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CRYOGENIC PROCESSES

PROCESELE CRIOGENICE

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Abstract: Cryogenic processes are quite numerous, but among them the most significant, from the viewpoint of influence on human activities, we mention frost swelling, thermokarst processes, thermal abrasion, thermal erosion, cryogenic cracking, and solifluction. *Frost heaving* represents a danger for motor roads, railroads and airfields, communication and transmission lines, bridges, and other structures. *Thermokarst* endangers the safety, stability, and normal operation of structures. *Thermoabrasion* affects industrial and civil site development, water transport, pipeline transport, mineral resource industry, hydropower engineering, and agriculture. *Frost cracking* constitutes a certain danger for the following engineering structures: motor roads (roadways may go over the discontinuity); residential and industrial buildings (breakage of continuous footings, cracks in the walls); airfields (damage to airfield pavements); pipelines (deformations and even breaks of underground steel pipelines); underground communication cables. The influences of fast and slow *solifluction* are the most urgent for the following kinds of human activity: mineral resource industry; transport (motor, rail, pipeline); and industrial and civil engineering. Thus, the present paper aims at rendering the global dimension of these processes stressing their consequences worldwide.

Key-words: cryogenic processes, frost swelling, thermokarst processes, thermal abrasion, thermal erosion, cryogenic cracking, solifluction.
Cuvinte cheie: procese criogenice, procese temocarstice, abraziune termică, eroziune termică, crăpături criogenice, solifluxiune

Cryogenic processes are those that take place in freezing and thawing rocks and in permafrost rocks under conditions of changing temperatures and the rocks' transitions through the melting of ice.

The area of *distribution* of cryogenic processes is considerable (Fig. 1). The area of the cryolithozone (permafrost zone) of the Earth is 38.15 million km^2, which corresponds to 25.6% of the land surface, and 21.35 million square kilometres fall in the northern hemisphere. Permafrost underlies 20–25% of Earth's land area, including about 99% of Greenland, 80% of Alaska, 50% of Russia, 40–50% of Canada, and 20% of China. Seasonally, frozen rocks are more widely

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distributed. They occupy vast territories with the exception of regions with tropical and subtropical climates.

The number of cryogenic processes is quite high, but among them the most significant processes, from the viewpoint of influence on human activities, are frost swelling, thermokarst processes, thermal abrasion, thermal erosion, cryogenic cracking, and solifluction.

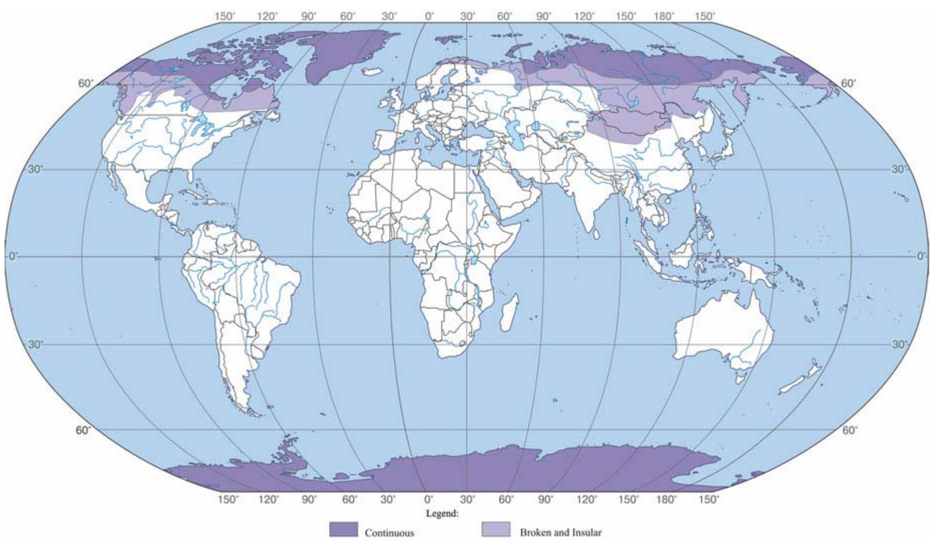

Figure 1. Distribution of permafrost (Resources and environment 1998. Reproduced with permission of the Institute of Geography of the Russian Academy of the Sciences)

1. Frost heaving

Frost heaving is a rising of the soil surface caused by an increase in its volume in the course of freezing due to the spreading of particles by growing ice crystals. *The intensity* of the swelling depends on the degree of water saturation, and it is especially high when the moisture content increases through inflow from neighbouring areas.

