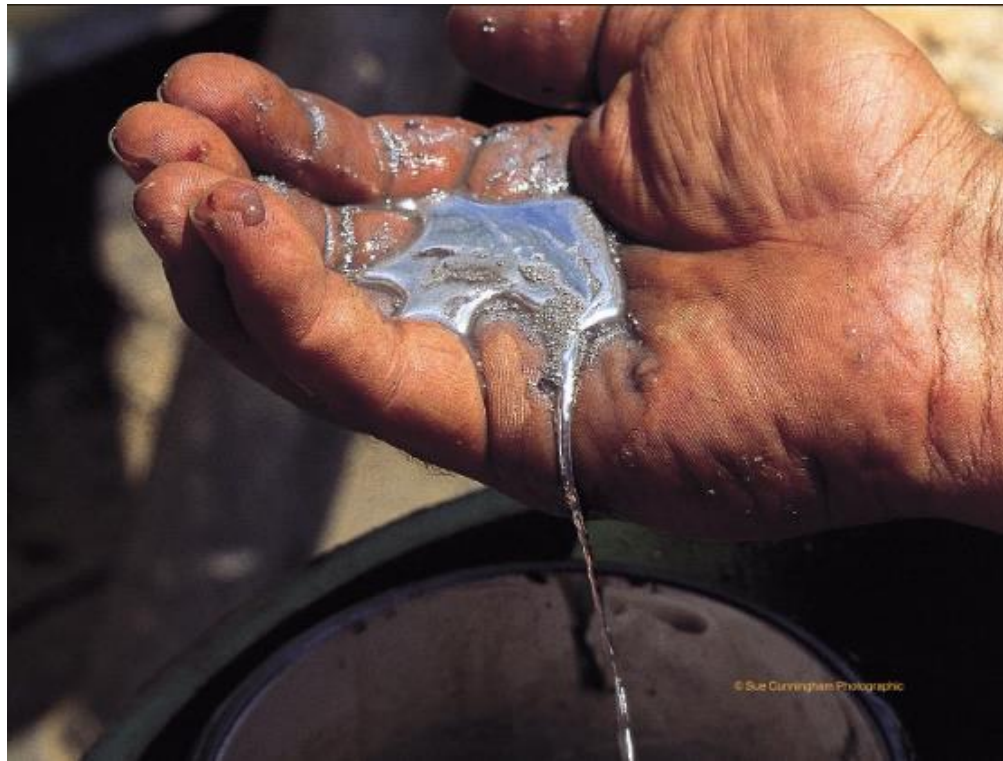


**Mercury Pollution in Aquatic Ecosystems**

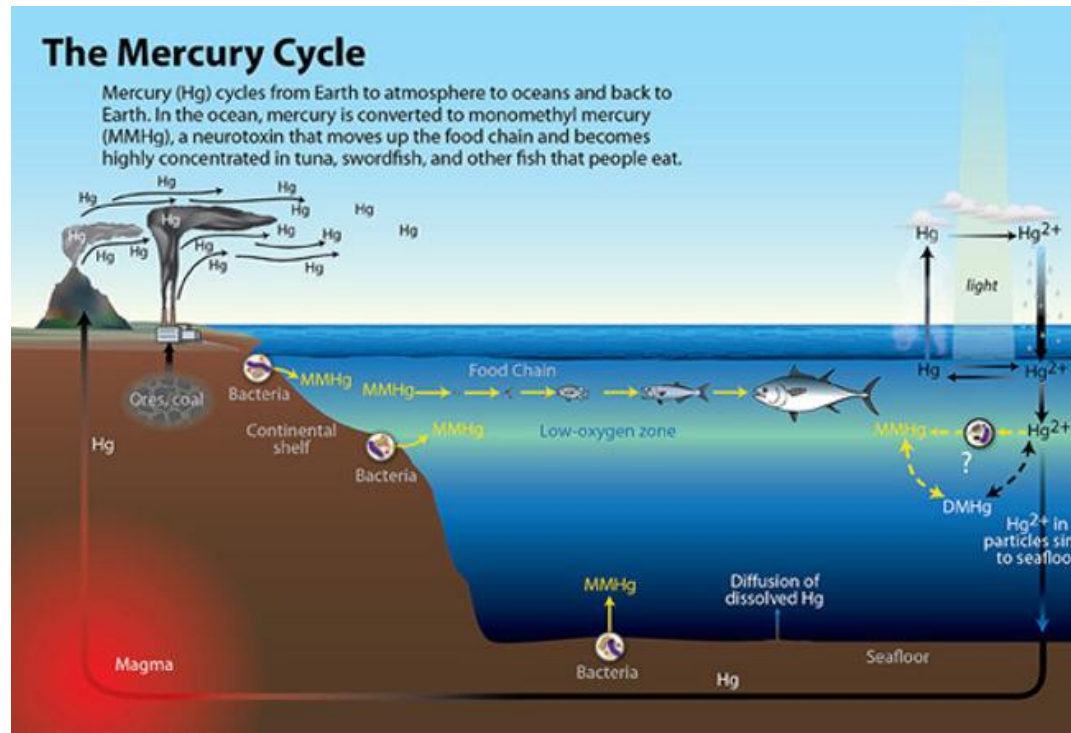
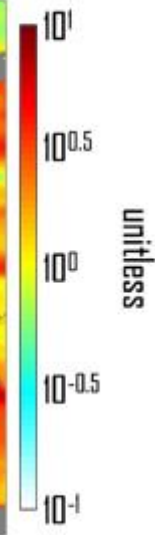
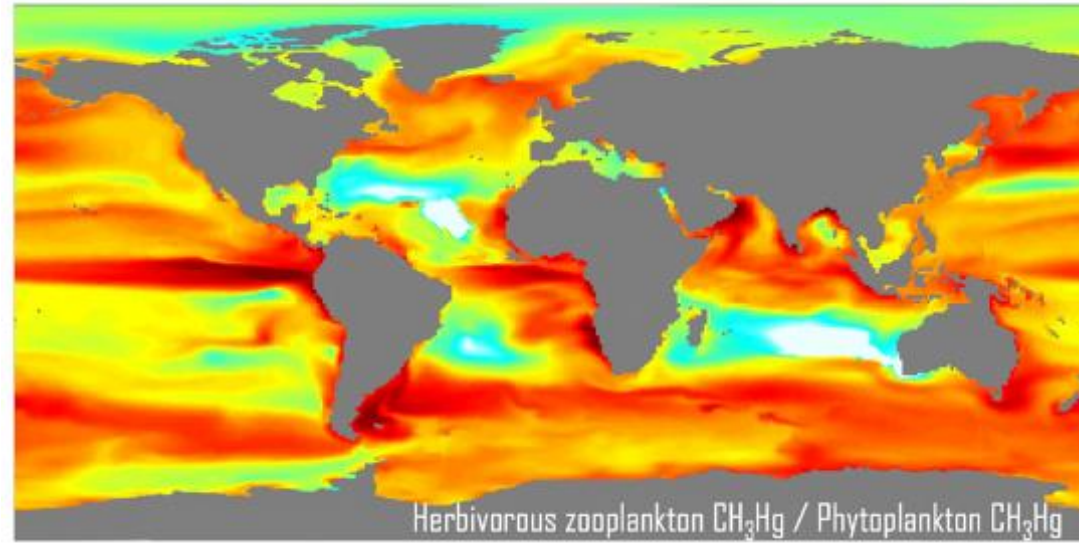
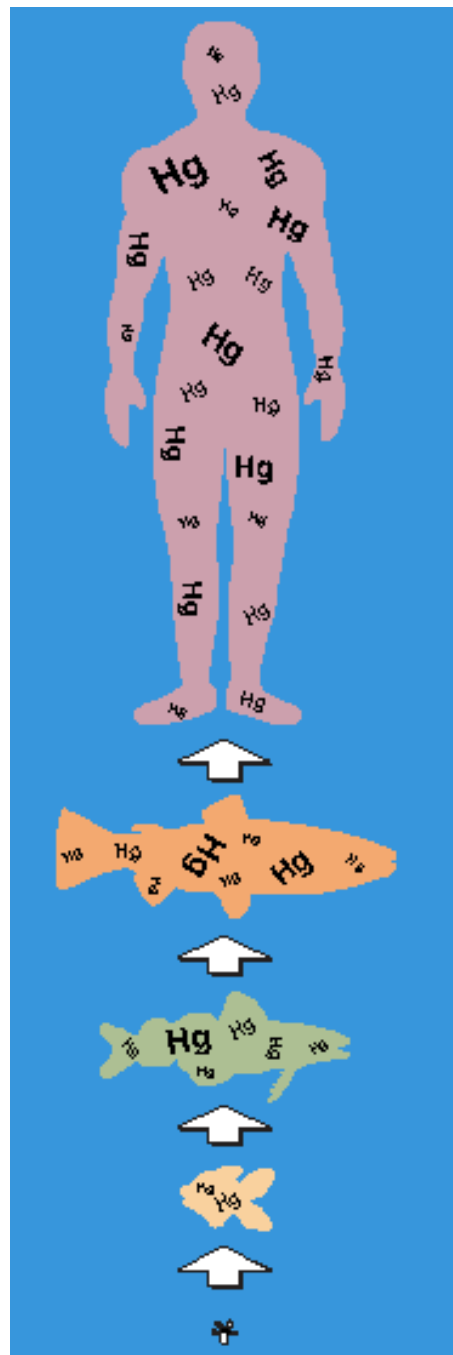


**Karen A. Merritt, PhD MPH**



# What do we know regarding the biomagnification process?

- Sulfate ( $\text{SO}_4^{2-}$ ) + low-to-no dissolved oxygen ( $\text{O}_2$ ) increases activity of sulfate-reducing **bacteria** (SRB);
- SRB in the presence of inorganic mercury ( $\text{Hg}^{2+}$ ) generate methyl mercury ( $\text{CH}_3\text{Hg}^+$ ) as an accident/**by-product of respiration**;
- Methyl mercury is **retained in biological tissue** more significantly than inorganic mercury because of the additional  $-\text{CH}_3$  (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)

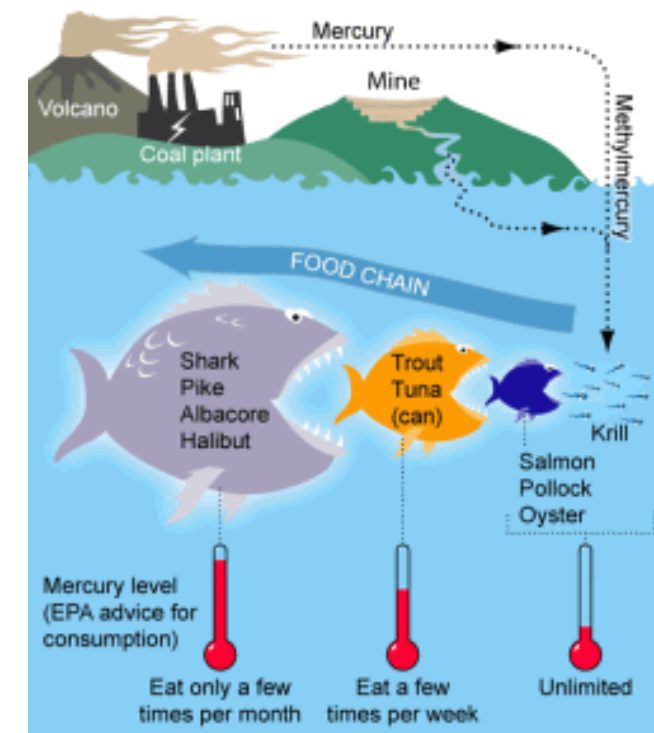


### A Global Model for Methylmercury Formation and Uptake at the Base of Marine Food Webs

Yanxu Zhang<sup>1,2</sup>, Anne L. Soerensen<sup>3,4</sup>, Amina T. Scharup<sup>5,6</sup>, and Elsie M. Sunderland<sup>2,3</sup>

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

**Abstract** Monomethylmercury (CH<sub>3</sub>Hg) is the only form of mercury (Hg) known to biomagnify in food webs. Here we investigate factors driving methylated mercury [MeHg = CH<sub>3</sub>Hg + (CH<sub>3</sub>)<sub>2</sub>Hg] 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 synchococcus 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 do 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 ( $\text{SO}_4^{2-}$ ) and biochemical oxygen demand (BOD) such that significant  $\text{O}_2$  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

