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ICE-DAMMED LAVAS FROM CLINKER MOUNTAIN, SOUTHWESTERN BRITISH COLUMBIA

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ABSTRACT. Lava flows from Clinker Mountain exhibit normal gradients and surface character wherever they came to rest at altitudes of more than about 4,000 feet, but distinctly anomalous features where they came to rest at appreciably lower levels. These anomalies include (1) precipitous, locally concave, terminal faces up to 1,500 feet high, subject to major landsliding, (2) unusual thickness of lava, as much as 800 feet in a single flow, and (3) accretion of lava as dribbles on at least one precipitous lava front. These anomalies are attributed to ponding of lava against the Cordilleran ice sheet at a time when it still filled valleys up to approximately the 4,000 foot level.

INTRODUCTION

VOLCANIC activity in close proximity to bodies of glacial ice has been demonstrated in Iceland (Nielsen, 1937; Noe-Nygaard, 1940) and in the Aleutian chain on Umnak Island (Byers *et al.*, 1947) and on Great Sitkin Island (Simons and Mathewson, 1947). Activity in glacial environments has also been inferred in Iceland (Peacock, 1926; Nielsen and Noe-Nygaard, 1936; Noe-Nygaard, 1940) and in British Columbia (Mathews, 1947, 1951b, 1952). Evidence suggesting the proximity of ice at the time of extrusion includes (1) the occurrence in the volcanic rocks of striated boulders, such as could have been dropped from the overlying glacier, plus the widespread development of breccia and pillows attributable to rapid quenching in meltwater or in water-soaked pyroclastic rocks under the ice, or (2) abnormal structures indicative of extrusion into standing meltwater or against ice, together with conformable relations with glacial till. The products of the volcanic activity may be described as *subglacial* if laid down entirely beneath the ice, as *intraglacial* if surrounded on all sides but not covered by ice at time of deposition, and as *supraglacial* if deposited partly or entirely

on the surface of the ice. Still a fourth class can be inferred, that in which the volcanic products are deposited against the margin of the ice. An example from the Mount Garibaldi map-area in southwestern British Columbia, the lava of Clinker Mountain, also known as Red Mountain and Mount Price, is believed to fall in the last-mentioned class. Geological investigation of this volcano indicates that the cone itself was built after the last Cordilleran ice sheet had receded from the uplands on which it was founded, for its surface exhibits the common characteristics of lava flows of subaerial origin, but little modified by weathering and erosion. However, where the latest flows from this volcano reached relatively low ground their termini exhibit such unusual thickness, steepness, and structure as to suggest that the lava had been impounded by the wasting ice sheet.

DESCRIPTION

The central mass of Clinker Mountain consists of a steep, truncated cone rising to an altitude of 6,721 feet, almost 2,000 feet above Garibaldi Lake which now laps against its northern flank (fig. 1). Its broad summit is marked by a shallow depression, the former vent. On the east, the lava buries an older glaciated cone or dome of buff-colored dacite. Quartz diorite is exposed at an altitude of 6,100 feet on the ridge southwest of Clinker Mountain and at an altitude of 5,500 feet at the southeast base of the cone. Though Clinker Mountain has been built almost on the crest of an older ridge, the relatively small bulk of the cone is enhanced by its long northern slope which extends not merely to the level of Garibaldi Lake (altitude 4,816 feet) but continues to a depth of about 800 feet below its surface. The form of the main mass of the mountain is complicated by two satellites, one a steep-sided cone on its northern slope, the other a breached ring on its southwestern shoulder.

Two lava flows, less conspicuous than the main cone itself as seen from the ground, but greater in both areal extent and volume, escaped from the southwestern satellite of Clinker Mountain. One of these flows swept down the northwestern slope of the mountain, spread out at its foot, buried the granitic upland and filled the neighboring valley of Rubble Creek to a depth of at least 800 feet, thereby creating the dam

which now ponds the waters of Garibaldi Lake. The other flow swept down the southern slope of the cone into the valley of Culliton Creek and thence westward for 3 miles. The head of each flow lies at a break in the crater wall of the southwestern satellite and though one flow may have breached the ring at a second point long after its counterpart had broken through the opposite wall, it seems more probable that the two flows emerged simultaneously from the common vent.

