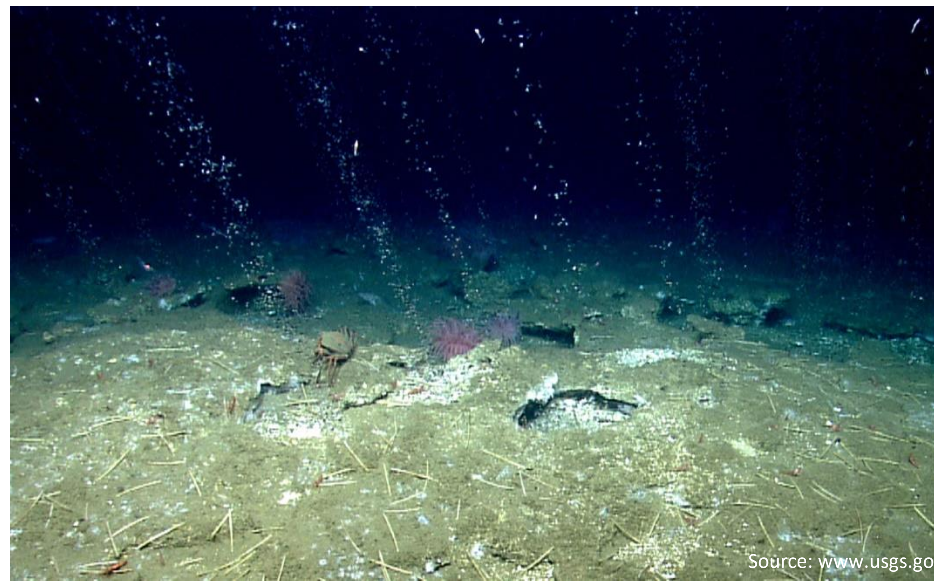
Food web structure in deep-sea cold seeps: a case study from Western Africa



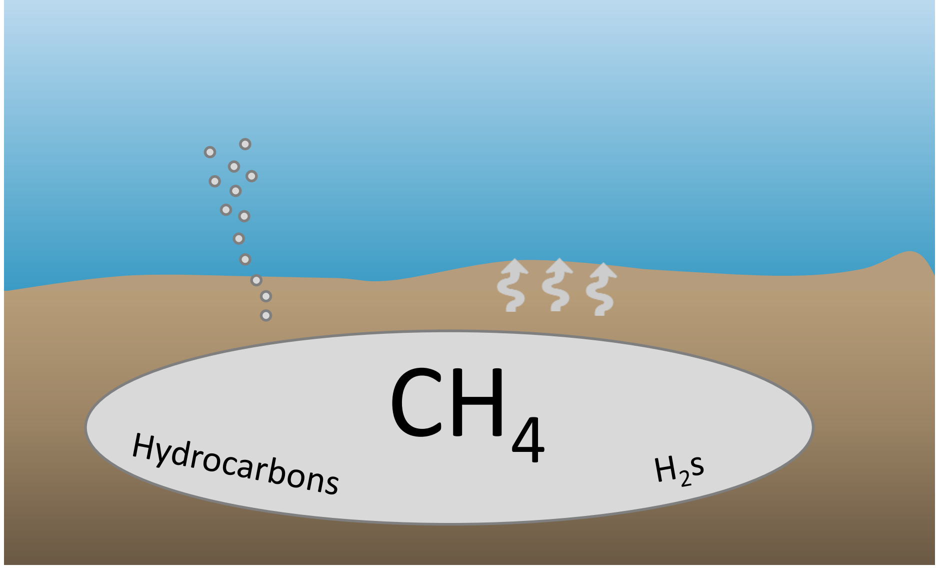
Loïc N. MICHEL, Marie PORTAIL, Dominique A. COWART, Pen-Yuan HSING, Karine OLU & Jozée SARRAZIN

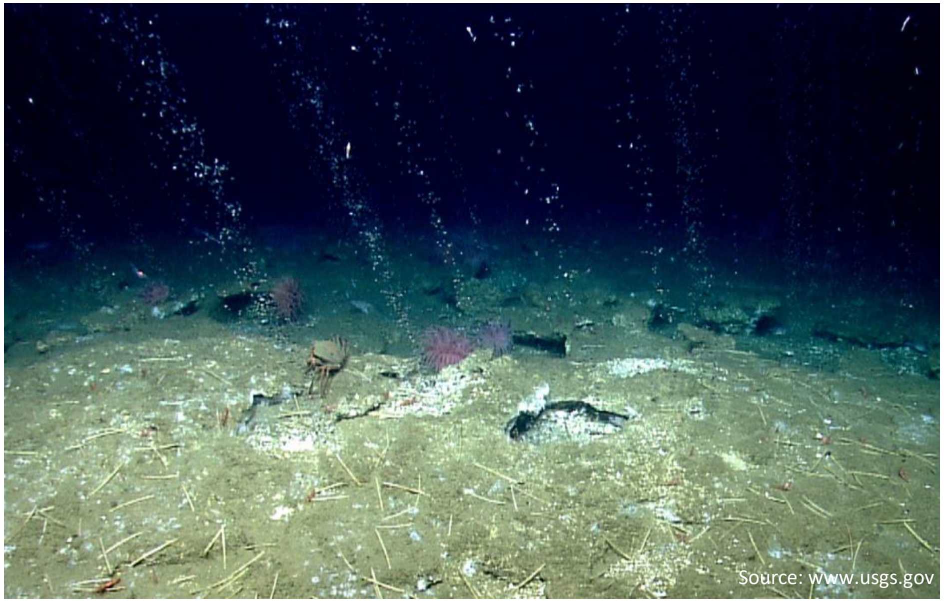
Contact: loicnmichel@gmail.com

Course "Etude des isotopes stables et applications au milieu marin"

Context: cold seeps & chemosynthesis

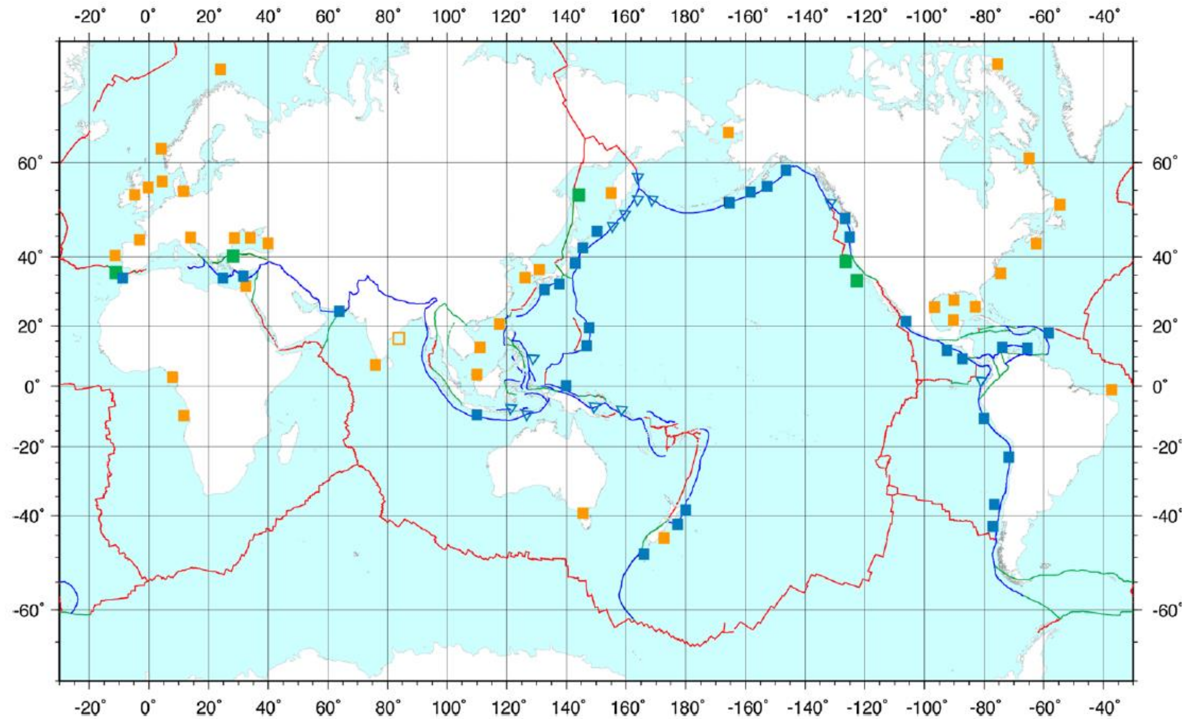
Cold seeps: areas of the ocean floor where gases and/or fluids emerge through the sediments

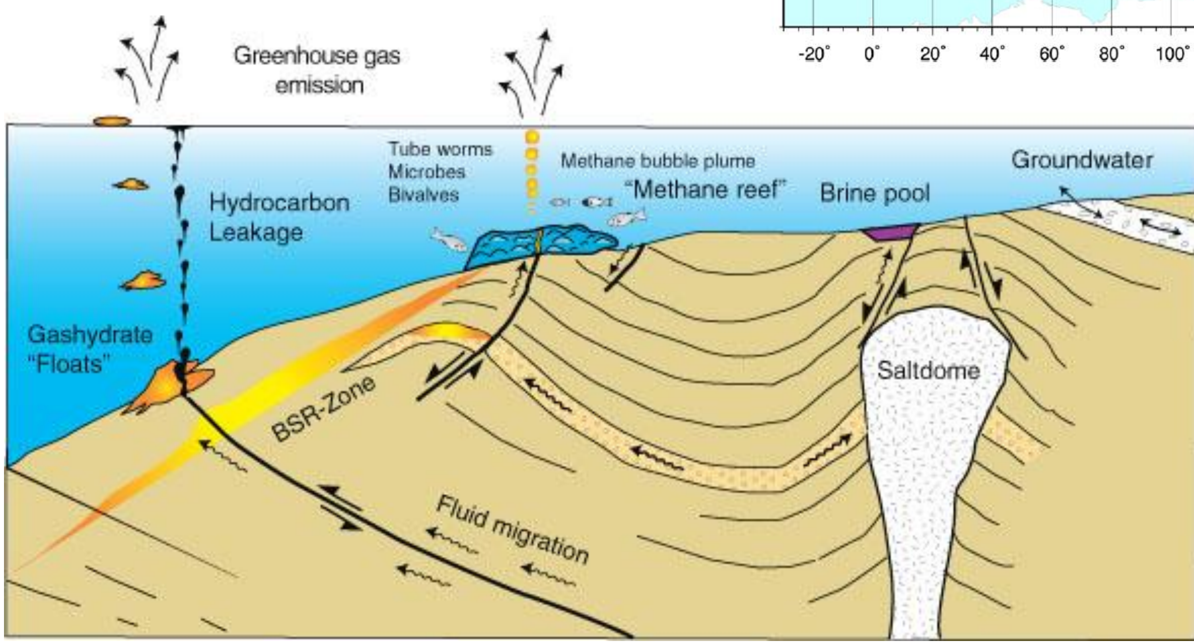




Context: cold seeps & chemosynthesis

Commonly found at tectonic plate margins, notably at oceanic and continental convergences





Images: Suess 2014, Int. J. Earth. Sci. 103:1889–1916

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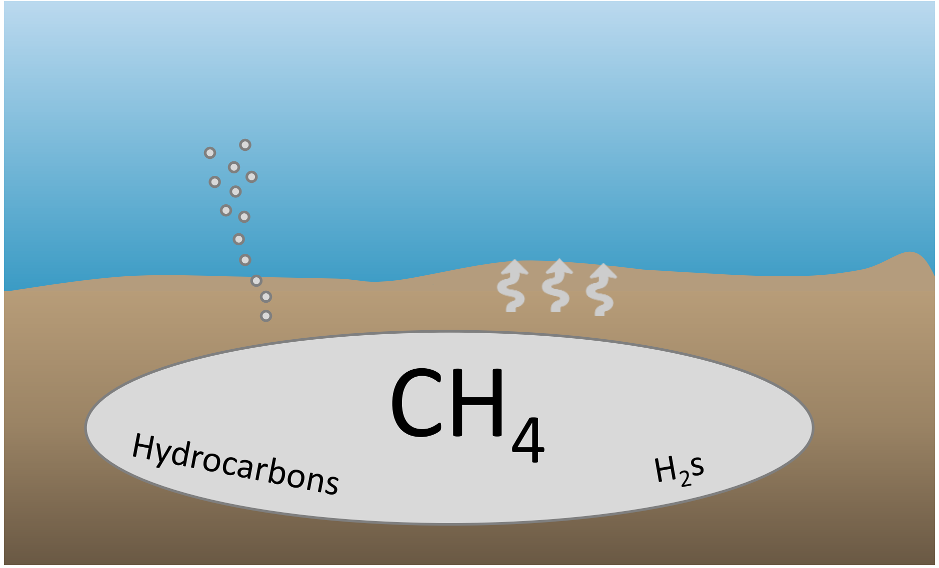
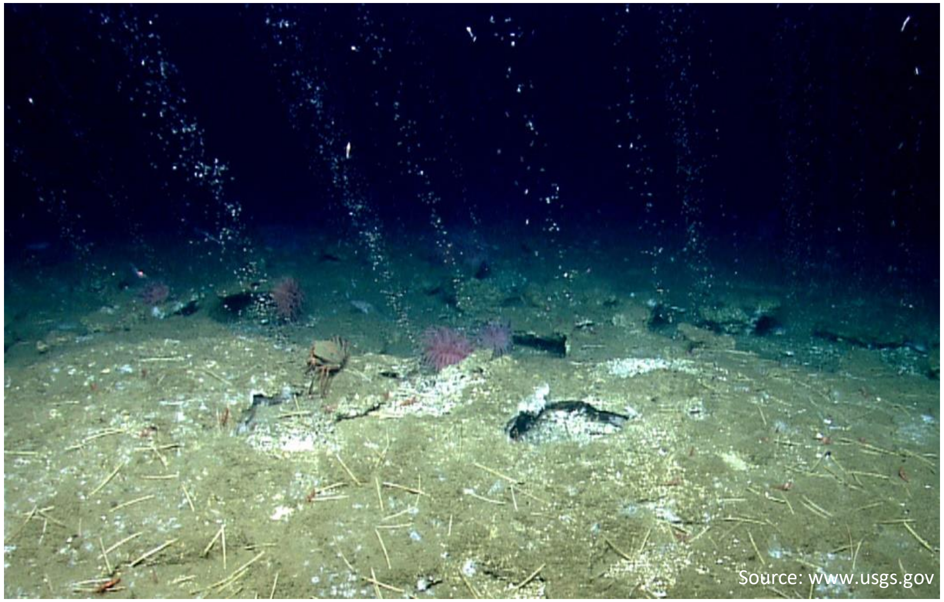
Methane seepage affects seabed features through physical and chemical processes: formation of pockmarks, carbonate deposits





Context: cold seeps & chemosynthesis

Anaerobic oxidation of methane (AOM)

$$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O$$

Autogenic
carbonates
deposition

Context: cold seeps & chemosynthesis

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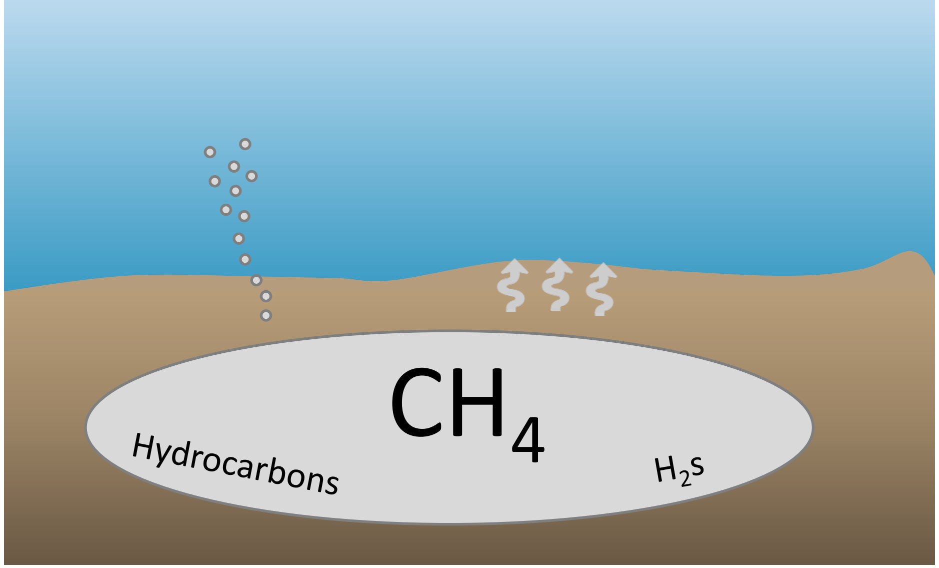


Endogenous microbial chemosynthetic production supports specific faunal communities

Deep-sea cold seeps are productive habitats based on foundation species which depend on symbiotic micro-organisms for their nutrition

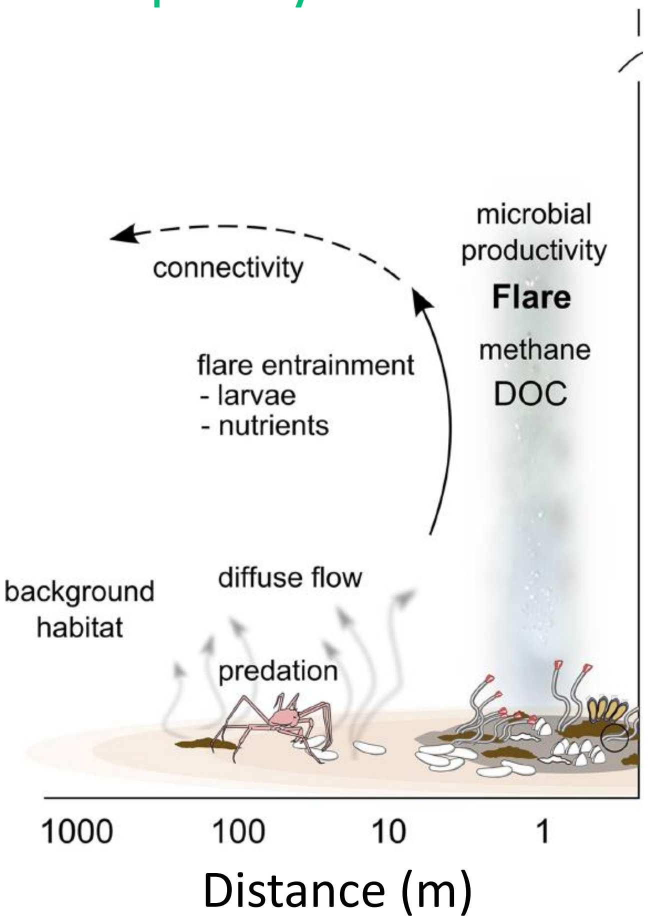
Context: cold seeps & chemosynthesis

Source: https://www.youtube.com/watch?v=QnLA1HyGahU

Context: cold seeps & chemosynthesis

Increasing evidence that deep-sea cold seeps are more widespread and more connected to surrounding ecosystems than initially thought