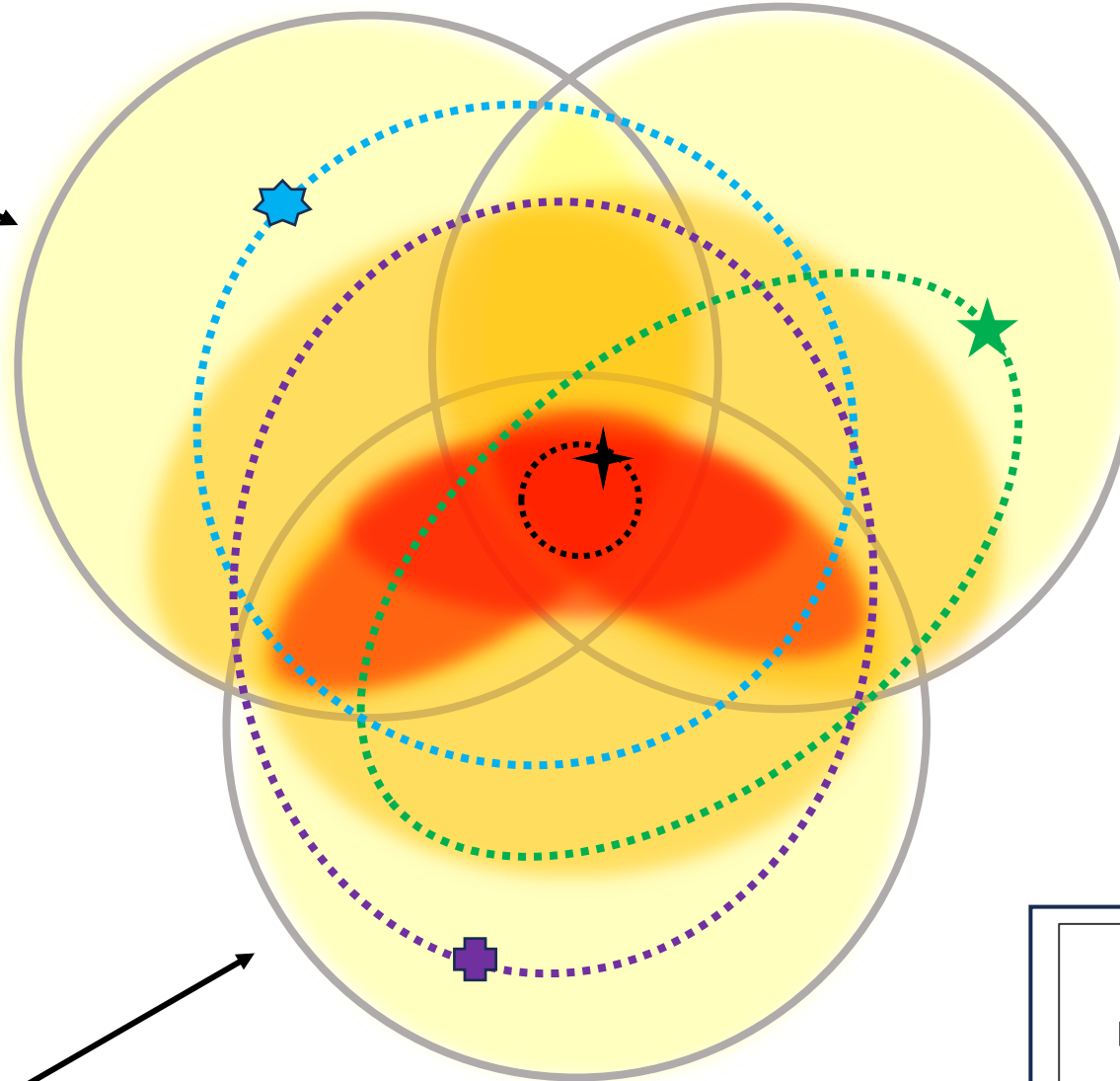
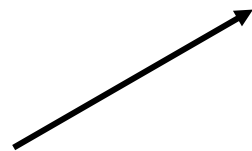
Multi-trophic level food chains with a top predator species that is frequently consumed



- ★ = [Wabigoon River, ON]
- ★ = [Penobscot Estuary, ME]
- ★ = [subtropical embayment]
- ✚ = [active margin slope]

# CHEMICAL

Factors that contribute BOD and sulfate ( $\text{SO}_4^{2-}$ ) and result in rapid  $\text{O}_2$  consumption



Think of this overview of risk profiles as describing orbits around a worst-case ecological and human health scenario

# Site Examples or Comparison

## Penobscot River Estuary, Maine

- Glaciated terrain and low sed. rates ( $\sim 0.5$  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 have consumption restrictions in place via licensing structure/programs.

## Wabigoon River, Ontario

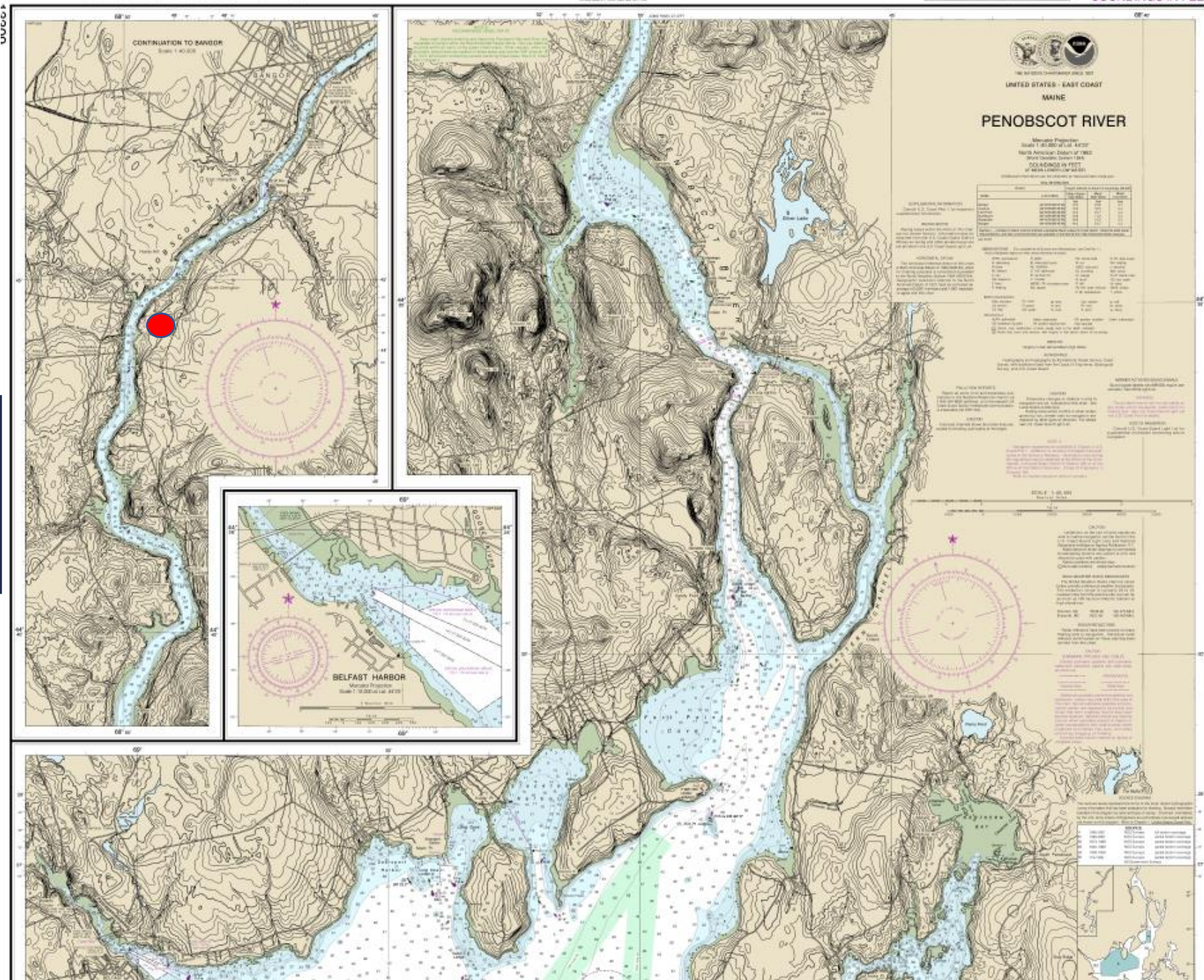
- Glaciated terrain and very low sed. rates ( $\sim 0.3$  cm /yr)
- Walleye and Northern pike as TL4 species; consumption is culturally significant
- Mill effluent renders the river suboxic/anoxic in summer; stratification of an in-river lake contributes to  $> 2$  ug/g in walleye.
- Surface sediment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

- 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 50+ years





**After two decades, Penobscot River cleanup fight to end with settlement of at least \$187 million**



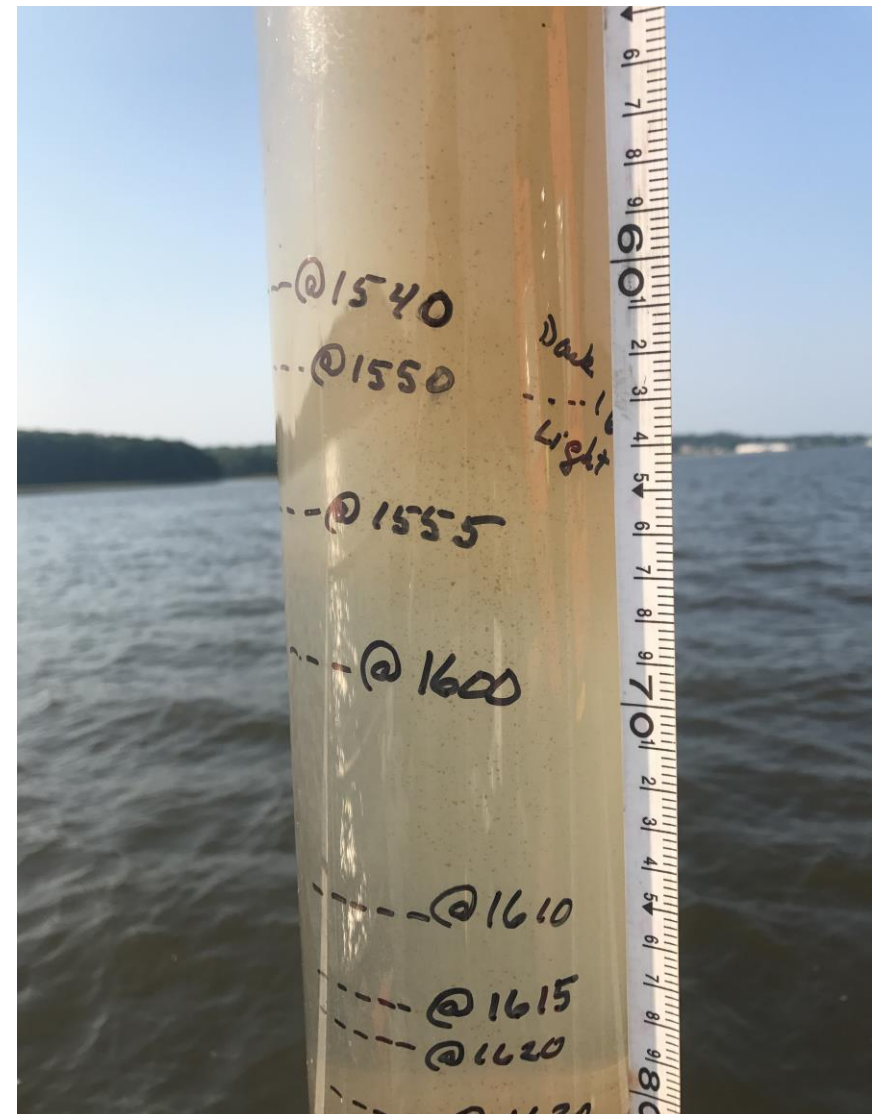
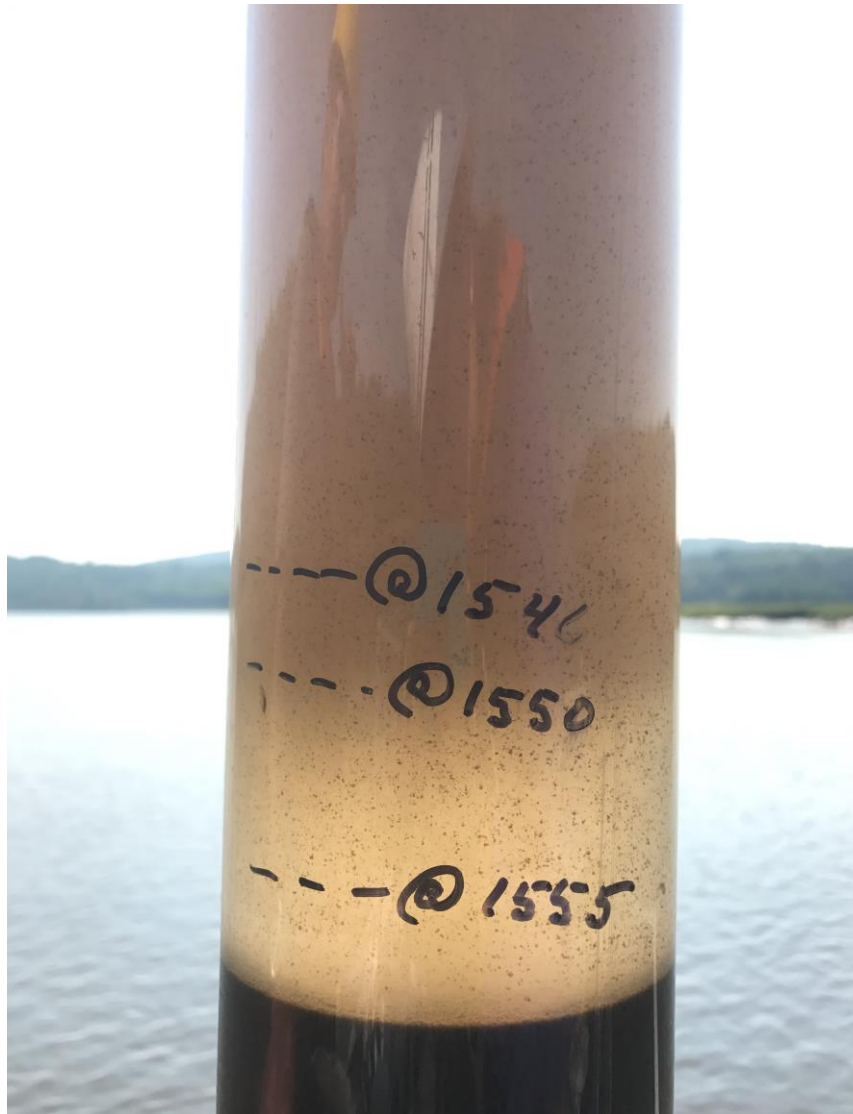
# The other industrial history of the river....



