KAME-COMPLEXES AND PERFORATION DEPOSITS

JOHN H. COOK.

ABSTRACT: The plural "kames" implies a singular "kame"; but, since "an assemblage of kames" is a unit formation, it would make for clarity if it were recognized as such under the name of *kame-complex.* Many of the single, unattached mounds, frequently called *"isolated kames,"* have had a unique origin; and for them a denotative term, *perforation deposits,* is proposed.

The probable mode of origin of these perforation deposits is discussed first, since they are sometimes one of the elements making up a kame-complex.

The several processes whose combined action produces one type of kame-complex (the kame-moraine) are stated; and an attempt is made to evaluate the relative importance of each process.

Other types of kame-complex await further study to determine their significance.

IN a discussion of deposits overlying the till of Scotland, James Geikie (1874) introduced into the literature of geology the word kame, a term that has been a prolific source of mischief. Being descriptive of form only, it was much too inclusive: any hillock of glacial materials might be called a kame irrespective of its content, structure or mode of origin.

Although any attempt to formulate a definition of the whole group is foredoomed to end in absurdity, "definitions" of kame and kames have been attempted; they still find place in dictionaries (1941) (1943). And, while in one textbook (Longwell, Knopf and Flint, 1939) the word appears but once (in the index: "see knoll"); in another (Emmons, Thiel, Stauffer and Allison, 1939) the circumstances under which "kames" are formed are not only stated but pictured. It is evident that: if the several origins of these heaps of glacial materials are to be inquired into profitably, it will be necessary either to discard Geikie's term altogether, or to clarify its meaning; for to proceed on the assumption that glacial knolls are all alike, and that a description of any one kind will stand as a description of all, is to commit an unpardonable extrapolation.

Let us first, then, attempt clarification.

The word *kame* is a variant of coomb or comb; and just how the people of Scotland and the north of England happened to be using it when it was taken into the terminology of geology, is beside the point—even supposing James Geikie understood the current usage correctly. A strictly etymological approach to the problem, such as that made by J. W. Gregory (1912), yields meagre results (and those misleading). Back of words are concepts, *i.e. pictures* that the speaker or writer hopes to convey *in their entireties;* but the modifications undergone by concepts are many and varied (extension, intention, transfer, etc.) and, even in living speech, we recognize "meanings" that are tropical, figurative, secondary and derived. In other languages of the Indo-European group the words most closely related to coomb signify a molar tooth, and (by extension) anything suggestive of the crown of a molar tooth. Different words were used for pointed teeth; and the ridge-and-hollow character of a molar crown was evidently familiar enough to serve as the sign for a concept whose underlying significance can be well enough expressed by an undulatory wave of the hand.

No single hillock is sufficiently suggestive of this progressive up-and-down-ness to have justified its being denoted by the primitive word-symbol, a symbol that has been used to denote: a serrate skyline, the comb of a barnyard cock, the wards of a key and (among adjectives) the quality: crooked. Yet, though it would hardly be applied to a single hillock, it could have been applied, in all appropriateness, to any *area of sag-and-swell topography* such as was called by Geikie "an assemblage of kames."

Now, whether or not the testimony of philology is reliable, it is too late to ask that "an assemblage of kames" be hereafter known as "a kame" or "a coomb"; so, in the discussion to follow, we shall call such an "assemblage," a kame-complex, with the understanding that a complex is a unified whole, and in no sense an association of discrete units.

Another type of hillock recognized by the same author, is the "isolated, solitary mound." Geikie avoids using the term kame for such hills: he calls them merely mounds, cones or conical hills; and, while a common origin for all solitary mounds cannot be taken for granted, certain of them have been formed by the collapse of columnar masses of detritus and may be grouped together under the name *perforation deposits.*

A considerable number referable to this class has been found, of which three conical examples had been opened from peak to base, exhibiting a structure which demands for its explanation: a cavity or vertical shaft through the glacier, of unknown depth and *without any outlet for water at the bottom.* The cores are composed of cross-bedded sand with a high-angle dip as though spilled in from a height; and these beds are covered by an enveloping layer in which the dips are predominantly parallel to the sides of the cores, as though, after deposition of the latter, more sand had fallen down over the apex. Fifteen years ago the writer failed to appreciate fully the significance of these solitary conical hills (Cook, 1930): it was recognized that they were deposits made at the bottom of ice-shafts (probably, it was thought, abandoned moulins) but why the fill did not run on into an (assumed) outlet-tunnel remained a mystery.

