



The basalts of Yellowstone Valley, southwestern Montana
by John Harold Bush

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Applied Science
Montana State University
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Abstract:

Remnants of the basalts of the Yellowstone Valley follow the general northeast trend of the valley for a distance of eleven miles from Point of Rocks to Emigrant, Montana. These basalts lie unconformably on gravels which in turn rest unconformably on late Miocene-early Pliocene sediments. Two flows can be distinguished and are designated as flow A (older) and flow B (younger). A K-Ar date of 8.4 m. y. for flow B indicates an early Pliocene age.

Flow A contains labradorite, augite, and olivine phenocrysts. In most places it is zoned, having light-gray basalt on top and bottom and dark-gray basalt in the center. The basalt is columnar: larger columns typify the outer zones, smaller columns the central zone. In places, inclined columns in the center indicate local movement of the flow after partial cooling.

Distinctive ophitic texture in the outer zones becomes less ophitic towards the center where the augite crystals are smaller and both augite and olivine more altered. Trappings of gases probably caused deuteric alteration, producing these changes in the central zone.

Flow B is columnar, black to dark-gray, commonly containing scattered plagioclase and olivine phenocrysts. The basalt exhibits non-ophitic texture characterized by a high content of magnetite and/or magnetite-rich glass.

Upstream, basalts cap a bench near the town of Gardiner. Five flows crop out at each end of the exposure. Comparisons suggest that six flows are represented. The upper two are similar to the basalts of flows A and B and may be erosional remnants of the same flows.

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SOUTHWESTERN MONTANA

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A thesis submitted to the Graduate Faculty in partial
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J.H.B.

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BASALTS OF THE YELLOWSTONE VALLEY,
SOUTHWESTERN MONTANA

ABSTRACT

Remnants of the basalts of the Yellowstone Valley follow the general northeast trend of the valley for a distance of eleven miles from Point of Rocks to Emigrant, Montana. These basalts lie unconformably on gravels which in turn rest unconformably on late Miocene-early Pliocene sediments. Two flows can be distinguished and are designated as flow A (older) and flow B (younger). A K-Ar date of 8.4 m. y. for flow B indicates an early Pliocene age.

Flow A contains labradorite, augite, and olivine phenocrysts. In most places it is zoned, having light-gray basalt on top and bottom and dark-gray basalt in the center. The basalt is columnar: larger columns typify the outer zones, smaller columns the central zone. In places, inclined columns in the center indicate local movement of the flow after partial cooling.

Distinctive ophitic texture in the outer zones becomes less ophitic towards the center where the augite crystals are smaller and both augite and olivine more altered. Trappings of gases probably caused deuteric alteration, producing these changes in the central zone.

Flow B is columnar, black to dark-gray, commonly containing scattered plagioclase and olivine phenocrysts. The basalt exhibits non-ophitic texture characterized by a high content of magnetite and/or magnetite-rich glass.

Upstream, basalts cap a bench near the town of Gardiner. Five flows crop out at each end of the exposure. Comparisons suggest that six flows are represented. The upper two are similar to the basalts of flows A and B and may be erosional remnants of the same flows.

BASALTS OF THE YELLOWSTONE VALLEY,
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INTRODUCTION

Location

The basalts of the Yellowstone Valley are located 25 to 35 miles south of Livingston in Park County, Montana. Outcrops of basalt follow the general northeast trend of the valley, capping mesas, buttes, and benches on both sides of the Yellowstone River. The outcrops extend for a distance of eleven miles from east of Point of Rocks northward to Emigrant, Montana (Figure One). Many of the basalt outcrops can be seen along U.S. Highway 89 which connects Gardiner with Livingston. The most complete section is preserved on a seven square mile mesa, locally called "Hepburn's Mesa" (Plate I, Figure 1).

Regional Setting

The Yellowstone Valley is bounded on the west by the Gallatin Range which consists mainly of Eocene andesite flows and breccias. To the east the valley is bounded by the uplift Beartooth block, consisting primarily of Precambrian crystalline rocks with a sequence of volcanics covering the block on its southern end. These volcanics are believed to correlate with the early acid and early basic breccias in Yellowstone National Park (Pierce, 1963). The valley is on the downthrown side of the Deep Creek fault which bounds the western side of the Beartooth Range and passes within several hundred feet of Hepburn's Mesa. The displacement on this fault is at least 5000 feet near Elbow Creek north of Hepburn's Mesa (Horberg, 1940).

Southward from Hepburn's Mesa the width of the Yellowstone Valley decreases rapidly where the Yellowstone River cuts into Precambrian rocks, forming Yankee Jim Canyon. The canyon extends southward for approximately 3 miles and ends approximately 1 mile north of Cinnabar Mountain.

On the northwest side of Cinnabar Mountain, the Gardiner Thrust fault appears from under a cover of Tertiary volcanics. The fault is traceable southward for 13 miles before it again disappears under Tertiary volcanics 3 miles east of Mount Everts in Yellowstone National Park (Wilson, 1934). Near Gardiner, outcrops of basalt form a bench on the east side of the Yellowstone River. They are distributed in an elongate belt along the northwest trend of the Gardiner fault plane. At Cinnabar Mountain and at Mount Everts are outcrops of Paleozoic and Mesozoic basement rocks which occur on the southwest side of the trace of the Gardiner fault.

The Gardiner fault was delimited by Wilson (1934). He states that the fault dips 35 degrees northeast and in the vicinity of Gardiner the minimum throw is approximately a mile and the minimum heave is approximately a mile and a half (Wilson, 1934). "The Gardiner fault provides a common southern boundary for part or both the Beartooth and Gallatin ranges" (Foose, 1961, p. 1163).

Previous Work

Iddings and Weed (1884) studied the Yellowstone Valley as part of the Livingston 1-degree quadrangle. Although geologic work was general, they concluded that the basalts represented the most recent volcanic activity in that part of the Yellowstone Valley.

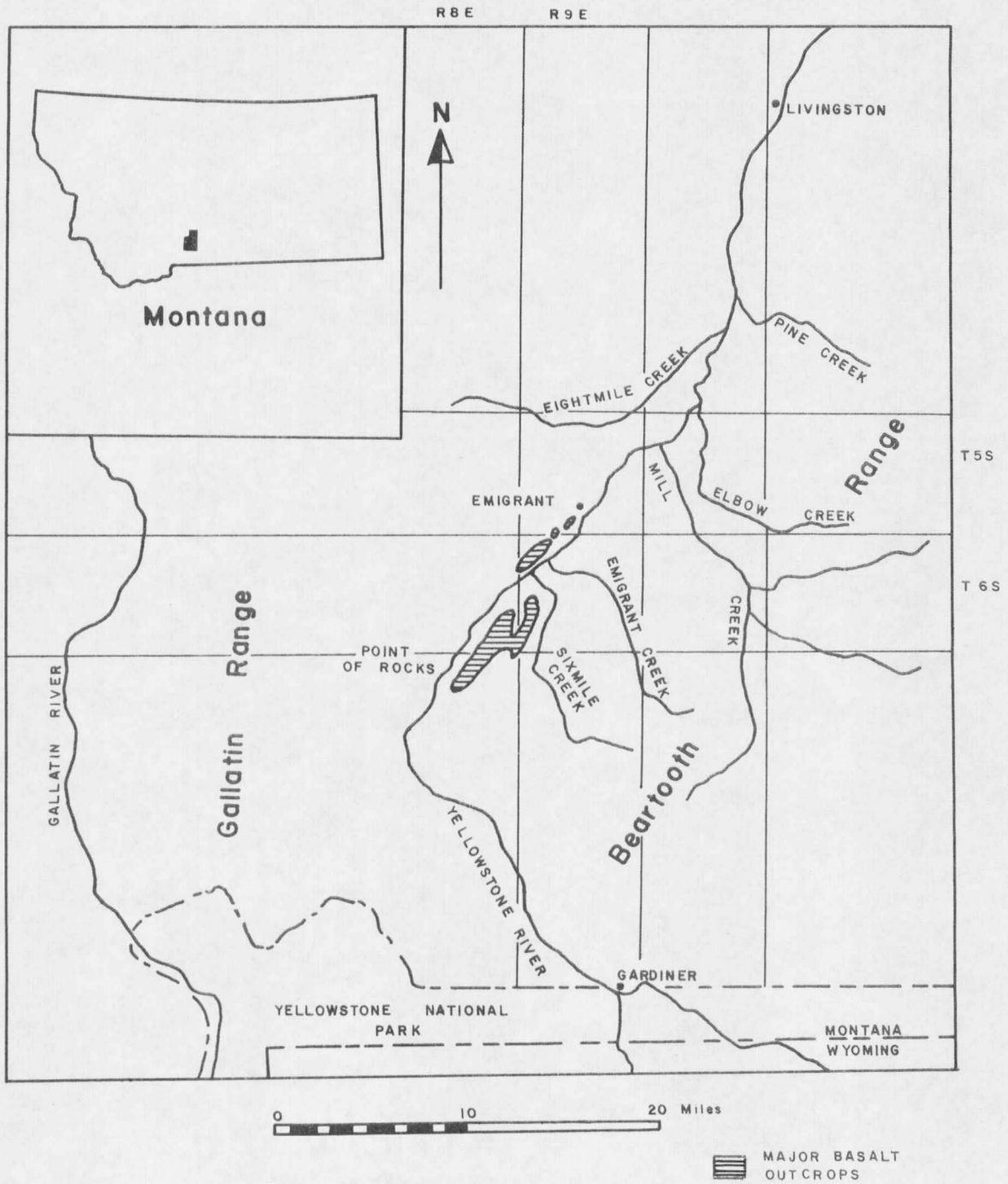


Figure 1 Index Map

Iddings (in Hague, 1899) described the basalts in Yellowstone National Park. His work includes both megascopic and petrographic descriptions.

Campbell (1916), in a guidebook of the Pacific Northwest, made passing mention of the basalt outcrops in the vicinity of Emigrant. He speculated that these were probably related to the basalts in Yellowstone Park.

Wilson (1934) cites "dike-like" structures in the basalts of the Gardiner exposure as evidence suggesting that basaltic lava came up the Gardiner Thrust plane. These "dike-like" structures are best exposed one mile east of Gardiner near the road to Jardine.

Howard (1937) made a detailed study in the area around the Yellowstone Canyon in Yellowstone National Park and distinguished six basalt groups: Jardine "basalt," Crescent Hill Basalt, Geode Creek Basalt, Elk Creek Basalt, Canyon Basalt and Oxbow Creek Basalt. On the basis of similar underlying gravels he suggested correlation of the basalt on Hepburn's Mesa to some of the older Canyon Basalts in Yellowstone Park. He also mapped the southern end of the basalts in the Gardiner area as belonging to the Canyon Basalts.

Horberg (1940), in a geomorphic study of Yellowstone Valley, discussed the basalts of the mapped area as "basalt flows" but did not separate the basalt sequence into individual flows. He suggested an early Pleistocene age for the basalts on the basis that an earlier date would present too many difficulties in explaining the geomorphic development of the valley.

Seager (1944) studied the Jardine Mining District which lies above the Yellowstone River about 12 miles southeast of Hepburn's Mesa. His report includes petrographic descriptions of the basalts exposed at



Figure 1 View of Hepburn's Mesa looking northeast.

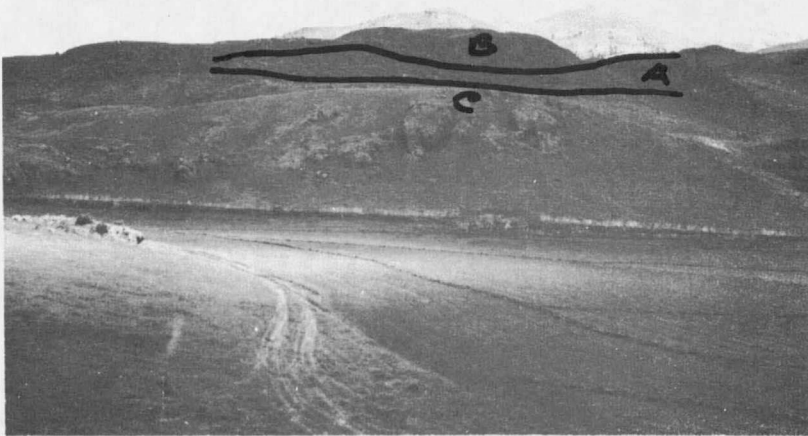


Figure 2 Outcrops south of Hepburn's Mesa.
A. Outcrops of flow A
B. Outcrops of flow B
C. Outcrops of Breccia

Deckard Flats along the Yellowstone River (approximately 2 miles south-east of Gardiner).

Brown (1961) mapped the southern end of the basalts near Gardiner as basalts of an undetermined age.

