Geology and Petrogenesis of the Island Park Caldera of Rhyolite and Basalt Eastern Idaho

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By WARREN HAMILTON

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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A study of the origin and occurrence of the products of eruption and collapse of a large magma chamber in which liquid rhyolite overlay liquid basalt

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By Warren Hamilton

ABSTRACT

The Island Park caldera, in the northeastern part of the Snake River Plain, is an elliptical collapse structure 18 by 23 miles in diameter that was dropped from the center of a shield volcano composed of rhyolite ash flows. The western semicircle of the caldera margin is a single scarp in the northwest and a composite scarp in the southwest. Rhyolite domes and lava flows were extruded along the western rim during and after the period of collapse. The eastern semicircle of the caldera scarp has been covered completely by rhyolite ash flows, domes, and lava flows that were extruded along it. The caldera is filled, in upward succession, by rhyolite ash flows, interbedded rhyolite ash flows and olivine-basalt lava flows, and flows of olivine basalt alone. Rhyolite domes protrude through the basalt. The exposed rocks are middle (?) and late Pleistocene in age. Basalt of the Snake River Plain, which laps onto the caldera shield from the west, was erupted from vents near the Island Park caldera during late Pleistocene and Recent time. The eastern part of the caldera is overlain by rhyolite ash flows and lava flows of late Pleistocene age from the Yellowstone Plateau.

The rocks of the caldera are bimodal, consisting of uniform olivine basalt on the one hand and uniform highly silicic rhyolite on the other. The basalt is holocrystalline and diabasic and consists of labradorite, subcalcic augite, and magnesian olivine. The rhyolite is largely vitric; ash flows are mostly welded; and crystals of sanidine, high-quartz, and oligoclase are ubiquitous. A single flow of latite was found on the caldera rim. Eleven specimens were analyzed for both major and minor elements.

The Island Park caldera is part of the Snake River–Yellowstone province of intense Pliocene and Quaternary volcanism of olivine basalt and rhyolite. In this province, as in other bimodal volcanic provinces, rhyolite and basalt erupted from vents interspersed in both time and space, and simultaneous eruptions of both liquids from the same or nearby vents are known to have occurred. In the Island Park caldera, the eruptive sequence and geometry suggest that the large magma chamber contained liquid rhyolite overlying liquid olivine basalt.

Several kinds of evidence indicate that the rhyolite of this and other bimodal volcanic provinces has formed by differentiation of basaltic magma. This differentiation cannot be explained in terms of fractional crystallization, but it can be explained in terms of an original tholeiitic basalt magma separating by liquid fractionation into rhyolite and olivine basaltic liquids in the proportion of about 1 to 5. Such fractionation may possibly occur in the uppermost mantle or lower crust; there, rising tholeiite magma might split into immiscible phases, one rich in volatiles and fusibles (rhyolite) and the other rich in refractories (olivine basalt), owing to instability of the initial homogeneous liquid caused by pressure decrease during ascent in a region of abnormally high thermal gradient.

INTRODUCTION

The Island Park caldera is perhaps the largest symmetrical caldera yet studied anywhere in the world. Rhyolite was erupted early in the period of collapse, then basalt and rhyolite were erupted alternately from vents interspersed throughout the caldera floor, and finally basalt was erupted alone. The caldera is so young that there has been little erosion of the tuffs, flows, extrusive domes, and fault scarps that comprise it, and there has been no apparent complication of the volcanic features by tectonism. The history of the growth of a broad shield volcano, the collapse of its central part, and the extrusion of magma during and after its collapse can be determined here with particular clarity.

The caldera is significant petrologically because its rocks are a bimodal assemblage of uniform olivine basalt and equally uniform highly silicic rhyolite. These contrasting rock types apparently existed together as magmas—the rhyolite above the basalt—in the large chamber into which the caldera collapsed.

The Island Park caldera lies in the northeastern part of the Snake River Plain of Idaho (fig. 1). The Yellowstone Plateau—the high northeast end of the Snake River Plain structural and volcanic province—extends to the east side of the caldera. The volcanic terrane rises gradually from an altitude of about 2,000 feet at the Oregon border to 8,000 feet on the Yellowstone Plateau. Flanking this terrane are still higher areas—the Basin and Range province to the south, the central Idaho highlands to the north, and the high mountain blocks to the northeast. In the eastern half of the plain, volcanism has been concentrated along a northeast-trending axis, so that this part of the plain is higher in its center than along its edges; rivers flow near the

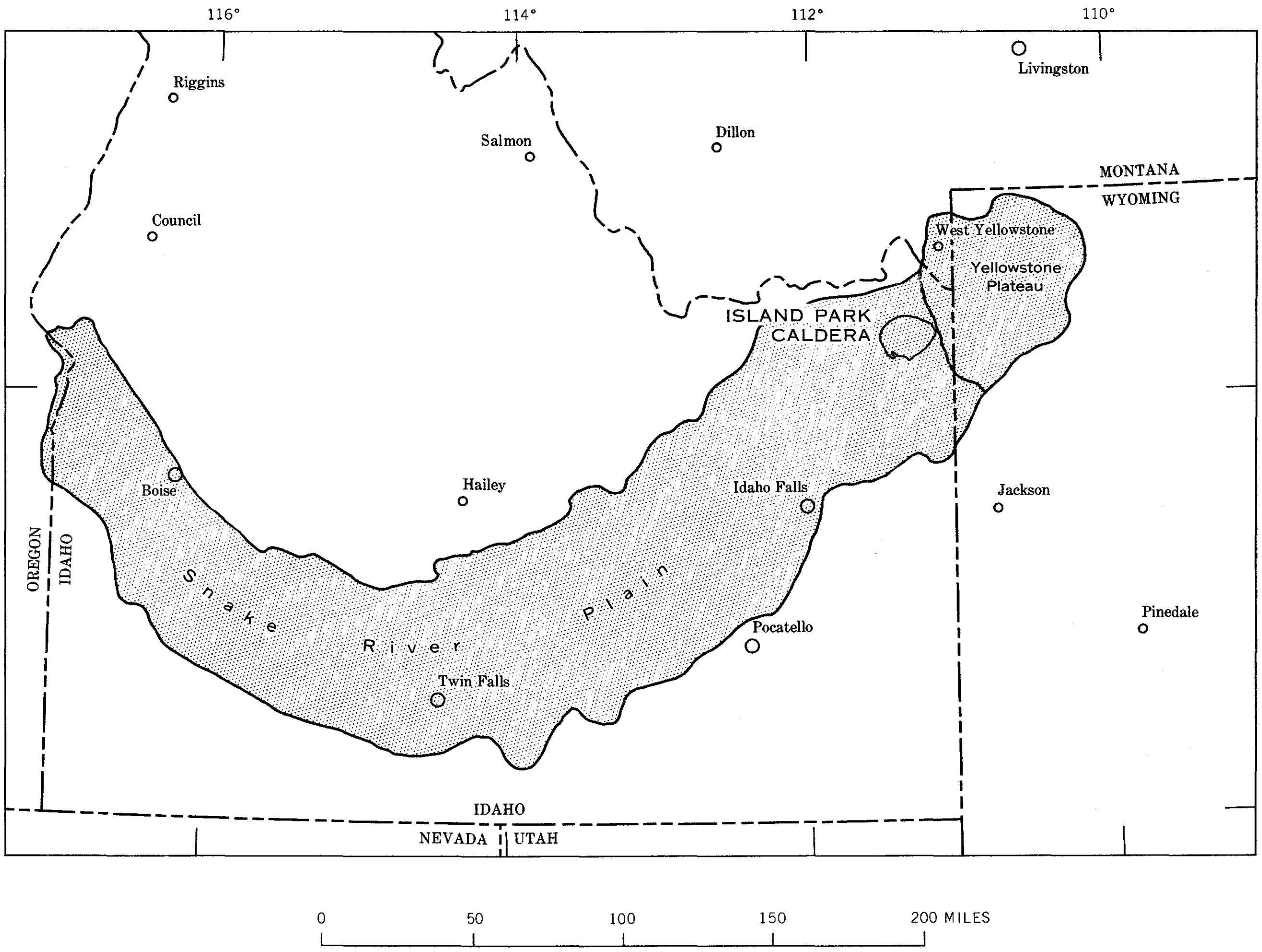

Figure 1.—Southern Idaho and adjacent areas, showing relation of Island Park caldera to Snake River Plain and Yellowstone Plateau.

margins rather than within the plain. The axial altitude of the Snake River Plain at the west side of the Island Park caldera is about 6,500 feet, 1,000 feet higher than the southern alluviated margin of the plain but only about 200 feet higher than the closer, northern margin. The Snake River Plain and the Yellowstone Plateau have been the site of intense bimodal basalt-and-rhyolite volcanism from Pliocene to Recent time.

Near the Island Park caldera, the Snake Plain is bounded by the Centennial Mountains on the north and by the Teton Range on the southeast. Both mountain ranges are high young fault blocks that rise from the plain along long gentle dip slopes and face outward along precipitous fault scarps bordering the downdropped blocks of Centennial Valley and Jackson Hole, respectively. Both mountain blocks have been much uplifted during late Quaternary time and may be entirely Quaternary structural features. Rhyolite tuff of early to late Pliocene age (Love, 1956) laps onto the Teton Range block and shares all or most of its tilting; similar rhyolite laps onto the Centennial Mountains block. The rhyolite forms the outer part of the Yellowstone Plateau on all sides but the southwest (Boyd, 1961). It is buried by younger basalt and rhyolite in the central and southwestern parts of the Yellowstone Plateau and in most of the adjoining Snake River Plain. The highlands flanking the Snake River Plain have been intensely block faulted during the Quaternary, yet the plain is virtually undeformed. Blocks lessen in structural relief near the plain and disappear within a short distance of the edge of the volcanic terrane.

Reconnaissance fieldwork for this report was done in July 1961. Most of the volcanic elements of this very young caldera are large, preserve their primary constructional topography, and can easily be outlined on the basis of their topographic form. Most geologic units are large enough for depiction at a scale of 1:250,000 (pl. 1). I mapped the caldera on aerial photographs before seeing it in the field; so clear are the morphological elements that the photogeologic map

(Hamilton, 1960a) was proved generally correct by the fieldwork. An abstract summarizing the field and petrologic features of the caldera has been published (Hamilton, 1962). That part of the caldera structure east of meridian 111° 15′ W. is shown on 1 : 62,500 topographic maps (Buffalo Lake quadrangle in the north, Warm River Butte quadrangle in the south), and many features of the rhyolite units can be recognized on these maps.

The Island Park basin was recognized as a caldera by Stearns, Bryan, and Crandall (1939, p. 28), but they did not describe it.

GEOLOGY

The Island Park caldera is an elliptical collapse structure 18 by 23 miles in diameter in the center of a rhyolite shield. The western semicircle of the scarp is exposed (fig. 2), but the eastern semicircle is buried beneath younger rhyolite. The interior of the caldera was flooded first by rhyolite, then by rhyolite and basalt, and finally by basalt alone, which erupted from vents scattered within the caldera. The contrasting magma types came from a single large magma chamber beneath the caldera.

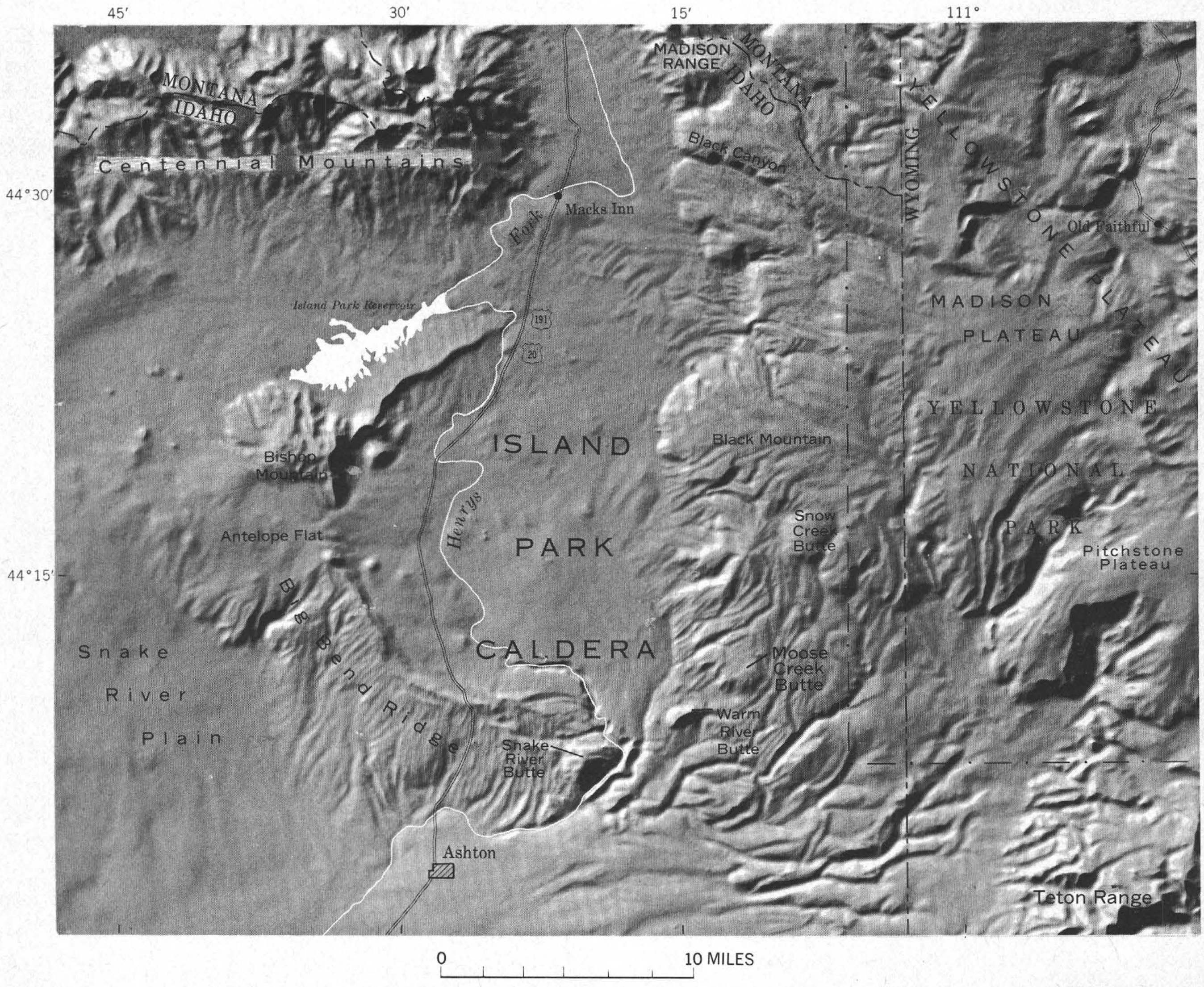

FIGURE 2.—Physiography of the Island Park region. The park, which is 18 miles across, is defined about its western half by the semicircular scarp of the Island Park caldera, and about its eastern half by the fronts of large rhyolite flows that erupted from the now buried scarp. The caldera rim is formed of welded rhyolite tuff, above which rise extrusive domes of rhyolite. The park is floored by basalt flows, and other basalt flows from outside the caldera lap onto the rim. Great flows of rhyolite, erupted from the crestal fissure on the Madison and Pitchstone Plateaus of the Yellowstone Plateau, cover caldera extrusives in the northeast. Photograph of pressed-relief edition of the Ashton 1 : 250,000 quadrangle, U.S. Army Map Service, 1959.

The rim of the caldera is the remnant of a broad shield of rhyolite in which ash flows predominate over ash falls and lava flows and which is truncated by the caldera scarp. The present crest of the rim stands 1,200 feet above the plain to the south. The altitude of the crest is generally between 6,400 and 6,800 feet, but because a younger basalt field laps onto the rim from the north, the western and northern slopes of the shield are much less exposed than is the southern slope.

The caldera scarp is a single arcuate structural feature in the northwest, where it dwindles gradually northeastward from a maximum height of about 500 feet. The scarp in the southwest is a composite of several arcuate structural features which have an aggregate maximum height of 600 feet.

Two or three rhyolite ash flows were erupted after the caldera collapsed, and these bury the caldera scarp in the north and in the southeast. The youngest of these ash flows is younger than all or most of the caldera fill and probably came from a vent near the caldera rim, but the other one or two ash flows came from vents in the Yellowstone Plateau.

High, steep-sided domes of rhyolite were extruded in the west and south on the rim near the caldera scarp late in the period of collapse. The largest dome, Bishop Mountain, stands 1,100 feet above the surrounding rim and was the source of a large lava flow of rhyolite that moved westward from the mountain. More extensive eruptions of viscous rhyolite along the caldera scarp produced thick lava flows and two or three low domes which completely cover the eastern semicircle of the caldera, but their vents define its position. These eastern flows are at least in part younger than the postcollapse ash flows.

The western semicircle of the caldera rim is overlapped from the outside by flows of basalt erupted from nearby vents. The eastern semicircle, after being buried by extrusions along its rim, was in part covered more deeply by very large lava flows of rhyolite erupted from a crestal fissure in the Madison Plateau part of the Yellowstone Plateau.

THE CALDERA

RHYOLITE OF PRECALDERA SHIELD VOLCANO

The shield volcano whose central part collapsed to form the caldera was a gently sloping circular cone. The shield is preserved as two arcs which together make semicircular Big Bend Ridge. The northwest arc is 9 miles long and 2 miles wide, and the southwest arc is 20 miles long and as much as 10 miles wide (pl. 1). The exposed rocks are rhyolite that dips radially outward at angles of a few degrees, parallel to the surface of the shield. Ash flows are much more abundant than are ash falls and lava flows.

The best exposures of the shield are in the high cuts on the south slope along U.S. Highway 20 and 191 north of Ashton. The lowest unit exposed in this section is a densely welded gray rhyolite ash-flow tuff (No. 1, fig. 3), and it is exposed almost continuously for 2.4 miles along the highway northward from Henrys Fork. No more than the upper 20 feet of the unit is exposed anywhere, and the highway climbs updip parallel to the bedding. Discontinuously exposed above the ash flow is an irregular layer of loess, 0–8 feet thick, moved by slump and water. The loess is overlain by an unconsolidated rhyolite ash-fall tuff which in most places is air sorted, being composed of bedded crystal-rich tuff beneath bedded pumice ash. The ash in many exposures is slumped, and its upper surface is irregularly eroded. The uppermost unit in highway cuts low on the shield is a soft, porous, orange-pink slightly welded rhyolite ash-flow tuff that is locally agglomeratic; this unit thickens updip to more than 60 feet, so that the underlying units disappear from view beneath it, and becomes a firmly welded pale-red lithic tuff. Near the highest part of the shield along the highway, a well-bedded unconsolidated crystal-rich ash-fall tuff overlies this pink tuff and is overlain in turn by as much as 50 feet of a slightly welded pale-red lithic ash-flow tuff. This uppermost unit also forms all the exposures along the highway in the two blocks dropped down between the three arcuate faults (pl. 1) that define the south rim of the caldera where crossed by the highway.

The two welded ash flows that overlie the two unconsolidated ash falls are not present at the base of the shield, and the upper of the flows extends only a short distance from the rim. This relation is interpreted as due to limited deposition of the flows rather than to their erosion from the lower slopes. The ash flows appear to feather out abruptly on the surface of the shield, and the lower limit of the upper ash flow is believed to be marked by a slight change in slope of the shield, which can be recognized on aerial photographs.

The basal, densely welded ash flow in the highway section is probably visible in several other places on and near the south flank of the shield. West of the community of Warm River and south of Snake River Butte, for instance, similar gray rhyolite is exposed discontinuously beneath a mantle of loess and till. Henrys Fork, where crossed by the bridge 2½ miles west of Ashton, is incised 100 feet into what is probably the same ash flow. The upper part is dark-gray vitric tuff that is firmly welded but lacks secondary flow features; the middle and lower parts are light gray and devitrified and show irregular flow structure.

The shield farther west is more complex, displaying rhyolite lava flows as well as ash flow tuffs. Two thick lobate rhyolite lava flows extend about 5 miles south-

FIGURE 3.—Rhyolite tuff of shield volcano, exposed in cut 60 feet high. 1, Densely welded gray rhyolite tuff; 2, unconsolidated loess; 3 and 4, unconsolidated bedded white tuff, sorted during airfall into quartz and sanidine crystals (3) and pumice (4); 5, soft, partially welded orange-pink rhyolite tuff that is agglomeratic at base. Roadcut along U.S. Highway 20 and 191, 0.8 mile north of Henrys Fork, 3 miles north of Ashton.

westward from the vicinity of High Point. Although mantled by younger tuff, the form of the flows controls the surface topography. The lava flows are best exposed along the southwest edge of the shield, where their steep, eroded fronts are preserved. Each flow is at least 200 feet thick and consists of gray flow-contorted rhyolite containing blocks of spherulitic obsidian. The canyon of Blue Creek is incised along the valley formed between the sides of the adjacent lava flows. Normal faults having displacements of several hundred feet cut this part of the shield and offset the surface as well as the rocks. Rhyolite ash-flow tuffs underlie and overlie the lava flows, and one or two small thin lava flows, not distinguished from the tuff on plate 1, lie on the upper ash flow southeast of Blue Creek. The ash-flow tuffs, which are poorly exposed, are mostly densely welded and gray.

