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Environmental impacts of mining seafloor massive sulfide deposits

by

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The LRET Research Collegium
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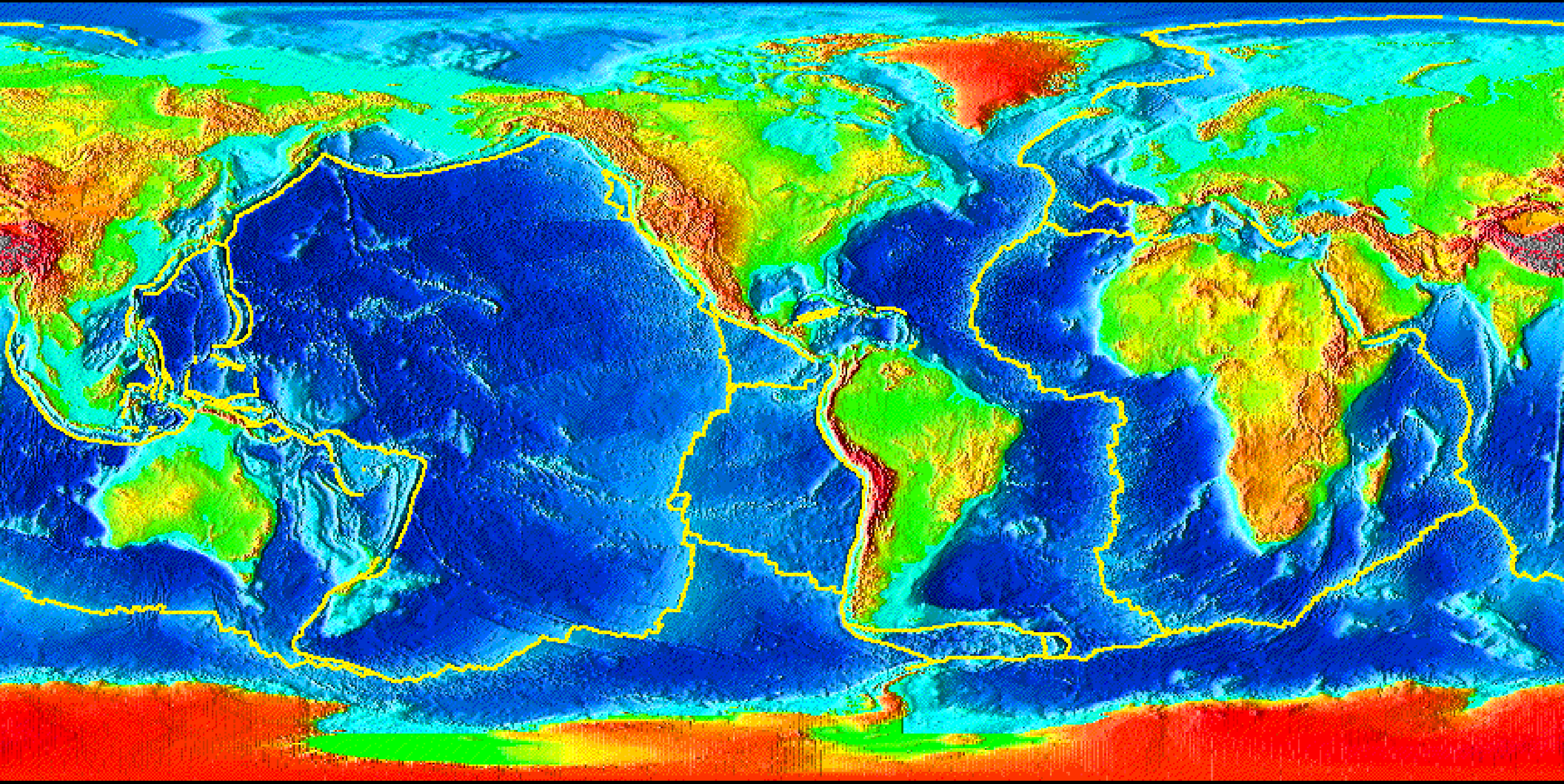
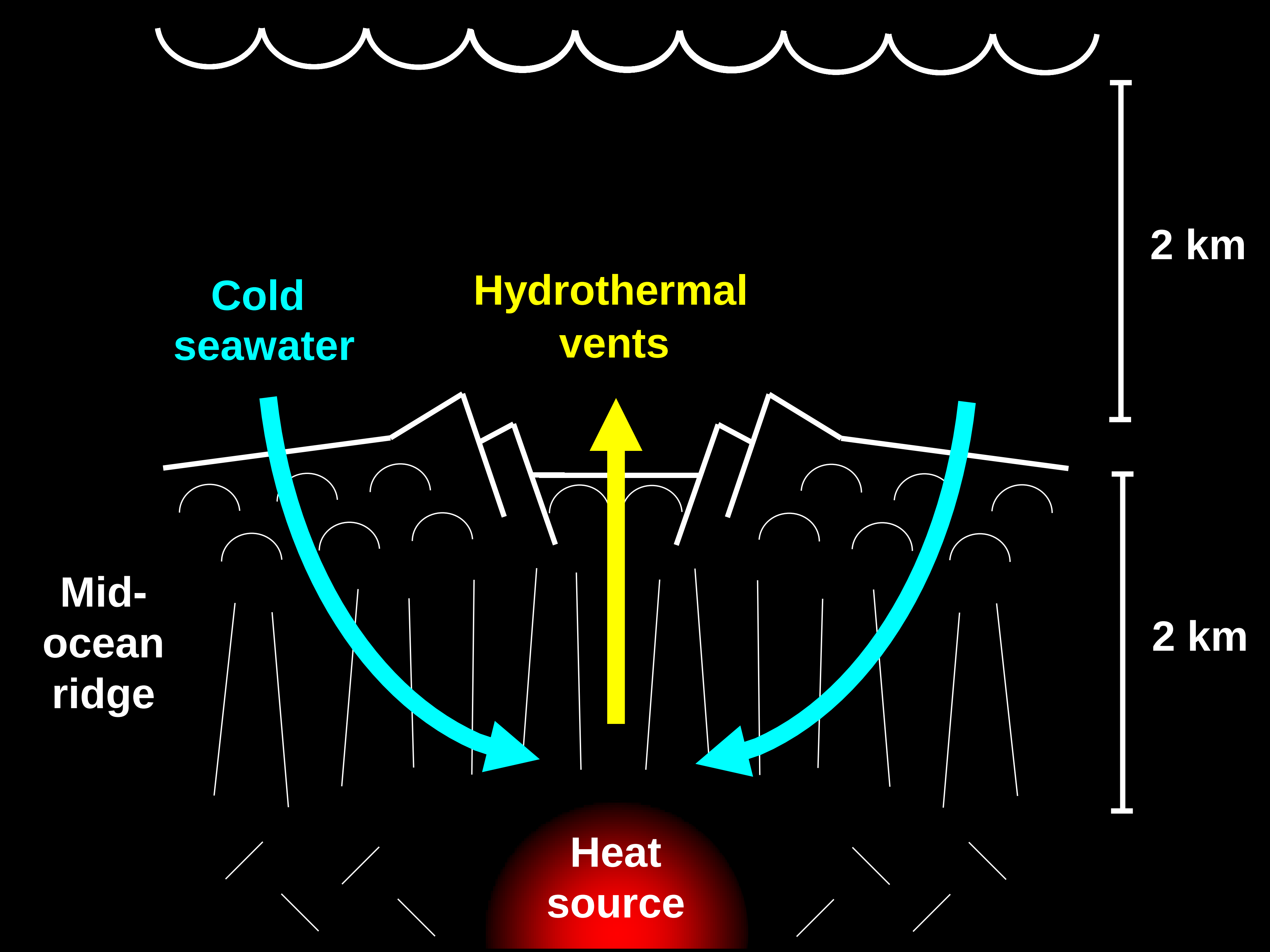



2 km
Cold
seawater
Hydrothermal
vents
Mid-
ocean
ridge
2 km
Heat
source

Hydrothermal circulation

* Entire global ocean volume passes through

hydrothermal circulation every ~10^4 years

* Removes Mg and SO_4 from seawater

* Adds H_2S, Mn, Fe, Cu, Zn, Pb, H_2, CH_4 (and many others)

* Primary (undiluted) vent fluids are typically:

  - hot (up to ~400 °C)

  - acidic (pH 3 to 5)

  - anoxic

* BUT vent fluid mixes rapidly with cold, oxygenated seawater

Vent fluids

* Primary vent fluid is clear in appearance

* Mixes with cold, oxygenated seawater

⇨ “black smoke” at >225 °C

* “Smoke” = precipitating mineral particles

(metal sulfides first, then oxides / oxyhydroxides)

* Greater mixing and conductive cooling can produce:

- “white smoke” at 100 to 225 °C

- “shimmering water” diffuse flow at lower temperature

Hydrothermal deposits

* Precipitating vent fluid ⇨ seafloor massive sulfide deposit

* SMS deposits are rich in copper and zinc sulfides

Insular nature of hydrothermal vents

* Hydrothermal vents occur in “fields”:

clusters of vent chimneys within an area of a few hundred m^2

* Occurrence of vent fields depends on underlying geology:

availability of a heat source, and pathways for circulation

* On a fast-spreading mid-ocean ridge (e.g. East Pacific Rise),

vent fields may be 10s of km apart

* On a slow-spreading mid-ocean ridge (e.g. Mid-Atlantic Ridge),

vent fields may be 100s of km apart

Ephemeral nature of hydrothermal vents

* Venting at an individual vent field does not last forever

* Volcanic eruptions or tectonic activity

can disrupt the “plumbing” of the vents

* How long a vent field lasts depends on how

frequently these types of disturbance occur

* Vent fields on a fast-spreading mid-ocean ridge

(e.g. East Pacific Rise) may only last for 10s of years

* Vent fields on a slow-spreading mid-ocean ridge

(e.g. Mid-Atlantic Ridge) may last for 1000s of years

Chemosynthetic environments

* Deep sea: usually exponential decline in biomass with depth

* BUT there are important exceptions to this general pattern:

CHEMOSYNTHETIC ENVIRONMENTS

* These are *in situ* sites of primary production in the deep sea

* Deep-sea vents are chemosynthetic environments

- support rich colonies of animal species

in the otherwise sparsely-populated abyss

Chemosynthetic primary production

* Fixation of inorganic carbon using chemical energy

* Proposed by Winogradsky in 19th century

* “Reduced” chemical compounds provide a source of electrons

(e.g. hydrogen sulfide H_2S)

* Process carried out by prokaryotic microbes

(i.e. Archaea and Bacteria)

* Process requires a terminal electron acceptor

(e.g. oxygen, in AEROBIC chemosynthesis)

Chemosynthesis at vents

* Sulfide oxidation appears to be the dominant form

of chemosynthesis in terms of carbon fixation

* H_2S readily available in vent fluids

* In some geological settings, CH_4 and H_2 may also be used

* Oxygen readily available in “background” deep-sea water

* Anaerobic pathways thought to be less important but

may dominate in high-temperature fluids (e.g. methanogenesis)

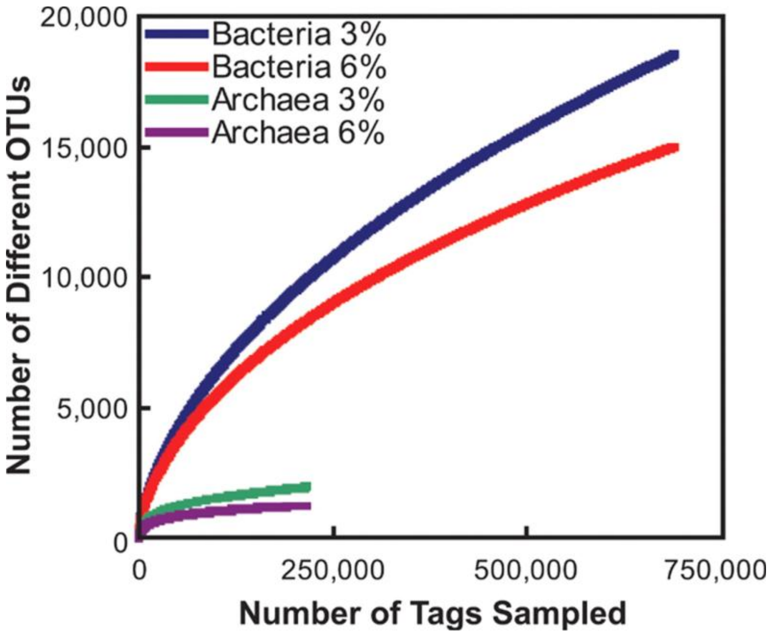
Chemosynthetic primary production

* High abundance of prokaryotes in chemosynthetic environments

*"Normal" deep sea 10^3 to 10^5 cells ml^{-1}

* Hydrothermal vent environments 10^6 to 10^7 cells ml^{-1}

* May also be high genetic diversity among bacteria at vents:



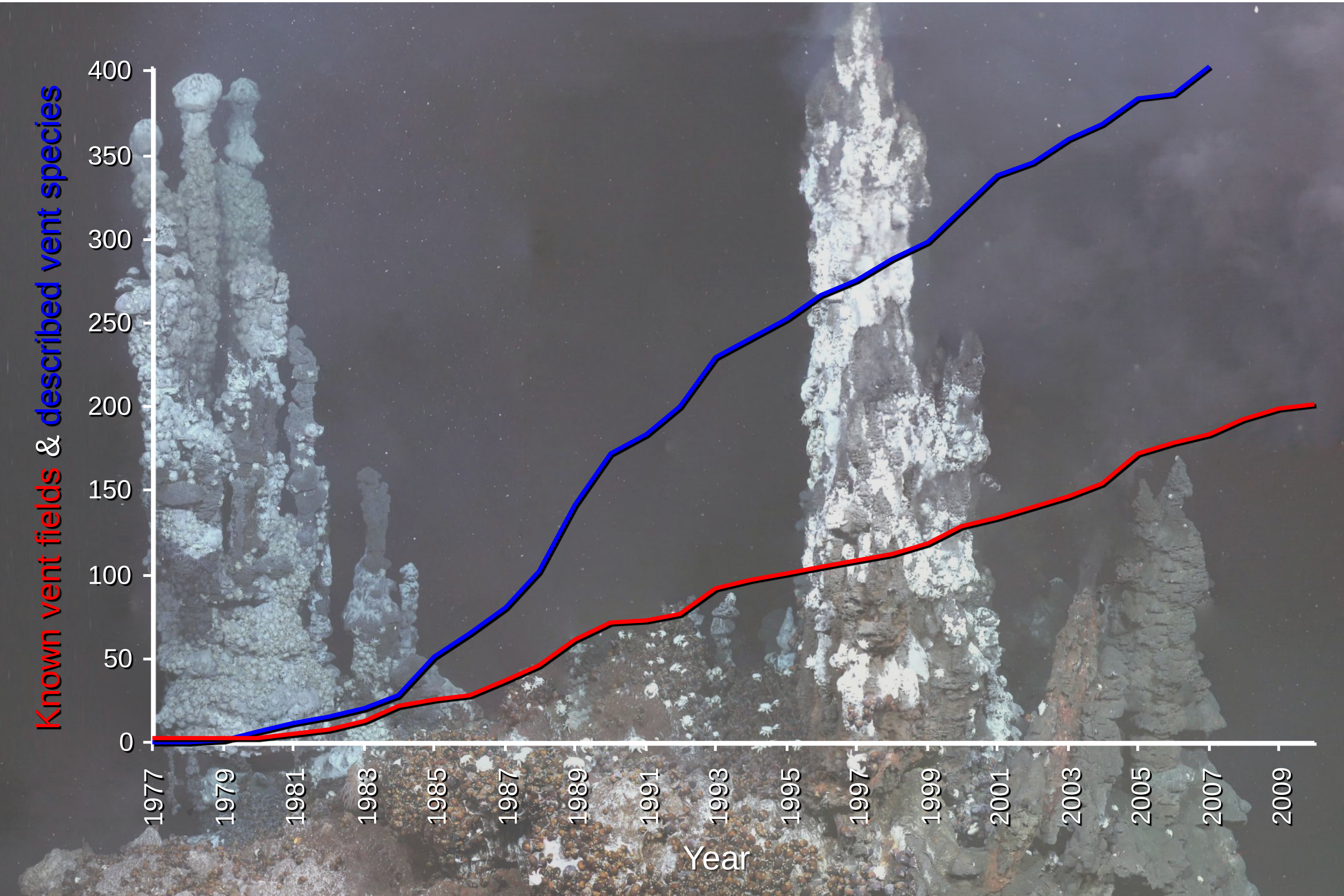
Huber *et al.* (2007)

Chemosynthetic primary production

* *In situ* chemosynthetic primary production can support faunal assemblages with high abundance and biomass in the deep sea

* Most animal species found at vents are new to science and not known from any other environments

Hydrothermal vent discoveries



From microbes to animals

* Animals can exploit chemosynthetic primary production

by microbes in a variety of ways:

- via endosymbiotic relationships

- via microbial epibionts

- by grazing or suspension feeding of free-living microbes

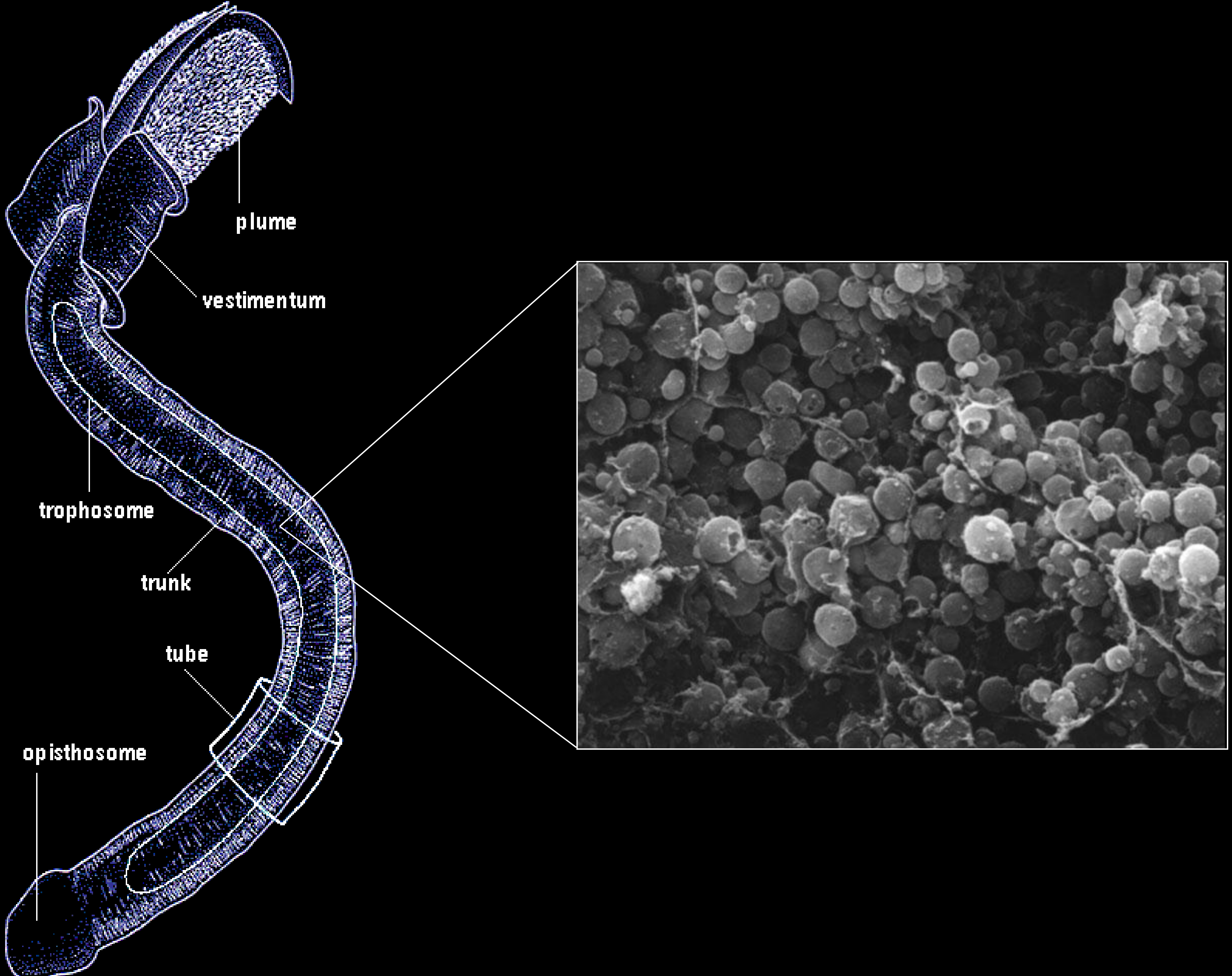
- by predation / scavenging on primary consumer animals

