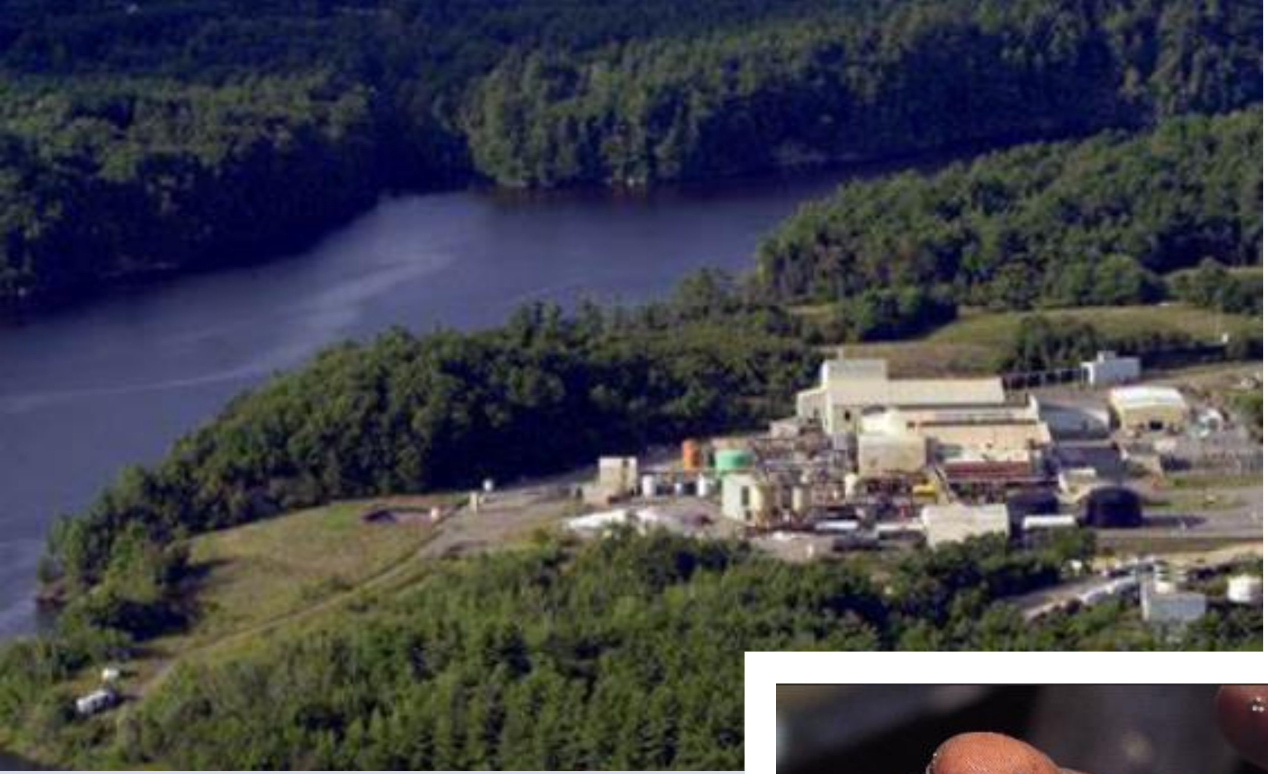
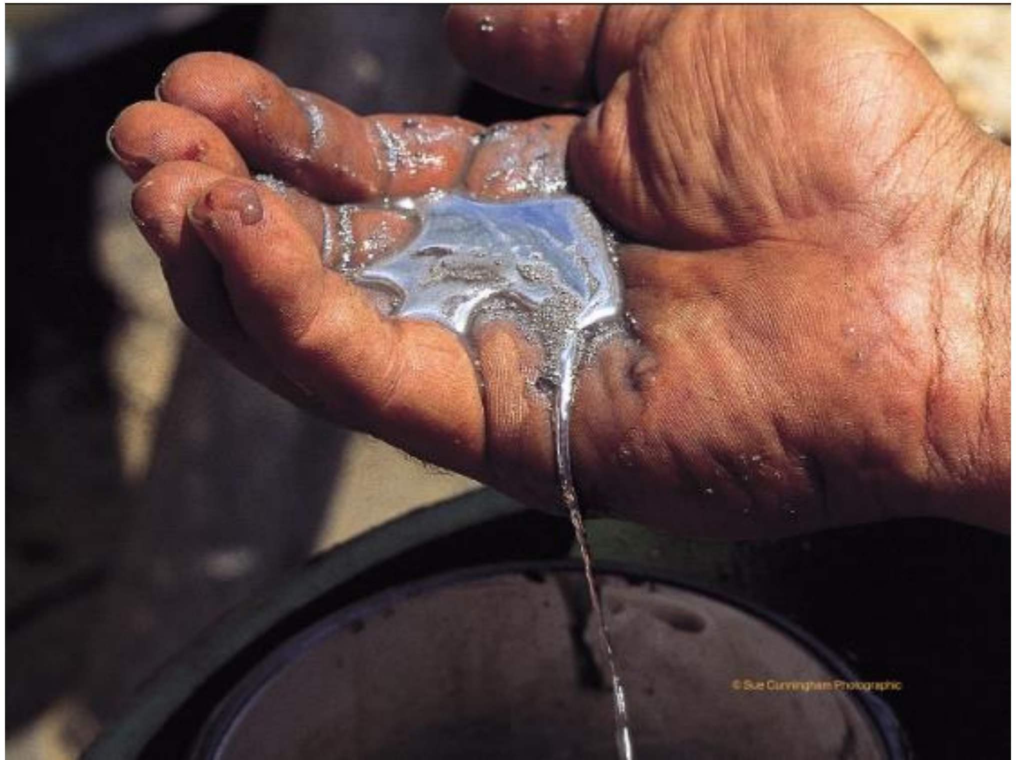


# Mercury Pollution in Aquatic Ecosystems

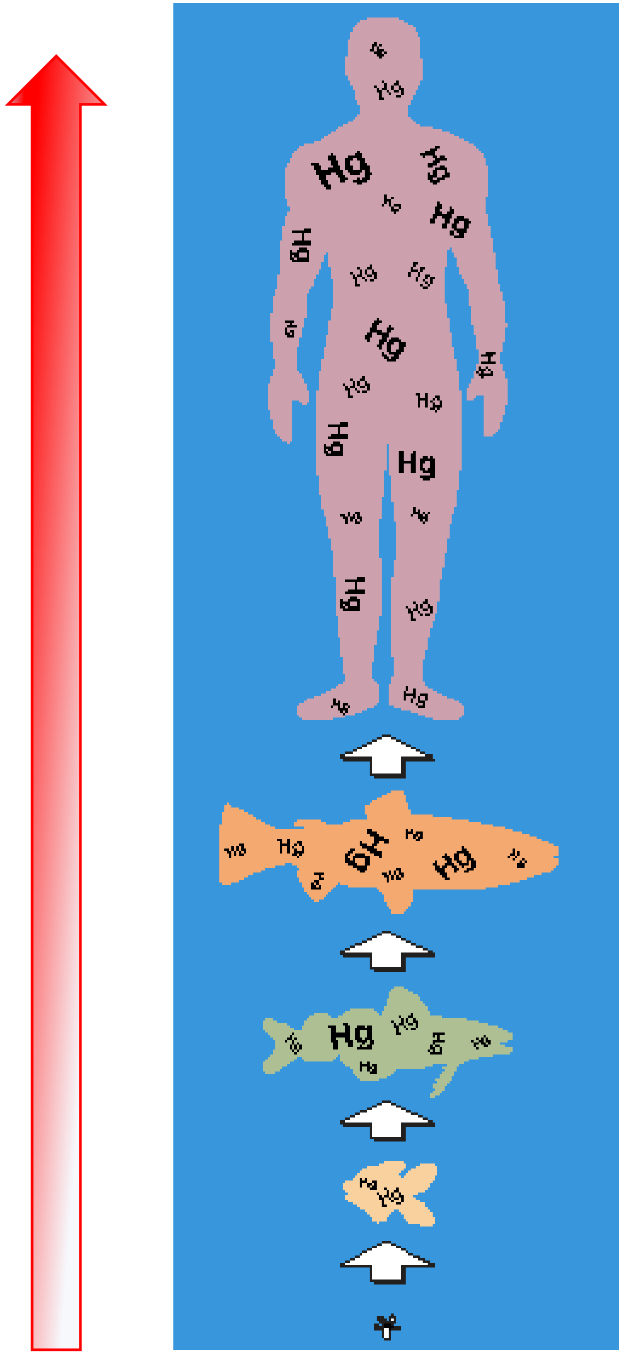


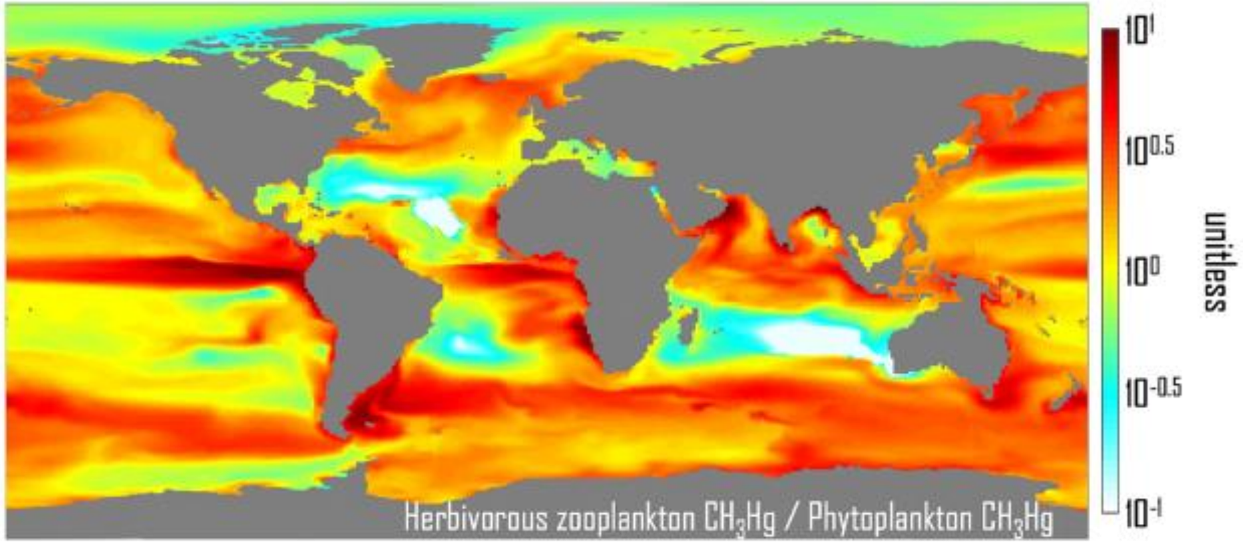

Karen A. Merritt, PhD MPH

# What do we know regarding the biomagnification process?

- Sulfate ($SO_4^{2-}$) + low-to-no dissolved oxygen ($O_2$) increases activity of sulfate-reducing bacteria (SRB);
- SRB in the presence of inorganic mercury ($Hg^{2+}$) generate methyl mercury ($CH_3Hg^+$) as an accident/by-product of respiration;
- Methyl mercury is retained in biological tissue more significantly than inorganic mercury because of the additional $-CH_3$ (methyl) group;
- Bioaccumulation of methyl mercury occurs because the depuration (loss) rate of methyl mercury from biological tissue is much lower/slower than the loss rate of inorganic mercury;
- Biomagnification happens through the trophic transfer of bioaccumulated methyl mercury from small prey species to larger prey (or predator) species to largest predator species (including humans)

