GLACIAL RESERVOIRS AND THEIR OUTBURSTS.

By CHARLES RABOT.

Glaciers, acting on the soil slowly but continuously in obedience to glacial dynamics, give rise from time to time to the violent torrential outbursts known in French by the name of *débâcles*. Far from being rare and accidental, as is commonly supposed, these outbursts are relatively frequent, constituting a normal form of glacial action.

The occurrence of such phenomena presupposes, first, a reservoir of water, and, secondly, its *sudden* evacuation.

The formation of the reservoir may be due to one of three principal causes—

1. The reservoir may be the result of a disturbance, effected by a temporary increase or decrease of a glacier, in the channels and outflow of streams external to it.

2. The reservoir may be the result of a disturbance, permanent throughout a period of considerable duration, effected by a glacier, in the channels and outflow of streams external to it.

3. The reservoir may be situated in the glacier itself, and its creation, as well as its alimentation, be due to the physical properties of the ice. Such a reservoir is the glacier lake, properly so called.

The first of these examples may have been produced in one of three different ways—

(*a*) A glacier, while advancing, chokes up a valley or glen at right angles or oblique to its own course, and by stopping the overflow of its waters causes the formation of a barrier lake (*lac de barrage*) during the period of advance. A well-known specimen is supplied by the Vernagt glacier in Tyrol.

(*b*) A glacier, encountering in its descent a cliff overhanging a valley, falls to pieces, which subsequently unite to form a new glacier (*glacier rémanié*) at the base of the precipice. Should the ice increase, the "*glacier rémanié*" may choke up the valley and give rise to a temporary barrier lake. The glacier of Giétroz in the Val de Bagnes is an example.

(*c*) Where, of two glaciers previously united at their lower extremity, one retreats more slowly than the other, so that the first blocks the passage of the waters issuing from the second, and compels them to accumulate in a lake. The glaciers of Otemma and of Crête Sèche in the Val de Bagnes, from 1892 to 1898, furnished a specimen of this class.

Let us now turn to our second example, in which the formation of the reservoir is due, not to glacial variations in length, but to topographical circumstances coincident with the general state of glaciation. A glacier chokes up, in a manner relatively permanent, a lateral ravine; or the ice may simply dam with its moraine a stream flowing off the enclosing mountains, thus giving rise to a Border Lake (*lac de bordure* in French, *Randsee* in German), which will endure as long as the barrier does. The best known example of the glacial *Randsee* is the Märjelen See near the Eggischhorn.

In our third example, that in which the reservoir is contained in the ice itself, three sub-varieties may be distinguished—

(*a*) When the surface meltings of the glacier fill an open hollow—a Surface Lake.

(*b*) Where a reservoir of water is formed in a hollow under the glacier—a Subglacial Lake.

Or (*c*) Where in the heart of the ice—at least in the case of the great glaciers of the Arctic and Himalayan regions—pools of water are formed, distinguishable as glacier Ice-pocket Lakes.

The second condition required for the production of a water-burst is the *sudden* collapse of the reservoir.

The action of water on ice resembles that it exercises on limestone, as has been demonstrated by Dr. R. Sieger in his "Die Karstformen der Gletscher," in *Geographische Zeitschrift*, 1895, 3 and 4 (Leipzig). The causes which tend to the formation of rock caverns go also to the formation of glacier cavities, namely, the preexistence of fissures, erosion, corrosion, and hydrostatic pressure, to which must be added the action of air having a temperature above 32° Fahr. The waters of a glacial Barrier or Border Lake, or of a Subglacial or Ice-pocket Lake, in this way tend to scoop themselves out a passage through the mass of ice confining them. Should the opening of the passage occur suddenly, the result is a burst; but if effected gradually, the emptying of the reservoir causes no more than a marked increase in the torrent issuing from the glacier.

The force of a burst is naturally proportioned to the cube of water suddenly set free. The volume of water discharged by the burst of Giétroz in 1818 has been estimated at 5,000,000 cubic metres (1,110,000,000 gallons); that of the bursts of the Crête Sèche in 1894 and 1898 at 1,000,000 cubic metres (220,000,000 gallons). In nine hours the Märjelen See, in 1878, evacuated 7,770,000 cubic metres (1,709,400,000 gallons).*

The passage of a flood of such dimensions, impelled in most cases by a very steep slope, naturally exerts erosive and transporting force on the ground over which it sweeps. The effects of such action have hitherto attracted little attention from geologists. The following statistics of glacial outbursts may, we hope, serve to show the importance and frequency of the phenomena, as also their bearing on the study of the Quaternary rocks.

The Alps.

I. *Outbursts caused by the Emptying of a Barrier Lake produced by a Temporary Glacier Variation in length.*

1. *Glacier of Rutor.*—Val d'Aosta. A northern branch of this glacier is liable to stop the overflow of a lake in the combe of the Osselettes, causing a considerable increase in its volume. Should the waters succeed in opening for themselves a passage under the bank blocking their normal outflow, a burst ensues.

From the end of the sixteenth century to 1752, not less than fifty outbursts were produced by the Lac des Osselettes. They corresponded with the periods of advance of the Rutor glacier. Trustworthy documents record outbursts in 1594, 1595, 1596, 1597, and 1598. According to Baretti, similar accidents occurred, in all probability, annually up to 1606. A second period of frequent floods began in 1629 or 1630 and lasted till 1646, a third from 1678 to 1680, and a fourth from 1738 to 1752. The great advance of the glacier during the first half of the nineteenth century did not produce any outburst. In 1864 the Lac des Osselettes, which was then of considerable extent, gradually wore for itself an outlet by the side of the glacier, and thus drained itself gradually without causing any disaster. After De Tillier ('Histoire du Duché d'Aoste,' 1738), the Lac des Osselettes had produced outbursts before 1594, of which the dates cannot be fixed.

* According to the calculations of Prof. Baretti, the Lac des Osselettes, produced by the dam of the Rutor glacier, discharged during an outburst 4,500,000 cubic metres of water in six hours.

A document of 1752 records the "frightful devastations" caused by these floods in the valley of La Thuile and in the valley of Aosta. They washed away the fields bordering on the river-bed, covered them with heaps of matter, and threatened the destruction of Morgex (cf. M. Barretti, "Il lago del Rutor," in *Boll. Club Alpino Italiano*, No. 41, 1880, Torino). Every time they happen, the inundations act with erosive and transporting force.

