THE KEWEENAWAN LAVAS OF LAKE SUPERIOR,
AN EXAMPLE OF FLOOD BASALTS*

WALTER S. WHITE

U. S. Geological Survey, Beltsville, Maryland

ABSTRACT. Individual lava flows of Keweenawan (late Precambrian) age in the Lake Superior basin are characterized by volumes that may exceed 100 cubic miles and by original surface slopes of the order of 10-20 feet per mile or less. In these respects they differ greatly from the flows of shield volcanoes from which so much of our knowledge of lava flowage stems. The volumes are estimated from field measurements. The slopes are estimated by subtracting reasonable initial dips of interbedded conglomerate beds (obtained by comparison with modern fan deposits of similar coarseness) from the angle between top and bottom of flows overlying conglomerate beds, since the lava flows and the gravel-depositing streams are believed to have flowed in opposite directions. Difference in volume alone seems adequate to explain a number of the physical differences between the Keweenawan flood basalts and those of shield volcanoes without appeal to differences in composition, volatile content, or temperature.

INTRODUCTION

As has often been observed, flood-basalt flows differ from the flows of shield volcanoes both in volume of lava and in slope. Since so much of what we know about the flow of lava comes from the keen observations of students of active shield volcanoes, one may be tempted, for lack of comparable observations on active basalt floods, to assume more similarity in mechanism than actually exists. It may be worthwhile, therefore, to make some quantitative comparisons between a group of flood basalts and the flows of shield volcanoes, and to note, if only briefly, some implications of the differences.

The mafic lavas of middle Keweenawan age in the Lake Superior region are one of the world’s major accumulations of plateau or flood basalt flows. Estimates of the thickness of the lava series range from 20,000 to 30,000 feet, and the total volume of lava must exceed 100,000 cubic miles. These mafic lavas have been arched downward to form a gigantic syncline, the Lake Superior basin or syncline, whose trough is now occupied largely by the lake itself. The rocks generally dip 25°-70° N. on the south limb and southward at somewhat lower angles on the north limb.

In the Michigan Copper district, on the south limb of the basin, the lava series consists of at least 200 flows, with a few beds of rhyolite conglomerate between some pairs of flows. Many of the stratigraphic units (flows and groups of flows) are remarkable for their persistence and uniform thickness (fig. 1).

VOLUME OF LAVA IN INDIVIDUAL FLOWS

The thickest flow in the Michigan Copper district is the Greenstone flow (Cornwall, 1951, p. 164-166), which has a maximum thickness of more than 1,400 feet and is demonstrably more than 1,000 feet thick for a distance along the strike of 27 miles. It averages more than 200 feet thick for an additional 20 miles. This flow also crops out on Isle Royale (Lane, 1898, p. 99-102), across the basin 50 miles away, where it averages 300 or more feet thick for a strike length of over 42 miles. Ignoring the probability that the thickest part of the flow is beneath the lake, the volume of lava in this flow is more than 200 cubic miles by very conservative estimate.

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Another flow, the Scales Creek ophite (White, Cornwall, and Swanson, 1953), is almost certainly persistent for a strike length of more than 55 miles, and its thickness, which is relatively constant, averages about 200 feet. If its areal extent even approaches the square of its strike length, the volume of lava is of the order of 100 cubic miles.

In the Michigan Copper district as a whole, 37 percent of the total volume of lava occurs in flows more than 100 feet thick, and 12 percent in flows more than 200 feet thick. A number of flows of this general size appear to be persistent with relatively constant thickness for distances of at least 25 to 30 miles, although one cannot normally prove this persistence for each flow individually because of the weaknesses inherent in correlating from drill hole to drill hole (fig. 1). But a flow only 100 feet thick covering an area 25 miles square has a volume of more than 10 cubic miles, and there are many tens, if not hundreds, of such flows in the Lake Superior basin as a whole.

That these volumes are not excessive for plateau lava flows may, perhaps, be shown best by an illustration from the Columbia Plateau. Waters (1955, p. 708) describes a flow 360-480 feet thick that can be traced 120 miles north-south and 50 miles east-west; the volume of lava in this flow may be conservatively estimated to be of the order of 300-400 cubic miles.

