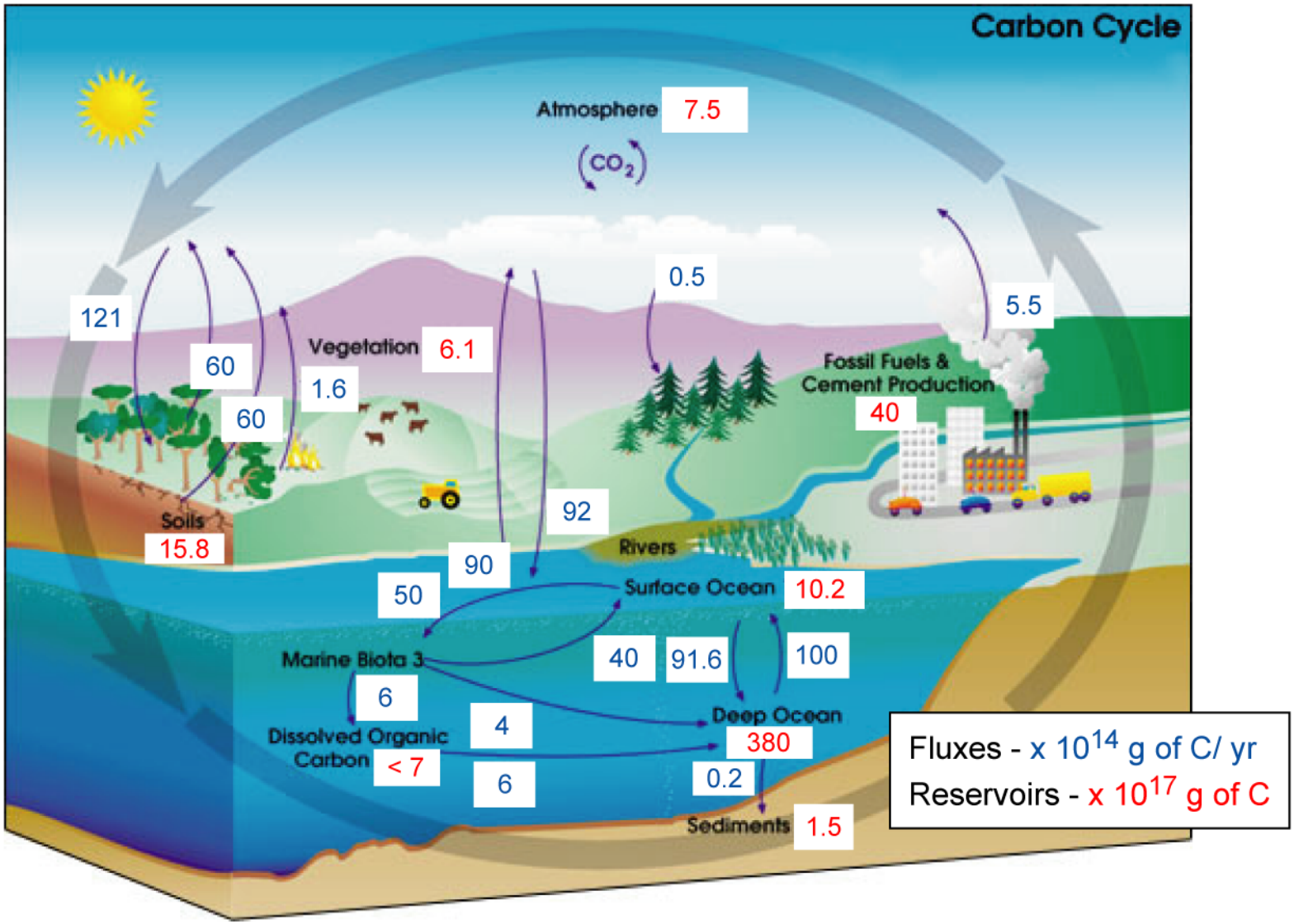
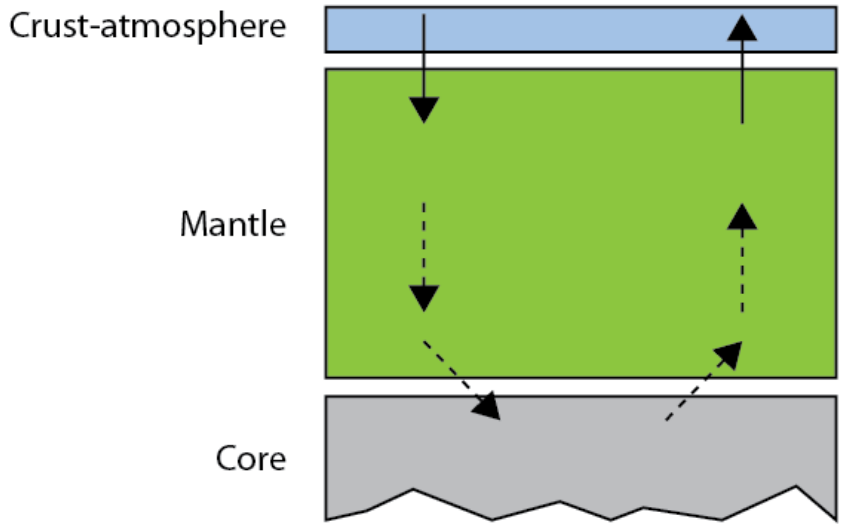
Modern-day fluxes and reservoirs of **carbon**



http://earthobservatory.nasa.gov/Library/CarbonCycle

Earth’s deep carbon cycle

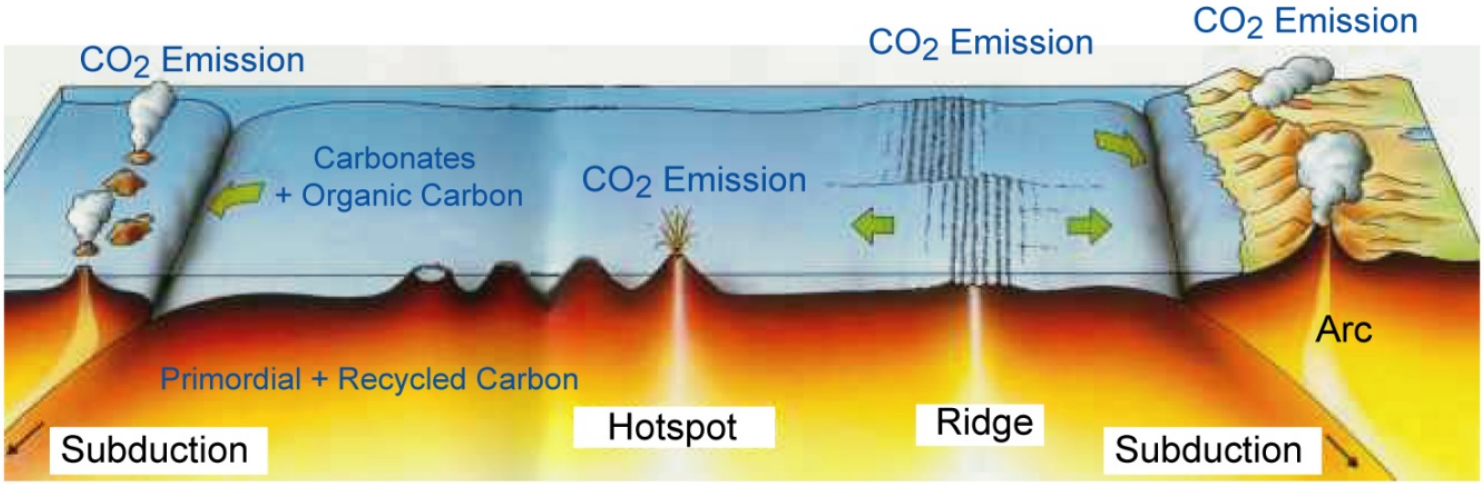


What are the reservoirs? How deep?