In determining *the mechanism* of the influence of frost heaving on engineering facilities, the tangential and normal forces of a swelling are identified. When freezing occurs near the foundation, the ground freezes to its side face. The swelling forces tend to move the foundation up, together with a layer of frozen ground. If the forces of ground freezing with the foundation are less than the mass of the structure, then the frozen layer moves relative to the foundation. The shear strength of the foundation when it freezes along with the ground determines the *tangential forces* of swelling.

When a frozen layer increases in thickness, the force of ground freezing with the foundation can exceed the load resistance. In this case, there will be ‘bulging’ of the foundation; that is, its heave, together with the ground will result in loss of stability and normal operation of the structure. The normal swelling forces act at right angles to the foundation. The straight freezing of the swelling ground near the side faces of a foundation results in their all-round pressurization. When this occurs, a swelling nonuniformity can lead to one-sided pressure and horizontal displacement. The soil freezing under a foundation determines the development of *normal forces of swelling* at its foot.

Under the action of the forces of frost ground heaving on a foundation, secondary stresses arise in the bearing members of the structure and result in deformations; these deformations can disturb the normal operation of the building or make it unusable. *Deformations* can cause the formation of cracks in foundations, ceilings, floors, and walls and skewing of door and window openings. These deformations have a cyclic, seasonal nature and repeat every year. During the spring melting of swelling ground, water permeability and compressibility increase, while the carrying capacity decreases, which results in differential settlement of a building.

Frost heaving represents a danger for *motor roads* and *railroads* and for *airfields*, causing disruptions in their continuity and evenness. These disruptions, in turn, can lead to emergency conditions in transport due to pushes and strokes in the course of its motion (bursting of rails, automobile accidents, and aircraft accidents on takeoff etc.). In Norway, 300 km of railroads go out of service due to frost swelling every year. In the United States, the railroads in the states of Wisconsin, North Dakota, Nebraska, and Idaho are affected, to the maximum extent, by this phenomenon (Geocryological dangers, 2000).

Frost heaving also constitutes a certain danger for *communication and transmission lines, bridges*, and other structures. The centre of one of the bridges in the Alaskan Railroad rose by 35.5 cm during the winter of 1952–1953. In order to replace the rails in their original position, the upper piles had to be cut (Anderson and Trigg 1981). Swelling is a primary cause of underground *pipeline* deformation, especially where the pipes cross rivers. So, in November 1972 through January 1973, a pipe break at a weld accompanied by a gas release happened as a result of frost swelling in a section of the Messoyakha-Norilsk pipeline where it crossed the Yenisey River (Atlas of natural and technogeneous dangers and risks, 2005).

Frost heaving also has adverse effects on *grassland farming* and *crop production*. During freezing, the soil (especially loose soil) is slightly raised, and as a result, the roots of plants are detached. After melting, the soil subsides and plants with detached roots remain under the sun and wither. To some extent, frost swelling also adversely affects *hydropower engineering*. The straight freezing of clayey dam cores results at times in destruction of their watertight integrity (Natural-anthropogenic processes and environmental risk, 2004).

In regions where permafrost is present, perennial mounds caused by cryogenic heaving (pingos) are abundant. Since they are observed in less developed regions of the world, damage related to them for the present is not great. The effects of frost swelling on human activities are illustrated by Photos 1 and 2.