**SLOPES**

Although it is, of course, impossible to measure directly the original slopes of the tilted Keweenawan lava flows of the Lake Superior region, these slopes must have been very gentle—probably no more than 10 or 20 feet per mile—to satisfy certain limiting conditions that can be measured. Two factors that help define these limiting conditions are the fact that stratigraphic units thicken towards the center of the basin, and the evidence that the direction of slope was periodically reversed.

**Thickening towards the center of the Lake Superior basin.**—Thickening of stratigraphic units toward the center of the Lake Superior basin was conclusively demonstrated some years ago by measurements in the mine workings...
of the deep Calumet and Hecla mine (Butler, and others, 1929, pl. 20). Although the measurements of rate and direction of thickening that can be made at this mine may long remain the best in the entire Lake Superior region, they can be supplemented by others of somewhat poorer quality over the much larger area in which there has been extensive drilling and underground exploration. All these measurements point to the same general conclusion: the rate of thinning in the Michigan Copper district, if persistent to the south, is such that the middle Keweenawan lava series must wedge out completely within 15 to 20 miles south of the present line of outcrop of the lava series. The picture of a basin subsiding as it was filled seems established beyond any reasonable doubt.

_Evidence for periodic reversals of slope._—Bent pipe amygdules at the base of lava flows are fairly common in the Michigan Copper district, and show that the prevailing direction of lava movement was towards the margin of the Lake Superior basin (Butler, and others, 1929, p. 26). Conglomerate and sandstone beds between some of the lava flows, on the other hand, seem to have been deposited by streams flowing in the opposite direction (White, 1952, 1957). The evidence is based primarily on imbrication of pebbles in three different conglomerate beds, and on scattered observations of cross-lamination. In addition, the thick (3,000-5,000 feet) conglomerate formation above the lavas, which has the same general suite of pebbles as the interflood conglomerates, was definitely deposited by streams flowing toward the basin, as shown by imbrication, changes of facies, local abundance of pebbles of pre-Keweenawan rocks, and more than 250 measurements of foreset lamination. Although four different authors have briefly mentioned cross-bedding that suggests stream flow toward the margins of the basin (Hotchkiss, 1923, p. 672; Butler, and others, 1929, p. 26; Aldrich, 1929, p. 111; Sandberg, 1938, p. 820), these exceptions to a more general trend of drainage toward the basin can probably be explained as local irregularities due to meandering or diversion of streams by lava.

The evidence for basinward flow of streams, contrasted with evidence that the lavas flowed toward the margins of the basin, shows that there were, at times, reversals of the prevailing slope over large areas. These reversals permit one to set rather stringent limits to the original surface slopes of the lava flows.

_Slope of Keweenawan lava flows._—The writer has suggested elsewhere (White, 1957, p. 6) that an imperfect balance between downwarping of the Lake Superior basin and filling of the basin by lava may have been responsible for the apparent reversals of slope. According to this interpretation, the lava was horizontal or sloped gently toward the margins of the basin as long as filling kept pace with downwarping. When extrusion was interrupted, however, downwarping produced basinward slopes over small to large areas. If this mechanism is correct, the angle between a conglomerate bed and the top of the immediately overlying flow is equal to the arithmetic sum of the initial dips of conglomerate bed and lava flow. At the time when deposition of a conglomerate bed was interrupted by renewed outpouring of lava, the conglomerate bed still had its initial dip, and the lava surface presumably had a small, but unknown slope in the opposite direction from that of the conglomerate. We could determine this unknown slope of the lava surface by subtraction if we
could (1) measure the angle between the top and bottom of a number of flows that overlie conglomerate beds, and (2) determine the approximate initial dip of the conglomerate beds.

The angle between the top and bottom of flows immediately overlying conglomerate beds can be measured in sections more or less normal to the axis of the Lake Superior basin at several places in the Michigan Copper district (table 1), although the data available are not as numerous or reliable as one might wish. Insofar as possible, the effect of local irregularities has been reduced by averaging a number of measurements, or, under still more favorable conditions, by making an isopach map of the flow and determining the angle from the spacing of contours.

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Column A. Name of underlying conglomerate bed (see White, Cornwall, and Swanson, 1953; or Butler, and others, 1929, pl. 15).

Column B. Angle between top and bottom of flow (ft/mi).

Column C. Average thickness of flow (ft) in area of measurement.

