

# Chapter 15

## Permafrost and Methane

**Abstract** Permafrost is defined as permanently frozen ground, except the upper part usually thaws during summer months. Most of the permafrost on Earth is in areas that were glaciated during the last ice age and are still cold enough to keep the ground frozen. There is a tremendous quantity of methane trapped in permafrost that is being released as the permafrost melts. Methane is 25 times more potent as a greenhouse gas than carbon dioxide, to which it eventually converts in the atmosphere. Methane clathrates are potentially the cause of relatively sudden climate changes in the geologic past (PETM) and today represent a potential clathrate gun hypothesis for future sudden climate change.

**Keywords** Methane • Permafrost • Line • Periglacial • Ice • Exothermic • NSIDC • PETM • Thermal • Maximum • Andes • Frozen • Gun • Peat • Clathrates • Paleocene • Eocene • EIA • Glaciation • Pleistocene • Drilling • Natural • Gas

### Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the “Things to Know” should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to Know	
Permafrost	Eocene
Horizontal Drilling	Periglacial
Dense Shale Deposits	Paleocene
Clathrates	Methane
18,000 Years Ago	Peat
24%	NSIDC

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Things to Know	
PETM	Methane Gun Hypothesis
North American Ice Line	Pleistocene
2.8 Miles	“Ice Age”
Eurasia	Exothermic
Methane Chemistry	Clathrate Gun Hypothesis

## 15.1 Introduction

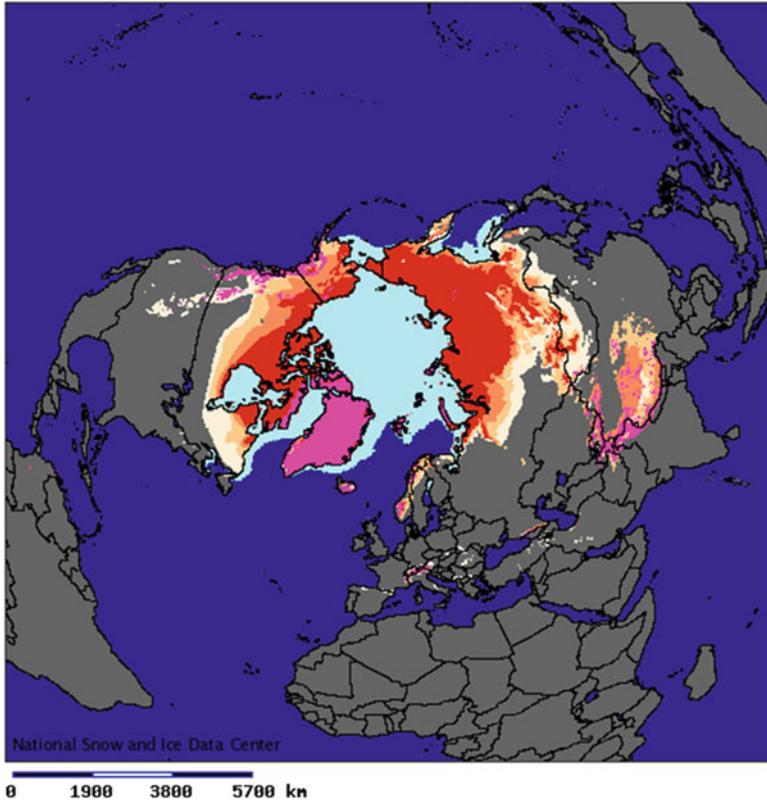
Permafrost is a common product of the last continental glaciation in North America and Eurasia in the Northern Hemisphere and mountain glaciation in the higher mountain regions of the world. Its official definition, according to the NSIDC, is “permanently frozen ground, soil, sediment, or rock that remains at or below 0°C for at least 2 years. It occurs both on land and beneath offshore Arctic continental shelves, and its thickness ranges from less than 1 meter to greater than 1,000 meters.” It can contain over 30% ice or practically no ice at all. It can be overlain by several meters of snow, or little or no snow. Permafrost is also a periglacial feature that is found around the edges of glacial ice today. Vast quantities of methane are bound up in permafrost and released to the atmosphere as it melts seasonally and due to global warming.

