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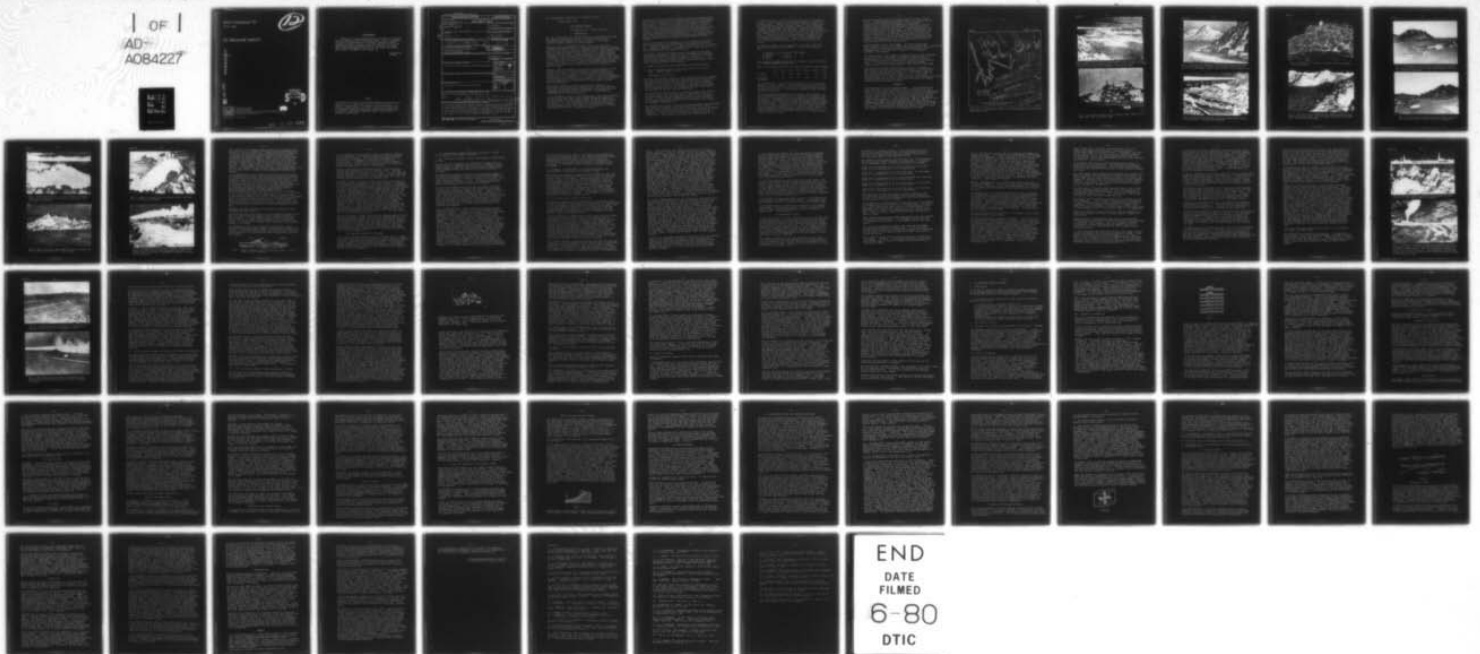
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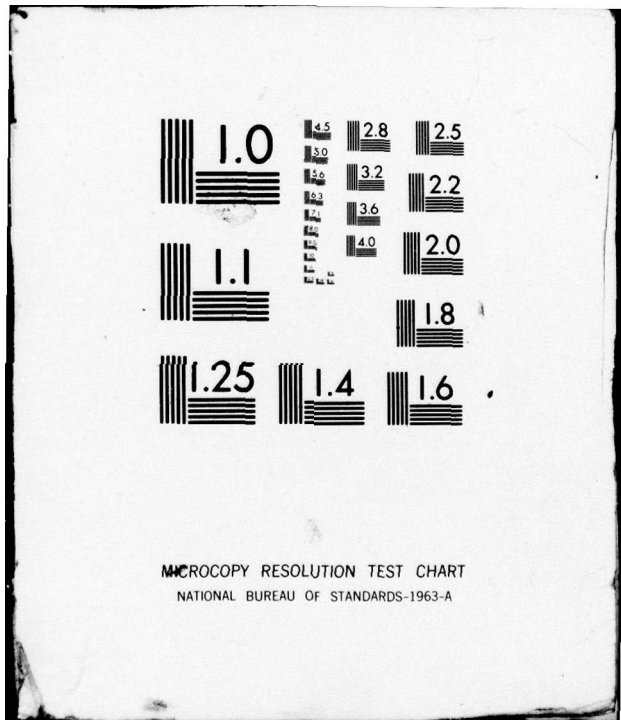
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# ICE PRESSURE RIDGES

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HANOVER, NEW HAMPSHIRE, U.S.A.



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Austin Kovacs  
USACRREL

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) In the first (descriptive) section, some of the greatest and most significant ice pressure ridges are discussed in order to derive from them the most important general conditions of formation. The second section brings up applications to general geological questions, particularly for tectonics. In the third section the ice pressure ridges are considered as a natural experiment with respect to the tectonic processes in the earth's crust.			

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Third Hydrological Conference of the Baltic States

Warsaw, May, 1930.

ICE PRESSURE RIDGES

by Professor Dr. E. Kraus (Latvia)

INTRODUCTION

The very severe Winter of 1928-29 provided an opportunity to study the unusually magnificent mounds of ice which heavy storms frequently thrust together on the coastlines of very large, tide-free bodies of water in colder climates.

There is still no comprehensive study of the most important phenomena associated with this, investigating the various conditions of formation; however, there are numerous papers on particular forms. These ice pressure ridges which seldom occur on a large scale at temperate latitudes were studied in geology 60-70 years ago with the intention of gaining an understanding of the erratic glacial phenomenon. Thus, the powerful ice pressure of January 15-16, 1863, on the Pernau Bay coast of the Gulf of Riga induced Count Keyserling /1/ to write a brief report to lessen the improbabilities of the glacial drift theory. C. Grewingk /2/ described the ice pressure ridges on the north shore of the Wirzjäärw Sea in Estonia on April 24, 1868.

However, since the theories of the inland ice distribution of the diluvial erratics, already promulgated in Germany but not yet heeded in the 1820's, rapidly received general recognition in the year 1875, that incentive for the study of the ice pressure ridges was lost. Nevertheless, it was believed that now a completely and generally valid solution to the question of block distribution and land formation on the coastlines of large bodies of water had also been found.

More recent research in arctic and antarctic regions (E. v. Drygalski) again checked such exaggerations, and direct observations such as those presented, for example, by the excellent and fundamental monographs on Lake Balaton /3/ strengthened the understanding of those processes /4/.

If the geologist, as well as the hydrologists, must also be actively concerned with them today, their general geological importance for the history of the sub-arctic region in the diluvium and, at the present time, for the sedimentation, motivates them in this direction /5/. On the other hand, the more precise evaluation of the phenomena, which come closer to an explanation of certain geomechanical problems, is another motivation.

To conceive of the ice pressure ridges as grandly designed experiments of nature carried out by comparatively simple, understandable means, was my inducement for working on and partially mapping the oceanic gulf. Conditions of formation and shapes of the hills, the crevasses, and their directions were not previously taken in detail into the range of consideration from the hydrological point of view. This is primarily a question of the determinations concerning the appearance and disappearance of the ice covers and their relationship to the temperature cycle. The detailed treatment of this borderline question between geography-hydrology and geology probably holds out promise of useful results for both aspects.

In the determination and character of the diversified literature and in the collection of observations, Consulting Professor Dr. E. v. Drygalski, Professor Dr. R. Meyer, and Professor Dr. R. Putnin, Dr. P. Thomson, Assistant L. Slaucitajs, and W. Zans have been of kind assistance and I am grateful to them.

In a first, descriptive section, some of the greatest and most significant ice pressure ridges will be discussed more precisely, specifically those of last year at Riga, in order to derive from them the most important general conditions of formation. The second section brings up applications to general geological questions, particularly also for tectonics.

#### A. LARGE ICE THRUSTS AND THE CONDITIONS FOR THEIR FORMATION.

##### I. The Ice Pressure Ridges on the South Shore of the Gulf of Riga (March 29-May 9, 1929).

Preliminary history [6].

The Ice. In the Gulf of Riga in 1929, the general ice cover formed 4-5 days earlier than normal, but considerably later than in the most extreme cases prior to that year, in the first ten days of February. At the end of February, the ice cover was unbroken, while as a rule, drift ice at the most is observed at the center. At the beginning of April, the continuous ice cover was bounded between Oesel on the west and the Libau coast.

The ice first softened on April 23, unusually late, later than in any spring since 1878, from the mouth of the Dvina, so that the ice cover endured for approximately two months, twice as long as normal. In spite of the energetic attempts of the icebreaker Kr. Waldemar, from March 6 until April 9, navigation was brought to a complete standstill [7].

The thickness of the ice in this period had increased extraordinarily and exceeded the maximum of the years 1910-1917 (45-50 cm at Pernau); since even the average for 1929 can be estimated at approximately 45 cm, the maximum in the Gulf was observed to be 65 cm. On March 29, however, the ice cover was no longer completely homogeneous. We disregard disintegrations brought about in the

northeast section of the Gulf at the Pernau shore in January by a storm. At this location, ice pressure ridges 6 m high had already formed. However, they did not become any larger later. The icebreaker had broken through on March 21 and 22 between Dünamünde and Zarnikau, and starting on March 23, had provided a channel between there and Domesnäs. In addition, the thaw had already begun, since the air temperatures in March rose above zero degrees C on the 12th to 14th, 21st to 25th, and 28th to 29th. A northwest storm of 18 meter-seconds on March 13 had already pushed together the first ice masses, admittedly not so strongly on the Riga shore. Here, a broad coastal strip out to the third sand bank had become solid ice down to the bottom.

The monthly average of the temperature for December 1928 and May 1929 was slightly above normal. On the other hand, in 1929,

in January, it was	1.9-3.4°	below	normal
in February, "	8.8-9.9°	"	"
in March, "	0.2-2.1°	"	"
in April, "	3.1-4.9°	"	"

The unusually intensive freeze, which in February often went below -20°, vanished rapidly on April 10.

Wind. The wind came from the following directions on the average:

	Nov.	Dec.	Jan.	Feb.	March.	April.	May.
in Riga	S	S	SE	NE	N	N	N
Provinces (Mersrags)	S	SW	SE	E	NW	W	NW

The ice pressure ridges were formed between the two observation stations, closer to Riga. Even in earlier years [8], the ice distribution had been found to be very strongly dependent on the primary wind direction. Particularly vigorous storms occurred starting on April 8.

The monthly wind distribution in the Gulf is very uniform. We have predominantly southerly wind in November and December with certain local preponderances of southwesterly and southeasterly directions. In January, a southeast wind very generally blows, in February an east wind, and in Riga and Hainasch (West Livonia), a northeast wind. In March the wind is predominantly northwest, and north in Riga, the same in April, while at other times the west and southwest winds prevail. It can be stated that in the winter semester, a uniform counterclockwise rotation of the primary wind directions takes place from south through southeast, east, and north, to west.

The great shearing motion then began during the night of March 28-29. On Maundy Thursday afternoon (March 28), persons on the shore of Bullen observed no pressure. A very severe northwest storm blew and met significant resistance on the ice surface which had become uneven because of hard snow drifts, thawing effects, and rift formation. At approximately 1:00 am in the morning on Good Friday (March 29) the storm shifted to a gale from the north. A large portion of the ice motion in the southerly section of the Gulf must thereby have been set into motion. Then, as the first fishermen (eye witness Lorenz from Bullen) were going to the beach, they found ice ramparts pushed together even approximately 300 m from the beach, of a size that had never before been observed here.

Pressure ridges of 5-6 m are common on the south and east shore; however, those 12-15 m high, which were piled up here chaotically from crushed ice plates particularly at Bilderlingshof-Bullen-Dünamünde, must have owed their formation to very specific favorable circumstances.

The immense zone of ice ramparts extended along the entire southern shore of the Gulf, admittedly with numerous interruptions, for approximately 100 km from Angern (Engure, southern provinces on the Courland coast) to Peterskapelle (Peterupe on the Livonian coast). The seaside resort of Bullen, where the highest ridges were formed, was approximately in the center of this area.

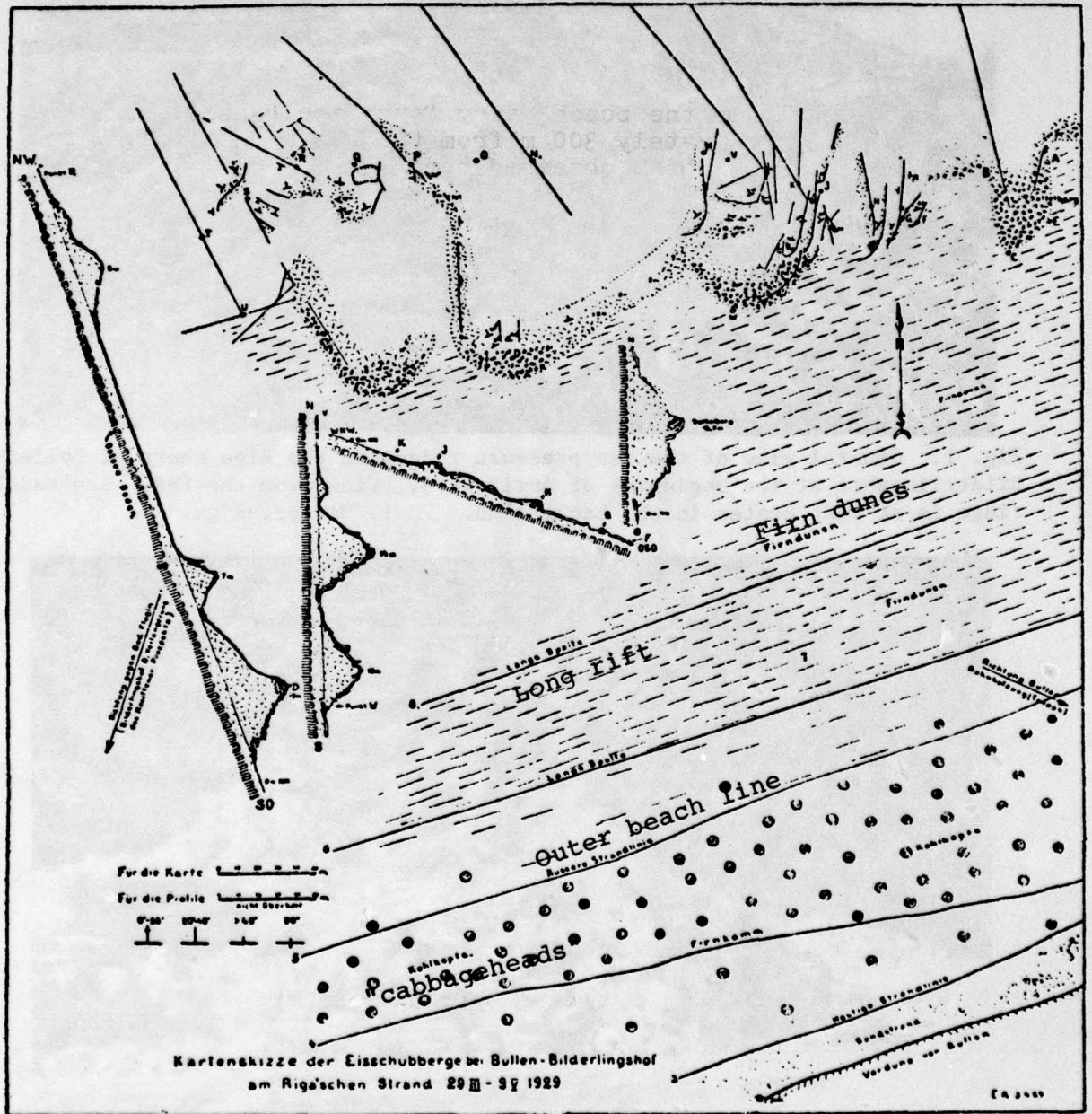
With Professor R. Meyer and Assistant N. Delle, I measured a particularly instructive section between Bullen and Bilderlingshof with simple tools (mountain compass, 30 m measurement range, in one case with theodolite) (cf. Table I). A selection from the many photographs is provided in Tables II-VII. The ridges remaining until May 9, 1929, offered excellent observation possibilities and are probably suitable for explaining in general many genetic questions about ice pressure ridges.

#### FORMATION

The structure of the ice pressure ridges. The attached photographs provide a good representation of the internal structure. This is a matter of blocks of ice plates, 40-50 cm thick, chaotically piled up on one another, and in which can be clearly differentiated the once lower clear ice with its smooth bottom surface and the higher, whitish firn ice. The latter is formed by the copious snowfall which frequently thawed somewhat, heavily loading the ice cover. The surface water also drained into the ice, and the combination became a firn ice mass which still allowed the passage of air. From this difference between bottom and top layers, it is very easy to see whether the crushed ice plates or pieces of them were tipped over even before the formation of the heap.

