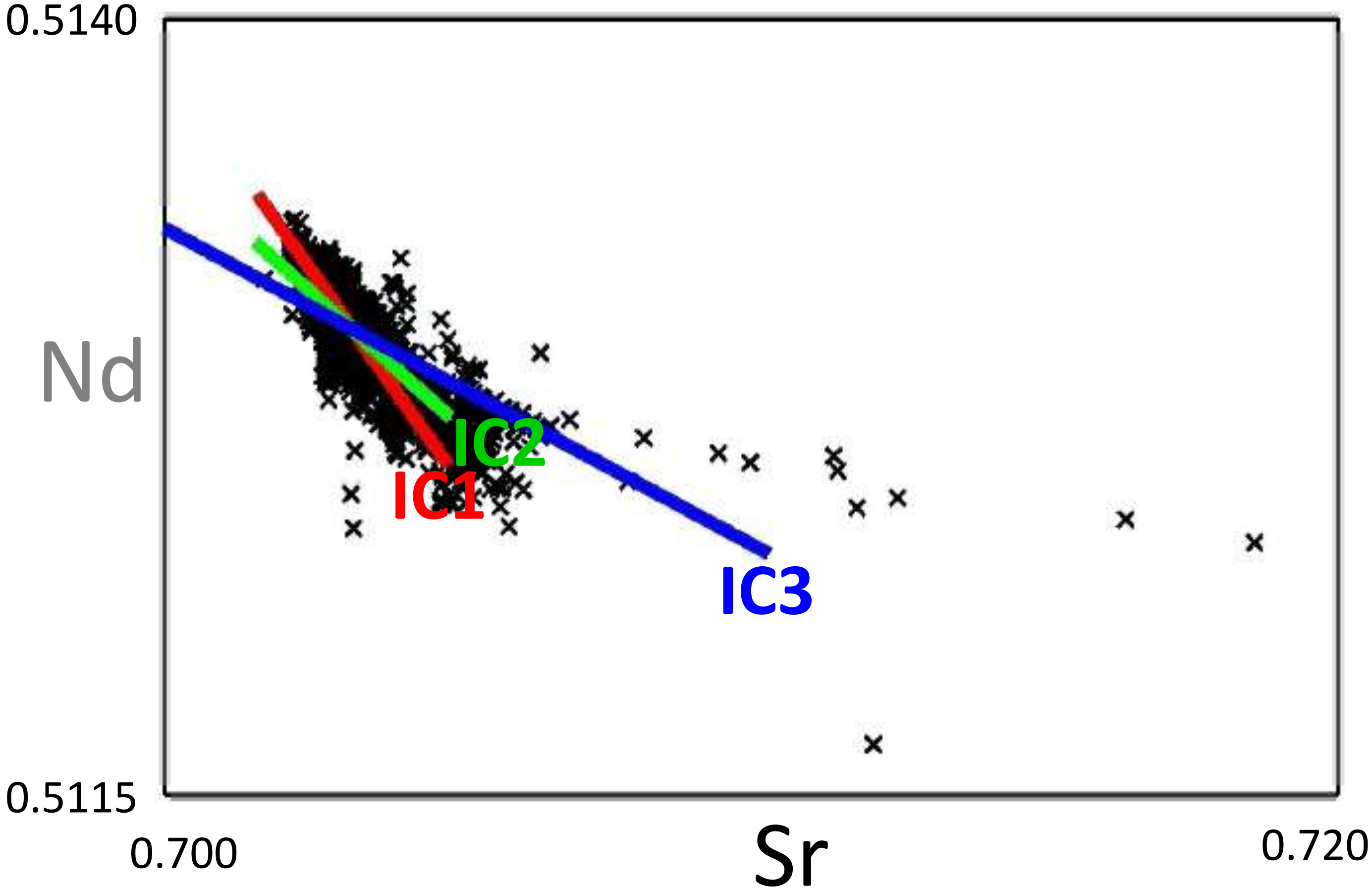


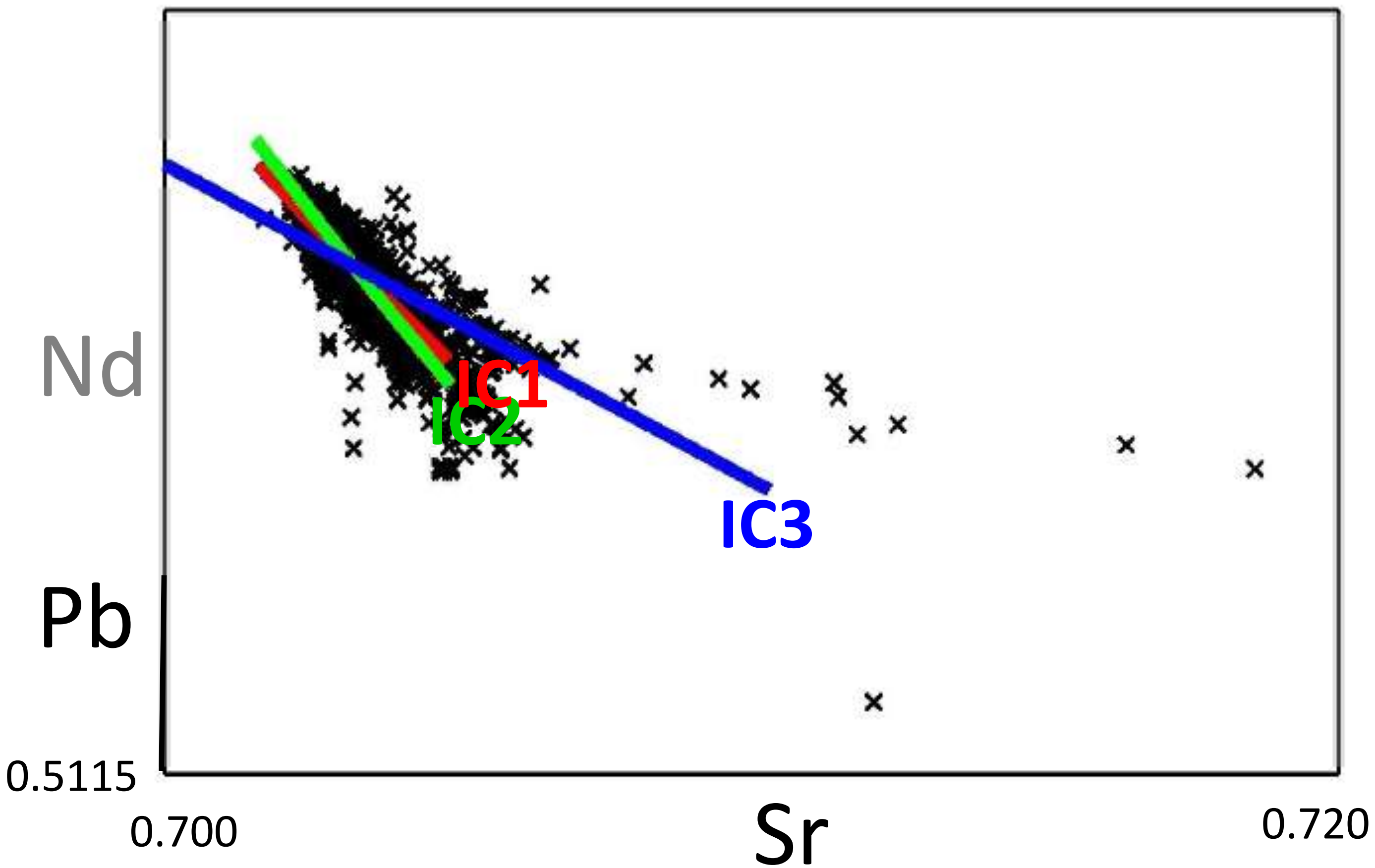
Oceanic Basalts 4308 data

Sr(-Rb), Nd(-Sm), Pb(-U-Th) 5 isotopic ratios

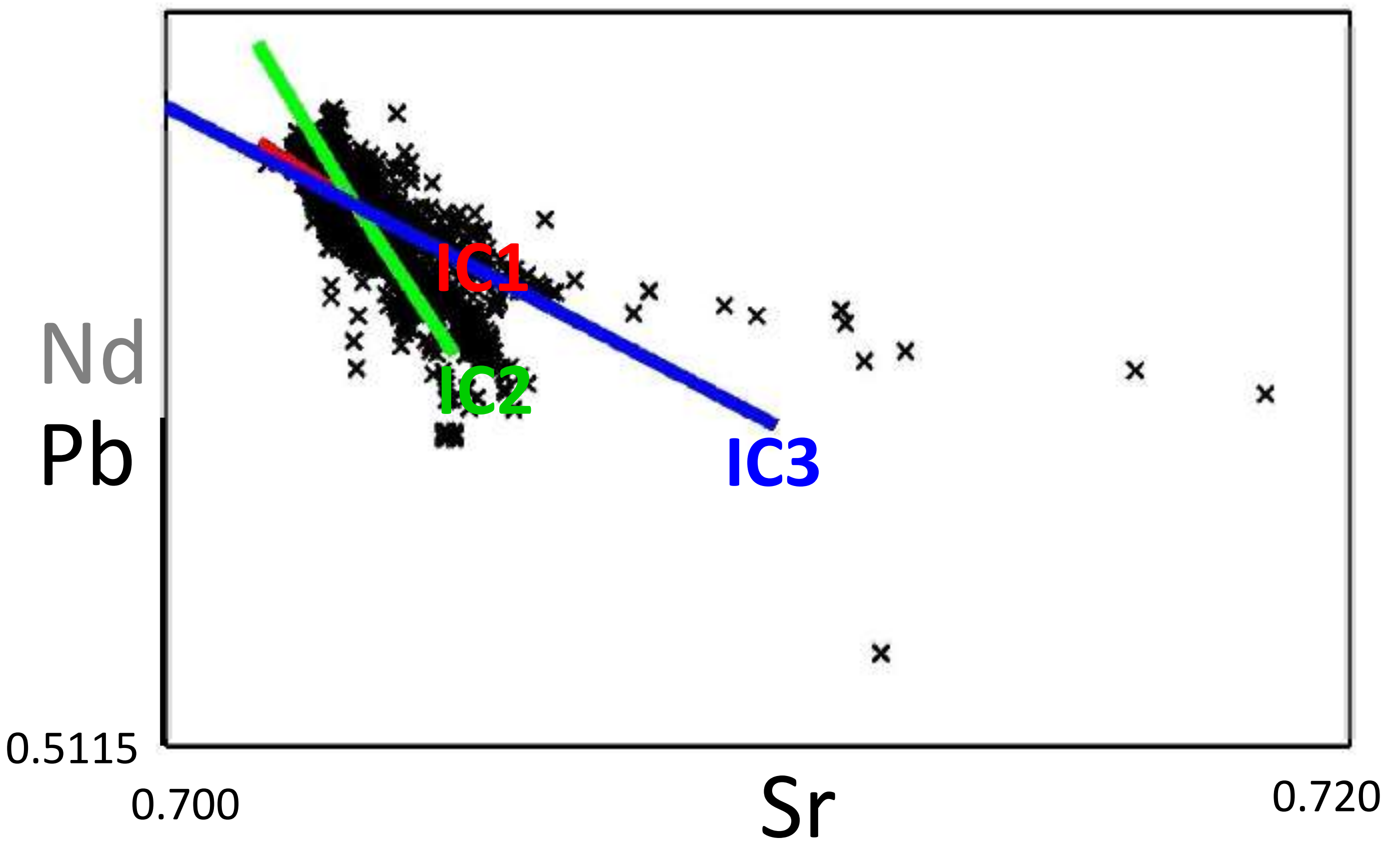
Only 3 (possibly 2) independent components



