The East Siberian Arctic Shelf: methane release from subsea permafrost (what was learned over a decade 2003-2014)

Natalia Shakhova & Igor Semiletov + many others

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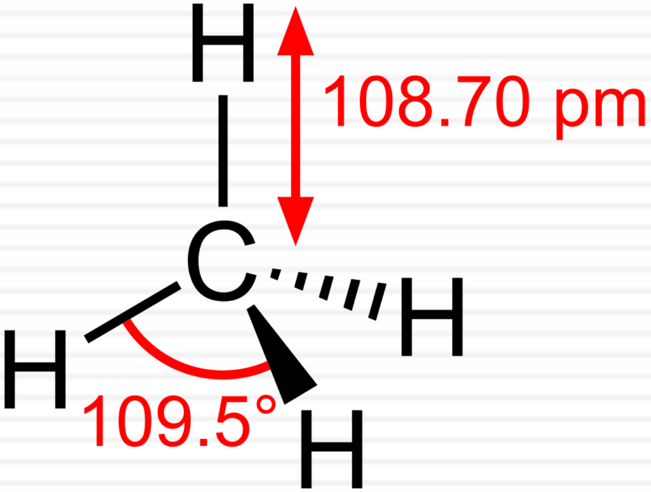
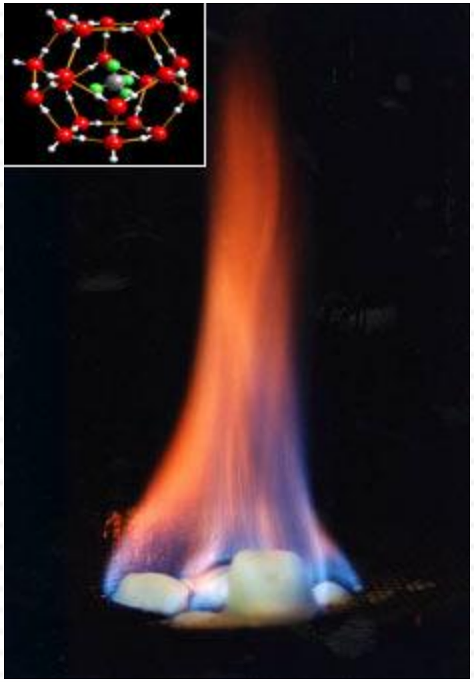
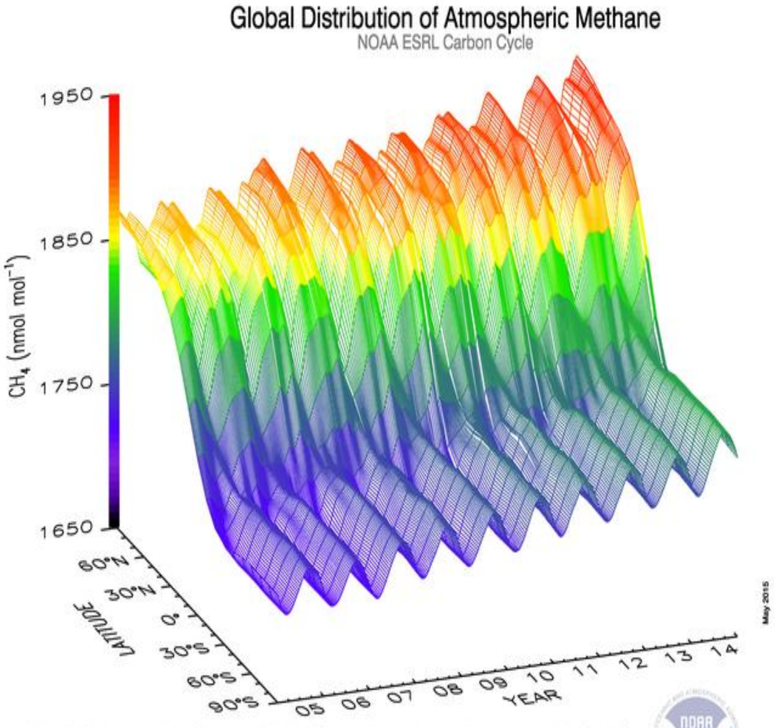
Methane





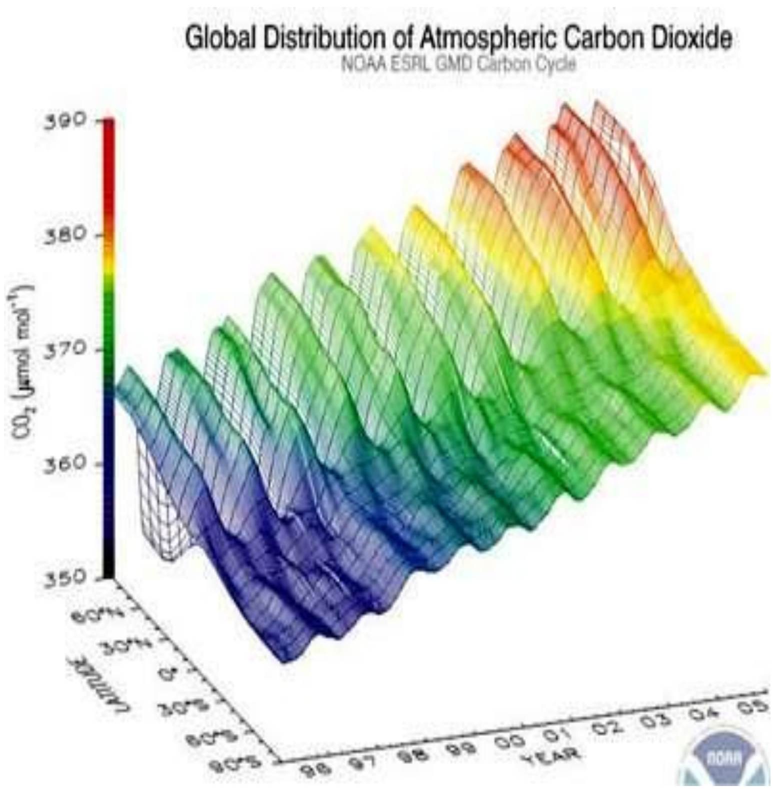
Atmospheric maximum of methane/carbon dioxide over the Arctic



Global Distribution of Atmospheric Methane

NOAA ESRL Carbon Cycle

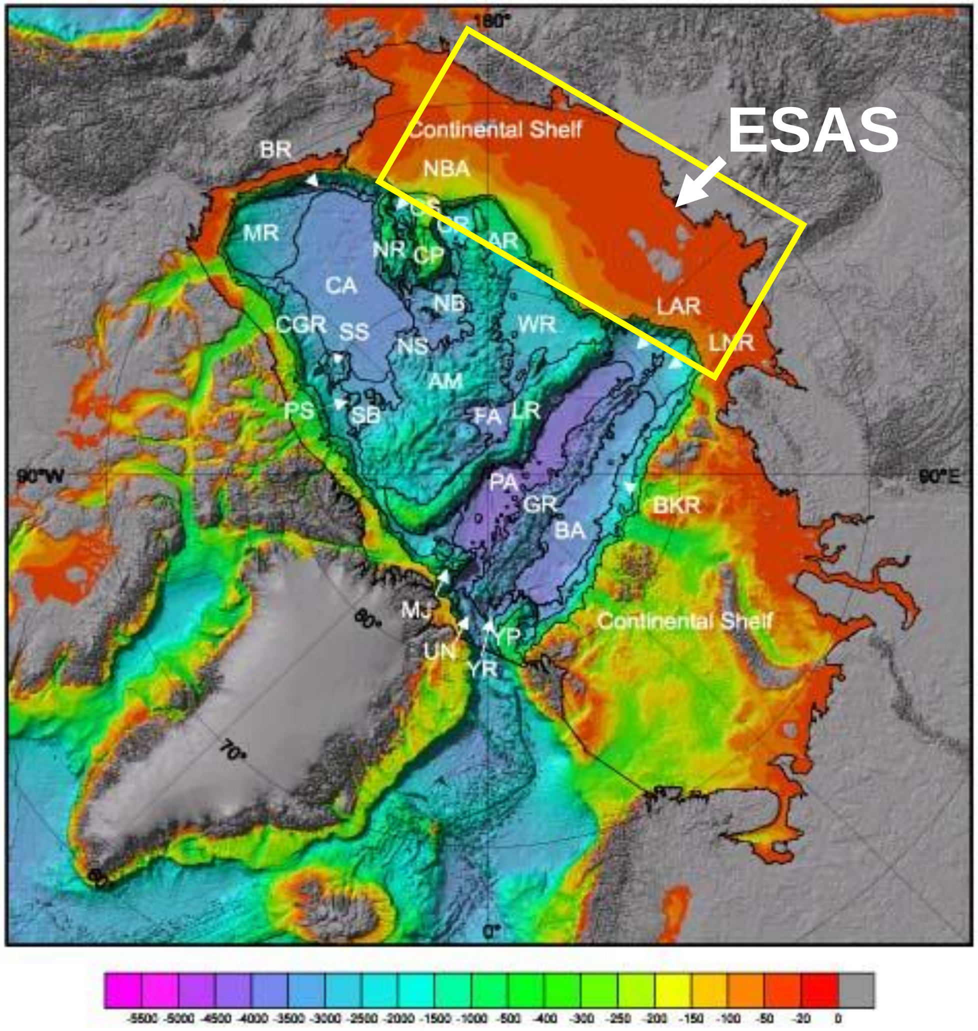
Three-dimensional representation of the latitudinal distribution of atmospheric methane in the marine boundary layer. Data from the Carbon Cycle cooperative air sampling network were used. The surface represents data smoothed in time and latitude. Contact: Dr. Ed Dlugokencky, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6228, ed.dlugokencky@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.



Global Distribution of Atmospheric Carbon Dioxide

NOAA ESRL GMD Carbon Cycle

Specific features of the study area

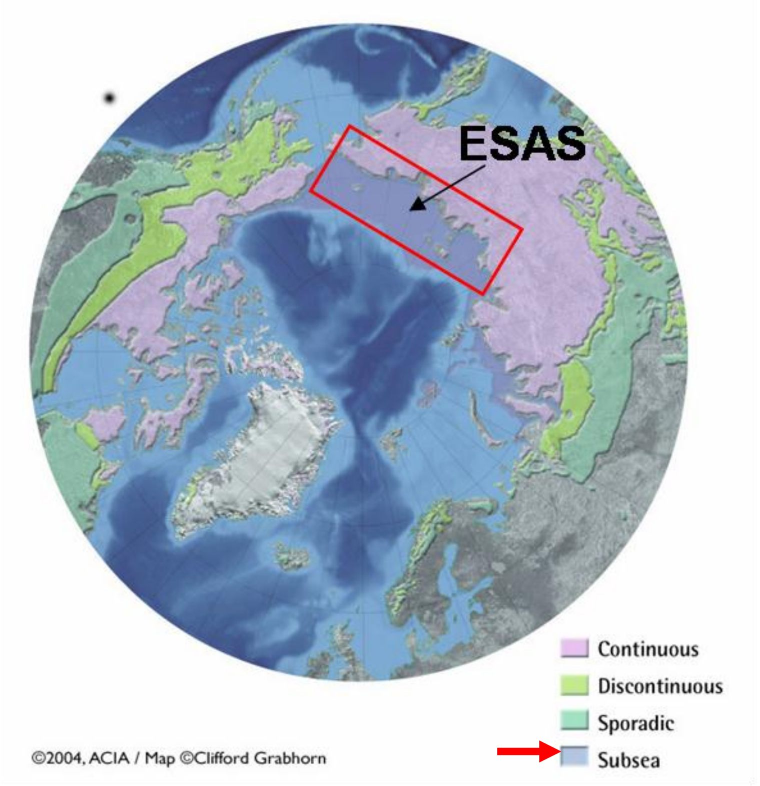


- The total area is **$2.1×10^6$ km^2** area **(~25%** of the Arctic Shelf, **~8%** of the World Ocean's continental shelf;

- **~75%** is shallower than **50 m** (mean depth of the continental shelf is **130 m**); sedimentary basins are up to **20 km** thick; C$_{org}$ content is up to **12%.**

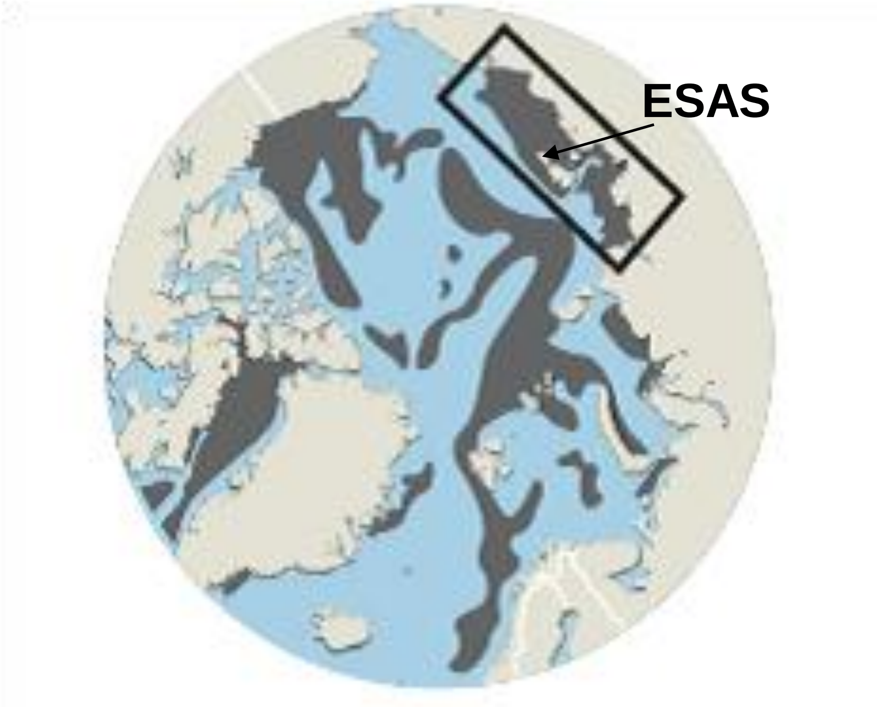
- shallowness determines alteration of dry position (cold epochs)/ submerged position (warm epochs), which occurs due to lea level fluctuation

Basic component of the ESAS environment is sub-sea permafrost



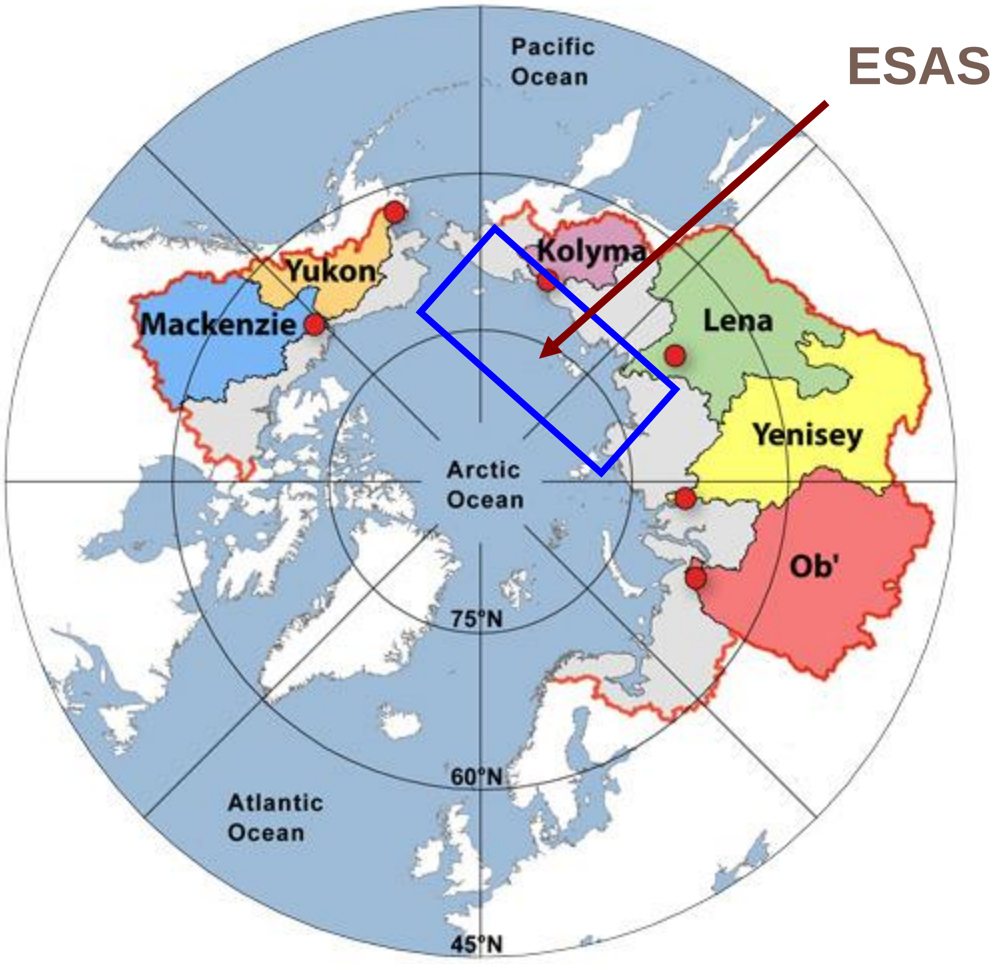
©2004, ACIA / Map ©Clifford Grabhorn

A) **80%** of the total area of sub-sea permafrost (shown in lilac) is in the ESAS;



B) Shallow hydrates underlain more than **80%** of the ESAS area (shown in grey).

