south, the thawed ground did not freeze completely in all places, so that along with the monolithic permafrost a two-layered structure of the permafrost is also widespread. The so-called relic frozen layer was formed, which attests to the major climatic changes that occurred in the past. It has remained to this day, even in those regions in which permafrost is absent at the surface (between latitudes 62°-63°N and 59°-60°N).

The depth to the permafrost table of the relic layer increases from 50-80 m at latitude 66°-67° to 150-200 m at 59°-60°N, and the thickness ranges from 100-150 m to 200 - 300 m. According to available data, the temperature of rocks from this layer is not less than -1°C. Also affecting the existence of the relic frozen layer, in addition to the climatic and paleoclimatic conditions, is the composition of the ground and the vegetation. The relic permafrost is best preserved in deposits with a low permeability.

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BASIC FEATURES IN THE CRYOGENESIS OF THE EUROPEAN PLAINS IN THE UPPER PLEISTOCENE

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For the study of general questions relating to the dynamics and origin of permafrost, the European area is of special interest. At present, the European area, with the exception of some very small zones located in the north of Scaninavia and the European part of the USSR, and also in the high Alps, is free from the influence of processes associated with permafrost. Nevertheless, at certain times in the past, beginning with the middle Pleistocene, and especially in the upper (late) Pleistocene, not only the mountains but also the vast European plains were in a permafrozen state. During this period, Europe and the northern half of Asia constituted a single cryogenous region, which seemed to emphasize the unity of some of the climatic and physical-geographic features of the European mainland. The subsequent existence of two extreme states--the total predominance throughout all of northern Eurasia of a region of permafrost and the subsequent falling away from this region of the entire western half of the mainland (Europe)--is a phenomenon that continues to await a fully substantiated explanation. It may be that the search for the causes of such striking changes in the structure of the cryogenous region will being to light properties of the process of cryogenesis as a whole.

A fairly extensive body of data has now been assembled with respect to the fossil and relic ancient permafrost formations that have been discovered and described in various regions of Europe.

The so-called periglacial phenomena in Poland have been described in papers by Dylik,[16,17] Yahn,[19] Moiskii,[9] and Ol'khovik-Kolyasinskaya.[14]

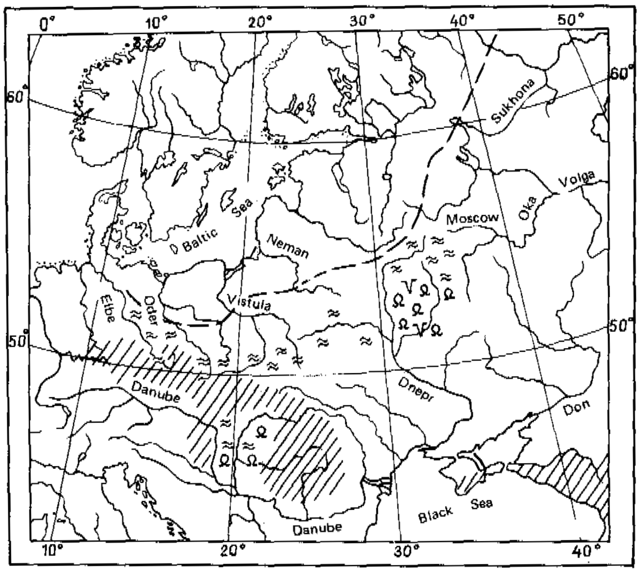
In Hungary they have been described by Pecsi. There are also data relating to the area comprising East Germany (Lembke *et al.*[8]) and Czechoslovakia (Demek,[15] Sekyra[23]). The cryogenous structures of France have been reported in papers by Tricart and Cailleux,[24,25] and also by Guillien,[18] while those in Belgium have been described by Paepe.[21] Some observations on cryogenous structures in East Germany, Czechoslovakia, Poland, Hungary, Austria, Belgium, and France have been obtained by the author during geological field trips in those countries

There are also extensive publications by various authors that relate to the European part of the USSR.

