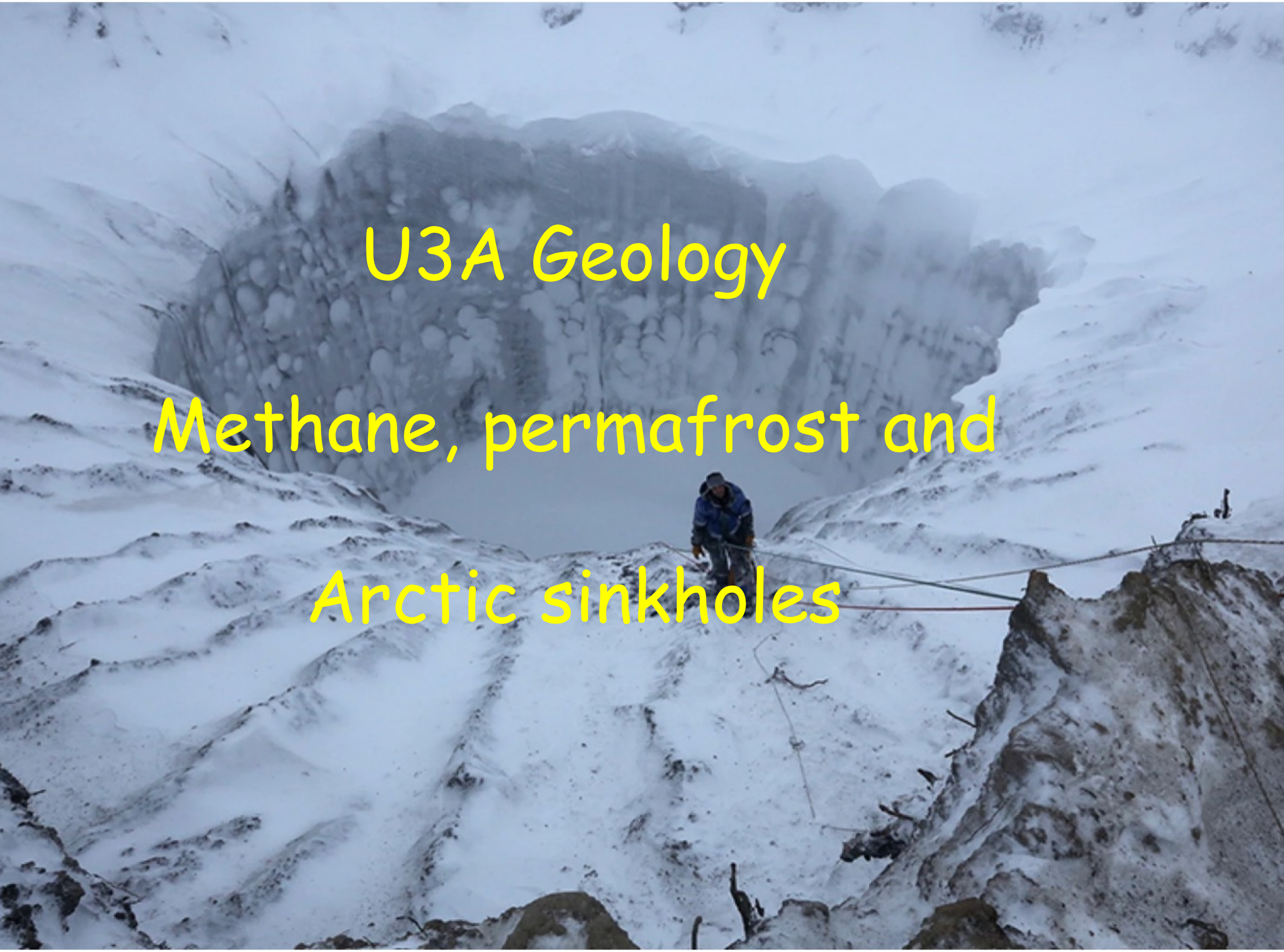

U3A Geology
Methane, permafrost and
Arctic sinkholes

Introduction

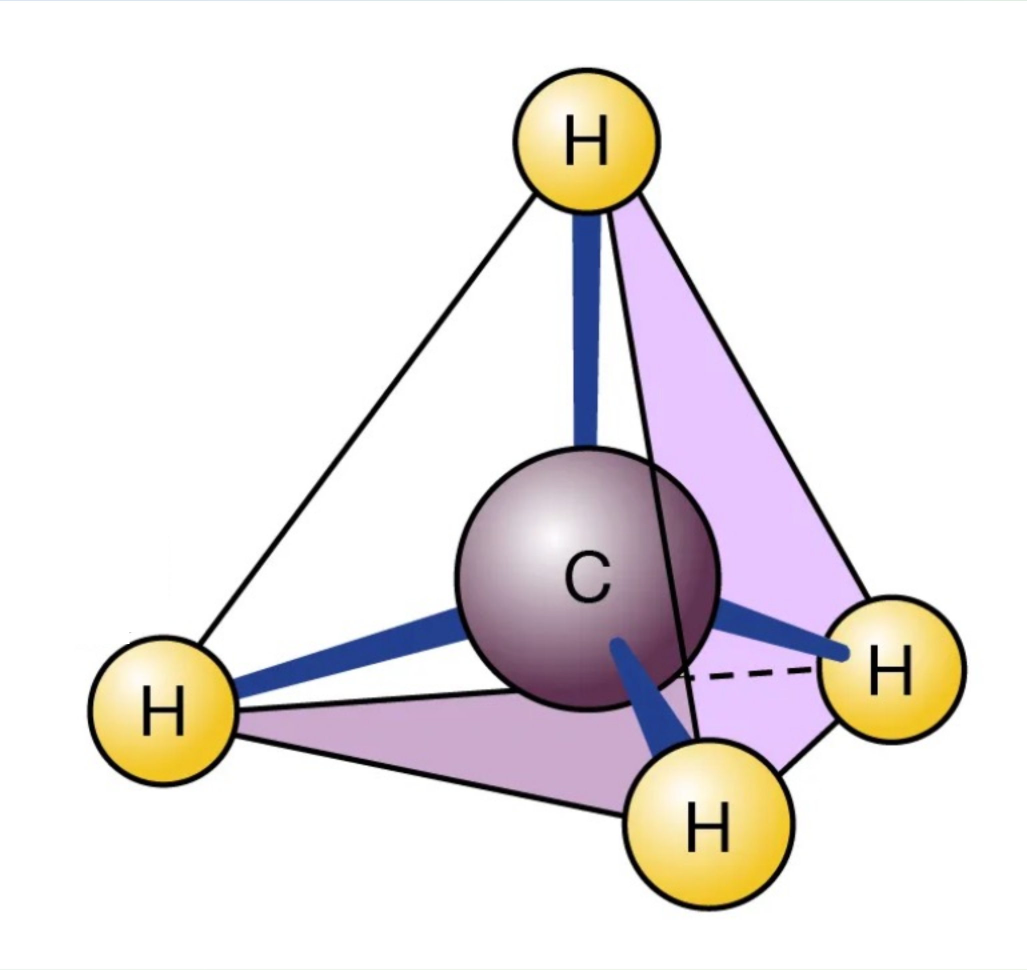
- Giant sinkholes have formed on a remote part of the seafloor and on land in the Arctic
- many massive sinkhole craters have been discovered in part of the Russian Arctic (Yakmal Peninsula)
- scientists believe that these craters formed when the buildup of pockets of methane gas in the ground spontaneously exploded
- the phenomena are believed to be due to climate change and the melting of permafrost

Methane

- Methane is a gaseous hydrocarbon that is a primary component of natural gas
- it is a much more powerful greenhouse gas than CO_2
- naturally occurring methane is found both beneath the ground and under the seafloor and is formed by both geological and biological processes
- the largest reservoir of methane is under the seafloor in the form of methane clathrates
- methane is produced at depth by anaerobic decay of organic matter and reworked methane from deep under the Earth's surface

