High-Temperature, Large-Volume, Lavalike Ash-Flow Tuffs Without Calderas In Southwestern Idaho

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By E. B. EKREN, D. H. MCINTYRE,
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Stratigraphy and petrology of rhyolites that were erupted as ash flows from depths too great to allow the development of calderas and at such high temperatures that the ash flows coalesced to form liquids before final emplacement and cooling

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CONTENTS

ILLUSTRATIONS

[Plates in pocket]

TABLES

HIGH-TEMPERATURE, LARGE-VOLUME, LAVALIKE ASH-FLOW TUFFS WITHOUT CALDERAS IN SOUTHWESTERN IDAHO

By E. B. EKREN, D. H. MCINTYRE, and E. H. BENNETT[1]

ABSTRACT

Rhyolitic rocks were erupted from vents in and adjacent to the Owyhee Mountains and Owyhee Plateau of southwestern Idaho from 16 m.y. ago to about 10 m.y. ago. They were deposited on a highly irregular surface developed on a variety of basement rocks that include granitic rocks of Cretaceous age, quartz latite and rhyodacite tuffs and lava flows of Eocene age, andesitic and basaltic lava flows of Oligocene age, and latitic and basaltic lava flows of early Miocene age.

The rhyolitic rocks are principally welded tuffs that, regardless of their source, have one feature in common—namely internal characteristics indicating en-masse, viscous lavalike flowage. The flowage features commonly include considerable thicknesses of flow breccia at the bases of various cooling units. On the basis of the tabular nature of the rhyolitic deposits, their broad areal extents, and the local preservation of pyroclastic textures at the bases, tops, and distal ends of some of the deposits, we have concluded that the rocks were emplaced as ash flows at extremely high temperatures and that they coalesced to liquids before final emplacement and cooling. Temperatures of 1090°C and higher are indicated by iron-titanium oxide compositions.

Rhyolites that are about 16 m.y. old are preserved mostly in the downdropped eastern and western flanks of the Silver City Range and they are inferred to have been erupted from the Silver City Range. They rarely contain more than about 2 percent phenocrysts that consist of quartz and subequal amounts of plagioclase and alkali feldspar; commonly, they contain biotite, and they are the only rhyolitic rocks in the area to do so. The several rhyolitic units that are 14 m.y. to about 10 m.y. old contain only pyroxene—principally ferriferous and intermediate pigeonites—as mafic constituents. The rhyolites of the Silver City Range comprise many cooling units, none of which can be traced for great distances.

Rocks erupted from the Owyhee Plateau include two sequences that were traced over areas having diameters of about 100 km. These two sheets are the herein-named Swisher Mountain Tuff, which is about 13.8 m.y. old, and the Little Jacks Tuff, which is about 10 m.y. old. The Swisher Mountain Tuff was erupted from the Juniper Mountain volcanic center, a gentle dome that is not bounded by arcuate faults indicative of cauldron subsidence. The tuff is 200 m thick over a considerable area in and adjacent to its source. It apparently thins gradually toward its distal edges, and it is inferred to be uniformly distributed around its source at Juniper Mountain. The unit contains vitrophyres at various intervals from base to top, and, although the vitrophyres are, in general, flow layered and commonly flow brecciated, they occasionally contain well-defined pumice clasts. The vitrophyres indicate compound cooling, and, near the distal edges of the sheet, some of them probably represent complete cooling breaks.

The Little Jacks Tuff onlaps the Swisher Mountain Tuff in exposures east of Juniper Mountain, and it is inferred to have been erupted from a source on the part of the Owyhee Plateau that lies just east of the area studied. This inferred source area, like that at Juniper Mountain, is also expressed today as a gentle dome without structural features indicative of cauldron subsidence. The Little Jacks Tuff, in most exposures in the deep canyons of the Plateau, consists of at least four cooling units, and, in places in the eastern part of the studied area near the source area, it possibly comprises as many as six. Although there is no obvious evidence of erosion between the various cooling units, magnetic polarity measurements indicate that there were at least two magnetic reversals during the eruption interval of the Little Jacks Tuff. Like the Swisher Mountain Tuff, the Little Jacks has flattened pumice clasts in a few outcrops—principally at the bases of the various cooling units.

The two tuff sequences are calc-alkalic rhyolites containing as much as 76 percent SiO_2. They are characterized by extremely low CaO and MgO content and relatively high iron content. The Swisher Mountain Tuff contains 15–23 percent phenocrysts of plagioclase, alkali feldspar, intermediate pigeonite, and sparse hypersthene. Most of the Little Jacks Tuff contains only sparse phenocrysts of plagioclase and ferriferous pigeonite. Rarely, the uppermost unit of the Little Jacks also contains quartz and, more rarely, alkali feldspar. Experimental data indicate that the crystal assemblage in the Little Jacks Tuff could have formed only in an extremely dry melt (2 percent or less H_2O) at high pressures (perhaps as great as 8 kilobars) at unusually high temperatures (>1000°C). The Swisher Mountain Tuff probably crystallized at lower pressures than the Little Jacks, as suggested by its phenocryst assemblage. The inferred high temperatures for both units are corroborated by iron-titanium oxide compositions. These data indicate a depth of origin of as much as 25 km for the Little Jacks Tuff, well within the thick lower crust as defined for the area by a seismic study. The Swisher Mountain Tuff probably crystallized at a somewhat shallower depth. Such depths of origin virtually preclude cauldron subsidence of the source area; indeed, none is recognized at the source area of either unit. The possibility seems good that underplating of the rhyolitic magma chambers by basalt or the actual injection of basalt into the magma chambers triggered the rhyolite eruptions from these great depths.