However, determinants of food web structure still poorly known…



Levin *et al* 2016, Front. Mar. Sci 3: 72

Study system: the Regab pockmark

- Gulf of Guinea, West Africa. Depth: 3160 m
- First observed in 1998

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Named after a Gabonese beer…

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- Emitted fluid: 99.1% CH_4
- Large (800 m wide, 30 m deep) pockmark with complex structure

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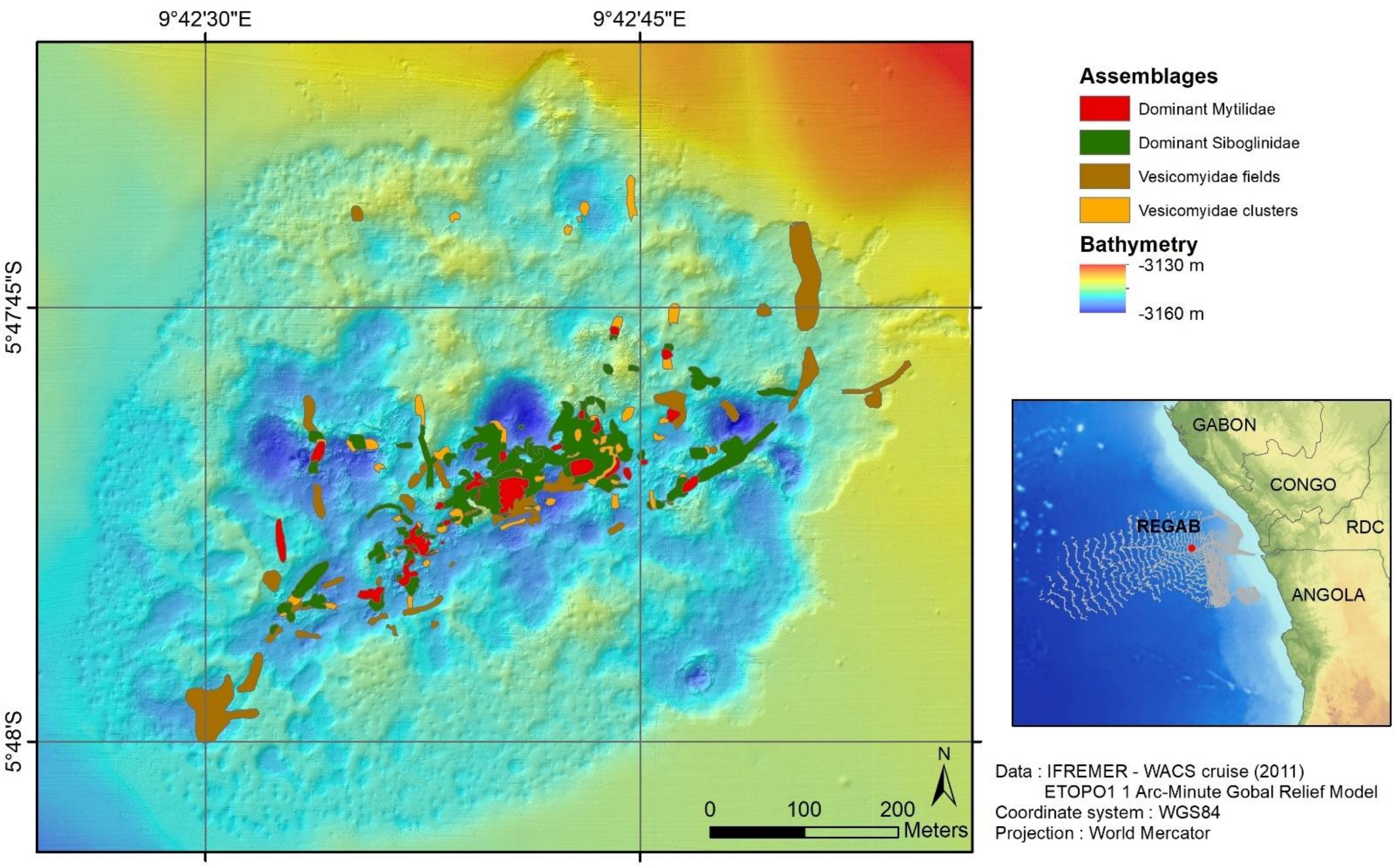
- Local variation in environmental parameters: habitat mosaic
- Each habitat is associated with a dominant foundation species



Objectives

- Besides CH_4-based chemosynthesis, are other production mechanisms fueling food webs?
- Do feeding habits of the dominant species vary across habitats?
- Is food web structure mostly driven by environmental parameters, or do biotic interactions matter?

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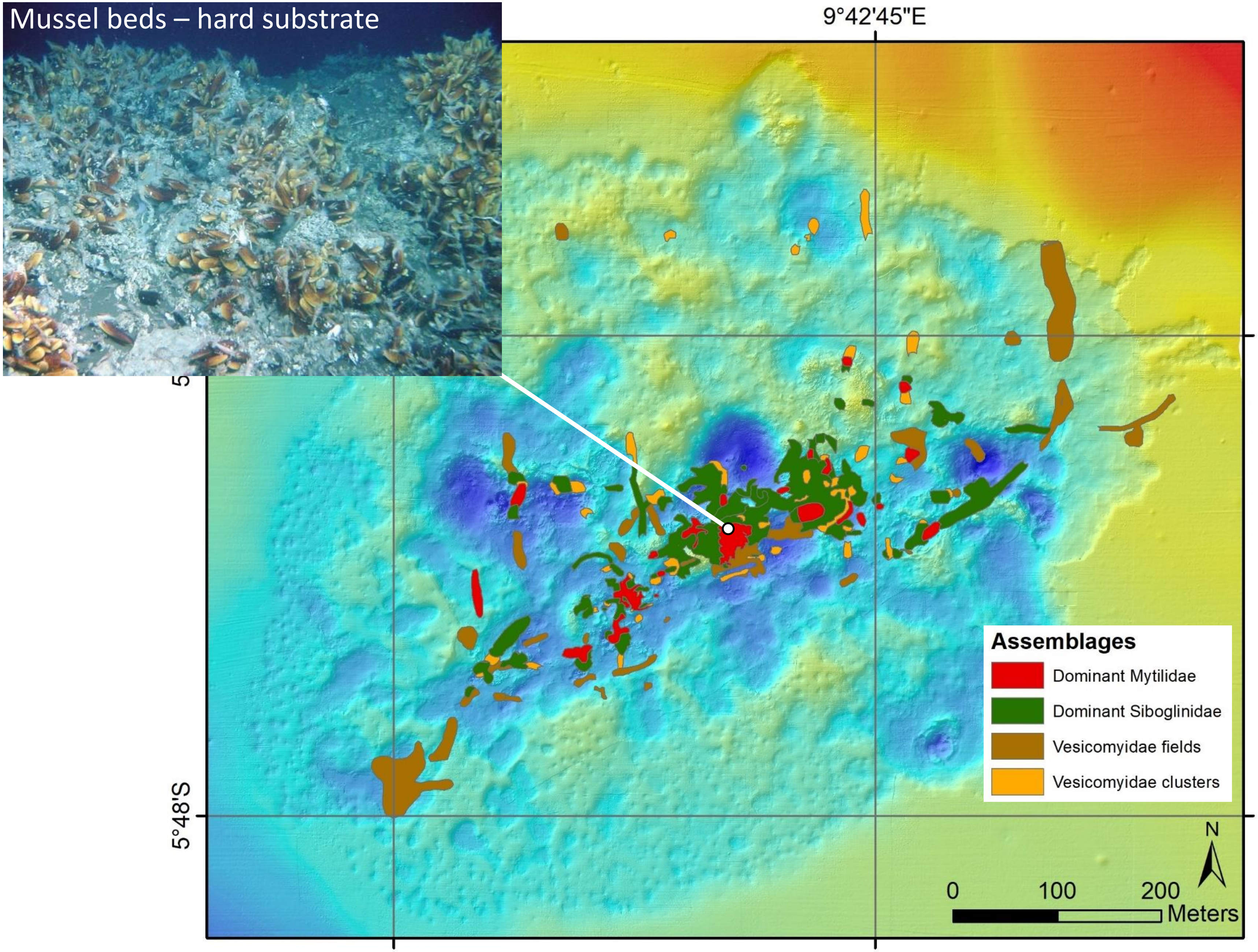
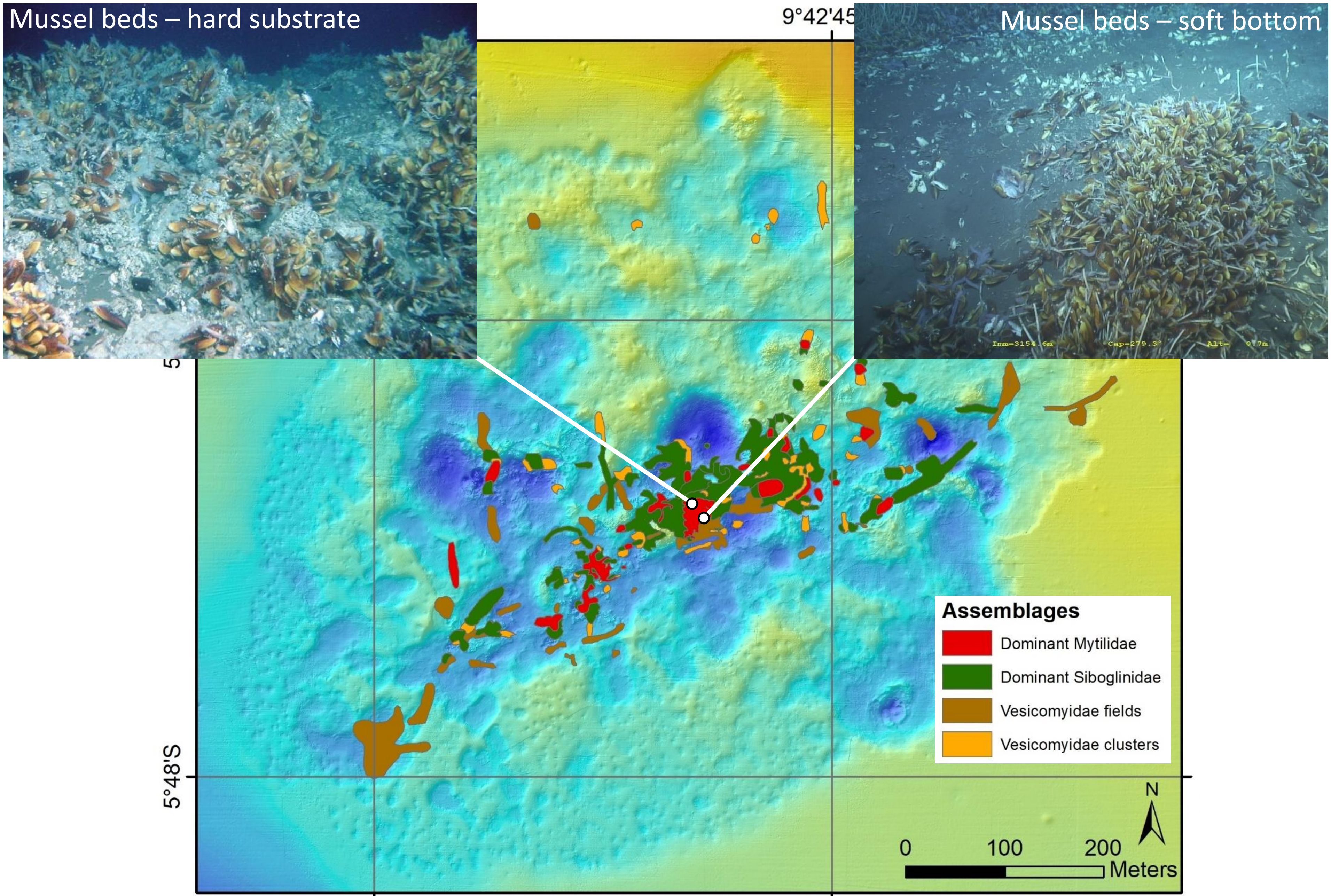
Use of stable isotope ratios of C and N to delineate trophic interactions in different habitats across the Regab pockmark

Objectives



Mussel beds – hard substrate
9°42'45"E
5°48'S
Assemblages
Dominant Mytilidae
Dominant Siboglinidae
Vesicomyidae fields
Vesicomyidae clusters
N
0
100
200
Meters

Objectives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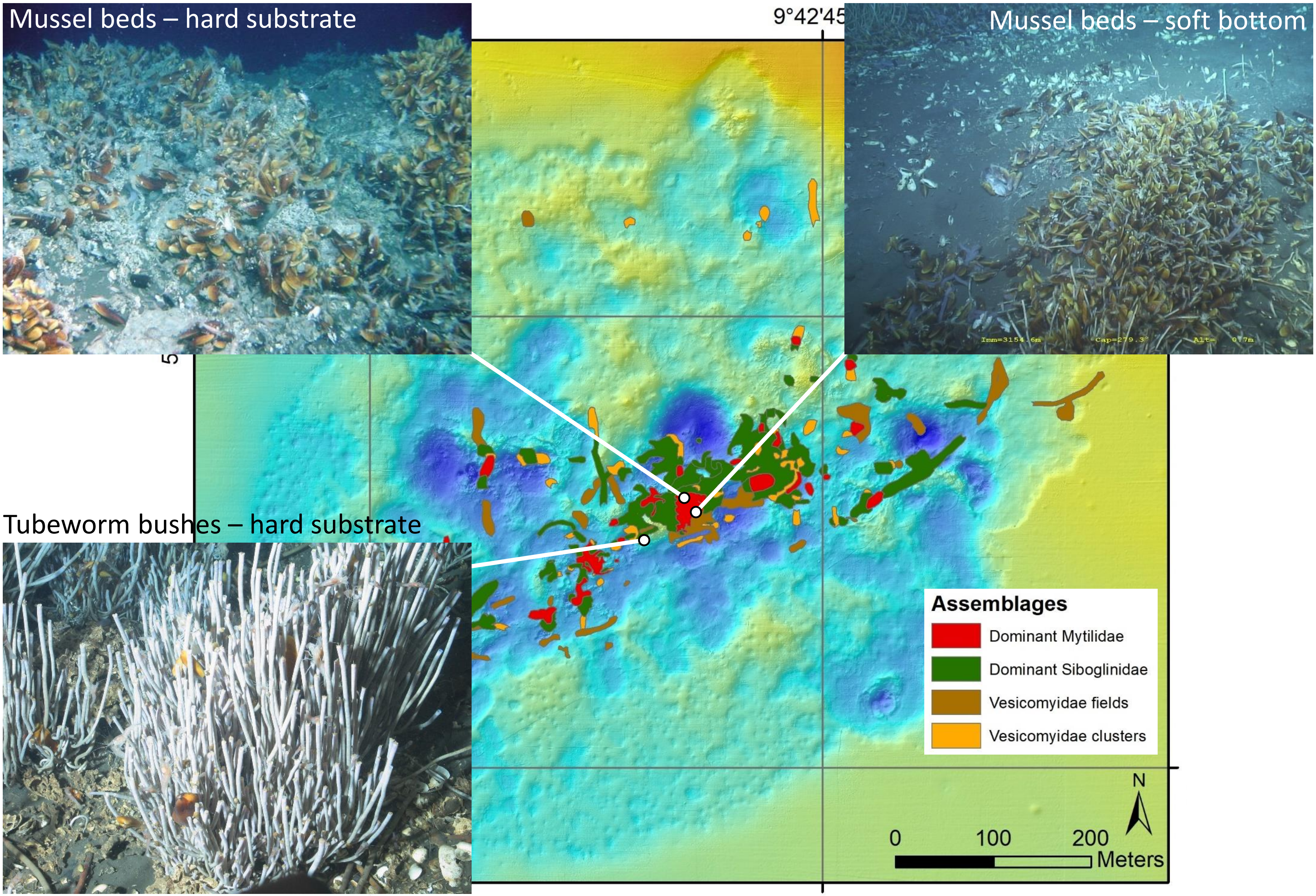
Mussel beds – hard substrate
9°42'45
Mussel beds – soft bottom
Tubeworm bushes – hard substrate
Assemblages
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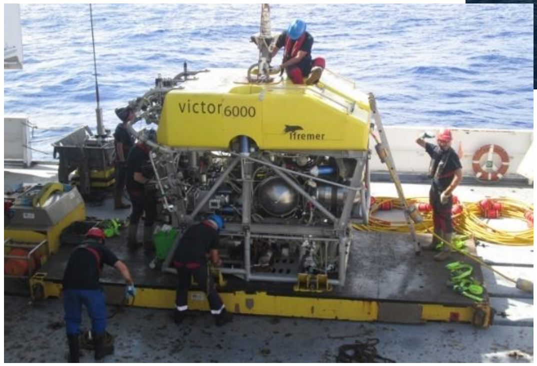
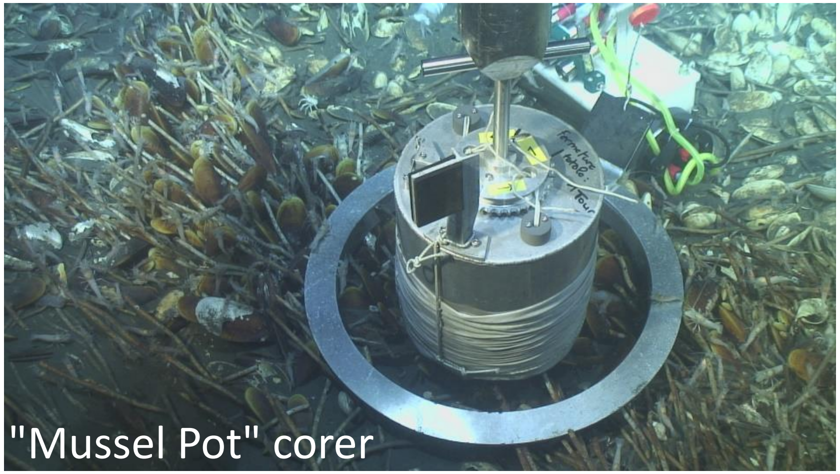
N
0
100
200
Meters