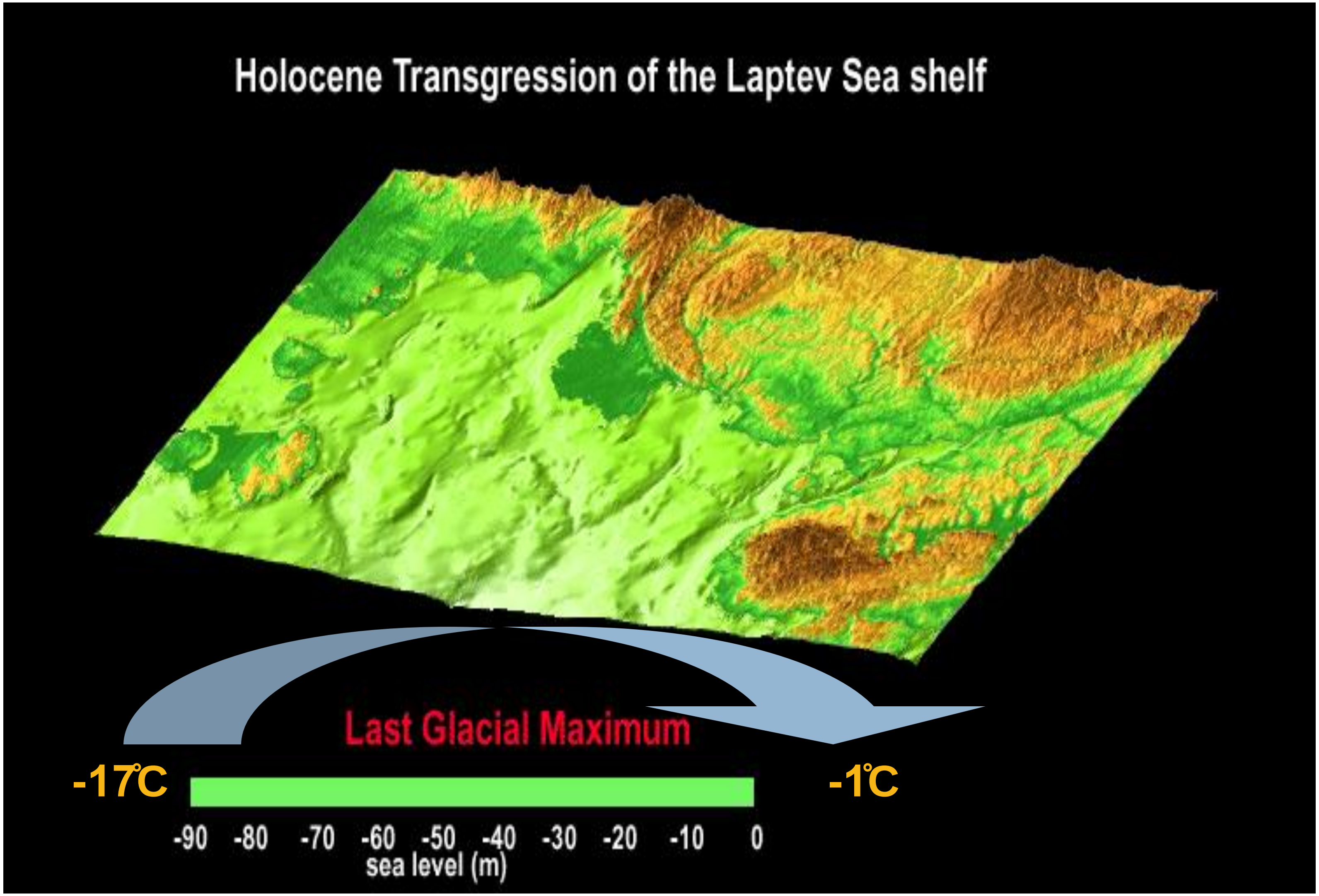
The ESAS accumulates fresh water from 6 Arctic Siberian Rivers and it is major ice factory of the Arctic Ocean



- 6 Siberian Rivers – Khatanga, Olenek, Lena, Yana, Indigirka and Kolyma bring their waters to the ESAS – $7x10^{11}$ m^3

- Total area of watershed of the Lena River alone is comparable with that of the ESAS ($2.5x10^6$) km^2

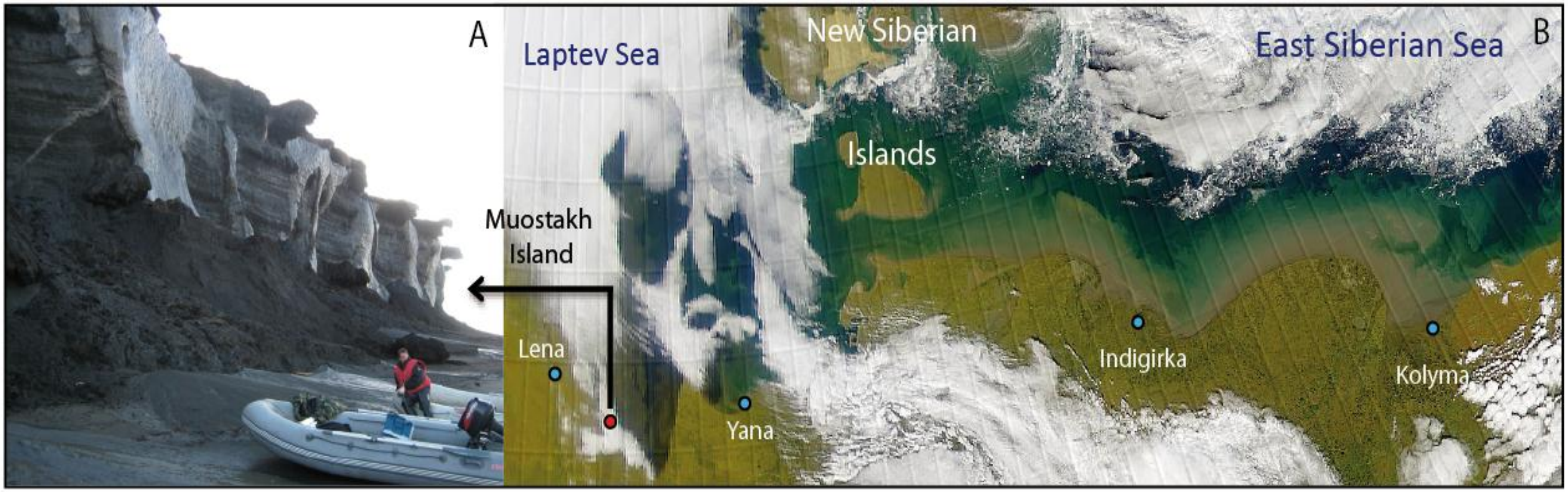
After inundation of the ESAS thermal regime of sediments changed dramatically.



-17℃

-1℃

Rates of coastal erosion are the highest in the World Ocean



Background and motivation

- Reported massive methane releases from shallow permafrost during exploration of Arctic natural sources in Russian Arctic (on-shore and off-shore);
- Discovery of natural hydrates by Makogon at al. in 1961; investigations of P/T conditions of GHSZ for Arctic hydrates (Ershov, Istomin, Yakushev et al. in 1980s-1990s);
- Hypothesizing of possible existence of hydrates out GHSZ due to self-preservation phenomenon (Yakushev, Chuvilin et al., 1990s);
- Modeling of subsea permafrost dynamics (Soloviev, Molochushkin, Fartyshev, Romanovskii, Shakhova and Nicolsky – 1980s-current);
- Observations of methane releases from subsea permafrost over the ESAS (Semiletov, Shakhova et al. - 2003-2007);
- Bringing up the topic to the international community (2007, Arctic Carbon Workshop in Seatle, ISSS, 2008 – current).

Scientific plan

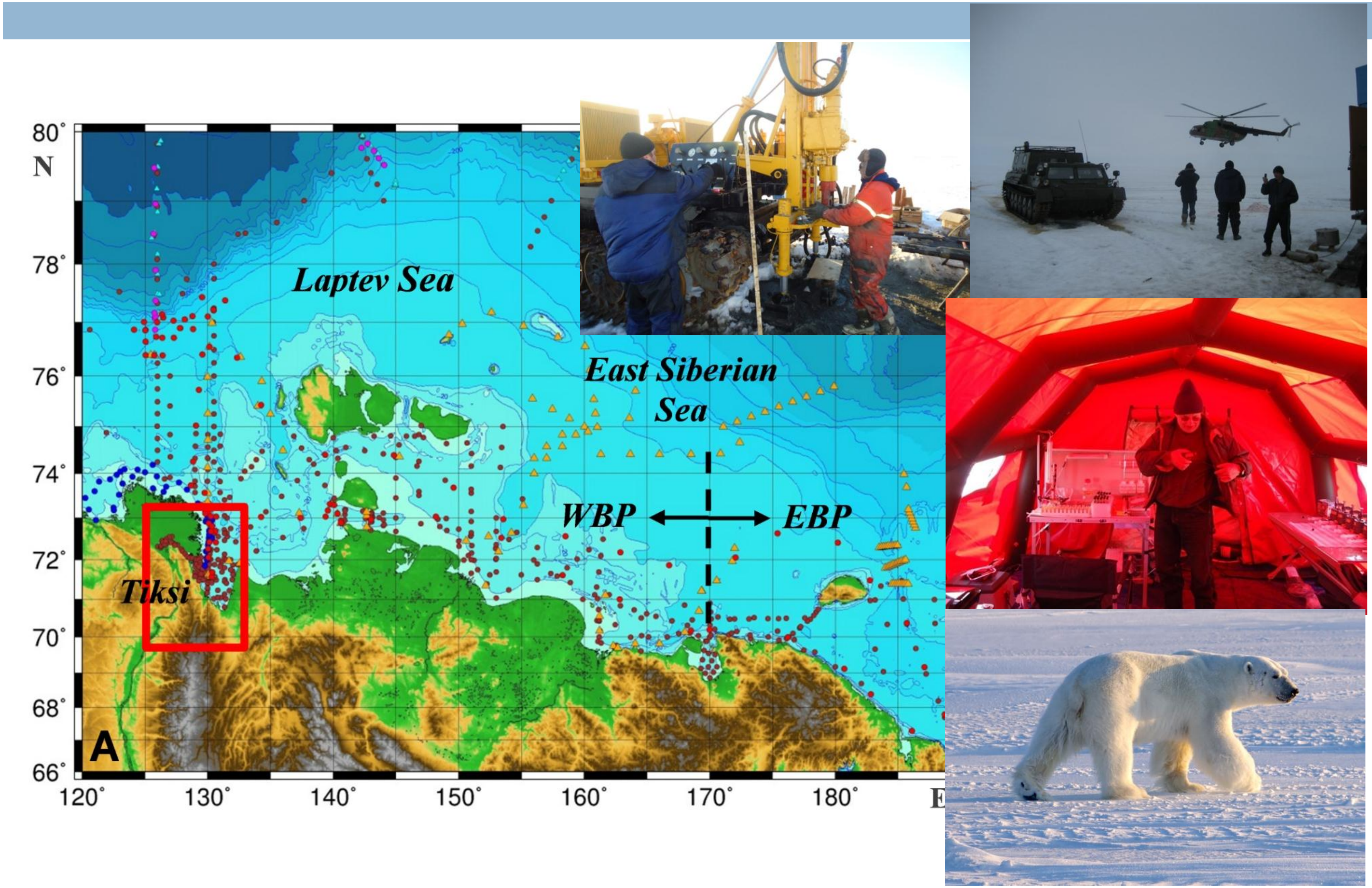
Central hypothesis: **Destabilization of subsea permafrost in the ESAS determines involvement of old carbon from thawed sediments and methane from seabed deposits (including hydrates) to the modern biogeochemical cycle increasing methane release to the water column and atmosphere.**

Goal: **Quantitative assessment of current and future emissions of methane from the ESAS**

Research areas:

1. Investigation of possible sources of methane and their contribution to methane releases in the ESAS;
2. Identifying major processes and factors controlling emissions;
3. Quantitative assessment of atmospheric fluxes;
4. Understanding future emissions.

<u>Accomplishment</u>: In total, ~30 all-seasonal expeditions, >2,000 oceanographic stations, >10,000 n. miles of geophysical survey, 15 deep-boreholes drilled



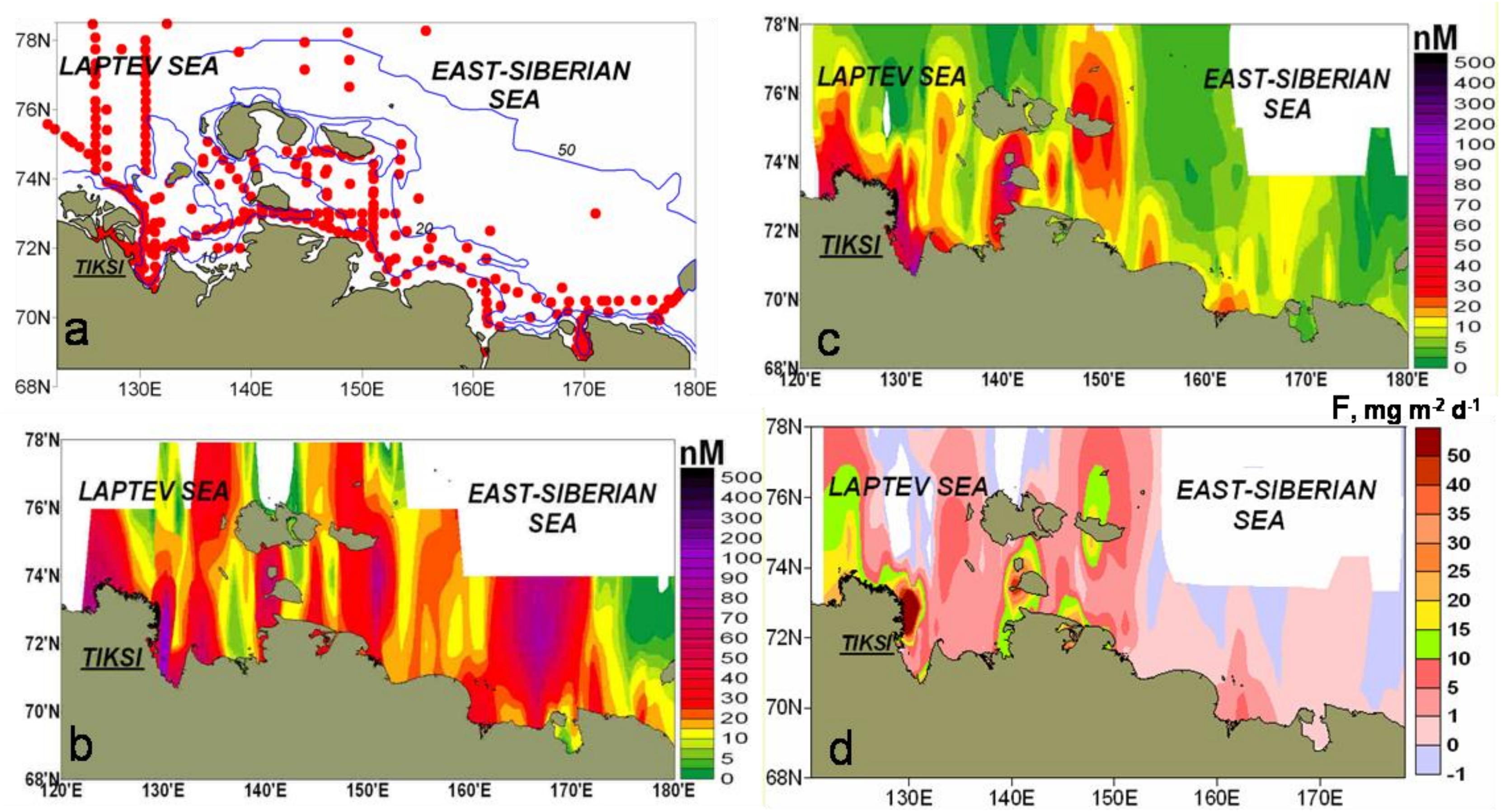
Study of methane cycling in the ESAS

Stage 1: Gaining the initial understanding of methane cycling in the ESAS

- Assessing the inventory of dissolved methane;
- Understanding of spatial and temporal variability of fluxes to the atmosphere;
- Initial assessment of the annual emission budget.

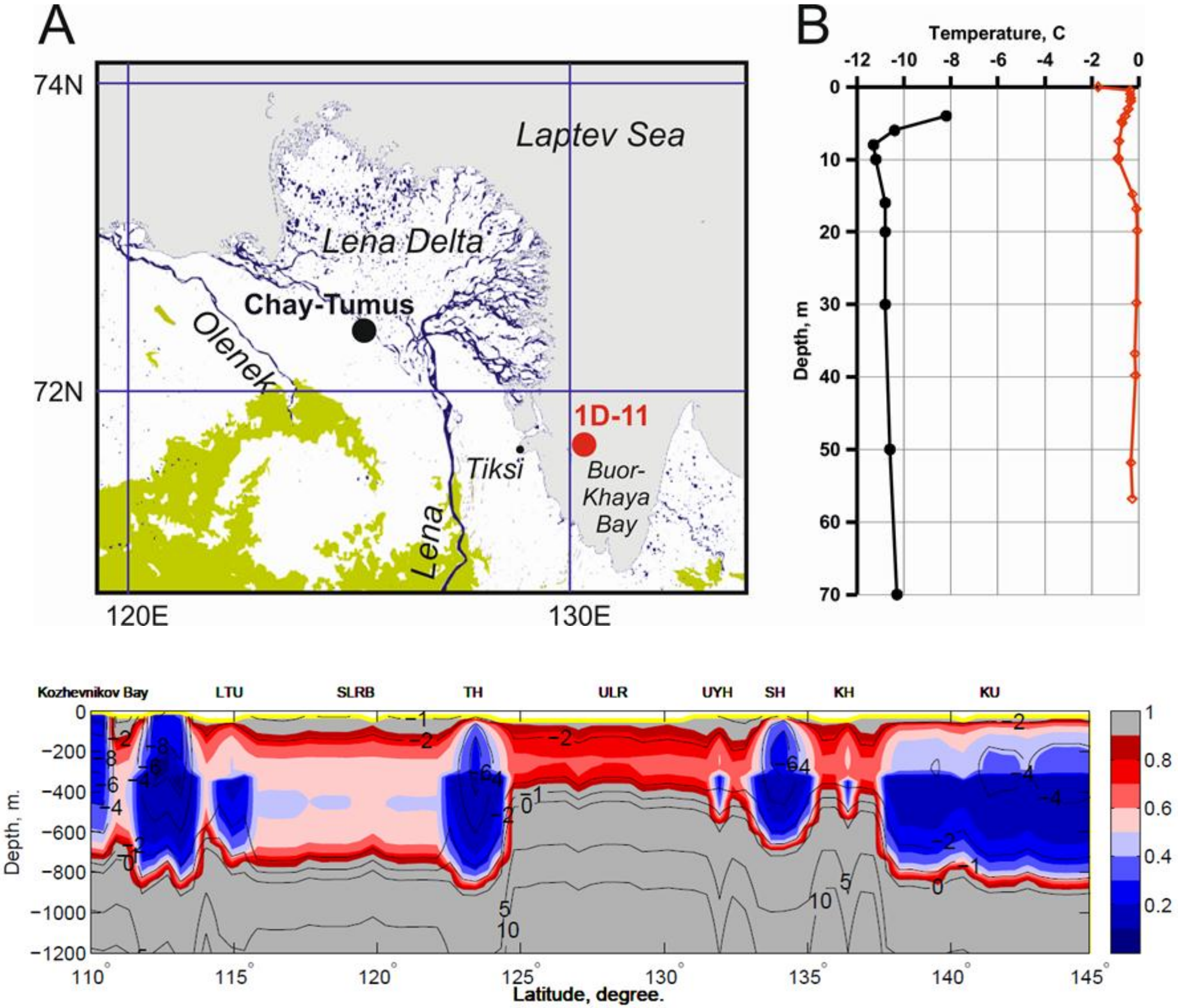
Key result 1: ESAS serves as a source of methane to the atmosphere