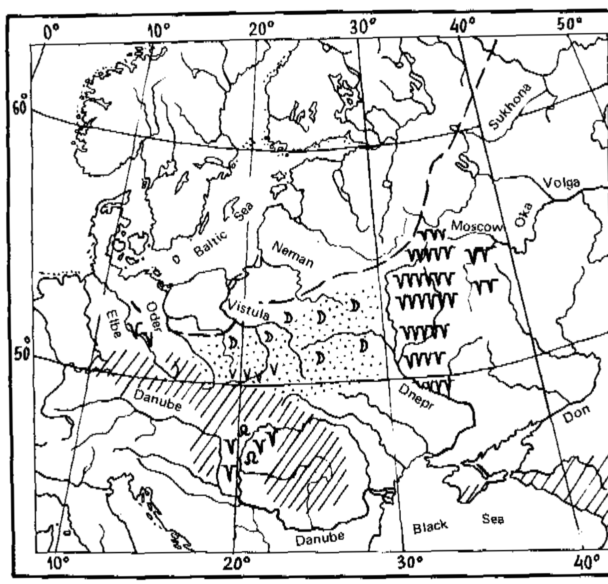
First and foremost among these, mention must be made of the papers by A. I. Moskvitin,[10] Yu. M. Vasil'ev,[2] Yu. V. Krylkov,[7] D. L. Nazarenko,[11] M. N. Grishchenko,[6] V. V. Berdnikov,[1] and also those of the author.

There also exists certain cartographic information reflecting the actual distribution of cryogenous formations. These include maps of ancient cryogenous phenomena with respect to Poland[16] and Hungary;[22] an atlas of the periglacial phenomena of France;[24] an outline map of locations of ancient cryogenous structures;[13] and a drawing illustrating the distribution of a relic cryogenous morphosculpture on the Russian plain.[3] Moreover, together with Berdnikov,[5] the author has made small-scale drawing illustrating the occurrence of cryogenous formations in the Valdai (Würm) epoch in the area comprising central and eastern Europe (Figure 1).

Currently, an attempt is being made to use the existing data as a basis for making a small-scale schematic map that would cover a more extensive area, embracing the principal European plains regions, the cryogenesis of which, as distinct from the mountainous regions, is more closely and di-



(a)



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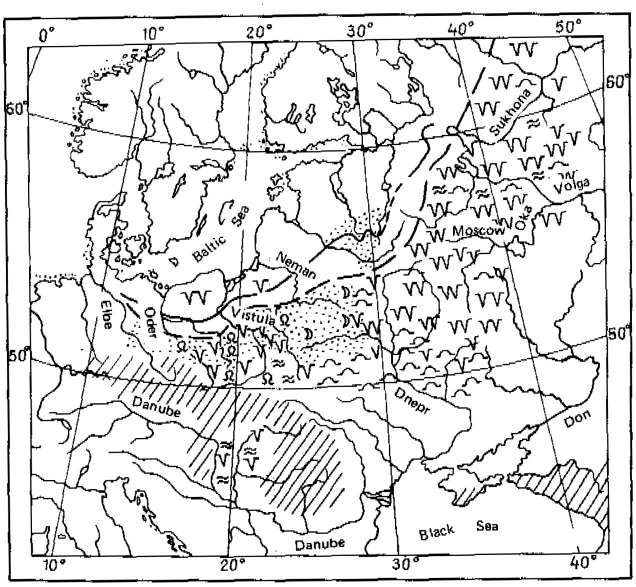

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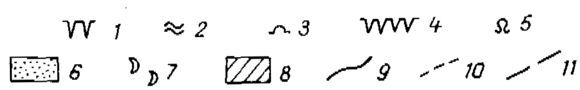

FIGURE 1 (a) Distribution of cryogenous structures dating from the early Pleistocene, (b) late Bryansk, and (c) late Pleistocene. 1--ice wedges and polygons bounded by ice wedges; 2--solifluction structures; 3--cryoturbations and other structural disturbances; 4--deformations of the Bryansk fossil topsoil; 5--thermokarst structures; 6--regions containing sand; 7--dunes; 8--mountainous regions containing a complex of periglacial-permafrost structures; 9--limit of the Valdai glacier in the Bologov stage; 10--southern limit of the early Valdai permafrost zone; 11--limit of maximum extent of the Valdai glacier.

rectly linked with the general climatic changes. Despite their inherent shortcomings and simplifications, which indeed are characteristic of any first attempt when large areas of land are involved, these schematic maps will nevertheless make it possible to reach certain general conclusions, a critical analysis of which, it may be hoped, will facilitate the compiling of more complete maps and charts through the efforts of scientists of various countries.