Sampling

WACS (West Africa Cold Seeps) campaign
RV Pourquoi Pas?
01-02/2011

ROV Victor 6000 + multiple tools

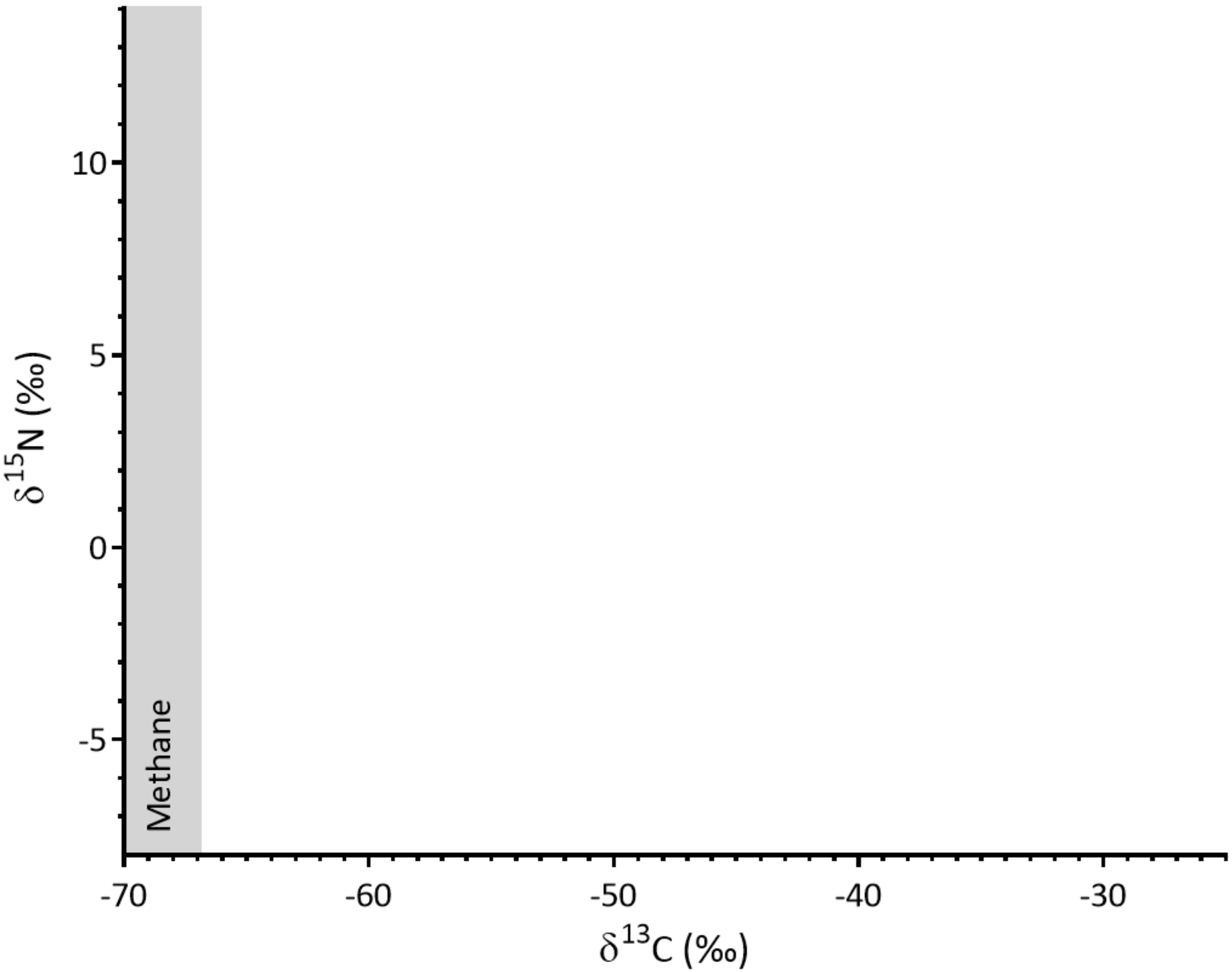



"Mussel Pot" corer


"Bushmaster Jr." tubeworm net

Suction sampler

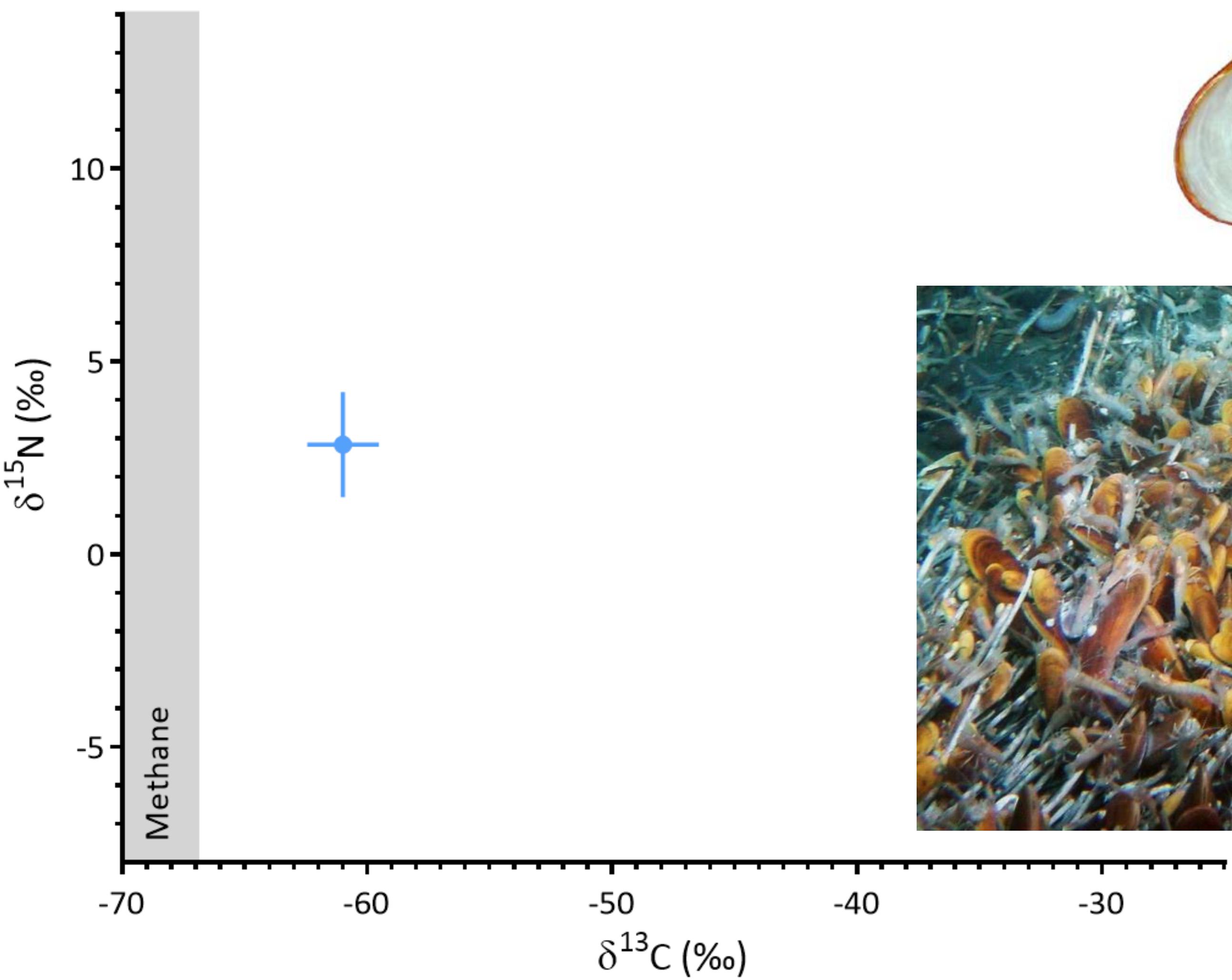
Results: Mussel beds – hard substrate



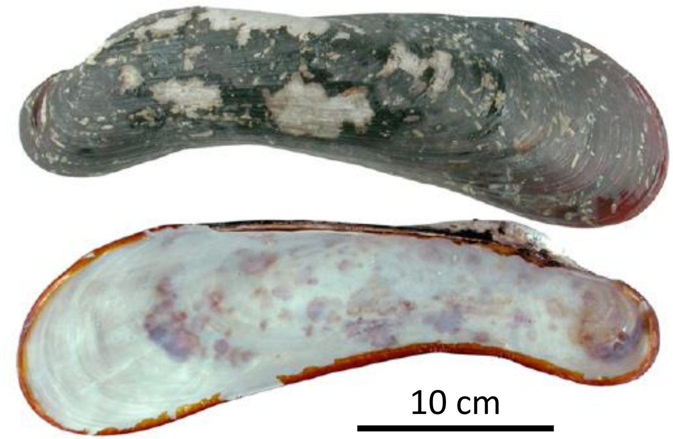
Results: Mussel beds – hard substrate

Symbiont-bearing spp.

● *Bathymodiolus* aff. *boomerang*



Olu-Le Roy *et al*. 2007 DSR I 54: 1890-1911



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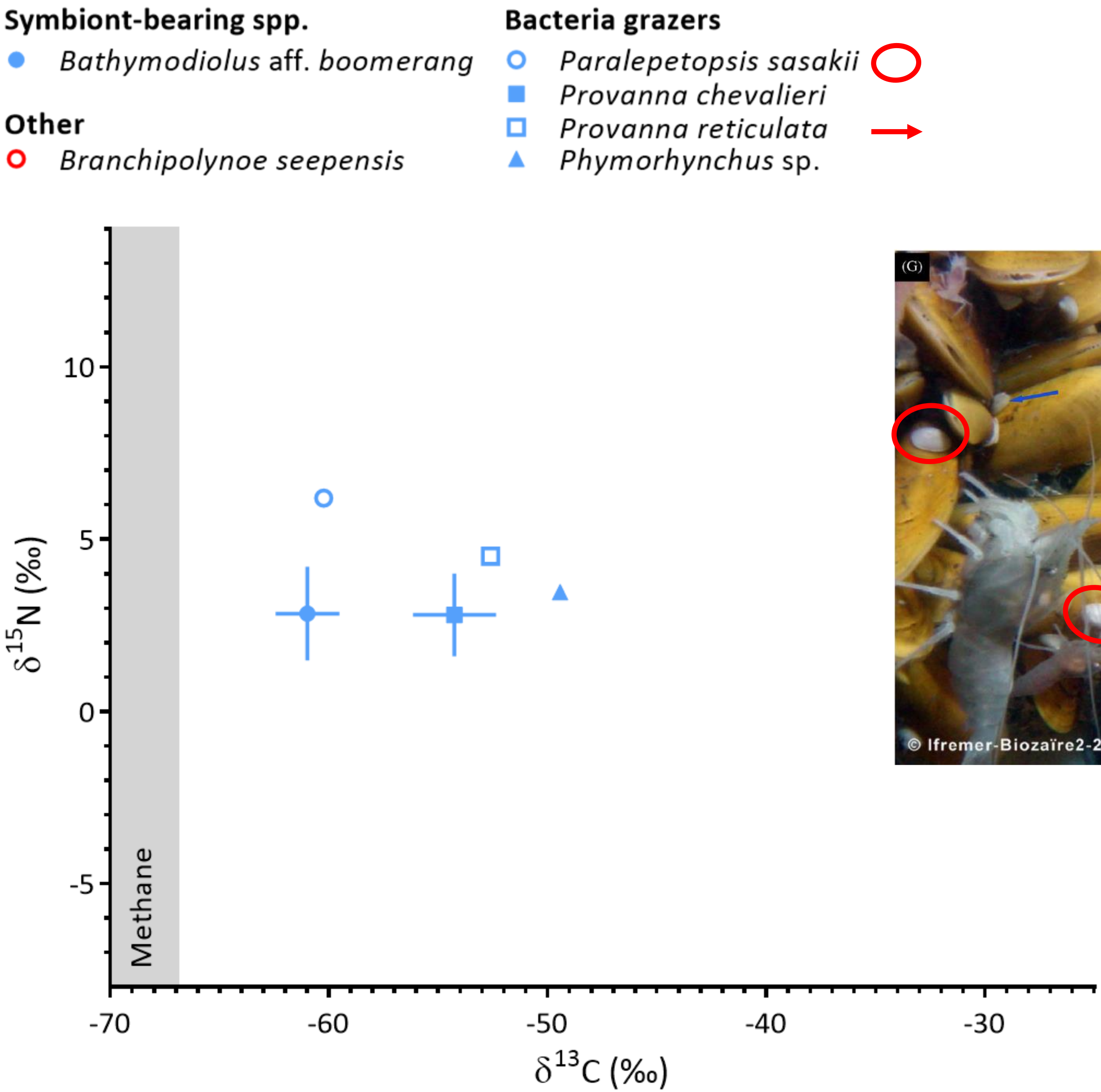


Warén & Bouchet 2009 DSR II 56: 2326-2349

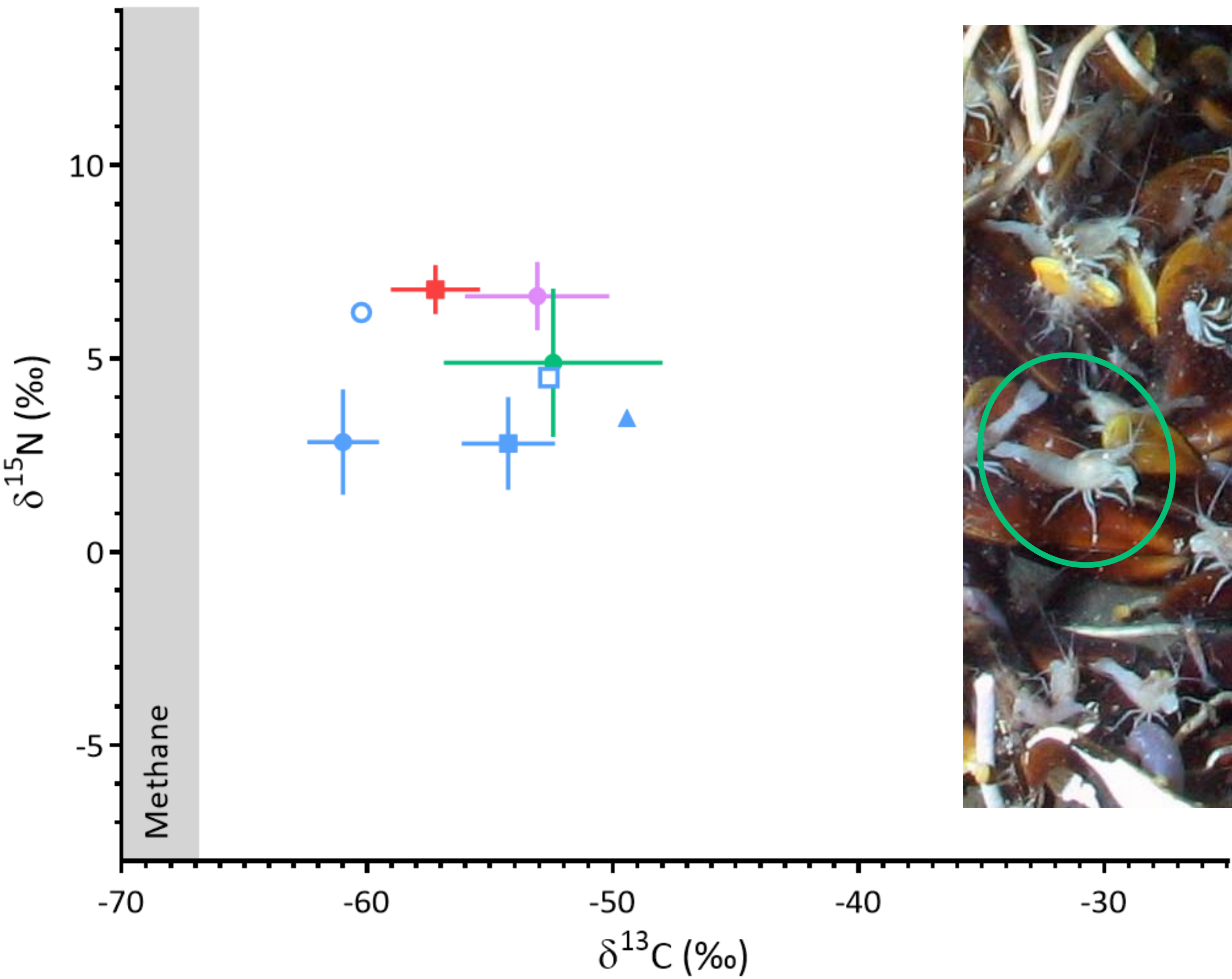
Results: Mussel beds – hard substrate

Symbiont-bearing spp.
- *Bathymodiolus* aff. *boomerang*

Other
- *Branchipolynoe seepensis*

Bacteria grazers
- *Paralepetopsis sasakii*
- *Provanna chevalieri*
- *Provanna reticulata*
- *Phymorhynchus* sp.

Grazers / deposit feeders
- *Alvinocaris muricola*
- *Prionospio* sp.
- *Chiridota* sp.



Alvinocaris muricola
Chiridota sp.