From Shakhova et al. (Science, vol.327, 5 March 2010)



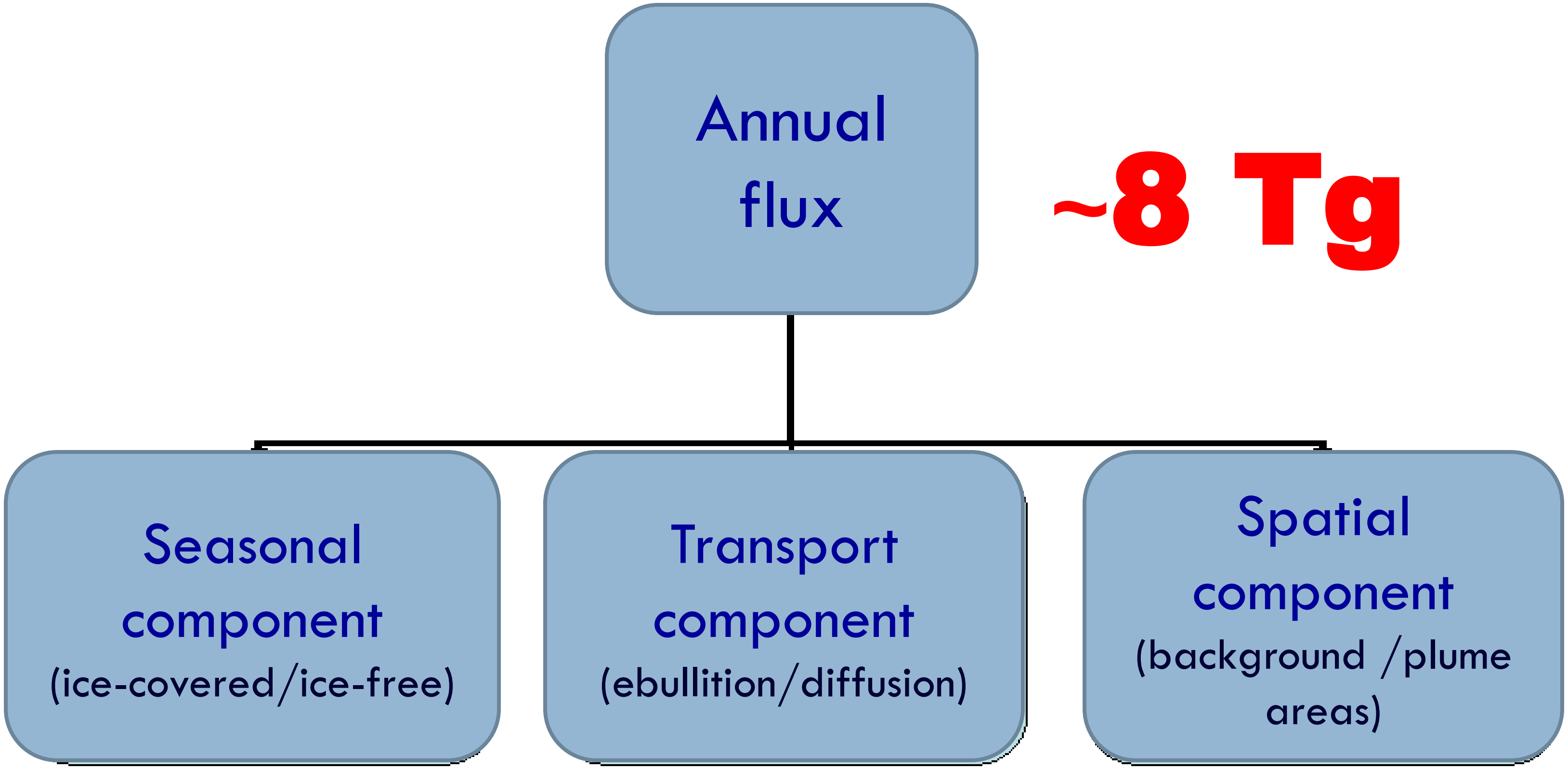
Mean flux: from background areas **3.67 mg/m^2/d**, from hot spots – **11.8 mg/m^2/d**

Key result 2: Disintegration of subsea permafrost is major factor driving methane emissions in the ESAS



- Thermal regime of subsea permafrost in the ESAS is up to 10°C warmer than thermal state of its terrestrial counterpart located just few miles away from the coast (A and B); this difference is determined by warming effect of seawater and other factors specific for the ESAS.
- Disintegration of subsea permafrost manifests as formation of taliks (layers or columns of thawed sediments throughout permafrost body, shown in blue on panel C). Taliks first form where subsea permafrost was submerged for longest (outer shelf, depth >50 m). In the shallow part (depth <50 m), taliks form in the areas underlain with fault zones, covered with submerged thaw lakes and influenced by warming effect of rivers.

Key result 3: Annual budget based on results of indirect estimates is equals to 8 Tg



Annual flux

~8 Tg

Seasonal component (ice-covered/ice-free)

Transport component (ebullition/diffusion)

Spatial component (background /plume areas)

27.4% и 72.5%;

41.9% и 58.1%;

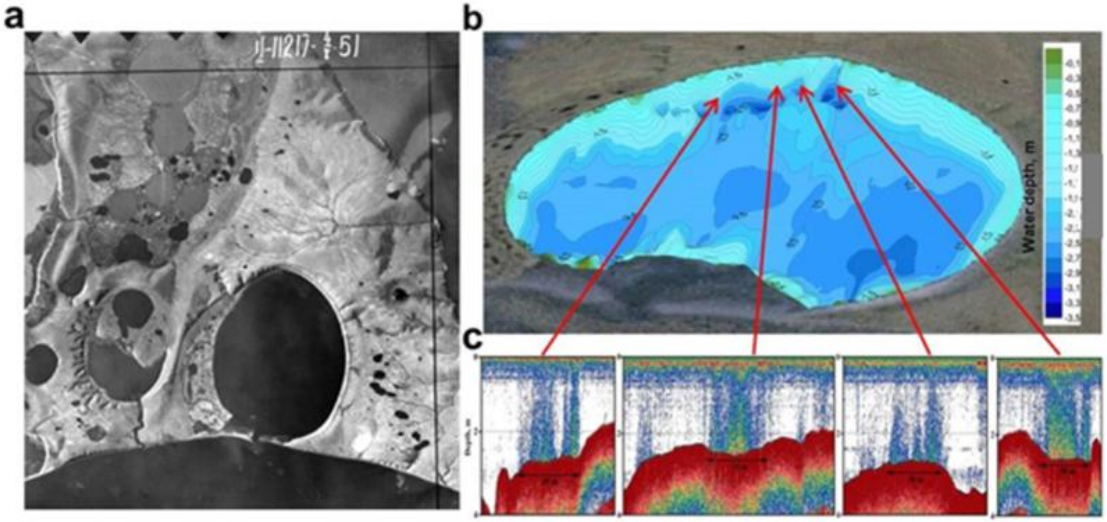
30.3% и 69.7%

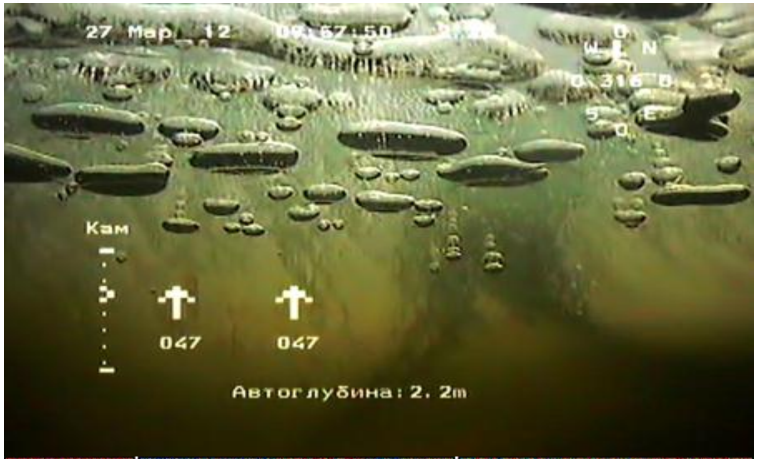
Stage 2: Digging deeper

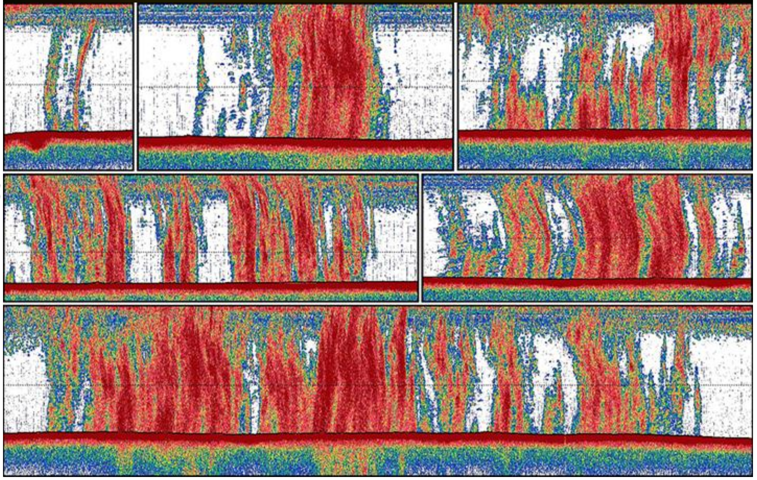
- Understanding factors controlling methane emissions;
- Establishing methods to assess bubble-induced fluxes;
- Understanding the sources of methane and their contribution to the methane cycling in the ESAS;
- Update of the annual methane budget of the ESAS;
- Contribution to the regional emissions.

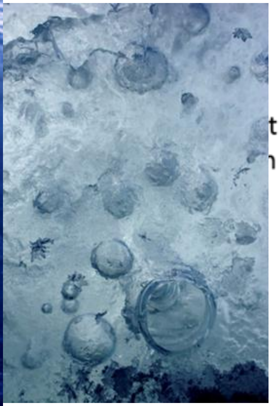
Key result 4: Bubble-induced fluxes is a predominant contributor to methane releases in the ESAS

On the shallow shelf



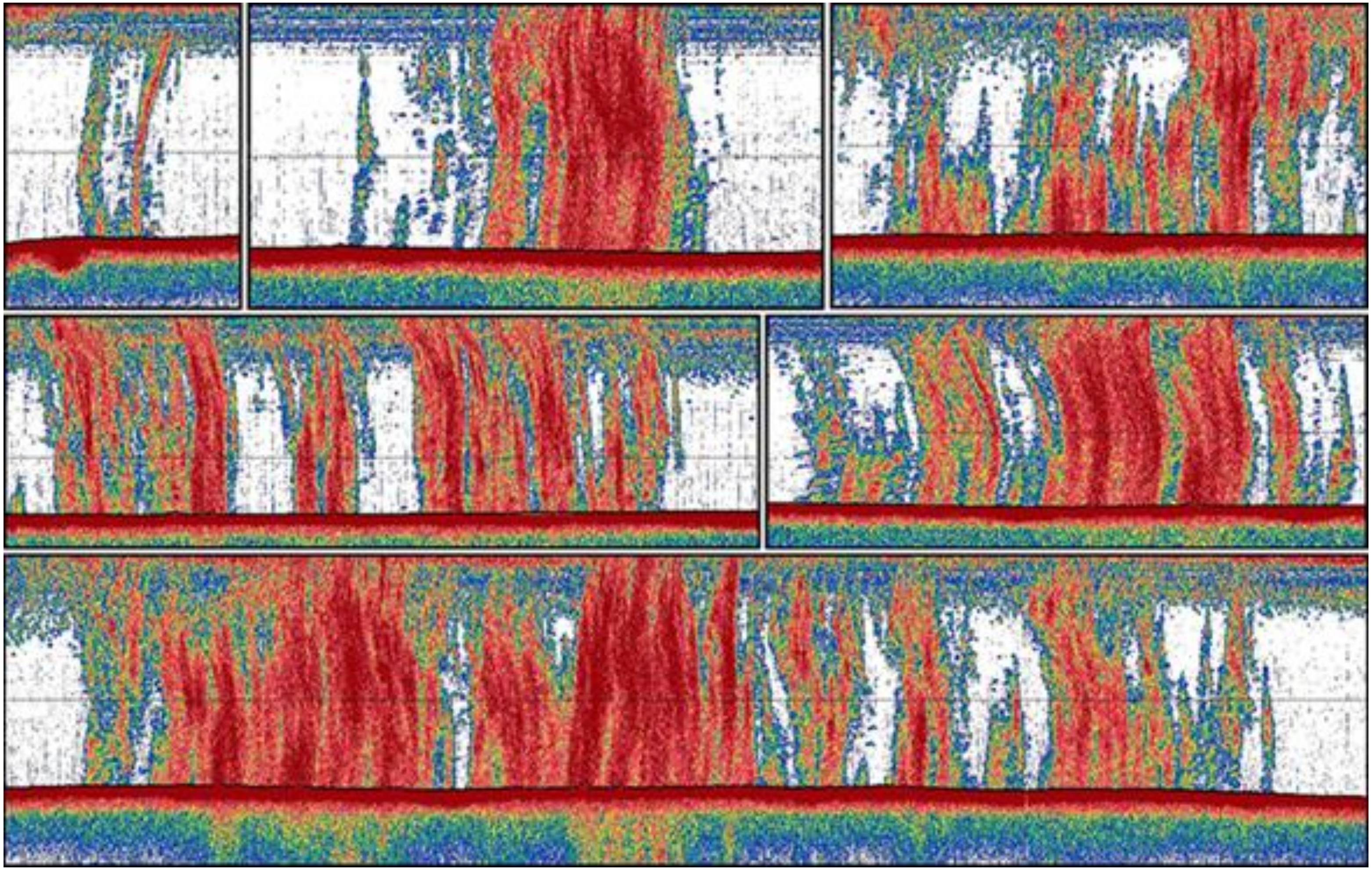




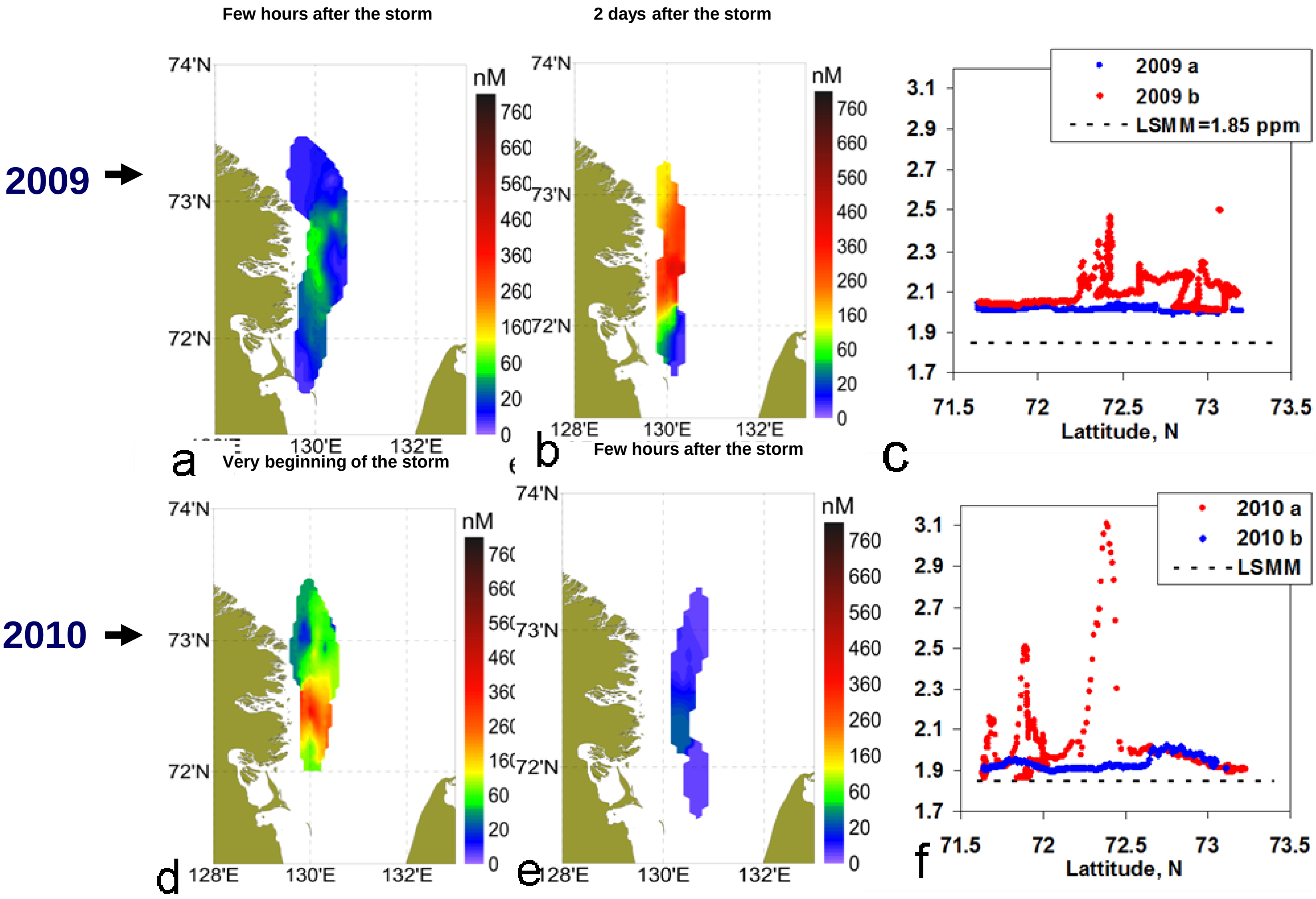


Key result **4**: Bubble-induced fluxes is a predominant contributor to methane releases in the ESAS

and on the outer shelf



Key result 5: Wind-driven mixing of the water column is an efficient factor driving methane emissions in the ESAS



Key results 6: Ice scouring provides an efficient mechanism for methane escape through the upper sediment layers