Evidence of high emplacement temperatures are not restricted to the Swisher Mountain and Little Jacks Tuffs; all ash-flow tuffs emplaced in the Owyhee region between 16 and 10 m.y. ago also show evidences of similar high temperatures, whether derived from sources within the highlands or in the adjacent western Snake River Plain.

Four sets of high-angle faults dominate the structure of the Owyhee Mountains and Owyhee Plateau: an oldest set that strikes northeast, offsets rocks dated at 43 m.y., and is intruded by dikes dated at 26 m.y.; a second set that strikes north to northwest and is intruded by dikes that have been dated at 16 m.y.; a third set that strikes northwest and west-northwest and borders the present-day southwestern margin of the western Snake River Plain; and a fourth set that strikes east and occurs along the Idaho-Oregon State line.

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INTRODUCTION

PURPOSE OF INVESTIGATION

Owyhee County, Idaho, west of long 116° W., was mapped at a scale of 1:125,000 (Ekren, McIntyre, and Bennett, 1978a; Ekren and others, 1981) as part of the U.S. Geological Survey's investigation of potential geothermal areas. The mapping and associated stratigraphic studies focused on the voluminous rhyolitic rocks exposed in the Silver City Range (Owyhee Mountains) and Owyhee Plateau (fig. 1; pl. 1, in pocket), because these strata comprise the principal recharge rocks and part of the thermal reservoir rocks of the Bruneau–Grand View geothermal area (Young and Whitehead, 1975). Previous geologic studies in the area (Littleton and Crosthwaite, 1957; McIntyre, 1972; Asher, 1968; Pansze, 1975; Bennett and Galbraith, 1975; Bennett, 1976; Neill, 1975) had shown that the rhyolites were most unusual and considerable doubt existed as to whether the rocks were lavas or flow-layered ash-flow tuffs. Because of the general confusion and controversy regarding the true nature of these unusual rhyolites, a field conference was held in April 1977 that was attended by geologists, most of whom had had considerable experience mapping a wide variety of welded tuffs and rhyolite lavas. These geologists were R. L. Christiansen, H. J. Prostka, D. H. McIntyre, R. R. Coats, E. B. Ekren, E. G. Crosthwaite, and H. E. Malde, all of the U.S. Geological Survey; and E. H. Bennett and B. Bonnichsen of the Idaho Bureau of Mines and Geology. The field conference ended with a unanimous opinion that the principal rock units were lavas, not tuffs. This conclusion was reached primarily because of the ubiquitous flow-layered nature of the rocks, the occurrences of flow breccia at the bases of most of the rhyolite cooling units and the virtual lack of pyroclastic textures throughout the units. The flow breccias in particular were considered to be irrefutable evidence that the rocks were emplaced as liquids. Although the authors of the present report concurred with the final conclusion of the field conference, doubts were quickly raised when mapping commenced. Many of the units were found to have such broad areal extents that a lava origin seemed unlikely; they were found to occur in tabular sheets that vary little in thickness over great distances; and, most important, a few outcrops of nearly all the principal units were found to contain well-flattened pumice fragments. To account for the common occurrences of basal flow breccia, the extensive flow layering, and the near absence of pyroclastic textures, we concluded (Ekren, McIntyre, and Bennett, 1978b) that the rhyolites originated as ash-flow tuffs but were remobilized to liquids before final emplacement and cooling.

Considerable doubt still exists, however, as to the nature of the ash flows that gave rise to these unusual rocks. Was the material in the flows actually ash in the sense of rigid, brittle shards, or could this material have been in the form of liquid droplets? What was the nature of the eruptive columns that gave rise to these rocks? These and other problems are considered in a summary discussion at the end of this report.

A geologic map of the area has been published in the U.S. Geological Survey Miscellaneous Investigations series (Ekren and others, 1981). This map is at a much larger scale (1:125,000) than the map (1:500,000) accompanying the present report and shows the distribution of several units that are described herein but that are not shown separately on the accompanying map. We urge, therefore, that the interested reader avail himself of the larger scale published map.