Zhang et al., 2020, https://doi.org/10.1029/2019GB006348





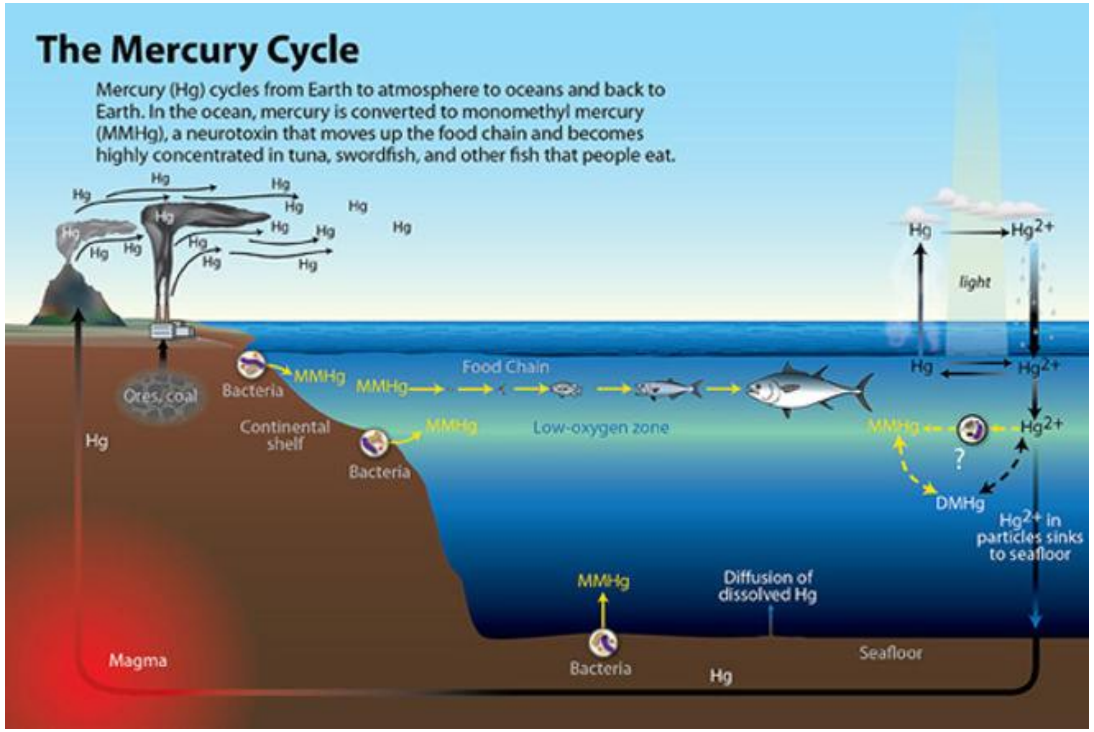

## A Global Model for Methylmercury Formation and Uptake at the Base of Marine Food Webs

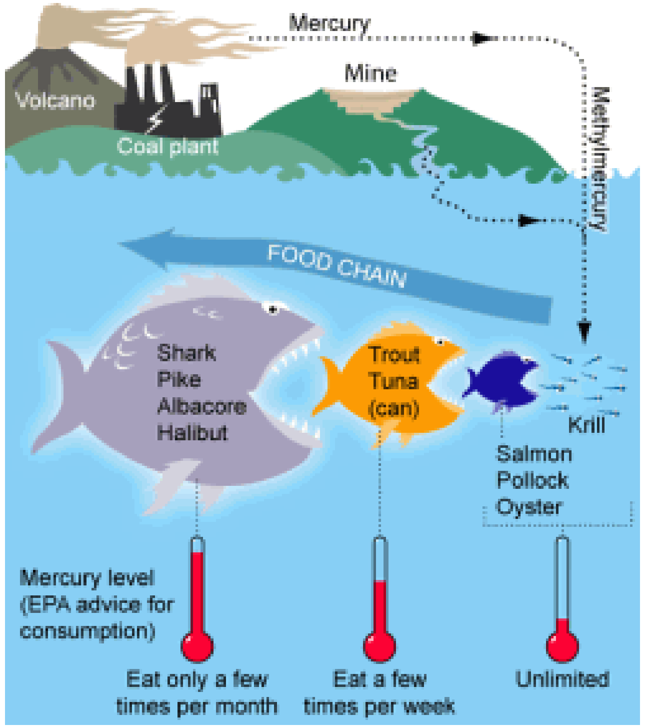

Yanxu Zhang[1,2], Anne L. Soerensen[2,3,4], Amina T. Schartup[2,3,5], and Elsie M. Sunderland[2,3]

[1]Joint International Research Laboratory of Atmospheric and Earth System Sciences, School of Atmospheric Sciences, Nanjing University, Nanjing, China, [2]Harvard John A. Paulson School of Engineering & Applied Sciences, Harvard University, Cambridge, MA, USA, [3]Department of Environmental Health, Harvard T. H. Chan School of Public Health, Harvard University, Boston, MA, USA, [4]Department of Environmental Science and Analytical Chemistry, Stockholm University, Stockholm, Sweden, [5]Scripps Institution of Oceanography, La Jolla, CA, USA



**Abstract** Monomethylmercury ($CH_3Hg$) is the only form of mercury (Hg) known to biomagnify in food webs. Here we investigate factors driving methylated mercury [MeHg = $CH_3Hg$ + $(CH_3)_2Hg$)] production and degradation across the global ocean and uptake and trophic transfer at the base of marine food webs. We develop a new global 3-D simulation of MeHg in seawater and phyto/zooplankton within the Massachusetts Institute of Technology general circulation model. We find that high modeled MeHg concentrations in polar regions are driven by reduced demethylation due to lower solar radiation and colder temperatures. In the eastern tropical subsurface waters of the Atlantic and Pacific Oceans, the model results suggest that high MeHg concentrations are associated with enhanced microbial activity and atmospheric inputs of inorganic Hg. Global budget analysis indicates that upward advection/diffusion from subsurface ocean provides 17% of MeHg in the surface ocean. Modeled open ocean phytoplankton concentrations are relatively uniform because lowest modeled seawater MeHg concentrations occur in oligotrophic regions with the smallest size classes of phytoplankton, with relatively high uptake of MeHg and vice versa. Diatoms and synechococcus are the two most important phytoplankton categories for transferring MeHg from seawater to herbivorous zooplankton, contributing 35% and 25%, respectively. Modeled ratios of MeHg concentrations between herbivorous zooplankton and phytoplankton are 0.74–0.78 for picoplankton (i.e., no biomagnification) and 2.6–4.5 for eukaryotic phytoplankton. The spatial distribution of the trophic magnification factor is largely determined by the zooplankton concentrations. Changing ocean biogeochemistry resulting from climate change is expected to have a significant impact on marine MeHg formation and bioaccumulation.

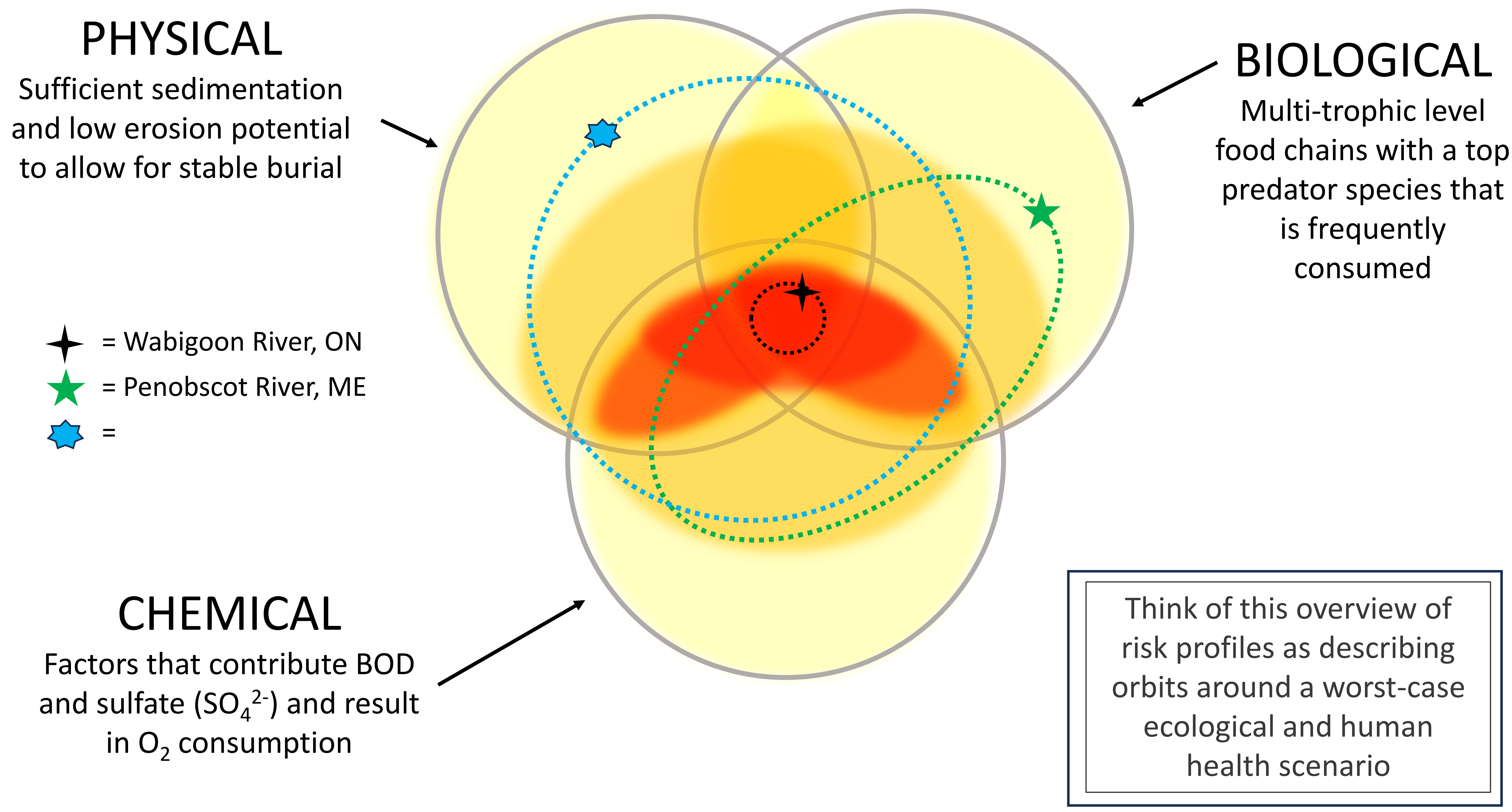



# Think about **risk profiles** for different locations in terms of:

- **Physical factors** – what is the burial rate of contamination based on the geological background (i.e., how much sediment is available for burying contamination quickly to a depth below the biological mixed depth or biologically active zone?); how to hydrodynamics impact stable burial?

- **Chemical factors** – what factors are present that can create the conditions in which SRB are active? Factors of concern are those that contribute sulfate ($SO_4^{2-}$) and biochemical oxygen demand (BOD) such that significant $O_2$ consumption occurs. Factors can be anthropogenic but aren't always.

- **Biological factors** – what are the species of concern and what do trophic transfer pathways look like? For human health concerns, what are the frequency and frameworks for consumption (i.e, recreational and infrequent vs frequent and culturally or socio-economically significant)?



PHYSICAL
Sufficient sedimentation and low erosion potential to allow for stable burial
BIOLOGICAL
Multi-trophic level food chains with a top predator species that is frequently consumed
CHEMICAL
Factors that contribute BOD and sulfate ($SO_4^{2-}$) and result in $O_2$ consumption
= Wabigoon River, ON
= Penobscot River, ME
=
Think of this overview of risk profiles as describing orbits around a worst-case ecological and human health scenario

# Site Comparison

## Penobscot River Estuary, Maine

- Glaciated terrain and low sed. rates (~ 0.5 cm/yr)
- Lobster as a TL2 species; in terms of frequency, consumption is not culturally significant; TL4 specie is American eel – may be an ecological concern, but not an acute HH concern.
- Biogeochemical concerns due to wood waste – elevated % methylation on marshes; most concerning trophic transfer pathway to marsh species is via terrestrial food web for migratory songbirds.
- Surface sediment concentrations < 10 mg/kg in vicinity of site and < 1 mg/kg across majority of the estuary.
- No acute, severe or obvious human health concerns; species of greatest consumption are lobster and ducks, both of which have consumption restrictions in place via licensing structure/programs.