Ward and Wier (1961), in a study of Hepburn's Mesa, concluded that one flow is represented on the mesa. They did some detailed petrographic work at Merriman Quarry north of Hepburn's Mesa and part of that work is presented later in this paper.

In mapping the basalts at Gardiner, George Fraser has identified five flows at Deckard Flats, south of the Gardiner area, and five flows north of Little Trail Creek, north of the same area. He concludes that the tilted and curved columns, cited by Wilson, in the Gardiner exposures are not "dikes" but extrusive depositional features and tilted recent fault blocks (George Fraser, written communication, 1966).

Purpose of the Study

Previously the basalt sequence was not divided into separate flows, their source and age were uncertain, and the petrographic work was scanty. Therefore, the principal objectives of this study were: (1) to do a more detailed petrographic analysis, (2) to distinguish separate flows within the basalt sequence, (3) to determine the age of the basalts, and (4) to trace the basalts to their source.

STRATIGRAPHY

The basalts can be subdivided into two flows, flow A and flow B (Plate VI), and there are various units associated with them on the valley floor. The stratigraphic sequence from the base upward at Hepburn's Mesa is: (1) Eocene "Early Basic Breccia," (2) late Miocene-early Pliocene siltstones, (3) gravels, (4) flow A, (5) inter-basalt gravels, (6) flow B, and (7) glacial till of Wisconsin age.

Early Basic Breccia

The "Early Basic Breccia" of the Yellowstone Park sequence, which may correlate with the abundant volcanics forming part of the Gallatin Range to the west of the Yellowstone Valley (Horberg, 1940), is exposed in limited areas on the valley floor. South of Hepburn's Mesa small outcrops of the valley basalt rest on breccia (Plate I, Figure 2). To the west of these basalt outcrops are ridges of breccia at elevations equal to and exceeding those of the basalts. To the east, breccia crops out at lower elevations than the basalts (Plate I, Figure 2). The precise contact between breccia and basalt is hidden by a narrow strip of talus and glacial drift. However, the basalts in this area probably rest on a stream-cut bench on the "Early Basic Breccia."

Breccia also crops out near basalt one mile northeast of Merriman Quarry along the old county road. Here a knob of breccia is at the same elevation as buttes of basalt 1000 feet to the north and northwest.

The breccia in the mapped area is red-colored, resembling the nearby red-breccia at Point of Rocks, and may be part of the vent complex described by Chadwick (1965). The red-breccia at Point of Rocks is

described by Chadwick as being "near-monolithologic breccia containing angular to subrounded pyroxene andesite fragments up to 5 feet in diameter with an oxidized, fragmental matrix." Dorf (1960) dates the Early Basic Breccia in Yellowstone Park as "early middle Eocene" on the basis of extensive study of fossil floras.

Siltstone

Resting unconformably on the "Early Basic Breccia" is a siltstone unit of late Miocene-early Pliocene age (Horberg, 1940). The siltstones are evenly bedded and dip 6 degrees northeast towards the Deep Creek fault which borders the eastern side of the valley (Horberg, 1940).

The most complete section of the siltstone unit is exposed at "White Bluffs" where it is overlain by gravel which in turn is overlain by basalt of flow A. (White Bluffs is at section 11 on Plate VI.) A general description of that section, as given by Van Voast (1964, Unpub. M.S. Thesis, Montana State Univ., Bozeman; quoting Montagne, personal communication, 1964); is reproduced below:

| | |
|------------------|--|
| 24 feet | Light tan siltstone with some layers of very tuffaceous material. Sharp contact with overlying gravel. |
| 12.6 feet | Tan siltstone as above but with thin, greenish, clayey zones. |
| 54.5 feet | Massive tan siltstone with some small shell fragments, possible gastropods. |
| 16.8 feet | Massive, tan poorly bedded, siliceous claystone. Small shell fragments common. |
| 27.8 feet | Massive greenish siltstone. Many small shell fragments, possibly gastropods. |
| 38.8 feet | Light tan, poorly bedded, massive, siliceous claystone. Highly tuffaceous. |
| <hr/> 174.5 feet | Bottom not exposed |

Siltstones, which are more tuffaceous than those described above, are exposed beneath gravel which is capped by basalt, one-half mile south of Emigrant, on the west side of the river. These siltstones are interbedded with discontinuous rubble zones; the rubble is composed primarily of basic breccia fragments. Here foreset beds dip to the east, and Horberg (1940) says that this suggests deposition by streams from uplands to the west.

Another good exposure of the siltstones crops out north of the Wan-i-gan in a road cut along old route 89. At this locality the overlying gravel and basalt are missing and the exposed 80 feet of siltstone is in direct contact with overlying glacial till. Vertebrate fragments of a "Camelid and a later three-toed horse" were collected at this exposure and identified as late Miocene-early Pliocene (Van Voast, 1964, Unpub. M.S. Thesis, Montana State Univ., Bozeman). This agrees with the age assigned to the siltstone at "White Bluffs" by Horberg.

Gravel

Resting unconformably on the siltstone unit and overlain unconformably by the basalt of flow A is a deposit of coarse gravel. The gravel fragments are well rounded and, in some places, well sorted. The average diameter of the cobbles is approximately 4 inches although boulders can be found up to a foot in diameter. The gravel is bound by a weakly cemented sandy matrix. The best exposure is at "White Bluffs" where 80 feet of gravel overlies the siltstone beds. Horberg (1940) gives the following composition for these gravels: basalt, 46 per cent; andesitic rock, 21 per cent; granite, 9 per cent; quartzite, 9 per cent; gneiss, 4 per cent;

and basic plutonics, 2 per cent. In addition, Van Voast (1964, Unpub. M.S. Thesis, Montana State Univ., Bozeman) reports finding clasts of sedimentary rock and a few cobbles resembling lithologies of the Precambrian Belt Series.

Except for the small area south of Hepburn's Mesa, where the basalts rest on "Early Basic Breccia," gravel underlies the basalt sequence. However, the basalt-gravel contact is, in most places, hidden by talus and/or glacial drift. The gravel was found (in some cases by digging) beneath flow A at all of the measured sections shown on Plate VI except sections 16 and 17.

Flow A

Unconformably overlying the gravel is the basalt of flow A. The basalt crops out along the western side of Hepburn's Mesa and in small exposures and benches on the eastern side of the mesa, where it is overlain by the basalt of flow B (Plate VI). The outcrops of basalt on the western side of the river north of the mesa are also remnants of flow A, (Plate VI). Because of erosion the flow has an average thickness of 30 feet although, in places, the basalt is less than 5 feet thick.

At the southern end of the valley the basalt of flow A probably had an original thickness of approximately 60 feet. The basalts at sections 10 and 14, Plate II on Hepburn's Mesa, have a scoriaceous top with the base exposed; the basalt is 55 feet thick at section 10 and 58 feet thick at section 14. At section 1 approximately 6 miles to the north of section 10, the basalt is only 25 feet thick. Since the basalt at section 1 has a scoriaceous top, the thinning of flow A was probably caused by extrusive depletion rather than by post-depositional erosion.

The measured sections shown on Plate II follow the general north-south trend of the valley floor (section numbers on Plate II correspond with section numbers on Plate VI). The elevations of the gravel-basalt contact indicate that the pre-basalt surface sloped to the north and that the base of section 1 was probably not a topographic high on that slope.

The basalt of flow A is universally columnar; however, the diameter of the columns varies from less than 1 foot to greater than 8 feet. Although commonly vertical, the columns are in places inclined.

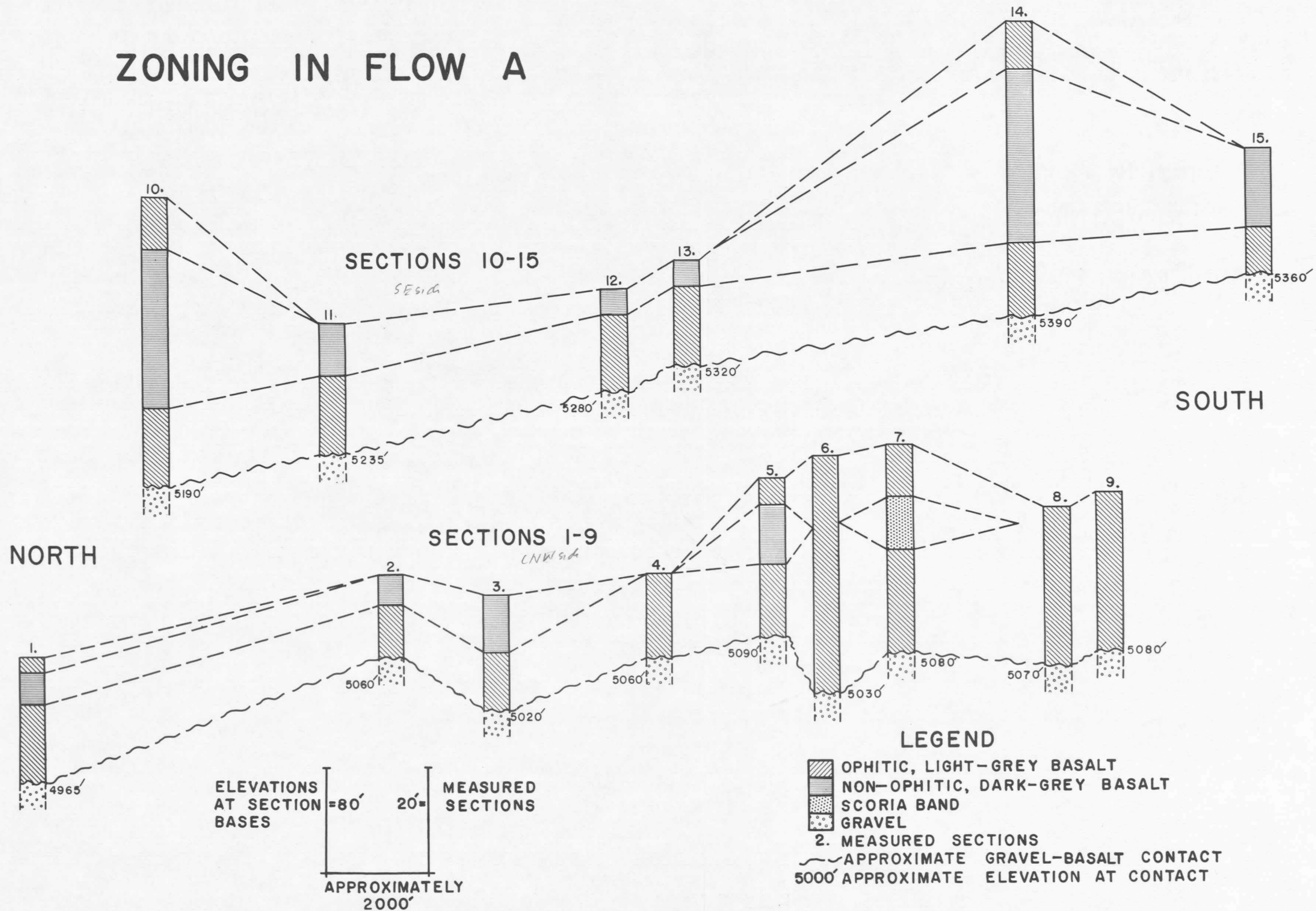
Megascopically, the basalt is universally porphyritic and commonly contains 2-4 per cent of olivine and plagioclase phenocrysts over 1 millimeter in diameter. However, two small areas, one north of Emigrant (section 1, Plate VI) and one south of Hepburn's Mesa, (Black-porphyrific facies, Plate VI) vary from the average and contain over 10 per cent phenocrysts.

The color of the basalt varies, both laterally and vertically, from light-gray to black. A major portion of the flow is zoned with light-gray basalt at the top and bottom of the flow and dark-gray basalt in the center. On the basis of lateral changes in phenocryst percentages, zoning structure, and color, flow A has been sub-divided into three lateral facies: (1) a zoned facies, (2) a light-gray facies, and (3) a porphyritic-black facies (Plate VI).

Zoned Facies:

In this facies, the flow is characteristically zoned with light-gray basalt at the top and bottom and dark-gray basalt in the center. For purposes of discussion, the zones have been labeled from the top

ZONING IN FLOW A



downward as zones 1, 2, and 3 (Plate III, Figure 1). The zoned facies is observable for five miles along the west-facing scarp of Hepburn's Mesa and at limited areas north of Merriman Quarry. Measured sections (1-5 and 10-15) show the extent and thickness of the zoning in this facies (Plate II).

All three zones have common phenocryst compositions. However, zones 1 and 3 are both megascopically and petrographically similar while zone 2 differs from both in color, column configuration, texture, and porosity. For purposes of clarity, the composition of the basalt of the zoned facies will be discussed before the zones are examined individually.

Relatively fresh phenocrysts of olivine and plagioclase are common in the zoned facies, where they comprise 1-4 per cent of the rock. The exception is at section 1 where the phenocrysts comprise over 10 per cent of the rock. There is no noticeable difference in percentages of phenocrysts between the three zones.