The Penobscot was a lumberman's dream. There were two and a half million acres of the finest White Pine forests in the world and all of it was accessible through the Penobscot River. As a lumber port, Bangor and the Penobscot were without peers. In the fifty-odd years from 1832 to 1888, a total of 8,738,000,000 board feet of lumber were shipped. At its zenith in 1872, Bangor was shipping 250,000,000 board feet of lumber a year. Old-timers today still talk of the times when ~~as boys they jumped from deck to deck of merchant ships to cross the river from Bangor to Brewer.~~ (5) At this time there were four-hundred-ten sawmills on the river and fifty-two of them were between Bangor and Old Town.

Today there are still great islands and bogs of sawdust in the estuary section of the Penobscot. Some of these deposits are up to thirty feet thick. A student hoping to do a thesis on the effect of this sawdust on bottom life in the lower Penobscot had to abandon his original plans when he could not find an area without sawdust present for a control area.

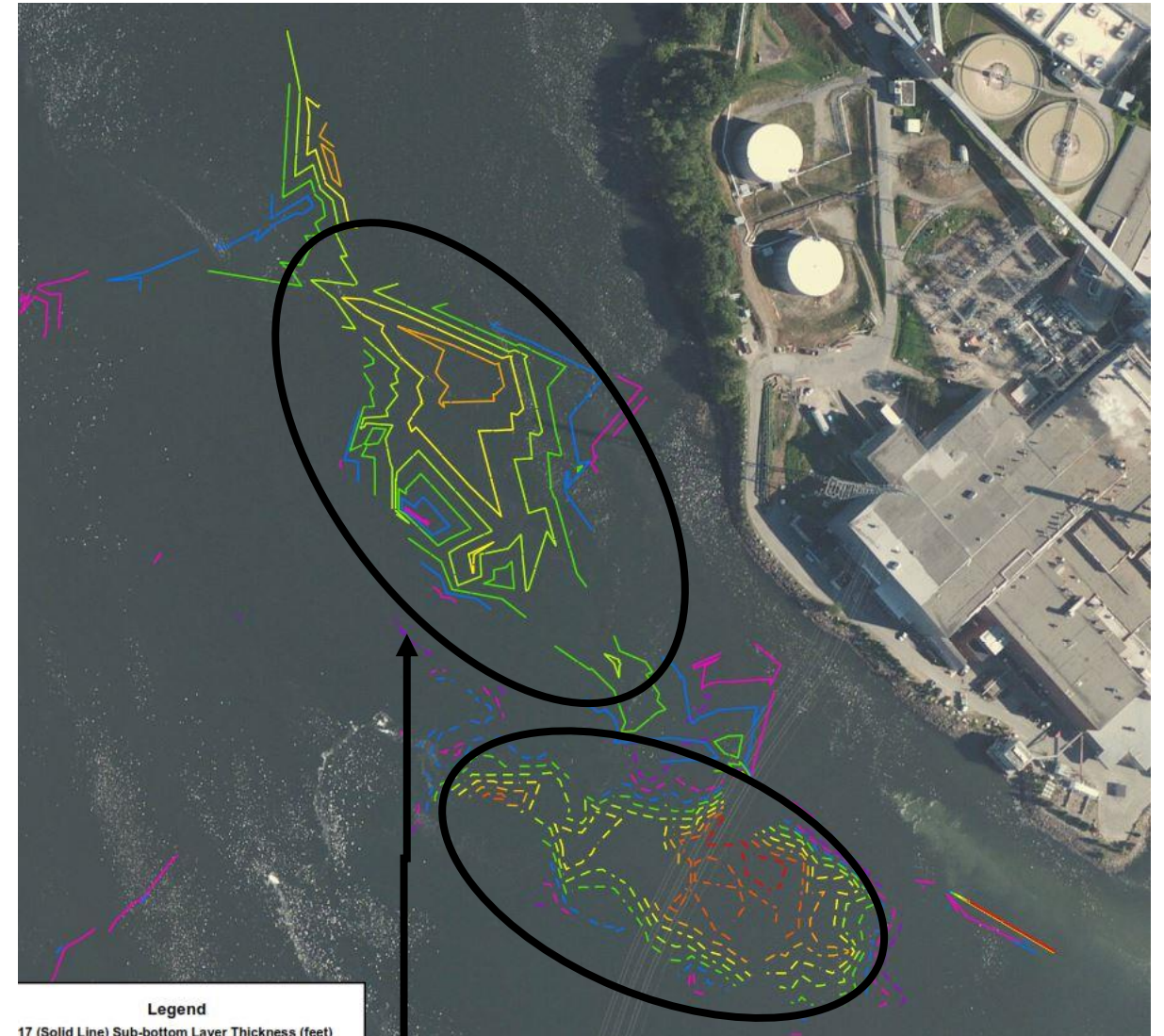
# Wood Waste – 2017 Field Sampling



# Wood Waste – Results 2017 Geophysical Survey

## Bucksport Mill Pile:

- Dotted contours = 2016
- Solid contours = 2017
- 2016 Thickness = 8 feet
- 2017 Thickness = 6 feet



2017 Location  
(Summer)

2016 Location  
(Spring)

# How does this information impact the restoration and recovery of the Penobscot estuary ecosystem?

- This material:
  - is lower density than mineral sediment and so is transported differently through the freshwater-saltwater mixing zone in the estuary;
  - has a higher water content than mineral sediment and so has different material handling needs if dredged as a component of restoration;
  - doesn't break down underwater so loss is mostly by washing out of the estuary; size of the tides makes this a very slow process (1-2% per year?);
  - has absorbed mercury discharge over the years
- Its transport onto marshes may partially explain very high mercury exposure and uptake rates for sparrows in the Penobscot estuary
- Its presence may still be impacting the benthic food web (lobster)
- (Whose responsibility is this co-occurring contaminant?)

# Site Examples or Comparison

## Penobscot River Estuary, Maine

- Glaciated terrain and low sed. rates ( $\sim 0.5$  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 have consumption restrictions in place via licensing structure/programs.

## Wabigoon River, Ontario

- Glaciated terrain and very low sed. rates ( $\sim 0.3$  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 a mill and are elevated consistently  $> 1$  mg/kg for a distance of  $\sim 40$  miles downstream.
- Downstream human health impacts are severe 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,<sup>1</sup> Aline Philibert,<sup>1</sup> Myriam Fillion,<sup>2,1</sup> and Judy Da Silva<sup>3</sup>



## 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](https://www.thelancet.com/planetary-health) on May 11, 2020, and further corrections have been made on July 15, 2020

Université du Québec à Montréal, Centre de recherche interdisciplinaire sur le bien-être, la santé, la société et l'environnement (Cinbiose), Montréal, QC, Canada (A Philibert PhD, Prof M Fillion PhD, Prof D Mergler PhD); and Département Science et Technologie, Université TÉLUQ, Montréal, QC, Canada (Prof M Fillion)

Correspondence to: Prof Donna Mergler, Centre de recherche interdisciplinaire sur le bien-être, la santé, la société et l'environnement (Cinbiose), Université du Québec à Montréal, Montréal, QC H3C 3P8, Canada [mergler.donna@uqam.ca](mailto:mergler.donna@uqam.ca)

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.

# Walleye (1970 – 2017)

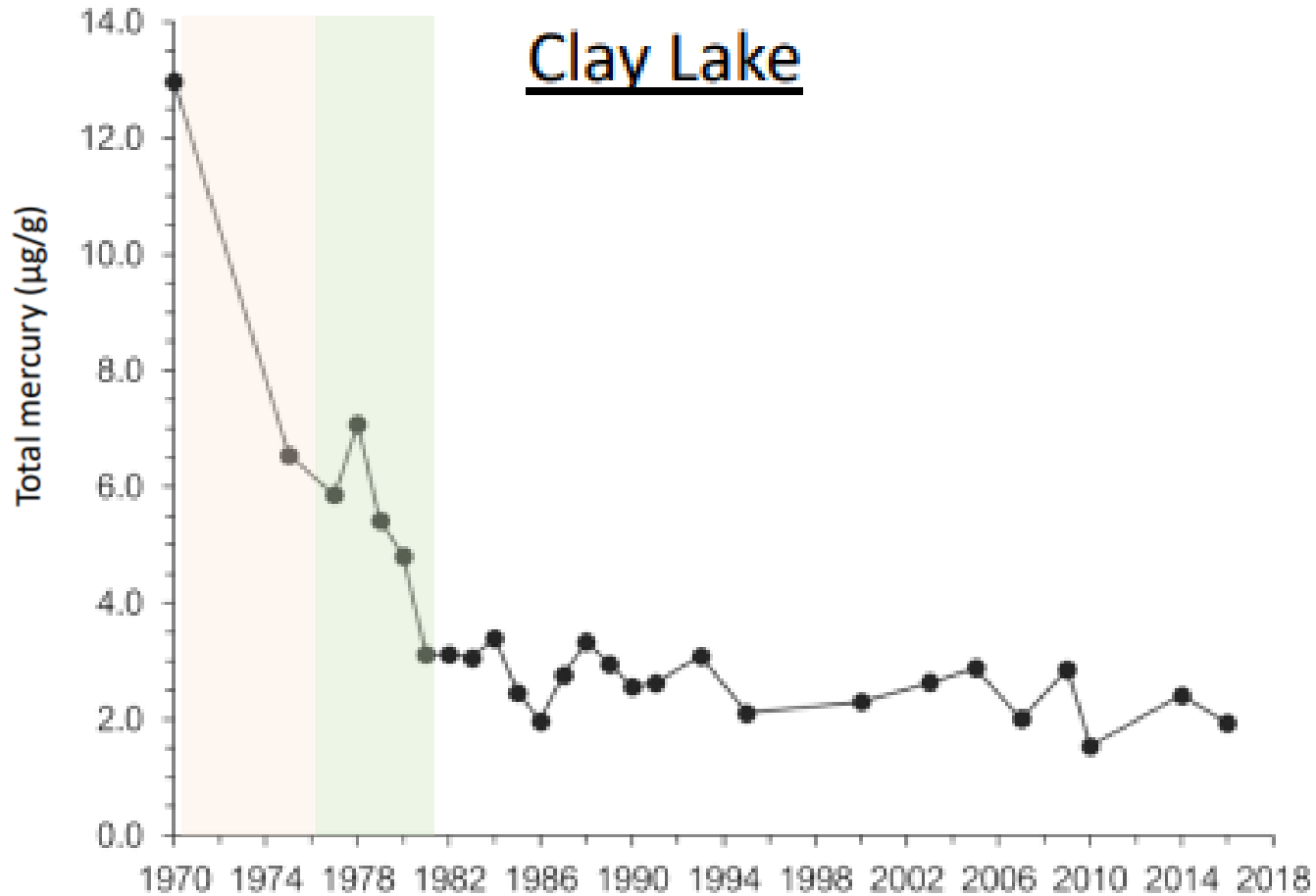


TABLE 7.1. Annual mercury discharges from the chlor-alkali plant, Great Lakes Forest Products Limited, Dryden.