Since when ascertaining the main cryogenous features of the European plains, a major role is attached to their relationship with the general climatic changes, it is important to establish the chronological-stratigraphic order of succession in which the cryogenous processes occurred and their correlation with the main natural events in the late Pleistocene.

In solving the chronological-stratigraphic problems, a more positive role was played by the information derived from studying the structure of the upper Pleistocene loess and fossil soil beds of Europe, since it is within these beds and their facies-related deposits that the numerous and diverse ancient cryogenous structures are localized, by virtue of which they have obtained a secure stratigraphic and age position.[20]

An analysis of the cryogenous processes at particular chronological and stratigraphic levels has made it possible to distinguish three main cryogenous stages in respect of the upper (late) Pleistocene. Furthermore, the great horizontal extent of these beds provided an opportunity of discerning certain spatial variations in the manifestations of the cryogenesis within the individual cryogenous stages.

THE FIRST (EARLY VALDAI) STAGE OF CRYOGENESIS

In the loess section, the characteristics of this stage were recorded in a soil profile belonging to the Mikulin (Riss-Würm) glaciation and the beginning of the Valdai (Würm) glaciation (the Shtillfried-A profile in Austrai, the Naumberg profile in East Germany, the RK-III + RK-II profile in Czechoslovakia, and the Mezino profile in the European part of the USSR). An early (loess) phase and a late (steppe) phase are distinguished in its structure. The extent to which the entire upper part of the soil profile is disturbed by deformations led us to the view that the early Valdai cryogenous stage originated immediately after the formation of the second--steppe--soil phase had ended. On the basis of the relationship between the structures belonging to this stage, the cultivated layers at the halting places in southeastern France, and the existing dates as to absolute age, the approximate limits of the early Valdai cryogenous stage can be set at between 65,000 and 60,000 yr ago.

On the plains of eastern Europe, frozen structures dating from this period extend southward to latitude 53°N, while in central and western Europe, they occur in East Germany, Poland, Czeckoslovakia, Hungary, Belgium, Austria, and France, reaching latitude 47°-48°N. This initial upper Pleistocene wave of cryogenesis was characterized by its own main type of permafrost formation: Throughout the entire area, the formations consisted chiefly of solifluction and cryoturbation deformations, combined into a single zone. Within this zone it is possible to trace at least two provinces: (1) a western province, extending from France to the western regions of East Germany and to the Czechoslovakian SSR (whereas here, the above-mentioned structureless deformations completely predominated; in the area comprising France, it is only the solifluction phenomena that are distinctly recorded); (2) an eastern (central-eastern European), in which together with the processes of plastic deformations there is evidence of a process involving the formation of small, elementary ice wedges measuing 15-20 cm wide in the upper part and 1.0-1.2 m high. It is typical that in the European part of the USSR, north of latitude 55°-56°N, this combination of cryogenous phenomena is accompanied by evidence of soil movement along the slope, not only in the spring, but also in the autumn, when blocks of the frozen upper parts of the seasonally thawed layer were subject to creep.

In general, the early Valdai cryogenous stage was characterized by the preeminent development of structureless deformations, by the absence of pronounced geomorphological manifestations in the form of specific topographic features within a gently undulating framework, by the high moisture content of the layer of seasonal freezing and thawing, by the moderate (0.5-0.8 m) thickness of the seasonal layer, and by the small temperature gradients.

THE SECOND STAGE OF CRYOGENESIS

This is the middle Valdai (middle Würm) stage. The onset of cryogenesis is seen to have occurred at the end of the bryansk (Shtillfried-B) period of soil formation and is well recorded in the loess sections of many European countries. The conclusion of the stage occurred at the beginning of the second post-Bryansk phase of loess accumulation. The period in which the cryogenous processes developed was about 25,000-22,000 yr ago.