The plagioclase phenocrysts commonly range from 1 to 5 millimeters in length but, in rare instances, the length may range up to 25 millimeters. The olivine phenocrysts average 1 millimeter in diameter but may range up to 3 millimeters. The plagioclase phenocrysts are commonly glassy and clear, whereas the olivine phenocrysts are green and glassy. In places, the plagioclase and olivine phenocrysts occur in clusters which average 15 millimeters in diameter but may be as large as 50 millimeters.

Although of uniform phenocryst composition, the zones differ in column configuration. Vertical changes in column size and regularity commonly correlate with changes in zone boundaries. These changes are



Figure 1 Basalt outcrop of zoned facies
1. Top zone of large columns, zone 1
2. Center zone of small columns, zone 2
3. Basal zone of large columns, zone 3

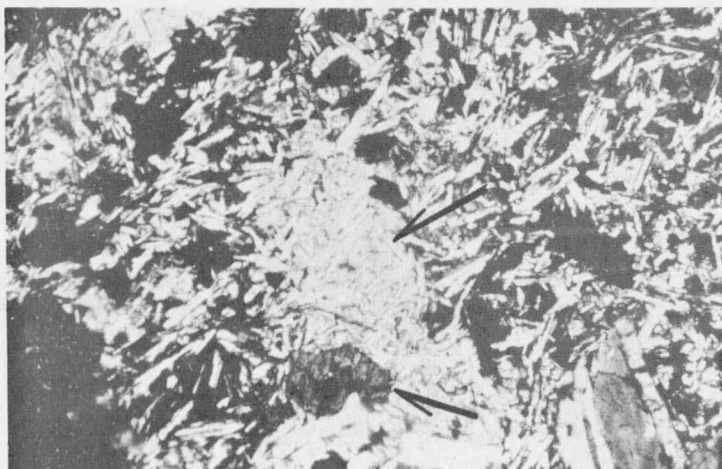


Figure 2 Ophitic texture of light-gray basalt
Arrows point to enclosing augite
crystal (1.5 millimeter in length)
and to a smaller olivine phenocryst.

either abrupt or gradational depending on the locality. The columns of zones 1 and 3 are consistently vertical and commonly larger (average diameter 5 feet) than the columns in the zone 2 (average diameter 2-3 feet) (Plate III, Figure 1). The columns in zone 2 are commonly irregular and, in places, inclined 30-40 degrees from the vertical. However, the direction of inclination is not consistent, and columns can be found dipping both north and south within a horizontal distance of a few feet.

The boundaries between zones are more distinct on the southern end of Hepburn's Mesa than on the northern end. North of Merriman Quarry the exposures are limited, and zones 1 and 2 are commonly missing because of erosion.

In addition to color and column differences, the basalt of zones 1 and 3 differs from the basalt of zone 2 in megascopic texture. The basalt of zones 1 and 3 is granular and porous; whereas, the basalt of zone 2 is dense and practically non-porous.

Although the basalt of zone 2 is dense and non-porous, this zone is less resistant to weathering than zones 1 and 3. This effect can be observed in places where the central zone forms a reentrant in relation to the steeper cliff faces formed by the overlying zone 1 and underlying zone 3.

In places where zone 1 has been removed by erosion, the scarp formed by zones 2 and 3 gives further evidence of the relative lack of resistance of the center zone. Here, the surface of zone 2 is a gentle incline and the cliff face of zone 3 is a generally vertical scarp, thus forming a gradually downward steepening slope.

Not all of the above characteristics are observable in a single locality, but the zones of the zoned facies of flow A can be distinguished by one or more of the following characteristics:

1. Changes in color with light-gray outer zones (1 and 3) contrasting with a darker-gray central zone (2).
2. Changes in column size with the columns of the outer zones (1 and 3) commonly larger in diameter than the columns of the central zone (2).
3. Inclined columns found, in places, in zone 2.
4. Abrupt boundaries between zones in some places.
5. Differences in megascopic texture, with the basalt of the outer zones (1 and 3) being granular and porous in contrast to the dense and non-porous basalt of the central zone (2).
6. Differences in weathering, with the outer zones (1 and 3) forming steeper scarps than those formed by the central zone (2).

At a few places the zoning is not easily distinguished in the field. However, at these places the presence or absence of the zones can be determined by a petrographic analysis of a vertical section (discussed in Petrography).

Light-Gray Facies:

The basalt of the light-gray facies is characteristically light-gray, porous, and granular, and is similar to the basalt of zones 1 and 3 of the zoned facies. On the west side of the Yellowstone River the basalt of the light-gray facies forms a major portion of a bench that is approximately 2 miles long and 1 mile wide (Plate VI). The best and most characteristic exposure of this facies is at Merriman Quarry. The observed thickness of the basalt in this area is recorded in measured sections 6-9 on Plate II where the maximum observed thickness was 45 feet. However,

no sections were found with a scoriaceous top to indicate the original thickness of flow A in this area. Petrographic studies (discussed later) suggest that the original thickness of the basalt in this facies was not much over 45 feet.

The basalt of the light-gray facies is columnar, commonly exhibiting large vertical columns having diameters ranging from 3 to 8 feet. However, in the quarry inclined columns occur at three localities.

A major variation in this facies is a scoria band in the center of the flow on the east facing scarp south of the quarry (section 7, Plate II). The scoria band is ten feet thick and several hundred feet long. To the south the scoria has been eroded away and to the west the scoria thins and pinches out. The scoria band can not be traced to the north because of quarrying. Light-gray basalt occurs above and below the band. The boundaries between the scoria and basalt are gradational with scoria grading into massive basalt both upward and downward through a zone of decreasingly vesicular basalt. Gravel was found at the base of the light-gray basalt at section 7 by digging a small pit.

As noted by Ward and Wier (1961), the basalt at the quarry exhibits a strange layering effect. The layers average 8 inches in thickness and are consistent across columns. Where the columns are inclined, the layers and vesicles are inclined to remain perpendicular to the columns. Ward and Wier (1961) noted that the texture was more coarse at the bases of these layers than at the tops. Although best displayed in the light-gray facies, the layers are also found locally in zones 1 and 3 of the zoned facies north of the quarry.

Thus, the light-gray facies can be distinguished by its consistent light-gray color, large, commonly vertical columns, and lack of zoning. In places, the strong layering effect characterizes the basalt, although this effect is not solely restricted to the light-gray facies.

Porphyritic-black facies:

In this facies, the basalt is typically dark-gray to black and very porphyritic. The basalt of the porphyritic-facies is exposed at the southeast corner of Hepburn's Mesa (section 16) and at small areas south of the mesa (Plate VI).

Phenocrysts of olivine and plagioclase comprise 10 to 20 per cent of the basalt in this facies. The phenocrysts of olivine (green and glassy) have an average diameter of 1 millimeter; the plagioclase phenocrysts average 10 millimeters in length. Although commonly coated with brown stain, the phenocrysts of plagioclase are glassy.

As mentioned above, outcrops of the porphyritic-black facies occur on the southeast corner of Hepburn's Mesa (section 16). Here the basalt is 10 feet thick, capped by a scoriaceous top, and with the base covered by talus and drift. Although drift conceals many of the exposures of this facies in this area, small outcrops can be traced around the southern end of the mesa from section 16 to section 15. At section 15 the basalt is zoned with a light-gray basal zone (3) and a dark-gray central zone (3). Phenocryst percentages decrease and the color intensity of the black facies lightens towards section 15. Thus, it was concluded that the porphyritic-black facies probably grades into the central dark-gray zone of the zoned facies.

The best exposures of this facies occur on the west facing scarps of two small outcrops south of the mesa (Plate I, Figure 2). Here the basalt is 30 feet thick with the base covered in talus. The columns at these two outcrops are vertical and have diameters of 3 to 5 feet.

Despite the fact that this facies is not extensive, the black color, lack of zoning, and high phenocryst content distinguish the basalt of this facies from the basalt of the other two facies of flow A.

Vesicularity:

Where exposed, the basal layer of flow A is scoria of variable thickness, with an average thickness of 4 to 6 inches. Locally the vesicles of the basal scoria band grade upward within a vertical distance of 1 to 1½ feet into large, elongated vesicles, which are scattered evenly throughout the basalt. Although lacking consistent vector orientation, these large elongated vesicles are commonly parallel to the pre-basalt surface, and comprise less than 1 per cent of the total basalt mass.

The upper scoriaceous portion of the flow ranges up to 6 feet in thickness. The vesicles grade from many small, spherical vesicles at the top downward into fewer, larger, more elongated vesicles. This gradation commonly occurs within three feet.

This downward and upward gradation is common to the basalt of the three facies of flow A. However, at some places in the zoned facies, pockets of vesicles, exceeding 10 per cent of the total basalt mass, occur at the top of zone (2) near to the boundary between zones (2) and (1).

Questionable area:

Northeast of Hepburn's Mesa, glacial drift covers most of the outcrops, and the relationship of the basalts is difficult to determine. Where the older basalt crops out, both light-gray and dark-gray basalt, similar to the basalt of the zoned facies, are found. However, the zones are not as consistent as on the western side of Hepburn's Mesa and their relationships could not be determined. At section 21, 10 feet of dark-gray basalt is overlain by 5 feet of scoriaceous basalt. Gravel was found beneath the base by digging. The total thickness of 15 feet suggests that the flow was thin in this area.

Although the relationships of the zones were indeterminable, the outcrops of flow A were mapped as belonging to the zoned facies on the basis that both light and dark-gray basalt were found.

Interbasalt Gravel

On the southeast side of Hepburn's Mesa, in the vicinity of sections 16 and 17, small outcrops of flow A are separated from outcrops of flow B by 3 to 4 feet in an area obscured by glacial drift. Three pits were dug in the vicinity of section 16 where the base of flow A appeared to be close to the surface. These pits revealed that the two flows are separated by a 3 to 4 foot thick fluvial gravel bed.

The gravel fragments are sub-rounded to rounded, averaging 2 to 3 inches in diameter, although a few cobbles as large as 6 inches in diameter were found. Over 90 per cent of the gravel is composed of andesitic pebbles resembling fragments of the "Early Basic Breccia." Scattered pebbles of quartzite and granite were also found. No fragments were

found that resembled the basalt of flow A. The gravels are weakly cemented in an argillaceous matrix.

No outcrop of the gravel was found. From section 17 northward on the eastern side of the mesa, talus and glacial drift cover the base of flow B, and it is not certain whether there is gravel between the two flows here. Westward across the mesa, flow B becomes entirely covered by glacial drift.

Flow B

Overlying the outcrops of flow A and the interbasalt gravel are the outcrops of flow B. The basalt crops out on the eastern side of Hepburn's Mesa and in small scarps and exposures both south and northeast of the mesa. The thickest sections measured were sections 20, 60 feet, on the northern end of the mesa, and section 18, 50 feet, north of Dailey's Lake. No scoriaceous top was found. Thus, the original thickness of flow B was at least 60 feet. Because of erosion the average thickness of flow B is now approximately 25 feet.

The basalt is consistently dark and fine-grained with scattered phenocrysts of plagioclase and rarer olivine phenocrysts commonly comprising less than 1 per cent of the rock. The basalt of this flow is rich in magnetite and magnetite-bearing glass and will deflect a compass needle up to 40 degrees when the compass is held against the rock.

The basalt is columnar; and, except for the area south of the mesa, the columns are consistently large and vertical, averaging 5 feet in diameter but occasionally diameters range up to 8 feet. Locally the columns have weathered into 1/8 inch to 6 inch plates perpendicular to the column joints.

South of the mesa the columns are smaller, ranging from 1 to 2½ feet in diameter. In places, the columns dip in various directions, probably caused by flow of the lava over a channel cut in the older basalt. Outcrops of flow B basalt can be traced to a position where they rest in the channel between two outcrops of flow A (Plate I, Figure 2). Here columns form a semi-radial pattern upward and outward from the basal portion of the exposure. Such structures may develop by lava moving over a stream (Waters, 1960).

The basalt is uniformly vesicular with scattered, elongated vesicles that are perpendicular to the column joints. These vesicles lack consistent vector orientation. The basal scoria zone is pitch black and is only revealed by digging pits through the talus and drift cover. Commonly the scoria is 3 to 6 inches thick.

Thus, the basalt of flow B is easily distinguished from the basalt of flow A by its: (1) uniform nature (lack of zoning and facies changes), (2) fine grained texture, (3) high magnetite content, (4) low content of olivine and plagioclase phenocrysts, and (5) dark color.

Age Date, Flow B Basalt:

A potassium-argon age date of 8.4 million years for the flow B basalt indicates that both basalt (A and B) and the interbasalt gravel beds are early Pliocene since all are underlain by late Miocene-early Pliocene sediments. The dated sample was collected from flow B south of Hepburn's Mesa (See Plate VI) and was analyzed by Geochron Laboratories Incorporated, Cambridge, Massachusetts. Part of their analysis is reproduced below: (Geochron Laboratories Incorporated, written communication, 1966)

Description: Basalt, crushed to -20/200 mesh, and analyzed as a whole rock sample.