It now appears that there are in stagnant glacial ice such things as vertical shafts that are not moulins, and that have no bottom outlets. They are today being gradually deepened in the stagnated termini and piedmont expansions of glaciers wherever an insulating blanket of detritus has, for any reason, accumulated on the surface of the ice. Eventually, it may be presumed, they will perforate their glaciers and permit the detritus to fall to the basement. Described in 1891 by Russell (1891), they were given a somewhat fuller treatment in 1902 by W. O. Crosby (1902); and the manner of their formation can be inferred from a recent paper by the writer (1946).

The temperature of meltwater at 0° Cent. cannot be raised by contact with warmer air more than about 3.9° Cent. as long as it remains in contact with ice; and, because of the poor thermal conductivity of water, heat "absorbed" by a pool from warmer air, would remain at the surface for an indefinitely long time, were it not for the fact that, within this narrow range (0° to 3.9°), the water's density *increases* as its temperature *rises.* Just before the temperature reaches 4° Cent., the surface water sinks to the bottom and all its heat in excess of 0° Cent., is *expended in melting the ice.* When heating of the surface stops, the bottom water soon parts with its excess heat and the pool is again in thermal equilibrium with the ice.

Ordinarily, the ablation of ice exposed to the air (in which constant evaporation plays a large part) is so much more rapid than the slow process of melting below a water level, that the effects of the latter are negligible until the rate at which ablation has been progressing is somehow checked. This occurs ordinarily when detritus accumulates on the glacier, as when a blanket of "ablation moraine" becomes thick enough to interfere seriously with evaporation. When this stage is reached, the penetrating shafts become notable features of any topography underlain by stagnant ice. They are necessarily full of water to the level of a (probably concealed) sill; and the lakelets appearing here and there in the midst of the covering of débris (Text Figs. 1 and 2) are often surprisingly deep. Crosby says that on the Malaspina glacier some have already attained a depth of "fifty to one hundred feet or more" (ref. p. 19).

Fig. 1. The stagnant end of an Alaskan glacier (Chitina), covered with ablation moraine. Slow reduction of the ice-surface is causing the blanket of débris to settle into each more rapidly ablating area (outlined by arcuate bluffs). Several of these areas have deepened until the débris has been carried down out of sight in shafts now marked by pools. Eventually, these pools will perforate the glacier. *From a photograph by Bradford Washburn.*

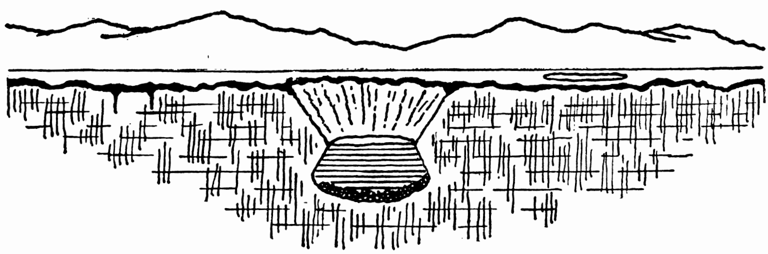

Fig. 2. Cross-section of a perforating basin and its contained detritus and water. The basin is deepened by heat absorbed at the surface of the pool and carried down as fast as the water's temperature is raised from 0° Cent. to its point of greatest density (about 3.9° Cent.). *After I. C. Russell.*

Masses of débris carried into a lakelet do not arrest the deepening of its basin, though they may affect the direction taken by the shaft; and insulation of the side walls is impos-