## 15.2 Distribution

The illustration below (Fig. 15.1) shows the extent of permafrost in the Northern Hemisphere. There are vast areas of permafrost in northern Canada, Alaska, Siberia, the Himalayas, Alps, and Rocky Mountains and Coastal ranges in the U.S. Not shown on the map are the locations of permafrost in the Southern Hemisphere in the high mountains of South America, the Andes Mountains. Permafrost areas also occur in Antarctica in regions not covered by glacial ice.

Permafrost regions occupy approximately 22.79 million km<sup>2</sup> (about 24% of the exposed land surface) of the Northern Hemisphere. In terms of area, permafrost can be characterized as continuous, discontinuous, sporadic, or isolated, but because these are descriptive terms, the boundaries separating different permafrost zones are gradational and not sharp.

Information about permafrost is critical to understanding climate change, other environmental concerns, construction, engineering, and architecture in areas underlain by permafrost. Construction in areas of permafrost is especially difficult as concrete cannot be used in foundations, roads, sidewalks, etc., because when concrete is settling it gives off heat (is exothermic) and melts the permafrost around it. Consequently, wood and plastic are often used in place of concrete and utilities and pipelines either are lined with insulation or constructed above ground.



**Fig. 15.1** Distribution of permafrost and ice in the Northern Hemisphere. Glaciers and the Greenland Ice Sheet are violet, and Arctic Sea Ice is *light blue* (From NSIDC/NOAA, Public Domain)

Land beneath glaciers would seem to always be frozen, but this is not the case. The historical approach to defining permafrost has been to assume that ground temperature equals air temperature, thus ground beneath glacial ice would be permafrost. Often the two temperatures are not the same and in some cases the ground is warmer than  $0^{\circ}\text{C}$ , especially near the terminus of the ice.

Permafrost underlies about 20% of the land in the Northern Hemisphere and is widespread within the Arctic Ocean's vast continental shelves and in parts of Antarctica. Most of the world's permafrost has been frozen for millennia and can be up to nearly 5,000 ft thick.

A 2009 study investigating the permafrost carbon-pool size estimates that 1,400–1,700 gigatonnes (Gt) of carbon are stored in permafrost soils worldwide. This carbon is both in methane ( $\text{CH}_4$ ) and frozen peat and is rapidly being released to the atmosphere as the Earth warms. There are eyewitness reports of methane bubbling up from lakes and shallow marine environments in regions of permafrost surrounding the Arctic Ocean. There are videos on the internet of burning methane bubbling from holes in lake ice in northern high latitudes.

A possible analog to modern global warming is the Paleocene – Eocene Thermal Maximum (PETM), an episode in Earth history about 55 million years ago when the Earth warmed by several degrees in a relatively short few thousand years. Earth's atmospheric temperature is a result of energy input from the Sun minus what escapes back to space, as has been discussed earlier in this text, amplified by certain feedbacks in the climate system. Carbon dioxide, methane and other greenhouse gases in the atmosphere absorb and trap heat that would otherwise return to space.

The PETM was accompanied by a massive carbon input to the atmosphere, with ocean acidification, and was characterized by a global temperature rise of about 5 or 6°C in a few thousand years, a recent April 2012 study in the scientific journal *Nature*, concludes. Until now, it has been difficult to account for the massive amounts of carbon required to cause such dramatic global warming events.

Historically, the warming during the PETM has been related to the release of methane from shallow sea deposits of methane clathrates. The April 2012 report in *Nature* ascribes the carbon source to the continents, in polar latitudes where permafrost can store massive amounts of carbon that can be released as CO<sub>2</sub> and methane when the permafrost thaws. This new view is supported by calculations estimating interactions of variables such as greenhouse gas levels, changes in Earth's tilt and orbit, ancient distributions of vegetation, and carbon stored in rocks and in frozen soil.