Average Ar⁴⁰ 0.00030₇ ppm.

Average K⁴⁰ 0.628 ppm.

Ar⁴⁰/K⁴⁰ 0.00049

Age 8.4 (^{+ 0.8} ₋) x 10⁶ years

Till

Glacial till of Wisconsin age (Horberg, 1940) overlies the basalt sequence. The till consists of unconsolidated, unsorted, unstratified, coarse debris, commonly containing large boulders of granite, gneiss, and basalt. In places, erratics rest directly on exposed basalt. The basalt is, in places, striated; Horberg (1940) gives the direction of the striations near "White Bluffs" as N 30 E. Other striations on the southern end of the mesa and at Merriman Quarry have the same orientation.

Northeast of the mesa the drift is extremely bouldery. Here, large boulder fields are composed primarily of erratics, and commonly the boulders were derived from flow B basalt. The top of Hepburn's Mesa is traversed by a series of east-west trending recessional moraines.

The age of the glacial deposits in Yellowstone Valley is uncertain. Horberg (1940) differentiated piedmont Wisconsin glaciation in the Yellowstone Valley into two distinct phases and termed them early Wisconsin (Bull Lake) and late Wisconsin (Pinedale). Horberg believed that the later piedmont glacier (Pinedale) advanced northward to about 2 miles north of the town of Emigrant. Van Voast (1964, Unpub. M.S. Thesis, Montana State Univ., Bozeman) and Montagne (personal communication, 1966) believe that

the Pinedale piedmont glacier advanced only as far north as Gardiner, as suggested by a terminal moraine just north of the Park boundary. Although the deposits have been largely eradicated by later glaciation and periglacial activity, both Horberg (1940) and Montagne (1963) have found some evidence for pre-Wisconsin glaciation in the Yellowstone Valley.

GEOMORPHIC PROBLEM

Hepburn's Mesa Slump Blocks

The most conspicuous features of the west-facing slope of Hepburn's Mesa are the numerous, large slump blocks of columnar basalt resting on the basalt talus (Figure Two). These blocks, which have moved as much as 150 feet down the talus slope from the scarp above, exhibit the following approximate dimensions: length; 100-400 feet; width 20-30 feet; height, 30-50 feet. In a few blocks, the columns tilt forward (down slope, block Y, Figure Two) whereas in a few others the columns incline back towards the parent scarp (block X, Figure Two). However, most of the blocks exhibit columns resting in a vertical or near-vertical position (block Z, Figure Two).

Observations and considerations of the properties of these basalt slump blocks suggest that the unique nature of the basalt columns and the basalt talus may have been factors in their creation.

Due to the unique columnar zonation (large columns of zones 1 and 3 and the smaller columns of zone 2) exhibited by the basalt of flow A on the west side of the mesa, the talus slope exhibits some unique properties. Commonly the size of the individual fragments falls into one of two extreme size ranges: some portions of the talus slope are composed primarily of small fragments (4 inch to 2 foot diameters) having irregular, angular shapes; other portions of the talus slope are composed primarily of large, broken columns (3 to 6 foot diameters) exhibiting regular (six-sided) angular shapes. The two size variations produced by the three fold vertical zonation of the basalt are of flow A, the large columns being derived from the outer zones (1 and 3) and the smaller irregular columns

from the central zone (2). Where the smaller fragments dominate, the slope is relatively unstable. Where the larger fragments dominate, the slope is steep but relatively stable because of the interlocking nature of the broken columns. In places, areas of large broken columns occur near the base of the scarp but may not be found to as far down the slope as 200 feet. Commonly, areas of the smaller fragments are held in place by lower areas of the larger, broken columns.

The slump blocks themselves also have unique properties. The strong columnar jointing produces a block with four near-perpendicular sides (Sides A, B, C, D on Figure Two). The important thing to note about the shape of these blocks is the proportions of the length (L) to height (H), to width (W). The width (W) is narrow in comparison to height (H) and extremely narrow in comparison to length (L). Because of the narrow width (W), the center of gravity in these blocks is close to the front of the block (side B). Also, although the densities were not determined, the basalt slumps on Hepburn's Mesa may be top heavy because of the three fold vertical zonation, thus placing the center of gravity slightly above exact center. This high center of gravity may be produced by the slight recessed position of the smaller columns of the center zone (2). Thus, when contrasted to slumps of other rock types, these slump blocks of basalt may be more rectangular in shape, different in length, width, height ratio and relatively different in location of the center of gravity.

Besides controlling the shape of the slump block itself, the columnar structures give the blocks a strong vertical axis (vertical axis same as H) that other slump blocks may lack.

FIGURE 2

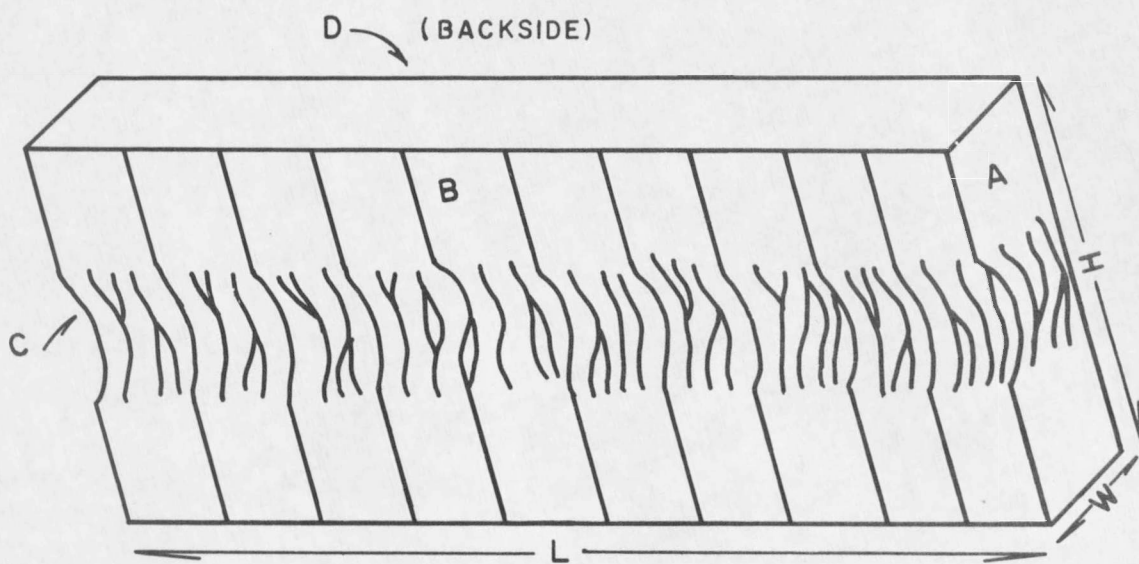
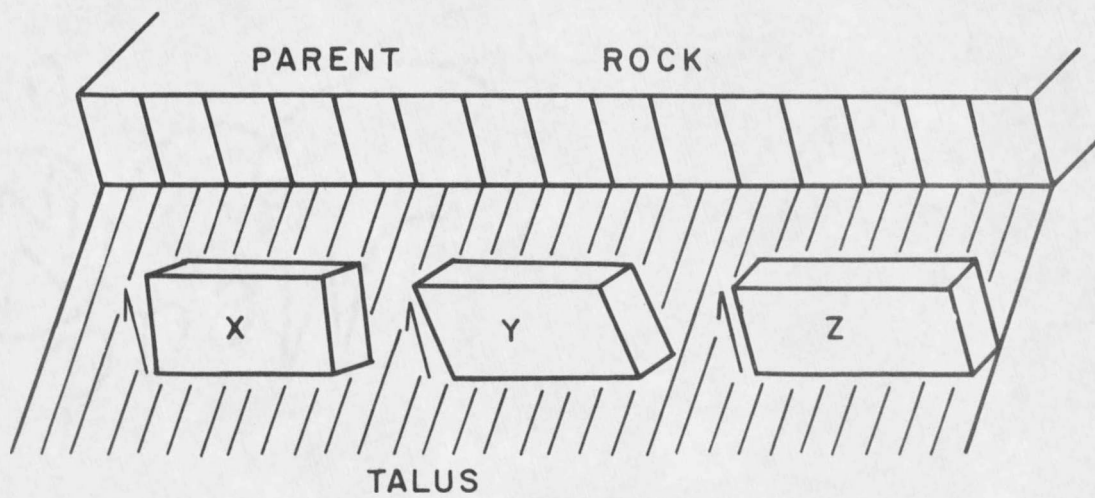


DIAGRAM OF BASALT SLUMPS

Therefore, it is assumed that if a basalt slump block were moving on a talus slope of small basalt fragments, it would probably tilt backwards into the slope (block X, Figure Two) in the normal manner. However, in the case of Hepburn's Mesa, it is theorized that a slumping block is restrained along its L axis upon encountering an area of large interlocking broken columns. This resistance may cause the top of the block to move forward relative to the base because of the location of its center of gravity. This forward tilting of the top relative to the base would be further aided by the strong vertical axis (H) produced by the columns.

Thus, the vertical, near vertical, and forward orientations of the basalt slumps may be produced by one or more of the following factors:

- (1) The large, angular, even sized, interlocking talus of broken columns commonly occurring below unstable talus of much smaller and irregular dimension.
- (2) The location of the center of gravity produced by the L to W to H ratios.
- (3) The rectangular shape of the slump blocks with their possible top heavy columns.
- (4) The strong vertical axis of a basalt slump produced by the columnar jointing.

The above proposal assumes that the slumps occurred where the slopes are covered in basalt talus. If they occurred where the underlying gravels and siltstones dominated the slope, then the factors involved in their formation would have been different and such factors as the effect of the rounded gravels and the plasticity of the siltstone beds would have to be taken into consideration.

PETROGRAPHY

Flow A

The basalt of flow A is primarily composed of plagioclase (labradorite), pyroxene (augite), olivine, magnetite, bowlingite? or limonite?, and unidentifiable altered pyroxene?. Sections exhibited no strong alignment of these minerals. The percentage composition, grain size, texture, and degree of alteration of the minerals vary from facies to facies within flow A. (The mineral percentages for the basalt of each facies are given in the Appendix.) However, the minerals do exhibit certain optical properties which do not vary significantly from facies to facies.

Augite- (+) maximum extinction angle 45° , $2V =$ approximately 55° , length fast, maximum birefringence: middle second order with sections cut parallel to (100) exhibiting low first order colors; a few individuals with maximum birefringence exhibit hourglass structure, high relief; brown to gray in plain light, pleochroism weak to absent.

Labradorite- (+) maximum extinction angle $32-35^\circ$, An_{60-65} , (Michel Levy Method, Moorhouse, 1959) for phenocrysts, $2V = 85^\circ$, clear in plain light, low relief.

Olivine- (+) extinction parallel to crystal faces, $2V =$ near 90° .

Magnetite- opaque, gray color in reflected light.

Bowlingite? or limonite?- pleochroic, yellow to red-yellow brown, replaces olivine with the 001 cleavage coinciding with 001 of olivine in places, (commonly restricted to zone 2 of zoned facies).

Iddingsite?- pleochroic, red-brown to ruby red, dispersion is strong $r > v$, (commonly restricted to zone 2 of zoned facies).

Altered pyroxene?- unidentified, speckled brown to opaque, altered material found on portions of some recognizable augite, (commonly restricted to zone 2 of zoned facies).

The basalt of the light-gray facies and the light-gray basalt of the zoned facies (zones (1) and (3)) are petrographically similar and are

discussed under one section entitled light-gray basalt. The basalt of the prophyritic-black facies and the dark-gray basalt of the zoned facies (zone 2) will be discussed separately.

Light-Gray Basalt:

The light-gray basalt is relatively fresh, porous, and holocrystalline. The rock is characterized by ophitic to sub-ophitic texture (Plate III, Figure 2), although in places it exhibits inter-granular texture. The use of these textural terms follows the definitions given by Williams, Turner, and Gilbert (1954, pp. 20-22).

In thin section if the feldspar laths, whose average length does not exceed the diameters of the pyroxene grains, appear to be largely or entirely enclosed in pyroxene, the texture is "ophitic." If the average length of the plagioclase laths exceed that of the pyroxene grains, and the latter only partly enclose a number of the former, the texture is "subophitic." Intergranular texture results when the angular interstices between the feldspar are occupied by ferromagnesian granules, usually olivine, pyroxene or iron ore of random orientation.