2. In 1717 the *glacier of Triolet* gave occasion to a burst. This accident was caused by the rupture of the bank confining a lake formed of the accumulated waters derived from the glacier of Mont Dolent. The inundation, following an increase of the glacier of Triolet, covered a pasture-land with "immense *débris*." This mountain pasturage is said to have been afterwards invaded by the glacier (Virgilio, "sui recenti studii circa le variazione periodiche dei ghiaccaij," in *Boll. Club Alpino Italiano*, 1883).

3. *Glacier de Miage*.—This glacier, according to Baretti, must have several times choked up the Val Veni. Thence the possibility of bursts. In a memoir published in 1867, in the *Bollettino* of the Italian Alpine Club, Canon Carrel of Aosta mentions the occurrence of such accidents, but without assigning any date to them.

4. The *Gouille de Valsorey*.—This small sheet of water, situated on the flank of the glacier of Valsorey, which, owing to the decrease of the glaciers, disappeared in 1879, has given rise to bursts. De Saussure, who visited it in 1778, reports that it was remarkable for the ravages it caused. The mass of water, he says, sometimes empties itself in a few hours with terrific impetuosity, causing an overflow of the Dranse, carrying away rocks, and producing inundations and frightful devastations all the way from the glacier whence this torrent issues to the Rhône.

Sources of information for the Gouille de Valsorey are—

(1) 'The Alpine Guide. The Western Alps, by the late John Ball,' a new edition reconstructed and revised by W. A. B. Coolidge (Longmans: London, 1898), p. 437.

(2) 'Voyages dans les Alpes.' Edition 1786, ii. S. 1013, p. 466.

5. *Glacier of Giétroz*.—In 1595 and in 1818 an increase in the volume of this glacier *rémanié* caused the Val de Bagnes to be blocked up and a lake to be formed. The dam of water attained, in 1818, a length of 2100 metres (6888 English feet, or nearly 1⅓ mile), a breadth of 200 metres (656 feet), and a depth of 55 metres (180 feet). In the above-mentioned years of 1595 and 1818, the bank of ice suddenly gave way, and there ensued a frightful flood which swept over the Val de Bagnes and extended its ravages over the whole of the Lower Vallais. Escher von der Linth estimates the volume of water let loose in 1818 at 530 millions of cubic feet (Escher von der Linth, 'Notice sur la Catastrophe de Bagnes,' in *Bibliothèque universelle de Génève*, VIII. Sciences et Arts). At the bridge of Mauvoisin the waters rose to a height of 90 feet above the normal level of the stream, while the streets of Martigny were flooded to a height of 3·25 metres (10·66 English feet).

The inundation of 1595 destroyed five hundred houses and chalets. No less disastrous was that of 1818. The flood was deeply erosive. According to an account written by the Syndics of the Valley (cf. 'Echo des Alpes' (Génève, 1887), p. 350), it seems to have even produced a displacement of the great blocks disseminated in the valleys. Moreover, as usual in such cases, "it converted the fairest pasture lands into a plain of pebbles rising to a height of 2 to 20 feet above the current. It further deposited on the plain of the Rhône a thick layer of mud, casting on it an enormous quantity of wood from the forests and chalets devastated and wrecked in its course."

6. *Glacier of Crête Sèche.*—During the great glacial retreat characterizing the second half of the nineteenth century, the glaciers of Otemma and of Crête Sèche, which in the previous period of increase formed confluent currents in their lower course, separated and withdrew each into its respective valley. The Otemma glacier having, however, receded less rapidly than its neighbour, and having dropped across the whole breadth of their ancient common valley a pile of "dead glacier" * and of moraines, the waters issuing from the Crête Sèche glacier found their way blocked by this barrier, and so accumulated into a lake. From 1894 to 1898 the evacuation of this sheet of water caused two violent floods, one in 1894, the other in 1898, to leave out of account two more that were harmless.

The accident of 1898 drifted away heavy blocks of stone and covered with layers of detritus cultivated fields and pasture lands. Lastly, at Lourtier the Dranse, quitting the bed it had followed since 1818, scooped out a new one across arable lands, and excavated it to a depth of 12 metres (39·36 feet). This last burst discharged into the Rhône an enormous mass of sediment. Prof. Oettli calculates the amount of slime borne on this occasion by the Rhône into the Lake of Geneva at 166,000 cubic metres.

7. *The Glacier of Allalin.*—When in process of increase, this glacier completely blocks the outflow of the Mattmark See, and then the rupture of the dam causes floods. Accidents of this kind happened in 1633, 1680, 1740, and 1772. The flood of 1633, destroyed eighteen houses and carried away six thousand trees in the Saasthal. It is worth while to call attention to the fact that the glacier floods traversing wooded valleys sweep off considerable quantities of trees, and then drop them in masses in regions where diminution in the slope causes an abatement in the current.

8. *Zufallferner (in the Ortler District).*—From 1887 to 1891 this glacier, with the concurrence of the Langenferner, has given rise to four bursts. The great decrease in the volume of glaciers in the second half of the nineteenth century has brought about in the upper valley of the Plima a topographical situation analogous to that of the glaciers of Otemma and Crête Sèche. The Zufallferner and the Langenferner, formerly united at their lower extremity, separated. In the open space left between the two glaciers, the waters issuing from the Langenferner formed two lakelets that flowed away below the terminal tongue of the Zufallferner, a tongue traversing the principal valley.

The Zufallferner having increased, thanks to the slight augmentation occurring at the end of the nineteenth century, stopped the outflow of the lakes, and a large sheet of water was formed behind this barrier.

The rupture of this dam caused sudden evacuations of the basin. In 1887 there was a first burst of no importance; in 1888 a second of somewhat greater force; in 1889 a third which proved disastrous; in 1891 a fourth, equally destructive.

These inundations have brought about profound modifications in the valley of the Plima. The torrent has changed its bed in the centre of the village of Gand, and has strewn over the valley enormous quantities of blocks and of detritus. "The floor of the valley is a sea of rocks" ("Die Thalsoble ist ein Steinmeer"), reports the *Mitteilungen des Deutschen und Oesterreichischen Alpenvereins*, 1891, Nos. 12 and 13.