What are the carriers or medium of transport? – storage

How fast does C cycle/move? – fluxes and processes

Carbon out of the deep Earth?



CO_2 fluxes from mid-ocean ridges, arcs and plumes

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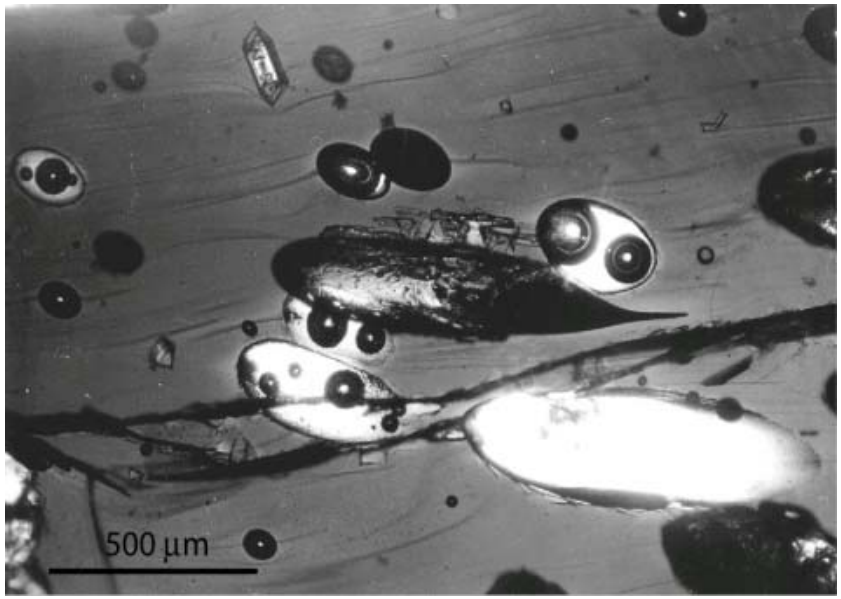
Estimating C Flux out of the mantle + mantle C abundance

- Direct measurement of CO_2 in mantle derived melts/ glasses (MORB, OIB, Arc Lavas and melt inclusions)

  (e.g., Dixon et al., 1997; Bureau et al., 1998)

- Direct measurement of CO_2 in mantle-derived fluids (trapped gas bubbles in basalts, hydrothermal vent fluids, plumes) and gases

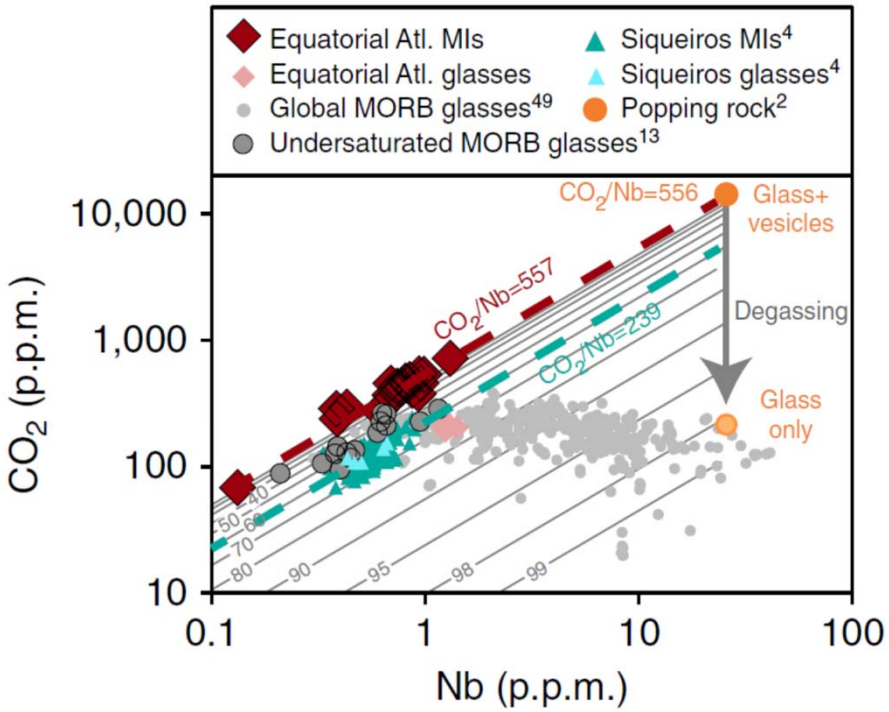
  (e.g., Aubaud et al., 2005)



Estimating C Flux out of the mantle + mantle C abundance

- Measurement of CO_2 and similarly incompatible elements in mantle-derived melts

CO_2/Nb or CO_2/Ba *(e.g., Saal et al., 2002; Cartigny et al., 2008; Rosenthal et al., 2015; Michael and Graham, 2015; Le Voyer et al., 2017)*



Le Voyer et al. (2017)

CO_2-undersaturated basalts!!

