McCARTYS BASALT FLOW, VALENCIA COUNTY, NEW MEXICO

ROBERT L NICHOLS

Geological Society of America Bulletin 1946;57;1049-1086

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Notes
**MCCARTYS BASALT FLOW, VALENCIA COUNTY, NEW MEXICO**

**BY ROBERT L. NICHOLS**

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The McCartys flow is approximately 30 miles long, in places several miles wide, approximately 1.7 cubic miles in volume, and it has an area of about 119 square miles. The flow is in the main unweathered, uneroded, and barren. Pueblo I potsherds have been found in a valley fill which is probably buried by the flow, indicating that extrusion occurred in the last 1200 years.

Minor features such as grooved lava, squeeze-ups, ropes, spatter cones, tree molds, cracks, banded lava, and cavities are present. The extrusion of the flow impeded the Rio San Jose and diverted drainage from it into the Rio Salado and Little Colorado. The flow moved by the flow-unit and single-unit mechanisms, and its velocity varied greatly from place to place.

Near the terminus of the flow are about 100 collapse depressions. Analysis of the probable strength of the roofs of lava tunnels indicates that they owe their origin not to the collapse of one large tunnel but to the partial collapse of several small tunnels. In some cases collapse occurred while liquid lava was still present and when the under side of the crust was still soft and plastic.

On the last mile of the flow pressure ridges are very common. They are as much as 1200 feet long, 25 feet high, and 100 feet wide. In transverse section they resemble the gable of a house. In general they parallel the flow and are close to its margin. They formed when liquid lava was beneath the crust. It is suggested that the collapse of a dome between 27 and 38 feet high, due to withdrawal of lava from beneath, resulted in compressional forces which buckled the crust and produced the pressure ridges.

INTRODUCTION

The McCartys basalt (Fig. 1) is a relatively fresh pahoehoe flow whose striking features have long excited interest in travelers on the Santa Fe Railroad between Albuquerque and Gallup, N. M. The flow originated southwest of the Rio San José and occupies the valley from a point about 7 miles east of Grants to the little Indian town of McCartys, a distance of about 6 miles. From U. S. Highway 66 much of this flow is visible as the highway passes across and beside it. The writer spent parts of the field seasons of 1933, 1934, and 1935 making a detailed study of the lower 6 miles of the flow. In 1938 he returned for a period of 3 days to obtain further details. The present paper resulted from this study.
ACKNOWLEDGMENTS

The writer is greatly indebted to Professor Kirk Bryan of Harvard University, under whose supervision the study was undertaken and completed. Professor Bryan critically read the manuscript, spent long hours with the writer in discussing the problems involved, contributed numerous ideas, and spent several days in the field with the author.

Warm thanks are also due Professor Esper S. Larsen for help in the laboratory and for many suggestions. Professor R. A. Daly's knowledge of the volcanologic literature was of great assistance, and discussion with Professor A. C. Lane on the rate of cooling of lava and on grain size was also of much help.

Thanks are due Mr. Gordon Taylor, Mr. Lawrence G. Ropes, Professor F. N. Weaver, Dr. Laurence LaForge, and Dr. Richard Tousey, who helped the writer apply engineering principles to the solution of the problems considered.

Figure 1.—Index map
Location of McCartys flow shown by diagonal lines.
To Karl Benedict, Robert S. Folsom, David Rose, Ralph Fellows, Edmund Shaw, Charles E. Stearns, and Charles E. Baker, of Tufts College, thanks are due for able field assistance.

GENERAL ASPECTS OF THE FLOW

The source of the McCartys flow is in a broad valley between mesas about 20 to 25 miles southwest of the point where the flow is crossed by U. S. Highway 66 (Fig. 2). Here, at a point about 1000 feet higher than the San José Valley, a small cinder cone rises approximately 50 feet above a broad lava cone (Pl. 1, fig. 1). From the lava cone the lava flowed northeastward to the San José Valley and then eastward down the valley, finally stopping a few hundred yards west of McCartys. Lava also flowed from this cone southwestward about 6 miles. Near its source the flow is several miles wide; it gets progressively narrower, however, until it is less than 200 feet wide where it enters the San José Valley. The average width in the valley is about 1000 feet. Figure 2 of Plate 1 shows the flow 1½ miles west of McCartys where it is about 1500 feet wide and fills the valley. Near the source gush after gush built up a lava cone at least 200 or 300 feet thick. The approximate thickness
Figure 1. Source of McCartys Flow

Figure 2. Flow 1½ Miles West of McCartys
Figure 1. Narrow thread of lava where McCarty's flow was confined by canyon.

Figure 2. Pond in one of the collapse depressions of the McCarty's flow.
of the last 6 miles of the McCartys flow may be obtained by studying the depth of the larger cracks, the edge of the flow, the depth of the collapse depressions, the edge of the flow around a kipuka, and by a comparison with the Laguna flow (Nichols, 1934), which is similar petrographically but eroded so that its thickness can be measured. Measurements around the kipuka (Fig. 3) indicate that the flow in this

![Diagram of McCartys Basalt Flow](image)

**Figure 3.**—Last six miles of McCartys flow

Area marked K is a kipuka. Position of collapse depression area and pressure ridge area indicated. Location of Figure 4 indicated by A.

area is about 15 feet thick; however, where the flow narrows it is probably as much as 50 feet thick. The last 6 miles of the flow is probably 30 to 40 feet thick. The average thickness of the Mull and Deccan flows is approximately 50 feet (Anderson, 1924; Fermor, 1925). The flow covers approximately 119 square miles, and if 75 feet is taken as the average thickness of the whole mass the volume is 1.7 cubic miles, which is much greater than that of the average basaltic flow in western United States. It has nevertheless only one-sixth the volume of the Veidivatnahraun basaltic flow of Iceland (Daly, 1933, p. 139). This flow, however, was erupted from a fissure 150 kilometers long, whereas the McCartys flow was erupted from a single vent.

Although the McCartys flow is not eroded and its floor has never been seen, it must rest either on Mesozoic sandstone and shale in which the valley is eroded, on the Laguna flow, or on the stream deposits which floored the valley at the time of extrusion.

**AGE OF THE FLOW**

The Rio San José lies in a valley a quarter of a mile to 2 miles wide which has been incised to a depth as great as 1200 feet in a basalt-covered erosion surface which Bryan and McCann (1936; 1938) consider to be late Pliocene or Pleistocene. As the McCartys basalt occupies the bottom of this valley, the flow cannot be older
than late Pleistocene; its fresh appearance and the retention of surface features herein described prove that it is Recent and probably about 1000 years old.

The McCartys basalt is younger than the Laguna basalt. Pressure ridges of the Laguna project through the McCartys as miniature steptoes. At several places the McCartys basalt filled collapse depressions of the Laguna basalt. The Laguna is in places eroded, whereas the McCartys is uneroded. A kipuka in the McCartys, floored by lava of the Laguna basalt, is shown in Figure 3.

The age relations of the Laguna and the McCartys are best revealed a few hundred yards south of the intersection of U. S. Highway 66 and the McCartys basalt. Here a cliff in the Laguna basalt 10 feet high is separated from the steep edge of the McCartys by a moat a few yards wide. This cliff is close to the original edge of the Laguna flow. After the extrusion of the Laguna basalt a canyon was carved along its border, and down this canyon the McCartys basalt later flowed (Fig. 4). The threadlike outline of the McCartys basalt south of the highway (Pl. 2, fig. 1) is undoubtedly due to the fact that this canyon confined the liquid lava to a narrow path. North of the highway, however, the flow becomes nearly a mile wide. This rapid widening may be due either to an overflow of the canyon walls or to the existence of a wider canyon. It seems unlikely, however, that the canyon would widen so rapidly. On the other hand, if the gradient became flatter, or if the canyon got shallower or narrower, or if the volume of the McCartys flow suddenly increased, it might well have overflowed the walls of the canyon.

The McCartys flow over most of its area is as fresh and unweathered as the historic flows of the Hawaiian Islands, Vesuvius, and other areas. Weathered lava is rare. Below the unweathered glassy surface of the flow, however, the lava is in places discolored by limonite. On the last 6 miles of the flow, widely scattered plants such as lichen, cactus, sage, and small juniper grow. In many places the south side of a pressure ridge is black and barren, while the shady north side is covered by lichen. Where the crust is fragmented (Nichols, 1938, p. 601–603) the surface is usually bare, but in places the north side of the fragments is covered with lichen.

Near the source of the basalt, more than 1000 feet higher than that part of the San José Valley occupied by the McCartys flow, each margin of the flow has a belt of vegetation less than a mile wide. In these marginal belts, the yellow pine is as much as 3 feet in diameter. However, with increasing distance from the edge of the flow the pines gradually decrease in size and number, and the central portion of the basalt is bare. These belts of vegetation grow on wind-borne soil. The wind picks up dust from the area marginal to the flow, and the dust cover thins with increasing distance from the edge of the flow. The relatively heavy vegetation near the source and the barreness of the terminus are apparently controlled by the difference in rainfall because of difference in elevation. Similar differences in vegetation are also found on Hawaiian flows. Yellow pine of this size on the flow indicates that it must be several hundred years old.