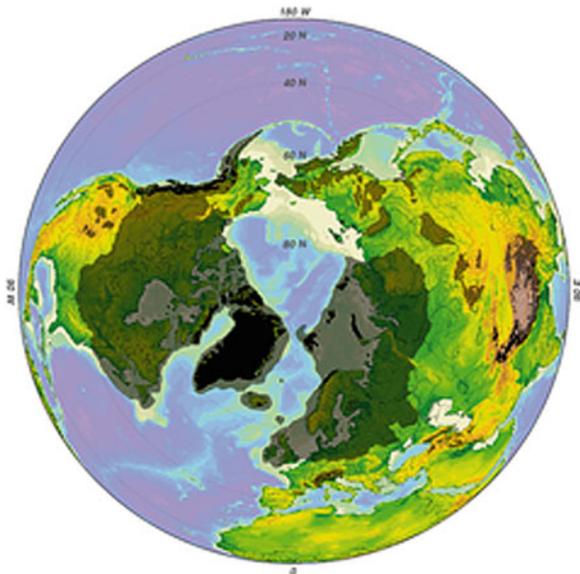
During the PETM, the positive feedback effect of melting ice reducing albedo, temperature increases would have been greatest at the poles, which reached an average annual temperature of 10–20°C (50–68°F); the surface waters of the northernmost Arctic ocean warmed, seasonally at least, enough to support tropical life forms requiring surface temperatures of over 22°C (72°F).

### 15.3 Origin of Permafrost

Much of the current permafrost is due to the Pleistocene glaciation that began to recede for the last time 20,000–18,000 years ago. Prior to the recession of the ice and during the early parts of the recession, large areas of continental shelves were exposed to the atmosphere. During this exposure, a great deal of peat was deposited on these exposed continental shelves and methane accumulated in areas where oxygen was absent, such as swamp environments, which were common. Environments without oxygen are called anoxic or anaerobic. So today, the shallow continental shelf areas in the Arctic have large stores of methane, peat, and carbon dioxide. A release of this material to the atmosphere would have disastrous consequences for present life on Earth.

As mentioned previously, the Earth is still in an ice age as we have glaciers present and ice at the poles. We are presently in an interglacial stage of the “ice age,” as glaciers are receding. But during an “ice age” glaciers contract and expand. During the maximum extent of the ice during the Pleistocene, permafrost was most likely more extensive than it is today as it was present around the edges of continental and mountain glaciers, in the exposed continental shelf areas, and beneath the glaciers themselves.

**Fig. 15.2** Minimum (interglacial, *black*) and maximum (glacial, *grey*) glaciation of the northern hemisphere (From Wikipedia, Hannes Grobe, Creative Commons Attribution/Share-Alike License)



In North America, the last continental glacier covered all of Canada and what is now the United States north of a line that can be drawn on a map from Long Island, NY through Pennsylvania, along the Ohio River to the Missouri River (Fig. 15.2). This line is called the North American Ice Line and north of it the land (Fig. 15.3) was covered by a continental glacier about 2.8 miles thick (thinning toward its edges) only about 20,000 years ago. Northern Eurasia was also covered by a continental glacier.

The Southern Hemisphere was also glaciated with the extensive continental glacier over Antarctica and smaller glaciers in the southern Andes Mountains (Fig. 15.4).

Figure 15.4 shows the maximum extent of glacial ice during the Pleistocene glaciation.

## 15.4 Methane Chemistry

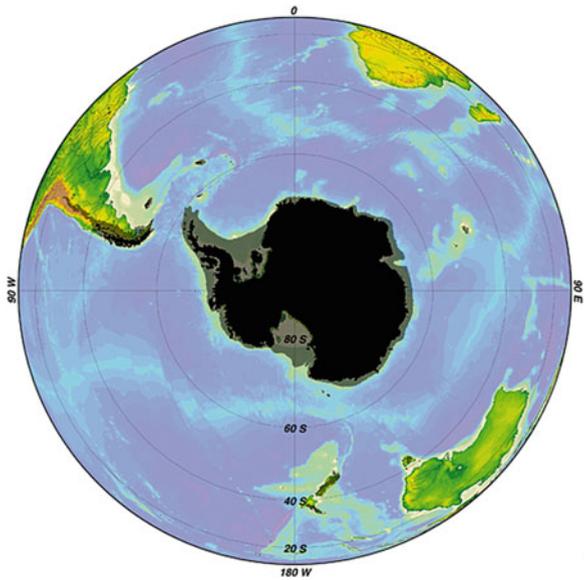
Methane is a simple molecule of one carbon atom surrounded by four atoms of hydrogen represented by its chemical formula of  $\text{CH}_4$ .