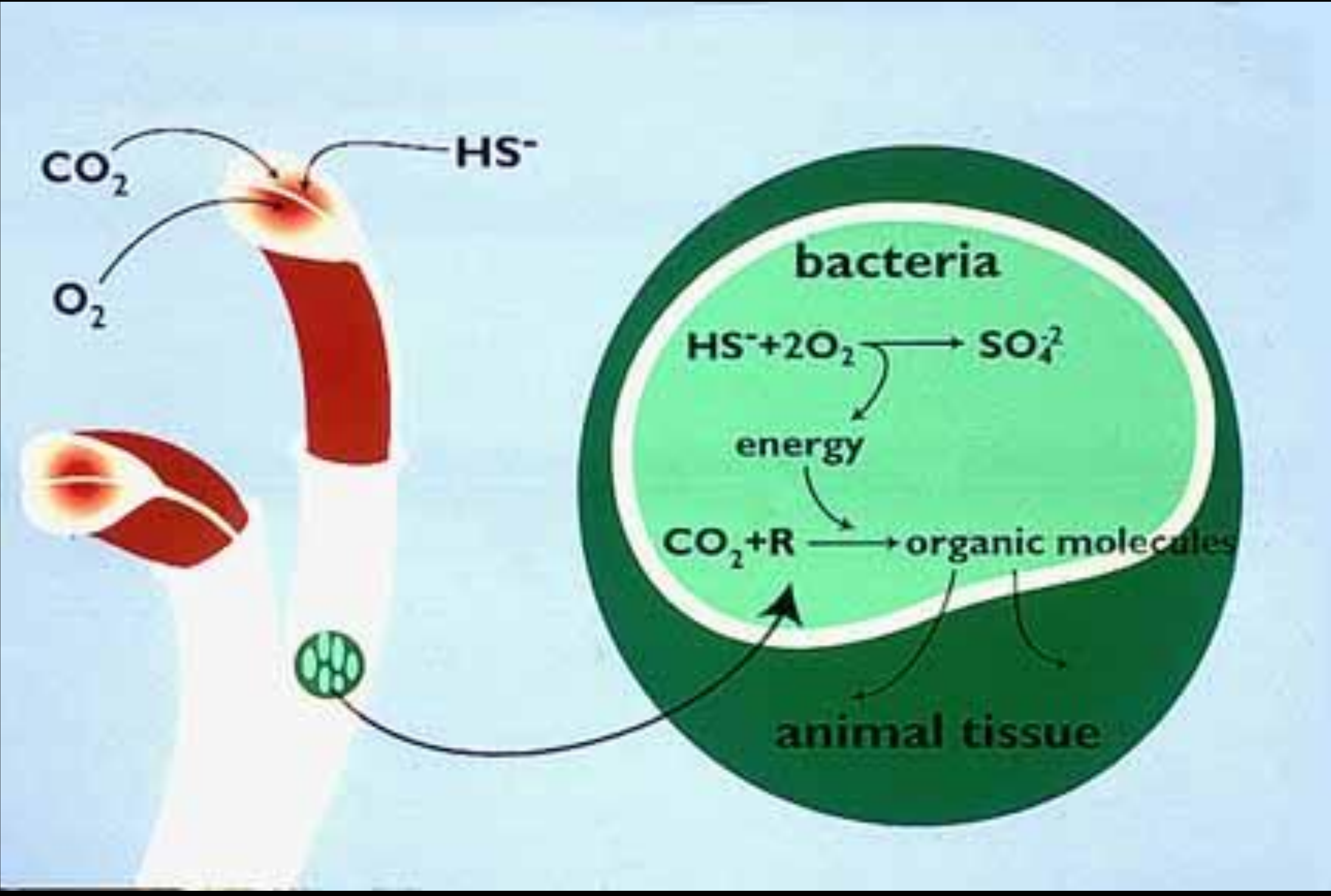
Animal-microbe endosymbioses at vents

* EXAMPLE: vent tubeworm *Riftia pachyptila*

* Originally placed in a new phylum (Vestimentifera)

* BUT now classified as a siboglinid polychaete


plume
vestimentum
trophosome
trunk
tube
opisthosome



CO_2
HS^-
O_2
bacteria
$HS^- + 2O_2 \rightarrow SO_4^{-2}$
energy
$CO_2 + R \rightarrow$ organic molecules
animal tissue

Other animal-microbe endosymbioses

* *Calyptogena* spp. clams:

- bacterial symbionts live inside cells of clam's gills

- sulfide acquired via clam foot, oxygen via gills

(supply of O_2 and H_2S separated in space)

- separate binding molecule for sulfide in clam's blood

Animals at vents with epibionts

* Some animals at vents have epibiotic bacteria

* Roles may include nutrition and detoxification

* Nutrition example: vent shrimp of the genus *Rimicaris*

* 3 x *Rimicaris* species currently known:

- *R. exoculata* (Mid-Atlantic Ridge)

- *R. kairei* (Central Indian Ridge & SW Indian Ridge)

- *R. hybisae* (Cayman Trough; Nye, Copley, Plouviez 2011)

Rimicaris exoculata

Rimicaris kairei

Rimicaris hybisae

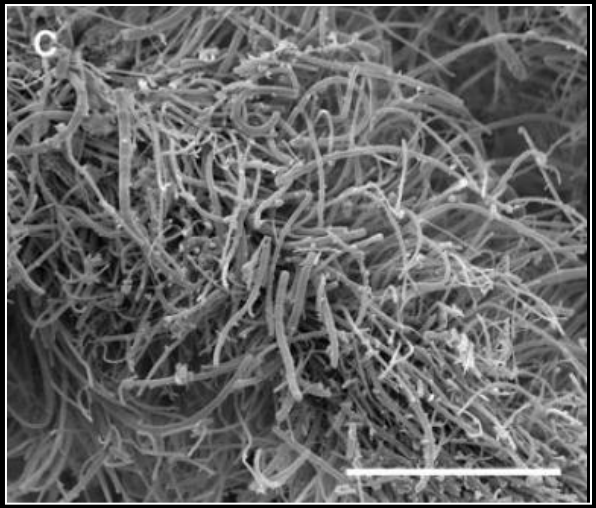
Animals at vents with epibionts

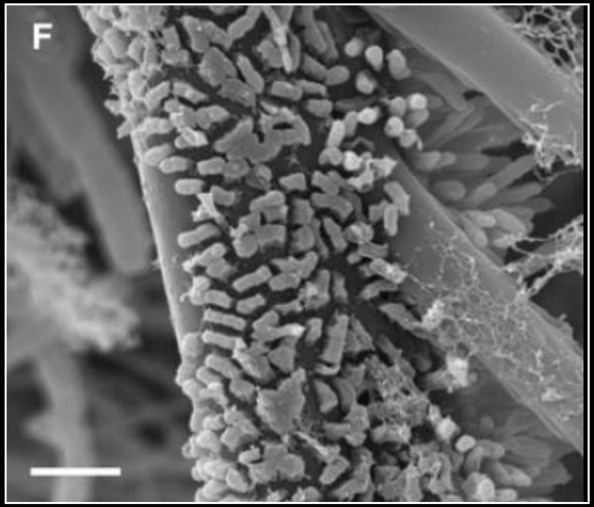
* Adult *Rimicaris* at vents appear to feed on epibiotic bacteria:

ε- and γ-proteobacteria grow inside carapace

and on mouthparts of the shrimp

(e.g. "bacteriophore" setae of maxillae)





Nye, Copley, Plouviez (2011)

Grazers at vents

* Other primary consumers at vents graze on bacteria

present either as biofilms or mats of filamentous bacteria

* Grazers include limpets (e.g. *Lepetodrilus* spp.) and polychaetes

Filter feeders at vents

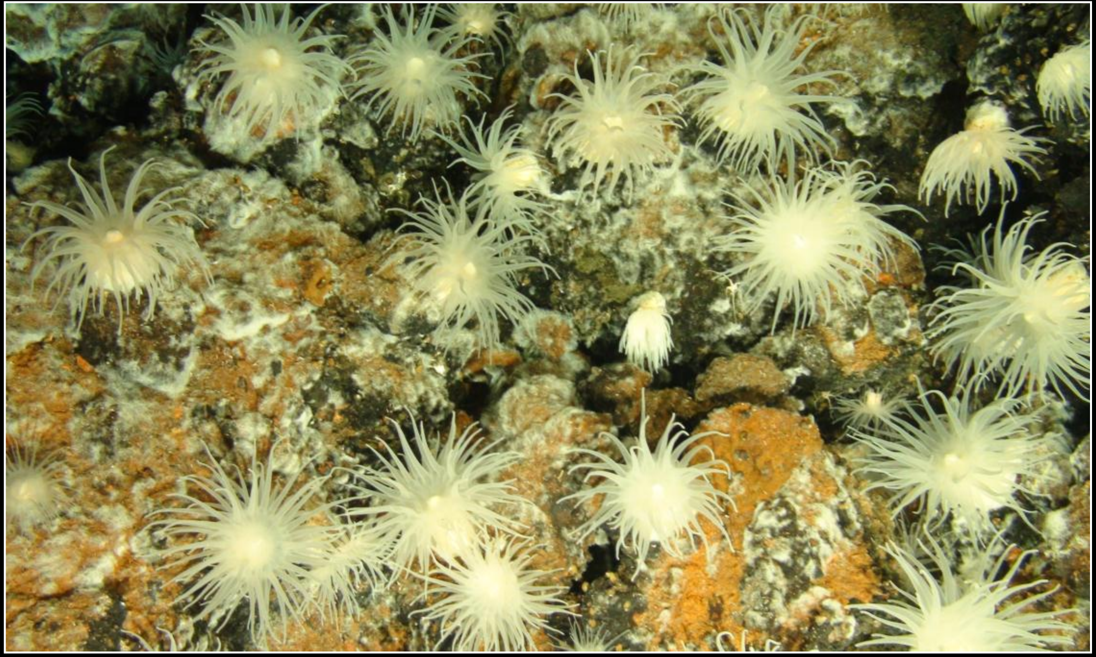
* Some species may also filter-feed on organic matter at vents