Methane structure

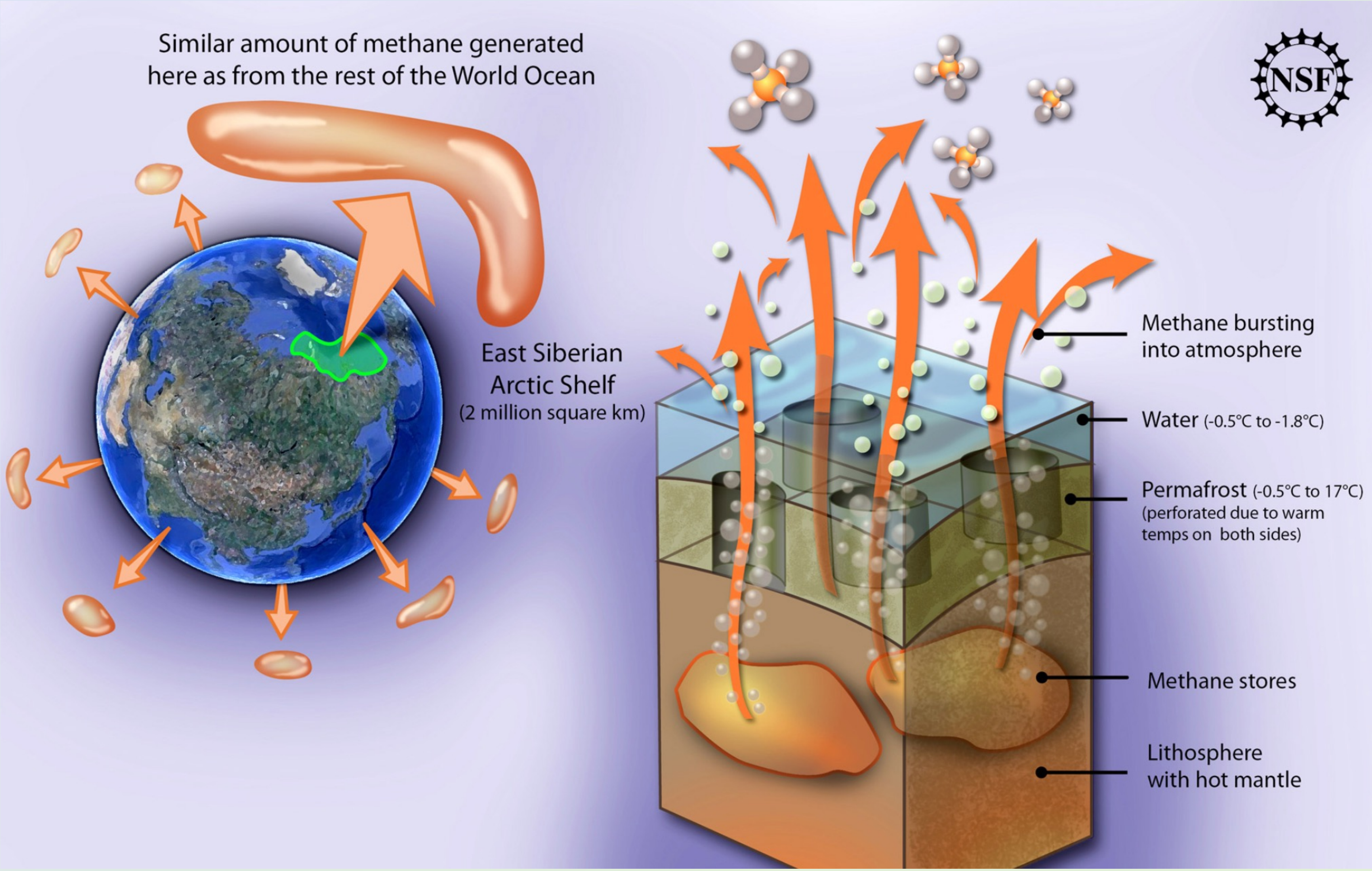
Methane has the chemical formula CH_4 with 4 C-H bonds



Methane generation

- Methane is generated by biological oxidation of organic substances (e.g. animal waste, plant refuse) in the absence of oxygen
- permafrost liberates frozen organic carbon that is decomposed into CO_2 and CH_4
- large quantities of methane are stored in the Arctic natural gas deposits and as clathrates under the sea floor
- global warming in the Arctic accelerates methane release from both existing stores and methanogenesis in rotting biomass
- since methanogenesis requires anaerobic conditions, it is frequently associated with arctic lakes where bubbles of methane are observed

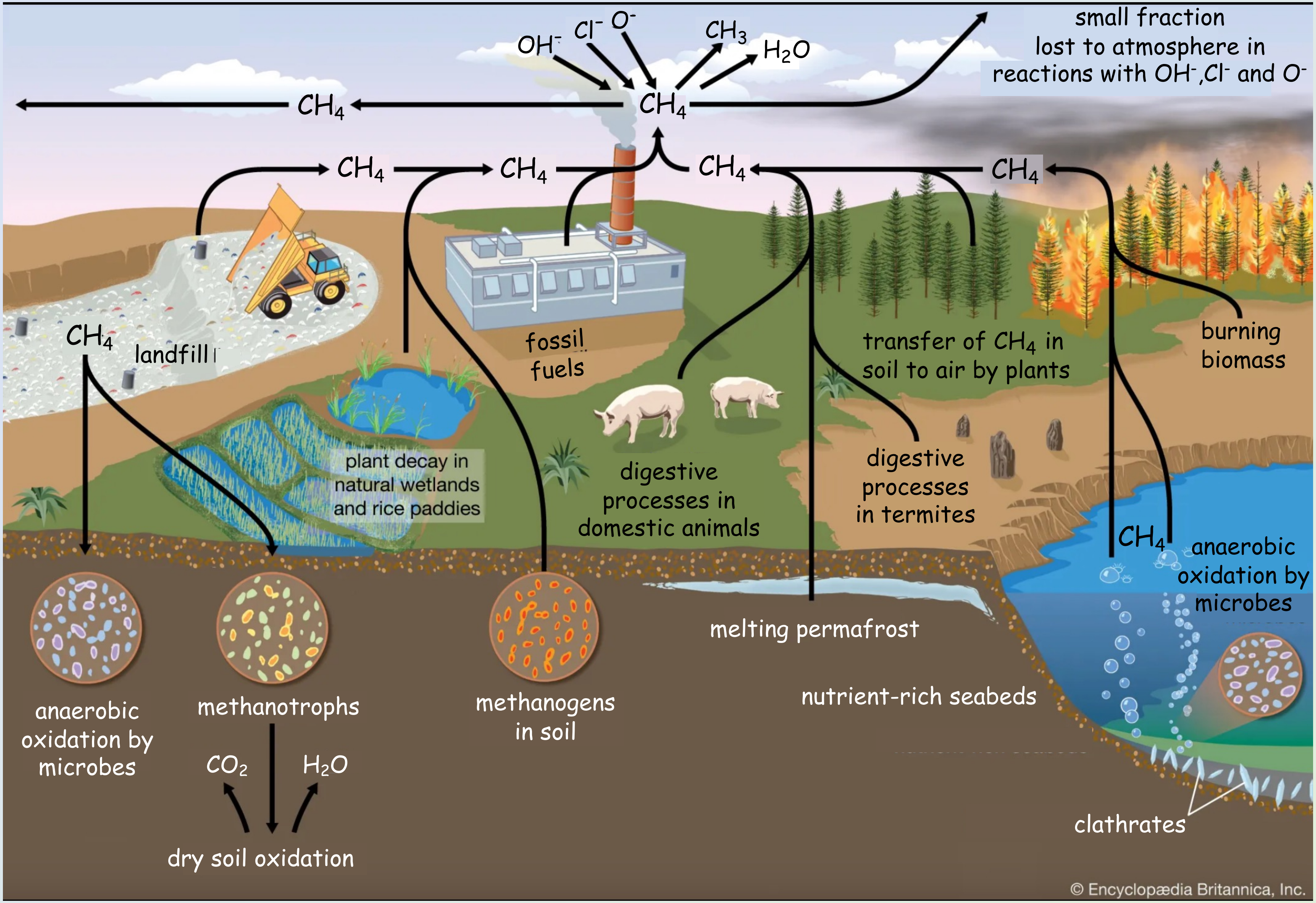
Methane generation



Methane cycle

- In nature, methane is produced by the anaerobic bacterial decomposition of organic matter under water
- wetlands are the major natural source of methane produced in this way
- other important sources → termites (result of digestive processes), volcanoes, sea floor vents and methane hydrate deposits
- methane hydrate (clathrate) deposits occur along continental margins, beneath Arctic and Antarctic permafrost and ocean floors