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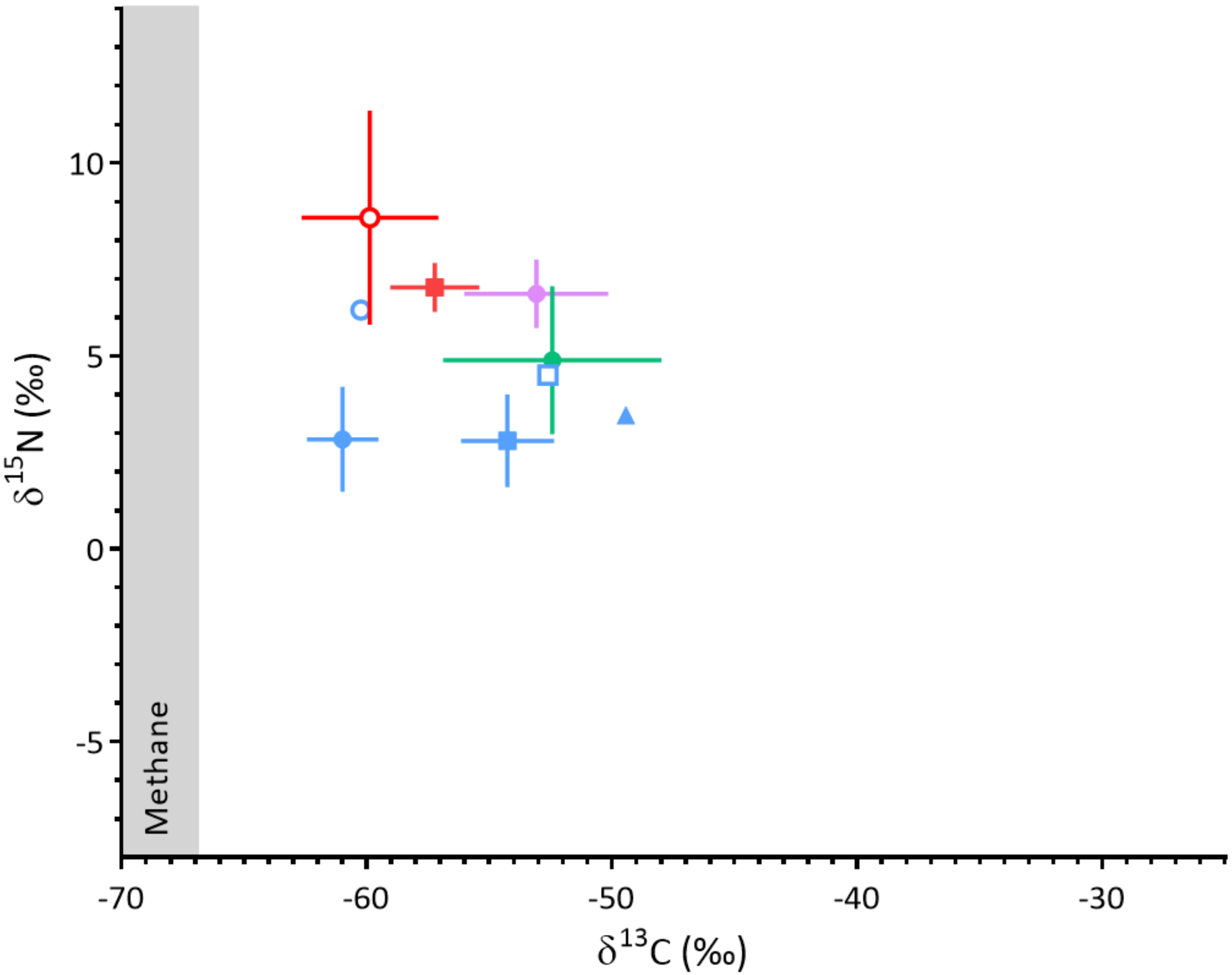
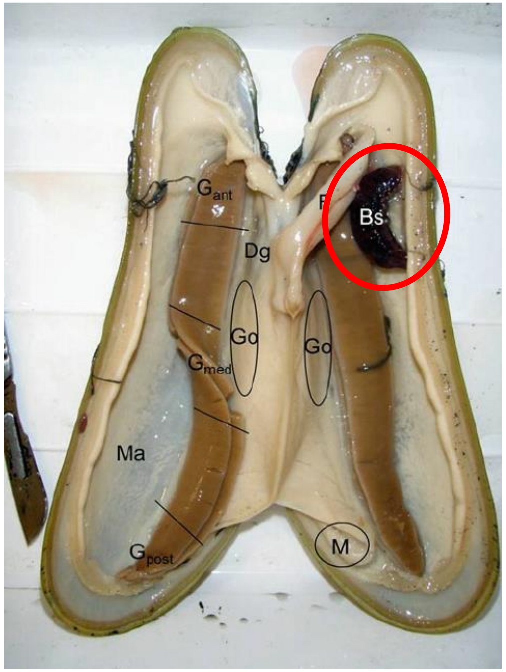
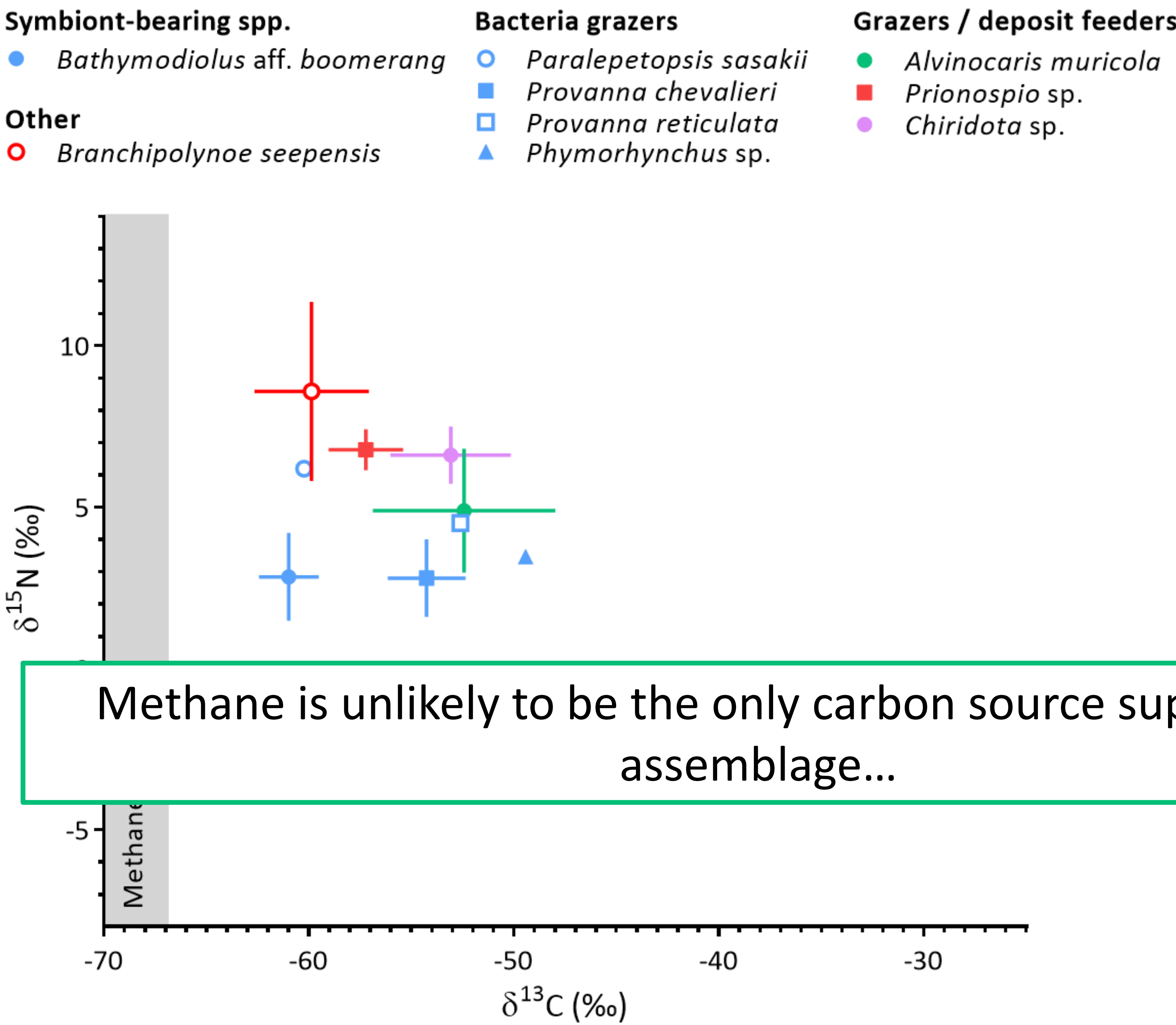


Source: chess.myspecies.info



Duperron 2015 Hydrocarbon and Lipid Microbiology Protocols 343-362

Results: Mussel beds – hard substrate



Methane is unlikely to be the only carbon source supporting the assemblage…

Results: Mussel beds – hard substrate

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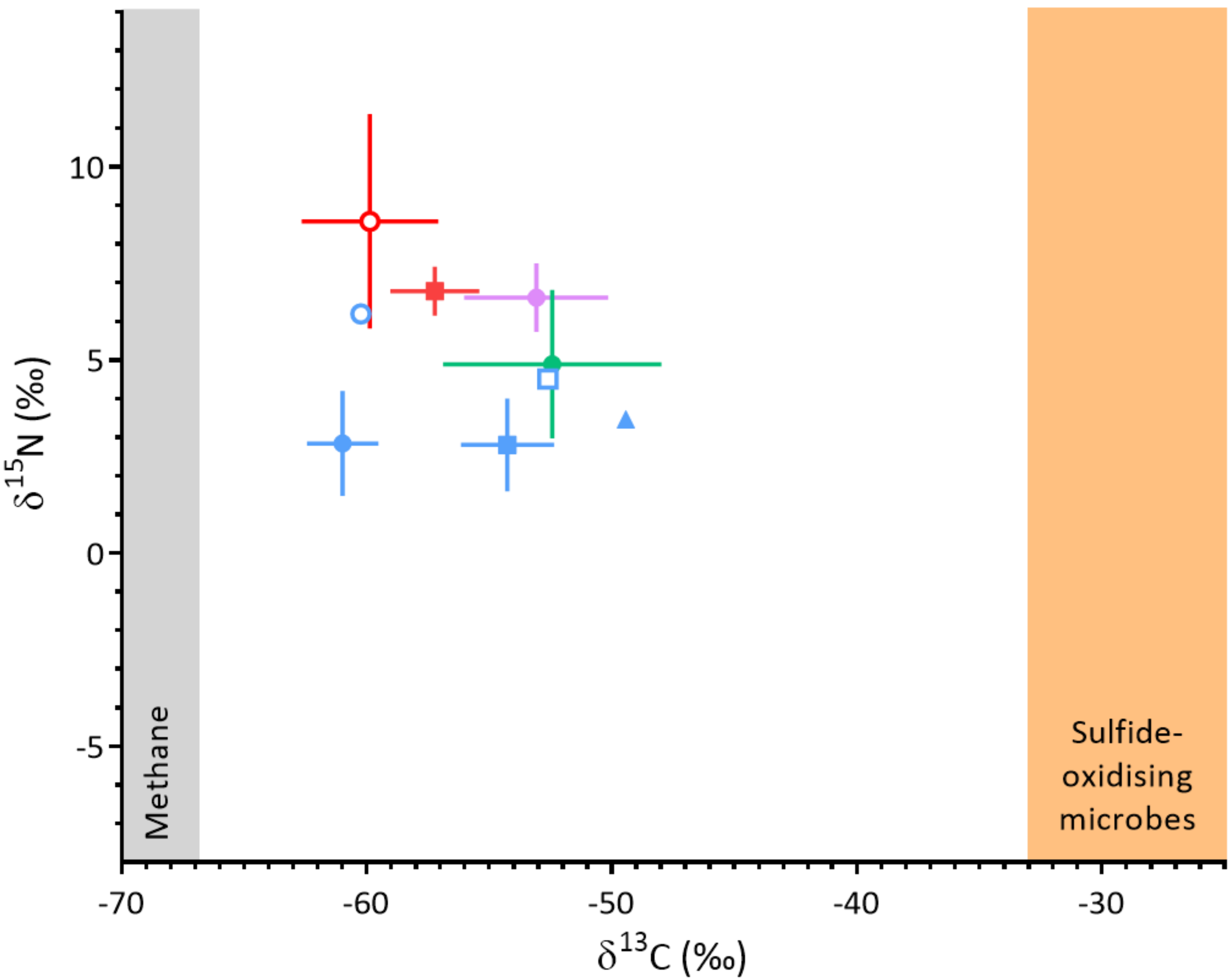

Source: Demopoulos *et al.* 2010 DSR II 57: 1972-1981;
Hügler & Sievert 2011 Annu. Rev. Mar. Sci. 3: 261-289

Results: Mussel beds – hard substrate

Anaerobic oxidation of methane (AOM)

Exploited by
sulfide
oxidisers

$$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O$$

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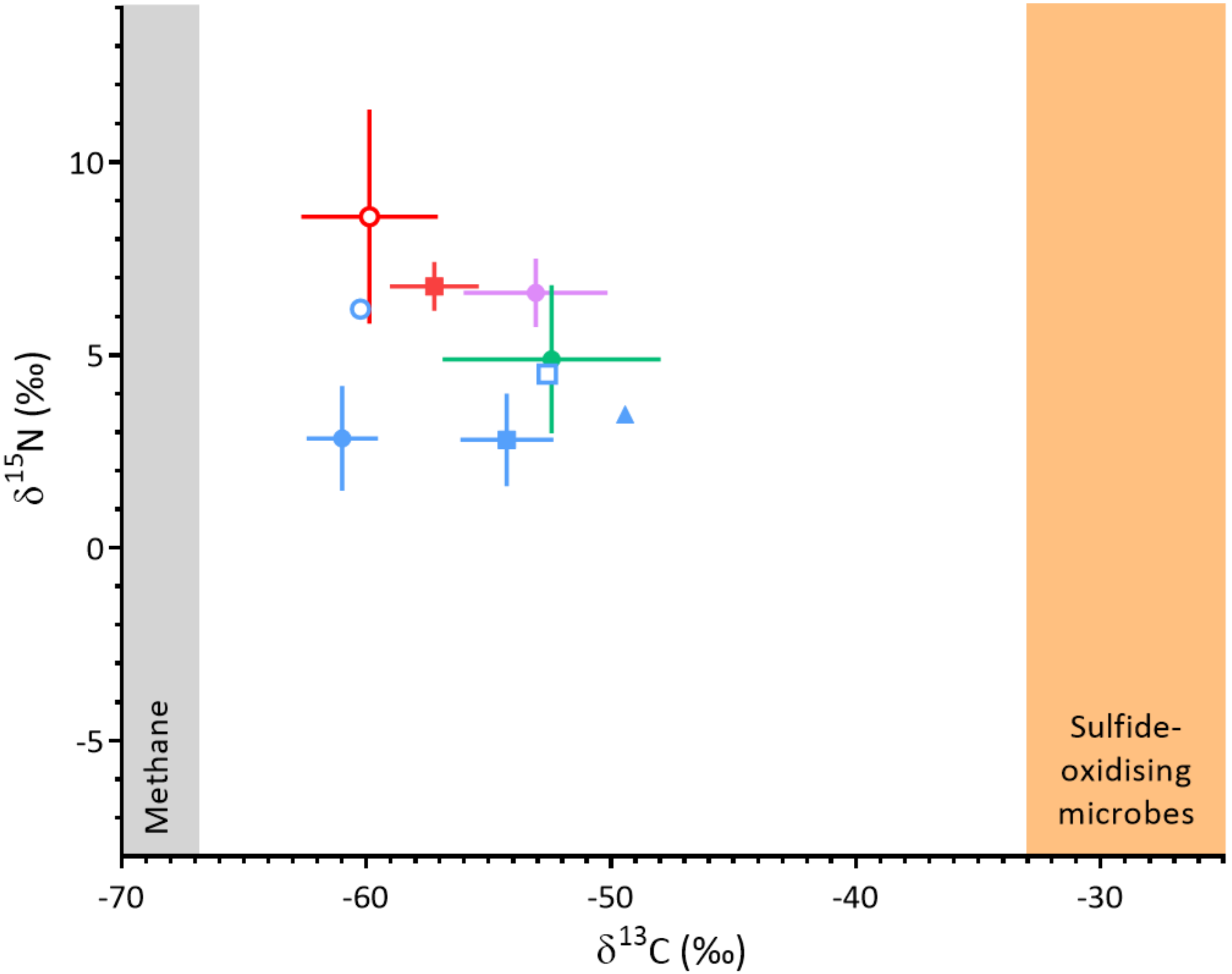

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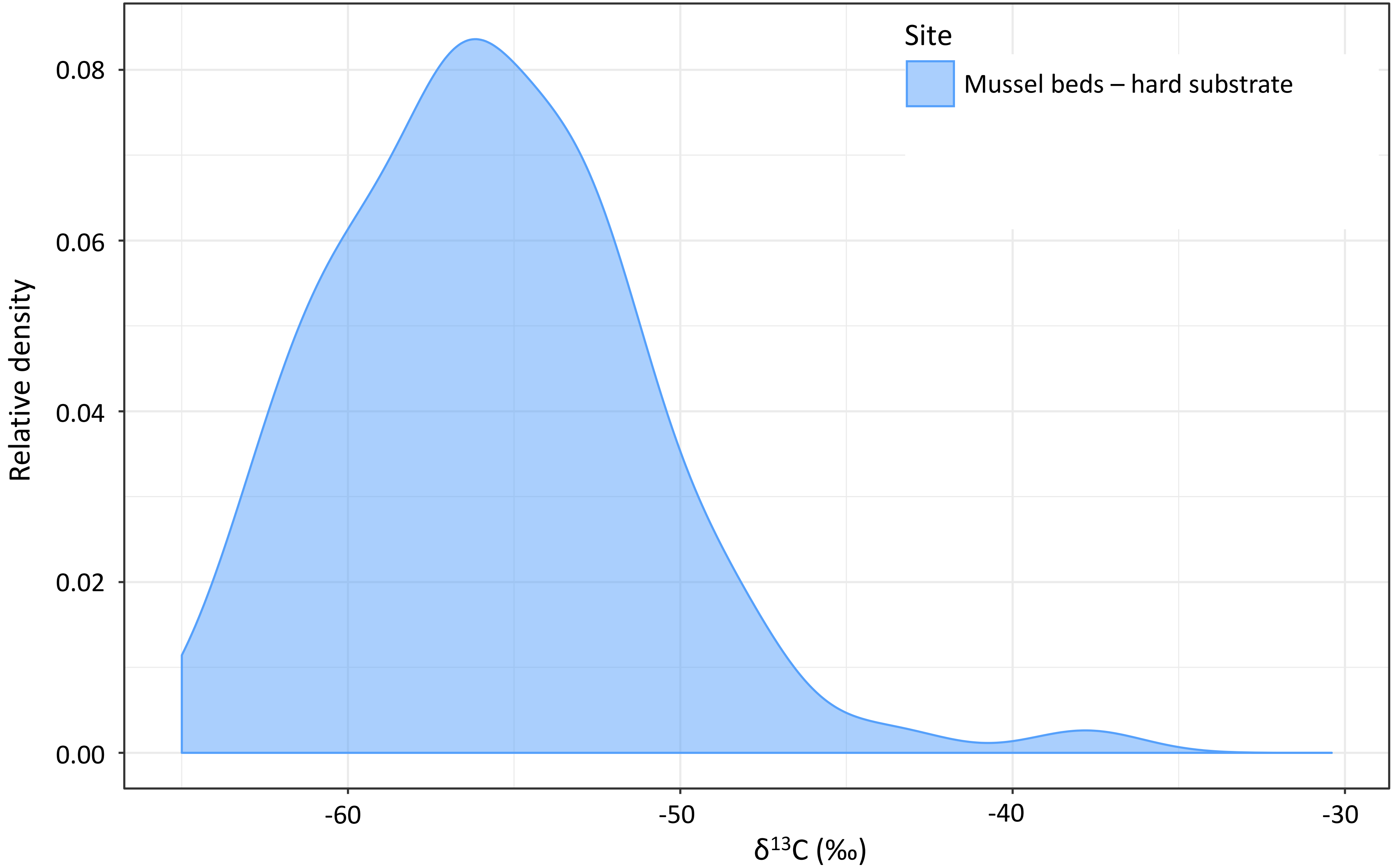
Inter-habitat variation in $\delta^{13}C$ spectrum