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

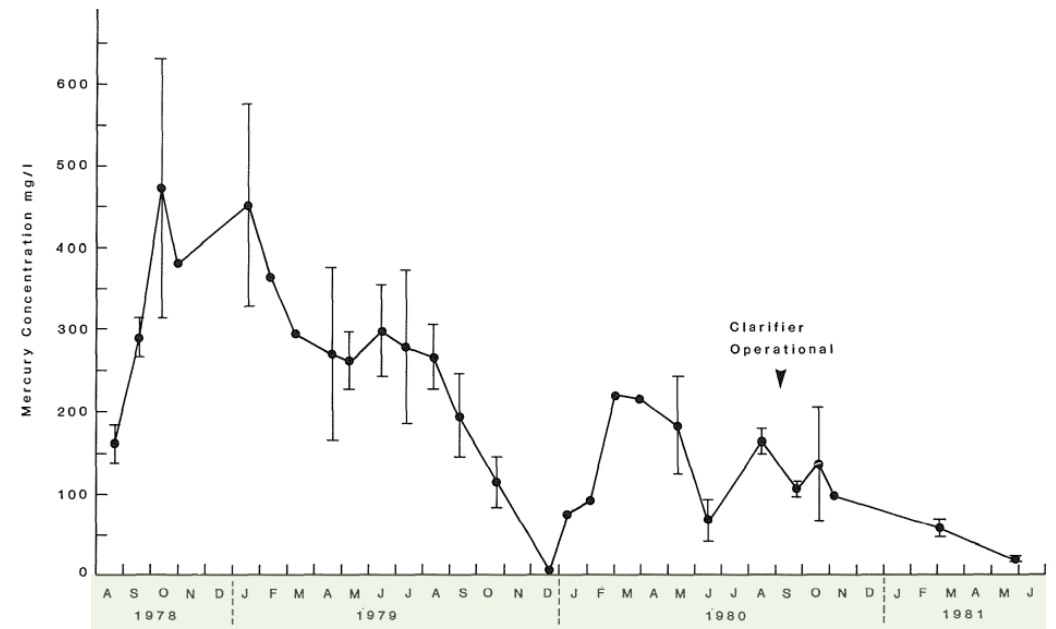


Figure 7.1 Mean monthly mercury concentrations of mill effluent, August, 197

# 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

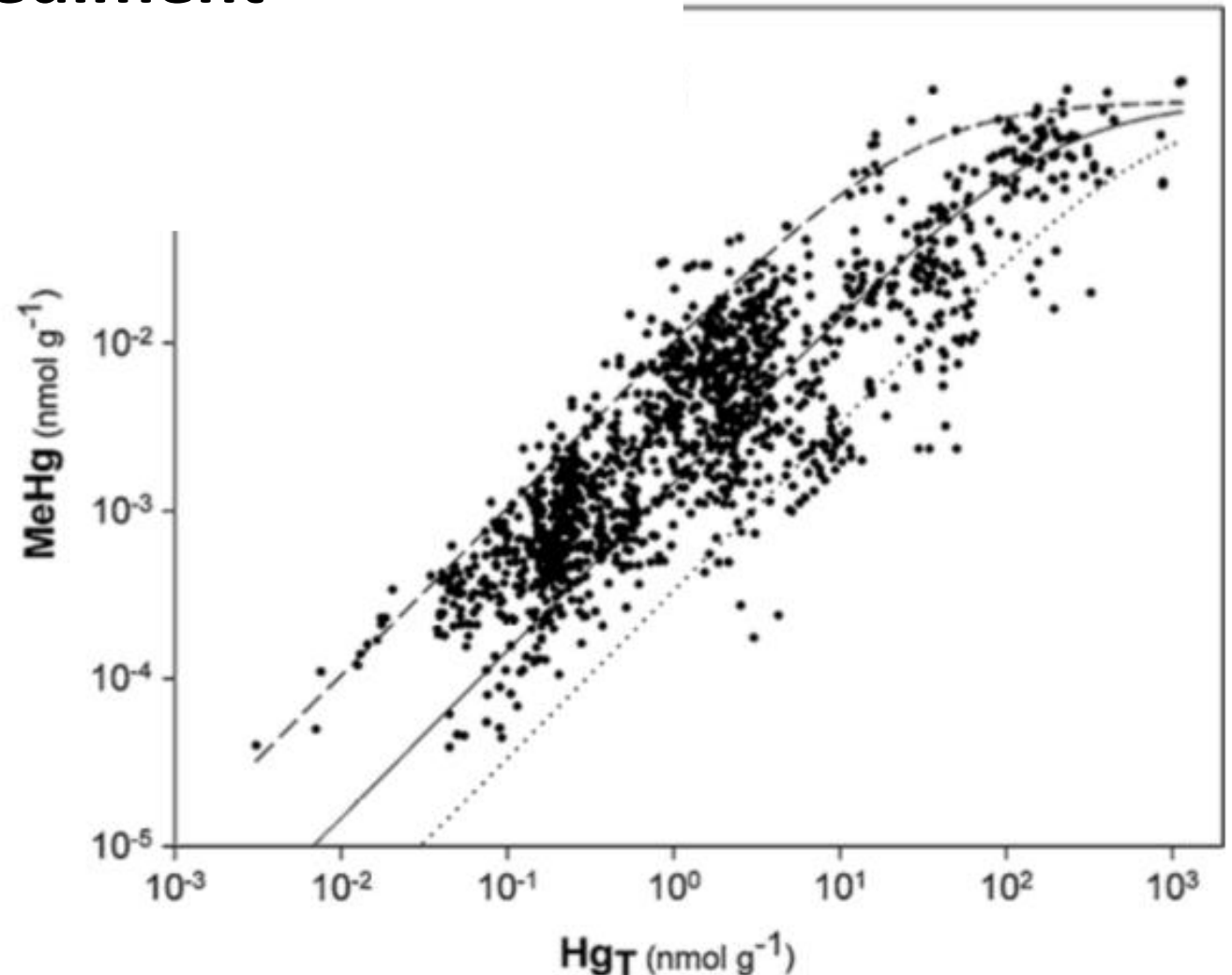


Rudy Turtle, chief of Grassy Narrows First Nation, addresses a rally against mining proposals on First Nations territory in Toronto in July 2023. (Evan Mitsui/CBC)

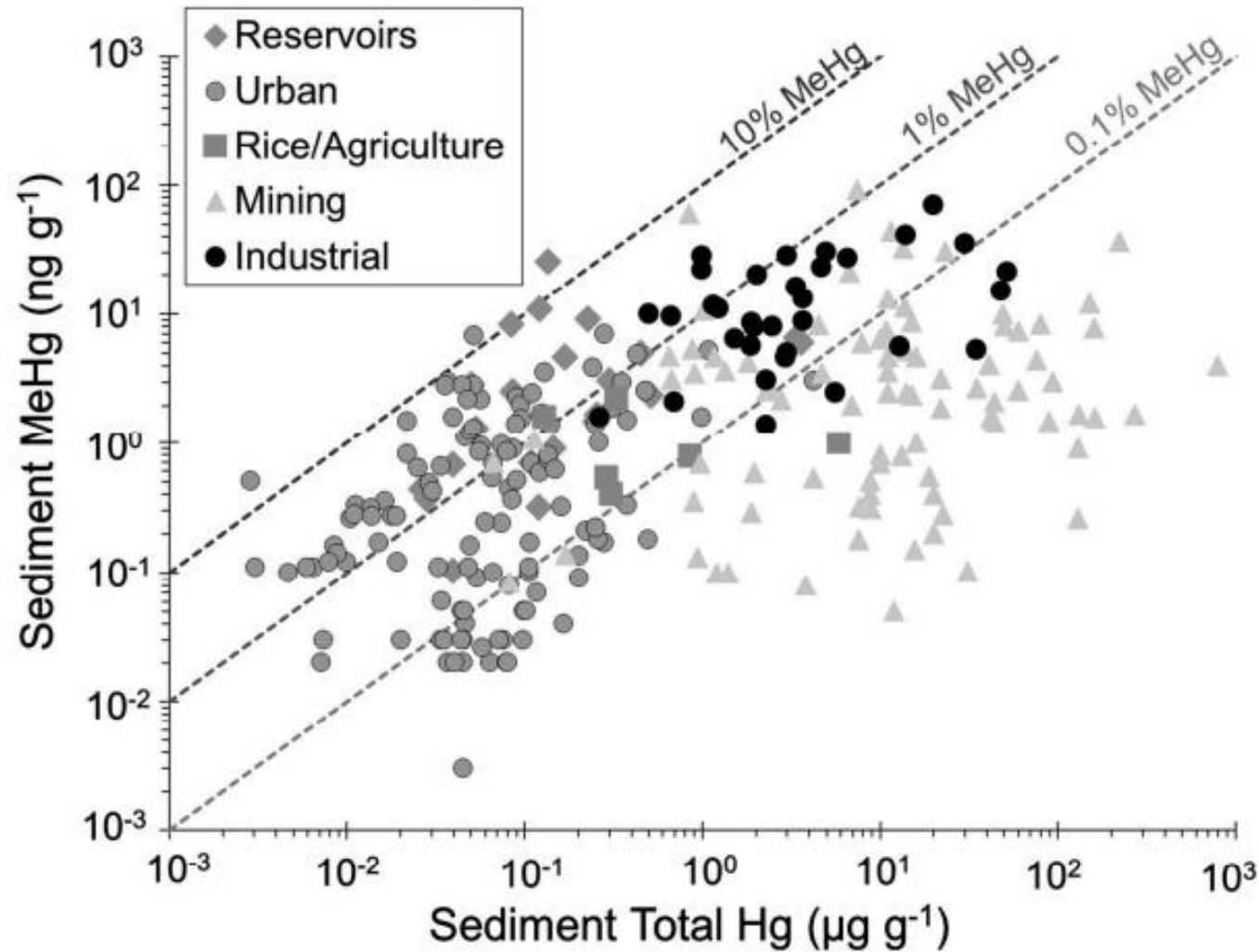
# Relationship between total mercury ( $\text{Hg}_T$ ) and methyl mercury (MeHg) in **sediment**

- 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  $\text{Hg}_T$  necessarily results in predictable declines in MeHg).



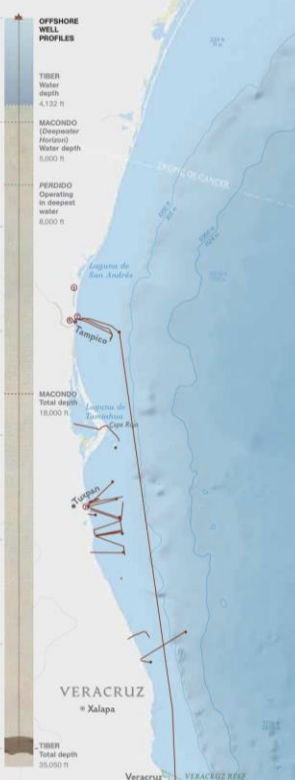
# How Do These Data Distribute by Source/Type of Environment?



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 overspecify the extent to which decreasing  $\text{Hg}_T$  necessarily results in predictable declines in MeHg).

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

**THE LOOP CURRENT**  
The Gulf's largest current, the Loop Current, enters from the Caribbean as the Yucatán Current. Running to depths of 2,600 feet, it can swing directly east to join the Gulf Stream or surge north before curling back through the Straits of Florida. If it penetrates deeply into the Gulf, it often sheds a great eddy, which drifts westward. The Loop Current could carry oil from a Gulf spill up the Atlantic coast.



- Map Legend**
- Coastal wetland
  - Coastal protected area
  - Active federal lease as of March 2010
  - Shallow water
  - Deep water (1,000 to 4,999 feet)
  - Ultradeep water (5,000 feet or more)
  - Oil or gas offshore platform
  - Oil or gas well
  - Crude oil or gas terminal
  - Oil refinery
  - Oil- or gas-related pipeline
  - Maritime boundary
  - Planning area boundary

NATIONAL GEOGRAPHIC

# Gulf of Mexico

## A GEOGRAPHY OF OFFSHORE OIL

For the past half century, oil has driven the economy of the Gulf of Mexico. A third of U.S. oil production flows from nearly 3,500 platforms in the Gulf, with thousands of miles of pipeline delivering oil and natural gas to shore. Since the first Gulf well was drilled off Louisiana in 1938, in less than 15 feet of water, close-in reserves have been depleted and exploration has marched off the continental shelf, onto the continental slope, and beyond. Today Gulf oil is deep oil; the bulk of U.S. production draws from wells in more than a thousand feet of water. U.S. Gulf oil reserves are estimated at 44.9 billion barrels, but as the *Deepwater Horizon* disaster showed, the challenges of deep drilling are formidable.