- Measurement of CO_2 and another species having similar vapor-melt partitioning

$CO_2/^3He$

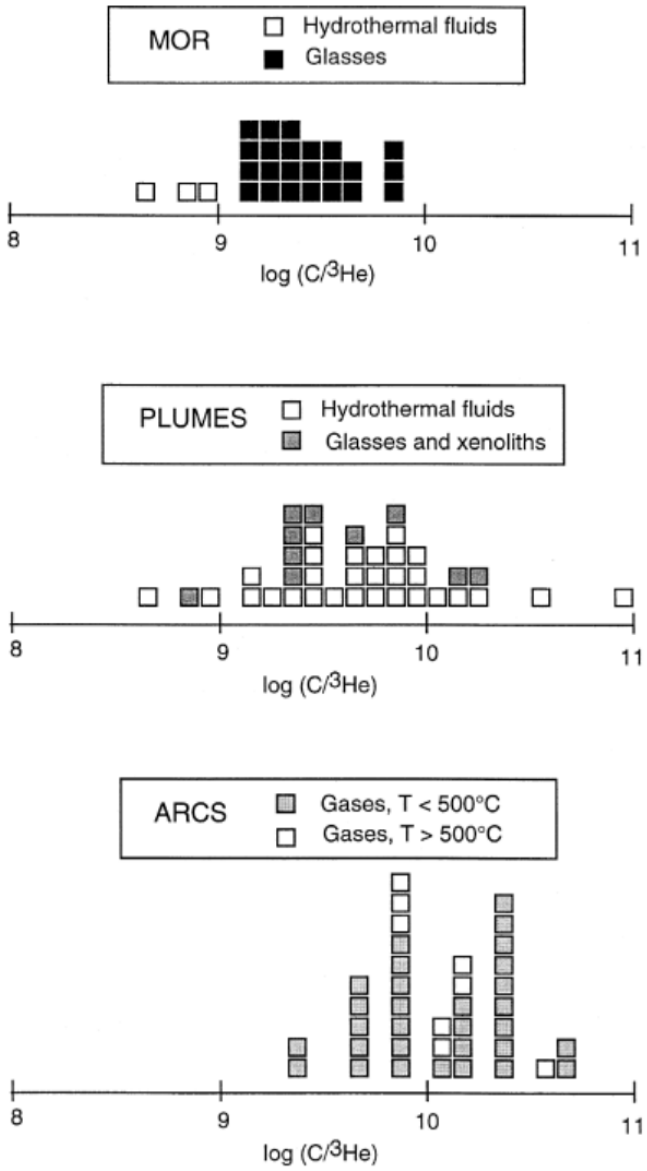
(e.g., Trull et al., 1993; Marty and Tolstikhin, 1998; Shaw et al., 2003; Resing et al., 2004)

CO_2/Ar

(e.g., Tingle, 1998; Cartigny et al., 2001)

Independent estimate of present-day ^3He flux of 1000 ± 250 mol/a

carbon flux at ridges $2.2 \pm 0.9 \times 10^{12}$ mol/a



Marty and Tolstikhin (1998)

Various units of C or CO_2 flux

- Mol/year
- g/year
- Gt/year

carbon flux at ridges $2.2 \pm 0.9 \times 10^{12}$ mol/year

carbon flux at ridges in g/year

$\times 12$

$= 2.6 \times 10^{13}$ g/year

carbon flux at ridges in Gt/year

$\div 10^{15}$ (1 Gt = 10^{15} g; 1 Tonne/Metric ton = 10^{6} g)

$= 2.6 \times 10^{-2}$ Gt/year

To convert to mass of CO_2/year → $\times 3.67$

Mantle C content from MORB degassing

Magma production rate (mass/year)

↓

C flux from ridges
(assume all C is released to fluid/vapor
OR
use more accurate C solubility model as a function of depth)

↓

C content of mantle primary basalts

↓

Independent estimation of extent of mantle melting

↓

Mantle C content $C_C^{mantle} = C_C^{basalt}.D_C^{mantle/basalt}(1-F) + C_C^{basalt}.F$

Mantle C from MORB degassing

- 3.1×10^{-6} mol/g *(Marty and Tolstikhin, 1998)*

= 37 μg/g

= 37 ppm C

=136 ppm CO_2

= 0.014 wt.% CO_2

Mass of mantle x C content
= Mass of C in the mantle
= 14.8×10^{23} g
= 14.8×10^{8} Gt

Residence time of C in the mantle

= reservoir mass/flux

~ >4 b.y !!!

What about other volcanic centers?

- Arcs?
- Intraplate magmatism?
- Ocean islands
- Continental magmatism (LIPs?)
- Rifts?

C out flux at volcanic arcs

(Marty and Tolstikhin, 1998)

$$\phi_{\mathrm{C,arc}} = \phi_{\mathrm{arc}} \times \left[{}^{3}\mathrm{He}\right]_{\mathrm{um}} \times \left(\mathrm{C}/{}^{3}\mathrm{He}\right)_{\mathrm{arc}} \times r_{\mathrm{arc}}^{-1}$$

2.5×10^{12} mol/year

$= 3.0 \times 10^{13}$ g/year

$= 3.0 \times 10^{-2}$ Gt/year

C flux via plume magmatism

$$\phi_{C,PL} = \phi_{PL} \times [^3He]_{PL} \times (C/^3He)_{PL} \times r_{PL}^{-1}$$

Lower melt flux than in ridges

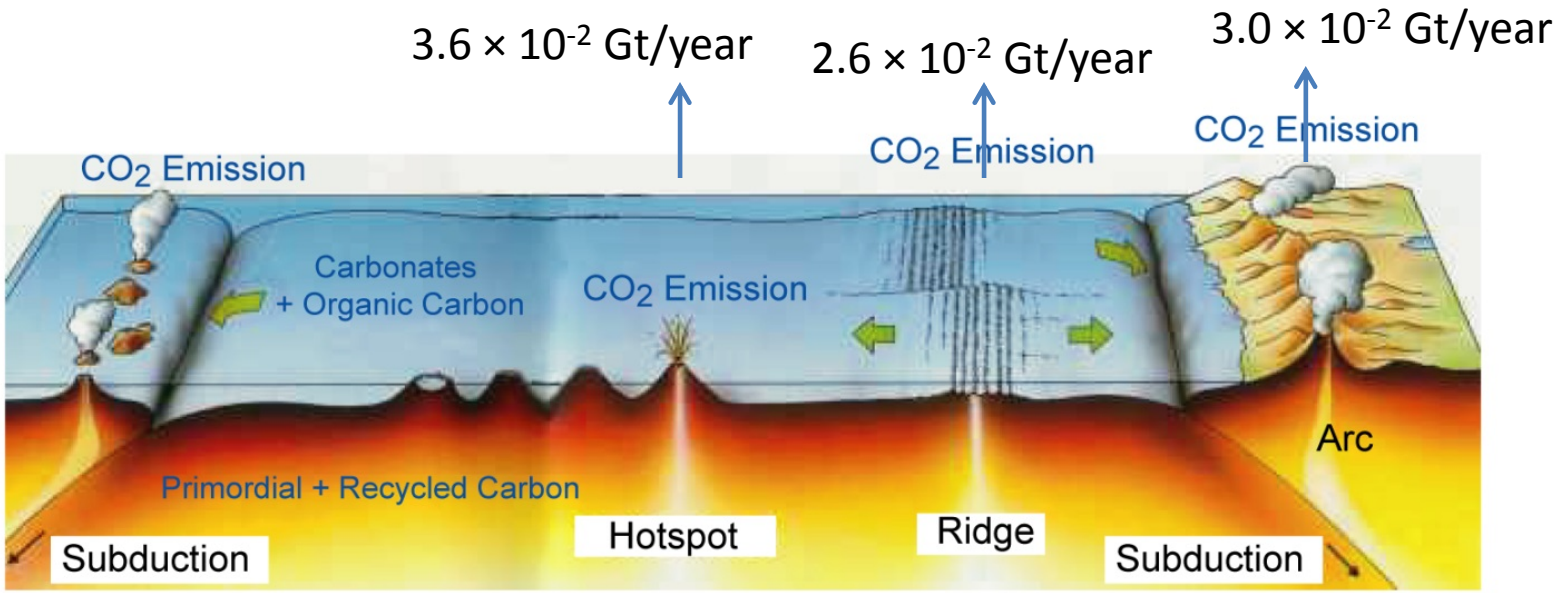
Somewhat elevated ratio compared to MORBs