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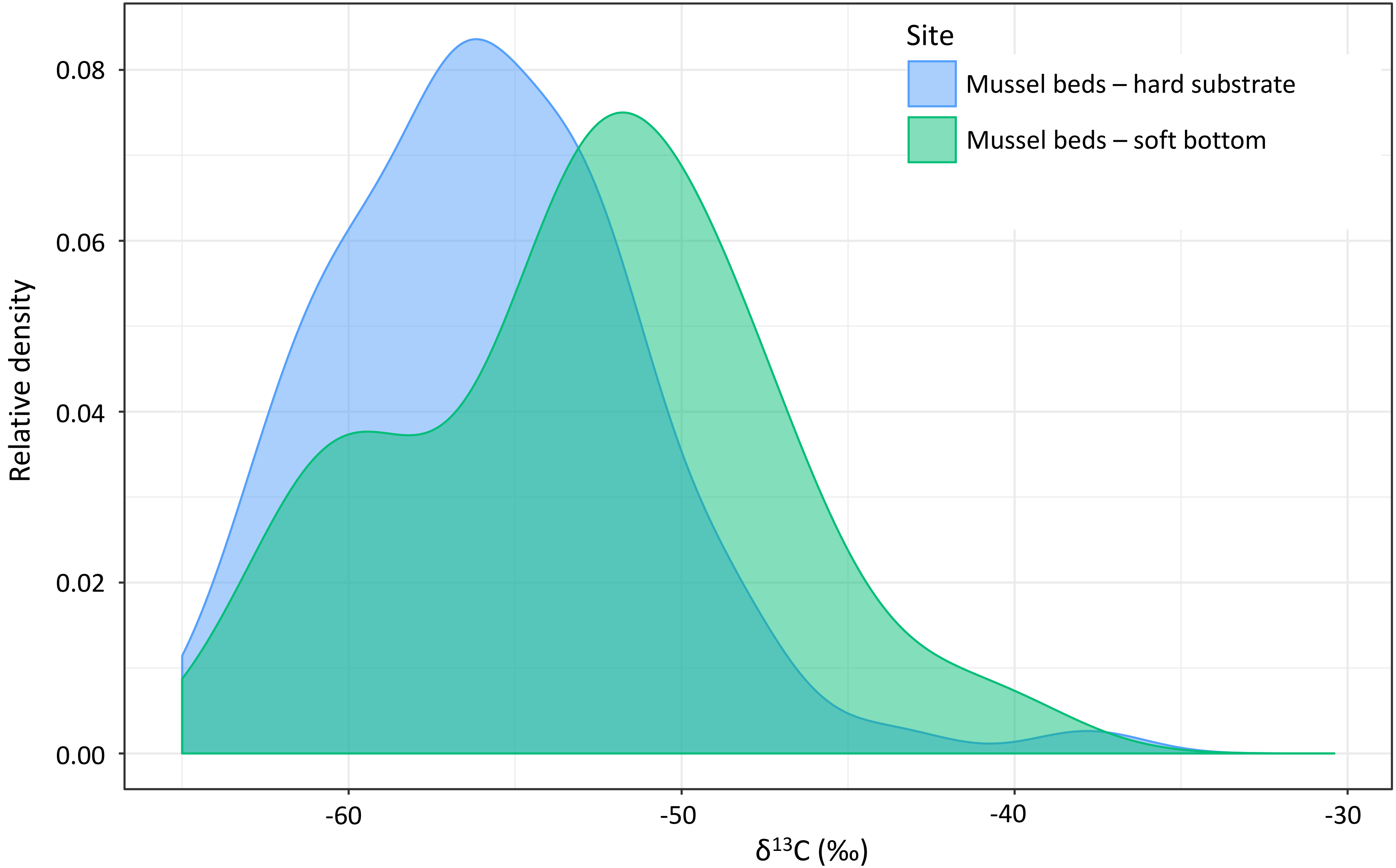

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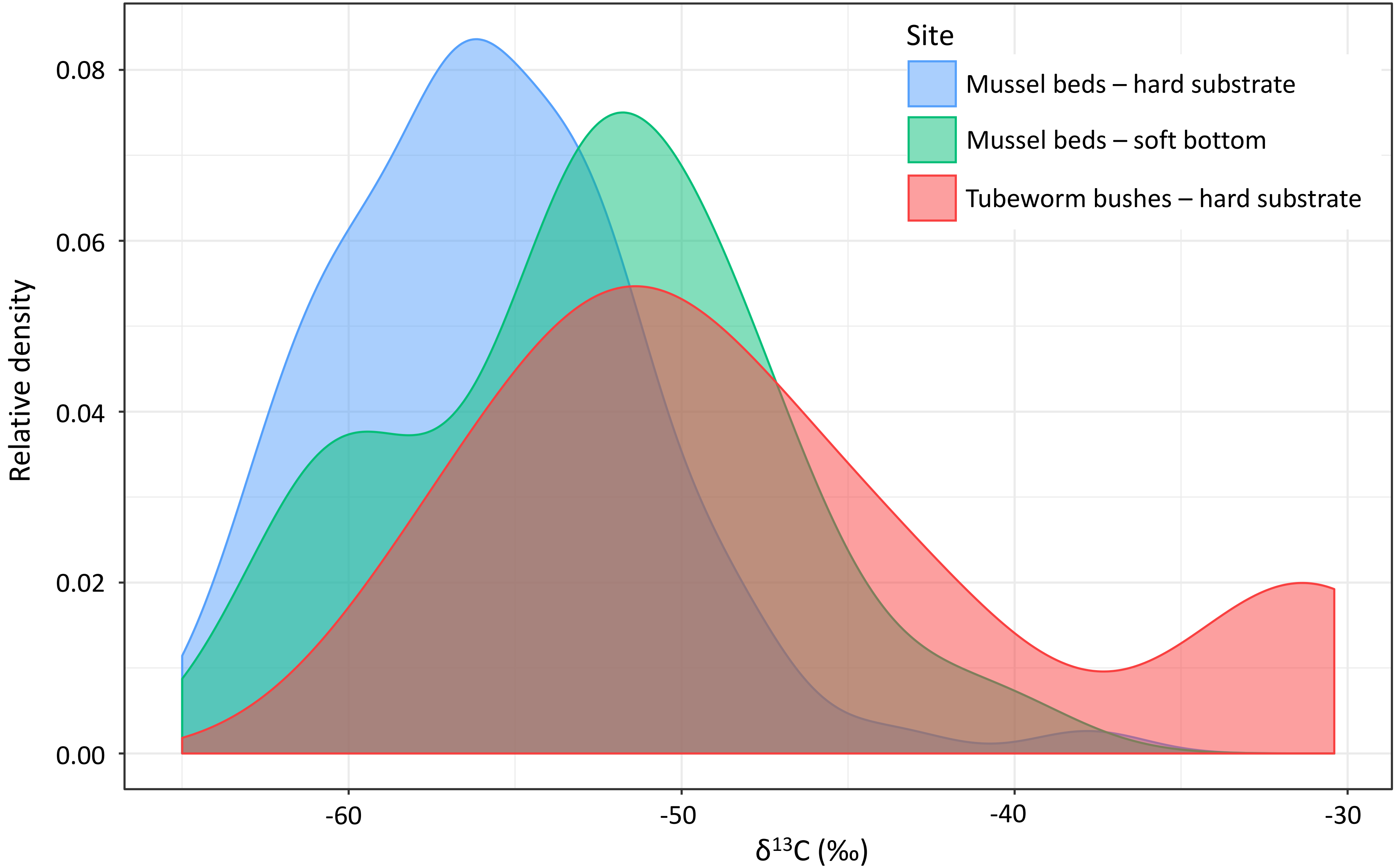

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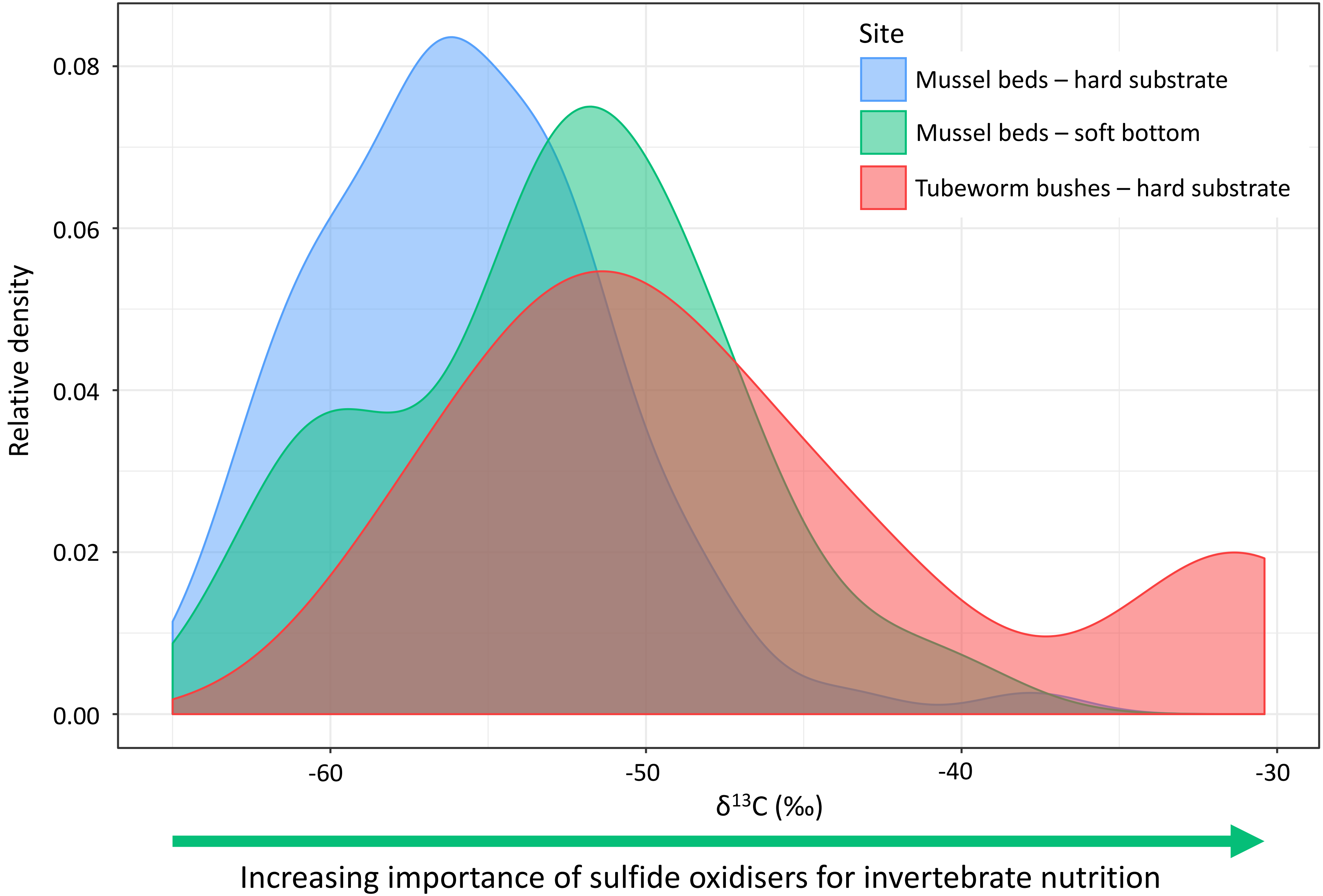
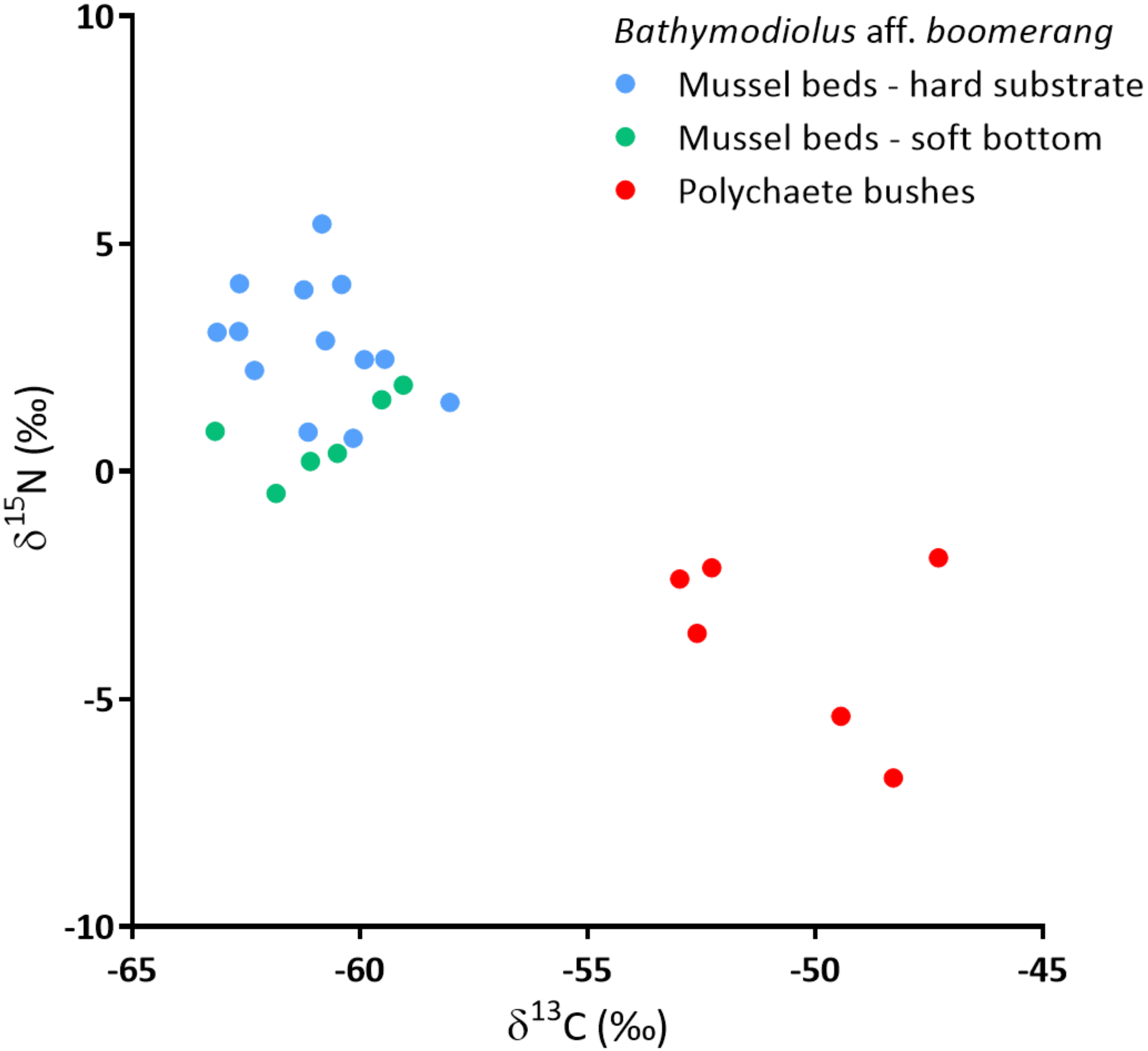


Isotopic shift in *Bathymodiolus* aff. *boomerang*

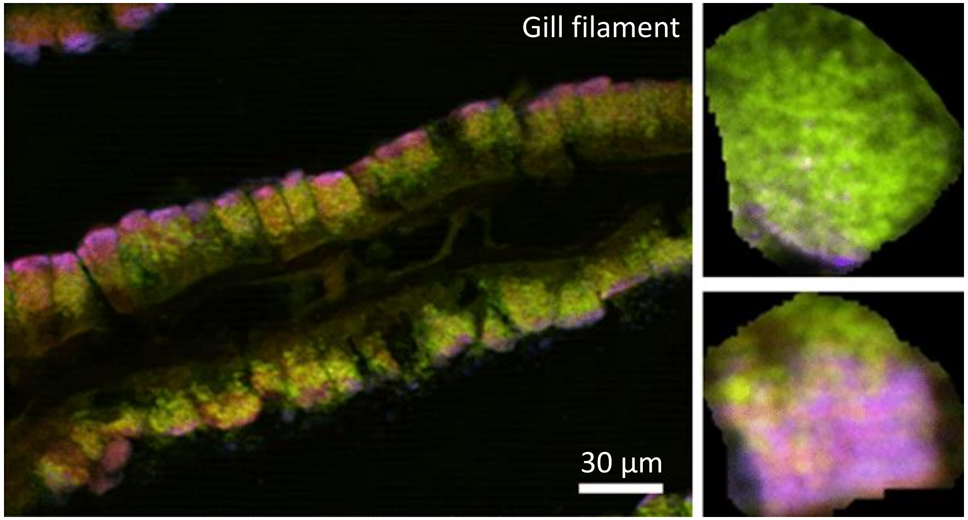


$\Delta^{13}C > 10$ ‰

Isotopic shift in *Bathymodiolus* aff. *boomerang*

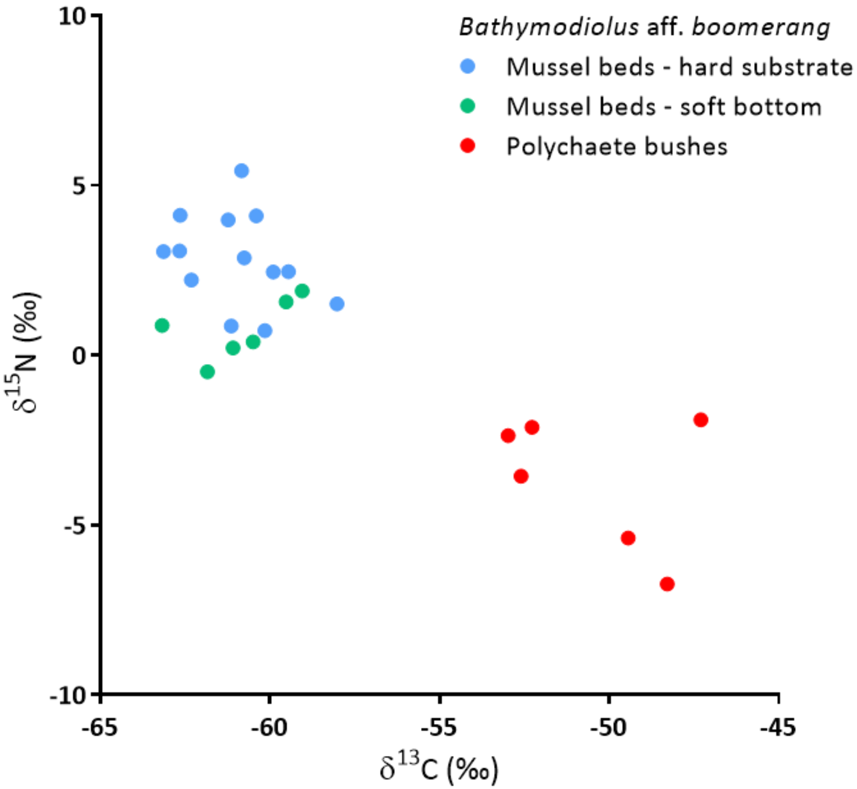
Bathymodiolus aff. *boomerang* can exploit both CH_4 and H_2S trough dual symbiosis

