The role of dust in the cycling of iron in the ocean

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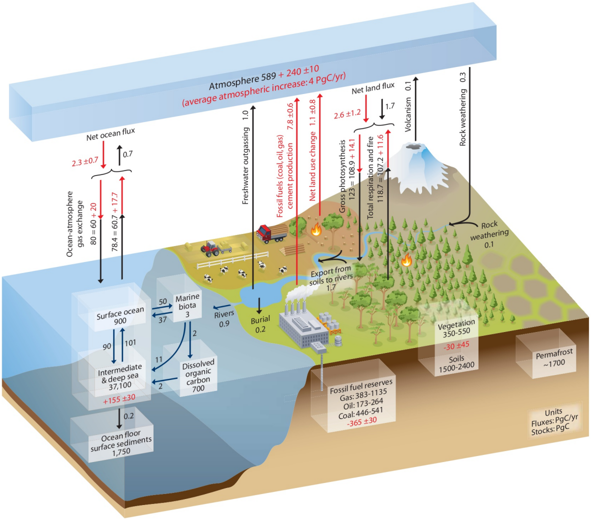
THE OCEAN IS IMPORTANT IN THE CARBON CYCLE

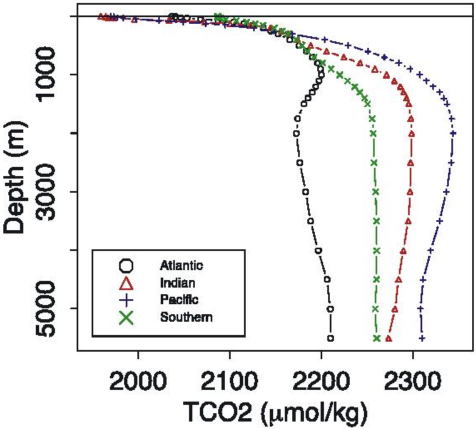


(IPCC AR5)

ocean contains ca. 50× as much carbon as the atmosphere

it currently takes up ca. 1/4 of anthropogenic carbon emissions

CARBON INCREASES WITH DEPTH



(Key et al., 2004)

dissolved inorganic carbon (DIC) is lower at the surface than at depth

this keeps atmospheric pCO_2 lower than for a 'well-mixed' ocean

in the deep ocean DIC increases with 'age'

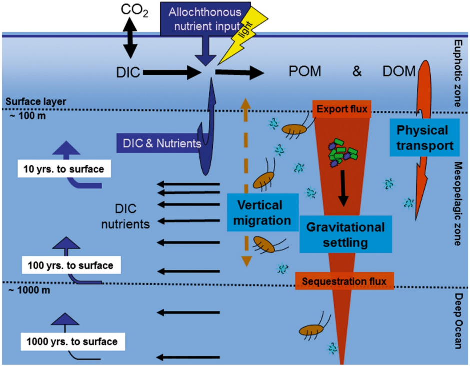
THE REASON: BIOLOGICAL CARBON PUMP

biological production in the ocean occurs mostly near the surface

aggregation & defecation produce particles that are large enough to sink

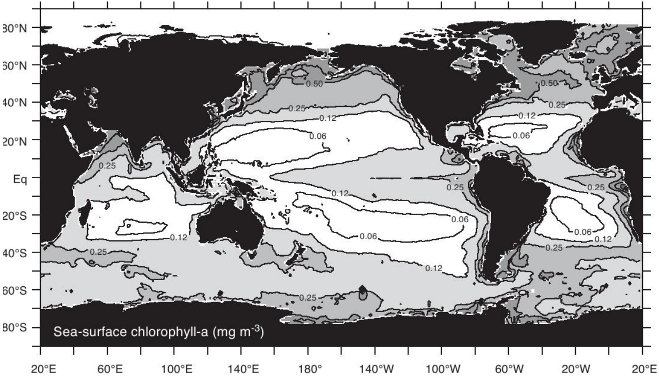
at depth, most of that organic material is respired by animals & bacteria, releasing nutrients

mixing & circulation bring nutrients & carbon back to the surface



(Passow et al., 2014)

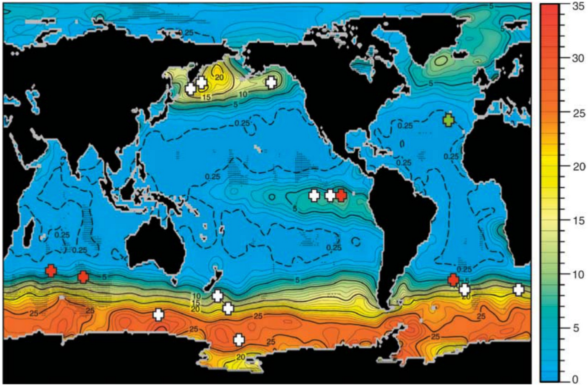
HOW IS BIOLOGICAL ACTIVITY DISTRIBUTED?