The Acoma Indians, on whose reservation a small part of the McCartys flow is found, have a legend that the flow covers land their ancestors tilled. This legend (Darton, 1915), if credible, dates the eruption of the basalt as pre-Spanish but later than about 700 A.D.—the beginning of the pueblo civilization.
These cross sections were made at the narrowest part of the flow shown in Figure 1 of Plate 2. Studies farther down the valley indicate that following the erosion of the Laguna a valley fill was deposited which was later buried by the McCartys.
Potsherds identified as Pueblo I have recently been found 4 feet below the top of the youngest valley fill near Laguna (Reiche, 1936), which is about 17 miles down the valley from the terminus of the McCartys flow. This valley fill is probably buried by the McCartys flow. This also indicates that the McCartys flow was extruded during the Indian occupation of the valley. As the Pueblo I period was between 700 A.D. and 900 A.D. (Hack, 1941) the potsherds suggest that the extrusion of the McCartys flow occurred either during this period or somewhat later.

**Figure 5—Drainage diversion resulting from extrusion of McCartys flow**

**DRAINAGE CHANGES EFFECTED BY THE FLOW**

The cone or cones from which the Laguna flow was extruded lie south of the McCartys flow. As the Laguna lava flowed northward into the San José, it seems reasonable to suppose that the post-Laguna drainage also flowed from the source of the Laguna northward. However, with the extrusion of the McCartys flow some of the drainage was apparently diverted from the San José southeastward into the Rio Salado and possibly southwestward into the Little Colorado River. Figure 5 not only shows the general relations of the Laguna and McCartys, but it also shows how the drainage divide between the Rio San José and the Rio Salado was shifted northward.

At the present time the Rio San José, in that part of the valley occupied by the McCartys flow, is broken up into several branches which flow beneath, on top of, or marginal to the McCartys. The branch which flows on top of the McCartys for a short distance has deposited some alluvium although it has not accomplished any significant erosion. Figure 6 shows four branches of the Rio San José at the terminus of the McCartys flow. Farther downstream these branches unite into one main stream.

Shallow lakes marginal to the flow, quite common after a heavy rainfall, indicate that the flow impedes drainage. Moreover, as is shown by Figure 2 of Plate 2, small ponds are at such times found in many of the collapse depressions of the flow.

**CLIMATE AT TIME OF EXTRUSION**

Only one tree mold was found on the McCartys flow. It is about 7 feet long and indicates that the tree was about 3 feet in diameter. Neither the tree nor its mold had been transported any great distance, as the mold was found only a few miles from the source of the flow. Only one traverse of the flow was made in this area, so that similar molds could probably be found. Such molds indicate a climate, at
the time of the extrusion of the McCartys flow, similar to the existing one or to one of greater rainfall.

The last 6 miles of the flow was studied in great detail, and no tree molds were found. Moreover, there is nothing to indicate that conditions existed which would have prevented the formation of tree molds. Hence, when the McCartys flow ran into this part of the valley the trees were not large or numerous enough to make tree molds. Today, juniper is abundant. If juniper were engulfed in molten lava it would probably be entirely consumed. Thus the climate in this part of the valley at the time the flow was extruded was either similar to that of the present or drier. As no significant diastrophic or topographic changes have taken place since the extrusion of the flow, the difference in climate between the area at its source and at its terminus must be about the same today as before the extrusion. It is concluded, therefore, that the climate at the time of the extrusion of the flow was similar to that of the present in all parts of the area.

FLOW MECHANISM

At the end of the flow (Fig. 6) are two tongues, one of which projects 1000 feet down the valley. A comparison of the surface gradient of the flow at this point
with a reasonable pre-McCartys gradient indicates that these tongues are not so thick as the main flow. They are therefore unburied flow units (Nichols, 1936), and their existence suggests that the flow, at least near its terminus, was advancing by the flow-unit mechanism.

The walls of a few of the larger cracks reveal miniature flow units which are a few inches to a few feet thick and can be traced for scores of feet along the walls. In places, only one miniature flow unit will be found on the main body of the flow; in other places, several such units exist, one upon the other. The existence of these flow units is indicated: (1) by the sharp contact between them; (2) by the columnar jointing which varies in size from unit to unit; and (3) by the ropy surfaces which were formed on top of the units and were buried by succeeding units. These flow units are much smaller than those described from the Laguna and Suwanee flows (Nichols, 1936). Undoubtedly the units broke out not from the sides or front of the advancing lava tongue, but from its surface. Apparently the flow thickened intermittently by the extrusion onto its surface of these miniature flow units. Richey (1924) has described similar features from the lavas of the island of Mull, and Jones (1937, p. 873) has observed them in Hawaiian flows in the process of formation.

The miniature flow units of the McCartys flow were found south of U. S. Highway 66 where the flow is narrow. There was a greater tendency for the crust to break here because the surges of the lava were stronger than where the flow was wider. Moreover, the crust would tend to be thinner here than elsewhere because of a more continuous flow of hot lava below the crust.

Ropes are common on the surface of the flow. They vary in size, shape, and in other respects. They are oriented in all possible directions. This suggests that they were not formed on the surface of molten lava flowing as a single unit, because all the currents in such a flow would be moving in the same general direction. The ropes were formed on flow units which at intervals poured from vents and cracks on the surface of the flow, each moving in various directions.

A short distance north of the point where U. S. Highway 66 crosses the flow there are several excellent examples of flow units. These flow units were not found by a study of the cross section of the flow but by an analysis of surface features.

That the flow was running with maximum velocity where it was confined by the canyon cut in the Laguna basalt (Pl. 2, fig. 1) is indicated by its greater thickness (Nichols, 1939c, p. 301) at this point and by the fact that the pre-McCartys gradient was at least as steep here as elsewhere. Because of this rapid movement, it seems likely that the flow was moving here by the single-unit mechanism.

The mechanism of flow was therefore complicated—advancing by the single-unit mechanism at one point, by the flow-unit mechanism at another; at one place slowly, at another rapidly.

MINOR FEATURES

CAVITIES

Cavities within a few feet from the surface of the McCartys flow are common. The largest observed are as much as 3 feet long, 5 inches deep, and often 3 feet or
Figure 1. CAVITIES IN LAVA SEEN ON THE WALLS OF A CRACK

Figure 2. A SPATTER CONE SIX MILES FROM THE TERMINUS OF THE MCCARTYS FLOW

CAVITIES AND SPATTER CONE
Figure 1. Aerial Photograph Showing Part of Collapse Depression Area of McCarty's Flow
Many depressions are filled with water. Santa Fe Railroad on left of flow, Rio San José on right.

Figure 2. Collapse Depression Floored with Alluvium and Vegetation
Man standing on right-hand edge of depression gives scale.
Minor Features

• more below the surface. Most of these cavities have no surface expression. However, as shown by Figure 1 of Plate 3, some of the larger cavities are associated with surface blisters. The hat shown in Figure 1 of Plate 3 is resting on such a blister. It is about 5 feet in diameter and raised about 1 foot above the general level of the flow. The largest cavities are associated with the largest blisters.

Although it is patent that many cavities and gashes in the flow are due to the accumulation of gas bubbles, the author is not certain whether these cavities are due to this mechanism, to successive withdrawals of lava from bulbous squeeze-ups, or to buckling of the crust by compressional forces.

If these cavities are due to the accumulation of small gas bubbles beneath the crust, they are similar to the jagged gashes found in the Keweenawan flows described by Butler and Burbank (1929, p. 29) and to cavities in lava described by Nichols (1936, p. 619). Their formation by this mechanism can be explained as follows.

If the crust of a flow is thickening slowly during a period of rapid vesiculation, one long continuous gas cavity will be formed wherever the bottom of the crust is flat. However, if the bottom is not flat, which will almost always be the case, the gas bubbles will accumulate most rapidly where the bottom is domed. In this way, unconnected cavities of a general lenticular shape, one under each dome, may be formed.

Broad swells or flat domes 10 feet across and a few inches high are found on the McCartys flow. Similar domes have been described and photographed by Anderson (1903) from the flows of Iceland. If the crust of somewhat smaller domes is sufficiently plastic and thin it will be slowly lifted, and blisters similar to those in the figure will be formed by the gas pressure. A period of rapid thickening of the crust with slow vesiculation will stop the growth of these gas cavities. After the crust has been thus thickened, conditions of rapid vesiculation and slow thickening may again obtain, and if the bottom of the crust is still domed at this point another group of gas cavities may be formed below the first. These lower cavities may also increase the size and height of the blisters. In this way superposed cavities associated with surface blisters may be formed. Such a mechanism was envisaged by Butler and Burbank (1929, p. 28) to explain the successive gashes or cavities in the Keweenawan flows. The upper cavities are older than the lower. The size and shape of the cavities depend upon the size and shape of the initial domes, the rapidity with which the crust thickened, and the rate of vesiculation. During the period of formation of these cavities the lava must have had low viscosity; otherwise the vesicles could not have migrated and coalesced.

Periods of rapid vesiculation with slow thickening of the crust followed by rapid thickening with slow vesiculation may be brought about if the forward progress of the flow is irregular rather than uniform. This condition will be satisfied if the flow is advancing by the flow-unit mechanism (Nichols, 1936) or by the single-unit mechanism if the lava was emitted from the vent with varying speeds. With such a flow mechanism, the lava would move through the carapace which surrounds it with varying velocity. During a period of rapid movement the crust would thicken slowly, and rapid vesiculation might take place, whereas during slow movement of the lava the crust would thicken rapidly, and vesiculation might also be slow.
The bottom of a gas cavity formed in this way would be flat if the lava were fluid. If the lava were viscous the cavity might be convex or concave downward, depending upon how rapidly and at what point the bubbles were added to the growing gas cavity. The top of such a gas cavity would in the main be convex upward.

