

## PART II

### PERMAFROST CO<sub>2</sub> STORAGE

The Potential for using Permafrost Terrains  
for the Geological Storage of Carbon Dioxide

# DISTRIBUTION OF PERMAFROST IN RUSSIA

## *Frozen ground and CO<sub>2</sub> sequestration*

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**Abstract:** Vast areas of the Russian north is underlain by permafrost, and many of these areas also host exploitable oil and gas reserves as well as various industries which are sources of atmospheric CO<sub>2</sub> pollution. It has been suggested that permafrost in this region could be used to host or to isolate man-made CO<sub>2</sub> in deep geological reservoirs, however an in-depth understanding of permafrost distribution, morphology, structure and stability is required in order to examine its feasibility and long-term safety. The present work outlines the spatial distribution of permafrost in Russia, defines the various formation histories, mechanisms and structures, and discusses the permafrost types which may be best suited to CO<sub>2</sub> sequestration.

**Key words:** Cryolithozone / permafrost distribution or extent / lithology / cryopeg / talik / sub-permafrost CO<sub>2</sub> sequestration

## 1. INTRODUCTION

Cryolithozone occupies 2/3 of the Russian Federation territory, including northern and north-eastern regions of Russia. Within these areas cryotic rocks containing ice inclusions make up a part or all of the near-surface part of the earth's crust. To the south, outside the cryolithozone, only seasonal soil freezing occurs.

The cryolithozone areas are primarily under-developed regions with inclement climatic conditions. The economics of these regions are basically dependent upon either traditional activities which have little affect on the geo-ecology of the area, or on natural resource development. The geocryological aspect is particularly important for petroleum and natural gas industries, since the most significant fields and prospects are situated in the

permafrost zone (fig.1). Permafrost conditions affect not only industrial and economic projects, but also surrounding infrastructure related to transport, heat-and-energy, housing, municipal services and so on.

The mineral resource and infrastructure industries involve the release of considerable volumes of waste, including mineral processing tailings, liquid and gas wastes. The majority of waste-gas production (i.e. CO<sub>2</sub>) is caused by the carbonic acid industry. The production and disposal of all types of wastes in the permafrost zone should be carried out taking into account the geocryological factor.

In most cases permafrost complicates resource recovery and waste management (loss of stability of thawing ground, propagation of disastrous exogenous processes, landscape degradation), but sometimes it can act as a favorable factor (providing safe foundations, forming aquicludes and reducing contaminant migration). In order to evaluate permafrost in regards to CO<sub>2</sub> sequestration one must consider the entire complex geocryological system. The basic characteristics of permafrost are its thickness, continuity, temperature, ice content, lithological and thermal ground properties, and the exogenous geological processes dependent on permafrost. Groundwater salinity frequently determines the rock's status under sub-zero temperatures and the formation of so-called cryopegs within these rocks.

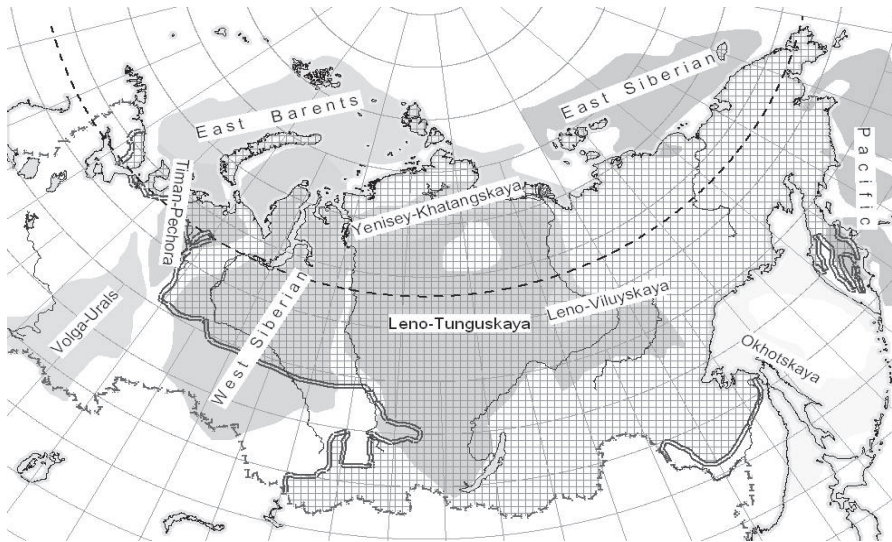


Figure 1. Oil-&-gas provinces (grey palette) and permafrost distribution (hatching) in Russia [www.igirgi.ru].