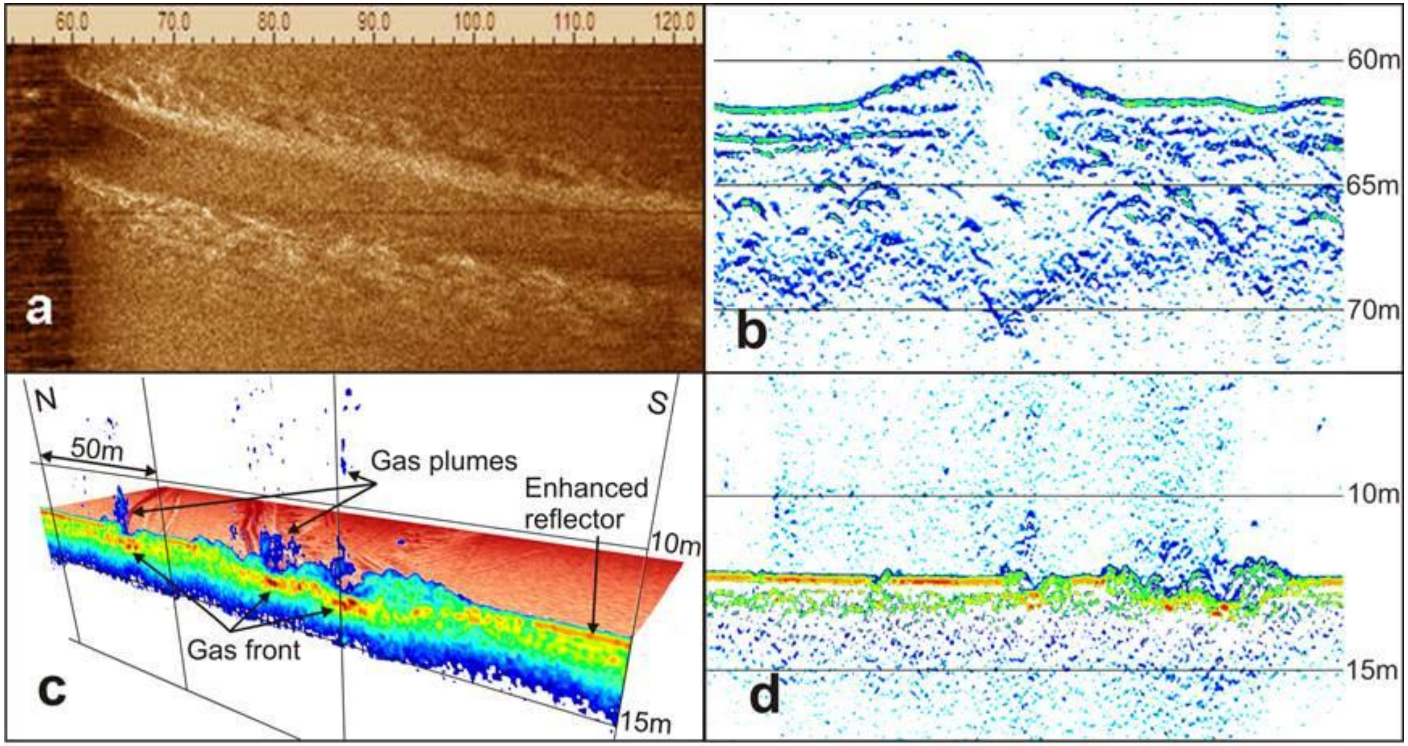
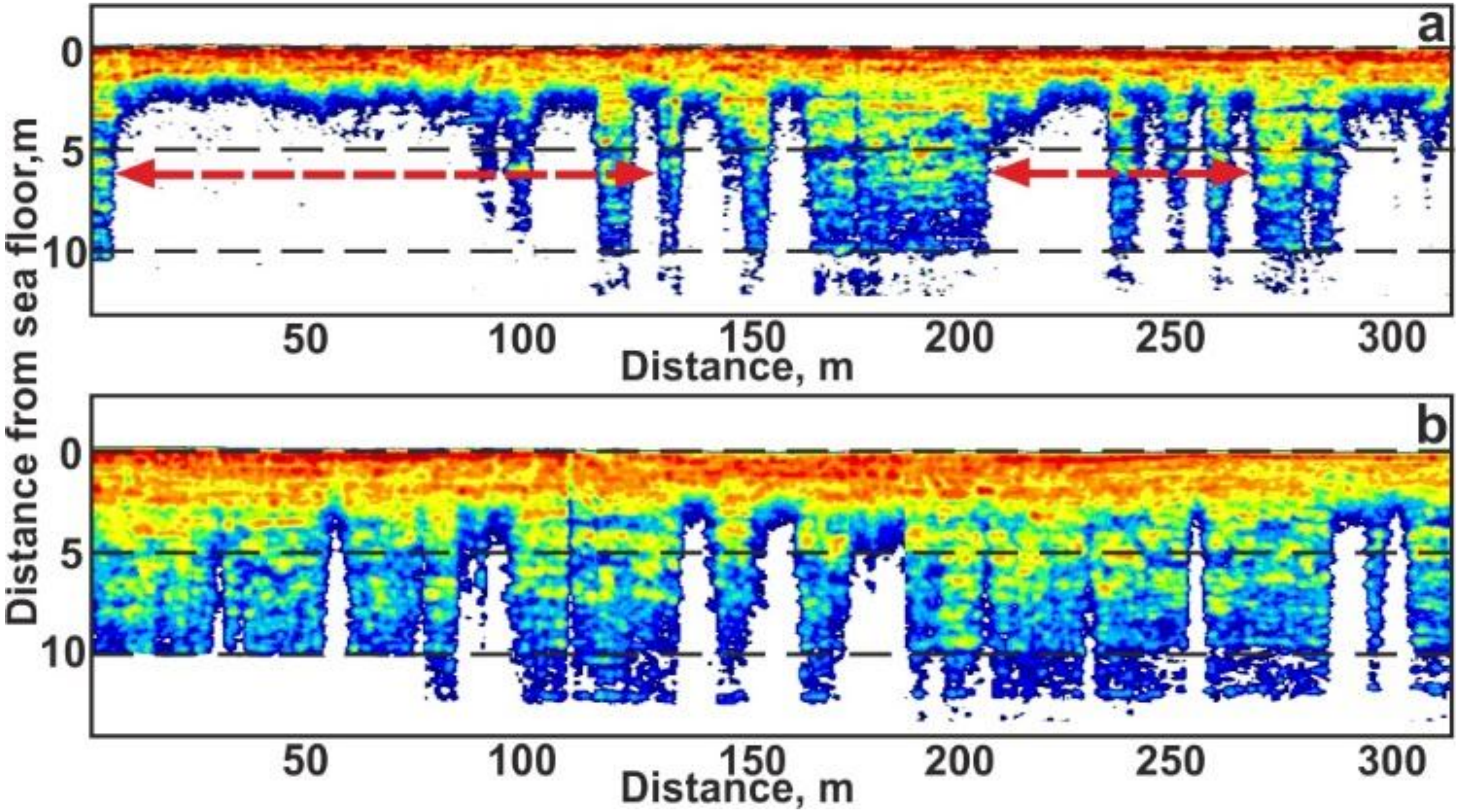


Figure 4 | Example of high-resolution seismic ice-scour images observed in the ESAS.

a) Backscatter image showing relative size of the ice scouring scar on the sea floor. **b)** vertical profile of the ice-scouring scar demonstrating penetration as much as 8 m into the sediment. **c)** 3D perspective view of ice scouring as a mechanism providing a gas migration pathway for shallow gas to escape to the water column. **d)** hydro-acoustical image of gas release due to ice scouring .

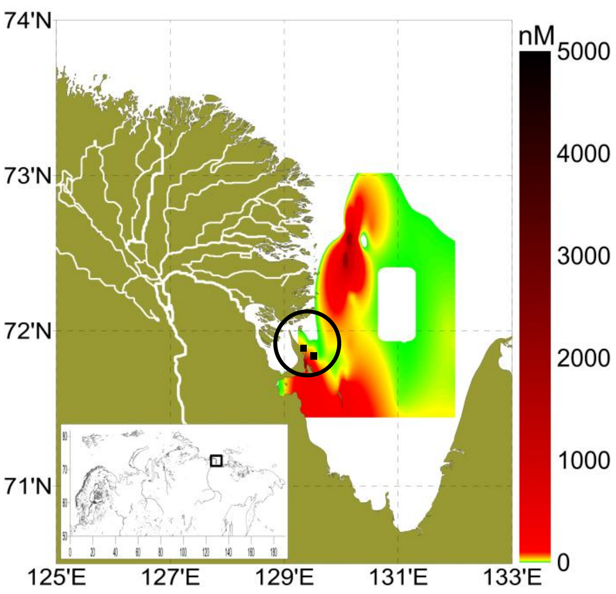
Key result 7: Gas front moves through the sediments at speed of few meters per year

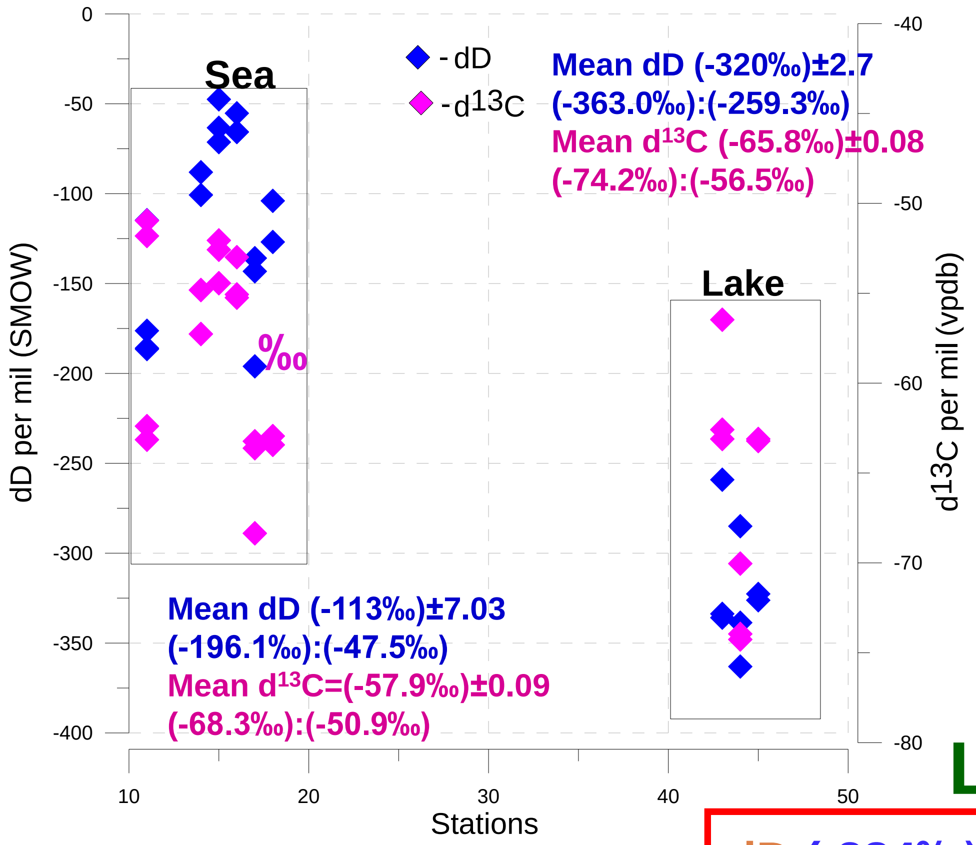


Key result 8: Isotopic signature of dissolved/bubble-borne methane suggests contribution of different sources

Sea

dD (- 57‰):(-325‰)
d^{13}C (-35.9‰):(-109‰)
14C (0-96% mC)





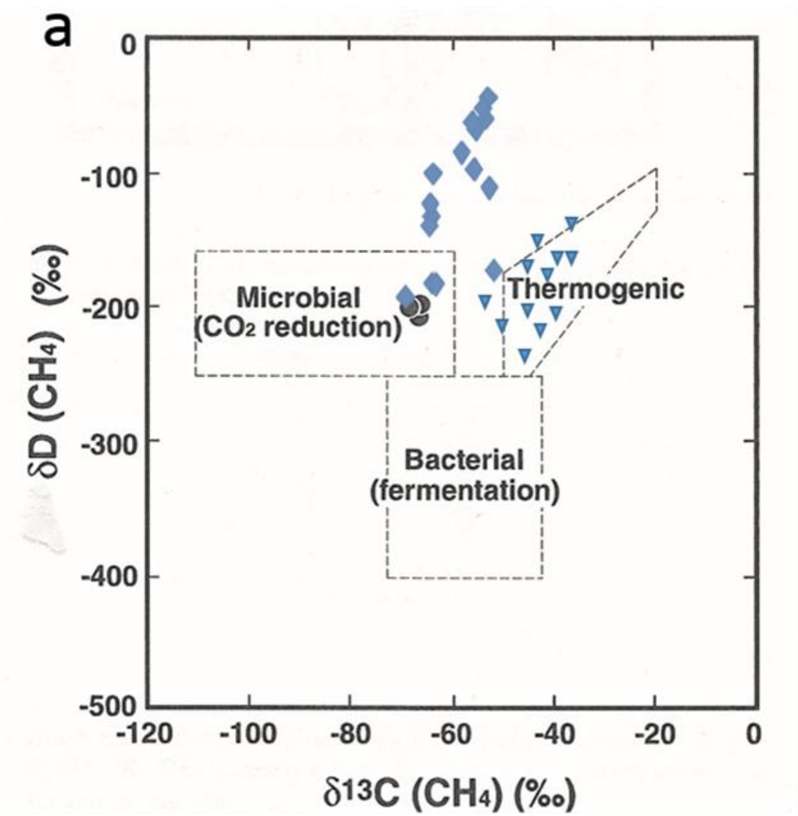
Mean dD (-320‰)±2.7
(-363.0‰):(-259.3‰)
Mean d^{13}C (-65.8‰)±0.08
(-74.2‰):(-56.5‰)

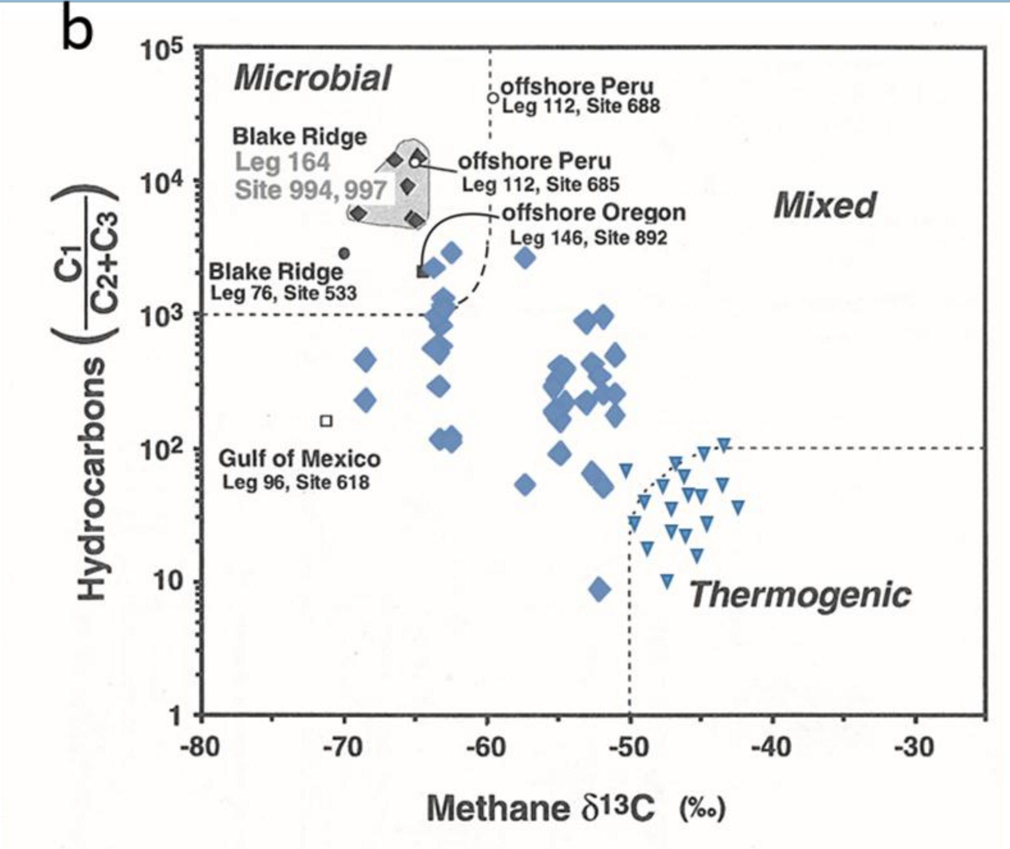
Mean dD (-113‰)±7.03
(-196.1‰):(-47.5‰)
Mean d^{13}C=(-57.9‰)±0.09
(-68.3‰):(-50.9‰)

Lake

dD (-284‰):(-363‰)
d^{13}C (-62.8‰):(-74‰)
14C (16-88% mC)

Key result 9: Isotopic signature of methane suggests involvement of hydrates shelf wide.