Plagioclase comprises 50-55 per cent of the basalt and is primarily restricted to the groundmass (crystals less than 0.5 millimeters in length). The phenocrysts (1 to 3 per cent) are labradorite and exhibit both carlsbad and albite twinning. The phenocrysts are commonly lath-shaped with well defined crystal faces exhibiting discontinuous zoning. In places the crystals are strongly corroded with crystal faces lacking.

Augite, which comprises 30-35 per cent of the basalt, commonly occurs both as anhedral phenocrysts (1 to 1.5 millimeters in length) and as small aggregates of granules (less than 0.5 millimeters in length) generally exhibiting common extinction and surrounding the groundmass plagioclase,

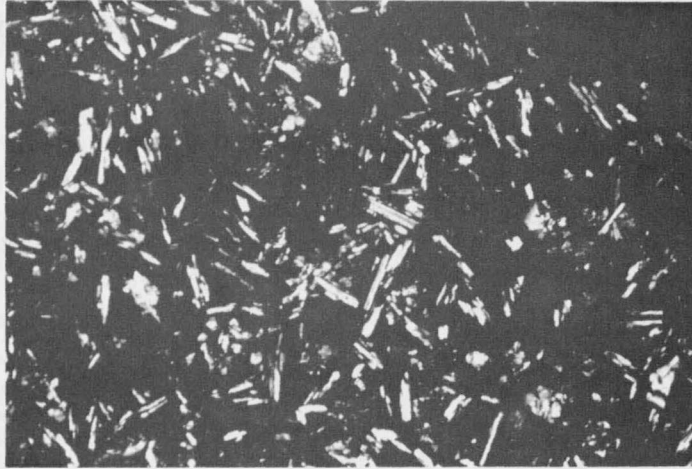


Figure 1 Non-ophitic texture of dark-gray basalt
Note fresh plagioclase crystals "floating"
in the opaque altered material

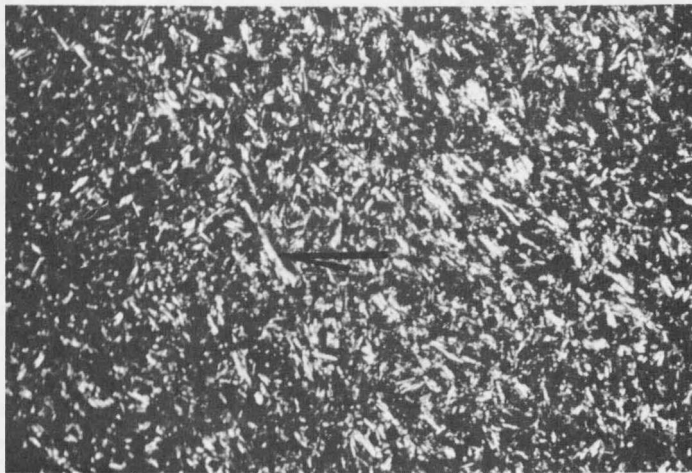


Figure 2 Fine grained intergranular texture of flow B
basalt.
Arrow points to largest plagioclase phenocryst
which is 1 millimeter in length.

thereby producing ophitic texture. The grains are commonly fresh although a few individuals exhibit zoning with dark rims on their borders.

Although the percentage composition of olivine varies with the locality, olivine occurs both as phenocrysts (average diameter 1 millimeter) comprising 1 to 3 per cent of the total mass and as small euhedral crystals (less than 0.5 millimeters in diameter) in the groundmass, comprising 4 to 10 per cent of the total rock. Commonly the phenocrysts are corroded, but a few individuals exhibit good crystal outlines. The olivine crystals are fresh to partly altered. Where altered, the alteration occurs primarily along crystal borders and along fractures. The altered material is, in some places, yellow-brown to yellow-red-brown (bowlingite? or limonite?); in other places, it is ruby red (iddingsite?).

Magnetite occurs as scattered opaque crystals in the groundmass. Although a few crystals are euhedral, most conform to the irregular interstices between the augite and labradorite.

Intergranular Texture and Original Thickness of the Light-Gray Facies

Close to the basal scoria where the basalt cooled quickly, the texture is, in places, intergranular with augite restricted to the groundmass (crystals less than 0.5 millimeter in diameter). At the base, a decrease in the percentage composition of augite is accompanied by a corresponding increase in percentage of glass.

Thin sections were made from samples taken at section 6 (Plate II), a 43 foot exposure of the light-gray facies. In the center of this measured section, 5 to 40 feet from the base, the basalt exhibits ophitic

texture with large augite crystals (1.5 millimeters in length) enclosing plagioclase crystals. However, at the top and bottom of the measured section, the texture is intergranular with augite restricted to the groundmass.

The scoriaceous top of this section and other exposures of the light-gray facies in this area has been eroded away. However, if intergranular texture is formed at the base because of faster cooling, then the intergranular texture of the basalt near the top of the measured section may suggest proximity to the original scoriaceous top. Thus, the original thickness of the flow in this area may not have been much over 45 feet.

Layering

Ward and Wier (1961) did a petrographic study of the microscopic layering previously mentioned, where it is best displayed at Merriman Quarry. They discovered a greater concentration of phenocrysts at the bottom portion of each layer than at the top of the same layer. No noticeable variation in texture was noted to correspond with this change. Table One, taken from Ward and Wier (1961), shows this difference by volume per cent and is reproduced on the following page.

TABLE ONE

MODES OF BASALT IN VOLUME PER CENT
(after Ward and Wier, 1961)

| | <u>Top of Band</u> | <u>Bottom of Band</u> |
|-------------|--------------------|-----------------------|
| Phenocrysts | 4.0 | 8.0 |
| Olivine | 2.0 | 0.9 |
| Pyroxene | 0.0 | 1.2 |
| Plagioclase | 2.1 | 5.7 |
| Groundmass | 96.0 | 92.0 |
| Olivine | 2.8 | 4.3 |
| Pyroxene | 37.9 | 34.2 |
| Plagioclase | 51.8 | 50.1 |
| Magnetite | 3.6 | 3.3 |

Summary

Although local exceptions exist, within the light-gray facies there seems to be a correlation between the grain size and the rock color as well as a correlation between porosity and the petrographic texture. Where the grains are coarser, the rock is generally lighter in color. Where ophitic texture is best developed, the rock is more porous and granular.

Dark-Gray Basalt:

The dark-gray basalt of zone 2 of the zoned facies is characterized by being non-ophitic (Plate IV, Figure 2) in contrast to the ophitic texture of the light-gray basalt (Plate III, Figure 2). Mineralogically, the two types differ solely in the amount of alteration of the ferromagnesian minerals. This alteration in the dark-gray basalt varies from place to place but generally increases downward towards the center of zone 2 and then decreases downward from the center to the top of the basal zone (3).

The plagioclase of the dark-gray basalt is similar to the plagioclase of the light-gray basalt in size, amount, zoning and composition (An60-65, Michel Levy Method, Moorhouse, 1959). The augite is altered to a brown speckled and/or opaque material, and the percentage of recognizable augite (5 to 25 per cent) varies inversely with the percentage of altered opaque material. Near the top of zone 2 and at the base of the same zone, the smaller granules of augite in the groundmass are more altered than the larger crystals, leaving the large, enclosing augite crystals "floating" in a speckled brown and/or opaque groundmass which is interspersed with fresh plagioclase. Towards the center of zone 2, the size of the recognizable augite decreases and the amount of altered material increases. Thus, as the degree of alteration increases towards the center of the facies, the texture becomes less and less ophitic until, in places, there is less than 5 per cent of recognizable augite.

The alteration of the augite is accompanied by the alteration of olivine. Commonly, the olivine alters to a yellow-brown or yellow-red-brown material (bowlingite? or limonite?) and in places to a ruby-red material (iddingsite?). Near the top and bottom of zone 2, the olivine is generally only partially altered. However, in the center, the alteration of olivine is practically complete except for center portions of a few large phenocrysts. Also, the color of the altered material commonly becomes redder towards the center of zone 2.

Thus, although the intensity of alteration varies from place to place within the facies, there is little doubt that the degree of alteration increases towards the center of zone 2.

Summary

Although local exceptions exist, there is a correlation between rock color and the amount of alteration of the ferro-magnesian minerals. Near the boundaries of the zones, the color of the rock may be intermediate between light-gray and dark-gray. Where this occurs, the alteration of the ferro-magnesian is incomplete; only the granules of augite and the borders of the olivine are altered. Where the rock color is definitely dark-gray, probably all ferro-magnesian are partially to completely altered.

Porphyritic-Black Facies:

The basalt of the porphyritic-black facies is characteristically non-ophitic and contains a higher phenocryst percentage than the basalts of the other facies. The amount of alteration as well as the mineral and phenocryst percentages vary from place to place within the facies.

Plagioclase, which occurs both as phenocrysts (larger than 0.5 millimeters in length) and as needle-like crystals in the groundmass, comprises 45 to 50 per cent of the basalt of this facies. The phenocrysts, which comprise 6 to 8 per cent of the rock, are labradorite in composition, An₆₅₋₇₀, (Michel Levy Method, Moorhouse, 1959). The phenocrysts are lath-shaped with well defined crystal faces and commonly range from 1 to 5 millimeters in length. Although a few isolated individuals are strongly zoned and slightly corroded, the phenocrysts commonly exhibit weak zoning with little corrosion. Some individuals that are fractured have a yellow stain on the fractures which was probably caused by local

weathering (the phenocrysts in hand specimen are brown stained).

The augite is commonly restricted to the groundmass; thus, the basalt of this facies exhibits intergranular texture. In places, the augite is practically all altered to a speckled brown and/or opaque material; however, some sections show little or no alteration. Thus, the recognizable augite comprises from 5 to 25 per cent of the total mass of the rock.

The olivine is fresh, exhibits good crystal outlines and is rarely corroded. Phenocrysts of olivine average 1 to 2 millimeters in diameter and comprise 3 to 5 per cent of the rock. No red or yellow alteration products were found on the olivine. Groundmass olivine comprises 4 to 6 per cent of the rock and is, like the phenocrysts, generally unaltered.

Magnetite is restricted to the groundmass, commonly comprising 1 to 4 per cent of the rock.

Summary

As in the dark-gray basalt, variations in color may correspond to variations in alteration. Thus the 'blacker' basalts commonly contain the most altered material whereas 'lighter' intensities contain correspondingly less altered material and more recognizable augite.

Petrogenesis of Flow A

Light-Gray vs. Dark-Gray Basalt:

Since the olivine is inclusion free, it was probably the first to crystallize. Corroded crystal faces indicate reaction with the remaining liquid. Following olivine, the crystallization of the first generation

plagioclase began (large phenocrysts); a few of the plagioclase phenocrysts contain inclusions of olivine. The discontinuous zoning and corrosion of some individual plagioclase phenocrysts suggest reaction with the liquid after crystallization.

The augite and remaining plagioclase may have crystallized simultaneously, producing the ophitic texture. According to Bowen (1928, p. 68):

The ophitic texture of basalts is probably to be taken as the result of simultaneous crystallization of two minerals, the one of which, plagioclase, has a greater specific tendency to idiomorphism under conditions of rapid growth.

Whereas ophitic texture may develop when crystallization has advanced practically to completion, the phenomenon of non-ophitic texture probably results from rapid crystallization from an undercooled state (Bowen, 1928). This may explain the intergranular texture present at the base of the flow.

The fact that most of the magnetite is found in the interstices between the groundmass plagioclase and augite may suggest its late crystallization. However, inclusions of magnetite can be found in the plagioclase and augite, indicating earlier crystallization. Thus, it is probable that the crystallization of magnetite began early and continued on into the groundmass period.

The formation of the dark-gray basalt of the central zone (2) of the zoned facies may have been caused by the trapping of gases, thereby producing deuteric alteration of the ferro-magnesian minerals.

Fuller (1938) noticed similar zoning of light-gray basalt with dark-gray basalt in a late volcanic sequence in southeastern Oregon. He found that the "light-gray resistant rock occurred as a rule at both the top

and bottom of the flow and in a zone of variable thickness adjacent to the major joint cracks" (Fuller, 1938, p. 161). Some of the flows were formed entirely of one type of basalt or the other. Fuller concluded that "gases retained in the center of the blocks resulted in the local alteration of the rock" (1938, p. 171). He goes on to attribute the trapping of gases to control by major joints in the lava and explains this as follows:

The surface of the flow would have solidified first due to chilling and loss of volatiles. Its consequent contraction presumably caused the initiation of the major joint cracks. These cracks would have permitted the local escape of volatiles and would thereby have hastened the solidification of the lava adjacent to their lower margins. The contraction of the solidified network thus formed appears to have resulted in the gradual advance of the cracks prior to the final consolidation of the lava in the center of the blocks (Fuller, 1938, p. 171).

If Fuller is correct in assuming that joints are routes for volatile escape and that the lava solidifies adjacent to major cracks before consolidation of the center of the blocks, then movement of the top of a cooling lava could truncate the forming joints and cause trapping of gases in the center of the flow.