(Gruber and Sarmiento, 2006)

- biological production is high where mixing and circulation bring nutrients to the surface and there is enough light
- net primary production in the ocean ≈ 50-60 PgC yr^{-1}, same as on land, but biomass lower by a factor of 100!

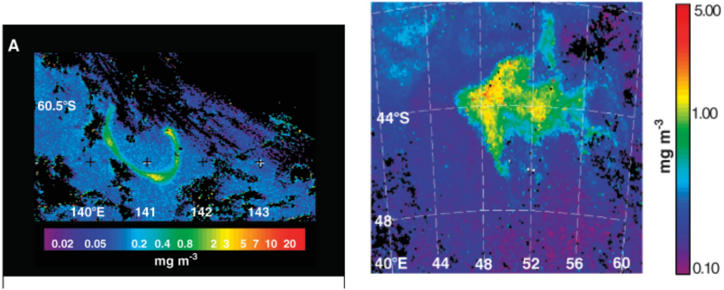
IN SOME AREAS, NITRATE NEVER GETS USED. WHY?



(Boyd et al., 2007)

- High-Nutrient-Low-Chlorophyll regions: despite enough nitrate and phosphate little net primary production
- what is missing is iron; crosses mark *iron fertilization* studies

ARTIFICAL AND NATURAL IRON FERTILIZATION

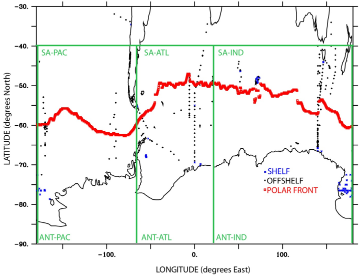


(Boyd et al., 2007)

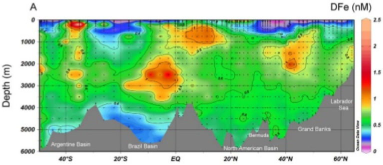
- articial iron fertilization (left, SOIREE): iron is distributed over a patch of $\approx 100\ \text{km}^2$
- natural iron fertilization (right, Crozet island): an island serves as iron source for its otherwise iron-poor surroundings

both have been shown to lead to elevated chlorophyll, NPP, . . .

IRON OBSERVATIONS ARE STILL SPARSE



all iron observations in the Southern Ocean as of 2012 (Tagliabue et al., 2012)



iron concentration along a section through the Western Atlantic (Rijkenberg et al., 2014)

iron is hard to measure in seawater; problem of contamination
reliable measuments start around 1985
so far, data coverage is still low; but with GEOTRACES a full picture is beginning to emerge

WHY IS IRON MISSING?

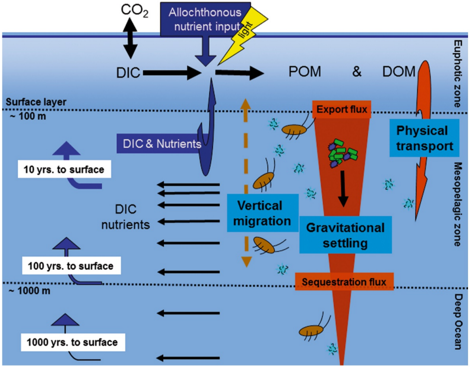
biological production in the surface ocean draws down nutrients (N, P, Fe, . . .)

sinking moves biomass down

at depth, biomass is remineralized by heterotrophs

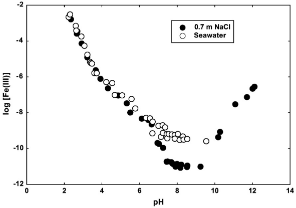
mixing & circulation bring nutrients back to the surface

but: additional removal of dissolved Fe by interaction with particles!