## Wabigoon River, Ontario

- Glaciated terrain and very low sed. rates (~ 0.3 cm /yr)
- Walleye and Northern pike as TL4 species; consumption is culturally significant
- Mill effluent renders the river suboxic/anoxic in summer; stratification of an in-river lake contributes to > 2 ug/g in walleye.
- Surface sediment mercury concentrations exceed 50 mg/kg in vicinity of mill and are elevated consistently > 1 mg/kg for a distance of ~ 40 miles downstream.
- Human health impacts are acute, severe and with multi-generational manifestation; fish are consumed whether or not a consumption restriction is in place.

# Grassy Narrows ANA Community – This is Living Downstream





Health in Grassy Narrows 'significantly worse' than other First Nations: report

# Grassy Narrows ANA Community

Research

A Section 508–conformant HTML version of this article is available at https://doi.org/10.1289/EHP11301.

## The Contribution across Three Generations of Mercury Exposure to Attempted Suicide among Children and Youth in Grassy Narrows First Nation, Canada: An Intergenerational Analysis

*Donna Mergler,[1] Aline Philibert,[1] Myriam Fillion,[2,1] and Judy Da Silva[3]*

## Mercury exposure and premature mortality in the Grassy Narrows First Nation community: a retrospective longitudinal study

*Aline Philibert, Myriam Fillion, Donna Mergler*

**Summary**

**Background** Little is known about the influence of toxic exposures on reduced life expectancy in First Nations people in Canada. The Grassy Narrows First Nation community have lived with the consequences of one of the worst environmental disasters in Canadian history. In the early 1960s, 10 000 kg of mercury (Hg) was released into their aquatic ecosystem. Although Hg concentration in fish, their dietary staple, decreased over time, it remains high. We aimed to examine whether elevated Hg exposure over time contributes to premature mortality (younger than 60 years) in this community.

**Methods** We did longitudinal and case-control analyses with data for individuals of the Grassy Narrows First Nation community. In 2019, the community obtained their historical Hg biomarker data from a government surveillance programme, which was then shared with the authors. A matched-pair approach allowed us to compare longitudinal hair Hg concentration between cases (individuals who died aged younger than 60 years) and controls (individuals who lived beyond 60 years). Matching criteria included year of birth (allowing 2 years either side), sex, and a minimum of four hair Hg concentration measures, of which at least two were in the same year. Analyses included change-point detection, interrupted time series, mixed models, and Cox survival models.

**Findings** We analysed data collected between Jan 1, 1970, and Jan 31, 1997, for 657 individuals (319 women and 338 men, born between 1884 and 1991) for whom we assembled a retrospective database of yearly measures of hair Hg concentration (n=3603). Hair Hg concentration decreased over time. A subgroup of 222 individuals (107 women and 115 men) reached or could have reached 60 years old by August, 2019. There was an increased risk of dying at a younger age among those with at least one hair Hg measure of 15 µg/g or more (adjusted hazard ratio 1·55, 95% CI 1·11–2·16; p=0·0088). Among the deceased individuals (n=154), longevity decreased by 1 year with every 6·25 µg/g (4·35–14·29) increase in hair Hg concentration. Analyses of 36 matched pairs showed that hair Hg concentration of those who died aged younger than 60 years was 4·7 µg/g higher (3·4–5·9) than controls.

**Interpretation** The consistent findings between our different analyses support an association between long-term Hg exposure from freshwater fish consumption and premature mortality in this First Nation community. There is a need to do risk-benefit analyses of freshwater fish consumption in environmentally contaminated regions.

*Lancet Planet Health* 2020; 4: e141–48

This online publication has been corrected. The corrected version first appeared at thelancet.com/planetary-health on May 11, 2020, and further corrections have been made on July 15, 2020

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CANADA

## Ontario knew about Grassy Narrows mercury site for decades, but kept it secret

Toronto Star
November 11, 2017

A confidential 2016 report says provincial officials were told in the 1990s that the site of a paper mill near Grassy Narrows First Nation was contaminated with mercury — and that the poison is likely still present.

LINK

# Walleye (1970 – 2017)

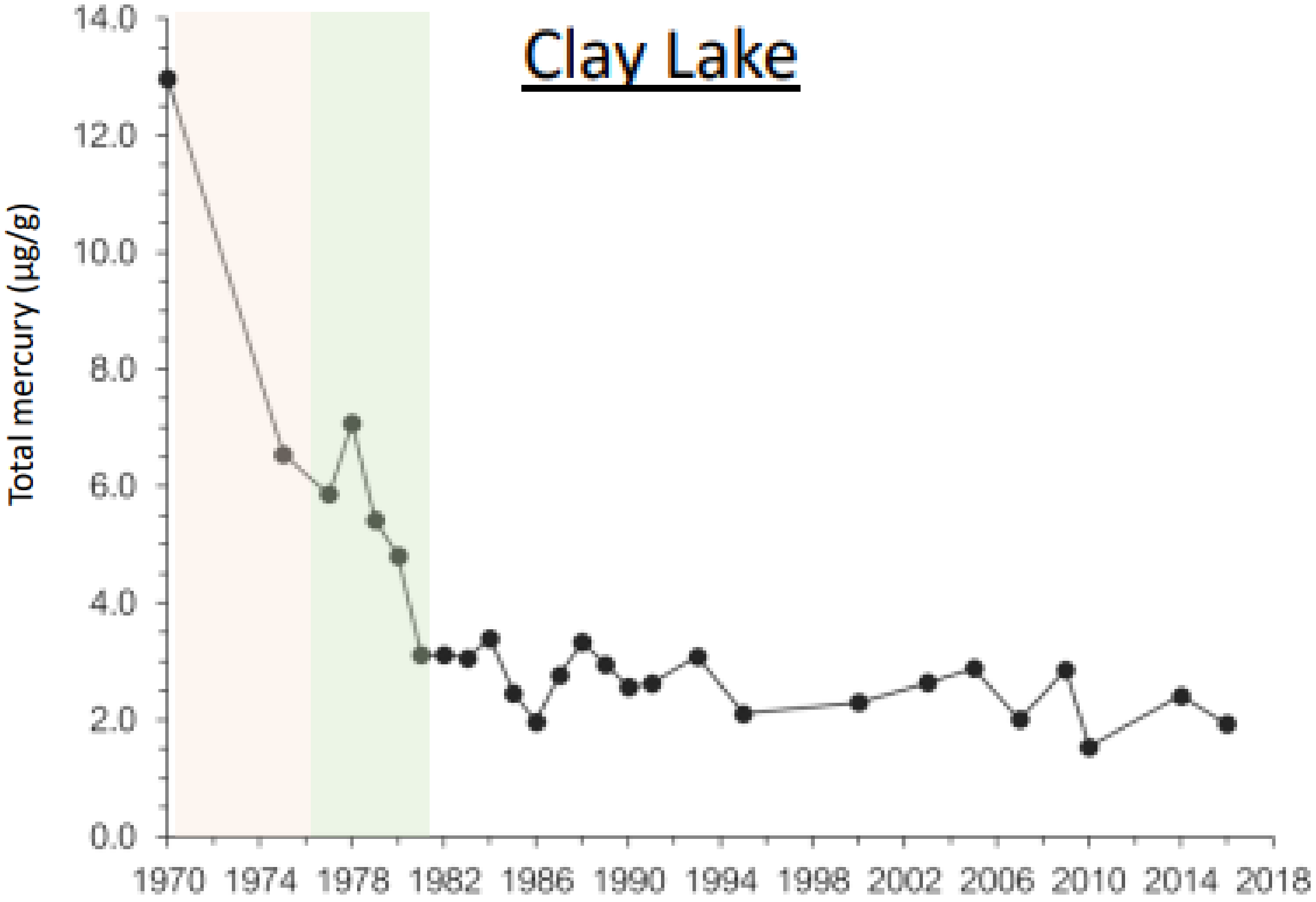



TABLE 7.1. Annual mercury discharges from the chlor-alkali plant, Great Lakes Forest Products Limited, Dryden.

| Year | Mercury Loss (kg) |
|---|---|
| 1962-69 | 1100 |
| 1970 | 350 |
| 1971 | 9.1 |
| 1972 | 2.3 |
| 1973 | 2.1 |
| 1974 | 1.7 |
| 1975 | 2.0 |
| 1976 | 1.2 |
| 1977 | 1.7 |

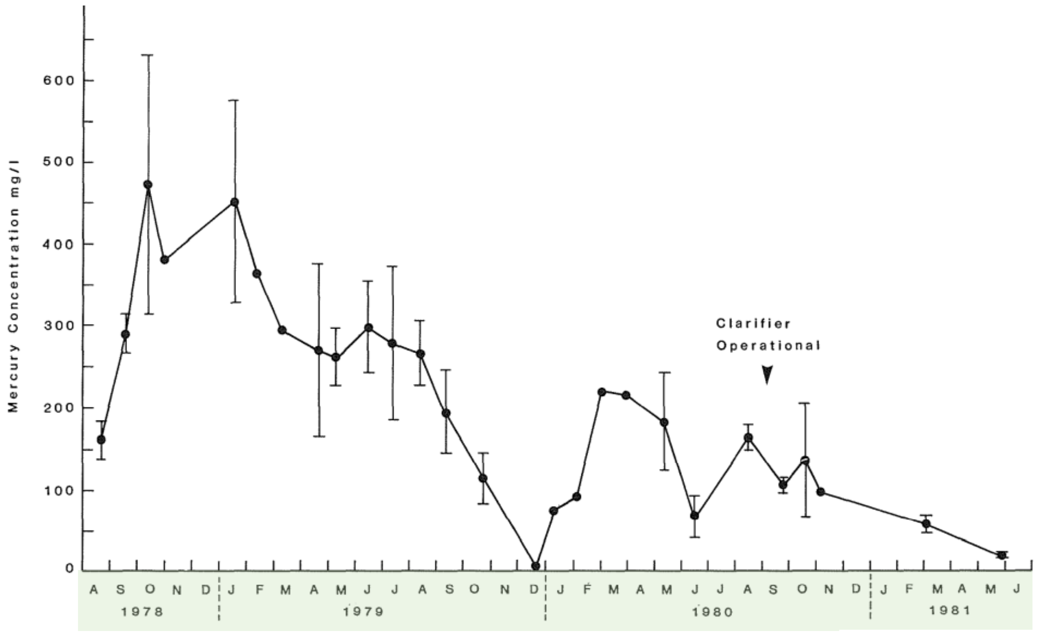



Figure 7.1 Mean monthly mercury concentrations of mill effluent, August, 197

# Waste from mill worsening mercury contamination in river near Grassy Narrows: study


Industrial discharge from a paper mill in northern Ontario is exacerbating mercury contamination in a river system near a First Nation that has been plagued with mercury poisoning for decades, a new study suggests. Grassy Narrows Chief Rudy Turtle holds a sign as he marches with supporters through downtown Toronto in a 2019 handout photo.