9. *Vernagt Glacier (Oetzthal).*—This glacier, in periods of advance, chokes up the Rofenthal and, blocking the waters issuing from the upper part of the valley, forms a lake. An occurrence of this kind happened from the spring of 1600 to September 9, 1601, from 1678 to 1683, from November, 1771, to 1774, and from May,

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* *Dead glacier* is ice left behind by a retreating glacier, the melting of which is delayed by its heavy cloak of morainic material.

1845, to November, 1848. During these periods of stoppage, five terrible floods were produced; on July 20, 1600; July 16, 1678; June 14, 1845; May 28, 1847; and June 13, 1848.

In 1845 the Schlagintweits estimated the volume of the lake at 7·9 million cubic metres (1,738,000,000 gallons).

The rush of these enormous masses of water must have overturned all the Pleistocene formations in the Fendthal and Oetzthal. The destructive inundations made themselves felt as far as the valley of the Inn.

During the periods of the existence of the lake its basin has, on the other hand, been the seat of an important sedimentation. Prof. Hess has estimated the volume of matter deposited during the last stoppage at not less than 723,000 cubic metres.

A part of this matter has been carried away by the glaciers from 1845 to 1848, and the rest by the torrents, after they had resumed their normal course.

10. *Uebelthalferner.*—In periods of advance, this glacier chokes the Senner Eggenthal, and thus produces a lake and then glacier floods. Such an inundation occurred in 1847. Now, in consequence of the glacier's retreat, the opening of the Senner Eggenthal has been freed, and the lake has disappeared.

The great glacier extension which occurred in the Alps in the first half of the nineteenth century occasioned the formation of a great number of barrier lakes. Thus in 1817 the glacier of Zigiorenove threw itself across the Borgne, and thus caused the accumulation of a little sheet of water above the dam (Forel, "Les variations periodiques des glaciers des Alpes," VII^{e} rapport, in *Jahr. d. S.A.C.*, xxii. 1866). In similar conditions the glacier of Trift has likewise given rise to a reservoir (*Jahr. d. S.A.C.*, ii. 1865, p. 61).

In any case, there is no doubt but that an exploration of the glaciers in Switzerland and in France * by scientists, and a search in the local archives, would bring to light a much greater number of such inundations than are at present known. So last summer Prof. P. Girardin discovered that during the first quarter of the nineteenth century, an advancing glacier of the valley of Champagny damned the torrent and formed a great lake. The rupture of the dam caused a terrible outburst. Traces of the lake and of the inundation are yet apparent.

II. *Floods caused by the Outflow of a Lake, independently of Glacier Variations.*

1. *Lac du Tacul*: Situated at the junction of the glaciers of Leschaux and Géant, at the northern base of the Pic de Tacul, this lake has occasioned floods at the lower extremity of the Mer de Glace ('Travels through the Alps,' by the late James Forbes. New edition revised and annotated by W. A. B. Coolidge, p. 85. London: A. & C. Black, 1900). On August 13, 1819, this Lac du Tacul gave rise to an inundation in the Valley of Chamonix (Delebecque, 'Les Lacs Français' (Paris, 1898), p. 250).

2. The *Gorner See* (not the tarn on the Gorner grat, but a pool at the base of Monte Rosa itself) causes by its evacuation an increase in the volume of the Visp. On August 23, 1900, the outflow of the lake poured into this torrent a flood of water which swept away a bridge and covered the fields with stones. The passage of this mass of water below the glacier must cleanse its bed of most of the detritus contained in it and carry it to the extremity of the glacier.

3. *Glacier of Hochbalmen.*—This glacier during the summer of 1755 gave rise

* Thanks to the late Prof. E. Richter's, of Graz, valuable book, 'Die Gletscher der Ostalpen,' on the Austrian alps, the local topography of the glaciers are better known than elsewhere.

to two floods caused by the discharge of a lake formed by it. These floods swept away a moraine and covered the cultivated lands with sand and rubbish ('Die Chronik des Thales Saas für die Thalbewohner, bearbeitet und herausgegeben von Peter Joseph Ruppen').

4. *Märjelen See.*—From 1813 to 1900, nineteen sudden evacuations of this lake under the Aletsch glacier have been recorded. In 1873 10,000,000 cubic metres (2,200,000,000 gallons) flowed away in eight hours. Such was the force of the torrent in boring itself a passage under the Aletsch glacier that jets of water burst forth through the openings of the crevasses. In 1878, 7,770,000 cubic metres (1,709,400,000 gallons) escaped in nine hours. It is evident that the passage of these masses of water must have to a considerable degree eroded the bed of the Aletsch glacier and the ravine of the Massa, the torrent issuing from its base.

5. *Glacier of Gurgl (Tyrol).*—The lake formed by the stoppage of the Langethal due to this glacier gave rise to a flood on June 30, 1717. Three hundred years previously, as reported by tradition, the Gurglerferner caused a formidable inundation brought about in the same way ('Forschungen zur deutschen Landes und Volkskunde,' vi. 4; E. Richter, 'Urkunden über die Ausbrüche der Vernagt und Gurglergletscher im 17 und 18 Jahrhundert.' Stuttgart: Engelhorn, 1892).

III. *Floods caused by Reservoirs situated on, under, or in the Glacier.*

1. *Glacier of La Rechasse (Savoy).*—In the night of September 5–6, 1899, the torrent escaping from this glacier suddenly deserted its usual mouth of outlet to issue thenceforth at a spot 300 metres (1000 feet) further off. It is impossible that the water can, in a single night, have scooped its way through a mass of ice 300 metres (1000 feet) thick. It is likely, therefore, that a network of sub-glacial passages existed at the lower extremity of the glacier of La Rechasse, and that no more was required than the rupture of one partition to divert the torrent into a new channel. This phenomenon was the reproduction on a small scale of that of St. Gervais. This hydrographic change has, of course, overthrown the moraines situated in front of the torrent's new mouth of outlet.

2. *Glacier de la Tête Rousse (Mont Blanc Chain).*—This little glacier, in the nights of July 11–12, 1892, sent forth a mass of water estimated at 200,000 cubic metres (440,000,000 gallons), producing the well-known terrible catastrophe of St. Gervais. The flood rushed with a mean speed of 50 kilometres (31 miles) an hour.