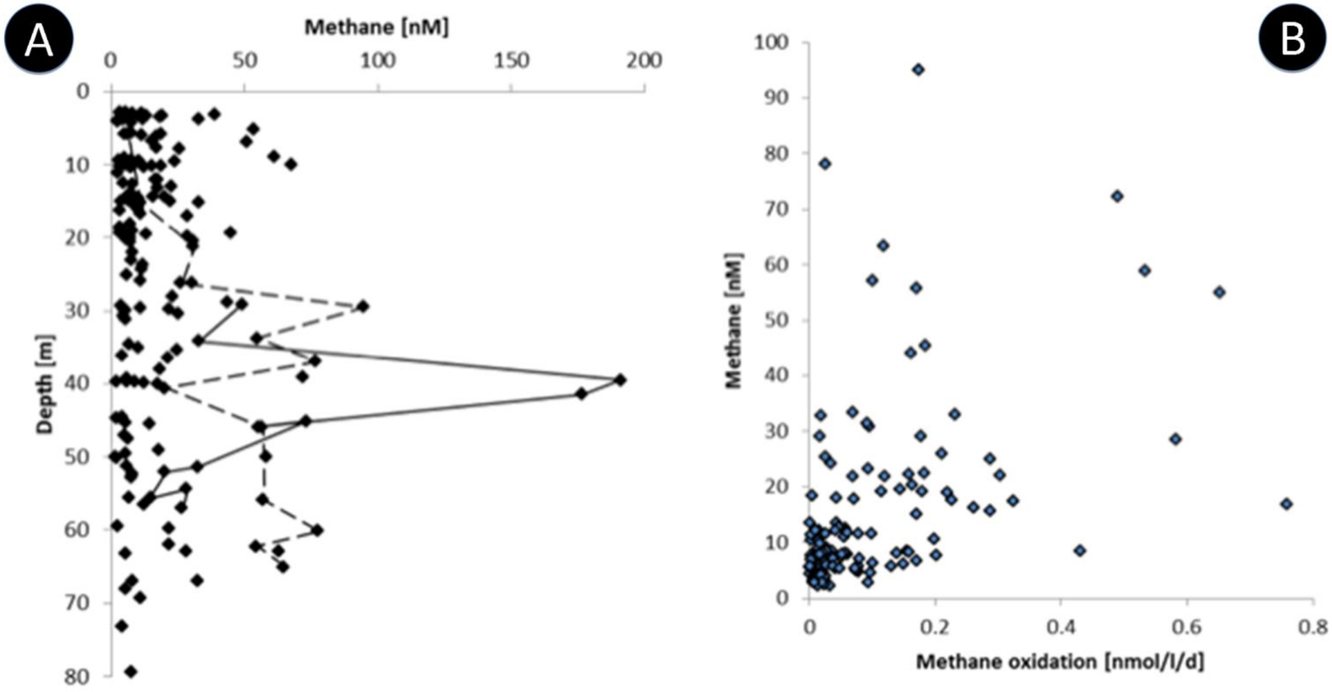




A) Interpretive plot of molecular ratios of hydrocarbons vs. carbon isotope composition of CH_4 in hydrates recovered from different locations (from Matsumoto et al., 2000) – data from the ESAS shown as blue rhombuses);

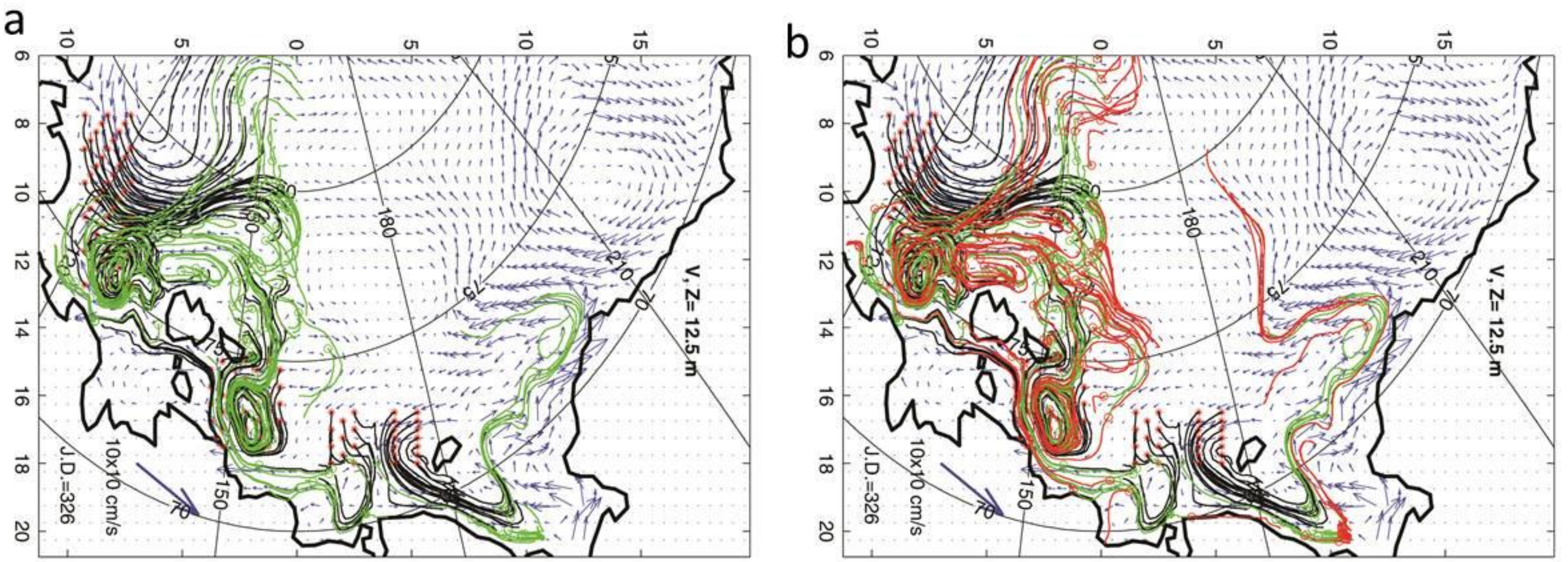
B). Interpretive plot of hydrogen and carbon isotope compositions of CH_4 in gas hydrates recovered on leg 164, Blake Ridge (from Matsumoto et al., 2000) – shown as black circles and methane from the ESAS (shown as blue rhombuses)

Key result 10: Turnover time of dissolved methane in the water column further from the river deltas comprises hundreds to thousand of years.

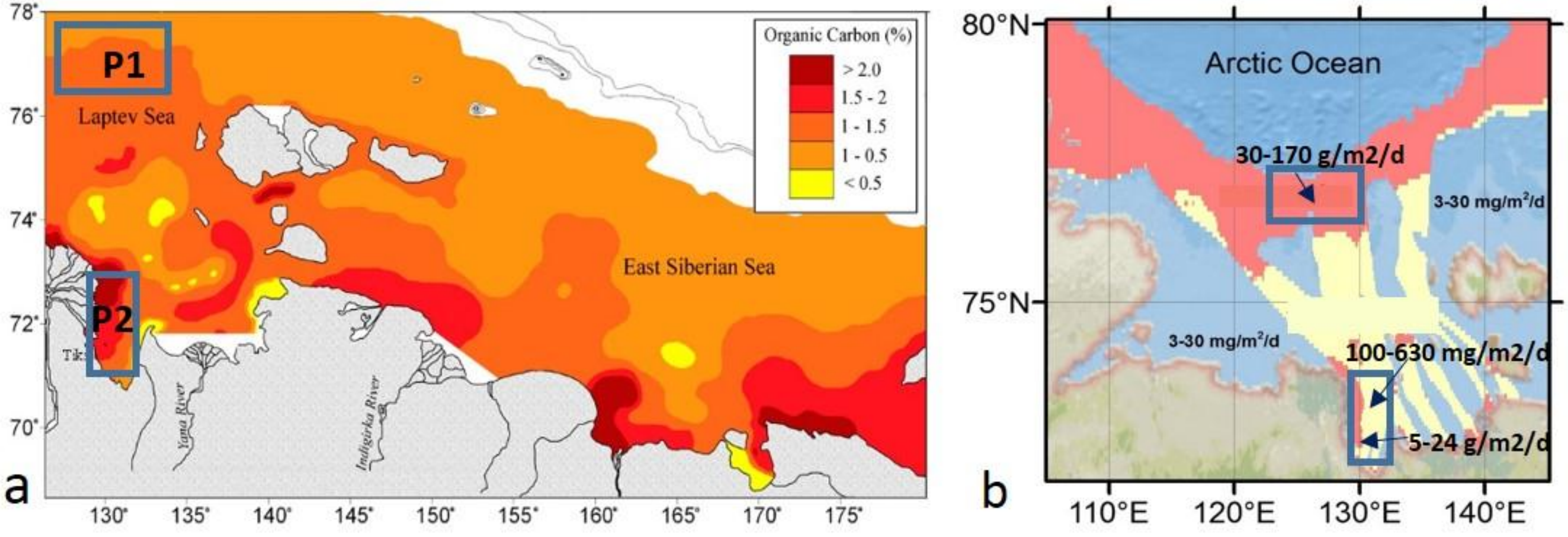


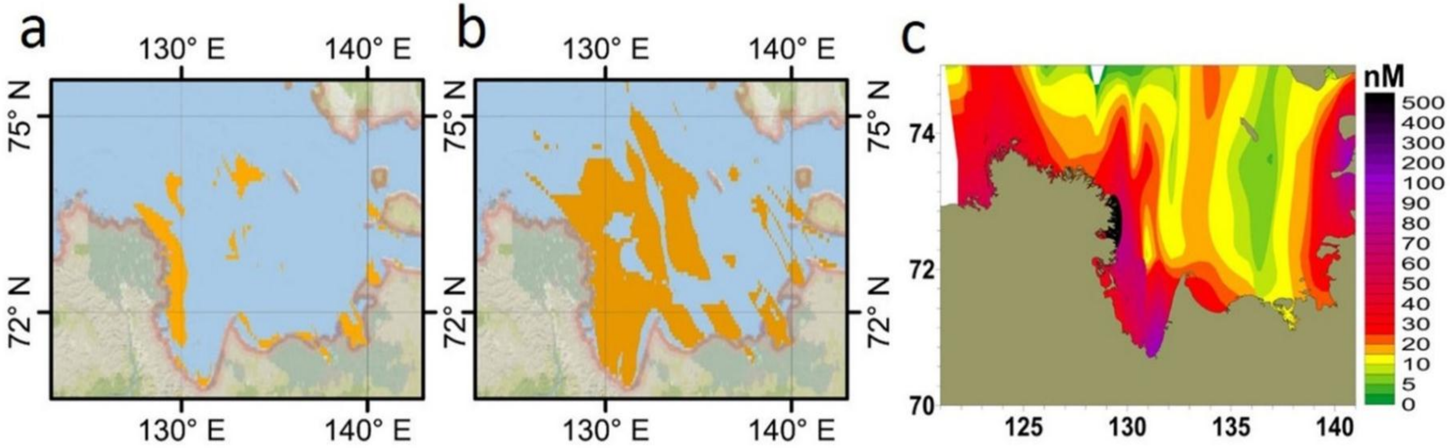
Methane oxidation rates determined with tritium-labeled methane tracer, were ranging from 10's of picomoles per liter per day to 3 nM per liter per day. The turnover time for the methane pool was estimated from *hundreds to thousands days*. ***This points to insufficiency of the microbial bio-filter in the ESAS waters*** *(M. Joye et al., AGU-2011 GC418-0808; 2 papers submitted).*

Key result 11: Methane from the ESAS can potentially be released to the atmosphere further from the ESAS due to lateral transport.

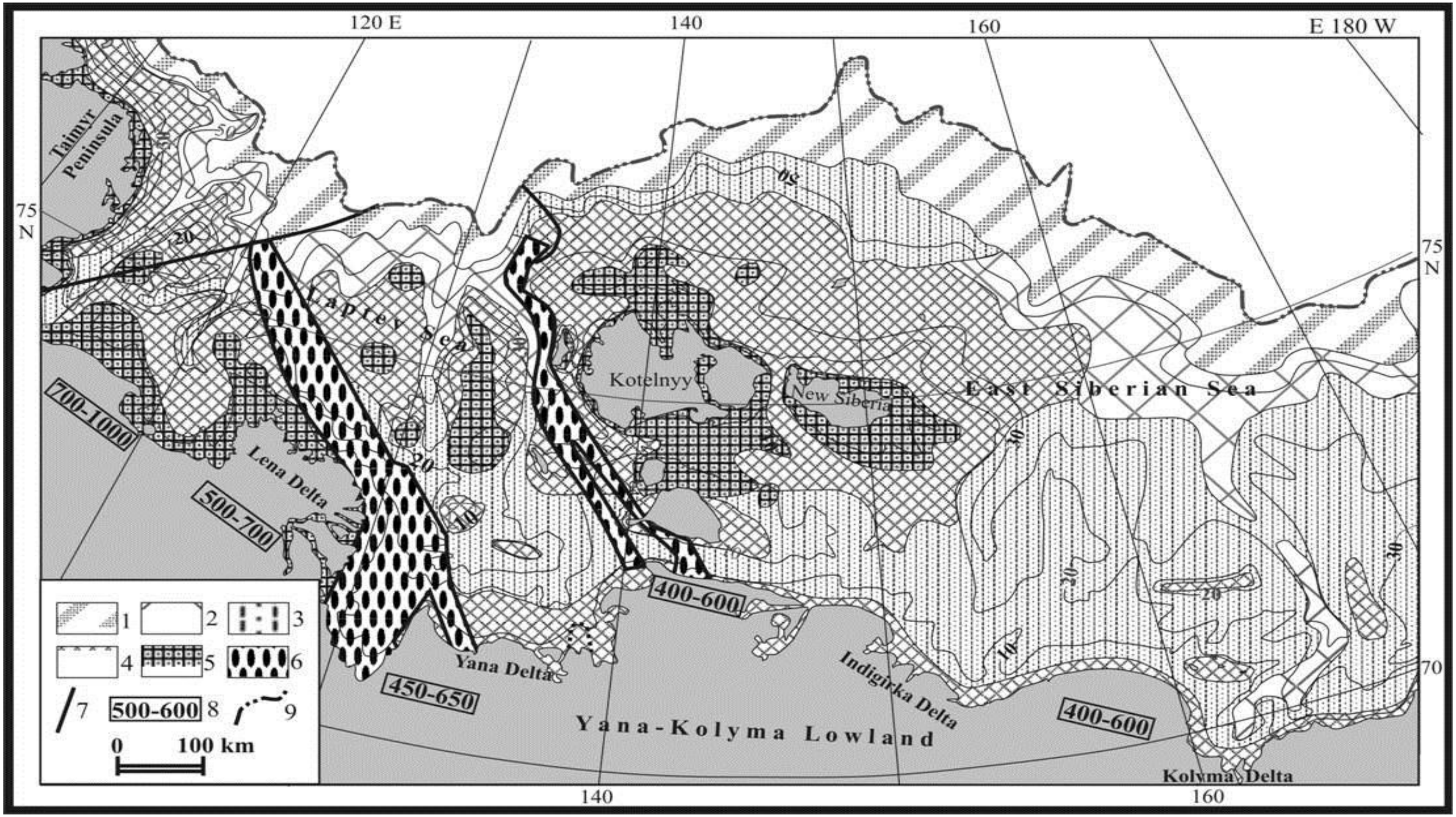


Key result 12: Area of taliks could lay a basis for spatial extrapolation of fluxes over the ESAS



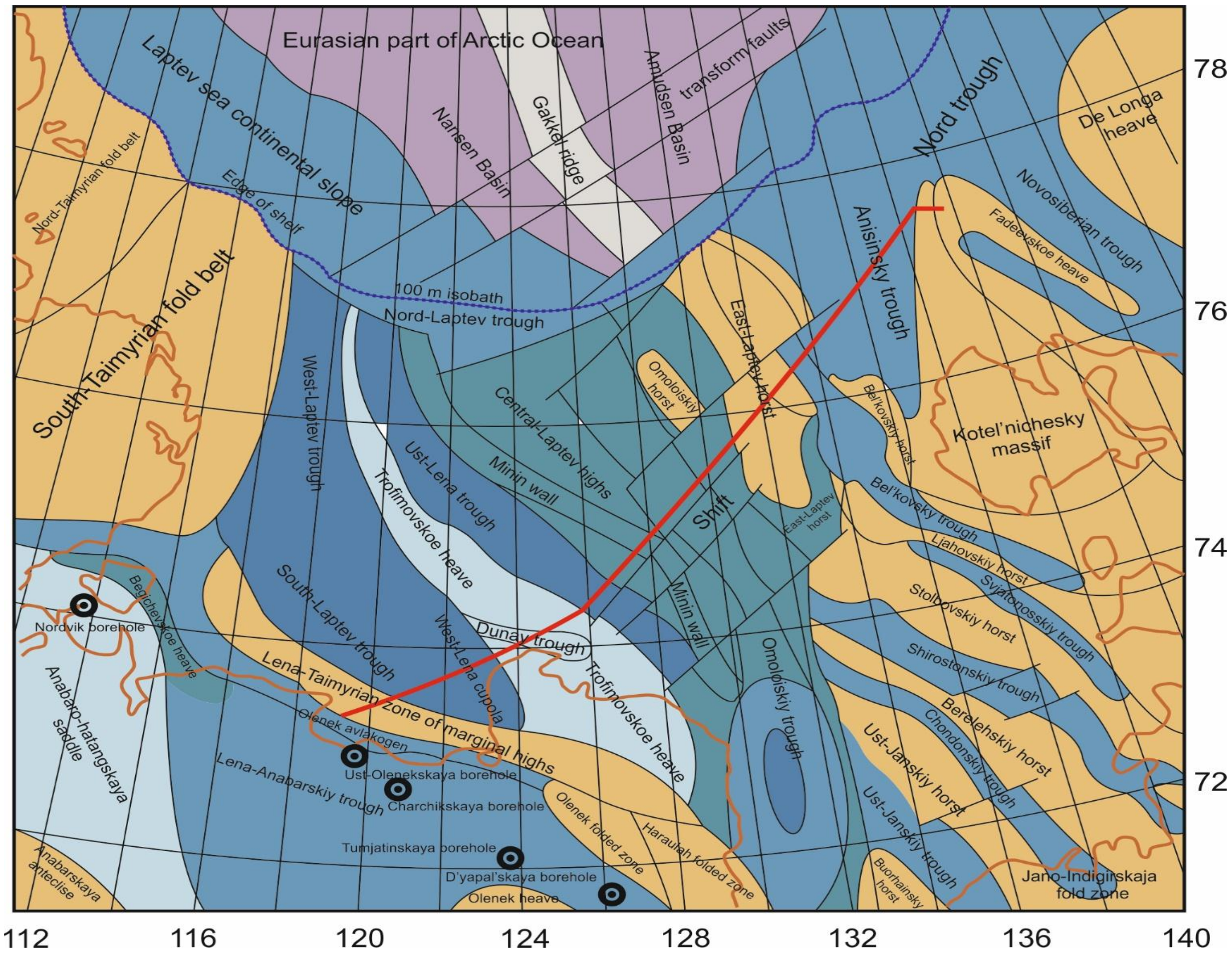


Stage 3: Understanding current state of subsea permafrost and gas migration pathways



Results of sub-sea permafrost modeling (*Romanovskii et al., 2005*)

Complexity of geological structure



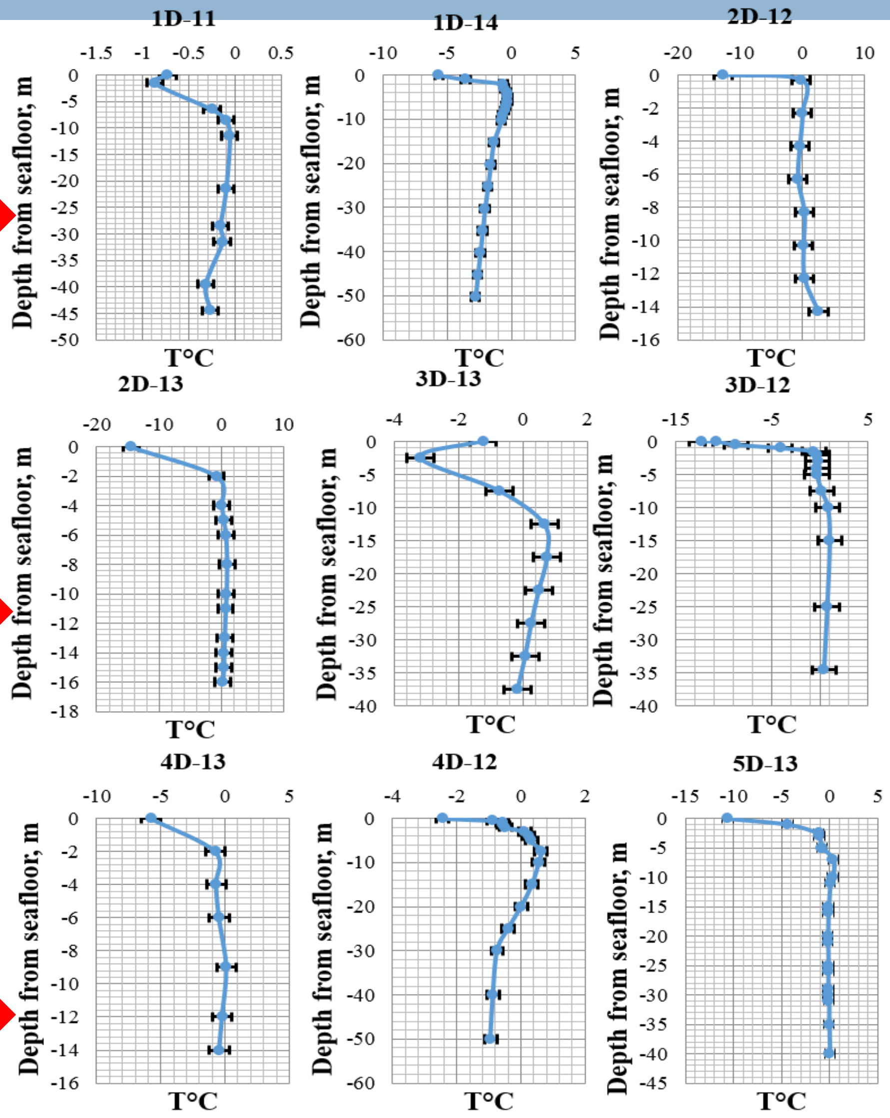
Key result 13: Current state of subsea permafrost is much warmer than was thought before, even in the near-shore area submerged recently (<200 years ago).