Permafrost stability is bound to complicated destructive exogenous geological processes. Generally anthropogenic impact greatly accelerates these processes, especially when melting and degradation occurs within ice-rich ground and rocks of so-called “icy complexes” or “massive ice beds”.

## 2. PERMAFROST ORIGIN, ICE CONTENT

Permafrost is a natural geological formation. There have been several periods of cooling during the geological evolution of the Earth which caused the formation of frozen strata in the Earth’s crust. Polar migration and continental drift give evidence of ancient freezing in various sites, including those that occur nowadays in equatorial latitudes. The most ancient freezing period during the Proterozoic (more than 2 billion years ago) corresponded to the Huronian glaciation. This was followed by Riphean, Vendian and Paleozoic glaciations. The permafrost underlying the Antarctic ice sheet (the age of the ice which permanently “flows” to the surrounding ocean doesn’t exceed a few hundreds of thousands of years) is probably the relict of Oligocene-Miocene glaciation that began 25 million years ago. The modern global distribution of permafrost (fig.2) started to form during the same period (i.e. during the Miocene). The most ancient permafrost relics of the last glaciations correspond to the upper Pliocene – Pleistocene (1.8 - 0.7 million years).

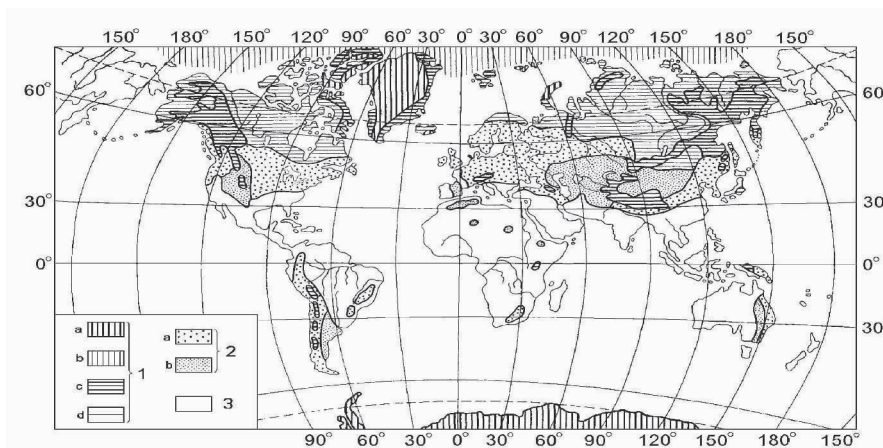
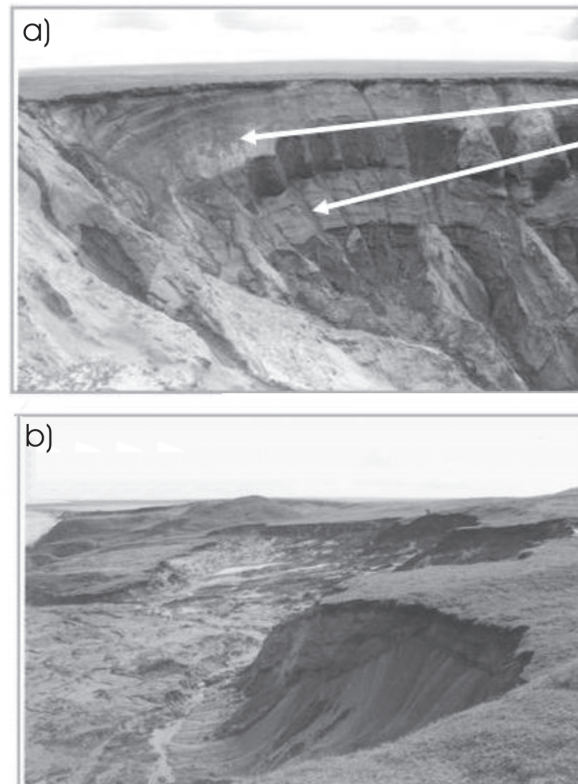


Figure 2. The world permafrost map: 1 – permafrost: a) under glaciers, b) in glaciers, c) in mountains, d) in plains; 2 – seasonally frozen ground: a) in wet climatic zone, b) in dry climatic zone; 3 – no freezing [Geocryology of the USSR: European territory of the USSR / Ed. E.D.Ershov. – Moscow: Nedra, 1988, p.15].