Lower mean extent of melting than beneath ridges

3.6×10^{-2} Gt/year

(Marty and Tolstikhin, 1998)

Total magmatic flux from the mantle



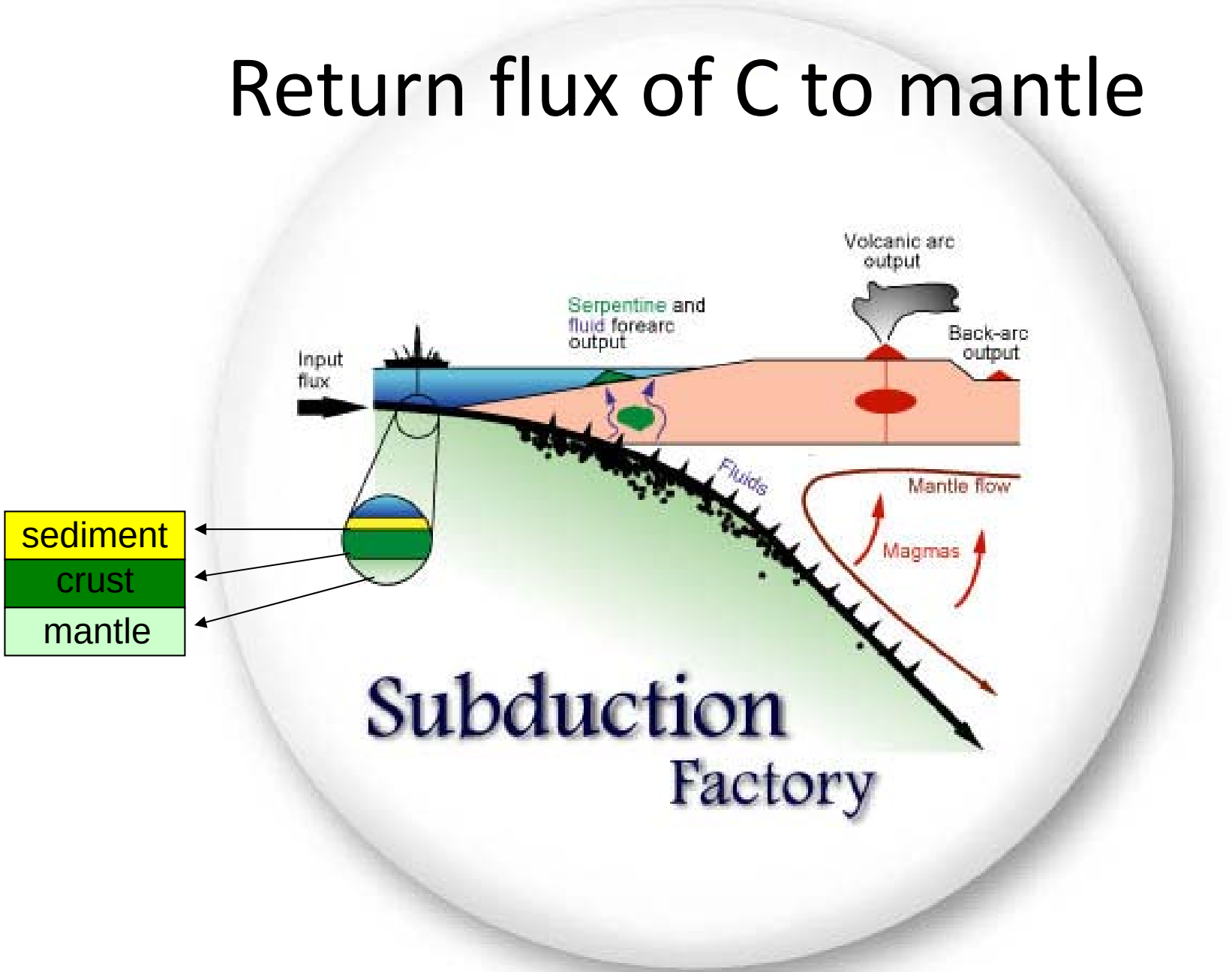
What is missing?

Continental magmatism?

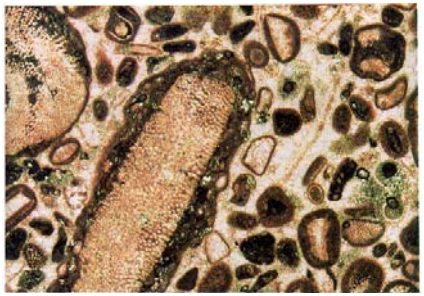
Diffused degassing?

Off-axis degassing?