Relative abundance of each type of symbiont is linked to environmental parameters



Green: methane-oxidising bacteria
Pink: sulfide-oxidising bacteria

Duperron *et al.* 2011 Geobiol. 9: 481-491



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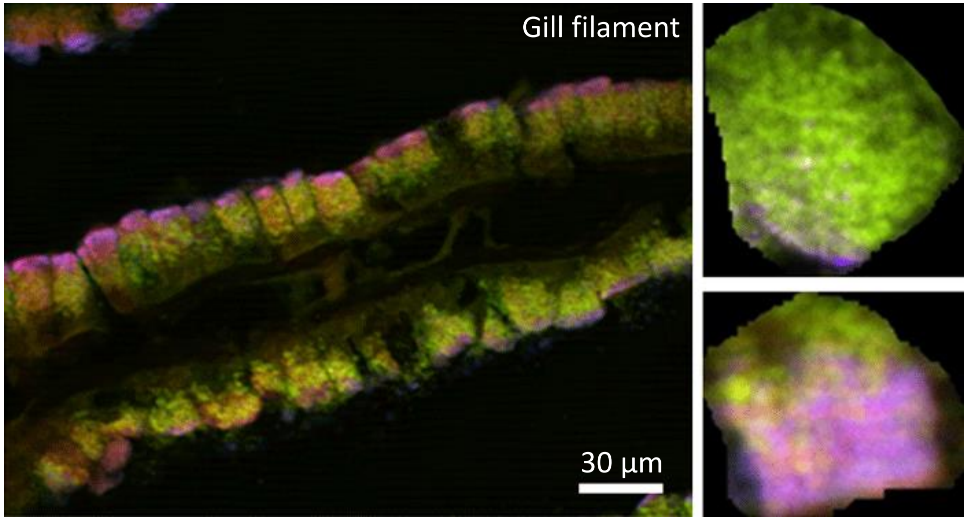

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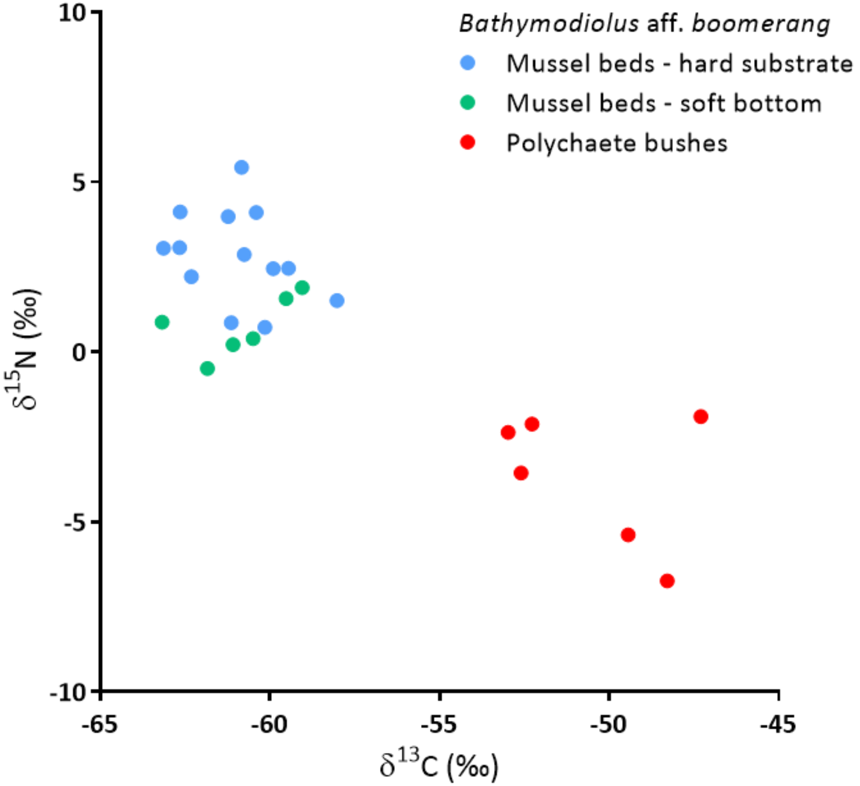


In tubeworm bushes: mussels could derive 38-52% of their carbon from sulfide oxidation

BUT no access to sedimentary S^{2-}, and sulfide concentration in the water column is low (not detectable)

Isotopic shift in *Bathymodiolus* aff. *boomerang*

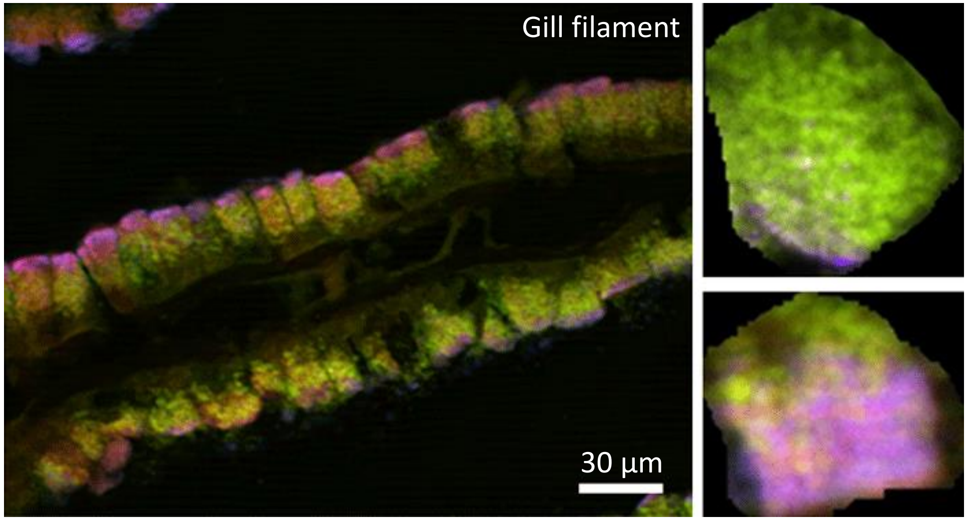
Site	T° (°C)	pH	$[CH_4]$ (µM)	$[S^{2-}]$ (µM)
Mussel beds – hard substrate	25.7	7.75	3.0 - 13.0	n.d. (< 10)
Mussel beds – soft bottoms	27.0	7.84	1.2 - 2.6	n.d. (< 10)
Tubeworm bushes	25.0	7.82	1.3 - 8.2	n.d. (< 10)

n.d.: not detectable

Isotopic shift in *Bathymodiolus* aff. *boomerang*

Bathymodiolus aff. *boomerang* can exploit both CH_4 and H_2S trough dual symbiosis

Relative abundance of each type of symbiont is linked to environmental parameters



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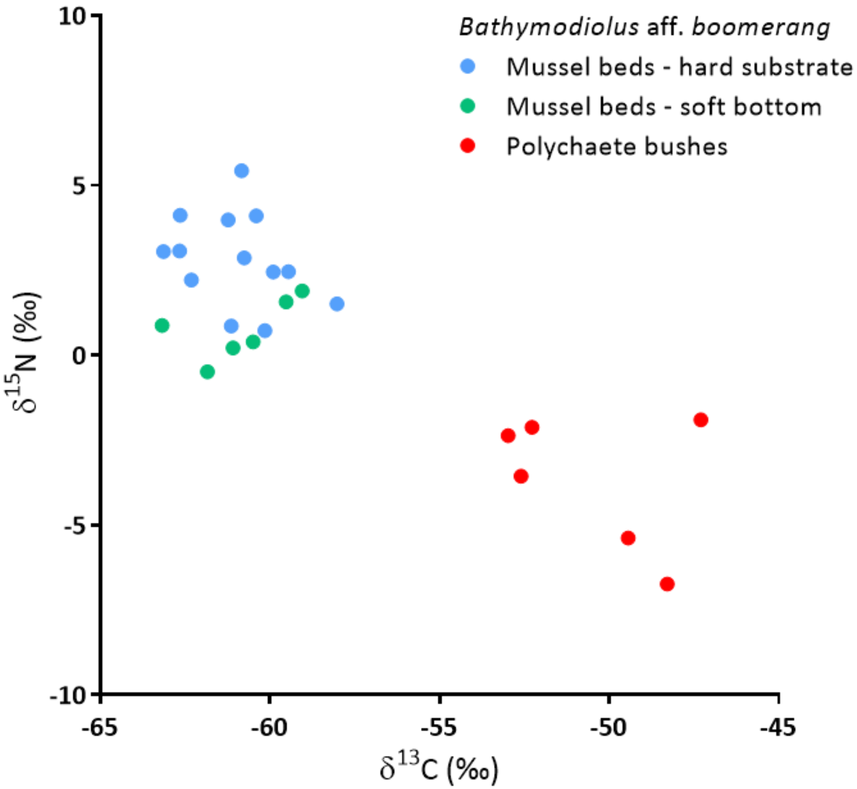

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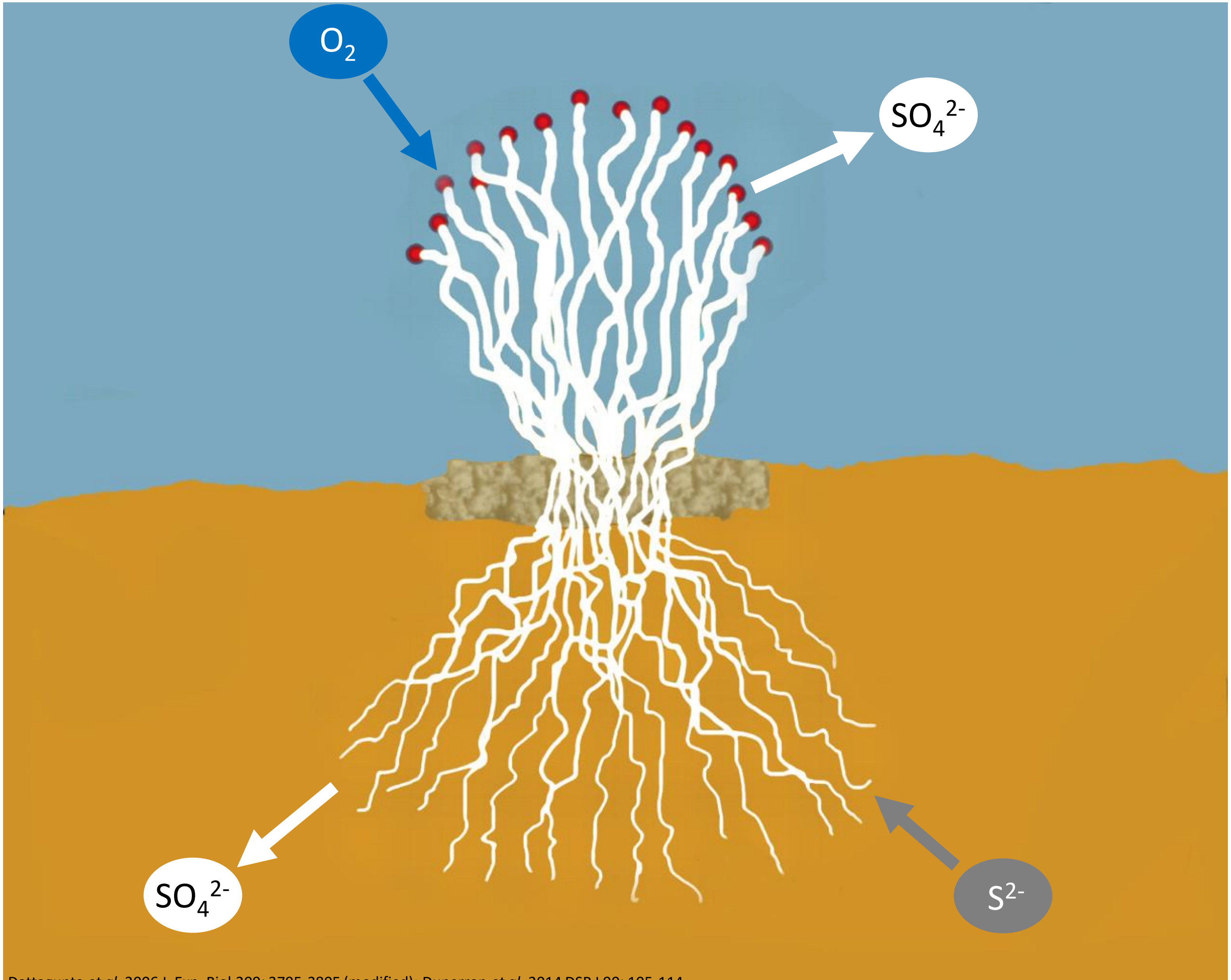
So… where do these sulfides come from?

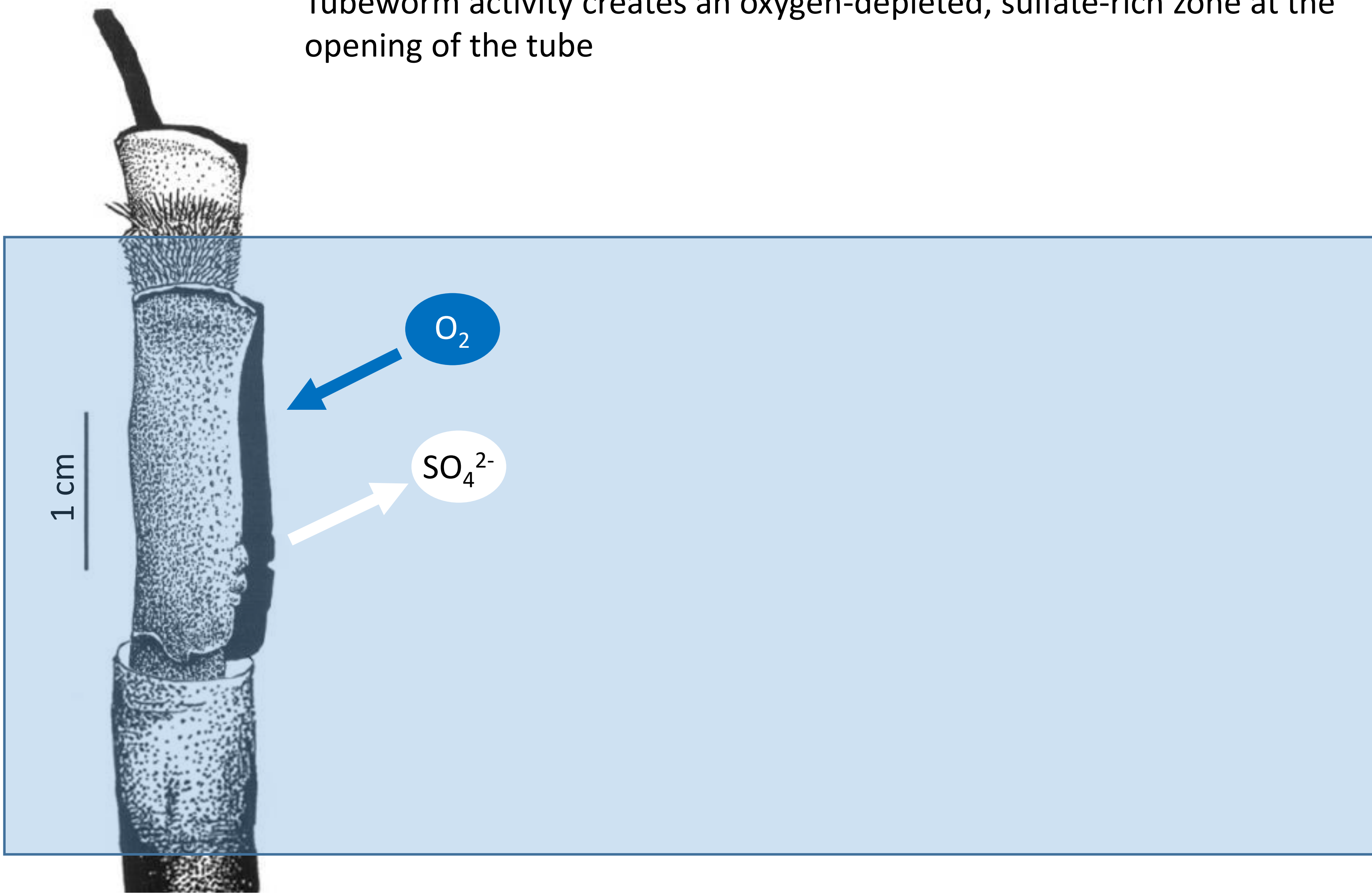
Escarpia southwardae influences local chemistry



Dattagupta *et al.* 2006 J. Exp. Biol 209: 3795-3805 (modified); Duperron *et al.* 2014 DSR I 90: 105-114

Escarpia southwardae influences local chemistry

Tubeworm activity creates an oxygen-depleted, sulfate-rich zone at the opening of the tube

