Methane release from the East Siberian Arctic Shelf and the Potential for Abrupt Climate Change

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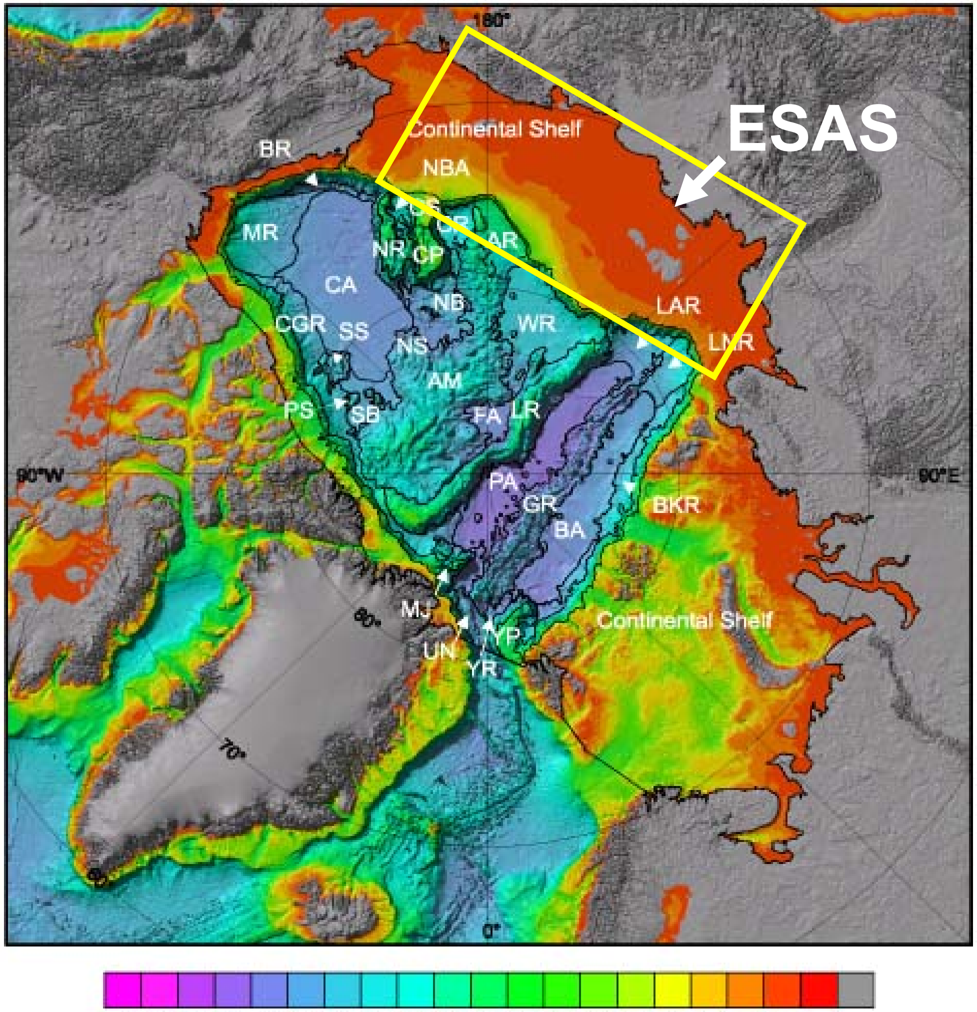
Outline:

- **What do we know about *methane potential* of the ESAS?**
- **Is there a *mechanism responsible* for transformation of methane potential to modern methane source?**
- **What are *triggers* forcing non-gradual mode of methane emission from the seabed?**
- **Is there a plausible mechanism, which could determine *massive and abrupt methane releases*?**

- **Why is the ESAS unique in its ability to accommodate huge methane potential?**

The ESAS is the most extensive and the shallowest shelf of the World Ocean



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

- **~75%** is shallower than **50 m** (*mean depth of the continental shelf is* ***130 m)***; this provides very short conduit for methane to escape to the atmosphere with almost no oxidation.

The ESAS provides favorable conditions for methanogenesis and accumulation of natural hydrocarbons

- The **highest rates of carbon rain** to the bottom provides required amount of organic carbon to be buried in the seabed; Annual sediment accumulation is about *10×10^12 g* **C_{org} yr^{-1}**, which approximately equals the amount of sediment accumulated over the entire pelagic zone of the World Ocean;

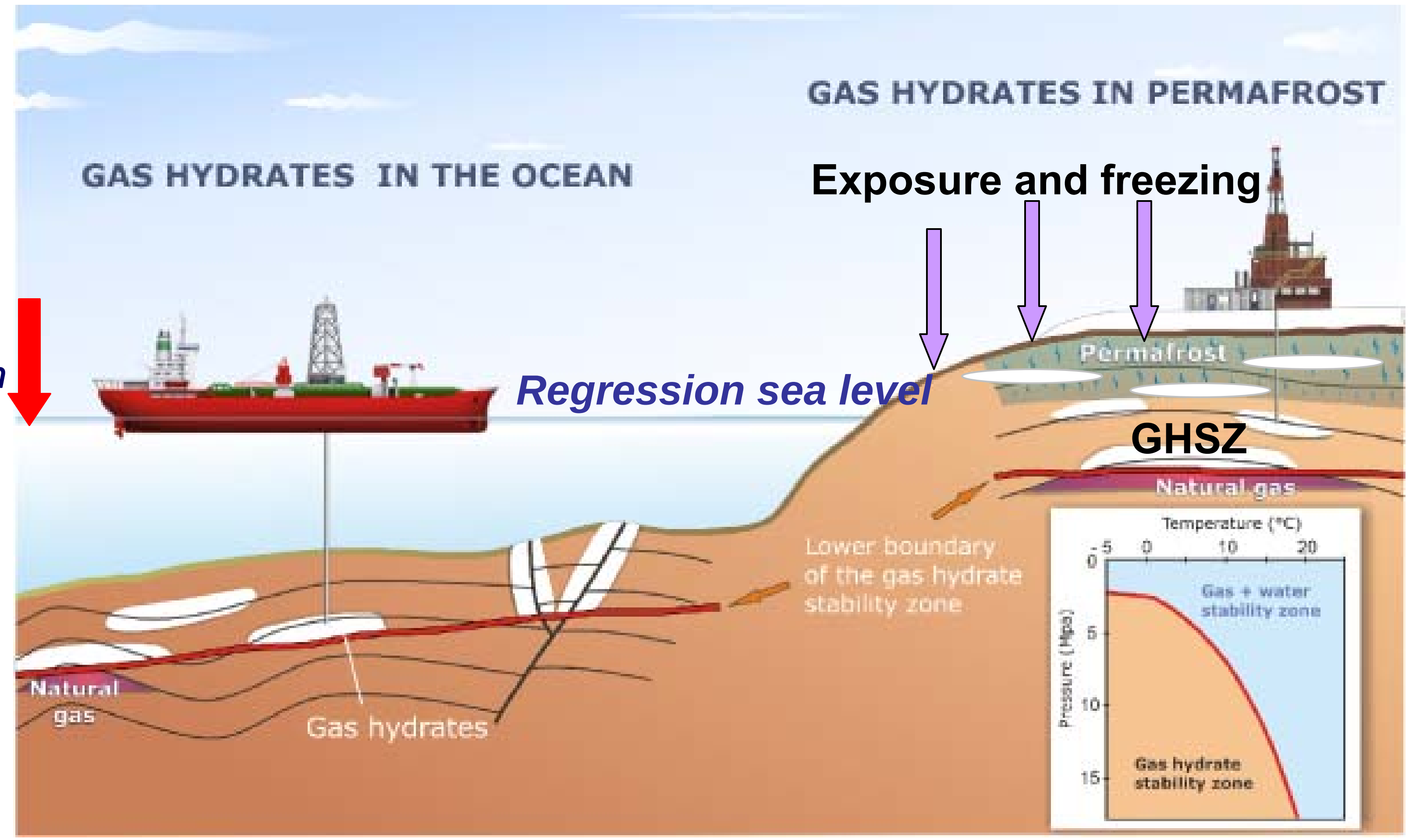
- Stable conditions of the continental margin lead to formation of **very thick sedimentary basins** (up to *20 km* thick), which provide temperature and pressure conditions required for methane production;

- Geological conditions are favorable for formation of all types of seabed deposits: **extensive coal beds**, **natural gas and oil fields; hydrate accumulations within and out of gas hydrate stability zone** (GHSZ);

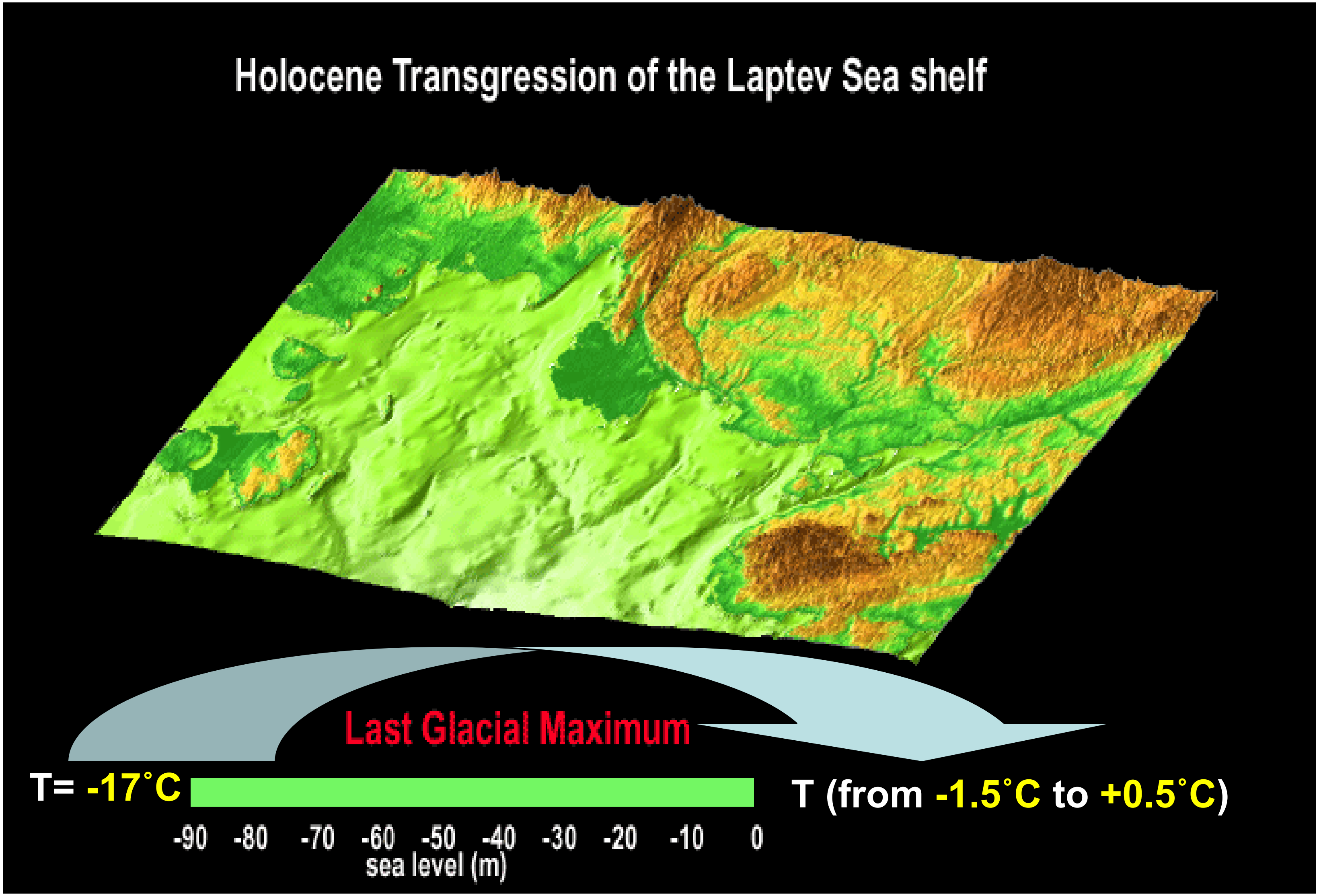
- **Upward moving geofluids** provide transport of hydrocarbons to the areas of gas hydrate stability zone (GHSZ);