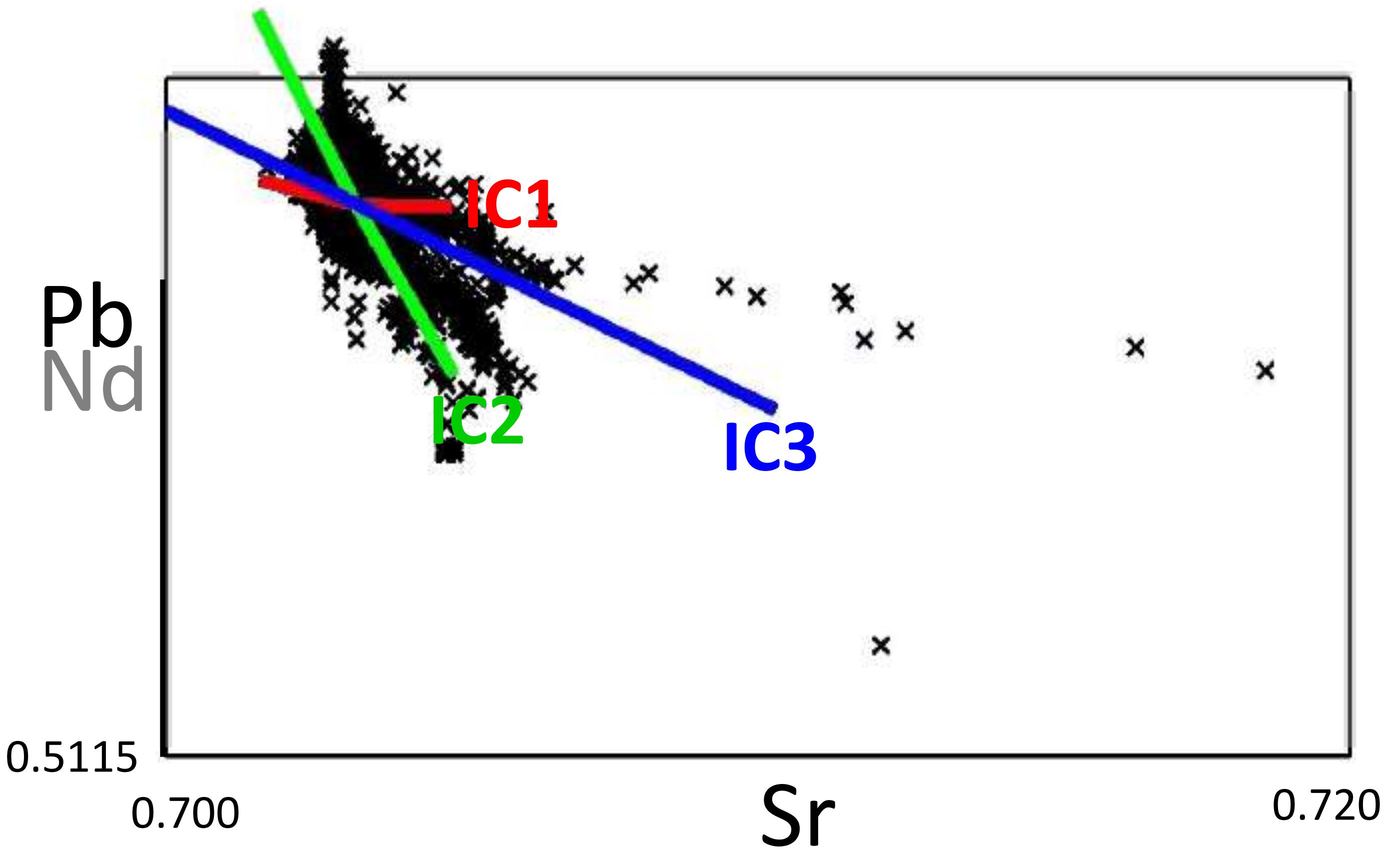

0.5140
Nd
0.5115
0.700
Sr
0.720
IC1
IC2
IC3

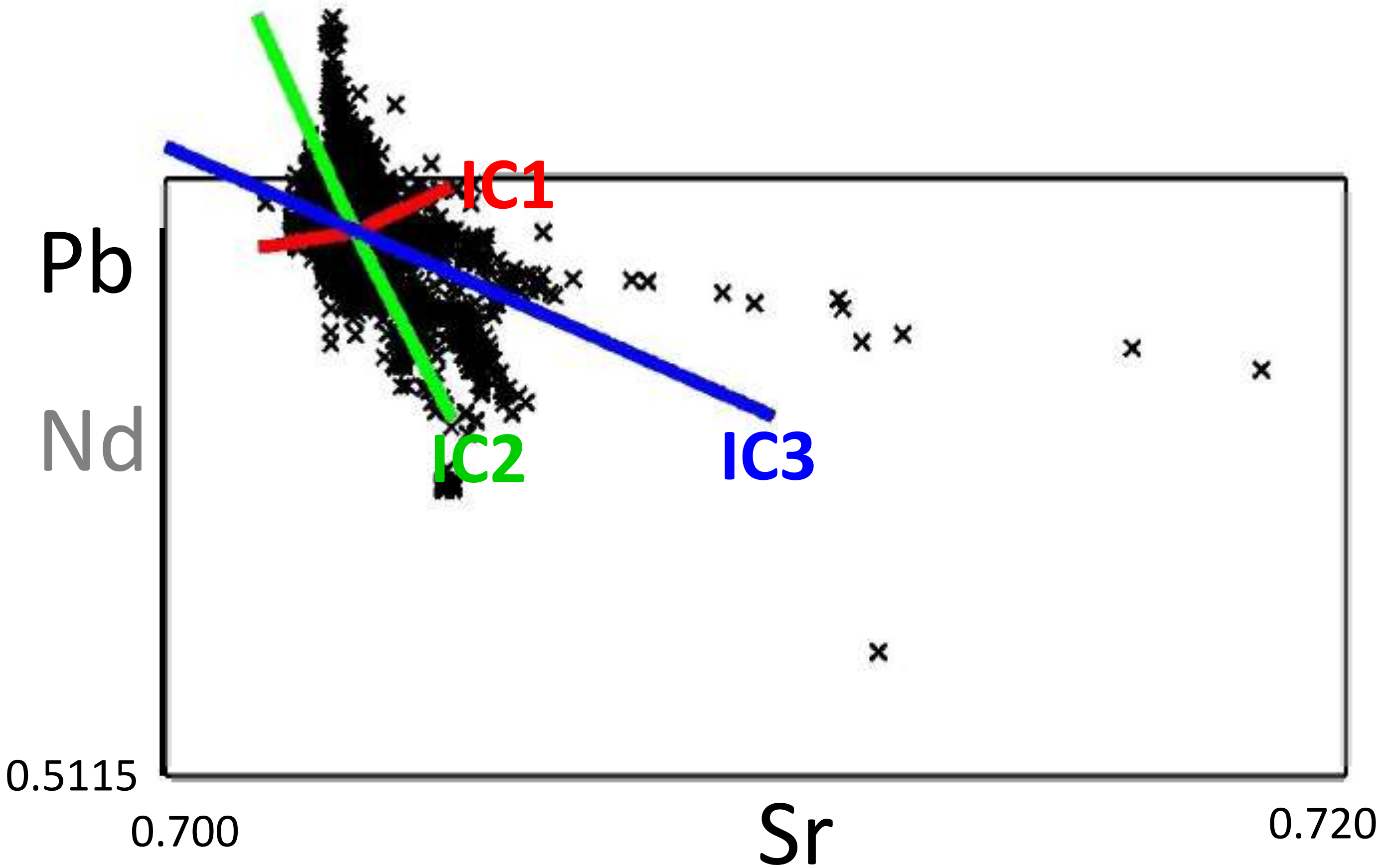


Nd
IC1
IC2
IC3
Pb
0.5115
0.700
Sr
0.720

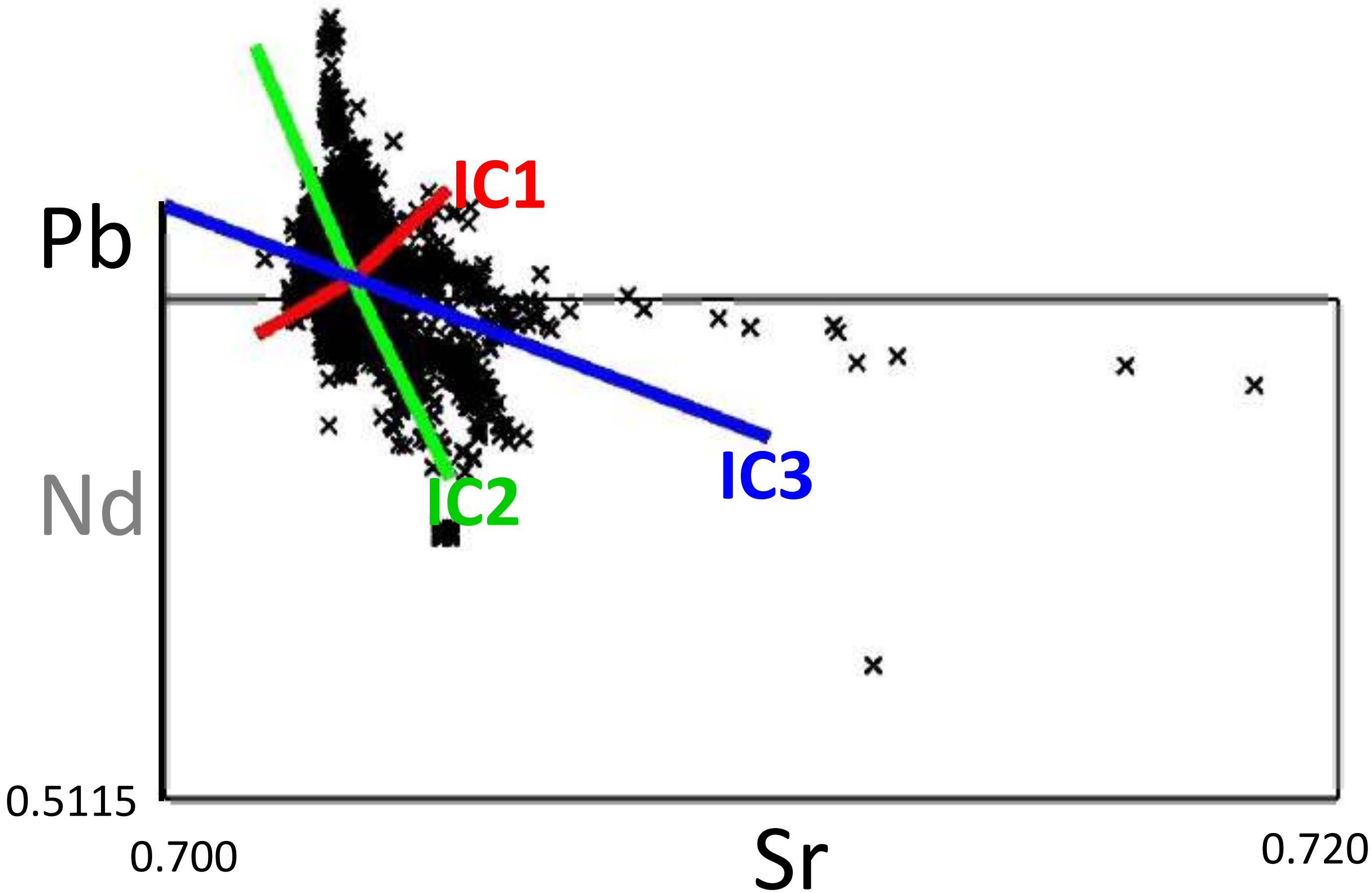


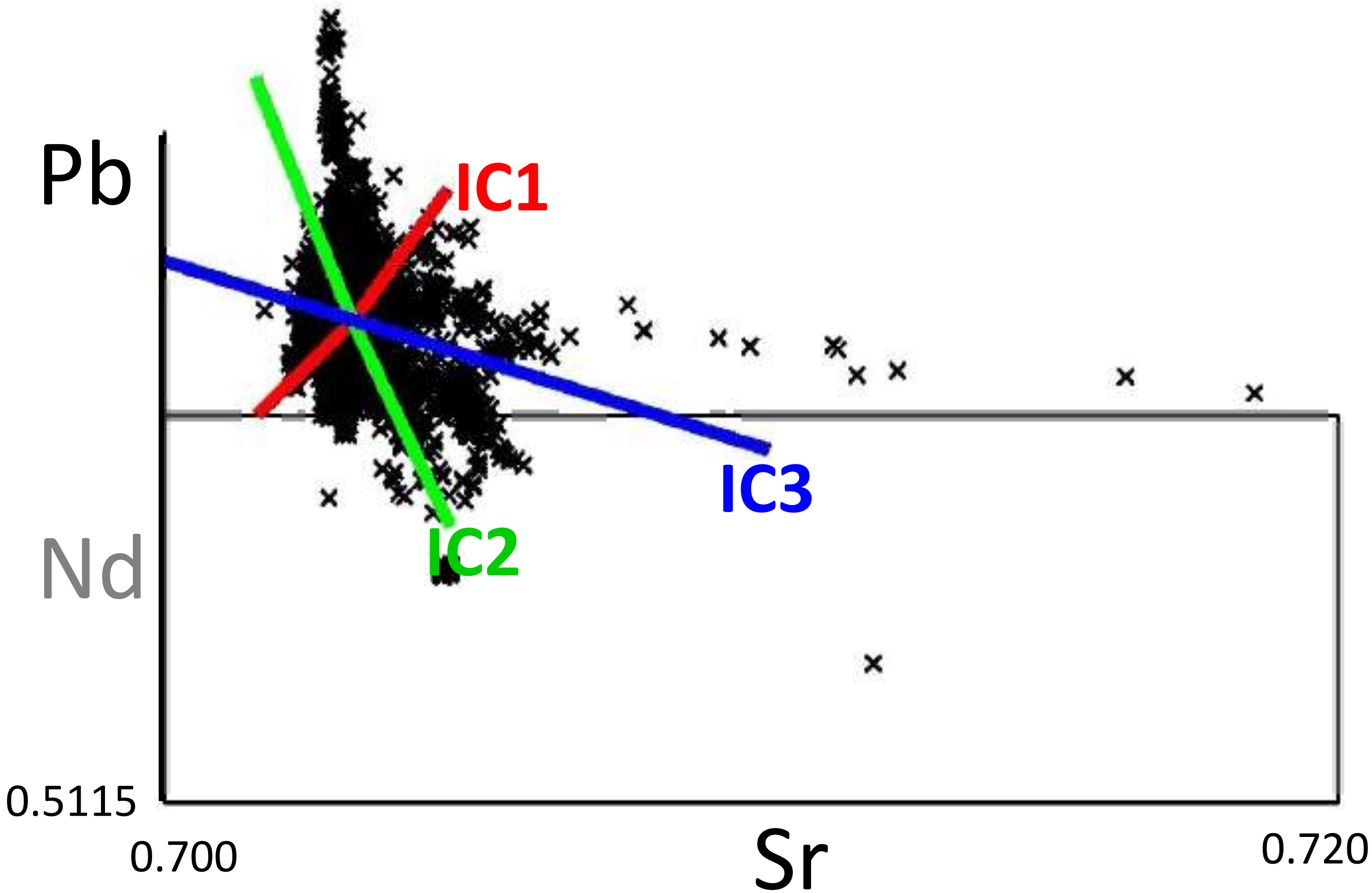
Nd
Pb
0.5115
0.700
Sr
0.720
IC1
IC2
IC3

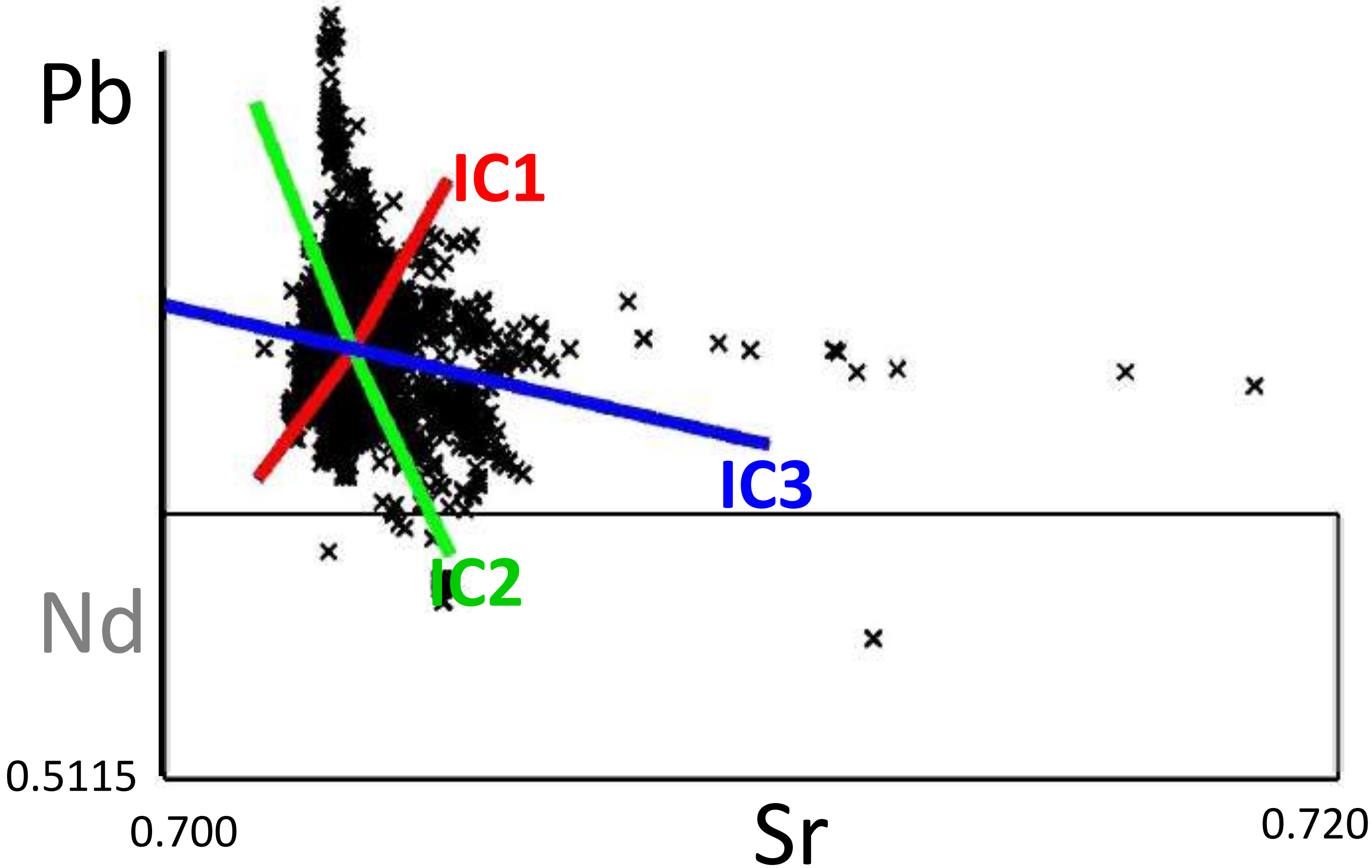

IC1
IC2
IC3
Pb
Nd