- e.g. eolepadid stalked barnacles

Predators / scavengers at vents

* Vent predators / scavengers include some crabs, zoarcid fish, anemones (e.g. *Maractis rimicarivora*), possible octopus species

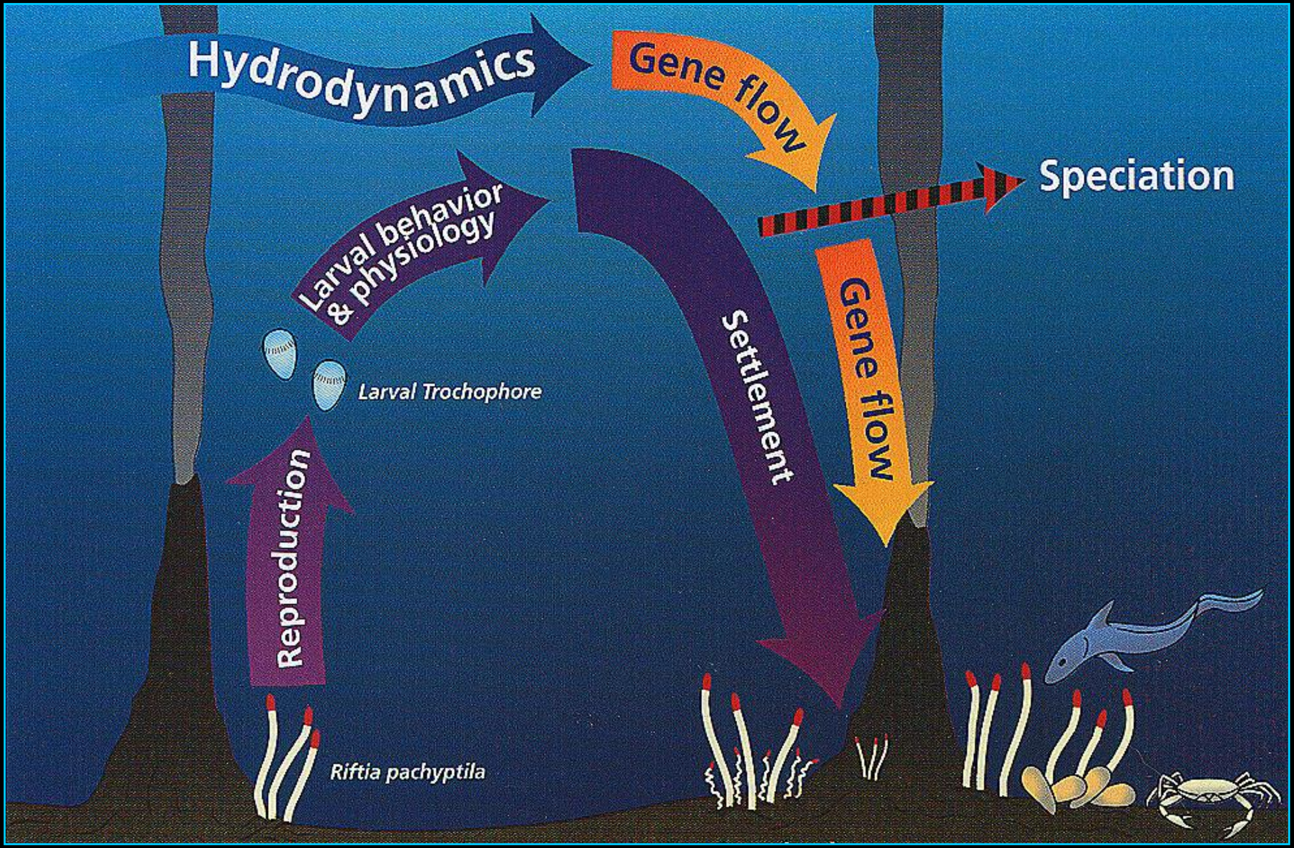
* May also have opportunistic “non-vent” predators / scavengers



Isolation, speciation, biogeography

* Chemosynthetic environments are insular and ephemeral

* Dispersal of fauna is usually achieved by larval stages



Isolation, speciation, biogeography

* Interruption to gene flow between populations ⇨ speciation

* Such interruptions can include:

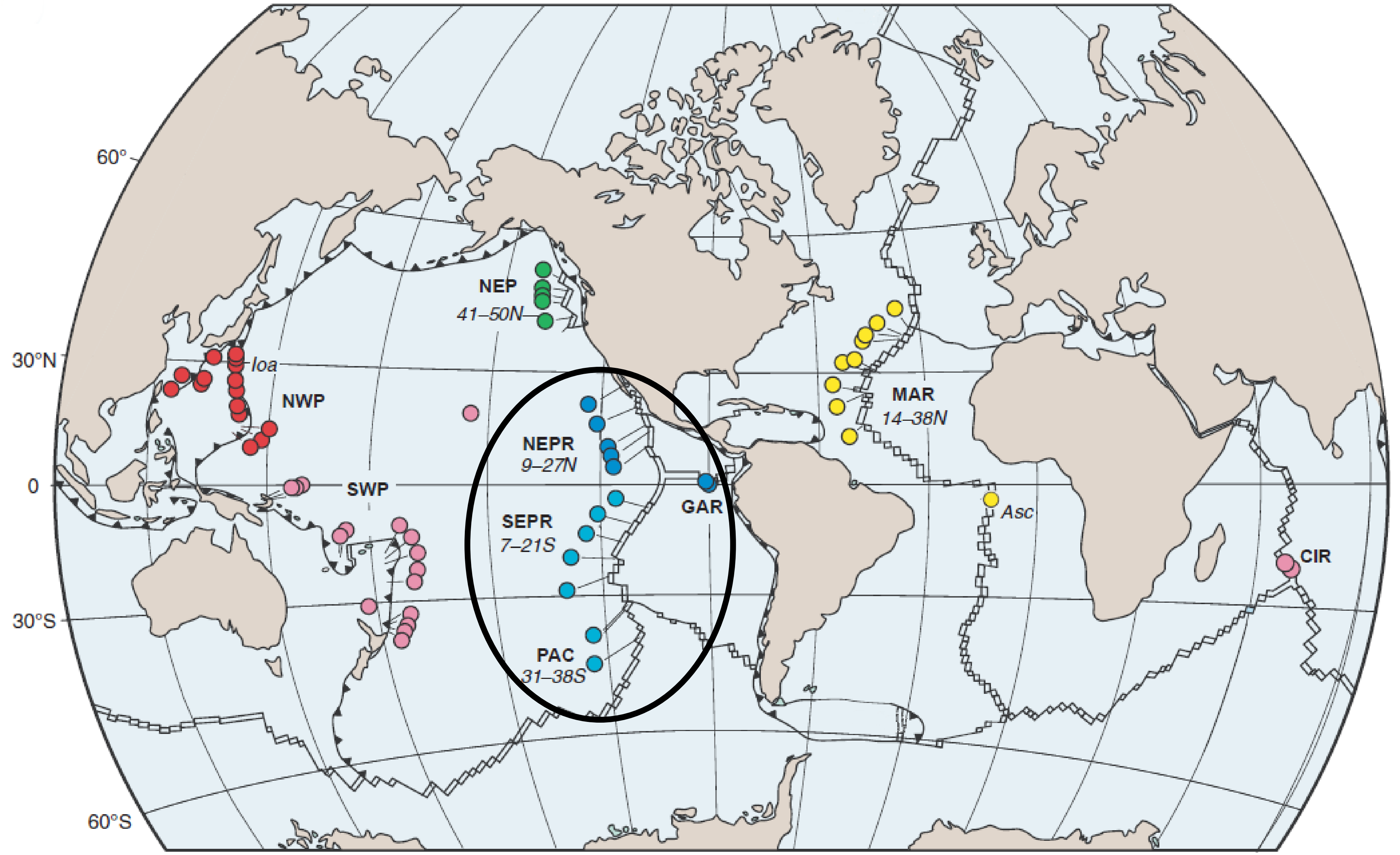
    - movements of plates, ridges, continents

    - changes in ocean currents

* Speciation ⇨ different species living in different regions

    - a biogeographic pattern

Vent biogeographic provinces



(Vrijenhoek 2010)