The ash-flow tuff of the shield is well exposed across the western caldera rim along a new forest-access road that runs westward to Antelope Flats from U.S. Highway 20 and 191 just south of Swan Lake. A thickness of 150 feet within a single tuff unit is exposed in high cuts where the road ascends the caldera rim. The ash flow consists of soft, pink and pale-red lithic rhyolite tuff and shows irregular flow structures which have a general dip of about 3° W.; this orientation indicates that the tuff is part of the precollapse shield.

A rhyolite complex unique among those seen is exposed in low outcrops 1 mile north-northeast of High Point. Squashed-vesicle welded tuff contains subordinate interlayers and lenses, each a few inches thick, of densely welded tuff. Both types, which vary widely in texture and appearance, are unusual in that they lack phenocrysts. Strike and dip are variable even within small outcrops, but the dominant dips are moderately to steeply northward. Two tight folds having nearly horizontal axes were recognized. The folds show that the tuff need not be a simple part of the tuff of the precollapse shield, for flow folds formed in the shield might be expected to have axes parallel to the tangential strike of the shield—here north-northwestward—rather than eastward. Possible modes of origin include extrusion over a structural or erosional scarp during or after collapse of the caldera or upward frothy flow within a rhyolite vent.

The northern part of the rhyolite shield was visited only north of the Bishop Mountain cluster of rhyolite domes. Dense forest and debris from the domes cover this part of the shield, but its form shows that it is composed of rhyolite ash flows that dip radially outward. Photointerpretation indicates that one certain radial normal fault and a nearby probable one each offset the surface of the shield 100–150 feet.

CALDERA RIM FAULT

The western half of the Island Park caldera is defined by a semicircular zone of fault scarps 18 miles in diameter. The central part of the rhyolite shield volcano collapsed along these faults. A single fault scarp bounds the caldera on the northwest, whereas concentric scarps bound it on the southwest. The eastern half of the fault zone is buried beneath younger rhyolite, most of which was erupted along an arcuate zone that is believed to coincide approximately with the caldera margin. If this projection is correct, the caldera is elliptical and its major diameter is 23 miles long and oriented west-southwestward.

The northwestern part of the exposed semicircle is a single curving scarp that rises from beneath the caldera fill at its northeast end to an even height of about 500 feet above the fill along its southwest half (figs. 2, 4). A rhyolite dome is offset by the fault near Green Canyon Pass, but the ash flows are offset more; so the dome was extruded during caldera collapse. The east face of the high rhyolite dome, Bishop Mountain, also must be a fault scarp, because the crest of the dome is at the top of the face; had the fault scarp been present when the dome was extruded, the rhyolite would have flowed east-

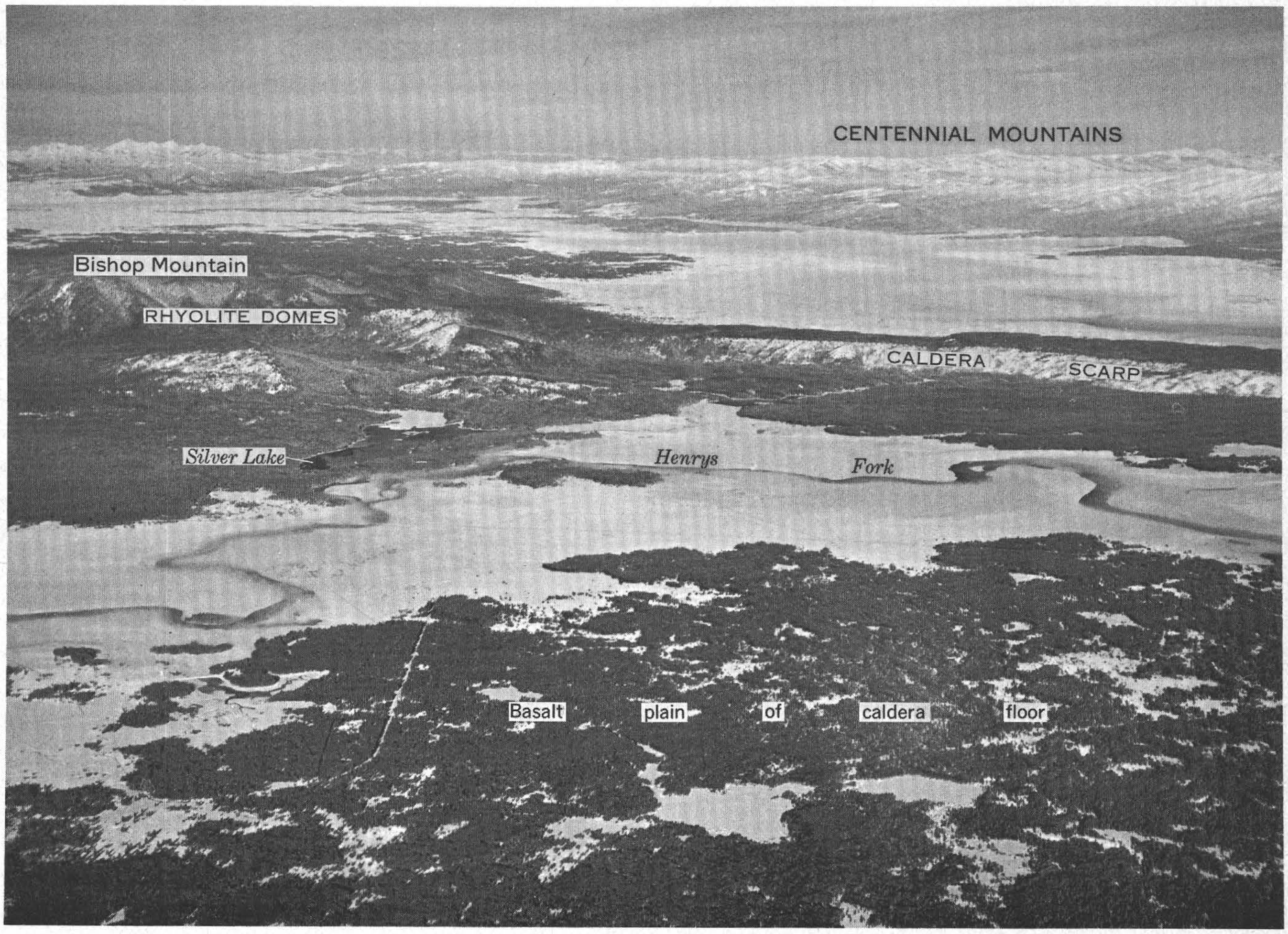

FIGURE 4.—Northwestern part of Island Park caldera. Aerial view in winter, taken west-northwestward from the center of the caldera.

ward down the scarp as well as westward down the rhyolite shield.

The caldera scarp is largely buried by basalt flows in a 3-mile-wide gap east of Antelope Flat, and all but the crest of the dip slope of the rhyolite shield there is also buried by mafic lava.

From Antelope Flat southeastward to the end of the exposed rhyolite shield at Henrys Fork, the caldera boundary consists of concentric arcuate scarps in a zone ½–2½ miles wide (fig. 5; pl. 1). Two faults are exposed in most of the zone, but three are present near the river. The faults branch and die out. Aggregate height of the scarps decreases from about 600 feet in the northwest to about 300 feet in the southeast. The same ash-flow tuff caps the crest of the main rhyolite shield and both of the lower blocks north of it along the highway north from Ashton; thus the caldera is the result of collapse of the interior of the rhyolite shield rather than of explosive removal of the center of the shield.

The scarps that mark the caldera-boundary faults are talus slopes that stand as steeply as 35°, although they generally are nearer 25°. The scale of the geologic map (pl. 1) requires that the faults be drawn at the foot of these slopes and that the talus not be shown as a unit distinct from rhyolite. The faults, however, are buried by the talus and are probably about vertical. As the scarps receded, talus buried their bases.

The basalt flows that floor the caldera lap against and over the boundary-fault scarps (fig. 5) and do not seem to be offset by the faults.

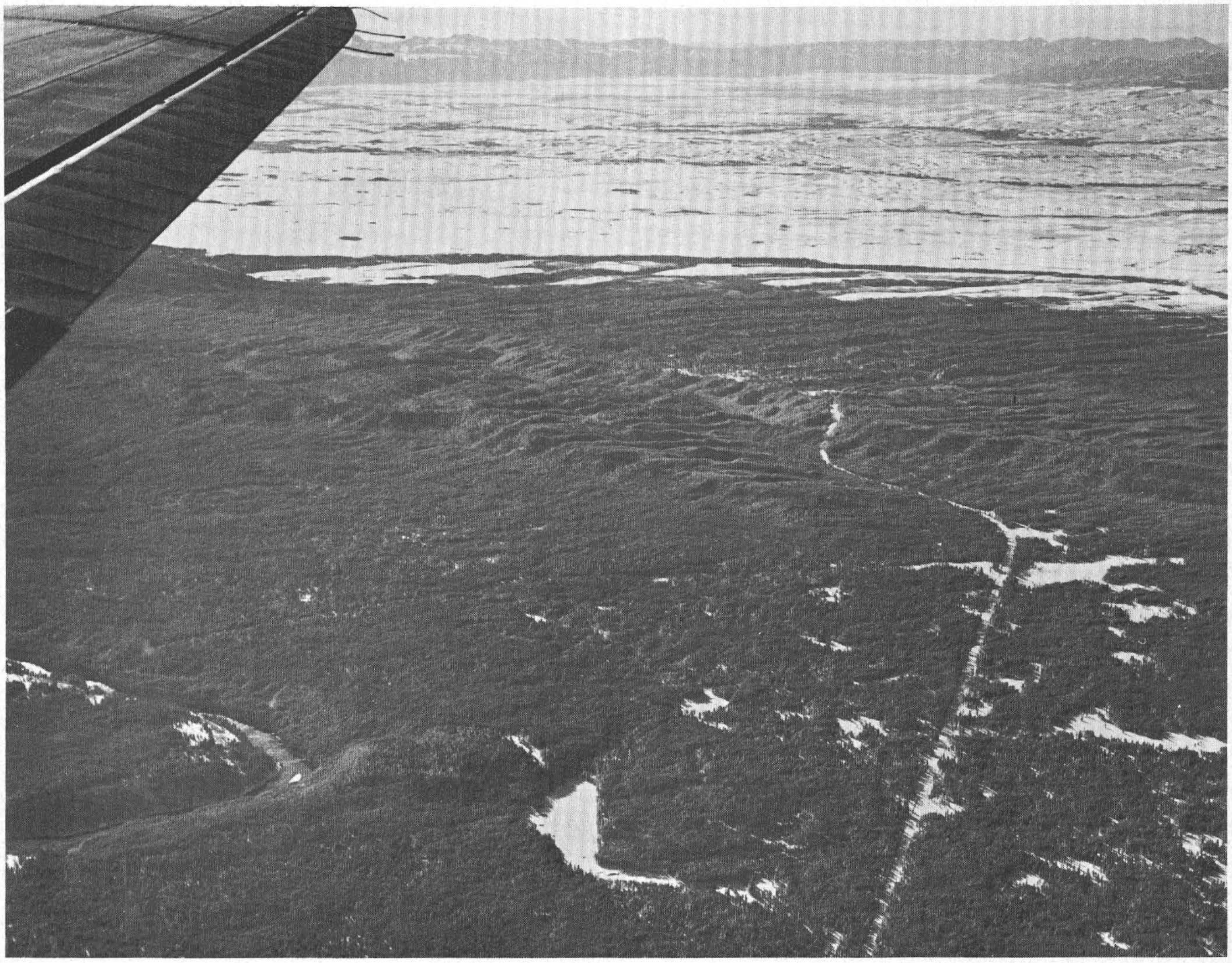

FIGURE 5.—Composite scarp at south edge of caldera. The rhyolite ash-flow shield in the middle distance, furrowed by radial gullies, dips gently south toward the snow-covered Snake River Plain. The inner (closer) of the two major caldera scarps visible in the middle distance dwindles to the right and is buried by postcollapse basalt flows near the highway. A rhyolite dome, Lookout Butte, projects through the basalt just to the right of Henrys Fork in the left foreground.

A rhyolite ash flow forms part of the south edge of the floor of the caldera. It dips very gently northward, opposite to the dip of the ash flows of the rhyolite shield. This rhyolite ash flow is considered part of the caldera fill, but it may actually be part of the rhyolite shield. More rhyolite is exposed beneath this ash flow in the gorge cut by Henrys Fork into the caldera floor, and it is not known whether any of this rhyolite is correlative with that of the shield. Total displacement on the caldera faults cannot be determined from the available data.

No scarps define the half of the caldera east of Henrys Fork. The northern caldera scarp dwindles gradually northeastward and vanishes beneath younger basalt, rhyolite tuff, and alluvium near the river. In the south the decrease in height east of the river is less regular, but the scarp also disappears beneath younger rocks. The lack of a scarp between the river and Moose Creek Butte might be due to cutting of a broad gap through the low rhyolite shield by Henrys Fork and the Warm River before the rivers cut their present gorges. The occurrence of river gravel (well exposed in a borrow pit by the old route of U.S. Highway 20 and 191) both on the divide between the present rivers and 400 feet above them east of Snake River Butte is consistent with this interpretation.

The position of the eastern caldera boundary can be inferred from the vents of rhyolite lava flows and a dome erupted along an arcuate zone that continues the trend of the exposed western semicircle. As rhyolite domes were extruded along the western semicircle, it is reasonable to assume that rhyolite domes and flows were erupted also along the eastern semicircle. If this is correct, the eastern flows were the more voluminous, for they completely bury the scarp. The vents that define the eastern semicircle are noted here in counterclockwise order. Warm River Butte is a rhyolite dome that is elongate east-northeastward. Moose Creek Butte is a steep-fronted lava flow (or broad dome) whose crest is on the same trend. High points along young rhyolite lava flows define other vents on the arcuate trend in the Snow Creek Butte-Buffalo Lake area of the east margin of the structure. On the northeastern perimeter, no vents were recognized for a distance of 15 miles, and the position of that part of the caldera boundary as shown on the map is inferred.

Because the exposed scarps decrease in height eastward in both the north and the south, it may be that the central collapse area had the geometry of a trap door, hinged in the east and dropped farthest in the west. If so, a scarp never existed in much or most of the inferred eastern half of the structural feature. This seems less likely than does the possibility that the eastern scarp has been buried by younger rhyolite. Even though the exposed scarps have an aggregate height of only about 300 feet near their southeastern end, the postcollapse caldera fill in the nearby gorge of Henrys Fork is at least 300 feet thick, so that the minimum offset along the caldera fault near Henrys Fork is 600 feet. It is unreasonable to infer disappearance of this displacement within 2 or 3 miles to the east along a structural feature that is so regular throughout its long exposed part.

The altitude of the caldera rim in the western semicircle increases from about 6,100 to 6,300 feet at its east ends to 6,500 to 6,850 feet in its western part. This is remarkably little variation, if one considers the size of the feature. The central part of the precaldera rhyolite shield collapsed very evenly.

RHYOLITE DOMES ON CALDERA RIM

Steep domes of rhyolite were erupted along the caldera scarp during collapse of the structural feature. Largest and highest of these domes is Bishop Mountain, in the west; other domes occur near Bishop Mountain, and still others form Snake River Butte and Warm River Butte, in the south. Constructional slopes preserved on the sides of the domes are as steep as 35°, and steeper slopes may have formed originally. The distinction between rhyolite lava flows and domes is arbitrary. Both spread laterally from their vents, and both generally have steep fronts. Domes have greater ratios of height to area, but they need be no higher than the flows are thick.

The domes are of various ages. Bishop Mountain and Snake River Butte are broken by the faults of the caldera rim and are older than all or much of the collapse. The unnamed dome adjacent to Bishop Mountain on the east is only slightly offset by one of the faults and is therefore older than only the latest part of the collapse. The two low domes southeast of this dome are entirely within the caldera, so that their age relative to that of collapse is unknown. Warm River Butte dome rises above tuff which hides the scarp, and the dome cannot be dated relative to the faulting.

Bishop Mountain (fig. 4) stands 1,600 feet above the broad caldera floor and 1,000 feet above the caldera rim. In the east the dome is broken by the caldera scarp; in the west the dome becomes a rhyolite lava flow that covers nearly 25 square miles to a depth of as much as 1,000 feet. Light-gray richly spherulitic lithoidal rhyolite containing sparse crystals dominates the surface rubble of both flow and dome. Blocks of spherulitic black obsidian are abundant on the crests of both. Because most very young rhyolite lava flows in the region are capped by unconsolidated agglomerate containing abundant blocks of similar obsidian, it is likely that this material once covered the entire flow but has since been largely eroded from its slopes.

The Bishop Mountain flow diverted Henrys Fork from a previous course along the north base of the rhyolite shield volcano to its present course southward across the caldera. Island Park Reservoir (pl. 1; fig. 2) broadens west-southwestward, away from the dam at its east end; the river previously flowed west-southwestward also, but it was dammed by the rhyolite flow and diverted into the caldera. Still younger basalt buries the old channel farther west. The old course of the river followed the broad constructional valley between the foot of the rhyolite shield and the rhyolite ash flows and basalt to the north.

The small, unnamed dome northeast of Bishop Mountain was also extruded from a vent on or very close to the caldera fault, and it stands 600 feet above the adjacent caldera rim. Green Canyon Pass is in the valley formed by the opposed fronts of the small dome and the Bishop Mountain dome. The small dome is crossed by the caldera scarp, and the part of it on the caldera side dropped about 200 feet. The caldera scarp where it cuts the adjacent tuff shield is 500 feet high, so the downdropped part of the dome has been offset less than has the shield. The dome is considered to have been extruded along the caldera fault during collapse. Poor outcrops near Green Canyon Pass show that both the small dome and the Bishop Mountain dome consist of light-gray finely porphyritic lithoidal rhyolite. Rubble of this material covers the slopes of the shield between these domes and Island Park Reservoir.

Another rhyolite dome of the Bishop Mountain cluster has an area of about 1 square mile and a height of 300 feet and stands entirely within the caldera east of Bishop Mountain. The rubble on this dome is light-gray sparsely porphyritic spherulitic rhyolite.

The extrusive rhyolite forming Snake River Butte dome rises 400 feet above the caldera rim in the south and is exposed in cliffs above Henrys Fork for a depth of several hundred feet beneath the rim level. The rhyolite in the cliffs is white and massive, but the bluffs at the southwest front of the dome expose richly phenocrystic brown rhyolite. The dome appears to be broken along its north side by a caldera-boundary fault (pl. 1; fig. 6, right edge); the adjacent part of the downdropped block of rhyolite was not visited, but a semicircular high area upon it is interpreted on the geologic map (pl. 1) to be the downdropped part of the same dome. A small, unnamed dome adjoins Snake River Butte on the west.

Warm River Butte dome rises 500 feet above flanking ash flows east of Henrys Fork (fig. 6). The dome is on the trend of the arc of the caldera rim and presumably

FIGURE 6.—Southeastern part of Island Park caldera. The extrusive rhyolite dome, Warm River Butte (center), projects through an ash flow that slopes gently to the right (west); the steep-fronted rhyolite lava flow, Moose Creek Butte, is at far left. The ash flow ends at an irregular primary front at the river canyon, toward which slopes the basalt of the caldera floor (plain, crossed by railroad). Aerial view southward. Teton Range on left skyline; Teton Valley in center distance.

was extruded along or near the rim fault. The eroded sides of the butte consist of uniform light-gray rhyolite containing abundant phenocrysts. Obscure flow layers on the south side strike parallel to the hillside and dip vertically or steeply into the hill. Some of the rhyolite encloses granules of dark glass. Much of the rhyolite in the crest of the dome is richly spheroidal and is apparently devitrified glass. Similar material has probably been eroded from the steep sides of the dome. Warm River Butte is elongate east-northeastward along the presumed trend of the caldera fault. A little dome only 100 feet high lies along the axial trend of the butte at its northeast base.

POSTCOLLAPSE RHYOLITE ASH FLOWS

The oldest rocks in the caldera margin that are certainly younger than the collapse are welded rhyolite ash-flow tuffs which crop out in the northern and southeastern parts (pl. 1). Surfaces of the thick ash flows slope gently toward the caldera and are considerably dissected. The caldera scarps trend toward the ash flows but do not displace them; the ash flows or unknown units buried by them have filled smoothly across the scarps. Two of the ash flows were probably erupted from a vent along or near the eastern part of the caldera fault zone and are described here; a third probably came from the Yellowstone Plateau northeast of the caldera and is discussed subsequently.

The ash-flow tuff bounding Island Park on the east side from Eccles Butte to Warm River Butte ends in an irregular bluff (fig. 6) that is probably the original front of the flow or at least of its welded part. Basalt flows correlative with those of the caldera floor cover the tuff on the rim of the gorge of the Warm River where the river leaves the caldera at the south. The youngest basalt flows of the floor cover the front of the ash flow in the south, but the exposed front of the rest of the ash flow indicates it to be younger than most of the caldera fill. The Warm River runs in and has slightly deepened the depression between the rhyolite front and the basalt sloping gently toward it.