0.5115
0.700
Sr
0.720

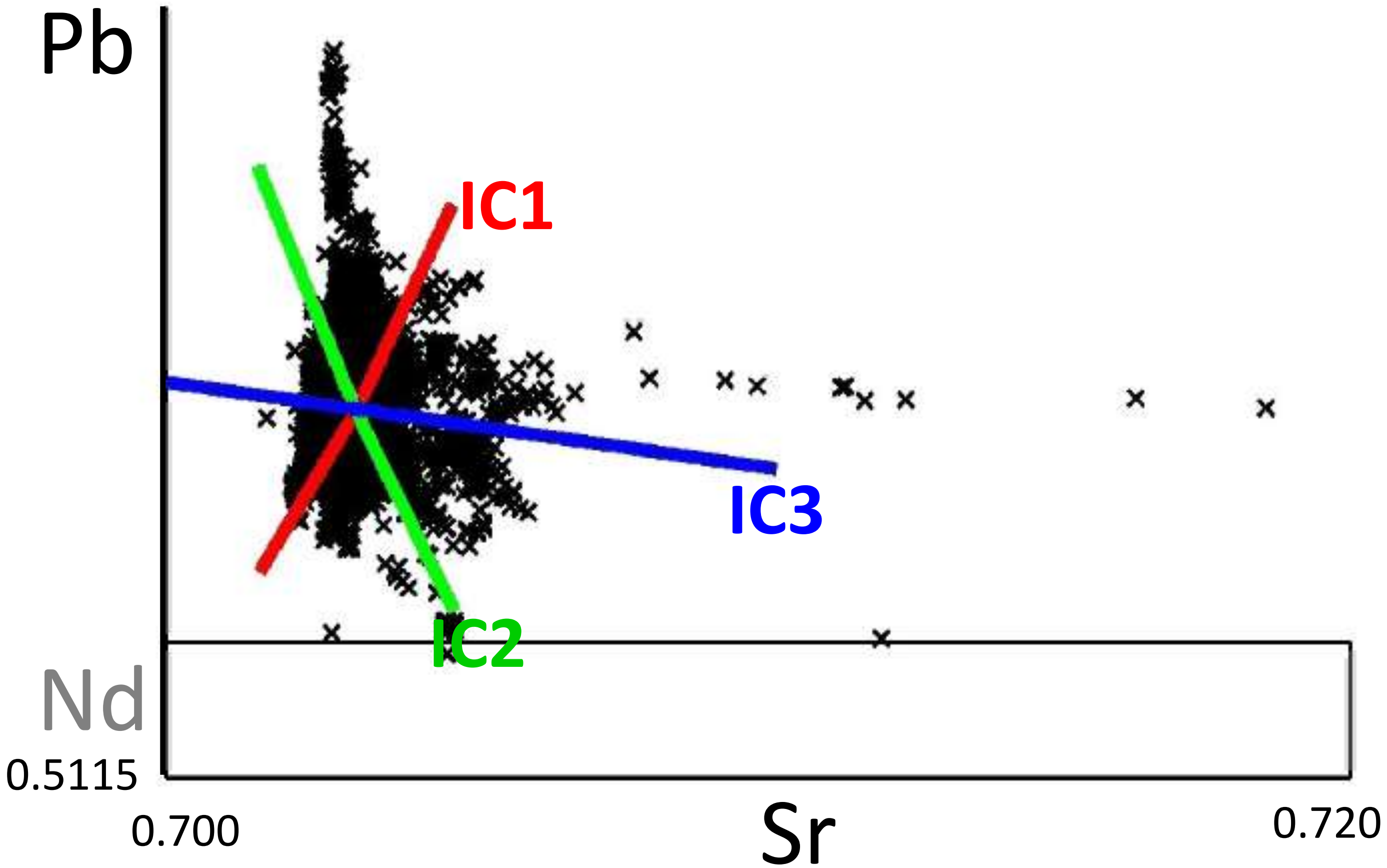


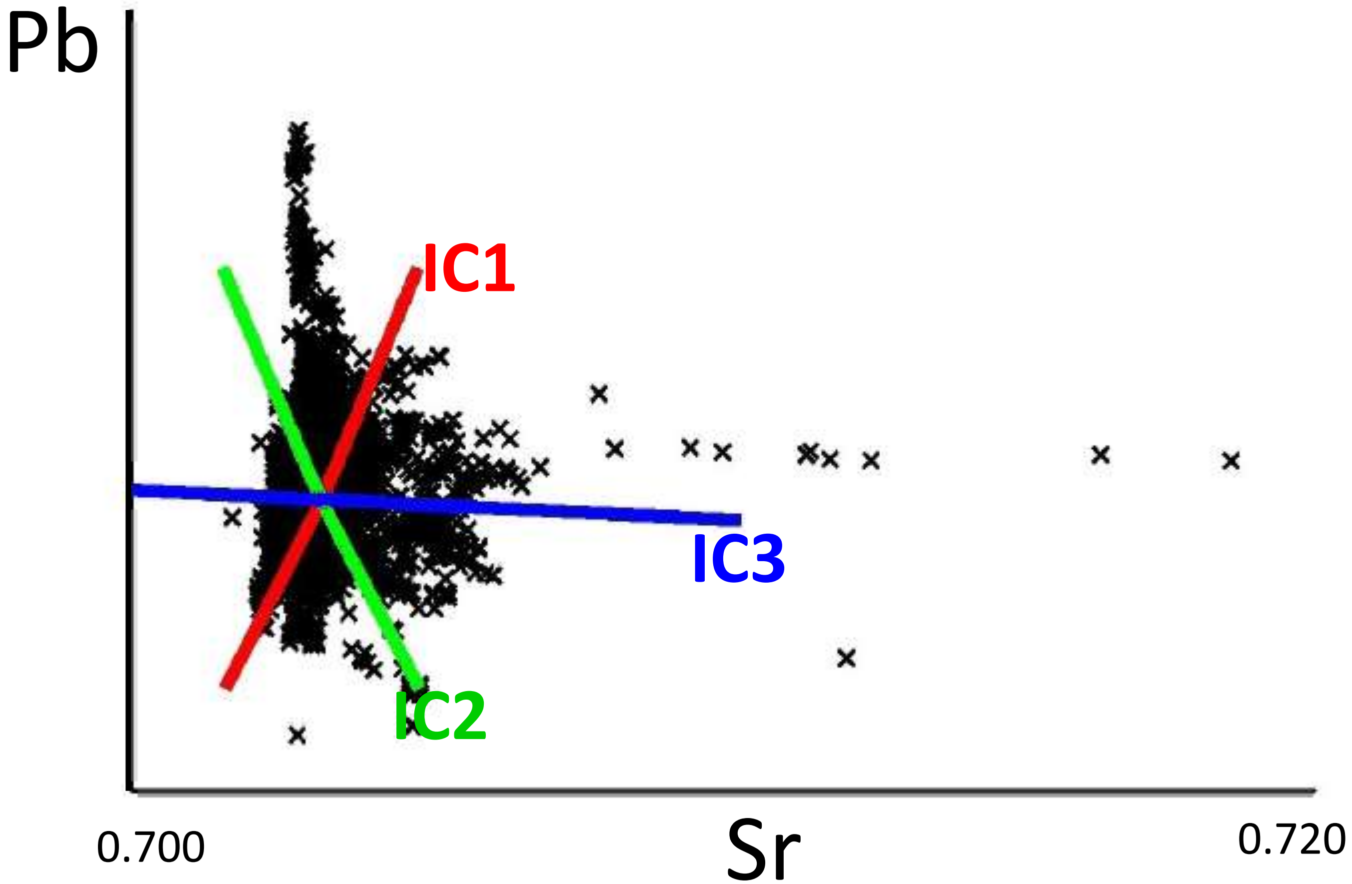
IC1
Pb
Nd
IC2
IC3
0.5115
0.700
Sr
0.720

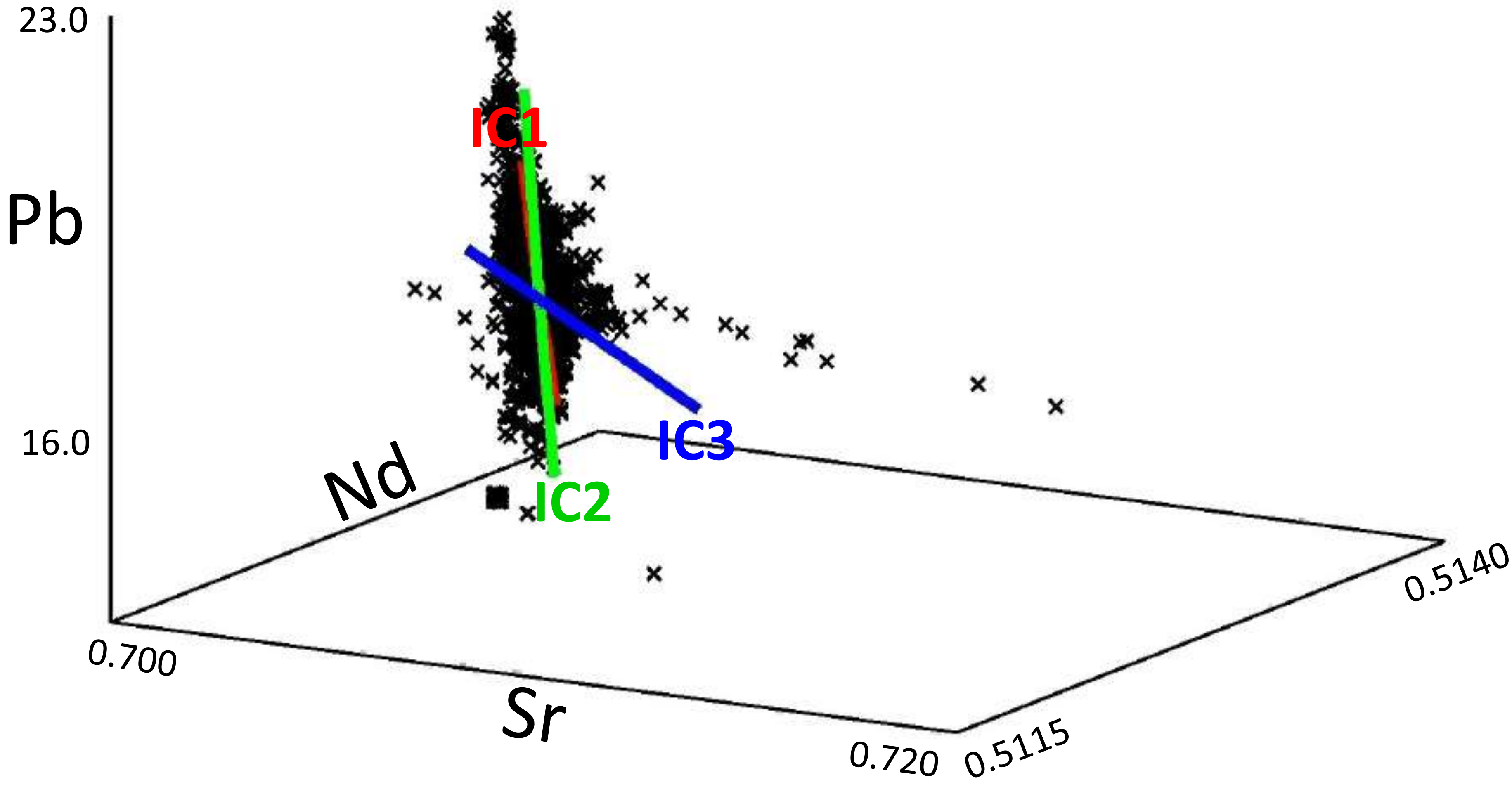

IC1
Pb
IC2
IC3
Nd
0.5115
0.700
Sr
0.720


Pb
IC1
IC2
IC3
Nd
0.5115
0.700
Sr
0.720

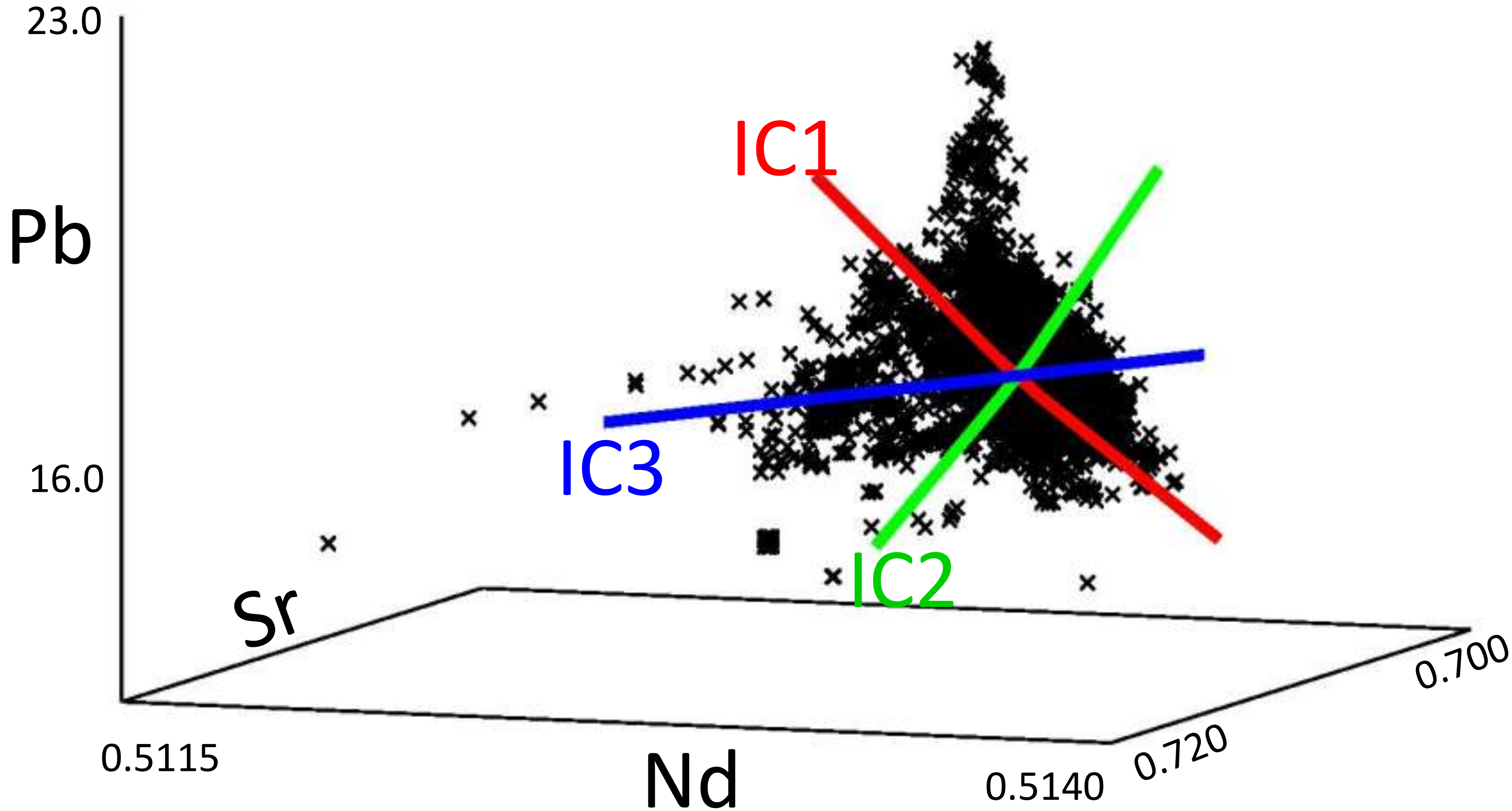

Pb
IC1
IC3
IC2
Nd
0.5115
0.700
Sr
0.720