PROBLEM OF RECOGNIZING HIGH-TEMPERATURE, FLOW-LAYERED WELDED TUFFS

The reader with a textbook knowledge of ash-flow tuffs as described, for example, by Smith (1960) and Ross and Smith (1961), but with limited or no experience in mapping lavas and welded tuffs may, at this point, be wondering how lavas and tuffs could ever be confused. To elucidate the problem and set the stage for the discussion that follows, some distinguishing but general features of lavas versus welded tuffs will be outlined.

We must point out at the start of this discussion that a "typical rhyolite lava flow" is easy to define, but that a "typical welded ash-flow tuff" is extremely difficult to define or describe. Welded tuffs throughout the Great Basin, for example, range from cold thick (300 m or more) cooling units in which flattening of the pumice is slight and restricted to the middle of the unit, to hot thin (<10 m) cooling units that are densely welded from base to top and in which all pumice fragments are extremely flattened. These two examples of welded tuffs have such disparate physical properties that a field geologist has difficulty realizing that both rocks are end products of the same volcanic process.

A welded ash-flow tuff cooling unit that we have found to be fairly common in western United States and that we consider to be fairly typical is shown diagrammatically in figure 2. Tuffs that conform more or less to this example have been described by Lipman, Christiansen, and O'Connor (1966); Rowley (1975); Mackin, Nelson, and Rowley (1976); and Ekren and others (1971). The Bandelier Tuff of the Jemez Mountains, N. Mex., described by Smith (1960) and Ross and Smith

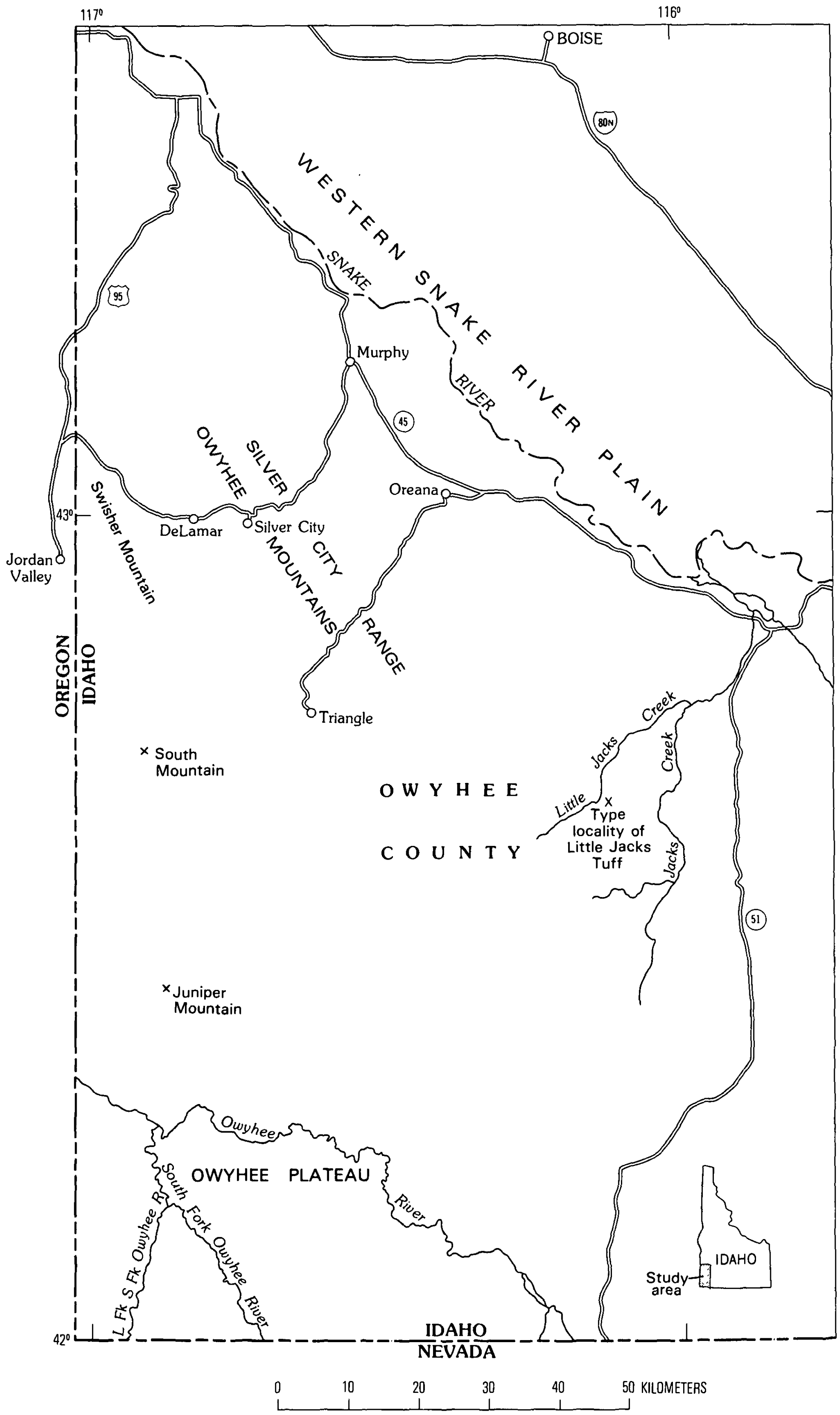

FIGURE 1.—Index map of study area, western Owyhee County, Idaho.