Frozen soils and rocks are regarded as geological formations which are characterized by negative temperatures and which contain non-freezing interfacial water and the ice that cements granular material and fills pores and cracks. Ground of any genesis, mineral composition, grain size (clastic, sandy, clay soils) and lithification (massive and fissured bedrocks) can be found in the frozen state. When ice is inter-granular it is considered a specific rock-forming mineral included in rock texture and structure descriptions, whereas ice bodies (such as various buried ices, wedge and segregation ices, massive ice beds) are regarded as mono-mineral geological bodies. Occasionally cryotic, but iceless, rocks are referred to as cryotic dry rock or dry permafrost.



*Figure 3.* Photographs showing surficial landscapes in permafrost regions. In (a) arrows highlight ground ice layers at the Yugorskii peninsula, while in (b) thermokarst and thermoerosion in picryogenic ice-rich soils at the Yugorskii peninsula. Photos by A.I.Kizyakov.

The frozen strata are subdivided into syngenetic and epigenetic according to the time of their formation versus the time of accumulation of the mineral and biogenic components. For the most part the frozen strata have had an epicyrogenic origin, i.e. previously accumulated or formed units had frozen during a cooling epoch. The ice content inside this ground shows an approximate correlation with the water content present before freezing. In some cases conditions are created for the redistribution of moisture throughout the section as a result of moisture addition to the freezing front throughout the aquifers. In these cases ice beds from tens of centimeters to tens of meters are formed inside the freezing rock strata (fig. 3).

Syngenetically frozen strata have frozen in parallel with mineral and/or biogenic rock accumulation. They include recent Upper-Pleistocene and Holocene clay and silt deposits of fluvial and littoral plains, shelf deposits (for example, in Yakutia), aeolian-alluvial-deluvial slopes of arctic rock masses, and depressions of large northern lakes. The moisture content in this ground, freezing while accumulated, is essentially unlimited. The ice accumulates in abundance within so-called “cryostructures” and often forms wedge ices. Their total volume can reach 80% and more (fig.4).

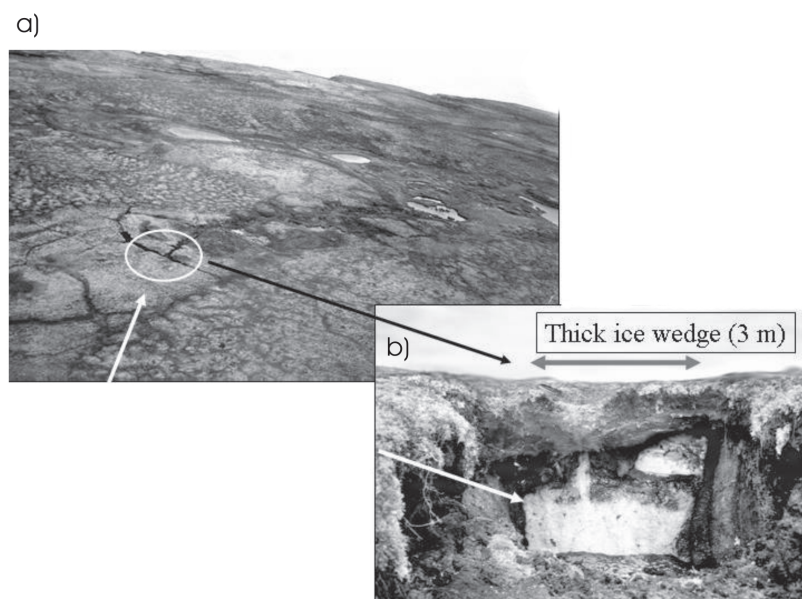


Figure 4. Photographs showing thermokarst in ice wedges at the Bolvanskii Peninsula, with (a) giving an areal view from a helicopter while (b) shows a cross-section of one of the ice wedges. Photos by M.Z.Kanevsky.