Pb
IC1
IC3
IC2
Nd
0.5115
0.700
Sr
0.720

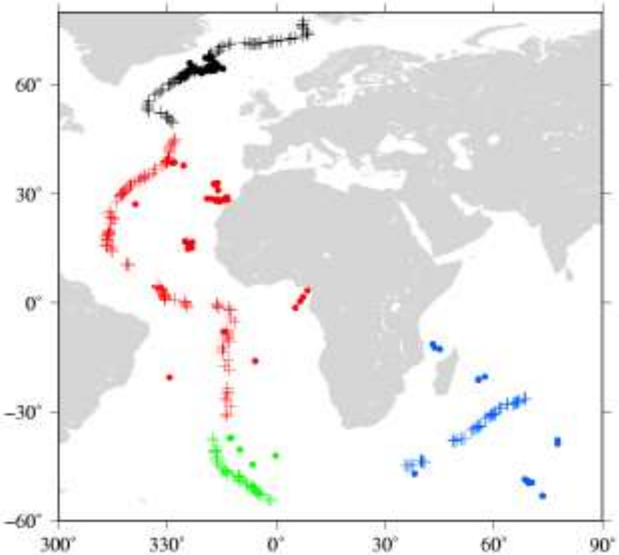

Pb
IC1
IC2
IC3
0.700
Sr
0.720

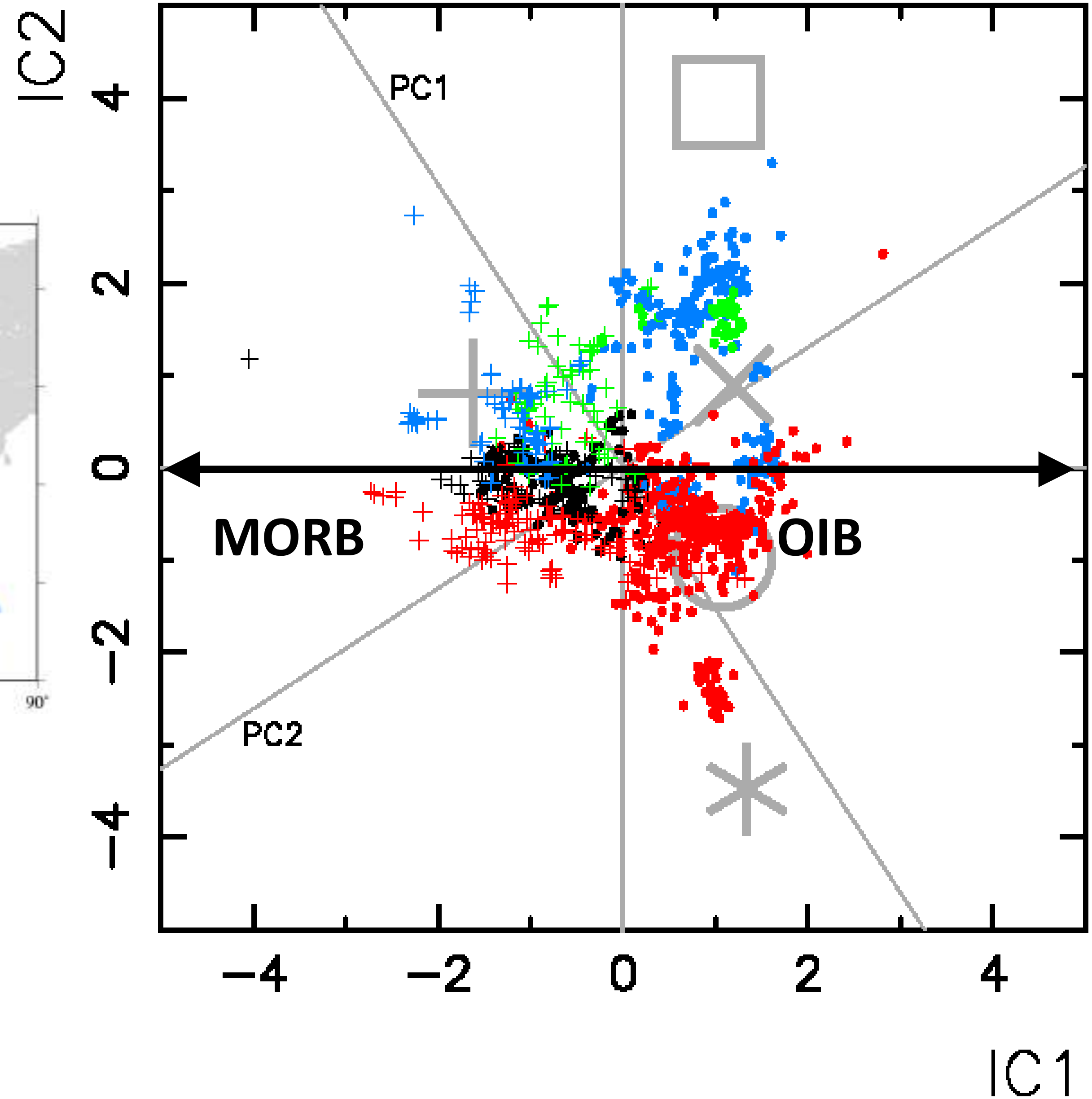


23.0
16.0
Pb
IC1
IC3
IC2
Nd
0.700
Sr
0.720
0.5115
0.5140

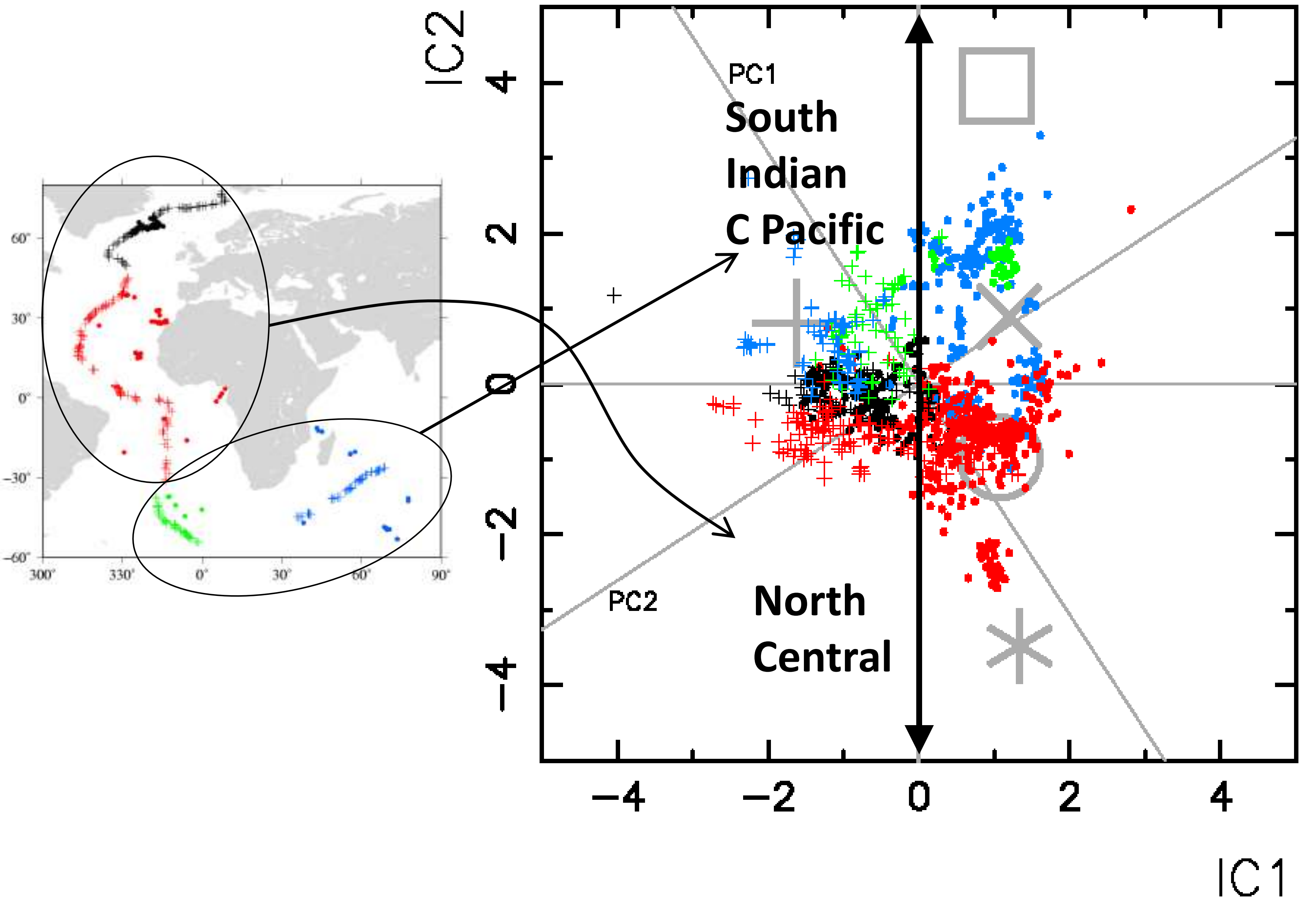


23.0
Pb
16.0
IC1
IC2
IC3
Sr
Nd
0.5115
0.5140
0.720
0.700





Iwamori and Albarede (2008)