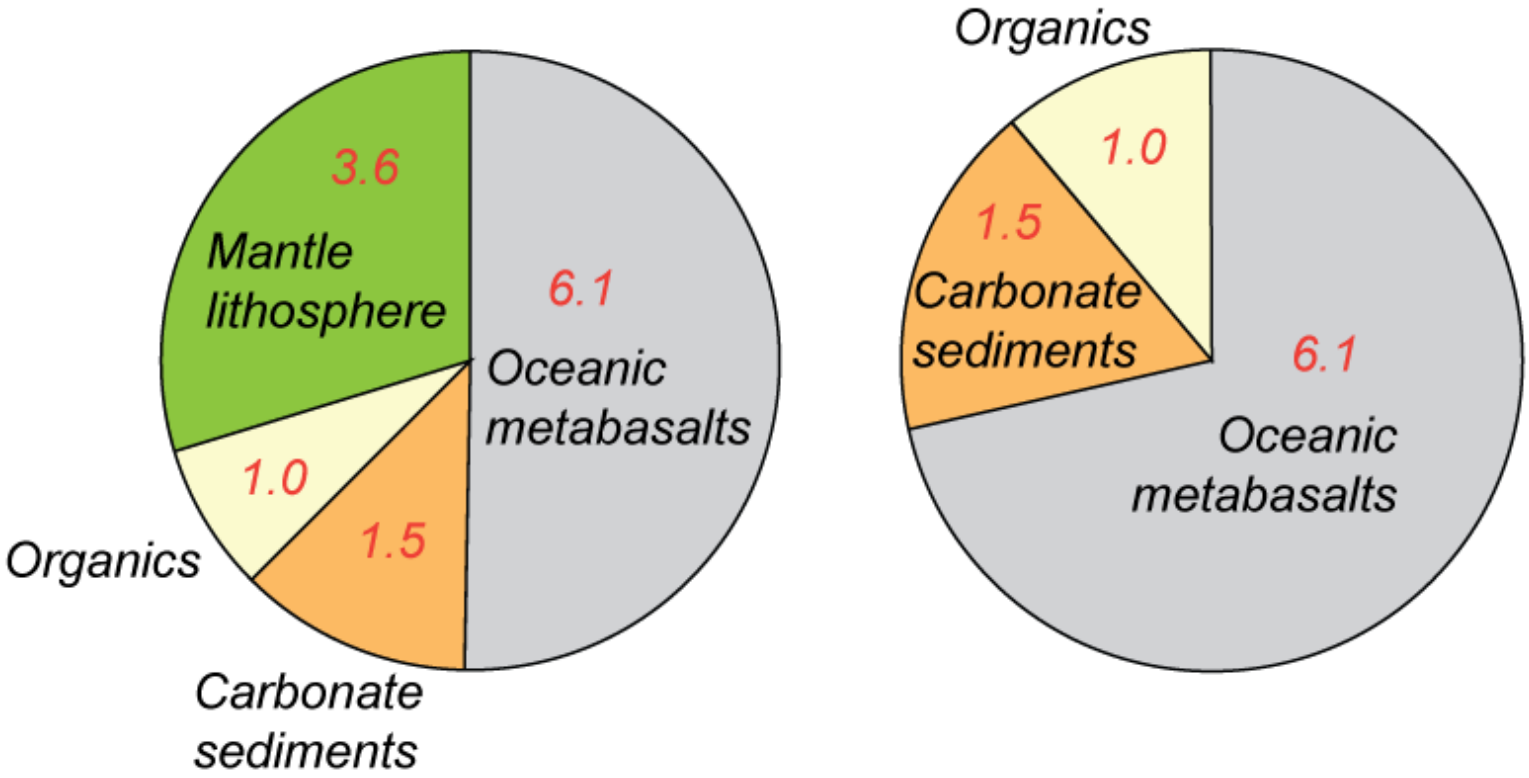
Return flux of C to mantle



sediment ***basalt*** ***peridotite***



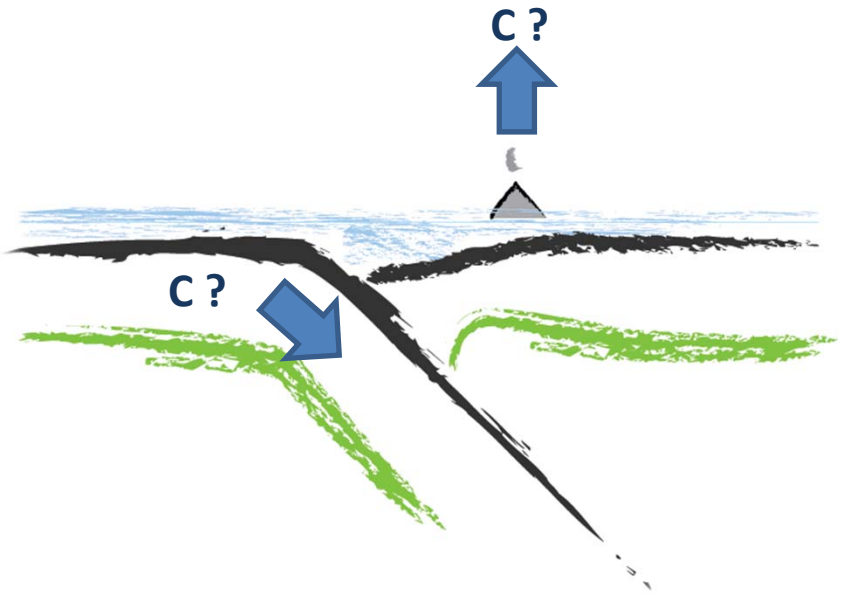
Mass flux of subducting ***Carbon*** *(x 10^{13} g/ yr)*

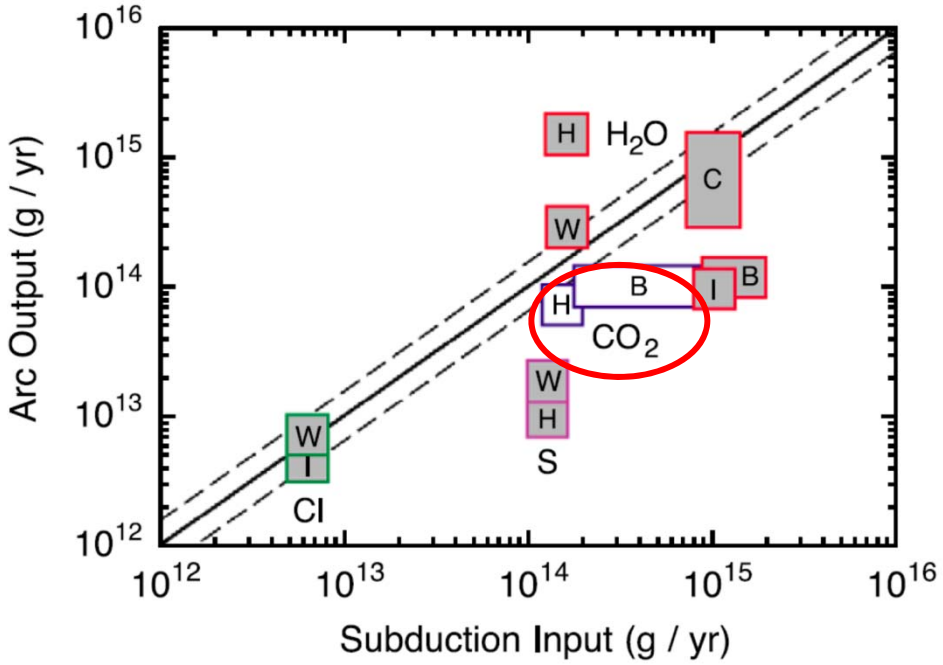


(Sciutto and Ottonello, 1995; Kerrick & Connolly, 2001; Sleep and Zahnle, 2001; Jarrard, 2003; Alt, 2004)

How much goes in and how much comes out?