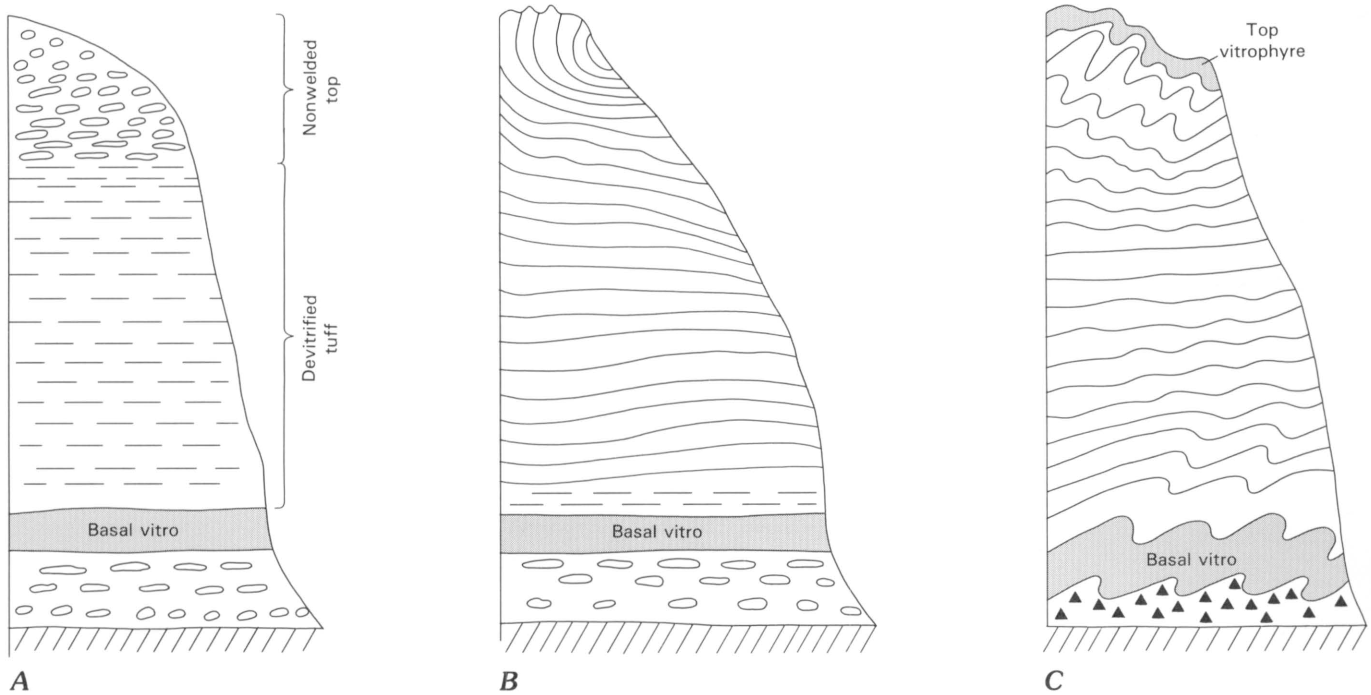

FIGURE 2.—Diagrammatic sketches of ash-flow tuff and rhyolite lava cooling units. *A*, Densely welded ash-flow tuff cooling unit without flow layering. Ellipses, partly flattened pumice fragments; dashed lines, well-flattened pumice fragments. *B*, Flow-layered, densely welded ash-flow tuff cooling unit. Solid lines, flow layers; note that in this hypothetical example flattened pumice fragments (dashed lines) are recognizable for a short interval above basal vitrophyre. *C*, Rhyolite lava cooling unit. Solid triangles, glassy flow-breccia part of basal vitrophyre.

(1961) comprises a colder sequence than the hypothetical cooling unit shown in figure 2*A* but, nevertheless, shows similar zonation patterns.