Methane cycle



Natural methane deposits

- Methane → restricted to shallow lithosphere (<2000m)
- necessary conditions only found in polar regions where the average surface temperature 0°C or in oceanic sediments at water depths >300m where water temperatures ~2°C
- deep water lakes may host methane hydrates e.g. Lake Baikal, Siberia
- Abraham Lake on the eastern side of the Rocky Mountains in Canada is known for frozen methane bubbles in Winter

Methane emissions

- Global warming in the Arctic accelerates methane release from both existing stores and and methanogenesis in rotting biomass
- since methanogenesis is associated with anaerobic conditions it is frequently associated with Arctic lakes where methane bubbles are observed
- not all methane produced reaches the atmosphere → some may be oxidised in the water column or in sediment
- wetlands are responsible for approximately 80% of global methane emissions from natural resources

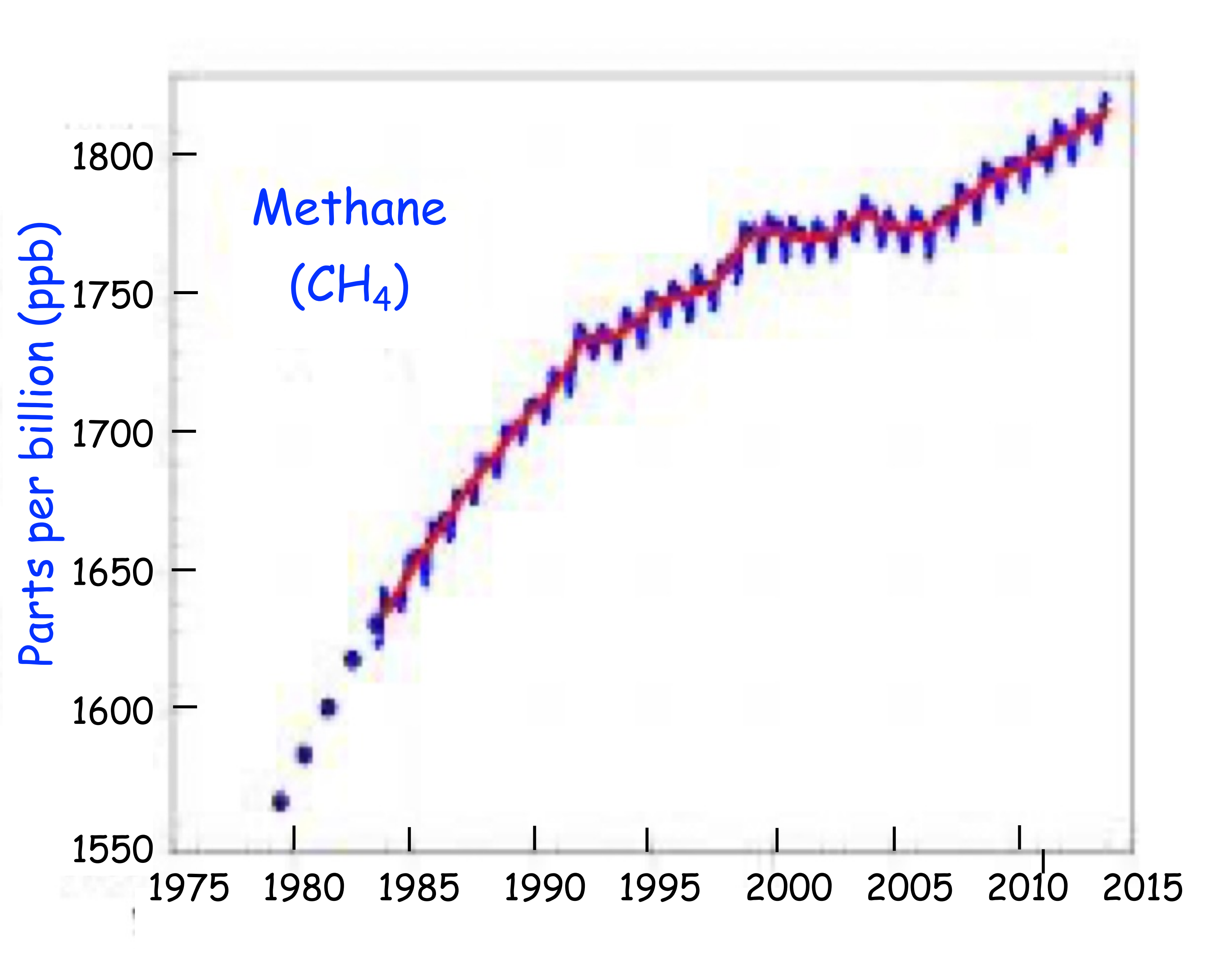
Arctic methane emissions

- Arctic methane release is the release from seas and soils in permafrost regions of the Arctic
- the Arctic region is one of the natural sources of the greenhouse gas methane
- large deposits of methane are stored in Arctic gas deposits and undersea clathrates
- another process that frequently results in methane emissions is the collapse of permafrost stabilised hillsides

Role of methane as a greenhouse gas

- Since 2007 methane concentrations in the Earth's atmosphere has increased by 6.8 – 10ppb
- by 2022 atmospheric methane reached 1909ppb ~3 times higher than preindustrial levels that were in the order 600 – 700ppb
- increased levels of methane contribute to the greenhouse effect → absorb infrared radiation and radiates it back to Earth
- although its atmospheric concentration is much less than CO_2, CH_4 is >30 times more effective in trapping greenhouse gases than CO_2
- the atmospheric residence time of methane is ~8years until oxidised into CO_2 and water

Atmospheric methane concentration



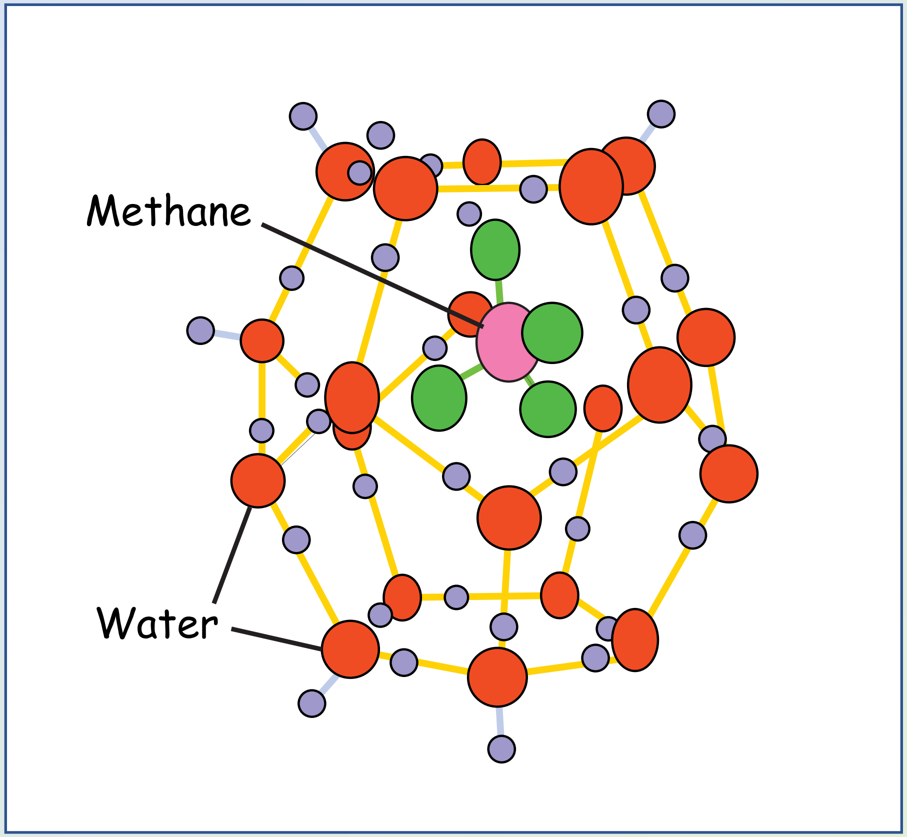
Methane contribution to climate change

- Due to relatively short lifetime of atmospheric methane, its global trends are more complex than those of CO_2
- since around 2018 there has been a consistent acceleration in annual methane increases
- there is no evidence connecting the Arctic to recent growth trends
- a 2022 paper connected tropical terrestrial emissions to 80% of global methane trends between 2010-2018

Methane clathrates (hydrates)