To a lesser extent the state difference (frozen/unfrozen) affects bedrock, and their cryogenesis is always epigenetic. Ice within fissures and cavities do not significantly influence rock strength, however permeability is changed appreciably, with frozen fractured saturated stratum being transformed into an aquiclude. The presence of spatially restricted taliks leads to active water exchange and enhanced leaching across them. The cryotic dry rocks only occur in the uppermost part of a geological section, (typically only 1-3 m below surface in granular rocks) and thus are of interest with respect to CO<sub>2</sub> sequestration only as an upper aquiclude above a CO<sub>2</sub> underground storage facility. In this case most attention should be paid to the chemically active residuals, because under the conditions of talik water exchange and in the presence of dissolved CO<sub>2</sub> fast reactions can take place which could lead to increased porosity and enhanced CO<sub>2</sub> escape out of the storage.

Pebbly, gravelly and sandy ground (except silty sands) in frozen or unfrozen states don't vary greatly from each other in ice content, but the difference in conductivity and strength is rather considerable. In the frozen state it is a strong foundation which can take an almost unlimited construction load and it is a stable aquiclude providing an effect barrier to gas and water migration even at moderate thicknesses of the frozen horizon.

The moisture content in frozen clastic and sandy ground is usually slightly higher than in thawed ground. However at an aquiclude's boundaries (for instance, thawed aquicludes – clays) massive ice beds up to several tens of meters thick (fig.3) can be generated while freezing sandy strata. In such places the total thickness of ice layers can reach 80% of the overall frozen strata thickness within near-surface zones which are intersected by constructions. If human engineering works affect the massive ice beds, they may initiate the potentially disastrous geocryological processes of thermokarst and thermoerosion, thereby destroying landscapes as well as nearby engineering infrastructure.

Silty and clayey ground attract the special attention of geocryologists, constructors and other experts, as they can accumulate significantly greater quantities of water during both epi- and syncryogenic freezing than in their thawed state. This is the result of their mineral and granulometric composition which ensures the abundant migration of moisture to the freezing front. Lenticular, layered, reticulate or honeycomb cryostructures are formed, and the mineral ground-mass is dissected by an ice net and layers. Their thickness and spaces between layers range from sub-millimetre to several centimetres. The ground-mass is also divided into polygons by macrocracks and filled syngenetic ice wedges. Several meters thick wedges can form a multilayer structure having a total thickness of tens of meters. Air filled pores are essentially absent and ice content can reach more than 80%. In this case thermokarst and thermoerosion lead to disastrous results.

Thus the frozen rock is of no interest as a material which can host the carbon dioxide. The ice-saturated ground is gas and water impermeable, explaining why it is impossible to create conditions for solution or chemical absorption (for example, as gas hydrate) of carbon dioxide in the frozen rocks. The cryotic dry rocks are extremely rare and are of no practical value. Therefore, it is reasonable to examine permafrost not as the enclosing medium for CO<sub>2</sub> sequestration but rather as a unit which can enhance the isolation of CO<sub>2</sub> in deep geological units.

### 3. PERMAFROST DISTRIBUTION, TEMPERATURE

According to its geographical position the cryolithozone is subdivided into subaeral, shelf and subglacial. The subaeral cryolithozone is the most widespread and is usually made up of surface-laying permafrost. The shelf cryolithozone is typical for arctic seas of the Siberian sector of the Russian Federation. The subglacial permafrost underlay glacial covers on the northern islands and in highlands. Strictly speaking permafrost is not restricted to the polar territories, but rather it extends both under glaciers and on iceless mountain ridges in lower latitudes (fig. 5 and also fig.2).