Arctic shelf hydrate formation: Cold climate epoch

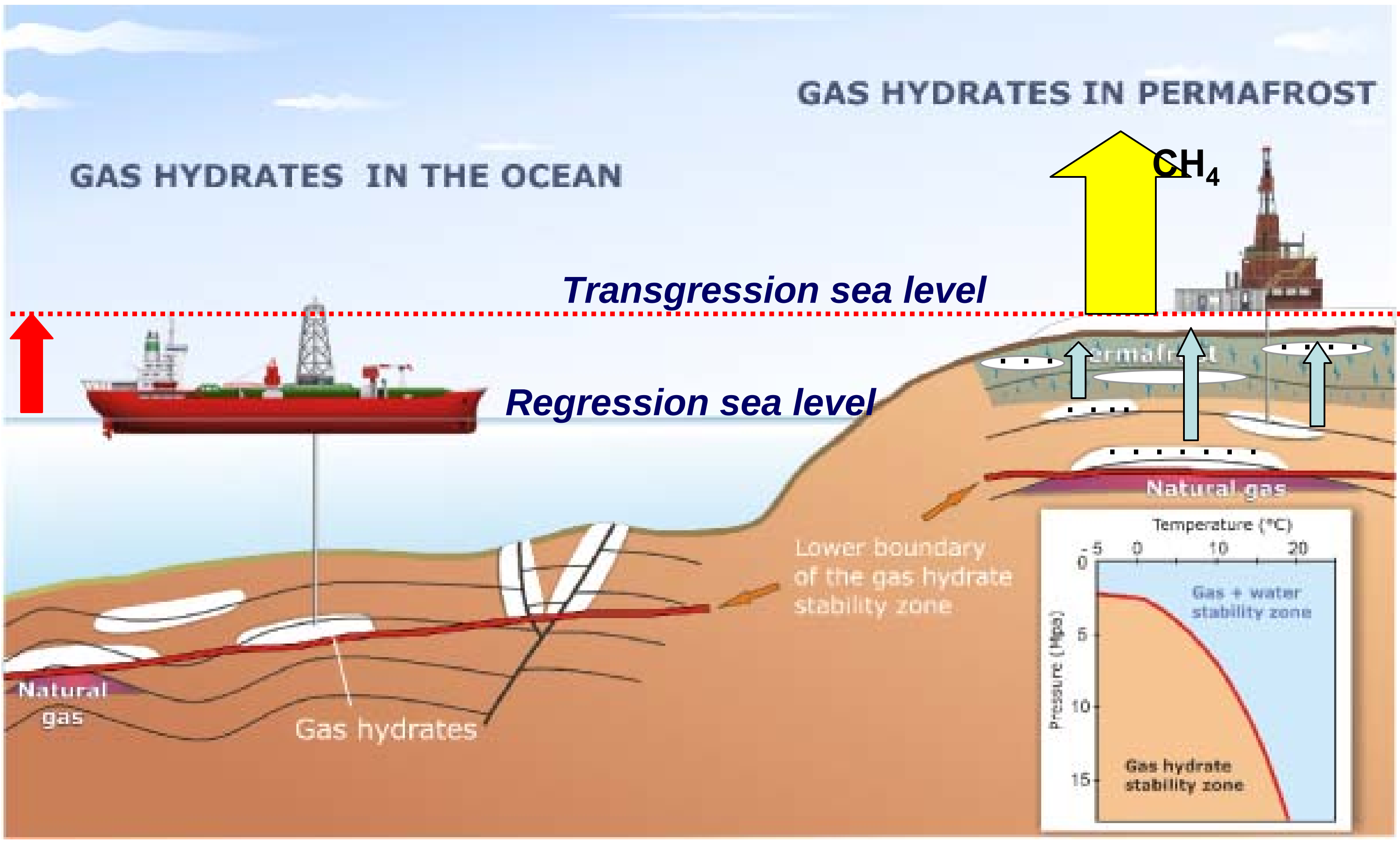
100 -
120 m



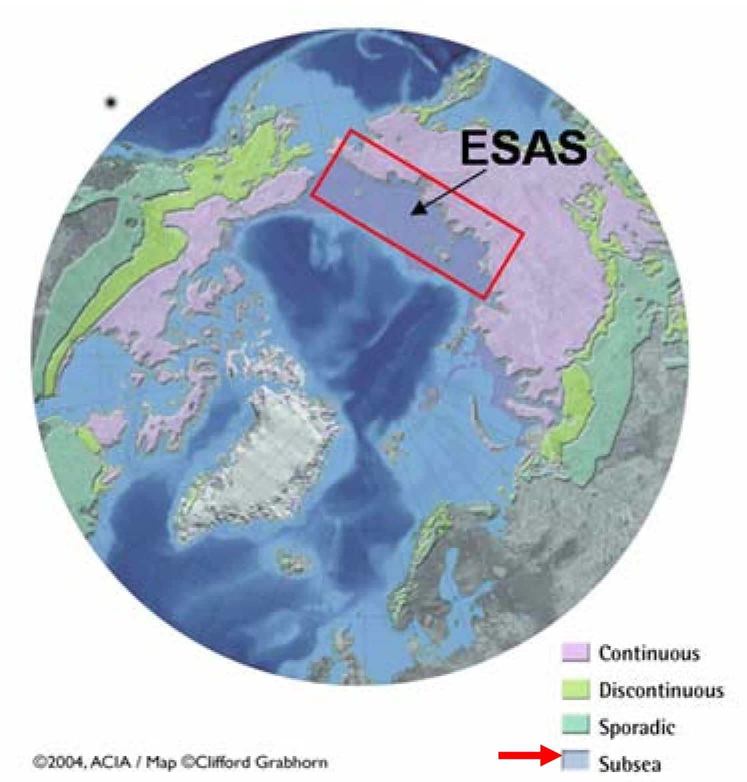
Inundation during sea transgression



Arctic shelf hydrate destabilization: Warm climate epoch



Stability of sub-sea permafrost is key to stability of permafrost-related hydrate deposits



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).

Specific features of the Arctic shelf methane hydrates

- *More sensitive to warming:*

  because only 1/3 of energy required to convert deep ocean hydrates to free gas (**54.2** kJ/mol) requires to convert to free gas Arctic hydrates (**18,2** kJ/mol);

- *More vulnerable*

  because they have naturally been experiencing warming by as much as **17˚C** while deep oceanic hydrates were warmed by less than **1˚C;**

- *More significant in their accumulations*:

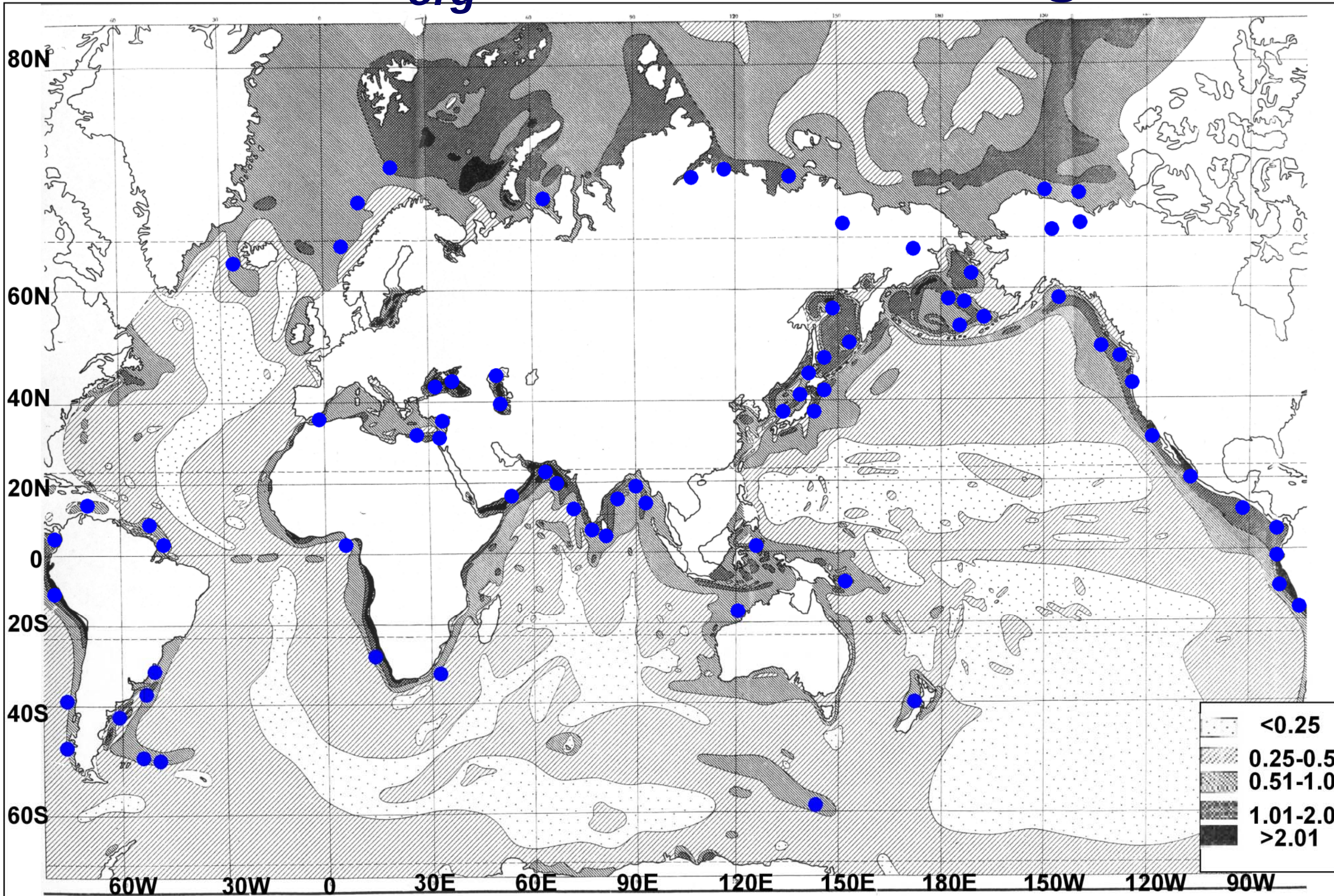
  because their spatial concentration is many folds greater as well as pore occupancy (**20-100%** vs. **1-2%** of deep oceanic hydrates);

- *More potential for abrupt releases*:

  - Long-lasting permafrost impermeability determines huge potential of postponed emissions (alike pressure-cooker keeps all the steam inside till you .