- Clathrates (gas hydrates) are water-based solids in which gas is trapped inside of frozen water molecules
- methane clathrate ($CH_4 \cdot 5.75H_2O$) is a clathrate in which a large amount of methane is trapped within a crystal structure of water, forming a solid similar to ice
- significant amounts of methane clathrates are found in sediments on the ocean floors of the Earth
- some clathrates in the Arctic are much shallower than elsewhere → more vulnerable to warming

Methane clathrate (hydrate) structure

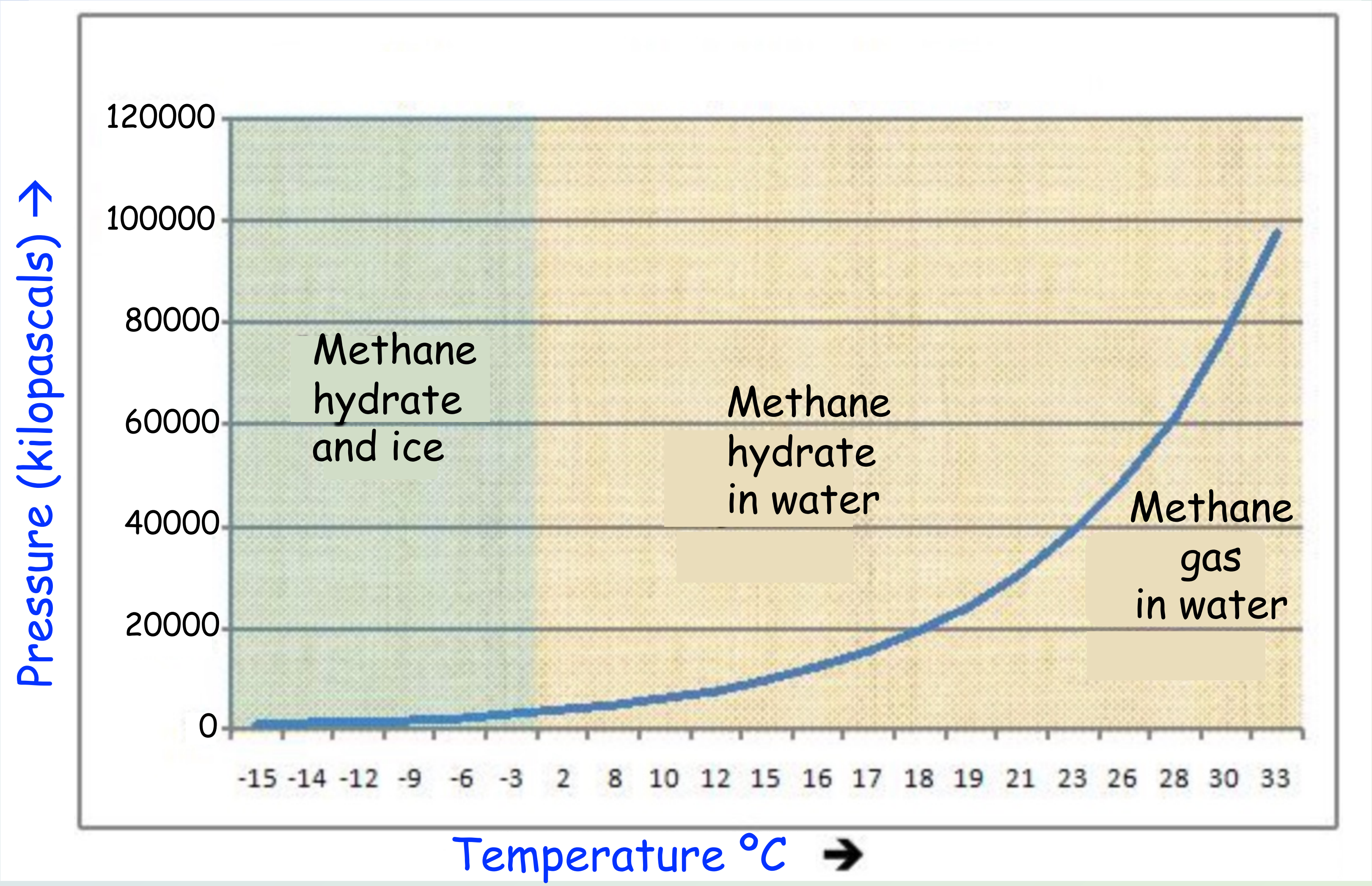


Methane clathrate formation

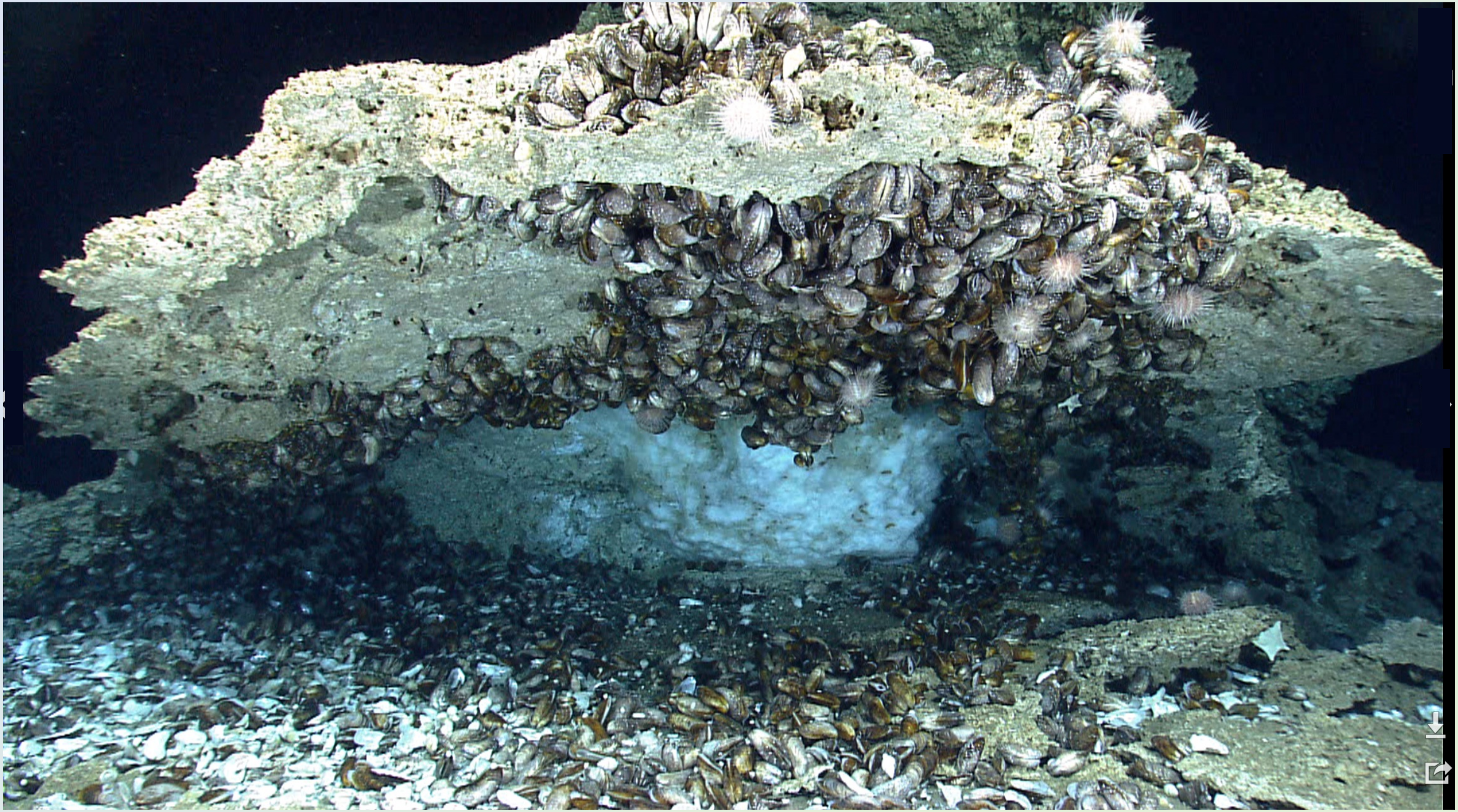
- Most clathrate deposits are formed when water and methane gas come into contact at high pressures and low temperatures in oceans
- they are thought to form by the precipitation of methane migrating from deep along geological faults
- a sustained increase in sea temperatures will slowly warm its way down through the sediment causing most shallow clathrates to break down → release methane
- the density of methane clathrates is around 0.9g/cm^3 that means that methane clathrates will float to the surface of the sea or lake unless anchored to the sediment