The southern flow descends from its source 1,500 feet in its first mile, then, sweeping west along the valley of Culliton Creek, it descends 500 feet in the next 1½ miles and 1,500 feet in the last mile of its course. On the slope of the cone the thickness of lava still remaining is small, possibly exceeding

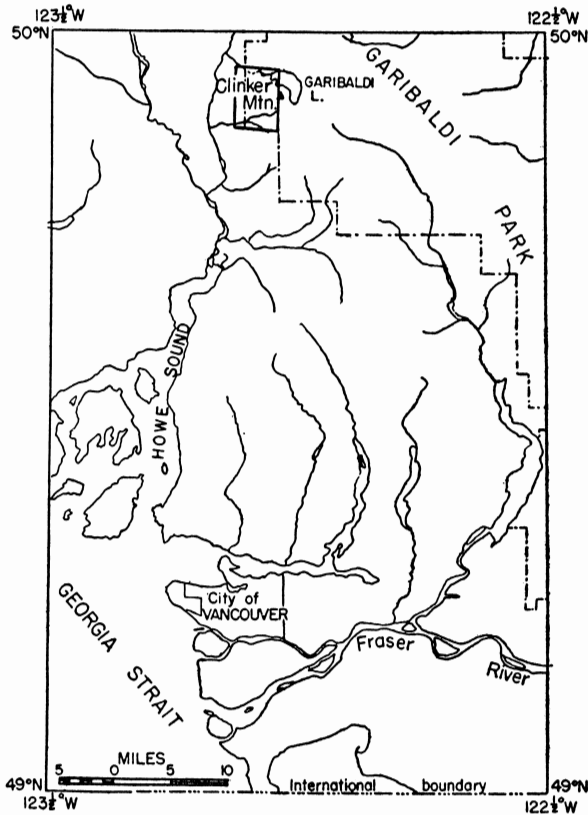


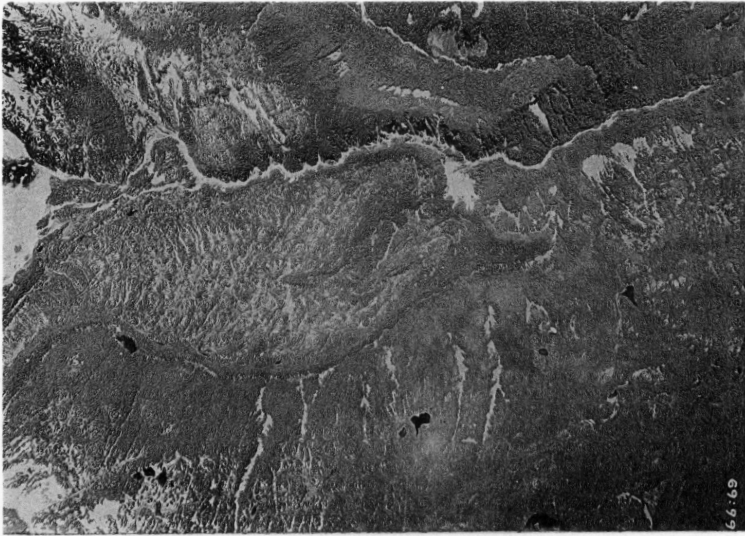
Fig. 1. Index map showing location of Clinker Mountain. Area covered by aerial photographs outlined with solid line.

200 feet only along the levees which here mark the lateral limits of the flow. In the valley itself the lava may locally attain a thickness of 1,000 feet, and it terminates in a scarp, now partly buried by talus, of almost this height. A subsidiary tongue of lava extends southwest from the main flow into the mouth of a large tributary valley. A second and smaller tongue extends for $\frac{1}{4}$ mile from the northern end of the main flow. The terminal face of the flow is thus distinctly concave. Culliton Creek has now cut through the southern lava tongue in a sheer-walled canyon about 800 feet deep and roughly 550 feet wide at its brim. This creek has sapped part of the lava front (plate 1) but the steep terminal face appears to be essentially an original feature. Relics of the flow are not found along the valley floor or on the lower slopes of the valley walls below the present terminal scarp. Both the shape and the height of the terminal face are distinctly anomalous.