The ash flow is poorly exposed. Where traversed along Fish Creek and its north fork, the sheet consists of densely to slightly welded gray and light-purplish-gray porphyritic rhyolite that is generally massive but locally shows flow structures that are mostly subhorizontal. Only a single ash flow may be present. The Warm River Butte rhyolite dome (fig. 6) projects through the tuff, which laps on to the lower slopes of the dome; whether the dome was extruded through the tuff or the ash flow was erupted around the dome is not known.

The ash-flow tuff east of Moose Creek Butte is similar lithologically to that around Warm River Butte and is probably part of the same unit. At its northern exposed limit, this eastern part of the ash flow consists of moderately welded light-gray tuff that contains fragments of stony rhyolite and is underlain by the densely welded purplish-gray tuff of the interior of the flow. The ash flow overlies the basalt flows exposed southeast of Moose Creek Butte and is in turn overlain by rhyolite lava flows that came from the northeast. The lava flow forming Moose Creek Butte probably also overlies the ash flow.

The surface of the ash-flow sheet slopes gently westward between Eccles Butte and Flat Canyon, west-southwestward between Flat Canyon and Warm River Butte, and southwestward south of Warm River Butte. East of Moose Creek Butte the surface slope changes gradually from southwestward to southward as the sheet rises toward Snow Creek Butte. These slopes converge upward toward Snow Creek Butte; so this area is presumed to contain the vent from which the ash flow was erupted. The vent apparently lay along or near the buried caldera fault zone. Any structural feature that formed when the collapse occurred and the ash flow was erupted has been overfilled by younger rhyolite lava flows.

The abrupt front of the ash flow (fig. 6) indicates that the tuff solidified from a dense mass that behaved mechanically like a flow rather than like a cloud. The effective viscosity of this flow was much less than that of the rhyolite lava flows described later, for its upper surface is smooth and its area is great. Unwelded tuff may have been eroded from the ash-flow front to expose the front of the welded part of the flow.

The northern part of the caldera margin in the Buffalo River area is covered by ash-flow tuff. Two sheets are present: a densely welded tuff and, overlying it in the east, a slightly welded tuff. The densely welded sheet, whose surface slopes southwestward, probably erupted within the Yellowstone Plateau; it is described subsequently. The slightly welded sheet, which consists of soft, gray to orange-pink rhyolite tuff and whose dissected surface slopes westward, presumably erupted near the caldera rim.

RHYOLITE LAVA FLOWS OF THE EASTERN RIM

Large lava flows of viscous rhyolite that were extruded from vents near the presumably buried eastern rim of the Island Park caldera form a plateau which is about 15 miles long from north to south and 10 miles wide. Rhyolite domes were extruded around the exposed western half of the caldera rim. The flows of the eastern group apparently represent more voluminous eruptions of slightly less viscous rhyolite than that of the domes; flows and domes bear a similar relation to the caldera structural feature.

Individual flows have generally steep fronts and sides, and their boundaries, where recognized, are shown on plate 1. About half the rhyolite pile is covered by what appears to be a single rhyolite flow whose high points and presumed vents are along an arcuate zone in the Buffalo Lake–Snow Creek Butte area. The largest lobe of the flow moved west-northwestward, formed Black Mountain, and reached the caldera floor; smaller lobes moved southward and northward. The flow is heavily forested, but concentric flow ridges are obvious on its little-eroded surface (fig. 7).

Next oldest among the rhyolite lava flows is the southeastern one, which flowed southward from vents now buried. Although this flow has been much more eroded than has the Black Mountain–Buffalo Lake flow, its primary lobate form is well preserved. The nearly round Moose Creek Butte flow, which is isolated from the others of the group, shows similar preservation of form and is perhaps of about the same age as the southeastern flow.

The front of the youngest rhyolite lava flow (that forming Black Mountain) on the eastern rim is particularly high (fig. 7), and its height remains unchanged as the flow is traced from the certainly older ash flow

FIGURE 7.—View northward along the front of the postcollapse rhyolite lava flow forming Black Mountain. Concentric flow ridges cross the flow above its steep primary front. The snow-covered and largely treeless plain is formed on alluvial obsidian sand.

of the eastern rim to the contact with basalt and alluvium. The flow must overlie all or most of the obsidian sand and basalt flows of the adjacent caldera fill.

MAFIC LAVA FLOWS ON WESTERN PART OF PRECALDERA SHIELD

Antelope Flat, on the western rim of the Island Park caldera, is a rolling plain formed of mafic lava largely covered by a thick deposit of loess. The topographic crest of this lava plain is within Antelope Flat several miles west of the caldera scarp. Presumably this crest is the vent area, although the topography is complicated by two long, low fault scarps striking west-northwestward (pl. 1). Cinders mark another vent north of the center of Antelope Flat, but any initial conical form of the cinder accumulation has been destroyed by erosion. High Point, at the southeast corner of Antelope Flat, is a large and considerably eroded mafic cinder cone. The only specimen collected from the lavas of Antelope Flat is an odd mafic latite. The mafic lava flows overlie the rhyolite ash flows of the precaldera shield volcano, but their relation to the large rhyolite lava flow forming Bishop Mountain was not determined.

CALDERA FILL

The volcanic rocks filling the Island Park caldera present a surface of olivine-basalt flows (figs. 4, 6), erupted from vents scattered within the caldera, through which project extrusive domes of rhyolite (figs. 4, 5). A section 500 feet thick is exposed in the gorge where Henrys Forks leaves the caldera. Rhyolite ash flows are at the bottom of the section, interlayered rhyolite ash flows and olivine-basalt lava flows are in the middle, and basalt flows are only near the top. The rest of the caldera floor is not eroded.

The older flows of the group are much eroded, and their fronts are greatly modified. The northernmost flow, here grouped with the flows of the eastern rim although it may have come from farther east in the Madison Plateau, lies on the rhyolite ash flow of the eastern rim and has been incised deeply by North Fork Split Creek. The two or more southern flows, crossed by Flat Canyon, are even more eroded. The uppermost southern flow may have been extruded in part from a vent near the highest preserved point on the flow, at an altitude of 7,490 feet, and it overlies and is thus younger than the ash flow of the eastern rim. Presumably the flow beneath the uppermost southern flow is also younger than the ash flow, because the surface of the ash flow is uninterrupted on both sides of that flow.

The rhyolite lava flows are very similar morphologically to those of the Yellowstone Plateau, which are described subsequently. They have an upper zone of obsidian agglomerate consisting of unsorted blocks of granular porphyritic black obsidian in an unconsolidated glass-shard matrix. Beneath the obsidian zone, as exposed along Split Creek, is a zone at least 300 feet thick of flow-contorted and chaotically interlayered glassy and lithoidal rhyolite. Analogy with the flows of the Yellowstone Plateau indicates that at a greater depth the flows are probably composed of wholly lithoidal rhyolite.

The obsidian of the uppermost southern flow cut by Flat Canyon is largely devitrified, a state presumably indicative of the relative age of the obsidian. The still older lower flow was not visited. Moose Creek Butte was visited only at its southeast slope, where massive gray lithoidal rhyolite forms large rounded outcrops.

Sparse blocks of welded rhyolite tuff and of basalt project through the thick loess and soil covering the uppermost southern flow where the flow was studied near North Fork Fish Creek. No exposures were seen which demonstrated whether these blocks are from rhyolite ash flows and basalt lava flows which overlie the rhyolite lava flow or whether they are glacial erratics, but the latter possibility seems more likely.

INTERLAYERED BASALT AND RHYOLITE

At Upper Mesa Falls, the gorge of Henrys Fork is 400 feet deep. The lowest "cooling unit" (Smith, 1960) of welded rhyolite ash flows has an exposed thickness of 125 feet, but the base of the unit is covered. Partings separate successive ash flows within this cooling unit, but columnar joints are continuous across the partings. On the east side of the river, an olivine-basalt flow overlies these ash flows and marks the base of a poorly exposed section about 200 feet thick of interbedded lava flows of olivine basalt and welded ash flows of rhyolite. This same section is exposed in cliffs on the inaccessible, west side of the river but, there, appears to consist of rhyolite ash flows only. The basal cooling unit, however, is exposed continuously across the river, and the reason for this apparent discrepancy between higher sections is not known. The upper 75 feet of the section on the east side of the river is made up of basalt flows alone; this interval was not seen on the west side.

Lower Mesa Falls are cut in a welded rhyolite ash flow which has an exposed thickness of 60 feet. Because units were not traced along the gorge, the relation of this ash flow to those at Upper Mesa Falls is unknown.

Interbedded rhyolite and basalt are poorly exposed in the broader part of the gorge 3 miles upstream from Upper Mesa Falls, where Sheep Falls cuts through an exposed thickness of 25 feet of a single massive flow of olivine basalt. Presumably the rhyolite-basalt section of the middle canyon walls at Upper Mesa Falls and the two mixed sections are equivalent.

Whether or not any of the rhyolite ash flows exposed in the gorge of Henrys Fork are correlative with ash flows in the rhyolite shield is not known. All the exposed flows may be younger than the collapse, having been confined within the caldera by the bounding scarp. Alternatively, the lower part of the rhyolite within the caldera might have been part of the ash-flow sheets that formed the shield and have been dropped when the caldera collapsed.

BASALT FLOWS

The basaltic, upper part of the caldera fill is well exposed in cuts along the old route of U.S. Highway 20 and 191 where the road descends from the basalt plain of the fill into the gorge of the Warm River at the south edge of the caldera. All the rock here is similar open-textured light-gray nonporphyritic olivine basalt; it occurs as seven flows, each 4–20 feet thick, totalling 75 feet in thickness. All the flows are of pahoehoe-type lava and have undulating tops, ropy upper surfaces, massive interiors, vesicular upper zones, and less vesicular bottom zones. None of the vesicles are filled. Fresh rock of each flow lies directly on fresh rock of the flow beneath with no trace of erosion, weathering, or deposition between. The upper vesicular zone of one flow has pipe vesicles that are overturned toward the southeast. Another flow, which is discontinuous in the roadcuts, consists of pods less than 4 feet thick outlined by vesicular zones.

The floor of the caldera is a basalt plain (figs. 4, 5, 6) composed of similar pahoehoe flows of open-textured olivine basalt. Most of this floor is uneroded, and only the top foot or two of the upper vesicular zone of the uppermost flow is normally exposed except in roadcuts. Surfaces of the flows are undulating, and the plain defined by the flows undulates correspondingly. Basins in the flow tops are typically filled by loess, whereas domes in many places have smooth, bare-rock pahoehoe surfaces. Local relief of the undulations is generally between 2 and 10 feet, but amplitudes of 20 feet are common, and amplitudes of 50 feet were seen in one area. That this relief is constructional is obvious in all cuts, for the ridges are coincident with pressure domes and the hollows with down-buckles. Surface slopes are as steep as 10°, and no systematic orientation to the undulations was recognized. The larger undulations are spaced 500–1,000 feet apart. Squeeze-ups—steeper compressional ridges broken by axial tension cracks and grabens—are rare.

Several irregular low scarps in the caldera floor mark abrupt changes in level of 10–20 feet each and have slopes of 10°–15°. These scarps are presumed to be flow fronts, although none is well enough exposed to allow confirmation. No agglomerate or aa lava flows were recognized within the caldera.

Swampy Swan Lake, which is west of the center of the caldera, apparently fills a small collapsed area that is enclosed by a scarp 6 feet high in the surrounding basalt flow.

Basaltic cinders were seen within the caldera at only two localities, marked on plate 1 as vents in the west-central part of the floor. The cinders northwest of Little Butte are yellowish brown and less than 3 inches long. They form a low hill that presumably was a cinder cone. The cinders northwest of Lookout Butte are red and similarly form a low hill.

At least four broad low hills within the caldera are composed of olivine basalt: Ripley, Eccles, and Hatchery Buttes, and the unnamed butte between Osborne Butte and Henrys Fork. Each is an evenly sloping basalt hill that rises above the basalt plain. Eccles and Ripley Buttes are 200–300 feet high and 2 miles across. Hatchery Butte is itself a little smaller but rises from a broad, very gentle dome 5 miles in diameter in the center of the caldera. Hatchery Butte has slopes typically of about 5°. Eccles and Ripley Buttes are steeper and have extensive 10° and local 15° slopes. All the buttes are densely forested, and no good outcrops were found. All blocks seen on the surfaces are of pahoehoe basalt like that of the basalt plain. No cinders or scoria were seen, and no summit craters were recognized, although the irregular crest of Hatchery Butte is termed a "crater" on the topographic map (pl. 1). These buttes are probably basaltic vent shields, but no convincing evidence was recognized. Another possible interpretation is that they are domes uplifted by rhyolite magma which did not break through to the surface.

Little Butte, which is near the west edge of the caldera floor, is basaltic according to Stearns, Bryan, and Crandall (1939, pl. 3). They also (1939, p. 35) described Olivine Butte, which is near the northwest edge of the caldera and which was not visited during the present reconnaissance, as a tuff cone of olivine basalt erupted through water-saturated alluvium. The cone has a summit crater, and a spatter cone on its flank is regarded as the vent for surrounding flows of basalt.

Basalt erupted near the caldera ring fault in the west formed a cinder cone at a vent and a flow sloping toward the caldera. Another possible vent is in the raised area 2 miles west of Lookout Butte, near the ring fault in the southwest. Along the east side of the caldera floor, the basalt plain slopes eastward, and its flows presumably came from vents near the center of the caldera. Basalt flowed south through the Henrys Fork-Warm River gap at the south edge of the caldera and is now preserved in benches above the present stream levels.

RHYOLITE DOMES

Several extrusive rhyolite domes are scattered on the caldera floor. The largest of these are the two domes

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(beyond Silver Lake in fig. 4) adjacent to the ring fault near Bishop Mountain and described earlier. Next largest is Osborne Butte, in the center of the caldera. This butte is a rounded hill 300 feet high composed of phenocryst-rich rhyolite which is mostly lithoidal but which locally contains abundant granules of dark obsidian. Large rounded outcrops of much-weathered rock are common on the south and southeast slopes of the butte down to the level of the basalt plain. Basalt surrounds the hill, but the slopes are entirely of rhyolite. There is no evidence for upbowing of the flanking basalt. The contact between rhyolite and basalt is not exposed, and whether the basalt laps onto an older rhyolite dome or the rhyolite was extruded on a basalt surface was not determined. Four small domes of similar rhyolite rise above the basalt plain near the southwest side of Osborne Butte. Lookout Butte, near the southwestern margin of the caldera floor (fig. 5), is also formed of granular-weathering porphyritic rhyolite, which crops out in large rounded masses. The butte 2 miles south-southeast of Hatchery Butte consists of rhyolite according to Stearns, Bryan, and Crandall (1939, pl. 3) ; I did not visit it.

Soft, pinkish-gray rhyolite tuff having a gently rolling surface forms part of the caldera floor between Lookout Butte and Swan Lake southwest of the caldera center. Unlike most of the rhyolite of the caldera region, this is almost devoid of phenocrysts.

RHYOLITE OF THE YELLOWSTONE PLATEAU

Rhyolite ash flows and lava flows erupted within the Yellowstone Plateau east of the Island Park caldera form the Yellowstone Plateau and extend into the area shown on plate 1 from the north, east, and south. Three subdivisions of these rocks are indicated on the geologic map (pl. 1): Precaldera ash flows, a postcaldera ash flow, and the lava flows of the Madison Plateau.

PRECALDERA RHYOLITE ASH FLOWS

Old rhyolite welded tuff underlies that part of the area shown on plate 1 southeast of the caldera complex. Extensive exposures were examined during this reconnaissance only in two gorges where crossed by Idaho State Highway 32: the gorges of the Falls River, 4 miles south-southeast of Ashton, and those of the North Fork Teton River, 4 miles south of the southeast corner of the area shown on plate 1. Continuity of the tuff throughout the area away from the highway traversed is, however, obvious on aerial photographs.

The rhyolite exposed low in the gorges of the rivers mentioned and between the rivers in uncommon low outcrops is light-gray to light-purplish-gray welded tuff containing abundant phenocrysts of sanidine. Both gorges expose probably only the one ash flow. The exposed thickness of the flow at the North Fork Teton River is 150 feet. The deep exposures are of densely welded tuff, whereas near-surface exposures high in the gorge walls and on the interfluves are of firmly welded but less dense material. At the Falls River by Idaho State Highway 32, the welded tuff is cut by three steep north-trending rhyolite dikes, 2, 5, and 50 feet thick, respectively.

The interfluve surface—the moderately eroded and variably mantled initial surface of the ash flow—rises regularly eastward to an altitude of about 6,000 feet south of the Falls River and to an altitude of about 5,800 feet north of the river. The unit was traversed only west of these limits. At about the altitudes noted, the slope steepens eastward, then flattens again to a slope like that to the west. The steepening might mark the much-eroded sloping front of an ash flow about 150 feet thick lying upon the flow examined. The upper(?) ash flow may form the surface of all of the eastern part of the unit within the mapped area. Canyons cut in the eastern part of the unit are as much as 500 feet deep, and layering of the rhyolite, which is visible on aerial photographs, may indicate the presence of separate ash flows each 50–200 feet thick. Iddings (1899a) described several of the eastern ash flows as having lithoidal interiors and glassy, locally agglomeratic bases.

The ash flows slope upward to the northeast and disappear beneath the young rhyolite lava flows of the Madison and Pitchstone Plateaus of the Yellowstone Plateau. Presumably the ash flows were erupted from vents within the central part of the Yellowstone Plateau and are part of the ash flows that now form the outer part of the Yellowstone Plateau. The ash flows were downfaulted in the interior and buried by younger lava flows (Boyd, 1961).

Low, elliptical Rising Butte was not visited, but its shape suggests that it is a rhyolite lava flow.

Basalt flows lie on the tuff in several places but are not separated on plate 1. The basalt also is overlain by the rhyolite lava flows of the Madison and Pitchstone Plateaus (Iddings, 1899a, b; Boyd, 1961).

The ash flows are much more dissected than are those of the rhyolite shield of the Island Park caldera and are presumably older; but the contact between them was not seen, and possibly some sheets of the tuff from the Yellowstone Plateau overlie the rhyolite of the caldera shield.

The ash flows, as seen in aerial photographs, bend abruptly upward at the northwest base of the Teton Range and form the dip slope of part of the range. The tuff has shared most of the deformation that produced the present range. The hinge line trends north-northeastward from the extreme southeast corner of the mapped area. Within the range the ash flows lap against a rugged erosion surface formed on pre-Pliocene rocks.

POSTCALDERA ASH FLOW

A rhyolite welded tuff, which probably consists of only one ash flow and which erupted northeast of the Island Park caldera, covers the north-central part of the area shown on plate 1. This ash flow, which was erupted after collapse of the caldera, extends uninterrupted southward across the trend of the caldera scarp. The surface of the ash flow rises to the northeast beyond the caldera, and thus a source outside the caldera in that direction is indicated. The ash flow is overlain by one of the rhyolite ash flows of the eastern rim, which is overlain in turn by at least two rhyolite lava flows that erupted along the eastern rim of the caldera.

The tuff sheet has been much gullied, and its interfluve surfaces have been eroded to a rolling plain. In the walls of the gorge of Henrys Fork from Macks Inn to Island Park Reservoir, the tuff is exposed as a single ash flow. About 200 feet of densely welded light-gray tuff is exposed at Macks Inn, where flow structures dip irregularly as much as 10° in any direction. Three miles west-southwest of Macks Inn, cliffs 100 feet high expose only the same ash flow.

LAVA FLOWS OF MADISON PLATEAU

Gigantic lava flows of viscous rhyolite that erupted from a fissure zone in the western part of the Yellowstone Plateau partly cover the easternmost elements of the Island Park caldera and form the northeastern part of the area shown on plate 1. Individual flows have average areas of 150 square miles, thicknesses of many hundreds of feet, and volumes of 5–10 cubic miles. The flows form the Madison and Pitchstone Plateaus, which combined form an area 30 miles long in a north-northwestward direction and 15–20 miles wide. The crestal fissure zone from which all the flows were erupted trends north-northwestward parallel to the long direction of the lava pile and crosses the northeast corner of the area shown on plate 1.

Flow fronts are steep, commonly sloping 20° or more for their first few hundred feet of rise. Slopes are more gentle above this, but a mile behind their fronts the flows are 400–1,000 feet higher. The flows rise abruptly above the surrounding area along their composite front. Within the area shown on plate 1, the flows lie on the rhyolites erupted along the eastern rim of the Island Park caldera. Features of the rhyolite lava flows within Yellowstone National Park were described by Hamilton (1960a, 1964).

Four lava flows of the Madison Plateau are distinguished on plate 1. The flows were diverted both northward and southward around the plateau formed by the postcaldera rhyolite-lava flows of the east margin of the caldera. They are therefore in general younger than any of the flows of the caldera group, although the small flow remnant east of Buffalo Lake may be older. The flow that forms Black Mountain is one of the caldera group, but it probably is younger than the older flows of the Madison Plateau.