These cavities imperceptibly grade in size and shape into those which are clearly due to the coalescing of vesicles, thus pointing to a formation by accumulation of gas bubbles. On the other hand, the position of the larger cavities indicates that the crust was more than a foot thick when they were formed. It seems doubtful that such a small quantity of gas as would have been trapped in these cavities could blister such a thick crust.

An alternative explanation for these larger cavities is that they are due to the withdrawal of lava from structures similar to bulbous squeeze-ups (Nichols, 1939b). These bulbous squeeze-ups are often hollow, due to a withdrawal of lava from them. According to this idea the hat in Figure 1 of Plate 3, is resting on a bulbous squeeze-up with similar structures on each side. Immediately after the extrusion of each of these supposed squeeze-ups a crust forms around them. If after the crusts of the squeeze-ups have formed and before the feeding vent is closed the hydrostatic pressure of the liquid lava is decreased, either due to the formation of a flow unit down-stream or to a reduction in the quantity of lava reaching the liquid thread from upstream, lava may be drained from them. If the crust of the squeeze-up is strong enough to support itself a cavity will be formed. Progressive solidification followed by renewed drainage of lava will form additional cavities. Finally the feeding vents will be closed by solidification.

Although cavities in adjacent bulbous squeeze-ups may be formed contemporaneously, they are not necessarily the same size or shape. The ease with which the lava can be withdrawn from a squeeze-up and the size and shape of the squeeze-ups will determine the size and shape of the cavities. Figure 7 illustrates the formation of these cavities by this mechanism. A cross section through the flow immediately after the extrusion of two bulbous squeeze-ups is shown by A of Figure 7, while B shows the squeeze-ups after a crust has formed around them. C shows how a withdrawal of lava due to a decrease in the hydrostatic pressure of the liquid lava below forms a cavity in each squeeze-up. Further solidification and withdrawal of lava result in the formation of two additional cavities as shown by D and E.

The bottom of a cavity formed in this way would tend to be flat if the lava were fluid and would be concave upward with the low point near the vent if the lava were viscous. The top might be irregular due to the formation of lava stalactites, but in the main it would be convex upward.

The feeding tubes required by this mechanism have not been found. The lack of feeding tubes, however, is not fatal to the theory as the observable cross section might not have intersected the tubes, and, moreover, the material of the tubes might be so similar to the material of the floor that differentiation would be impossible.

A third explanation for these cavities is that they are due to a buckling of the crust by compressional forces, the cavities representing the space between the crust and the more or less liquid substratum. However, if this mechanism had taken place one would expect a greater abundance of tension cracks and more fragmentation of the crust.
It may well be that combined gas pressure, withdrawal of lava, and even buckling formed these cavities.

Schollendomes, low domical hills on pahoehoe flows, may be as much as 100 feet long and 15 feet high. Many are hollow. The controversy with regard to their origin is somewhat similar to the problem of the origin of the cavities under discussion. Many volcanologists believe that they are due to the accumulation of gas beneath the crust (Sapper, 1927; Perret, 1913, p. 154). On the other hand Daly (1933, p. 155) and Jaggar (1931) believe that they are due to the hydrostatic pressure of the subcrustal liquid lava. If they are formed in this way the cavity which is sometimes found be-
neath the crust of the schollendomes is due to a withdrawal of lava after the dome formed.

The walls of many of the cavities shown in Figure 1 of Plate 3 are covered with stalactites coated with a microscopic film of glass. These stalactites formed from lava which dripped from the roofs of the cavities. The surface of the stalactites cooled rapidly forming this film of glass. On the surface of the flow the glass, which may be as much as half an inch thick, is always black, while the glass on the stalactites is invariably green. As the green glass is much thinner the color difference might be due to the difference in the thickness of the two glass films. However, several specimens of the lava were fused in a blast lamp and in every case a black glass formed. As the glass films formed in the blast lamp were as thin as the green glass films, thickness does not seem to be the determining factor. This color difference may be due to a difference in the chemical composition of the two glasses. No difference in the optics of the glasses could be detected, so that if any chemical difference exists it is very small. Such a chemical difference may have been caused by the differences in composition between the gases in the cavities and those in the atmosphere at the time the glasses were formed.

**SPATTER CONES**

The last 6 miles of the McCartys flow was intensively studied, and in this area only one spatter cone was found. Spatter cones are common on the lava flows of Iceland (Geikie, 1897), Hawaiian Islands (Perret, 1913, p. 152-153; Stearns, 1930, p. 122-123), and elsewhere. The spatter cone on the McCartys flow has an approximately circular base; it is about 4½ feet high and about 10 feet wide. The clots of lava which formed it were all liquid when ejected, and many of the larger ones show evidence of flowage. Most of them are shaped like pancakes. As the cone grew upward its walls converged, forming the bee-hive shape shown in Figure 2 of Plate 3. Apparently the horizontal component of the trajectory of the clots gradually decreased as the cone grew. This decrease is best explained by assuming that the vent out of which the clots were emitted became progressively smaller and deeper as the crust thickened. The walls are thin, and there is a large chamber within the cone. The walls of this chamber are lined with lava stalactites. The smaller ones are commonly dumbbell-shaped due to the solidification of a large drop of lava at the end of the stalactite. The larger stalactites are often covered with small drops of lava, many of which are spherical but some of which are pear-shaped. The stalactites vary from three quarters of an inch to 1½ inches in length and represent the drip from the clots which made the walls of the cone.

**CRACKS**

Two kinds of cracks are found in the McCartys flow: wedge-shaped cracks which may be as much as 6 feet wide, 13 feet deep, and more than 100 feet long, and much smaller nearly parallel-walled cracks which are in most places too small to map (Fig. 4, F). In many places these parallel-walled cracks have saw-toothed walls because the break took place along columnar joints. The width of the flow measured along
the top of the cross section of Figure 4, G is 190 feet, and the sum of the widths of the cracks shown and not shown in the cross section is about 16 feet.

That the contraction resulting from the change of glassy to crystalline basalt is only partly involved in the formation of these cracks is evident. The volume of any crystal formed in the cooling liquid lava was approximately 10 per cent (Daly, 1933, p. 50) less than the volume of the liquid from which it was derived. However, this crystallization did not necessarily result in a general contraction of the cross section because additional liquid lava may have flowed in as the contraction proceeded. If a crystal mesh was ever developed in which liquid lava was completely surrounded by crystals this residual liquid might crystallize and cause a contraction which could not be offset by the addition of new liquid. However, it is difficult to see how such contraction could produce the type of cracks under discussion, and moreover it is doubtful if such a crystal mesh was ever developed.

The work of Day, Sosman, and Hostetter (Daly, 1933, p. 48) showed that there was about a 3 per cent decrease in volume in the change from crystalline Palisade diabase at 1200°C. to crystalline Palisade diabase at 20°C. The McCartys basalt is comparable to the Palisade diabase and as the McCartys basalt may have crystallized around 800°C. it could have contracted about 2 per cent in cooling from its crystallization temperature to 20°C. As it is 190 feet wide this would account for something less than 4 feet of contraction. Hence the magnitude of these cracks is too great to be explained by thermal contraction alone. Moreover, if they were due to thermal contraction one would expect all of them to have nearly parallel walls.

On the other hand, if the initial transverse section of the flow was approximately as shown in Figure 4, E and if the crust was elevated to its present position either by a constriction which prevented flow downstream or by an increase in the volume of lava coming from upstream, then the crust would be stretched approximately 10 feet by this uplift. This together with the contraction which must have taken place when the lava cooled, from approximately 800°C. to 20°C., can account for the formation of the cracks. The large wedge-shaped cracks were probably produced mainly by the stretching consequent on uplift, while the smaller, nearly parallel-walled cracks are due to thermal contraction. Uplift also explains the present domical cross section of the flow as the transverse section of a basaltic flow usually has steep sides and a relatively flat top.

However, the bottom of the uplifted crust should be stretched practically as much as the top. This should produce not wedge-shaped cracks but parallel-walled cracks which would be as deep as the crust was thick. That the cracks are wedge-shaped may be explained as follows: (1) If the crust acted as a rigid member there would be formed wedge-shaped cracks in the bottom part of the crust opening downward, as well as those in the top part of the crust opening upward. (2) If the bottom of the elevated crust was somewhat viscous, flowage of this viscous material into the bottoms of the cracks might make them wedge-shaped. (3) If the crust was slowly uplifted while it was progressively thickening, the cracks formed should be wedge-shaped as the upper parts of the crust having been crystallized the longest would be stretched more than the bottom part of the crust which would have been liquid during all except the last stages of the uplift.
The wedge-shaped cracks contain banded lava and shark’s-tooth projections (Nichols, 1939a, p. 188-192). These phenomena can be explained easily if the cracks were formed by the stretching of the crust, as the liquid lava responsible for the uplift could supply the necessary gases to form the banded lava and the shark’s-tooth projections could be formed by movements which resulted from the uplift. On the other hand, it would be difficult to explain them if these cracks were due to thermal contraction. Moreover, the rapid widening of the flow downstream from this cross section may be due to a spreading of the flow consequent upon the same increase in the volume of lava which has been postulated to explain the doming (Pl. 2, fig. 1).