# Grassy Narrows chief calls out Ottawa for 'ridiculous' delays to mercury treatment centre construction

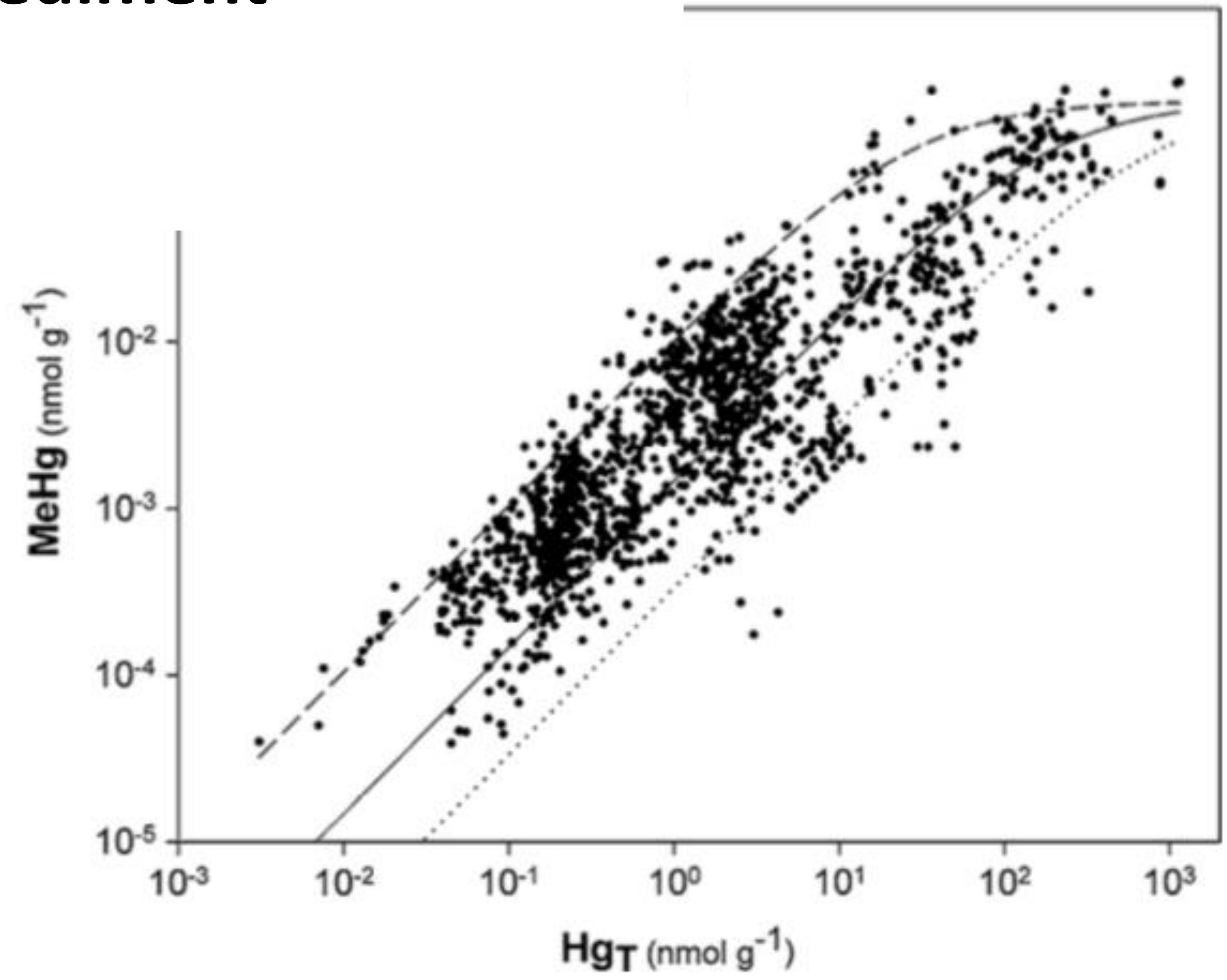
Trudeau said 'money is not the objection' to building the centre during 2019 election debate

Brett Forester · CBC News · Posted: Feb 16, 2024 12:42 PM EST | Last Updated: February 16

Rudy Turtle, chief of Grassy Narrows First Nation, addresses a rally against mining proposals on First Nations territory in Toronto in July 2023. (Evan Mitsui/CBC)

# Relationship between total mercury ($Hg_T$) and methyl mercury (MeHg) in **sediment**

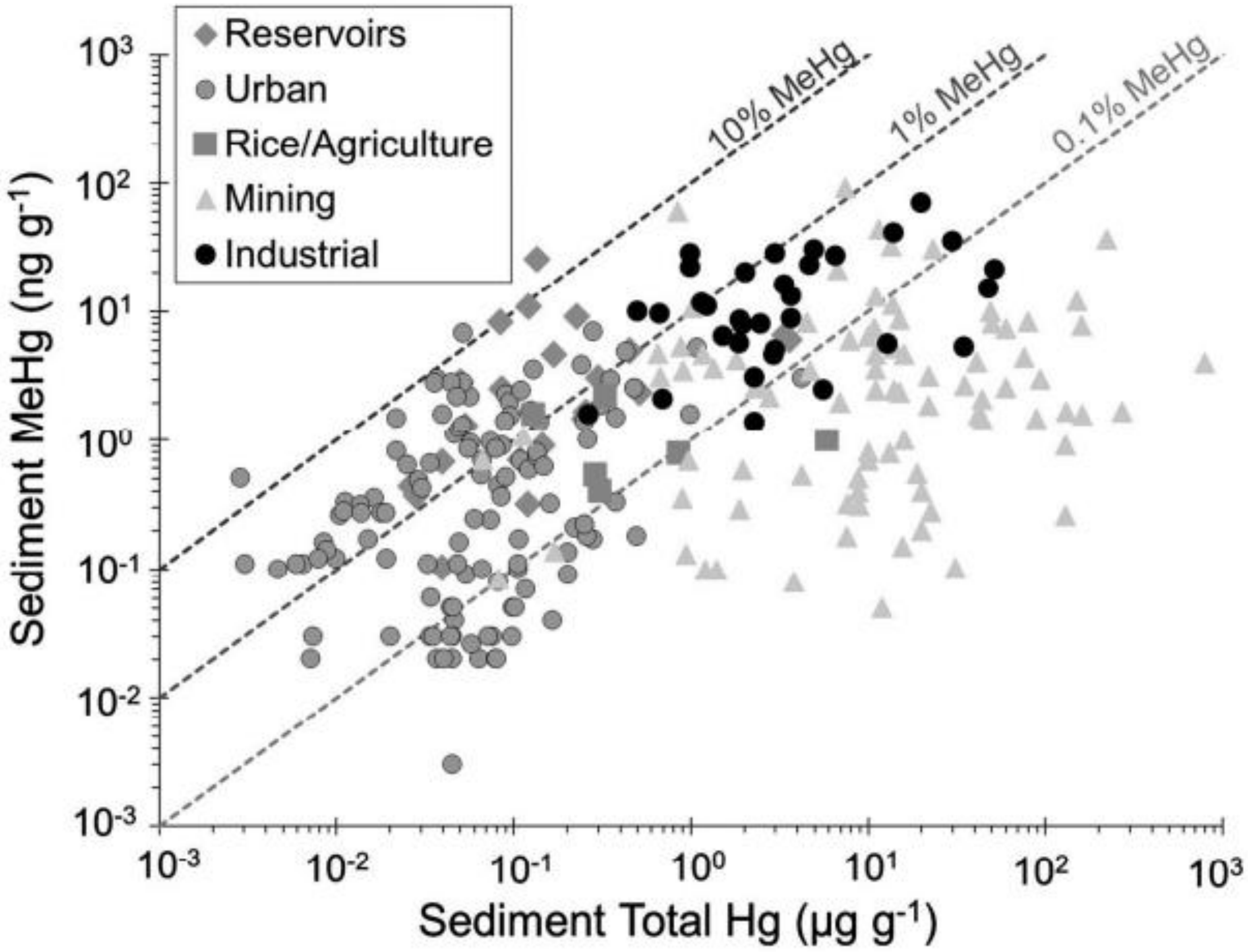
- 1400 data pairs
- Salinity continuum
- Range in organic carbon concentration and quality
- Range in level of contamination
- Variable sources




Note that the relationship in this graph is descriptive of sampling conditions; it is not predictive of remedial response (meaning: we should be careful of trying to over-specify the extent to which decreasing $Hg_T$ necessarily results in predictable declines in MeHg).

Figure from: Cossa et al. 2013. A Michaelis–Menten type equation for describing methylmercury dependence on inorganic mercury in aquatic sediments. Biogeochemistry. 119, 35–43.

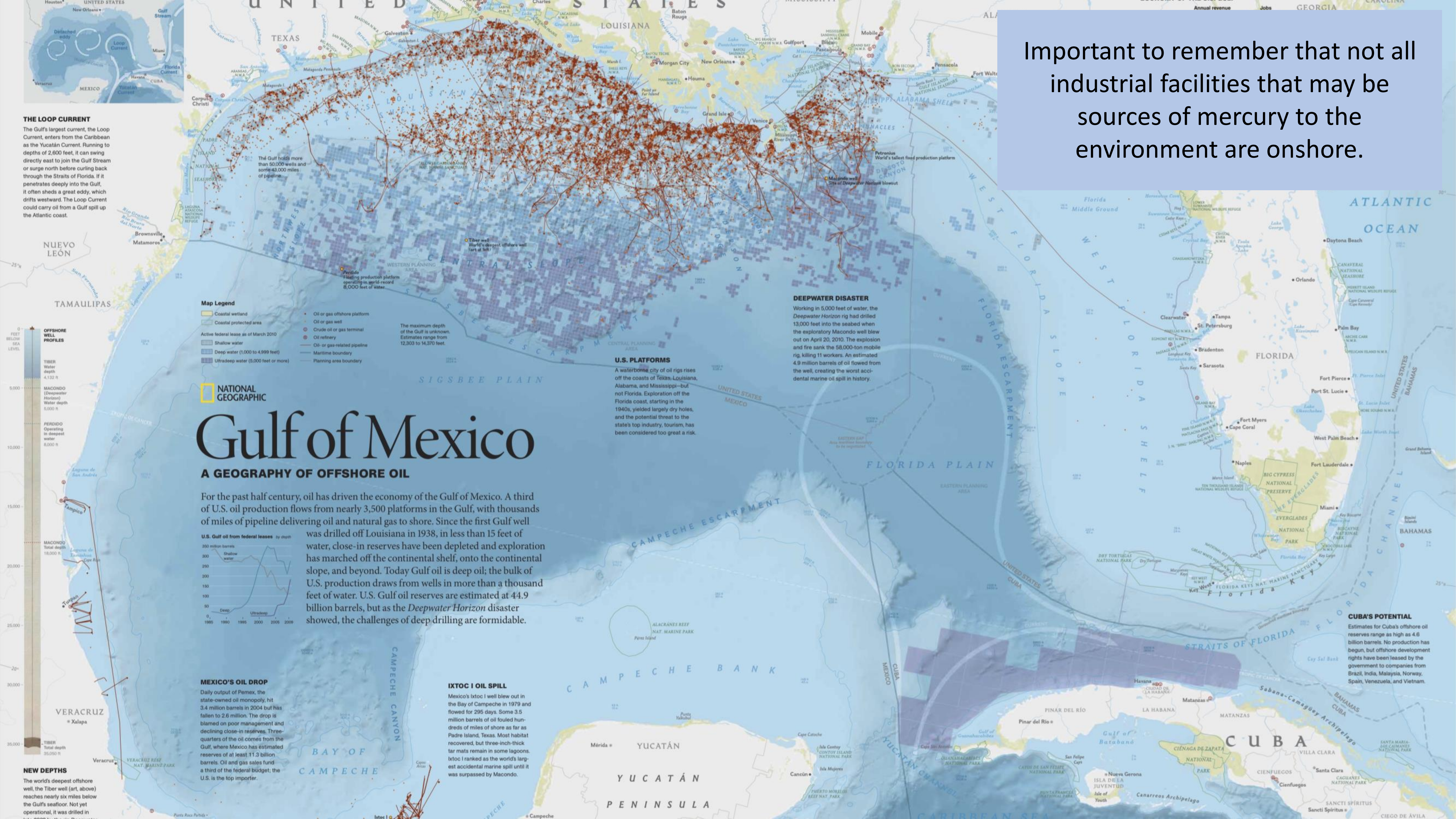
# How Do These Data Distribute by Source/Type of Environment?




Note that the relationships in this graph are descriptive of sampling conditions; they are not predictive of remedial response (meaning: we should be careful of trying to over-specify the extent to which decreasing $Hg_T$ necessarily results in predictable declines in MeHg).