The burst widened the bed occupied by the torrent of Bionnassay, levelled part of the moraine of the Bionnassay glacier, carried away all the blocks it encountered on its passage, several of 200 cubic metres, and deposited the whole cargo, estimated at 1,000,000 cubic metres, either in the lower part of the valley of St. Gervais, where the slope diminished, or in the valley of the Arve by the village of Le Fayet.

3. *Glacier des Bossons.*—Every four or five years, according to the report of the inhabitants of Chamonix, the eastern part of this glacier gives rise to small bursts due to the outflow of sub-glacial reservoirs. On August 11, 1892, a relatively strong glacial flood was produced, which carried away a great mass of gravel and pebbles ('Ministère de l'Agriculture, Administration des Eaux et Fôrets; Exposition universelle internationale de 1900 à Paris; Les torrents glaciers,' per M. Kuss, Inspecteur des Eaux et Forêts, p. 42. Paris: Imprimerie Nationale, 1900).

4. *Glacier des Pelerins.*—According to the information which M. Henri Vallot was good enough to supply me, the small frozen sheet of water situated directly under the Aiguille du Midi and commanding Pierre Pointue gave rise to a little burst in 1898. The flood carried away the vegetation, laid bare the fixed rocks, and swept off trains of small stones and gravel.

5. *Glacier de la Neuvaz.*—On June 22, 1898, a small burst of no importance was caused by the outflow of a glacier-pocket pool. Its action, however, resulted only in the transport of sand and mud.

6. *Glacier of Festi.*—On August 1, 1899, the breach of a glacier-pocket pool caused a sudden swell in the torrent which, in consequence, carried away great blocks of stones (F. A. Forel, M. Lugeon, and E. Muret, "Les variations periodiques des glaciers des Alpes," XX^e rapport, 1899, in *Jahrb. d. S.A.C.*, xxxv. p. 215). In 1875 Sir Martin Conway witnessed a sudden swell of this torrent, connected, in all likelihood, with the evacuation of a glacier reservoir.

7. In 1899 *Zmutt glacier* set loose a flood capacious enough to cause at Sion a rise of 0·5 metre (1·64 foot) in the level of the Rhône (see authority last cited, p. 216).

8. *Glacier de Hohberg.*—On August 21, 1898, a pool of water in the interior of this glacier burst. The flood carried away a part of the moraine, swept off blocks of 50 to 60 cubic metres (*circa* 1760 to 2120 cubic feet), cut the railway from Visp to Zermatt at two points, and in both places covered the line with a layer of materials 2·5 metres (8·2 feet) deep, comprising blocks of 2 to 3 cubic metres (70 to 106 cubic feet) each (see authority previously cited, XIX^e rapport, 1898, in *Jahrb.* xxxiv.).

9. Every year the *glacier of Puntaiglas* (Tödi) swells the torrent it feeds. For twelve hours the waters continue to rise, making off with heavy materials. Thereafter they again subside.

10. *Schwenser Ferner* (*Oetzthal District*).—On July 9, 1891, the Schwenser Ferner gave rise to a flood, consequent on the evacuation of superficial cavities 35 to 40 metres (115 to 131 feet) long, and about 20 metres (65½ feet) broad. Inconsiderable mass of water though it was, it yet wrought great damage by reason of the rapidity of the slope down which it rushed. The Langgrubthal, a dale situated below the Schwenser Ferner, was covered with stones. The torrent, moreover, exerted erosive force on the banks and caused displacements. It further brought about changes in the disposition of its bed above Kurzhof (observations of Dr. Greim).

Besides the cases above enumerated, Alpine publications record various outbursts of water discharged by glaciers, the information about which is not sufficient to enable them to be traced to their causes. Thus in 1850, according to the testimony gathered by Prof. Forel (F. A. Forel, "Les Variations periodiques des Glaciers des Alpes," XIV^e rapport, 1893, in *Jahrb. d. S.A.C.*, xxix., 1894), the glacier of Tré-la-Tête appears to have given rise to a strong flood. In 1866 that of Macugnaga likewise caused an inundation, destroying a part of the moraine and covering the mountain pastures with enormous blocks of stone and with sand ("Excursion dal 1886 al 1868. Notizie dell ingegnere Felice Giordano," in *Boll. del C.A.I.* (Turin, 1868), 2 Sem. No. 13, p. 282). In 1892, again, the glacier of Weingarten on the Simplon likewise gave rise to a sudden rise in the torrent, which swept down an "enormous mass of materials" (F. A. Forel, as above cited, XIII^e rapport, 1892, in *Jahrb.* xxviii.) and destroyed the Simplon road and several chalets.

The number of floods produced by the outflow of glacier reservoirs is undoubtedly much greater than the list above adduced. It is only within the last ten years that these phenomena have been noticed. Moreover, as very frequently they devastate only the high pasture lands, they often escape attention and record.

Norway.

The great increase in the volume of Norwegian glaciers which prevailed in the first half of the eighteenth century, causing an advance on their part of 2 to 3 kilometres (1·24 to 1·86 English mile), must have given rise to numerous barrier-lakes, and consequently to frequent floods. The facts, however, have not been noted. We must therefore restrict our investigations to more recent inundations.

I. *Floods produced by Evacuation of Border or Barrier Lakes.*

1. In the Lyngenfjord chain the *glacier of Strupen* forms a border lake, similar to the Märjelen See, 1600 metres (5248 feet) according to some, 3000 metres (9840 feet) according to others, in length, and 800 metres (2624 feet) broad. On July 17, 1898, Messrs. Slingsby, Hastings, and Haskett-Smith discovered this basin, and found it full (W. Cecil Slingsby, "Mountaineering in Arctic Norway," in *Alp. J.*, May, 1899). A few days later it was found to be empty, the waters having run away under the glacier. This outflow must have produced in the lower valley, if not a flood, at least an inundation. Since, however, this lower valley is uninhabited, the event passed unobserved. Similar evacuations must happen frequently enough, as at the Märjelen See, causing erosions and transport of material.