COLLAPSE DEPRESSIONS

DESCRIPTION

Collapse depressions are among the most characteristic features of the last 6 miles of the McCartys flow (Fig. 3). They vary greatly in size. The largest depression is nearly a mile long and in places as much as 300 feet wide, while the smallest is only a few feet in diameter. However, most of them are a few hundred feet long, 50 to 100 feet wide, and 15 to 20 feet deep. In shape, too, they vary greatly; some are round and others oblong, while most are quite irregular. The variations in size and shape are shown by Figure 8, a map of the last 3 miles of the flow. In an area about 2 miles long there are approximately 100 collapse depressions, 50 of which have been mapped. This area will be referred to as the collapse depression area (Pl. 4, fig. 1; Pl. 5). The depressions are commonly filled with water or floored with alluvium and vegetation. The long axes invariably parallel the long axis of the flow, and the surface of the flow between the depressions is relatively flat. These depressions are similar to those described by Russell (1902, p. 101; 1903, p. 54; 1905) and others and are formed by the collapse of the roofs of lava tunnels.
PART OF COLLAPSE DEPRESSION AREA OF McCARTYS FLOW

Flow covered with scattered vegetation, mostly sage, 1 to 3 feet high.
Figure 1. Small Pond in Collapse Depression
Man seated at end of depression gives scale. Depression bordered by overhanging cliffs and by sloping surfaces.

Figure 2. Small Collapse Depression Approximately 15 Feet in Diameter
Collapse depressions containing water and vegetation.
At the bottom of many of the collapse depressions angular blocks are piled one on the other. That these blocks were derived from the collapsed roof of a tunnel is shown by their vesicular nature. Some of the blocks have a ropy surface such as is characteristic of the surface of the McCartys flow in this area. In by far the greater number of depressions, however, no blocks are visible because the original floor is covered by water, alluvium, or vegetation (Pl. 4, fig. 2; Pl. 6, figs. 1, 2). The height of the water in the collapse depressions is controlled by the height of the water in the Rio San José as is shown by a comparison of Figure 2 of Plate 2 and Plate 5. Figure 2 of Plate 2 shows a portion of the McCartys flow and the flood plain of the Rio San José shortly after a heavy rainstorm. The stream channel is overflowing, the flood plain in the foreground is partly covered with water, and a Y-shaped collapse depression is partially filled, making a small pond within the basalt flow. On the other hand, Plate 5 shows the same area at a time when the discharge of the Rio San José was much lower, and the flood plain and also this Y-shaped collapse depression were dry. The basalt flow is permeable, for even a casual examination of the flow shows it to be filled with ramifying joints and cracks. The depressions near the center of the flow contain the deepest water. The water in the depressions is often quite muddy after a rain. Only a small part of this mud is derived from the drainage basins of the collapse depressions as most of it is the mud carried by the flood waters which have penetrated the basalt flow. It is this mud and silt which is mainly responsible for the burial of the blocks, although wind-borne dust and vegetal remains also accumulate. In general, if the water table of the basalt and near-by alluvium lies below the floor of a collapse depression uncovered blocks are present; if the water table lies above the floor, for even part of the year, the blocks are covered by water, alluvium, or vegetal remains.

Many of these depressions have a characteristic assemblage of water plants, although the general vegetation of the valley is drought-resisting and adapted to about 10 inches of rainfall.


With regard to these plants Dr. Goodwin (personal communication) reports:

"This association of plants indicates that the habitat is wet throughout the year and that it is rather saline in nature. Similar associations were not observed elsewhere in the valley except in the neighborhood of salty springs."

Each depression has its own characteristic flora depending upon its relation to the water table. The decay of this vegetation generates considerable quantities of marsh gas which is responsible for the disagreeable odor near the depressions. The pools of water also contain small fish, tadpoles, and frogs, and they act as places of refuge for ducks in the migratory seasons.
The depressions in which the blocks derived from the collapsed roof can still be seen may be as much as 28 feet deep. Twelve to 15 feet is a reasonable figure for the depth of those depressions whose blocks are covered (Fig. 9; Pl. 6, fig. 1).

In those collapse depressions where the blocks can still be seen, the depth of the depression gives roughly the height of the lava tunnel, the partial collapse of which produced the depression.

**ORIGIN**

The distribution of the collapse depressions (Fig. 8) indicates an origin due either to the partial collapse of the roof of one large lava tunnel or of several small distributary tunnels. However, analysis of the probable strength of the roofs of lava tunnels indicates it is unlikely that the roof of a tunnel as large as would be required to span this area could have been maintained even in part. The following calculations lead to this conclusion.

The following assumptions are made. (1) The specific gravity of the upper part of the flow is 2.5; (2) the roofs of the tunnels were, on the average, 8 feet thick; and
(3) the ultimate tensile strength of the not wholly cooled basalt was 1000 pounds per square inch (Swain, 1924), although it may have been lower as the basalt was cracked and jointed. By substituting these somewhat imperfect data in the beam formula (Timoshenko and MacCullough, 1935, p. 111) familiar to engineers:

\[ S = \frac{Mc}{I} \]

where \( S \) is unit fiber stress, \( M \) is the bending moment, \( I \) is the moment of inertia of the cross section, and \( c \) is \( \frac{1}{6} \) the depth of the beam, \( M \) can be calculated for the unsupported roof. By assuming that the beam is uniformly loaded and using the value of \( M \) thus obtained, the maximum length of beam which could support itself is found to be approximately 100 feet, as calculated from the following formula (Timoshenko and MacCullough, 1935, p. 93):

\[ M = \frac{wP}{8} \]

where \( M \) is the bending moment at the center of the span, \( w \) is pounds per linear foot of the beam, and \( I \) is the length of the beam.

These calculations assume that the roof was supported only as a simple beam. However, Professor F. N. Weaver of Tufts College says that a roof 8 feet thick, over a tunnel not more than 30 feet high with a curved cross section, would undoubtedly support itself in part by arch action. However, he thinks that a 150-foot span supported in part as a simple beam and in part by arch action would probably be the maximum width which could maintain itself under these conditions.

The length of the span which will support itself is a function of the thickness of the roof and the strength of the crust. However, calculation shows that if the roofs of the tunnels were 24 feet thick, an impossible figure, and if the basalt had a tensile strength of 4000 pounds per square inch, which is much greater than allowable values, the span could not have been as much as 400 feet.

If the collapse depressions resulted from the partial collapse of one large tunnel, this tunnel would have to be as much as 1000 feet wide (Fig. 8). The above calculations show, however, that the roof of such a tunnel would be unable to maintain itself even partially, and that its collapse would result in one wide continuous collapse depression. It would seem, therefore, that the collapse depressions are the result of the partial collapse of many distributary tunnels most of which were probably not much more than 150 feet wide. Collapse occurred where the tunnel was wider or the roof thinner than usual, where the roof was much jointed and cracked, or where the shape of the tunnel did not allow arch action to support the roof. The lava was being supplied to the front of the flow by a system of distributary tunnels as suggested by Figure 6. Moreover, according to Jaggar (1936) this is what is customarily found in the case of the pahoehoe flows of the Hawaiian Islands.

Although the long axes of the collapse depressions, almost without exception, are aligned in the direction of the flow, nevertheless, their arrangement does not indicate the number, position, or direction of the tunnels.
The low-lying area—A, B, C, D on Figure 8—is covered with alluvium for practically its entire length and apparently resulted from the more or less complete collapse of one continuous lava tunnel. Such a depression or collapsed tunnel has been called a mawai (Jones, 1937, p. 878) by the Hawaiians. This tunnel must have been nearly a mile long, in places as much as 350 feet wide, and oriented in about the same direction as the flow. The peninsular-shaped body marked P on Figure 8 might be a lateral tongue which diverged from the flow rather than an uncollapsed portion of the main mass of the flow. If this is correct, the area between the peninsula and the main body of the flow, marked CD on Figure 8 is not a collapsed area but is low-lying because it was never covered with lava. However, the outline of the flow at F would be difficult to explain, if P were a lateral tongue, for it would be necessary to assume that F ran back up the valley. Moreover, the absence of such lateral diverging tongues elsewhere on the McCartys flow also makes it doubtful that P is a tongue. Also, the shape of the area CD indicates that it is a continuation of the undoubted collapsed area AB, and this fact strengthens the argument that CD, too, is a collapsed area. The ridge labeled G in Figure 8, which is found within the collapse area ABCD, is either an uncollapsed portion of the roof of the tunnel or a pressure ridge which was formed before the collapse depression.

The main factors which determine whether a roof will support itself or not are its thickness and the width of its arch. It seems unlikely that complete collapse occurred in the ABCD collapse depression because the roof of this tunnel was thinner than those of others. On the contrary, the crust of a solidifying flow would normally be thickest near its edge. It seems, therefore, that the complete collapse of the roof of this tunnel must have been due to its great width. However, if for any reason this tunnel was formed before the others it might well have had a thinner crust.

Although the collapse depressions just described are best explained as resulting from the partial collapse of the roofs of many lava tunnels, the depression marked “General Collapse Area” on Figure 8 is apparently due to the collapse of the roof of a large tunnel formed by a general subcrustal drainage. This is indicated by the fact that in these depressed areas the crust is everywhere depressed about the same amount. The surface of these areas as shown by Figure 10 is between 5 and 15 feet below the general surface of the flow. Such general subcrustal drainage is common and examples have been described by Daly (1925, p. 21), Glangeaud (1913), Russell (1903, p. 39–40), and others.

Facing in toward the general collapsed area and also around the depression labeled ABCD on Figure 8 are several excellent slump-scarps (Finch, 1933) produced by the collapse.

This marked concentration of collapse depressions, unique along the whole 30 miles of the flow, indicates that the conditions necessary for their formation were not everywhere existent.