A cooling unit like that shown diagrammatically in figure 2*A* is defined by Smith (1960, p. 795–841) as an ash flow or a series of flows that were emplaced in close enough succession so that "they cooled virtually simultaneously or in continuum over an extended period of time.*** A cooling unit is *simple* if it exhibits the zonation of a single flow unit, or *compound* if the zonal pattern deviates from that expectable in a single flow." The ash-flow tuff cooling unit (fig. 2*A*) contains zones and zonal variations that are not present in lava flows. The lowest zone consists of partially welded or nonwelded tuff that is characterized by pumice fragments that are only slightly flattened or equant, and these are enclosed in a matrix of ash (glass shards). This tuff grades upward into rock that contains distinctly flattened pumice clasts; shards in the matrix commonly are still readily visible with a hand lens. In high-temperature ash-flow tuffs (Byers and others 1976; Ekren and others, 1980), this partially welded rock grades upward in a vertical distance of a few meters or less into dense vitrophyre, which most commonly is black or shades of gray. The vitrophyre may have well-flattened pumice clasts or it may not. In some vitrophyres, the pumice clasts and shard matrices were completely destroyed by melting or fusing during the welding process and the melted product then chilled to form homogeneous glass. In these vitrophyres, neither pumice nor shards are visible in outcrop or in thin section because they no longer exist. The basal vitrophyre (so termed to avoid confusion with the upper vitrophyre, see next paragraph) in turn, grades upward into devitrified (stony) rock in which flattened pumice fragments give the rock a distinctive eutaxitic structure—a structure that is quite unlike the flow-layering characteristic of lava flows. The flattened fragments are shown diagrammatically by dashed lines in figure 2*A*. In many welded tuffs, however, the flattened pumice fragments may be so highly stretched that they appear as thin wisps or delicate laminae. The amount of flattening of the pumice fragments in all welded tuffs is a function of the degree of welding, but the distortion of pumice fragments to thin wisps and laminations is primarily a function of the amount of flowage (mass movement) that occurred prior to final consolidation of the tuffs.

The devitrified rock in some densely welded tuff cooling units is overlain by, or "capped" with, an upper or top vitrophyre (not shown in figs. 2*A*, *B*), that, in turn, is overlain by partially welded vitric tuff that grades upward into nonwelded tuff. More often, however, the devitrified rock grades upward into less densely welded porous tuff that contains abundant tiny vapor-phase crystals (Smith, 1960). The vapor-phase zone thence grades upward into vitric partially welded or nonwelded ash (Rowley, 1975).

The welded tuff cooling unit just described is not easily confused with a lava flow, especially if all the tuff zones are present. The lava flow does, however, have some features in common with the densely welded ash-flow cooling unit. It commonly has a basal black or gray vitrophyre, a devitrified interior, and a glassy top (fig. 2*C*). In contrast to the welded tuff, however, the lava-flow cooling unit contains no rock that can be confused as ash and is, in most examples, flow layered from base to top. Typically, it is flow brecciated at base and top. Thus, the typical rhyolite lava flow is a much different type of rock unit than the fairly common ash-flow tuff cooling unit shown diagrammatically in figure 2*A*.

Distinguishing between a welded tuff and a lava flow becomes a problem only when extremely hot tuffs, as previously alluded to, have moved en masse during the welding process. This movement creates flowage textures that are indistinguishable from lava-flow textures. The en masse movement occurs when hot ash flows are deposited on irregular terrains and most important, it occurs when extremely hot ash flows are deposited over any kind of terrain. Apparently, when the latter tuffs avalanche from the eruption column they start to coalesce to viscous liquids while still moving outward (away from) the eruption column.

Many welded-tuff cooling units have been described that have flowage textures similar to lavas. Examples of the latter include the tuff of Wagontire Mountain in Oregon (Walker and Swanson, 1968), the Grouse Canyon Member of the Belted Range Tuff in southern Nevada (Hoover 1964; Sargent, Noble, and Ekren, 1965), and certain tuffs of Precambrian age in southeastern Missouri (Anderson 1970). Many others have been described. All these described units, however, are recognizable as welded tuffs because they at least have vitroclastic zones at their bases. These zones commonly include partially welded tuff at ultimate base that grades upward into basal vitrophyre that displays well-flattened pumice fragments; and thence upward into devitrified tuff that not uncommonly also has well-flattened pumice fragments in a short interval directly above the vitrophyre. These relationships are shown diagrammatically in figure 2*B*.

Easily seen when comparing figure 2*A* with 2*B*, is that with increasing eruption temperatures the final product of extremely hot ash-flow tuff eruptions could well be a rock unit that is virtually identical to figure 2*C*—a classic rhyolite lava flow. For the most part, the cooling units that are described in this report are like those in figure 2*C*, and have all the characteristic structures and textures of classic lava flows including, in many exposures, flow-brecciated bases. They differ, however, in one most important way—they are distributed over many thousands of square kilometers. Rhyolite lava flows, in contrast, rarely are distributed over more than a few square kilometers; commonly they are as thick as they are broad.

SIGNIFICANCE OF BASAL FLOW BRECCIA

Because rhyolite lavas (and also intermediate lavas) are viscous, they rarely occur without glassy flow breccia at base. This association is due to the fact that the lavas move so slowly that their outer margins chill, and as the lavas continue to move, the chilled margins are broken and overridden by the liquid interiors. The product of this breakage and overriding is basal flow breccia. Mapping of several thousand square kilometers of volcanic terrain in southern, central, and western Nevada by the senior author has shown that rhyolite lavas rarely occur without a few meters of flow breccia at base, even in close proximity to their vents.