Table I

E. Kraus. — Eisschubberge.



Sketch map of the ice pressure ridges at Bullen Bilderlingshof on the Riga Shore, March 29-May 9, 1929.



Fig. 1. General view of the ice pressure ridges on the Riga shore at Bullen-Bilderlingshof at the beginning of April 1929. View from the ENE. The saddle ridge is at left center in the background. Phot. Walter, Riga.



Fig. 2. The crushed lee side of the ice pressure ridge at Bullen, early April 1929. Phot. by O. Walter, Riga.

Table III



Fig. 3. Lee side of the saddle ridge from the East (people on the ridge) and (in the foreground) the somewhat lower pressured pre-depth slab in front of the block rampart; Bullen, early April 1929. From commercial photo.



Fig. 4. View of the forward front of the ice pressure ridge at Bullen, early April 1929. From commercial photograph.



Fig. 5. Crushing of the ice plate in rising to form an ice rampart; luff side at Bullen.

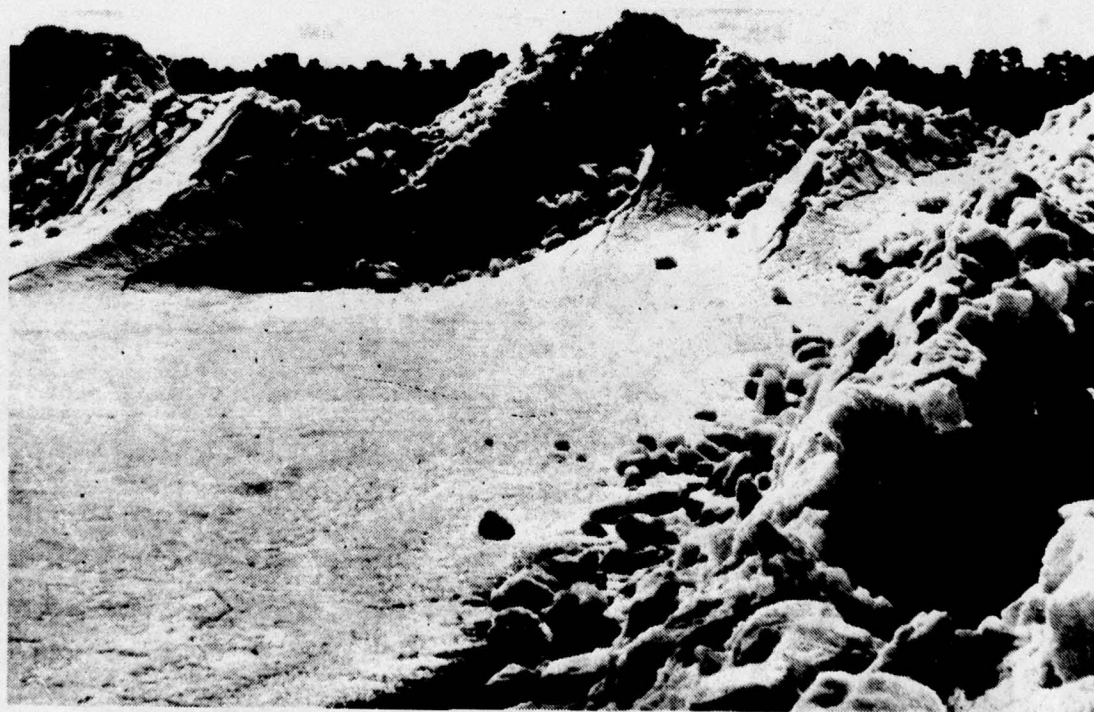


Fig. 6. Last rise of the ice plate with rift formation above the rear; vertical plates, far right. Left, the saddle ridge, Bullen, early April 1929. From commercial photograph.

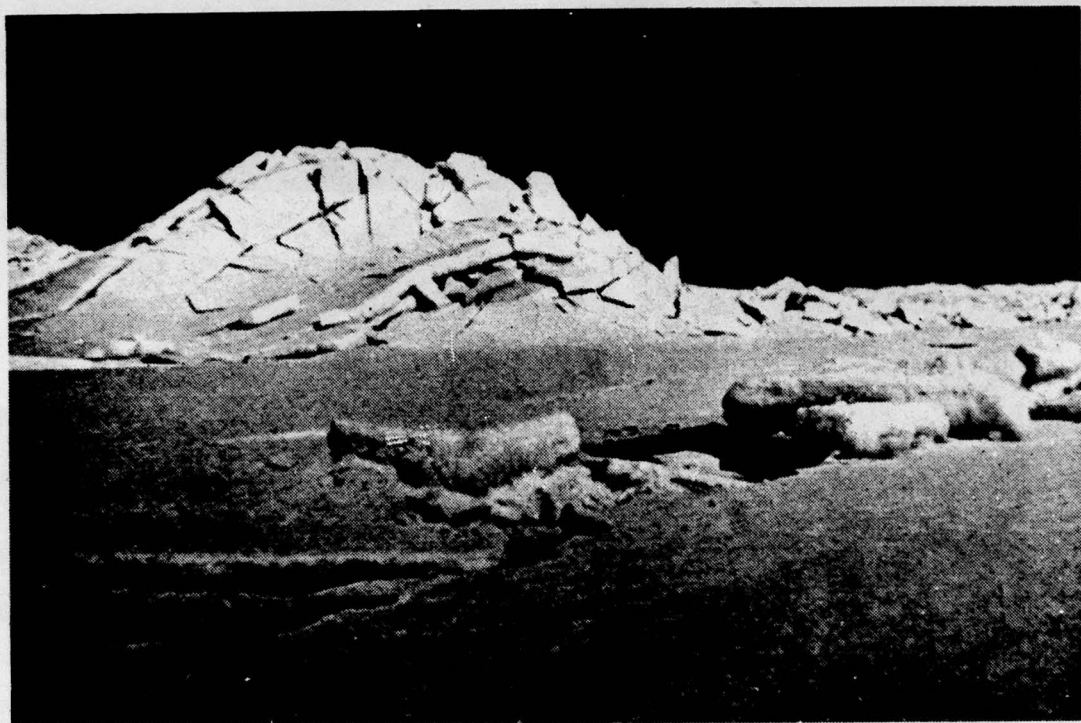


Fig. 7. Rift formation in the ice plate in overriding the obstacles (ice block upthrusts) from the luff side, Bilderlingshof, early April 1929. Photo by H. Bielenstein.

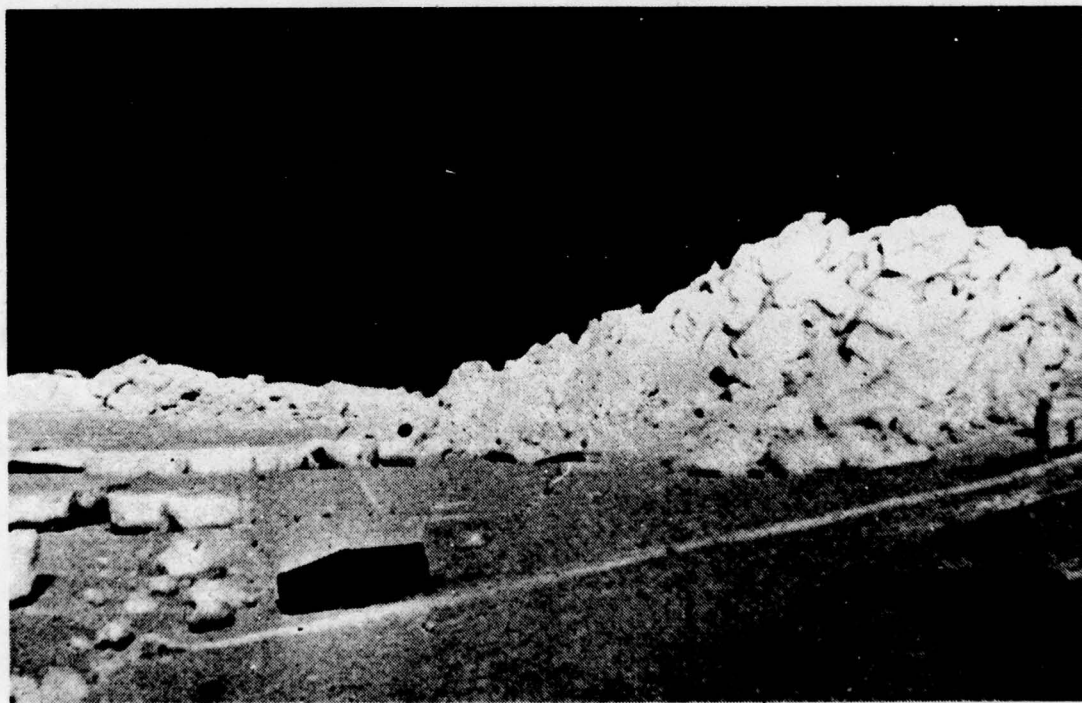


Fig. 8. Rise of the ice plate against the ice rampart (luff side) with rifts, May 5, 1929, at Bullen. Photo by H. Bielenstein.



Fig. 9. Split restraining ridge. At center distance, very long and broken-up ice pressure ridge on the Riga shore, early April, 1929. From commercial photograph.



Fig. 10. Side view of the ice plate upthrust to the left (against the shore at Bullen), early April 1929. Photo by Walter.

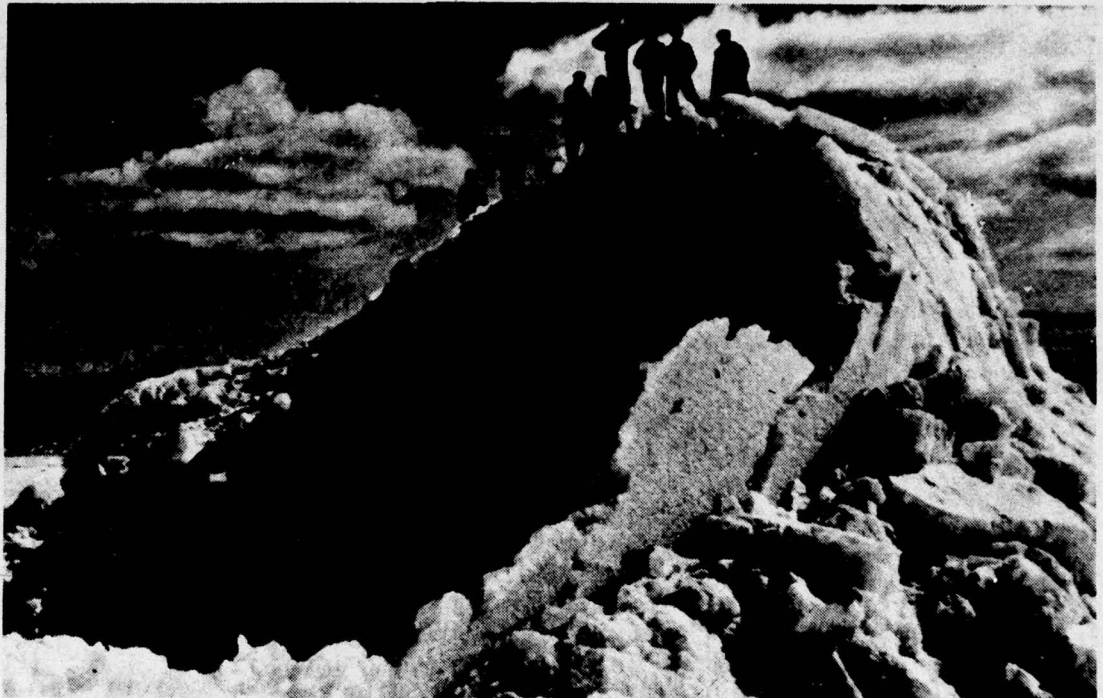


Fig. 11. Summit of the saddle ridge from the NNW, Bullen, early April 1929. From commercial photograph.

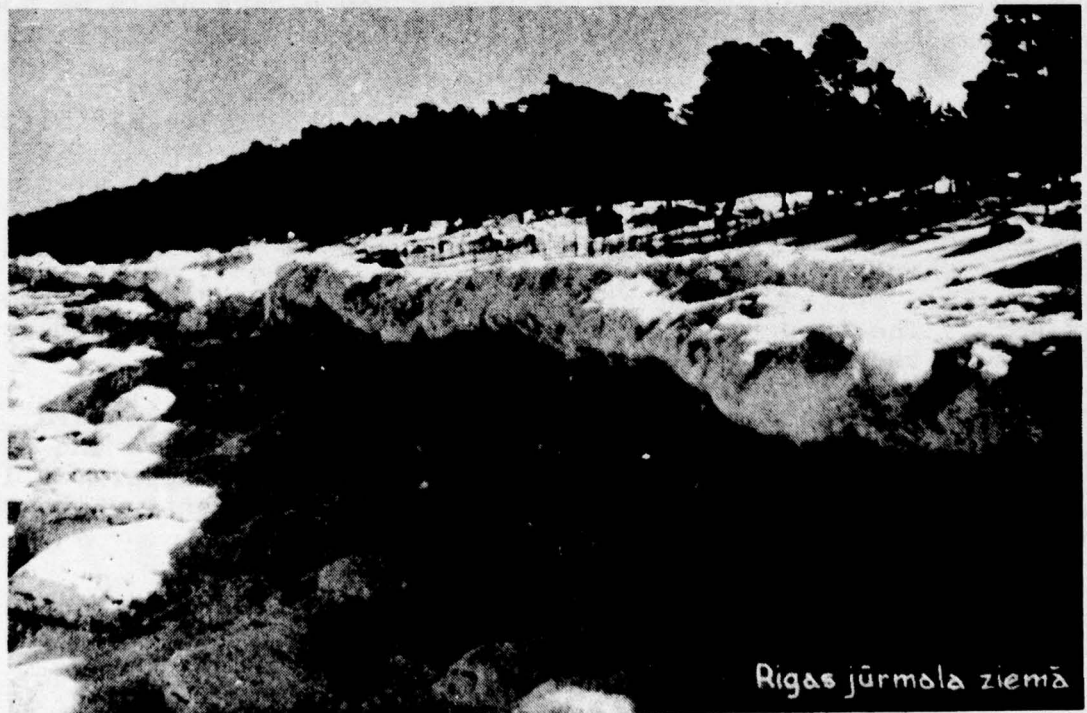


Fig. 12. The Riga shore in the winter of 1928-29. The storms have formed a new cliff in front of the snow-covered first dunes. The rounded rubble is snow rubble ("cabbageheads," pancakes). From commercial photograph.

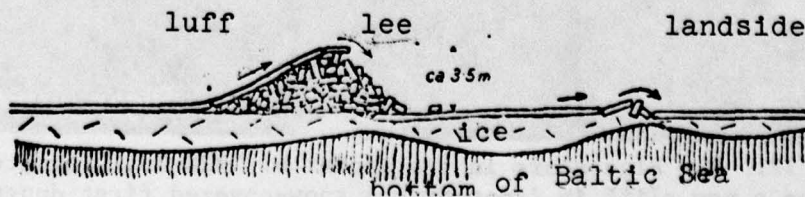
The interior of the ramparts always consist of an irregular block packing which lies together very loosely and whose interstices are either not filled or which has a looser interstitial packing of ice powder from powerful crushing in higher ramparts (easily recognizable in the photograph of Figure 11 of the saddle ridge). The blocks here were also mostly of much smaller head-sized to apple-sized dimensions. However, this could not be observed anywhere towards the land side of the ridges, which we call the lee side. Here, there is only a slope of gigantic "sugar lumps" (Figure 3) thrown loosely over one another. In climbing over them, it was necessary to be careful, since a foot could easily slide into the deep rifts. Sunday visitors frequently sustained leg injuries.

It was believed that the smoothing of the often somewhat cubical, but generally still rather more plate-like slabs of floes would not permit such a loose and high pile that the slabs had to slip forward and pile up on one another more with their upper or lower surfaces. When this did not occur, the sudden force of the motion manifested itself therein, but also the supplementary action of instantly freezing sea water and of refreezing processes. It is obvious that in the hurricane, which piled  $\frac{1}{2}$  m-thick floes 15 m high, seawater was also sprayed upward. The air temperature during the night of the storm on the shore is not known, but must have been very close to 0°C. In any event, the ice blocks jammed into one another with the greatest force became cemented together when a brief thawing occurred at the contact point, as a result of the pressure, and a subsequent refreezing occurred with the release of the pressure. The stability of the block structure, in which only very few blocks could be shown to be movable later, can probably be explained primarily in this way.

Naturally, the low brittleness of the firn ice layers was also favorable for high pileup.

The generally high slope angles of the ice ramparts formed in this way is no less steep, for example, than limestone blocks in a pile of debris. I measured an average of 35°-45°, while the north slope of the saddle ridge dropped at 42°, and at the top, at 48°. The insertion of larger plates generally caused multiple breaks in the slopes.

The difference between the landward lee side and the seaward luff side of the ice pressure ridge is very distinctive and always recurs. The normal profile (illus. 1) shows the uppermost ice plate rising out of the seaward ice level, first gently, and then more steeply.