Methane is the principal component of natural gas and its use as a fuel is important. However, since it is a gas at normal physical and chemical conditions, it is difficult to transport from its source. At room temperature, methane is a colorless, odorless gas. The odor commonly associated with natural gas is due to an additive used as a safety factor.



**Fig. 15.3** The North American Ice Line (white line) and the trail followed by Lewis and Clark (From <http://www.carnegiemnh.org/ip/tours/trail/red/4.jpg>)

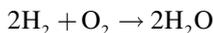
**Fig. 15.4** Minimum (interglacial, *black*) and maximum (glacial, *grey*) glaciation of the southern hemisphere (From Wikipedia, Hannes Grobe, Creative Commons Attribution/Share-Alike License)



Methane has a boiling point of  $-161^{\circ}\text{C}$  ( $-257.8^{\circ}\text{F}$ ) at a pressure of one atmosphere. As a gas it is flammable only over a narrow range of concentrations (5–15%) in air. Liquid methane does not burn unless subjected to high pressure (normally 4–5 atm). Methane easily converts to carbon dioxide and water upon oxidation.



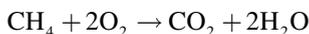
The resulting  $\text{H}_2$  oxidizes to  $\text{H}_2\text{O}$ , releasing heat. This reaction occurs very quickly, usually in significantly less than a millisecond.



Finally, the CO oxidizes, forming  $\text{CO}_2$  and releasing more heat. This process is generally slower than the other chemical steps, and typically requires a few to several milliseconds to occur.



The result of the above is the following total equation:



Natural gas, of which methane is the principle component, is a relatively clean-burning fuel and is transported by tankers and truck as liquid natural gas (LNG) and by pipelines. It produces less carbon dioxide than other hydrocarbons such as gasoline, diesel, and coal.

Sources of methane are coal deposits, gas fields related to petroleum deposits, landfills, and livestock. The majority of coal mine explosions are the result of methane. Methane is also the main constituent of swamp gas, is produced in the cultivation of rice and other agriculture, is a product of manure and rumination. Perhaps the largest reservoir of methane is methane clathrates found in shallow continental shelf areas that were previously exposed to anaerobic conditions in swamps during the low stand of sea level during the Pleistocene glacial advances.

Methane is a potent greenhouse gas and remains in the atmosphere for approximately 10–15 years before it is completely converted to carbon dioxide and water. It has a Global Warming Potential (GWP) of 21 over 100 years. In 2010, methane levels in the Arctic were measured at over twice as high as at any time in the previous 400,000 years. Historically, methane concentrations in the world's atmosphere have ranged between 300 and 400 ppb (parts per billion) during glacial periods commonly known as ice ages, and between 600 and 700 ppb during the warm interglacial periods. It has a high global warming potential; 72 times that of carbon dioxide over 20 years, and 21 times over 100 years, and the levels are rising except for a recent leveling off and mysterious decline.

Relatively recent discoveries of natural gas from dense, organic shale deposits have added to the world's inventory of fuels. Natural gas is an efficient energy source and the cleanest-burning fossil fuel. Natural gas extracted from dense carbonaceous shale rock formations has become the fastest-growing source of gas in the United States and other parts of the world and could become a significant new global

energy source. Although the energy industry has long known about huge gas resources trapped in dense shale rock formations in the United States, it is over the past decade (2002–2012) that energy companies have combined two established technologies, (1) hydraulic fracturing (“fracking”) and (2) horizontal drilling, to successfully unlock this resource.

Natural gas from these shale deposits has grown to 25% of U.S. gas production in just a decade and will be 50% by 2035, according to the U.S. Energy Information Administration (EIA). Developing this resource can help enhance energy security and strengthen economies. Shale gas is the largest contributor to the projected growth in natural gas production, and by 2035 shale gas production will account for 46% of the total U.S. natural gas production according to oil and gas companies.