Column D. Method of measuring; a numeral gives number of drill holes involved where measurement was between pairs or groups of deep and shallow drill holes, respectively.

Column E. Relative reliability of measurement.

The angle between top and bottom of the flows listed in table 1 ranges from 0 to 85 feet per mile. The Wolverine sandstone is a fine-grained sandstone, and may well have been essentially flat when deposited. The surface of the flow above it, therefore, probably had initial dips ranging from 0 to 20 feet per mile. From all the other angles, however, one must subtract an unknown amount for the initial dip of conglomerate beds in order to obtain the initial dip of the flows. According to the data of the table, this initial dip of the conglomerate beds was no more than 85 feet per mile (about 1 degree), and is therefore much less than the 3 degrees once suggested by the writer in an attempt to explain a peculiar characteristic of the imbrication in a conglomerate bed (White, 1952, p. 197). Although there are clearly too many unknowns to venture a calculation of the dip from hydrologic formulae, analogy with modern or near-modern conglomerates may be helpful.

The interflow conglomerate beds of the Michigan Copper district may be briefly characterized as follows: they are sheetlike bodies with lateral dimen-
visions that range from a few feet up to tens of miles, and thicknesses that range from a fraction of an inch up to several tens of feet (thicknesses in excess of 50 feet are uncommon); pebble conglomerate with a median particle size in the general range of 1-4 inches is very common, and boulders up to 3 feet across are found in some of the coarser grained beds. It might be pointed out, in passing, that the conglomerate beds (Alouez and Kingston) beneath the two flows with the largest angles in table 1 are among the most persistent and coarse grained of all the interflow conglomerate beds. The upper parts of conglomerate beds are not characteristically more silty or sandy than the lower parts. This suggests that the beds were deposited in some environment like an alluvial fan where aggrading streams sweep back and forth across the surface in very shallow channels, rather than in an environment of gentler slope such as (1) the flood plain of a river, where the gravel of the bed load in the channel is generally blanketed by finer grained material in the stream banks and on the surface of the flood plain (Hack, 1955, p. 33-35; Schlee, 1957, p. 1396-1398), or (2) the lower, very gently sloping part of a piedmont fan, which has the same general characteristics (Eckis, 1934, p. 87-88).

Gravel comparable in coarseness to the interflow conglomerate beds is generally associated, on fans, with slopes greater than 1 degree (about 92 feet per mile). On a fan 4 miles long in the Santa Catalina Mountains of Arizona, Blissvenbach (1952) found slopes of 1 degree associated with maximum pebble sizes of only 12 inches (30 cm). On three smaller fans in the same region, the material was even finer grained at this slope. The gravel fans of the Elkton area, Virginia (King, 1950, p. 58-62, pl. 1), which are presumably representative of fans 2-3 miles long in a fairly humid region, have slopes that are almost everywhere more than 100 feet per mile.

On larger fans, Eckis (1934) found slopes as low as 90 feet per mile at a place where the maximum pebble size was about 30 inches; the median size in a measured sample (Sample G81, Eckis, 1934, Appendix) from approximately, if not exactly, this same locality, was about 1 inch (16-32 mm).

Although no gravels of recent origin have been deposited in an environment that is directly comparable to that of the interflow conglomerates of the Michigan Copper district, it seems safe to conclude from the observed relationships between slope and pebble size in modern fans—probably their nearest counterparts—that the slopes of the streams of middle Keweenawan time were at least several tens of feet per mile. Deducting such gradients from the angles of table 1 leaves little, if any, remainder for the initial dips of many of the flow tops. The flows, therefore, had very low gradients indeed, probably in the general range of 0 to 20 feet per mile. Judging from the persistence and uniform thickness of many flows and conglomerate beds (fig. 1), the areas over which such low gradients were characteristic were many tens, if not hundreds of square miles in extent. Very thick and widespread flows like the Greenstone flow probably had almost horizontal surfaces over areas of several thousand square miles.