Photo 1. Pingos emerge in areas of permafrost or seasonally frozen ground due to non-uniform ice formation within the ground. Long-term pingos appear in the course of frost penetration into thawed grounds, usually below lakes, should the lake grow shallow or completely dry up. The largest pingos reach 50 m high and 600 m in diameter. The photo shows pingos near Tuktoyaktuk, Northwest Territories, Canada (Photo credit: Emma Pike)

Photo 2. Mounds of heaving ground do not have considerable impacts on humans since the lands where they occur are usually sparsely inhabited and poorly developed. The photo shows mounds of heaving ground on the Tynda–Zeysk section of the Baykal—Amur Railroad, Russia (Photo credit: V.S. Afanasenko, Department of Geocryology, Moscow State University, Russia)

2. Thermokarst, thermoerosion and thermoabrasion

The term *thermokarst processes* means a melting of ground ice accompanied by strain in beds (initiation of subsidence and depressions or formation of cavities in these beds).

Thermokarst constitutes a serious danger to the safety, stability, and normal operation of structures (*railroads, motor roads, pipelines, buildings*, etc.). For example, in the summer of 1984, subsidence of the Tynda-Berkakit village railroad body base near the village of Magot, Russia, took place due to thawing of ice-saturated ground. As a result, the rail track was destroyed, and a train was derailed (Atlas of natural and technogeneous dangers and risks, 2005). Practically, all the buildings erected in Magadan oblast (Russia) prior to 1951 (when they were constructed without regard for the frozen subsoil properties) were deformed due to ground bearing capacity failure as a result of thawing (Russian Arctic, 1996).

The cause of damage to the buildings was generally the formation of a thawing basin, resulting in irregular settlement of foundations and, as a consequence, initiation of cracks, subsidence of quoins, warping of door frames, etc. Thermokarst subsidence deforms the beds of *motor roads* and *railroads* and surface and underground pipelines, frequently resulting in accidents.

The term *thermoabrasion* means a process of destruction of shores composed of perennially frozen rocks or ice due to the heating effects of water. Thermoabrasion (thermal abrasion) is an important process in forming the shores of Arctic seas (primarily in Russia, the United States, and Canada). Distribution of thermoabrasive shores is shown in Fig. 2.

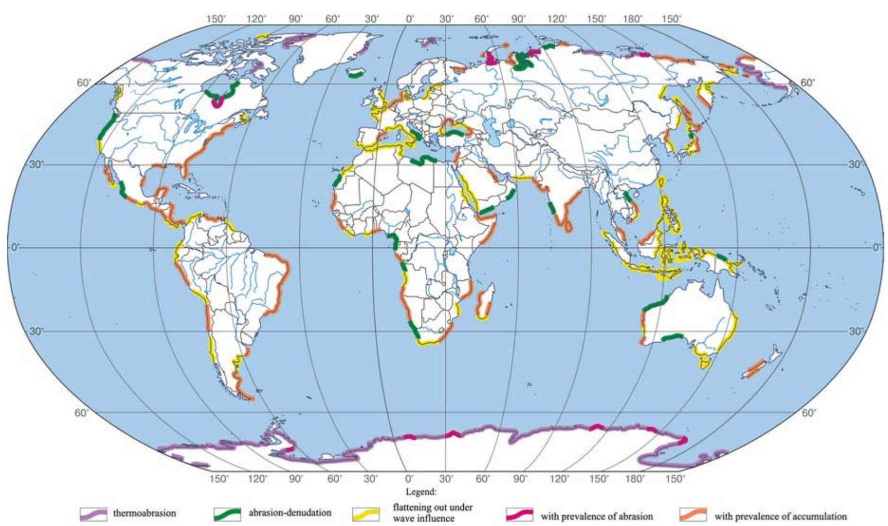

Figure 2. Distribution of thermoabrasive, abrasive, and accumulative shores (Shores 1991. Reproduced with permission of Moscow State University, Russia)

The *basic process* of thermoabrasion is a washout of the underwater shoreface under the action of roughness and currents. It results in the formation of a niche, and further deepening causes frozen rock blocks to fall. The rate of thermoabrasion depends on the lithological composition (the likelihood of washing out of rocks increases in the following order: clays, loams, clay sands, sands) and the ice content in the rocks (the greater the ice content, the higher the erosion rates).