Viscous lava, a flat gradient, slow outwelling of the lava at its source, and topographic irregularities on the valley floor would favor the production of many ramifying tubes. These conditions are also those favoring flow by the flow-unit mechanism (Nichols, 1936, p. 629), which is dependent upon the existence of many ramifying tubes. The drainage of these tubes, after the formation of a partially self-supporting crust, would produce the collapse depression area.
COLLAPSE DEPRESSIONS

Fluid lava, a steeper gradient, and a rapid outpouring of a large quantity of lava would favor the production of one central feeding tube. Such a flow would advance by the single-unit flow mechanism, and as the result of subcrustal drainage a general collapse area would be produced similar to the ones shown in Figure 8. The viscosity and quantity of lava extruded must have been about the same when the lava was advancing over the collapse depression area as when advancing over the general collapse area. Therefore, it seems likely that a difference in the gradient of the floor of the valley may have been responsible for the two different kinds of collapses. A steep slope producing the general collapse area and a flatter slope producing the collapse depression area. However, the gradient cannot have been too flat or the tubes, when lava was no longer supplied to them, would not have been drained to form the tunnels.

Drainage of tubes is a prerequisite for collapse. In order that drainage should occur, the flow of the liquid lava from upstream must stop. Such stoppage may be due either to a failure of extrusion of liquid lava at the source or to the obstruction of the channel of flow at some point upstream. Presumably that part of the tube nearest the source or obstruction would be emptied first, and as drainage proceeded the open tunnel would extend itself downstream.

In the triangular area around the kipuka (Fig. 3) the basalt flow probably advanced by means of a number of tongues which coalesced to form this broad triangular lava plain. As depressions are not common above the triangular area, it would seem as if a plugging of the tubes in this area might have been responsible for the drainage of the lava tubes downstream. As the tubes in the triangular area would be smaller than where the flow advanced as one tongue, and as many of them had to make a sharp turn in their progress down the valley, it seems likely that they might have become plugged. No significant collapse occurred between the triangular area and the collapse depression area because the roof was strong enough to support itself.

TIME OF DRAINAGE OF TUBES

The roof of only one lava tunnel (Fig. 8) was more or less completely collapsed indicating that the crust had considerable thickness at the time of the withdrawal of the lava from the lava tubes. Had the crust been only a few inches thick, the roofs over the drained tubes would have everywhere collapsed, and elongated depressions similar to the one marked ABCD on Figure 8 would have been produced. The size and quantity of the blocks found in the bottoms of some of the depressions also indi-
cate a considerable thickness of the crust at the time of the withdrawal. That thick crusts had been formed by the time of withdrawal is further indicated by a cave found in the flow, the roof of which is 8 feet thick. This figure gives only a minimum thickness for the crust at the time of the withdrawal, for the cave has undoubtedly enlarged itself upward by the falling of blocks from the under side of its roof.

If it is assumed that the crust was 8 feet thick at the time of the withdrawal of the lava, that the necessary stiffness had been achieved at 900°C. (Daly, 1933, p. 66), that the flow was 32 feet thick at this point, that the temperature of the top and bottom of the flow was maintained at 0°C., that the initial temperature of the lava was 1200°C. (Verhoogen, 1939; Day and Shepherd, 1913), that the diffusivity of the lava was that assumed by Thomson and Tait (1883), and that the point of slowest cooling was at the middle of the flow; then by using the method and curves of Lane (1898) it is found that approximately 16 days would be necessary to form such a crust. However, if it is assumed that the point of slowest cooling was about a third of the way from the bottom of the flow to the top, as this is usually the true condition according to Prof. A. C. Lane (personal communication), and that 2 feet of the roof had fallen to 900°C. and was therefore practically crystallized, and that the other 6 feet was a stiff glass that could maintain itself at the time of the withdrawal of the lava, then Lane's curves (1898) show that such a roof would have been formed in approximately 17 hours. These calculations assume a closed cooling system during the formation of the crust. However, this was not the case as liquid lava was undoubtedly flowing beneath the crust as it was slowly thickening. This would increase the time necessary to form the crust by a small amount, and because of this fact and the necessity of making so many assumptions this figure should be taken only as indicating the order of magnitude of the time involved.

These calculations indicate that approximately 17 hours elapsed between the arrival of the molten lava at the point where the cave is found and the time when that part of the tube in which the cave is found was drained.

The drainage of this tube caused further advance of the flow down stream and as the end of the flow is 1½ miles from the cave it appears that more than 17 hours were required for the flow to advance this distance. The flow was therefore, moving slowly. Some of the Hawaiian flows have been known to advance so rapidly that no real crust was formed until the front had progressed several miles past the point of crust formation.

**TIME OF FORMATION OF THE DEPRESSIONS**

Collapse of the roofs of lava tunnels may occur long after the drainage of the tubes and complete solidification of the flow (Russell, 1902, p. 101; Williams, 1932).

Some of the depressions on the McCartys flow no doubt have been formed quite recently; indeed, collapse depressions could be produced at the present time if heavy loads were placed on the roofs of some of the existing tunnels. On the other hand, in some localities, collapse occurred while liquid lava was still present and when the under side of the crust was still soft and plastic.

Thus a cavelike collapse depression was found in the McCartys flow which has a
vertical opening about 5 feet in diameter and 5 feet long. The lower 2½ feet of the opening is grooved and striated. These grooves and striations could have been formed only when the lava was soft and plastic. Soon after the lava tunnel was formed, a portion of its roof collapsed. The upper part of the crust was solid, whereas the lower part was still soft and plastic. When the upper solid part of the crust in falling scraped across the lower plastic part of the crust, grooves and striations were produced (Nichols, 1938, p. 607–608). This collapse took place, therefore, after the drainage of the tube and while the lower part of the crust was still soft and plastic, or, according to the calculations above, about 17 hours after the lava first arrived at this point.

The collapse depression labeled E on Figure 8 is of average width and length, but the roof, instead of having collapsed 15, 20, or 25 feet, as is the case with other depressions, has fallen only between 5 and 10 feet. That liquid lava was still present when collapse first occurred is proved by the following: (1) Within and around the margins of this collapse depression are an unusual number of squeeze-ups (Nichols, 1939b) which were extruded from the cracks in the crust produced by the collapse; (2) the squeeze-ups ran toward the depression, showing that they were extruded after the collapse began; and (3) the squeeze-up lava in places has partly buried fragments of the crust broken by collapse.

On the other hand, there appears to have been a small amount of additional collapse after the extrusion of the squeeze-ups, which is indicated by their joint systems and by the fact that these squeeze-ups have been bent downward after their formation. Apparently the collapse occurred while the lava in the tube was slowly being drained away.

The shallow depth of this depression, 5 to 10 feet, may be due to the fact that this tube was not so large as the other tubes, or that drainage was not complete, or that the extrusion of the secondary lava, together with a thickening of the crust by the addition of lava from below, within a brief interval after the initial collapse may have so stiffened the crust that significant additional collapse was impossible.

VOLUME OF THE DRAINED LAVA

Calculation shows that a drainage of lava equal in volume to about 1900 feet of the lower end of the flow was responsible for the lava tunnels in the “Collapse Depression Area” shown on Figure 8.

COLLAPSE DEPRESSIONS AND KIPUKAS IN CROSS SECTION

The cliff which faces in toward a collapse depression is often overhanging; however, the edge of the lava which surrounds a kipuka does not overhang. In cross section a collapse depression consists of a floor of unbroken lava, the bottom crust of the flow, above which there is a chaotic layer of blocks of lava derived from the collapsed roof of the tunnel. The greater part of the area of a kipuka, on the other hand, contains no lava from the flow which formed it, except possibly a few blocks which rolled off the edge of the flow a short distance into the kipuka. The cross section of a kipuka or collapse depression if buried by a later flow might be outlined by a layer of vesicular lava at the bottom of the later flow.
PRESSURE RIDGES

DESCRIPTION

Pressure ridges are common features on many lava flows. They have been described and photographed by Russell (1902, p. 95–97; 1903, p. 54), Stearns and Clark (1930, Pl. 14A), and others. Some of them are similar to the pressure ridges found on sea-ice (Wright and Priestley, 1922, p. 341–354; Leffingwell, 1919; Stefansson, 1910). Such ridges are the most spectacular feature on the McCartys flow. Those on the last mile of the flow were studied in detail (Fig. 3). The shortest is only 130 feet long, while the longest is more than 1200 feet. They vary in height from 10 to 25 feet and are as much as 100 feet wide. However, the pressure ridges of this area are relatively small, as some of those near the source of the McCartys flow are more than 40 feet high. In transverse section the sides of the pressure ridges are steep, suggesting the gable of a house or the cross section of a broken anticline. In no place was overthrusting of one side of a ridge onto the other observed. These pressure ridges have medial cracks running along the crest of the ridge, shown by Figure 1 of Plate 7, a transverse view of one of the 50 pressure ridges on the last mile of the McCartys flow. These medial cracks are usually less than 15 feet wide. The brittle lava on most of the pressure ridges is also broken up into many secondary cracks (Pl. 7, fig. 2). The lava surrounding this pressure ridge is buried by a thin veneer of alluvium. This ridge, although spectacular, is not so representative of the pressure ridges of the McCartys flow as those which are longer in proportion to their width. Figure 11 shows that its sides are, in places, as steep as 45°; most of the ridges, however, are flatter. The position of this ridge on the last mile of the McCartys flow is indicated by R on Figure 8. Although most of the pressure ridges consist of a single ridge somewhat resembling an esker, many have secondary ridges branching out at various angles (Fig. 8).