Illus. 1. Normal formation of an ice pressure ridge. On the right, initial tendency.

In the adaptation to the general shape of the barrier required by the ascension, the plate would already be bent and thereby more or less broken up. Upon reaching the highest point of the barrier, the remainder of the plate then falls on the lee side. Therefore, the slope of an inclined upward-rising ice plate surface does not develop here, but rather the natural heaping slope of the ice plate debris.

This lee side therefore corresponds largely to the loose and steeper sand embankment on the lee side of a dune. We have already mentioned the steepness of its angle. The luff side has greater diversity, since there is no accumulation here, which must lead to very uniform results with material of the same kind, but extremely varied obstacles must be overcome here.

According to this, the angle at which the plate climbs from its horizontal position towards the land varies widely. In general, at a distance of approximately 20 m, a rise of only a few degrees and then a rapidly increasing upward bending were to be seen (Figure 6), until with smaller ice pressure ridges the mound summit was reached at approximately  $30^\circ$ . On higher ramparts, however, the ice plate climbed upward steeply to more than  $60^\circ$ , and in fact it was not infrequent that the end of the floe was bent up into a vertical position and that it even tipped over backwards. The luff side was thereby also covered by a floe of rubble, which either slid down to the foot of the upward slope or could also pile up and grow upward almost to the crest of the rampart. (Figures 2, 10). Also, the entire rising plate could break up (Figure 5, 9) or in very steep position could first enclose the peak rampart as a broad, repeatedly broken ridge (Figures 3, 11), and then could be dumped as debris on the broken-up luff side (Figure 11 and "saddle" profile on Table I), so that the crushed core of the ridge was then visible.

Often, particularly towards the top of the smaller rampart, several ice plates rising up on the luff side were superimposed on one another in parallel (Figure 10 and at H in the profile, Table I). This apparently took place when the plate broke through crosswise at the foot of the rise in each case, and then the floe at the rear lifted up in parallel over the climbing one. The floes extending freely into the air, often with areas of many square meters and 2-3 m high, represented well the suddenly solidified, violent motion (Figures 2, 10).

#### The regional location of the ridges

showed very clear relationships to their external shape. Figure 1 provides an overview of the ramparts at Bullen and Bilderlingshof, and Table I represents an outline of the ridges, which are also shown in Figure 1 (in the background, center). Two different rampart directions can clearly be differentiated, which must be evaluated differently at the same time according to the structure and the history of formation:

1. The "longitudinal ramparts" running uniformly to a great extent along the entire WSW - ENE coast.
2. The "transverse ramparts" running approximately perpendicular to them.

The two sections of ramparts are extensively combined with one another, which is suggested specifically by the rampart curves convex towards the SW, with which in each case a powerfully projecting rampart section goes westerly to the end, parallel to the coast.

The longitudinal ramparts are either of normal shape (Illus. 1) or frequent combinations of them, in which several bundles of flakes built up behind one another and piled up over their joint block structure (Figures 1, 4, 10). Here also, there are certain analogies to dunes, in which the high migrating dunes seem to be combinations piled up above one another.

The transverse ramparts are often, but not always, connected clearly to the location of large rifts aiming from the broad ice surfaces transversely towards the coast. A good example of a representative transverse rampart is shown in Figure 7. A ridge crest can be seen over a somewhat splintered transverse rift. The ice plate was thrust upward over an obstacle in front which was not wide but only narrow, and attempted to mold it with the formation of a ridge, but it shattered in two places at which the relief of the obstacle was particularly sharp. Thereupon, the portion of the small ridge lying close to the observer sank downward.

This is unquestionably a case of narrow but strong obstacles which have forced the ice plate into local transverse rises, ("obstacle ridges"). Because the luff side of the longitudinal ramparts by nature also produced no uniform slope for the following ice floes because of the different block motion and pileup, the rising ice plate must have given rise to the formation of such obstacle ridges at a wide variety of positions (Figure 6). Since in addition, in the coastal region also at the beginning of the great thrust, the resistances to pressure differed very much in location, shape, and size from place to place, and extremely variable results were produced in spite of the similarity of the thrusting objects. Narrow obstacles broke up even earlier forced premature ridge-like rises and produced extended transverse ridges which already ran a good distance seaward in front of the location of the principal longitudinal rampart. The foreground shows a shorter obstruction ridge of this type, and in the central region of Figure 9 is a transverse rampart several hundred meters long. Such a long transverse rampart is also shown northwesterly of point D on the profile of Table I, and the same is at the right in Figure 6. In these cases, there is no pronounced difference

between the luff and lee sides. The edges of the neighboring flat ice plate generally rise up very rapidly against one another symmetrically from both sides, into the vertical position. Depending on the local partial motions and the possibility of lifting the block rubble thereby formed, or carrying it off laterally, the transverse rampart obtained a different height and width.

The blending of longitudinal and transverse ramparts is characteristic of the form of ice pressure ridges.

The sizes of the ridges are substantially determined by the type and position of the thrust obstacles, just as are the locations and the slopes of the ridges. The unusual height of the ice ridges in April, 1929, has already been emphasized, of which the photographs give some idea if it is imagined in looking at them that the average ice floe thickness is almost 1/2 m. In the principal longitudinal rampart, the height varied between approximately 10 and 15 m. Measurement of the saddle ridge by theodolite and other measurements with a 20 m long measurement range have shown 12.5 m, while other ridges in the vicinity were unquestionably 2-3 m higher. At Dünamünde (1.5 km out to sea from the jetty) they reached 8-10 m.

The crest heights went rapidly up and down.

If the entire rampart zone is imagined to be divided into equal intervals by lines perpendicular to the coastline, the total volumes of the ice ramparts in the individual sections are not equal, but are of very different magnitudes. As we shall see, this may be attributable only partly to different strengths of the compressive thrust in the transverse sections frequently, but not always, isolated by transverse rifts.

I also calculated the minimum size of the thrust width for various cases from the sizes of some rampart cross sections and the thickness of the ice floes. A volume of superimposed ice 15-20 times the ice area of the base resulted for the saddle ridge. If only 5 m is considered as the average height instead of 6 m (because of the loose packing), a compressive thrust 300 m wide results, which was necessary for the formation of a ridge. In other transverse sections, the ice plate must have been pushed forward some distance further towards the land, but in other sections which are hardly noticeably separated from these by long transverse rifts, the volume development of the longitudinal ramparts is very much smaller, and from this alone, only a very much smaller compressive thrust could be calculated.

This contrast between a transverse section with high ice pressure ridges and a directly adjacent section without them is particularly conspicuous, on the west edge of the ice field which I mapped (Table I). At this point, we come upon a profile of ice pressure ridges from point Q in a southerly direction, which permits the calculation overall of a compressive thrust of approximately

400 m. The transverse rift running through point S towards the NW separates it from the adjacent floe on the west. Westerly from it for a long distance, no other larger ice pressure ridges were present. That being the case, was the easterly floe pushed forward by 400 m towards the land at that NW rift, while at the same time easterly from it no compressive thrust took place at all? The difference on the two sides of the rift is reduced if it is observed that an overthrust of the seaward ice plate over the landward ice plate took place at a longitudinal rift running through point U towards the ENE. The head of the reef of the overthrust floe could be traced quite clearly and for a long distance. The difference from the easterly vicinity was apparently principally the fact that at that point greater obstacles had been opposed to the thrust, which led to irregular segment motion, disintegration and heaping up on one another, while thrust of the ice plate proceeding essentially without disintegration was possible in the west at a long longitudinal breach. It would only have been possible to determine what dimensions this had and whether it also included the entire or only a portion of the thrust width of 400 m to the east, by drilling holes further out. Extensive overthrust would not have been surprising, in view of the smooth under-surface of the ice and the flat top surface, if after all a smooth marginal uplift of the seaward plate had occurred. So much the less the overriding floe had to push down on the underlying floe, and thus a gently rising, easily passable thrust path was formed.

It is also unquestionable that the easterly ice plate whose front was piled up and broken up to form ice ramparts, had thus been pushed at least some distance over the ice lying closer to the land. This is true since I was able to observe at one time at point Q the window left open locally by partial motions, through which the lower ice mass looked up. In the second place, the ice pressure ridges without doubt must have accumulated over an ice which reached down to the floor of the Baltic Sea. This resulted directly from the fact that the high, heavy masses had been able to push the wide, flat ice surface only very slightly upwards. In fact, the frontal gorge formed by the burden at the lee side of the foot of the ice rampart can be seen clearly (Figure 3, foreground). However, the heavy load would certainly have pressed the plate down to the mud substratum if the plate was still floating on water at this point. This did not happen, so the ice must have reached to the bottom previously at this point, which was actually confirmed also by the observations of the fishermen. They very often drilled holes through the ice to fish, ("which brought them very good results in this unusual winter").

If we ask in this connection how the situation of the ice pressure ridges can be explained in general, it can be stated that a critical zone must have been decisive here, specifically that zone in which the free-floating ice plate of the Baltic Sea changed into the ice mass next to the coast which had formed almost to the bottom. In this critical zone, two processes may have occurred:

1) The seaward floe farther out can be pushed by the growing storm at large longitudinal rifts over the landward marginal rift and then, while pushing it down, can be pushed forward farther towards the land. As the shear front came into the critical zone, the ice resting firmly below could not be bent further downward. Therefore, a large longitudinal fracture had to form everywhere at its outer edge in the overthrust plate. The immense ice mass measuring many km<sup>2</sup> then pushed heavily against this. Disintegrations, jams, pileups of blocks had to be the result. The seaward ice plate thrust itself over them, broke up, and scattered its blocks beyond or broke up into flakes. In this way, the ice pressure ridge grew higher and higher and yet the firmly resting ice at the base could only be pressed down very little.

2) The free-floating ice cover turned into large waves by the storm can also form a system of large longitudinal rifts at the critical zone because of its differential motion with respect to the firmly resting coastal ice with which it was previously joined, against which the ice plate, previously not thrust over it, was pushed and pressed over with jamming and disintegration. Even the very much thicker masses of calving glaciers in the polar seas are actually separated away from the firmly supported land ice by the motion of the water.

In both cases, the main resistance lay at the outer edge of the solid coastal ice extending to the bottom. Its marginal zone was generally the zone of formation of the ice pressure ridges.

If we therefore wish to evaluate the situation of the ramparts with respect to their deeper causes, it must be asked why the solid coastal ice had developed exactly up to the later ice rampart zone. The main cause is

the sublittoral relief.

A more precise picture of the underwater relief at the Riga shore is not known to me. The ocean maps contain only more general information concerning the water depths increasing out to sea. At the position at which lay the described ice pressure ridges, water depths of 2-3 m are indicated. The fishermen, who also observed the seasonal change of relief, know in greater detail. From their information and from that of our two assistants W. Zans and L. Slaucitajs, who made observations by boat at my suggestion after the disappearance of the ice ridges, a truly good picture could be obtained.

The general condition is that which prevails on most sandy, flat coastlines and which was described recently more precisely for the Pomeranian coast [9] and which was illustrated in its generality in K. Andrée's "Geology of the sea floor" (II, § 74, 1920, with tables by Th. Otto).

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Thereafter, 3-5 sandbars parallel to the coastline had to be dealt with, whose outermost thick wall was 300-400 m from the shoreline (I am ignoring the very flat sandbars which go out into the deeper water to approximately 700 m).

The figures for the distance from the shore, for the water depths, and for the mound height naturally vary strongly. In general, on the Pomeranian coast is found an outermost, often merged

mound zone I approximately 20 m from the shore, at a sea water depth of 0.8 m reaching up to 0.3 m at mean water,

mound zone II approximately 65 m from the shore, at a sea water depth of 2 m reaching up to 0.8 m at mean water,

mound zone III approximately 140 m from the shore, at a sea water depth of 3 m reaching up to 1.6 m at mean water,

mound zone IV approximately 230 m from the shore, at a sea water depth of 4 m reaching up to 2.5 m at mean water,

mound zone V approximately 430 m from the shore, at a sea water depth of 6.3 m reaching up to 5.1 m at mean water.

The depressions between the mounds are quite pronounced, and when they rise up undisturbed above mean sea level because of lifting, in my opinion they represent the depressions described on the coast of Courland as "Johmen".

The conditions are quite similar to those which can be ascertained by swimming out to the third reef at the Riga beach. The outermost, thick sandbar zone which rises up to approximately 3 m at mean water, and starting from which the sea (5-6 m deep) then gains rapidly in depth, lies approximately 400 m from the shoreline. The ice pressure ridges piled up between 370 and 450 m from the beach.

Their position therefore coincides approximately with the position of this last, heavy sandbar. The fishermen confirm that the ice ramparts were principally on the seaward side of this sand mound.

The causative relationship between sand mound and ice rampart was then unquestionably an indirect one. It is valid only because more and more ice has accumulated between the sand mounds in the course of the winter, whether as flotsam or as locally formed bottom ice.

The history of growth of this coastal ice was still visible to some extent. In Table 1 I have illustrated the largely invariable primary zones of this ice between the shoreline and the ice pressure ridges.

Next to the shore ran an ice zone 125 m wide on the average, of uniform structure. It consisted very preponderantly of "cabbage heads" frozen together. These are known to be the rotated floes (pancakes in English) which are formed from the ice floes by the motion of water [10]. They constantly jolt against one another and are mutually rounded off; the edges often bulge upwards. In addition, a concentric ice growth also often seems to accumulate around it, since the heads, on the average of the size of a human head (also smaller and larger) often showed rings of ice mixed with various quantities of dirt, which possibly were formed by rolling of the rubble on the beach (Figure 12 shows such ice rubble thrown up on the beach). The uncontaminated ice heads also reveal a very distinct concentric structure on melting. The name "cabbage heads" is therefore very descriptive. Others speak of "roses".

Whitish, irregular firn ice of snow crust areas lay on this coastal conglomerate. It was quite sandy on the beach because of blowing. There was a firn ridge approximately 20 m wide and up to 1 m high running diagonally over everything 25-60 m from the shore.

The seaward edge of the cabbage head zone was quite pronounced. I have called it the outer shoreline since a very large amount of flotsam had accumulated at a width of approximately 4 m. Everything to be found on an actual sand beach was to be found here also: black masses of seaweed, driftwood, sand, mussel shells, etc. After the cabbage heads washed together, ran aground, and stuck together, a solid strand must have been formed here after some time. As far as the eye could see, the black line of this strand stretched along the coastline. It can be seen well in Figure 11 on the left).

A first footprint in the formation of the coastal ice was therefore beautifully distinct here.

The later processes were apparently uniform. At least the ice surface appeared very uniform and consisted of dense, clear ice over which lay a thin covering of firn ice or firn. This covering exhibited beautiful shallow dunes (Figure 4) whose crests parallel to the beach, were 1-3 m apart from one another. Surface water had formed repeatedly in the depressions between them, and had frozen again. People slid across their mirror-smooth surface rapidly in order to get a new start at each new firn crest. However, near the foot of the ice pressure ridge, this water had flowed out of the depressions even before it could form more than a thin ice cover, towards the depression in the vicinity of the heavy ice rampart. For this reason, there was only a concave, thin, uppermost ice crust in the depressions here.

From the mere fact that those load depressions around the ridges were shallow, we were able to conclude that the ice was solid down to the ocean bottom. Following the time of the zone in front of the beach, this ice mass was gradually frozen together at the very low temperatures from bottom ice and water ice. Only a few cabbageheads from the outer shoreline contributed to this initially.

In the entire zone near the coast, nothing was to be seen of overthrusts or ridge formation. The ice pressure ridges were formed only at the steep slope of the outermost, heavy sandbar zone up to which apparently the coastal ice had developed outward as a block.

The relationship between sandbar and ice mound was therefore such that the sandbar zone promoted the formation of the coastal ice block, which was no longer possible in deeper, moving water, although much bottom ice had still formed far out, as the fishermen related. The edge of the ice block was then the main resistance over which the ice floe, driven by the wind, had to break up and over which it accumulated.

The fact that no bottom ice participated actively in the thrust could be directly recognized from the fact that nowhere in the ice pressure ridges could anything be seen of rock boulders, or anything more than dirty ice. Only the ice sheet still freely floating on water had moved towards the coast.

The overall picture becomes even clearer if we consider also the rift formation. Little attention has previously been devoted to the circumstances of ice rifts, although rifts are observed everywhere. The phenomenon reported by E. R. Buckley [11], that rifts close up downward in a wedge shape in fresh water lakes is said elsewhere, by E. V. Cholnoky in 1909, to be exaggerated.

There would probably be many rifts which close up downward, but that would originate from their freezing together towards the bottom later.

Cholnoky spoke of other regularities such as the necessary rift distances in freezing, but they were generally only mentioned in passing by other authors. They are of special interest to geologists, since relationships are suggested here to the regularities of those fissures exhibited by so many areas of the earth's crust.