The drainage disturbance brought about by this flow is clearly apparent. Above the point where the flow joins the valley, the valley floor is broad, underlain in part by a flat outwash plain aggraded by the heavily laden stream leaving the north part of Warren Glacier and in part by hummocky moraine burying stagnant ice left by the south half of this same glacier. The recent ravine of Culliton Creek leaving this part of the valley follows the contact of the flow with the south wall of the valley, becoming deeper with distance until the spectacular canyon near the end of the flow is reached. A more recent disturbance of drainage has been caused by the advance of Warren Glacier, probably in the early 1800's (Mathews, 1951a), and the construction of a terminal moraine which has diverted waters from the outwash plain onto the surface of the lava flow. A tortuous course is now followed by this stream over the flow for a distance of almost a mile. Dead and rotting stumps remain standing in its waters. A quarter of a mile west of the moraine a lava wall only 15 feet high separates the newly diverted stream from the much deeper valley to the south. The absence of any significant cutting by this stream after fully a century of occupation pro-

Plate 1. Stereoscopic aerial photos of southern flow from Clinker Mountain. Limits of the flow indicated by a dotted line where they are not obvious from topography.

British Columbia Government air photographs.



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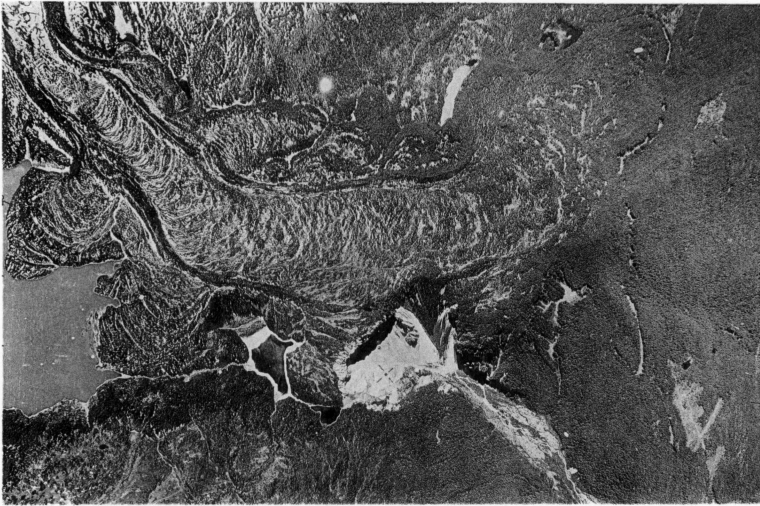
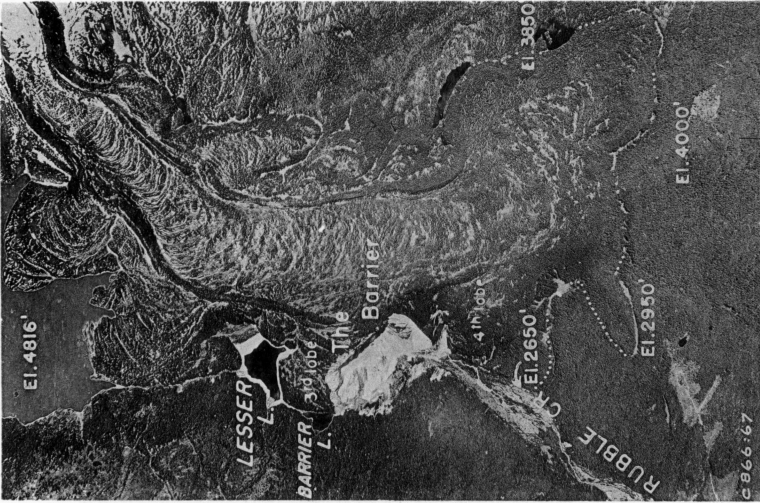
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vides a striking contrast with the deep canyon of Culliton Creek farther west and clearly indicates that the age of this canyon must be measured in thousands of years.