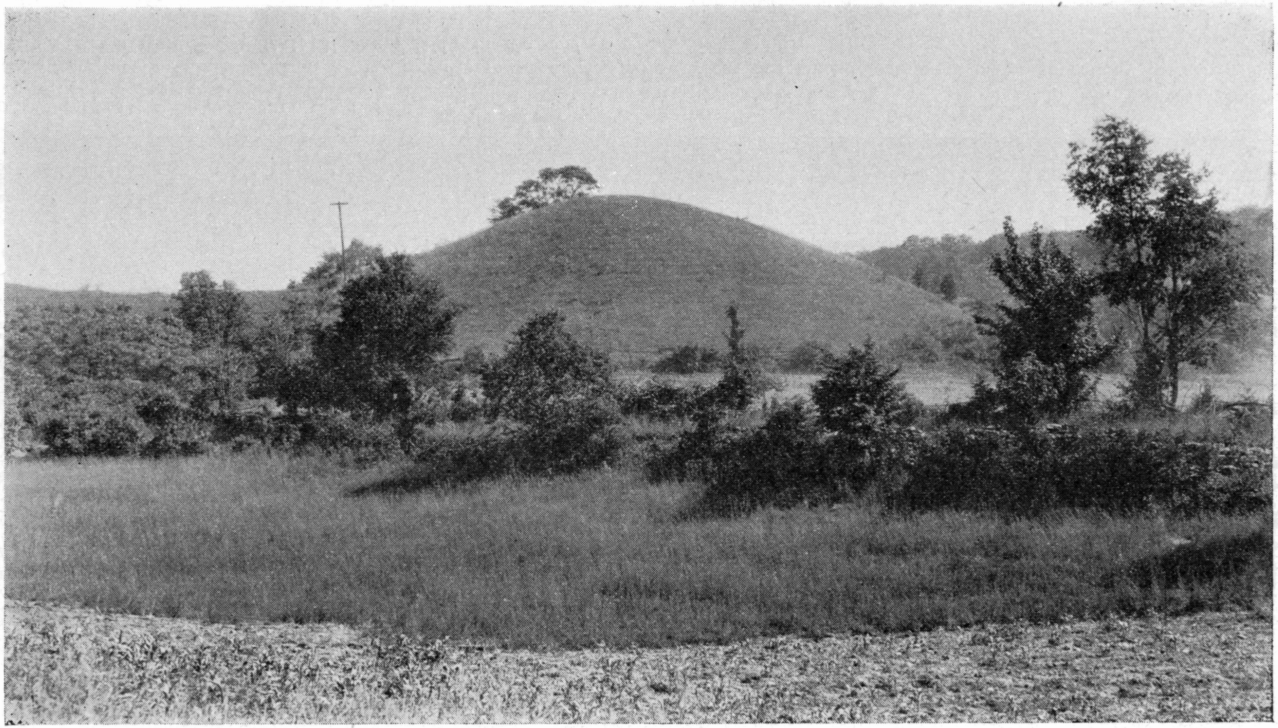

Plate 1. Perforation cone composed almost wholly of cobblestones. *From New York State Museum Bulletin No. 332.*

Plate 2. A cavity-filling (platform) of stratified sand. Where the whole glacier has become thin, the process that in thicker ice produces perforation basins, results in broader, shallower cavities whose form may be preserved by inwashed sediments. *From New York State Museum Bulletin No. 331.*

sible as long as the basin contains any water. A filling of cobblestones would offer little opposition to the vertical descent of heat-carrying water, while a layer of rock-flour or very fine sand, being an impenetrable barrier, would deflect its movement horizontally.

Presumably, the development of shafts may begin at any time until the glacier has been reduced locally to the final stages of dissipation; and those that are formed late are cavities* rather than shafts. When cavities are obliterated, as such, by sedimentary fillings, the fillings remain, after the ice has gone, as platforms. Besides the perfect cone (Plate 1) and the perfect platform (Plate 2) there are many irregular and compound forms that have had essentially the same origin, and whose containing basins were doubtless made in the same way.

We have, of course, in each case, the very last episode only from which to reconstruct a history that may not have been as brief as casual observation in the field would suggest.

These, then, are perforation deposits; and whether they are conical or not, they have nothing in common with "kames" as kames have been defined by lexicographers and writers of text-books.

We may now consider those deposits with which the floors of many Scottish valleys are cluttered, giving to them a billowy or rapidly undulating appearance: the "assemblages of kames" or, as we shall call them, coombs or kame-complexes. These occur most frequently, and are most typically developed "at or near where the rivers escape from the confined mountain-glens or upland dales to enter upon the broad low grounds" (Geikie, page 187) *i.e.* in situations where stagnant piedmont expansions might be expected to have melted out.