Significance of Arctic shelf hydrates vs. hydrate accumulations in the deep ocean

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



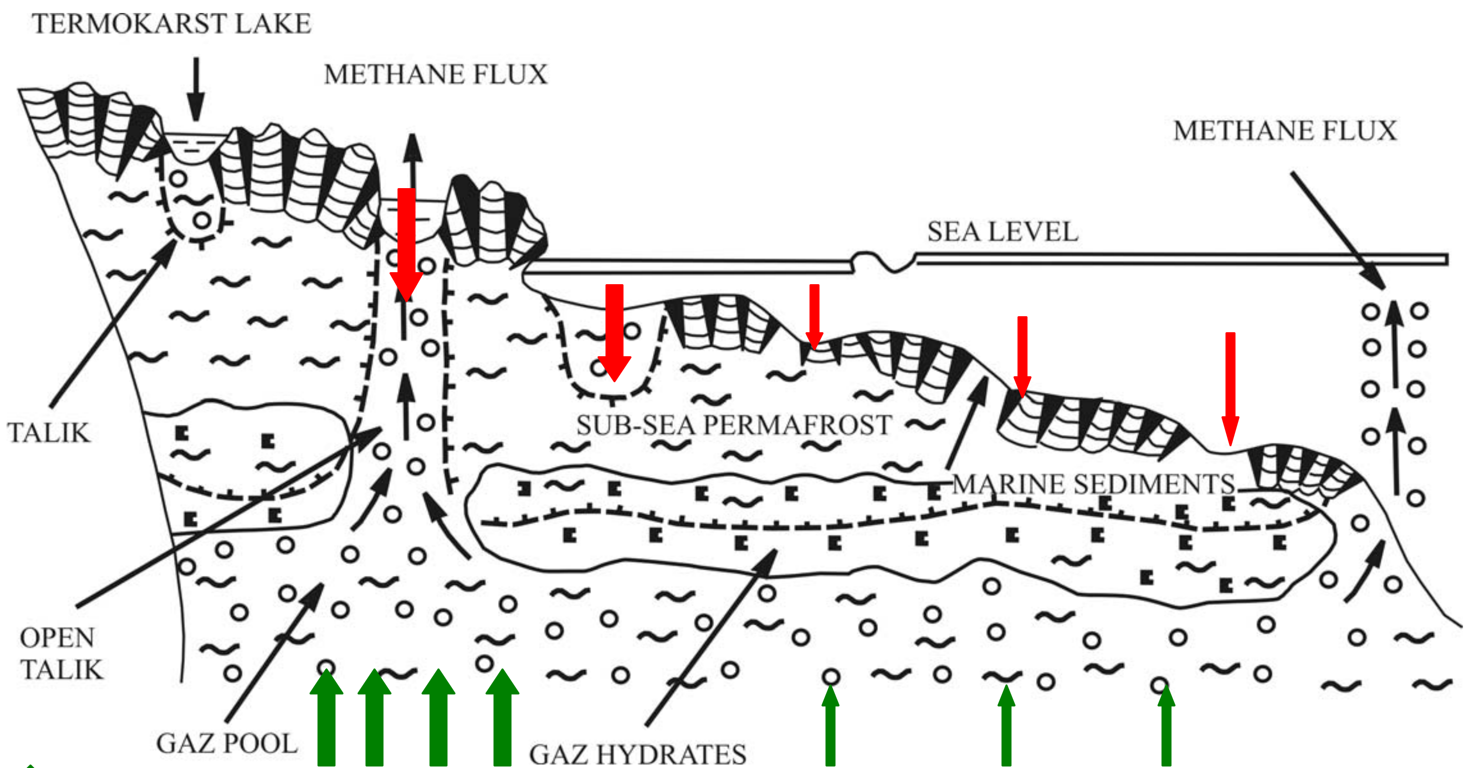
What is known about mechanisms of permafrost destabilization associated with formation of gas migration pathways?

There are two basic mechanisms of permafrost destabilization:

1) Natural process of **permafrost equilibration** with its warmer environment determines talik formation (*gradual process*); the process is ongoing faster in the fault zones;

2) Natural process of **tectonic and seismic activity** in the region (*non-gradual process*) causes permafrost breaks; the process is occurring wherever such events take place.

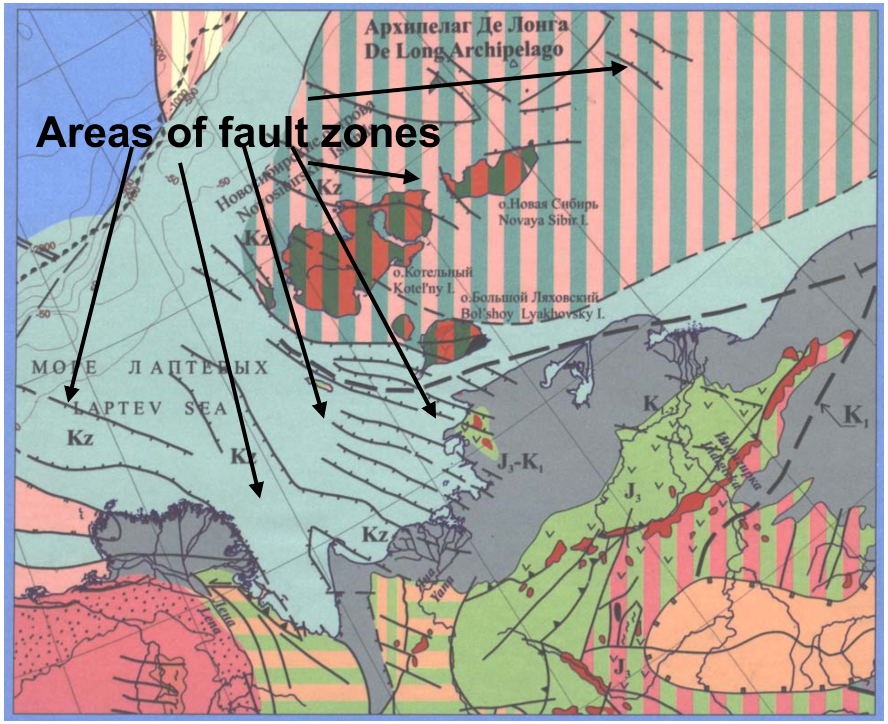
Mechanism of combined talik formation (geothermal heat + thermokarst)

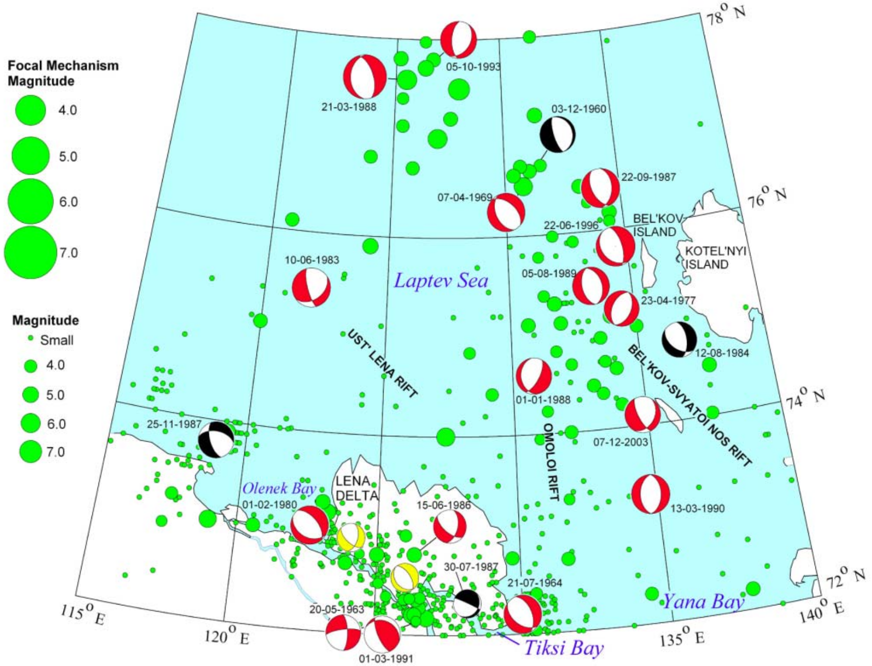


- Upward mechanism under geothermal heat flux

- Downward mechanism under warming effect of sea/river water

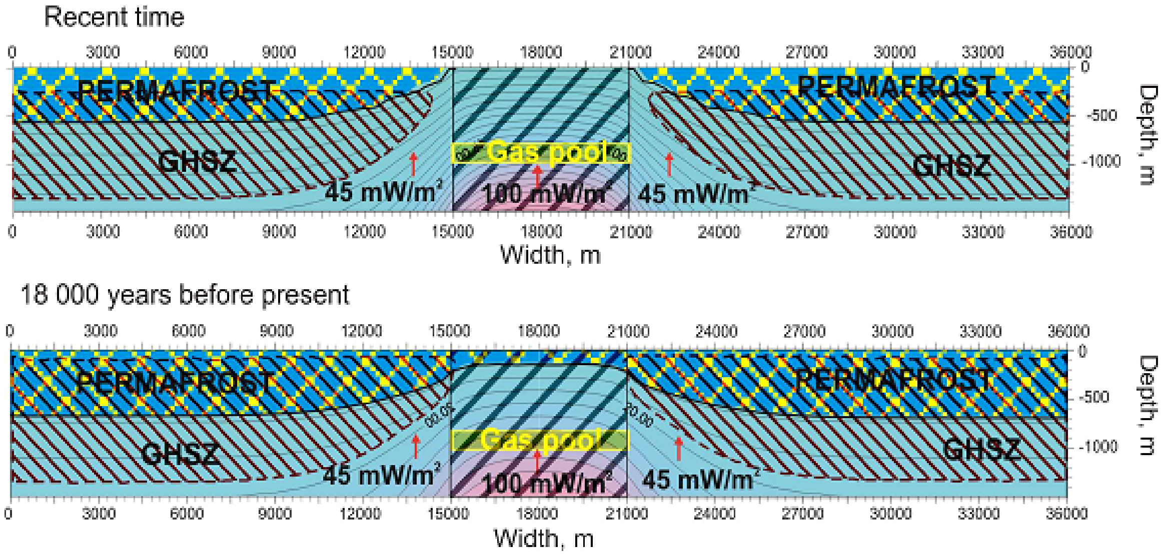
Most of the ESAS area is affected by tectonic and seismic activities