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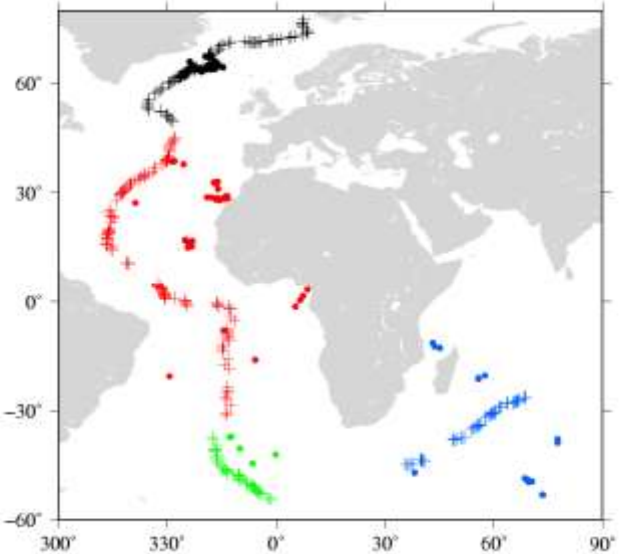
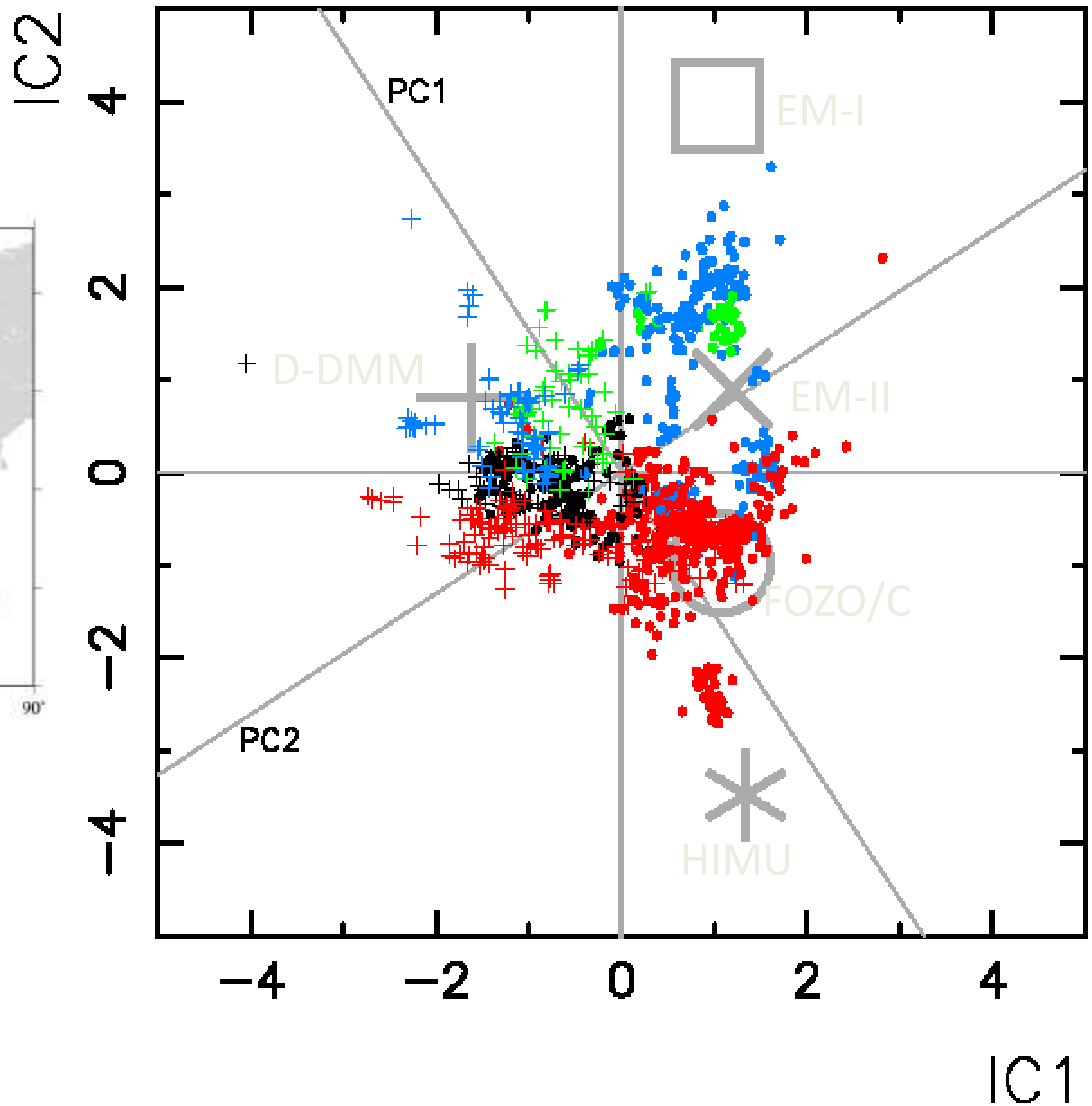
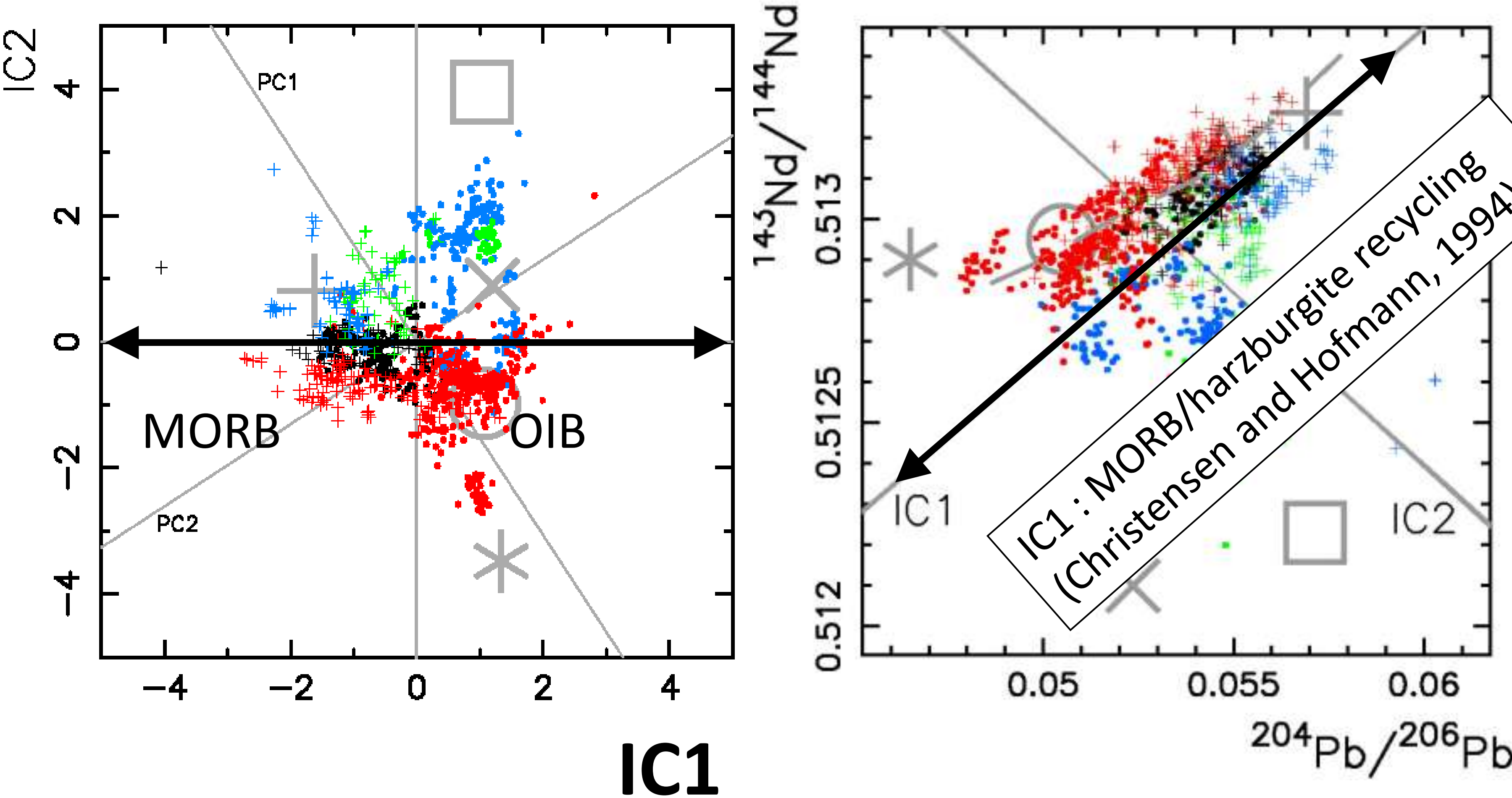
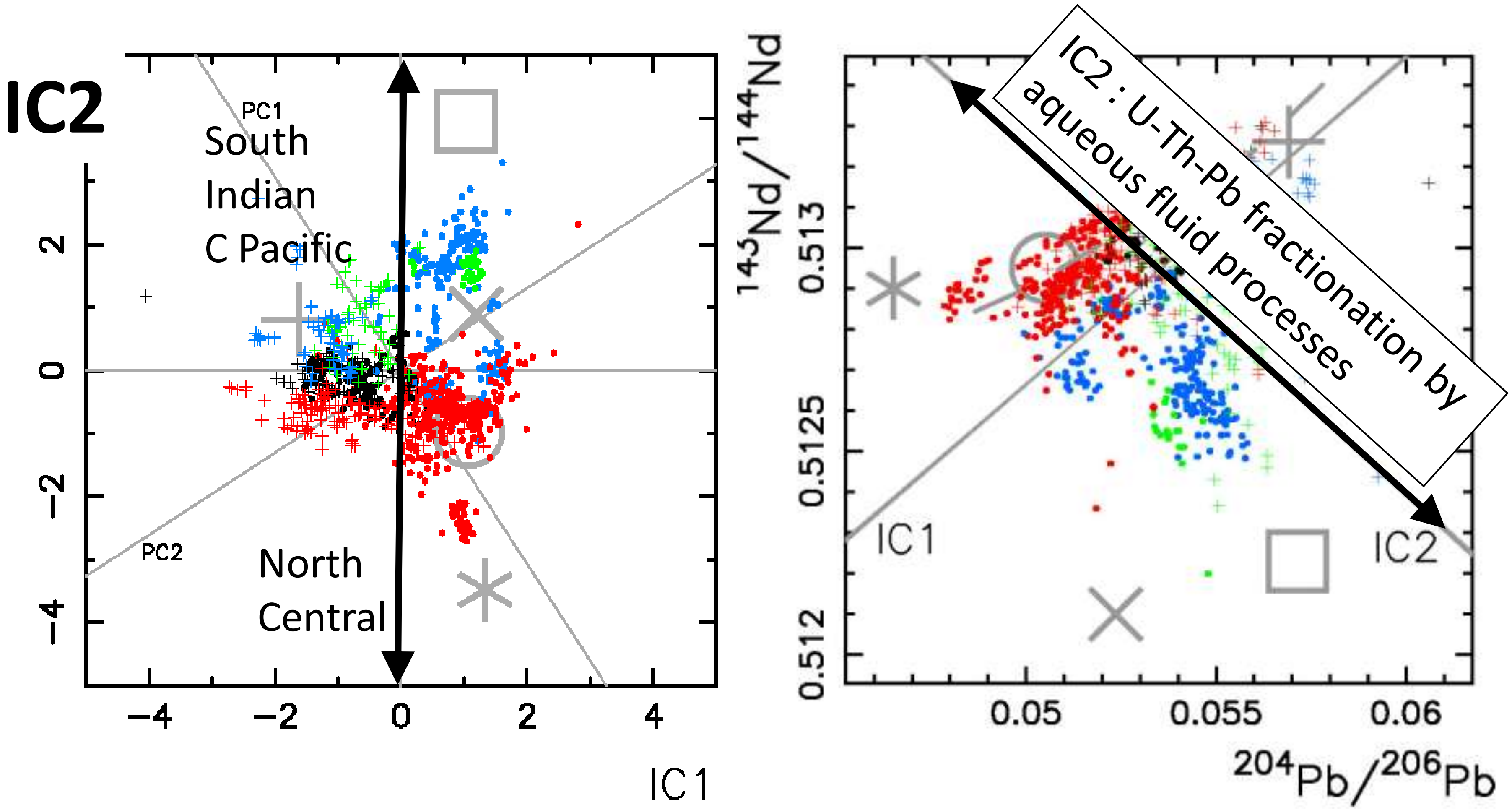




Iwamori and Albarede (2008)



Iwamori and Albarede (2008)