The pressure ridges may be divided into two types (Fig. 8): longitudinal pressure ridges with axes more or less parallel to the flow, and transverse pressure ridges with axes more or less transverse to it. The longitudinal pressure ridges are more numerous and longer and in general are close to the margin of the flow. Although the shorter ridges are usually straight the longer ones invariably are gently curved with a sinuous ground plan. In a few places several parallel longitudinal ridges occur, and occasionally they are arranged en echelon (Fig. 8).

Many of the medial cracks of the pressure ridges have a surficial layer or veneer on their walls (Pl. 7, fig. 1). The veneer consists of bands of dark and less-dark material that extends in from the faces of the cracks not more than one eighth of an inch and which are more or less parallel to the surface of the flow. The bands are 1 to 4 inches wide and scores of feet long. The bands consist of glassy lava alternating with bands of duller, less-glassy lava, the whole forming a veneer on the crystalline basalt that normally forms the walls of the cracks. Usually the glass is black but may also be red, purple, bluish black, or green. This banding described by Nichols (1939a, p. 188–191) is undoubtedly due to refusion of the walls by the oxidation of combustible gases emitted from the base of the cracks, the glassy bands being more thoroughly re-fused than the duller bands.
Figure 1. Transverse View of Pressure Ridge on McCarty's Flow
Lava on the walls of the medial crack is banded. Bands can best be seen above and to the right of the rod. Bands should not be confused with lava ropes to right and left of rod.

Figure 2. Longitudinal View of the Pressure Ridge Shown in Figure 1 of Plate 7

Transverse and longitudinal view of pressure ridge.
1. Ropy billowy lava which flowed out of medial crack of pressure ridge.

2. Secondary lava in medial crack of a pressure ridge.
The sides of these ridges are often covered with ropy lava whose orientation and arcuate form bear no relation to the pressure-ridge topography, proving that the ridges formed after the crust solidified. Most of the medial cracks in the pressure ridges are empty, though some are filled in part with secondary lava (Pl. 8). The bulbous shape of the lava extruded from the medial crack of the pressure ridge indicates that it was quite viscous when extruded (Pl. 8, fig. 1). The viscosity was no doubt due to rapid cooling after extrusion because of the small quantity. That the pressure ridges were more or less completely formed at the time of the extrusion of the secondary lava is indicated by its lack of cracks and joints as compared to the lava of the pressure ridges. The absence of secondary lava from many of the medial cracks may be due to one of the following: (1) Liquid lava was no longer present when these cracks were formed; (2) the cracks were not continuous from the top of the crust to the bottom; (3) the lava was too viscous to move up into the cracks; (4) the top of
the liquid lava did not reach the bottom of the medial cracks; (5) the hydrostatic head of the lava was not sufficient to move it up into the cracks.

The medial cracks of many pressure ridges also contain wedges of lava, the thin edges of which point upward. These wedges are vertically grooved and fluted and vary greatly in size. The largest are 30 feet long, 10 feet high, and 4 feet thick at the bottom, while the top is usually about 1 inch wide. They resulted from the extrusion of viscous lava into progressively widening medial cracks (Nichols, 1938, p. 609–613). They indicate, therefore, that liquid lava was present when the pressure ridges which contain them were being formed.

Figure 12 is a cross section along line $CD$ of the pressure ridge shown in Figure 11. It shows that the length of the crust which was buckled to form this pressure ridge was about 87 feet. In the buckling, granulation would take place in the three major joints of the pressure ridge. A reasonable estimate of the depth of the granulation zone is one fourth the thickness of the crust (Fig. 12). The thickness of that part of the crust which was buckled to form this pressure ridge was about 20 feet, as determined by measuring the depth of the medial crack and assuming the depth of the granulation zone to be one fourth the thickness of the crust. The ratio of the length of the buckled member to its thickness is therefore about 4 to 1. A column of concrete, granite, basalt, or any other similar material with a ratio of 4 to 1 will not fail by buckling but rather by shearing or by crushing. The minimum ratio of length to thickness which will yield by buckling is usually said to be about 10 to 1 (Dunham, 1939) and even with this ratio, shearing or crushing rather than buckling is liable to take place. However, if a compressional member has a ratio of 15 or more to 1 it will usually fail by buckling. This ratio applies to perfectly straight, homogeneous, vertical columns. That the lava crust is not perfectly straight should not seriously affect the ratio as the deviation from perfect straightness is never great. Nor should the fact that the crust is cracked and jointed affect it, as these cracks and joints would be closed as soon as the crust was placed under compression. As the crust during the period of solidification was progressively weaker with increasing distance from the surface of the flow, the tendency was for the crust to buckle upward. However, as the
lava crust is a horizontal column, its weight tends to prevent upward buckling. This tends to increase the ratio necessary to insure buckling, but this factor is probably offset by the fact that the nonhomogeneity of the crust tends to lower it. As the lava crust was cracked, jointed, and soft at the bottom, it was undoubtedly considerably weaker than the solid homogeneous basalt used for building purposes; however, this should in no way affect the 10 to 1 ratio.

If we assume that when the crust first started to buckle it had about the same strength as cold basalt, it is found by applying the 10 to 1 ratio to the pressure ridge of Figure 11 that the crust could not have been more than 8 or 9 feet thick. This means that the crust has thickened progressively from about 9 feet to its present thickness of 20 feet since it first started to buckle. Moreover the crust may be more than 20 feet thick because of thickening following the completion of buckling. The grooved squeeze-ups and secondary lava found in the medial cracks of the pressure ridges indicate that the crust was in contact with liquid lava making possible progressive thickening during the period of pressure-ridge formation. That the crust had considerable thickness when buckling first started is indicated by the fact that no secondary lava broke out from the sides of any of the pressure ridges. Moreover, it is doubtful if it could have been less than 6 feet thick at the time of buckling, as a column much thinner than this would break in spans shorter than 87 feet. The depth of the medial crack indicates that the pressure ridge was slowly raised while the crust thickened from 9 to 20 feet. If the pressure ridge had been raised to its maximum height while the crust was 9 feet thick, and if the crust was then progressively thickened to 20 feet, the medial crack would not have had its present depth but would have been about 6 feet deep and similar to the one shown in Figure 13.

By making assumptions similar to those above and using Lane's curve (1898), it is found that several days were required for the crust to thicken from 9 to 20 feet. This means that this pressure ridge was several days in forming, and, as the other pressure ridges are similar in essential characteristics, very likely all the pressure ridges on the McCartys flow were several days in forming.

**CRUSTAL SHORTENING INVOLVED IN FORMATION OF PRESSURE RIDGES**

The difference in length between the sum of lines $AB$ and $CD$ and line $EF$ in Figure 12 gives a figure for the crustal shortening involved in the formation of this pressure ridge.
ridge. This difference indicates a crustal shortening of 3.25 feet. However, this pressure ridge is not only shorter and higher than most of the others, but it contains a wider medial crack, so that 3.25 feet is perhaps too high a figure for the crustal shortening involved in the formation of the average pressure ridge. If 1.5 feet is the probable shortening Figure 8 shows that 2 to 4 feet would be a good figure for the maximum total transverse shortening of the crust involved in the formation of all the pressure ridges. The distribution of the pressure ridges (Fig. 8) and their variation in size and shape indicate that the total shortening of the crust varied somewhat from place to place.

**ORIGIN OF PRESSURE RIDGES**

As these pressure ridges are not to be confused with schollendomes (lava blisters) it is hardly necessary to point out that they could not have resulted from the accumulation of gas pressure beneath the crust or from local hydrostatic pressure exerted by fluid lava beneath the crust.

Bradley (1873, p. 204-205) in discussing the low mounds (probably pressure ridges) on the Snake River Lava's, writes:

"Whatever the source (referring to the lava of the Snake River Plains), the material had evidently become quite viscid; for, at some points, where it ran over small inequalities of the surface beneath, it now stands in low mounds, which would not have been the case if it had been very fluid. That these mounds were not all formed by an undermining and sinking of the surrounding mass, to which some of them have very properly been referred, is proved by the tapering shape of the closely-fitting blocks which form the arch. But there is still room for study on all these points."

That the pressure ridges of the McCarys flow are not the result of the mechanism suggested by Bradley is indicated by: (1) The theory demands an improbable pre-McCarys topography; (2) if such topographic irregularities existed, they would undoubtedly have been buried by the lava without forming surface features on the flow.

That these ridges were not formed by a withdrawal of lava and a collapse of the surface except where supported by pre-McCarys ridges is proved by the following: (1) This theory demands an improbable pre-McCarys topography; (2) the surface of the flow on one or both sides of many of the ridges gives no indication that its present position resulted from collapse; (3) in no place where collapse has occurred on one or both sides of a pressure ridge can the collapse be considered to have formed the ridge; and (4) the fact that the medial cracks are not open at the bottom and that there are no open cracks marginal to the ridges is better explained by compressional forces acting on the surface of the flow than by tension resulting from differential collapse. However, this mechanism has been used to explain certain so-called pressure ridges in ice observed by Wright and Priestly (1922, p.356) in the Antarctic.

In describing the lava of Red Mountain in Lassen Volcanic National Park, Williams (1932) writes:

"Here may be found a remarkable group of collapsed lava tubes, now represented by a series of north-south ridges separated by gullies from 10 to 50 yards in width, partly infilled with angular blocks through the cave-in of tubes . . . . Where the lava tubes are closely spaced, the intervening ridges are roughly V-shaped in section, due to the arching of the lava over the tubes."