The use of horizontal drilling in conjunction with hydraulic fracturing has greatly expanded the ability of producers to profitably produce natural gas from low permeability geologic formations, particularly dense shale formations. Application of fracturing techniques to stimulate oil and gas production grew rapidly in the 1950s, although experimentation dates back to the nineteenth century. Starting in the mid-1970s, a partnership of private operators, the U.S. Department of Energy (DOE) and the Gas Research Institute (GRI) began to develop technologies for the commercial production of natural gas from relatively shallow shale deposits in the Eastern United States. This partnership helped foster technologies that eventually became crucial to producing natural gas from shale rock, including horizontal wells, multi-stage fracturing, and slick-water fracturing. Practical application of horizontal drilling to oil production began in the early 1980s, by which time the advent of improved downhole drilling motors and the invention of other necessary supporting equipment, materials, and technologies, particularly downhole telemetry equipment, had brought some applications within the realm of commercial viability.

## 15.5 Future Projections for Permafrost and Methane

In the context of the future climate change, there are two key concerns associated with the thawing of permafrost; the detrimental impact on the infrastructure built upon it, and the feedback to the global climate system through potential emissions of greenhouse gases.

The upper part of permafrost, a few inches to a few feet in thickness, is called the “active layer.” It is this layer that melts in the warmer months of the year. The projection for the future is for the active layer to become deeper and thicker as the Earth warms.

A critical factor influencing the response of areas of permafrost to warming is the presence of ground ice. Ground ice generally is concentrated in the upper 10 m of permafrost; the very layers that will thaw first as permafrost degrades. This loss is effectively irreversible because once the ground ice melts it cannot be replaced for millennia, even if the climate subsequently cools. The response of the permafrost

landscape to warming will be profound, but it also will vary greatly at the local scale, depending on ground-ice content. As substantial ice in permafrost is melted, there will be land subsidence, as ice occupies more space than its liquid equivalent.

A forerunner of future landscapes can be seen today in areas of massive ground ice areas such as in Siberia, where past climatic warming has altered the landscape by producing extensive flat-bottomed valleys. Ponds within such an area will eventually grow into thaw lakes. These thaw lakes continue to enlarge for decades to centuries because of wave action and continued thermal erosion of the banks. Liquefaction of the thawed layer will result in mudflows on slopes in terrain that is poorly drained or contains ice-rich permafrost. On steeper slopes there also will be landslides and mudslides.

The most sensitive permafrost areas are sea coasts bordered by ice-bearing permafrost that are exposed to the Arctic Ocean. Mean annual erosion rates vary from 2.5 to 3.0 m per year for the ice-rich coasts to 1.0 m per year for the ice-poor permafrost coasts along the Russian Arctic Coast. Over the Alaskan Beaufort Sea Coast, mean annual erosion rates range from 0.7 to 3.2 m per year with maximum rates up to 16.7 m per year. As global warming continues, these rates are certain to increase.

Observations show a consistent picture of surface warming and reduction in all components of the cryosphere, except Antarctic sea ice, which exhibits a small positive but insignificant trend since 1978.

## 15.6 Methane Gun Hypothesis

The methane gun hypothesis (also named the clathrate gun hypothesis) is an explanation for the rapid and continuing rise in temperature due to a sudden irreversible release of methane, with no chance of retrieval much like the firing of a gun.

During a geologically short amount of time at the transition between the Paleocene and Eocene epochs about 55 million years ago, carbon isotope ratios everywhere (the deep sea, on land, at the poles, and in the tropics) suddenly changed to favor the lighter  $^{12}\text{C}$  isotope of carbon at the expense of heavier  $^{13}\text{C}$ . The rapidity and size of this change was unprecedented in the interval that followed the demise of the dinosaurs, and this excursion was simultaneous with a short period of extreme global warming (around 3–4° globally, more in the higher latitudes). This interval was the Paleocene – Eocene Thermal Maximum (PETM) mentioned previously.