From Fujita et al., 2009

Formation of gas migration pathways within fault zones

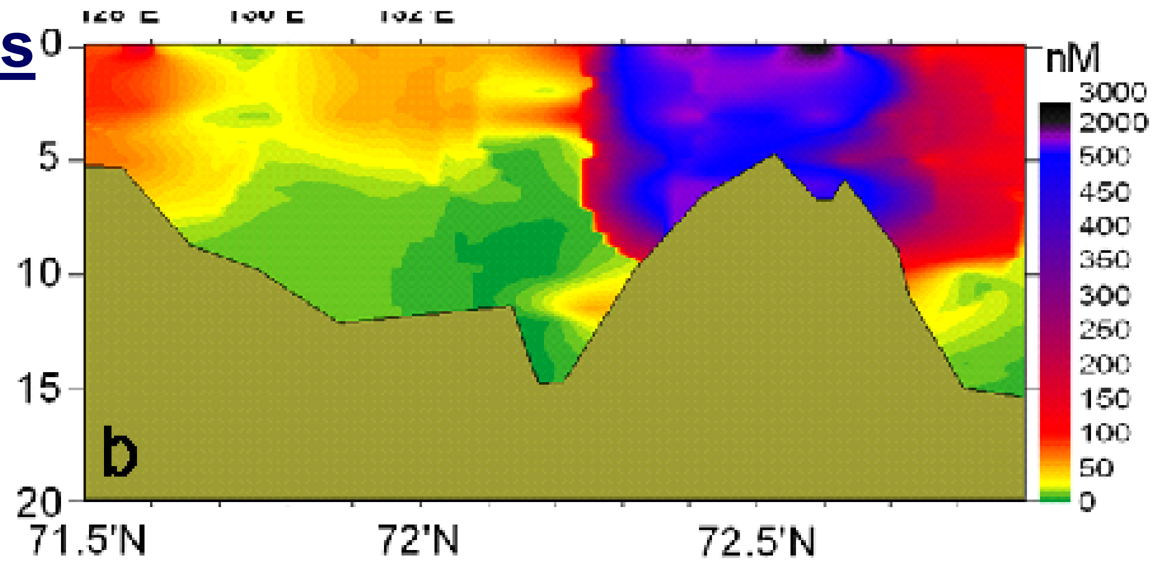


A) Modeling results

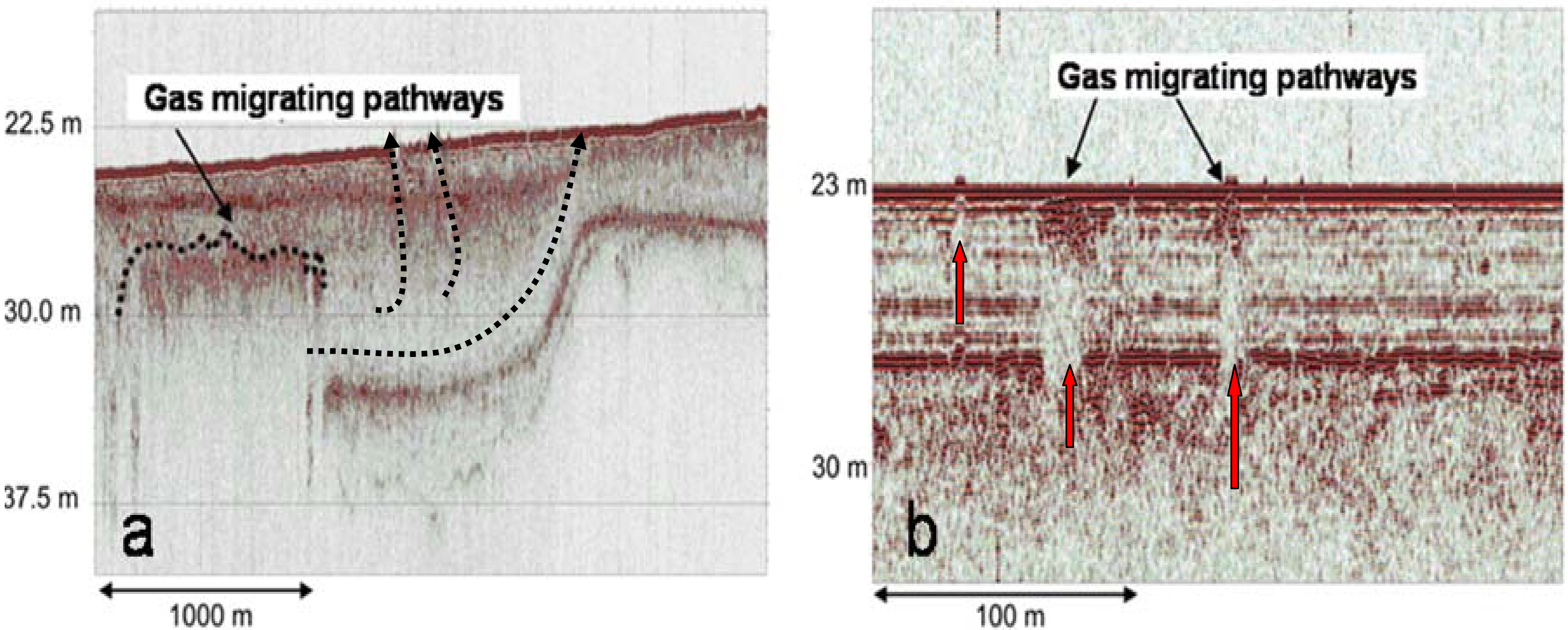
Modeling results suggest that first signs of destabilization will occur where geothermal heat flux is higher (fault zones)

B) Observational results

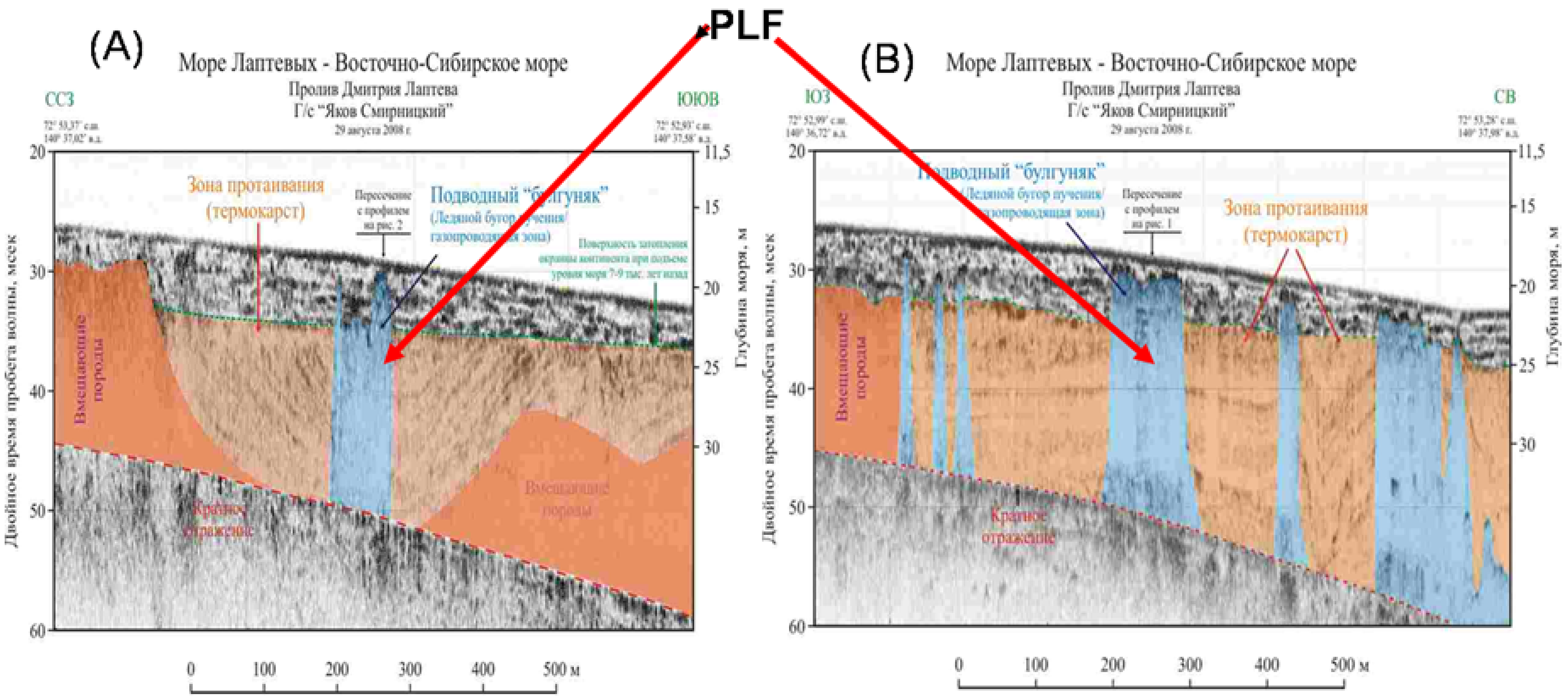
Observational data confirms modeling results and suggest that warming effect of sea water, rivers and inundated lakes play significant role in permafrost destabilization



Over pressured gas fronts serve as a powerful geological force to build up migration pathways

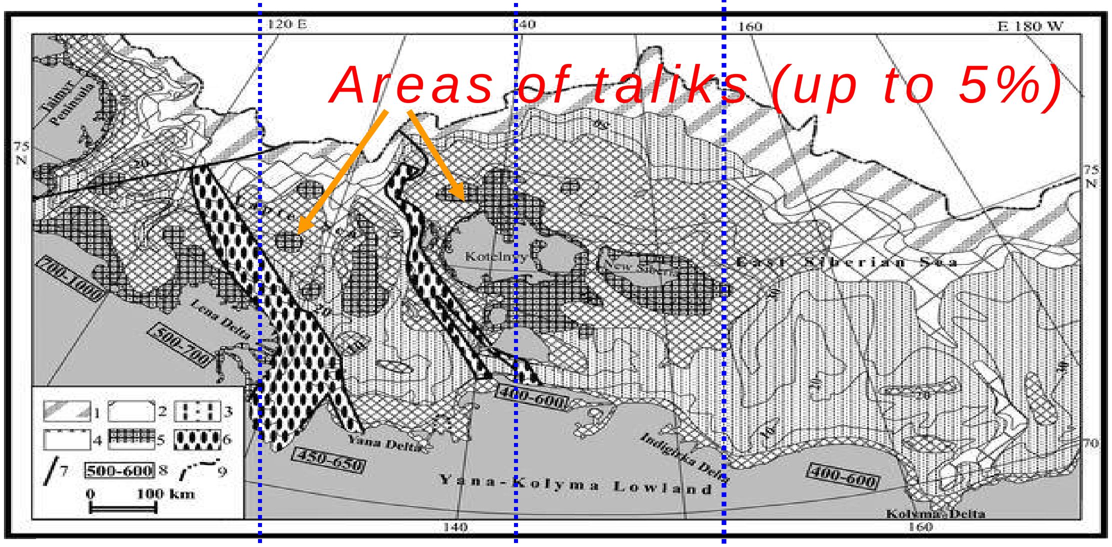


Pingo-like features as a gas migration pathway

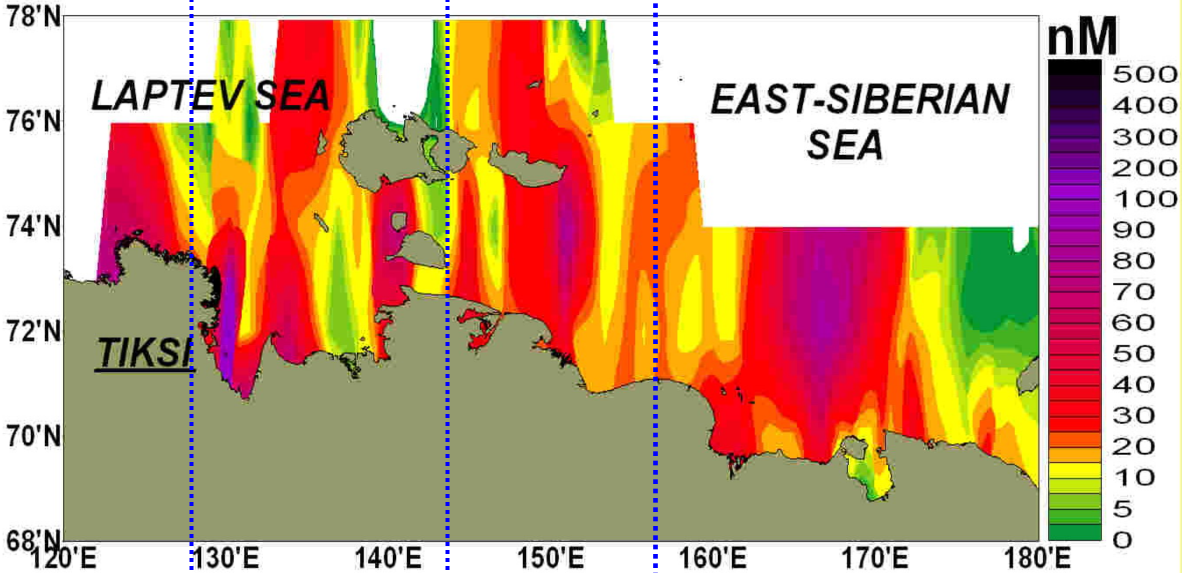


Pingo-like features observed in the Dmitry Laptev Strait (August, 2008)

How far has permafrost destabilization gone by now?