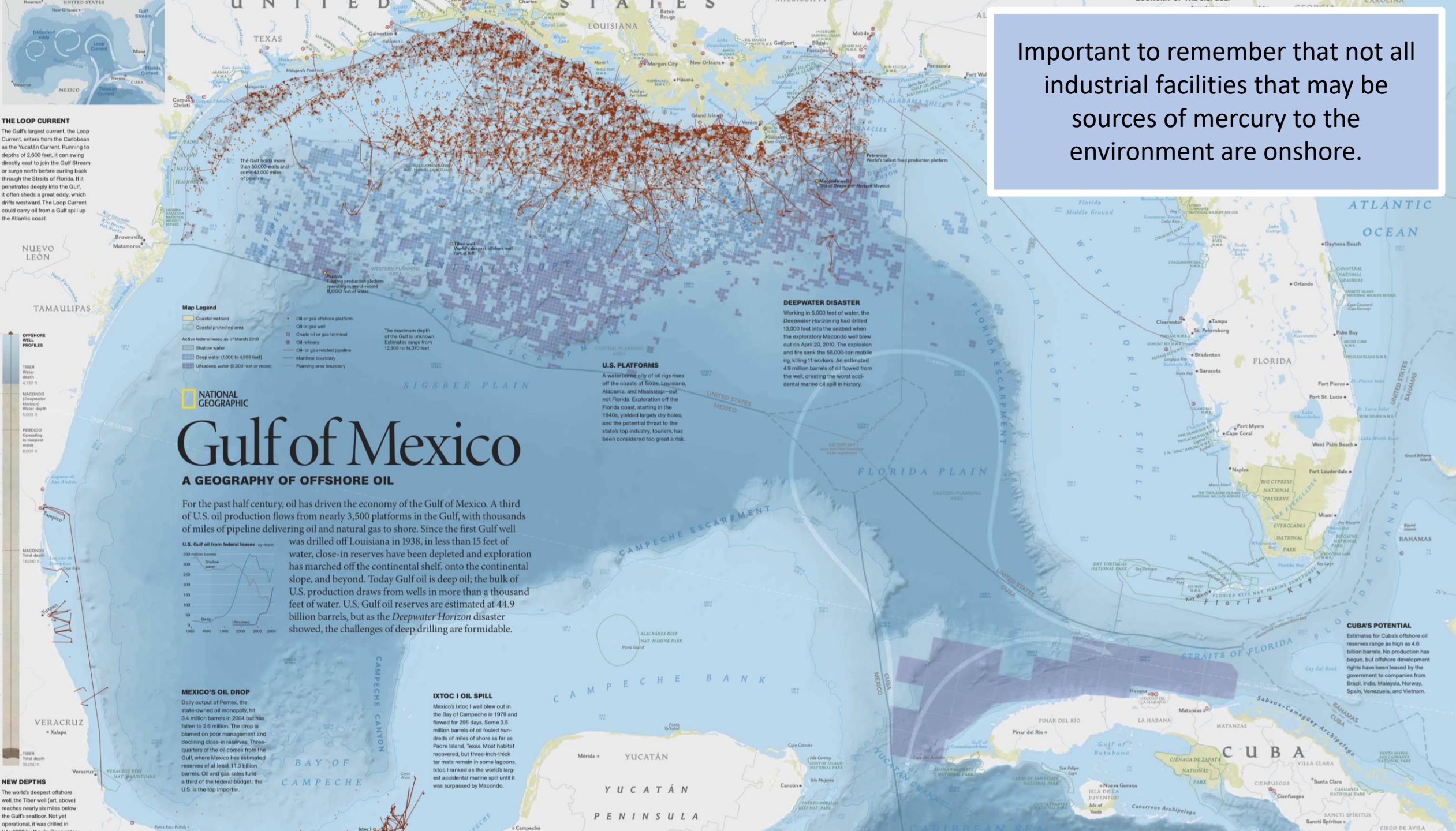
**MEXICO'S OIL DROP**  
Daily output of Pemex, the state-owned oil monopoly, hit 3.4 million barrels in 2004 but has fallen to 2.6 million. The drop is blamed on poor management and declining close-in reserves. Three-quarters of the oil comes from the Gulf, where Mexico has estimated reserves of at least 11.3 billion barrels. Oil and gas sales fund a third of the federal budget; the U.S. is the top importer.

**IXTOC 1 OIL SPILL**  
Mexico's Ixtoc 1 well blew out in the Bay of Campeche in 1979 and flowed for 295 days. Some 3.5 million barrels of oil fouled hundreds of miles of shore as far as Padre Island, Texas. Most habitat recovered, but three-inch-thick tar mats remain in some lagoons. Ixtoc 1 ranked as the world's largest accidental marine spill until it was surpassed by Macondo.

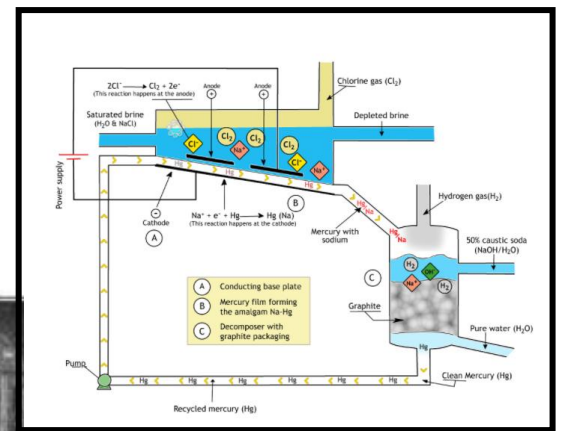
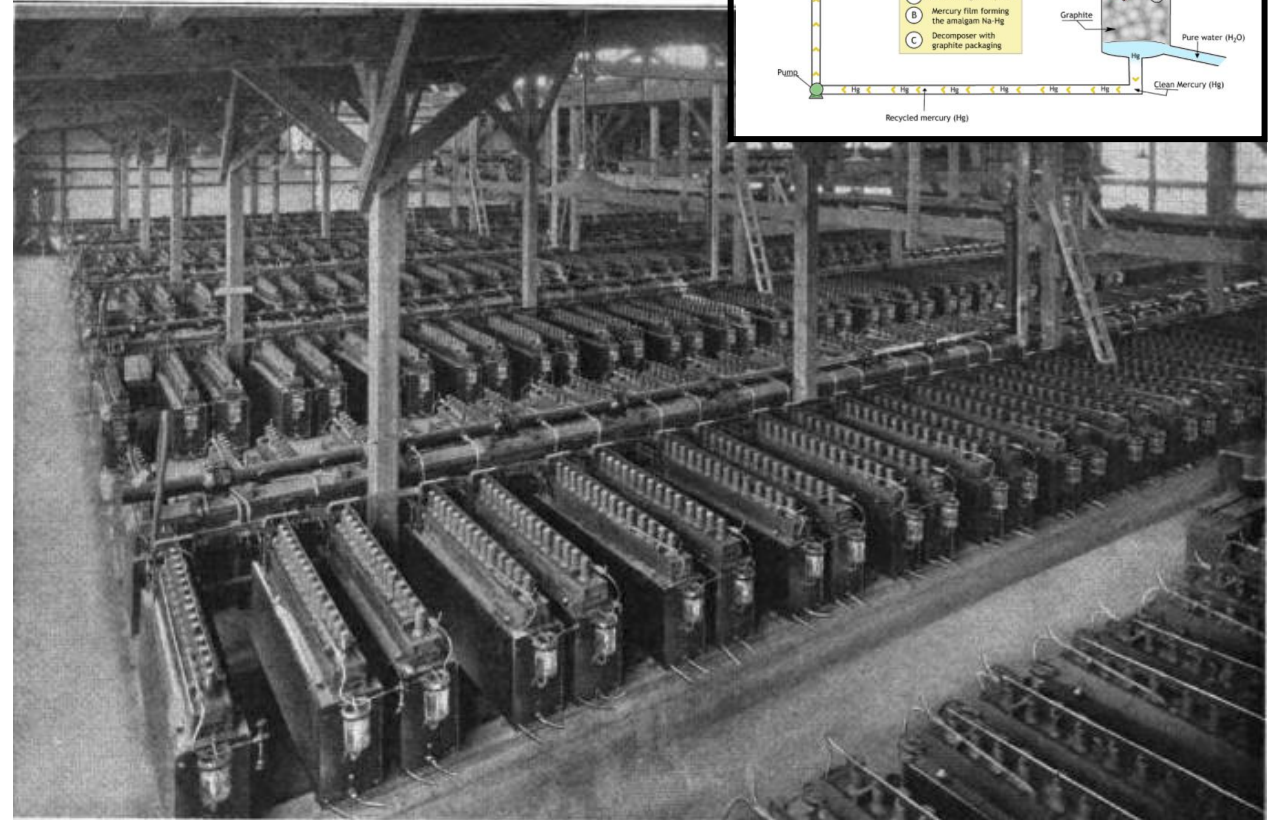
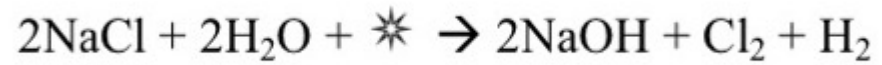
**U.S. PLATFORMS**  
A waterborne city of oil rigs rises off the coasts of Texas, Louisiana, Alabama, and Mississippi—but not Florida. Exploration off the Florida coast, starting in the 1940s, yielded largely dry holes, and the potential threat to the state's top industry, tourism, has been considered too great a risk.

**DEEPWATER DISASTER**  
Working in 5,000 feet of water, the *Deepwater Horizon* rig had drilled 13,000 feet into the seabed when the exploratory Macondo well blew out on April 20, 2010. The explosion and fire sank the 58,000-ton mobile rig, killing 11 workers. An estimated 4.9 million barrels of oil flowed from the well, creating the worst accidental marine oil spill in history.

**CUBA'S POTENTIAL**  
Estimates for Cuba's offshore oil reserves range as high as 4.6 billion barrels. No production has begun, but offshore development rights have been leased by the government to companies from Brazil, India, Malaysia, Norway, Spain, Venezuela, and Vietnam.



# Mercury cell chlor-alkali process



Facility operations not uncommonly released  
~ 10 tons of mercury into adjacent waters (plus  
poorly quantified volumes volatilized into the  
atmosphere and spilled onto site soils)

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

Chaleur Bay / Dalhousie, NB  
 Arvida / Saguenay, QC  
 Beauharnois, QC  
 Lac Quevillon, QC  
 Shawinigan, QC  
 Marathon, ON  
 Cornwall, ON  
 Samia, ON  
 Thunder Bay, ON  
 Hamilton, ON  
**Dryden, ON**  
 Port Abercrombie, NS  
 Saskatoon, SK  
 Squamish, BC  
 Acme, NC  
 Ashtabula, OH  
 Augusta, GA  
 Bellingham Bay, WA  
 Berlin, NH  
 Brunswick, GA  
 Calvert City, KY (×2)  
 Charleston, TN  
 Deer Park, TX  
 Sauget, IL  
 Geismar, LA  
 Westlake, LA  
 Point Comfort, TX  
 Lemoyne, AL  
 Linden, NJ  
 McIntosh, AL  
 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 (×2)  
 Guayanilla, PR  
 Coatzacoalcos-Minatitlán, MX  
 García Nuevo León, MX  
 Ecatepec de Morelos, MX  
 Salamanca, MX  
 Santa Clara, MX

Sagua la Grande, Cuba  
 Managua, Nicaragua  
 Cartagena, Colombia  
 Maracaibo, Venezuela  
 Morón, Venezuela  
 Lima, Peru  
 Callao, Peru  
 Lenga, Chile  
 La Laja, Chile  
 San Jose de Mayo, Uruguay  
 Cinco Saltos / Upper Negro River, Argentina  
 Bahía Blanca, Argentina  
 Ciudad de Río Tercero, Argentina  
 Itapagipe, Bahia, Brazil  
 Camacari - Botafogo River, Brazil  
 Igarrasu, Brazil  
 Santo André, São Paulo, Brazil  
 Santos- Cubatão, Brazil  
 Acari-São João de Meriti River, Brazil

Porsgrunn, Norway  
 Sarpsborg, Norway  
 Norway - 3  
 Bohus, Sweden  
 Stenungsund, Sweden  
 Skoghäll, Sweden  
 Domsjö, Sweden  
 Koepmanholmen, Sweden  
 Sweden - 6  
 Sweden - 7  
 Sweden - 8  
 Kokemäenjoki, Finland  
 Oulu, Finland  
 Aetna, Finland  
 Kuusankoski, Finland  
 Runcorn, UK  
 Sandbach, UK  
 Staveley, UK  
 Hillhouse, UK  
 Ellesmere Port, UK  
 Fermoy, Ireland  
 Vieux-Thann, France  
 Harbonnières, France  
 Tavaux, France  
 St. Auban, France  
 Jarrie, France  
 Loos, France  
 Lavéra, France  
 Mazingarbe, France  
 Jemeppe-sur-Sambre, Belgium  
 Lillo, Belgium  
 Antwerp, Belgium  
 Tessenderlo, Belgium  
 Botlek-Rotterdam, Netherlands  
 Beek Geleen, Netherlands  
 Delfzijl, Netherlands  
 Linne Herten, Netherlands  
 Hengelo, Netherlands  
 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  
 Lülldorf, GR  
 Marl, GR  
 Marktrechwitz, GR  
 Rheinfelden, GR  
 Schkopau, GR  
 Schkopau, GR  
 Uerdingen-Krefeld, GR  
 Wilhelmshafen, GR  
 Zurzach, Switzerland  
 Monthey, Switzerland  
 Pratteln, Switzerland  
 Hallein, Austria  
 Brückl, Austria  
 Neratovice, Czech Republic  
 Ústí nad Labem, Czech Republic  
 Pardubice, Czech Republic  
 Nováky, Slovakia

Martorell, Spain  
 Pontevedra, Spain  
 Torrelavega, Spain  
 Vilaseca, Spain  
 Huelva, Spain  
 Flix, Spain  
 Jodar, Spain  
 Monzon, Spain  
 Hernani, Spain  
 Sabinanigo/Huesca, Spain  
 Povoa de Santa Iria, Portugal  
 Estarreja, Portugal  
 Ria de Aveiro, Portugal  
 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  
 Santa Gilla (Sardinia), Italy  
 Ravenna, Italy  
 Tamów, Poland  
 Bydgoszcz, Poland  
 Brzeg Dony, Poland  
 Varna, Bulgaria  
 Kazincbarcika, Hungary  
 Opiřani (Torda), Romania  
 Ramnicu Valcea, Romania  
 Vlora, Albania  
 Split, Croatia  
 Thessaloniki, Greece  
 Tuzla, Bosnia and Herzegovina  
 Slovenia - 1  
 Serbia - 1  
 Skopje, North Macedonia  
 Aliaga, Turkey  
 Kyiv, 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  
 Pavlodar, Kazakhstan  
 Temirtau, Kazakhstan  
 Navoi, Uzbekistan  
 Yavan, Tajikistan  
 Sumgait, Azerbaijan (×2)

Bandar Imam, Iran  
 Shiraz, Iran  
 Kor River site, Iran (?)