2. The *glacier of Melkedal* (Jotunheim) blocks a lacustrine valley, open at its base, and separates Övre Melkedalsvand from Store Melkedalsvand. From time to time Övre Melkedalsvand breaks through the ice-dam and causes a burst. An accident of this nature happened in 1855 or 1856, in 1879, in 1894, and on August 11, 1901. The rush of water sweeps away all the land and vegetation in its course, and rolls down blocks as "large as houses."

3. The *Rembesdalskaak*, a branch of the Hardangerjökull, in the same manner as the Strupen, causes a border lake, and called the Dæmmevand. Whenever its evacuation is brought about suddenly, it produces floods in the lower valley, the Simodal. Such an occurrence happened in 1891, 1892, and 1893. The inundation of 1893 was particularly terrible. "Everything the torrent encountered on its course—bridges, trees, blocks of stones—were swept off and scattered in the valley. The trees along its line of route were torn up and borne away. Prairies and natural-grass lands were, in places, covered with great blocks. The Simodalsfjord, into which the torrent empties, became, it is said, so filled with floating wood that the mail steamer had to describe a semicircle round the obstruction, and was unable to put in at the entrance of the Simodal (Vibe, 'Söndre Bergenhus Amt.,' p. 244 : Kristiania, 1896).

II. *Floods caused by Evacuation of Reservoirs situated on, or in the Interior of the Glacier.*

1. On July 1, 1904, in the district of Lunde, M.E.A. Martell saw an avalanche of ice fall from the upper portion of the Jostedalsbræ. Through the gaping hole left by the severance of the ice there burst forth an enormous waterspout. This is a conclusive proof of the existence of sub-glacial or glacier-pocket reservoirs (E. A. Martel, "Ruptures de poches d'eau des glaciers," in *La Nature*, Paris, No. of 25 Mars 1895).

2. In 1900 and 1903, the *Tunsbergdalsbræ* produced a great flood caused by the outflow of a sub-glacial lake. This sheet of water is formed under a tributary of the Tunsbergdalsbræ, the Store Brimkjedlebræ, at the junction of the two glaciers. It is probable that the bed of the Store Brimkjedlebræ presents a depression favouring the union of the waters. The formation of the lake is a consequence of the actual retreat of the glacier. The Store Brimkjedlebræ being no longer able to fill up the depression it formerly occupied, the void thus left by it is occupied by the waters in question.

The inundation of 1900 has caused a displacement of the junction of the torrent (Tunsbergdalselv) with the main watercourse in the Jostedal valley, the junction being situated 15 kilometres (9 miles) from the glacier. The floods have done no more than transport mud and gravel (J. Rekstad, "Opdæmning ved Tunsbergdalsbræen, i Sogn," in *Naturen*, Bergen xxv., No. 3, March, 1901, and xxviii., No. 1, January, 1904).

III. *Floods the Causes of which are unknown.*

1. The *Kvalvikselv*, fed by the glaciers of the Ruksisvagge and of the Goalssevaggegaisse (Lyngenfjord), sometimes undergoes sudden swellings ('Beskrivelse af Tromsö Amt.,' p. 10: Christiania, 1870).

2. The glacier of *Vetlefjord* (Jostedalsbræ) gave rise in 1820 to a flood which overturned and scattered the moraines and destroyed the forests and dwelling-places in the valley. In 1868 the traces of this catastrophe were still discernible (C. de Sene, 'Le Névé de Jostedal,' p. 10: Christiana, 1870).

3. Towards 1830 the glacier of Kjærringbotn (Folgefond) discharged a flood of water which covered the banks of the torrent with gravel, sand, stones, and blocks of ice (Sexe, 'Om Snebræen Folgefond,' p. 15: Christiania, 1864).

4. In 1857 the *Buerbræ* (Folgefond) launched a similar mass of water (see authority last cited).

5. In 1893, the *Riingsbræ*, on the Horungtinder, was pierced at its lower extremity by a long tunnel. The natives ventured into this cavern to a distance of several hundred yards, when they were stopped by a deep body of water (W. Cecil Slingsby, "New Expeditions in 1894, Norway," in *Alp. J.*, No. 127, February, 1895). Perhaps it had given passage to an outburst.

ICELAND.

The glaciers of Iceland, the most extensive in Europe,* produce floods so terrible and so frequent that the Icelandic language has a special word, *jökulhlaupt* ("glacial outbreak"), to denote this phenomenon.

The "Jökulhlaupt" are the products of phenomena of two different kinds. Several Icelandic *ice-caps* are pierced by volcanic craters. When one of these volcanoes is in eruption, it dislocates the glacier, melts it, and causes the outflow of veritable deluges of ice, water, and blocks of stone. By the side of these "Jökulhlaupt" of volcanic origin, there are others of sufficient frequency, plainly of glacial origin, produced by the outflow of barrier or border lakes or glacier reservoirs. These floods, though less powerful than the volcanic Jökulhlaupt, are yet, in a singular degree, more important than those produced in the Alps. So frequent are such outbursts, that Sveinn Pálson, an Icelandic scientist, who observed very accurately the glaciers of Iceland from 1792 to 1794, names these floods ordinary jökulhlaupt, and the volcanic jökulhlaupt extraordinary jokulhlaupt.

Dr. Thoroddsen, the eminent Icelandic geologist, and the man most conversant with this island, enumerates the following glaciers as productive of glacial "jökulhlaupt":—

(1) *Solheima Jökull* (massif of the Myrdals Jökull). The floods are due to the outflow of a *Randsee* (or border-lake). They often occur several times in one summer. "The flood of water levels the moraines and transports their materials into the bed of the torrent, which sweeps off to the sea an enormous mass of gravel, drift-ice, and vast blocks" (Thoroddsen, "Rejse i Vester-Skaptafells Syssel paa Island i Sommeren 1893," in *Geogr. Tidsk.*, 1893–1894, xii. 7, p. 171).

* The most extensive glacier, the Vatnajökull, has an area of 8500 square kilometres (3281 square miles).

(2) The south-west branch of the Vatna Jökull, which feeds the Djupa, likewise gives rise to floods, consequent on the evacuation of a border-lake.

(3) A lake situated on the same glacier, at the foot of a *nunatak*, also produces inundations.