**VOLUME, SLOPES, AND MOTION OF THE FLOWS OF SHIELD VOLCANOES**

The average volume above sea level of the 20 largest historic flank flows
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of Mauna Loa and Kilauea (Wentworth and Macdonald, 1953, p. 31) is 0.037 cubic mile, and the volume of the largest flow is 0.11 cubic mile. If nine-tenths of the largest flow were below sea level, its volume may exceed a cubic mile. Even the famous 1783 flow from the Laki fissure in Iceland is estimated to have a volume of only 3 cubic miles, plus another cubic mile expelled as ash, lapilli, and bombs (Thoroddsen, 1925, p. 60). Compared with historic flows from central or shield volcanoes, therefore, plateau lava flows like those of Michigan or the Columbia Plateau can demonstrably attain volumes an order of magnitude or two larger, and it is only one's imagination that sets an upper limit to their possible size.

The slopes of shield volcanoes are steep compared with the surfaces of plateau lavas. The slopes of Mauna Loa are mostly between 600 and 400 feet per mile, except close to sea level. Over most of the island of Hawaii, gradients are more than 200 feet per mile, and gradients of less than 100 feet per mile are of only local extent, as in saddles or along the crests of rift zones. Where the main 1783 flow from the Laki fissure in Iceland poured out on a coastal flat 30 miles and more below its source, an area of about 20 square miles has an over-all gradient as low as 10 feet per mile (gradients scaled from topographic maps), although over most of the coastal flat, 15-20 feet per mile is a more common gradient. The gradients between the coastal flat and the fissure itself are much steeper. Only locally, therefore, do the flows of shield volcanoes have slopes as gentle as those that seem to characterize flood basalts.

Motion of lava on shields necessarily ceases on relatively steep slopes. In an flows, the center becomes increasingly crystalline and too viscous to move, and the whole flow stops. Pahoehoe flows of shields, during their extrusion, are normally covered by a continuous crust a short distance downstream from their vents; because the steep slopes of shields tend to make the flows both thin and narrow, this crust soon becomes anchored. Whereupon movement of lava becomes increasingly confined to tunnels and the configuration of the flow as a whole is frozen.

MECHANISM OF BASALT FLOODING

The principal consequence of the great volume of lava floods is that on a relatively flat surface a flow may come approximately to rest while its interior, at least, is still molten, giving the top time to approach a hydrostatic level (Sandberg, 1938, p. 818). The near-level surface of such a flow provides the floor for a succeeding flow, making the upper and lower surfaces of successive flows nearly parallel over large areas (fig. 1). As envisaged here, the formation of a basalt flood has its closest observed counterpart in the initial burst of lava from vents on shields. The great volume of lava and the gentle slope keep the flow thick, molten, and exceedingly wide, and do not permit the top to become anchored or tunnels to form. Motion stops primarily because the lava is ponded, either against an uphill slope or behind the dam of its own frozen margin. After eruption ceased, there would, of course, be some movement of lava from central to marginal parts of the flow, and some local advances of the front itself as long as the leveling process continued, but these movements would be minor compared with those of the initial flooding. The
crystallization of a large part of the interiors of flows would thus take place under essentially static conditions.

CONCLUSION

The large volume of the flows and the probability that they crystallized in good part after movement ceased explain certain characteristics of the Keweenawan lavas that distinguish them from Hawaiian-type lavas. Among these may be listed (1) the fact that flows thin, rather than thicken, in the direction of flow: (2) the apparent absence of lava tunnels; (3) the differentiation shown by many flows (Broderick. 1935; Cornwall. 1951); (4) the complete lack of true tripartite aa flows (Wentworth and Macdonald. 1953. p. 59-62), and the abundance, instead, of flows that are fragmental only at the top (upper 18 percent of flow, on the average) and not at the bottom, and whose rubbly tops are composed of material that appears to be broken-up vesicular pahoehoe crust rather than spinose aa fragments. Columnar jointing, relatively rare in the Keweenawan lavas but exceedingly common in the Columbia River and other plateau lavas, might be added to this list. The first four characteristics, at least, seem to be independent of the composition of the Keweenanwan lavas, which mainly range from olivine basalt to andesite (Cornwall. 1951. p. 193-196). It is beyond the scope of this paper to inquire into the reasons why flood basalt flows like those of Michigan may have generally been about two orders of magnitude larger than those of shield volcanoes, but it seems entirely possible that this greater volume alone, rather than greater fluidity (Washington. 1922. p. 766, 803) due to differences in composition, volatile content, or temperature at the vent, is responsible for the major physical differences between the two types.

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REFERENCES CITED