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

Iraq - 1  
 Iraq - 2  
 UAE - 1  
 Syria - 1  
 Haifa, Israel

Airoli, India  
 Mumbai, India  
 Ganjam, India  
 Singrauli, India  
 Vadodara, India  
 Kota, Rajasthan, India  
 Renukoot, Uttar Pradesh, India  
 Nagda, Madhya Pradesh, India  
 India - 9  
 India - 10  
 Kala Shah Kaku, Pakistan  
 Myanmar - 1  
 Bangkok, Thailand  
 Perai, Malaysia  
 Merak, Banten Province, Indonesia  
 Indonesia - 2

[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  
 Kitakyushu, Japan  
 + 22 additional sites in Japan as per Yarime (2008)

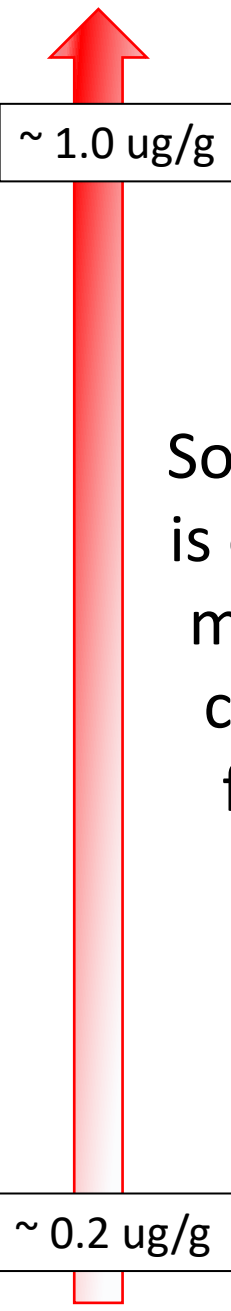
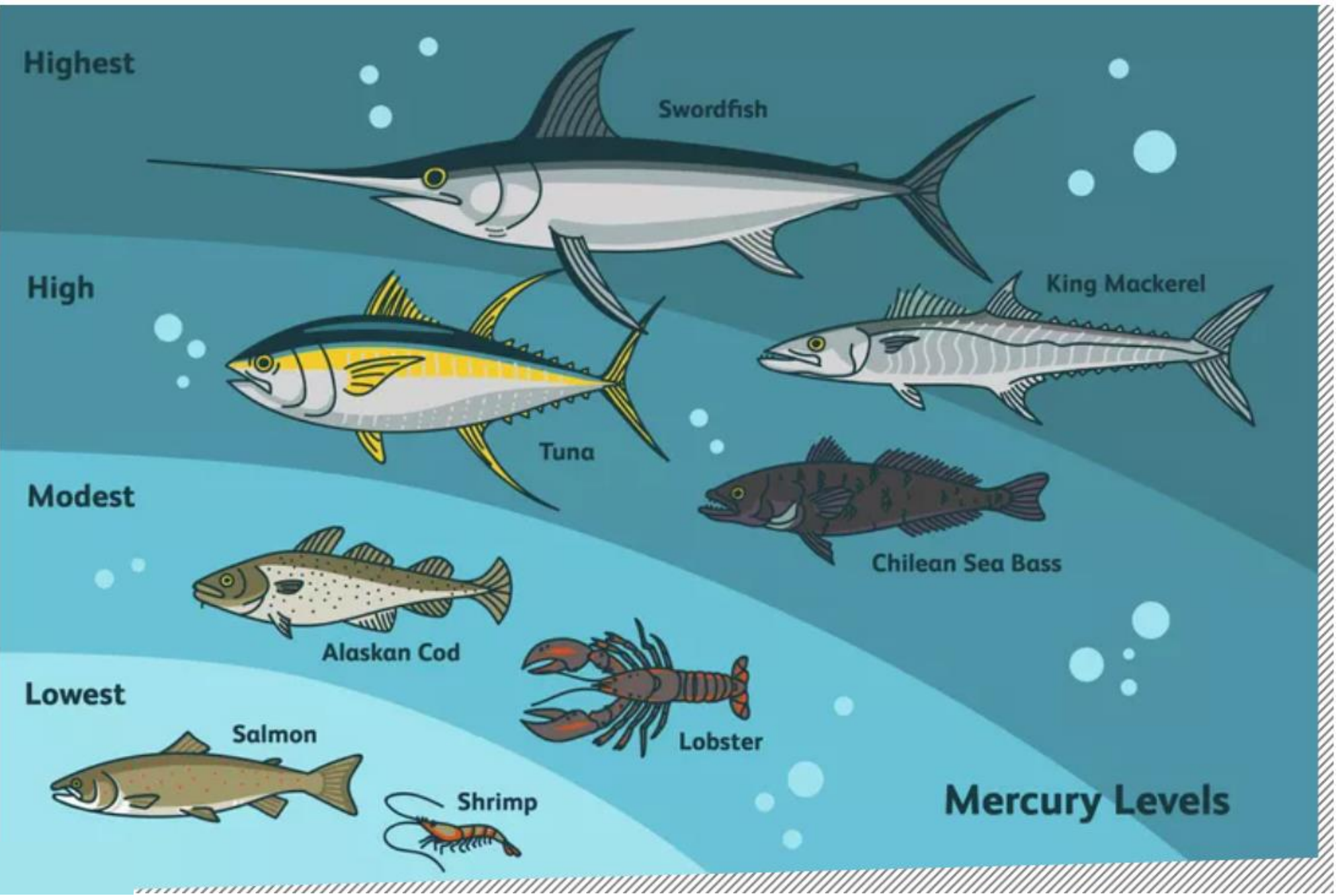
Ezhou City, China  
 Wuda District, Inner Mongolia, China  
 Shihezi, China  
 An Ning, China  
 Huludao, China  
 Tianjin, China  
 Yongjing, China  
 Qingzhen, China  
 Jilin City, China  
 Dezhou City, Shandong Province, China  
 Lanzhou, China  
 Kaohsiung City, Taiwan  
 Tainan City, Taiwan  
 Iligan City, Mindanao, Philippines  
[Hamhung, North Korea](#)  
 North Korea - 2

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

Matraville, Australia  
 Adelaide, Australia  
 Melbourne, Australia  
 Burnie, Tasmania

Mercury Cell Chlor-Alkali Facility – identified  
 Acetaldehyde Facility – identified  
 Mercury Chlor-Alkali Facility – not confirmed; facility may have operated with an asbestos diaphragm

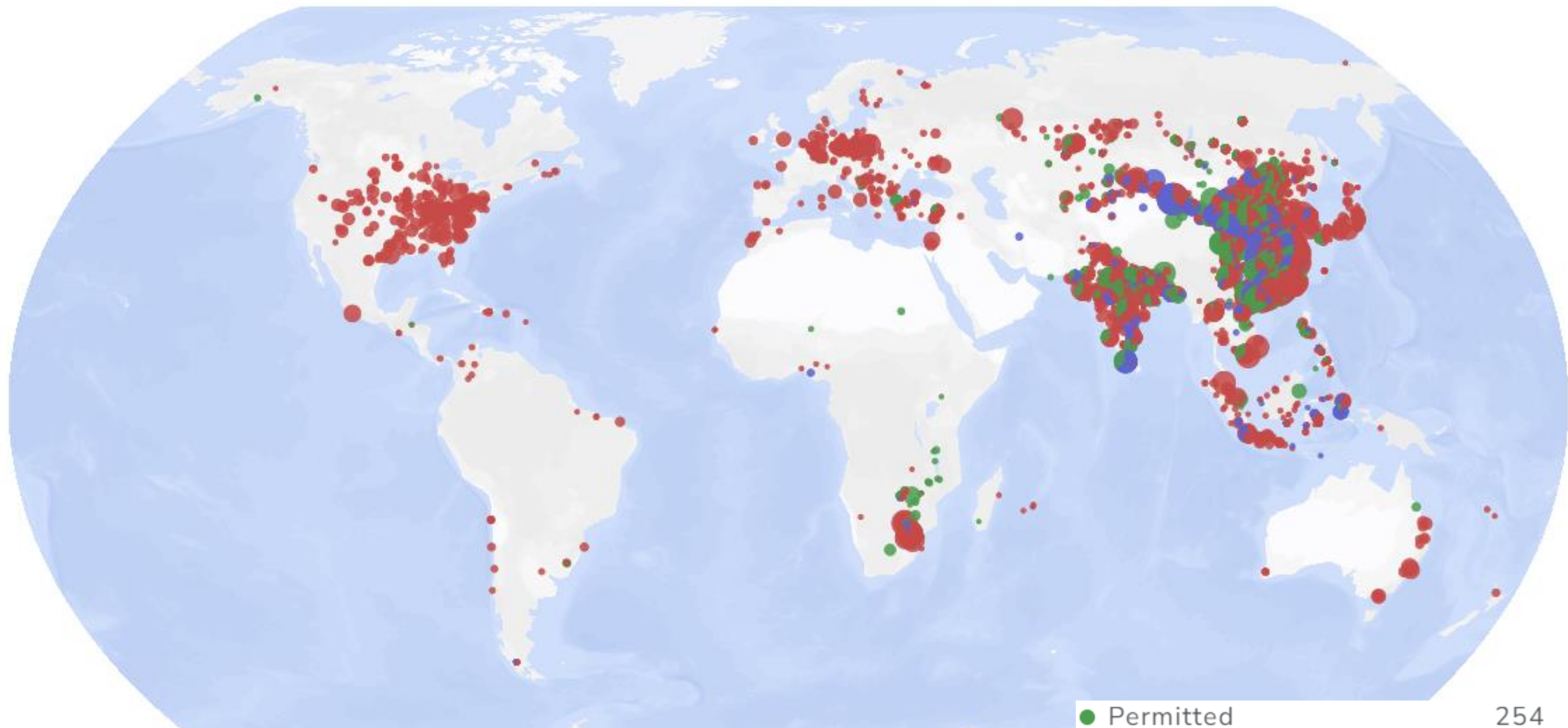




So, where is oceanic mercury coming from?

**Mercury Levels**

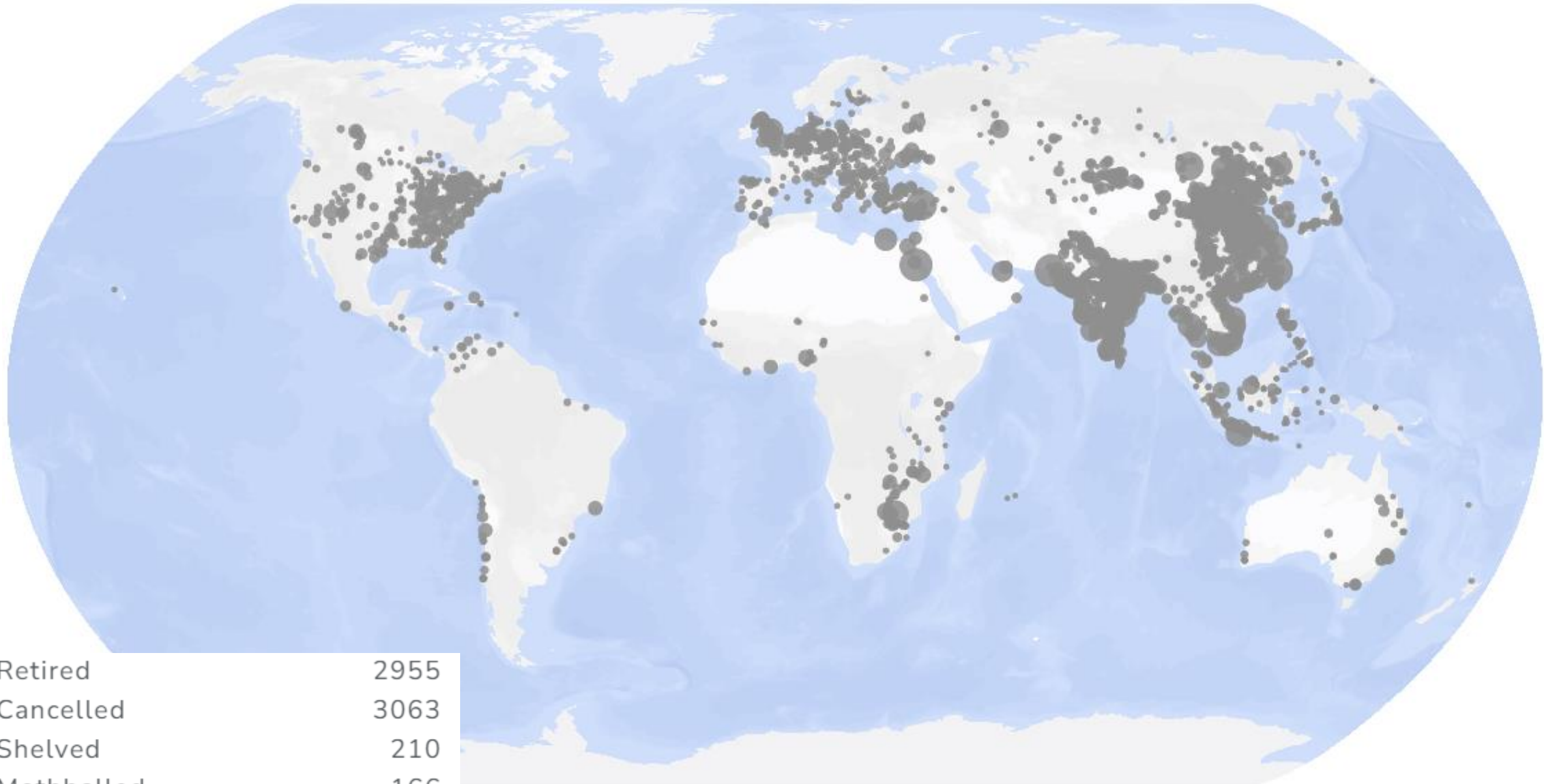




<input checked="" type="checkbox"/>	● Operating	6525
<input checked="" type="checkbox"/>	● Construction	421

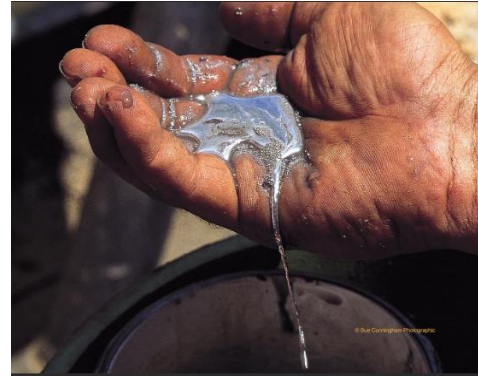
● Permitted	254
● Pre-Permit	229
● Announced	181

Also...is this what a **tipping point** looks like...?