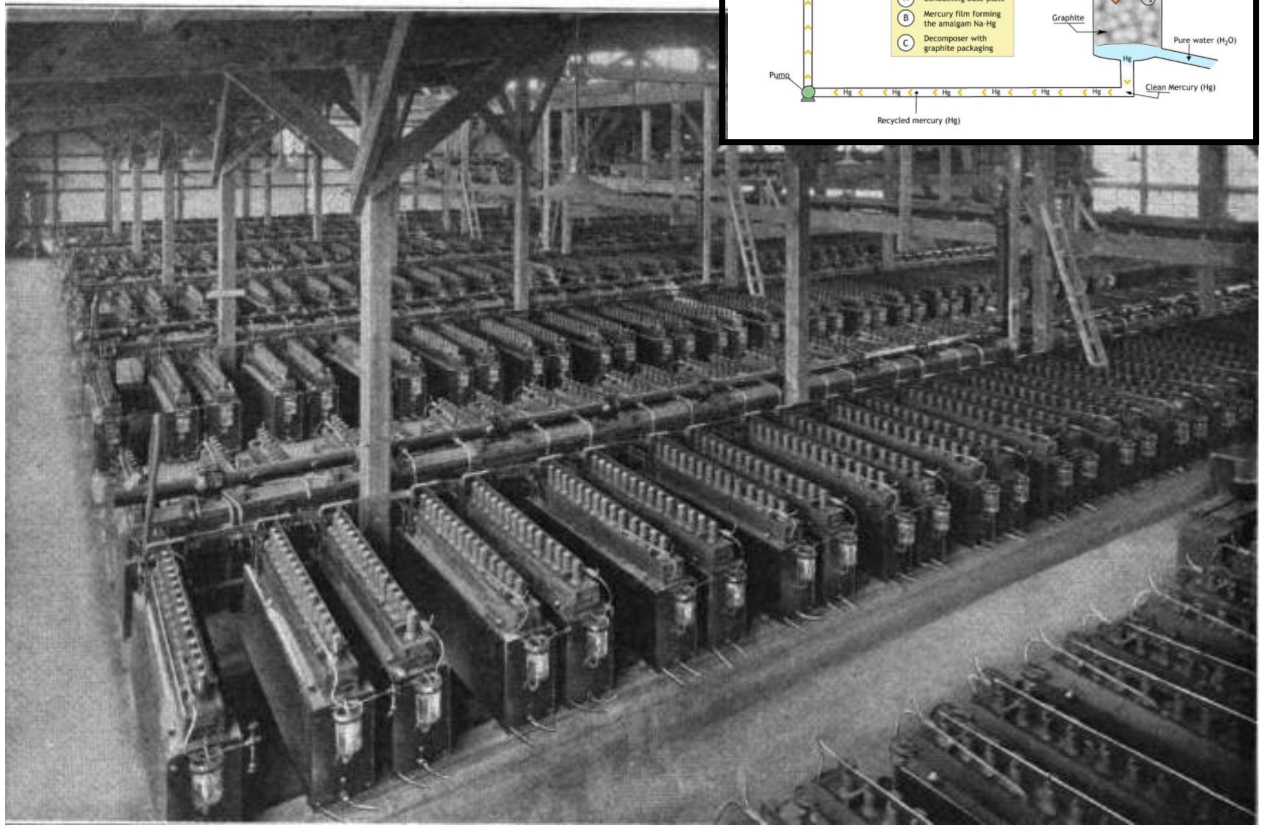
Figure from: Hsu-Kim et al. 2018. Challenges and Opportunities for managing aquatic mercury pollution in altered landscapes. Ambio. 47: 141-169.

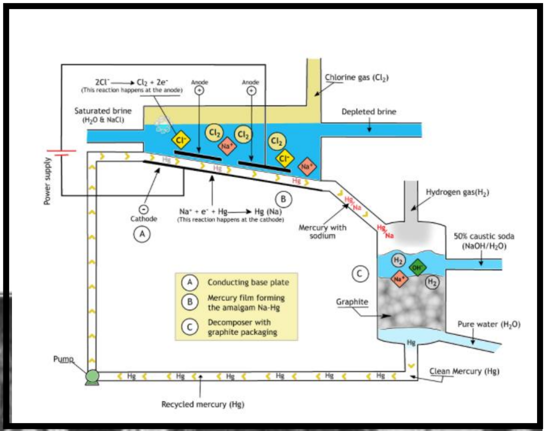
Important to remember that not all industrial facilities that may be sources of mercury to the environment are onshore.



# Mercury cell chlor-alkali process

$$2NaCl + 2H_2O + ✷ \rightarrow 2NaOH + Cl_2 + H_2$$






Facility operations commonly released ~ 10 tons of mercury into adjacent waters (plus unquantified volumes into the atmosphere)

**Locations of Former or Current Mercury Cell Chlor-Alkali Facilities**

Acme, NC
Ashtabula, OH
Augusta, GA
Bellingham Bay, WA
Berlin, NH
Brunswick, GA
Calvert City, KY
Charleston, TN
Deer Park, TX
Delaware City, DE
East St. Louis, IL
Geismar, LA
Lake Charles, LA
Lavaca Bay, TX
Lemoyne, AL
Linden, NJ
McIntosh, AL
Midland, MI
Mobile, AL
Moundsville, WV
Muscle Shoals, AL
New Castle, DE
New Martinsville, WV
~~Niagara Falls, NY~~ (×2)
Orrington, ME
Plaquemine, LA
Port Edwards, WI
St. Gabriel, LA
Syracuse, NY
Dalhousie, NB
Saguenay, Quebec
Beauharnois, Quebec
Marathon, ON
Cornwall, ON
Sarnia, ON
Dryden, ON
Port Abercrombie, NS
Squamish, BC
Coatzacoalcos-Minatitlán, Mexico
García Nuevo León, Mexico
Ecatepec de Morelos, Mexico
Santa Clara, Mexico

Sagua la Grande, Cuba
Cartagena, Colombia
Itapagipe, Bahia, Brazil
Botafogo River estuary, Brazil
Ribeira Bay, Brazil
Santo André, São Paulo, Brazil
Santos- Cubatão, Brazil
Acarí-São João de Meriti River, Brazil
Cinco Saltos / Upper Negro River, Argentina
Bahia Blanca, Argentina
Argentina -3
Montevideo, Uruguay
Lima, Peru
Callao, Peru
Maracaibo, Venezuela

Alexandria, Egypt
Mohammedia, Morocco
Algeria-1
Angola-1
Libya - 1

Bohus, Sweden
Stenungsund, Sweden
Skoghall, Sweden
Domsjø, Sweden
Koepmanholmen, Sweden
Sweden-6
Sarpsborg, Norway
Kokemäenjoki, Finland
Oulu, Finland
Aetna, Finland
Kuusankoski, Finland
Pallanza Bay, Italy
Priolo, Italy
Augusta Bay, Italy
Montova, Italy
Tavazzano, Italy
Gela, Italy
Saline di Volterra Italy
Rosignano Solvay, Italy
Brescia, Italy
Bussi, Italy
Pieve Vergonte, Italy
Volterra, Italy
Toreviscosa, Italy
Porto Marghera/Venice, Italy
Ravenna, Italy
Hallein, Austria
Brückl, Austria
Vieux-Thann, France
Tavaux, France
St. Auban, France
Jarrie, France
Loos, France
Lavéra, France
Mazingarbe, France
Jemeppe -sur-Sambre, Belgium
Antwerp, Belgium
Tessenderlo, Belgium
Botlek-Rotterdam, Netherlands
Beek Geleen, Netherlands
Delfzijl, Netherlands
Linne Herten, Netherlands
Hengelo, Netherlands
Slovenia -1
Bosnia - 1
Serbia -1
Montenegro -1
Aliaga, Turkey
Runcorn, UK
Sandbach, UK
Staveley, UK

**Locations of Former or Current Mercury Cell Chlor-Alkali Facilities**

Fleetwood, UK
Ellesmere Port, UK
Fermoy, Ireland
Torrelavega, Spain
Vilaseca, Spain
Huelva, Spain
Flix, Spain
Jodar, Spain
Monzon, Spain
Hernani, Spain
Sabinanigo/Huesca, Spain
Povoa de Santa Ir. , Portugal
Ria de Aveiro, Portugal
Thessaloniki, Greece
Bitterfeld, GR
Burghausen, GR
Dormagen, GR
Frankfurt, GR
Gendorf, GR
Gersthofen, GR
Ibbenbüren, GR
Hürth-Knapsack, GR
Krefeld-Uerdingen, GR
Lampertheim, GR
Leverkusen, GR
Ludwigshafen, GR
Lülsdorf, GR (×2)
Marl, GR (×2)
Marktredwitz, GR
Rheinfelden, GR
Schkopau, GR
Schkopau, GR
Uerdingen, GR
Wilhelmshafen, GR
Neratovice, Czech Republic
Ústí nad Labem, Czech Republic
Pardubice, Czech Republic
Nováky, Slovakia
Tarnów, Poland
Bydgoszcz, Poland
Brzeg Dony, Poland
Varna, Bulgaria
Kazincbarcika, Hungary
Ramnicu Valcea, Romania
Vlora, Albania
Kyiv, Ukraine
Kalush, Ukraine (?)

Kirovo-Chepetsk, Russia
Sterlitamak, Russia (possibly ×2)
Volgograd, Russia (possibly ×2)
Sayansk, Russia
Ufa, Russia
Dzerzhinsk, Russia
Novodvinsk, Russia
Chapaevsk, Russia
Irkutsk, Russia
Komsomolsk-on-Amur, Russia