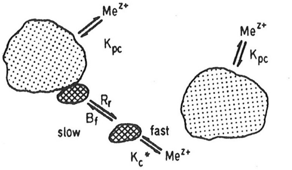


(Passow et al., 2014)

IRON IS PARTICLE REACTIVE



(Liu and Millero, 2002)



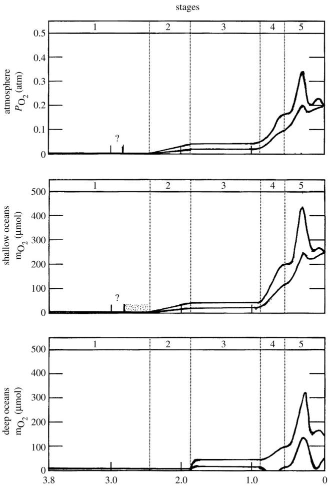
(Honeyman and Santschi, 1989)

iron in oxic seawater is mostly Fe(III)

solubility of inorganic Fe(III) is extremely low:
< 0.1 nmol kg^{-1}

$\rightarrow$ iron is lost much faster from the ocean than nitrogen or phosphorus

A CRISIS A LONG TIME AGO



Holland, 2006

ocean oxygenation caused iron to precipitate; many of todays exploited iron ores are created this way; especially the 'banded iron formations' e.g. in South Africa

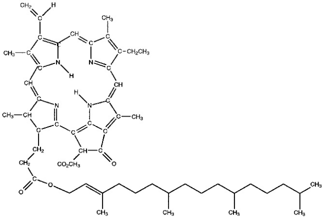
IRON CHEMISTRY IS COMPLICATED

Iron can exist in many different forms in seawater:

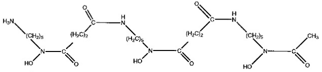
- inorganically bound in redox states Fe(III) and Fe(II)
- Fe(II) is soluble, Fe(III) precipitates
- in oxic seawater, Fe(II) is quickly oxidised
- photochemical processes can produce Fe(II)
- strong organic iron-binding substances exist in seawater
- typically, 99% of iron is bound to these ligands

This iron *speciation* greatly affects iron loss, dust iron solubility, iron uptake . . .

FE-BINDING LIGANDS AS NATURES REMEDY



Phaeophytin
(porphyrin)

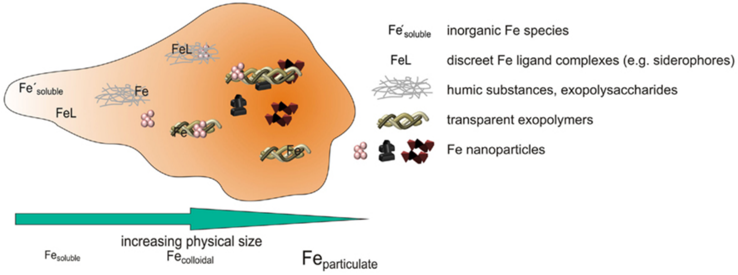


Desferrioxamine
(hydroxamate)

Witter et al., 2000

- binding if iron to organic ligands prevents rapid scavenging
- two main types of ligands proposed: degradation products, such as porphyrins, and siderophores, produced by bacteria under iron limitation
- production / degradation pathways probably as varied as ligand origins

IT IS EVEN WORSE..



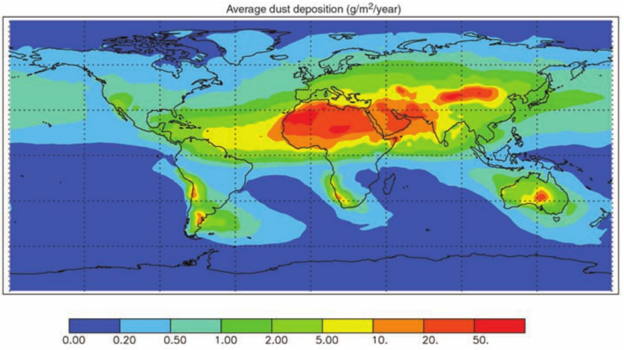
Gledhill et al., 2012

besides redox speciation and organic complexation, iron species can be anything between dissolved, colloidal and small particles

speciation influences residence time

modelling iron cycling in the ocean is not trivial! Iron model intercomparison (FEMIP) (Tagliabue et al. 2016)