Methane hydrate P-T phase diagram

Methane clathrate is released as gas into water/soil when ambient temperature increases



Clathrates trapped below limestone, Gulf of Mexico



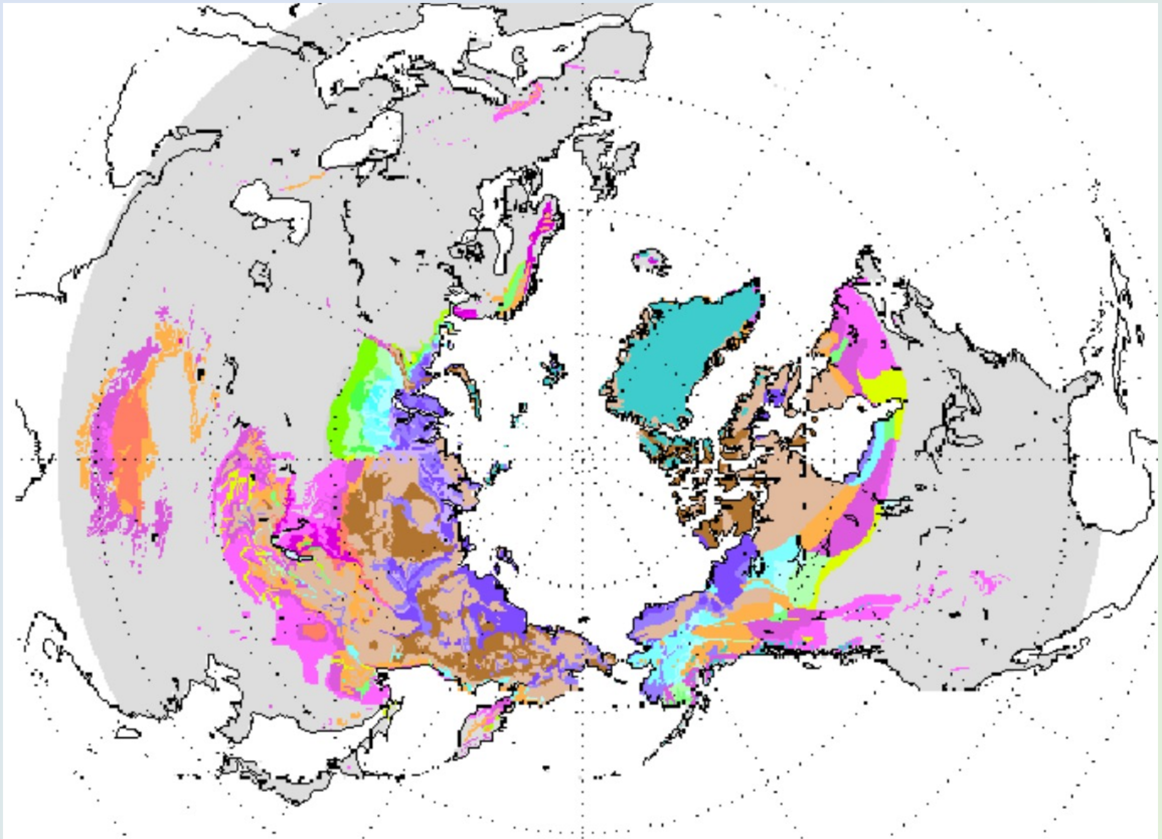
Permafrost

- Permafrost → permanently frozen layer on or under the Earth's surface
- consists of soil, gravel, sand and organic material usually bound together by ice
- permafrost usually remains at or below 0°C for at least 2 years
- permafrost thickness can range from 1->3000m
- permafrost can be found on land and below the sea floor
- ~ $\frac{1}{4}$ of land in the Northern Hemisphere is underlain by permafrost including Greenland, Alaska, Russia, China and Eastern Europe

Permafrost

- When permafrost thaws, large amounts of organic material may be available for methanogenesis and be ultimately released as clathrates
- permafrost contains large amounts of dead biomass accumulated over millenia without fully decomposing
- oldest permafrost has been continuously frozen for ~700,000 years
- ~15% of northern hemisphere and 11% of the global surface is underlain by permafrost with total area ~18million km^2
- only a minority of permafrost exists in the southern hemisphere on mountain slopes of the Andes, Patagonia; Southern Alps of NZ and highest mountains of Antarctica

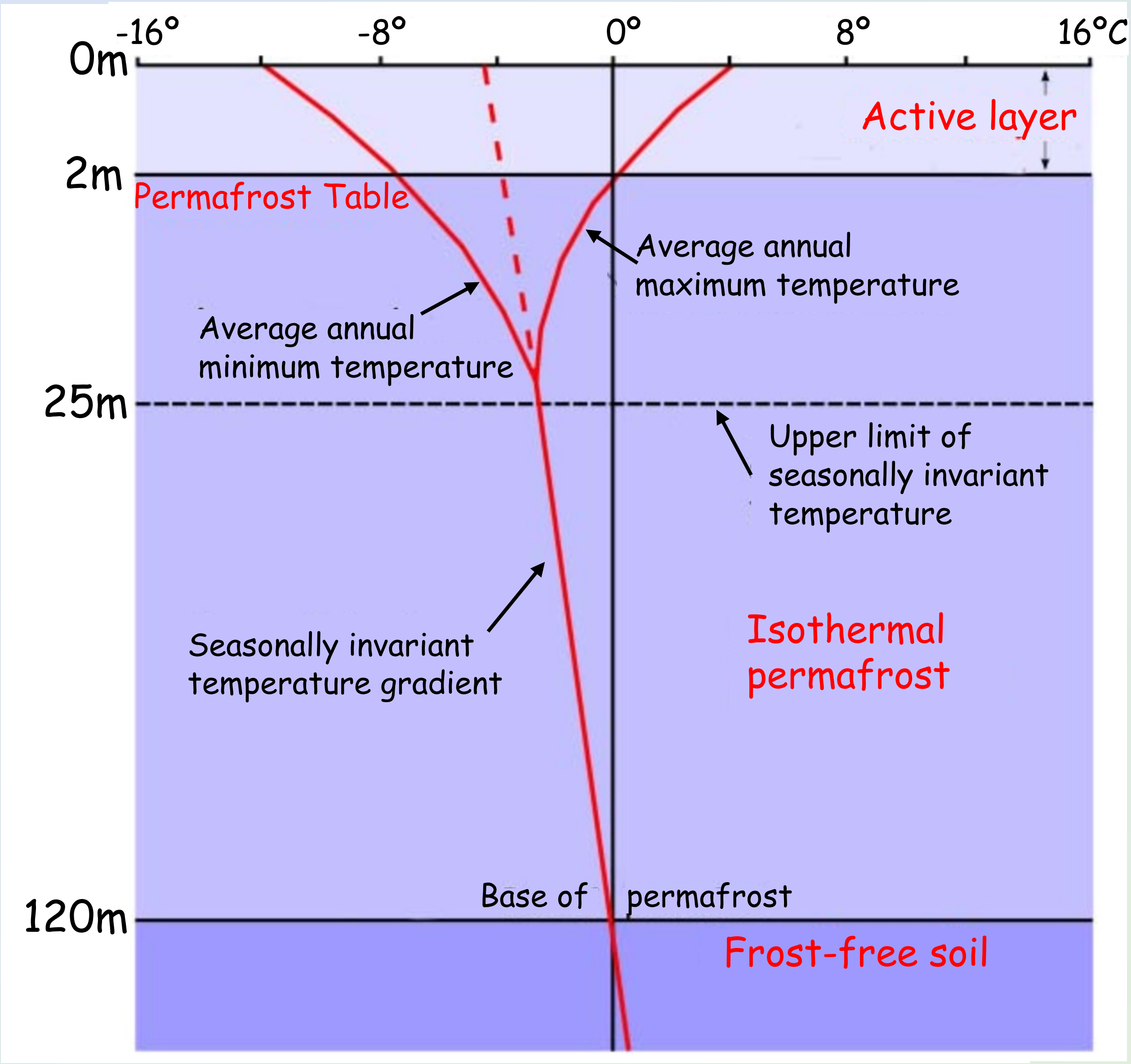
Permafrost extent



Permafrost Extent (% of area)	Ground ice content (visible ice in upper 10-20m of the ground % by volume)				
	Lowlands, highlands and interim montane depressions characterized by thick overburden cover (>5-10m)			Mountains, highlands, ridges, and plateau characterized by thin overburden cover (<5-10% and exposed bedrock)	
	High (>20%)	Medium (10-20%)	Low (0-10%)	High-medium (>10%)	Low (0-10%)
Continuous (90-100%)					
Discontinuous (50-90%)					
Sporadic (10-50%)					
Isol. patches (0-10%)					