Since the discovery and exploration of the Alaskan glaciers, much has been learned about terminal "dead ends" and motionless piedmont expansions; and it is now generally recognized that increase in the rate at which ablation takes place (relative to alimentation) results in thinning; and that protracted thinning may result in terminal or peripheral stagnation. This paper deals with the final liquefaction and vaporization of such

* Whatever their shape, such cavities are not crevasses; and Salisbury's term "crevasse-filling" should be dropped.

stagnant bodies of ice; and the discussion that follows may be summarized by the statement that: should the present rate of melting continue until the stagnant, débris-covered marginal zone of one of the Alaskan glaciers is completely dissipated, there will remain a subdued kame-complex consisting largely of till. If, however, climatic conditions favoring the production of copious meltwater should overtake the dead terminus while some of the ice remains, there will result a kame-complex comparable in all respects to a Scottish coomb.

The first task, then, is to analyze the process by which such a stagnant marginal zone is reduced; and to determine, as far as may be possible, the relative efficacy of the several factors entering into that process.

The factors are: gravity, evaporation, perforation, surface melting, undermelting and bottom-melting. The term perforation may be applied to the melting out of cylindrical or irregular shafts as previously discussed; undermelting will be used to denote what is essentially the same thing but taking place in basins not completely walled by ice.

In the Antarctic regions, where comparatively little rock débris is being carried by the glaciers, and where the temperature seldom rises above 0° Cent., certain of the outlets from the great central ice-dome have been so reduced by evaporation alone that they have stagnated; and, in time, the stagnant remnants may be completely removed without ever having melted at all. Alimentation must exceed evaporation if a body of ice is to persist. When the temperature of the air bathing such a body rises above 0° Cent., the rate of evaporation is increased, and liquefaction becomes an *added* means for removing the ice.

The presence of englacial débris and superglacial moraines affect the rates of both evaporation and melting profoundly; and, because typical kame-complexes are often made up in large measure of such materials, it will be convenient to rehearse matter with which glacial geologists may be supposed to be thoroughly familiar. For nearly a century now, James D. Ford's explanation of the frontal dip of the veined structure at the end of a glacier (*i.e.* that it is due to basal ice "being forced upward by the action of frontal resistance") has been verified or rediscovered time and time again; and the conventional diagram used to illustrate it need not be repeated here. One

