

THE SNAKE RIVER PLAIN, IDAHO: REPRESENTATIVE OF A NEW CATEGORY OF VOLCANISM

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Studies of the volcanic geology of the Snake River Plain, Idaho, and comparison with other basaltic regions suggest a new category of volcanic activity, termed basaltic plains volcanism. Typified by the Snake River Plain, this style of volcanism is intermediate between basaltic flood (or plateau) eruptions and Hawaiian volcanism. Characteristics that are common to both Hawaiian and plains volcanism are: multiple lava flow units which erupt primarily from point sources, formation of low shields, and frequent emplacement through lava tubes or channels. Characteristics that are common to both flood basalts and plains volcanism are: high volume flows, vents aligned along rift zones, and planar surfaces. The recognition of plains volcanism in other areas provides a means to interpret the style of eruption and volcanic history.

Introduction

Analysis of the morphology of the eastern Snake River Plain and comparisons with other basaltic regions lead to the conclusion that the plain represents a style of volcanism distinctive from flood basalts and shield volcanoes. Although often included in discussions [Macdonald, 1972; Bullard, 1976] of the Columbia Plateau (a flood basalt region), the eastern Snake River Plain (Figure 1) and regions similar to it is considered sufficiently different from flood basalts in the characteristics of the flows and the resulting surface morphology to warrant its consideration as a separate volcanic category.

Several authors have recognized the distinctive character of the eastern Snake River Plain in comparison to the Columbia Plateau. The geochemical differences have been addressed by Waters [1961], Powers [1960], Jones [1970], Leeman [1974, 1975], and others. The differences in the lava flow morphology of the plain and the Columbia Plateau are discussed by Jones [1970], Bullard [1976], and Greeley and King [1975a]. The general volcanic geology of the eastern Snake River Plain is described here and compared with other types of basaltic terrains. The expression basaltic plains was tentatively proposed [Greeley, 1976, 1977] for the style of volcanism represented by the Snake River Plain and is here formalized.

Volcanic Geology

The Snake River Plain extends 550 km westward across southern Idaho from the Island Park Caldera to near the Oregon border. It ranges in width from 80 to 200 km with maximum widths in the east. The youngest rocks are in the central and eastern part of the plain; they comprise the Snake River Group basalts of late Pleistocene to Holocene age. The lavas are principally olivine tholeiites with low SiO_2 and alkalis and high iron contents [Stone, 1967].

Flow Characteristics

The prevailing flow type in the Snake River Plain is pahoehoe basalt that was emplaced as multiple flow units (compound lava flows of Walker [1972]). Cross sectional exposures of lava flows are rather limited in the eastern Snake River Plain because of the lack of erosion. Although some flows are exposed in the walls of summit craters, they are probably not typical for the main bodies of the flows that

make up the plains away from the vents. Where exposed away from the vents, flow units average about 1 to 5 m. Compound flow thicknesses, or the total of all flow units for a given eruptive sequence, may be 35 m or more thick, as in the Hell's Half Acre field of the Wapi field [Champion, 1973].

Fresh surfaces of the pahoehoe flows are hummocky, with local relief as much as 10 m. So-called collapse depressions [Hatheway, 1971] are common on some flows, as are pressure plateaus, pressure ridges, and flow ridges (Figure 2). These features are all typical of compound lava flows and apparently result from the manner in which the flows advance through a series of budding toes described by Wentworth and Macdonald [1953] and others. Weathering of the surface features and accumulation of windblown sediments in low-lying parts of the flow result in a smoothing of the surface relief to the degree that in older flows only remnants of the prominent features, such as some ridges, are visible. Local relief is also formed by flow fronts. Flows that encroach topographically high features, such as tuff cones, often form a shallow depression between the flow front and the preflow feature.

Aa flows are also present in the Snake River Plain. Some are of considerable extent, such as the aa flow complex erupted from fissures in Craters of the Moon that covers 150 km^2 . Some aa flows appear to be of the simple lava flow type [Walker, 1972], emplaced as a single surge of lava. However, they are relatively thin, similar to the individual pahoehoe flow units of the compound lava flows, and emplacement of comparatively viscous aa over so large an area is problematical. Some of the large, thin aa flows in the Snake River Plain may have been erupted and essentially emplaced as pahoehoe but transformed to aa in the final stages of flow. Although this transition is difficult to substantiate for prehistoric flows, some flows on the plain suggest this possibility, as shown in Figure 3; a similar process has been observed in active flows [Peterson and Tilling, 1980; Guest et al., 1980].