Inverse or observational approach



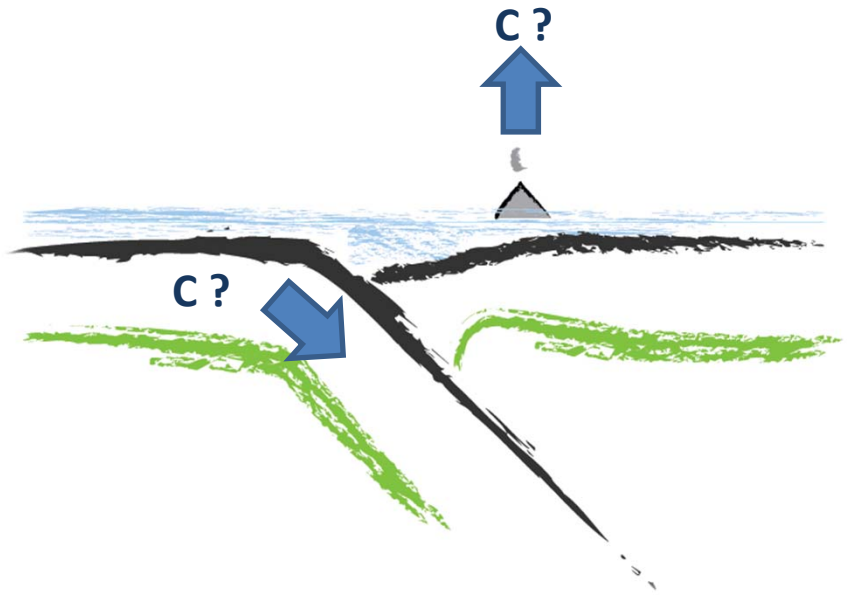


Wallace (2005)

Is the deep C cycle in steady state?

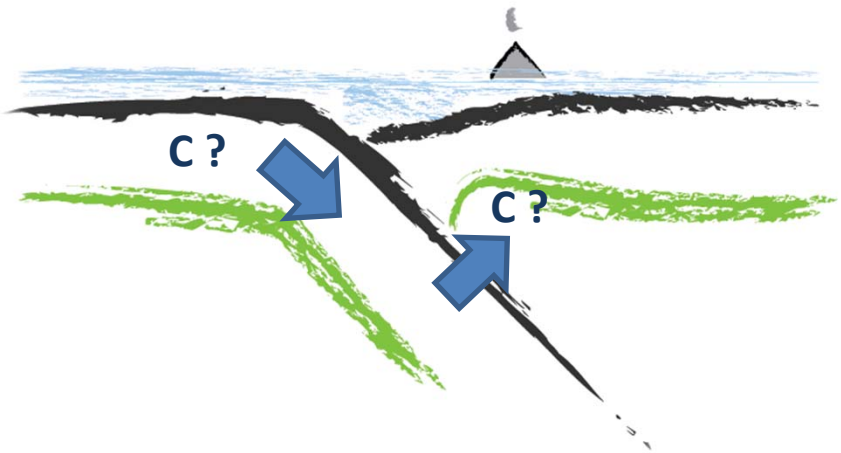
Challenges in the inverse approach of subduction zone C cycle

- Flux out of forearcs?
- Storage in the mantle wedge or over-riding plate?
- Arc flux contributed by upper plate?
- Release at depths deeper than sub-arc depth and release through back-arcs?



How much goes in and how much comes out?

Forward approach



Fate of carbon-bearing subducting lithologies during subduction

→ stability of C-bearing minerals (carbonates, organics, graphite, diamond)

→ Solubility or saturation of C (as CO_2, CO_3^{2-}, other species) in slab-derived fluids or melts

→ thermal structure of subduction zones

PNAS

Reevaluating carbon fluxes in subduction zones, what goes down, mostly comes up

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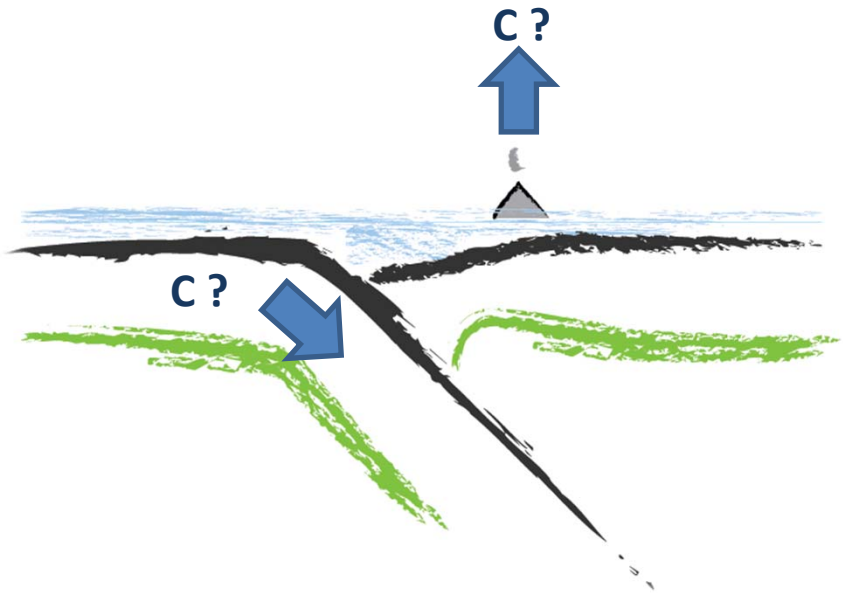
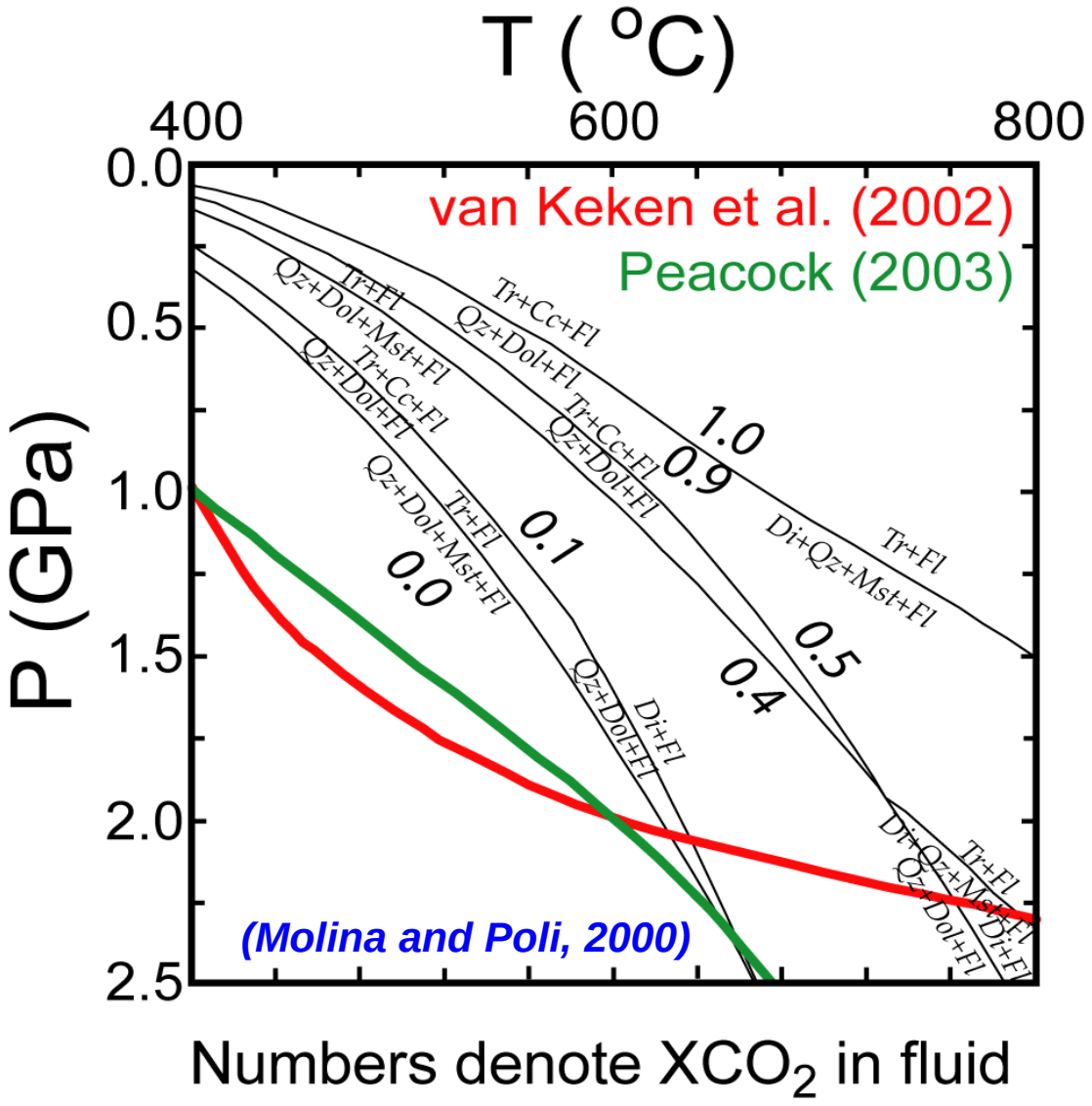
Contributed by Peter B. Kelemen, April 23, 2015 (sent for review August 7, 2014; reviewed by Jay J. Ague, James Connolly, Rajdeep Dasgupta, and Dimitri Sverjensky)