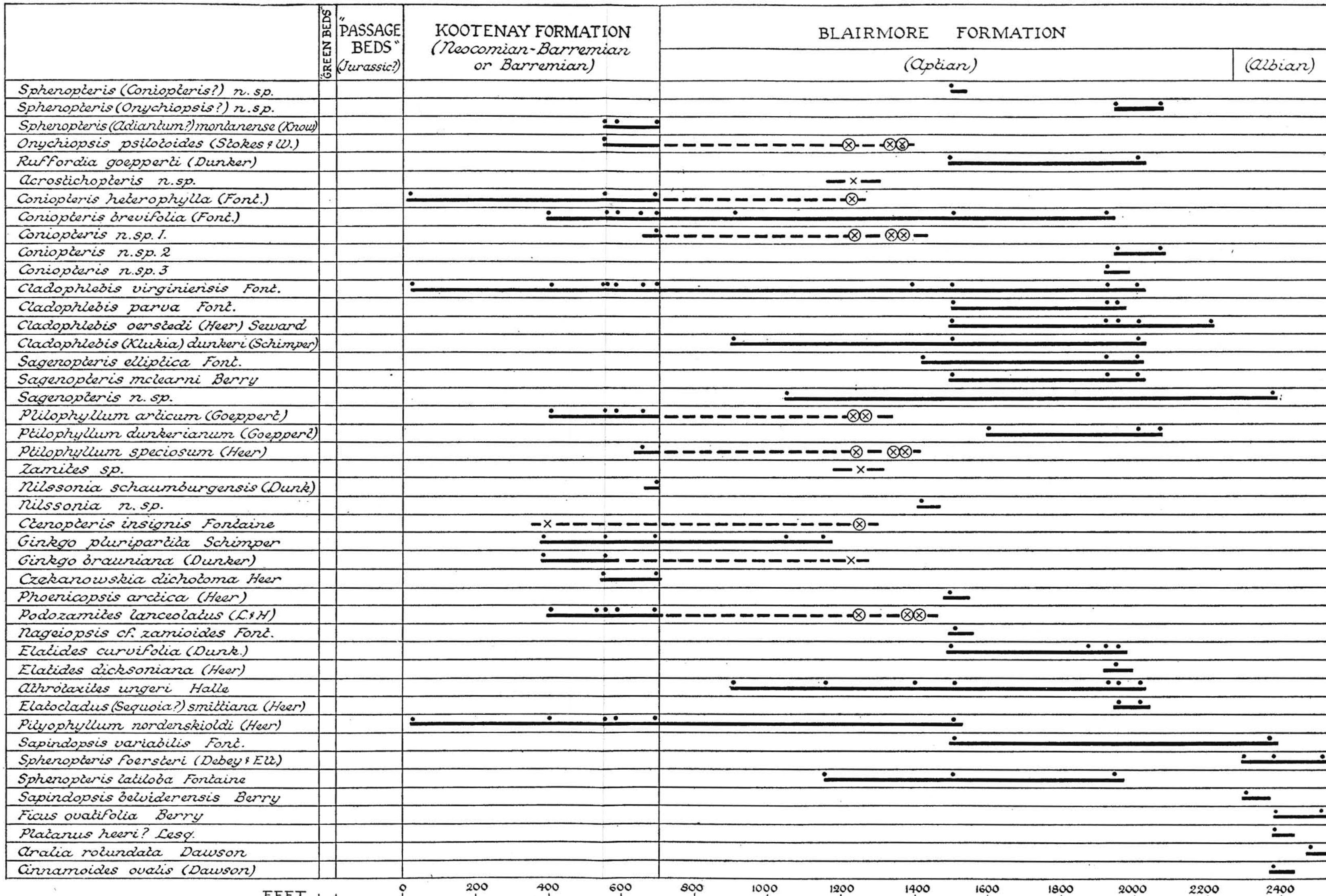

FIGURE SHOWING STRATIGRAPHIC RANGES OF SPECIES

LEGEND

Certified ranges in Kootenay and Blairmore formations .... ———

Horizon of collections .... •

Horizon within Blairmore formation undefined .... —×—

Horizon within equivalent Luscar formation undefined .... – – –⊗

Horizon within equivalent Gething formation undefined .... – – –⊗⊗

criticism of the diagram, however, should be made at this point: perhaps half a dozen bands of upthrust ground moraine are represented in longitudinal section; enough to illustrate the principle involved, but too few to suggest the circumstances attending formation of any but the smallest, most terminal-morainelike of kame-complexes. Since each upcurving line stands for a forward movement that failed against the dead nose, there should be no implication that the number of such feeble advances was limited to six; there may have been forty or a hundred.

Whatever the number of these exhibitions of waning power: if the "receding hemicycle" has set in, a day must arrive when the last one has been made. Either the position of the front of active ice withdraws from its dead nose gradually; or the section back of the nose also stagnates; so that, after an interval during which thinning takes place, it offers "frontal resistance" to a subsequent advance of the glacier *farther up-valley*. Since, however, a determination of the special manner in which the distal clean ice was removed is not of importance in the present discussion, we choose to fill out the picture by regarding that ice as inert. In either case it would disappear by evaporation (or, in warmer air, ablation) long before the drift-impregnated section from whose included till a kame-complex will be, in part, fashioned.

The melting down of this ice has been described by Prof. Richard F. Flint (1940), and by Prof. John L. Rich (1943); and, if there were nothing to add to these descriptions, there would be no point in repeating what has already appeared in print.

Before we undertake to evaluate the work of the several processes that eventually remove stagnant ice from under a protective cover of ablation moraine, it should be pointed out that the environments in which removal takes place are various; and, if we are to arrive at the general view that is our aim, many of the variant factors of which the reader will be aware must be touched upon lightly or ignored altogether. Among these variables there is one that must be taken into account, namely; the position of the "snow ceiling" or (atmospheric) isothermal layer of 32° Fahr. at the time when stagnation sets in, for the nearer this lies to the locus of kame-complex formation the less will meltwater enter into the picture. If it lies close, valley trains, aprons and outwash plains may have a feeble development or none; if much higher, the moving ice will be far up-glacier because the same climatic conditions will not be conducive to both active ice and copious meltwater at one and the same time.