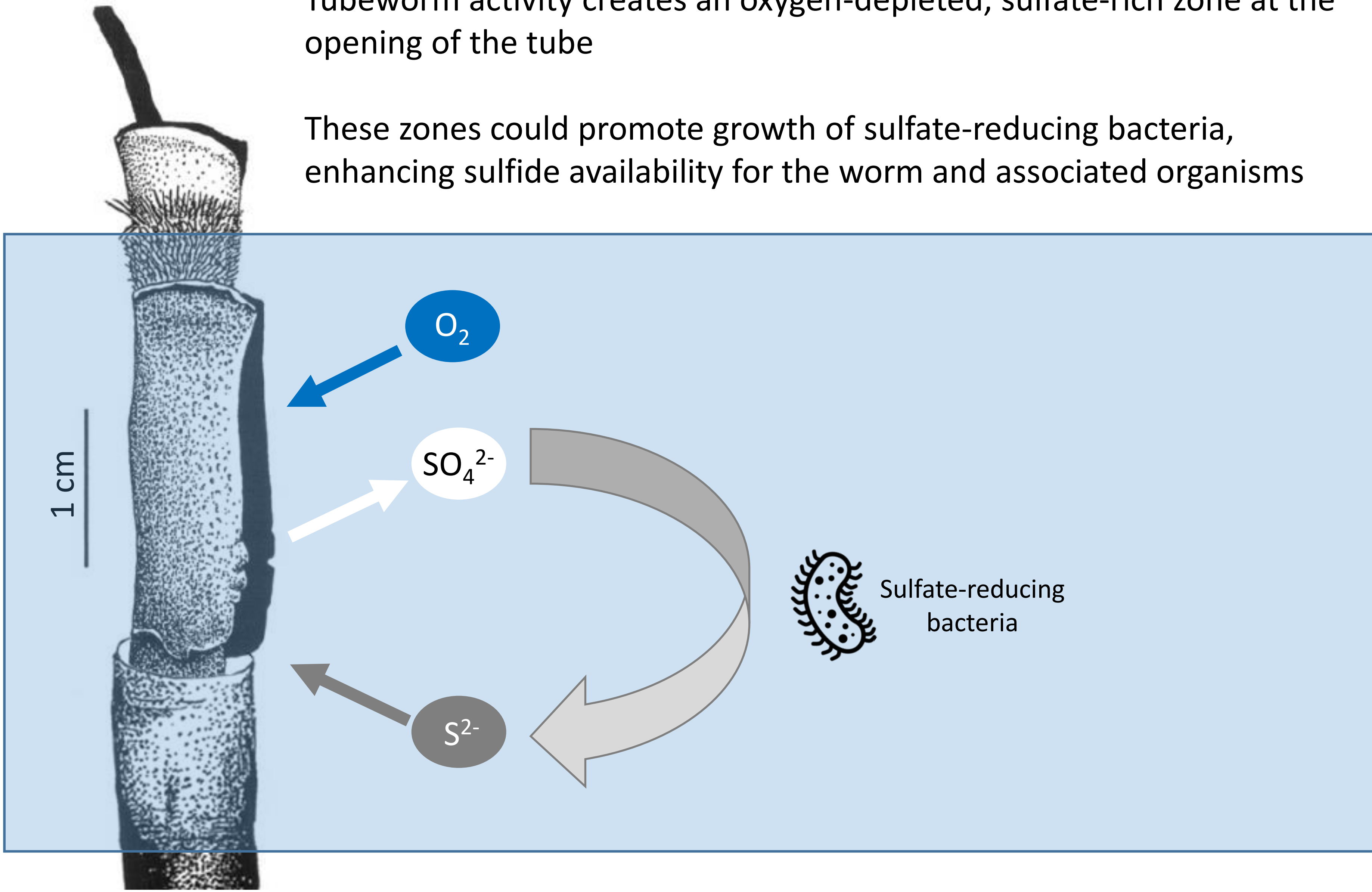


Malakhov & Galkin 2000 Rus. J. Mar. Biol 26: 311-324 (modified); Duperron *et al.* 2014 DSR I 90: 105-114

Escarpia southwardae influences local chemistry

Tubeworm activity creates an oxygen-depleted, sulfate-rich zone at the opening of the tube

These zones could promote growth of sulfate-reducing bacteria, enhancing sulfide availability for the worm and associated organisms



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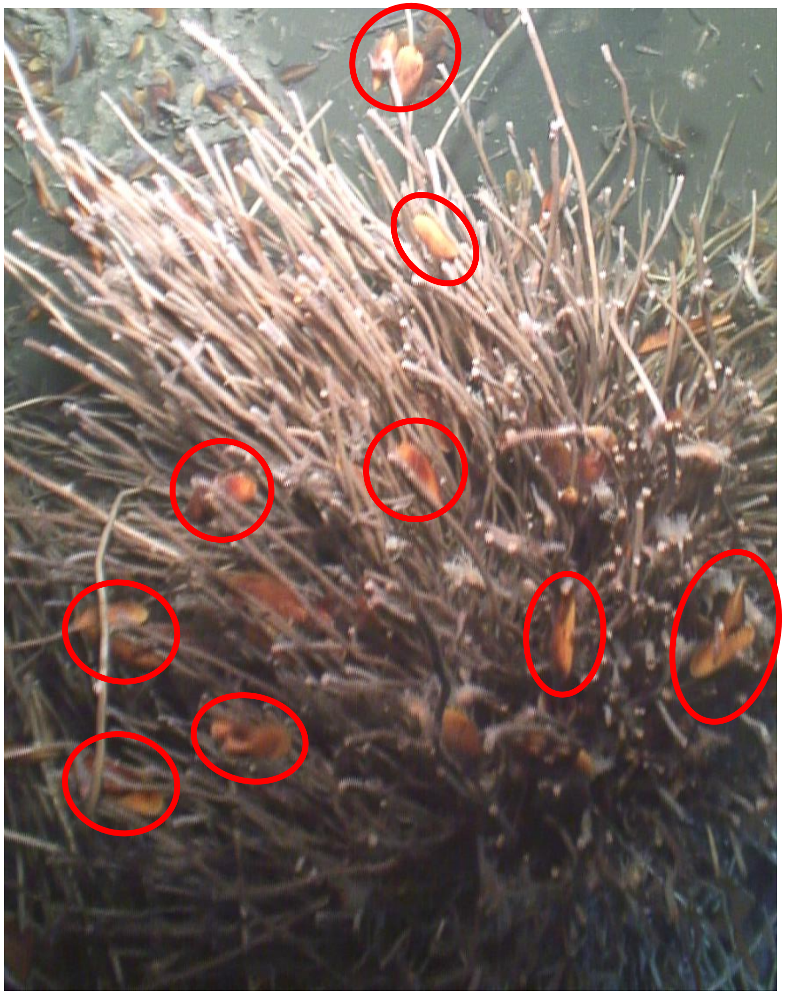
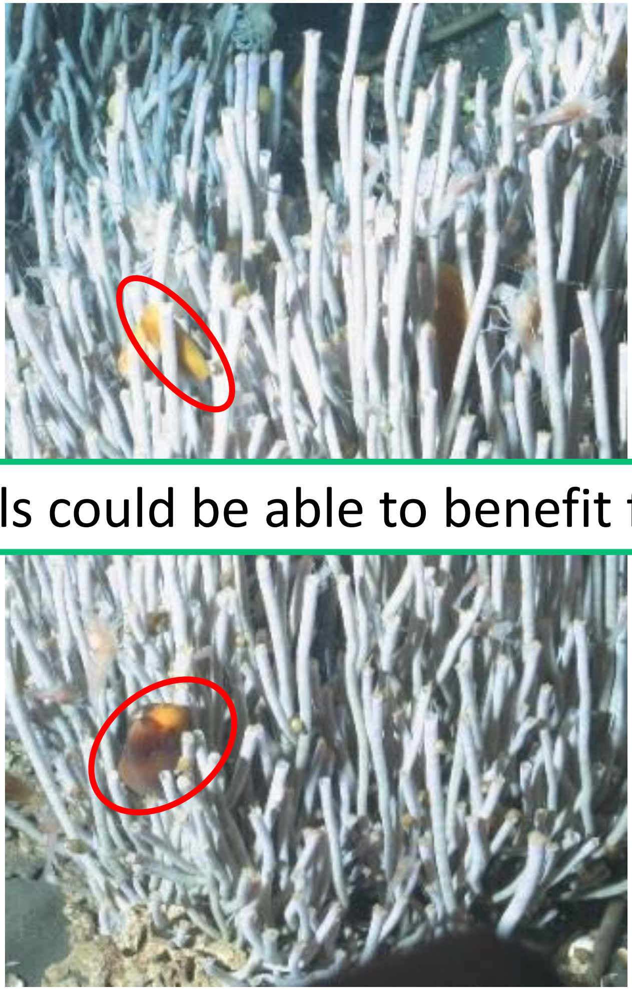
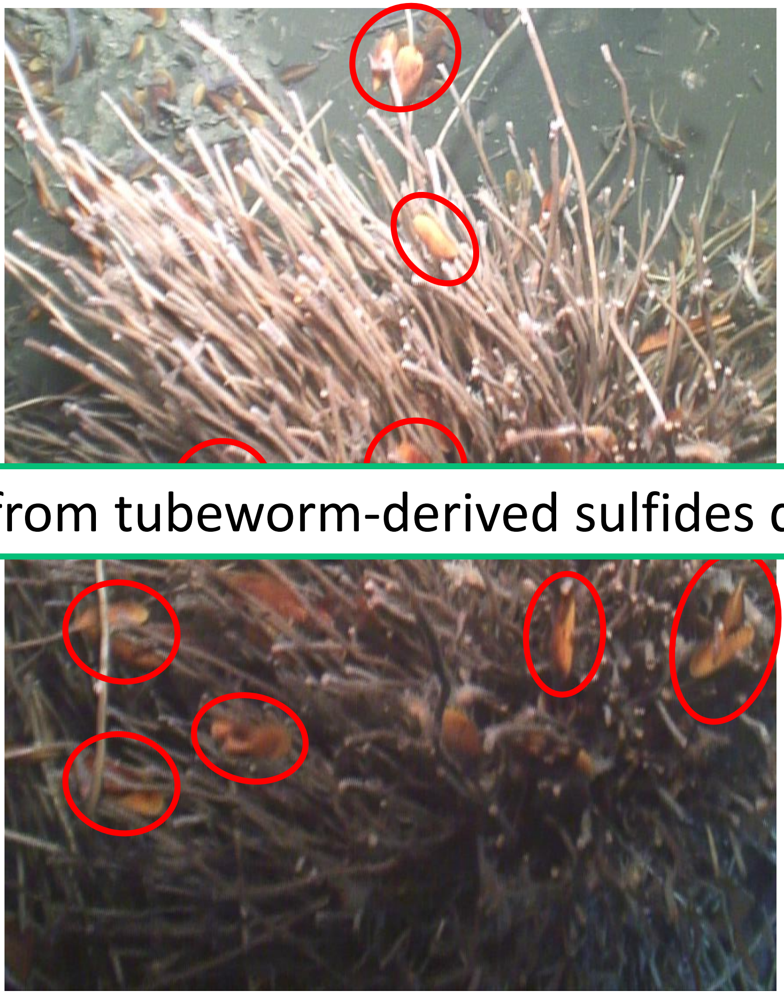
B. aff. *boomerang* in tubeworm bushes



In *Escarpia southwardae* bushes from the Regab pockmark, *Bathymodiolus* aff. *boomerang* is frequently observed living perched on the tubeworms, near the open end…

B. aff. *boomerang* in tubeworm bushes





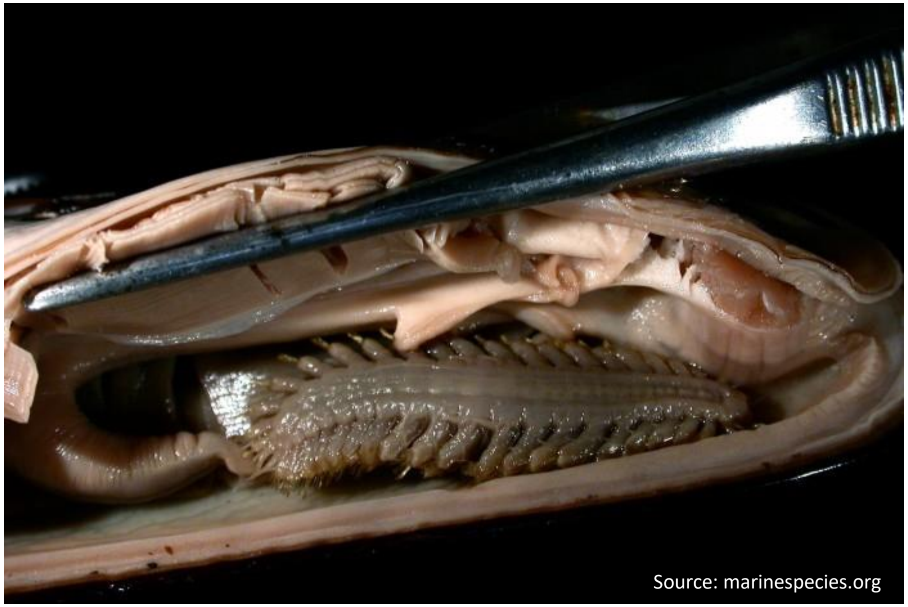
Mussels could be able to benefit from tubeworm-derived sulfides directly

In *Escarpia southwardae* bushes from the Regab pockmark, *Bathymodiolus* aff. *boomerang* is frequently observed living perched on the tubeworms, near the open end…

Mussels – polynoids associations

- Associations between *Bathymodiolus* mussels and *Branchipolynoe* scale worms are ubiquitous in deep-sea vents and seeps. Evidence of co-evolution (Jollivet 2018, HDR thesis).

- At Regab: *Branchipolynoe seepensis* was never observed alone. Obligate symbiont?



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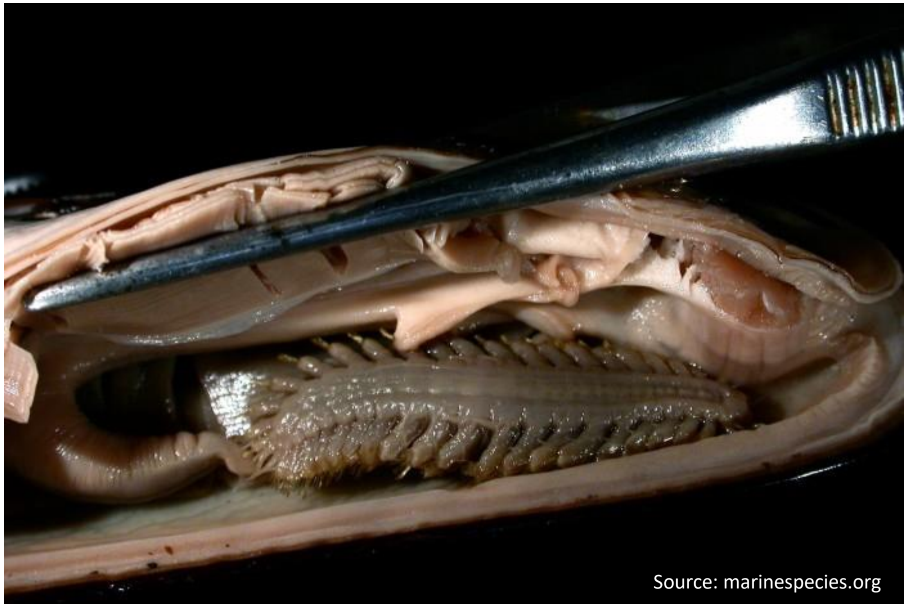
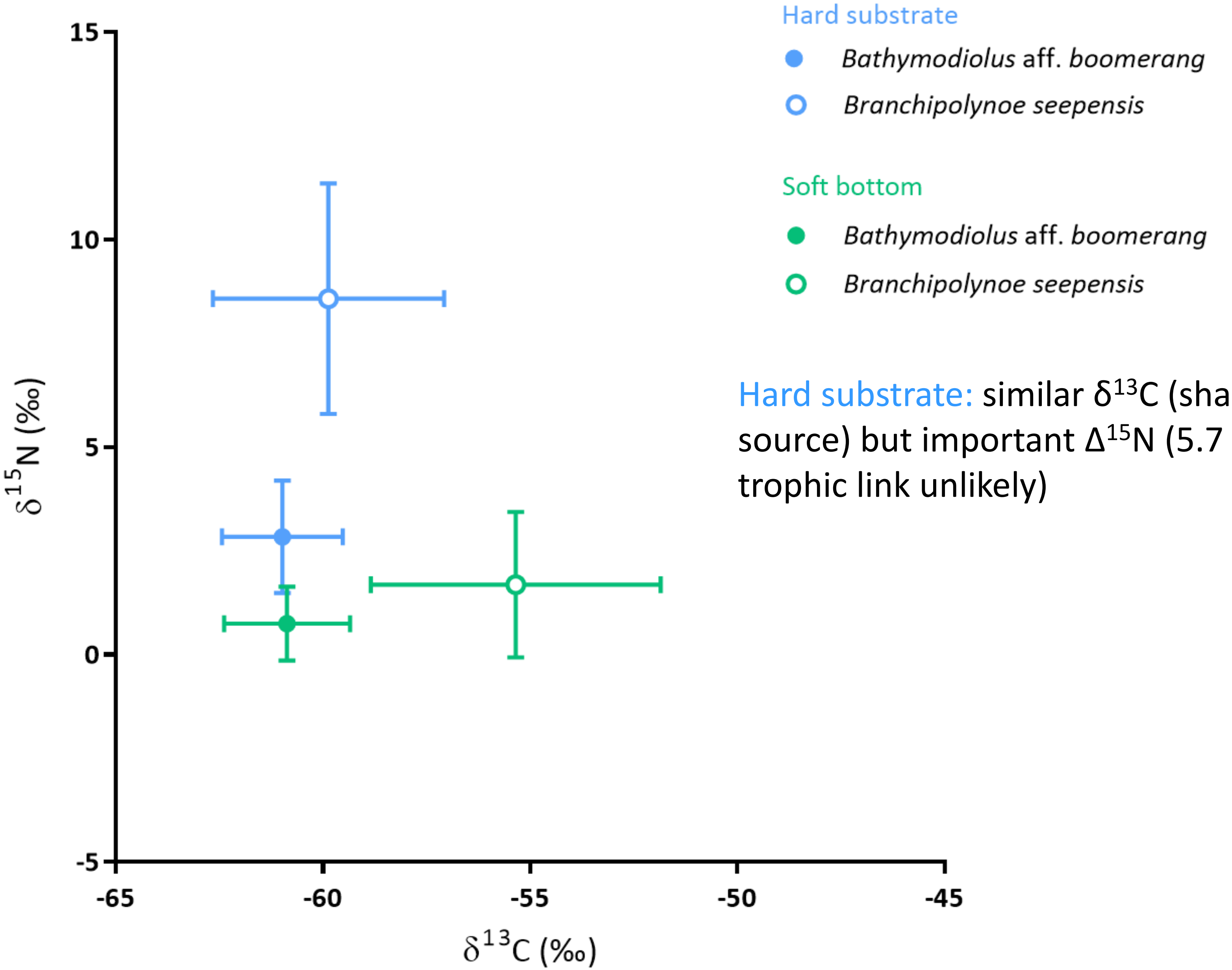
- At Regab: *Branchipolynoe seepensis* was never observed alone. Obligate symbiont?
- Nature of the symbiosis is unclear. Commensalism? Parasitism? Mutualism?
- Existence of a direct (parasitism) or indirect (kleptocommensalism) trophic link between the worm and its mussel host is often suggested