Most ash flows, in contrast to rhyolite lavas, were emplaced at speeds of 100 km/h (kilometers per hour) or faster (Smith, 1960). This rapid emplacement, coupled with the chilling of the ash against the cold ground, precluded (for most documented ash-flow tuffs) the development of any marginally chilled densely welded fraction at the bases, flanks, or tops that subsequently could be broken to form flow breccia. The bases of "typical" ash-flow cooling units, in fact, are marked by several meters of nonwelded or partially welded tuff that under no conceivable circumstances could ever become flow brecciated. The basal material simply does not have the mechanical strength necessary to break into coherent blocks. Atypical ash-flow tuff cooling units, however, have recently been described that are densely welded from base to top. The bases of these tuffs are marked by homogeneous black vitrophyres (Proffett and Proffett, 1976; Ekren and others, 1980). These vitrophyres do have the mechanical strength necessary to break into coherent blocks. Although no basal flow breccias were described by the authors just cited, the occurrences of these tuffs are significant because they represent a type of hot cooling unit that is merely one step away from the tuffs described in the present report. Stated another way, the knowledge that ash-flow tuffs can and do become densely welded through their basal parts indicates that post-vitrophyre en-masse movements of a still-mobile overlying sheet could easily disrupt the lowermost chilled fraction and cause a flow breccia to form. That this does, indeed, happen is indicated by numerous basal breccias of ash-flow tuff cooling units in southwestern

Idaho. As will be described on later pages, some of these breccias contain abundant blocks of densely welded tuff derived mostly from disrupted vitrophyre. Brecciation of some of the flows probably is due to incipient landsliding that occurred after the base of the sheet was chilled, but for many of the tabular sheets the cause of the brecciation must have been en-masse movement that occurred at the same time the ash was welding and the basal part was being chilled.

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TOPOGRAPHIC AND GEOLOGIC SETTING

The Owyhee Mountains and Owyhee Plateau form the highlands that border the western Snake River Plain on the southwest (fig. 1.; pl. 1). The northern, mountainous part is underlain by Cretaceous granitic rocks and is veneered by Miocene, and, locally, by Oligocene and Eocene volcanic rocks. The granitic terrane reaches altitudes of about 2,500 m, and available evidence indicates that it has been mountainous since at least Miocene time (McIntyre, 1972).

The granitic rocks exposed in the Owyhee Mountains are chiefly granodiorite and quartz monzonite, but locally they include large masses of granite and porphyritic diorite or granodiorite. Near South Mountain (pl. 1) the granitic rocks are bordered by hornblende gabbro and roofed by metasedimentary rocks of pre-Cretaceous age (Sorenson, 1927; Bennett, 1976). We concur with Taubeneck (1971) and earlier workers (for example, Lindgren, 1900) that the granitic rocks of the Owyhee Mountains are an integral part of the Idaho batholith. A deep drill hole at the edge of the western Snake River Plain that bottomed in granitic rock tends to confirm this interpretation (McIntyre, 1979). Several Cretaceous potassium-argon ages for the granitic rocks in the Owyhee Mountains have been determined that range from about 87 to 64 m.y. (Armstrong, 1975). Eocene intermediate lavas and quartz latite ash-flow tuffs that were correlated with the Challis Volcanics by Axelrod (1968) are locally exposed 38 km to the east of South Mountain. One of these ash-flow tuffs yielded a K-Ar age of 44.7 ± 0.8 m.y. (Armstrong and others, 1980).

The Cretaceous granitic rocks and the locally preserved Eocene volcanic rocks form the eroded surface upon which the relatively restricted Oligocene and the more widely distributed Miocene volcanic rocks were erupted. The Oligocene sequence consists of a local accumulation of olivine basalt and andesite that is chemically dissimilar to the overlying Miocene rocks (table 1). The Oligocene rocks contain olivine or pyroxene phenocrysts or both (table 1) and yield a K-Ar age of 30.6 m.y. (middle Oligocene, table 2).

The Oligocene rocks and their granitic substrate are unconformably overlain by widespread Miocene lava flows of interbedded olivine basalt and latite (table 1). A basalt from this sequence collected by Pansze (1975) yielded a K-Ar age of 16.6 m.y. (17 m.y. using constants of table 2). In the Silver City–De Lamar area, the basalt-latite sequence is capped and intruded by rhyolite lavas[1], ash flows, domes, and dikes, with K-Ar ages that average about 16 m.y. (Pansze, 1975; Armstrong, 1975; this report, tables 2, 3). Silver- and gold-bearing veins were emplaced during this episode of rhyolitic volcanism, and these veins supported a major mining boom, chiefly in the late 1800's and early 1900's (Lindgren, 1900; Piper and Laney, 1926; Asher, 1968). The mineralized area at De Lamar is now the site of a large open-pit silver mine operated by Earth Resources Corporation. In Reynolds Basin, north of the Silver City Range, basin-fill sedimentary rocks, including diatomite and siliceous tephra, intertongue with the upper part of the basalt-latite sequence. Near the top of the sedimentary sequence at the northern end of Reynolds Basin is a pumice-rich subaqueous pyroclastic flow that was probably emplaced during eruption of the rhyolites in the Silver City–De Lamar area.