It can be observed very often that the main rifts always develop at the same location and in the same direction on lakes. This apparently depends on the relief configuration of the water basin. Such a statement can only be made partially concerning the rifts which formed on the Gulf of Riga. We can again differentiate here, as in the case of the pressure ridges, elements oriented along the shore and perpendicular to it.

As far as was observed, longitudinal rifts were formed to any great extent only in the solid coastal ice. Thus, two straight (or gently bent), smooth fissures ran through the firn dune zone parallel to the shore, at km distances (Table I). Inwardly, the one nearer the shore lay quite clearly on a gentle arch perhaps 20 cm high, and opened upward. It appeared like a flat ridge broken open upward by stretching, pressed against the ridge of the neighboring ice. Possibly it is a matter of a zone of pressure equalization in the ice field changing its volume greatly from sharp temperature changes. There is no clue that the great ice pressure operated here. The intermediate ice field is completely undisturbed.

As stated, longitudinal rifts might also lie below the longitudinal ridges and might have caused their formation. In addition, they must also have broken open in the rise of the ice sheet on ice ridges of great longitudinal extent, because of excess bending of the ice plate (for example, Figure 8 on the right). However, irregular rifts also formed here because of the generally very non-uniform resistance.

Furthermore, large longitudinal rifts were only seldom observed in the photography (at points L, U). Admittedly, the ice area was suitable only for the observation of the larger rifts. The smaller ones were covered over under the firn ice. The fact that longitudinal rifts also occur to a greater extent farther out is shown, for example, by the aerial photograph with the icebreaker Kr. Waldemar published by L. Slaucitajs in 1929.

However, the transverse rifts were not prominent here among the large rifts, as in Table I. They were missing entirely from the firmly-based coastal ice. Apparently, their formation is related to the special motion processes on the liquid base.

We have already indicated a definite relationship of the transverse rifts with the transverse ramparts of the ice. The transverse ramparts always appear at points of stronger restraint on the great ice thrust. Frequently it is seen that a significant transverse rift runs towards such points from the ocean side. This might be associated with the irregular distribution of the resistance encountered by the extremely large ice floe towards the land.

The importance of the transverse rifts is that of the "horizontal transverse displacement" (A. Rothpletz) or of the plates or of the Q-fissures in tectonics. At these points, the strata of a rock mass are separated and sheared away from their foundations more or less completely. These are pushed forward horizontally for varying distances. They are therefore rather large shear areas which are approximately vertical.

That they have nothing directly to do with the ocean basin can be seen well merely from their direction lying diagonally to its shape. On the other hand, the fact that they were broken open or at least were very active in the hours of the primary shear motion of our ice plate is shown by the sharpness and freshness of these huge, extensive rifts. This is shown above all by the fact that they are approximately parallel in the NW-SE direction. The entire floe carried these same NW-SE rifts for a long distance, as the aerial photographs showed.

If we make an exception of possible earlier effects, the last and most powerful exertion of force must have been the non-uniform restraint of the entire ice sheet at the obstacle of the littoral ice barrier built up in front in the WSW-ENE direction, i.e., the resistance to the motion from the gale. It created a general horizontal pressure which, judging from the shape of the longitudinal ice ramparts, ran in the NW-SW direction. The storm had this direction according to the observations before 1 am at night, and the rifts opened up in this same direction.

Farther out in similar material, a truly regular transverse fissure system of parallel NW-SE fissures developed. However, towards the land, where the partial resistances prevailed, still other partial forces came into play and broke up the sheet into pieces. It can be seen clearly in Table I how the individual far-reaching rifts splintered towards the land and branch rifts developed. It is very significant that these partial rifts, which broke open shortly before the weakening of the great thrust motion in front of the obstacles, are very predominantly oriented N-S. In my opinion, this is an expression of the general turning of the wind towards the N-S which occurred in the meantime. The high accumulation of numerous restraining ramparts can probably also be well explained by the pressure forces coming primarily from the N at the last: the floe mass pressed towards the SE initially was forced more to move together by the pressure towards the S. If one is willing to consider the NW-SE rifts and the N-S rifts as the two component forces in a parallelogram of forces, whose diagonal in the NNW-SSE direction indicates the direction of the general primary pressure, it would not be understandable why the first-mentioned direction prevails so very strongly over the latter, and why southeasterly rifts were able to develop over such broad areas distant from the coast.

The oldest rifts were observed on the Gulf in 1929 on March 1 (cf. Figure 14, Table VIII).

The observed rifts opened up only slightly. The smaller of them appeared to have more the significance of ordinary fissures, without large lateral displacement. Radial motions, or floe depressions, were observed only in case of unequal support of the base, such as the small fault at the right in Figure 8, for example.



Fig. 13. The great icepack on the Dūna at Riga (towards the east), April 21-25, 1929. From a commercial photograph.

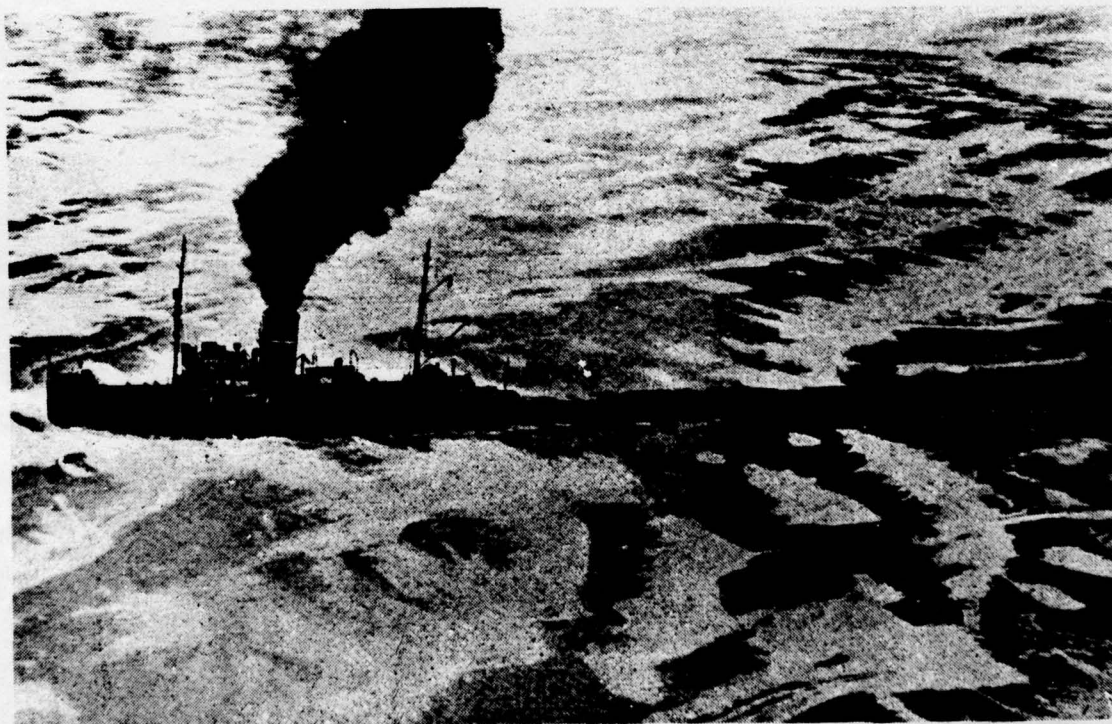


Fig. 14. Uniform rift formation, formed by snow dispersion, on the ice of the Gulf of Riga. Main rifts approximately NW-SE; subsidiary rifts approximately perpendicular to them. The icebreaker Kr. Waldemar (beam 16.5 m) as a scale for the picture. Aerial photograph by L. Slaucitajs in March 1929. From the collection of the Institute of Physical Geography of the University of Riga.

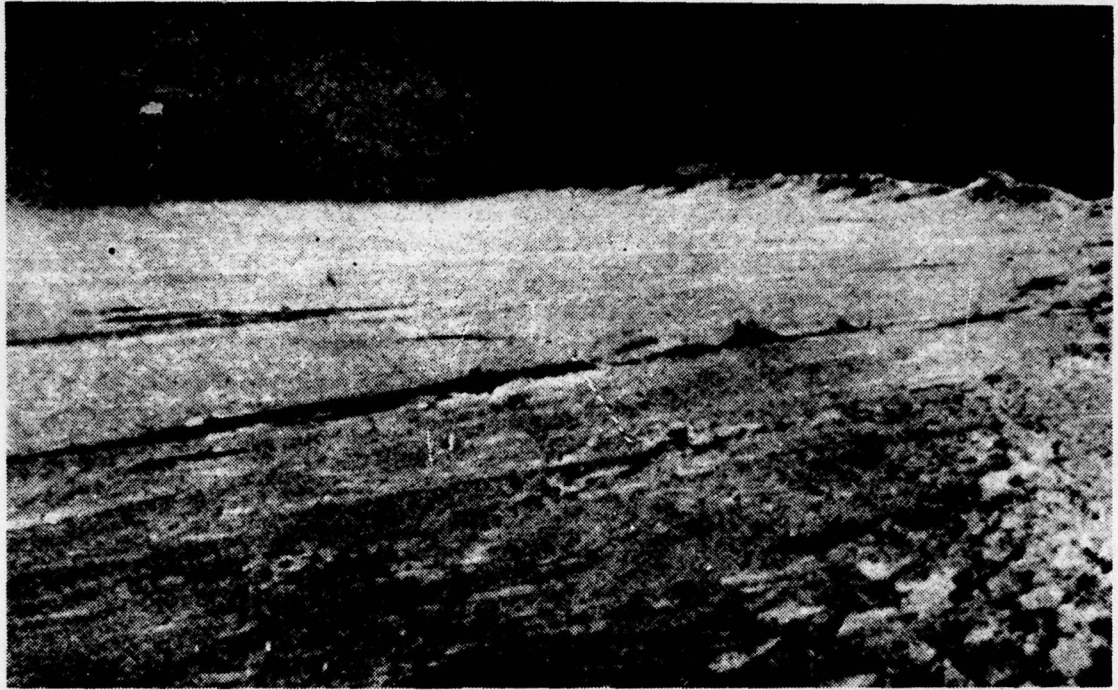


Fig. 15. Ice pressure wall at the Haff River, at the east end of the Vistula Lagoon, Spring 1922. Photograph by E. Kraus.

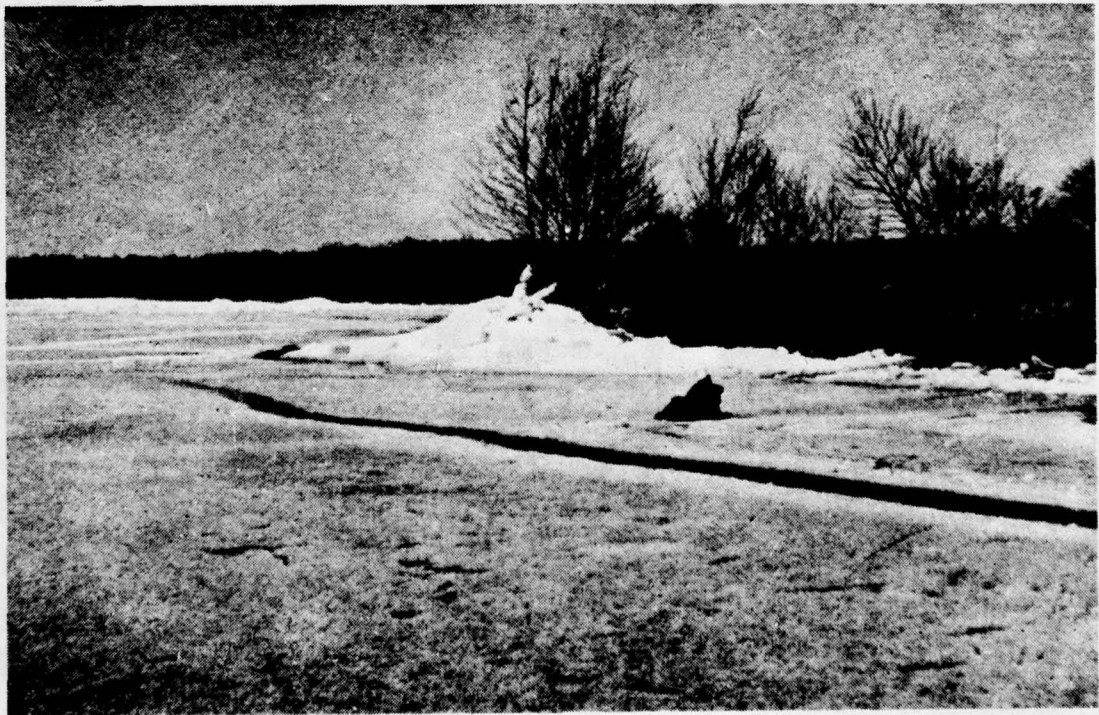


Fig. 16. Encroachment of the ice sheet of the Mauersee on the beach projection at Gross Steinart on April 8, 1922. Photograph by E. Kraus.

Other geomechanically important points will be discussed later.

Associated with the consequences of the ice pressure formation at Riga was also the temporary damming of the Düna flood, which was associated with a large icepack (Figure 13). The icebreaker Kr. Waldemar had vainly attempted to break up the ice barrier extending to the ground, which blocked the Düna trench 1.5 km from the jetty at a water depth of ca. 7 m. The water had risen to a dangerous level at the lower course of the river and overflowed into lower sections of the city of Riga, when strong winds provided relief and drove the ice away.

The thaw. The ice pressure ridges, as mentioned, were still visible until May 9, 1929. Only when the average daily temperature of the air was above 10° and the water temperature was approximately 8° did the last ice vanish. On the Day of Ascension (May 9), the ice ramparts were still easily seen. The first of the final waters spouted into the ocean from the rather high ice walls. During the day, the ramparts noticeably disappeared and the pieces slowly drifted away with a small breeze. In the evening, almost nothing was recognizable any longer. Later yet, for example on Sunday, May 12, the ice could be seen at the bottom under the boat where the ice ramparts had been.

The bottom had changed significantly from previously, according to statements of the fishermen. Around the foot of the ice pressure ridges, the water swirled the mud more deeply so that channels approximately 1/2 m deep formed here. On the other hand, the depressions (Johmen) between the sandbars on May 14 were found to be no longer as deep as previously, although on this date the bottom ice could no longer be seen in them (communication from W. Zans). Two days previously, I still saw along the beach a strip of drifting ice 150 m wide, strongly broken up, for as far as the primary ice ramparts had been deposited.

## II. The ice pressure ridges of January 15-18, 1863, in Pernau Bay.

The only known ice pressure movement comparable in extent to that in 1929 at Riga also took place in the Gulf of Riga, specifically in Pernau Bay in the northeast [12]. Count Keyserling wrote as follows about this ice pressure ridge formed in the stormy night of January 15-16, 1863 (loc. cit., p. 192):

"In the first winter freezes of this year, an ice cover 2-2-1/2 feet (0.6-0.76 m) thick had formed from the land far out to sea. As a result of steady southwest winds with mild weather, the water at the coast rose by approximately 4 feet, not an unusual occurrence in Pernau Bay. A covering of water was thereby formed first over the ice clinging to the coast; then, however, the entire ice sheet, with the exception of a few areas protected by the shape of the coastline and grounded particularly securely, was lifted off by the water and formed a freely floating ice field of enormous size. During the night of January 15 to 16, a

strong storm drove this ice field against the shore and pushed it over the land with extraordinary force."

Never within memory had such a mighty ice pack been driven over the land with such force and to such heights. It reached up to 60 feet (18 m) above sea level and came 1023 feet (312 m) up on the land, overcoming even steep coastlines (in this connection, see p. 194, Fig. 3): (ref. 12)

"At the other locations that I visited, the shore went down to the sea with a sand cliff almost 30 feet (9 m) high. Over the upper edge of this cliff lay rather large fragments of the ice sheet from the sea piled up to 10 feet high, which did not rest on the ground with their broad faces, however, but were turned up rather steeply and presented their free edge to the sea. Their surface was covered with clinging gravel and with stones and had obviously been in contact with the ground, while their lower surface showed pure ice and apparently belonged originally to the upper surface of the ice sheet from the ocean. Therefore, the ice sheet had not only been thrust upward, but had also been overturned in such a way that it is not easy to obtain a clear picture of this process. The ice must have fallen in fragments when pushed up, but so that the steeply erect fragments had been pushed even further onto the land by the pursuing ice, and had been brought into an overturned position. In any case, this observation confirms the interpretation that a floating ice sheet can climb upward on steep coastlines like a carpet and can penetrate for a certain distance into the land."

The rigid ice field of a bay, which had not lifted with the general sheet, was separated from the other ice sheet towards the sea by a saddle-shaped zone of ice pressure ridges on which had formed a series of 40'-60' (12-18 m) high piles of ice cakes packed above one another. "Within such a pile lying next to the holm, I saw at a height of 30' above the ice sheet a granite block weighing approximately 60 poods (982 kg) lying between the ice blocks, which the ice had obviously seized from the sea bottom at the foot of the holm with interlocked ice cakes, and had lifted up high, packed together with its own floes."