Ice caps and glaciers

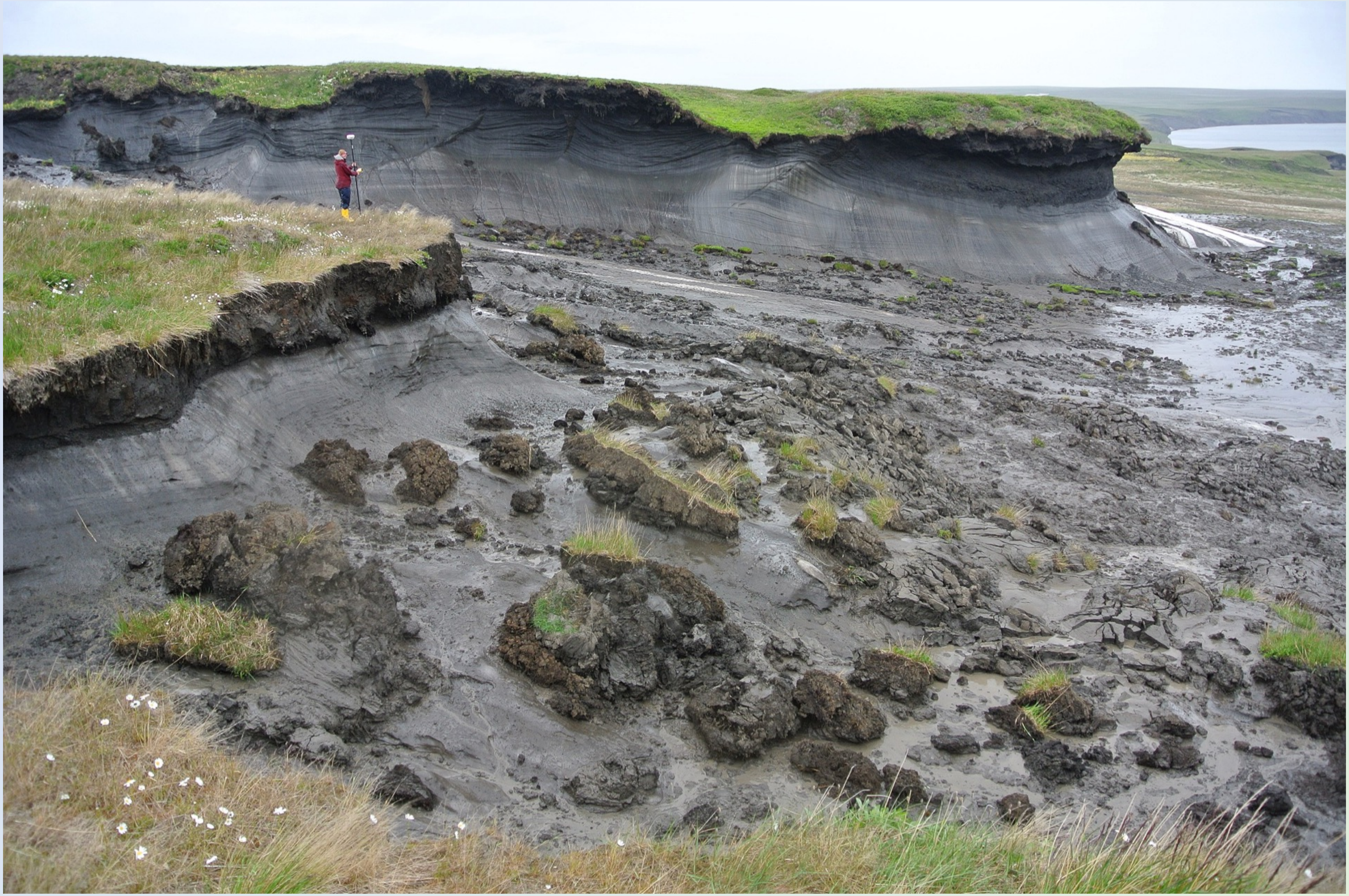
Permafrost profile



Thawing of permafrost

- Studies indicate that permafrost warmed by 6°C during the 20th century, widespread thawing of permafrost predicted by 2100
- thawing permafrost can raise water levels in the Earth's oceans and increase erosion
- less than 20% of northern hemisphere permafrost is susceptible to rapid thaw that occurs where permafrost contains high levels of ice in the soil
- permafrost degradation normally a slow process of a few cm/year → rates greatly increased
- the increased change in rate of melting of permafrost has surprised Russian scientists

Melting permafrost

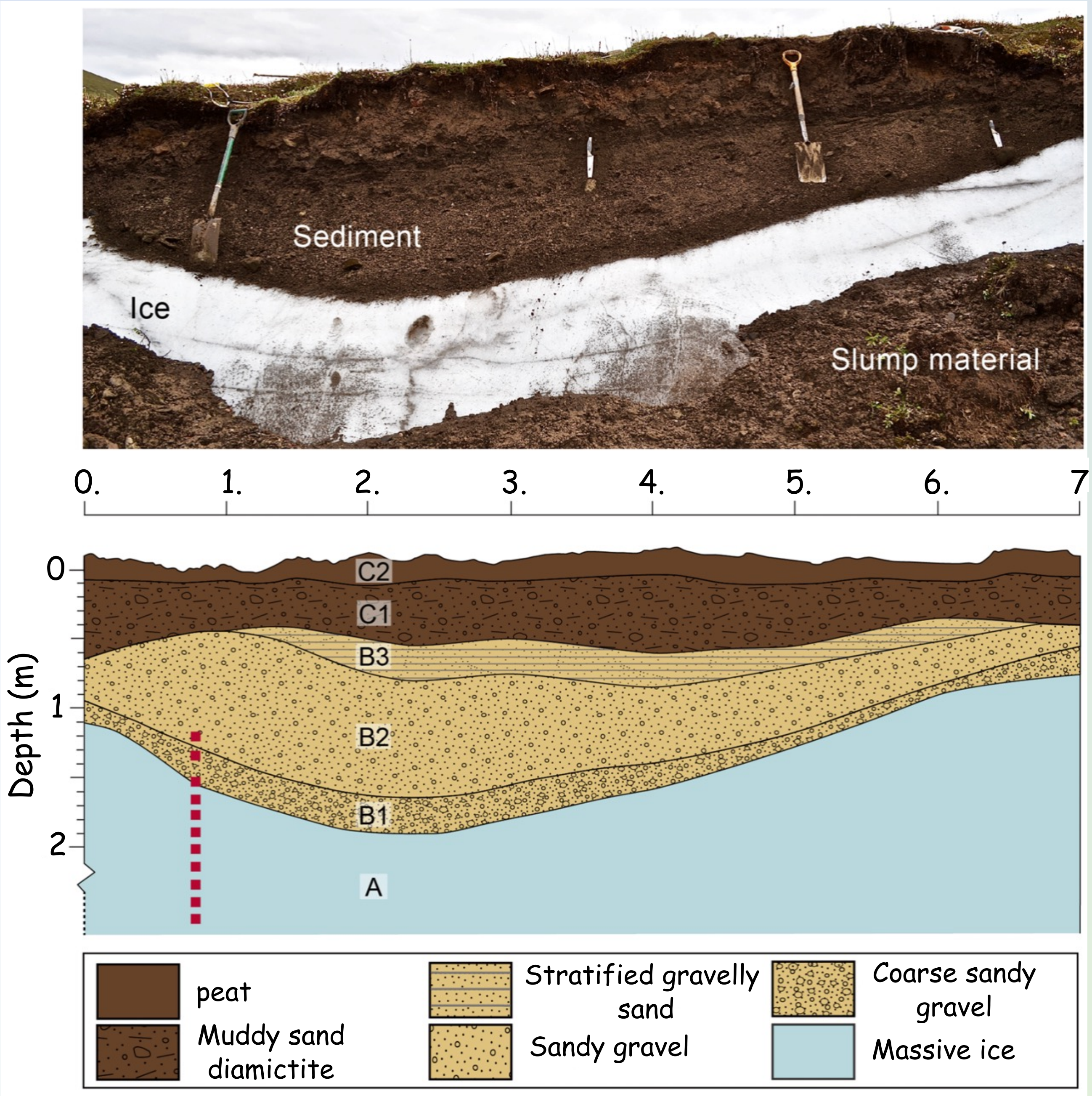


Melting permafrost, Herschel Island, Canada

Thermokarst

- When ice-rich permafrost thaws, it leads to a phenomenon called thermokarst
- thermokarst is an erosional process unique to permafrost with excess ice and forming characteristic landforms e.g. marshy hollows, depressions, small lakes and small depressions
- thermokarst depressions or landslides occur very quickly in a matter of days or weeks
- small domes that form due to frost heaving with onset of winter, collapse during following summer leaving small surface depressions
- thermokarst land surfaces occur in Arctic and mountainous areas