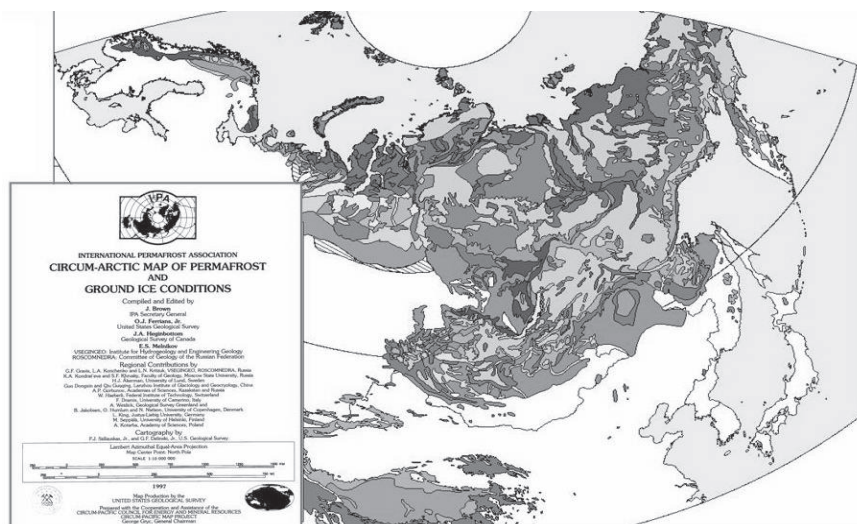


Figure 5. Circumpolar map of permafrost. Eurasian sector.

Alpine permafrost can be found in the Caucasus, in Mongolia and in Tien Shan. In Tien Shan (i.e. at the latitude south of the Caspian Sea and Japan) the alpine permafrost areas are more than the whole Northland. Nevertheless alpine permafrost in low latitudes is rather an exotic event, and thus northern and eastern regions are the dominant areas of permafrost distribution.

Permafrost can be subdivided into 4 types based on unit continuity: i) continuous (frozen rocks occupy 90-100% of the territory); ii) discontinuous (50-90% permafrost); iii) island or sporadic (10-50% permafrost); and iv) isolated patches (0-10% permafrost). Their distribution is controlled by strict latitudinal (for plains and mountains) and altitude (for mountains) zonality (fig. 6). The boundary of the continuous permafrost distribution shifts more and more southward as it moves from west to east. Permafrost temperature decreases in the same direction (from  $-2$  to  $-100^{\circ}$  C and below), while its thickness increases in the plains (from the first tens of meters to 300 - 500 m and more) and in mountain ridges (up to 1500 m).

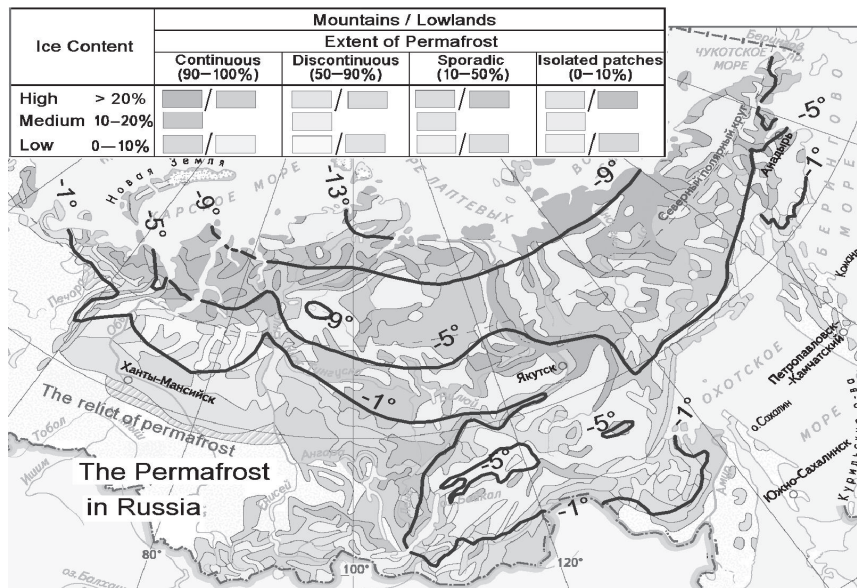


Figure 6. Permafrost in Russia: Space distribution, iciness and temperature at the depths of zero seasonal amplitudes. [by E.S. Melnikov, K.A.Kondratieva, G.F.Gravis].

Local natural and human factors are superimposed on the zonal and altitude regularities of the permafrost distribution, thus highlighting the local changeability of the geocryological conditions. For example, taliks can appear in continuous permafrost in river valleys and lake depressions due to the defrosting effect of the hydrosphere, while frozen sites can disappear

completely in the sporadic permafrost zone. Various natural and man-made cooling factors (for instance, wind erosion or snow removal) can cause the formation of permafrost islands even outside the cryolithozone.