Usolye-Sibirskoye, Russia
Koryazhma, Russia

Yavan, Tajikistan
Sumgait, Azerbajain
Pavlodar, Kazakhstan
Temirtau, Kazakhstan

Bandar Imam, Iran
Kor River site, Iran (?)
Iran -3
Iraq -1
Israel-1
Syria-1

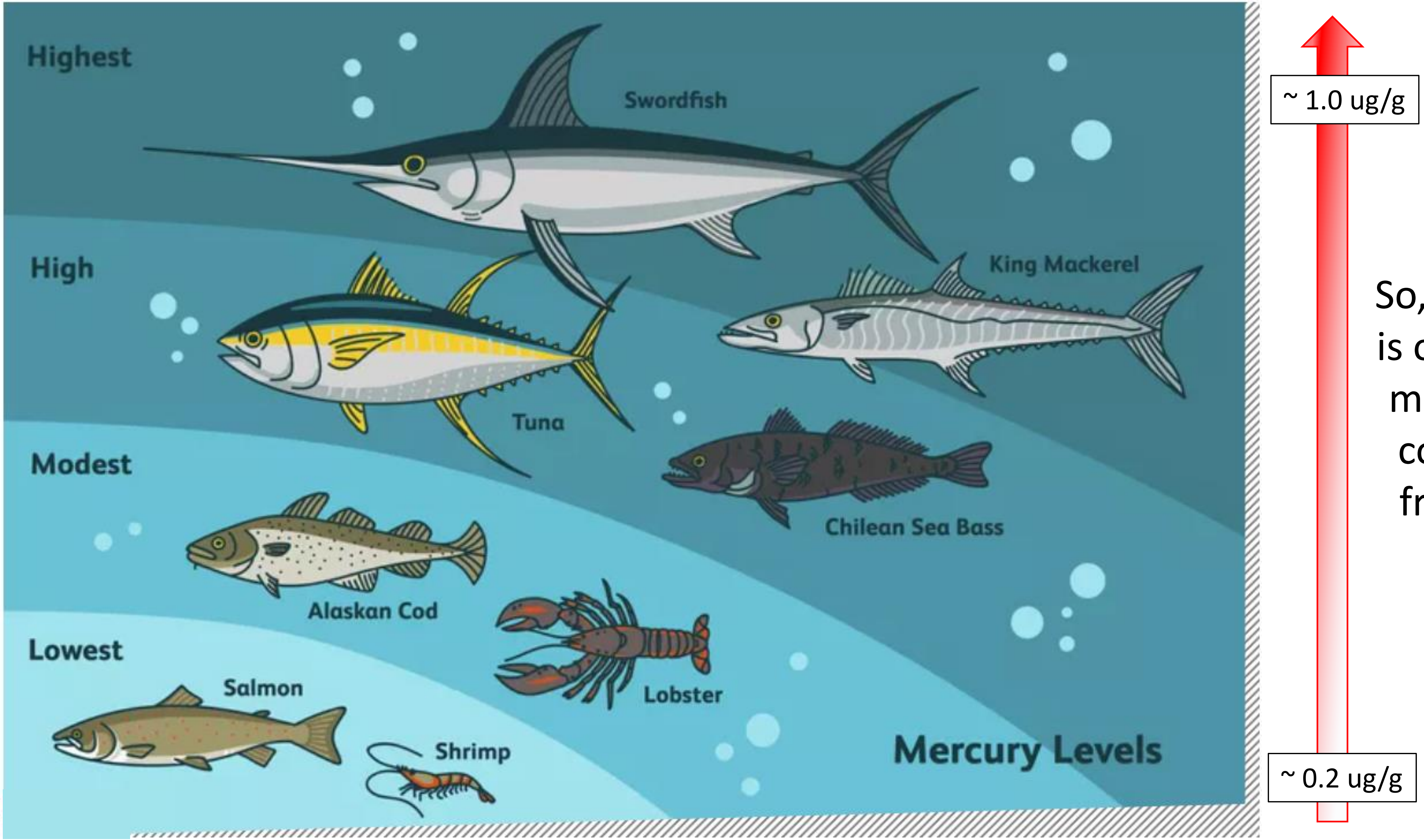
Alroli, India
Mumbai, India
Ganjam, India
Singrauli, India
Kota, Rajasthan, India
Renukoot, Uttar Pradesh, India
Nagda, Madhya Pradesh, India
Kala Shah Kaku, Pakistan
Myanmar -1
Minamata Bay, Japan
Niigata, Japan
Omi, Japan
Arai/Kosai, Japan
Uto, Japan
Shin-Nanyo, Yamaguchi, Japan
Tokuyama, Yamaguchi, Japan
Mizushima, Kurashiki, Okayama, Japan
Takasago, Hyōgo, Japan
Nobeoka City, Miyazaki, Japan
Kashima, Ibaraki, Japan
Ichihara City, Chiba, Japan
An Ning, China
Huludao, China
Tianjin, China
Yongjing, China
Qingzhen, China
Jilin City, China
Dezhou City, Shandong Province, China
Kaohsiung City, Taiwan
Merak, Banten Province, Indonesia
Indonesia-2
Phillipines-1
Hamhung, North Korea
North Korea-2

Mercury Cell Chlor-Alkali Facility – identified
Mercury Cell Chlor-Alkali Facility – newly added
Mercury Chlor-Alkali Facility– not confirmed*
Acetaldehyde Facility – identified

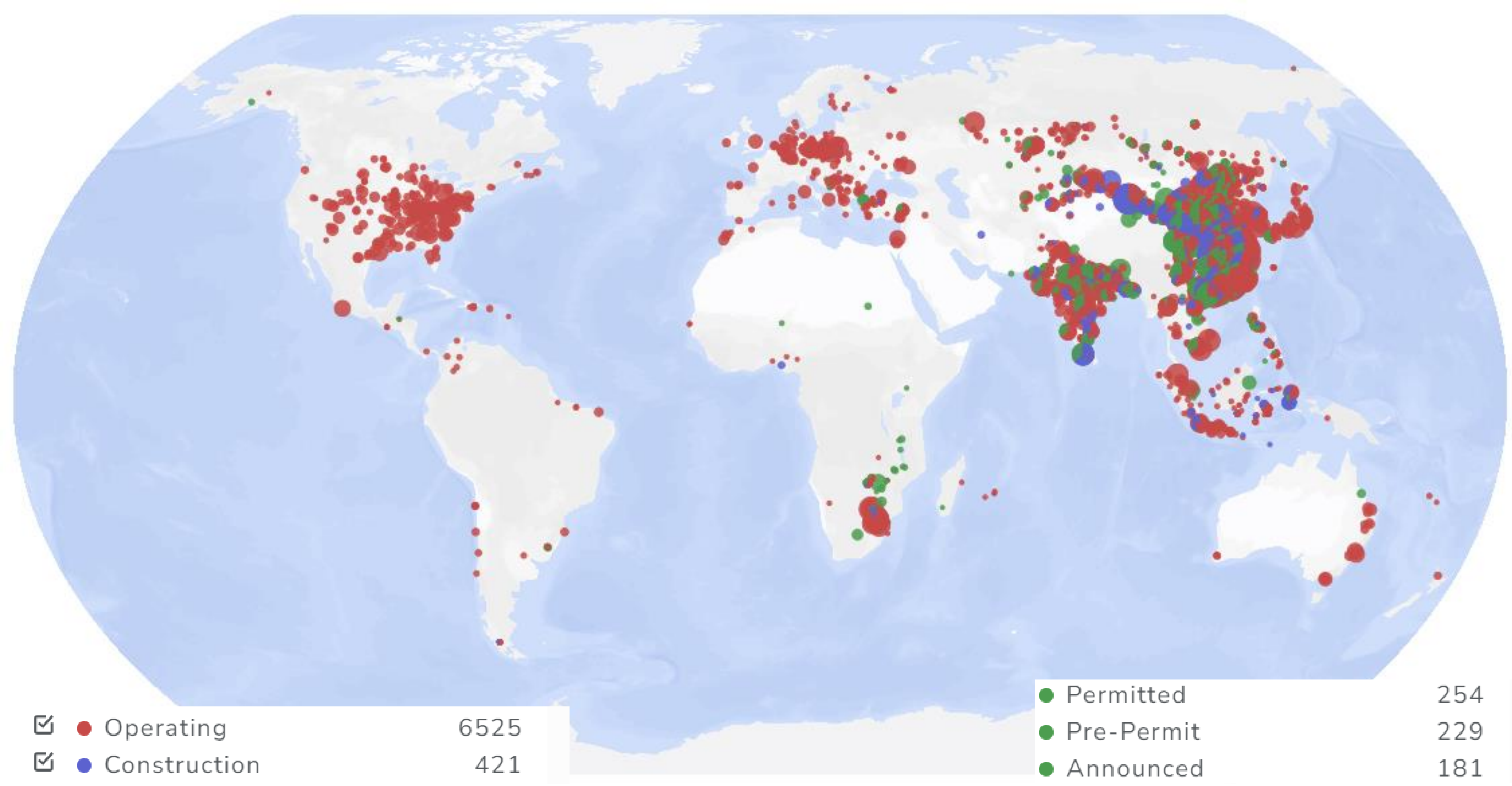
*Facility may have operated with an asbestos diaphragm

- The **Penobscot River** is the second largest river system in New England
- The estuary is:
  - ~20 miles long
  - 12 ft tidal range
- Seasonally variable discharge:
  - 5000 – 60,000 cfs
- Glaciated terrain and a long narrow river channel upgradient of Frankfort
- A mercury cell chlor-alkali facility operated in the estuary from 1967 – 2000
- Preceding history of wood products industry complicates remediation of the estuary and extends a recovery timeline to 70+ years

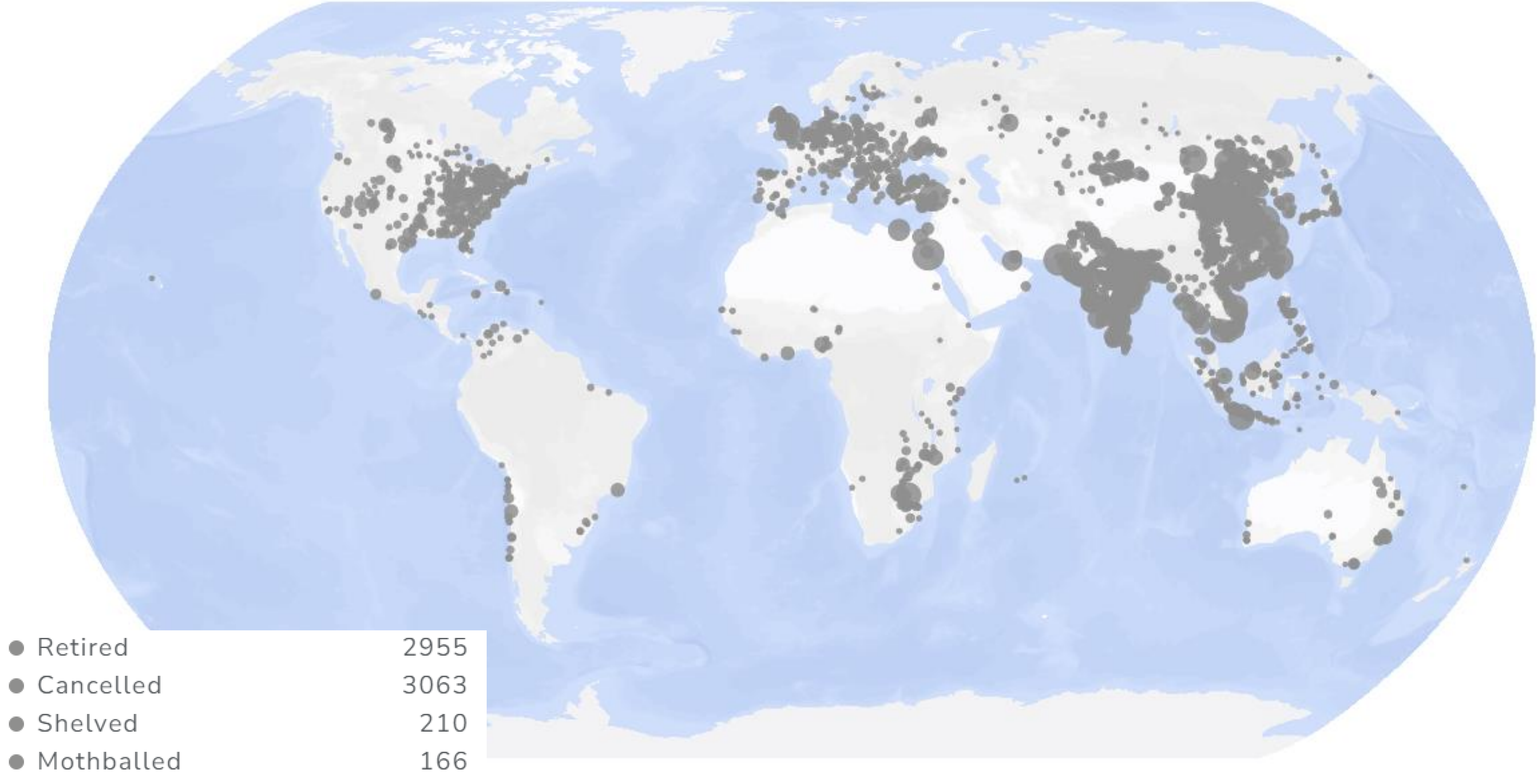

NORTH AMERICA
SOUTH AMERICA
ATLANTIC OCEAN
PACIFIC OCEAN
ASIA
SOUTHERN OCEAN



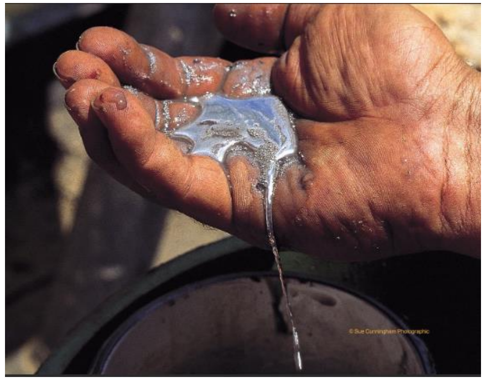

So, where is oceanic mercury coming from??


Operating 6525
Construction 421
Permitted 254
Pre-Permit 229
Announced 181

# Also…is this what a tipping point looks like…?



And on a smaller (individually) but no less dangerous (individually AND globally) scale....