The eastern Snake River Plain developed by accumulation of lavas in four main forms: (1) low shields, (2) fissure flows, (3) major tube flows, and (4) intracanyon flows. The relationships of these constructs are shown in Figure 4.

Low Shields

Noe-Nygaard [1968] called certain shield volcanoes in the Faroe Islands shield volcanoes of scutulum type (from the Latin scutulum, the diminutive of scutum, = shield). They are very flat shields having slopes of about $1/2^\circ$ underlain by compound lava flows. Typically, they are about 15

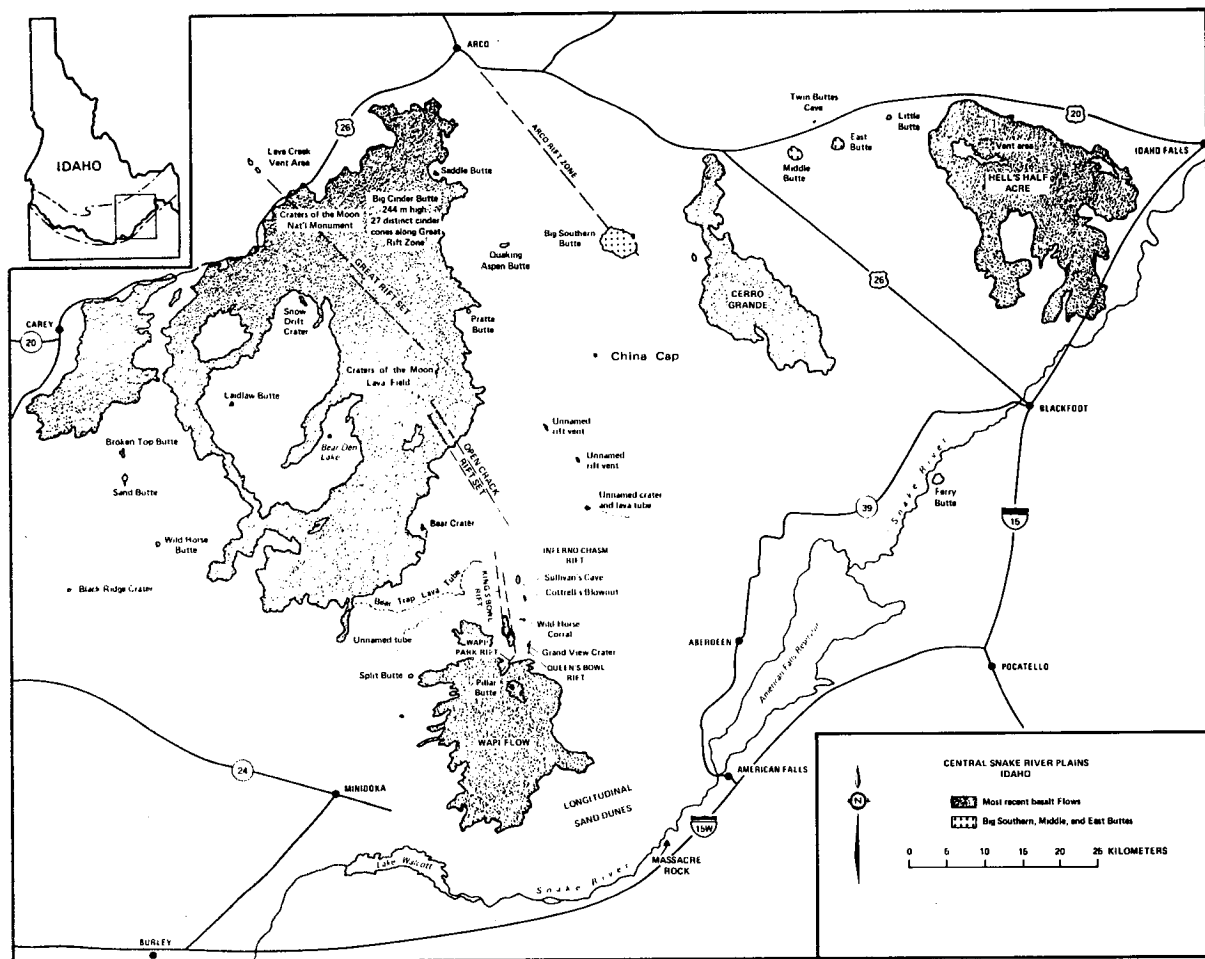


Fig. 1. Sketch map showing location of features discussed in the text.