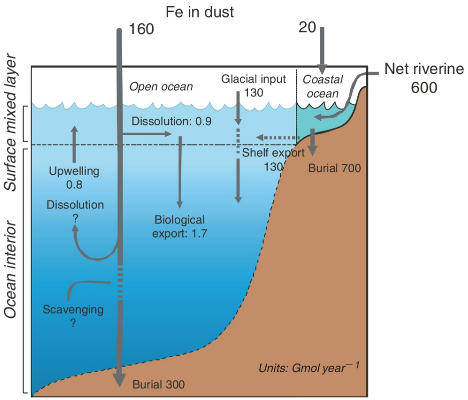
THE MAIN EXTERNAL IRON SOURCE: DUST DEPOSITION



(Jickells et al., 2005)

- dust carries lots of iron into the ocean
- but only a small (and variable) fraction dissolves!
- dissolution depends on wet/dry deposition, atmospheric history, but especially iron chemistry in the water

OTHER SOURCES OF IRON



(Hunter, 2007)

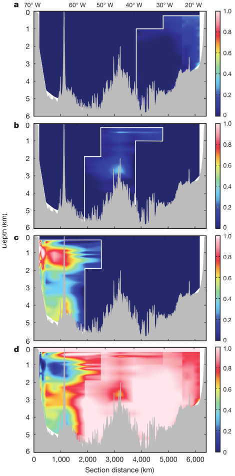
besides dust, there are also other sources of iron:

- rivers
- sediment diagenesis
- glacial scour
- hydrothermalism

but for all of them, most of the iron is lost as particles close to the source.

iron sources are not well quantified

TROPICAL ATLANTIC: DOMINATED BY DUST



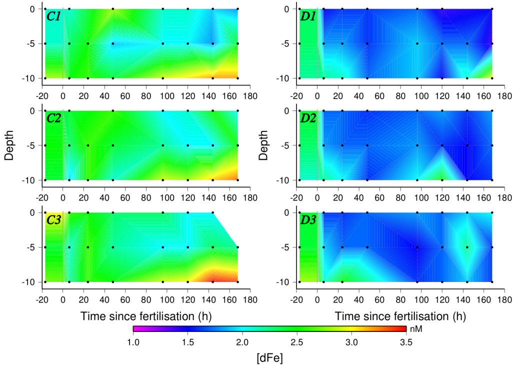
(Conway et al, 2014)

relative role of the different iron sources along a section across the subtropical/tropical Atlantic estimated from isotopic composition of dissolved iron

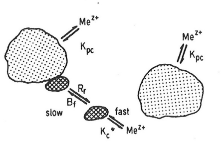
- sediment diagenesis
- hydrothermalism
- suspended sediment particles
- saharan dust

→ in the tropical and subtropical Atlantic, dust dominates as a source of iron

BUT: DUST ALSO SCAVENGES DISSOLVED IRON



(Wagener et al. 2010)

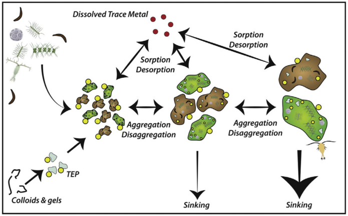


(Honeyman & Santschi 1989)
colloidal pumping mechanism

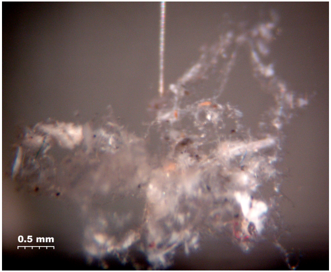
dissolved iron decreases after dust addition in mesocosms;
dust can act as dFe sink

is that important in the open Atlantic, where often biogenic particles dominate?
needs understanding & modelling of particle dynamics!

PARTICLE DYNAMICS



aggregation processes (Jackson and Burd 2015)



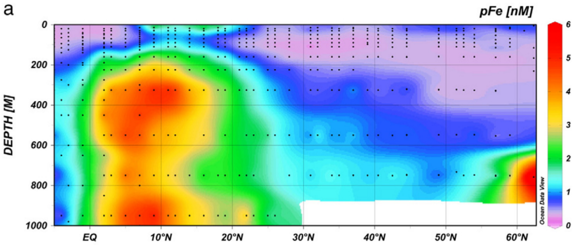
typical marine aggregate (Iversen, pers. comm.)

dust brings in mostly micrometer-sized particles

these hardly sink on their own

sinking dominated by larger, mixed organic/inorganic aggregates

LITHOGENIC MATERIAL IN THE ATLANTIC



particulate Fe along section A16N (Barrett et al. 2012)