Therefore, the ice here was even 10-12 cm thicker, and the height of the ice pressure ridges was even somewhat greater than at the Riga shore in 1929. Furthermore, the greater participation of bottom ice with mud and stones and the overcoming of a steep coastline are of special interest here. Other details are still to be evaluated.

### III. The ice pressure ridges at Reval of February 2-3, 1869.

Very powerful and carefully observed compressive thrusts of the ice took place at the southern edge of the Gulf of Finland, to the east and north of Reval in the stormy night of February 2-3, 1869 [13].

I shall give here sections of the detailed report by an author designated by -ss- in the Reval'schen Zeitung 1869, No. 63. The Gulf covered over by solid ice showed three ice pressure ramparts after the thrust. One, 5-6 m high, was along the beach between Katharinenthal and the mouth of the Kosch Stream. A second higher one,  $1/2 - 3/4$  of a werst (1 werst = 1.0667 km) from land and parallel to it ran from the harbor entrance towards Brigitten and a third, the largest, was several werst farther out in the roads. The entire formation apparently formed between 3:30 and 5:00 a.m. on February 3 with thunder-like uproar in an extremely heavy gale, according to the statement of a worker who was on the shore at Brigitten at this time. "It is fairly certain that the Gulf before that night was about half covered over with solid, continuous ice  $1/2 - 1'$  thick. The northwest storm broke loose immense ice cakes, wersts long, at the edge of the ice....". "The continuous ice surface, resting everywhere on the shore in the Gulf must have been convulsed, split up, shifted, and pushed back. Heaps piled up on the beach and on the boulders and sandbars farther out as well. In the open sea, the edges of the driving floes may have broken up and built up on those of the fixed ones and may have been pushed down in floes at the areas pushing together, and may have also probably been pushed sometimes under the ice surface. The third, outermost rampart thus probably designates the boundary of the previously fixed ice towards the open sea."

A rather large number of granite blocks were pushed towards the land, apparently carried by bottom ice, and were lifted up to rather great heights (cf. Illus. 2). "Personal observation shows that floes had been interjected beneath the blocks and thus a gradual lifting of the blocks had taken place with difficulty. Nowhere was evidence to be found of an underthrust of ice floes, but everywhere at the location studied only the overthrust of the ice sheets was noticeable".

The ice litter of the second rampart  $1/2$  werst from the shore, along whose wersts-long line one could comfortably travel for sledding, was of different dimensions than that on the beach. The ramparts of ice floes lying on the ice surface might have measured 30-40' and more, its height was 15' in the vicinity of the harbor entrance, 20' farther out, and 30' at Brigitten (even farther out on the Weims point, 40' high masses are said to have been piled up). The westerly, lower arm of the rampart was located above the deeper water, the height of the walls increased towards the E with the shallowness of the water, and they were piled up the highest above the sandbars in front of the mouth of the Kosch Brook. The direction of the second rampart up to this point follows approximately the outer boundary line of a mass of erratic blocks beneath the ridge in question, which juts out of the ocean, visible in the summer from a long distance. Here and there granite blocks look out from the lumps of ice, sometimes significantly larger than those mentioned above, but unmeasurable because only a portion of one side was exposed; the diameter of only one of these could be estimated more precisely as 6-7 feet.

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Illus. 2. Lee side of an ice litter rampart 5 m high with two granite blocks 4 and 5 feet in diameter, ca. 3 m above the surface of the sea. On the road to the sugar factory in East Reval, February, 1869. Drawn from nature by L. Petzhold, furnished by R. Meyer, Riga.

On the other hand, they did not lie as high up as those mentioned above, with their bases lifted up 4, 5, or 6 feet at the most above the surface of the ice and of the sea. The thickness of the ice floes here was only 1/2 foot everywhere. All of the boulders here were also located on the southern slope of the ice ridge, towards the land. The ramparts descended more steeply everywhere towards the ocean side than towards the side facing the land. The ridges, whose wavy profile was like that of a chain of hills, were sharp and descended down to sea level only at a few places".

The opinion of the apparently careful observer concerning the manner of formation of the ice rampart is largely in agreement with our concepts formed at Riga. The ice fields driven from the N, in this view, were driven against the boulders and sandbars. "The fragments thrust themselves above the edges of the fixed ice, the succeeding sheets thrust themselves above the fragmented lumps, and the ice areas driven on with great force in turn thrust themselves above these sloping planes; they all remained as long as they had a firm foundation, but broke into chunks as soon as they lost it, and projected out beyond the crests of the ridges, and their remains then tumbled down to the south side onto the fixed ice cover. In climbing over the ice rampart towards the ocean side, one saw everywhere the most distinct tracks of the upwards thrust, the overthrust of the ice fields, but nowhere were there indications of an underthrust of the floes. Entire ramparts several fathoms in

extent, often 5-10, stood upright, frequently almost vertically, but mostly at an angle of ca.  $45^{\circ}$ , and sometimes they were split and torn at many places, but the gaping spaces fit precisely into one another. Frequently, however, the floes had also tumbled backwards again and their fragments covered the north side of the rampart also. The upward thrust was noticeable not only at the shallow or craggy places, but also at the westerly offshoots of the chain across the greater depths of the sea, even where large ships can pass."

"Between the shore and the second rampart, as stated, the ice was fixed. It was composed of large ice sheets whose interstices were filled with transparent, fresh ice. The surface was almost level, and only individual sheets were found to be somewhat pushed and lifted against one another. At some places, large erratic blocks lying firmly on the ground projected above the ice surface. The advancing ice sheets had broken up and split on them, and beyond them towards the land were found lengthy fractures in the ice sheets in question, now again frozen over, which seemed intact in front of them towards the north and towards the sea. These fracture lines provide a scale for the thrusts of the ice sheets. An edge of the large drifting sheet at least  $1/2$  werst wide must have been dashed to pieces".

The largest zone of ice ramparts farthest from the shore had not been investigated closely. When they became of interest, the ice was already in drifting motion.

This report shows the many agreements between the ice pressure ridges at Reval and those at Riga. Differences exist in the appearance of very changeable, craggy obstacles, abundant erratic blocks, the significantly lower ice thickness, the stronger separation of the driving ice into individual large floes, and the lower rampart heights.

#### IV. The ice thrust ridges of April 24, 1868, at Lake Wirzjärw (Livonia).

The ice pressure zone on the north shore of Lake Wirzjärw in North Livonia (Southern Estonia), which is 276 km long and only 6 m deep, was described in detail by C. Grewingk and elsewhere. For the first time, we also find profile drawings here, and also noteworthy reports of two eye witnesses, one of which follows below.

The ice thrust took place on April 24, 1868, in the morning at 5:45-6:15, in a SSW-SSE storm and at  $2^{\circ}$ - $3^{\circ}$  C.

The thickness of the Spring ice covering over the entire lake was 1 -  $1-1/2$  feet on the day before. It was at its weakest and frequently had already disappeared on a coastal strip 10 fathoms wide. The ice sheet was set into motion in the evening, so that the ice gaps at the shore were closed up, and the ice was pushed firmly to the shore. The storm then mounted until it changed over at 5:45 in the morning into a SSW-SSE gale.

At this time, one man observed the spectacle on the north shore (page 13). "He noticed first a rapid rise of the ice and water, and felt compelled to place a rock on the ground in order to be better able to follow the rise. He had scarcely done this when he saw the ice beside him, at the slope of the rock attachment, approach rapidly over a period of 1-2 minutes with a mighty roar, thundering, and ringing, push, pile up, lift blocks of rock, and move forward. Terrified, he hurried away to warn families living in the vicinity of the approaching danger, he then returned after 10-15 minutes, and found a forward-thrust high ice rampart on the land which was in the act of completing the destruction of the eastern wooden top (stable and wagon area) of the inn building with the collapse of its roof. His great apprehension and grave concern for averting further mishaps were soon allayed, since the advancing and climbing motion of the ice mass mitigated as the wind ceased or abated, and only a few smaller hillocks formed on the surface of the ice further out."

"At the same time, a second observer was concerned, because of the strong wind, with fastening down the blades of a windmill which lay a few hundred paces behind the inn and on the crest of a ground elevation stretching NNW-SSE, already mentioned above. He then suddenly heard a loud roaring, clanking, and ringing and became aware at the same time from his high viewpoint that the ocean ice was coming onto the land, rising up high, and burying a guardhouse. Hurrying rapidly down to this guardhouse, he also found the destruction here almost complete, the ice pushed forward into the westerly peak of the adjacent inn, and still pushing forward only a little, but the innkeeper in the act of escaping through the window of the rear wall of the house." Also, the watchman awakened by the uproar was able to get away from his guardhouse just before its destruction.

The further description of the ice pressure ramparts, all of which here again were steeper on the lee side (up to  $48\frac{1}{2}^{\circ}$ ) than on the luff side, the thrust motion extending up to 35 fathoms onto the land, and their dependence on the obstacles present, confirm the facts already known to us.

#### V. Other ice thrusts.

Other ice thrusts, of smaller extent without exception, are known in quantity.

G. Forchhammer wrote [14] of the ice tide of January 7 and 8, 1839: "The deeper shoals were frozen and had become covered over with ice. As the high tide then came in with great intensity and to great heights, it brought along with it such enormous quantities of the ice permeated with clay that it later left behind a layer of mud 8" (21 cm) thick at many places. Such an ice tide is also able to cover the sandy bottom with mud...." Other compressive ice thrusts are also known elsewhere on the shore of the North Sea, but the tidal motion here hinders the formation of larger ridges.

More powerful ice jams such as those which occurred in the early spring of 1917 on the Samland coast, for example [15], are frequent phenomena in the Eastern Baltic Sea. I was able to observe a beautiful ice rampart on the east shore of the Vistula Lagoon at Haffstrom west of Königsberg in Prussia in 1922. Here also, the 6 m high ice rampart had been formed in approximately 1 hour during a stormy night. Here also, a fisherman's house on the beach was threatened, but the rampart finally came to a halt before reaching it (15).

A bay on the island of Aspo in the Gulf of Finland is frequently sealed off by 6 m high ice pressure ridges. According to K. E. von Baer, an English ship once had to spend the winter sealed in here until into June, a month longer than normal. The ice rampart at that time had filled up to 12 m high.

The ice pressure ridges on Lake Balaton in Hungary were studied even more closely [16]. The stronger shearing action of the fresh, hard winter ice, in contrast to the weaker thrust of the softer spring ice, is emphasized here. The theory of the rampart formation is somewhat different here. After shattering of the large ice sheet pushed against the land, one surge after another is thought to have tossed its load of ice floes onto the rampart, so that the ice sheets are piled up much higher than the mounds generally reached. Major rifts at which the volume changes of the ice sheets equalize to the sea, which also frequently exhibit shattering and ice pressure ramparts ("turolas") at the edge are considered to be freezing rifts whose course depends only on the relief of the sea floor. The essential collaboration of the wind here is probably not given enough consideration.

The ice ramparts at the Mauersee in East Prussia, in the first half of April, 1922, for example, were also very interesting. Of course they scarcely reached 4 m in height. Figure 16 shows the destruction by the ice at the shore. At this lake also, the same major rifts reappear every year. They lie between Könighödener and Faulhödener Points, between the island of Upalten and the land in the W and run from the island to the N, SE, and S (communication from Mr. Lehrer Quednau, Stobben). At these rifts, there are tears 3 m wide, while on the other hand, the ice floes are pressed together at them in such a way that they rise up to heights of 2-3 m like roofs or walls. Folds are also thereby formed. These are occasionally present in North German lakes and in lakes of the East Baltic provinces (Burtnieksee and others) at the shore, when the ice sheets expanding because of a temperature rise are obstructed in their expansion [17].

Much has been reported of the Antarctic and Arctic ice pressures (Admiral Koltshak, Malmgreen; vivid descriptions of the "pressure ramparts" by E. von Drygalski [18]). Arctowski described the hummocks and rows of hummocks, ice pressure ridges 4-5 m high, Gourdon described them 2 m high, and S. Heim

et al. described ridges from the Weddell Sea, and Fr. Nansen described ice ramparts up to 10 m high from the North Polar Sea. It is generally observed that in these, the ice ramparts in the more brittle ice may be higher than in the area of the Antarctic. However, the dimensions of the ice pressure ridges observed at the Gulf of Riga are not known to me even from the Arctic regions.

The subpolar-subarctic ice thrusts are much more widespread than is generally assumed. The frequency of the phenomenon increases strongly towards the poles, but not the magnitude of the ramparts, which is particularly extraordinary at the White Sea and in Northern Siberia. The Nordic coasts of the sea and large lakes are surrounded everywhere by boulders still exposed today or already sunken.

Nothing can be discussed here of the immense significance of the bottom ice for the entire coastal configuration of North Siberia, particularly of the New Siberian Islands and of Arctic North America. The outlines of the sandy-muddy shores, and those carrying boulders also, would undoubtedly be quite different, specifically much narrower, in the absence of the bottom ice which lifts them above sealevel. The river actions would be completely different. The direct ice thrusts transport extraordinary amounts of rock from place to place. All of this also belongs among the most important geological effects of the cold [19].

If we consider the long duration of the late glacial era, we must admit that this phenomenon at that time was very extensive even in the more moderate climatic region of today. We can understand properly a very large number of older zones and boulder walls set down at higher and lower high-water marks only with this consideration. For example, I would like to attribute the scattered boulders on the south side of the island of Oesel, many of those on the Finnish coast, those in the Reval Bay, at the north and south points of the island of Hochland, and numerous other islands of the Gulf of Finland [20], to ice thrusts. It is clear that in addition, diluvial boulder burdens, and eroded moraines such as those on the Mauersee in East Prussia, for example, also come into the question. At the Spirdingsee (East Prussia), the increase in the coastal boulders from ice thrust and bottom ice motion has been established even in the most recent decades.

Sunken and spilled coastal boulder burdens of this type must be especially characteristic in profile.

Prerequisites for extended boulder motion are minima of the water areas, the ice thickness, the load capacity and freshness of the ice, and the storm activity. All of this prevails in the northern spring months and in late winter.

However, with this we have already arrived at the general discussions of ice thrusts and their effects. They should be further developed from the materials now presented.

## B. ICE PRESSURE RIDGES IN GENERAL.

### I. Nomenclature

It is best to observe as precise a labeling method as possible in our publication and to thus define our terms. The following are terms that pertain to the present subject:

1. Ice formed in large water basins (seas, lakes): ice sheets, drift ice, floe ice;
  - a) on the bottom of the basin: bottom ice,
  - b) in shallow coastal water; ice base, on the White Sea "pripaj",
  - c) thrust together on the water and more or less frozen together isolated or at a rampart: pressure ramparts, aurolas, hummocks, hummock rows, sometimes toross (plural torossu, torosse), larger accumulations: pack ice (generally in a seasonally agitated sea).
  - d) pushed together on shallows, coastal ice, or on the land itself: ice pressure ridge, sometimes toross, stamucha?
2. Ice formed on rivers.
3. Floating ice formed by calving glacial or inland ice: icebergs.

The foregoing review makes no claim for completeness. It also includes any completely separable component phenomena in particular. However, the foregoing grouping, which is adequate for us here, seems to have much in its favor. In any event, I would like to be able to avoid the designation "iceberg" for our ice ramparts, as well as the word "toross". This apparently includes all ice ramparts driven together, both at sea and on the shore. It might frequently be difficult or impossible to recognize the actual "ice pressure ridges" among them, and yet their differentiation in view of their specific character to be defined below, which appears extraordinarily widespread, might seem completely justified.

### II. Rate of formation.

All of the more precise reports are in agreement that the ice pressure ridges are the product of a single hour or of only a few hours. At the Wirzjärw Sea, they lifted up between 5:45 and 7:15 in the morning on April 24, 1868. The inhabitants were just able to save their lives. At Haffstrom it happened in 1-2 hours. A fisherman had gone around his house just previously without seeing ice, and was thereupon startled by the rumble when he had just fallen asleep again. At Pernau in the night of January 15-16, 1863, it was no less rapid; in this case, three rural dwellings at the projection of the coast named Tackerort were so suddenly attacked and knocked down by the ice that the occupants lost their possessions and livestock and had just enough time to save their lives". (Count Keyserling

loc. cit. 193). At Reval [21] during the night of March 28-29, 1929, it happened in a few hours. It was always in the second half of the night, always at the time of a very intense gale. The large ice thrusts are always accompanied by deafening noise, clattering, and crashing. Later motions can complete the picture even with smaller thrusts, which was not previously disclosed. In any event, the principal motion and the motion on the largest scale always occurs as if in one torrent.