km across and consist of less than 7 km^3 of lava. Similar flat shields occur in Iceland and Hawaii, and Macdonald [1972] used the term lava cone for examples such as Mauna Iki and other similar low-profile shields in Hawaii. The small sizes and low profiles of these shields are the features that led Noe-Nygaard and Macdonald to distinguish them from major Hawaiian and Icelandic shields. However, to prevent confusion with composite cones (and to avoid the awkward phrase shield volcano of scutulum type), the term low shield is proposed to describe volcanoes of this type.

Most of the eastern Snake River Plain consists of multiple low shields, typified by the Wapi and Hell's Half Acre lava field. The Wapi lava field covers more than 300 km^2 and is composed of a compound lava flow consisting of pahoehoe lavas of the 'degassed' variety [Swanson, 1973]. Charcoal dug from beneath lavas at the northern margin of the flow yield a C^{14} date of 2270 ± 50 years before present (date determined by U.S. Geological Survey, courtesy of D. Champion). Lava toes, collapse depressions, flow ridges, and pressure ridges are common, but no lava tubes have been found on the main part of the field [Champion, 1973]. The areal extent of the Wapi field, one of the largest young flows on the plain, is considerably less than classic flood basalts such as the $40,000 \text{ km}^2$ Roza Member of the Yakima Basalt [Swanson et al., 1975].

In profile (Figure 5) the Wapi low shield displays two

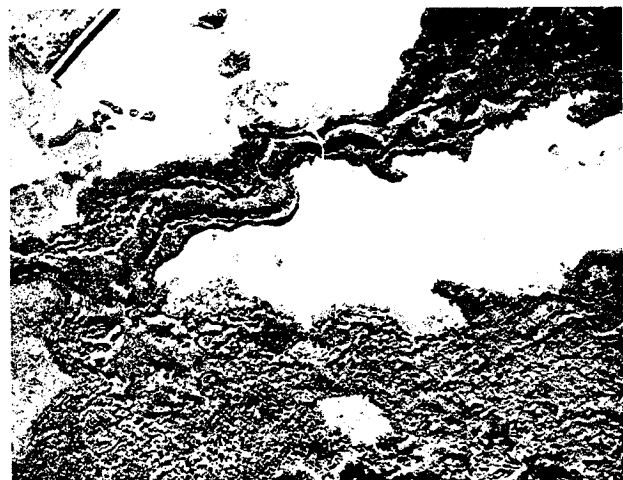


Fig. 2. Vertical aerial photograph of the eastern margin of the Wapi flow, showing flow ridge [Champion, 1973], which formed parallel to the direction of flow, pressure plateau (elevated areas on the flow), and collapse depressions (small circular features in the flow). Dark areas are flow units of the Wapi field; light areas are older flows (NASA-Ames photograph 878-5-7; October 1968).



Fig. 3. Vertical aerial photograph of a small basalt flow erupted southeast of Big Southern Butte; vent area is marked with an arrow. Flow surface exhibits both pahoehoe and aa flow textures; emplacement of most of the flow is considered to have taken place essentially in the pahoehoe state; then in the final stages of emplacement the lava transformed to aa. Incomplete transition is indicated by irregular slabs of pahoehoe (light-toned surfaces) (U.S. Department of Agriculture photograph CXN-4R-106; October 1968).

prominent slopes: the general slope is less than $1/20^\circ$; the summit region steepens to about 5° . A similar profile is seen in Hell's Half Acre and in older low shields on the plain. Where older shields are encroached by later flows from other vents, the steeper 'upper story' often remains unburied. The steeper summit of low shields is partly explained by the textures of the flows that make up the summit region. For ex-

ample, the summit region—named Pillar Butte—of the Wapi low shield has a high proportion of short, low-volume aa flows around the vent. These flows were more viscous than the pahoehoe lavas of the main field, and they may represent the final stages of eruption. However, the complex sequence of development from steep cone to low shield to spatter rampart observed during the short history of Mauna Ulu [Swanson et al., 1979] would caution against assuming that earlier, steeper summit regions might not be buried at Pillar Butte.