East Pacific Rise

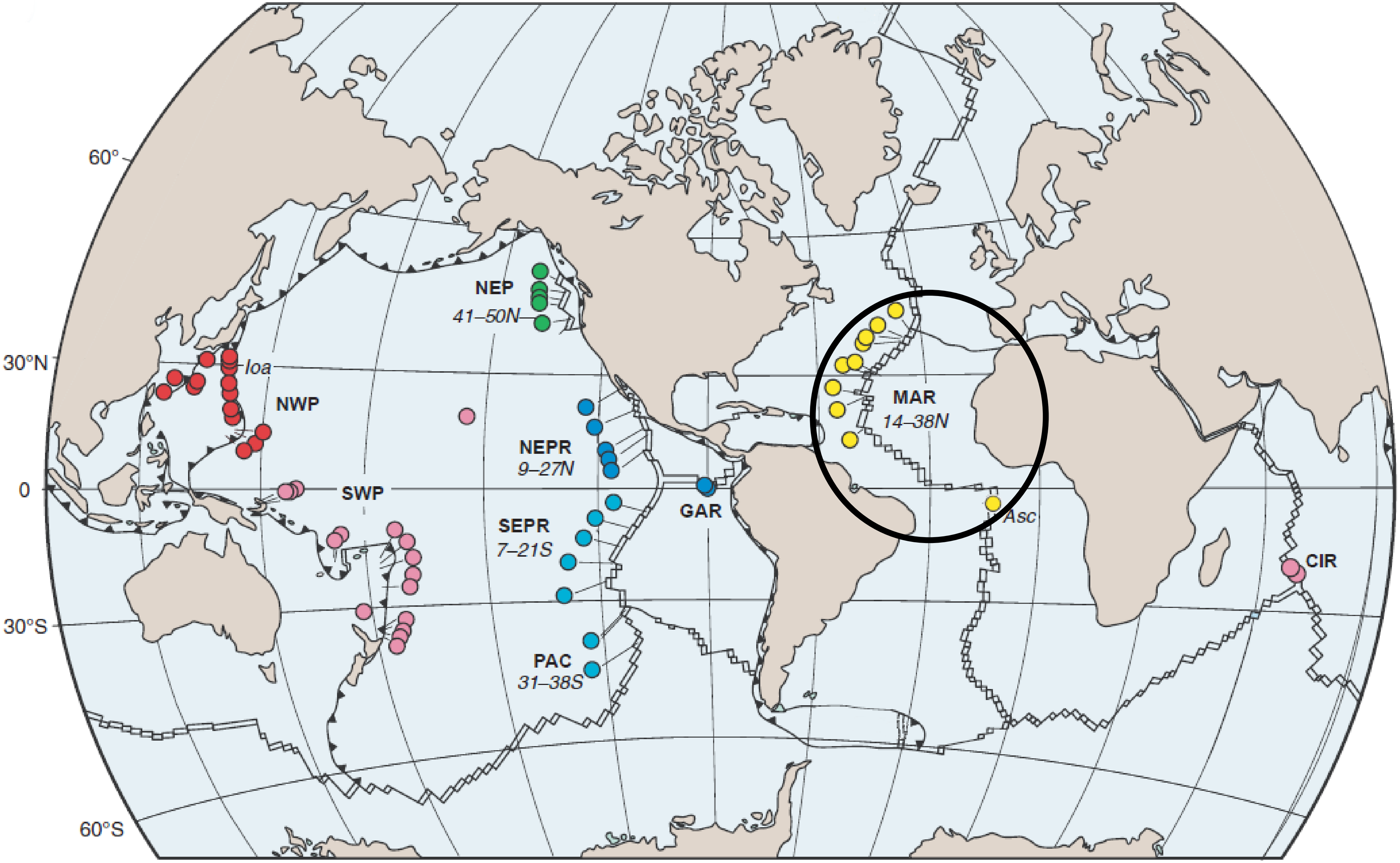
Alvinellid polychaetes
"Pompeii worm"
Alvinella pompejana

East Pacific Rise

East Pacific Rise

Bathymodiolin mussels
Bathymodiolus thermophilus

Vent biogeographic provinces

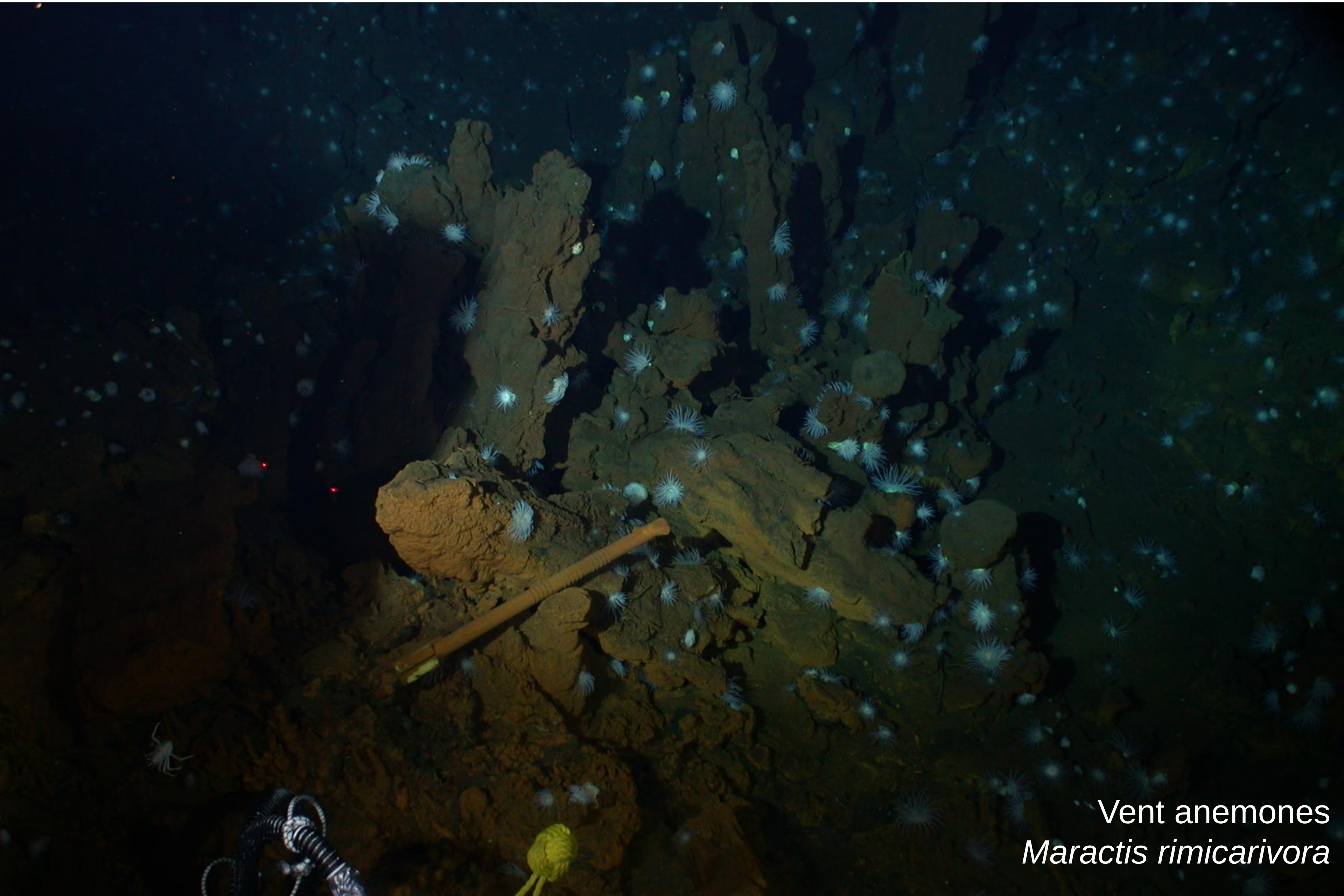


(Vrijenhoek 2010)

Mid-Atlantic Ridge

Vent shrimp
e.g. *Rimicaris exoculata*

Mid-Atlantic Ridge

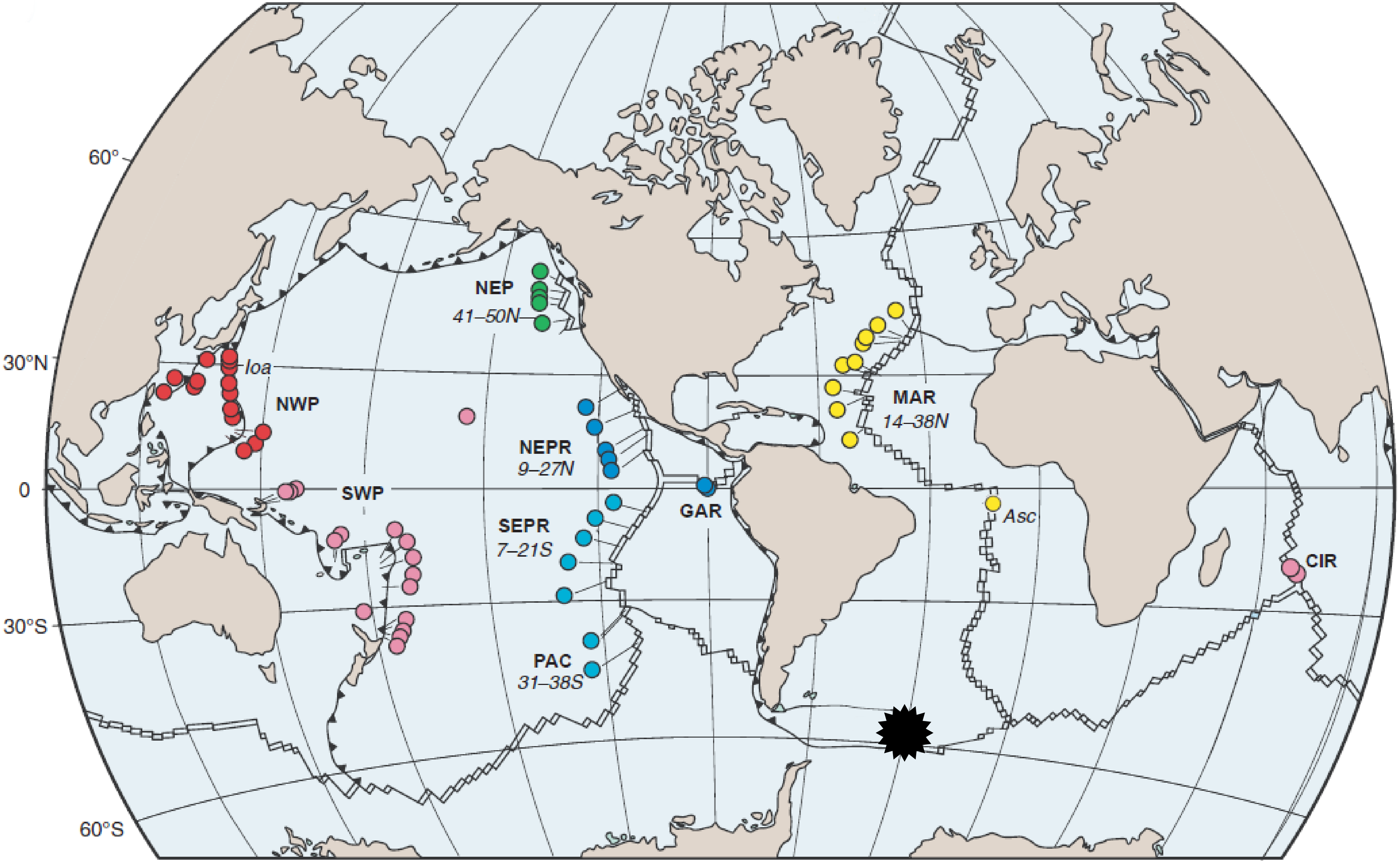


Vent anemones
Maractis rimicarivora

Mid-Atlantic Ridge

Bathymodiolin mussels
e.g. *Bathymodiolus azoricus*

Filling in the gaps (1): East Scotia Ridge



E9 segment vent field, 60°S, 2400 m depth

Kiwa n. sp.