The flows which form most of the surface of the Madison and Pitchstone Plateaus are of very late Pleistocene age. The flow underlying the northeast corner of the area shown on plate 1 lies on the large terminal moraines of Bull Lake Glaciation in the southern part of the West Yellowstone basin but was cut by ice of Pinedale Glaciation (latest Pleistocene) in Madison Canyon (Richmond and Hamilton, 1960). The flow capping the Madison Plateau, which extends almost to the east edge of the southern part of the area shown on plate 1, is similarly of post-Bull Lake, pre-Pinedale age and lies upon a glacially grooved pre-Bull Lake flow (Hamilton, 1960a). Small domes and flows at the crest of the Madison Plateau, east of the area shown on plate 1, are of Recent age (Hamilton, 1960a).

From oldest to youngest, the four lava bodies that flowed into the map area are designated the northwestern, north-central, northeastern, and eastern flows. (These are numbered 1, 2, 3, and 4, respectively, on the geologic map, pl. 1.) The eastern flow largely lacks forest cover and has very well preserved flow ridges. The northeastern flow is older than the eastern flow and also is little eroded, has little soil cover, and has well-preserved flow ridges, but it is completed forested. The north-central flow is still older; it is more eroded and has less rock exposed. The northwestern flow is still more eroded, has relatively few outcrops, and has the thickest cover of loess and soil. The small flow remnant east of Buffalo Lake is interpreted to be part of this northwestern flow. None of these flows, however, show any glacial grooving like that of the pre-Bull Lake flow of the Pitchstone Plateau, and no glacial erratics were recognized on the flow surfaces. Probably they are all younger than the Bull Lake Glaciation, although the Bull Lake ice may instead have been dammed by the east side of the rhyolite flows and been unable to cross this part of the Yellowstone Plateau.

Each flow consists of an upper zone of obsidian agglomerate about 100 feet thick that grades downward into flow-contorted rhyolite that is several hundred feet thick. Beneath this is massive rhyolite, which rests on an obsidian agglomerate base.

The upper agglomeratic zone consists mainly of blocks of black obsidian in a matrix of sandlike unconsolidated glass shards. Exposures (fig. 8) are particularly good in the north-central flow along the road at the north crest of Black Canyon. Obsidian fragments range in size from granules to blocks more than

FIGURE 8.—Obsidian agglomerate at top of rhyolite lava flow. Blocks of black obsidian lie in an unconsolidated matrix of shards, strands, and granules of clear glass. Shards of the dark matrix at top are coated by ferric oxide dust. Roadcut, 20 feet high, on top of flow at north side of Back Canyon, 2 miles north of area of plate 1.

50 feet in length. The obsidian is minutely fractured and crumbles readily to granules. Many blocks of unweathered obsidian are so granulated that they can be dug into with a shovel. All the obsidian contains phenocrysts of clear sanidine, and much obsidian is spherulitic. Flow structures are restricted to individual blocks and are oriented chaotically. The rock also contains blocks of pumice, scoriaceous glass, brown obsidian, and light-gray lithoidal rhyolite.

The matrix is made up of shards, short fibers, and sandlike grains of clear glass that are evenly sized (0.02–0.2 mm), unsquashed, and unconsolidated. Larger grains are ropy and pumiceous. Most grains are colorless, but some are very light gray or light yellowish gray, and small granules of black obsidian are mixed throughout. No welded tuff was seen.

On the forested surfaces of the flows, abundant obsidian blocks project through the soil. The unconsolidated matrix is exposed only where there has been rapid erosion. The older the flow, the fewer the exposed blocks.

Scattered pipelike masses of steeply dipping gray pumice probably represent upward surges of lava that occurred after differential movement within the agglomerate was nearly complete. The agglomerate has been altered locally by fumarolic activity that presumably accompanied cooling of the interior. Siliceous sinter is widespread as thin coatings on obsidian blocks. Rarely, hematite and limonite coat the shards of the matrix. Sulfur is abundant in sinter in rare places. The rhyolite flows have been eroded little within the area shown on plate 1, and only their upper, obsidian-agglomerate zones can be seen. The interior of the large flow in the northeast corner of the mapped area is, however, exposed farther northeast along the canyons of the Madison and Firehole Rivers in Yellowstone National Park (Hamilton, 1964). The flow-contorted rhyolite beneath the agglomerate is well exposed along the Firehole River near Madison Junction and also in cliffs along the south side of Madison Canyon east of Mount Haynes. The underlying massive rhyolite is well exposed also east of Mount Haynes, where the thickness of the flow is 1,000 feet. Boyd (1961) reported a basal obsidian agglomerate at the bottom of a similar flow in Bechler Canyon in the southwest corner of Yellowstone Park.

BASALT FLOWS SOUTHEAST OF CALDERA

Flows of olivine basalt lie on the precaldera rhyolite ash flows in several parts of the mapped area southeast of the caldera. Flows having a maximum aggregate thickness of at least 100 feet form a discontinuous veneer on the rhyolite tuff in the southeastern part of the area and are overlain in turn by the rhyolite lava flows in the Madison and Pitchstone Plateaus (Iddings, 1899a, b; Boyd, 1961). Thin flows of olivine basalt underlie the postcaldera rhyolite ash flow at the eastern rim south of Moose Creek Butte along the middle reaches of North Fork Fish Creek. Inspection of aerial photographs shows that basalt overlies the precaldera rhyolite tuff north of Robinson Creek.

BASALT FLOWS OF SNAKE RIVER PLAIN

Flows of olivine basalt, which include the youngest volcanic rocks within the area shown on plate 1, lap onto the precaldera rhyolite shield from the west. These basalt flows were erupted from numerous vents that were mostly within a broad west-southwest-trending zone west of the rhyolite dome and flow forming Bishop Mountain (pl. 1 and fig. 9; see also Stearns,

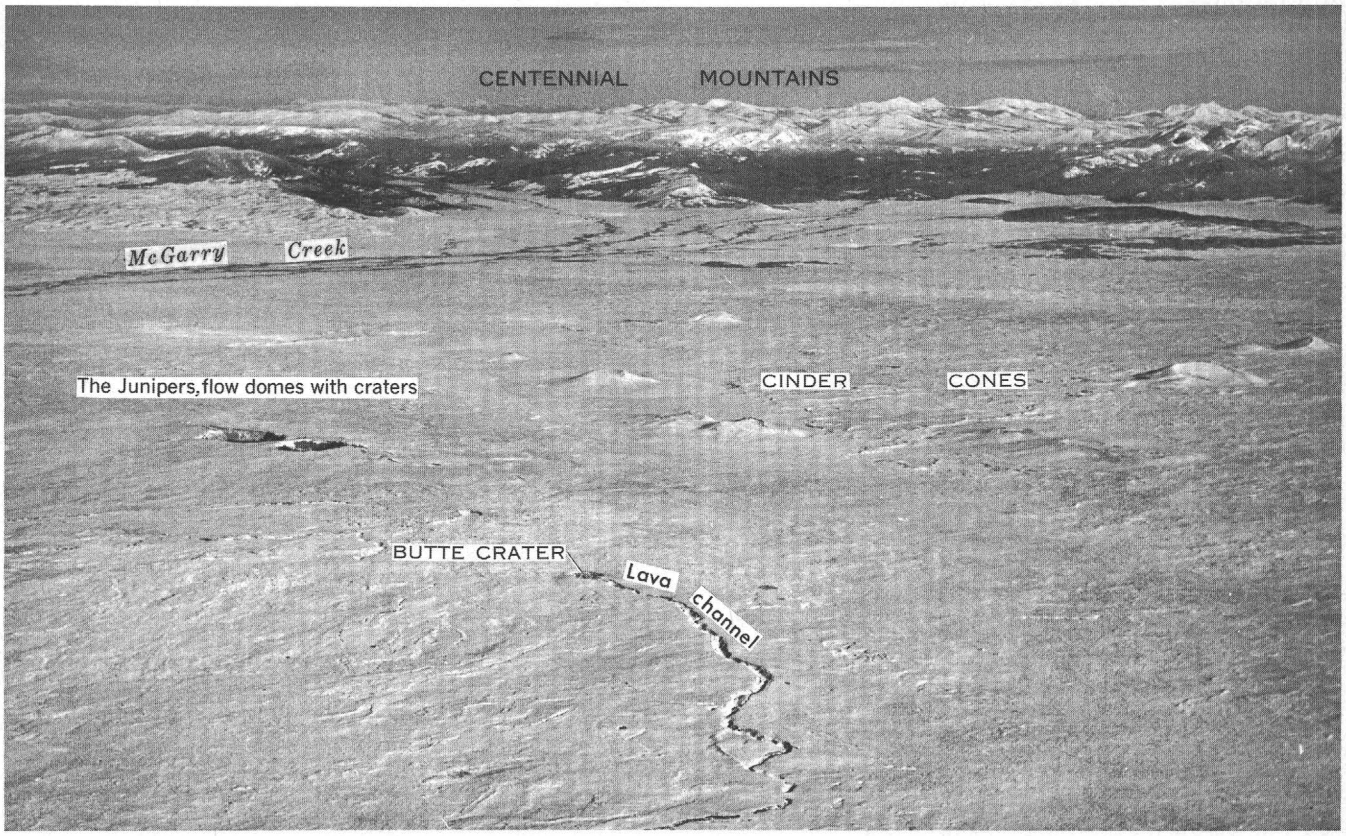


Figure 9.—Vent zone in basalt of Snake River Plain. Craters and cones of the vent zone, which trends southwestward from west of Bishop Mountain, are of latest Pleistocene or Recent age. Winter view northwestward from above the west edge of the area shown on plate 1, 5 miles southwest of Crystal Butte.

Bryan, and Crandall, 1939, pl. 3). The basalt shields—with or without central craters—and cones of the broad vent zone are virtually uneroded (fig. 9). Lava flowed 15 miles southward from the vent zone. The flows are of pahoehoe-type lava near the vents but of aa-type lava near the margins. Aa flows exposed southwest of the caldera are in general successively younger northward, in the direction of the main vent region. The surface of the youngest flows consists largely of bare jagged rock, whereas the surface of older flows is overlain by considerable loess and, in the southwestern part of the mapped area, by sand dunes.

Among the older flows exposed is one that forms the surface north of Bishop Mountain, at the west end of Island Park Reservoir. This basalt flow is similar in preservation to the flows inside the caldera. Broad low outcrops of its original pahoehoe surface coincide with the crests of primary undulations, but the primary basins are largely filled by loess and rubble.

SURFICIAL DEPOSITS

Unconsolidated alluvial, eolian, and glacial deposits completely cover parts of the area and discontinuously veneer larger parts. The following observations are relevant to interpretation of the age of the rocks and structures of the caldera.

Glacial deposits are referred here to the Pinedale (youngest), Bull Lake, and pre-Bull Lake glaciations. The names Pinedale and Bull Lake were introduced by Blackwelder (1915) for the moraines in the Wind River Mountains of Wyoming. Although a confusing variety of other names have been used since for correlative materials, Blackwelder's names have been used increasingly in the Rocky Mountain region. Three main advances of ice during Pinedale time and two during Bull Lake time have been generally recognized (for example, Richmond, 1960). In the Yellowstone region the Bull Lake ice was the more extensive and left larger moraines than did Pinedale ice (for example, Blackwelder, 1915; Richmond and Hamilton, 1960). Pinedale moraines are little weathered and have many kettle lakes. Bull Lake moraines are more subdued and generally lack lakes. Pre-Bull Lake till normally lacks obvious morainal form.

The use of provincial names such as Pinedale and Bull Lake is unfortunate but is apparently still necessary. Although correlation of Pinedale with late Wisconsin of the Great Lakes region, of Bull Lake with early Wisconsin, and of pre-Bull Lake with pre-Wisconsin (Illinoian and older) has long been inferred (Blackwelder, 1915; Richmond, 1962), current disputes regarding status and correlation of early Wisconsin, Illinoian, and intermediate tills even in the Great Lakes area render such correlations uncertain. Pinedale correlates with some part of the Wisconsin, but any other correlations are indefinite.

Following the conventional use in the Rocky Mountain region, Pinedale and Bull Lake are here referred to as within the late Pleistocene; and pre-Bull Lake, as middle Pleistocene and older. Middle Pleistocene thus defined may include much later time than middle Pleistocene defined on the basis of marine deposits and fossils. Post-Pinedale time is referred to as Recent.

Till older than Bull Lake glaciation and the cutting of the gorges was recognized by Blackwelder (1915) to be widespread on the rhyolite ash flows of the Yellowstone Plateau in and south of the southeastern part of the area shown on plate 1. Thick loess overlies this till. Stearns, Bryan, and Crandall (1939) recognized but did not describe similar old till near Warm River community south of the Island Park caldera. This till is well exposed in cuts along the old route of U.S. Highway 20 and 191 southwest of the community; in these places the till contains blocks as much as 5 feet across in a silty matrix. A thick brown soil has developed on this till, and caliche impregnates the upper part of the till. The till overlies the rhyolite ash flows of the precaldera shield.

Ice of probable Bull Lake age scoured an old rhyolite lava flow on the Pitchstone Plateau in Yellowstone National Park, but the scoured surface is overlain by a post-Bull Lake flow which was in turn eroded by ice probably of Pinedale age (Hamilton, 1960a). Most of the rhyolite lava flows of the Madison Plateau within the mapped area are considered to be of post-Bull Lake age, although such an age has been demonstrated only for the eastern and northeastern flows (Hamilton, 1960a; Richmond and Hamilton, 1960).

A possible till is exposed in highway cuts on the basalt floor of the northern part of the caldera 3.2–3.4 miles south of the Buffalo River. The till(?) lies on a 40-foot riser that separates two levels of the basalt plain. The deposit consists of angular to subangular blocks of basalt, mostly less than 1 foot across, and sparse cobbles of quartzite, in an unsorted unbedded matrix of silt and fine sand. No soil has developed on the deposit, and very little soil lies on the overlying 1–3 feet of loess although near-surface loess is oxidized. The deposit is exposed through a vertical range of 40 feet, but no more than 15 feet is visible in any section.

A low ridge trending westward 100 yards south of this deposit may be a moraine. The ridge consists of a 5-foot-thick deposit of basalt blocks in a silt matrix, overlain by 2 feet of loess. Another low ridge 0.2 mile farther south is formed of gravel composed of well-rounded cobbles less than 4 inches long of basalt and subordinate rhyolite and quartzite in a poorly sorted silty matrix; it may be an esker or a kame terrace. No other materials of possible glacial origin were recognized within the caldera.

The lack of soil on these possible glacial deposits suggests that they may be of Bull Lake or younger age. As Pinedale glaciers extended little beyond the mouths of the major deep canyons draining the west side of the Yellowstone Plateau, (Richmond and Hamilton, 1960), these deposits must be of pre-Pinedale age. They are about as far from the Yellowstone Plateau as are the known Bull Lake tills of the southeastern part of the mapped area, and correlation with Bull Lake is suggested.

Ice of Pinedale age scoured the youngest large rhyolite lava flows of the Madison Plateau (including the eastern and northeastern flows of the mapped area) and Pitchstone Plateau, but small flows and domes on the Madison Plateau east of the mapped area are post-Pinedale (Richmond and Hamilton, 1960; Hamilton, 1960a).

River gravels and finer alluvium are widespread along river flats, notably those west of Last Chance within the caldera and near Ashton, and on terraces above the rivers. The highest gravels seen lie 400 feet above present stream level on the divide between the Warm River and Henrys Fork. Loess covers large areas of the river deposits. Broad swampy areas in the northern part of the caldera suggest continuing subsidence.

The alluvial deposits east of Macks Inn near the north edge of the caldera and those in the southeastern half of the large alluvial area (pl. 1; fig. 7) that extends from Ripley Butte to Island Park Reservoir consist of obsidian sand. Granules of black obsidian lie in glass sand. This material was derived from the unconsolidated obsidian agglomerate upper zones of the nearby rhyolite lava flows.

Loess is widespread on all volcanic units of the mapped area except the younger of the basalts west of the caldera. Ten feet or more of loess is common on the rhyolite ash flow southeast of Ashton. Loess several feet thick characteristically lies on the precaldera rhyolite shield and on the other postcaldera rhyolite ash flows and lava flows of the eastern rim. Loess also lies between two tuffs in the rhyolite shield. The loess layer is generally thinner and less continuous on the rocks of the caldera floor and on the younger rhyolite lava flows of the eastern rim and of the Madison Plateau. Dunes of loess and sand occur on the older basalt flows near the southwest corner of the mapped area.

AGE OF VOLCANIC ROCKS

The oldest unit of the mapped area is probably the rhyolite-ash-flow sequence of the Yellowstone Plateau that is exposed southeast of the caldera. This sequence is not younger than middle Pleistocene. Love (1956) found the rhyolite tuffs in the Teton region to be of Pleistocene and early, middle, and late Pliocene ages; but the tuff within the mapped area apparently has not been dated except as older than the pre-Bull Lake glaciation.

The precaldera rhyolite shield also is older than the pre-Bull Lake glaciation and, therefore, is not younger than middle Pleistocene. It is, however, so little eroded that substantially greater age is unlikely, and accordingly it is tentatively assigned a middle Pleistocene age.

The floor of the caldera lacks pre-Bull Lake till; hence its basalt is younger than that glaciation. A possible Bull Lake till lies on basalt in one part of the caldera; if this deposit has been identified correctly, then that basalt is of late middle or early late Pleistocene age. Basalt in the western and southern parts of the basalt plain has broad areas of outcrop and, in places, unfilled squeezeups; it may be of late Pleistocene age.

Probably all the rhyolite lava flows of the Madison Plateau within the mapped area and the youngest postcaldera rhyolite lava flow of the eastern caldera rim were erupted in the interval between the Bull Lake and Pinedale Glaciations and are thus of late Pleistocene age.

The other elements of the caldera are bracketed between the middle Pleistocene age of the precaldera shield and the late Pleistocene age of the rhyolite flows. Collapse of the caldera probably occurred in middle or late Pleistocene time.

The basalt flows of the Snake River Plain west of the caldera shield include units that almost totally lack loess cover or any modification of jagged flow surfaces or vent structures (fig. 9). These young flows are probably of Recent age. Other flows, their surfaces now somewhat subdued and their depressions filled by loess, are considered to be of late Pleistocene age.

The basalt of the caldera floor is younger than the rhyolite of the caldera shield, but it is probably older than the postcaldera rhyolite ash flow (fig. 6) and the lava flows of the eastern caldera rim.

PETROLOGY

The rhyolites of the Island Park caldera and the adjacent Yellowstone Plateau vary widely in appearance but little in composition. All are highly silicic rocks containing phenocrysts of sanidine, quartz, and, commonly, oligoclase, but containing almost no mafic minerals. Precollapse and postcollapse rocks, and those from Island Park and Yellowstone Plateau sources, are indistinguishable compositionally.

Basalt of the caldera fill is holocrystalline olivine-augite basalt that also varies little in composition. Basalt flows outside the caldera are of different olivine-augite basalt. Except for a single mass of latite, the rocks of the caldera suite are completely bimodal—silicic rhyolite and olivine basalt.

PETROGRAPHY

RHYOLITE

The rhyolite occurs as tuffs, mostly welded, and as flows and domes. All forms contain phenocrysts or crystal fragments of clear sanidine and subordinate high-quartz, and most also contain crystals of oligoclase. Mafic minerals total much less than 1 percent of any specimen; green augite and variably altered fayalite are common, and biotite and muscovite are rare.

The most abundant rocks are light-gray, light-purplish-gray, and pale-red welded tuffs. They are massive to streaky rocks of lithoidal aspect despite their almost wholly vitric groundmass. Although the rocks vary in hardness from those which ring when struck with a hammer to those which thud and crumble, all those examined in thin section show flattened-shard structure (fig. 10*A*) such as that described by Boyd (1961) and by Ross and Smith (1961) as typical of welded rhyolite ash flows. Welding in the denser rocks has variably obliterated shard outlines (fig. 10*B*). Shards are now lenses a few tenths of a millimeter long, oriented parallel in crystal-poor rocks but irregularly in crystal-rich ones (fig. 10*C*). Lenses of squashed pumice or, less commonly, of devitrified rhyolite streak many rocks. Groundmasses of most are completely or largely glassy. Devitrification is generally restricted to tiny lenses of collapsed pumice or other enclosed rhyolite clasts.

Rhyolite from the domes examined around the western and southern caldera rim is mostly very light gray, chalky-looking rock that contains a few percent of small (1 mm) phenocrysts of sanidine, high-quartz, and oligoclase. Groundmasses are composed of microcrystalline quartz and alkali feldspar in hazy intergrowths; one specimen has irregular patches of micrographophyre. Biotite, which is lacking in the welded tuffs, is a rare component of dome rocks. Devitrification spherulites are abundant in once-glassy rocks on the crest of the Bishop Mountain dome and flow (fig. 10*D*). The rhyolite of a small dome, Osborne Butte, in the center of the caldera contains more and larger phenocrysts than does the rhyolite of the rim domes, and it is similar in this respect to much of the welded tuff of the area.