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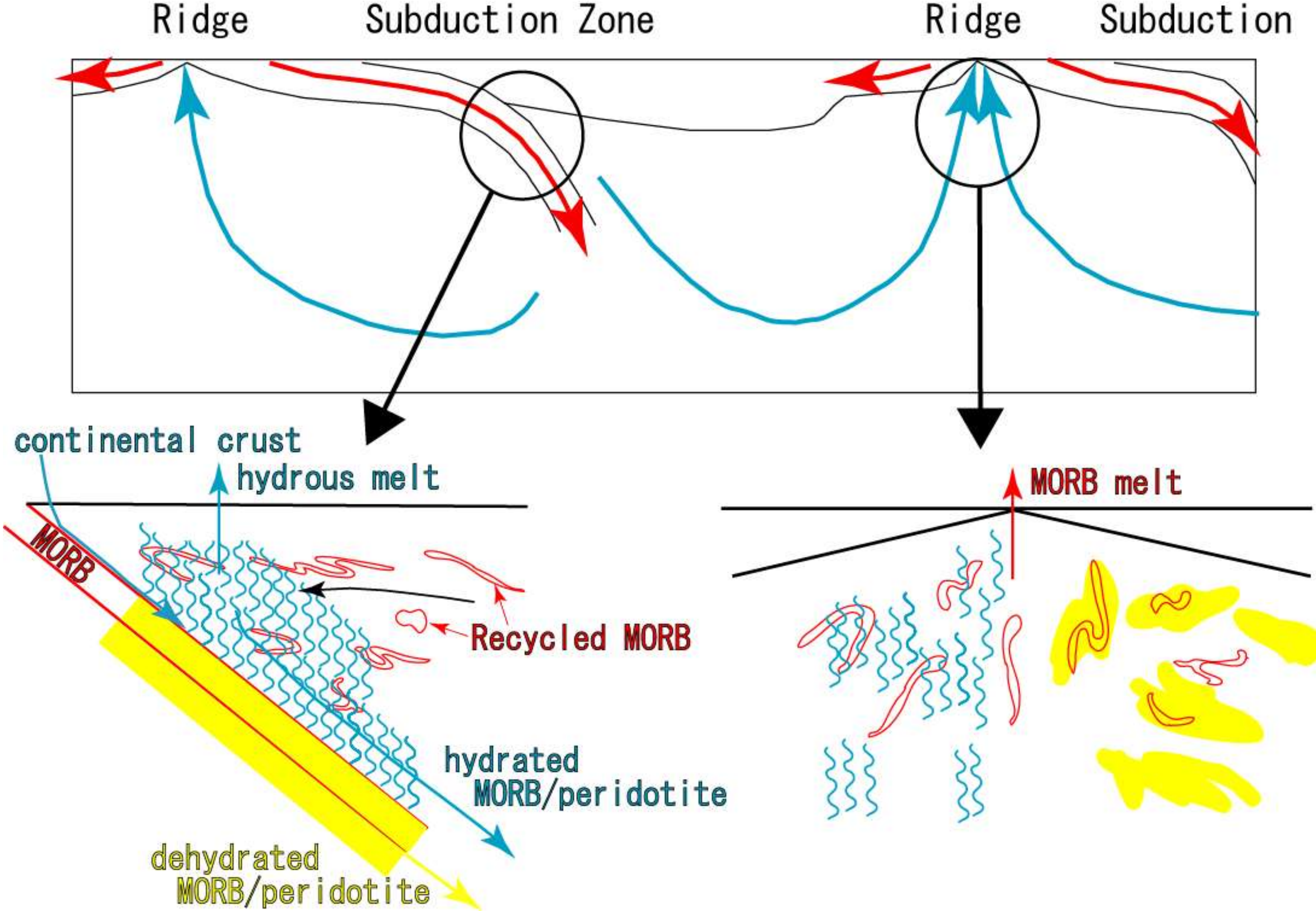
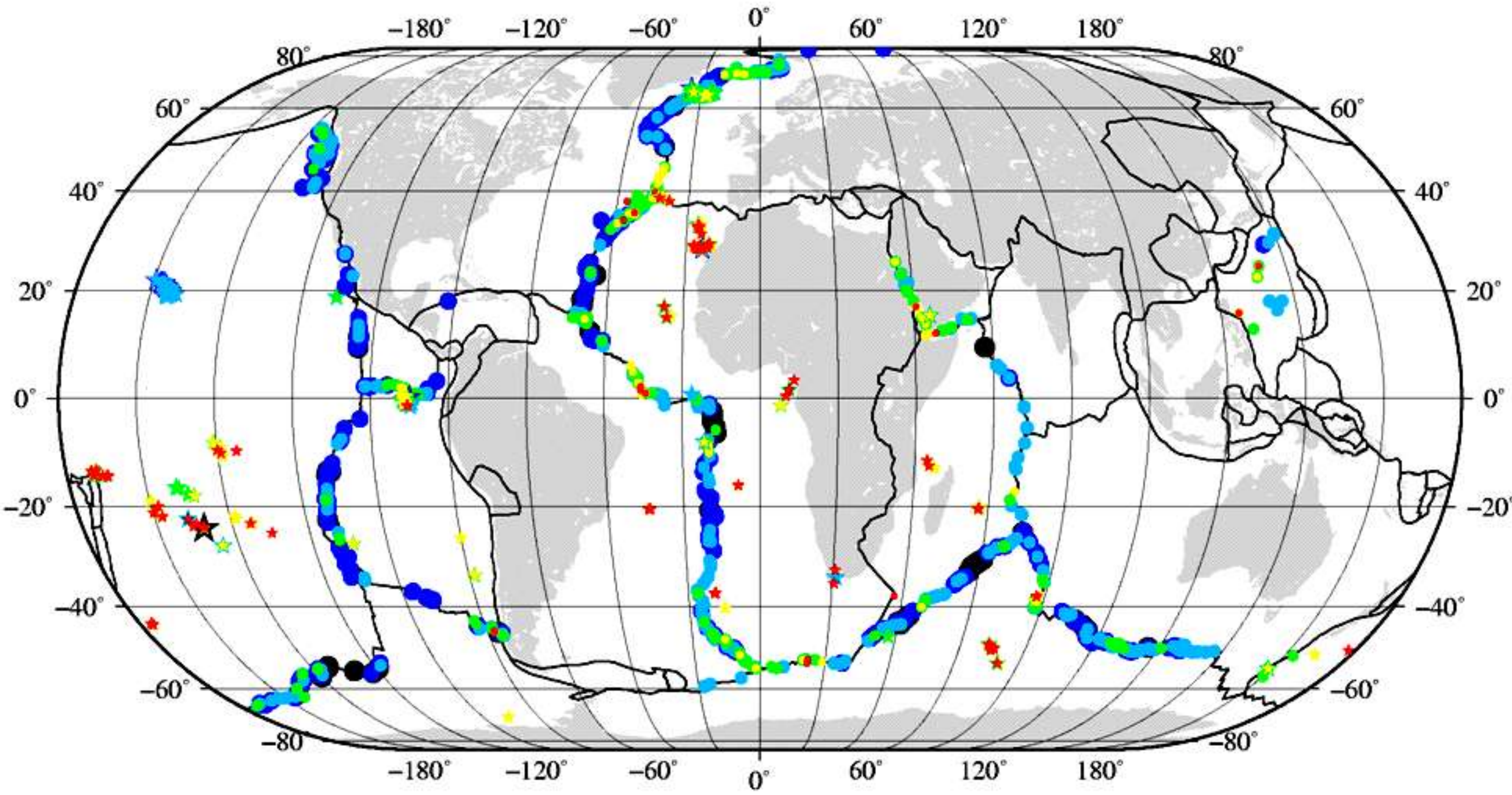
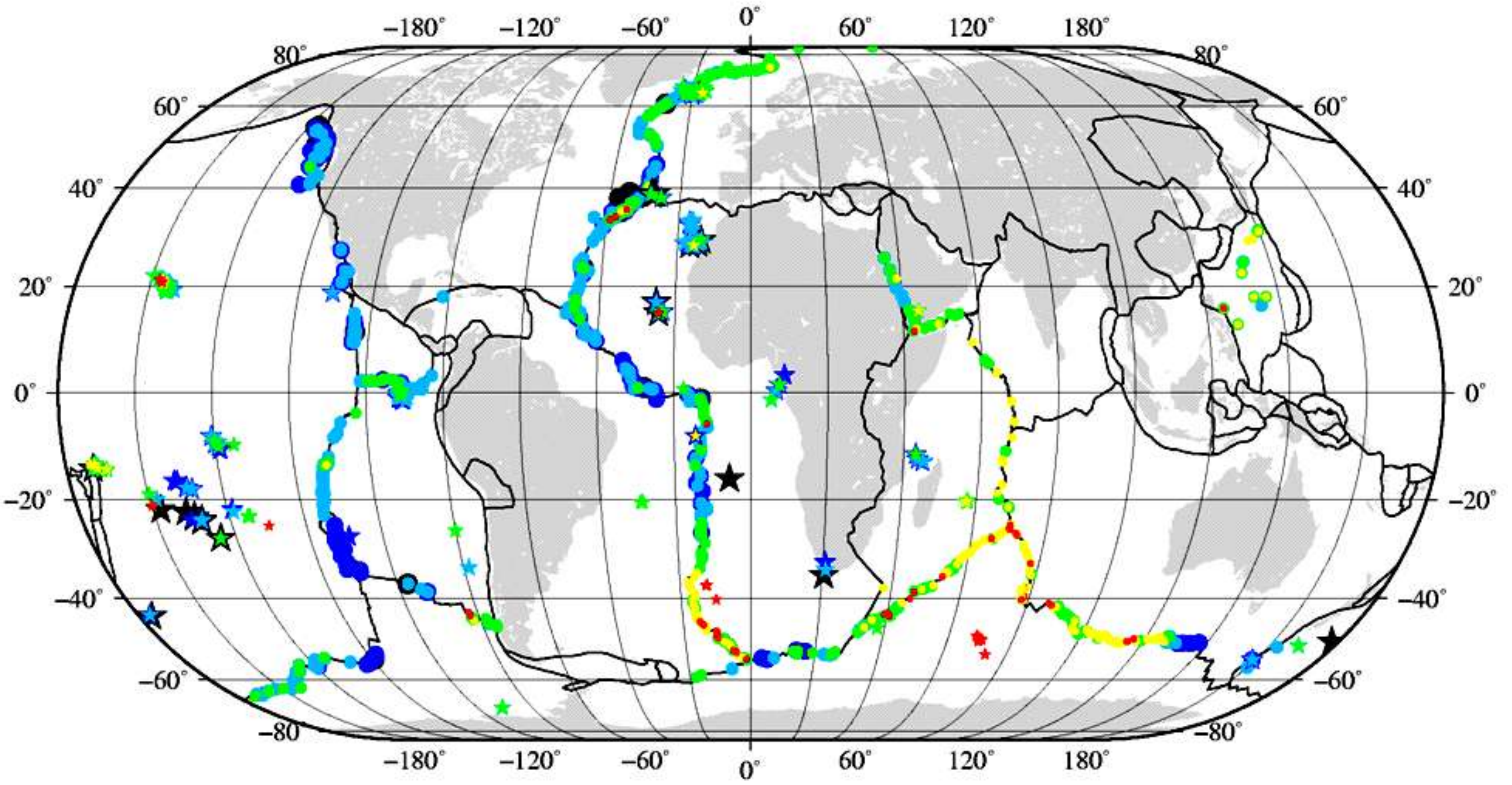


Ridge
Subduction Zone
Ridge
Subduction
continental crust
hydrous melt
MORB
Recycled MORB
hydrated
MORB/peridotite
dehydrated
MORB/peridotite
MORB melt

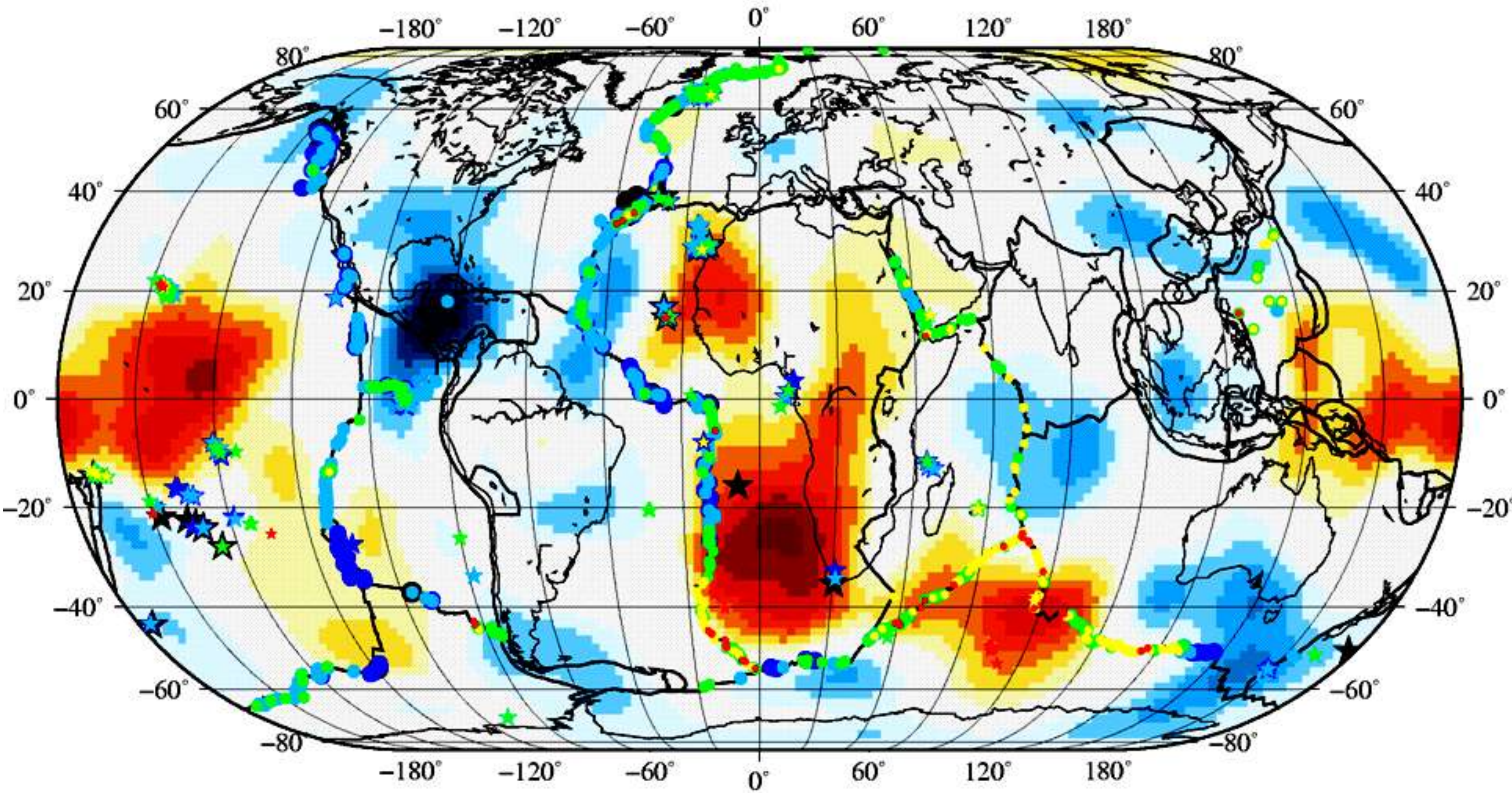
Global IC1 (s5_Si53-35-Srle0723)