[Artisanal and Small-Scale Gold Mining (ASGM)]

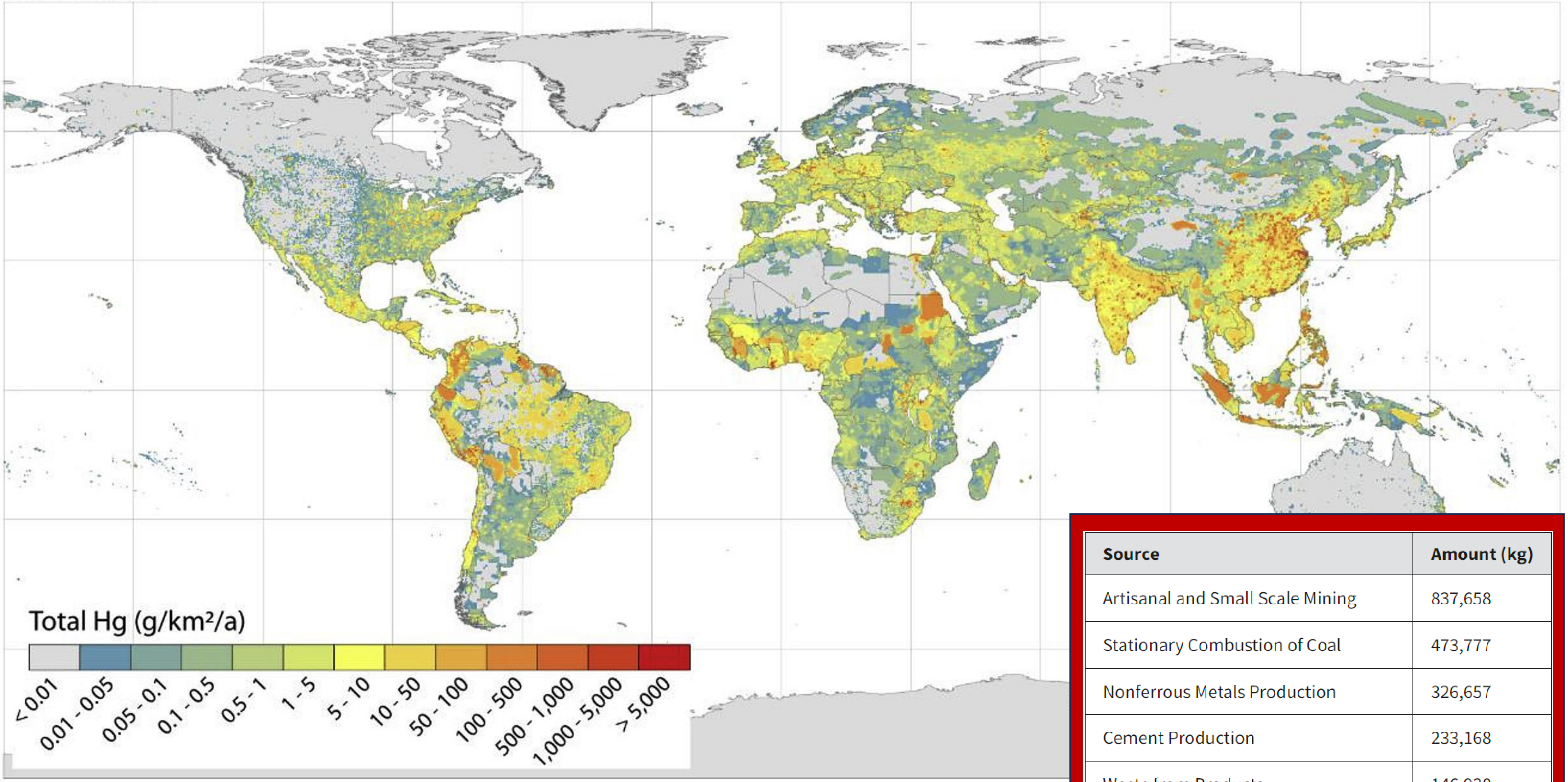
(gold mining is extraordinarily dangerous for those who have to feed their families this way....)

# Serra Pelada, Brazil

Photographer:
Sebastiao Salgado
(1944 - 2025)

1986 – 1989 | gold mine

# All sectors - Atmospheric emissions




| Source | Amount (kg) |
|---|---|
| Artisanal and Small Scale Mining | 837,658 |
| Stationary Combustion of Coal | 473,777 |
| Nonferrous Metals Production | 326,657 |
| Cement Production | 233,168 |
| Waste from Products | 146,938 |

# LETTER

doi:10.1038/nature13563

## A global ocean inventory of anthropogenic mercury based on water column measurements

Carl H. Lamborg[1], Chad R. Hammerschmidt[2], Katlin L. Bowman[2], Gretchen J. Swarr[1], Kathleen M. Munson[1], Daniel C. Ohnemus[1], Phoebe J. Lam[1], Lars-Eric Heimbürger[3], Micha J. A. Rijkenberg[4] & Mak A. Saito[1]

**Abstract** Monomethylmercury ($CH_3Hg$) is the only form of mercury (Hg) known to biomagnify in food webs. Here we investigate factors driving methylated mercury [MeHg = $CH_3Hg$ + $(CH_3)_2Hg$)] production and degradation across the global ocean and uptake and trophic transfer at the base of marine food webs. We develop a new global 3-D simulation of MeHg in seawater and phyto/zooplankton within the Massachusetts Institute of Technology general circulation model. We find that high modeled MeHg concentrations in polar regions are driven by reduced demethylation due to lower solar radiation and colder temperatures. In the eastern tropical subsurface waters of the Atlantic and Pacific Oceans, the model results suggest that high MeHg concentrations are associated with enhanced microbial activity and atmospheric inputs of inorganic Hg. Global budget analysis indicates that upward advection/diffusion from subsurface ocean provides 17% of MeHg in the surface ocean. Modeled open ocean phytoplankton concentrations are relatively uniform because lowest modeled seawater MeHg concentrations occur in oligotrophic regions with the smallest size classes of phytoplankton, with relatively high uptake of MeHg and vice versa. Diatoms and synechococcus are the two most important phytoplankton categories for transferring MeHg from seawater to herbivorous zooplankton, contributing 35% and 25%, respectively. Modeled ratios of MeHg concentrations between herbivorous zooplankton and phytoplankton are 0.74–0.78 for picoplankton (i.e., no biomagnification) and 2.6–4.5 for eukaryotic phytoplankton. The spatial distribution of the trophic magnification factor is largely determined by the zooplankton concentrations. Changing ocean biogeochemistry resulting from climate change is expected to have a significant impact on marine MeHg formation and bioaccumulation.

https://doi.org/10.1029/2019GB006348

ELSEVIER

Marine Chemistry

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## Distribution of mercury species across a zonal section of the eastern tropical South Pacific Ocean (U.S. GEOTRACES GP16)

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### Highlights

- Total mercury was enriched in the Peru upwelling region and up to 20% of the upwelling flux was as monomethyl-mercury.
- Subsurface maxima of monomethyl-mercury and dimethyl-mercury were found in oxic and suboxic water.
- Methylated mercury concentrations were greatest in the eastern part of the section underlying productive surface waters.
- Mercury was not elevated in a metal-rich hydrothermal vent plume extending 4000 km west from the East Pacific Rise.
- Deep water below 2500 m was enriched with Hg, especially in warm bottom waters in the eastern part of the section.