Buried ice deposit, Bylot Is. Canada



Methane from permafrost below lakes

- Two things happen as the permafrost layer thaws beneath lakes
  → microbial activity increases and pathways form in the permafrost
- microbes digest dead plants and other organic matter in the previously frozen soil → produces CO_2 and CH_4
- more rarely, permafrost thaw can produce chimneys under lakes
  → allow methane and other trapped gases to escape
- as lake freezes in winter, gas bubbles can prevent ice forming creating open areas that continue emitting methane
- in other areas methane bubbles form frozen domes on lake surface

Methane from below Lake Esieh, Alaska

Methane bubbles Lake Esieh, Alaska

Methane ignition, Lake Esieh

Frozen methane bubbles, Lake Abraham, Canada

The effects of global warming on permafrost

- As global warming heats the ecosystem, frozen soil thaws and becomes warm enough for decomposition
- decomposition can either release CO_2 or CH_4 and these greenhouse gas emissions act as climate change feedback
- rapidly thawing permafrost in the Arctic, causes hillsides to collapse and massive sinkholes to open

Pingos

- Pingo → intrapermafrost ice-cored hills covered by a soil layer, 3-70m high and 30-1000m in diameter. They grow and persist only in permafrost areas
- evidence of collapsed pingos in an area indicates that there was once permafrost
- pingos collapse due to melting of supporting ice creating a depression in the landscape
- it is estimated that there are more than 11,000 pingos on Earth

Pingos

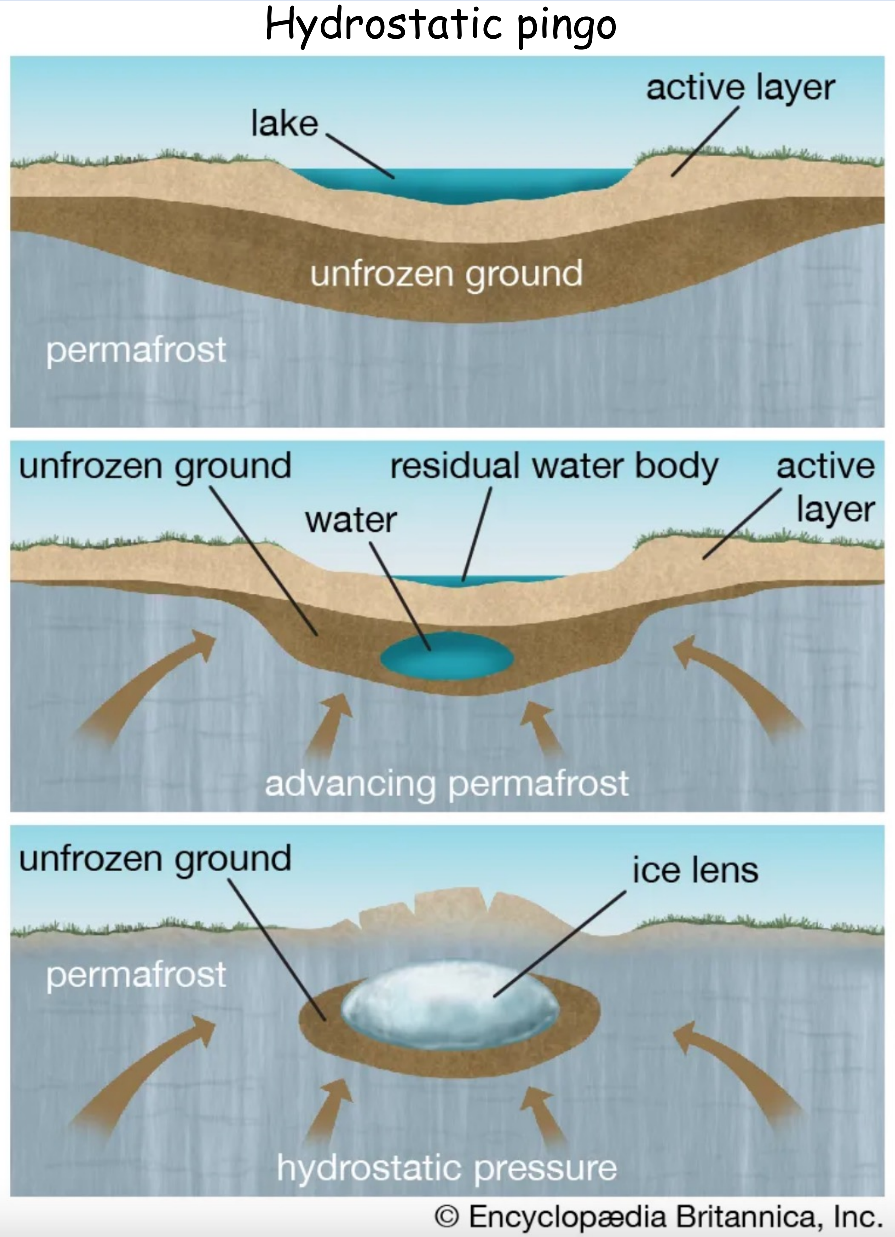
Pingos, Northern Canada

Collapsed pingo in the McKenzie belt, Canada. Outline of previous lake is evident

Hydrostatic pingos

- Hydrostatic pingos are formed as a result of hydrostatic pressure built up in pingos due to water
- found in flat, poorly drained areas with limited groundwater available
- formation of these landforms occurs when layers of permafrost generate upwards movement or pressure resulting in soil freezing → pushes material upwards