Variably devitrified and spherulitic black obsidian forms abundant blocks in the agglomerates at the top of the rhyolite lava flows. The obsidian where undevitrified is granular and crumbles readily. A few to 10 percent of the rock is phenocrysts. The most dissected flows contain the smallest amount of glassy obsidian and the greatest amount of gray devitrified rhyolite. Lithoidal and glassy rhyolite blocks in the upper part of the flows vary greatly in texture and appearance. Flow structures defined by microlites pass without interruption through spherulites, which indicates that the spherulites are products of devitrification.

The mineralogy of the various textural types of rhyolite is similar. Sanidine is in clear, generally euhedral grains that are 1–5 mm long, are commonly embayed, and have a $-2V$ of 10°–20°. These optic angles indicate a composition of about $Or_{62-70}Ab_{28-36}An_2$ according to Tröger's (1956, p. 96) tables. Quartz forms unstrained bipyramids as much as 2 mm long. Tridymite occurs as feathery sheaves. Oligoclase shows albite twinning but generally shows no zoning.

Clinopyroxene occurs as pale-green equant granules and as sparse microlitic needles; it has large extinction angles and large optic angles. Fayalite ($-2V=50°$–$60°$) is in euhedral microprisms and ranges from fresh to completely altered. The rare biotite is light brown and generally is altered. No amphibole was seen.

A few magnetite granules are present in most thin sections, and some granules have hematite rims. Howard A. Powers (oral commun., 1961) crushed a large sample (table 1, no. 5) and found chevkinite (a Ca-Fe-Ti-rare earth silicate, pleochroic from reddish brown to opaque) to be abundant in the sparse heavy concentrate derived from it.

BASALT

The basalt flows of the caldera vary little in mineral composition and texture. Most of the basalt is open textured, diabasic, and nearly holocrystalline (fig. 11 *A*). Its dominant mineral is calcic labradorite in thin laths about 0.5 mm long. These are enclosed in variably ophitic plates of pale-olive or pale-green augite that has a small optic angle ($+2V=30°$–$40°$), which indicates a composition that probably is high in magnesium and low in calcium. Prisms and granules of forsteritic olivine ($2V=90°$) are partially altered in some specimens. No pigeonite or orthopyroxene was noted. Ilmenite occurs as plates, and magnetite as granules. Plagioclase crystals project into the abundant tiny intergranular cavities and appear white, giving the rocks their light color.

A basalt specimen from Hatchery Butte is markedly different in texture and contains plagioclase laths and aggregates of olivine granules in a fine-grained groundmass of plagioclase laths, clinopyroxene granules, opaque minerals, and minor cryptocrystalline matter.

The one basalt specimen studied from the Snake River Plain outside the caldera (table 1, No. 1) is olivine-

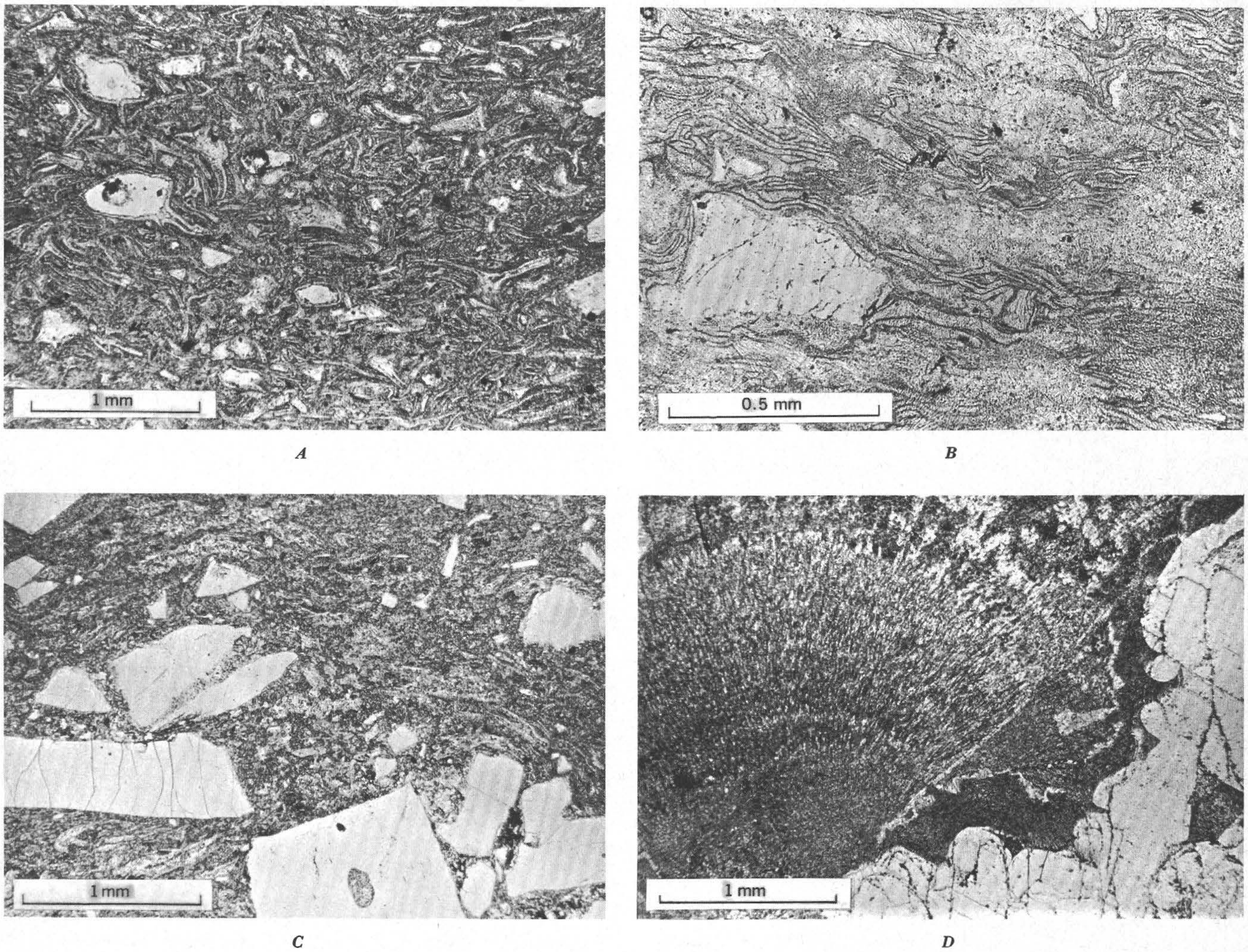


FIGURE 10.—Photomicrographs of rhyolite. *A*, Welded rhyolite tuff. Squashed shards in rhyolite ash flow of caldera floor, from highway cut 3 miles east-southeast of Little Butte. *B*, Welded rhyolite tuff. Refusion has obliterated the outlines of many of the squashed shards. The large crystal fragment above the scale is sanidine. Postcollapse ash flow of the eastern caldera rim, by forest road at southeast base of Moose Creek Butte. *C*, Crystal-rich rhyolite welded tuff. The shards are deformed around the crystals of sanidine, quartz, and oligoclase. Many squashed fragments of microcrystalline rhyolite and partially divitrified pumice. Analyzed specimen 5 (table 1), rhyolite of caldera shield, from highway cut 6 miles north-northeast of Ashton. *D*, Devitrification spherulite in obsidian. The large crystal of sanidine (clear, right and bottom) has been partially resorbed and converted to microcrystalline material. Analyzed specimen 6 (table 1), obsidian block on surface of rhyolite dome, Bishop Mountain.

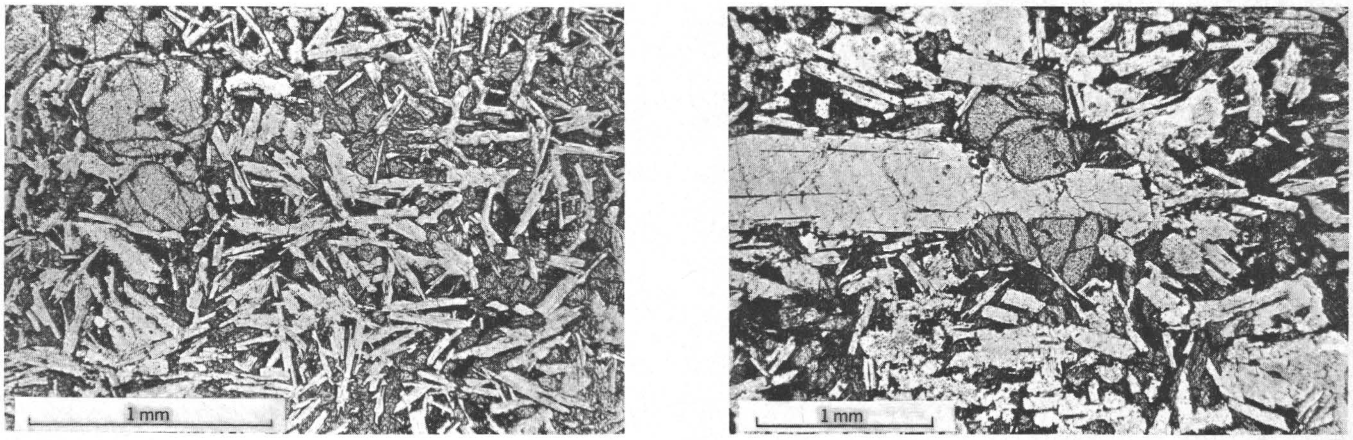
augite basalt that is markedly different from the caldera basalt. The pyroxene of this basalt is brown, has a large optic angle ($+2V \approx 65°$), and is probably more calcic than that of the basalt of the caldera. The plagioclase is calcic andesine (An_{45}); so the rock might be designated basaltic andesite. The only common opaque mineral is ilmenite, which occurs as thin plates. The texture of this rock, as of the caldera basalt, is diabasic and almost holocrystalline (fig. 11*B*).

The one specimen of latite collected from Antelope Flat on the caldera rim is described in table 1 (No. 4).

CHEMISTRY

Chemical analyses for both major and minor elements were made of 11 specimens of volcanic rocks from the Island Park caldera and vicinity (table 1). Included were two analyses of basalt from the caldera fill, one of basalt from outside the caldera, one of latite, and seven of rhyolite from ash flows and domes.

The volcanic assemblage is remarkably bimodal and consists of olivine basalt on the one hand and highly silicic rhyolite on the other. The one specimen of latite analyzed is from the only area of intermediate rocks



A B

FIGURE 11.—Photomicrographs of basalt. *A*, Diabasic olivine basalt of caldera fill. Labradorite laths are enclosed in subcalcic augite. Three equant granules of olivine are in upper left. Analyzed specimen 3 (table 1), from gorge of Henrys Fork at Upper Mesa Falls. *B*, Diabasic olivine basalt of Snake River Plain. A phenocryst of labradorite with attached olivine granules lies in a nearly holocrystalline groundmass of plagioclase laths and augite plates. Analyzed specimn 1 (table 1) from a flow near Blue Creek, southwest of caldera.

seen in the field; all other rocks noted are either basalt or rhyolite.

BASALT

The basalt of the caldera (table 1, Nos. 2, 3) contains silica, total iron, magnesium, and calcium in amounts typical of most olivine basalts elsewhere. (For comparisons, see Green and Poldervaart, 1955.) Sodium, potassium, titanium, and phosphorus, however, are markedly less abundant in this rock than in typical olivine basalt. These four elements are less abundant

NOTES TO TABLE 1

1. Olivine-augite basalt from Snake River Plain outside caldera. Diabasic texture (fig. 11*B*); nearly holocrystalline; laths 0.5 mm long of plagioclase (An_{50}) partly enclosed in plates of brown augite (+2V≈65°); olivine (2V≈90°) granules are unaltered; ilmenite in plates; cryptocrystalline brown material minor. Vesicular medium-gray rock from top of an aa flow of Recent age that laps onto the rhyolite shield on the southwest near Blue Creek.
2. Olivine-augite basalt of caldera fill. Open textured, diabasic, holocrystalline. Labradorite (An_{65}) laths 0.5 mm long are partly enclosed in plates as much as 1.5 mm long of pale-olive augite (+2V≈35°); olivine (2V≈90°) granules as much as 1.5 mm long, altered along margins and cracks; ilmenite plates and magnetite granules; no cryptocrystalline material. Medium-light-gray nonvesicular basalt, having slight purplish cast, from the middle of pahoehoe flow at the top of the section in the gorge of Henrys Fork at Upper Mesa Falls, near junction of highway and road to falls.
3. Olivine-augite basalt of caldera fill. Open textured, diabasic, holocrystalline (fig. 11*A*). Labradorite (An_{65}) laths 0.5 mm long are partly enclosed in plates as much as 1 mm long of pale-green augite (2V=30°); 1=mm granules (2V=90°) are unaltered; ilmenite plates and magnetite granules; no cryptocrystalline material. Medium-light-gray nonvesicular basalt, having olive cast, from 10 ft above base of lowest pahoehoe flow in gorge of Henrys Fork at Upper Mesa Falls, south of falls parking area, above rhyolite welded tuff that forms the falls.
4. Latite from mafic lava flow on western part of caldera shield. Seriate microphenocrysts 0.1–2 mm long of andesine lie in a very fine grained matrix of flow-alined oligoclase (An_{20}) laths 0.05 mm long, clinopyroxene granules 0.01 mm in diameter, tiny anhedra of alkali feldspar, opaque granules, brown glass and brown cryptocrystalline material. Sparse microphenocrysts of olivine (about Fo_{70}) and of a green clinoamphibole having a small extinction angle. Dark-gray rock containing abundant flow-alined vesicles, from Antelope Flat.
5. Welded rhyolite tuff from ash flow of the precaldera shield. Pale-red rock containing about 10 percent euhedral and fragmental crystals mostly 1–2 mm in diameter; clear sanidine (−2V=10°) is more abundant than are bipyramids of high-quartz; minor unzoned oligoclase; sparse magnetite granules with oxidized rims; rare altered fayalite (−2≈60°) and chevkinite. Matrix is completely welded and partly refused vitric tuff showing secondary flowage; contains many squashed fragments of pumice and devitrified rhyolite (fig. 10*C*). Collected in caldera shield from cut on U.S. Highway 20 and 191.
6. Spherulitic rhyolite from Bishop Mountain dome. Light-reddish-gray flow-layered rock containing abundant 1–3 mm spherulites (fig. 10*D*). Contains about 5 percent phenocrysts of sanidine (−2V≈10°) and high-quartz, and rare biotite. Pyroxene microlites show flow structure in the groundmass that continues without interruption through spherules: the spherules are devitrification products. Groundmass consists of devitrification microgranules and feathery aggregates of alkali feldspar and quartz and numerous tiny sheaves of tridymite. Collected beside road to Bishop Mountain Lookout near south flank of flow north of Antelope Flat.
7. Lithoidal rhyolite from Warm River Butte dome. Pinkish-gray rock containing about 7 percent phenocrysts in a massive aphanitic groundmass. Phenocrysts are euhedral crystals 1-4 mm long of sanidine (−2V≈20°) and subordinate oligoclase and quartz. Matrix is a microcrystalline to granophyric mush of quartz and alkali feldspar crystals 0.01–0.05 mm in diameter; mush also contains sparse granules of magnetite. There are sparse crystals of much-altered light-brown biotite and wavy-extinction muscovite and a few completely altered microphenocrysts of an unidentified mafic mineral that has been replaced by decussate biotite containing granular magnetite and hematite. Numerous elliptical sheaves of tridymite.
8. Welded rhyolite tuff from caldera fill. Medium-light-gray rock. Crystal rich; contains about 20 percent crystals and fragments 1–5 mm long of clear sanidine and subordinate amounts of oligoclase and high-quartz. Many crystals of green clinopyroxene; some of magnetite. Groundmass is largely glass but is partially devitrified and shows complete squashing and welding of shards. Collected at top of Upper Mesa Falls from thick ash flow in gorge of Henrys Fork.
9. Welded rhyolite tuff from caldera fill. Light-purplish-gray rock. Contains about 3 percent crystals and crystal fragments of sanidine, subordinate high-quartz, and traces of clinopyroxene and magnetite in a vitric, completely welded tuff matrix. The squashed shards are about 0.2 mm long and are very thin. The crystals are oriented parallel to flattening of shards. Collected from ash flow in section of interlayered rhyolite and basalt (above samples 3 and 8 but below 2 and 11) in gorge of Henrys Fork above Upper Mesa Falls.
10. Welded rhyolite tuff from postcaldera ash flow north of caldera. Light-purplish-gray rock that has conspicuous horizontal structure formed by squashed-pumice lenses. Contains only about 1 percent sanidine crystals about 1 mm long and rare high-quartz, clinopyroxene, and altered fayalite(?). Matrix shards are completely squashed and welded and are almost entirely vitric although speckled by feldspar microlites. Collected by Henrys Fork from cliffs on upper part of a thick ash flow that was erupted probably from a vent in the Yellowstone Plateau.
11. Welded rhyolite tuff of caldera fill. Pale-red rock streaked by gray lenses of collapsed pumice typically about 0.5 mm thick and 5–10 mm long. Contains about 5 percent crystals and fragments, mostly of sanidine and quartz; sparse pseudomorphs after fayalite(?). Recognizable shards are few and tiny: reflowage has largely obliterated clastic texture. Collapsed-pumice lenses show comb-structure devitrification, but rest of rock is largely glass. Collected from highest ash flow in section in gorge of Henrys Fork at Upper Mesa Falls, below capping sequence of basalt flows.

in most tholeiite than in most olivine basalt; the sodium, titanium, and phosphorus of the Island Park rocks are in amounts characteristic of tholeiite, whereas potassium is uncommonly scarce even for tholeiite. The basalt in the Island Park caldera thus presents an unusual combination of components.

The basalt of the Snake River Plain outside the caldera is represented by only one analysis (table 1, No. 1). This basalt differs markedly from that inside the caldera in its content of most major components except silica (fig. 12) and more generally resembles typical olivine basalt. This basalt contains three times as much potassium, twice as much titanium and phosphorus, and a little more sodium than does the basalt inside the caldera. The basalt outside has a higher content of total iron and lower contents of aluminum, magnesium, and calcium than does the basalt inside.

These differences in chemical composition are reflected in the mineralogical contrasts. The basalt inside the caldera has more magnesian pyroxene and more calcic plagioclase than does the basalt outside. The basalt outside the caldera has brown augite that presumably contains considerable titanium, and it has ilmenite as its only conspicuous opaque mineral. Both basalts, however, are properly classed as olivine basalt.