In addition to steeper profiles, the summits of many of the low shields are marked by one or more irregular craters, commonly pit craters. Many of these show evidence of multiple collapse (Figure 6) and were source vents for large lava tubes or channels. Rarely, spatter ramparts built of pasty agglutinate occur at the summit.

Many low shields appear to be aligned in distinctive rift zones, with shields along each zone being roughly contemporaneous in age. An example is the Inferno Chasm rift zone [Greeley and King, 1975b, and Figure 7]. The aligned shields represent fissure eruptions in which effusion was localized at various points along the fissure. Individual shields, however, are built of flow units similar to those in Hawaiian type eruptions. For some unknown reason, once the low shields on the plain reached a certain size, the eruption vent shut off, with subsequent eruptions occurring elsewhere.

Lava Tubes

The role of lava tubes and channels in the emplacement of basalt flows is poorly understood. However, a study of Mauna Loa [Greeley et al., 1976] shows that more than 80% of the flows exposed on the surface were at least partly emplaced through lava tubes and channels. Such tubes and channels can be very long. Lava tube systems longer than 20 km are common in many areas on earth, and structures on the Moon and Mars interpreted as lava tubes exceed 100 km in length.

Lava tubes and channels develop in Hawaiian flows for which the rates of effusion are moderately high (e.g., 10 to $100 \text{ m}^3 \text{ s}^{-1}$ [Macdonald, 1972]) but not as high as during flood eruptions. There are no known lava tubes in the flood lava flows of the Columbia Plateau. Tube formation also

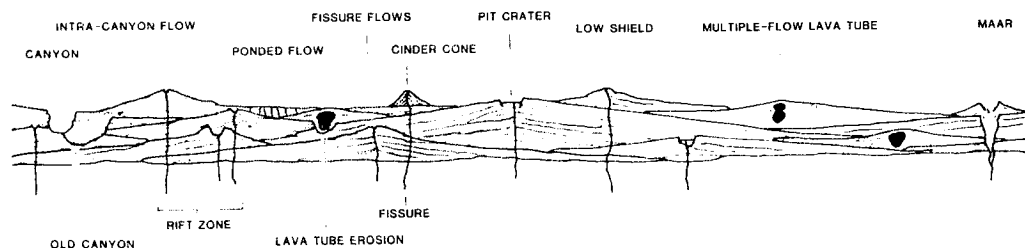


Fig. 4a. Schematic cross section to show the salient features of a plains basalt region, typified by the central Snake River Plain. The vertical scale and surface relief are greatly exaggerated in order to show detail that would otherwise be lost. The predominant lava is pahoehoe basalt in the form of flow units that seldom exceed 3 to 10 m in thickness. The primary forms are as follows: (1) Low shields, many of which have summit pit craters; the summits of most low shields are marked by steeper profiles, resulting partly from late-stage, low-volume eruptions of aa lava. (2) Flows fed by large lava tubes that wind between coalescing low shields; in some instances lava tubes may entrench into older flows by erosion. (3) Fissures produce thin flows with relatively low surface gradients; the flows may be pahoehoe or aa, some of which are emplaced by networks of small tubes and channels. 'Point source' eruptions along fissures can result in infrequent cinder-and-spatter cones. (4) Flows more than 10 m thick are occasionally found in 'plains' type regions. These may represent flood-type eruptions, but more frequently, they are the result of lava ponding in low-lying regions and as intracanyon flows (left side of diagram). Regardless of origin, thick flows are infrequent and appear to contribute comparatively little to the total volume of the plains region. (5) Maar craters that result from ground water and magma interactions.