Waters (1960) states that inclined columns in the center portion of lava flows indicates movement of the top relative to the bottom after partial cooling. The inconsistency of the inclination of the inclined columns exhibited by flow A suggests that the movement may have been a local rafting of small blocks in the top portion of the flow before the center was completely cooled. If the joints had been acting as escape routes for the volatiles, this movement of the top portion of the flow

may have truncated the joints as they were forming, thereby preventing the escape of gases. Further field evidence for the trapping of gases in the center portion of the flow are the vesicles which are found, in some places, in concentrations or pockets at the top of zone 2.

Thus, the alteration exhibited by the central zone (2) of flow A of the zoned facies may have been a function of gas content. The altered material gives the basalt its non-ophitic appearance. However, the exact causal relationships producing this non-ophitic texture were not determined. Such non-ophitic texture may have resulted from the deuteric alteration of the augite or from the incomplete formation of the augite during crystallization.

Small Irregular Columns

According to James (1920) and Waters (1960) rapid cooling is a major factor in producing small irregular columns. However, "the importance of homogeneity as a factor in columnar formation cannot be emphasized too much" (James, 1920, p. 459). Thus, irregular mixing of gases in the central zone (2) may have been responsible for the smaller irregular columns of that zone in the zoned facies of flow A. This hypothesis is supported by the variation in degree of alteration from sample to sample. Such variations are especially evidenced by the variable percentages of recognizable augite (5 to 25 per cent) noted in the dark-gray basalt. Other factors besides rate of cooling and homogeneity which control the attitude, size, shape, and regularity of columns, as given by James (1920, p. 458), are as follows: (1) Viscosity of the lava, (2) Temperature of the lava, and (3) Regularity of cooling. Thus, these factors

may also have been responsible for the smaller columns of the central zone. However, the homogeneity and gas content of the lava probably influenced viscosity, temperature, and rate of cooling, thereby promoting the formation of the smaller irregular columns.

Flow B

The basalt of flow B is composed of plagioclase, augite, magnetite and magnetite-rich glass, and olivine. With the exception of the basalt from the small outcrops south of Hepburn's Mesa, the basalt of this flow exhibits little variation. (The Appendix lists the mineral percentages for the basalt of flow B.) Although two sections exhibited similar orientation of the plagioclase laths, flow alignment of the minerals is not commonly present. The basalt of flow B is so fine grained that petrographic work is difficult.

The basalt exhibits intergranular texture with augite commonly restricted to the groundmass (Plate IV, Figure 2). In comparison to the basalts of flow A, it has a low phenocryst content (1 to 2 per cent) and a high content of magnetite and magnetite-rich glass (commonly 15 to 20 per cent).

The augite occurs as minute crystals (less than 0.1 millimeters), making the determination of its optical properties difficult. The birefringence is generally low to middle order with some individuals exhibiting high second order. The high second order crystals are difficult to distinguish from olivine.

The plagioclase is labradorite in composition An60-65 (Michel Levy Method, Moorhouse, 1959). These phenocrysts (more than 0.5 millimeters in length) comprise 1 to 2 per cent of the rock and are commonly lath-shaped with well defined crystal faces. They exhibit slight to strong normal zoning, with a few individuals exhibiting weak discontinuous zoning. The groundmass plagioclase is commonly needle-like.

Magnetite occurs both as euhedral crystals and as irregular crystals which, with augite, fill the angular interstices of the groundmass plagioclase. The magnetite is evenly dispersed throughout the rock.

Olivine occurs as scattered granules in the groundmass and only rarely as phenocrysts. The phenocrysts (diameters larger than 0.5 millimeters) are commonly fresh, with good crystal faces lacking.

The basalt from the small outcrops south of the mesa differs from the previously described rock. Here olivine phenocrysts are more common, as is a higher content of opaque material (magnetite and magnetite-rich glass) which, in places, exceeds 40 per cent. The mineral percentages of opaque material, augite, and olivine vary from place to place. In most places, higher percentages of opaque material are accompanied by lesser percentages of recognizable augite.

The columns from the small outcrops south of the mesa are smaller than those on the mesa proper and may have been formed by rapid crystallization (relative to the flow B basalts on the mesa) as the lava moved into the stream channel, thereby producing the higher content of opaque groundmass. This rapid cooling may also account for the higher content of

of olivine which did not have extensive opportunity to react with the remaining liquid.

Normative Mineral Content

From a chemical analysis of flow B basalt the normative mineral content was calculated by the CIPW system. The analyzed sample was collected from the outcrops south of the mesa and the chemical analysis was performed by Technical Service Laboratories, Toronto 2B, Ontario, Canada. The chemical data and normative minerals are shown in Table Two.

Nockolds (Barth, 1962, pp. 58-59) lists the average chemical compositions of basalt types. When compared to these types the silica content of 49.86 per cent suggests that flow B would be best classed as a tholeiitic basalt. However, the alumina content of 18.41 per cent is high for most types and may class flow B basalt in the "high-alumina series."

TABLE TWO

Chemical Composition and Normative Minerals
(in percentages of total)

| <u>Chemical Composition</u> | | <u>Normative Minerals</u> | |
|--------------------------------|--------|---------------------------|-------|
| SiO ₂ | 49.86% | Quartz | 1.8% |
| Al ₂ O ₃ | 18.41% | Orthoclase | 3.3% |
| Fe ₂ O ₃ | 2.39% | Albite | 23.6% |
| FeO | 9.16% | Anorthite | 35.9% |
| CaO | 6.48% | Wollastonite | 6.3% |
| MgO | 3.93% | Ferrosilite | 14.8% |
| Na ₂ O | 2.79% | Magnetite | 3.5% |
| K ₂ O | 0.58% | | |
| Loss of Ignition | 0.9 % | Total | 99.0% |

Summary

In flow B there is probably a correlation between column size and petrographic properties. The basalt on the mesa exhibits consistent petrographic similarities and the columns, as noted, are consistently similar. However, south of the mesa where the columns are smaller, there is more opaque material and more olivine.

In thin section the basalts of flow B can be easily distinguished from the basalts of flow A by their non-ophitic texture, common restriction of augite to the groundmass, relative absence of olivine, high percentage of magnetite and/or magnetite-rich glass, and finer texture

of the plagioclase groundmass crystals. Also, in comparison to the light-gray basalt of flow A, the basalt of flow B contains less pore space.

GARDINER BASALTS

Introduction

Twenty miles south of Hepburn's Mesa, basalts cap a bench east of the Yellowstone River. These outcrops extend from south of Bear Creek (2 miles southeast of Gardiner) northward to just north of Little Trail Creek. "Five flows can be counted at Deckard Flats south of Bear Creek (Plate V, Figure 1) and in the uplifted block north of Little Trail Creek at the two ends of the Gardiner Exposure," (George Fraser, written communication, 1966).

On the bench between Bear Creek and Little Trail Creek the basalt sequence is difficult to recognize because of talus and glacial debris which generally hides contacts between individual flows. Commonly the basalts exhibit tilted and/or curved columnar structures (Plate V, Figure 2). Wilson (1934) interpreted the curved columns at one locality to be a basalt dike. He based his conclusions on: (1) the curved columns, (2) the presence of Precambrian wall rock, and (3) the fact that the curved columns seemed to tilt back into the Gardiner fault plane. From the above observations he suggested that the basalts came up the Gardiner fault (Wilson, 1934).

Fraser (written communication, 1966) believes that the "dike" to which Wilson refers is extrusive and that the curved columns resulted from deposition on an uneven surface. He also noted that the "dike" is located some distance southwest of the covered trace of the main part of the Gardiner fault and that there is no exposed Precambrian wall rock where Wilson has inferred it (Fraser, written communication, 1966).

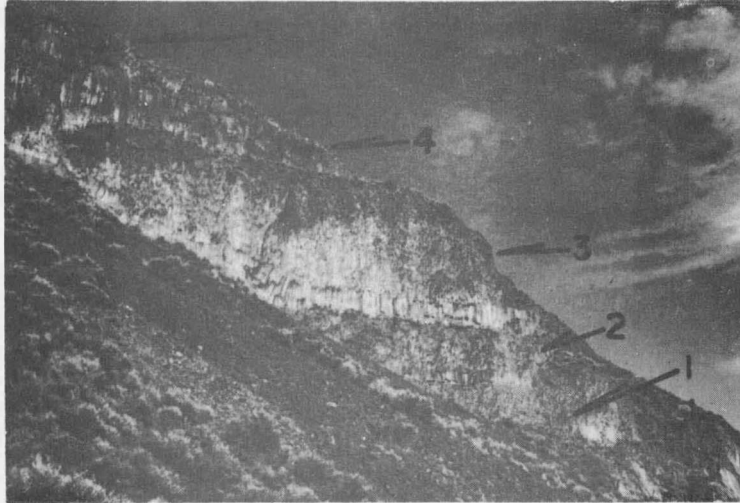


Figure 1 View of Deckard Flats exposure
Flow remnants labeled 1 through 5



Figure 2 Curved Columns near Jardine in
Gardiner basalts.

Fraser (written communication, 1966) also believes that 2 or 3 of the earlier flows were channel fills. At Deckard Flats the bottom two flow remnants are lenticular in cross section suggesting that they are resting in old stream channels. The columns of the third flow at one place are inclined to the south over a gravel bed, suggesting movement of lava into and out of a stream channel during deposition. Thus, the curved columns in the Gardiner area are probably extrusive features formed by deposition on uneven surfaces.

Besides outcrops with curved columns, numerous tilted blocks of basalt can be found on the northern end of the Gardiner exposure. Fraser (written communication, 1966) has interpreted these blocks to be small, recent, (post-glaciation) tilted fault blocks and states that the structural failure of the basalt bench was aided by the following:

- (1) Vertical altitude (before failure) of the subjacent Cretaceous rocks.
- (2) Weak shales and bentonite
- (3) Melting of permafrost
- (4) Excavation of the Yellowstone and Little Trail Creek Valleys
- (5) Earthquakes

The outcrops of the five flows at the two ends of the Gardiner exposure (Deckard Flats and north of Little Trail Creek) were examined for this report. The findings suggest that at least six flows exist in the Gardiner area and that the upper two may have extended into Yellowstone Valley to the north.

Deckard Flats

Five basalt flows and five interbasalt gravel beds are exposed on the west facing cliff at Deckard Flats south of Gardiner. These basalts

(Plate V, Figure 1) were first described by Seager (1944) in a report on the Jardine Mining district. Discontinuous gravel beds occur beneath each flow. The basalt-gravel sequence (approximately 250 feet thick) rests on Precambrian rocks. For purposes of discussion the flows have been labeled from base upward as 1 through 5.

The upper two flows (4 and 5) are horizontal and continuous across the cliff face. The lower three flow remnants (1, 2 and 3) are lenticular in cross-section and thin to the north.

It is probable that all the basalts exposed here belong to the same general episode of basalt deposition, since "There are no significant unconformities between flows," (Fraser, written communication, 1966). Unfortunately, the basalts do not rest on any unit younger than Precambrian so as to allow accurate dating. Seager (1944) suggested a Pleistocene age for the basalt-gravel sequence. To the south the Yellowstone Tuff, which may be less than 0.7 million years old (Robert Christiansen, written communication, 1967), occurs on Mt. Everts; here the tuff remnants are higher topographically than are the basalt remnants. If the tuff and the basalts are considered to be terrace deposits, the tuff would seem to be older. However, no recognizable tuff was found by the author, or by Fraser (written communication, 1966) in the gravels beneath the basalts at Deckard Flats. Although not conclusive evidence, the lack of tuff suggests that the basalts at Deckard Flats are older than the Yellowstone tuff.

The basal three flows (1, 2 and 3) exhibit two fold vertical zonation with large, vertical, basal columns and smaller, irregular upper

columns. The thicknesses, column sizes and shapes, and the petrographic textures for these are given in Table Three. The thickness ratio of the upper columns to the basal columns is approximately $2/3$ to $1/3$ for the three flows. Waters (1960) states that such ratios are produced by normal cooling processes. Flow 2 has a scoriaceous top suggesting that the original thickness was not much over 30 feet in this area.

The top two flows exhibit three fold vertical zonation with larger vertical columns comprising the outer zones (basal and top) and smaller, irregular columns in the central zone (See Table Three). The top of flow 4 is scoriaceous suggesting that the original thickness was not much over 25 feet in this area. The zonation in the fifth flow (5) is both petrographically and megascopically similar to the zonation exhibited by the basalt of flow A in Yellowstone Valley to the north (discussed in next section).