Spectrographic analyses are too few for statistical reliability, but they reveal that contents of some minor elements appear to vary in parallel fashion with those of major elements. Reported as more abundant in the basalt outside the caldera are barium (with potassium?), cobalt (with ferrous iron?), niobium (with titanium?), strontium (affinity for potassium being more significant here than affinity for calcium?), and yttrium, ytterbium, and zirconium. On the other hand, the vari-

TABLE 1.—*Chemical analyses of volcanic rocks from Island Park caldera and vicinity*

[Major-oxide analyses made by standard silicate methods by Dorothy F. Powers, Denver, Colo., 1962; fluorine and chlorine analyses by Elaine Munson, Denver, 1962; minor-element analyses made by semiquantitative spectrographic methods by J. C. Hamilton, Denver, 1961, and reported as midpoints of logarithmic-sixth divisions. Location of specimens is marked on the geologic map (pl. 1)]

	Basalt flows			Latite	Rhyolite							
	Outside caldera	Inside caldera			Tuff of Caldera rim	Caldera rim		Tuff erupted during and after collapse of caldera				Average of samples 5–11
						Flow	Dome					
	1	2	3	4	5	6	7	8	9	10	11	12
Major oxides, in weight percent												
SiO_2	47.35	47.22	47.61	61.33	75.67	77.08	77.22	74.79	75.88	75.63	76.53	76.1
Al_2O_3	14.55	16.16	16.07	16.34	12.69	12.16	11.90	12.71	12.50	12.54	12.14	12.4
Fe_2O_3	1.99	2.55	1.22	3.45	1.52	.86	1.36	1.41	1.34	1.35	1.52	1.3
FeO	12.58	9.54	9.85	4.50	.29	.36	.16	.72	.45	.30	.08	.3
MgO	6.28	8.46	8.68	.47	.07	.08	.08	.13	.08	.03	.03	.07
CaO	8.93	11.02	11.28	2.48	.59	.48	.53	.84	.57	.45	.51	.6
Na_2O	2.62	2.44	2.26	4.44	3.27	3.29	3.24	3.35	3.50	3.59	3.15	3.3
K_2O	.83	.17	.37	4.27	5.32	4.97	5.07	5.25	5.01	5.19	5.18	5.1
TiO_2	3.45	1.68	1.77	.72	.18	.15	.17	.23	.17	.16	.18	.18
P_2O_5	.62	.20	.30	.19	.02	.01	.01	.02	.03	.01	.01	.02
MnO	.22	.20	.20	.19	.04	.03	.02	.04	.05	.02	.02	.03
H_2O+	.32	.17	.30	.56	.26	.29	.20	.22	.15	.28	.17	.3
H_2O-	.08	.10	.13	.56	.08	.06	.05	.19	.08	.18	.12	
CO_2	.00	.00	.00	.00	.01	.00	.00	.01	.00	.00	.00	.00
Cl	.01	.01	.01	.03	.01	.05	.01	.02	.01	.04	.01	.02
F	.06	.02	.03	.02	.01	.06	.02	.02	.01	.01	.01	.02
Subtotal	99.89	99.94	100.08	99.55	100.03	99.93	100.04	99.95	99.83	99.78	99.66	----------
Less O	.03	.01	.01	.02	.00	.04	.01	.01	.00	.01	.00	----------
Total	99.86	99.93	100.07	99.53	100.03	99.89	100.03	99.94	99.83	99.77	99.66	----------
Minor elements, in weight percent												
Ba	0.07	0.02	0.05	0.5	0.1	0.015	0.05	0.15	0.07	0.07	0.07	
Be	<.0001	<.0001	<.0001	.0005	.0003	.0005	.0005	.0003	.0005	.0005	.0003	
Ce	<.01	<.01	<.01	.03	.02	.02	.015	.02	.02	.015	.015	
Co	.007	.005	.005	<.0002	<.0002	<.0002	<.0002	<.0002	<.0002	<.0002	<.0002	
Cr	.02	.05	.05	<.0001	.0002	.0003	.0003	.0005	.001	.0003	.0003	
Cu	.007	.007	.007	.001	.001	.0007	.0007	.001	.001	.001	.0007	
Ga	.003	.002	.002	.005	.003	.003	.003	.003	.005	.003	.003	
La	<.002	<.002	<.002	.03	.015	.01	.007	.01	.015	.01	.01	
Mo	<.0002	<.0002	<.0002	.0007	.0003	.0005	.0005	.0005	.0005	.0005	<.0002	
Nb	.003	<.0005	.0015	.01	.005	.005	.005	.005	.007	.007	.005	
Nd	<.005	<.005	<.005	.02	.015	.015	<.005	.015	.015	.015	.015	
Ni	.01	.01	.007	.0007	<.0002	<.0002	<.0002	<.0002	<.0002	<.0002	<.0002	
Pb	<.0005	<.0005	<.0005	.003	.003	.003	.002	.002	.003	.003	.003	
Sc	.005	.005	.005	.003	<.0007	<.0005	<.0005	.0007	<.0005	<.0005	<.0005	
Sn	.001	.001	<.0002	.001	<.0002	<.0002	<.0002	<.0002	<.0002	<.0002	.001	
Sr	.07	.05	.05	.05	.005	.0015	.003	.01	.002	.0015	.005	
V	.05	.03	.03	<.0005	<.0005	<.0005	<.0005	.001	.0015	<.0005	.001	
Y	.007	.003	.003	.015	.007	.007	.005	.007	.01	.005	.005	
Yb	.0007	.0005	.0005	.002	.001	.001	.0007	.0007	.001	.0007	.0007	
Zr	.02	.007	.01	.1	.02	.01	.02	.02	.03	.02	.02	
Powder density	3.04	3.06	3.04	2.69	2.55	2.49	2.58	2.58	2.53	2.50	2.54	
Field No.	YS 88C	YS 57G	YS 57B	YS 77	YS 34	YS 79	YS 66A	YS 57D	YS 57D	YS 55	YS 57F	
Laboratory No.	H 3579	H 3575	H 3572	H 3577	H 3569	H 3578	H 3576	H 3571	H 3573	H 3570	H 3574	

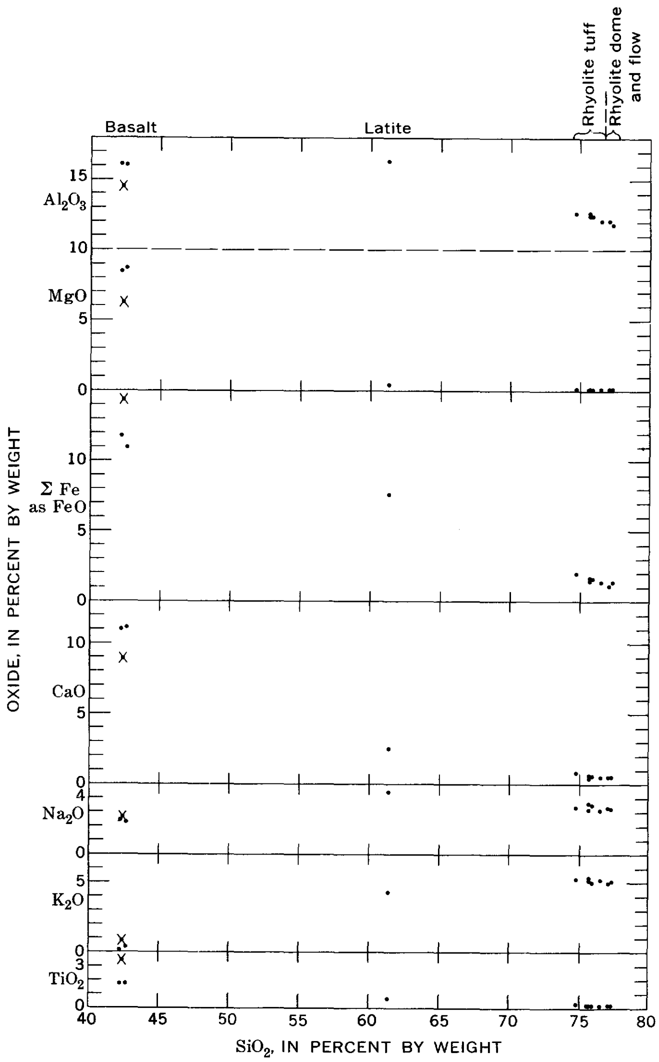


FIGURE 12.—Silica-variation diagram for rocks of Island Park caldera. Data from table 1. ×, basalt from outside the caldera.

ations reported in contents of chromium, gallium, and vanadium are opposite to those predictable in terms of common ionic substitutions.

Chlorine is equally abundant in all three basalt specimens, but fluorine is markedly more abundant in the basalt outside the caldera.

The basalt inside the caldera differs most conspicuously from that outside by having smaller contents of the more volatile elements, both major and minor, and larger contents of the more refractory elements. Water contents of both rock types, however, are equally low, and neither shows appreciable mineral alteration.

LATITE

The one specimen of latite analyzed (table 1, No. 4) has a large content of K_2O and Na_2O (each more than 4 percent by weight) and a small content of silica (61 percent). The rock also has a high content of iron, much of it oxidized. Barium (0.5 percent), niobium, zirconium (0.1 percent), and the rare earths and allied elements (cerium, lanthanum, neodymium, yttrium, and ytterbium) are all uncommonly abundant in the latite.

RHYOLITE

The seven specimens of rhyolite analyzed represent the precaldera ash-flow shield (table 1, No. 5), flows and domes on the shield (Nos. 6, 7), ash flows of the caldera fill (Nos. 8, 9, 11), and a postcollapse ash flow erupted in the Yellowstone Plateau (No. 10). These rhyolites vary remarkably little in composition, as is shown by their ranges:

	Weight percent		*Weight percent*
SiO_2	74.8 –77.2	Na_2O	3.1 – 3.6
Al_2O_3	11.9 –12.7	K_2O	5.0 – 5.3
Iron as FeO	1.1 – 2.0	TiO_2	.15– .23
MgO	.03– .13	P_2O_5	.01– .03
CaO	.45– .8	MnO	.02– .05

Despite the narrowness of this compositional range, the contents of aluminum and total iron in the rocks decrease systematically with increasing silica, and all other major oxides show slight and irregular decreases (fig. 12). This contrast indicates that had the rhyolites crystallized, the least silicic would contain substantially more iron oxide and iron-rich mafic minerals but only slightly more feldspar than would the most silicic rocks.

Phenocrysts and crystal fragments range in abundance from 1 to 25 percent of the rhyolite. Among the analyzed rocks (table 1), No. 10 has 1 percent total crystals, No. 8 has 20 percent, and the others each have between 3 and 10 percent. Chemical compositions show no variation reflecting this range: the bulk composition of groundmass and phenocrysts must be nearly the same. The only possible exception is No. 8, which has slightly more aluminum and calcium (though not sodium) than have most of the other rhyolites; this possibly indicates enrichment in crystals of oligoclase.

Potassium is dominant over sodium by weight but is about equal to it in molecular proportion. The molecular ratio $K_2O : Na_2O : CaO$ in the average rhyolite (table 1, No. 12) is about 48 : 44 : 8. The molecular sum of these components is almost exactly equal to that of alumina. The two dome and flow rocks have slightly less potassium than do four of the five specimens of welded tuff.

Iron in the rhyolite is mostly oxidized; the ratio $Fe_2O_3 : FeO$ by weight ranges from 2.4 : 1 to 19 : 1. The lowest ratio is in the rock of one of the flows (table 1, No. 6); this same rock also has the highest reported contents of chlorine and fluorine. These features perhaps indicate that the rock has undergone minimal mixing with atmospheric oxygen and has lost a minimum of magmatic volatiles. The slight variation in water content among specimens has no apparent correlation with occurrence, and all are dry rocks.

Of the minor elements, barium is clearly less abundant in the flow and dome rocks than it is in the tuffs; and copper, lanthanum, neodymium, phosphorus, strontium, and zirconium seen to be less abundant also, although the data for them are statistically inconclusive. The more volatile of the rock-forming components—potassium and the elements just listed—seem to be slightly concentrated in the ash flows relative to the domes.

INTERPRETATION OF THE ISLAND PARK CALDERA

ASH FLOWS

Welded rhyolite ash-flow tuff is a major component of the caldera edifice. Recent literature on origin of such tuff is extensive—among the more significant papers are those by Boyd (1961) and by Ross and Smith (1961)—and no detailed review is given here.

The rhyolite ash flows form with smooth upper surfaces that slope but a few degrees, and at least one of the ash flows ends at a steep front (fig. 6). Such ash flows form from material that flowed as a dense fluid and not from ash carried in a cloud and rained from the sky. The fluid of the ash flows must have had two phases—liquid and gas—for the squashed-shard structure seems inexplicable in other terms. Such a two-phase fluid can be pictured as a pyroclastic flow containing nearly molten glass shards dispersed in gas, as a froth flow containing abundant gas dispersed in nearly molten lava, or as some intermediate between the two. The froth-flow concept seems to explain better the steep front and the smooth, evenly sloping upper surface; but the upper, lowest pressure part of a froth flow might be expected to be like a pyroclastic flow. Very rapid eruption seems required.

PHYSICAL HISTORY

The Island Park caldera probably formed simultaneously with the building of the broad rhyolite shield which it displaces. The repeated virtually instantaneous eruptions of the large rhyolite ash flows which provided most of the substance of the shield must have resulted in collapse of the roof of the large magma chamber from which the flows came. The collapse presumably occurred in increments that were synchronized with eruptions, and the accumulation of loess between two tuff units in one part of the rhyolite shield suggests that intervals thousands of years long separated some eruptions. The magma chamber was at least as large in plan as the caldera, 18 by 23 miles, near the surface, but may have narrowed downward.

The collapsed part of the caldera was filled first by rhyolite whose eruption was probably synchronous with the collapse and with the building of the rhyolite shield around the caldera. Subsequent eruptions within the caldera floor were of both basalt and rhyolite, but although small domes of rhyolite were erupted late in the period of caldera filling, final eruptions were mostly of basalt. This age sequence in magmas erupted from vents interspersed about the caldera floor indicates that the single large magma chamber probably contained both basalt and rhyolite magmas simultaneously, and that the rhyolite magma probably overlay the basalt magma, for it generally erupted first.

Domes and lava flows of rhyolite were erupted near the caldera scarp before final collapse, at least on the western rim. An ash flow and subsequent lava flows were erupted from the eastern rim after collapse and after much of the caldera fill had been erupted.

Eruptions of gas-charged rhyolite that produced ash flows were apparently followed in several instances by eruptions of gas-poor rhyolite that formed domes and thick lava flows. The two big rhyolite lava flows and interbedded ash flows of the southwestern part of the shield may represent viscous eruptions following one of the ash-flow-and-collapse episodes. The domes of the western rim were extruded on the ash flows and were themselves broken by the caldera fault. Following this ash-flow-and-dome cycle, the basalt in the caldera floor was erupted. Still later, the eastern rim and all but possibly the youngest part of the caldera fill were buried by the products of another rhyolite cycle in which eruption of a large ash flow preceded eruption of lava flows.

The building of the exposed elements of the caldera has occupied the latter part of Quaternary time—perhaps the last million years. The youngest volcanism within the caldera probably occurred in pre-Pinedale time, but future volcanism is likely to occur. Basalt has been erupted widely just west of the caledera during Recent time.

PETROGENESIS

The Island Park caldera is made up of rhyolite and olivine basalt erupted from a single large magma chamber. Progressions of eruptions with time suggest that, in general, volatile-rich (ash flow) rhyolite magma lay above volatile-poor (lava flow and dome) rhyolite magma, and that both these rhyolite liquids lay above basalt liquid in the magma chamber.

This layering within the magma is interpreted to be the product of liquid fractionation of initially tholeiitic basalt magma into contrasted rhyolite and olivine basalt magmas. This process is suggested to be generally applicable to provinces of bimodal rhyolite-and-olivine-basalt volcanism and is discussed in detail following the presentation of data from other such provinces.

GEOLOGIC AND PETROLOGIC COMPARISONS

YELLOWSTONE PLATEAU

Rhyolite lava flows and ash flows of the Yellowstone Plateau overlap the Island Park caldera from the east. Rhyolites of the caldera and plateau suites are virtually identical chemically, the basalts of the two suites are closely similar, and the occurrences of the two suites are so alike that related origins are required. The plateau is about 50 miles across and is surfaced largely by rhyolite, which fills a broad basin defined by high mountains to the north, east, and south, but spills into the Island Park region to the southwest. The outer part of the plateau, except in the southwest, is formed largely of enormous ash flows of rhyolite erupted during Pliocene and Pleistocene time (Boyd, 1961; Love, 1956; Hamilton, 1960a, 1964). Collapse of the interior of the plateau—a consequence of the eruption of the ash flows—during Pliocene(?) and Pleistocene time produced an irregular depression 30 miles across (Boyd, 1961) that has since been flooded by the huge viscous rhyolite lava flows of the Central, Madison, and Pitchstone Plateau sectors of the Yellowstone Plateau (Boyd, 1961; Hamilton, 1960a, 1964).

All rhyolites—ash flows, lava flows, and domes—of the Yellowstone Plateau vary little in mineralogy and less in chemistry. Phenocrysts of sanidine and high-quartz are abundant throughout the rocks, and those of oligoclase are common; mafic minerals, mostly fayalite and clinopyroxene rather than biotite or hornblende, are sparse (Iddings, 1899a; Boyd, 1961; Hamilton 1964). The uniformity in composition of the rhyolite is shown by the average and range of eight analyses given by Hamilton (1963a) for all types of rhyolite from the northwestern part of the plateau:

	Weight percent	
	Average	*Range*
SiO_2	76. 4	75. 7–77. 3
Al_2O_3	12. 2	11. 9–12. 7
Fe_2O_3	. 9 }	. 9– 1. 9
FeO	. 6 }	as FeO
MgO	. 13	. 07– 0. 2
CaO	. 4	. 2– 0. 6
Na_2O	3. 3	3. 0– 3. 6
K_2O	4. 9	4. 6– 5. 0
H_2O	. 6	. 3– 1. 1
TiO_2	. 13	. 1– 0. 2
P_2O_5	. 02	. 01– 0. 4
MnO	. 04	. 02– 0. 06
F	. 08	. 01– 0. 14
Cl	. 05	. 01– 0. 09

(Eleven other published modern analyses give an almost identical average but a slightly greater range—from 73.1 to 78.0 percent SiO_2 [Hamilton, 1959]; the wider range may reflect analytical biases rather than true variation in the rocks.) Welded tuffs analyzed contain less fluorine and chlorine and more highly oxidized iron than do lava-flow or dome rocks, but the rocks are otherwise indistinguishable compositionally from each other and from the rhyolite of the Island Park caldera.

Basalt is greatly subordinate to rhyolite among the exposed rocks of the Yellowstone Plateau occurring mostly as small flows on the rhyolite ash flows of the outer part of the plateau. The basalt varies from diabasic olivine basalt to basalt andesite (Iddings, 1899b; Wilcox, 1944; Boyd, 1961; Hamilton, 1960a, 1964). The average and range of seven analyses of basalt from Fenner (1938; three analyses of one flow are weighted as a single analysis) and from Hamilton (1963a) are

	Weight percent	
	Average	*Range*
SiO_2	49. 3	46. 7–51. 5
Al_2O_3	15. 6	15. 2–15. 9
Fe_2O_3	2. 3 }	10. 4–14. 1
FeO	9. 7 }	as FeO
MgO	6. 9	6. 0– 7. 8
CaO	9. 6	8. 5–11. 1
Na_2O	2. 9	2. 3– 3. 3
K_2O	. 6	. 4– 1. 1
H_2O	. 4	. 3– 1. 2
TiO_2	2. 0	1. 7– 2. 4
P_2O_5	. 3	. 2– 0. 4
MnO	. 2	. 13–0. 22

These basalts overlap the basalt of the Island Park caldera in silica content. However, the basalt of the Yellowstone Plateau is on the average less mafic than that of Island Park, having less magnesium and calcium and more silica, sodium, potassium, and titanium.

Basalt and rhyolite liquids were erupted simultaneously and mixed physically in two known instances in the Yellowstone Plateau (Wilcox, 1944; Boyd, 1961). Basalt containing rhyolite blebs grades into rhyolite containing basalt blebs, and as Boyd (1961, p. 403) concluded, "The character of this lava suggests mixing of rhyolite and basalt [liquids] at depth and extrusion as a single flow."

Olivine basalt must be extensive beneath the young rhyolite lava flows of the Yellowstone Plateau. South of West Yellowstone, large Bull Lake moraines were deposited by ice that flowed westward from the plateau. These moraines are younger than the rhyolite ash flows of the plateau but are overlain by the rhyolite lava of the Madison Plateau (Richmond and Hamilton, 1960). South from the latitude of West Yellowstone to the end of the exposed moraines, erratic blocks in the till are almost exclusively of uniform diabasic olivine basalt. Such rock is not present in appreciable quantity anywhere in the exposed source region of the ice, so the basalt must have come from the terrane buried by the post-Bull Lake rhyolite lava flows on the Central and Madison Plateaus. The large irregular caldera of the Yellowstone Plateau was probably flooded by uniform olivine basalt in pre-Bull Lake time, and during Bull Lake Glaciation the region now filled by the rhyolite of the Central and Madison Plateaus was probably a broad basalt plain rimmed by high-standing precollapse ash flows; the assemblage was analogous to that now present in the Island Park caldera. Rhyolite erupted subsequently has completely covered the basalt on the caldera floor.

Pakiser and Baldwin (1961) found that the Yellowstone Plateau has low Bouguer gravity and interpreted this to indicate that the plateau is probably underlain directly by a disk-shaped mass 2–4 miles thick of rhyolite or its plutonic equivalent that represents a thickened silicic crust, a collapsed magma chamber, or a roofless batholith. They assumed in making this interpretation that all pre-Pliocene rocks have the same density and that no faults juxtapose pre-Pliocene rocks of different density. Other quite different interpretations can be made if it is assumed instead that pre-Pliocene structure is as complex beneath the plateau as in the surrounding highlands. The Buffalo Fork thrust, for example, carries relatively heavy Paleozoic strata and still heavier Precambrian crystalline rocks over the thick and very light Upper Cretaceous section (Love, 1956). The fault disappears under the rhyolite of the plateau south of Yellowstone Lake, and its continuation beneath the rhyolite could account for the gravity gradient, southeast of the lake, that Pakiser and Baldwin inferred to be due to great thickening of the rhyolite. The normal-fault blocks of the Teton and Madison Ranges project toward each other from opposite sides of the Yellowstone Plateau and may be continuous beneath the volcanic rocks; if they are continuous, then gravity interpretation is more complicated than is now realized. The possibility that large masses of magma still exist in the Yellowstone magma chamber makes the interpretation still more ambiguous. The Bouguer gravity intensity (−210 to −240 mgal) of the plateau is that to be expected in a region in isostatic equilibrium at this altitude (7,500–8,500 ft) and does not prove the causative light mass to be at the top of the crust.

The rhyolite-and-basalt complex of the Yellowstone Plateau is larger than that of Island Park, but the two complexes may share a common history. In the Yellowstone Plateau, a large central region collapsed while rhyolite ash flows were being erupted from a huge magma chamber. The resulting collapse basin was filled at some later stage by olivine basalt flows, and these in turn have since been buried by great flows of rhyolite lava. The Plateau complex of the Yellowstone has advanced one step further than has the complex of Island Park: in the Island Park caldera, the rhyolite lava flows and ash flows of the eastern rim have only partly buried the basalt that surfaces the caldera floor, whereas in the Yellowstone collapse depression the basalt has been hidden completely beneath younger rhyolite flows.