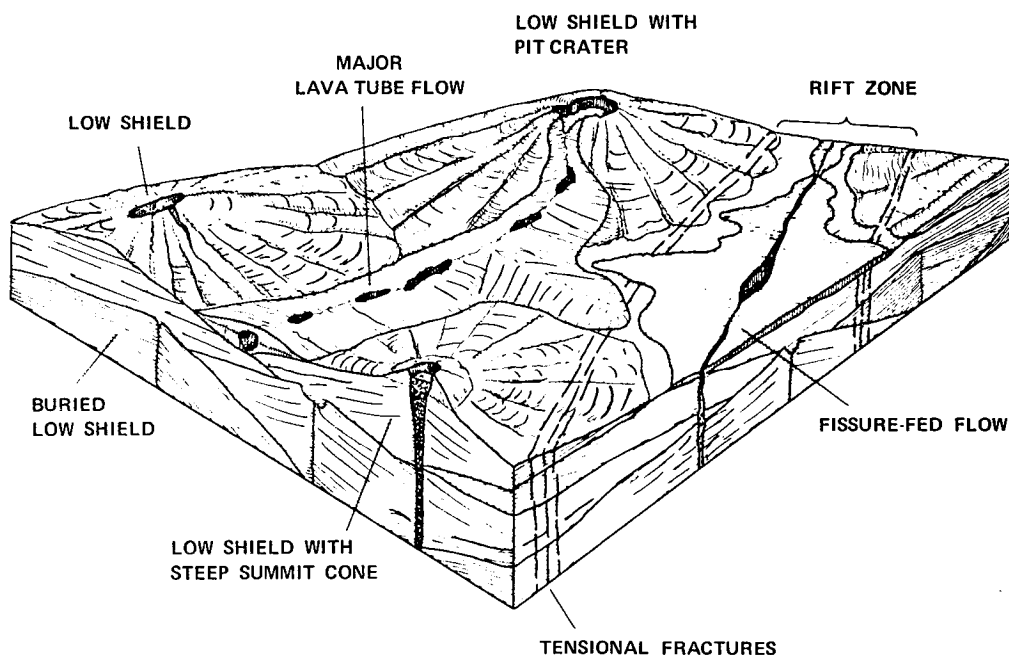


Fig. 4b. Block diagram showing the relationship of low shields, major lava tube flows, and fissure flows. Compare with Figure 7.

seems enhanced by sporadic eruption of multiple flow units with intervening periods of quiescence. This kind of activity was typical for the approximately 6-year history of Mauna Ulu, Hawaii, a low shield having complex networks of lava tubes [Greeley, 1971, 1972; Peterson and Swanson, 1974; Swanson et al., 1979].

Although lava tubes and channels predominantly cause constructional features in that they emplace lava flows, the flows in tubes can also erode by melting and 'plucking' of preflow terrain and flows previously emplaced by the lava tube [Greeley and Hyde, 1972; Peterson and Swanson, 1974]. Complex sequences of construction and erosion by multiple flow units can develop in this type of flow (Figure 8).

Lava tubes played an important role in the emplacement of some of the flows in the Snake River Plain. Although not as common as the Hawaii tubes, some are larger. A survey of part of the plain shows that more than a fifth of the flows involved lava tubes and channels. Although the sources for the tubes are not always obvious, examples can be cited in

which shields, pit craters, and possibly fissures were the source for major lava tube flows.

Bear Trap lava tube and the flows associated with it make up one of several tube-flow systems which originated in the vicinity of the King's Bowl rift and are examples of major lava tube flows. The tube can be traced more than 21 km by a series of collapsed segments and is then buried by Holocene basalt flows from Craters of the Moon [Greeley and King, 1975a]. The axial trace of the tube is defined by a broad topographic swell that has, to some degree, controlled the emplacement of subsequent lava flows. Most of the lava tube system is collapsed, but there are two uncollapsed segments close to the Arco-Minidoka road that are readily accessible. Although the total extent of the flows associated with Bear Trap lava tube cannot be determined because the flanks of the tube-arch and distal end of the flows are buried, the exposed part of the flow is estimated to be about 60 km².

In contrast to the voluminous lavas in low shields and the large fissure flows, major lava tube flows are small. They contribute substantially to maintaining the flatness of the plain,