That the pressure ridges of the McCarys flow were not formed in this way is suggested by the fact that these ridges are not associated with collapse features.
similar to those described by Williams, and by the fact that ridges formed in this way
would not have medial cracks such as are found in the pressure ridges on the Mc-
Cartys flow.

Russell (1902, p. 95-97), in discussing the pressure ridges of the Snake River Plains,
suggests that they were produced by lateral pressure acting on the surface portion of
the lava flows, arising from the viscous drag of slowly moving subcrustal lava. In
this respect, states Russell, they are similar to the ropy texture so common on the
surface of pahoehoe flows which, as is well known, is due to the viscous drag of slowly
moving subcrustal lava on a plastic crust.

The author believes that the pressure ridges on the McCartys flow are the result of
lateral pressure acting on the crust. Lateral pressure is not the result of viscous sub-
crustal drag on the crust for, if a viscous subcrustal drag were the force that formed
the pressure ridges, one would expect them to be oriented in general transverse to the
direction of the flow. However, the pressure ridges on the McCartys flow are in
general oriented with their long axes parallel to the flow. The size and shape of the
pressure ridges near the end of the flow are similar to those farther upstream. As
the ridges upstream were formed when the crust was several feet thick, a similar thick-
ess is indicated for the crust from which the pressure ridges near the end of the flow
were formed. However, as the flow probably reached its terminal position long be-
fore this part of the crust could have been thickened so much, it would seem that
viscous drag could not have been operative when these ridges were formed. It seems,
therefore, that some other mechanism must be considered as responsible for these
pressure ridges.

Because the crust of the flow was a continuous carapace of solid lava which sur-
rounded the liquid thread, the top crust was everywhere tied to the margins and
bottom of the flow. Before viscous drag could buckle the crust, the top of the crust
had to be sheared free from the margins and this block had to be dragged free from the
top crust of the upstream part of the flow. Then viscous drag would have to move
this block downstream against the unsheared upper crust of the downstream part of
the flow. The downstream part of the dragged member might then buckle itself
against this abutment if the viscous drag were strong enough (Fig. 14). Moreover,
in the early stages of the process the viscous drag would in all probability have to
shear and buckle simultaneously.

The following calculations show that the viscous drag would probably not be strong
enough to shear the top crust from the margins of the flow. If we assume: (1) that
the liquid thread running within the carapace was 25 feet thick (only the upper 12.5
feet of the liquid thread dragged at the bottom of the top crust as the lower 12.5 feet
dragged on the bottom crust); (2) that the specific gravity of the liquid lava was 2.5;
(3) that the crust was 8 feet thick at the time of shear (that the crust was
sheared when it was much thinner than 8 feet and then remained free while the crust:
thickened to 8 feet seems unlikely, as the injection of liquid lava from below into the
shear planes and tension cracks would in all probability refasten the sheared member
back into the carapace); (4) that the gradient of the flow was about 30 feet per mile;
(5) that the viscous drag was equal to that component of the weight of the lava which
acted downstream;—then calculation shows that the viscous drag on the bottom of
an area 1000 feet across the flow and 1 foot up and down the flow was 4.8 tons. To get the total force, we must add to this the component of the weight of the dragged unit of crust which acted downstream. If the specific gravity of the solid crust was 2.5, then this force is 3.10 tons. The total shearing force is therefore approximately 7.9 tons. As the dimensions of the planes at the two margins of the flow which must be sheared by the unit area under consideration are 8 feet by 1 foot, the total area to be sheared is 16 square feet. The force acting on each square foot is therefore approximately .5 ton. The shearing strength of good quality basalt used for building purposes is probably about 150 tons per square foot (Merriman and Wiggin, 1930). Although the crust was undoubtedly jointed, cracked, and hot on the bottom, it seems very unlikely that its shearing strength was as low as .5 ton per square foot. As the viscous drag would always be lower than that calculated, and as no allowance was made for the fact that the crust had to be pulled apart and probably buckled while it was being sheared, these calculations show that there is a very strong probability that viscous drag cannot shear the crust and therefore could not have formed the pressure ridges.

If, however, we assume that a block of the top crust could be sheared from the margins and dragged free from the crust upstream, then the following calculations show that buckling could not have taken place.
If we assume that the block which was dragged and which buckled on its downstream end was 12,000 feet long, 1000 feet wide, and 8 feet thick, then the total force acting at the end of the block would be 94,800 tons. This force would be applied on a surface 1000 feet wide and 8 feet deep so that the pressure would be approximately 11.8 tons per square foot. As the end of the flow is not straight (Fig. 8) the component of the drag which is effective in buckling the downstream end of the block must be considerably less than the total drag. The compressive strength of good quality basalt used for building purposes is approximately 1400 tons per square foot (Merriam and Wiggin, 1930). In view of this, it seems unlikely that the compressive strength of the crust was as low as 11.8 tons per square foot, so that these calculations indicate that viscous drag could not buckle the crust and therefore the pressure ridges could not be formed in this way.

DOMICAL THEORY FOR ORIGIN OF PRESSURE RIDGES

While lava was supplied from upstream to the lava tubes in the collapse depression area, the front of the flow advanced down the valley. A time finally came, however, when lava was no longer supplied to these tubes. At this time the flow, in the pressure ridge area, undoubtedly had steep marginal sides and a flat top. This is suggested by the fact that this type of cross section is found along practically the entire extent of the flow. Following this, the lava in the tubes slowly drained away. Possibly most of this lava made room for itself by doming up that part of the flow which is now occupied by the general collapse area (Fig. 8). The marginal portions of this part of the flow were not domed as the crust was too rigid. During the formation of the dome, tension cracks tended to form from which liquid lava might have been extruded. This secondary lava was not found, however, as that part of the flow where it would be expected is in large part covered with alluvium.

While the dome was forming the crust tended to slide down the sides of the dome. This sliding force was greatest when the dome was highest, and the tendency to buckle because of this sliding was greatest at the bottom of the dome. The sliding of a lava crust on viscous subcrustal lava has been described by Daly (1925, p. 18–20), and it results in the buckling of the crust downstream and in the formation of tension cracks upstream. The buckling might produce pressure ridges; however, no tension cracks or trenches formed as the result of the pulling apart of the crust at the top of the dome were found. It will be shown below that the force resulting from the tendency to slide on a dome of any reasonable height is not strong enough to buckle a crust of the necessary thickness.

When the crust was between 6 and 9 feet thick the lava in the dome started to drain downstream. Continued drainage left more and more of the dome unsupported. Finally the crust could no longer support itself and collapse took place. However, the crust was too wide to accommodate itself to its new position and it buckled near the margin of the dome. Continued drainage caused continued collapse and the ridges formed by the buckling slowly grew. Whether the dome fell gradually or with a series of jerks would depend upon the way the lava was drained and upon the strength of the crust. As the pressure ridges were days in forming the lava must have drained very slowly from under the dome. The variations in the size and shape
of the pressure ridges resulted because the crust was not homogeneous and the dome varied in dimensions from place to place. As the highest part of the dome would produce on collapse the greatest shortening, the pressure ridges marginal to this area should be more numerous or higher than elsewhere. The collapse of such a dome would result in compressional forces perpendicular to its margin; the pressure ridges formed would therefore in general be parallel to the margin of the dome. That the ridges should be close to the margin of the dome is due to the following: (1) The compression resulting from collapse is at a maximum near the margin; (2) the compression resulting from sliding is also at a maximum near the margin; and (3) the hydrostatic pressure of the liquid lava, which is directed vertically and therefore aids buckling, is also at a maximum in the area marginal to the dome.

Finally, the dome became flat and the pressure ridges reached their maximum size. Further drainage produced the general collapse area and was responsible for the fact that a few of the pressure ridges have in part fallen into collapse depressions. As the crust was in tension rather than in compression at this time, the medial cracks of some of the pressure ridges may have slowly opened, so that the liquid lava which was still present below could be intruded, forming the grooved squeeze-ups and the fluid secondary lava. The thickness of the grooved squeeze-ups at their bases indicates the amount of separation of the sides of the pressure ridges which took place during this period of relaxation.

In many places the grooved squeeze-ups and the secondary lava filling the medial cracks are higher than either the present general collapse area or the initial position of the crust. However, the collapse from the horizontal position to the present position probably could have squeezed up the liquid lava to this height. Moreover, the squeeze-ups and the secondary lava may have been formed when the dome was high. Although in general the medial cracks would be closed at this time, yet parts of some of them might have opened, especially if there was any lateral movement of one side of the pressure ridges past the other and if the medial cracks were not straight. The height of the squeeze-ups and secondary lava can easily be explained by this mechanism as the lava in the dome would be higher than the pressure ridges. The medial cracks are not straight and it seems likely that some lateral movement of the sides of the pressure ridges did occur during growth.

Figure 15 is a series of sketches illustrating the formation of these pressure ridges. A is the initial cross section of the flow. B is the cross section after the dome was formed. The formation of embryonic pressure ridges marginal to the dome due to partial collapse is shown in C. D represents a more advanced stage of collapse, while E is the final stage—the general collapse area, the pressure ridges, and the grooved squeeze-ups have been formed, and the flow is completely solidified.