I concluded previously (Hamilton, 1959) that the petrology of the rhyolite of the Yellowstone Plateau indicates a probable origin in the differentiation of basalt. Confirmation of this conclusion is afforded by the strontium-rubidium isotope studies of Yellowstone rocks by Pinson and others (1962): the proportions of radiogenic strontium, common strontium, and rubidium oppose origin of the rhyolite by mobilization of silicic crustal materials and affirm its origin from material such as basalt. Because the rhyolite ash flows fill a broad topographic basin, I suggested that the volcanic rocks are in effect a gigantic lava flow rather than the crust of a roofless batholith as Daly (1911) suggested. The bulk of the hidden rock of this megaflow may be basaltic rather than rhyolitic: the rhyolite may be its differentiated scum, and the complex may be a lopolith. Probably most lopoliths are extrusive (Hamilton, 1960b). A stocklike chamber in which rhyolite magma overlay basalt magma may have reached the surface, and the rhyolite may have spread across the topographic basin; this theory is not greatly different from that proposed by Daly.

SNAKE RIVER PLAIN

The eastern half of the Snake River Plain, from the Island Park caldera to the vicinity of Twin Falls, is underlain by young olivine basalt flows that form a broad axial crest along the plain. The margins of the plain are alluvial lowlands within which flow the Snake and other rivers. Dipping under these lowlands from both north and south are Pliocene rhyolite ash flows and subordinate basalt lava flows (Stearns, Bryan, and Crandall, 1939; Mansfield, 1952; Malde and Powers, 1962). Some rhyolite vents were outside the present plain, but others were within it; and the inward dips of tuffs erupted from vents within the plain indicate tectonic tilting (Donald E. Trimble, oral commun., 1962). The silicic rocks thus far analyzed are from the margins of the plain at points more than 100 miles southwest of the Island Park caldera and are mostly within the following compositional ranges (Howard A. Powers and Donald E. Trimble, written commun., 1962):

	Weight percent		*Weight percent*
SiO_2	68 –75	TiO_2	0.2 – 0.5
Al_2O_3	11.5 –13.3	MnO	.03– 0.07
Iron as FeO	1.5 – 3.5	P_2O_5	.03– 0.09
MgO	.01– 0.4	H_2O	.4 – 3
CaO	.3 – 1.1	F	.06– 0.11
Na_2O	2.0 – 3.5	Cl	.02– 0.12
K_2O	5.0 – 5.8		

These rocks generally contain less silica and more iron and magnesium than do the rhyolites of the Yellowstone Plateau and the Island Park caldera, but the assemblages overlap in composition.

The average and range of 38 unpublished analyses (Howard A. Powers, written commun., 1962) of olivine-augite basalt of Pliocene, Pleistocene, and Recent age in the central part of the Snake River Plain are as follows:

	Weight percent	
	Average	Range
SiO_2	46.1	44.3 -48.0
Al_2O_3	14.5	12.5 -17.3
Fe_2O_3	2.7	.7 - 5.8
FeO	10.2	8.1 -13.4
MgO	7.5	4.3 -10.3
CaO	9.7	8.7 -10.6
Na_2O	2.4	2.0 - 2.9
K_2O	.6	.2 - 1.1
TiO_2	2.9	1.7 - 4.0
P_2O_5	.7	.3 - 1.2
MnO	.20	.17- 0.23
H_2O	1.0	.1 - 3

According to Powers, there are compositional differences between rocks of different ages in this analyzed suite. The older rocks are on the average less silicic, aluminous, and magnesian, and more titaniferous; they have more total iron, and a larger proportion of it is oxidized.

The basalt of the Snake River Plain outside the Island Park caldera (table 1, No. 1) is well within these ranges for all components. The basalt inside the caldera (table 1, Nos. 2, 3), however, has more aluminum and calcium and less potassium, titanium, and phosphorus than does nearly all the basalt of the central Snake River Plain; its composition more closely resembles that of the basalt of the Yellowstone Plateau. The high, northeast end—Island Park and the Yellowstone Plateau—of the Snake River–Yellowstone volcanic province differs compositionally from the rest, but the province throughout is one of bimodal olivine basalt and rhyolite.

Rhyolite is also exposed along the axial crest of the eastern Snake River Plain. Three extrusive rhyolite domes rise above the plain between Idaho Falls and Arco, about 80 miles southwest of the Island Park caldera. Easternmost of the three is East Twin Butte, from which a specimen was collected by Howard A. Powers and analyzed by Dorothy F. Powers (U.S. Geological Survey, Denver, Colo.) in 1958; the results of the analysis are as follows:

	Weight percent		Weight percent
SiO_2	74.89	F	0.17
Al_2O_3	12.47	MnO	.05
Fe_2O_3	2.11	H_2O-	.05
FeO	.20	H_2O+	.01
MgO	.07	CO_2	.01
CaO	.59		
Na_2O	3.84	Subtotal	99.90
K_2O	5.13	Less O for F	.07
TiO_2	.18		
P_2O_5	.02	Total	99.83

This rhyolite is compositionally like that of the Island Park caldera and the Yellowstone Plateau.

Despite the cover of olivine basalt throughout the Snake River Plain, there may be much rhyolite beneath the central part. The rocks underlying the plain were tilted up during the extrusion of the westernmost and largest of the three rhyolite domes, Big Southern Butte, and were examined by W. Bradley Myers and me at the northeast flank of the dome. Of the 800 feet of volcanic rocks exposed, the upper 300 feet is interlayered basalt and rhyolite; the lower 500 feet is basalt flows alone.

The eastern Snake River Plain is a province of bimodal volcanism of rhyolite and olivine basalt with little intermediate rock. Basalt dominates the surface exposures throughout most of the plain except in its upper end, in the Island Park and Yellowstone region, but the characteristics of the rocks are similar throughout.

COLUMBIA RIVER BASALT

Washington (1922) applied the term "Oregonian basalts" to the basalt of the Snake River Plain, the Columbia River Basalt of the Columbia Plateau to the northwest, and various Tertiary volcanic rocks of Oregon. The Columbia River Basalt is well known to be tholeiitic, and Washington's misapprehension that the basalt of the Snake River Plain is part of the same tholeiitic province still persists. (See, for example, Turner and Verhoogen, 1960.) Buwalda (1923), Kirkham (1931), and others have recognized, however, that the Columbia River Basalt is older than and unrelated to the basalt of the Snake River Plain. The basalt of the Snake River Plain is uniformly olivine bearing and nontholeiitic (Powers, 1960), whereas the Columbia River Basalt is everywhere tholeiitic (Waters, 1961). Basalts of the Snake River and Columbia River provinces are distinctly different in their occurrence, and rhyolite is not associated with the Columbia River Basalt.

BIMODAL VOLCANIC PROVINCES

In many volcanic provinces throughout the world, basalt and rhyolite have been erupted alternately or even simultaneously from interspersed vents. The genesis of these contrasting rock types must be closely related. Intermediate rocks—andesite and dacite—are subordinate or lacking in such bimodal provinces. Several Cenozoic volcanic fields in the Basin and Range province, south and southwest of the Snake River Plain, consist of rholite and quartz latite on the one hand and subordinate basalt on the other.

In other bimodal provinces, basalt is dominant. Volcanic terranes of early, middle, and late Precambrian age in northern Michigan include bimodal basalt-and-rhyolite assemblages. The lavas of the Keweenawan Series (late Precambrian) consist largely of basalt

(SiO_2 mostly between 46 and 50 weight percent) and subordinate rhyolite (SiO_2 near 74 percent); intermediate types are of minor abundance (Broderick, 1935; Cornwall, 1951). Middle Precambrian metavolcanic rocks of Iron County are basalt and subordinate rhyolite (Gair and Wier, 1956). Early Precambrian metavolcanic rocks near Marquette are similarly bimodal, basalt being dominant over silicic rhyolite; these rocks are of "Keewatin" type and are the oldest rocks in this part of the Canadian Shield (Jacob E. Gair, oral commun., 1962). The processes that produce bimodal volcanism have operated throughout geologic time.

The Tertiary volcanic province of western Scotland (Richey, 1948) consists of basalt, both tholeiitic and olivine bearing, and subordinate rhyolite and trachyte. The related plutonic complexes are of gabbro, and even ultramafic rocks, on the one hand, and of granophyre and granite on the other. Silicic rocks outbulk mafic ones at exposed levels in the plutonic complexes, but relative proportions vary widely among them. Silicic and mafic liquids were present simultaneously in each complex, and intermediate rocks are uncommon. Erosion of the Island Park and Yellowstone centers might reveal gabbro-and-granite plutonic centers similar to those exposed in Scotland.

Basaltic and silicic lavas have generally been erupted alternately from the Iceland volcanoes Hekla and Askja during Recent time, and the siliceousness of the eruptions is a direct function of the length of time between them (Thorarinsson, 1954). Askja simultaneously erupted rhyolite from its summit and basalt from its flank in 1875 (Spethmann, 1908); but in 1921–23 and in 1961, it erupted basalt from its summit (Thorarinsson and Sigvaldason, 1962). Differentiation of silicic magma from basalt within single magma chambers seems required. An extensive Tertiary quartz latite tuff sheet contains bubbles of basaltic pumice throughout that total about 2 percent of the rock (Walker, 1962); simultaneous eruption of liquid quartz latite and liquid basalt is required to explain this sheet and also other rhyolite-and-basalt flows and dikes (Gibson and Walker, 1962). Crustal structure of Iceland is oceanic, not continental (Tryggvason, 1962).

All the basalt in some of these bimodal provinces, and much of it in all of them, is olivine basalt. By differentiation processes, only tholeiite might be expected to yield a rhyolitic residuum; perhaps the olivine basalt accompanying the rhyolite is itself a differentiate rather than a parent magma.

Olivine basalt of olivine-basalt-only and of olivine-basalt-and-trachyte provinces in general contains more alkalies, titanium, and phosphorus than do either most olivine basalt of the bimodal basalt-and-rhyolite provinces or nearly all tholeiite. It is perhaps because he was primarily concerned with the olivine basalt of a bimodal province (the British Tertiary) that W. Q. Kennedy (1933) concluded erroneously, in establishing the valuable concept of the contrast between olivine and tholeiitic basalts, that olivine basalt of all associations has a lesser content of alkalies than does tholeiite.

LARGE CALDERAS

The Island Park caldera is larger than any other caldera having a regular circular or elliptical shape to which I have found reference. Numerous calderas as much as 15 miles across have many features like those of the Island Park caldera. Many irregular volcanic collapse depressions are larger.

All or most very large calderas are at sites of voluminous eruptions of silicic ash flows. Among calderas associated with more mafic or less silicic eruptions, Ngorongoro (12 miles in diameter) in Tanganyika is perhaps the largest known, and calderas larger than 6 miles in diameter are rare. Ash-flow calderas by contrast commonly have diameters of 10–15 miles. Williams (1941) and Matumoto (1963) described three such ash-flow calderas in Kyushu, Japan, each of which is the collapsed central elliptical part of a broad shield volcano built by the accumulation of thick silicic ash flows on an irregular foundation of more mafic volcanic rocks. Williams attributed the formation of these calderas, as of calderas in general, to collapse due to rapid extrusion of the supporting magma beneath them. Katsui (1963) demonstrated that this mechanism operated in Hokkaido, Japan.

The elliptical Valles caldera (Smith and others, 1961), 12 by 15 miles, in north-central New Mexico resulted from the catastrophic eruption of about 50 cubic miles of rhyolite ash flows in a region of previous andesitic and basaltic volcanism. Following collapse, the caldera floor was domed, and flows of viscous rhyolite were erupted about a concentric ring within the caldera.

The Creede caldera (Steven and Ratté, 1960) in southwestern Colorado is about 10 miles across and probably originated as a result of eruptions of vast rhyolite ash flows and, later, quartz latite ash. The flat floor of the caldera was subsequently domed by intrusions, and viscous quartz latite formed local flows and domes around the margin of the caldera.

The Timber Mountain caldera (Hinrichs and Orkild, 1961; Byers and others, 1964) of southern Nevada is a complex caldera 15 by 18 miles that dropped from the center of a broad shield volcano composed of extensive thick rhyolite ash flows. Rhyolite flows and domes were extruded along the caldera scarp after collapse, and thin basalt flows were erupted locally.

The Tibesti Mountains of the Sahara Desert consist of six major broad shield volcanoes of andesite and basalt, each having a caldera 6–12 miles in diameter at its summit. The calderas are partly filled and the volcanic shields are variably mantled by thick rhyolite ash flows that erupted from the calderas during collapse (Gèze and others, 1959). Small flows of basalt have been erupted on the rhyolite of most of the shields.

Still larger but irregular collapse depressions have formed in ash-flow plateaus as a result of extremely voluminous eruptions. The Lake Toba depression in northwestern Sumatra is 60 by 20 miles in plan and is as much as 1,500 feet deep (Bemmelen, 1952). The large lakes in the ash-flow plateau of central North Island, New Zealand—the largest lake, Taupo, is 15 by 20 miles—occupy irregular structural collapse depressions that are defined by faults and downwarps produced during ash-flow extrusion (Grange, 1937). An oval collapse depression 14 by 28 miles has been recognized in the volcanic San Juan Mountains of Colorado (Luedke and Burbank, 1961, 1962). The collapse depression of the Yellowstone Plateau (Boyd, 1961), 30 miles in diameter, is another irregular feature.

All these calderas and larger irregular collapse depressions resulted from the very rapid extrusion of voluminous silicic ash flows. As some of the authors cited have emphasized, such calderas collapse when eruption is so rapid that the upper part of the magma chamber is emptied without being simultaneously refilled by magma from beneath. Explosive discharge and collapse of frothy magma after overflow probably both contribute to caldera collapse.

PETROGENESIS OF THE BASALT-RHYOLITE ASSOCIATION

The Island Park caldera was apparently the scene of eruption of both rhyolite and basalt magmas from a single magma chamber. The problem of the origin of these contrasting magmas is shared with the rest of the Snake River–Yellowstone province and with other bimodal rhyolite-and-basalt volcanic terranes.

A popular hypothesis is that rhyolite of this type (and all other types) forms by fusion of silicic rocks of the continental crust. Such conjecture does not explain the intimate association of rhyolite and basalt liquids, is inapplicable to oceanic Iceland, and is not supported by the meager isotopic data; it therefore is not considered further here. An explanation is made instead in terms of liquid fractionation of basaltic magma into rhyolitic and basaltic magmas. Reasons for rejecting crystallization fractionation in this instance are given subsequently.

Some bimodal volcanic provinces, including the Snake River Plain, contain broadly uniform olivine basalt as their dominant mafic rock type. Other provinces, such as the British Tertiary, include large amounts of both olivine and tholeiitic basalts as well as rhyolite, and some of these provinces also contain a variety of alkalic rocks in small volume. Much of the basalt associated with rhyolite in bimodal suites is olivine bearing and is markedly more mafic than tholeiite. The fractionation of tholeiite into olivine basalt and rhyolite is quantitatively adequate to account for the bimodal volcanic provinces, and a mechanism for such differentiation can be inferred.

The compositional relationships are illustrated by figure 13. Plots of data representing tholeiite provinces scatter between those of data for the basalt and rhyolite of bimodal provinces; so the compositions of associated basalt and rhyolite can be accounted for in terms of a tholeiitic parent. None of the plots representing oxides in a tholeiite province falls exactly on the connecting line of any basalt-and-rhyolite province, but there is general concordance. The geometric relationships (the ratios of sides of the similar triangles whose hypotenuses are the line joining olivine basalt, tholeiite, and rhyolite) indicate that if tholeiite does fractionate into olivine basalt plus rhyolite, between 5 and 30 percent of the initial magmatic mass could become rhyolite, and the remainder, olivine basalt. The proportion varies with the provinces selected for comparison.

Tholeiite is in general intermediate in composition between the basalts and rhyolites of the Snake River–Yellowstone subprovinces, with respect to the principal oxides and their ratios. This fact is illustrated by figures 14 and 15, in which data are plotted for the olivine basalt and rhyolite of the Snake River–Yellowstone province and for the rocks of the adjacent Columbia River Basalt tholeiitic province. In some oxides or ratios the tholeiite and the olivine basalt overlap.

The Columbia River Basalt is unusual among tholeiites in that it has an uncommonly high content of iron and an uncommonly low content of magnesium (fig. 13; Powers, 1960). The total of iron and magnesium is, however, typical for tholeiite, and because it is a good index of variation in rocks, it is used as the abscissa in figure 14. In the iron-magnesium variation diagram, the plot representing the Columbia River Basalt can be seen to be on average near a straight line between olivine basalts and rhyolites of the Snake River–Yellowstone province for silica, calcium, sodium, and titanium. The relationships of aluminum and potassium are in the same direction but are not linear.

Figure 15 illustrates the intermediate character of the tholeiitic Columbia River Basalt with respect to some other oxides. The relationship is linear on the potassium-calcium diagram and on the average linear but with scatter on the aluminum-calcium graph. There is still more scatter in the magnesium total-iron dia-

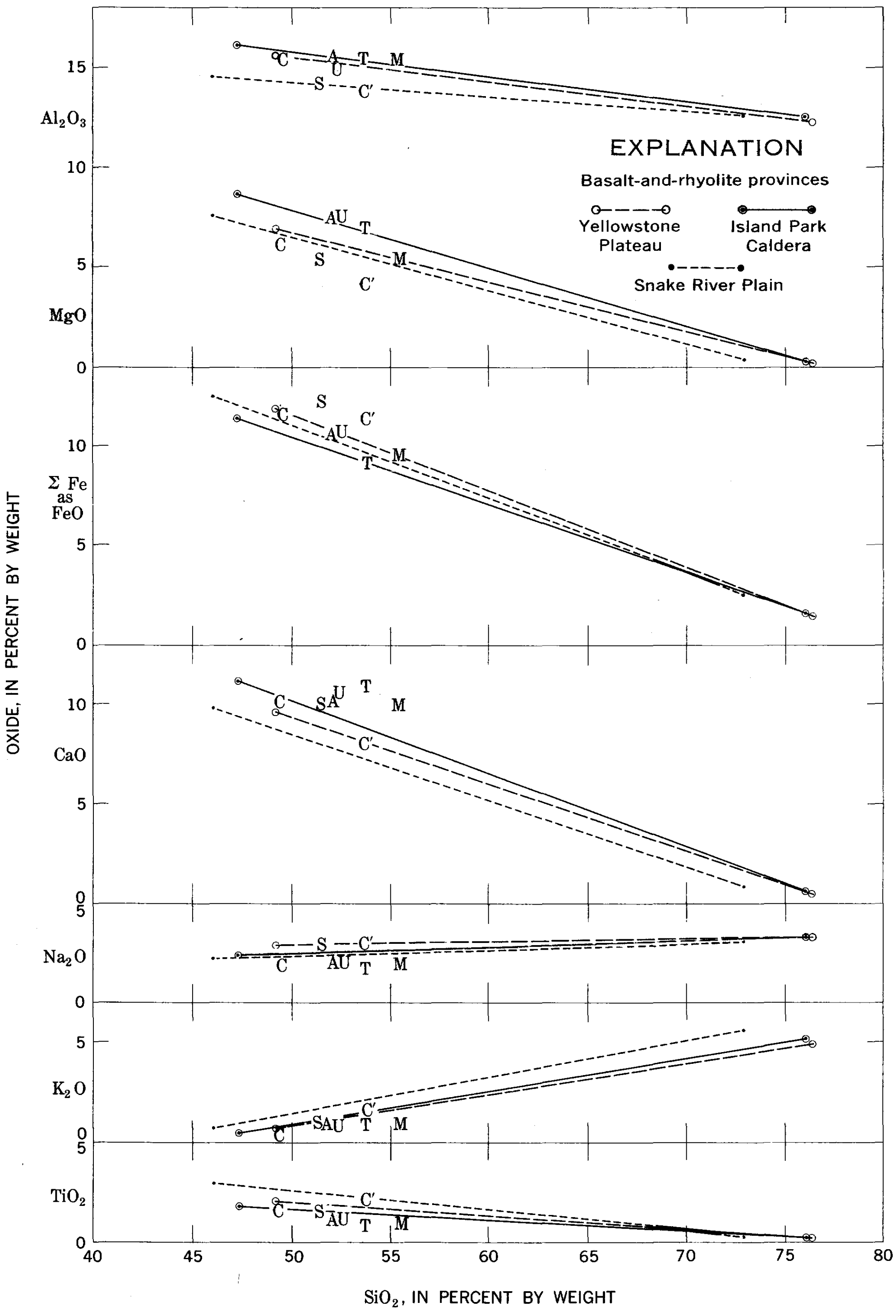


FIGURE 13.—Generalized silica-variation diagram for rhyolite and basalt of selected bimodal volcanic assemblages and for tholeiitic basalt and diabase. The average compositions of associated rhyolite and basalt of three subprovinces of the Snake River–Yellowstone province are connected by lines; data and their source are given in the text. Letters show average compositions of tholeiitic basalt and of chilled margins of tholeiitic diabase sheets from various provinces, from these sources: Karroo diabase of South Africa (A) (Walker and Poldervaart, 1949, table 17, cols. 3–5); Jurassic diabase sheets of McMurdo Sound region, Antarctica (M) (Gunn, 1962; Hamilton, unpub. data); diabase sheets of Tasmania (T) (McDougall, 1962, table 7); Triassic diabase of Pennsylvania and New Jersey (U) (Hotz, 1953, table 5, cols. 1–5; Columbia River basalt, Picture Gorge (C) and Yakima (C') Basalts plotted separately (Waters, 1961); and tholeiite (S, "Nonporphyritic central magma type") of northwestern Scotland (Walker and Poldervaart, 1949).