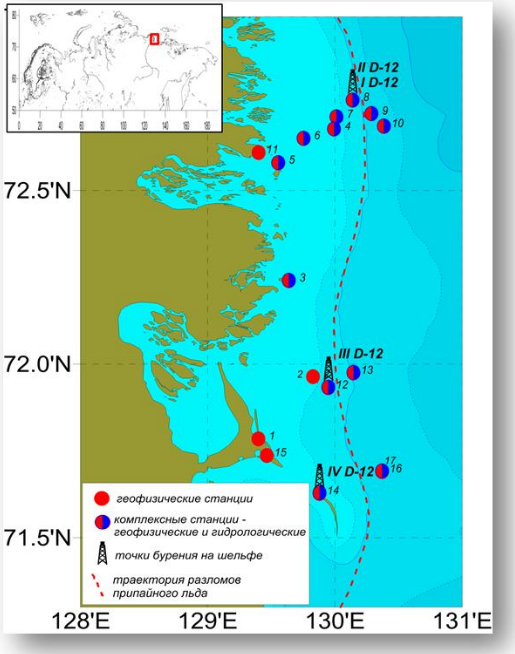
Water+ice depth:

12 m

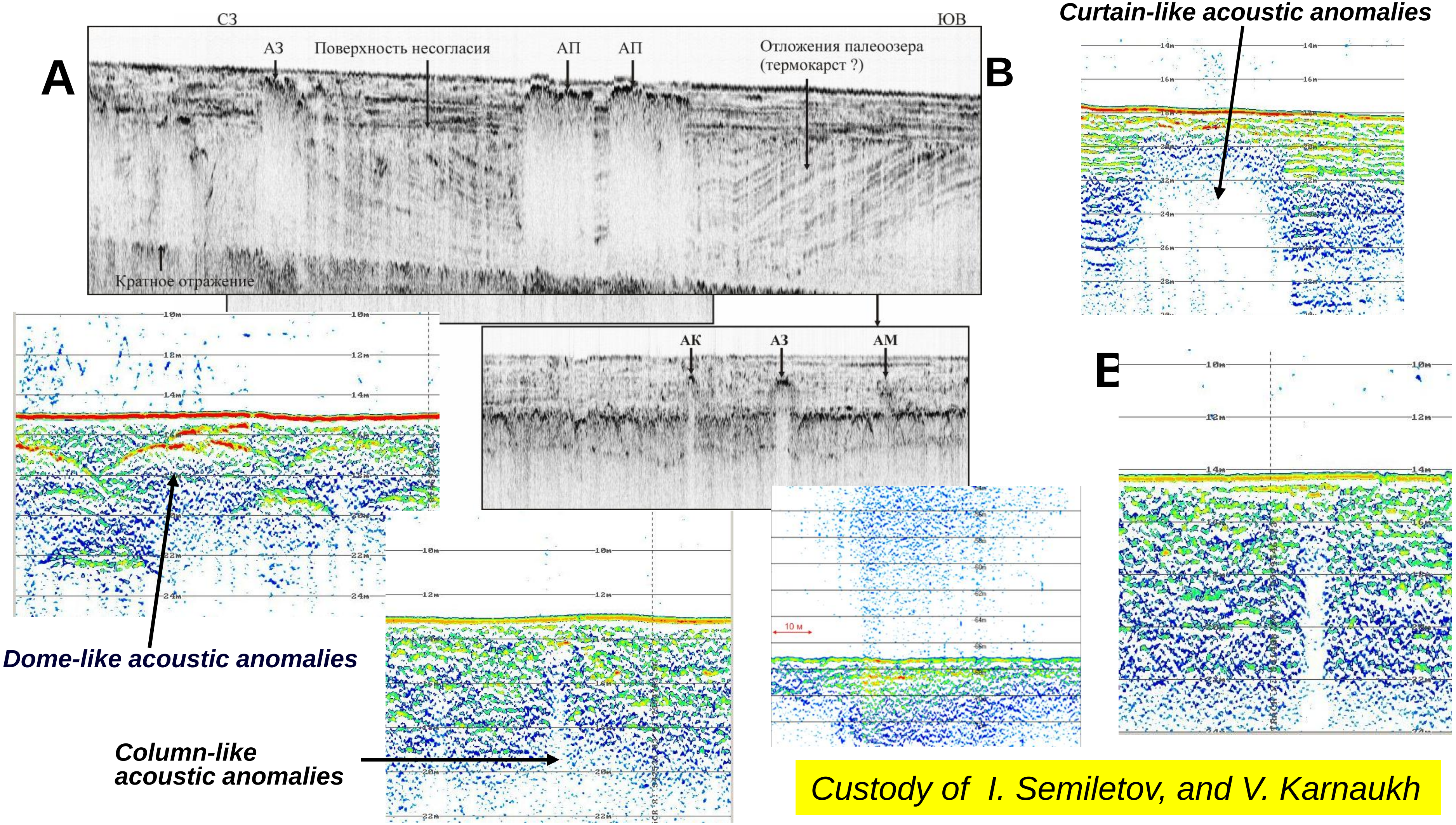
2 m

2 m





Key result 14: Existence of gas migration paths manifests as acoustic anomalies within sediments.



Curtain-like acoustic anomalies

Dome-like acoustic anomalies

Column-like acoustic anomalies

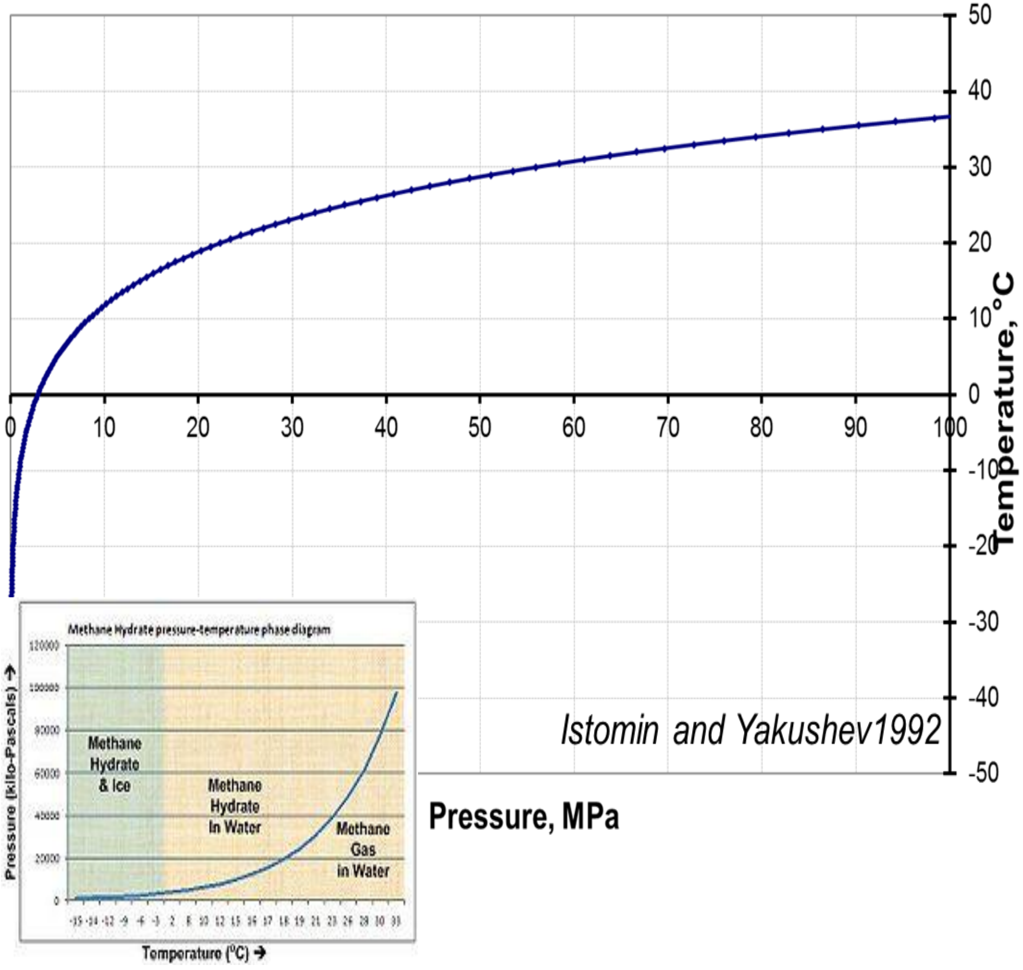
Custody of I. Semiletov, and V. Karnaukh

Stage 4: **Understanding current and future emissions**

- Comparison emissions from different areas of the ESAS as representing fluxes from areas with different **methane potential;**
- Comparison emissions from different areas of the ESAS (outer-shelf, mid-shelf and inner-shelf) as representing **different stages of sub-sea permafrost degradation** and gas pathways formation.
- (to be continued)

Misunderstanding 1. GHSZ in the oceans only exists where the water depth is ≥300 m; thus, GHSZ on the shallow ESAS can not exist, because water is too shallow.

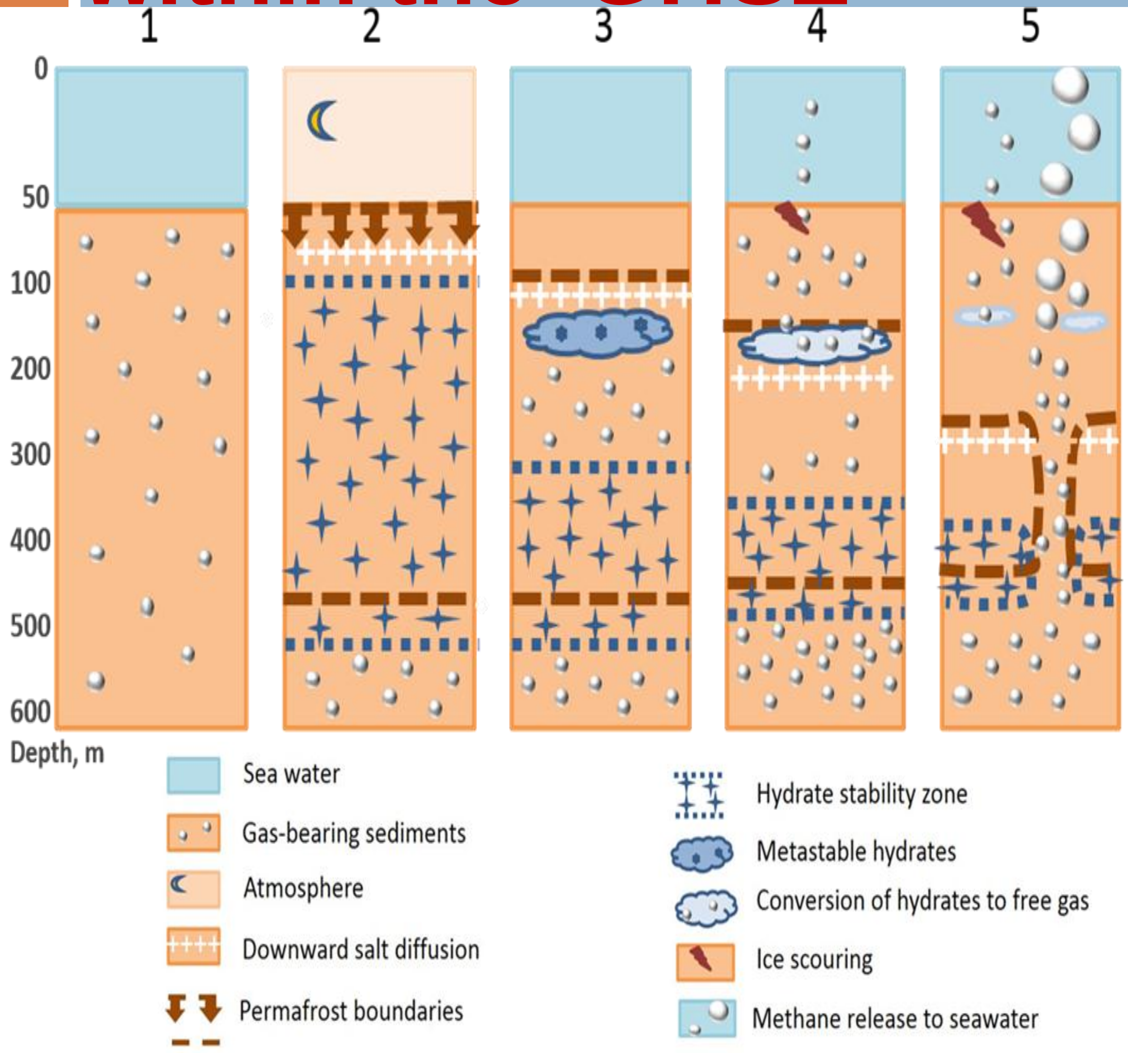
$GHSZ = CH_4 + T + P$



Istomin and Yakushev1992

- Pressure and Temperature (P/T) conditions are pared with each other - they are inter-related;
- The lower the temperature, the lower pressure required; lack of hydrostatic pressure could be compensated by geostatic pressure; 1 atm of hydrostatic pressure equals to 0.5-0.75 atm of geostatic pressure as density of the ground is ~1.5-2 times greater;
- P conditions could be determined by sum of hydrostatic and geostatic pressure, which allows the upper boundary of GHSZ to exists at some depth below the seafloor;
- Growing ice crystals developing during freezing of the ground

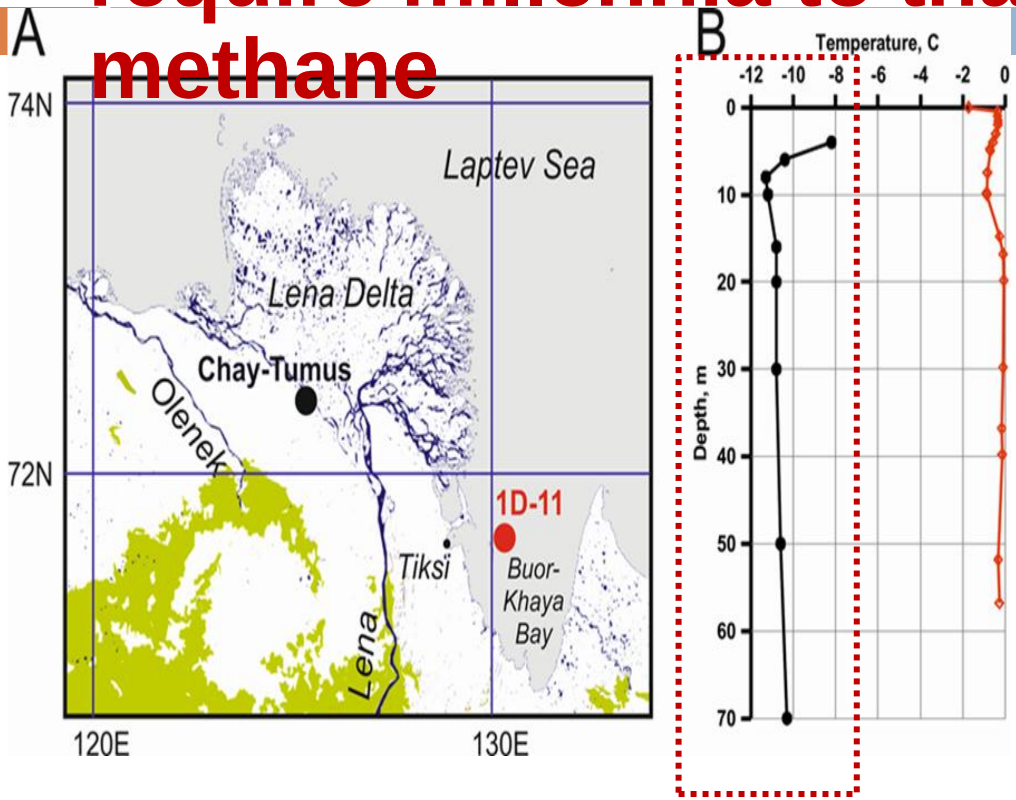
Misunderstanding 2: Methane hydrates can only exist within the GHSZ