TABLE THREE

FLOW REMNANTS OF DECKARD FLATS

| Flow | Thickness (in feet) | Column Diameter (in feet) | Column Shape | Petrographic Texture |
|----------|------------------------|---------------------------------|-----------------|-------------------------|
| top | 15 | 5-6 | Vertical | Ophitic |
| 5 center | 40-45 | 1-3 | Irregular | Non-ophitic |
| base | 15 | 5-6 | Vertical | Ophitic |
| top | 10 | 4 | Vertical | Non-ophitic |
| 4 center | 5-6 | 1-2 | Irregular | Sub-oph. & Non-oph. |
| base | 10 | 4 | Vertical | Ophitic |
| 3 top | 50 | ½-1½ | Irregular | Sub-ophitic |
| base | 25 | 2½-3½ | Vertical | Non-ophitic |
| 2 top | 20 | ½-1½ | Irregular | Sub-oph. & Non-oph. |
| base | 10 | 2-3 | Vertical | Non-ophitic |
| 1 top | 20 | 1-1½ | Irregular | Non-ophitic |
| base | 10 | 2-3 | Vertical | Sub-ophitic |

TABLE FOUR

FLOW REMNANTS OF LITTLE TRAIL CREEK

| Flow | Thickness (in feet) | Column Diameter (in feet) | Column Shape | Petrographic Texture |
|---------|------------------------|---------------------------------|-----------------|-------------------------|
| V | 30-40 | 1-1½ | Irregular | Non-ophitic* |
| IV | 25-40 | 1-1½ | Irregular | Non-ophitic |
| III top | 50 | ½-1½ | Irregular | Non-ophitic |
| base | 15 | 2½-3 | Vertical | Sub-ophitic |
| II | 20 | 2-2½ | Vertical | Sub-ophitic |
| I | 15-20 | ½-1 | Irregular | Non-ophitic |

* The non-ophitic texture of Flow IV differs from the non-ophitic texture of flow V in that the former exhibits "shadows" of large enclosing augite crystals.

Mineralogically, the basalts of Deckard Flats are composed of plagioclase augite, olivine, magnetite, opaque and/or speckled brown material, iddingsite? and bowlingite? or limonite?. The percentages of these minerals vary from flow to flow and are given in the Appendix.

Flow 5:

The fifth flow is 70-80 feet thick and exhibits three-fold vertical zonation. Near the base, large phenocrysts of glassy plagioclase (up to 4 inches in length) comprise 8 to 12 per cent of the rock but diminish; within 5 to 7 vertical feet, to 2 to 4 per cent. The basal scoria contains similar plagioclase phenocrysts. The basalt also contains scattered through much smaller phenocrysts of olivine. The basal columns are vertical and large (5 foot diameters) and composed of light-gray, granular, porous, porphyritic basalt. The central zone (40 to 45 feet) has smaller irregular columns (1 to 3 foot diameters) composed of dark-gray, dense, non-porous basalt. The change in column size between the basal and central zone is abrupt in places and gradational at others.

The central zone forms the top of the cliff face, but 600 feet to the east and back from the cliff face is a 10 foot scarp of basalt. The topographic surface between the two exposures is probably an erosional feature cut down into the central zone.

The basalt of the upper scarp is light-gray, granular, and porous exhibiting large vertical columns with 5 to 6 foot diameters. This basalt forms the top zone of the fifth flow and completes the three fold vertical zonation. Petrographic changes in texture correspond to the

megascope changes in column size, color, and texture and show an ophitic basal zone, a non-ophitic central zone, and an ophitic top zone.

Plagioclase (50 to 55 per cent) occurs both as lath-shaped phenocrysts and as needle-shaped crystals in the groundmass. The lath-shaped phenocrysts of plagioclase are labradorite, An60-65 in composition (Michel Levy Method, Moorhouse, 1959). Crystals are generally euhedral but, in places, a few are corroded.

The augite (30 per cent) occurs as crystals enclosing the groundmass plagioclase and as smaller granules in the groundmass of the light-gray basalt of the outer ophitic zones. In the central zone the decrease in amount of recognizable augite is accompanied by a corresponding increase in speckled brown and/or opaque material. In the center of the central zone less than 5 per cent of augite can be recognized.

The olivine is relatively fresh in the basalt of the outer zones, but, like the augite, the olivine is more altered in the central zone. In the outer zones the alteration product is a yellow-brown material (bowlingite? or limonite?) and occurs primarily on the rims of the olivine. In the central zone the altered material coats the olivine grains except for the centers of some of the larger phenocrysts.

Summary

Except for the uppermost fifth flow (5), the basalt remnants at Deckard Flats were studied only where the vertical sequence was the thickest. Thus, whether lateral petrographic variations occur could not be determined.

The megascopic and petrographic characteristics of the three-fold zonation of the fifth flow (5) are similar to the zoning of the basalt of flow A in Yellowstone Valley to the north suggesting that they may be erosional remnants of the same flow. If correlation is assumed, the thickness of flow 5 (75 feet) at Deckard Flats, seems reasonable.

Little Trail Creek

At the northern end of the Gardiner exposure north of Little Trail Creek, remnants of five basalt flows are exposed. For purposes of discussion these five flows have been designated from base upward as flows I through V. Here they are at higher elevations than the Gardiner basalts because they are part of an uplifted fault block (Fraser, written communication, 1966). Gravel crops out between flows I and II and II and III but talus conceals the contacts between flows II and IV and IV and V. The entire basalt-gravel sequence rests on Precambrian rocks. Thicknesses, column sizes and shapes, and petrographic textures noted are shown in Table Four. (The mineral percentages for each flow (I-V) are given in the Appendix.)

Comparisons of the flows from Little Trail Creek with the flows at Deckard Flats suggest that: (1) the fourth flow (IV) at Little Trail Creek may correlate with the center zone of flow 5 at Deckard Flats, (2) flow 4 at Deckard Flats is missing or not exposed at Little Trail Creek, and (3) flow V is petrographically different from the other flows and represents a sixth flow (See Figure Three).

The fourth flow (4) at Deckard Flats is 25 feet thick and has a scoriaceous top, three-fold vertical zonation and a 5-6 foot thick central zone of small irregular columns (See Table Three). Flow IV at Little Trail Creek is 35-40 feet thick, exhibits small irregular columns and lacks a scoriaceous top. The base of flow IV is covered in talus, 40 feet of which separates that flow from flow III.

In thin section the non-ophitic texture of flow IV basalt exhibits olivine and augite alteration similar to that of the central zone of flow 5 at Deckard Flats. (See Tables Three and Four) Thus, correlation of the central zone of flow 5 to flow IV is suggested by the similarities in thickness, column configuration, petrographic texture, and alteration of the ferromagnesian minerals.

There are several possible explanations for the absence of flow 4 of Deckard Flats in the Little Trail Creek sequence. It may have thinned out before reaching the latter area; it may have been eroded away before deposition of the later basalts; or it could be hidden in the talus.

Although the basalt of flow V at Little Trail Creek is petrographically different from the basalts of the other flows, it is similar to the basalt of flow B in Yellowstone Valley suggesting that they may be remnants of the same flow (Figure Three). In hand specimen the basalt of flow V is dark colored, fine grained, and dense and contains scattered phenocrysts of plagioclase with rare phenocrysts of olivine. Compared to the basalts of the other flows in the Gardiner area flow V is magnetite-rich and strongly deflects a compass needle. In thin section the basalt exhibits two types of non-ophitic texture. The first type is characteristically

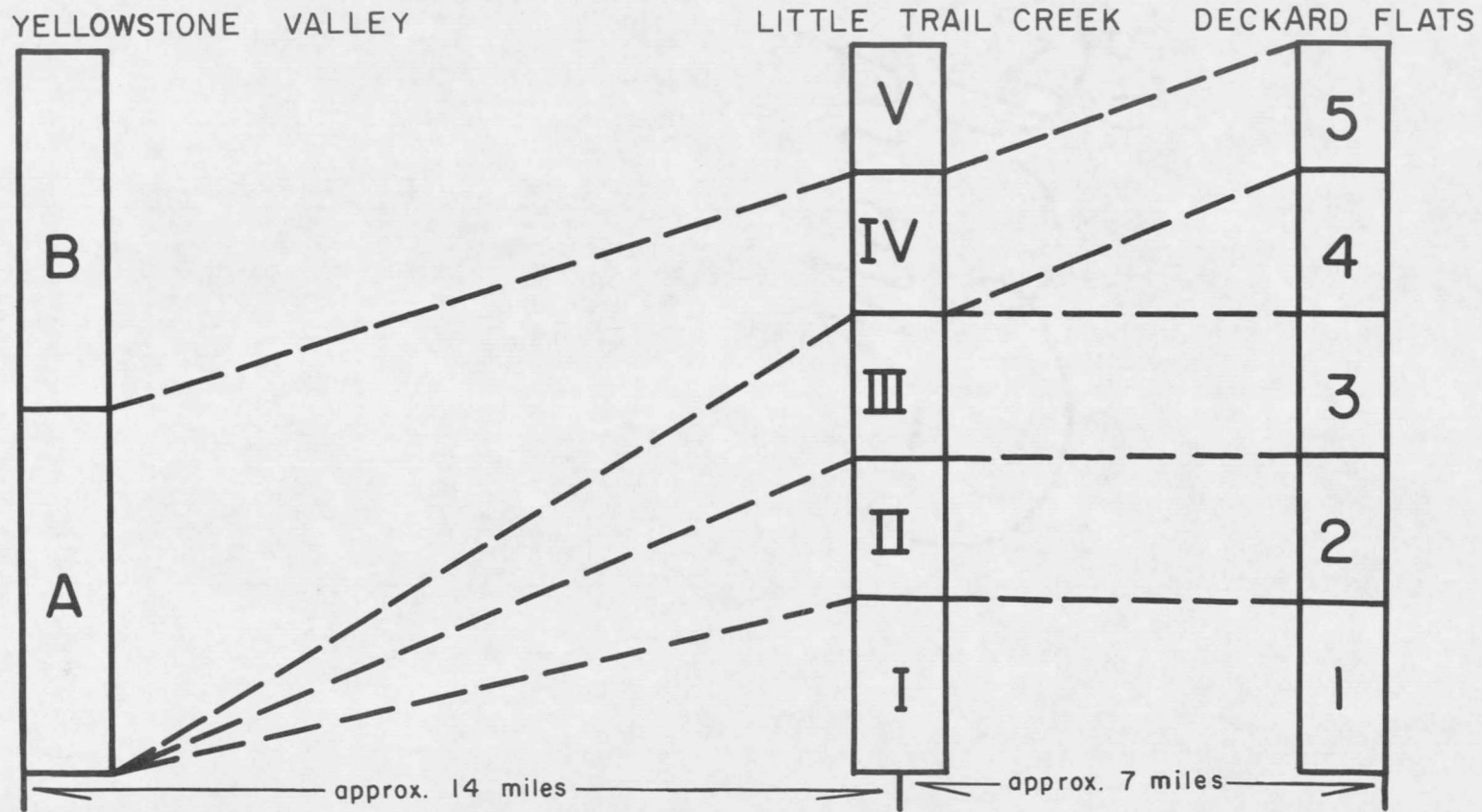


FIGURE 3 SUGGESTED CORRELATIONS OF FLOW REMNANTS

fine grained with only 1 to 2 per cent of plagioclase phenocrysts. Augite, 30 per cent, is entirely restricted to the groundmass; olivine is sparse and relatively fresh; and 16 per cent of the rock is magnetite and/or magnetite-rich glass. The second type has up to 50 per cent of opaque material (magnetite-rich glass and opaque glass). Phenocrysts of olivine are more abundant while recognizable augite is less abundant. These two variations are similar to the two variations noted in the basalt of flow B in Yellowstone Valley. The basalt of flow V is so different from the basalt of flows 4 and 5 at Deckard Flats that it probably represents at least a sixth flow in the Gardiner area. It should be noted that south of Deckard Flats near the junction of Blacktail Creek and the Yellowstone River, Howard (1937) recognized six basalt flow remnants.

Discussion of Gravels

Although composition varies from place to place, the gravels beneath the basalts at Little Trail Creek and at Deckard Flats are primarily composed of dark volcanics, mostly andesite with some basalt. Schist and granitic rock are abundant locally. In places quartzite and basic plutonics are concentrated in small pockets. No recognizable tuff was found.

Although statistical comparisons were not made, these gravels may be similar to the gravels beneath flow A in Yellowstone Valley in that (1) they are primarily composed of dark volcanics and (2) no recognizable tuff was found in the gravels from either locality. However, the gravels beneath flow A have a higher content of basalt, 46 per cent (Horberg, 1940)

than do the gravels beneath the basalts in the Gardiner area. If correlation of flow remnant 5 at Deckard Flats to flow A is assumed, the higher content of basalt in the gravel beneath flow A would be expected because of erosion of the pre-existing four flows.

CONCLUSIONS

Two flows, A and B, were distinguished and mapped in the Yellowstone Valley, and an age date of 8.4 million years was obtained for the younger flow B. Since both basalts are underlain by siltstones of late Miocene-early Pliocene, it is indicated that both basalts are early Pliocene in age. Study of the pre-basalt surface, beneath flow A, indicates that the lava was extruded from a source area to the south and flowed down a northward sloping valley.