The *rates* of shore retreat in the case of *marine thermoabrasion* range from 0.2 to 8 m/year. The total value of thermoabrasion for the Russian segment of the Arctic is estimated at 338 million tons per year; this much sediment comes to the coastal zone, owing to thermoabrasion (Stolbovoi, 2002). The volume of deposits entering the Laptev Sea due to washout of the islands in the Lena River delta reaches 1.8 million tons per year (Grigoriev and Schneider 2002). A number of in situ observations have been aimed at estimating the losses of land. So, according to data of J. Brown and J. Jorgenson (2002), an 11-km sector of the shore near Barrow (north-western Alaska) lost 28.2 ha during a period of 50 years.

Long-term average annual rates of *lake thermoabrasion* are frequently 2–10 m/year. The intensity of land elimination on inland water bodies may also be extremely high. For example, over 25 years of the Bratsk Reservoir (Russia) storage operation, thermoabrasion has destroyed about 270 km^2 of the coast (Theoretical principles of engineering geology, 1985). Here, events of extremely high intensity were recorded. So, in 1962–1967, the shore retreated by 759 m near the Artumei settlement, and the erosion rates reached 435 m/year and 150 m/day (Myagkov, 1995).

Thermoabrasion affects the following *kinds* of human activity: (1) industrial and civil site development; (2) water transport; (3) pipeline transport; (4) mineral resource industry; (5) hydropower engineering; and (6) agriculture.

The effects on *site development* are expressed as a threat to beach installations. In September 1986, a sharp intensification of thermoabrasion on the Alaskan coast of the Chukchi Sea took place as a consequence of two storms. The boroughs of Barrow and Wainwright experienced serious losses. In the first settlement, 152 people were evacuated and, later, 32 houses were transported to a new site (Walker 2001). Several power transmission line poles also had to be moved and, in addition, the storm damaged an archaeological monument: peat houses (Walker, 1991). Effects on *water transport* involve changes in navigation conditions. Thermoabrasion processes result in a reduction in depths and create problems for shipping. Water transport is also affected by the demolition of lighthouses and navigation markers. In addition, thermoabrasion causes problems where *underwater pipelines* make landfall. The influences of thermoabrasion on the *mineral resource industry* are rather positive and lie in the fact that, to a large degree, it forms off-shore placer deposits of minerals.

The impact on *hydropower engineering* lies in the fact that thermoabrasion creates an abundance of solid particles. This causes the sedimentation of reservoirs and reduces their usable storage. When woody and peaty shores are destroyed, there is also clogging of waterways and chemical pollution. The effects on *agriculture* are expressed as the destruction of croplands and grazing lands; however, considering the small scales of this kind of human activity in the regions subjected to thermoabrasion, the effects are considered to be minor.

Thermoerosion is a process that causes the break-up of frozen rocks. Simultaneous thermal and mechanical actions of water flows result in intrusion of the water flow into the frozen mass, with the formation of fur rows, ruts, and cavities. Thermoerosion is initiated where the vegetation cover is discontinuous, which can be caused by both natural factors (frost crack formation, solifluction, slip-outs, etc.) and anthropogenic factors. For thermoerosion to develop, the following conditions are necessary (Dynamic geocryology 2001): (1) presence of perennially frozen ground; (2) a grade of more than 1.5°; and (3) sufficient rainfall intensity. The *intensity* of gully erosion is high. Elongation of gullies occurs at rates of 1–2 to 5–7 m/year, reaching, in some cases, 20–30 m/year, while, within ravines and hollows, they can be up to 100–150 m/year.