The pressure ridges which are marginal to the flow and lined up longitudinally with it were formed by compressional forces acting transverse to the flow, which resulted from the collapse of the dome. Compressional forces acting longitudinal with the flow were also produced by the collapse of the dome. These forces would form pressure ridges transverse to the flow. Those ridges which are transverse to the main direction of the flow and near the area labeled S on Figure 8 were formed by compressional forces resulting from the collapse of that part of the dome which faced
PRESSURE RIDGES

A. Initial cross-section of flow

B. Cross-section after formation of dome

C. Dome partially collapsed. Embryonic pressure ridges formed.

D. Additional collapse. Further growth of pressure ridges.

E. Additional collapse. Formation of general collapse area. Complete solidification of flow.

Figure 15.—Formation of pressure ridges by collapse of dome

upstream. The alignment of several of these ridges is difficult to explain by the collapse of the dome; however, the cracks, joints, and general heterogeneity of the crust are probably responsible. The ridges labeled L on Figure 8 which are nearest the end of the flow resulted from the collapse of that part of the dome which faced down-
stream. Those labeled \( K \) (Fig. 8) resulted from a buckling of the crust of the top of the dome. This may have been due to the fact that the crust was weaker here than elsewhere and therefore buckled when collapse occurred; or they may have been formed because the dome was lower here than elsewhere and was therefore subjected to compressional forces directed against it from the higher portions of the dome. The formation of the pressure ridges at \( K \) on the downstream side of a collapsed dome is an alternative hypothesis. Following the collapse, a smaller dome was formed downstream, the collapse of which produced those labeled \( L \). The drainage of these two domes would produce the two general collapse areas separated by the ridges at \( K \).

The drainage of the smaller dome advanced the flow to its present terminal position. This hypothesis is, however, not favored, as the other explains the facts and is simpler. In a part of the pressure ridge area as shown in Figure 8, the ridges are found on only one side of the flow. If the crust was stronger on one side of the dome than on the other in this area—and this might well be the case—collapse probably would have produced pressure ridges only on the weak side. The volume of lava downstream from the pressure ridges labeled \( L \) should be at least as great as the volume of lava which drained from the dome. The following calculations show that this is probably the case. If we assume that the dome was 800 feet wide (it might have been narrower), 4000 feet long, and 27 feet high at its highest point, and that it rose gradually from its margins to its highest point, then the volume of the dome together with the lava, the drainage of which produced the general collapse areas, was about 30,000,000 cubic feet. The volume of the visible lava downstream from the pressure ridges at \( L \) is also approximately 30,000,000 cubic feet, and there is undoubtedly a considerable volume which has been buried by alluvium.

The following facts suggest that the existence of this dome was possible: (1) Schollendomes may be as much as 100 feet long and 15 feet high. Daly (1933, p. 155) believes that they are due to the hydrostatic pressure of the subcrustal liquid lava. If he is correct, the dome postulated for the origin of these pressure ridges is a very large schollendome. (2) Because the cross section of the flow shown in Figure 4, \( F \) is the result of hydrostatic pressure by subcrustal lava, belief is strengthened in the existence of the dome the collapse of which is thought to have formed the pressure ridges.

Several parallel ridges which are longitudinal to the flow are shown in Figure 8. If the ratio of the length to the thickness in a compressional member is 10 or 15 to 1, it will generally fail by buckling. This means that wherever the width of the area under compression was more than 30 or 40 times the thickness of the crust at the time of buckling, two or more parallel pressure ridges might have been formed if the compressional forces were strong enough to cause buckling. Whether these parallel ridges were formed contemporaneously or whether those nearest to the center or nearest to the edge were formed first cannot be analyzed, as the strength of the crust and the way in which the dome collapsed are not known.

Many of the pressure ridges are sinuous in ground plan (Fig. 8). The lines of equal strength in the flow would at no time be straight because the margin of the flow is not straight, the thickness of the flow is not uniform, and the joints and cracks in the crust are irregularly distributed. Moreover, the outward thrust of the unsupported dome
Pressure ridges would vary from place to place because the height and width of the dome would vary and because the thickness of the crust in the dome would also vary. The combination of these factors would result in pressure ridges with a serpentine ground plan.

An analysis of the distribution of the pressure ridges indicates that the dome would have to be about 800 feet wide and nearly a mile long in order to account for them. The approximate outline of the dome is shown by dotted lines in Figure 8. The pressure ridges involved a crustal shortening of 2-4 feet. If the dome were 27 feet high with a base 800 feet wide, the distance along the dome would be about 802 feet. The collapse of this dome would produce then about 2 feet of shortening. If the dome were 38 feet high, 4 feet of shortening would result on collapse. A dome, therefore, between 27 and 38 feet high could account for the necessary shortening on collapse.

The pressure at the base of the dome due to the sliding action of the crust over the liquid lava is calculated by resolving the vertical weight of the crust into components—one perpendicular to the surface of the liquid lava and one parallel to it. The force parallel to it is the one tending to buckle the crust at the base of the dome. If we assume a frictionless base under the crust, a dome 27 feet high with a base 800 feet long, a specific gravity for the solid basalt of 2.5 (low because of vesiculation), and that the crust of the dome was about as thick as that where the pressure ridges were formed, calculation shows that this force would be about 2.1 tons per square foot. The crushing strength of basalt is about 1400 tons per square foot. As the crust of the flow is jointed and cracked, a good figure for its crushing strength is probably about 350 tons per square foot. Although the force necessary to buckle the crust was much less than the crushing strength of the material (Timoshenko and MacCullough, 1935, p. 259-271, p. 278-282), it could hardly have been as low as 2.1 tons per square foot. These calculations show, then, that the sliding force on a dome 27 feet high is insufficient to buckle the crust and form these pressure ridges. If the dome were 38 feet high, the sliding force would still be too small to cause buckling, as it would be only about 3.0 tons per square foot.

The dome is supported only by the sides of the flow after the drainage of the liquid lava from beneath it. An arch is therefore formed, the abutments of which are the sides of the flow. As the crust is thickest at the sides of the flow, due to more rapid cooling, it seems reasonable to suppose that these abutments were strong enough to carry the horizontal thrust of the arch.

If it is assumed that the specific gravity of the solid crust was 2.5, that the crust was 8 feet thick throughout the dome, and also at the point of buckling at the base of the dome, that the dome was 800 feet wide and 27 feet high, then the average pressure at the base of the dome as computed by the method of analysis of a three-hinged arch, assuming hinges at the crown and at the abutments, is found to be about 232 tons per square foot. As the thrust at the base of the dome probably does not act at the center of the crust, the pressure at the top of the crust is likely to be at least twice the average pressure or 464 tons per square foot. As the crushing strength of the crust was probably about 350 tons per square foot and as the force necessary to cause buckling was much less than the crushing strength, it is apparent that the dome when unsupported would collapse and buckle the crust. If the dome
were 38 feet high, the average pressure at the base would be 165 tons per square foot. Such a dome might well collapse, but there is less certainty of collapse than in a dome 27 feet high. While this method of analysis is not exact, it should give approximately the correct amount of thrust at the base of the dome; moreover, the available data do not justify a more exact computation.

SUMMARY

(1) The McCartys flow is approximately 30 miles long and several miles wide near its source; it has an area of approximately 119 square miles. The last 6 miles is between 30 and 40 feet thick. If the average thickness of the whole of the flow is taken as 75 feet, the volume is approximately 1.7 cubic miles.

(2) The flow is in the main unweathered, uneroded, bare, and barren. The Acoma Indians have a legend that the flow covers land their ancestors tilled. Pueblo I potsherds have been found in a valley fill which is probably buried by the flow. This indicates that it was extruded within the last 1200 years.

(3) Because the flow is not eroded, minor features such as grooved lava, squeeze-ups, ropes, spatter cones, tree molds, cracks, banded lava, and cavities are still present.

(4) The extrusion of the McCartys flow apparently diverted drainage from the Rio San José into the Rio Salado and Little Colorado. The Rio San José is in Atlantic drainage, the Little Colorado in Pacific.

(5) The presence of flow units, revealed physiographically, of tongues at the end of the flow, and of miniature flow units, and the orientation of the ropes, all indicate that in places the flow moved by the flow-unit mechanism. The varying thickness of the flow indicates that its velocity varied from place to place.

(6) The distribution of tree molds indicates that the climate at the time of extrusion was similar to that of the present.

(7) In an area approximately 2 miles long, near the terminus of the flow, there are about 100 collapse depressions. The largest depression is nearly a mile long and in places more than 300 feet wide, whereas the smallest is only a few feet in diameter. These depressions have been formed by the collapse of the roofs of lava tunnels. Analysis of the probable strength of the roofs of lava tunnels indicates that they owe their origin not to the collapse of one large tunnel but to the partial collapse of several small tunnels. Although many of the depressions may have been formed quite recently, in some cases collapse occurred while liquid lava was still present and the under side of the crust was still soft and plastic.

(8) On the last mile of the flow pressure ridges are very common. The shortest are about 130 feet long while the longest are more than 1200 feet. They are from 10 to 25 feet high and as much as 100 feet wide. In transverse section the sides of the pressure ridges are steep, resembling the gable of a house or the cross section of a broken anticline. They have a medial crack, running along the crest of the ridge, which may be as much as 15 feet wide. They are, in general, parallel to the flow, and close to its margin. That these pressure ridges were formed when liquid lava was still present below the crust is proved by the fact that some of the medial cracks
are filled in part with secondary lava which welled up into them after the formation of the ridges. It is suggested that the collapse of a dome between 27 and 38 feet in height, due to withdrawal of lava from beneath it, resulted in the compressional forces which buckled the crust and produced the pressure ridges.

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