● Retired	2955
● Cancelled	3063
● Shelved	210
● Mothballed	166

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



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



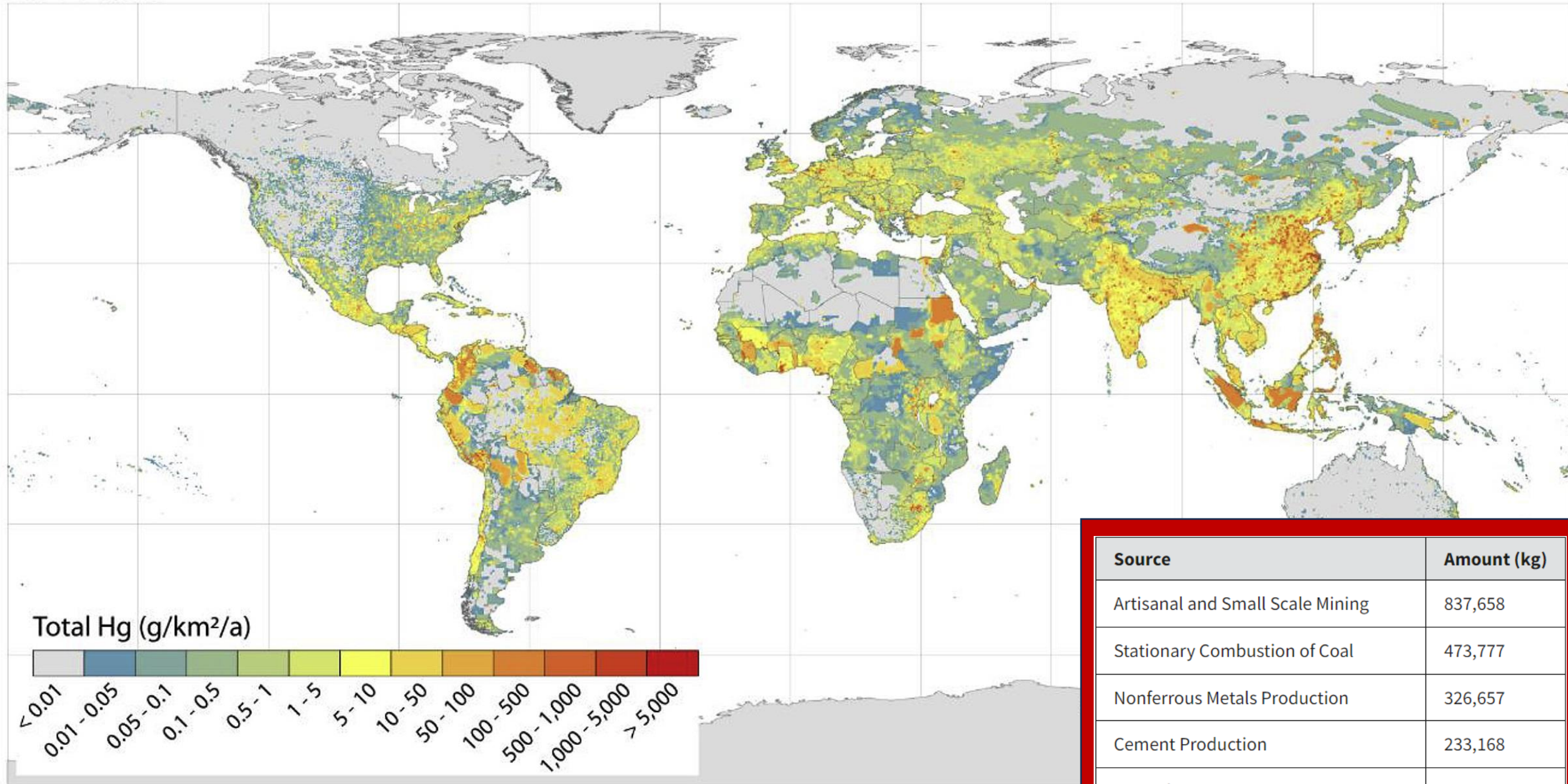
## Serra Pelada, Brazil

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

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

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

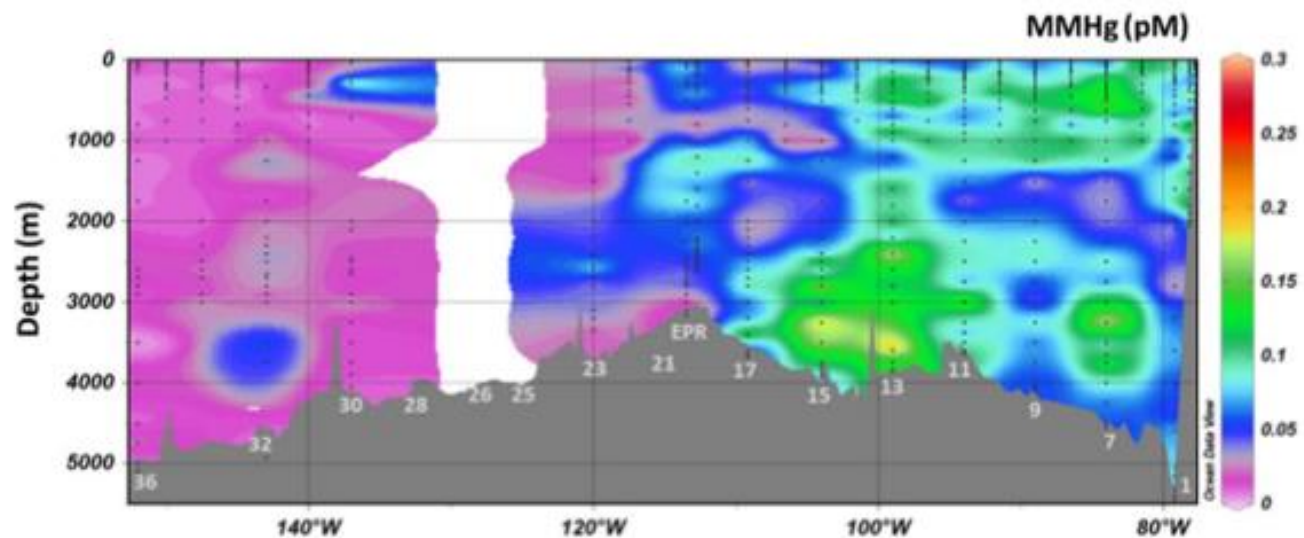
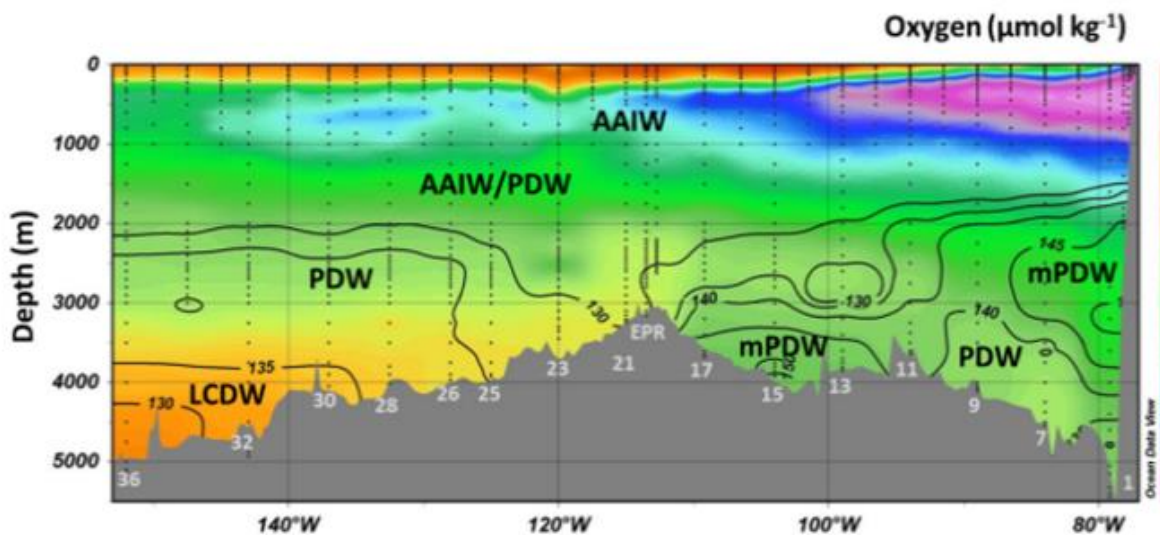
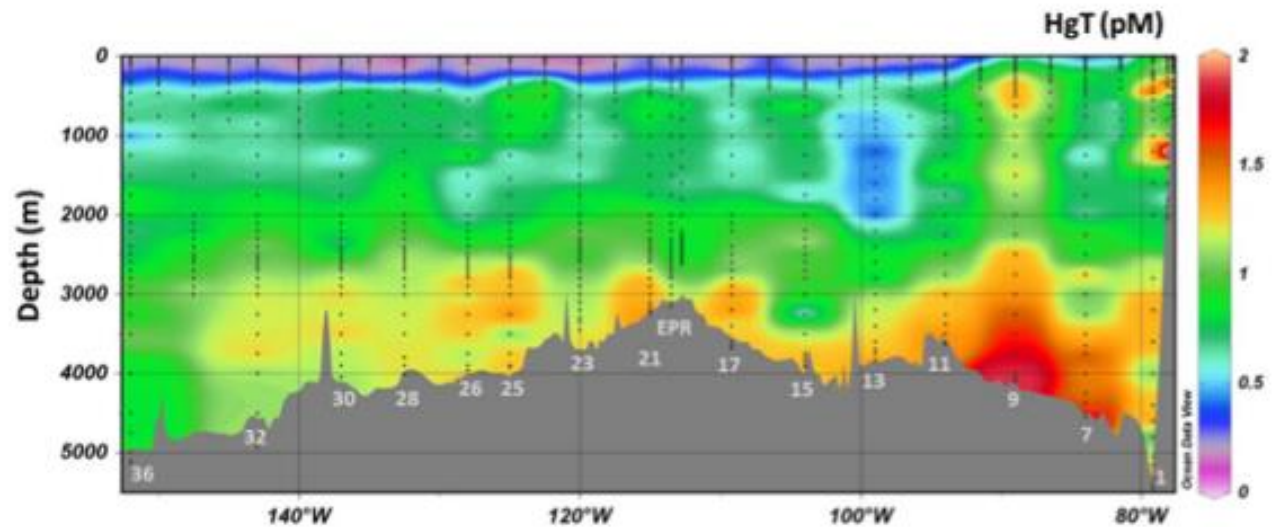
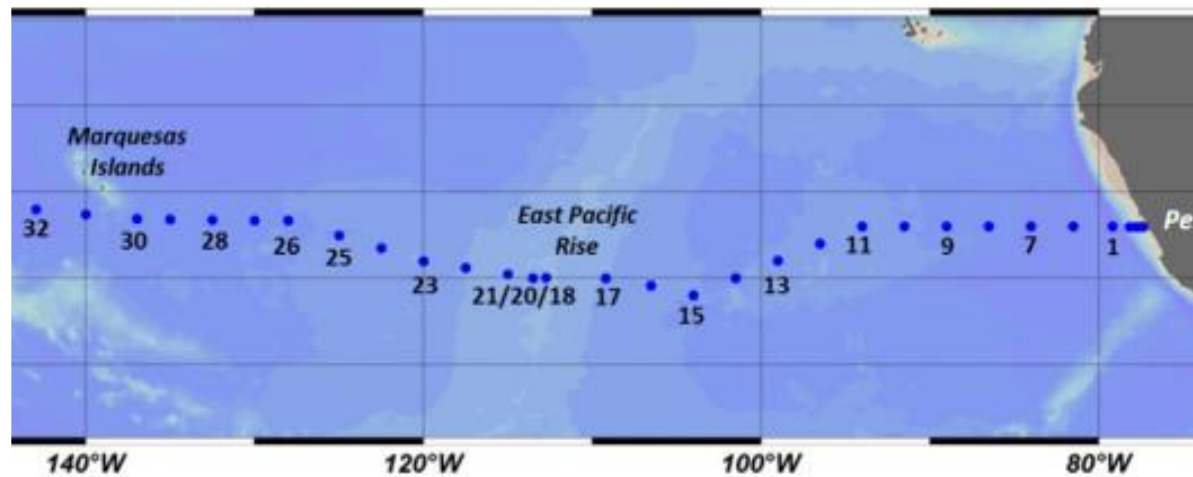
**Abstract** Monomethylmercury (CH<sub>3</sub>Hg) is the only form of mercury (Hg) known to biomagnify in food webs. Here we investigate factors driving methylated mercury [MeHg = CH<sub>3</sub>Hg + (CH<sub>3</sub>)<sub>2</sub>Hg] production and degradation across the global ocean and uptake and trophic 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.