In comparison with the early Valdai stage, the climatic conditions under which this stage of cryogenesis took place were more severe, and the area of the permafrost region extends to latitude 49°N. The following are the specific spatial peculiarities of the cryogenesis. In the latitudinal direction, two provinces are distinguished. During this period, as in the first stage, beginning with the area comprising Volyn-Podolia in the European part of the USSR, Poland, Czechoslovakia, East Germany, and farther west, solifluction and, in part, cryoturbation processes predominated. These, however, were much more active and dynamic than those in the early Valdai stage. Of the other structures, only rudimentary cracks 0.2-0.3 m high and 5-8 cm wide were sporadically noted there (for example, in Belgium).

The eastern European province differed significantly and qualitatively from the western

European province during this stage. It was characterized by the extensive occurrence of fissure-forming processes, although these were on a small scale (the length of the sides of the polygons ranged from ~2.0-2.5 m, the heights of the wedges was ~1.5 m and they exhibited a two-layer structure). This polygonal fissuring was accompanied by processes of plastic soil flow, which arose as a result of the dynamic stresses in the layer of seasonal freezing and led to the formation of clay boil type structures that were quite clearly defined in the surface microtopography.

Another typical feature of the middle Valdai cryogenous stage consists of the very weak meridional variability of the cryomorphic processes throughout the entire eastern European province. The morphotype, i.e., the clay boils, predominated between the central Ukraine and the region lying to the north of Moscow (the Vladimir Oblast'). Its distinctiveness, however, varied in the north-south direction, there being a worsening toward the north, since in this direction the thickness of the seasonally thawed layer decreased (from 1.0 m to 0.5-0.3 m), along with an accompanying increase in the dynamic processes in the dynamic processes in the soil near the surface.

In general, the moisture content of the soil in this stage remained high, especially in the western province. Toward the east it diminished and there was a rise in the temperature gradient in this direction, which reached a maximum when systematic fissure formation began, even though this was on a very small scale.

THE THIRD STAGE OF CRYOGENESIS

This is the late Valdai (late Würm) stage. The upper parts of the cryogenous structures are in contact with the top of the loess strata. An approximate estimate of the time segments in which this stage existed is between 15,000 and 10,000 yr ago. The third, most recent, stage was characterized by very complete and active development of cryogenesis. It was during this period that the cryogenous region reached its southernmost limit of 45°-46°N, and the climatic conditions leading to cryogenesis became most severe and attained their maximum continental extent. All the European plains came to be characterized by polygonal crack formation processes in which the "normal" size of the polygons was 20-40 m and ice wedges were formed. Under the gently undulating conditions that obtained (with the exception of areas with a high rate of sedimentation, for example, floodplains), these latter were preeminently of the epigenetic type.

Judging from the map of this stage, certain features were noted in the structure of the late Valdai cryogenous zone that connect it with the contemporary Siberian region of permafrost. Thus, in eastern Europe, in the north-south direction, there were three broad belts whose features resemble the northern, central, and southern zones of the permafrost region in Siberia.

In the west-east direction, the plains of Europe were subdivided into the following four provinces, in which cryogenesis underwent modificiations, depending on the increasing continentality in this direction: (1) a western European, (2) a central European, (3) a western Russian, (4) an eastern Russian.

There is reason to suppose that in the late Pleistocene the overall structure of the European cryogenous zone was characterized by considerable originality. First, it is probable that in western and central Europe the mountainous and flatland regions of permafrost were interlocking, thereby forming a single area. In eastern Europe, on the other hand, there was a hiatus between the permafrost regions on the plain and in the mountains (the Caucasus and in the Crimea). There, these regions were most likely divided by the area situated in the lower regions of the Dnieper and Volga and characterized by processes of deep-seated seasonal freezing (the third latitudinal belt in the western Russian province). It is as if the belt of seasonal freezing in eastern Europe had become wedged into the zone of Pleistocene permafrost. On the whole, in comparison with the preceding stages, the third and latest European stage of cryogenesis was characterized by the lowest moisture content of the soil under the prevailing gently undulating conditions (especially in the eastern regions) and by the highest temperature gradients, which coincided with the greatest thickness of the seasonally thawed layer (2-3 m).