The main part of the flow on the northwest side of Clinker Mountain descends 1,100 feet in the first mile of its course and 1,500 feet in the remaining 2 miles. It ends in a convex rubble face 200 to 300 feet high, much like the flow termini of many of the more acid lavas elsewhere in the world but wholly unlike the terminus of the Culliton Creek flow only 2 miles to the south.

To anyone standing on the central part of the flow, its surface seems to consist of a totally irregular jumble of angular reddened blocks, some many feet in diameter, some teetering and some firmly lodged, some with several smooth faces, others scoriaceous throughout. Between these blocks are numerous cavities extending to unknown depths, some large enough to admit the entrance of a human, but many of a size that only small animals find shelter within them. The apparently complete chaos of this surface is resolved into several distinct patterns if seen from the air (plates 1, 2). The main lava stream, for example, is bounded by two conspicuous levees such as characterize many lava flows throughout the world. Each of the levees of the Clinker Mountain flow has from one to three crests which near its source rise as much as 300 feet above the flat-floored "trough" along the axis of the flow. The depth of this trough or "lava gutter" below the adjoining levees diminishes downstream until about a mile from the terminus the levees lose their identity and the upper surface of the flow extends without sharp break from one lateral margin to the other. The levees of the upper part of the flow, like the lateral walls in the lower part, have clearly been built by accumulation of blocky debris deposited along the flank of the flow and left, like lateral moraines, as the more fluid lava between them drained away. Downstream, where this fluid lava came to rest, the central part of the flow is filled to the level of its walls.

A pattern of low, closely-spaced arcuate wrinkles shows on

Plate 2. Stereoscopic aerial photos of northwest flow from Clinker Mountain. Limits of the flow indicated by a dotted line where they are not obvious from topography.

British Columbia Government air photographs.

the lava surface between the levees, each wrinkle convex downstream. This pattern evidently reflects the more rapid movement of lava in midstream than along the margins of the flow.

A series of lava lobes extends from the margins of the central flow on either side. The surfaces of these lobes are marked by concentric ridges like those within the central trough of the main flow. Several buckles in the otherwise continuous lines of the levees are situated at the foci of concentric ridges of several of these lobes and evidently mark the points where lava escaped from the central flow to form the lobes. With one possible exception, however, the levees are only bent, not breached, at these points and the lava from the central flow must have passed through, not over, its confining walls.

The form of the two main lobes on the south side of the flow was clearly influenced by the pre-existing topography, the lava spreading down valleys and into recesses. The lava did not, however, form a flat plain and though it entered the mouths of recesses it did not completely fill them, leaving, instead, hollows now occupied by small lakes.

Whatever effect the pre-existing topography on the north side of the flow may have had on the form of the lava lobes, the lobes themselves have played an important part in the development of the present topography. The easternmost lobe now appears as a conspicuous if low promontory extending for almost half a mile into Garibaldi Lake, and soundings reveal that the lava extends beneath the surface of the lake for another half mile. The next lobe to the west extends for about half a mile from the central flow and, coming in contact with the older rocks of the north wall of Rubble Creek Valley, it has created the dam which holds back the waters of Garibaldi Lake. Two of the low arcuate ridges on the east side of this lobe are now partly submerged by the water and give rise to a double chain of islets known locally as "The Battleships." A few scattered trees, standing like masts on these islets, accentuate the similarity to a fleet of naval craft. The third lava lobe also extended to the north wall of the valley and, in turn, formed a dam which holds back the waters of Lesser Lake and, by blocking a tributary valley from the north, it created still another and smaller body of water, Barrier Lake. To the west of the outlet of Barrier Lake the face of this lobe and the north wall of the valley diverge and no other body

of water exists, or has existed, along the contact. The fourth and westernmost lobe did not reach the north wall of the valley.