We will, then, assume an environment in which the snow ceiling is, at first, near the section of blanketed ice, but later moves to a relatively higher position. The earliest reduction will be due almost wholly to evaporation; and presently the drift content in the distal part begins to conceal the surface of the ice. Due to heat "absorbed by" and "reflected from" stony matter, this becomes pitted and, finally, almost impassably rough as general ablation lowers it to the point where accumulated débris retards melting and almost prevents further evaporation, except where the cover is thin. Meantime, the cleaner ice up-glacier continues to evaporate until its surface stands at a lower level than that of the ablation moraine. (It may even disappear while the protected section still stands like a great mound of dirt.) We may now consider the effects produced by elevating the snow ceiling. Air temperature will rise and, in consequence, liquefaction of the ice under the dirt-mound will become the *obvious* manner in which it is being reduced. An insulating blanket retards but does not prevent melting: so that the bottom of the ablation moraine is soon water-soaked, while every point where it is thin or absent becomes the site of a shallow basin destined to develop into a cylindrical or irregular shaft that, in time, will perforate the ice.

This much in the way of reduction may be accomplished without any modification due to the presence of lateral waters; and, if there is free run off of glacio-natant streams, the end product will be a type of kame-complex that is little more than a mass of till. Nearly all kame-complexes, however, are more than this; so, once more, we must consider the matter of environment: there may have been an inheritance of frontal moraine (push, dump or lodge) or of outwash; and, if so, meltwater may be ponded behind the obstruction, and undermelting of the ice at its base begins, efficient in proportion to the area of water-surface exposed to the air. Recesses, melted out of the basal ice, become deep pockets and blind tunnels; and, in spite of the slowness of underwater melting, such tunnels may meet perforating shafts; broken off cornices may be afloat against the thicker, unlifted ice; and, in general, the separated glacier-remnant may be pretty well honeycombed and shattered before sediments arrive in quantities great enough to put a stop to melting below the water level, and to preserve the particular stage of local glacier-decay that has been reached. That most of this underwater decay is finished before sedimentation begins goes without saying: undisturbed sediments mean spaces which have been filled; and to be filled, the spaces must have been previously made.

What has happened thereafter, in any given case, can be determined only by studying the internal structure of the mass, a structure seldom sufficiently exposed to vindicate a casual judgment.

Some ice outlasted the deposition of those sediments out of which kame-terraces, platforms, and flat-topped stratified elements of the complex were built. Not only was it insulated by the surrounding or abutting sediments, but it was burdened, above water level, by whatever of ablation moraine had not slid or been rinsed off. The water table fell: the pools drained away; the last ton of ice melted; and the kame-complex was finished.

Nothing has been said about bottom-melting. Presumably, there was bottom-melting; and, in many instances, there was subglacial drainage through tunnels, parts of which tunnels became clogged with sand and gravel. The occurrence of a longitudinal ose or two running toward or into a kame-complex, early gave rise to the facile conclusion that the complex itself was vomited forth from the mouths of these tunnels, a conclusion that, in the absence of revealing sections, became almost an article of faith among glacial geologists. In the preceding paragraphs an alternative to this conception has been presented.

Thus far, we have considered only the Scottish type of kame-complex, the type that has been called kame-moraine, a term that is appropriate in that the accumulation marks an ice-front or margin, albeit a deserted and fossil position of such front. But to assume that, because the kame-moraine is a marginal formation, every kame-complex must be a kame-moraine indicating an ice-edge (in interpretations of Pleistocene continental glaciers: *the* ice-edge), is to overlook the possibility of different origins for these mounded deposits. The external form known as kame-kettle topography is not infrequently merely a cast in stratified sand of floating masses of ice. Kame-complexes of this character were doubtless built by the incursion of sediments into water-filled basins that had not developed beyond the incipient stage: had the basins been somewhat larger or freer from floating ice when their development was arrested, it might be easier to recognize an affinity between the deposits that filled them and terraces or platforms. Although aware that there were many kame-complexes "disposed without evident relationship to [other ?] glacial phenomena," and, although recognizing that the morainic phenomena of eastern New York were obscure and feebly developed, T. C. Chamberlin (1883) deliberately chose to identify as kame-moraines certain of the valley-bottom terrace-accumulations of the Susquehanna drainage system, and mapped them (ref. Plate XXXIII) as indicating frontal positions of the diminishing Wisconsin ice-sheet.

That so eminent a student of glaciology could be misled by a predilection for interpreting in a particular way (ref. p. 376) deposits mounded and kettled by association with masses of ice, is our justification for holding that there are probably many kame-complexes the significance of which we have not as yet learned to appreciate; at any rate, they do not fall readily into the categories that have been discussed in this paper. Certain of these we hope to describe in a future article.

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