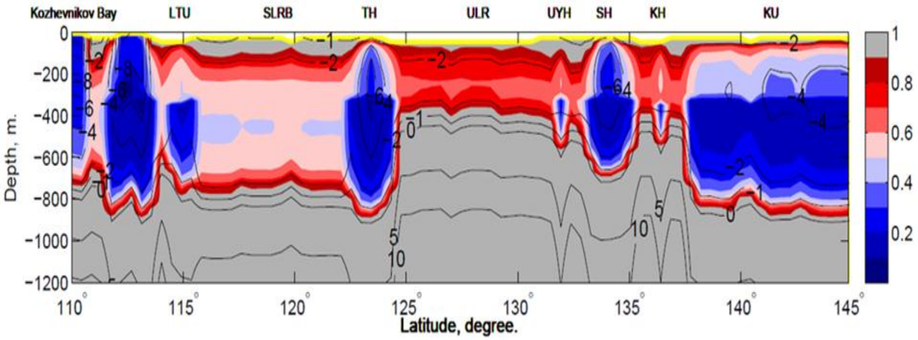


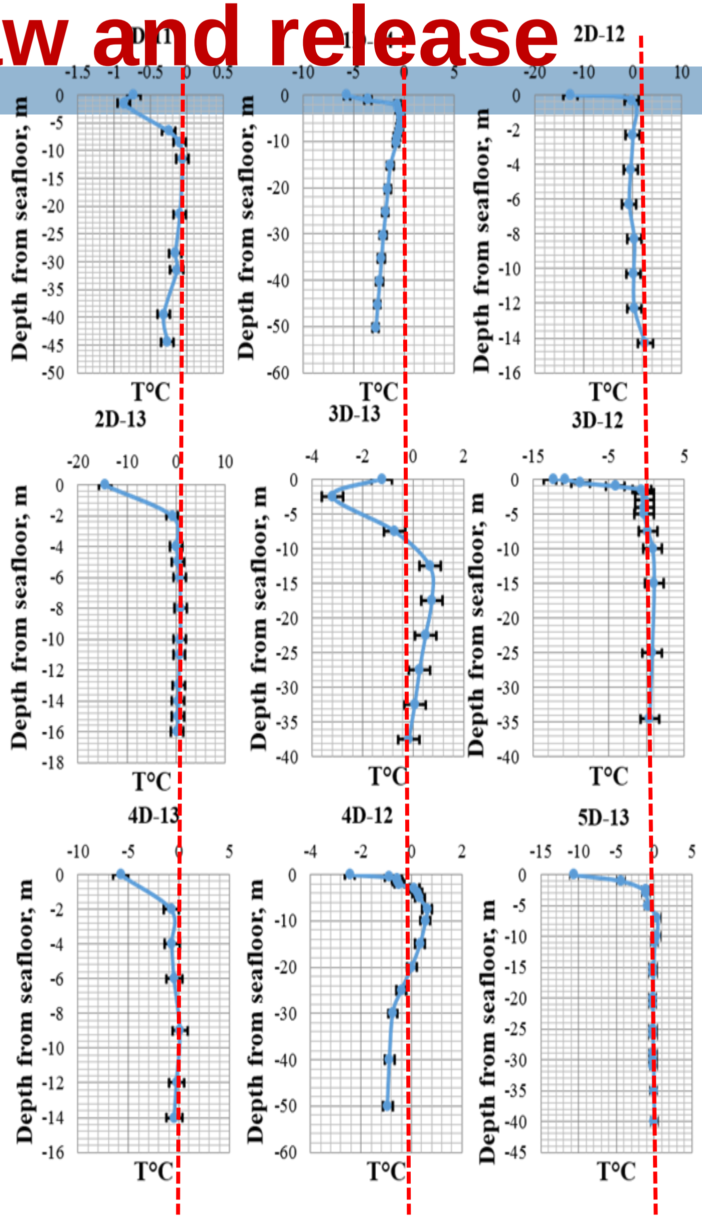
Principal diagram showing formation of different types of hydrate deposits in permafrost-bearing environment and their interaction with seawater in the East Siberian Arctic Shelf (ESAS).

1 – Initial conditions: **Warm epoch** - shelf sediments bear methane produced at different depth in the seabed; 2 – **Cold epoch**: shallow shelf is exposed above the sea surface; sediment freeze downwards – permafrost forms; salt ions incorporate to permafrost; methane converts to hydrates within hydrate stability zone (HSZ) that forms at depth where temperature-pressure conditions meet requirements for HSZ (very low temperatures - up to -20°C - and combination of hydrostatic/geostatic pressure); free gas accumulates beneath HSZ; 3 – **Warm epoch**: shelf is inundated; warming effect of seawater deepens position of the permafrost table (PT) and upper boundary (UB) of HSZ (depth >250-300 m); hydrates partially convert to free gas; ascending gas converts to metastable hydrates due to self-preservation phenomenon; accumulations of metastable hydrates form at shallow permafrost depth (<100 m); salt ions keep propagating downwards; 4 – **Warm epoch**: continuing warming serves to further deepening of the PT and UB of HSZ; salt

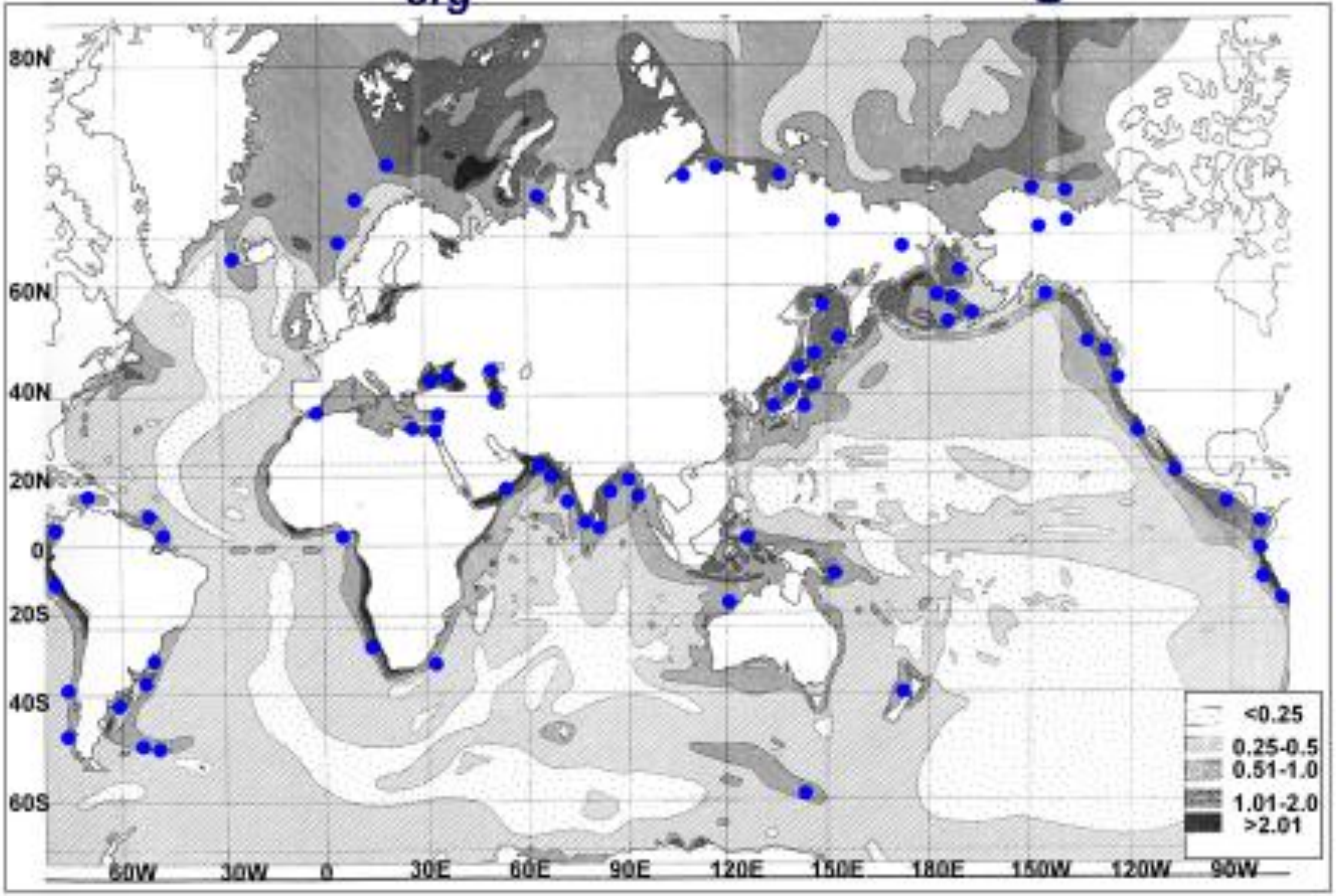
Misunderstanding 3: Subsea permafrost along with hydrates on the ESAS will require millennia to thaw and release methane



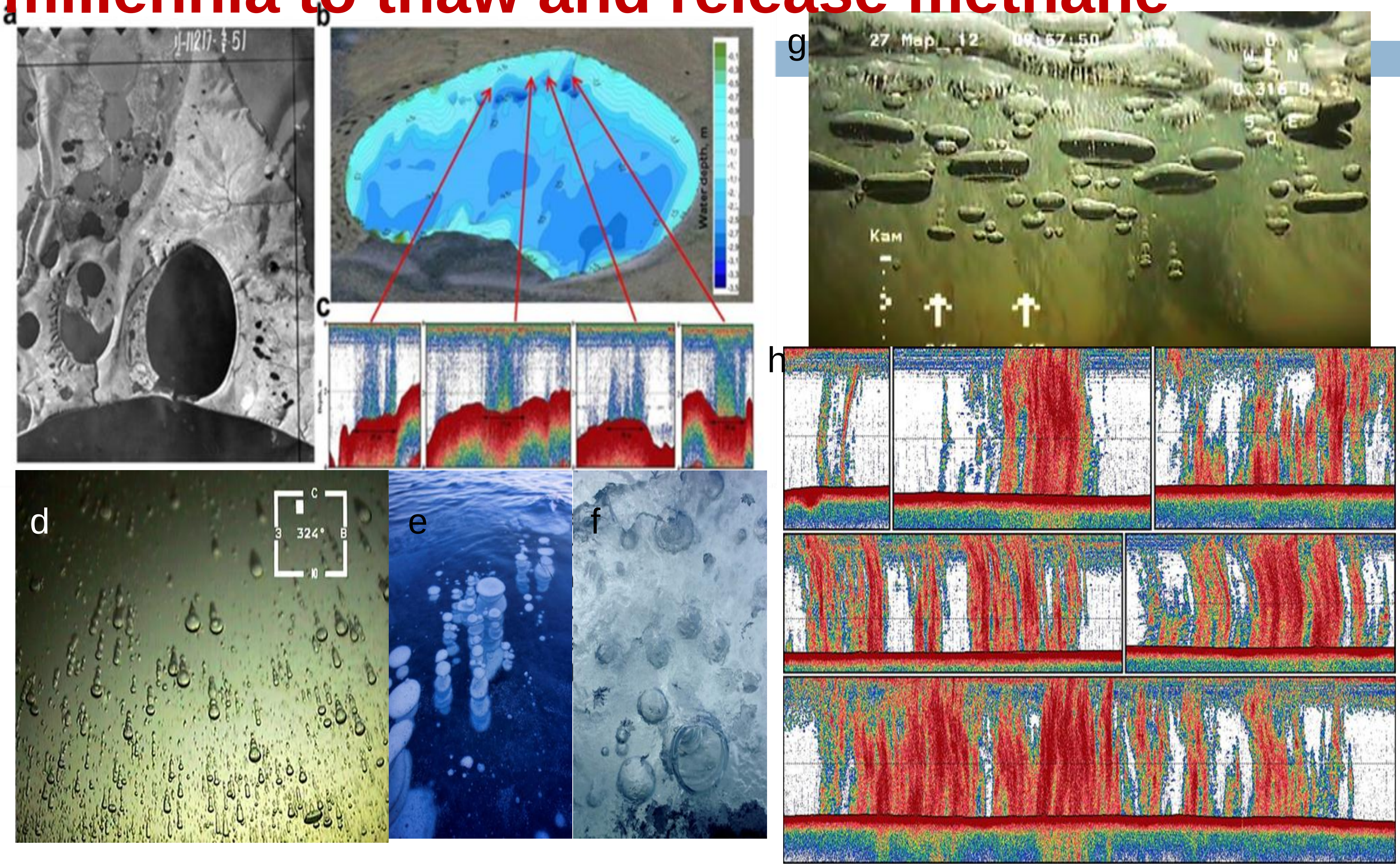




Hydrates (●) in the World Ocean are found where C_{org} in sediments is highest

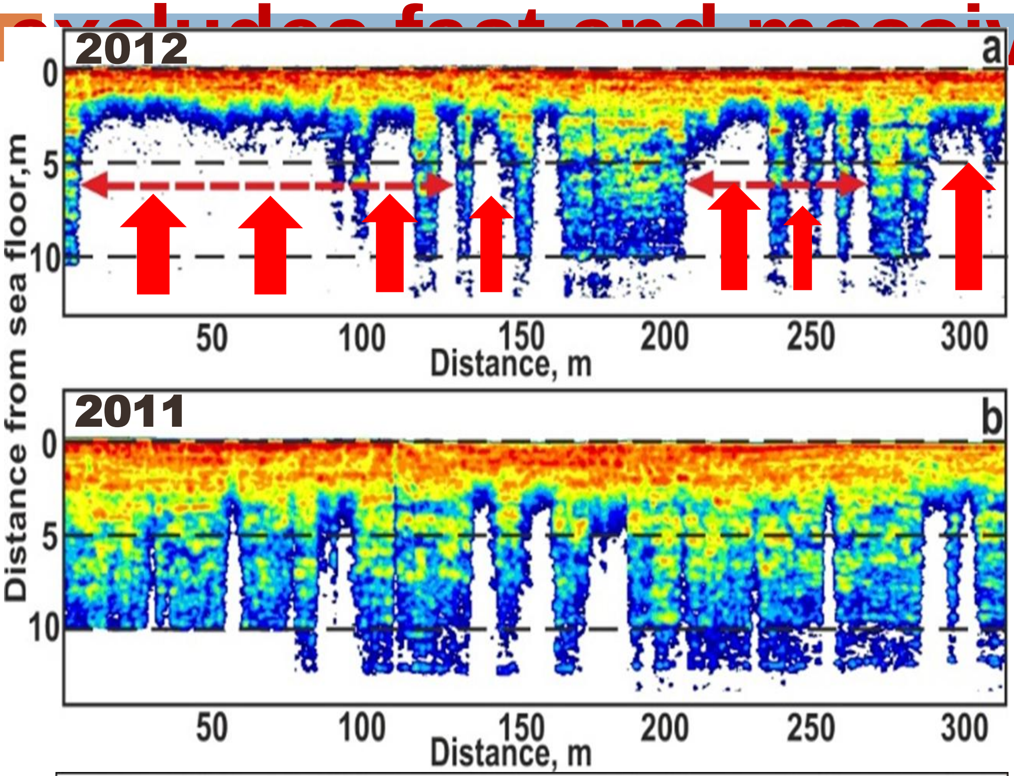


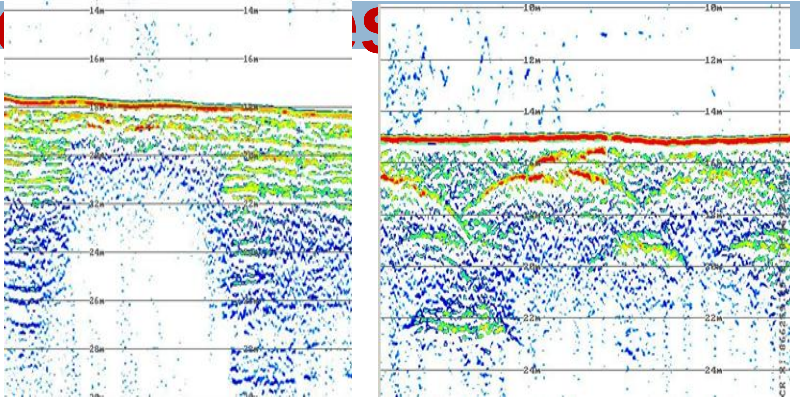
Misunderstanding 3: Subsea permafrost/hydrates on the ESAS will require millennia to thaw and release methane

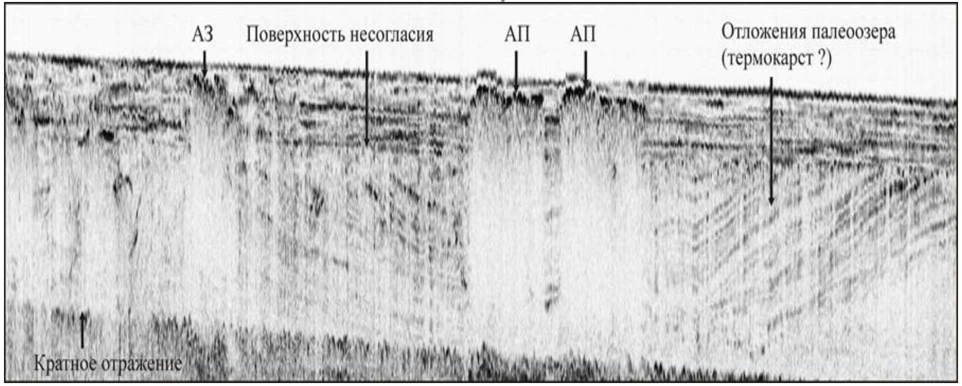


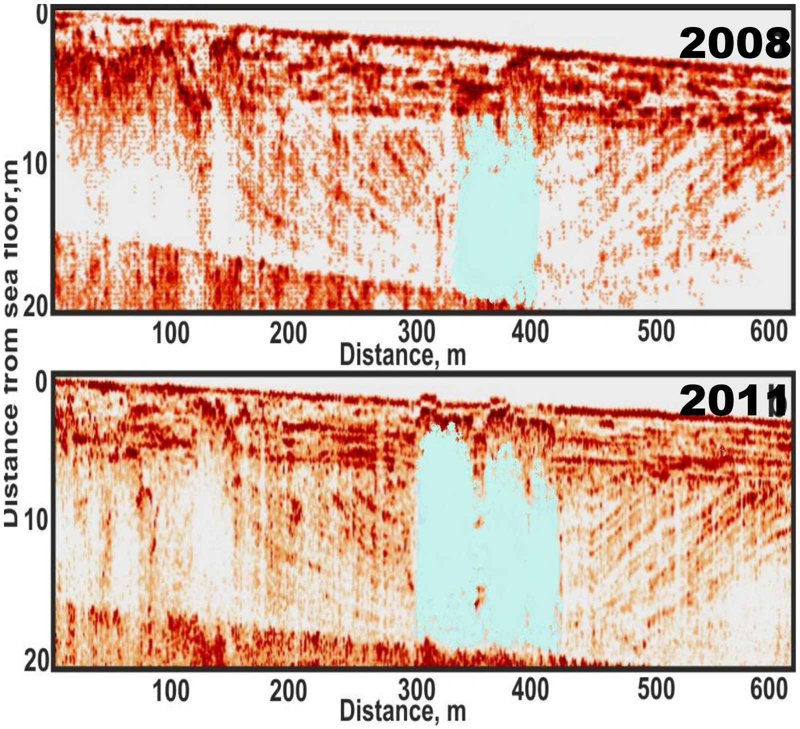
(a)-(g) – near-shore areas of the ESAS; (h) –