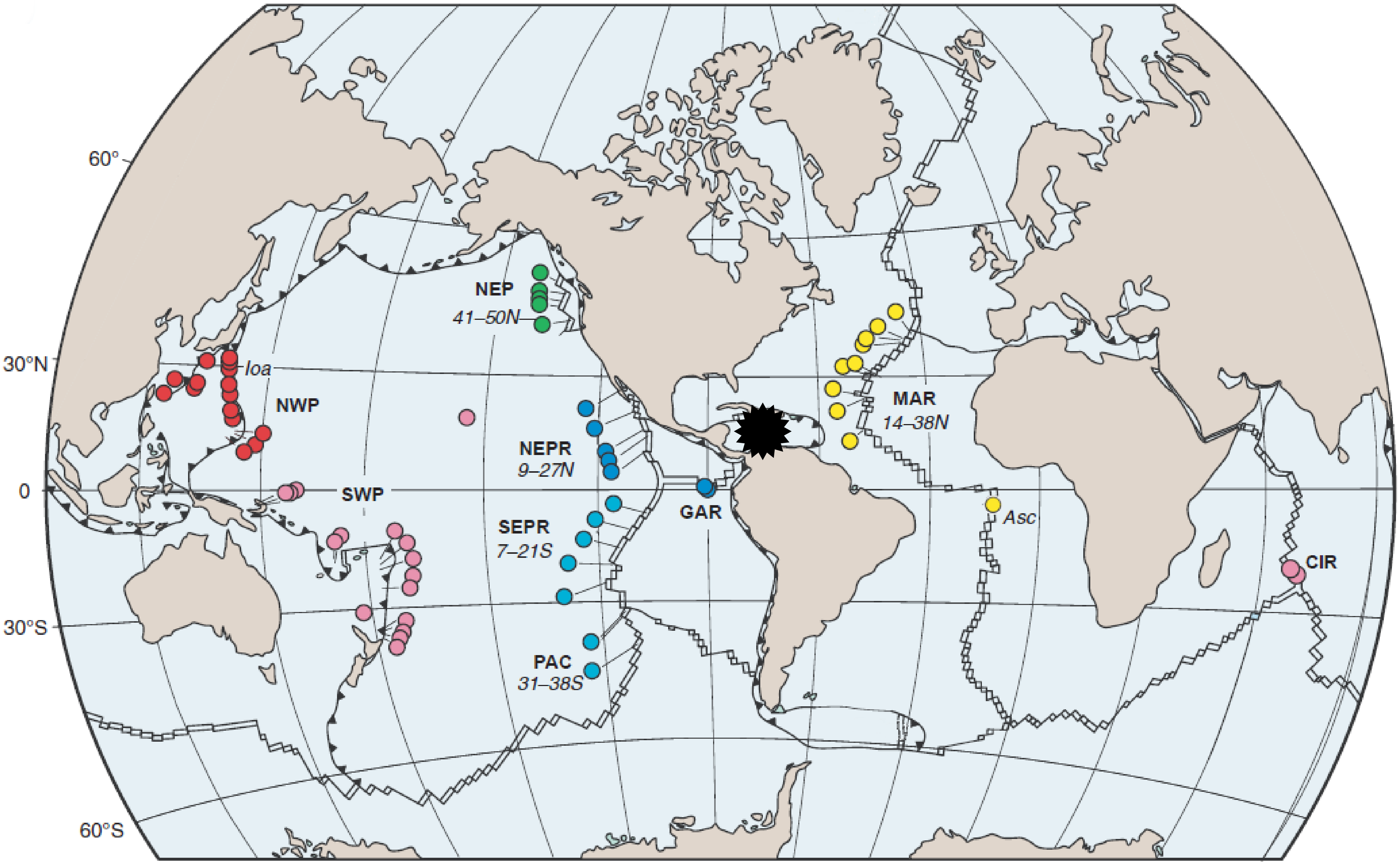
Photos by Dr Sven Thatje

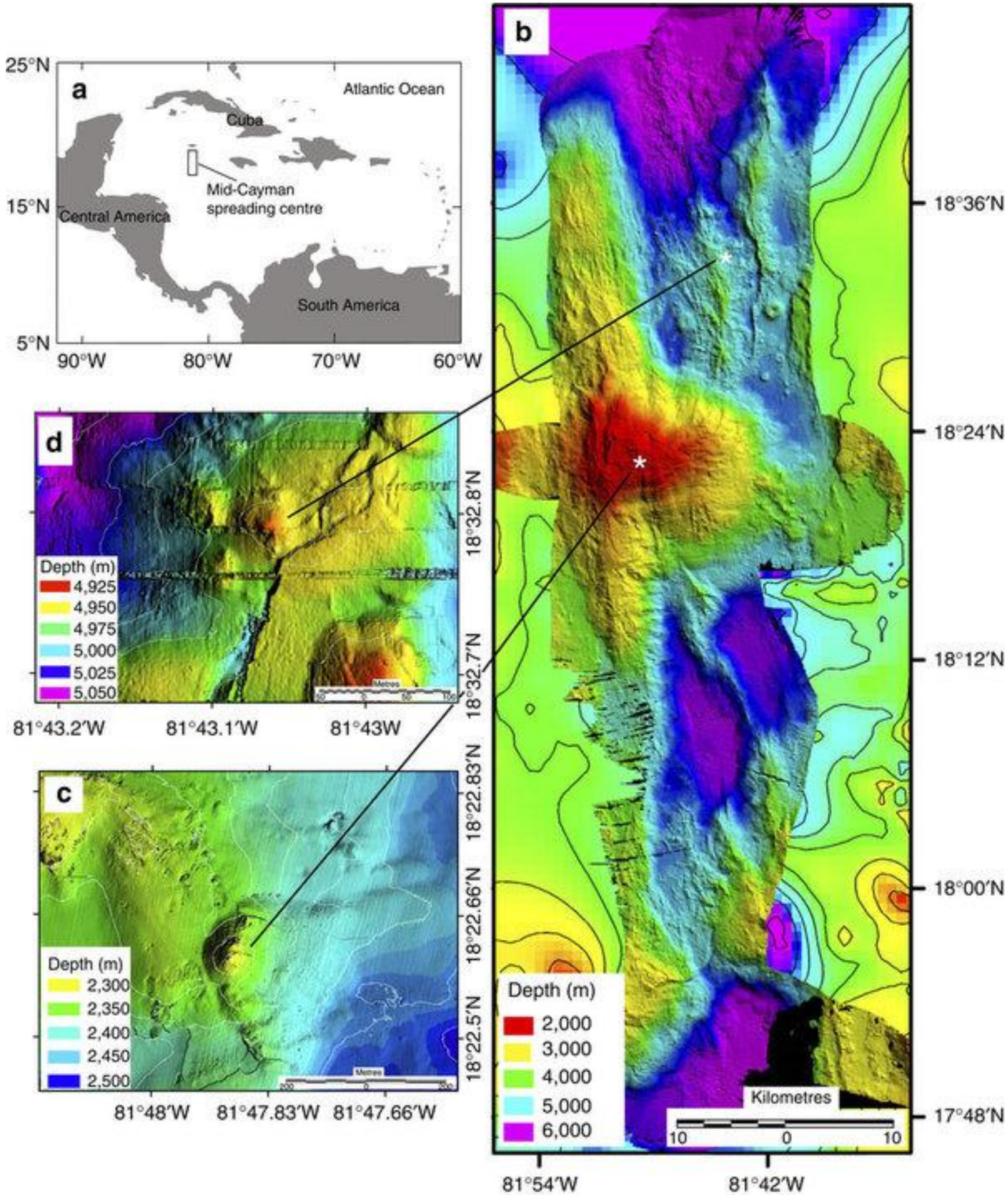
Peltospirid n. sp.