The continuous permafrost zone is the largest (fig.6). On the plains of the Russian European north it stretches out along the coast in a 100 to 200 km wide strip. Its southern limit coincides approximately with the polar circle in the ranges of the West-Siberian Lowland, and it reaches the latitude of Lake Baikal in eastern Siberia and Yakutia.

The discontinuous permafrost zone stretches out in a very narrow strip in the European north, and then in western Siberia it widens up to several hundreds of kilometres. Eastward discontinuous permafrost is basically localized to the intermountain troughs or to the coastal plains south of the 60th parallel.

Sporadic permafrost and isolated patches of permafrost extend up to the latitude of the polar circle in Europe and up to the 60th parallel in western Siberia. In the more eastern regions it extends to the southern frontier of the Russian Federation.

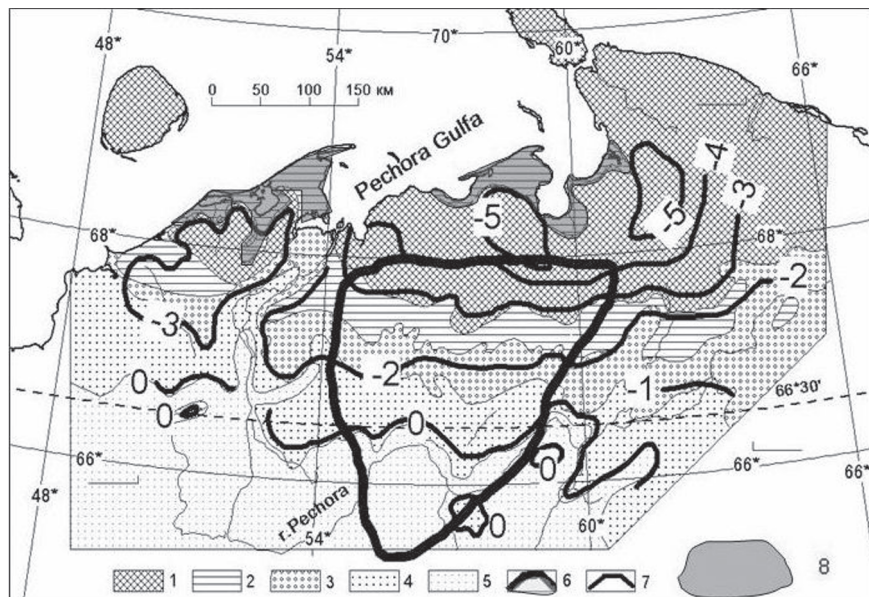


Figure 7. The extent and temperature of permafrost in the Timan-Pechora oil and gas province: 1-4 – permafrost types: 1 – continuous, 2 – discontinuous, 3 – sporadic, 4 – isolated patches; 5 – non frozen and thawed soils; 6 – permafrost relict contour; 7 – permafrost temperature isograms; 8 – cryopegs.

Relict permafrost bedding occurs at a depth of tens to hundreds of meters below the earth's surface, often separated by thawed (lateral) ground horizons from the overlying modern superficial permafrost. The relict permafrost can form a single stratum, layers or separate fragments. The vast lobe of relict permafrost in the south of western Siberia is well seen on fig.6, while the zone of relict permafrost in the European north is well seen on fig.7.

Relict permafrost has been the result of cyclic changes in climate and the alternation of warm and cool epochs, with many being due to the heritage of ancient Upper-Pleistocene cooling epochs. However it would be incorrect to assume that relict permafrost layers are a single dimensional formation. The long-term history of its evolution has resulted in the formation of numerous taliks that have broken down the single whole into many isolated patches (fig.8).