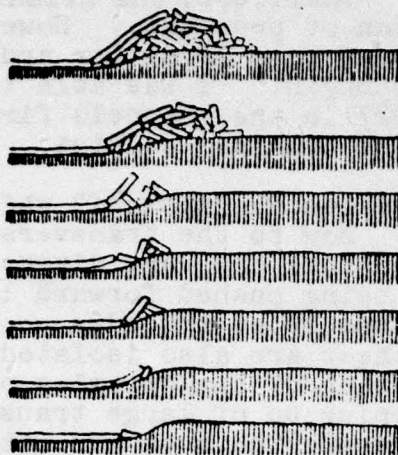
This, like any other, is a geologically significant process: For a long time nothing happens, perhaps the phenomena occur periodically to a very small degree, until, often only after decades or centuries ("not within the memory of man") truly large catastrophes occur. These, then, determine the entire picture over a long period of time. The system of small catastrophes always repeats itself, which by no means contradicts the current theories (W. Salomon).

### III. Mechanics of formation.

Since the constants which are decisive for the mechanics of formation and their computationally more precise formulations can only be tested experimentally, only the development of general fundamentals can be considered here.

If the ice sheet were to encounter only weak resistances, which could be overcome by bending or rift formation without complicated sector motions, then as long as the wind pressure was in action, it would advance towards the land without the formation of ice ramparts. This case was observed, for example, at Lake Wirzjärw.

However, as soon as the ice sheet encounters a first, damming resistance, its leading edge will be shattered. In this way, only a few ice cakes can form, which mitigate the relief resistance, by compensating for its slope. The ice sheet can then rise over the shallow obstacle without further complications and, possibly with rift formation as in Figure 7, can advance further towards the land sliding downward on the other side. This is particularly the case when the relief resistance is not wide, but is narrow, so that the ice can slide past it more laterally. However, if more numerous ice fragments are formed in front of a wide obstacle, a large number of which are fixed firmly in the ground and cannot be pushed away, then an ice rampart is erected rapidly (Illus. 3), since in moving up on it, longitudinal rifts must form in the ice because of the excessively sharp upward bending, and upon falling down, the floes fall forward and downward and pile up irregularly, which also causes a growing pileup of the block chaos beyond the summit. Thus, the ice pressure ridge grows toward the land as well as more slowly upward.



Illus. 3.

If such a wall is now first formed, so that when crossing it, the ice sheet is broken up and the pieces are tossed about, then the sheet can no longer move forward on the other side: therefore, if we have two or more such ice pressure ridges in succession, it is true as a rule that the rampart closest to land was formed first at the first large damming obstacle. It is also true that the ice front then runs aground with the formation of this wall and then a second, weaker obstacle towards the sea is sufficient to build up a second, newer wall at that point, and that in a similar way, perhaps only beginning with the formation of a longitudinal saddle immediately breaking into fragments, walls are formed even farther out to sea. The sequence of formation is therefore established by the pressure ridge mechanics: the age of the walls is highest on the land, and lowest in the sea. Of course, the age difference is probably often to be measured in quarters of an hour. The fact that walls out to sea are formed later was actually observed at Wirzjärw.

There were also good examples (Riga) for the smooth traversing of the ice sheet towards the sea above that towards the land at an extended longitudinal fissure, where no further segment motions led to a fracture. It is conceivable that this process also repeated itself frequently before the face of the rearmost, highest deposited overthrust sheet probably broke up on the land and shattered into an ice pressure rampart.

Ordinary saddle upthrusts reach only the shallow angles, since the saddle soon breaks up on the ridge because of stretching, and the arm of the saddle towards the sea can then push out of the way over the one towards the land. Other obstacles to the front then cause the formation of longitudinal saddle

rifts and overthrust edges. Therefore, the orientation here is perpendicular to the direction of pressure. However, as soon as the overridden obstacle becomes more irregular and higher, diagonal directions of migration also begin. I was able to find useful examples in the Winter of 1927 in the channels first opened up by a steamer in the ice of the Stintsee at Riga.

These are some important fundamentals "in brief" which concern the longitudinal elements. Now to the transverse mechanics. It has already been discussed that the very diverse frontal resistance to the ice sheet being pushed forward leads to shattering of the ice front not only directly at the edge. Individual transverse sections of the sheet are also isolated thereby, depending on the size distribution of the opposing obstacle. This breakup results from the opening up of large transverse rifts, plate shear rifts, which separate the segments with different forward motion capabilities from one another. Also, non-uniform segment pressures of the transverse sections against one another can be equalized here in small upthrusts.

According to the observations, the diversity of motion which makes these transverse rifts necessary may generally not amount to very much. They soon change towards the sea into the type of "common fissures" with cleavage but without permanent displacement. Nevertheless, even in this formation they appear to be very extensive.

It was previously assumed that the ice sheet which broke up in its great thrust motion at the end of March with these extensive NW-SE rifts was essentially homogeneous. However, it is also quite possible that only cracks that had been started earlier were again activated here. Two aerial photographs are available to me, of which one has been illustrated already by L. Slaucitajs in Table 44 in the Annalen der Hydrogr. 1929, while I present the second here in Figure 14, Table VIII (from the Institute for Physical Geography, University of Riga). It can be seen that the snow over the ice sheet broken up by the icebreaker Kr. Waldemar was not spread out irregularly, but that there are two principal directions here: one NW-SE which intersects the direction of the steamer in the picture from left front to right rear, and a direction perpendicular to this, more weakly defined. It cannot be assumed that the wind forms such regular chains of snow drifts on completely unoriented ice sheets, whose regularity can be seen even better in the picture in Anal. d. Hydrogr.

A checkerboard structure of the ice in the NW-SE directions, even if only a weak one, and one perpendicular to it must therefore be deduced, which is manifested in the picture by the ice surface, and in which the NW-SE direction apparently predominates.

The two pictures, which illustrate the trip of the Kr. Waldemar inside the Gulf towards Domesnäs, were both taken on March 1, 1929. No other pictures are known to Mr. Slaucitajs or to me, and

probably none exist. In any event, it can be seen that the ice sheet already had a diagonal structure almost one month before the great ice thrust (i.e., along the diagonals of the grid). What kind they were cannot be stated in detail. They probably involved not only the ice surface, but the entire ice thickness, and were probably created as stress compensation in temperature changes, with the participation of a SE storm which were strongly pronounced in January.

Since it is important in the mechanical assessment of our phenomenon to discover whether perhaps only old rift networks were used anew (posthumously) or whether the fissures were formed solely by the action of wind pressure and coastal resistance, we must consider in more detail

#### the causes of the rifts

as far as our material permits. Four possibilities can be differentiated here: the temperature fluctuation, the wind pressure, the water motion, and the relief.

#### Temperature Fluctuation

While the temperature of the ice surface fluctuates sharply with the cycle of the atmospheric temperature and direct sunlight and can drop very low, temperature of the lower edge of thick ice remains close to below 0°. If it becomes lower here, it is known that the water located below the next salt-containing water layer crystallizes. On cooling, therefore, there are contractions at the top but not at the bottom. Stresses are formed similar to those in the bare rocks of the desert with strong fluctuation of the insulation. The contraction at the top only causes a volume reduction which strives to produce a concave shape of the ice sheet towards the air. This generally uniformly strong tension in sufficiently homogeneous ice of approximately uniform thickness must produce geometrically regular stresses and ultimately ruptures.

It seems that a calculation made possible with the necessary constants which would be observable, would reveal the formation of checkerboard rifts as a necessary result. In miniature, the known phenomena of stalk ice or candle ice which become so distinct in the spring probably have a significance similar to the contraction fissures of eruptive rock already forming prismatically for a long time from the surface perpendicular to the cooling surface.

Anyone living on a large lake can tell about the magnificent concert which develops in nights of strong freezes, including the rumbling, the cracking like gunfire, the ringing and brilliant tones. It is the musical accompaniment to the formation of these rupture rifts.

#### Wind pressure

will exert a great effect on the formation of the ice structure at such times as the ice is still thin, and specifically before that.

40

A special pressure component must become active. Isolated ice floes are driven against obstacles such as reefs, stationary ice masses, icebergs, and the land. Larger ice floes come upon one another, are broken up, and are pushed together and over one another. Because of the horizontal pressure, and also because of simultaneous distortions (when burdened), multi-directional rifts are formed.

Very large ice areas are pushed so strongly by strong storms that they are set into motion and the strength of the ice at the front to which the pressure is transferred, is exceeded. The more cohesive, the larger, and the heavier the ice sheet, the greater and the more homogeneous is the effect. Fr. Boas [22] observed a beautiful example. In 1882, he saw a gigantic ice island 15-20 m in height, 13 km in length and 6 km wide, and therefore 9-10 km<sup>3</sup> run into a rock island in Cumberland Bay at a speed of 1.5 m/s. In this case, one rift after another was formed, and in two weeks the brittle mass was splintered into many plate-like pieces, all with perpendicular fractures, which frequently ran in straight lines for long distances. To what extent the water flow also acted here is not clear.

The formation of the transverse rifts because of obstacles at the front has already been discussed above.

The water motion,

dependent on the wind or other factors, can likewise not be underestimated. Just the separation of the ice sheet from the land, facilitated by the temperature jump generally prevailing here, is the cause not only of the edge rifts but also other complications. The ice thrust towards the land, as is known, is strongly favored by the rising of the water in the direction of the storm motion. Also for this reason, rifts open up parallel to the land, which then promote the ice invasion and therefore its breakup.

The jerky, gusty character of the wind in case of thin ice over the water must also develop oscillations of the entire ice sheet upwards and downwards, which are manifested in gentle saddles and depressions or ramparts with a principal axis lying transverse to the principal wind direction. The partial stresses associated with this, even if only temporary, in tension, pressure, and bending could possibly be sufficient to cause the formation of an oriented ice structure, and perhaps even rifts.

E. v. Drygalski in 1921 described very vividly the breakup of the Gauss field taking place with increasing water motion. We shall not discuss in further detail here the participation of the ocean currents.

The relief

of the water basin probably plays a rather large role in general in lakes, specifically in smaller lakes, and in the coastal zones. This also results from the position of the main rifts recurring

every year, and from the lack of uniformity elsewhere. From Wirzjärw, C. Grewingk reports about the fact that such rupture rifts of kilometer lengths can become up to 4 m wide with continued cold; that on the other hand, they can close up again with continuing thaw as a result of the extension of the neighboring ice field, and in fact that the rifts' edges run up against one another and rise up to 2 m.

E. v. Cholnoky states that most of these rifts again freeze up well, because after the formation of the fissure the tension is relieved. However, in the first place, the cementing together is probably never complete, and in the second place, advantage is always taken of the weakened zones in the appearance of later sectional stresses, just for the reason that they are in favorable positions. Cholnoky assumes the mentioned posthumous effect only for the main rifts.

The course of the main rifts are governed by the shoreline and certain of the arcs determined by it on Lake Balaton also. Where two of these arcs run into one another, a straight crack or even two rifts intersecting one another are formed. This is confirmed on other lakes. We have already briefly discussed the Mauersee in East Prussia, where connecting cracks willingly form between the peninsulas facing one another.

All in all, we find a truly considerable number of causes for the formation of rifts. It is all the more striking that we are nevertheless able to establish conspicuous uniformities in the rifts, just as in the earth's crust, where many great differences in the conditions of formation still exist. This can apparently be explained by the posthumous addition. Perhaps if a principal direction is once formed by the action of wind and waves on a thin ice sheet, then later stresses diagonal to it are always resolved into two components, one in the direction of the previous weakening, but the other approximately perpendicular to it. Provision is therefore made not for the obliteration, but on the contrary, for further loosening along directions of weakness once established, and the freezing may always be operating to renew the homogeneity. Nevertheless, very strong stresses like the great Spring ice thrusts always find the old scars. It is therefore not probable that the rifts thereby broken open are formed by the storm alone and in its direction.

Another comment must still be added concerning the  
nature of the wind action.

The transfer of pressure to the rough ice surface is clear. We frequently read of the powerful rising of the water under the ice sheet, which is advancing toward the land. And yet another element of explanation seems to me to be lacking.

C. Grewingk (loc. cit. 21) concluded from the steep leeside and flat luff side of the main ice rampart at Wirzjärw that the ice layers in general would be driven rather uniformly up to the same distance

from a given point on the shore. And further: "the wind pressure therefore grew approximately to the same degree as the resistance brought about by the increasing height of the ice rampart".

Therefore, in the opinion of the author, if I understand him correctly, in the case of wind of constant strength, the ice floes (already considered isolated on the sea as a separate matter) would not all have been pushed up to the main ice rampart, but would sometimes have stayed in place even sooner if they were shattered.

Because the storm subsided very suddenly after 1/2 hour of fury, the ice mass once set into motion would still have only the power to push together some low knolls in the area of the floating ice. In addition, the asymmetry of luff and lee remained unchanged at the main rampart.

If the storm had died down just as uniformly as it had grown, the luff side would have had to be just as steep as the lee side. A rampart would have formed as at Reval.

According to other observations concerning ice pressure ridges, namely those at Riga, I cannot completely share such an interpretation. Instead, the formation of a larger ice rampart at the position of the larger resistance and relief discontinuity, over which the large, continuous ice sheet was thrust is probably always the normal. The flatter luff side and the steeper lee side is likewise normal, which has quite similar significance to the flanks of a dune with the same configuration. Also normal is the formation of ice ramparts laid down backwards, which were formed somewhat later when the forward ice front had already run aground. To explain all of these phenomena, we do not need a completely special, very sudden abatement of the strength of the storm.

This results from the fact that even at Riga, in the same ice pressure ridge system, along with gentle luff and steep lee slopes, we also observe, for example at the saddle ridge, the same, even greater steepness on the luff as on the lee side, wherein -- just as in Reval -- the pile of ice cakes at the luff slope was just as developed as on the lee. Because of the nature of such cases, it is not possible to speak of the variability of the wind action.

The same storm that heaps up ridges in one place, for example, can elsewhere only smash and carry off laterally. For example, while ice ramparts were formed at Reval up to 6 m high in the stormy night of February 2-3, 1869, at the same time, the Baltic Sea rose up at Bolderaa at the Düna, smashed the ice, and opened up the mouth of the Düna.

#### Magnitude of the Thrust Forces.

The magnitude of the thrust forces is very significant. If it is considered that according to personal observation of ramparts, floes

approximately 40 m<sup>2</sup> in size with an ice thickness of 1/2 m were lifted in a very short time by 2-6 m in height, not seldom, but often over long distances, and that the weight of almost 20 tons was dammed upwards by ice slabs of 1 m<sup>2</sup> cross section, this gives some idea of the order of magnitude of those wind forces.

Vertically standing slabs weighing several tons towered up to 10 and 15 m in height like rocky needles (Figures 2, 10). At Reval, granite boulders with diameters of 1.5 and more meters were pushed up to 3 m above sea level from the rocky ground onto the ice ramparts. At Pernau Bay, Count Keyserling observed a granite boulder weighing 800 kg lifted 9 m up over the ice sheet between the cakes of the ice pressure ridge. At parts of the shore of Pernau Bay climbing up more steeply, the entire ice sheet was jammed up 60' (18 m) above the level of the sea. At other places, a less steep shoreline 4 m high was first overcome; then the ice ran into a pine woods and broke off the trunks, some of which had a diameter of 32 cm, and then finally slid over them. It is not surprising that even rather large houses are pushed in by such forces. Thus, for example, three peasants' houses on Tackerort Point (at Pernau) were completely destroyed in 1863.

The effect on the subsoil can generally be said to be small. It is also obvious that the force was applied essentially horizontally and not diagonally downward. Only in case of small irregularities of the forward-migrating base of the sheet did some excavation and grooving take place because of entrained boulders, ice floes, etc., and not only the irregularities were eliminated. At Haffstrom just as infrequently as at Wirzjärw, a rather large sand mound was also found.

Naturally, the hardness of the ice is also important. If the ice has already strongly thawed, and has changed over to soft candle ice, its debris can even have a protective effect up to a certain degree.

#### Width of Thrust.

The minimum width of thrust can easily be calculated from the height, base size, and icethickness in the pressure ridges. For the Riga shore, the result was at least 300-400 m. For the Wirzjärw Sea, where the ice went over the land up to 80 m, at least 170 m is calculated (from Grewingk's Profile I), 120 m (from Profile V); Grewingk himself estimated 100 fathoms (213 m). At Reval, at least 250 m is estimated.

At Pernau Bay, the ice floes penetrated not less than 1,023 feet (312 m) landward on low-lying coastal hayfields of the Uhla Farm according to Count Keyserling after precise measurements, the greatest definitely known distance.

The ice sheet on the whole has a certain adaptability to the ground. Like every substance with a stress which is not too sudden, the ice also, on the whole, is plastic. The smoothness of the bottom surface, and its relatively low weight, enable the ice sheet to climb up on obstacles and to slide over them, which naturally promotes the width of the thrust to a great extent.

Primarily, however, the width of thrust depends on the position of the resistances which cannot be moved. Thus, at Wirzjärw, the ice stopped at the shore road which was well reinforced with rocks, near to the shore, with the formation of a particularly high rampart. Where the shore rose gently, the sheet advanced much further, and the smoother the relief towards the land, the farther it advanced (without the formation of ice mounds). Thus, it advanced 80 m into the land and would have gone even further, if it had not finally formed a zone of rubble at the break in the shore, at the rift running parallel to the shore at this point, on which the ice sheet towards the ocean then ran aground. The same upward sliding on the flat beach occurred at Reval.