Vulcanolepas n. sp. & new anemone species

New species of seven-armed seastar

Filling in the gaps (2): Cayman Trough





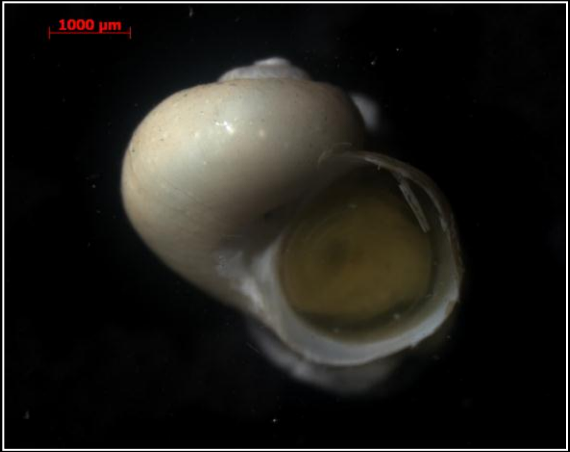
Connelly, Copley, Murton, Stansfield, Tyler *et al.* (2012)

Beebe Vent Field, depth 4960 m

Von Damm Vent Field, depth 2300 m

Rimicaris hybisae

Other fauna at Cayman Trough vents



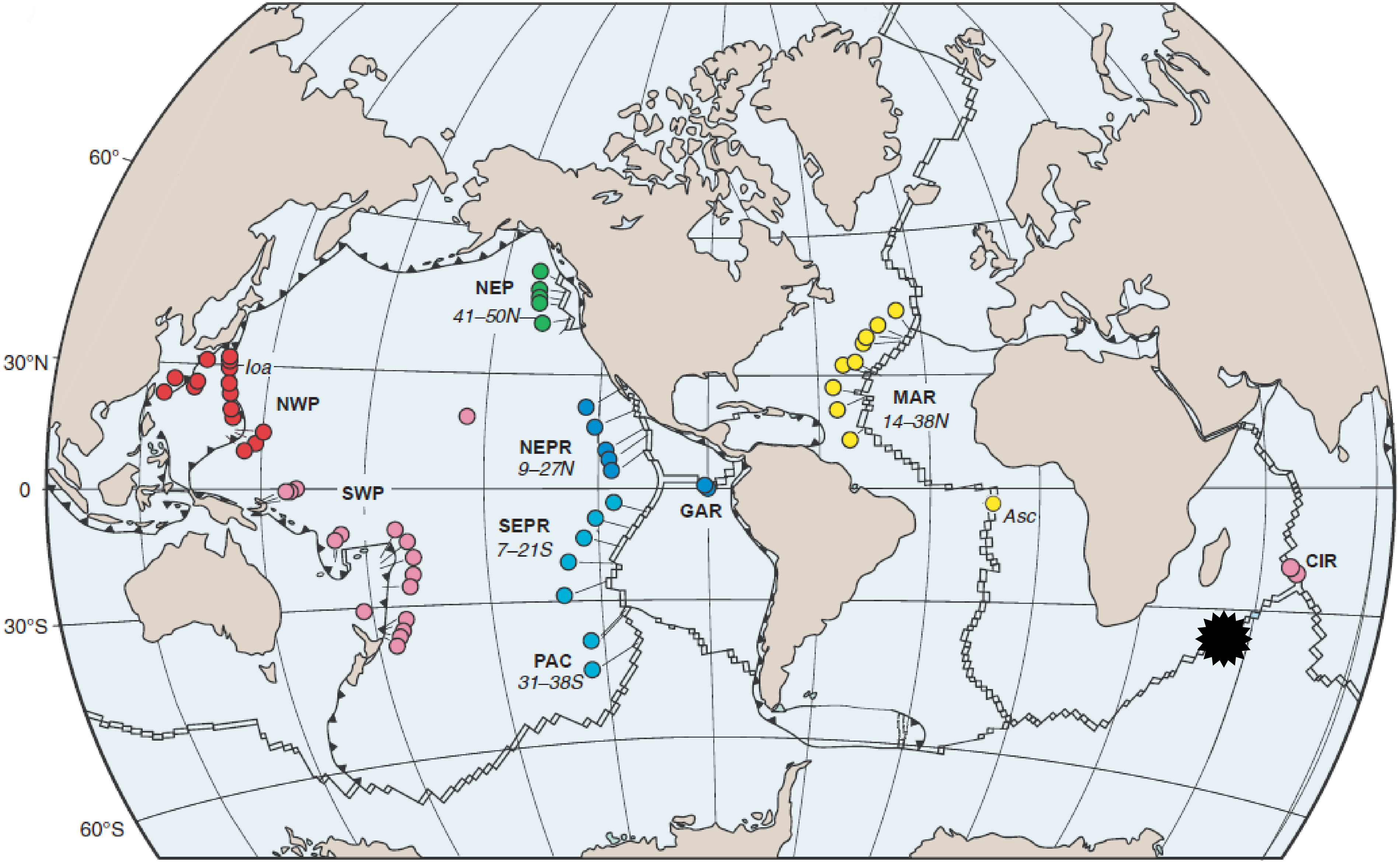
Iheyaspira bathycodon n. sp.
(Nye, Copley, Linse, Plouviez, in press)

Lebbeus virentova n. sp.
(Nye, Copley, Plouviez, Van Dover, in press)

Lysianassoid amphipod
Onesimoides sp.

Zoarcid fish
Pachycara sp.

Filling in the gaps (3): SW Indian Ridge



SW Indian Ridge vents

* Indian Ocean contains a “triple junction”

where three branches of mid-ocean ridge join

* Central Indian Ridge and SE Indian Ridge

are “intermediate-spreading” ridges

* But SW Indian Ridge is “ultraslow-spreading”

∴ Vents on SW Indian Ridge may be further apart and longer-lived

Q: does this influence the types of animals that live there?

(photos by David Shale)

Kiwa n. sp. (closely related to species from East Scotia Ridge)

(photos by David Shale)

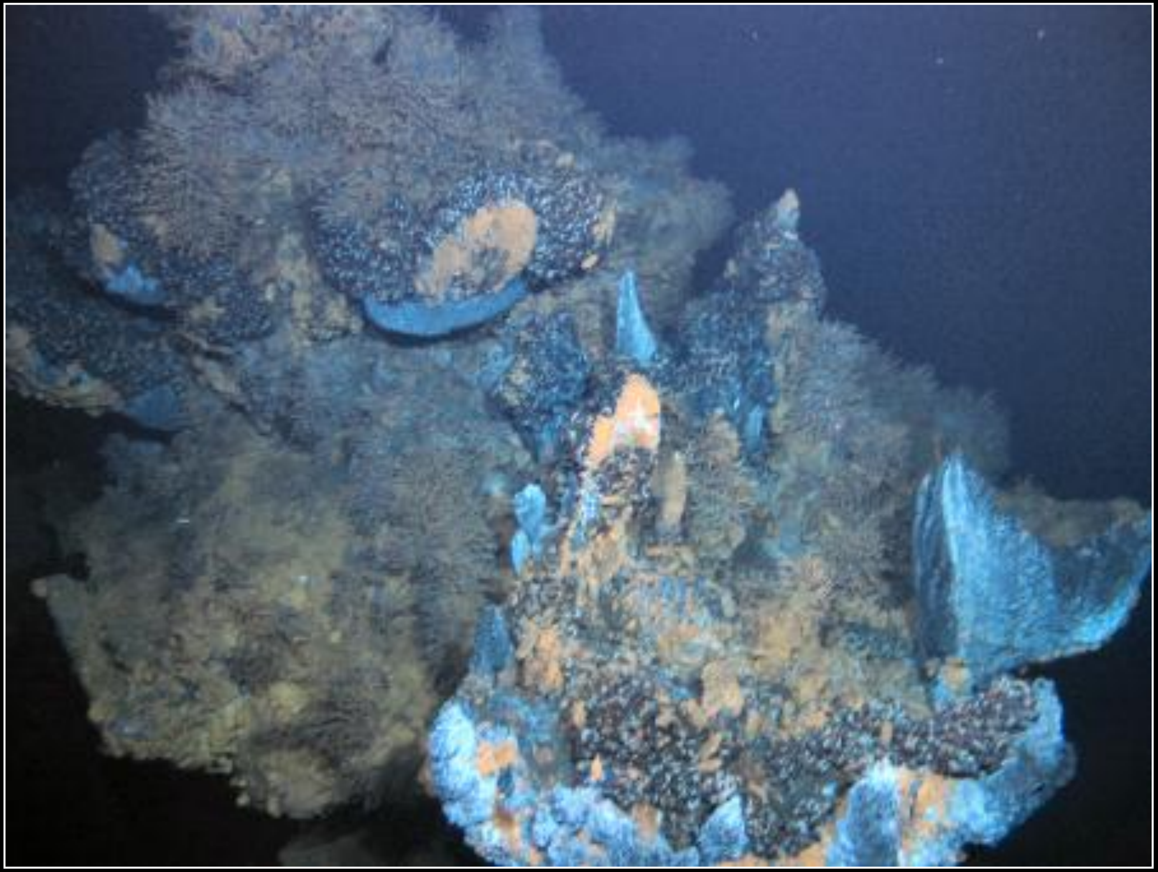
“Scaly-foot” gastropod (known from Central Indian Ridge)

Rimicaris kairei (known from Central Indian Ridge)

SW Indian Ridge vents

* May be a “crossroads”: some new species, but also

several species known from vents in neighbouring provinces



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Scientific expeditions exploring deep-sea volcanic vents

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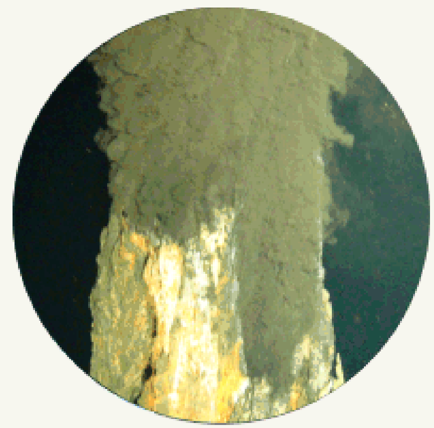
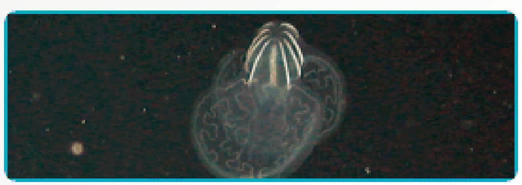


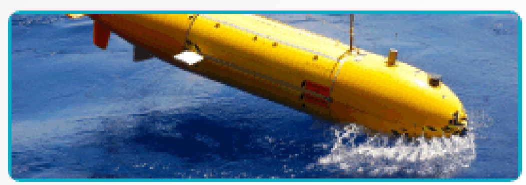
SW Indian Ridge



Follow our latest expedition exploring deep-sea vents in the Indian Ocean aboard the research ship James Cook.

What did we investigate?

Cayman Trough



Follow the story of the expedition that revealed the world's deepest known undersea volcanic vents.

What did we find?

Future voyages

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Where are we going?