(4) The Skeidarar Jökull (south slope of the Vatna Jökull), when swelling, bars the courses of the Sula and the Nupsa, and causes the formation of barrier-lakes, and consequently of outbursts. In 1892 this glacier launched a frightful "jökulhlaupt," due, in the opinion of Thoroddsen, to the outflow of enormous masses of water contained in the interior of the glacier or on its surface. The flood wrenched considerable projections from the Skeidarar Jökull, and covered with drift-ice large spaces between the glacier and the sea. At one point these formed a barrier 7 kilometres (4·35 miles) broad. Many of the blocks had a height of 15 to 20 metres (49 to 65½ feet). This mass of ice, blackened with sand, gravel, and lumps of rock, looked like a lava torrent. The inundation affected a territory of 600 to 700 square kilometres (231 to 270 English square miles). Consequent on this burst, several watercourses changed their direction" (*vide* Thoroddsen, 'Rejse i Vester-Skaptafellsyssel,' p. 196).

(5) The Breidamerkur Jökull gives rise to barrier lakes, the sudden outflow of which produces floods.

(6) Another branch of the Breidamerkur Jökull, which feeds the Jökulsá da Breidamerkursandi, gives rise to "jokulhlaupt" (Sveinn Pálsson, "Försog Til en Physisk Geografisk, og Historiske Beskrivelse over de islandske Is-biœrge, I Anledning af en Reise til de fornemeste deraf i Aarene 1792 til 1794," in *Den Norske Turisforenings Aarbog* for 1882, p. 37: Kristiania).

(7) The eastern branch of the Heinabergs Jökull, barring a lateral valley, forms a lake, and, on the breaking through of the glacier dam, a flood. Near the torrent the sand shows circular cavities hollowed out by the melting of the blocks of ice carried away and stranded by the flood (Thoroddsen, "Fra det sydöstlige Island," in *Geogr. Tidsk.*, xiii., 1895–1896, 1 and 2, p. 8).

(8) On the north-east slope of the Vatna Jökull, the variations in length of the glaciers cause the formation of extensive barrier lakes, the evacuation of which is not brought about without floods (Thoroddsen, 'Islands Jökler i Fortid og Nutid,' p. 16, separate impression).

The whole area lying between the Vatna Jökull and the sea, as also the coast land to the south-east of the Myrdals Jökull, is composed of sand, in great part of glacial origin. The "Jökulhlaupt," passing through this territory of characteristically loose build, are incessantly overturning its soil. In one case, moreover, they hurl into the sea enormous masses of heavy material. These constitute the understratum of new deposits to be added to and built up by slow stages. The "Jökulhlaupt" are thus one of the most powerful agents in the formation of these lowlands.

Spitsbergen.

During the few weeks of the Arctic summer, from June 15 to August 15, the glaciers of Spitsbergen generally, but especially those in the western part of the archipelago, are subjected to intense fusion. As we are told by Sir Martin Conway and Prof. E. J. Garwood, the glaciers are furrowed by copious torrents, floating large masses of melting snow. There is accordingly a superabundance of water for the formation of barrier and border lakes, as also of numerous sub- and intra-glacier pools, which in emptying themselves give rise to floods. In the interest of the science of glaciers, the explorations of Sir Martin Conway and Prof. Garwood have therefore been specially important. On the Nordenskiöld glacier, as also those in the neighbourhood of King's bay, these travellers encountered frequent border lakes and surface glacier pools, and have determined the effects of their floods. These effects consist mostly in the transport of glacial materials, their transformation, and their accumulation at certain points. Thus the outburst of a border lake on the King's glacier carried away into the ice-tunnel by which it emptied itself, rubbish and materials belonging to moraines. "The direction of this channel was at right angles to the main lie of the valley, so that, on the valley becoming free of ice as the climate ameliorated, this water-worn glacial material would be deposited as a gravelly ridge running roughly at right angles to the valley and forming a kame" ("Additional Notes on the Glacial Phenomena of Spitsbergen" in *Quart. Journal of the Geological Society*, November, 1879, lv. p. 686). This observation of Prof. Garwood's is very important, and should cast distrust on the method which consists in diagnosing the origin of Pleistocene substances according to their facies.

Greenland.

On the west coast of Greenland, up to 72° 25′ N. at least, the inland ice experiences, from the first half of June to the beginning of September, an ablation of the most intense kind, resulting in the formation of a very great number of glacial torrents and of glacier surface lakes. The surface of the inland ice is, so to say, cut up with watercourses, which leave between them hillocks of ice. It looks like an archipelago divided by a network of canals. The maps of the border of the inland ice, again, prepared by the Danish officers, show the frequency of border lakes in this region. All the conditions, therefore, are present for the production of frequent floods. If we hear but seldom any mention of this phenomenon in Greenland, the reason is that, the country being, so to say, a desert, such inundations mostly pass unobserved. The accounts of Danish explorers, who within the last twenty-five years have studied the western skirts of the inland ice, leave no doubt as to the frequency of this phenomenon. Jensen, for example, reports that the Tasersuak, barred by the ice of Frederikshaab, will produce outbreaks ('Meddelelser om Grönland,' i. p. 43: Copenhagen); how such floods are also produced by two lakes to the east of Godthaab (*ibid.*, viii. p. 88), and by a fourth basin situated on the inland ice to the east of Strömfjörd, 66-67° N. (*ibid.*, viii. p. 66). One day, reports this officer, Eskimos were hunting in a valley beneath the inland ice. Suddenly the torrent began to swell, inundating the valley and drowning one of the hunters. Another time the inundation of a torrent issuing from the inland ice, probably caused by the yielding of a glacier-barrier, carried away four oumiaks (Greenland boats), which their owners had drawn up on the dry land a long way from the river ('Meddelelser om Grönland,' i. p. 132). These accounts prove the existence of glacial floods in Greenland.

Alaska.

Hitherto no glacial outbreaks have been reported from Alaska, but that is no reason for assuming that none occur. In fact, the reservoirs necessary for the production of such inundations are very abundant in that region; barrier and border lakes, as also glacier lakes proper. One of the affluents of the Stikine river, for example, is obstructed by a glacier. After noting this topographic fact, Prof. Israel Russell adds that basins of water of this kind are common in the region lying farther to the north ("The Glaciers of North America," in the *Geogr. Journ.*, xii., December 6, 1898, p. 558). One of the branches of the Muir glacier forms a barrier-lake 6·5 kilometres (4 English miles) long and 600 metres (1968 English feet) broad. Between the Chaix and Hitchcock hills and the Malaspina glacier are numerous border lakes. What happens in the glacier *massifs* of the rest of the world must likewise happen in Alaska—glacier floods. The lakes in Alaska empty themselves frequently, and in emptying themselves they cause glacier outbursts.