Misunderstanding 4: Free gas converted from hydrates will diffuse through the sediments on millennia/centurial scale that excludes fast and massiv[illegible]es

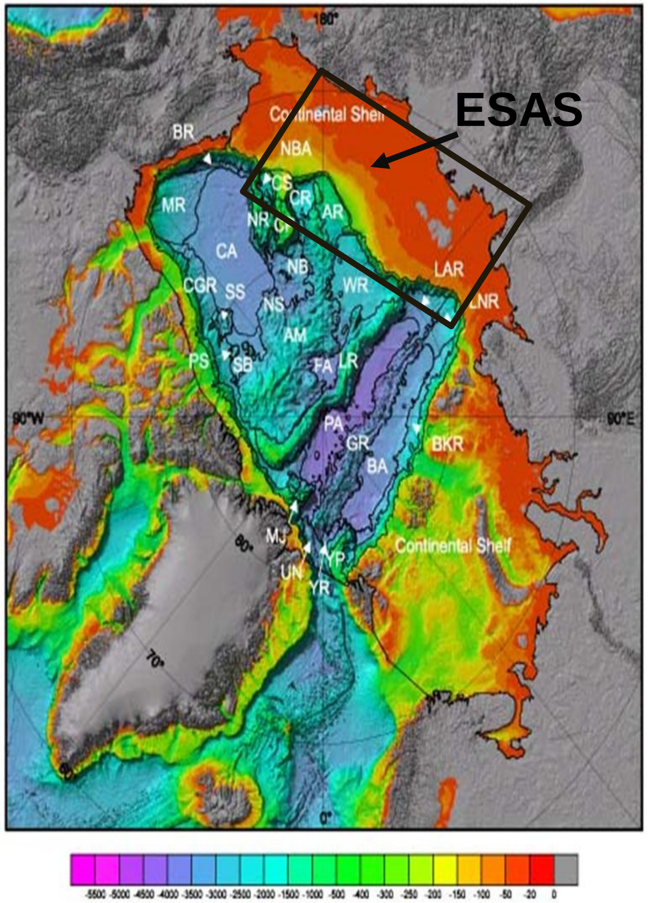




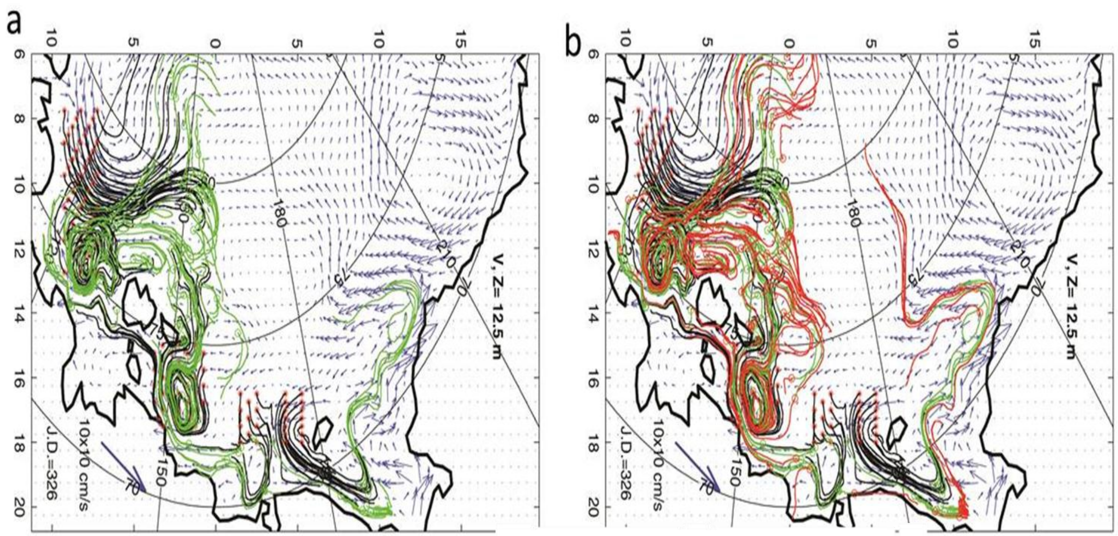




Misunderstanding 5: Methane will dissolve in the water column, oxidize there and

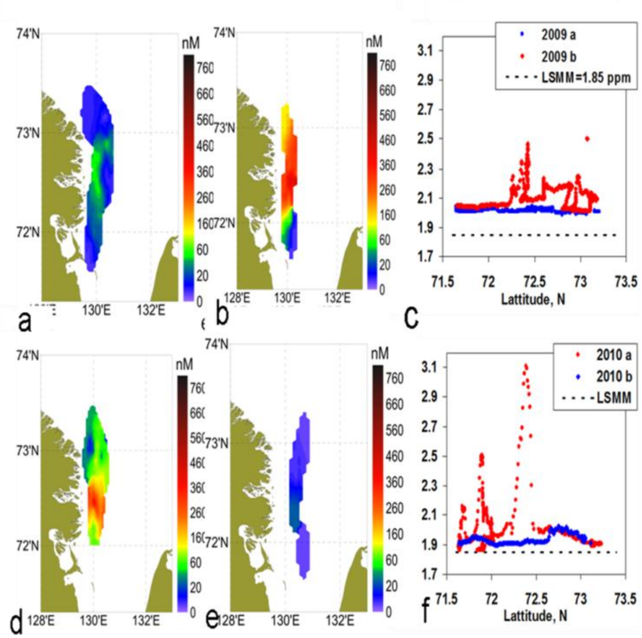


Mean depth of the ESAS is **50 m**; bubble rise velocity vary from **20 to 40 cm/s**; bubble pass from the seafloor to the sea surface takes from **2 to 5 min** to reach the sea surface.

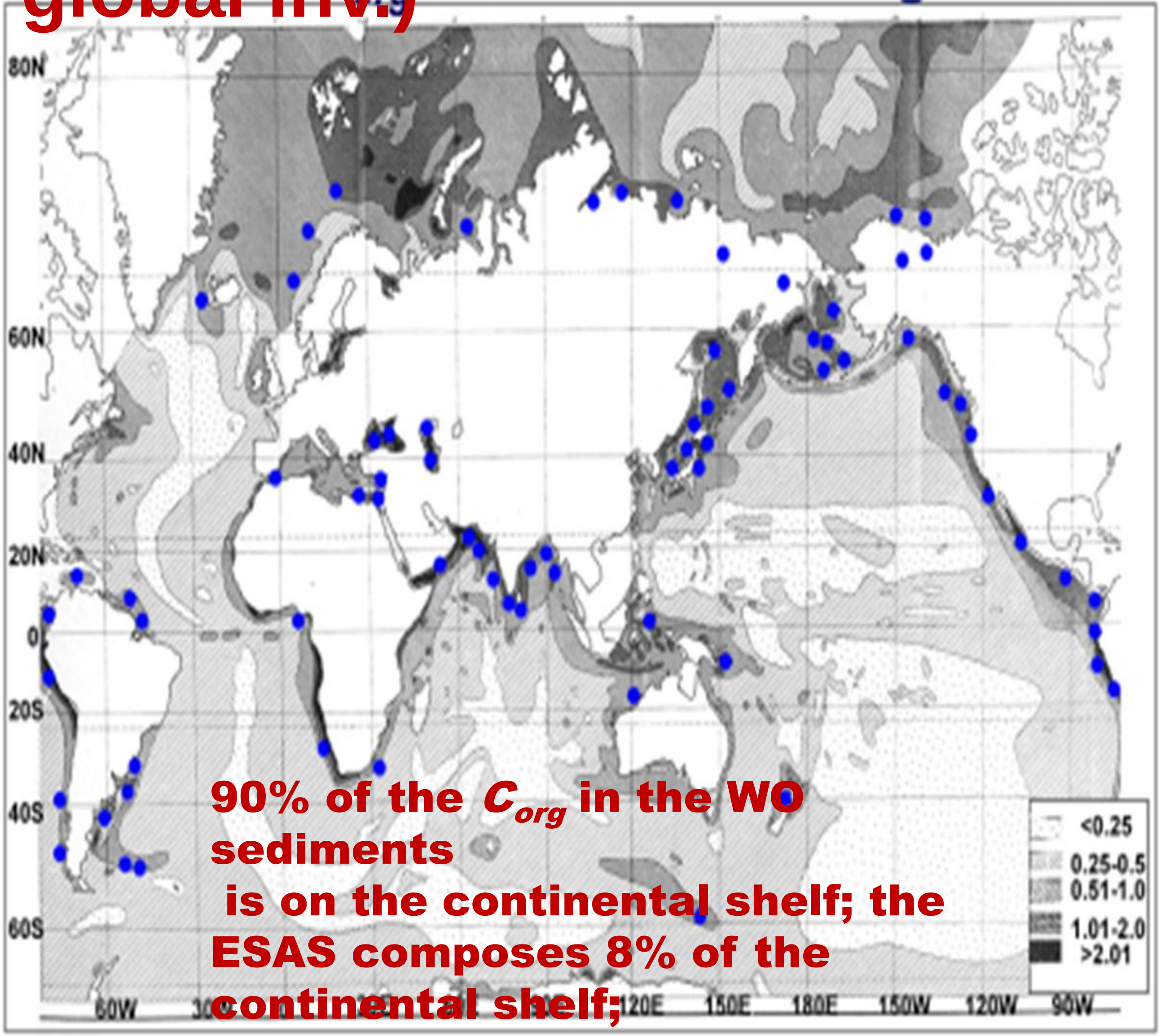


The turnover time for the methane pool was estimated from *hundreds to thousands days*. ***This points to insufficiency of the microbial bio-filter in the ESAS waters*** *(M. Joye et al., 2011);*

Wind-driven mixing of the water column is an efficient mechanism driving methane



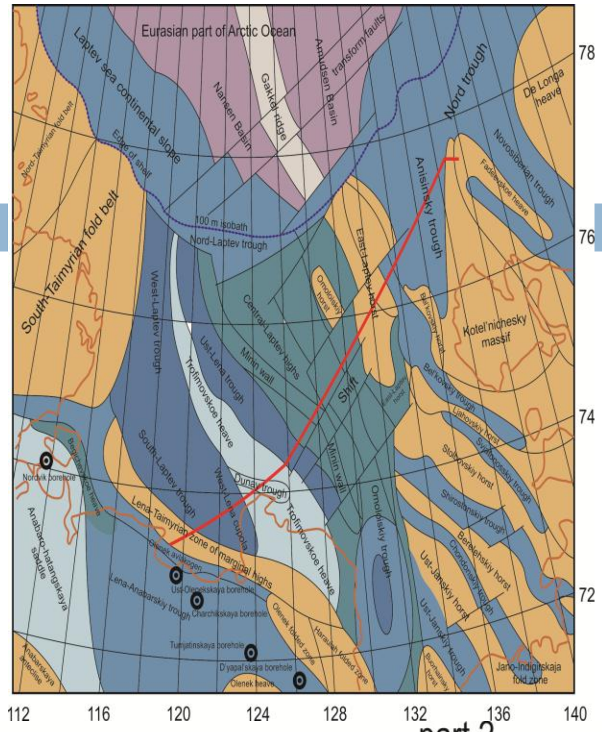
Misunderstanding 6: Hydrate inventory of the Arctic shelves is negligible (<0.1% of global inv.)

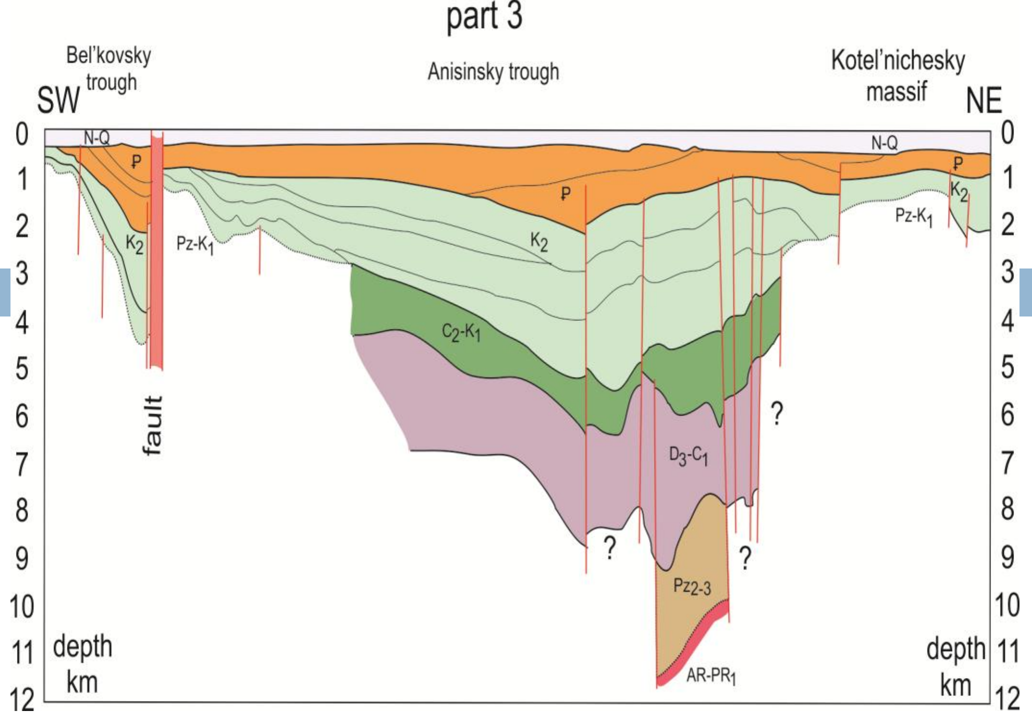


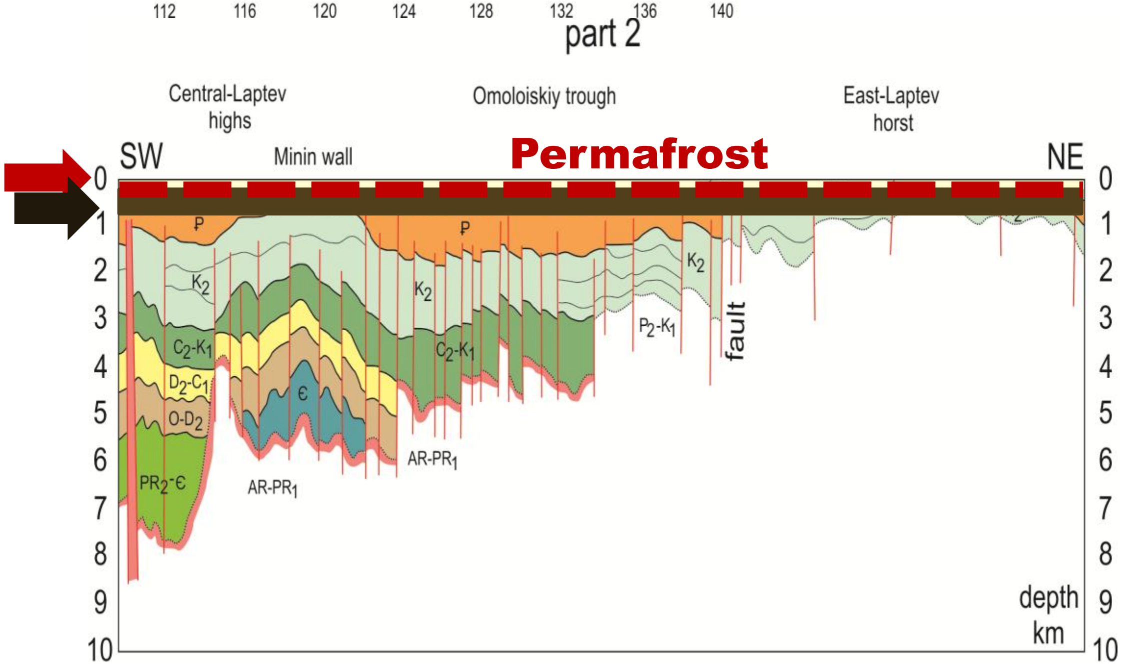
90% of the C_{org} in the WO sediments is on the continental shelf; the ESAS composes 8% of the continental shelf;

Sedimentary basins of the ESAS

- Siberian Rivers bring **7×10^{11} m^3** of POC-loaded waters;
- **Rates of sedimentation in the ESAS are the highest** in the World Ocean;
- Amount of C_{org} **accumulated annually in the ESAS**







- Mean thickness of the sediments in the World Ocean (WO) is **~1 km**;

- Thickness of the sediments on the continental shelf of the WO reaches **3-4 km**; thickness of the sedimentary basins on the ESAS reaches **10-15 km**;

- ESAS composes **~8%** of the WO continental shelf; area-weighted fraction of the ESAS

Conclusions

- Permafrost failure in the ESAS uncorks largest in the world storage of permafrost-related shelf hydrates, leading **to large scale methane releases** to the water column and to the atmosphere;
- The observed range in methane emissions associated with different degrees of subsea permafrost disintegration implies **substantial and potent emission enhancement in the ESAS** as the process of subsea permafrost thawing progresses coastward with time. The current process of Arctic warming and associated sea ice loss will accelerate this process;
- Given that methane emissions from the ESAS depend on occurrence of gas migration pathways, which develop due to permafrost thaw and permafrost breaks, that the ESAS is tectonically and seismically active area, and that methane releasing from decaying hydrates is significantly over pressurized, combination of all these factors determines **non-gradual emission mode over substantial fraction of the ESAS**;
- Given methane's potency as a greenhouse gas, the significance of the ESAS methane reservoir and progressing mechanism of its destabilization, methane release from the ESAS has **important implications for global climate**. Inclusion of the ESAS as a source of methane in global climate models (GCMs) should be considered a high priority;
- As mechanism of hydrate destabilization is determined by state of subsea permafrost, which is reaching and at places has already reached the thaw point, **this mechanism will progress over time exponentially; a massive**