[1]The rhyolites of the Silver City–De Lamar area and others that are mentioned in this section will be described in considerable detail on later pages.

Beginning about 11 m.y. ago, quartz-latite and rhyolite ash flows were erupted from centers located within the current western Snake River Plain area (fig. 3). These volcanic units flowed into the Reynolds Basin area and filled paleocanyons cut in older rocks of the Owyhee Mountains. The units include the Jump Creek Rhyolite of Kittleman and others (1965), the tuff of Wilson Creek, and the tuff of Browns Creek.

The Owyhee Plateau, south of the Owyhee Mountains, is a bleak, windswept tableland whose major streams occupy deep canyons carved into the plateau surface. Juniper Mountain rises as a low eminence above the general level. The plateau is underlain by rhyolitic rocks, ranging in age from 13.8 to 9.4 m.y., that are the principal subject of this paper. The rhyolites in turn, are overlain by widespread, but generally thin (mostly <100 m thick) olivine basalt lavas and interbedded sedimentary rocks that have been correlated with the Banbury Basalt of Malde, Powers, and Marshall (1963, and our table 1).

High-angle faults dominate the structure of the Owyhee Mountains and Plateau. The faults consist of four sets: an oldest set that strikes northeast, that offsets rocks dated at 44.7 m.y., and that is intruded by dikes dated at 26 m.y.; a second set that strikes north to northwest and that is intruded by rhyolite dikes dated at 16 m.y.; a third set that strikes northwest and west-northwest and that borders the present-day southwestern margin of the western Snake River Plain (it started to form prior to 16 m.y. ago and has continued into Holocene time); and a fourth set that strikes east and that occurs along the Idaho-Oregon State line.

The north- to northwest-striking faults that are intruded by 16-m.y.-old dikes extend southward into Nevada and have their greatest displacement near the Nevada State line in the Duck Valley Indian Reservation (pl. 1). The valley there is a large graben, controlled on the east andwest flanks by a series of normal faults that drop the Banbury Basalt several hundred meters into the graben-valley. Displacements along these faults diminish northward, where the faults form a series of small horsts and grabens; throws there rarely exceed a few tens of meters. The belt of faulting is deflected westward as granitic outcrops at the south end of the Owyhee Mountains (Silver City Range) are approached; it then passes west of the main mass of granitic rocks, narrowing as it passes between the Silver City Range and the granitic rocks of South Mountain. Because this entire area is probably underlain by granitic rock (see following discussion), the deflection of the belt of faulting around the Silver City Range and South Mountain must indicate that these localities are underlain by relatively thicker masses of granitic rock. Farther north, the fault belt forms the west margin of the Owyhee Mountains where the faults have throws of 100 m or more. North of the northernmost granitic outcrops, the fault belt swings to a northeast orientation before intersecting the faults that bound the margin of the western Snake River Plain. Location of this belt of north-northwest high-angle faults clearly is controlled by the thicker masses of granitic rock that underlie the Owyhee Mountains.

The other belt of northwest-trending faults occurs along the southwestern margin of the western Snake River Plain and virtually forms that margin. The belt is fairly broad, however, and no single fault of major displacement forms a sharp boundary at the margin. Aggregate basinward downdropping of key stratigraphic units across this fault belt is approximately equivalent to that which would result from a 10° or less basinward dip if faults were not present (see Young and Whitehead, 1975, fig. 5; Ekren and others, 1981). A major rift zone marked by a series of basalt vents of early Quaternary age that are alined along the Snake River about 25 km northeast of the southwestern margin of the plain (Malde, 1965; not shown on our pl. 1), parallels the northwest-trending fault zone. The amount of stratigraphic displacement along this rift is unknown because the relations there are obscured by basalt lavas of late Quaternary age that are not affected by the faulting.

The age of the northwest-trending fault belt is not known with certainty, but the fact that along the southwestern margin of the plain several northeast-flowing streams had carved deep canyons into the northeast flank of the Silver City Range prior to 16 m.y. ago suggests strongly that the western Snake River Plain and its boundary faults were well expressed by that time. At least one rhyolite ash-flow tuff flowed down these canyons from a vent in the Silver City Range; another ash-flow tuff flowed up-canyon from a source in the plain (see later pages). Fault scarps in Quaternary alluvial fans at the plain margin in the vicinity of Little Jacks Creek (Ekren and others, 1981) suggest that, locally, the marginal faults still are active. Elsewhere along the plain margin, evidence for Quaternary faulting is absent.