…and free ebook at bit.ly/oceanlifebook

Conclusions

* Chemosynthetic primary production can support faunal assemblages with high abundance and biomass in the deep sea

* Chemosynthetic environments are insular and ephemeral

⇨ provide a model system for studying processes of dispersal and evolution in our planet's largest biome

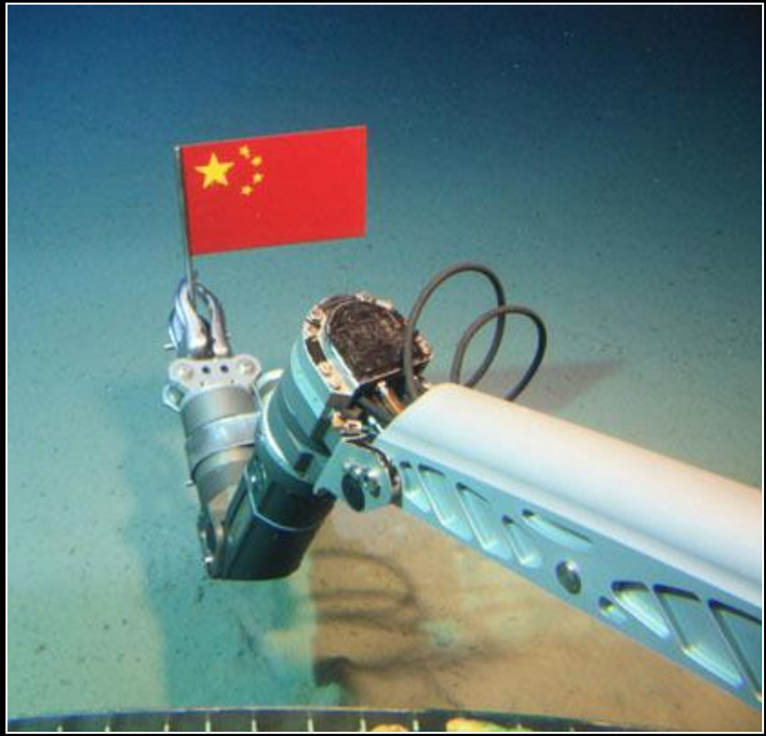
* Our exploration of these environments has only just begun

- still finding new species, provinces, types of environment

The future?

* Growing interest in mining of metals at hydrothermal vents

* Impacts of seafloor mining on vent fauna are uncertain



Mining massive sulfides at vents

Attraction / advantages:

* World demand for metals continues to rise

* Land resources are stretched

* Seafloor massive sulfides have minimal overburden

* Smaller physical footprint than land-based counterparts

(e.g. no construction of haul roads)

* No toxic chemicals, no blasting

* Minimal social disturbance

Mining massive sulfides at vents

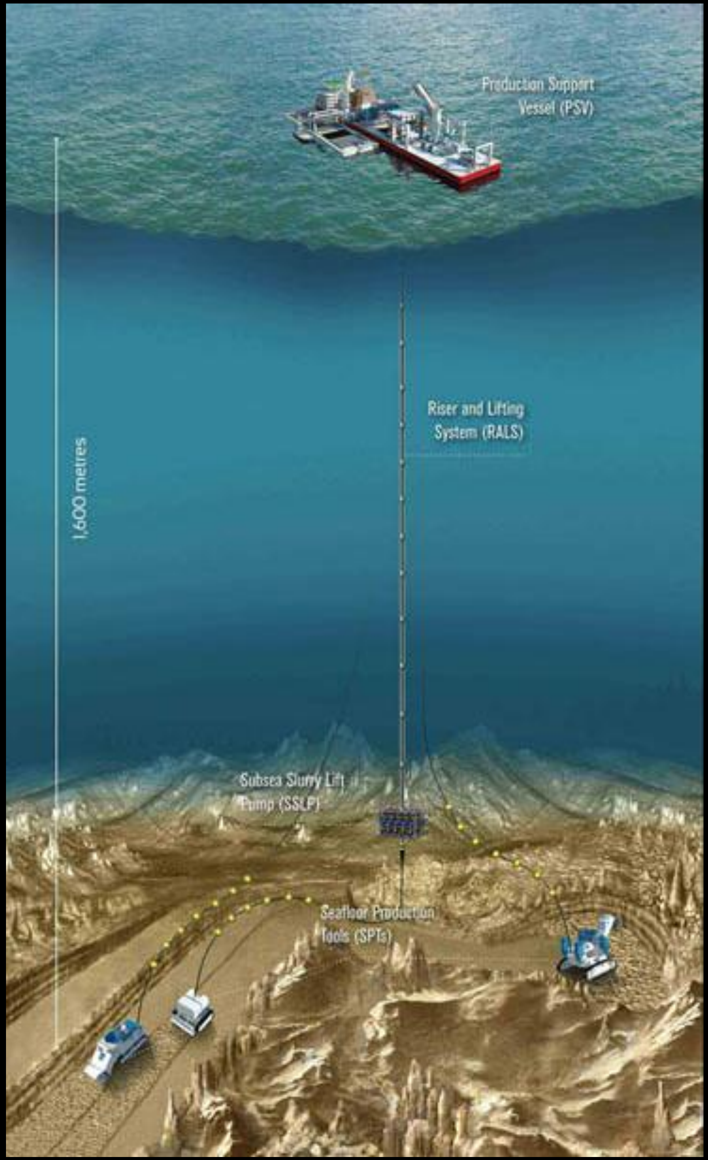
Steps required:

(i) Disaggregate seafloor material

(ii) Transport material to a surface vessel or platform for processing

(iii) Dispose of waste from processing

(iv) Transport processed material to market



Mining massive sulfides at vents

Legal framework:

* In international waters, seafloor mining is governed

by UNCLOS via the International Seabed Authority

* Also governed by UN Convention on Biodiversity (CBD),

which embodies a precautionary principle

* CBD requires safeguarding of ecosystems,

species, and genetic diversity

* May also apply to any mining in territorial waters

of nations that are signatories of the CBD

Mining massive sulfides at vents

Key potential impact:

(1) Mortality of vent faunal populations from step (i)

Possible mitigation:

(1) Set aside “reserve” areas of vent habitat within

a vent field to provide local sources for recolonisation

BUT vent field needs to be large enough to provide “unimpacted” area

for the reserve

(not an option for most vent fields on slow-spreading ridges?)

Mining massive sulfides at vents

Q: As vent activity is ephemeral at an individual vent field, isn't mining just simulating a "natural" disturbance by "resetting" the vent field to "time zero" in its colonisation?

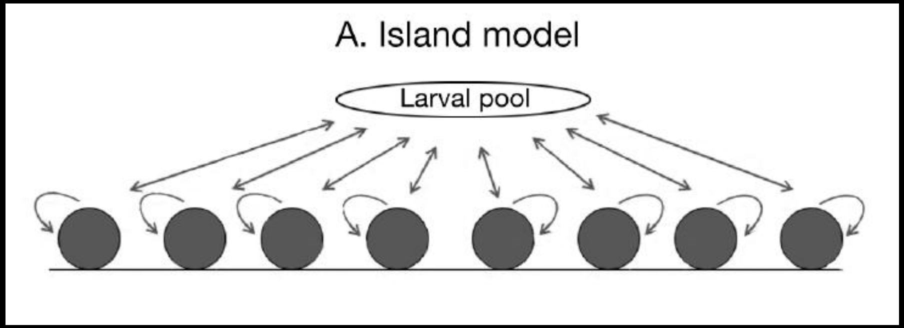
A: Yes; but what matters is the rate at which vent fields are "reset"; natural rate of such disturbance on slow-spreading ridges may be 1 event per 1000 years

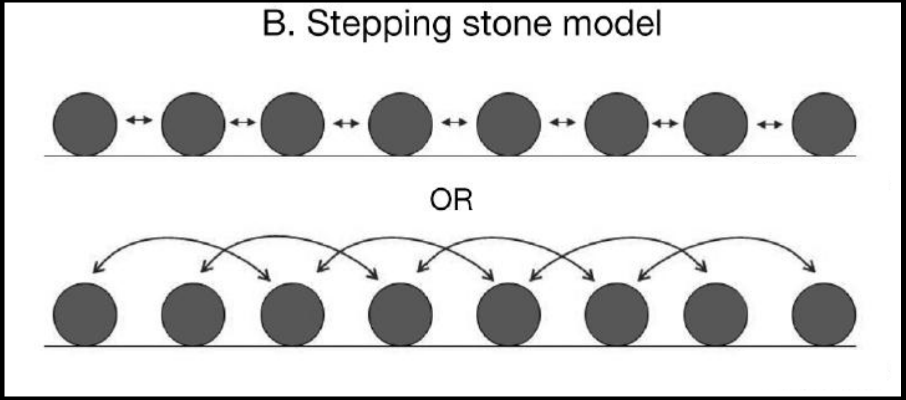
Mining massive sulfides at vents

Other possible mitigation:

* A "network" of reserve vent fields, that maintain the connectivity of species populations throughout a region

* BUT need to understand connectivity of species populations; understanding of vent population genetics is still in its infancy





Mining massive sulfides at vents

Other possible impacts of SMS mining include:

(2) Mortality of seabed and mid-water fauna from step (iii)

- physical smothering of seabed by tailings

- increased local water temperature from uncooled tailings

- increased turbidity of deep waters

Mining massive sulfides at vents

Other possible impacts include:

(2) Mortality of seabed and mid-water fauna from step (iii)

- physical smothering of seabed by tailings

- increased local water temperature from uncooled tailings

- increased turbidity of deep waters

Mining massive sulfides at vents

What about "extinct" sites?

* When activity ceases at a vent field, vent fauna die off

* Massive sulfide deposit remains on the seafloor until

eventually buried by pelagic sediments (10^5 to 10^6 years)

* So for every active vent field, there are >10s of extinct ones

* Assuming there are no species "endemic" to extinct sulfides,

these inactive vent deposits offer a low-impact target for mining

* BUT extinct vent fields are harder to find

(no plumes of vent fluids to guide surveys to their sources)

Further reading

Van Dover CL (2011). Mining seafloor massive sulfides and biodiversity: what's at risk? *ICES Journal of Marine Science*, 68: 341-348

Van Dover CL (2011). Tighten regulations on deep-sea mining. *Nature*, 470: 31-33

Deep-sea gold rush: mining hydrothermal vents, by Peter Aldhous; *New Scientist*, 29 June 2011