Mussels – polynoids associations



Hard substrate: similar $\delta^{13}C$ (shared carbon source) but important $\Delta^{15}N$ (5.7 ‰, direct trophic link unlikely)

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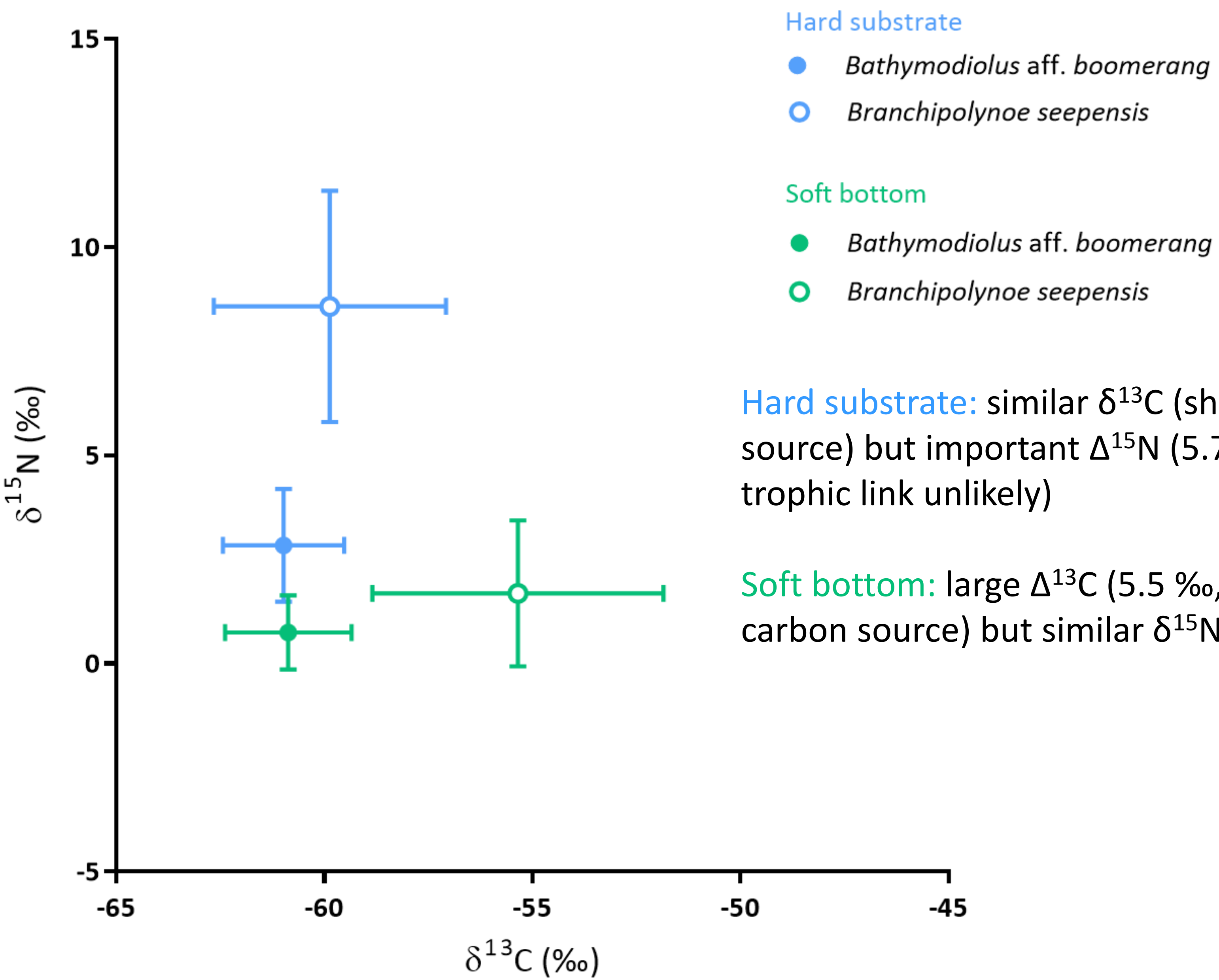
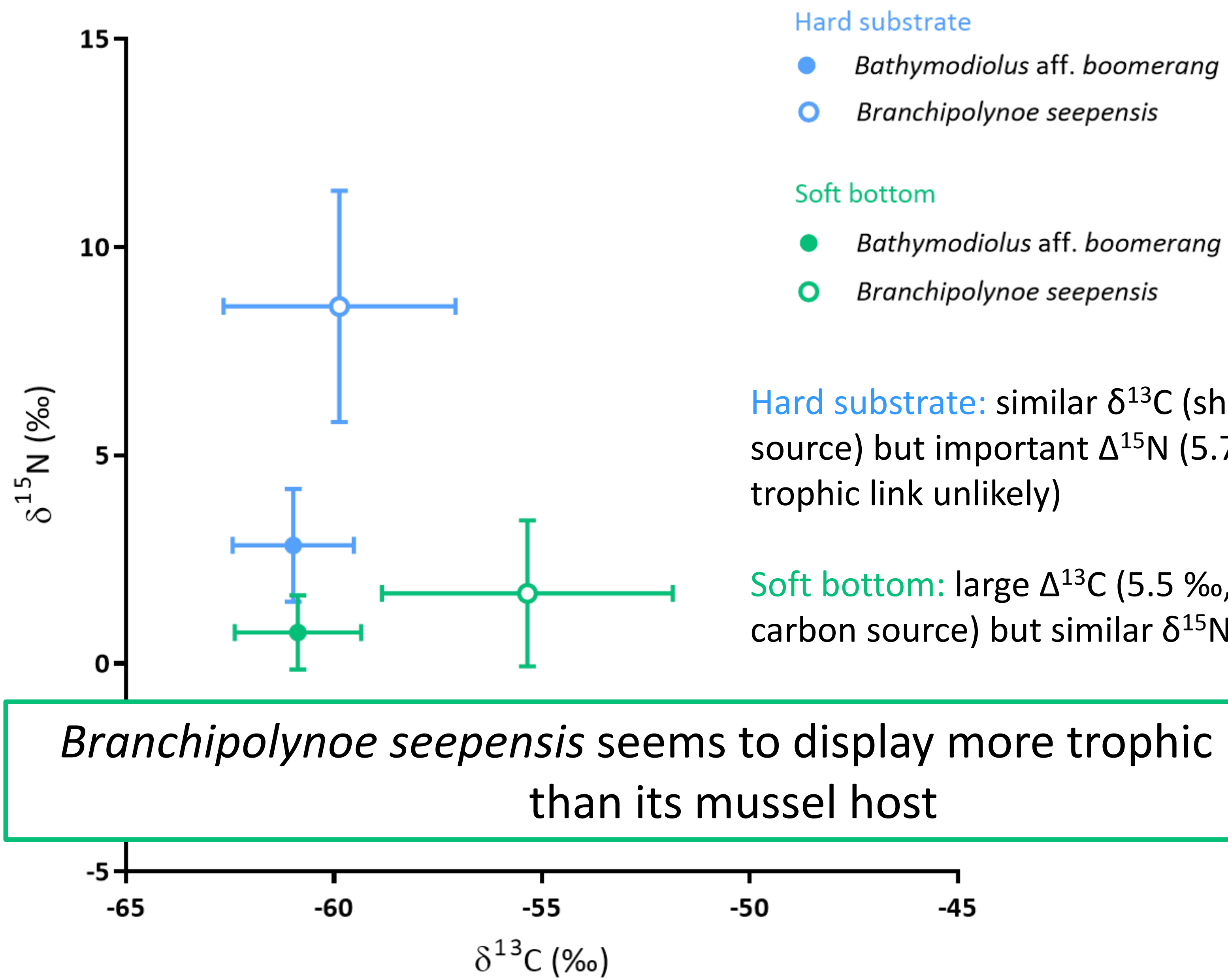


Hard substrate: similar $\delta^{13}C$ (shared carbon source) but important $\Delta^{15}N$ (5.7 ‰, direct trophic link unlikely)

Soft bottom: large $\Delta^{13}C$ (5.5 ‰, different carbon source) but similar $\delta^{15}N$

Mussels – polynoids associations



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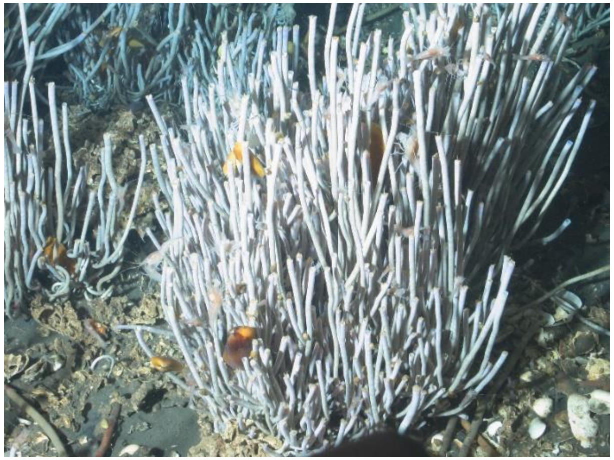
Branchipolynoe seepensis seems to display more trophic plasticity than its mussel host

Conclusions & perspectives

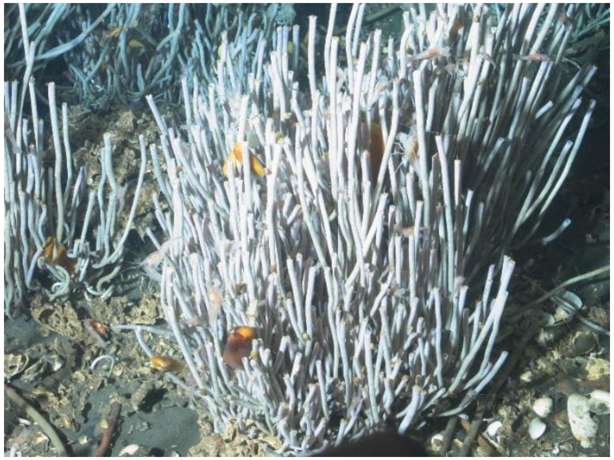
- In all 3 habitats, animal communities rely on both methane and sulfide oxidation



Conclusions & perspectives

- In all 3 habitats, animal communities rely on both methane and sulfide oxidation

- Relative importance of mechanisms is habitat-dependent. Sulfide oxidation seems more important in tubeworm bushes than in mussel beds.



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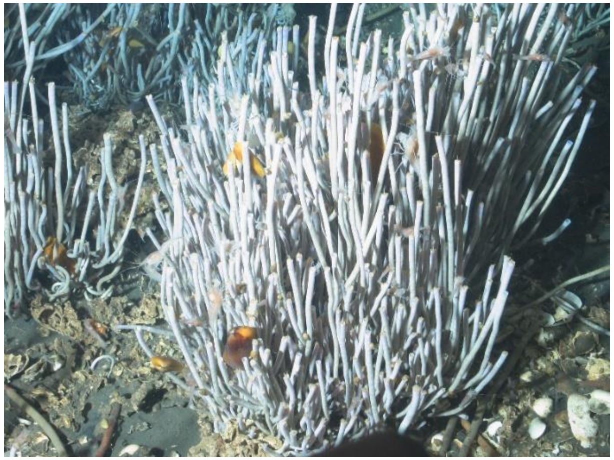

- Tubeworms actively mine sulfides from sediment and enhance their availability for associated organisms. Double ecosystem engineering role: physical and chemical.

Conclusions & perspectives

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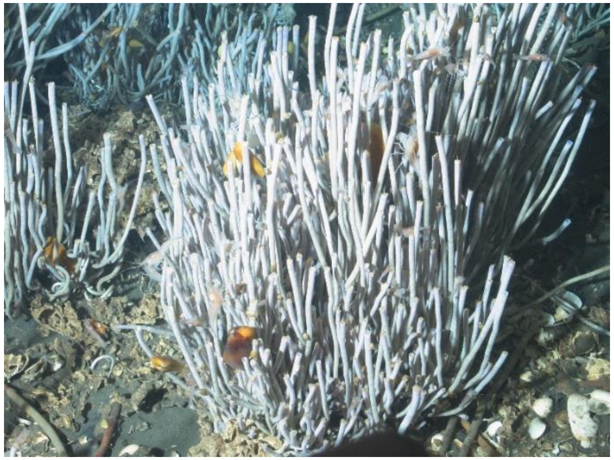

- Tubeworms actively mine sulfides from sediment and enhance their availability for associated organisms. Double ecosystem engineering role: physical and chemical.
- Many open questions... Relative influence of environmental drivers and biotic associations? Temporal dynamics of food web structure?

Thanks for your attention


EV Nautilus – Ocean Exploration Trust


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References & further reading

DATTAGUPTA, S., MILES, L.L., BARNABEI, M.S. & FISHER, C.R. 2006. The hydrocarbon seep tubeworm *Lamellibrachia luymesi* primarily eliminates sulfate and hydrogen ions across its roots to conserve energy and ensure sulfide supply. *Journal of Experimental Biology*, **209**, 3795–3805, https://doi.org/10.1242/jeb.02413.

DEMOPOULOS, A.W.J., GUALTIERI, D. & KOVACS, K. 2010. Food-web structure of seep sediment macrobenthos from the Gulf of Mexico. *Deep Sea Research Part II: Topical Studies in Oceanography*, **57**, 1972–1981, https://doi.org/10.1016/j.dsr2.2010.05.011.

DUPERRON, S. 2015. Characterization of bacterial symbionts in deep-sea fauna: protocols for sample conditioning, fluorescence in situ hybridization, and image analysis. In *Hydrocarbon and Lipid Microbiology Protocols,* Springer Protocols Handbooks, pp. 343-362, https://doi.org/10.1007/8623_2015_73.

DUPERRON, S., GAUDRON, S.M., LEMAITRE, N. & BAYON, G. 2014. A microbiological and biogeochemical investigation of the cold seep tubeworm *Escarpia southwardae* (Annelida: Siboglinidae): Symbiosis and trace element composition of the tube. *Deep-Sea Research Part I: Oceanographic Research Papers*, **90**, 105–114, https://doi.org/10.1016/j.dsr.2014.05.006.

DUPERRON, S., GUEZI, H., GAUDRON, S.M., POP RISTOVA, P., WENZHÖFER, F. & BOETIUS, A. 2011. Relative abundances of methane- and sulphur-oxidising symbionts in the gills of a cold seep mussel and link to their potential energy sources. *Geobiology*, **9**, 481–491, https://doi.org/10.1111/j.1472-4669.2011.00300.x.

GUILLON, E., MENOT, L., DECKER, C., KRYLOVA, E. & OLU, K. 2017. The vesicomyid bivalve habitat at cold seeps supports heterogeneous and dynamic macrofaunal assemblages. *Deep-Sea Research Part I: Oceanographic Research Papers*, **120**, 1–13, https://doi.org/10.1016/j.dsr.2016.12.008.

HÜGLER, M. & SIEVERT, S.M. 2011. Beyond the Calvin Cycle: Autotrophic Carbon Fixation in the Ocean. *Annual Review of Marine Science*, **3**, 261–289, https://doi.org/10.1146/annurev-marine-120709-142712.

References & further reading

JOLLIVET, D. 2018. Dispersion et évolution des espèces hydrothermales profondes. HDR Thesis, Université Pierre et Marie Curie – Paris VI, 79 pp.

LEVIN, L.A., BACO, A.R., BOWDEN, D.A., COLACO, A., CORDES, E.E., CUNHA, M.R., DEMOPOULOS, A.W.J., et al. 2016. Hydrothermal Vents and Methane Seeps: Rethinking the Sphere of Influence. *Frontiers in Marine Science*, **3**, 1–23, https://doi.org/10.3389/fmars.2016.00072.

MALAKHOV, V.V. & GALKIN, S.V. 2000. A synopsis of the vestimentiferan system. *Russian Journal of Marine Biology*, **26**, 311–324, https://doi.org/10.1007/BF02759472.

OLU, K. 2011. WACS cruise, R/V Pourquoi pas ?, https://doi.org/10.17600/11030010.

OLU, K., CAPRAIS, J.C., GALÉRON, J., CAUSSE, R., VON COSEL, R., BUDZINSKI, H., MÉNACH, K.L., et al. 2009. Influence of seep emission on the non-symbiont-bearing fauna and vagrant species at an active giant pockmark in the Gulf of Guinea (Congo–Angola margin). *Deep Sea Research Part II: Topical Studies in Oceanography*, **56**, 2380–2393, https://doi.org/10.1016/j.dsr2.2009.04.017.

OLU-LE ROY, K., CAPRAIS, J.C., FIFIS, A., FABRI, M.C., GALÉRON, J., BUDZINSKY, H., LE MÉNACH, K., KHRIPOUNOFF, A., ONDRÉAS, H. & SIBUET, M. 2007. Cold-seep assemblages on a giant pockmark off West Africa: Spatial patterns and environmental control. *Marine Ecology*, **28**, 115–130, https://doi.org/10.1111/j.1439-0485.2006.00145.x.

ONDRÉAS, H., OLU, K., FOUQUET, Y., CHARLOU, J.L., GAY, A., DENNIELOU, B., DONVAL, J.P., et al. 2005. ROV study of a giant pockmark on the Gabon continental margin. *Geo-Marine Letters*, **25**, 281–292, https://doi.org/10.1007/s00367-005-0213-6.

RAINEAULT, N.A., FLANDERS, J. & BOWMAN, A. 2018. New Frontiers in Ocean Exploration - The E/V Nautilus, NOAA Ship Okeanos Explorer, and R/V Falkor 2017 Field Season. *Oceanography*, **31**, 1–126, https://doi.org/10.5670/oceanog.2016.supplement.01.

References & further reading

SUESS, E. 2014. Marine cold seeps and their manifestations: geological control, biogeochemical criteria and environmental conditions. *International Journal of Earth Sciences*, **103**, 1889–1916, https://doi.org/10.5670/10.1007/s00531-014-1010-0.

WARÉN, A. & BOUCHET, P. 2009. New gastropods from deep-sea hydrocarbon seeps off West Africa. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **56**, 2326–2349, https://doi.org/10.1016/j.dsr2.2009.04.013.