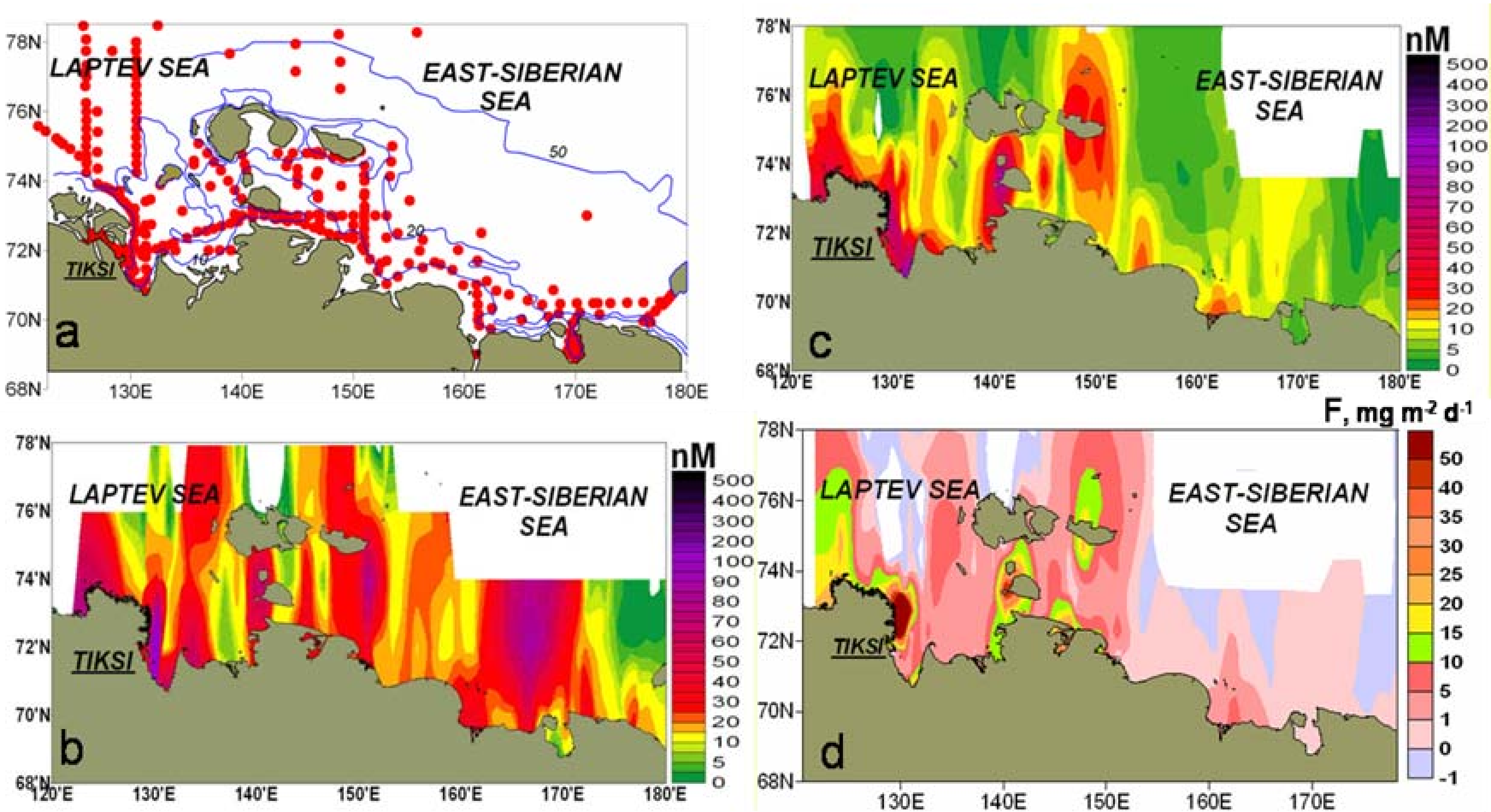


A) Modeling results suggest that area of predicted taliks over the ESAS composes **3-5%** of the total area (***Romanovskii et al., 2005***).

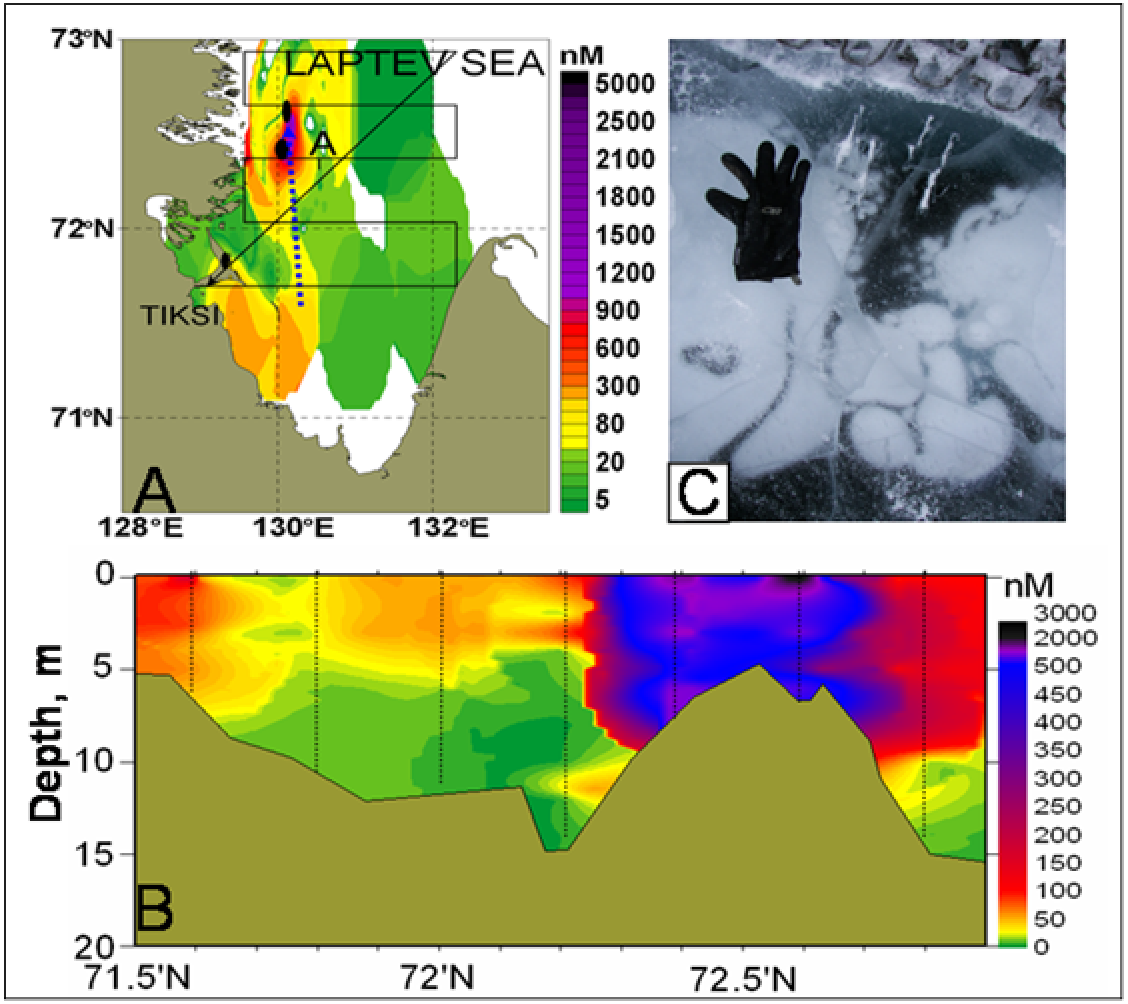


B) Observational data suggest **>80%** of the ESAS sea floor serves as a source of methane to the water column (***Shakhova et al., 2010***).

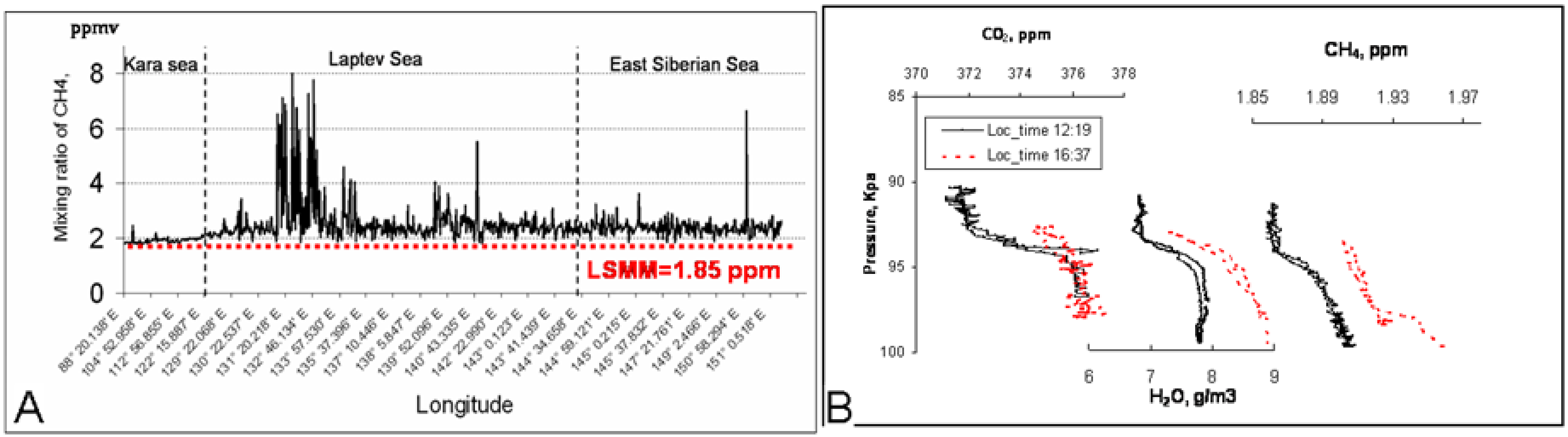
Manifestations of methane release from the ESAS



Methane release in the winter



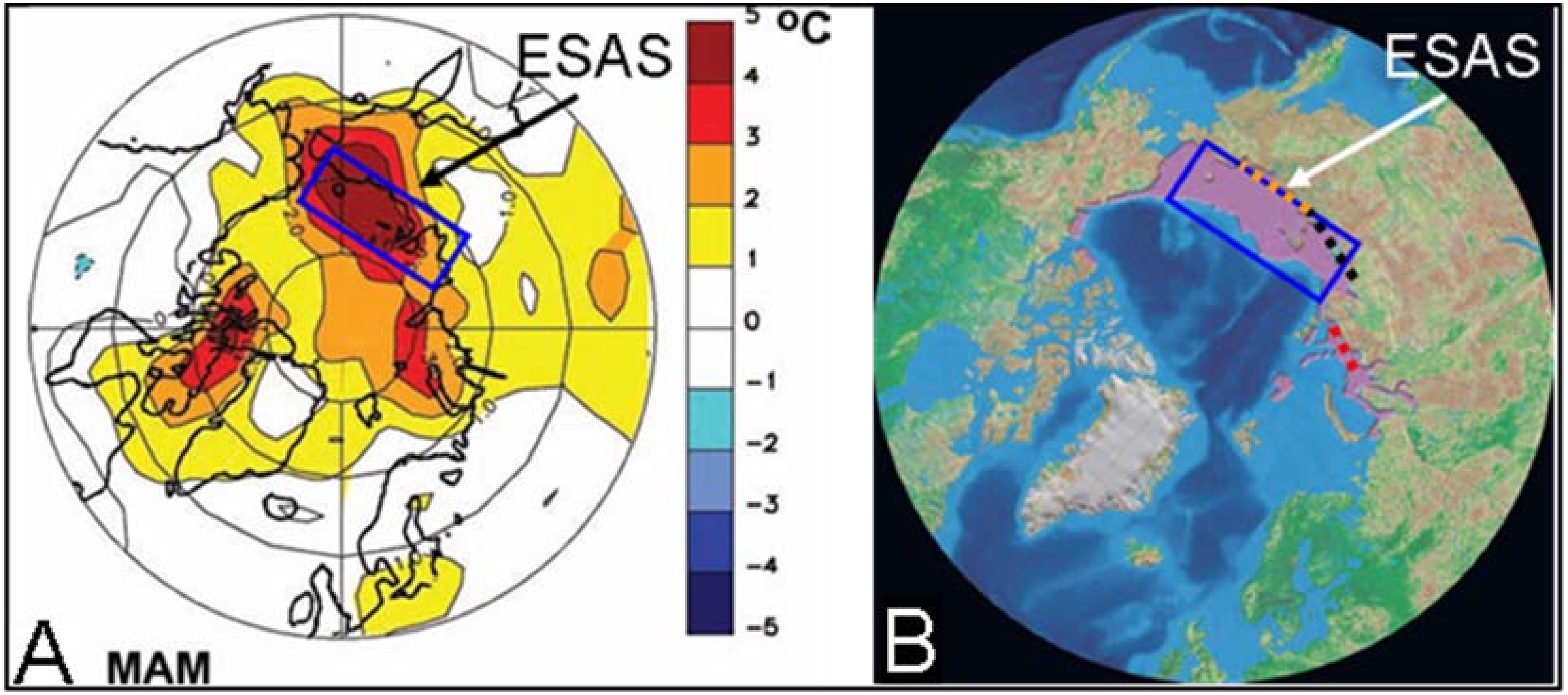
Non-gradual emission mode determines strong methane pulses to the atmosphere