Fate of Subducting Carbon (in altered ocean crust, AOC)



Carbonates remain as refractory phase in the residue as AOC dehydrates

Liberation of fluid with low CO_2/H_2O via metamorphic decarbonation

(Yaxley and Green, 1994; Molina and Poli, 2000; Kerrick and Connolly, 2001)

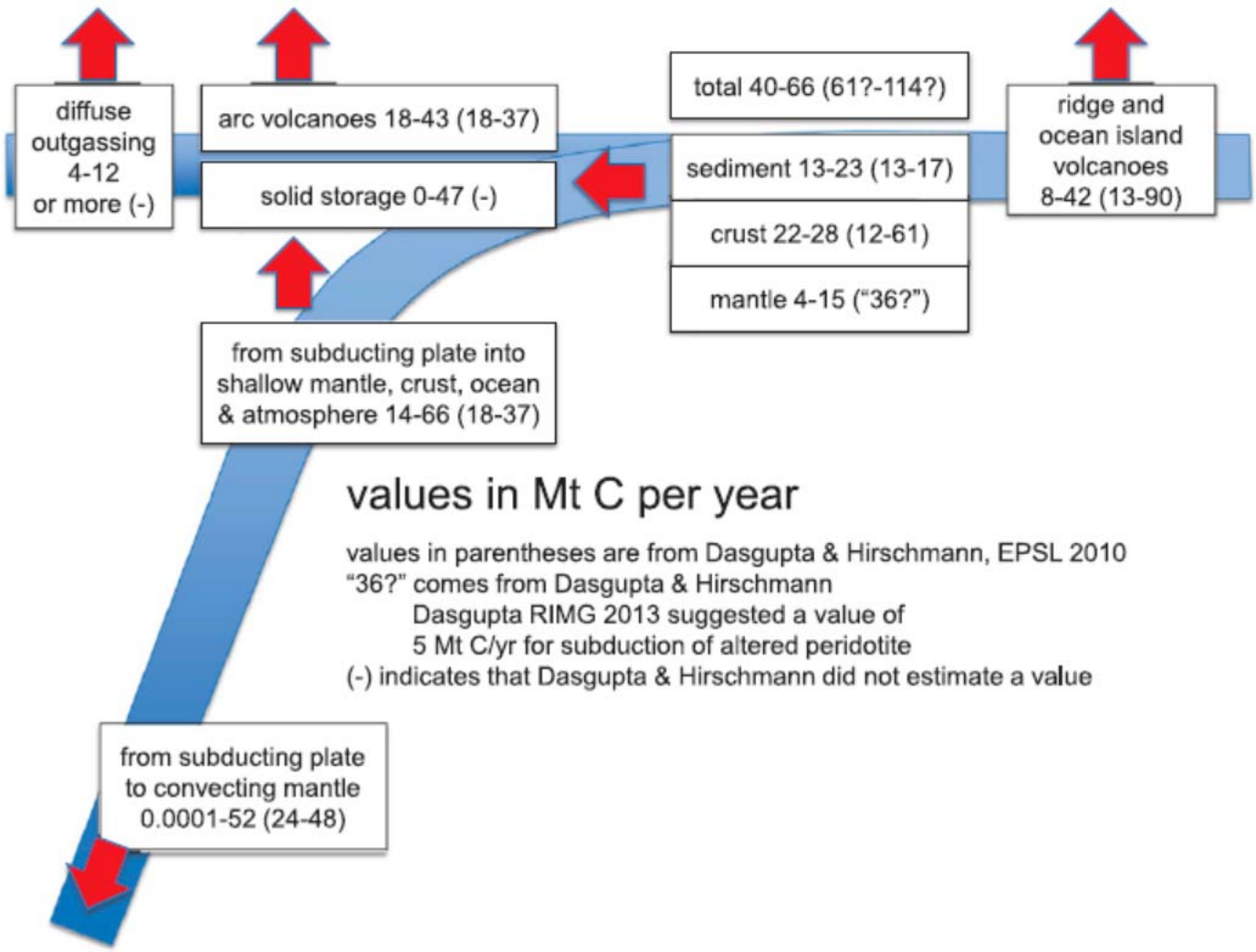
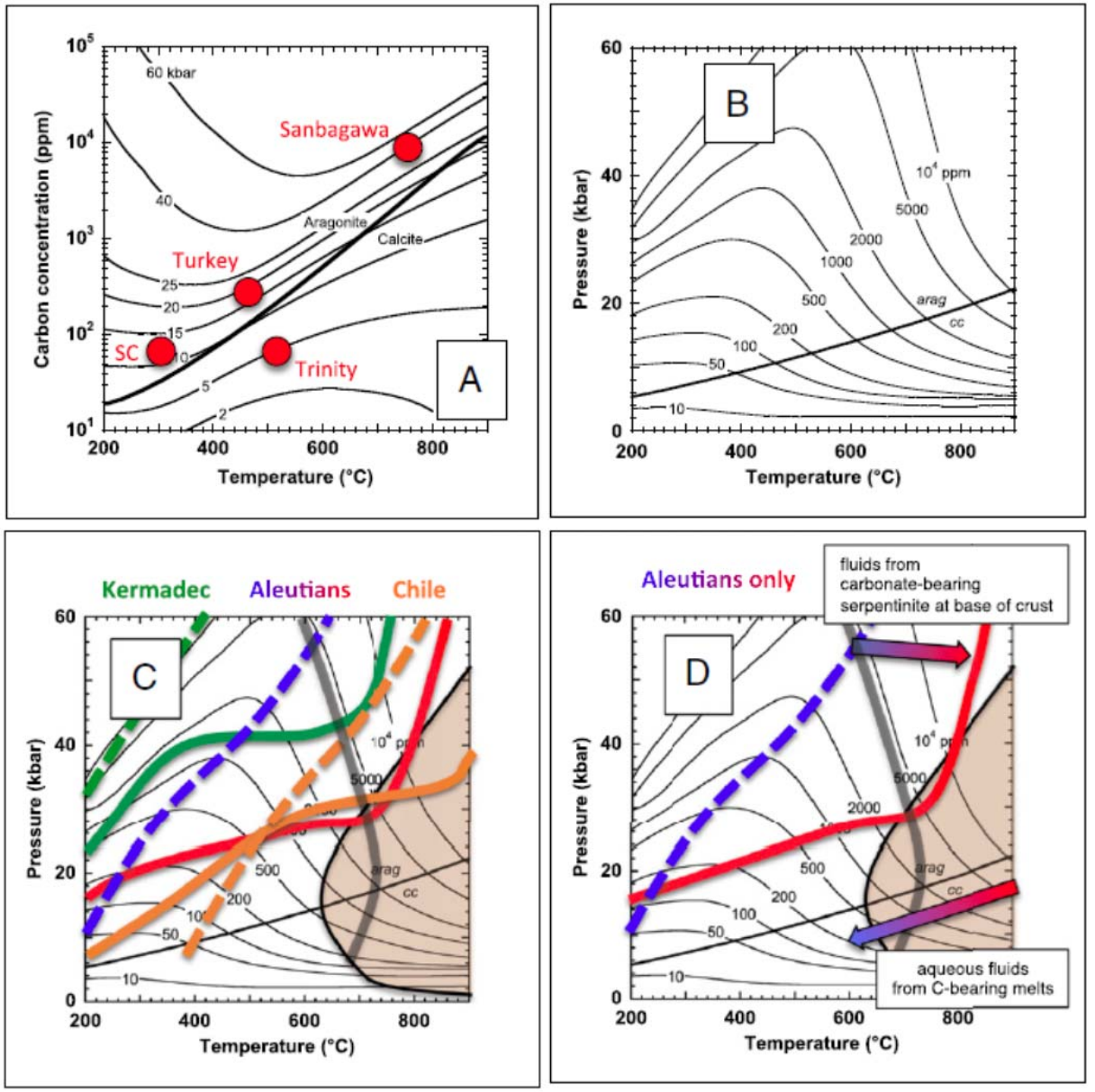