The available information pertaining to the development in Europe of permafrost processes in the upper Pleistocene affords a basis for making a comparative analysis of the various stages of cryogenesis and leads on to certain general concepts.

In the upper Pleistocene in the European plains, cryogenesis was dissimilar both in time and in space. At the present level of understanding, it remains difficult to arrive at a fully substantiated classification of the types of cryogenesis that existed in the late Pleistocene in Europe, the more so if geophysical and quantitative criteria are to be used. There are even grounds for assuming that today, complete analogue types that existed in antiquity are lacking. In particular, in the case of the ancient Valdai stage, there are no analogues such as high soil moisture, small gradients, and structureless deformations. This type can be provisionally called the Atlantic type of cryogenesis. As its opposite, the eastern Siberian type can be distinguished (abruptly continental conditions and large temperature gradients). Between these extreme types, it is possible to distinguish an intermediate-transitional type.

In that case one can speak of the fact that in the ancient Valdai stage, a greater degree of uniformity of the cryogenous conditions was typical of the European plains, although at the level of the gentlest, Atlantic type of cryogenesis (Figure 2). The differences between the west and the east did not overstep the bounds of the same type, although some increase in continental extent is to be seen toward the east.

The European cryogenous region was characterized by a different type of structure during the middle Valdai stage of cryogenesis. Here, fairly

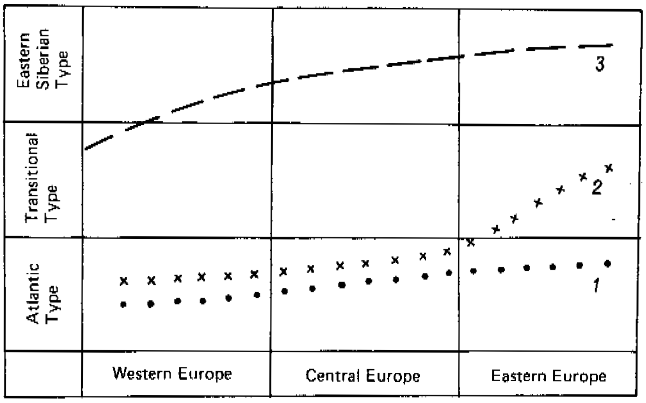

FIGURE 2 Variation in the structure of the permafrost region of the European plains in the (1) early, (2) middle, and (3) late Valdai stages.

marked differences between the western and eastern regions are to be seen. Whereas the western regions have remained at the level of the Atlantic type (even though the processes in the seasonally thawed layer are characterized by increased activity), the eastern regions fall within the more severe type of cryogenous conditions, which can be termed transitional. The conditions of this type are such that the processes leading to plastic deformations of the soil are accompanied by polygonal cracking, although this is rudimentary.

Another typical feature of this stage, which has yet to be explained, is the absence of a succession of cryogenous morphotypes in the meridional direction, in other words, the simplified morphoclimatic structure of the cryogenous region as a whole.

Finally, in the third, late Valdai stage, some equalization of the cryogenous conditions again appears, although here it is at a qualitatively different level than in the first, early Valdai stage. The development of cryogenosis in the late Valdai in the European plains is patterned on the eastern Siberian type, although within the cryogenous region of Europe there also existed differences associated with the increase in the degree of continentality from west to east. It should be noted that the use of the term "eastern Siberian type" must not be taken to mean a complete analogy, since undoubtedly, the moisture content of the ground in eastern Europe was lower than in the coastal lowlands of eastern Siberia today.

The analysis of the development of cryogenesis in the late Pleistocene of Europe is suggestive of a discreteness (discontinuity) of this process with time. Evidence in support of this notion is to be seen in the presence of three well-defined, independent cryogenous horizons (stages). Did permafrost exist in the intervals between them, during the main periods of ice accumulation? If this was the case, then the dynamic processes accompanying it were in an extremely depressed state. This depression could have been caused by the high aridity of the climate and the very low ice content of the soil, rather than by unfavorable temperature conditions.