Thermoerosion is subdivided into two types: bed and gully. The mechanism of *bed thermoerosion* is, to a large extent, similar to that of thermoabrasion. When a shore is being undercut, thermoerosion niches are formed, followed by the fall of blocks. When *gully thermoerosion* develops, gravitational failures result in blockages in channels and, as a consequence, intense cutting and detachment of sides. Riverbed thermoerosion affects different installations located within the coastal zone (harbour installations, transmission and communication lines, roads, pipelines, and other structures). H.J. Walker (2001) uses as an example the thermoerosion effects on the Nigilik village in the Colville River delta (Alaska, United States). From 1949 to 1986, a shore retreated there by more than 50 m, and a threat of one house failure appeared. In order to prevent the destruction, the house was transported over a distance of 30 m from shore. The effects of thermokarst processes, thermoabrasion, and thermoerosion on human activities are illustrated by Photos 3–7.

Photo 3. The photo shows a wall collapse in a dwelling in Yakutsk, Russia, caused by thermokarst. Nobody was injured. To prevent such collapses, houses must be built on piles. Hereby, the air space under the house should prevent the heat impact on the frozen ground. This house was erected 'low-sitting', and for the long time it was occupied, the air space became stuffed with finely dispersed material. This led to gradual melting of frozen grounds lying below (Photo credit: Y.A. Murzin, Institute of Permafrost Studies, Russian Academy of Sciences, July 1993)

Photo 4. Thermokarst poses a formidable threat to railroad maintenance. The photo illustrates the numerous deformations of the Northwestern Railway near Strelna, 75 miles northeast of Valdez, Alaska (United States). The thermal equilibrium of the fine-grained sediments underlying the roadbed was disrupted during construction, and the permafrost started to thaw differentially. Maintenance and use of the railroad were discontinued in 1938. Subsidence, as well as lateral displacement, has continued (Photo credit: U.S. Geological Survey, September 1960)

Photo. 5. The average rate of thermoabrasion does not exceed 0.5–1.0 m/year; however, it may become as high as 10 m/year. Coastal retreat occurs mostly during 2–3 summer months; the process dramatically intensifies at times of heavy storms. The photo shows the coast of the Chukchi Sea in Alaska, near the Wainwright settlement. The severe storm of October 1986 exposed ice wedges, and by that, speeded up coastal destruction which imperilled dwellings (Photo credit: H.J. Walker, July 1987)

Photo 6. The nature of riverbed thermoerosion is, in many ways, similar to that of thermoabrasion. Coastal cut-down forms thermoerosion niches, after which, large blocks fall down. The photo demonstrates the process of coastal destruction in the Colville River delta, Alaska (United States) (Photo credit: H.J. Walker, 21 June 1966)

Photo 7. Thermoerosion also intensifies in cases of human-related breaching of vegetation cover. The construction of a pipeline and parallel power line triggered thermoerosion processes along the pipeline, which threatened the balance of power transmission towers (Photo credit: A.N. Kozlov, Department of Geocryology, Moscow State University, Russia)

3. Cryogenic cracking and solifluction

Cryogenic (frost) cracking is a dissection of a frozen rock mass with cracks that develop when temperatures fall. It occurs in regions of both permafrost and seasonally frozen rocks. The cracks form during the fall through winter period. They are most pronounced in areas with an acutely continental climate and insignificant snow depths. *The widths and depths of cracks* depend on the composition of the rocks, their uniformity, and temperature distribution. Their maximum lengths reach tens and hundreds of metres, while depths are 5–6 m. The widths of cracks at the top are generally 2–4 cm, though cracks more than 10 cm wide occur. Frost cracking constitutes a certain danger for the following engineering *structures*: (1) motor roads (roadways may go over the discontinuity); (2) residential and industrial buildings (breakage of continuous footings, cracks in the walls); (3) airfields (damage to airfield pavements); (4) pipelines (deformations and even breaks of underground steel pipelines); and (5) underground communication cables.

Solifluction is a slow viscous plastic flow of thawing waterlogged soils and fine-dispersed ground on gentle slopes. It occurs in Russia, the United States (Alaska), Canada, Norway (especially on the Svalbard Islands), the Falkland Islands, and mountain regions of central Asia.