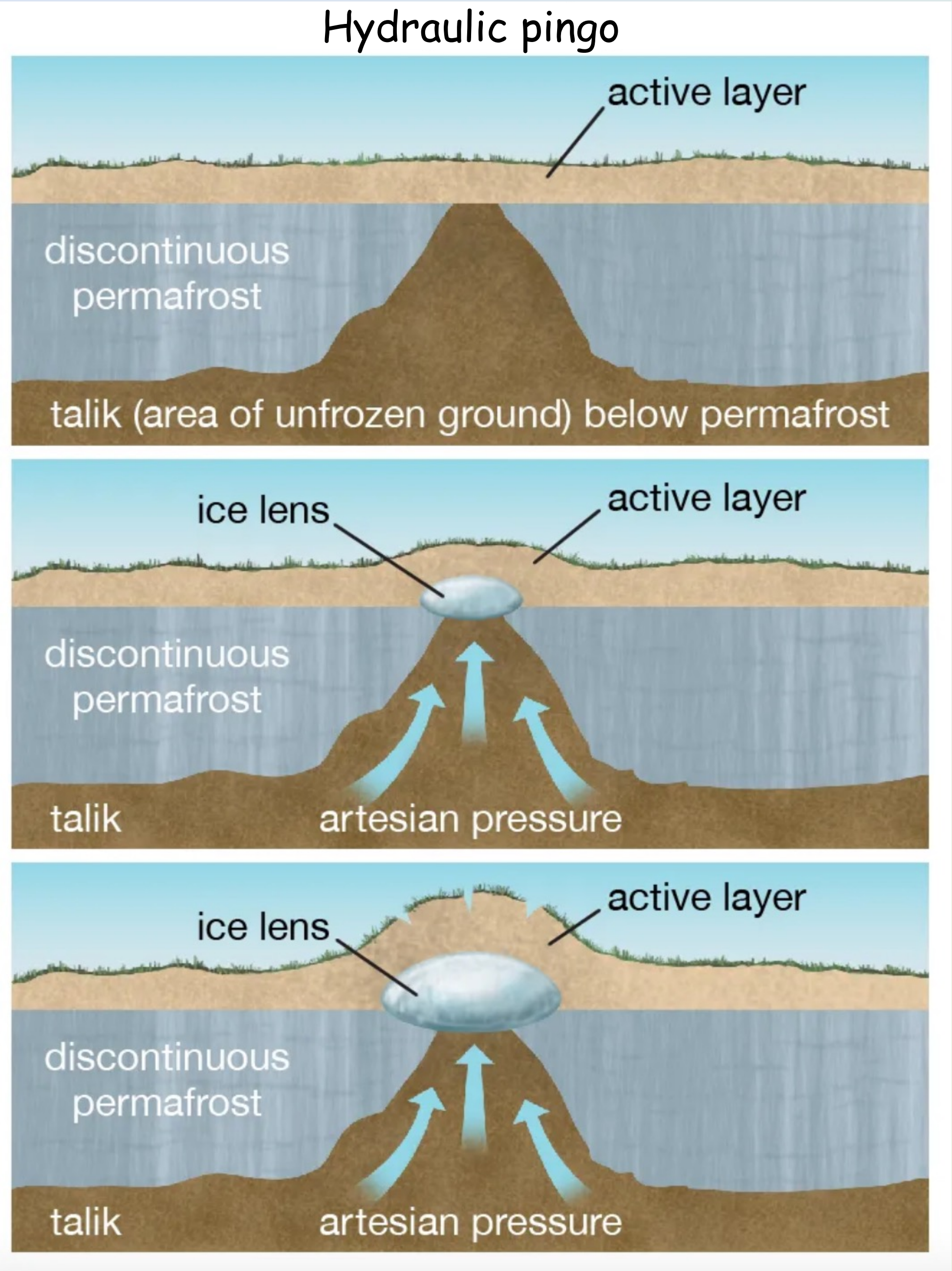
Formation of hydrostatic pingo



Hydraulic pingos

- Hydraulic pingos result from groundwater flowing from an outside source i.e. sub-permafrost or intra-permafrost aquifers
- they often occur at the base of slopes
- groundwater is under artesian pressure and forces the ground upwards as it makes an expanding ice core
- it is not artesian pressure that forces the ground up, but the ice core being fed water from the aquifer

Formation of hydraulic pingo



Taliks

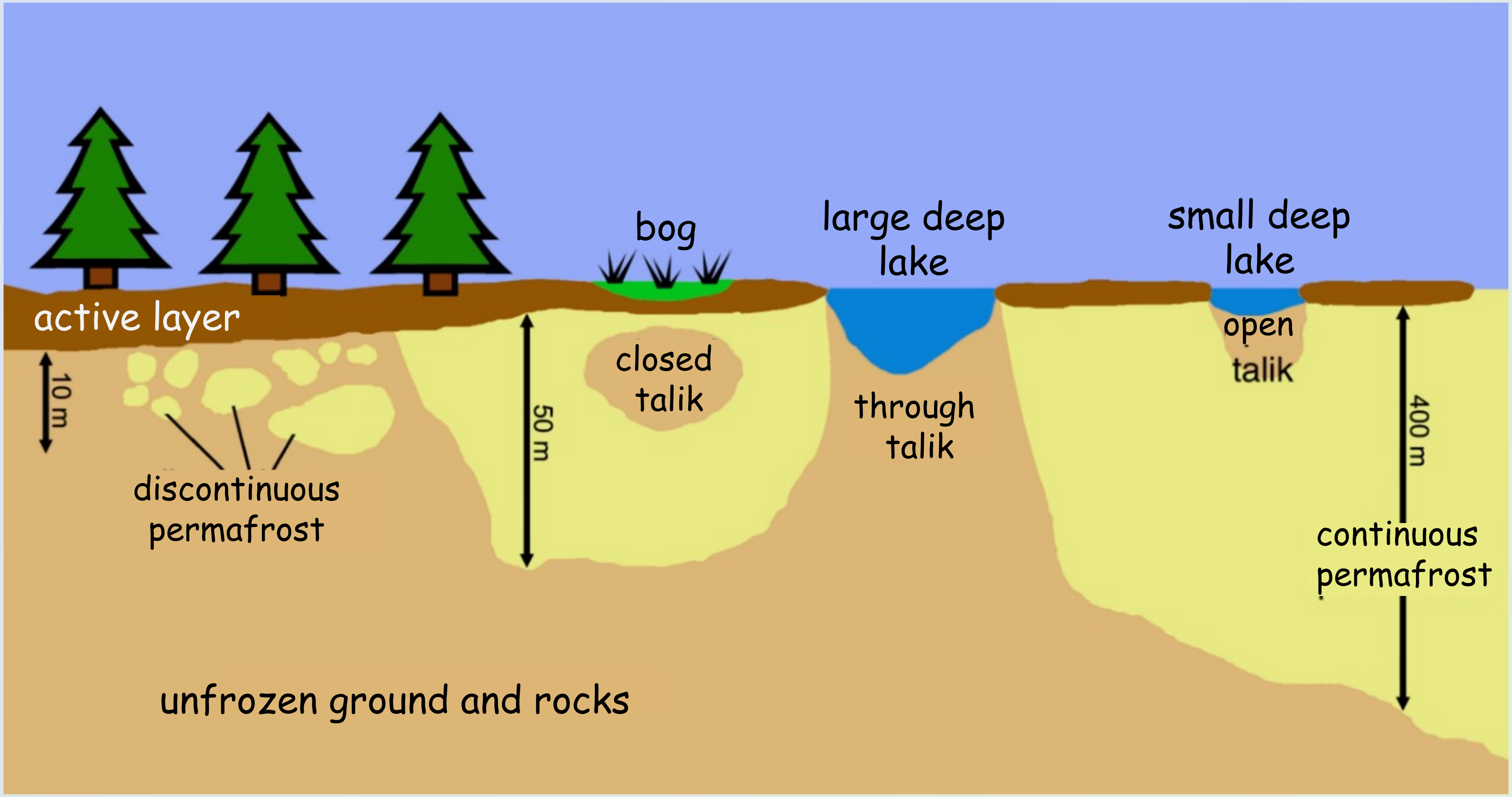
- Talik → layer of year round unfrozen ground that lies in permafrost areas

- often occur beneath shallow thermokarst lakes and rivers where water and soil do not freeze in winter

- taliks are sometimes closed, open or through

- these terms refer to whether the talik is surrounded by permafrost, open at the surface or, open both at the surface and above an unfrozen layer beneath the permafrost

Taliks



bog
large deep lake
small deep lake
active layer
closed talik
open talik
10 m
50 m
through talik
400 m
discontinuous permafrost
continuous permafrost
unfrozen ground and rocks

Arctic sinkholes

- On land, thawing permafrost has caused radical changes to the landscape
- these include formation and disappearance of lakes, emergence of pingos and blowouts of methane gas contained in permafrost
- over the last decade, residents of a remote corner of Siberia have reported huge explosions and boulders flying through the air
- new large holes were discovered with the longest 25m wide and 45m deep
- according to measurements made by Russian scientists, methane concentrations at the bottom of one of the holes was thousands of times higher than the atmosphere

Arctic sinkholes

Sinkhole on Yamal Peninsula, Siberia

Arctic sinkholes

- In Alaska, large lakes ere discovered with bubbling methane derived from vast layers of the gas trapped under rapidly melting subsoil
- scientists discovered that Arctic landscapes are ticking time bombs with vast amounts of methane released by melting permafrost
- the warming has started to decompose gas hydrates
- the pressure increased so high that it actually erupted material out of the crater
- the Siberian craters are located in a primary area of natural gas extraction

Sinkholes on the Arctic sea floor

- Sinkholes are opening on the Arctic seafloor some as large as city blocks
- this observation was based on high resolution bathymetric surveys of the Canadian Beaufort Sea
- high levels of methane have been detected down to a depth of 350m in the Laptev Sea near Russia
- slope sediments in the Arctic contain huge amounts of frozen methane and other gas hydrates
- international teams on the Russian research ship stated that gas bubbles were dissolving in water but methane levels were 4 to 8 times normal

Why are sinkholes forming in the Arctic?

- Global warming has been melting the Arctic's permafrost (including sub-sea permafrost) for years
- between 2010-19 41 sinkholes have emerged within 2.5km^2 in Canada's Beaufort Sea
- most of these sinkholes average 6m deep with some 95m deep and 225m in diameter
- rising sea temperatures associated with climate change will likely accelerate this process