THE HIMALAYA.

The high valleys of the Western Himalaya and the Karakoram are, as is well known, traversed by torrents of mud, called by the natives of Baltistan "shwas," and analogous to the torrential "lave" of the French foresters in the Alps. If in many cases these "shwas" are due to the dilution of glacial mud, encumbering the high Himalayan valleys, with the melting from the snow and ice, they are also very frequently produced by glacier outbreaks, properly so called. On this last point, all the explorers of the Kashmir glaciers—Colonel Godwin-Austen, Sir Martin Conway, and Prof. Norman Collie—are agreed. In these regions inundations produced by the outflow of glacier lakes are extremely frequent, and to be regarded, not as an accident, but rather as a normal occurrence.

I. *Floods caused by a Barrier-lake due to Glacier Variation.*

The high valleys of Kashmir are, in general, very narrow, and their lateral crests, from the great altitude they attain, are clad in extensive glaciers. As often, therefore, as the lateral glaciers make a rapid advance, they bar the principal valley, and there give rise to the formation of lakes, which, in turn, produce floods. Such is the situation in the case of the glacier of the Tashing, which in 1850 blocked the valley of Rupal (Norman Collie, 'Climbing in the Himalaya and other Mountain Ranges.' Edinburgh: Douglas, 1902). Such is equally the case with the great glacier of Biafo. This latter glacier, when in advance, closed the valley of Braldoh, and led to the formation of a barrier-lake of "several miles long," the sudden outflow from which produced a terrible flood. It was to an inundation of this kind, in all likelihood, that was due the destruction of a village reported by local tradition. The inhabitants, when relating the event to Godwin-Austen in 1861, referred its date to two centuries before that time.

II. *Floods caused by Lakes independent of Glacier Variations and by Glacier Lakes.*

The great glaciers of the Karakoram—the Baltoro, Biafo, Hispar, etc.—are, together with the Seward of Alaska, the greatest ice-streams of the Alpine type at present in existence. These enormous streams, 50 to 68 kilometres (31 to 42 miles) long, have a very gentle slope, averaging 3·5°. The lower limit of the *névés* is accordingly found at a very great altitude, 5700–5800 metres (18,696–19,024 English feet) on the Baltoro in 1902 (Dr. Jacob Guillarmod, 'Six mois dans l'Himalaya.' Sandoz, Neuchâtel). A vast surface of ice thus lies exposed to fusion, a fusion all the more intense inasmuch as the climate is very hot. During his stay of nine weeks on the Baltoro, Dr. Jacob Guillarmod found the daily maximums invariably above 32° Fahr., and frequently saw the thermometer mount to 68° Fahr., as also four times to 95° Fahr. Under these conditions, the melting is very rapid, and consequently the glaciers of the Karakoram are furrowed by numerous and powerful torrents, while beside their banks flow copious watercourses. These rivers give rise to numerous border and glacier surface lakes.

On the Hispar, Sir Martin Conway reports frequent surface sheets of water. On the glacier of Punmah, Godwin-Austen encountered several surface glacier lakes, and also border lakes. In 1861 the Baltoro comprised numerous surface basins 450 metres (1476 English feet) long by 60 to 90 metres (196 to 295 English feet) broad. On the passage of the Conway Expedition of 1892, these bodies of water were no less abundant than in 1861. In 1902, Dr. Jacob Guillarmod record the presence of frequent border and glacier surface lakes. The phenomenon is therefore a constant occurrence on this glacier.

It appears that the great glaciers enclose, besides, glacier pocket reservoirs. Twenty-two kilometres (13½ English miles) from the front of the Baltoro, M. Guillarmod found a basin of considerable dimensions, which had emptied itself by a fissure at the bottom. On one side of this basin there opened, in the thickness of the glacier, a cavity more than 30 metres (98 English feet) deep, which no doubt served as bed of an intra-glacier torrent.

Colonel Godwin-Austen noticed that the glacier surface cisterns often emptied themselves in a night, and then filled again very rapidly from the contributions of numerous inter-glacier drains. On the sides of these cisterns, he relates, are little holes, through which the water runs out as through so many taps.

On the glacier of Biafo, again, Mrs. F. Bullock Workman reports irregular openings, the diameter of which does not exceed the breadth of a human head, leading to profound abysses.

All these border and glacier lakes empty themselves at irregular intervals. The arrival of the floods of water at the lower extremities of the glaciers is a signal for the issue of torrents of mud. In the environs of the village of Tisir, in the valley of Basha, Godwin-Austen saw the fields covered with sand, detritus, and great blocks of stone, eight or ten houses buried, and great trees overturned. The disaster was the effect, so the natives told him, of a flood caused by the sudden evacuation of a glacier lake. Whoever has not witnessed one of these floods, writes this admirable observer of glaciers, can form no idea of the transporting power of those masses of water and melting snow.

The floods level the moraines, sweep away their materials, push before and with them all the blocks of stone they encounter, and carry off an enormous mass of mud. There is no need, however, to exaggerate the power of these phenomena. Their effects are strictly limited to the valley bottoms. Godwin-Austen estimates the breadth of the "shwa" he witnessed at 27 metres (88·58 English feet), and its depth at 4·5 metres (14·76 English feet). Conway reckoned the "shwa" he witnessed at 12 metres (39·37 feet) broad.

This long catalogue may show that glacial outbursts are produced in all regions covered with glaciers, and that their frequency is proportioned to the extent of the glaciers. In the Alps, where glacial phenomena are reduced to a very small compass in comparison with their development in the Karakoram, Alaska, Spitsbergen, and Greenland, no less than nineteen such outbursts have been duly authenticated since 1890.