An especially fine vertical cross-section of the third lava lobe is revealed in a spectacular cliff known as "The Barrier," a half mile long and up to 800 feet high. Flow planes in the lava, bowed downward in the middle part of the cliff section and apparently conforming with the base of the flow, consist of alternating layers a few inches to a few feet thick of dark reddish and dark gray dacite. A variety of joint patterns can be recognized. Columnar jointing on a grand scale is developed, for example, near the western end of the cliff; tabular jointing is conspicuous in several other parts. Steep joints predominate in all but the uppermost 200 feet of the lava and are partly responsible for the steepness of the cliff. The uppermost 200 feet of the lava is, however, made up of highly fractured red dacite and dacite rubble like that seen on the surface of the flow elsewhere.

The rate of cliff recession on The Barrier is notable. Blocks of dacite break loose repeatedly from the upper zone of the cliff during warm dry days in the summer and, tumbling over the precipice, provide a never-ending source of delight for spectators. When, under such circumstances, a high wind blows up Rubble Creek Valley, a pink dust-cloud, visible for miles, may hang over the disintegrating cliff face. On cool foggy days, on the other hand, the rock falls are much less common, and in winter fresh snow may lie completely unscarred at the base of the cliff for at least a day. The recession has continued until the upper part of the cliff-face has attained a slope of about 40 to 50 degrees, but the steepness of the cliff as a whole testifies to its extreme youth.

The present cliff face was first exposed in a recent landslide of major proportions. Judging from the fresh scar on and adjacent to The Barrier, a mass of rock about 1,750 feet across, 1,200 feet from front to rear, and up to 1,200 feet deep, totaling about 50 million tons, fell at this time. The great bulk of the material involved in the slide, judging from the present cliff face and from the debris in the valley below, was derived from the lava lobe, but some underlying masses of black dacite, which are not clearly a part of this lava mass, may have been included. The slide was so sudden that some debris was carried the full length of Rubble Creek Valley,

leaving in its upper part a sheet of coarse material and in its lower part a valley fill of ill-sorted rubble exhibiting a series of elongated mounds, up to 20 feet high, like those of the Javanese slides (Cotton, 1944, pp. 247-252). In Cheakamus Valley the debris spread out as a broad fan which terminated $3\frac{1}{2}$ miles from its source. Vegetation was completely destroyed along the course of the slide and much timber was drowned where drainage was blocked or diverted by the slide. William Downie, who explored Cheakamus Valley in 1858 (British Columbia Archives), reported crossing at this point a wash-out $2\frac{1}{2}$ miles wide on which not a stump remained standing. This part of the slide must have been quickly reforested for 90 years later it was covered by timber sufficiently old and dense to encourage logging operations. It is evident, therefore, that the slide took place not many years before Downie's visit. One old Indian still living in 1947, at Pemberton, B. C., remembered the valley before the slide (Father F. M. Patterson, Lillooet, B. C., personal communication).

A cliff existed at the head of Rubble Creek Valley before the landslide of the middle 1800's, judging from reports of the Indians that they had previously trapped deer at this locality by driving them out to the rim of a cliff. The height and form of this cliff is not known, nor is it absolutely certain that it was the original face of the lava lobe. However, no lava is known to occur in place beyond the limits of the fresh scar on the north side of Rubble Creek Valley even at points 1,300 feet below the top surface of the lobe and only 1,500 feet from the present face of The Barrier. It would appear, therefore, that the original face of the lava lobe rose 1,300 feet above the floor of Rubble Creek Valley in a distance appreciably less than 1,500 feet. It was almost certainly the presence of an unstable rock face of such great height and steepness that led to the landslide of the middle 1800's.

The original appearance of the northwestern face of the third lava lobe is probably duplicated by the cliff at the northern limit of the fourth lobe. This cliff, 1,000 feet high, is no fresh scar like The Barrier but a rock face which has stood long enough to permit a vegetation of lichens and scattered trees to gain foothold on its surface. The piles of talus at its foot are small, though perhaps their predecessors were swept away with the landslide of the past century. The

cliff itself is composed of black glassy dacite in which columnar structure is well developed. The pattern of this jointing is complex, varying abruptly from place to place, but columns with gentle dips seem common. Only at the foot of the cliff, however, can the pattern be clearly deciphered and the irregular surface normal to the columns, and hence roughly parallel to the original cooling surface, reconstructed. This surface suggests more than anything else the forms assumed by wax drippings on the side of a candle, but tens of feet rather than fractions of an inch across, and indicates the former presence of a highly irregular but generally steep and locally overhanging north wall to the dacite mass. The glassy matrix of the dacite here indicates a rapid rate of chilling such as would not be expected if the lobe had solidified as a unit, and suggests instead that the lava accumulated by successive accretions on a precipitous surface. A greater contrast in appearance between the lava of this face and that of the upper surface of the flow could hardly be expected, but microscopic examination shows no significant difference in the two rocks other than in the amount of glass in the groundmass.