Survey of CH_4 mixing ratio in the atmospheric boundary layer along the northern Eurasian seaboard. A) Mixing ratio of methane in the air above the water surface measured along the ship route in September 2005 (red dotted line shows the Latitude Specific Monthly Mean of 1.85 ppmv established for the Barrow, Alaska, USA, monitoring station at 71o 19' N, 156o 35' W (http://www.cmdl.noaa.gov/ccgg/insitu.html);

Acceleration mechanisms

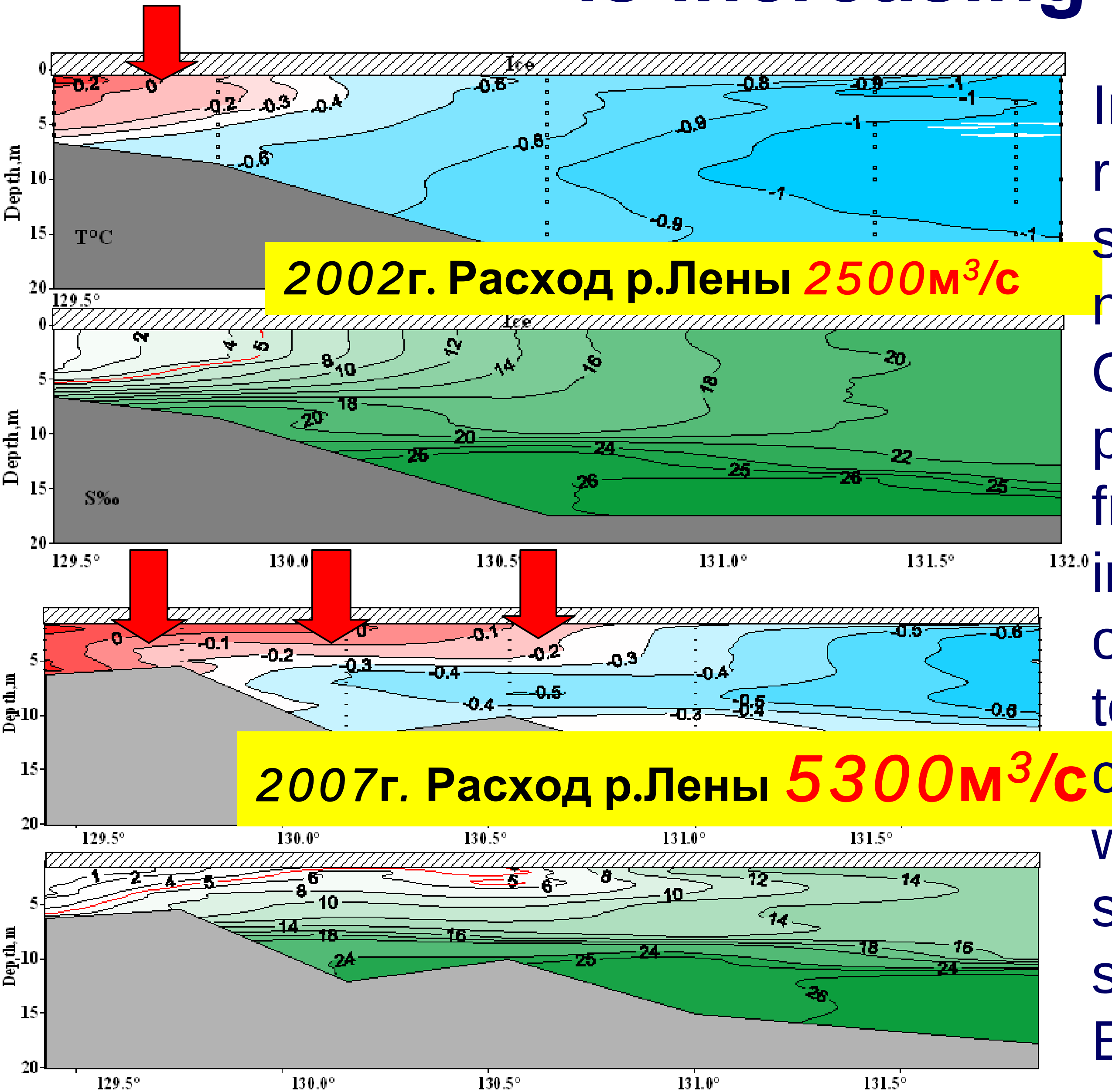
Arctic warming affects the ESAS the strongest



A) Observed warming on the ESAS (March-April-May; MAM, 2000-2005 versus 1970-1999, NOAA) is the strongest in the entire Arctic and the region is now 5˚C warmer compared with average springtime temperature registered during the 20th century;

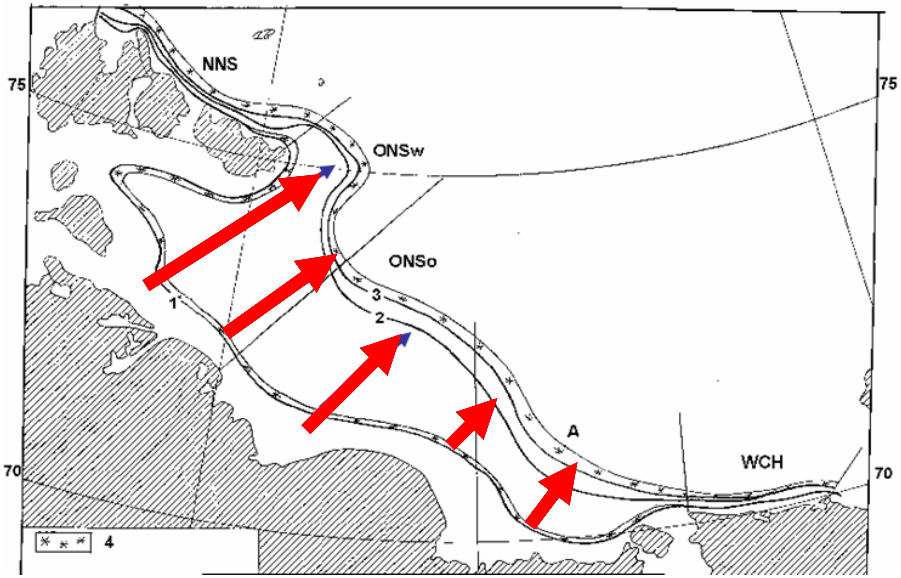
B) Circum-Arctic map of sub-sea permafrost (shown in purple) (ACIA, 2005). This compilation suggests that most (~ 80%) of the relict submarine permafrost is predicted on the ESAS;

Warming effect of Arctic rivers runoff is increasing



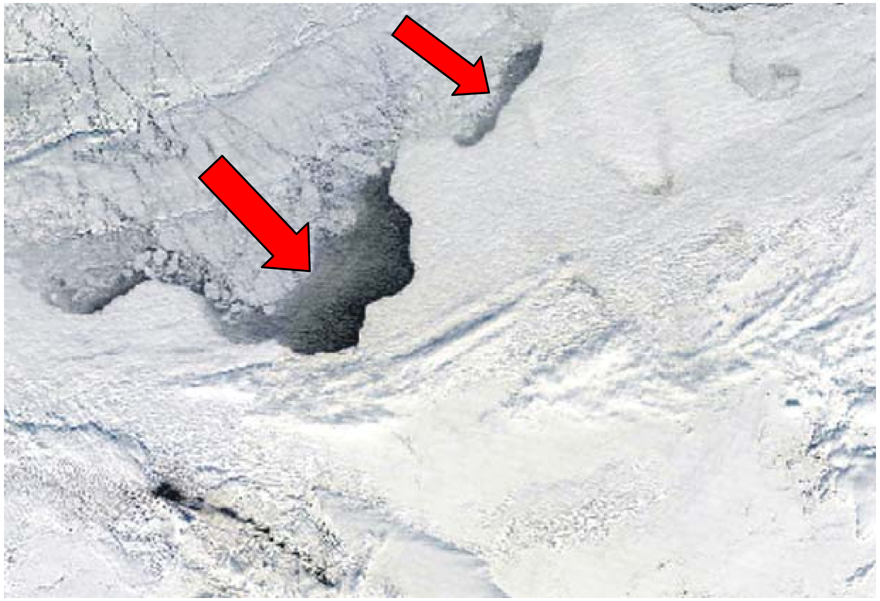
Increase in riverine runoff to the ESAS is significantly noticeable in winter. Owning to it, propagation of warm fresh waters is increasing and occurs laterally and top-down. This causes further warming of the sub-sea permafrost in shallower part of the ESAS.