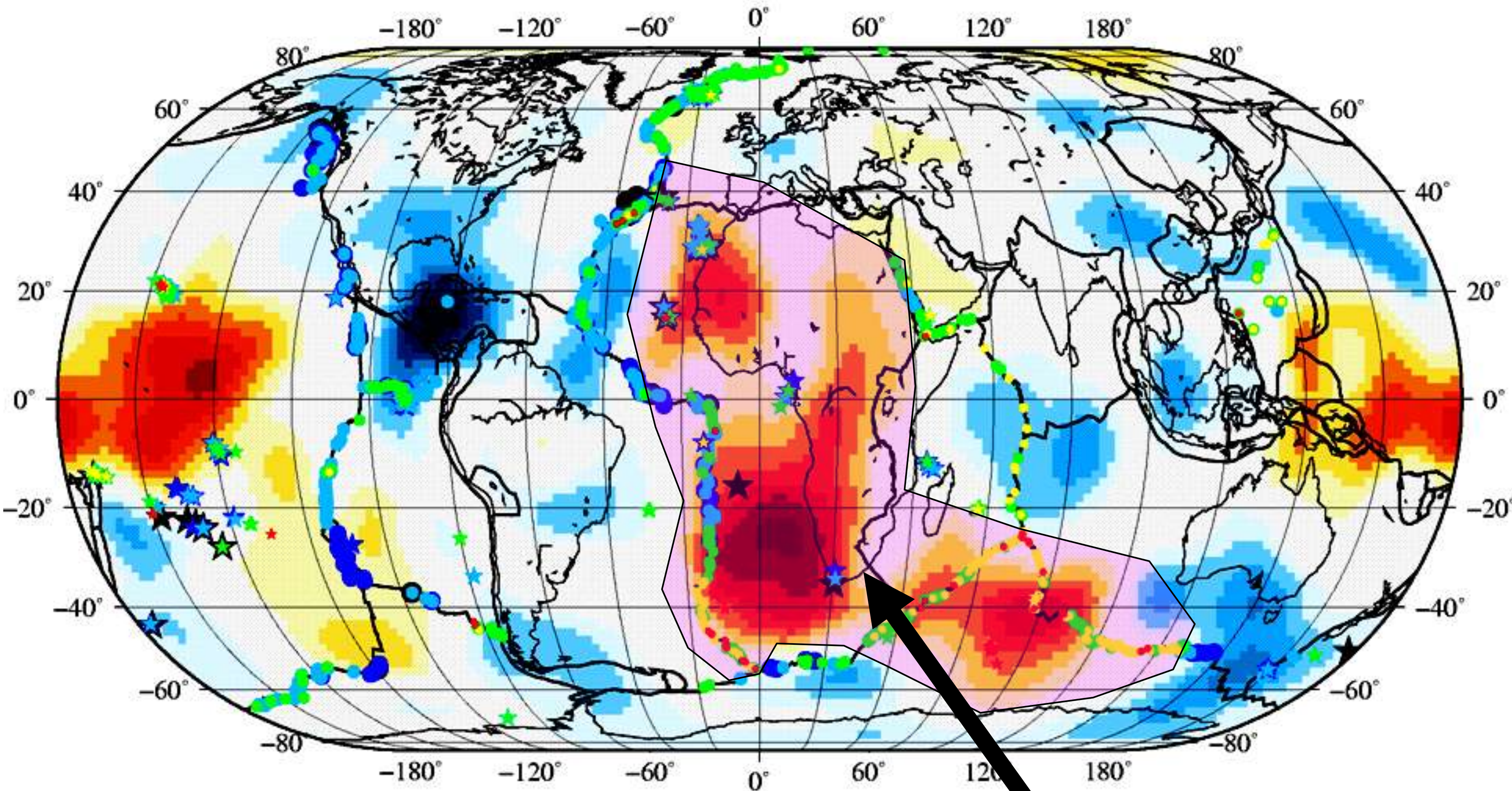
IC2 (s5_Si53-35-Srle0723)



IC2 + Vs near CMB (Takeuchi, 2007)

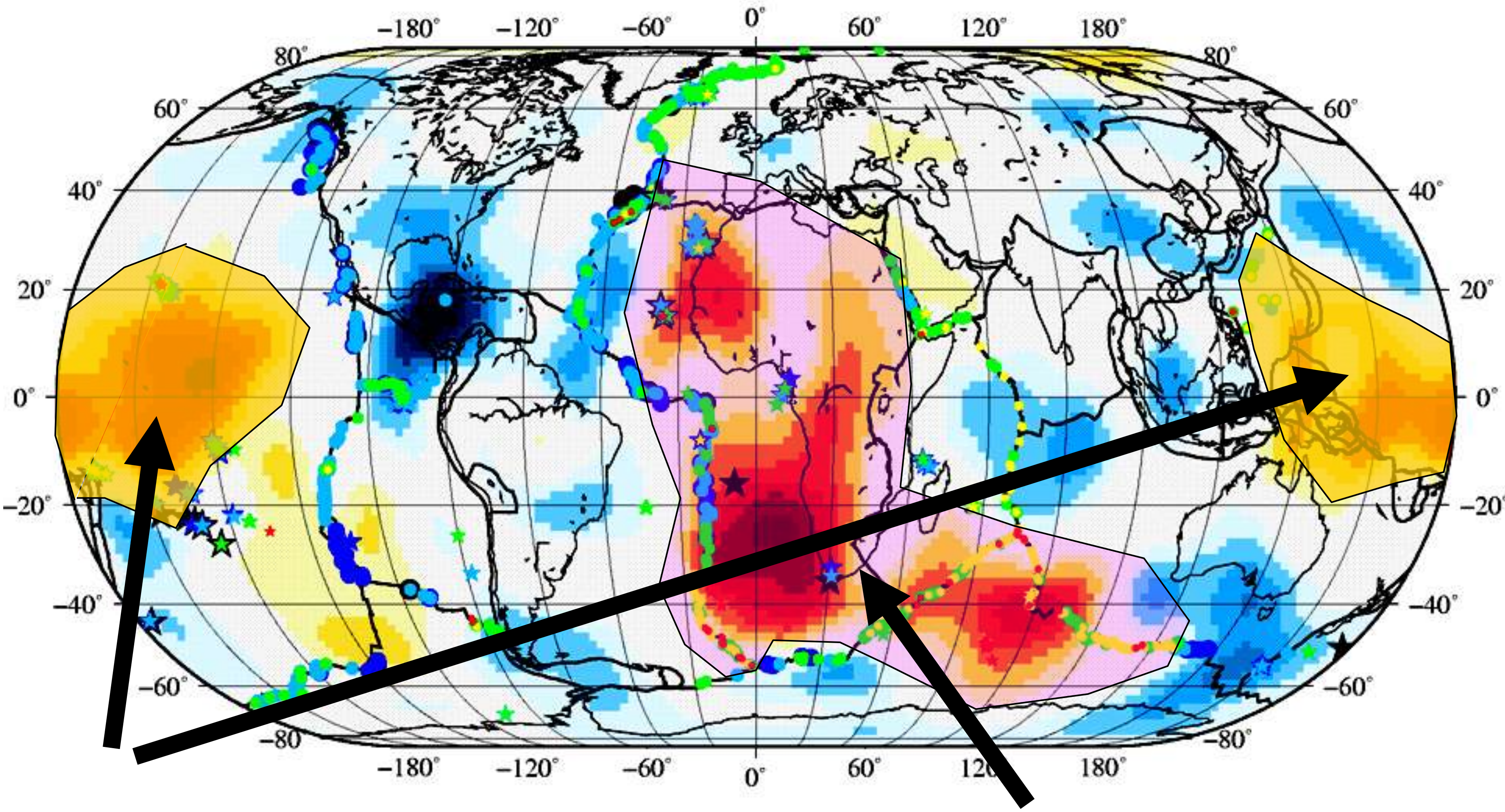


IC2 + Vs near CMB (Takeuchi, 2007)



Pangea: 300 Ma

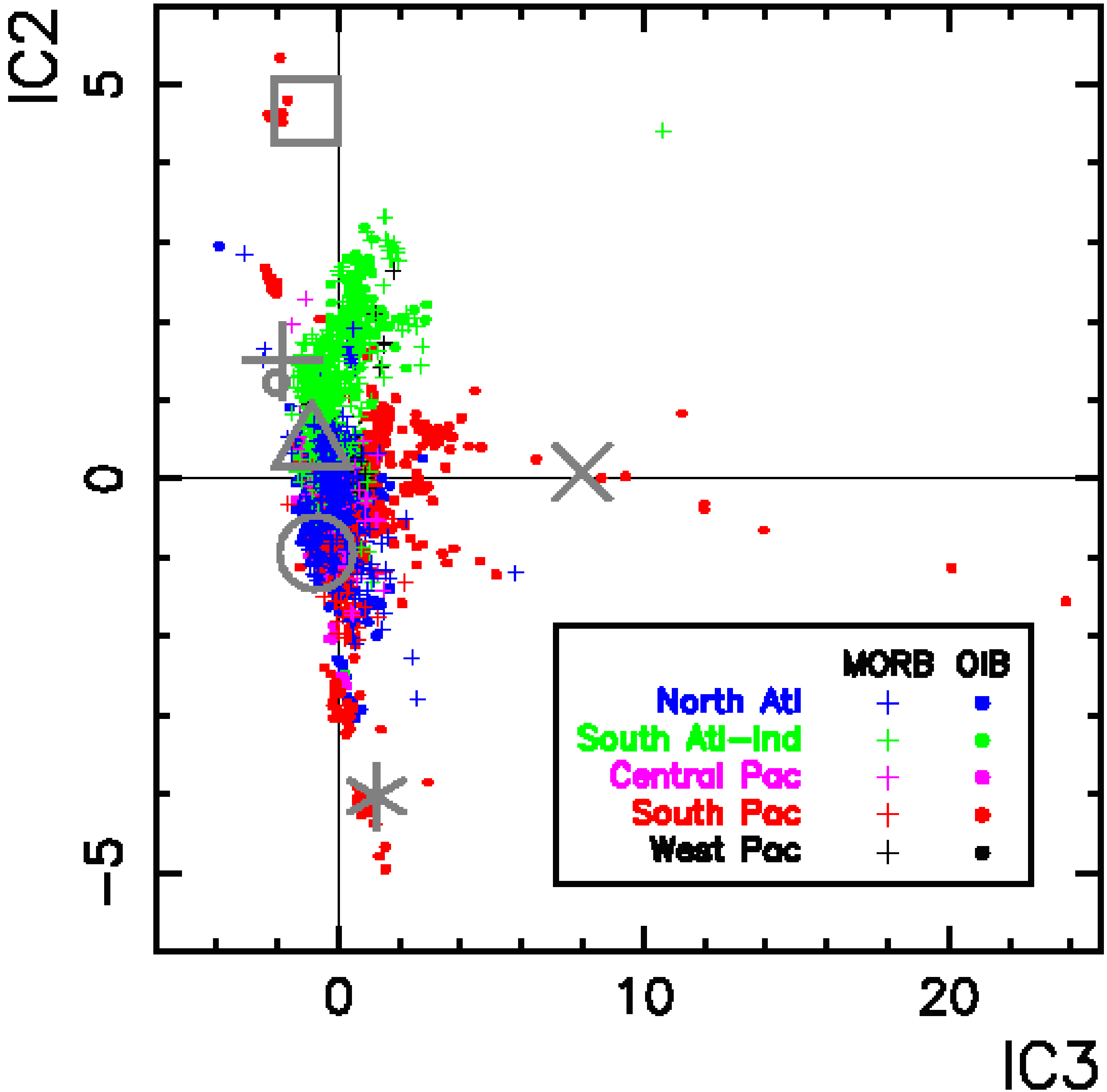
IC2 + Vs near CMB (Takeuchi, 2007)