DISCUSSION

Those parts of the Clinker Mountain lava flows which came to rest on surfaces above the 4,000-foot level show no significant features to distinguish them from many flows of similar composition elsewhere in the world. Their surfaces are rough but a normal flow pattern can be recognized. Their surface gradients along the axis of the flows vary from 400 to 1,500 feet in a mile, and appreciably steeper slopes are to be found along the levees and margins of the flows though these do not exceed 300 feet in height.

Those parts of the flows which came to rest on surfaces below the 4,000-foot level are clearly anomalous. A steep concave terminal face, almost 1,000 feet high, is to be seen in the Culliton Creek flow where its base lies at about the 3,000-foot level. The third lava lobe on the north side of the northwestern flow, with its base at about the 4,000-foot level, came to rest in the upper part of a deep valley down which it might have flowed with an initial surface gradient in excess of 1,500 feet per mile. Not only did it come to rest at the head of such a steep slope but it accumulated to a depth of 800 feet. And the

fourth lava lobe developed a face which is even now about 1,000 feet high and slopes at an average angle of about 57° . Accretion of successive thin sheets or dribbles of lavas on such a precipitous face may, perhaps, be duplicated on a small scale in modern flows, but hardly in a cliff of this height.

The approximate age of the Clinker Mountain lavas can be inferred from the degree of erosion by Culliton Creek to be not less than several thousand years (pages 556-57). However, the upper surfaces of the flows have not been glaciated nor do they bear erratics; hence the lavas must have been extruded after the disappearance in late Wisconsin times of the Cordilleran ice sheet from the higher altitudes. These two lines of evidence indicate that the lava was laid down either at a very late stage in the recession of this ice sheet, or very shortly thereafter.

Extrusion of lava at the time the dwindling Cordilleran ice sheet still filled the valleys up to about the 4,000-foot level is suggested in explanation of the anomalies described above. Lava coming to rest on higher, ice-free ground would exhibit normal gradients and surface characters. Flows extending to lower levels would, however, come in contact with the ice and abnormal conditions of cooling and solidification would develop.

The mechanism by which lava can be ponded against a large mass of ice is as yet conjectural, but observations made in Okmok Caldera (R. E. Wilcox, personal communication) during the 1945 eruption (Robinson, 1947; Byers *et al.*, 1947), when a stream of lava flowed along the foot of a mass of firn and ice, are helpful in reconstructing the events that may have taken place west of Clinker Mountain. In the Okmok eruption accelerated melting of the ice foot adjacent to the lava flow led to the development of a precipitous and caving ice wall up to about 200 feet high. In this instance the ice provided no barrier to the main lava flow but it may have ponded some smaller streams of lava nearby. The relict mass of the Pleistocene ice sheet occupying the lower ground west of Clinker Mountain could, however, provide an effective dam, for even in its waning stages it blocked the mouths of Rubble and Culliton valleys to depths of 3,000 feet. Lava streams encountering the edge of this frozen barrier would at first, by melting the ice before them, continue their advance, though