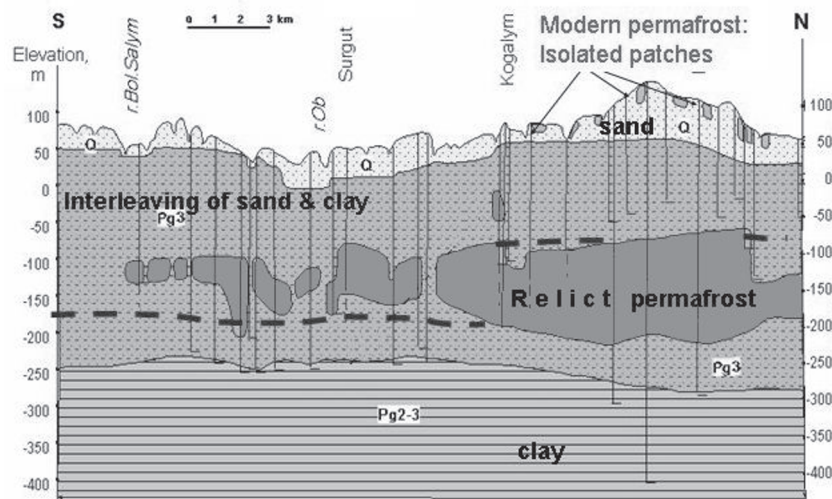


Figure 8. Relict permafrost. The thickness of relict permafrost decreases gradually from the north to the south. Local isolated subsurface patches of modern (Holocene) permafrost can be found to the north of Kogalym city. Their thickness could achieve 20-30 m. [by G.V.Malkova].

Continuous permafrost is a good aquiclude, and it is a reliable foundation for construction if the proper technologies are applied. The active exchange between supra- and sub-permafrost ground waters takes place in the zone of discontinuous permafrost, and pre-thawing is required before building at temperatures close to 0°C. Sporadic and island permafrost is also a complicating factor from a hydrogeological and engineering point of view.

The sites of unfrozen rocks in all types of permafrost are referred to as taliks, which can be subdivided into closed, open and lateral taliks. Their formation has been conditioned both by geological and paleoenvironmental evolution and by recent warming factors. So-called “cryopegs” occupy a unique place in talik classification, as they are unfrozen sites and horizons, despite sub-zero temperatures, within rocks hosting saline waters. Predominantly these are either deep horizons of ancient rocks under many-hundred-meters thick permafrost strata saturated with brines, or the shallow-laying bedrocks or sedimentary rocks with marine saline waters along the northern coasts (fig. 7). The presence of cryopegs testifies to the importance of geochemical and hydrogeochemical factors in the distribution of frozen and unfrozen rocks in the cryolithozone.

#### **4. PERMAFROST AND CO<sub>2</sub> SEQUESTRATION**

Since in most cases frozen ground is impermeable and can't be considered as a possible natural reservoir for man-made gases and liquids, only taliks, cryopegs and sub-permafrost aquifers are of interest for CO<sub>2</sub> burial.

Not considering here any possible ecological consequences, let us address the main possible variants of CO<sub>2</sub> burial in diverse geocryological conditions. Continuous permafrost is practically an ideal aquiclude and it theoretically permits CO<sub>2</sub> injection into sub-permafrost porous reservoirs. Sites which have a domal structure of the permafrost base and without taliks are most favourable. The low reservoir temperature, the high geostatic pressure, as well as the extra pressure of the injected gas could create auspicious conditions for CO<sub>2</sub>-oriented gas hydrate formation. This may essentially increase the sub-permafrost reservoir effective capacity and ensure the high stability of the sequestered CO<sub>2</sub>.

In the view of CO<sub>2</sub> burial the sites with discontinuous permafrost must be examined carefully, paying special attention to the selection of permafrost masses undisturbed by taliks.

The sites within sporadic or isolated permafrost are not very promising for CO<sub>2</sub> sequestration due to the possibility of active water- and gas-exchange between relatively deep horizons and the surface. The cryogenic factor may, however, play a positive role in the presence of an ideal lithologic-and-petrographic aquiclude (for example, a thick unit of dense clays and argillites), providing the minimal reservoir temperatures at the depth of CO<sub>2</sub> burial and the opportunity for proper gas hydrate formation.

With respect to CO<sub>2</sub> burial cryopegs should attract particular attention. On the one hand cryopeg distribution areas can coincide with areas of open

taliks formed by both thermal and chemogenic processes. This fact reduces the insulating reliability of the waterproof stratum. On the other hand the temperature of the cryopeg-reservoir is 1 to 20° C lower than the temperature of the fresh-water reservoir, which is a significant point when one considers the possibility of underground gas hydrate formation. In addition, one can expect that some part of the injected CO<sub>2</sub> will react with the cryopeg brines and generate stable carbonate minerals. The last two factors are important if one wishes to examine the problem of CO<sub>2</sub> sequestration in the European north of Russia, where active prospecting and the development of continental, shelf and island oil-and-gas fields are being performed today.