These inundations exert considerable erosive power, modify markedly the line of the valley bottoms they follow, in the way both of enlargement and of displacement. They also exert important transporting force, displacing great blocks and carrying away enormous masses of mobile material, which they accumulate at the mouths of glens opening into the principal valley, and at points where the slope suddenly lightens. Consequently, in the valleys subject to these phenomena the actual glacial formations are transported to a distance, and receive a new facies, while the Pleistocene deposits are refashioned throughout the whole zone touched by the inundation. It has to be further observed that the floods destroy the forests they overtake, and deposit enormous quantities of wood on the places where they stop or lose velocity. The catastrophe of Giétroz in 1818, for example, floated into the valley of the Rhône vast masses of wood. A part of it was derived from the destruction of a great number of chalets. The inter-glacial lignites might be traced to this origin.

The action of bursts may be compared to that of the shoots of water artificially produced in some of the ports on the French coast of the English Channel, in order to clear their entrances of pebbly obstructions and throw them back into the deep sea.

These inundations must have been produced in the Glacial period under the same conditions as to-day in Greenland and other Arctic regions. This being incontestible, it is in our opinion proper to observe a very great reserve in determining the origin of the Quaternary formations. In a number of cases geologists are certainly in error in attributing exclusively to glaciers formations which are the combined product of glaciers and of running waters. The "fluvio-glaciaires" deposits cover a greater surface than "formations glaciaires" properly so called. The part played by floods issuing from glaciers has hitherto been too much neglected. Now, in our opinion the part played by such waters is considerable. The water circulating under the glacier is charged with mineral particles. It is thus a particularly active agent of erosion. When it runs in a broad bed, the water acts as a polisher; perhaps many *roches moutonnées* result from this effect of the glacial waters; when enclosed in a ravine, it acts as a saw; lastly, when a great flood of water is produced, it transports to a distance materials supplied to it by the glacier, and with these materials it fills all the depressions it meets.

We must not, however, go from one extreme to another, and we must guard against exaggerating the effects of glacial outbursts. In the present epoch they affect only the banks of the river-beds and the lower parts of the valleys; during the Quarternary period their power was also limited to the valley bottoms they followed.

NOTE.

By Douglas W. Freshfield.

M. Charles Rabot's article, and the copious statistics with which it is accompanied, will, I trust, fulfil his object by attracting the attention of glaciologists, geologists, and travellers to the class of catastrophes which he describes. Heim has well compared a glacier to a sledge, which, picking up the heavy burden entrusted to it by the forces that split the mountain cliffs, carries down its load slowly to the valleys. We may, perhaps, compare these torrential outbursts to a motor car, which, catching up a portion of the packages, whirls off with them to the spot where the diminution of the slope puts an end, if not to its own progress, to its carrying power. I tread with trembling on the confines of geology, but I shall hardly be wrong in endorsing M. Rabot's argument that the effects of these outbursts in past times of more extensive glaciation in the Alps must have been on a scale vastly in excess of what we witness to-day, and that sufficient attention has not hitherto been paid to them as agents in earth-sculpture. Is it not possible that a certain number of the more lowlying so-called "erratic blocks" may have been caught up by these floods and carried to their present positions? The suggestion seems at least worth considering. I should further like to point out the undesigned coincidence of M. Rabot's reference to the saw-like action of subglacial torrents with a passage in my address, printed in the October number of the *Journal*.

I am unwilling to add to the length of M. Rabot's valuable and suggestive paper. I will, therefore, only mention here, without going further into detail, the two very important catastrophes recorded in recent times in the Caucasus: the periodical outbursts proceeding from the Devdoraki glacier under Kasbek in the middle of the last century, which on more than one occasion destroyed the Dariel road, and the great flood of the torrent of the Gezel Don glacier in the same district in 1892. In the Sikhim Himalaya under Kangchenjunga I did not discern any traces of changes brought about by the sudden collapse of lakes, the origin of which was due, in one way or another, to glacial action. There was no scarcity of glacial surface lakes and barrier lakes, but, owing partly perhaps to the warmth and perennial rainfall, they appear to drain themselves in a less spasmodic manner.

THE INDIAN EARTHQUAKE.

On April 4 a severe shock of earthquake visited northern India, doing an immense amount of damage, principally at Lahore, Mussuri, and Dharmsala, and causing a lamentable loss of life. At Lahore the cathedral was seriously damaged, as well as the Juma Masjid, one of the finest mosques in India, and many other buildings, both public and private. Some loss of life occurred here, but this was far exceeded at Dharmsala, where both the cantonment and civil station were practically destroyed, many Europeans being among the victims. Owing to the collapse of the stone-built barracks, the Gurkha regiments, especially the 7th Gurkhas, suffered terribly, no fewer than 470 in all being killed. At Kangra three European missionaries were among the victims. Other places at which damage was done were Delhi, Amritsar, Dehra Dun, Amballa, Simla, and Srinagar, though at none of these was the loss of life exceptionally high. The disastrous shocks, which seem to have been repeated several times, occurred in the early morning of the 4th, but further slight shocks are said to have been felt during the following night.

The following remarks are made by Mr. R. D. Oldham:—

The telegraphic reports enable us to form an approximate idea of the magnitude of the earthquake. It undoubtedly ranks as a great earthquake, whose violence exceeded 10 degrees—the maximum of the accepted scales of earthquake classification—over a considerable area, but it was far from coming up to that of 1897 either in extent or violence. It is too soon to form an estimate of the latter, but the extent of country over which it was felt cannot have been more than one-quarter of that affected in 1897, though the death rate was probably more than four times as great. The focus evidently lay in the Kangra valley, or between it and the Dhaoladhar range, but, if newspaper accounts are to be trusted, the shock seems to have been more violent at Mussuri than would have been anticipated, and this suggests the possibility that it originated in a movement along the great boundary fault of the Himalayas; it will be interesting if the investigation, which we may trust the Indian Government to make, should establish a renewal of movement along this great structural feature which has played an important part in the elevation of the Himalaya.

The following comments on the earthquake have been sent by Dr. Charles Davison:—

At or shortly after 6 a.m. on April 4 North-West India was visited by one of those great earthquakes which not only devastate extensive areas, but give rise to undulations that are recorded by seismographs in every part of the globe. During the previous night two slight shocks were felt at Mussuri, and probably also at other places; but the great earthquake itself occurred so suddenly and with so little warning that most of those indoors were unable to escape. The position of the epicentral district is still unknown, but it probably includes the towns of Dharmsala, Kangra, and Palampur, which are situated about 160 or 170 miles