On the other hand, the analysis of the cryogenesis being discussed reveals the direction they have taken, both in time and in space. Between the early and late Valdai, the area of cryogenesis became greater, and at the end of the Valdai it had advanced farthest towards the south. Throughout the Valdai stage there was also an increase intensity and severity of the cryogenesis, so that at the end of the Valdai there arose, not only territorially but also structurally, a single cryolithozone. This was the vast cryogenous region of the whole of northern Eurasia, the area of which, equalling approximately 22 million km^2, was almost double the area of the contemporary permafrost on that continent (approximately 12 million km^2), while its limit, in contrast to the contemporary submeridional limit, occupied a latitudinal position.

We shall now turn to one of the most important moments in the history of the cryogenesis of Europe and Eurasia as a whole. During the change-over from the Pleistocene to the Holocene, the vast cryogenous region, which had only reached the peak of its development, both spatially and in content, right at the end of the Pleistocene, began to undergo very rapid degradation (Figure 3). According to palynological data, accompanied by radiocarbon datings,[12] for the most part the degradation of the permafrost in Europe could have embraced a period of 1,000-1,500 yr. This rapidity of the degradation process was close to being catastrophic, while the rearrangement that occurred throughout the entire cryogenous region by the falling away from it of Europe was of a radical nature. Naturally, the rapidity of this degradation and its areal dimensions gradually diminished from west to east with increasing proximity to the region of contemporary permafrost, which can be regarded as the remaining, preserved portion of the vast Eurasian cryogenous region of the late Pleistocene.

The question that naturally arises is: What is at the root of the unique process whereby the late Pleistocene region of Eurasian permafrost underwent progressive development and degradation? We have already drawn attention to the fact that

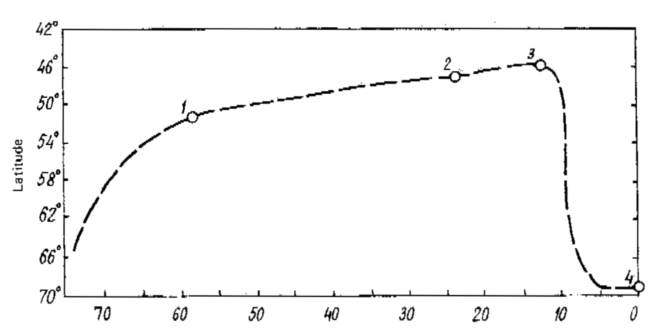

FIGURE 3 Changes in the position of the southern limit of permafrost in eastern Europe in the upper Pleistocene period. 1--early Valdai stage, 2--middle Valdai, 3--late Valdai, 4--contemporary stage.

this process cannot be directly linked with the history of the continental ice sheet and that the explanation for it must be sought primarily in the overall climatic changes of the late Pleistocene.[4]

It was in the late Pleistocene that the onset occurred of the specifically continental, cold conditions throughout the entire extratropical expanse of the Northern Hemisphere (the indigenous stage of cryogenesis). This led to a very marked expansion of the area occupied by sea ice, to its southward advance and to rearrangement of the surface structure of the hemispheric mantle, and also of the climate, since the ocean, being covered by ice for a long period, could not be the source of solid precipitation in Europe. As is well known, in the late Pleistocene the overall climatic changes were superimposed by a major regression (northern 100 m) of the sea, which was likewise conducive to an increasingly continental type of climate. Presumably the vast dry expanses of the present-day shelf were also an arena for the development of permafrost.

The overall climatic warming, with which is associated the beginning of the holocene, led primarily to the degradation of the thin sea ice, which reacted very quickly everywhere, even to minor variations in the air temperature (this is a well-known phenomenon in the history of the Holocene). Together with the retreat of the sea ice and the general warming trend there was also a change in the structure of the Earth's mantle: the European continent began to receive war Atlantic air masses carrying precipitation, with the result that rapid degradation of the permafrost began.

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