The water depth must not have played too large a role, if tidal motion, etc., did not take part. However, the ice thickness probably did play a role. With the greatest ice thicknesses (Riga 0.5 m, Pernau 0.6-0.65 m) we also found the greatest thrust width. In these cases, the pressure transfer is apparently more general and the resistance force of the ice sheet to smaller path obstacles is particularly great.

It should be noted practically that well-strengthened seawalls, even if they extend upwards by only a few meters, provide a generally effective protection against the further advances of destructive ice sheets. Only with especially thick ice such as at the Pernau thrust, will even such obstacles be overcome.

#### Sites for Formation of Ice Pressure Ridges

The reasons for the formation of ice pressure ridges always at large relief obstacles have come to be known. Rising shorelines, deltas, sandy reefs, islands, peninsulas, rocky shoals, boulder reefs, and the outer edges of shore ice adhering closely to the ground provide ridge formation sites. There are frequently several ice ramparts in succession, of which very often the ones nearest the land, which owe their formation to the first great ice motion, are the highest. However, this can also vary locally, as at Reval. At this location, the highest ice pressure ridges were not in the protected bay, but were found at the area of transition to the open sea.

Ice ramparts of moderate size have only seldom been found over deeper water in polar regions. The greatest pressure ridges are formed in the beach zone of tide-free large interior basins in temperate climates. The preference for the shore zones is probably also associated with the greater ice thickness at these points.

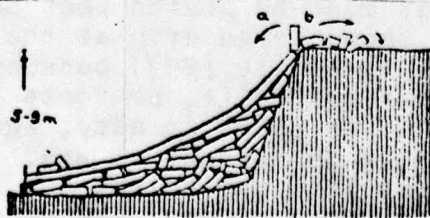
If the ice sheet farther out in the basin already has rather large gaps of open water, this apparently facilitates the motion of very large floes. Thus, it can also be assumed that the trips of the Kr. Waldemar from Dünamünde to Domesnäs and to Zarnikau just before the great ice thrust at the end of March in 1929 very much favored the powerful ice floe motion which was caused by the storm.

### Form of the Ice Pressure Ridges.

The form of the ice pressure ridges is normally determined by the opposition of the steep lee side and the flatter luff side. For the former, we have frequently measured  $45^\circ$ , and Grewingk measured  $48.5^\circ$ , while for the latter, angles of  $5-10^\circ$  predominate, and at Wirzjärw  $18.5^\circ$ . At the impact side, the ice sheet bends steeply upward and shows a profile like a volcano. On the lee side, there is always a pile of ice chunks, whose edge lengths generally exceed the ice thickness (at Riga, 0.5 times 0.3 -- 1 times 0.5-3m). The angle is the maximum slope angle pertinent to this material.

If there are also rock boulders, these apparently always lie on the lee side.

If the opposing land resistance, perhaps at shorelines rising up steeply, cannot be overcome, the front of the ice sheet shatters, until the slope becomes so shallow because of the piling up of the debris that a continuation of the ice sheet following later can slide up over it essentially unbroken, like a sheet of paper. Having reached the top, the sheet either primarily tumbles over backwards and delivers a cascade of lumps (a in *Illus. 4*) when the uppermost section of the slope is still almost vertical, or (b) it bends down towards the land on the rampart plateau. It then simultaneously obtains rifts, and can then form a new, small ice pressure rampart as at Pernau, where a structure 3 m high built up even beyond the cliff 9 m high (*Illus. 4*). The ice sheet still clambers over this mound as if it were a tank. However, a continuation of the forward thrust would then probably place too great a demand on the plasticity. In any case, no further great advances have been yet observed after overcoming such obstacles. Specifically, they were not seen with the ice ridges in Riga, where the sheet itself had built up its frontal obstacle in the shape of the thrust ridges up to 16 m high, and where therefore the downward bending on the other side, towards the land, was so powerful that everything had to be broken up at that time.



*Illus. 4*

Nevertheless, a truly unusual flexibility has frequently been observed exactly at this point. Thus, in particular the "saddle

ridge", so often photographed, showed a doubling back of the saddle at its peak by 180°, with a radius of perhaps 3 m, almost without any large longitudinal rifts (Figure 3, 11). On the other hand, before this and afterwards, most of the sheet sections had broken off sometimes backwards and sometimes forward upon passing over this ridge, and had produced the huge pile of cakes on the luff and lee sides. Not infrequently, the floes tip over and lie partially or predominantly with the bottoms of clear ice facing upward.

The ice sheet overcomes this obstacle by virtue of the extraordinary smoothness of its bottom surface, and, if the thickness is sufficient, by virtue of its truly great flex strength, even when such extremely irregular substrata are present as a pile of floes or a plowed-up woods. Such a wooded area was traversed in 1863 by a completely intact ice sheet.

#### Ice Thrust Transport

Depending on whether bottom ice and earth, boulders or rocks which have been sheared off from the substrata, participate in the thrust, or not, these materials appear in the ice ridges. At the Riga shore, these were not to be seen at all. C. Grewingk (page 9) discussed a characteristic example. At Lake Wirzjärw, an easily recognizable rock boundary was produced along with the pastureland and meadow shrubs from the shore of Rosen Island, 5 km wide through the lake into a bay of the lakeshore. The examples of K. E. v. Baer and the Reval boulders have already been mentioned briefly (cf. also W. Ramsay, Fennia XI, 1894), as well as the large formation in North Siberia. For example, the ice thrust rock ramparts there at the lower Jenissei, called "korgä" by Lopatin, as well as those at Kola, are very pronounced. Nordenskjoeld spoke of the gigantic ice-dredging work in operation during almost the entire year in Northern Eurasia.

Buildup and demolition also correspond here. R. Pohle has described the eroded coastal forms.

These processes can only be touched upon here. As mentioned, they have the greatest importance for the coastal forms of the Arctic Ocean, where the tidal motion has also in fact participated vigorously. Admittedly, it must be stated that the breaking up of the continuous ice sheet encountered even at the pole (cf. for example, the photographs by Nobile [23]) because of just that tidal motion along with storms and drift, prevents the uniform motion of thick ice sheets, 20 or 50 m<sup>2</sup> in size, against the land. Such sheets are generally split up far out at sea. This is also probably associated with the fact that the height and longitudinal extension of the polar ice pressure ridges are generally rather small.

Favorable conditions for such particularly huge ice thrusts are present in non-tidal shores of very large lakes or of tributary lakes in those winters of temperate climate which have produced particularly heavy ice.

### C. ICE PRESSURE RIDGES AS A NATURAL EXPERIMENT

Analogies of ice structure with the structure of the earth's crust have been emphasized frequently. In particular, we owe special thanks to E. v. Drygalski, whose well-known excellent ice research in the far north and south have led again and again to such comparisons. I refer only to the interesting analogies between the structure of the Greenland gneiss and that of the inland ice lying above [24], and to the conclusions for the mountains from the observed narrowing of the weight of the Gauss [25]: those floes by which the motion was transmitted experienced the greatest disturbance, while the sections of the new ice which lay at the eastern floes of the mainland, and therefore against a solid abutment, remained undisturbed. Also important is the observation on the limits of the floe ice [26]. These are largely determined by the shape of the coast, but are jagged in detail, because the prevailing winds push forward complexes of floes which either arrange themselves into tongues in the wind direction (Table 17) or scatter in front of the margin. A prerequisite for this is that longitudinal rifts generally open up parallel to the direction of the wind.

Buckley [27], van Hise, and particularly E. v. Cholnoky [28] have drawn further comparisons between ice and the earth's crust. In these comparisons, the ice thrust processes under discussion were primarily considered. The last-mentioned wrote (75): "The ice ramparts extend along the flat ice sheet like actual mountain chains, but where they are thrust on the shore, we are forcibly reminded of folded mountains modelled on massifs. The comparison is particularly suggested here, where the dirty ice and the rubble frozen together are sufficiently plastic to produce actual folds, and the phenomena are strikingly similar even in their smaller details".

"Or do not the rifts and ice ramparts (aurolás) traversing the ice completely resemble the Ural Mountains, which run between two untouched, completely serene, motionless tables? The overthrust visible in Figure 3 reminds us of the structure of the Balkan Mountains whose steep slope, exceptionally, is on the outside of the arc, while the shape in Figure 102 is reminiscent of the types of the Eurasian System, the Carpathians and the Apennines. In the form of springs of water, we also come upon the volcanic eruptions instead of the lava gushing up from the depths. Also, this lava covers over many large areas in undisturbed layers, like the water gushing up at the rifts, which unites the snow crystals for long distances."

"However, we must proceed very cautiously with this comparison. The material and the force which come to play in the two phenomena are basically different. The differing rigid, plastic, or loose components of the solid crust of the earth are difficult to compare with the ice which has completely different properties. As Tyndall has already stated, every individual molecule of the ice is in complete order, primarily because of which it differs from the glassy materials with which it is so often compared initially.

The ice is stored as a solid substance without any transition into liquid water." "How different are the conditions in the earth's crust!"..... "The ice of the Balaton can be included in our consideration quite simply as a flat sheet, while the earth's crust represents a bulge in which quite different tensions and stresses prevail than on a flat surface".

"The forces themselves are also not one and the same". In the ice of the Balaton, contractions and elongations alternate periodically, while in the earth's crust, meanwhile, there is no trace of a relative contraction". (Page 96). "We search in vain the earth's crust for the analogies to the rifts occurring in the Balaton ice". "A loosening can occur when the horizontal stress in the earth's crust appears. However, this can only result in depressions, never gaping rifts".

E. v. Cholnoky adds to these differences between ice and earth's crust by emphasizing many details, for example, the fact that with ice, no folds occur arranged in succession, as perhaps in crystalline shale, the fact that stretched ice does not show plastic behavior, the fact that plates openly resting against one another do not occur in the earth's crust, etc.

Does it therefore make sense after all to search for comparison between the mechanics in ice and in the earth's crust?

I must answer this question completely in the affirmative. Thus, it must be completely clear to us that the more extraordinary are the differences between the two processes, the more valuable it is nevertheless to establish common features in spite of them, since a genetic evaluation can also be approached under these circumstances. We say that the situation is obviously similar to comparing a wooden farm cottage with a concrete skyscraper. And yet there are sufficient comparable features which can give us information there about the concept of "house", since we are not comparing an apple or a cuttlefish with the skyscraper, but something similar after all. I even consider it very necessary to learn from comparisons of this type, admittedly being careful that they have as few "hitches" as possible, since at least as far as the scope of the natural experiment is concerned, this cannot be attained with artificial experiments. And also, artificial experiments operate otherwise, quite certainly with completely different materials and generally under completely different conditions than does nature in the earth's crust. It is always well to remind ourselves of the fact that our previously used theories in tectonics were derived from the everyday concepts of mechanical nature, very little refined by observations of physical processes, which are just accessible to mankind on the surface of the earth. At such a stage, every experiment is useful which on the one hand approaches the processes taking place in the earth's crust with respect to scope, material, and conditions, and on the other hand has the advantage of obeying simpler, more easily surveyable factors. Reflections as critical as possible, and later perhaps even an exact mathematical treatment will guard against improper application. All applicable information concerning the matter

should have been taken already from the available experiences of the mechanical sciences. Admittedly, whoever seeks such useful examples today finds only very little. Mechanics today is tailored to the requirements and the experiences of engineering and theoretical principles. The examples of engineering are not sufficiently comparable and for theoretical considerations, the conditions involved in the earth's crust are still not clear enough by far.

This should be stated beforehand to explain why in the present case we do in fact call upon comparisons, but we give weight only to what is worthy of comparison in our opinion. For relationships with specific mountain ranges, only comparative tectonic studies of mountains of similar nature must clarify our view, and even then, we will be able at the most to relate the external outline of the ice pressure ridge with that of mountain chains.

It appears to me specifically that a noteworthy analogy lies in the fact that the ice ramparts appear arc-shaped in the direction of thrust, precisely as do the folding chains. This garland structure specifically pointed out by E. Suess can be seen clearly in Table I, and is also often repeated in other ice pressure ramparts.

It must be asked here, which of the possible main causes is probably involved. Is it a question of the locations of particular restraint on the freely shifting material in addition to the points of suspension of the garland, or is it a question of transverse sections isolated from one another in which the forward-pushing force has completely different upward strengths? Was it therefore local restraint of a force acting generally with equal strength, or force applied locally with different strengths with approximately equal resistances? In the first case, higher ramparts must stand in front of the obstacle than in the previously arched arc, and the reverse in the latter case.

It seems that both the ice pressure ridges and mountain ranges exhibit these two cases. The first case, for example, was exemplified at Lake Wirzjärw, where the highest ridges actually were dammed up in front of the strongest obstacles, which at the same time stood in the restraint indentations of the garland. On the other hand, the highest ice ramparts on the Riga Beach generally were raised in the arcs projecting towards the land, without any indication that basal resistances on them were particularly strong. The arc of folded hills seems to belong to this second group with respect to the piling up of its folds. I shall not discuss tectonic examples here, on the one hand because they would only be formally like those perhaps in the striking suspension points of the Himalaya Range and on the other hand, because the height of the ice pressure ridges cannot be compared with the intensity of the forces acting without further observations.

#### Formation of Fissures and Rifts.

The natural experiment of the ice pressure ridges provides a rather clear explanation in the partial separation of individual floes from one another, as can likewise be observed in comparatively solid rocks near the surface of the earth. Two situations should probably first be differentiated:

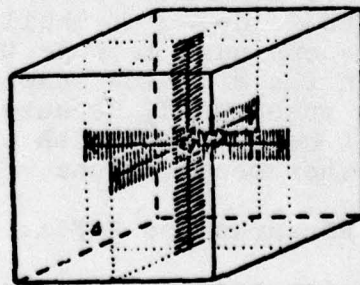
1) The regular fissure network consisting of common fissures perpendicular to one another.

2) The fracture rift formation with irreversible horizontal motions (sheet displacement).

1) The network of common fissures seems to be just as well developed in ice as in similar hard rock of the earth's crust. At least, the aerial photographs permit no other probable interpretation. If this is confirmed by further observations, then the general regularity found in the rock is thereby broadened. I have already mentioned a number of times [29] that in principle, the processes in the transmission of kinetic energy by earthquake waves can be compared with that in the formation of uniform fissure systems. Two types of waves are propagated outward from the focus in solid rock: The compression waves resulting from the resistance of the material to volume change, and the shear waves because of the resistance to change of shape. The first are formed by the vibration of the rock particles in the direction in which the mechanical pulse is propagated outward into the surroundings (longitudinal waves), and the latter perpendicular to the direction (transverse waves). Accordingly, a particle motion develops in directions approximately perpendicular to one another (actually radial or tangential to the sphere whose center is the focus).

In general, shock or pressure, generally tensile or compressive stresses in solid bodies, must be transmitted according to this scheme in which maximum motions are produced in the direction of the stress and perpendicular to it. If this stress is very powerful, the cohesion or adhesion must be overcome in these directions, and fissures must therefore be formed.

Illus. 5 indicates the position of the fissures which can form because of excessive longitudinal wave vibration. It appears that the internal stresses established in the ice with strong temperature fluctuations because of compulsory volume change, or occurring in the cooling of magma or because of strong general expansion or contraction of a tectonic nature, are powerful enough to exceed the elasticity of the rock and to lead to regular cleavage.



Illus. 5.

The possible reasons that the fissures open up parallel to the diagonal to the network of latitudes and longitudes of the earth in one case, but parallel to the lines themselves in another case [30], will not be discussed further here. We will also omit the third element of so many fissure systems, which runs approximately perpendicular to the two aforementioned systems and at the same time parallel to irregularities (e.g., to the surface of the earth or to layer structures), because corresponding rift surfaces have not yet been disclosed in ice.

2) The network of irreversible rifts. Well-observed and unequivocal relationships are found here between ice and earth's crust. We had to differentiate the following in ice:

- a) transverse rifts corresponding to the sheet displacement,
- b) longitudinal rifts corresponding to the cutting irregularities in the earth's crust.

a. Transverse Rifts.

We have discussed two possibilities for the formation of the NW-SE rifts in the ice sheet of the Gulf of Riga. Either they are the pure expression of the shear stress from the NW wind in whose direction they therefore open up, because irregular frontal obstacles presented resistance to a uniform forward motion, or they are determined in direction by the previously existing diagonal rift network. Its NW-SE component, according to the aerial photographs, was already especially pronounced, and when the general pressure then changed from NW to N, this direction of weakness was then utilized in the formation of transverse rifts.

We also face these two possibilities, which can also naturally be combined, but which is certainly not always the case, in the analysis of the earth's crust. For example, no analogous, preexisting network of fissures could be found for the fan-shaped transverse rift system radiating outward towards the S, SE, and SW in the southern section of the Central Rhine mass. The same is true of the large fan of rifts in the Molasse which radiates towards the N where the Iller leaves the North Alps. In this case, therefore, a visible, preexisting fissure network was not decisive for the establishment of the large transverse rifts. On the other hand, however, for example, it has become clear from the work of J. Walther's student H. Lehmann [33] that extremely intimate relationships exist between folding orogenesis and fissure networks. Each of the two fissure networks developed on the Harz can be assigned to a specific period of folding, the Halle fissure network to the Franconian folding, and the Mansfeld to the Saxon folding. The faults, which have predominantly the character of plate shifts, extend essentially in the direction of the main fissure.