only at the expense of much of their heat content (fig. 2). The close approach of hot lava to the ice front and contact between lava and meltwater would be marked by copious amounts of steam, such as was seen at times in the early stages of the Okmok eruption, and would lead to a more rapid dissipation of heat than prevailed when the lava flowed across dry ground. Melting at the foot of the ice wall and caving of great slabs outward onto the lava might further accelerate cooling by providing a large area of contact between ice and heated rock. In time a solid and presumably steep-sided skin or wall of lava would be developed against the ice face, separating this from the molten material upstream. Heat radiated from this solid, though still warm, mass of lava would cause continued melting of the ice face, and any open space created this way might or might not become occupied by meltwater. During the earlier parts of the eruption this lava dam might be broken or overwhelmed by the mass of molten rock behind it; later, however, as the main stream became cooler and more viscous, the solid lava wall could persist and the stiff magma might become banked up to a considerable height above the dam without exerting the pressure necessary to cause its failure. Local threads of fluid lava might, nonetheless, break over or through the lava dam, and, on entering space between it and the ice, congeal as relatively small sheets or dribbles like those seen on the north face of the fourth lava lobe (page 561) and on The Table (Mathews, 1951b). Although the ice front would be extensively modified by melting and caving, its broader outlines might persist and impart to the lava walls certain irregularities in form which would not have been developed in the absence of ice. Such features as the concave terminus of the Culliton Creek flow may, for example, have originated as a cast of a convex ice front. The unduly high and steep face of both this flow and the fourth lava lobe may likewise be attributed to moulding against a steep, or even precipitous, ice front. Pressure of the ice or of impounded meltwater against the steep lava front might be sufficient to prevent its collapse after cooling and fracturing had taken place. With the disappearance of the ice, however, the steep faces would be potentially unstable and liable, sooner or later, to fall in one or more enormous landslides, like the one which so recently exposed The Barrier. It would seem, then, that

the major anomalies of the Clinker Mountain flows, so difficult to account for in the absence of ice, are readily explained by the hypothesis that the advance of the lavas was impeded at several places along the margins of the dwindling Pleistocene ice sheet.

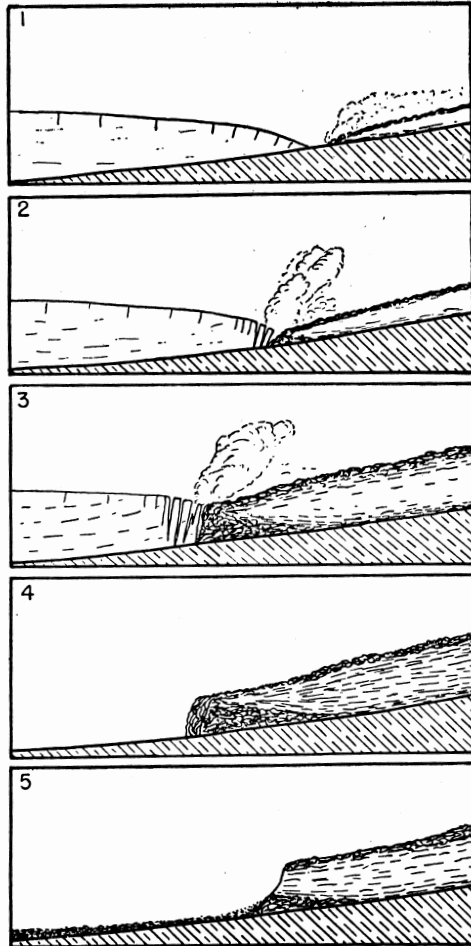


Fig. 2. Conjectural history of an ice-dammed lava flow.

1. First approach of lava (right) to the ice (left). Relatively rapid advance of the flow probably accompanied by only minor emission of steam from the magma or generated from small amounts of water on the ice-free ground.

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Fig. 2 (cont.)

2. Continued advance of lava, though at a slower rate, onto ground previously covered by ice. Increased emission of steam developed by direct contact of lava with meltwater, with fallen blocks of ice, or with the main ice wall. Rapid chilling of magma at the flow terminus leading to development of low, temporary lava dams.
3. Overriding by the main lava stream across the earliest dams followed by the development of an effective dam when the bulk of the lava upstream becomes stiffer. Local threads of fluid lava may break out and overflow into the gap between the lava front and the ice wall to cool and solidify as accretions.
4. Disappearance of the ice, exposing the steep terminal face of the main flow and the coating of accretions. (Fourth lava lobe, page 561.)
5. Collapse of the terminal face, exposing the interior of the flow. (The Barrier.)