Area of open water in winter is increasing drastically

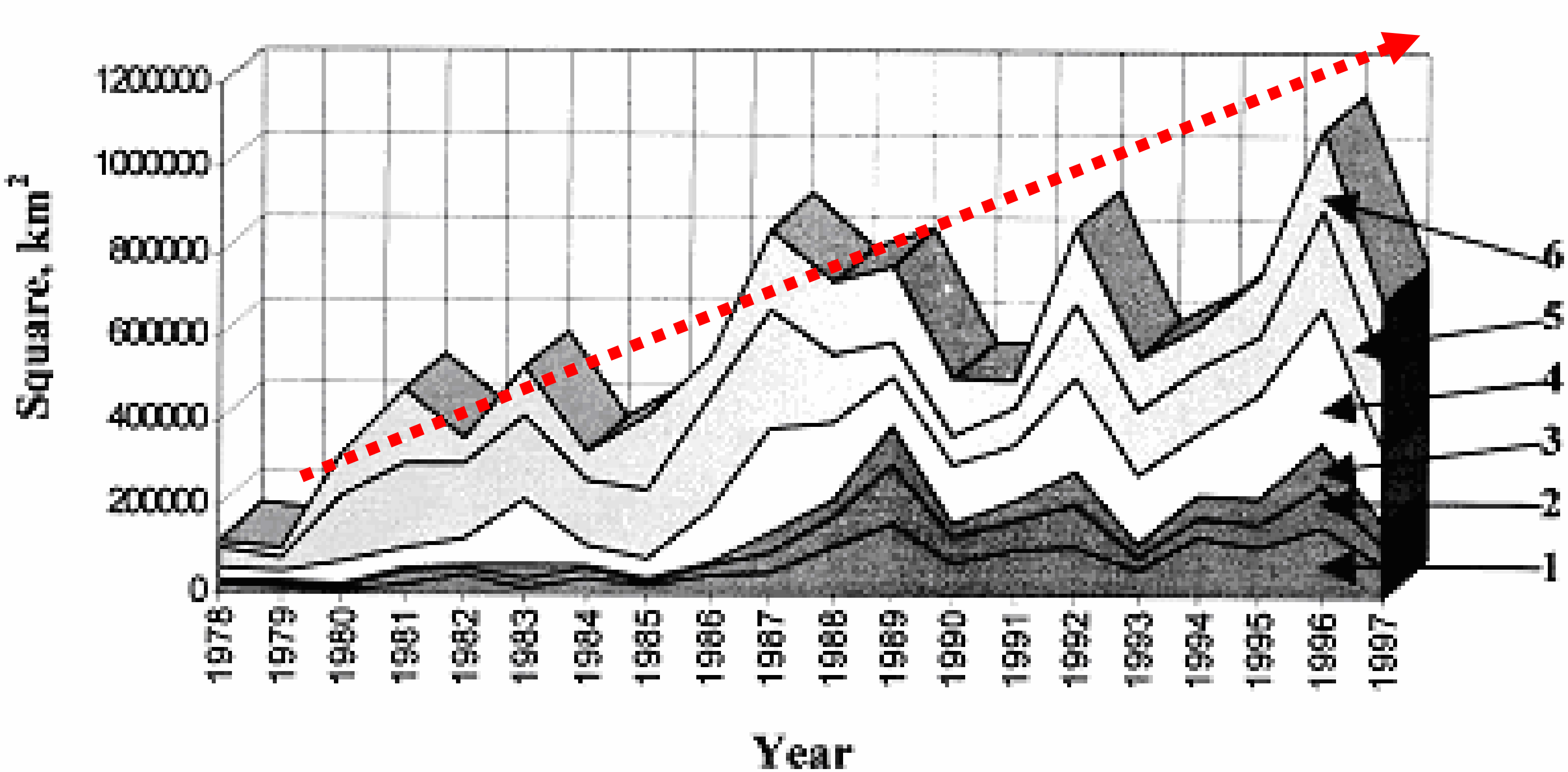


Flaw polynyas (open sea water) start their formation in November, when wind breaks apart fast ice and drifting sea ice.

Area of the ESAS open water in winter **is equal to the total area of Siberian thermokarst lakes open in summer.**



During the last two decades areas of flaw polynyas in the ESAS increased 5 times



Flaw polynyas allow atmospheric methane emissions during the ice-covered period.

Additional factors serving to enhance permafrost destabilization in the ESAS:

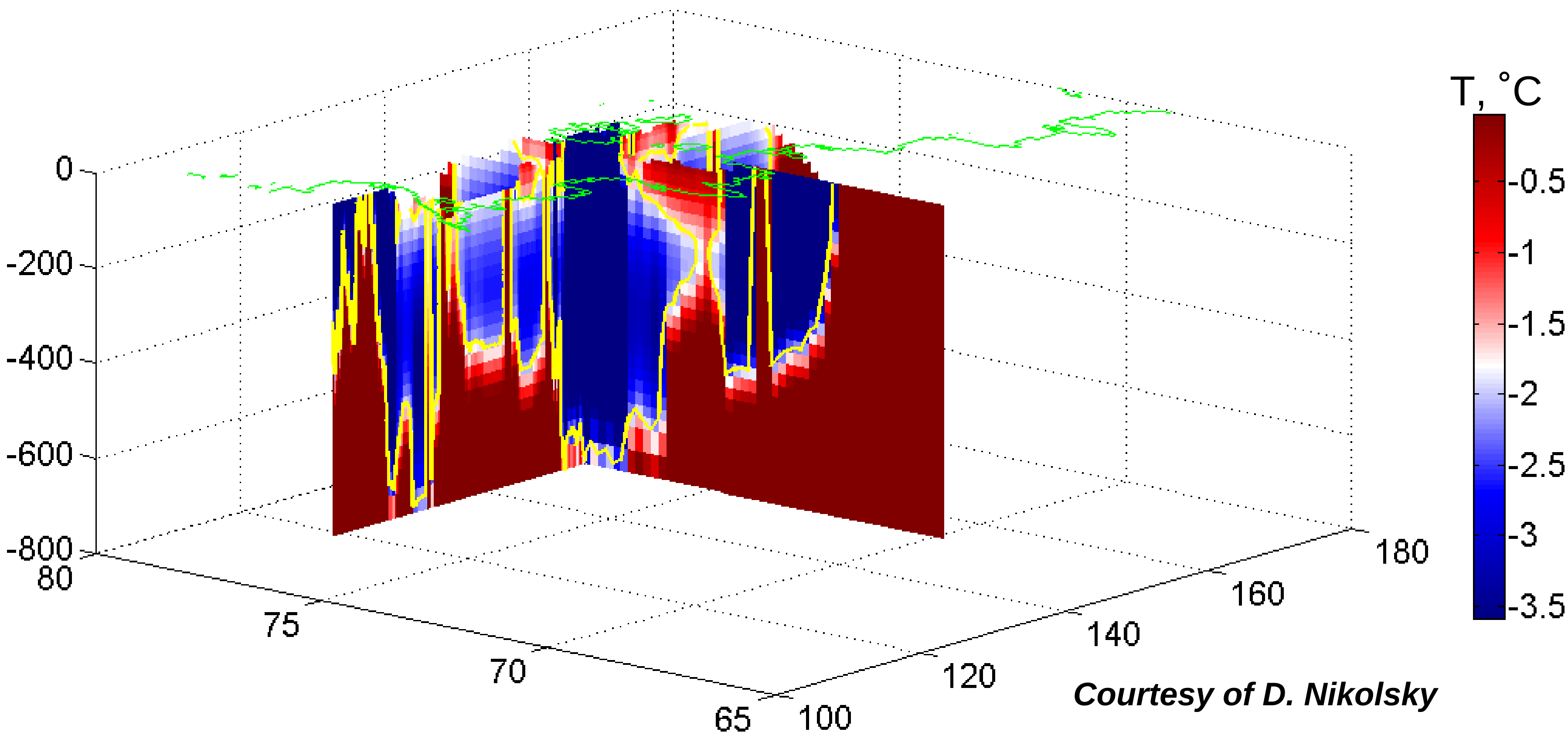
- Decreasing sea ice extent;

- Change in hydrological pattern:

- increasing frequency of high speed winds;
- increasing frequency of deep convection events (mixing to the bottom) during summer;

- Warming of bottom water (up to 3°C during the last three decades)

Recent modeling results suggest wide scaled sub-sea permafrost disintegration



Courtesy of D. Nikolsky

How much is the methane potential of the ESAS?

Accumulated methane potential of the ESAS:

1) ***C**$_{org}$* **in permafrost** ~*500 Gt*;

2) Methane accumulation in **hydrate deposits** (GHSZ=100m) ~***1000*** *Gt*;

3) Free gas beneath the GHSZ ~*700 Gt*;

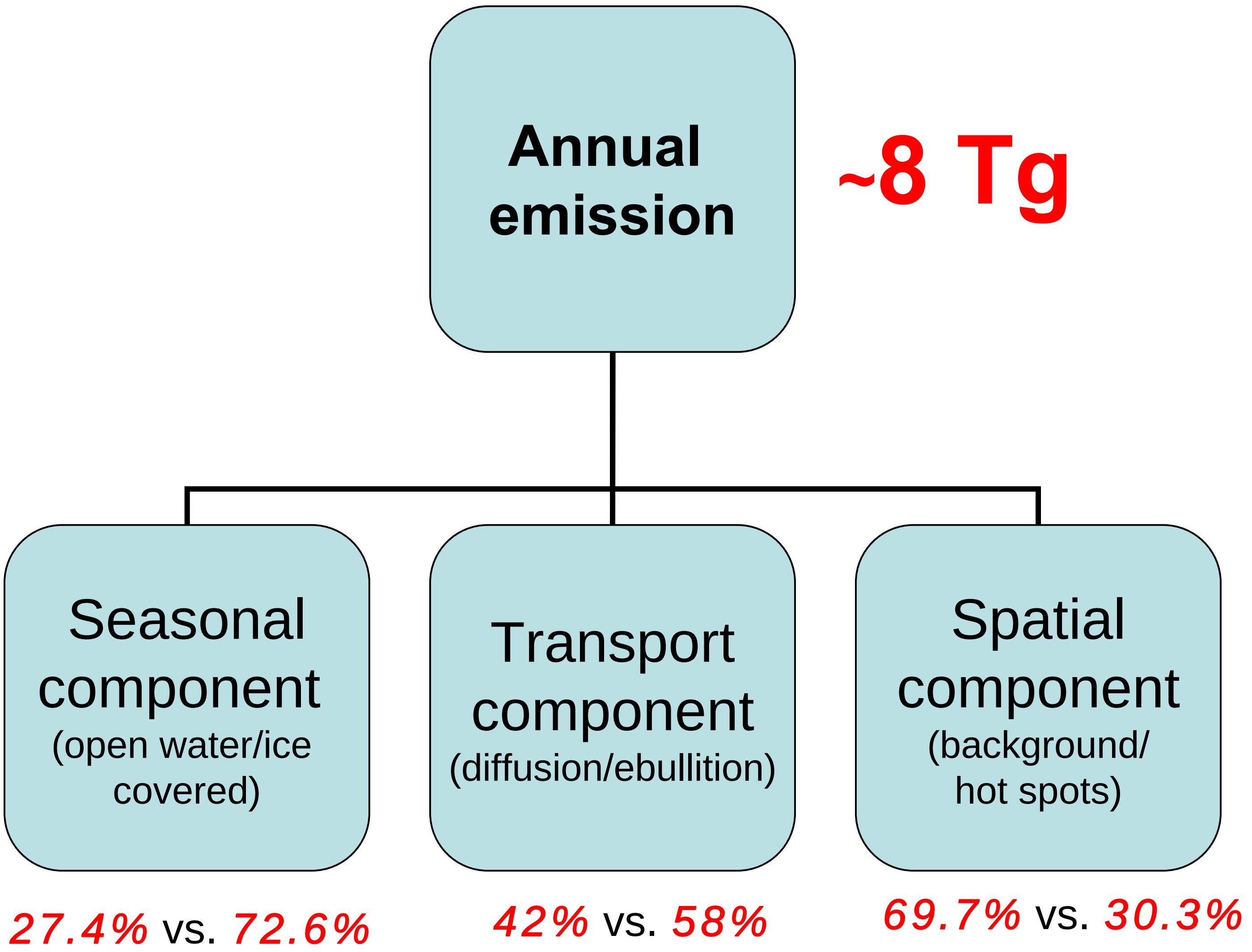
<u>OR</u>:

- **Postponed emissions**:

1 year – 8Tg (Tg=10^{12} g); 1000 years – 8Gt (Gt=10^{15}g); 90 000 years – *720 Gt*;

How much has been currently involved?