The *conditions* necessary for the development of solifluction include the following (Romanovsky 1993): (1) increased content of pulverescent particles, (2) increased humidity, (3) presence of surface slopes (usually 2–3 to 10–15°), and (4) absence of woody and large shrub vegetation.

A *distinction* is made between mantled and differential solifluction. For the former, relative areal uniformity, low drift velocity (2–10 cm/year), and an absence of sinter relief forms are characteristic. The distinctive feature of *differential solifluction* is the presence of characteristic forms of micro- and mesorelief: solifluction ‘tongues’, flows strips, terraces, etc. Their formation is caused by differences in drift velocities of thawing rocks on different parts of a slope. The rate of this type of solifluction may reach 10 cm/day. The areas of the solifluction relief forms range from several square metres to thousands of square metres.

One kind of solifluction is the *slip-out* (so-called fast solifluction). It is characteristic of steeper slopes (not less than 10°) formed by silt sandy loams or clay loams; fast solifluction has a catastrophic character but develops within relatively small areas. In the case of fast solifluction, rates reach tens of metres per day (Geocryologic dangers, 2000).

The influences of fast and slow solifluction are most urgent for the following *kinds* of human activity: (1) mineral resource industry; (2) transport (motor, rail, pipeline); and (3) industrial and civil engineering.

A negative influence on the *mineral resource industry* is expressed as the *complication of operation* of enterprises due to sloughing of pit walls. Another consequence is *dilution* (reduction in concentrations of the commercial component). During mining operations, rocks containing the commercial component are stored in certain places for the purpose of downstream processing. Grounds that move under the action of solifluction increase the volume of rocks requiring processing, which reduces the economic efficiency of the operation of a mining enterprise. At the same time, slow solifluction has a certain *positive importance* for the transportation of heavy minerals to the valleys of rivers and streams and the formation of *placer mineral deposits*.

The effects on *transport* lie, first of all, in the deformation of hollows in the bodies of motor roads and railroads and complications in the operation of surface pipelines. Problems for *industrial and civil engineering* are similar and consist mainly of sloughing of construction pit walls. The effects of cryogenic cracking and solifluction on human activities are illustrated by Photos 8–11.

Photo 8. Cryogenic cracking is generated by stretching strains developing in frozen ground. In spring, water from melting snow penetrates into the ground and freezes. Repetition of the process leads to cavern-load ice formation. The photo shows polygon wedge ice (and melting pingo) near Tuktoyaktuk, Northwest Territories, Canada (Photo credit: Emma Pike)

Photo 9. Cryogenic cracking oftentimes creates problems for auto road and railroad exploitation. The photo shows frost-induced cracks that deform a roadbed in Zabaikalye, Russia (Photo credit: S.Y. Parmuzin, Department of Geocryology, Moscow State University, 1967)

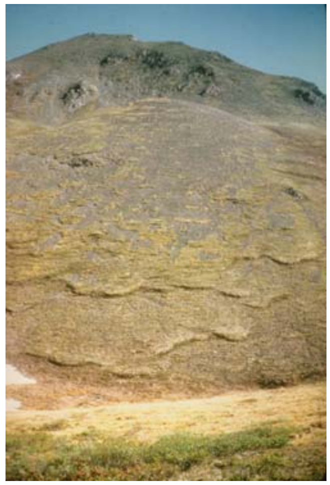

Photo 10. A feature of differential solifluction is generation of micro- and mezo-landforms that are conditioned by different velocities of shifting of melting ground on different spots of the slope. At times, the speed of this kind of solifluction can reach 10 cm/ day, but customarily it does not exceed 10 cm/year. The photo shows solifluctional flows near Suslositna Creek, Alaska (United States) (Photo credit: U.S. National Geophysical Data Center)

Photo 11. A slip-out (so-called fast solifluction) is one kind of solifluction. It is characteristic of the steeper slopes formed by silty loams or sandy clays. Rates reach several tens of metres perday. The photo shows solifluction slip-out on a bank slope in Yakutia, Russia (Photo credit: V.E. Tumskoy, Department of Geocryology, Moscow State University, Russia)

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