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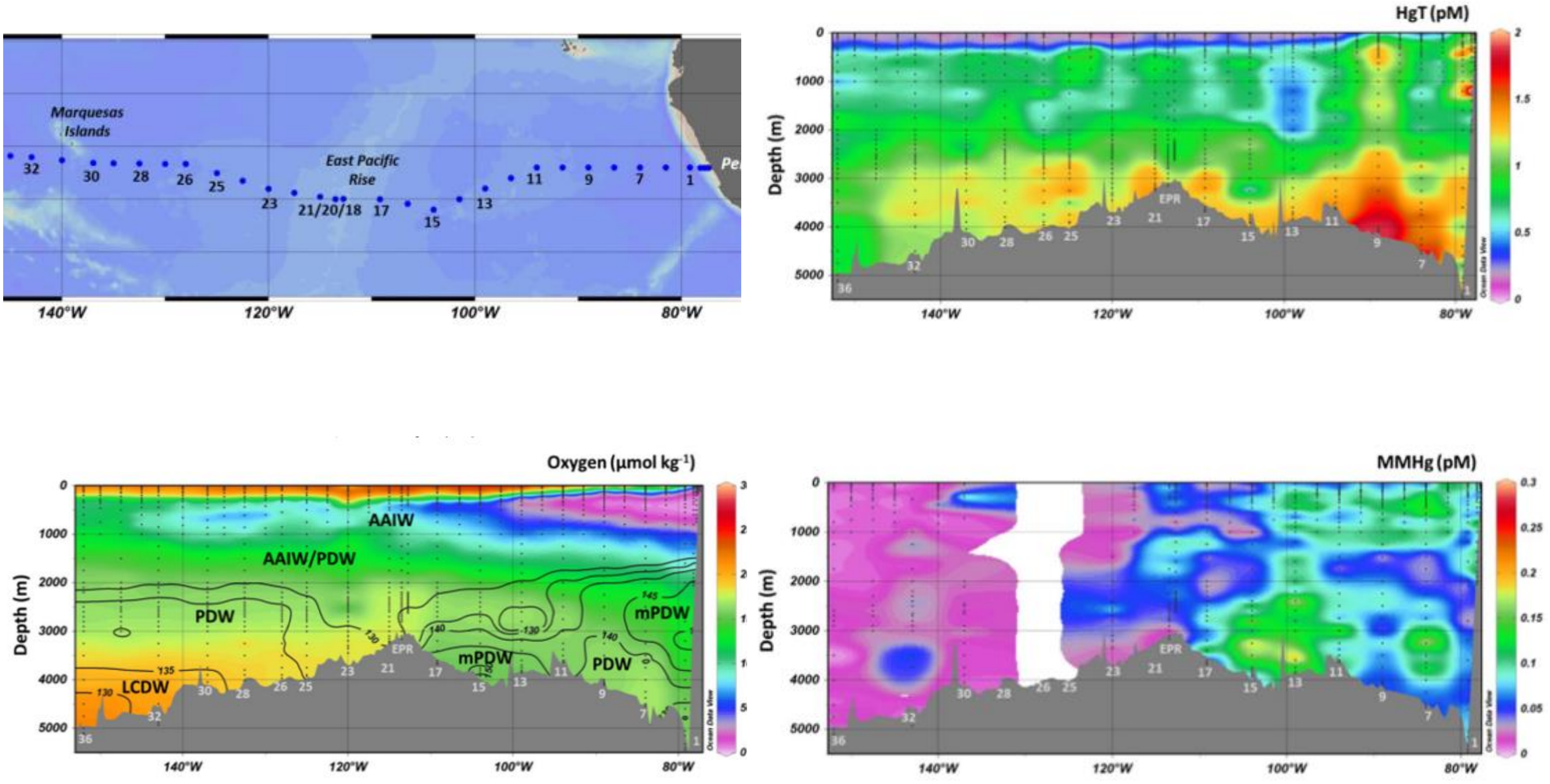
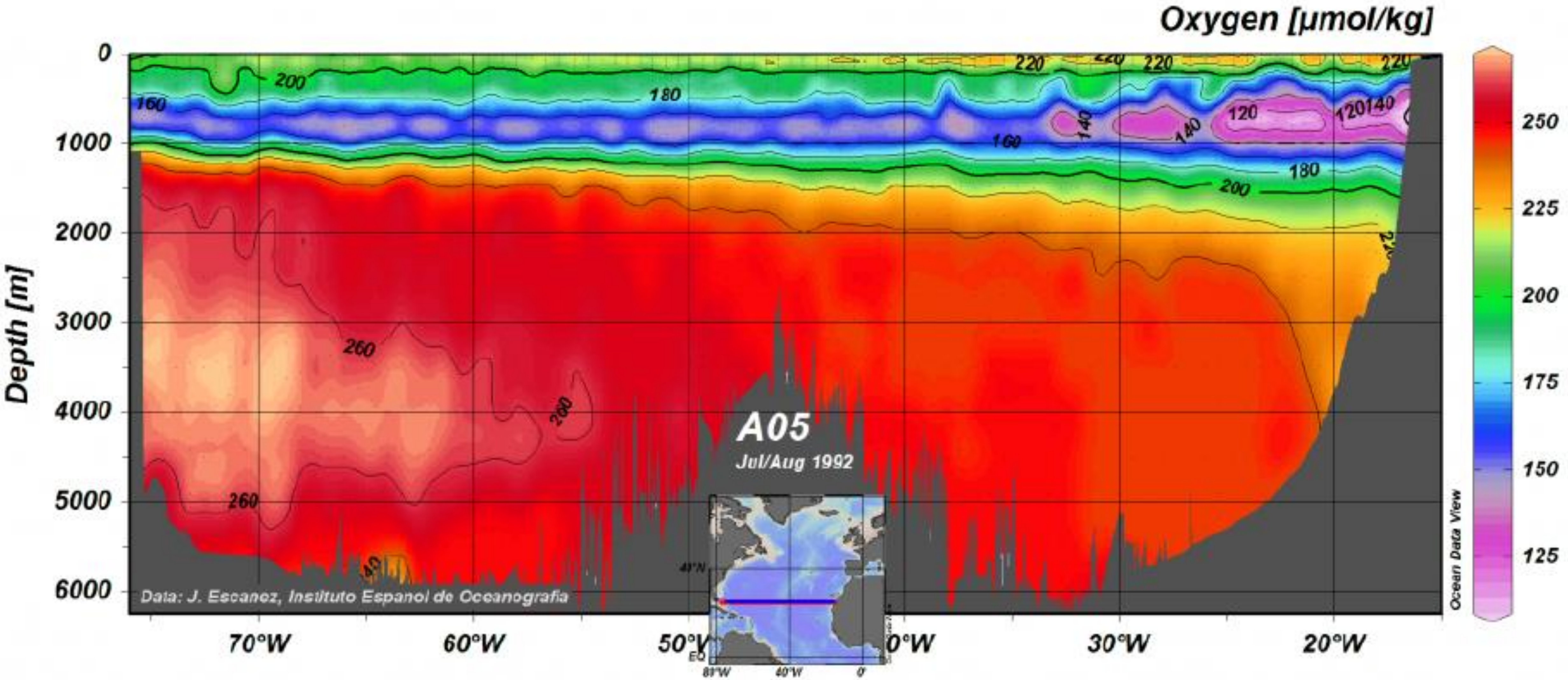
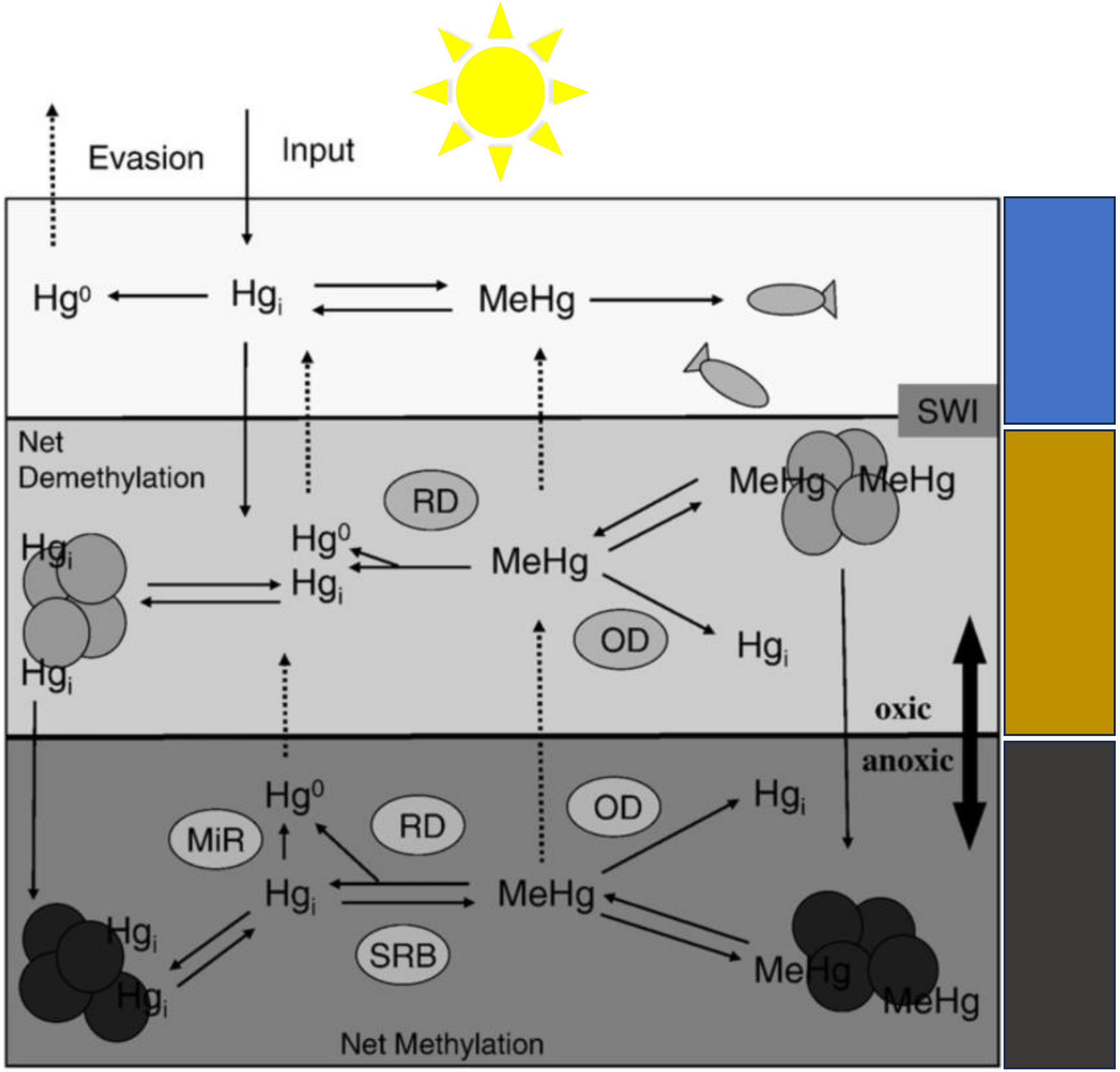


Marquesas Islands
East Pacific Rise
32
30
28
26
25
23
21/20/18
17
15
13
11
9
7
1
140°W
120°W
100°W
80°W
HgT (pM)
Depth (m)
EPR
Oxygen (µmol kg-1)
AAIW
AAIW/PDW
PDW
mPDW
LCDW
MMHg (pM)
Ocean Data View



Oxygen [µmol/kg]
Depth [m]
0
1000
2000
3000
4000
5000
6000
70°W
60°W
50°W
30°W
20°W
250
225
200
175
150
125
220
200
180
160
140
120
260
A05
Jul/Aug 1992
Data: J. Escanez, Instituto Espanol de Oceanografia
Ocean Data View



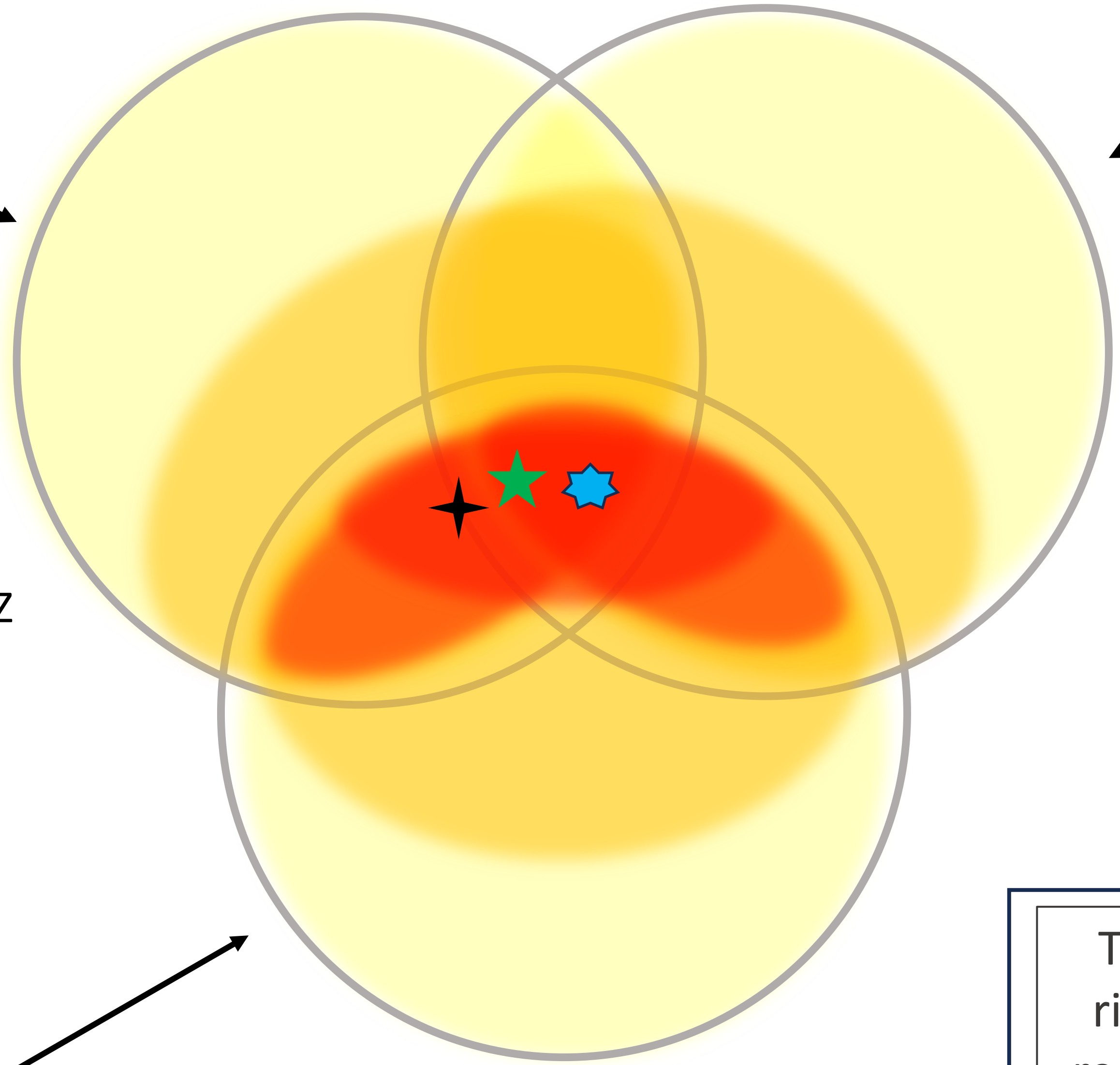

- Significant organic matter breakdown consumes dissolved oxygen ($dO_2$);
- Sulfate ($SO_4^{2-}$) + very low $dO_2$ increases activity of sulfate-reducing bacteria (SRB);
- SRB in the presence of inorganic mercury ($Hg^{2+}$) generate methyl mercury ($CH_3Hg^+$) as a by-product of respiration;
- $CH_3Hg^+$ is 100× more toxic than $Hg^{2+}$ and is retained in biological tissue to a greater extent than $Hg^{2+}$

# PHYSICAL

Thermohaline Circulation (+ time since the Industrial Revolution and significant global increase in coal combustion)

# BIOLOGICAL

Single most significant bioaccumulation step is between water column and uptake by phytoplankton



= North Atlantic (+ Polar)

= Upwelling Zones and OMZ

= Photic Zone (CMZ)

# CHEMICAL

Factors that contribute BOD and result in $O_2$ consumption (there's no shortage of $SO_4^{2-}$); consider this spatially

Think of this overview of risk profiles as describing regions of the global ocean and considering residence time (τ) in the oceans