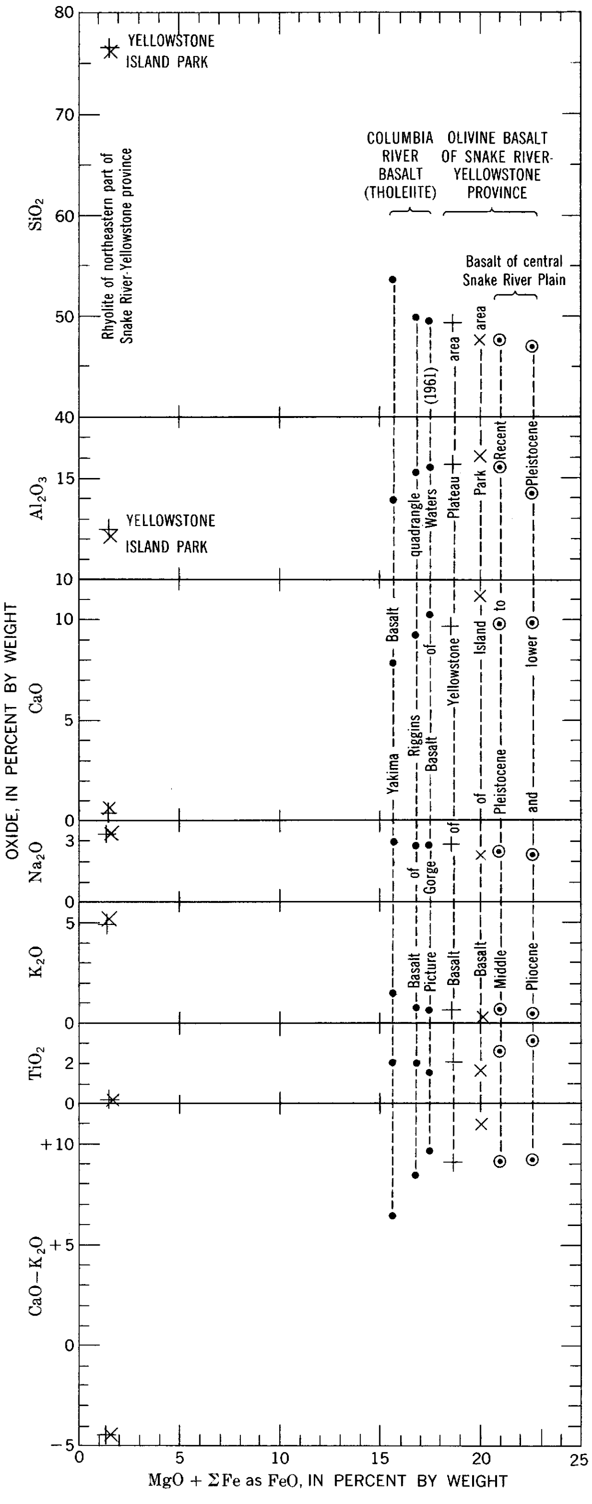


Figure 14.—Iron-magnesium variation diagram for basalt and rhyolite of Snake River–Yellowstone province and for Columbia River Basalt. The points represent averages of analyses of rocks from the following sources: Yellowstone and Island Park rocks (this report); Yakima Basalt and Picture Gorge Basalt, both of Columbia River Basalt (Waters, 1961); Columbia River Basalt in Riggins Quadrangle, western Idaho (Hamilton, 1963b); and basalts of central Snake River Plain (H. A. Powers, written commun., 1962).

gram, but again the tholeiite is intermediate on the average.

No pair of the separate averages plotted gives a linear fit with respect to all oxides, and the average of the averages for rocks in each group gives a better fit than does any one triplet of olivine basalt, tholeiite, and rhyolite. When the average of both rhyolite averages is compared with the average of the three suites of tholeiitic basalts from the Columbia River Basalt and the average of the four averages of olivine basalts from the Snake River–Yellowstone province, it is seen that the composition of tholeiite can be approximated by a mixture of about 1 part rhyolite and 6–8 parts olivine basalt. This is shown by the following tabulation, in which Δ_1 and Δ_2 are the differences between the adjacent averages:

Constituent	*Olivine basalt, Snake River-Yellowstone Province*	Δ_1	*Tholeiite, Columbia River Basalt*	Δ_2	*Rhyolite, Island Park and Yellowstone*	$\frac{\Delta_2}{\Delta_1}$
SiO_2	47.8	3.3	51.1	25.2	76.2	8
Al_2O_3	15.4	.5	14.9	2.6	12.3	5
ΣFeO	12.9	1.5	11.4	9.9	1.5	7
MgO	7.7	2.5	5.2	5.1	.10	2
CaO	10.1	1.0	9.1	8.6	.5	9
Na_2O	2.4	.5	2.9	.4	3.3	.8
K_2O	.4	.6	1.0	4.0	5.0	7
TiO_2	2.4	.6	1.8	1.6	.16	3

The aberrant oxides, for which the smallest values appear in the last column, are magnesium, sodium, and titanium. The magnesium aberration would vanish if a more typical tholeiite province (see fig. 13) were plotted, for most tholeiite is more magnesian than the Columbia River Basalt. The sodium anomaly has little significance, because sodium differences between the suites are small. Titanium is rather variable between provinces of otherwise similar rocks, so that its anomaly also may not be significant.

The rhyolite and the olivine basalt of the Snake River–Yellowstone province can thus be interpreted as complementary differentiates of tholeiitic basalt. Similar reasoning is applicable to other bimodal basalt-and-rhyolite provinces.

The history of the Island Park caldera must be explainable in terms of a satisfactory petrogenetic theory. Such a theory must take into account the following main facts and reasonable inferences. Eruptions of volatile-rich rhyolite ash flows resulted in the collapse of the caldera into a magma chamber having a minimum size of 18 by 23 miles. Smaller ash flows and eruptions of viscous, volatile-poor rhyolite followed. Flows of olivine basalt are interlayered with the younger rhyolites within the caldera, and late volcanic material has been largely or entirely basaltic. The basalt and rhyolite are each of subuniform composition, yet both were erupted from vents interspersed within the caldera; this fact indicates that the magma chamber contained both magma types simultaneously. The erup-

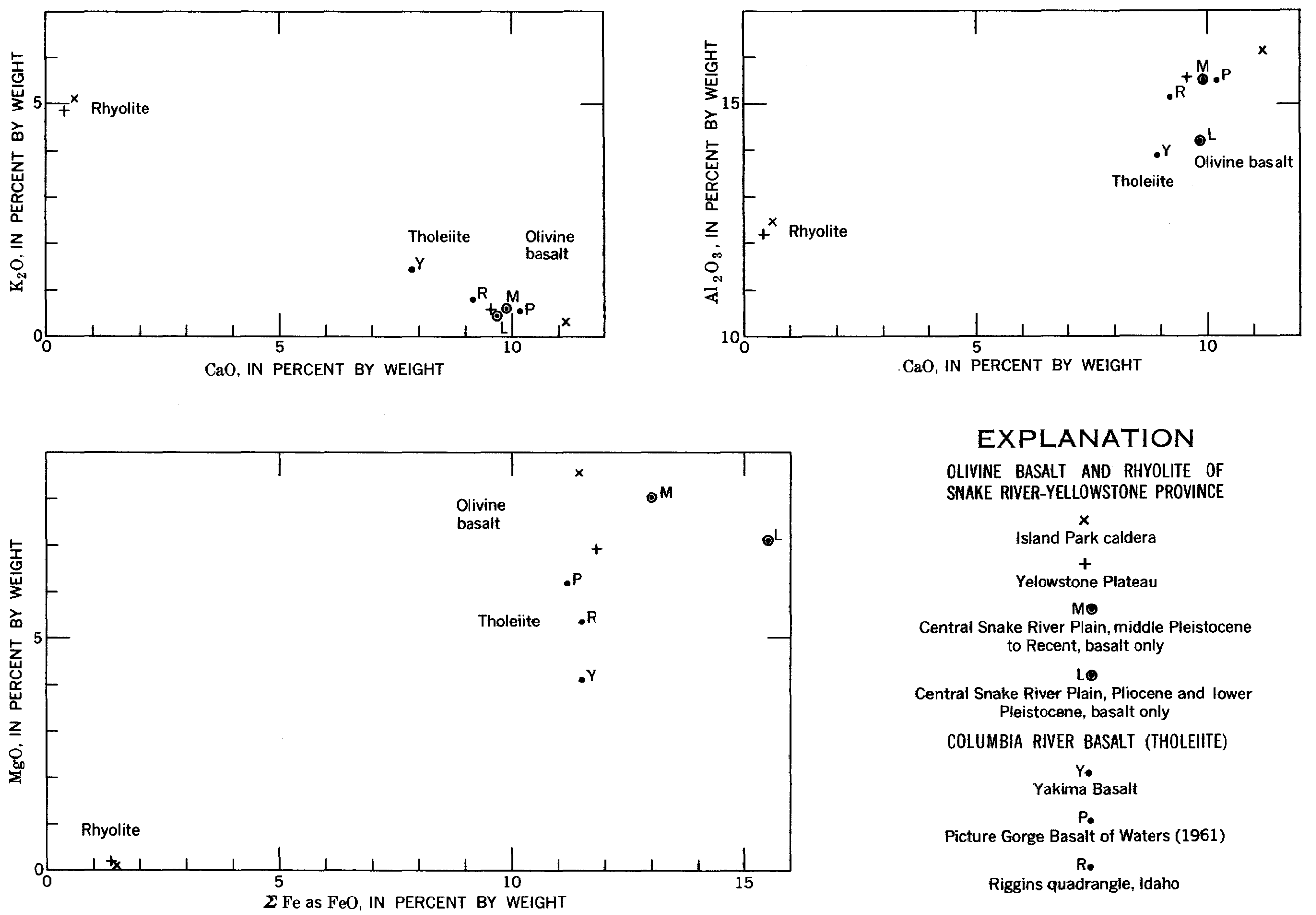


FIGURE 15.—Potassium-calcium, aluminum-calcium, and magnesium-iron ratios in basalt and rhyolite of Snake River–Yellowstone province and in Columbia River Basalt. Sources of data same as for figure 14.

tive sequence indicates that liquid rhyolite probably overlay liquid basalt without intervening intermediate liquid and that the fraction of the rhyolite richest in volatiles lay on top. The basalt is nonporphyritic. Both rhyolite and basalt were erupted as liquids; if they are complementary differentiates from tholeiite, then fractionation must have taken place in the liquid state. Further, the differentiation must have been completed at depth, because no tholeiite reached the surface.

The isotopic ratios of strontium and rubidium in the rhyolite of the Yellowstone Plateau suggest that until geologically recent time the strontium had been in an environment where the rubidium content was typical of basalt and where rubidium was far less abundant than in either the present rhyolite or in silicic basement rocks. Origin of the rhyolite by any process of fusion of sialic crustal rocks is therefore unlikely. The rhyolite may have formed from basalt (or its high-pressure polymorphs) either by selective fusion or by differentiation. The bimodality of the volcanic province indicates, however, that a spectrum of varying degrees of fusion of basalt cannot account for the rocks and that the origin apparently lies in the differentiation of basalt. The rhyolites are similar in composition to the silicic cap rocks of lopoliths, which also must have differentiated from basaltic magma.

Tholeiite is the most voluminous basalt type of non-eugeosynclinal continental regions and also of the very active volcanic oceanic islands of Iceland and the Hawaiian Islands and of the ocean floors (Engel and Engel, 1963). That the rocks of the Snake River–Yellowstone volcanic assemblage are due to the differentiation of tholeiite is accepted here as a working hypothesis.

Crystallization fractionation is generally considered to be the only significant process of basaltic differentiation, but there is no evidence that it has operated significantly here. Had crystallization differentiation operated, the eruptive products should be varied because of the control of differentiation by the varying volume and speed of rising magma. Lava that is erupted soon after mobilization in the mantle should be undifferentiated tholeiite, but there is none on the Snake River Plain. Crystal differentiation should have been interrupted at times by the eruption of partly differentiated lava, which also is lacking. (The rare latite of the Island Park caldera is highly alkalic and cannot be the simple product of incomplete crystal settling.) Within the Island Park and Yellowstone rhyolites, the bulk composition varies little as the proportion of phenocrysts changes: crystals and glass have similar compositions, and their separation would not affect major differentiation. The graphs (figs. 13, 14, 15) show that the plot of the composition of primary tholeiite lies on straight lines between the plots for complementary rhyolite and olivine basalt; crystallization differentiation would necessarily result in curved lines.

The basalt that now floors the Island Park caldera lay beneath the rhyolite in the magma chamber before collapse. This basalt has markedly less potassium, a little less sodium, and markedly more magnesium, calcium, and aluminum than does either the basalt outside the caldera to the west or the basalt of the rest of the Snake River Plain. Silica contents of basalt inside and outside the caldera are similar. There are no proportions in which caldera basalt and caldera rhyolite could be combined to yield basalt of common Snake River type, but the contrasts noted do suggest that the basalt in the caldera magma chamber was impoverished in those metals which are most soluble in water.

The rhyolite is composed mainly of those components of igneous rocks that have the lowest melting points and are most volatile: its composition is approximately a mixture of equal parts, by weight, of orthoclase, albite, and quartz. Its iron is mostly oxidized. The minor-element proportions are those expected if low melting, high solubility, and high volatility were significant in the formation of the magma.

Differentiation within the rhyolite was influenced by volatiles, if it is correct that ash-flow magma lay above lava-flow magma in the chamber. The difference between the two rhyolite magma types must have been primarily in water content, the ash-flow magma having been much wetter. Iron is more highly oxidized in the ash flows than in the lava flows—this is better shown by the Yellowstone data (Hamilton, 1963a) than by the Island Park data—and this fact suggests that the water content was greater in the ash flows. The slightly greater amounts of potassium, phosphorus, and barium in the ash flows than in the lava flows suggest concentration of those elements also because of their greater volatility. (Some other effect such as devitrification might, however, explain some of the differences; see Lipman, 1964.)

Upward concentration of volatile components within the rhyolite is related to temperature and pressure gradients within the magma chamber. The water content must vary with pressure—hence with depth—and with temperature, and water must diffuse through the chamber to concentrate in the cooler and higher parts (Goranson, 1937; Verhoogen, 1949). The more volatile metals should migrate with the water (G. C. Kennedy, 1955). The common progression of basaltic eruptions from explosive and highly oxidized early stages to less fluid and less oxidized later stages indicates the operation of this mechanism (G. C. Kennedy, 1955).

The separation of tholeiitic parent magma into olivine-basalt and rhyolite fractions might also be due to diffusion within the liquid in response to pressure and temperature gradients. Differentiation of this sort was suggested as a major process by Evans (1914), Fenner (1926), Lindgren (1933), Broderick (1935), Wahl (1946), Neumann (1948), Dickson (1958), Katsui (1963), Boone (1962), and Peterson and Roberts (1962). Although such processes have generally been assumed to be of minor significance, they operate in the direction needed to account for much differentiation that has not otherwise been explained.

Sodium and potassium metasilicate and disilicate are highly soluble in water (although feldspars are relatively insoluble). Their transportation by water results in a transported liquid richer in alkalis, particularly potassium, and in silicon, but poorer in aluminum than was the original liquid (Morey and Hesselgesser, 1951, 1952; Morey, 1957). Ferrous iron is oxidized under high steam pressure and is then easily transferred as ferric iron (G. C. Kennedy, 1948; Robert C. Newton, oral commun., 1962). Magnesium, calcium, and aluminum have very low solubilities in steam, in contrast to silicon, potassium, and sodium. Differential diffusion results in greater fractionation of minor components than associated major components (Wahl, 1946), and the typically exponential abundance relations between associated minor and major elements in igneous rock suites can be thus explained. All these processes will produce compositional gradients within a magma chamber in response to pressure and temperature gradients, and all operate in the correct direction to produce the contrasting rhyolitic and basaltic magmas. Whether the processes are adequate to yield such opposite magma types cannot yet be evaluated quantitatively. The processes must operate; the unknown factor is their significance.

The lack of erupted rocks of intermediate composition in the Snake River–Yellowstone region suggests that the process of differentiation was largely accomplished before the magmas rose near the surface. A mechanism that might cause a rising magma to fractionate into sharply contrasting liquids was suggested by the work of G. C. Kennedy and others (1962). Solid silica at high temperature and pressure is in equilibrium with two fluids: one rich in silica, and the other rich in water. Compositions of these two fluids converge gradually with increasing pressure until a pressure of about 8,000 bars is reached. As pressure continues to increase, the compositions converge rapidly and merge into a homogeneous fluid at 9,500 or 10,000 bars (a pressure which corresponds to that at a depth of about 35 km). Conversely, a homogeneous fluid rising through the pressure region of rapidly changing equilibrium compositions might split into immiscible phases as pressure decreased; slight changes in pressure and temperature could greatly alter the composition of the phases, and quite different trends of differentiation could result.

Although laboratory data indicate generally greater miscibilities in complex magmas than in the silica-water system, it appears possible that rising tholeiitic magma could split into two phases: one relatively rich in volatiles (rhyolite), and the other relatively poor in them (olivine basalt). Gravitational separation of the two fluid phases would produce a layered magma having liquid rhyolite overlying liquid basalt. Water and the more volatile components would be concentrated in the upper part of the rhyolite layer. The eruptive sequences of the Island Park caldera are well accounted for in these terms.

The bimodal Island Park and Yellowstone assemblage of olivine basalt and subordinate rhyolite may have been produced by the liquid fractionation of tholeiitic magma in response to changing pressure and temperature as the initial magma rose through the uppermost mantle and the crust after its fusion in the upper mantle. The two main mechanisms perhaps involved were the separation of immiscible phases and the formation of compositional gradients in response to pressure and temperature gradients. Both mechanisms would concentrate the more volatile components high in the magma chamber.

This process if operative could produce 10–20 percent rhyolite and 80–90 percent olivine basalt from tholeiitic magma. The exposed areas of rhyolite and of basalt in the Snake River Plain, Island Park caldera, and Yellowstone Plateau differ widely in both directions from this ratio, but the exposed abundances need not indicate true abundances of all rocks, both buried and exposed. As rhyolite magma is about 10 percent lighter than basalt magma, and as it will be largely concentrated in the upper part of any layered magma chamber, it is more likely to be erupted and less likely to crystallize at depth than is basalt magma.

The geothermal gradient of the Snake River–Yellowstone province is abnormally high, and the splitting of rising magma into olivine basalt and rhyolite is perhaps due to the uncommon pressure-temperature combinations produced by this gradient.

Further differentiation can of course modify the olivine-basalt magma if it is not erupted rapidly. Alkaline mafic and intermediate rock—such as oligoclase basalt, trachybasalt, and trachyte—may form either from magmas residual after partial crystallization or from basaltic magma enriched in rising volatiles high in a chamber. Little of such second-generation differentiation has occurred in the Snake River–Yellowstone province, but the mafic latites of the rim of the Island Park caldera and of the Craters of the Moon can be cited as two possible examples of this process. In some other provinces, as in northwestern Scotland and northeastern Ireland, secondary differentiation of olivine basalt may have been an active process.

Liquid fractionation of magmas as they rise toward the surface may provide an explanation for other igneous rock occurrences also. For example, lopoliths might be largely fractionated into olivine-basaltic and rhyolitic liquids prior to eruption, and posteruption differentiation might largely affect the basaltic part.

RELATION OF ISLAND PARK CALDERA TO SNAKE RIVER PLAIN

The Island Park caldera is but a small part of the Snake River Plain, and the origins of caldera and plain are linked inextricably. It is appropriate to speculate briefly on the tectonic cause of the volcanism.

Following the suggestion by Carey (1958) that the structure of the Western United States is controlled by strike-slip faulting and related tension and compression, I (Hamilton, 1963c) hypothesized that the Snake River Plain formed as a tensional feature in the lee of the northwestward-drifting plate of the Idaho batholith. This hypothesis requires that the silicic crust beneath the plain has been thinned by tension and implies that, to account for the considerable altitude of the region above sea level, the underlying intermediate crust has been thickened by igneous processes. The hypothesis is supported by seismic-refraction evidence that the silicic crust is only a few kilometers thick beneath the plain and by gravity evidence that the intermediate crust is 40 km or more thick (Pakiser, 1963).

The volcanism of the Snake River Plain may be the result of increased heat flow caused by tensional thinning of the silicic crust, and the thickening of the intermediate crust may be due to magmatic transfer of basalt from mantle to crust. If the petrogenetic mechanism advocated here is correct, rising tholeiitic magma has differentiated into olivine-basaltic and rhyolitic liquids. The denser basalt has tended to be intruded within the crust, whereas the lighter rhyolite has tended to be extruded. The crustal masses of heavy rock suggested by the gravity interpretation of Hill (1963) might represent intrusions of basalt. The basalt-and-rhyolite caldera complexes of Yellowstone and Island Park resulted where great magma chambers containing rhyolite liquid above basalt liquid reached the surface.

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