It was believed that in the case of general strong horizontal compressive stress, a regular or irregular fissure network first developed, depending on the rock, from which rift systems with transverse displacement then grew because of overthrust;

and therefore, that the fissure network was a necessary stage of horizontal disintegration to be passed through. However, this is by no means the case. Even if the NW-SE rift direction was utilized in the case of the ice field at the Riga shore in the formation of transverse rifts, the latter were nevertheless not formed as the first result of the growing wind pressure on March 29, 1929. In this case, in fact, the fissure would have to have been freshly activated, which was not the case. However, at best, the direction of a weak point which was impressed on the ice at least a month previously was utilized. It appears questionable whether such a posthumous repeat motion took place after all.

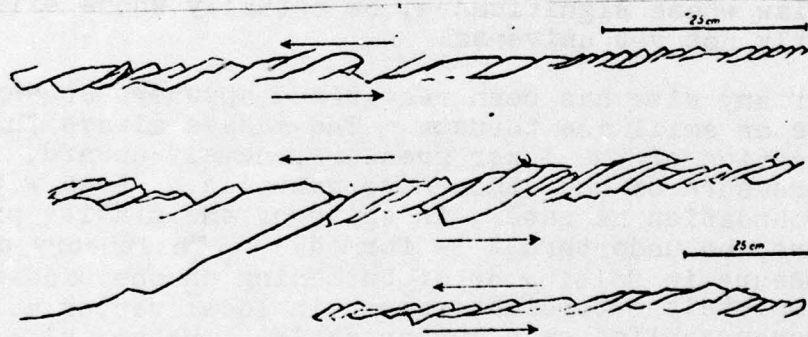
In any case, it results from the comparison of our experiment in nature on the gigantic ice sheets with observations on the earth's crust, that parallel trains of transverse rifts can very probably be produced also without any preformation at all by means of corresponding fissures. Lower forms of rock reactions are therefore omitted. The reason for this can be sought in the different rates of growth of the compressive force. Slow increase and low maximum strength produce fissure systems, but rapid, powerful, vigorous action produces rift systems. In any case, such differences did materialize in our ice sheet. Admittedly, thought could also be given to the fact that because the fissure system in the ice was caused not by the horizontal wind pressure but very probably by strong temperature changes, and therefore from general internal stresses, the different type of stress leads to the formation of fissure networks. This case could also apply to cooling eruptive rock, even for the entire crust of the earth, if the change from geognosic to thalassocratic emphasis is perhaps associated with a change of volume and pressure.

These are questions which can only be articulated and suggested here, but no explanation can be procured with the use of the ice thrust observations up to this time.

The splintering at the end of the transverse rifts towards the land is very characteristic. It can be seen clearly, for example, how a series of rifts develops between point S and R, and also between M and I in Table I, i.e., how the most strongly hindered front of the sheet is broken up into flat wedges wherever transverse motions in the advancing ice sheet were needed to a special degree.

I have also established various analogies for this by mapping. For example, the northern ends of the large Central Rhine transverse rifts are splintered in a highly characteristic fashion, exactly where ore-mining operations have deposited their freight [34]. Even more beautiful formations of flat wedges and feather-rift formations showed up for me on the Immenstadt 1:25,000 sheet or the Kempten 1:100,000 sheet [35] at the point where the restraining foreland came up against the Alpine upheaval. There are still other examples wherever large rock masses broke up against restraining abutments.

On February 9, 1930, I observed a beautiful example of feather rifts at a shear rift zone between two ice sheets sliding by one another approximately 100 m from the head of the breakwater of the Harbor Yacht Club on the Stintsee at Riga. Illus. 6 shows three partial sections of this transverse rift; the arrows indicate the relative motion of the ice apparently resulting from this on both sides of the zone of motion. The feather rifts, which according to H. Cloos and W. Riedel [36] lie at an acute angle to the direction of pressure, rose from left to right, stood roughly vertical, and often also united downward in a spade shape in the ice, which was approximately 25 cm thick. The rectangles of ice isolated by the feather rifts broke off from the surrounding ice at the rifts often approximately perpendicular to the feather direction, and yet the motion was not great enough to isolate the feather rectangles all the way around. A pattern was formed which was reminiscent perhaps of compression lenses (cf. the lowest section in Illus. 6). However, these were formed by being rolled out at the interface between two objects moving in directions opposite to one another.



Illus. 6

Longitudinal Rifts.

There are many longitudinal rifts and very few folding bends in ice. The two are mutually interchangeable, in which the more brittle, less stressed ice rather infrequently permits a certain migrating distortion, which signifies the normal reaction in mobile rock. Greater migrating disturbances, the longitudinal disturbances, will be found in general with lower mobility, lower overload at the time of disturbance, or in rocks of greater rigidity with considerable basal protection from rigid substructures. These are actually the conditions under which our longitudinal rifts were formed on the Riga shore.

In fact, we can also find this materialized everywhere in the earth's crust where geosynclinal thrusts gradually come to a standstill at gradually rising massifs. I refer to the long, elongated longitudinal faults at the north edge of the Variscan

and to the Alpine foredeep on the huge saddle ridge faults in the Alpine Molasse, the gigantic longitudinal fault which separates the Molasse and the flysch so profoundly.

If we assume with Fr. Kossmat that the crustal bulge presses down on the substructure because of its weight, we have an analogy for this in ice sheets blown against the land. In both cases, the longitudinal fault could be attributed to these downward bends. Admittedly, I can accept this theory only partially for the geosynclines. However, the active thrust seems to me to lie in the deep floes which cause an active sinking of the foreland plate. In addition, the general tendency for the formation of separate troughs unquestionably participates in the formation of the geosynclinal longitudinal faults. Between the troughs, which subside at different rates, and which later become the tectonic crustal units, longitudinal faults must naturally occur [37].

#### Overthrusts.

The ice thrust observations with respect to the overthrust processes can no less clarify or confirm prior theories. A completely general law whose significance, or actually whose existence, is apparently not yet universal

No underthrust of any size has been recognized anywhere at any time in the large or small ice thrusts. The masses always turn aside in the direction of the lower pressure, namely upward, where only the pressure of one atmosphere prevails. Even with such a movable foundation as water, in spite of the gravity prevailing everywhere, no underthrust is formed. The theory of the downward pressure in folding or of burdening on one side applies only in completely subordinate cases in local sector motions, but absolutely never applies on a larger scale. We are also justified in using the example of ice here, since our earth's crust also unquestionably floats on a foundation which -- at rest -- is plastic, even if only latently.

Certainly the ice floe or the sclerosphere are depressed with expulsion of the foundation when sufficient loads are placed on them. However, with a rock plate estimated to be 60 or 100 km, gigantic rock masses are necessary for this. These can probably be piled up only in very infrequent cases by exogenous processes, and the great oceanic depths can perhaps never be formed in this way. It can be clearly seen that the large forms of the earth's crust cannot be produced exogenously-isostatically, but only endogenously, i.e., by active motions of the depths.

Also, this basic principle is no less meaningful for the question of the mantle. Our ice thrust experiment is an ideal demonstration of the mechanics of formation of large plates, still supported by many. These should move over their foreland actively, i.e., not on the back of masses flowing actively beneath them, but for other reasons which might perhaps be associated with contractions or buoyancy of the earth. The activity lies not inside, but rather outside as in the case of the ice sheet, which responds to wind pressure.

If we are once willing to set aside all objections raised from another direction, specifically by O. Ampferer, then with such an explanation we could absolutely not understand the fact that the number of sheet developments necessarily assumed, the downward dips of the sheet fronts, becomes larger and larger in recent times. In no way could we understand the change in the depth of the deposit of the main pressure considered necessary to explain the overall situation at the large Dinaric-Alpine boundary root. The fact that local, secondary sectional motions cannot be involved here is probably clear, however. Our natural experiment teaches us: with active pressure in the outer crust, there are no patterns of motion pointing to the depths unless other completely different tendencies of motion also set in. However, this must be assumed to be of particular importance for the large plate motions of the Alps.

I have attempted to analyze the dependence of the plate migration on the type of motion of the overthrust substratum for the lake regions. When we have such good relief possibilities and smoothing lubricants which compensate for unevenness or sector motions in the foreland, there are truly extensive, smooth overthrusts as at the Wirzjärw or at Pernau, or in the East Alps and the Folded Mountains.

The ice thrust experiment gives a special indication in the geo-mechanical direction with respect to the omnipresence of gravity. This does in fact participate everywhere. We find that even with our pressure in the sheet acting only horizontally, structural complications occur immediately when the thrust sheet encounters an uneven base. With a bending stress, folding or, in brittle material, fracture formations must then take place immediately. However, this means weakening of the entire plate, complexities, sectional resistances, sectional relief by motion, which can lead to new fractures and folds. If the horizontal thrust proceeds further and further, then the resistance is thereby enlarged by heaping up of the sectionally moved complex. Similar to the way in which a small resistance to flight in a sand field gives rise to the formation of a dune, a rock in the river to the formation of a stationary whirlpool, a first factor probably initiates the greatest structural complications, whose expression, for example, is an ice pressure ridge.

This naturally does not occur if the resistances are not solid enough, such as perhaps boulders, pieces of earth, trees, or houses in the case of ice. They are then simply pushed aside. The shearings so often also sliced from the overthrust surfaces signify direct analogs to the granite boulders which were brought ashore 6 m high in the lee at the Reval embankments.

If the immovable frontal obstacles were built up on a slope, and if they remained so at least over certain sections, a non-uniformly sloping, overthrusting sectional component would always occur. We have a large number of well-known examples of these, for example, in the Alps.

Elsewhere, there exists an important difference between ice thrust and mountain thrust, in the fact that the simultaneous stretching processes with the ice are accounted for by the withdrawal from one another of the edges of the floes, but with the mountains, by the formation of radial downfalls. If the dimensions had been greater and the strength relationships in the ice more comparable, then these stepped downfalls would also have had to form at the edges of the ice floes. This mutual withdrawal can therefore be compared only with very significant horizontal stretching in the earth's crust. Accordingly, after the subsidence perhaps of a Leine\* valley and a Central Rhine valley, or a Lake Magdalen or Dead Sea graben, with stronger stretching, the patterns of the Red Sea would have to form, or according to A. Wegener, those of the Atlantic Rift.

#### Solidification

One last analogy should be pointed out. With ice, it is not long before rifts or fissures are mended, as long as the temperature remains chiefly below 0°. Water is actually present everywhere, and can close up the wounds solidly. It is therefore not probable that the motions in the ice always and everywhere follow older lines of weakness posthumously.

The same is true, again naturally on a correspondingly larger scale and in this case also on a longer time scale, for the earth's crust. Here also, sufficient water is generally available, which in fact in the salt mountains brings up the comparatively plastic salt to cement together the fissures and rifts. In addition, however, the water provides for true solidification by transport of the predominating carbonate or of quartz. Added to this also is the cement from volcanic processes. Therefore, the longer a newly applied pressure force, whether it be of the wind on the ice or of an orogenic phase is unable to reopen the separation seams of the rock, the stronger the solidification can be. After a lengthy diagenetic mending, it is possible to reopen fissures and rifts only with extremely powerful attacks, in which probably only very small posthumous facilitation can be utilized.

Similar to the situation at an earthquake station in which particularly strong earthquakes are generally found after particularly long pauses (Japan), and also in the case of the ice thrusts, only the strongest storms can set in motion the still unweakened winter ice, only pressure forces of the dimensions of the Alpine forces could move the earth's crust again after the long mesozoic quiescence. We are also reminded of the thickening of the outer crust by crystallizing magma as we think of the growth of the ice on its foundation.

#### SUMMARY

It is not possible for us, at the present stage, to follow exactly the path of a comparison between the ice sheet and the earth's crust. If the necessary constants with regard to pressure, bending and stretching, strength, expansion and contraction with temperature change, etc., are available, then we will advance much further and also be able to understand numerically for both cases, for example, separations and positions of rifts, extent of thrust, and other matters.

\*This may be a misprint for Seine--Translator's note

Meanwhile, we have had to be satisfied with the following. In the first section was presented probably the most important of the observation material available to us today, in particular details for the ice pressure ridges of the late Winter of 1929 at Riga. It was possible to describe, briefly in general, the individual results established here for the ice thrust process, in the second section.

After a terminological classification of the ice mounds, the high rate of formation in one or several hours, always in the second half of the night, according to observations to date, is initially stressed here.

As a result of the mechanics of formation, the ice thrust ramparts nearest to the land are generally the oldest. Posthumous action of existing fissures appears to have low probability. The regular rifts form from the action of temperature change, wind pressure, water motion, and ground relief. The shear forces caused by the wind are very large, and the shear width often varies between 200-400 meters. Thrusts are observed up to more than 200 m overland. The pressure ridges form at obstacles to the thrust. The largest ramparts were observed in the shore zone of non-tidal large interior reservoirs with cool, moderate climate. Sub-polar ramparts are more frequent but smaller. The pressure ridge shape generally shows a gently rising luff and a more steeply declining lee side with cake formation. The thrusts can cause significant material transport and changes of relief.

In the third section, finally, the ice pressure ridges were considered as a natural experiment with respect to the tectonic processes in the earth's crust. If only comparable phenomena are compared, the tectonics geologist can derive much that is instructive with respect to the mechanics of very large, floating plates.

The outline of the ice pressure ridge shows a garland structure similar to those of large folded mountains. There are many correlations between ice and the shape of geological structures in the formation of fissures and rifts. The network of common fissures can be considered as embryonically laid out by those vibrations produced in earthquakes by the elastic longitudinal and transverse waves. With the irreversible transverse rifts, the case of plate displacement in the direction of the wind (by the wind or mountain pressure) becomes significant, and it turns out, for instance, that the fissure formation does not have to be a necessary preliminary stage. Typical end splitting and feather rift formation occur at the transverse rifts. The longitudinal rifts are related to the large, extended faults in the geosynclinal folded mountains. In the overthrusts, the masses also weaken in the natural experiment generally in the direction of lower pressure, namely upward. Entanglement and underthrust can be explained only by actively subsiding subterranean movements.

The participation of gravity in all of this, and ultimately the significance of diagenetic solidification, are reflected in the ice thrust and in mountain thrust in the same way.

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21. During the night of February 2-3, 1869, apparently between 3:30 and 5:00 in the morning, according to the reports.
22. Petermanns Mitt., Erg.-Heft 80, 1885, p. 5.
23. Navigating the "Norge". The National Geogr. Magazine Washington 1927, 52, pp. 208-209.
24. E. v. Drygalski. Greenland Expedition of the Berlin Society of Earth Sciences, 1891-1893, Volume: The Ice of Greenland and its Approaches. 1897, p. 537.
25. E. v. Drygalski. On the continent of the icy south. German South Polar Expedition. Travels and studies of the "Gauss" 1901-1903. Berlin 1904, by G. Reimer, p. 500.
26. E. v. Drygalski. German South Polar Expedition 1901-1903. I. Geography, Verlag W. de. Gruyter and Co. Berlin 1921, p. 621.
27. E. R. Buckley. Ice ramparts. Transact. Wisconsin Acad., Madison 1901, 13, Part I., cited by v. Chohnocky.
28. "The ice of Lake Balaton", loc. cit. 1909, pp. 95 ff.
29. For example, "The problem of Latvian geology". Acta Univ. Latviensis, Riga 13, 1926, pp. 447.

30. E. Kraus. "The orogenic cycle and its stages". Geolog. Zentralbl. 1927, p. 229. "East Baltic II". Gebr. Bornträger, Berlin, 1928, pp. 135 ff.
31. "Alsace". Gebr. Bornträger, Berlin 1924, p. 83, 100, Table I, Geol. Archiv. IV, 1927, p. 219.
32. E. Kraus. "Geological research in the Allgäu, I." Geol. Archiv IV, 1927, p. 219.
33. H. Lehmann. "The rock fissures of the Eastern Harz foreland". Geol. Archiv I., Königsberg Pr. 1923, p. 31.
34. E. Kraus. "Alsace". Bornträger Brothers, Berlin, 1924, p. 83, 100, Table I. Geol. Archiv. IV, 1927, p. 219.
35. Immenstadt sheet issued by the Bavarian Board of Mines, Munich, 1929. Kempten sheet issued by Piloty and Loehle, Munich, 1930.
36. W. Riedel. "The mechanics of geological fracture phenomena". Centralblatt f. Min., B., 1929, p. 354 ff.
37. Geological Research in the Allgäu I., loc. cit. 214, 218 II. "The North Alpine Chalk Flysch" 1930 (in press).
38. "Geological research in the lake region I", p. 213 ff., cf. also, for example, papers by E. Spengler.