The only conceivable perturbation to the global carbon cycle that fits these data from the PETM is a massive input of light carbon that had been stored as methane clathrates, which are observed to be particularly high in  $^{12}\text{C}$ . Nothing else could have been as fast-acting or have enough of the lighter isotope to have had the observed effects. Given that both  $\text{CH}_4$  and its oxidization product  $\text{CO}_2$  are greenhouse gases, this might explain the global warming leading up to the PETM as well.

In ocean sediments offshore of California, scientists from Woods Hole Oceanographic Institution recently (2011) found geochemical traces of clathrate releases at the same time as warming detected in the Greenland ice core records. In some records, there are spikes in the carbon isotope record, similar to the Paleocene-Eocene spike but of lower amplitude. This has led some scientists to propose the so-called clathrate gun hypothesis; that methane builds up in clathrates during cold periods and as a warming starts, it is explosively released leading to enhanced further rapid climate warming.

Some scientists think that the clathrate gun hypothesis may not be widely accepted because the records of methane in the ice cores seem to lag the temperature changes, and the magnitudes involved do not appear large enough to significantly perturb the radiative balance of the planet. There are others that disagree and argue that the data do not provide enough detail to resolve the time difference and that there has been plenty of methane in the past to provide the necessary climate change perturbation. There is also the possibility that estimates of methane bound up in clathrates have been low.

An alternative explanation for the PETM is that as the climate warms there is increased rain in the tropics and thus increased emissions of methane from tropical wetlands which need to have been large enough to counteract a probable increase in the methane sink. There is, however, much that we don't understand about the methane cycle during the ice ages, and maybe methane clathrates will eventually be considered a large part of the rapid climate change story.

## Additional Readings

- Alley, R. B. (2000). *The two-mile time machine: Ice cores, abrupt climate change, and our future*. Princeton: Princeton University Press.
- Christensen, T. R., et al. (2004). Thawing sub-arctic permafrost: Effects on vegetation and methane emissions. *Geophysical Research Letters*, 31, L04501. doi:[10.1029/2003GL018680](https://doi.org/10.1029/2003GL018680).
- EPICA Community Members. (2004). Eight glacial cycles from an Antarctic ice core. *Nature*, 429, 623–628. doi:[10.1038/nature02599](https://doi.org/10.1038/nature02599).
- Hinrichs, K. U., et al. (2003). Molecular fossil record of elevated methane levels in late Pleistocene coastal waters. *Science*, 299, 1214–1217. doi:[10.1126/science.1079601](https://doi.org/10.1126/science.1079601).
- Intergovernmental Panel on Climate Change. (2001). *Climate change 2001: The scientific basis*. Cambridge: Cambridge University Press.
- Intergovernmental Panel on Climate Change. (2007). *Climate change 2007: The scientific basis*. Cambridge: Cambridge University Press.
- Kennett, J. P., et al. (2003). *Methane hydrates in Quaternary climate change: The clathrate gun hypothesis*. Washington, DC: American Geophysical Union.
- Lamb, H. H. (1972). *Climate past, present and future* (Vol. 1). London: Methuen & Co Ltd.
- Ruddiman, W. (2003). The anthropogenic greenhouse era began thousands of years ago. *Climatic Change*, 61, 261–293. doi:[10.1023/B:CLIM.0000004577.17928.f8](https://doi.org/10.1023/B:CLIM.0000004577.17928.f8).
- Schmidt, G. A., & Shindell, D. T. (2003). Atmospheric composition, radiative forcing and climate change as a consequence of a massive methane release from gas hydrates. *Paleoceanography*, 18. doi:[10.1029/2002PA000757](https://doi.org/10.1029/2002PA000757).

- Severinghaus, J. P., & Brook, E. J. (1999). Abrupt climate change at the end of the last glacial period inferred from trapped air in polar ice. *Science*, 286, 930–934. doi:[10.1126/science.286.5441.930](https://doi.org/10.1126/science.286.5441.930).
- Wang, W. C., et al. (1976). Greenhouse effects due to man-made perturbation of trace gases. *Science*, 194, 685–690.