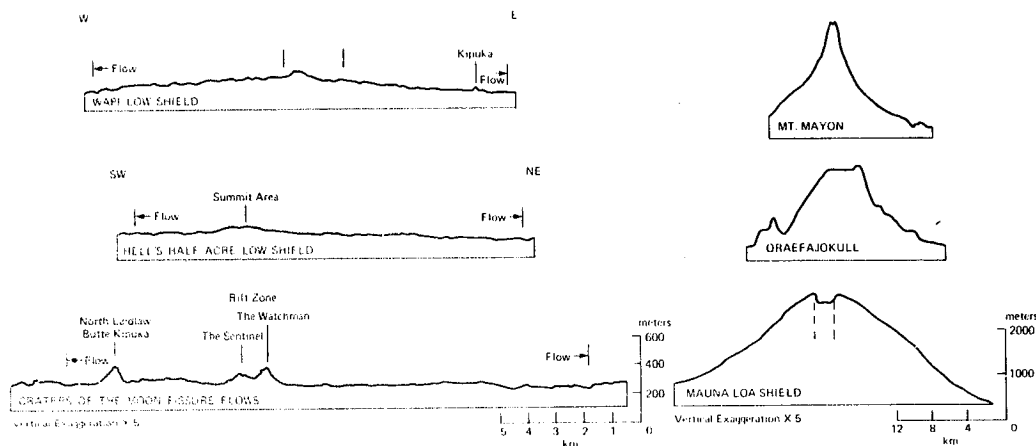


Fig. 5. Topographic profiles comparing Icelandic (Oraefajokull) and Hawaiian shield volcanoes (Mauna Loa), a composite cone (Mt. Mayon), and low-shield volcanoes of the Snake River Plain. Note the difference in scales for comparison.

however, in that they fill in the low-lying region between adjacent low shields.

Fissure Flows

Most fissure vents are associated with rift zones. Typically, fissure flows in the central and eastern Snake River Plain are composed of multiple flow units. The two youngest fissure flows on the plain are the King's Bowl flow, and flows in the Craters of the Moon where two flow units have been dated by C^{14} methods at 2085 ± 85 and 2255 ± 60 years before present [Bullard, 1971]. The flows cover nearly 1500 km^2 and consist of multiple aa and pahoehoe flows erupted from the fissures along the Great Rift (Figure 1). Although this compound flow is the largest fissure flow on the plain, it is much smaller than typical flood basalt flows on the Columbia Plateau, as discussed later.

The King's Bowl flow (Figure 9) has been dated at 2130 ± 130 years before present [Prinz, 1970]. It was erupted from a prominent fissure, and covers only about 3 km^2 . The flow consists of several units [Greeley and King, 1975a], some of which were ponded as small lava lakes. Thickness of individual flows is less than about 1.5 m, but some of the lava lakes may have been more than 4 m deep in places.

Although the main characteristic of fissure flows in the eastern Snake River Plain is the nearly continuous effusion of lava along several kilometers or more of the fissure, eruption at 'point sources' along the fissure may also occur. These eruptions may take place either independently or contemporaneously with fissure effusion, and they produce small spatter cones, or rarely, substantial cinder cones, as in Craters of

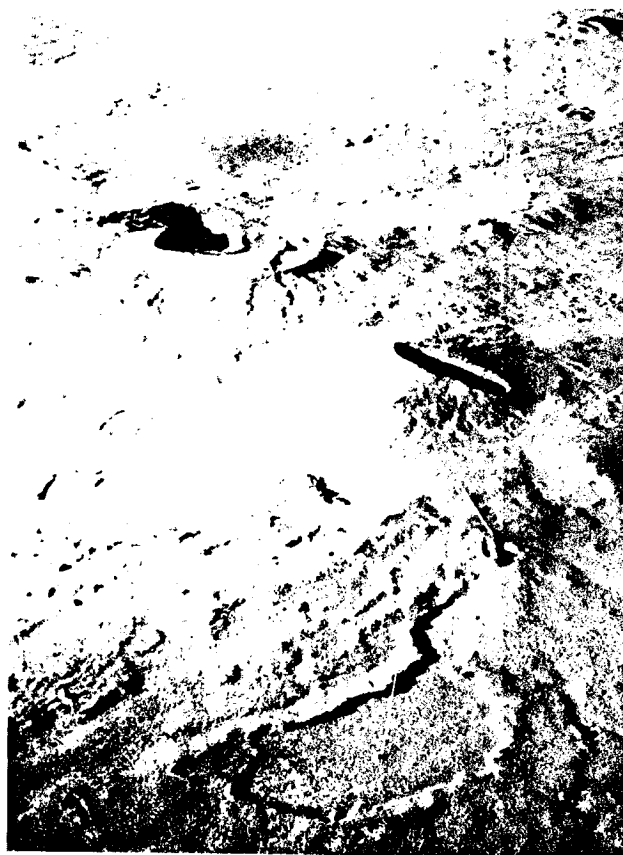


Fig. 7. Oblique aerial view northeastward across vents of the Inferno Chasm rift zone (Inferno Chasm vent is just out of view to the right) [from Greeley and King, 1975a].

the Moon [Stearns, 1928; Murtaugh, 1961]. Phreatic eruption may also occur along fissures as at King's Bowl. Such 'point source' structures are scarce on the plain and contribute little to the total accumulation of volcanic materials.