Good news: conservative estimate



Bad news: directly observed fluxes exceed estimated by up **3 orders of magnitude**

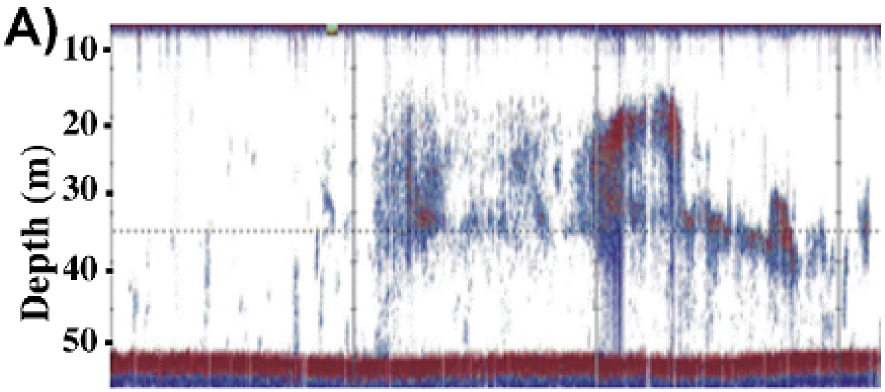
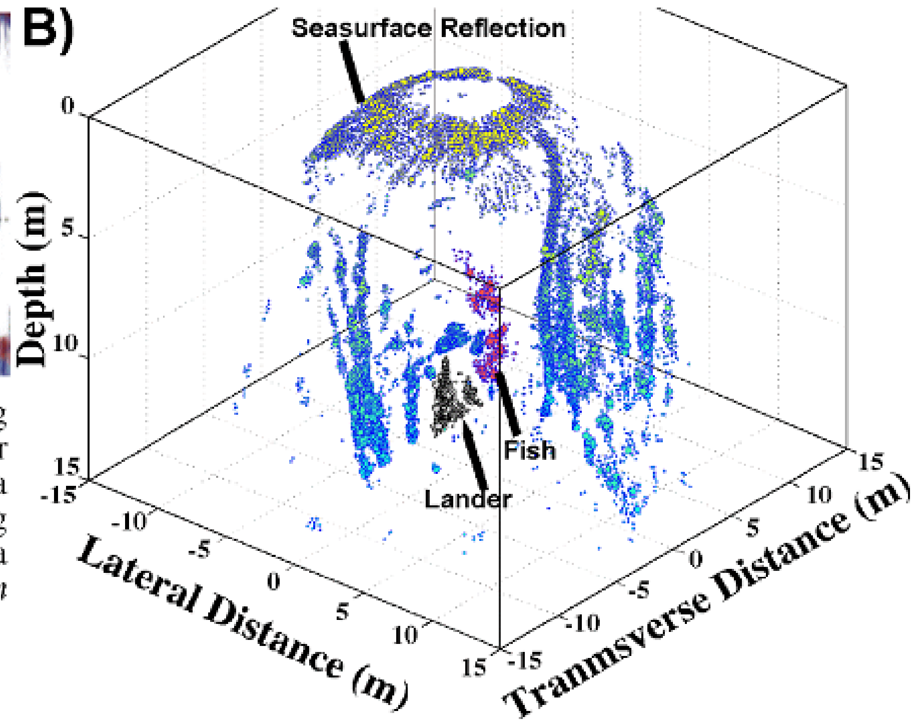
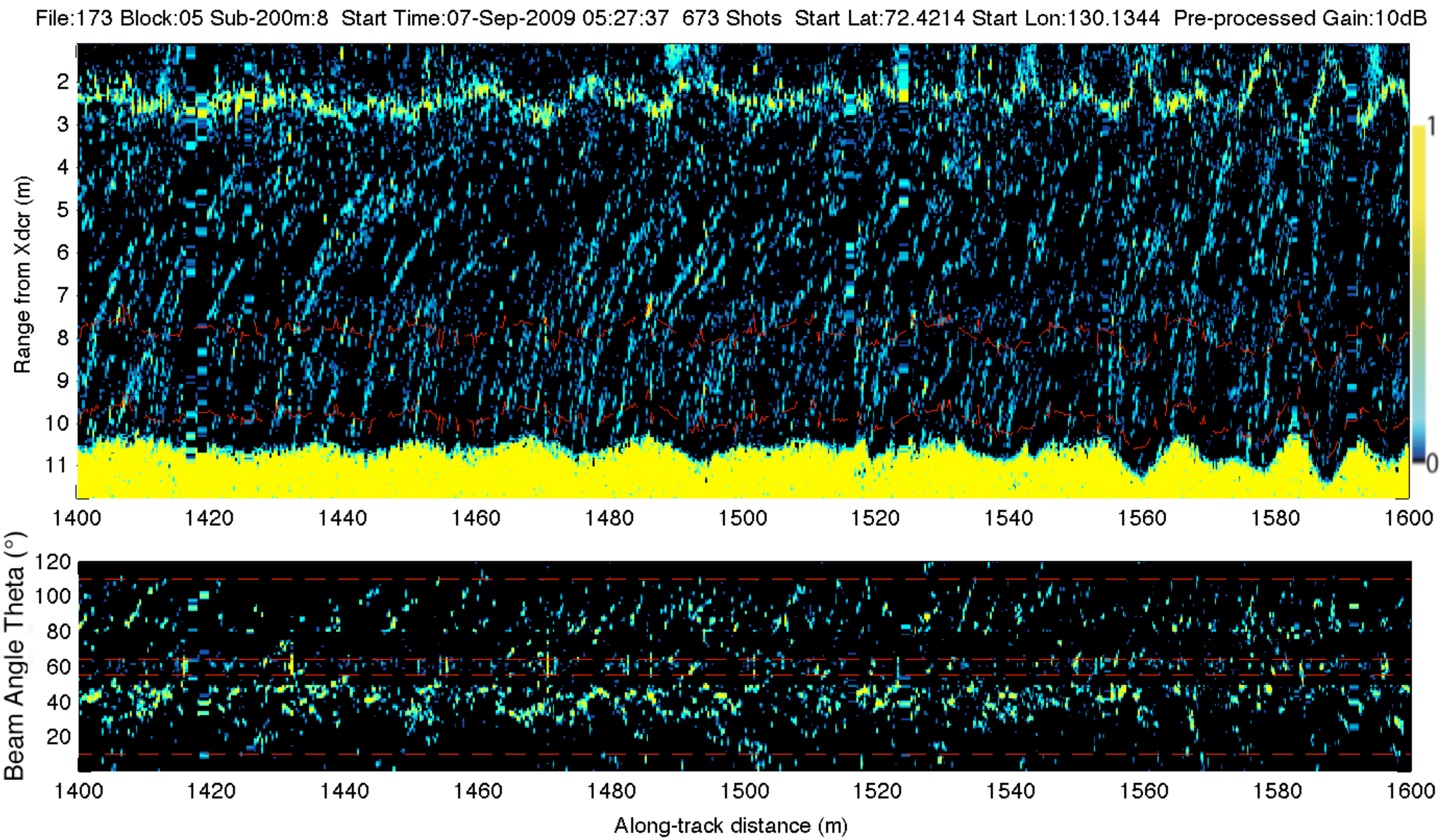


Fig. 2A) Transect of ~500 m in the Laptev Sea showing bubble plume sonar return features, and also zooplankton or other non-bubble scatterers (fish). **2B)** Sonar scanner data (10-min average) from shallow ESAS deployment showing spatial distribution of seep bubble plumes and motions of a fish school of fish (strong sonar returns indicate fish). *From Leifer et al* (2009-in prep).



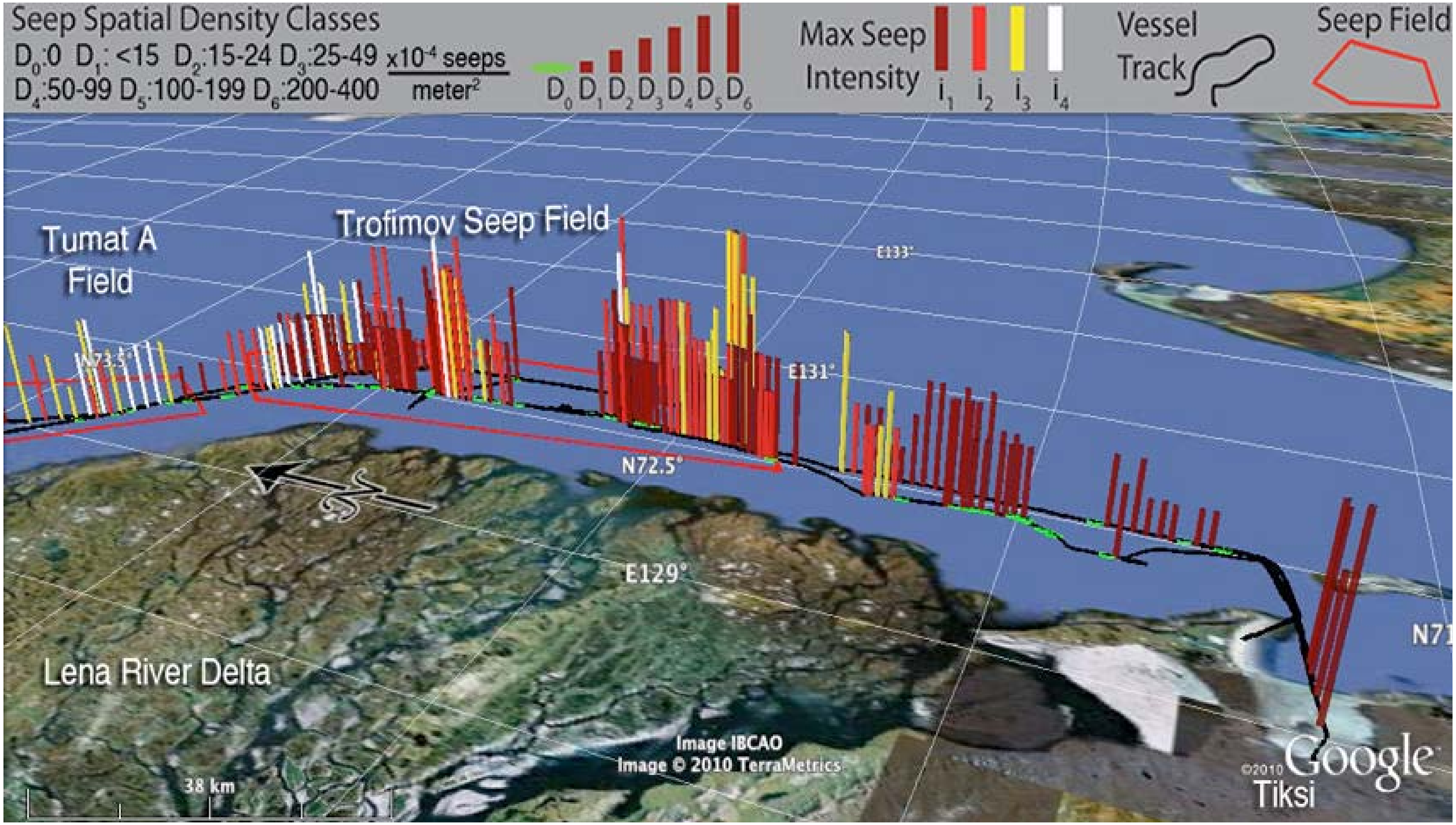
Interpretation of acoustical data recorded with deployed multibeam sonar allowed moderate quantification of bottom fluxes as high as 44 $g/m^2/d$ (*Leifer et al., in preparation*). Prorating these numbers to the areas of hot spots (210×10^3 km^2) adds 3.5Gt to annual methane release from the ESAS. This is enough to trigger abrupt climate change (*Archer, 2005*).

Example from the Trofimov seep field



Examples of plume spatial density class d6: ~40-80 ***seeps per 200 m.***

Map of the Trofimov seep field offshore of the Trofimov Channels, Lena River Delta.



Conclusions:

•Permafrost failure uncorks huge gas reservoir, leading **to large scale releases** of methane from seabed;

•Methane emissions from the ESAS depend on occurrence of gas migration pathways, developing through permafrost body (open taliks; permafrost breaks, discontinuity in sediment layers, fault zones, sediment settlement and adjustment etc.); this determines **non-gradual emission mode**;

•Given that the ESAS is tectonically and seismically active area, seismic events (including endogenous seismicity) might cause **abrupt methane releases;**

Conclusions

- Studying the current state of sub-sea permafrost is **of critical importance in order to elucidate the time scale of the ongoing process;**
- Given that spatial and temporal variability of methane releases is very high, this underscores importance of **establishing monitoring network over the ESAS;**
- Considering the significance of the ESAS methane reservoir and enhancing mechanism of its destabilization, <u>**this region should be considered the most potential in terms of possible climate change caused by abrupt release of methane.**</u>

Thank you for your attention!