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

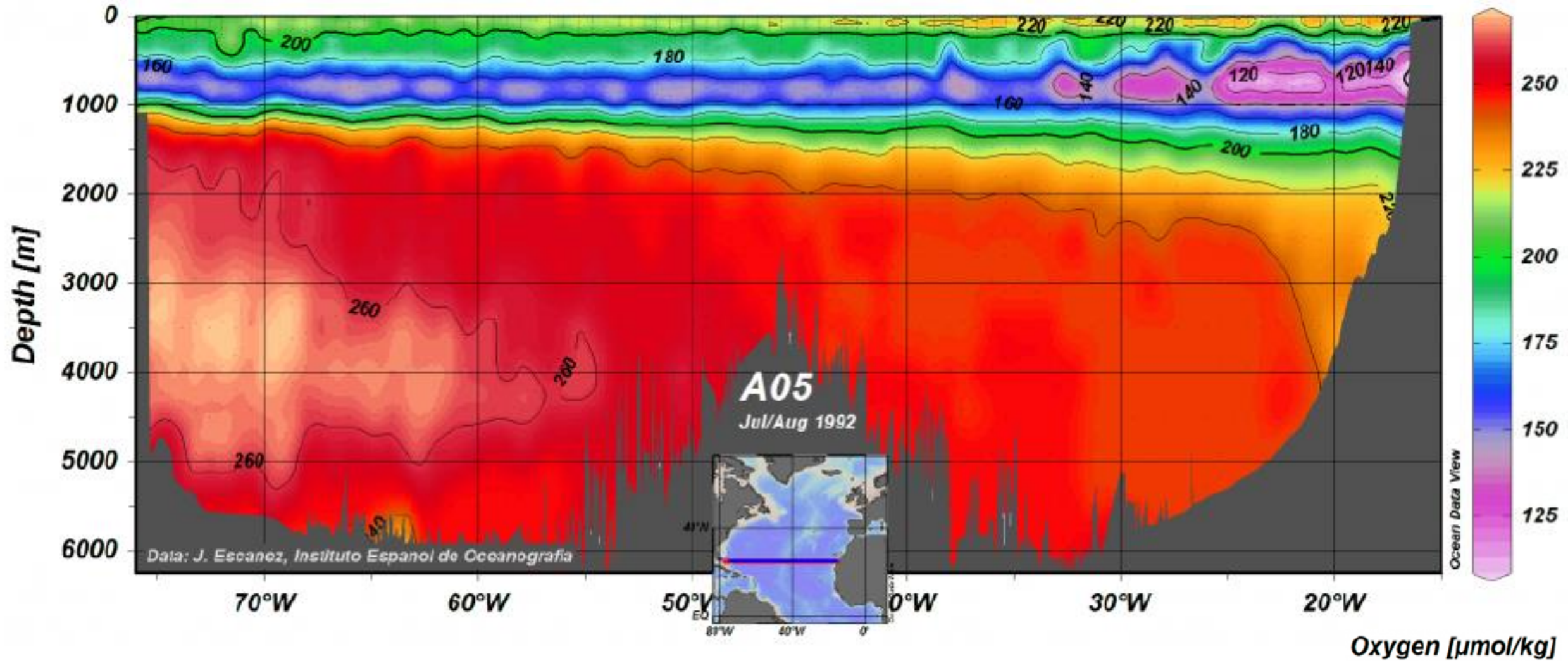
Katlin L. Bowman<sup>a</sup>  , Chad R. Hammerschmidt<sup>a</sup> , Carl H. Lamborg<sup>b 1</sup> ,  
Gretchen J. Swarr<sup>b</sup> , Alison M. Agather<sup>a</sup> 

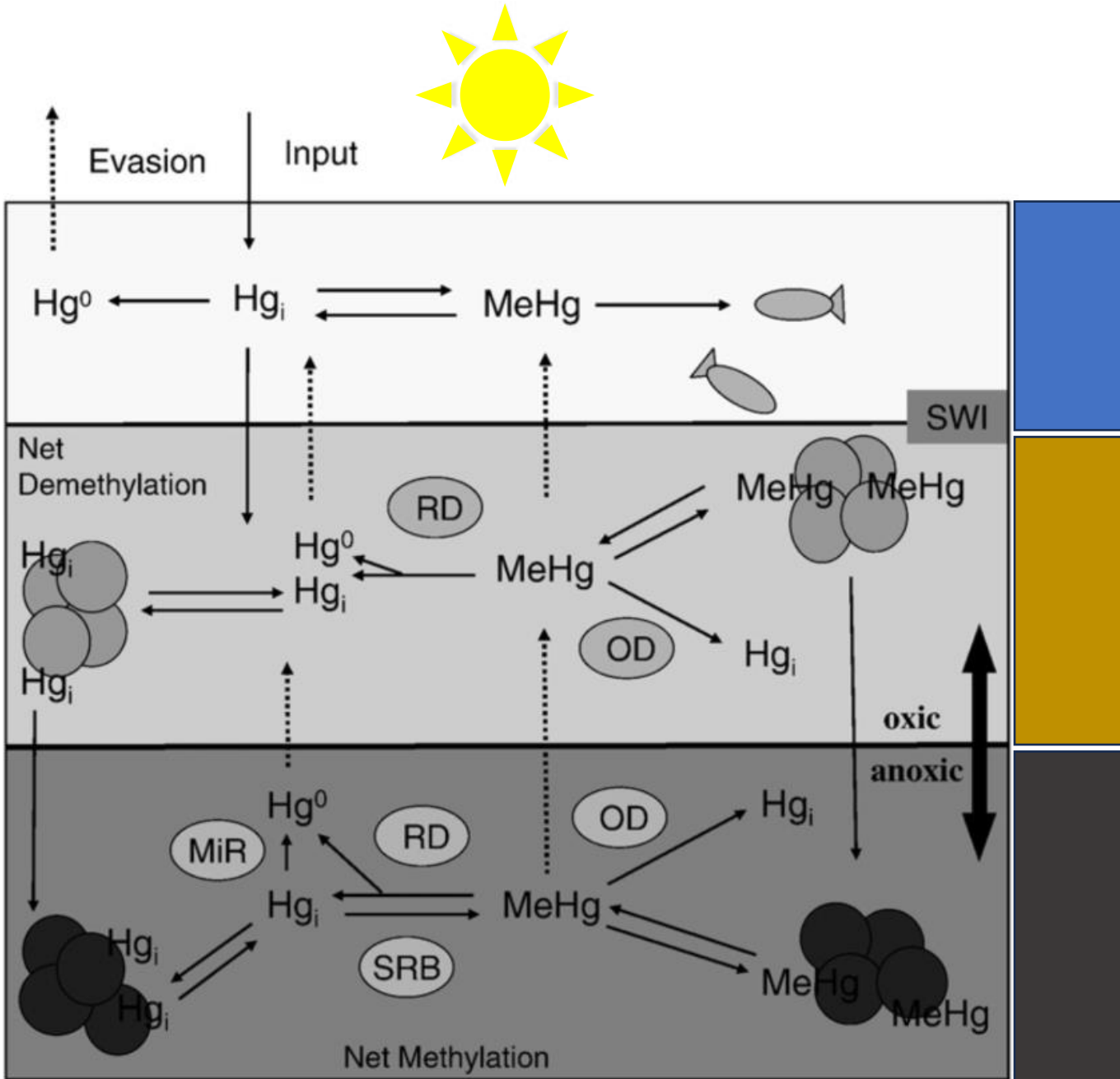
### Highlights

- 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 4000km west from the East Pacific Rise.
- Deep water below 2500m was enriched with Hg, especially in warm bottom waters in the eastern part of the section.



Consider this as a typical  $dO_2$  profile & Atlantic basin transect under a past version of ocean conditions and what warming of the oceans is changing





- 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  $Hg^{2+}$

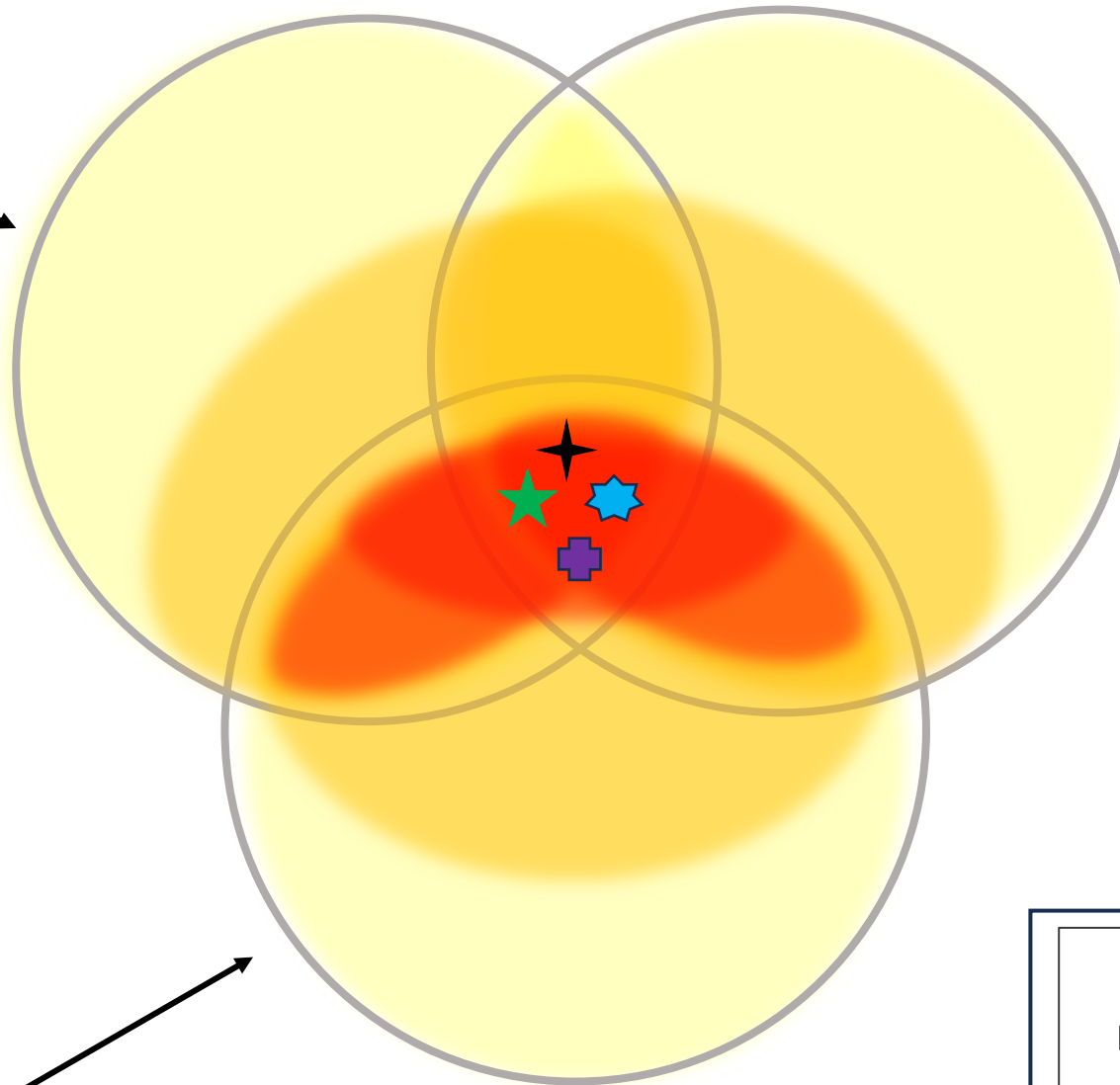
# PHYSICAL

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

- ✦ = North Atlantic + Polar
- ★ = Upwelling Zones
- ★ = Photic Zone (CMZ)
- ✦ = OMZ

# CHEMICAL

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



# BIOLOGICAL

Most significant  
bioaccumulation step  
is between water  
column and uptake by  
phytoplankton

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