Intracanyon Flows

Several rivers cut the Snake River Plain, forming deep canyons. During the relatively short history of the plain, older canyons apparently existed [Stearns et al., 1938; Trimble and Carr, 1961], but their presence is now mostly obscured by lava flows. Outcrops exposed by erosion along the present Snake River show that lavas spilled into the canyons, forming intracanyon flows, some of which ponded to depths exceeding 30 m. Columnar jointing and entablature structures are evidence for possible ponding of the flow prior to cooling. Sources for intracanyon flows may have been low shield, fissures, or major lava tubes. A tube-fed intracanyon flow occurs in the western Snake River Plain, mapped by Howard and Shervais [1973].

Because exposures of intracanyon flows in the central and eastern Snake River Plain are rather limited, their significance in the accumulation of lavas in the plain cannot be assessed fully.

Miscellaneous Vent Structures and Flows

Relatively minor accumulations of lava flows and other volcanic products occur on the plain and on the margins of the plain. These features include tuff-and-cinder cones, such as China Cap, and maar craters such as Sand Crater (Figure



Fig. 6. Vertical aerial photograph of Wildhorse Corral (north is to the bottom). The vent is about 52 m deep and 1 km long, its length being oriented north-south on the Inferno Chasm rift zone. Wildhorse Corral appears to have a complex eruptive history, indicated by terraces within the crater walls and multiple flow units, some of which were tube fed (from Greeley and King [1975a]; NASA-Ames photograph 951, 8-15, 17; May 1969).

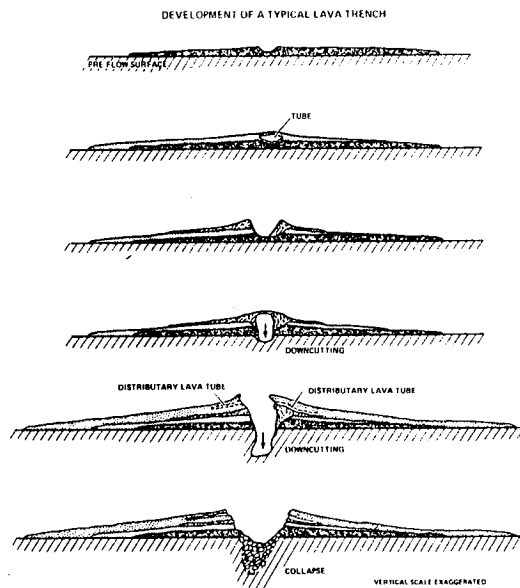


Fig. 8. Sequence to show some of the stages in the development of a tube-fed compound lava flow. Stage 1 is a single flow unit emplaced by a shallow lava channel. Stage 2 involves a second flow unit in which lavas occupied the previous channel and formed a roof. Stage 3 includes a third flow unit that was turbulent and formed a large channel. Continued eruption of the same flow resulted in the formation of a roof, with downward erosion by melting and physical removal of some of the previous flow and preflow rocks. In stage 5 a fourth flow unit was erupted at a high rate; it initially used the previous tube as the feeding conduit, but because the volume of lava was large, the previous tube was destroyed and an open-flow channel developed, segments of which may have become roofed. Overflow from the channel formed distributary lava tubes and small channels. Stage 6 marks the end of eruption with collapse of roofed segments by bank collapse. Although this sequence is hypothetical, elements of each stage are based on observations of active lava tubes and channels and studies of cooled structures.

10), and Split Butte [Womer et al., 1981]. Cinder and spatter cones are rare and appear to be associated with fissures, as discussed above. Some elongate vents and flows are aligned over fissures and may be transitional between fissure flows and low shields associated with rift zones.

Some flows from tubes, central vents, or fissures formed natural levees and developed into lava lakes. The lakes may have been centered over the vent, as at King's Bowl and Split Butte, or they may have formed 'perched' lava ponds [Holcomb et al., 1974] on the flanks of low shields (Figure 7).