Petrographic and field study revealed that the basalt of flow A is characterized by lateral facies changes. Thus, flow A was divided into three facies: the zoned facies, the light-gray facies, and the porphyritic-black facies. The basalt of the zoned facies exhibits ophitic texture in the outer zones and non-ophitic texture in the central zone. Although many factors may have influenced the formation of the central zone, it is theorized that local movement of the flow after partial cooling caused trapping of gases, thus promoting alteration and/or non-ophitic texture.

Comparisons of the basalts of the Little Trail Creek and Deckard Flats sequences indicate that at least six flows are represented in the Gardiner area. Correlation of the basalts of the Yellowstone Valley with the basalts near Gardiner is suggested by the petrographic and zonal similarities of flow 5 at Deckard Flats and flow A in the Yellowstone Valley. Correlation of the two areas is further suggested by the petrographic and compositional similarities of the basalts of flow V (Little Trail Creek) and flow B (Yellowstone Valley).

The above conclusions suggest that the Yellowstone Valley and the Gardiner area were connected by an ancestral Yellowstone River in early Pliocene. The south to north trend of the flow remnants and the south to north thinning of flow A suggest that the source for the basalts was south of Gardiner, probably in Yellowstone Park.

Suggestions for Further Work

The possible presence of an early Pliocene, ancestral Yellowstone Valley presents many geomorphic problems. Thus, verification of the early Pliocene age by dating of the Gardiner sequence is needed, and if verified, a re-examination of the geomorphic development of the Valley would be warranted. In order to determine the source area for these basalts, detailed comparisons of the Gardiner basalts to the basalts in Yellowstone Park would be necessary.

APPENDIX

APPENDIX

Mineral Percentages Flow A

(Based on the average of two 500 counts 0.5 millimeters apart in 8 rows 1 millimeter apart.)

| Mineral | Zoned Facies | | Light-Gray Facies | Porphyritic-Black Facies |
|------------------------------------|--------------|--------------|-------------------|--------------------------|
| | Outer zones | Central zone | | |
| Plagioclase | 53.5 | 53.7 | 50.2 | 47.7 |
| Augite | 30.2 | 8.9 | 29.3 | 12.3 |
| Olivine | 5.3 | 2 | 7.4 | 9 |
| Magnetite | 3 | 4.3 | 4 | 3.8 |
| Opaque and speckled brown material | .5 | 23.1 | 1.5 | 15.1 |
| Yellow and red material | 2 | 6 | .6 | - |
| Pore space* | 5.5 | 2 | 6.5 | 2.1 |

Mineral Percentages Flow B

(Based on the average of two 500 counts 0.5 millimeters apart in 8 rows 1 millimeter apart.)

| Mineral | Basalt from | Basalt south of |
|-------------|----------------|-----------------|
| | Hepburn's Mesa | Hepburn's Mesa |
| Plagioclase | 48 | 47.5 |
| Augite | 30.5 | 11.5 |
| Olivine | .75 | 4.5 |
| Opagues** | 19.5 | 35.5 |
| Pore Space* | 1 | 1 |

*Pore space was difficult to distinguish from open voids left by minerals which plucked out during thin section making. Thus, these figures may be erroneous.

**Opagues include magnetite, magnetite-rich glass.

Mineral Percentages for Flow Remnants at Deckard Flats
(Based on estimates)

| Mineral | Flow 1 | | Flow 2 | | Flow 3 | | Flow 4 | | | Flow 5 | | |
|------------------------------------|--------|------|--------|------|--------|------|--------|--------|------|--------|--------|------|
| | Top | Base | Top | Base | Top | Base | Top | Center | Base | Top | Center | Base |
| Plagioclase | 55 | 55 | 50 | 50 | 55 | 55 | 50 | 50 | 50 | 53 | 52 | 51 |
| Augite | 10 | 25 | 20 | 15 | 20 | 33 | 16 | 19 | 32 | 30 | 11 | 32 |
| Olivine | 5 | 7 | 6 | 8 | 4 | 4 | 5 | 5 | 4 | 6 | 5 | 5 |
| Opaque and speckled brown Material | 12 | - | 15 | 20 | 10 | - | 10 | 17 | 2 | 1 | 24 | 1 |
| Yellow and red material | 3 | 1 | - | 1 | - | - | 4 | 1 | - | - | 2 | - |
| Magnetite | 2 | 3 | 3 | 2 | 5 | 7 | 3 | 2 | 3 | 2 | 3 | 2 |
| Pore Space* | 3 | 9 | 6 | 4 | 6 | 6 | 12 | 6 | 9 | 8 | 3 | 9 |

*Pore space was difficult to distinguish from open voids left by minerals which plucked out during thin section making. Thus, these figures may be erroneous.

Mineral Percentages for Flow Remnants at Little Trail Creek
(Based on estimates)

| Mineral | Flow I | Flow II | Flow III | | Flow IV | Flow V* | |
|------------------------------------|--------|---------|----------|------|---------|----------|----------|
| | | | Top | Base | | Type one | Type Two |
| Plagioclase | 55 | 49 | 55 | 55 | 54 | 45 | 50 |
| Augite | 23 | 30 | 11 | 28 | 13 | 5 | 30 |
| Olivine | 1 | 5 | 1 | 5 | 5 | 2 | 1 |
| Opaque and speckled brown material | 2 | 4 | 13 | 2 | 18 | - | - |
| Yellow and red material | 10 | 1 | 5 | 1 | 3 | - | - |
| Magnetite | 2 | 3 | 3 | 5 | 2 | 47 | 16 |
| Pore Space** | 4 | 8 | 2 | 4 | 3 | 1 | 3 |

*For Flow V magnetite and magnetite-rich glass and opaques were grouped and shown under magnetite.

**Pore space was difficult to distinguish from open voids left by minerals which plucked out during thin section making. Thus, these figures may be erroneous.

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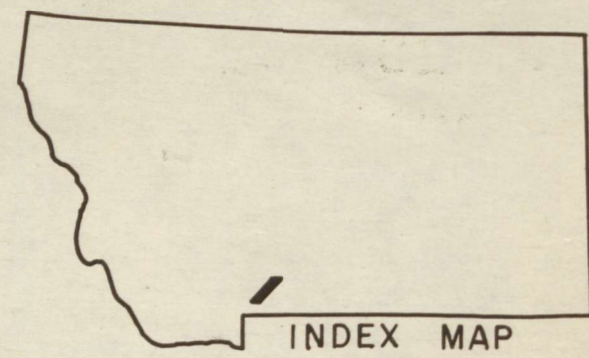
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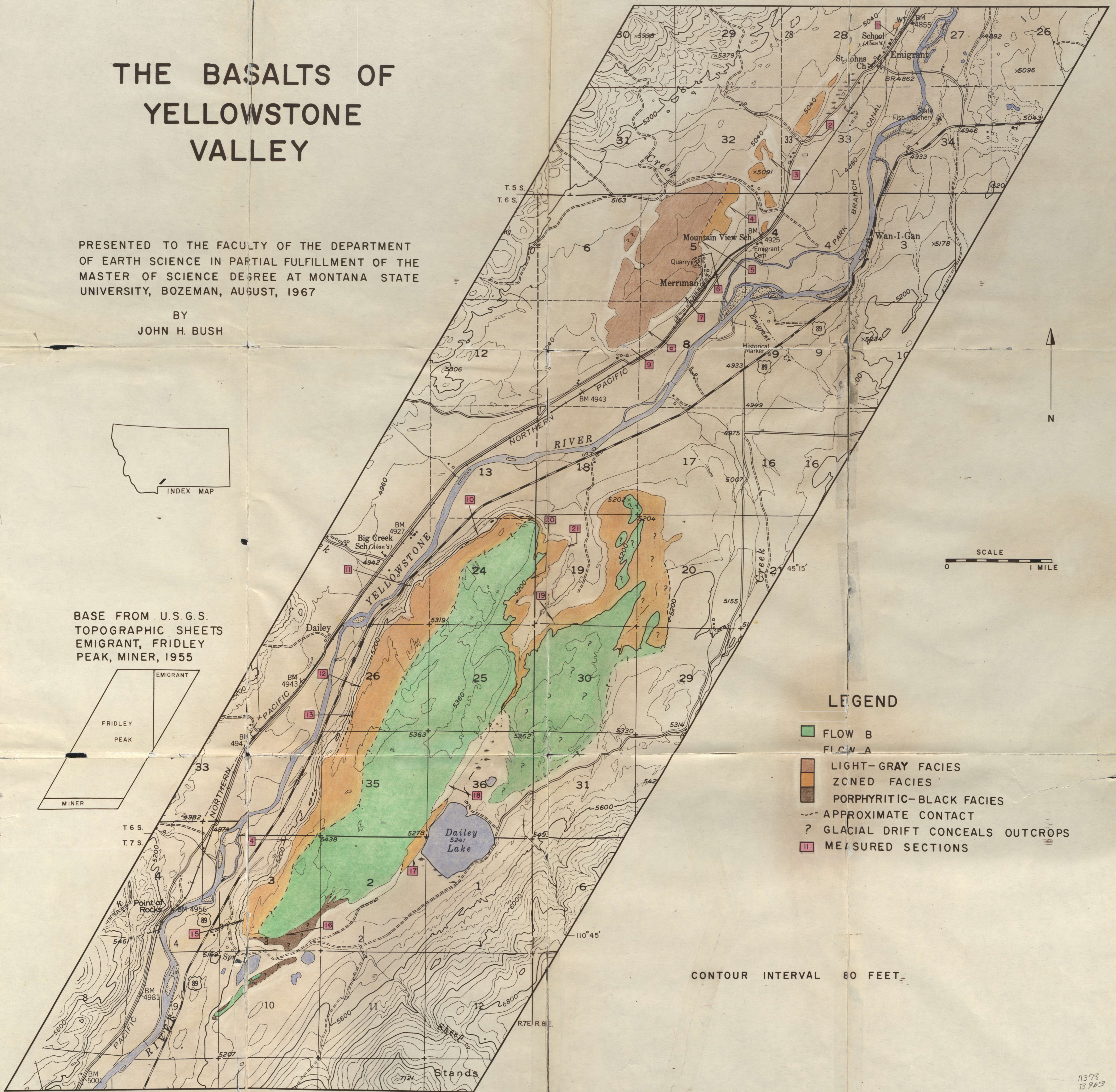
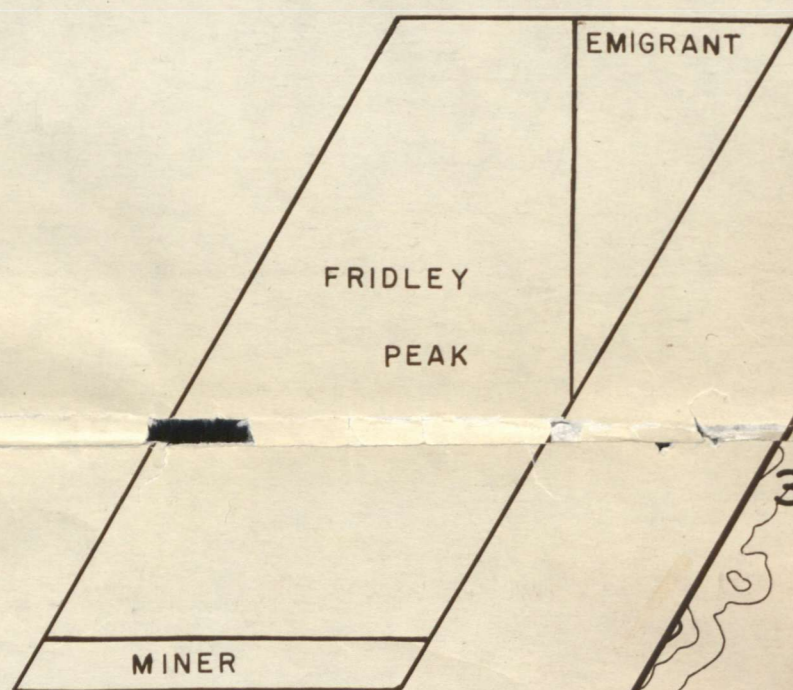
THE BASALTS OF YELLOWSTONE VALLEY

PRESENTED TO THE FACULTY OF THE DEPARTMENT
OF EARTH SCIENCE IN PARTIAL FULFILLMENT OF THE
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UNIVERSITY, BOZEMAN, AUGUST, 1967

BY
JOHN H. BUSH



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LEGEND

- FLOW B
- FLOW A
- LIGHT-GRAY FACIES
- ZONED FACIES
- PORPHYRITIC-BLACK FACIES
- APPROXIMATE CONTACT
- GLACIAL DRIFT CONCEALS OUTCROPS
- MEASURED SECTIONS

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