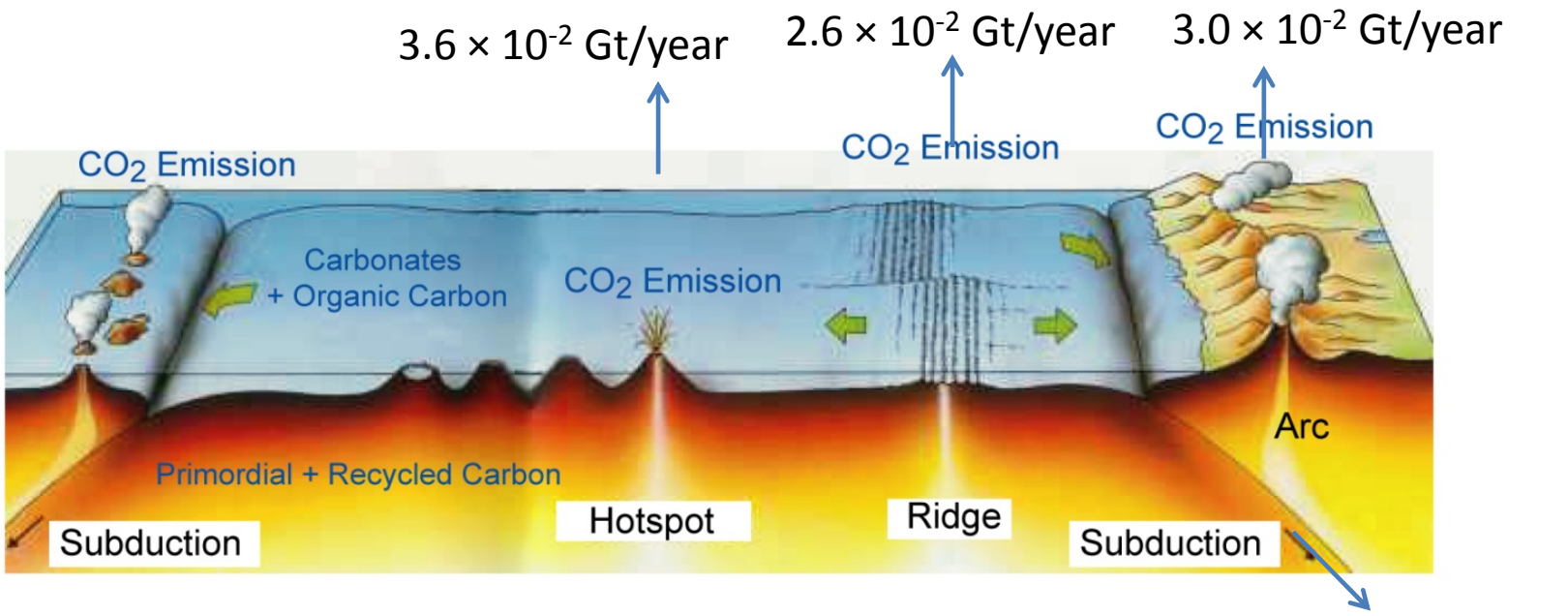
Fig. 5. Major fluxes of carbon estimated in this paper, with values from Dasgupta and Hirschmann (1) for comparison.

Calcite solubility in aqueous fluid

The role of mineral (carbonate) dissolution

Kelemen and Manning (2015)




3.6 × 10-2 Gt/year
2.6 × 10-2 Gt/year
3.0 × 10-2 Gt/year
CO2 Emission
CO2 Emission
CO2 Emission
CO2 Emission
Carbonates
+ Organic Carbon
Primordial + Recycled Carbon
Subduction
Hotspot
Ridge
Subduction
Arc
(0-5) × 10-2 Gt/year

Stady state?

What are the reservoirs? How deep?

What are the carriers or medium of transport? – storage

How fast does C cycle/move? – fluxes and processes

Through time?