Discussion

Basaltic volcanism produces a wide range of volcanic landforms, including small cones and domes, shield volcanoes, and basaltic plateaus which cover thousands of square kilometers. This diversity is primarily a reflection of the wide range of eruptive styles that basaltic magma can assume. The Snake River Plain and similar regions display characteristics intermediate between eruptions of flood lava flows and of lavas that form shield volcanoes. The three principal basaltic styles of eruption and their resulting landforms are summarized as follows:

Flood basalts. Flood basalts form extensive, often thick flows erupted at very high rates from fissure vents and produce vast basalt plateaus. The Yakima Basalt of the Columbia Plateau is a typical flood basalt [Swanson et al., 1975]. It is comprised of the Roza Member (1500 km^3), which was

erupted from a linear vent system more than 130 km long and several kilometers wide, and several other, lesser members, such as the Ice Harbor Member. Vent areas are difficult to identify because they are buried by their own flows, but dikes and remnants of small pyroclastic cones indicate the general locations of fissure zones. Eruption rates for the Ice Harbor flows were about $2 \times 10^{-3} \text{ km}^3$ per day, comparable to those for Kilauea. The rate for the Roza Member is estimated at $1 \text{ km}^3/\text{day}$, some 3 orders of magnitude larger, and hundreds of cubic kilometers of lava were erupted over a period of at most 2 or 3 weeks [Swanson et al., 1975]. Throughout most of its $40,000 \text{ km}^2$ extent, the Roza Member consists of two or more single cooling units that must have been ponded as vast lava lakes over much of the area, taking years to solidify, as indicated by massive columnar jointing. Lava tubes, lava channels, and other large scale flow features are lacking, either because they did not form or be-



Fig. 9. Vertical aerial photograph of the King's Bowl rift and the King's Bowl lava field, a compound lava flow fed by the main fissure. A phreatic eruption and subsequent collapse created King's Bowl, the elongate crater on the fissure. Prevailing winds from the west (left) at the time of the eruptions carried ash and other fine particles eastward from the fissure (U.S. Department of Agriculture photograph).



Fig. 10. Oblique aerial view northeastward across Sand Butte, a tephra cone 1.2 km in diameter that contains a 650 m crater. Although most of the inner and outer slopes are covered with vegetation, several outcrops show the outward-dipping tephra layers that make up the cone. Sand Butte is astride a north-south fissure along which flow has occurred, and which has given rise to other vents, such as the series of low spatter ramparts in the upper left part of the photograph. The lower flanks of the cone have been covered by pahoehoe flows, identified by the hummocky surface and pressure ridges (photograph by R. Greeley).

cause they were destroyed by activity within the emplaced lavas, such as lava lake circulation. A review of the literature reveals that there are virtually no lava tubes or channels in the other flood basalts of the Columbia Plateau.

The only known surface features of large size preserved on the Roza flow are 'sag-flowouts.' These are described by McKee and Stradling [1970] as circular depressions surrounded by concentric dikes (some of which are more than 250 m across) that appear to have formed by crustal foundering. Recent studies indicate that some structures may result from phreatic activity after flow emplacement [Hodges, 1978].

Volcanic shields. Volcanic shields are produced by moderate rates of eruption, but the total volumes of lava per eruption sequence are lower than those for flood basalts and the vents are commonly central rather than linear. The nature of the shield-forming eruptions is markedly different from that of flood eruptions. For example, eruptions at Kilauea volcano, Hawaii, are sporadic and produce thin flows, the longer lasting of which may develop tubes. Average flow unit thickness is about 5 m, in contrast to 10 to 30 m thick flows in the Columbia Plateau. Rapid outbursts of high volume but short duration also occur on shield volcanoes, as evidenced by the 17-hour summit eruption of Mauna Loa in 1975 (R. Tilling, personal communication, 1977.)

Basaltic plains. Basaltic plains combine some of the characteristics of both flood basalts and shield volcanoes and are proposed as a separate category of volcanic activity,

typified by the Snake River Plain. Basaltic plains are made up of lava flows about 10 m thick erupted from both central vents that produced low shields and short fissures that formed thin sheet flows; the combined thickness of all flows in the Snake River Plain locally exceeds 1500 m [LaFehr and Pakiser, 1962]. As with shield volcanoes, flow features such as lava tubes and lava flow channels are relatively common on basaltic plains and are important in emplacing lava flows in the low-lying areas between the low shields, thus maintaining a regionally planar surface.

It is important to note that the classification of flood basalts, shield basalts, and plains basalts applies in a regional context. Seldom will any given area be uniquely one or the other. For example, many of the Tertiary basalts in Iceland are of the flood or plateau form, but younger basalts occur both as large, classic shield volcanoes, such as Skjaldbreithur, and as plains basalts, as in the Reykjanes peninsula.

The identification and classification of various basaltic terrains enable at least qualitative estimates of the styles of volcanism involved in their development.

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