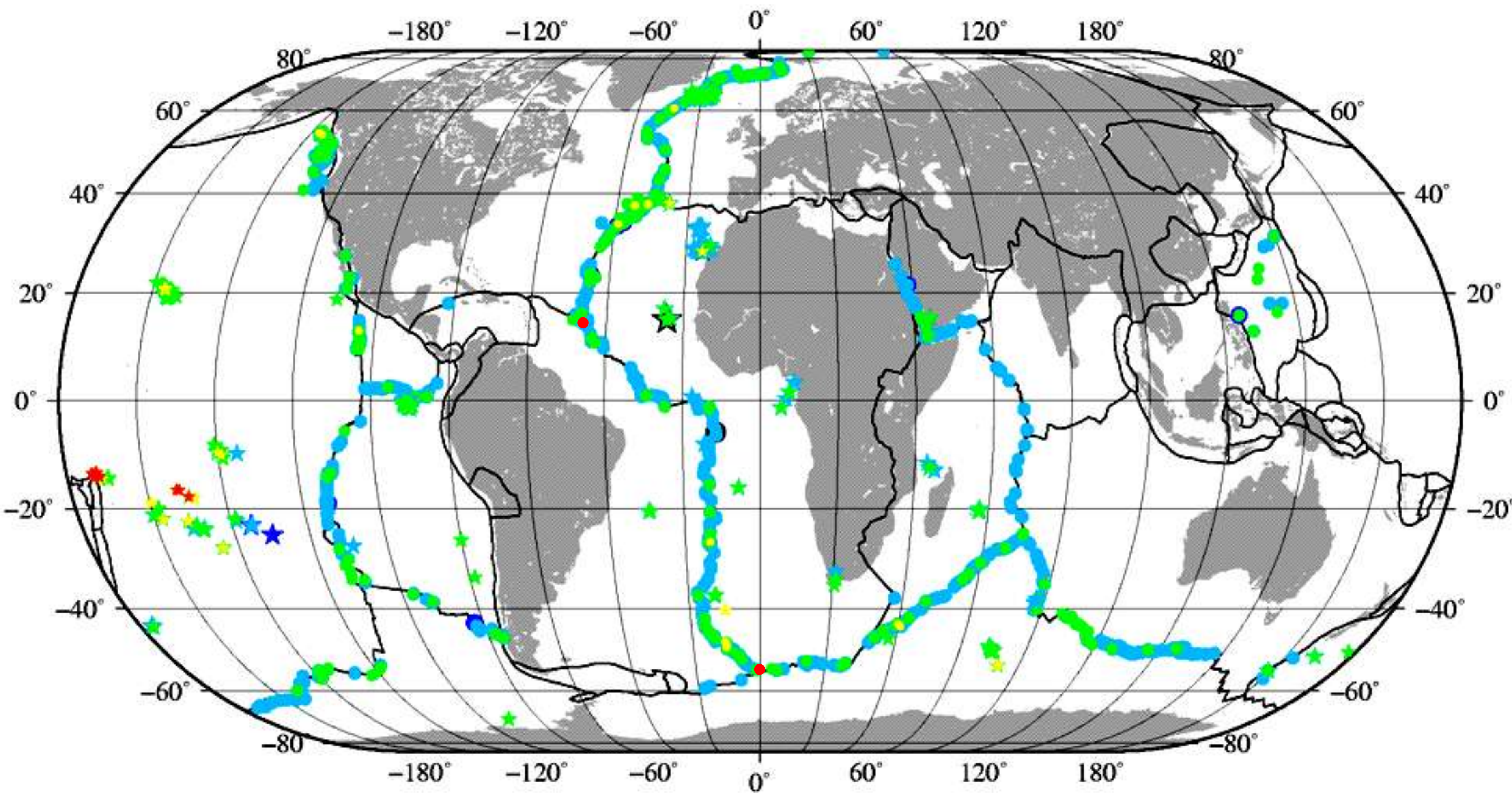
Gondwana: 500Ma ?

Rhodinia : 800 Ma ?

Pangea: 300 Ma


IC2
5
0
−5
0
10
20
IC3
MORB
OIB
North Atl
South Atl−Ind
Central Pac
South Pac
West Pac

Global IC3 (s5_Si53-35-Srle0723)

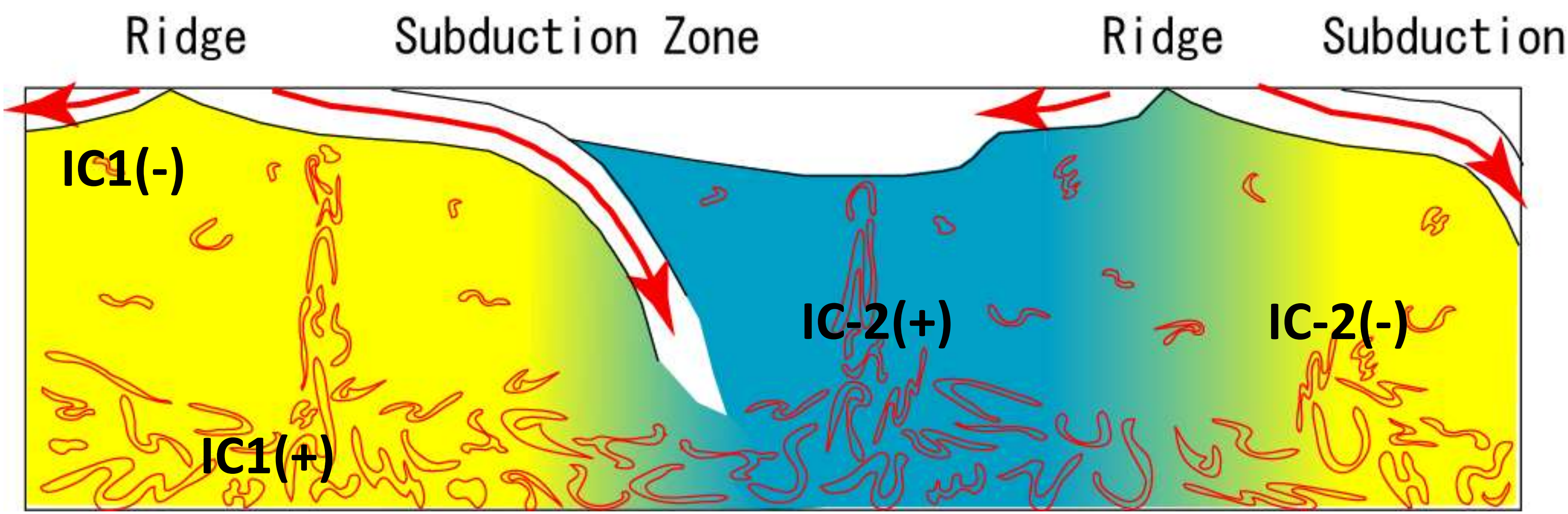


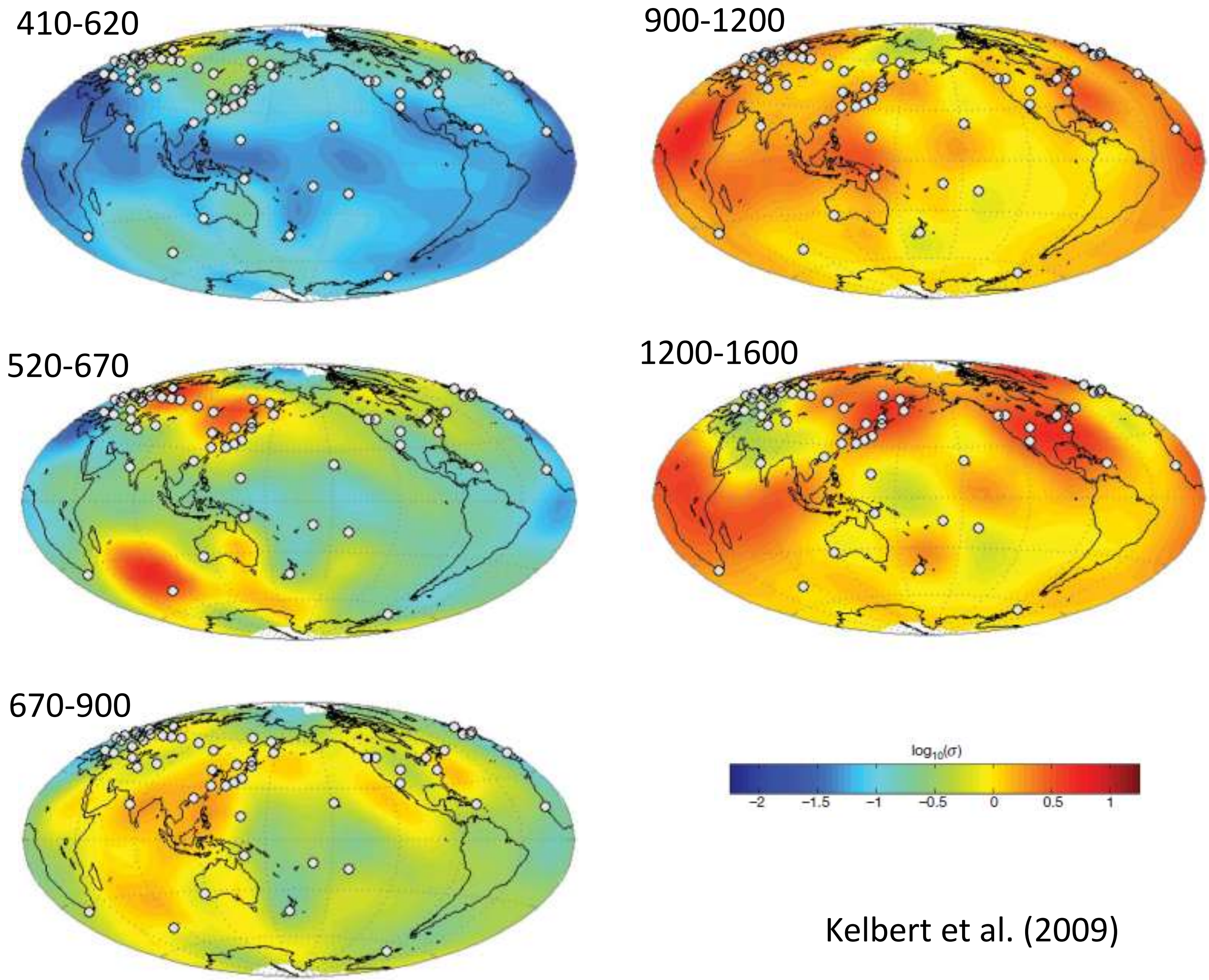
Model and Summary

(1) Two overlapping ICs in oceanic basalt isotopes
= mantle heterogeneity by two differentiation processes

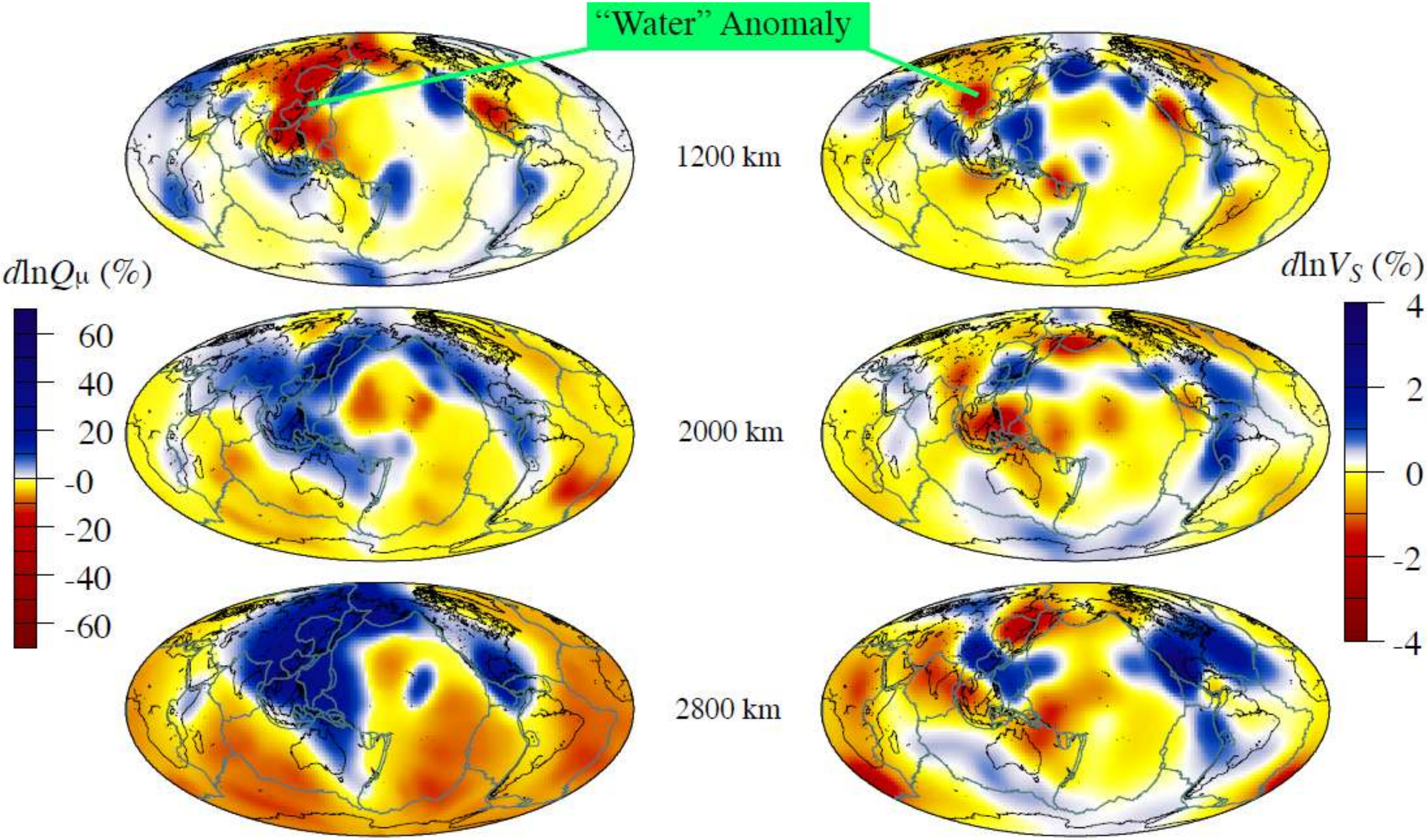
(2) IC1 separates OIB from MORB
= differentiation due to melting, long-recycling 1-2 Ga

(3) IC2 discriminates spatial distribution
= differentiation due to aqueous fluid , short recycling 0.3-1 Ga





Kelbert et al. (2009)



Lawrence & Wysession (2006)

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