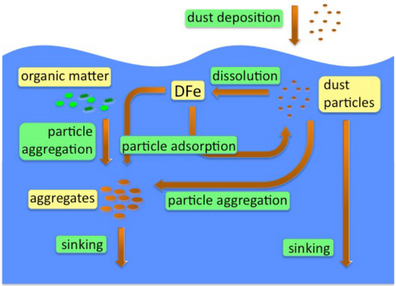
much new information on lithogenic particles from A16N and US Geotraces Atlantic Zonal Transect (Barrett at al. 2012, 2015, Lam et al. 2015, Ohnemus et al. 2015)

- increased pFe under dust plume
- high pFe at the surface, mimimum around 100m depth, then again increase
- deep lithogenic particle concentration dominated by small particles
- large fraction of lithogenics highest around 100 m depth, higher towards African coast

indicates dynamic aggregation / disaggregation cycle

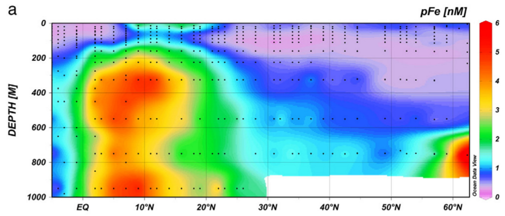
MODEL SETUP

global biogeochemical model REcoM including the iron cycle (Hauck et al. 2013, Völker and Tagliabue 2015)

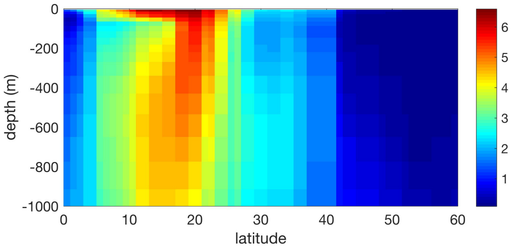


- added model for lithogenic particles with two size classes (fine dust and faster-sinking aggregates)
- quadratic aggregation and linear disaggregation of particles
- lithogenic particles included as additional scavenging agents for dissolved iron
- scavenging proportional to particle concentration
- rate equal for organic and lithogenic particles

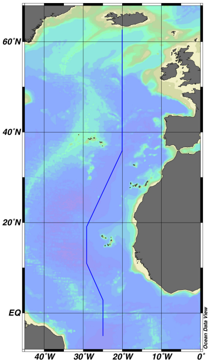
MODELLED VS. OBSERVED PARTICULATE FE



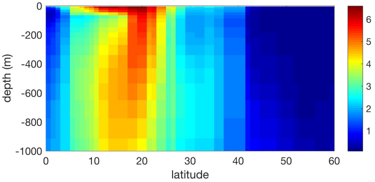
particulate Fe along section A16N (Barrett et al. 2012)



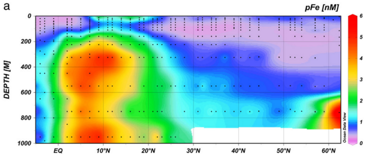
modelled particulate Fe (nM) along section A16N



MODELLED VS. OBSERVED PFE



modelled pFe (nM) along A16N

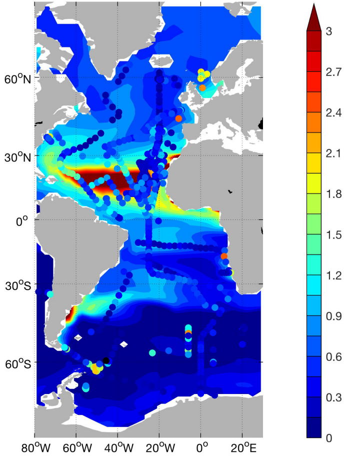


obs’d pFe along A16N (Barrett et al. 2012)

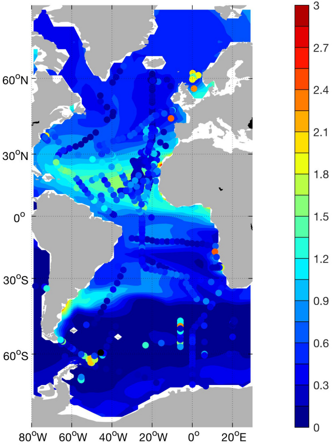
some agreement, but also some disagreement:

+ pFe concentration in the right order of magnitude
+ minimum in particle concentration around 100m depth
+ size-class distribution consistent with Ohnemus et al. (2015)
– surface pFe concentration somewhat high → aggregation rate?
– deep pFe maximum too deep → variable disaggregation?
– deep pFe maximum too far north → dust deposition?
– shelf-derived nepheloid layers absent

EFFECT ON DISSOLVED FE

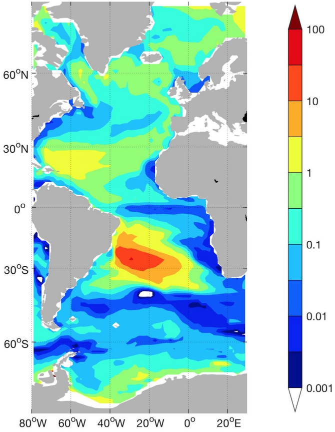


dFe with dust only as Fe source



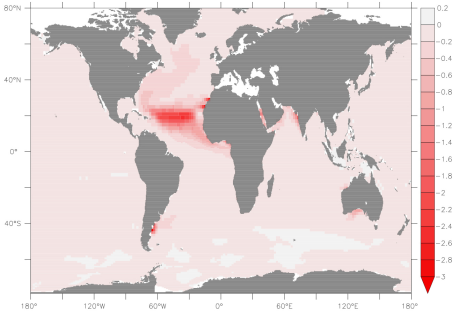
dFe with dust as Fe source and as additional scavenging

WHY THE REDUCTION? RESIDENCE TIME OF DFE



- residence time (stock/total loss rate in years) of dissolved iron varies by several orders of magnitude
- affected by scavenging on dust/biological particles and biological uptake
- distribution of residence time agrees quite well with data-based estimates (Usher et al. 2013)

GLOBAL EFFECT AT SURFACE

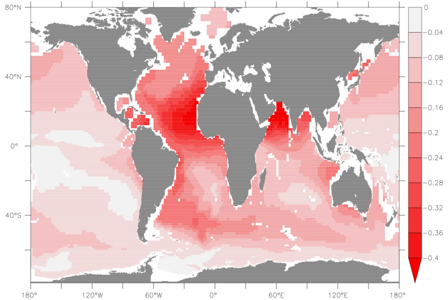


surface dFe difference between a run with/without lithogenic particles present as scavenging agent

scavenging by lithogenic particles

- reduces surface dFe directly in high-deposition regions
- but hardly everywhere else

Global effect at depth

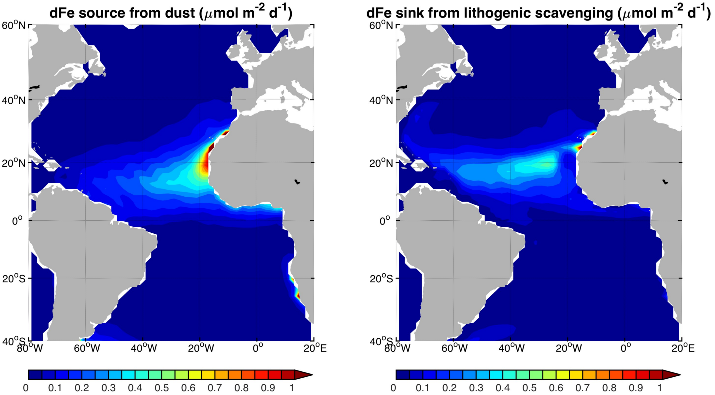


dFe difference (2000 m depth) between a run with/without lithogenic particles

- dFe reduction more widespread at depth
- 1st cause: lateral transport of fine lithogenic material
- 2nd cause: downstream effect of localized scavenging
- reduces deep water dFe Atlantic – Pacific gradient

caveats: strength of effect depends on scavenging residence time, at present highly tuned in ocean iron models (Tagliabue et al., 2016)
also affected by ligand excess (Völker and Tagliabue, 2015)

SO, IS DUST A SOURCE OR A SINK OF DFE?



so: how much source, how much sink?
generally, dFe source stronger than vertically integrated sink; but depends somewhat where you look!

SOME CONCLUSIONS

- lithogenic particles in the Atlantic modeled with a 2-size-class model
- both aggregation and disaggregation important
- reproduces some features of observed distributions of lithogenic particles
- brings surface dFe distributions under the dust plume more in line with observations
- affects on the global deep dFe distribution through lateral transport
- allows to quantify the role of scavenging and compare it to local sources
- need to go further in developing more process-oriented iron models, making use of the available and coming GEOTRACES data