East-west fault zones, prominent in eastern Oregon (Walker and Repenning, 1966), extend into Idaho, and terminate a few kilometers east of the Oregon-Idaho State line. One of these fault zones is in the trough between South Mountain and Juniper Mountain; a second, expressed in Idaho as a series of small east-west striking normal faults, is near lat 43° N. The latter zone coincides with a lineament visible on Landsat images that extends into the De Lamar–Silver City area. The De Lamar Mountain silver-gold mine, currently active,

TABLE 1.—*Chemical analyses and CIPW norms for mafic and intermediate volcanic rocks, Owyhee Mountains, Idaho*

[All analyses but one (HN-1) by X-ray fluorescence spectroscopy (analysts: D. Hopping, R. Villarreal, and K. Wong) with chemical determinations of FeO, H_2O^+, H_2O^-, and CO_2 by P. Klock and S. Neil. HN-1 is standard rock analysis by Dorothy F. Powers, quoted from McIntyre (1972). All values in weight percent]

Sample No.--	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Field No.---	OM-53	OM-57	OM-62	OM-69	HN-1	OM-59	OM-61	OM-60	OM-43-B	OM-54	OM-12	OM-30	OM-39-B	BE-2
						Chemical composition								
SiO_2--------	48.30	54.89	57.81	57.10	47.28	47.92	54.08	55.29	67.05	65.56	46.81	46.45	46.40	48.33
Al_2O_3-------	15.94	17.39	17.03	17.43	15.34	15.81	14.80	15.50	13.33	13.86	16.15	15.93	15.77	16.38
Fe_2O_3-------	3.33	4.22	4.30	3.57	2.64	3.84	1.88	1.96	2.24	1.01	1.90	1.65	2.16	3.48
FeO---------	6.67	2.44	1.76	2.46	8.97	7.52	9.26	6.23	3.16	3.59	10.82	10.70	10.85	7.23
MgO---------	7.47	4.09	3.33	4.50	8.29	7.78	3.82	5.79	0.96	2.73	7.28	7.76	7.83	8.15
CaO---------	8.42	6.94	6.07	6.42	10.00	9.77	7.14	7.45	2.96	3.58	9.71	10.17	10.24	11.04
Na_2O--------	3.48	4.33	4.39	4.10	2.69	2.80	2.89	2.91	3.00	2.38	2.48	2.70	2.59	2.39
K_2O---------	1.13	1.79	2.05	1.57	0.41	0.44	1.93	1.43	3.68	4.42	0.42	0.32	0.47	0.37
H_2O^+--------	1.30	0.60	0.66	0.88	0.98	0.48	1.22	1.12	1.56	1.98	0.47	0.53	0.27	0.44
H_2O^---------	0.79	1.08	1.29	0.64	0.70	0.71	0.65	0.54	0.84	0.30	0.74	0.72	0.22	0.30
TiO_2--------	2.05	1.05	1.01	0.81	1.92	1.81	2.42	1.11	0.85	0.45	2.42	2.02	2.37	1.29
P_2O_5--------	0.71	0.44	0.49	0.32	0.27	0.26	0.42	0.26	0.17	0.06	0.36	0.37	0.45	0.18
MnO---------	0.15	0.12	0.09	0.10	0.19	0.16	0.18	0.13	0.00	0.00	0.18	0.19	0.25	0.17
CO_2---------	0.22	0.03	0.03	0.05	0.17	0.06	0.03	0.05	0.03	0.03	0.08	0.04	0.13	0.21
Sum-------	99.97	99.42	100.32	99.98	99.85	99.37	100.72	99.80	99.83	99.96	99.84	99.55	100.01	99.97
						Normative composition								
Q----------	0	5.19	9.38	8.83	0	0	7.20	7.71	28.16	22.22	0	0	0	0
C----------	0	0	0	0	0	0	0	0	0	0	0	0	0	0
or----------	6.81	10.82	12.31	9.42	2.47	2.65	11.53	8.61	22.32	26.73	2.52	1.92	2.79	2.20
ab----------	30.08	37.48	37.76	35.24	23.19	24.12	24.73	25.09	26.04	20.62	21.28	23.24	22.01	20.38
an----------	25.06	23.25	21.04	24.90	29.09	29.81	21.95	25.48	12.36	14.42	32.13	30.94	30.15	33.13
di-wo-------	4.78	3.69	2.55	2.09	7.74	7.28	4.55	4.23	0.58	1.32	5.77	7.38	7.14	8.16
di-en-------	3.28	3.19	2.21	1.76	4.70	4.80	2.02	2.55	0.28	0.73	3.09	3.98	3.92	5.33
di-fs-------	1.13	0	0	0.07	2.61	1.97	2.51	1.45	0.29	0.54	2.49	3.15	2.96	2.26
hy-en-------	6.71	7.23	6.22	9.62	7.27	10.77	7.60	12.15	2.18	6.23	8.22	3.16	4.01	11.46
hy-fs-------	2.31	0	0	0.36	4.04	4.42	9.42	6.93	2.32	4.59	6.64	2.50	3.02	4.85
ol-fo-------	6.31	0	0	0	6.35	2.92	0	0	0	0	4.96	8.77	8.17	2.56
ol-fa-------	2.39	0	0	0	3.89	1.32	0	0	0	0	4.41	7.65	6.79	1.20
mt----------	4.93	5.33	3.09	5.26	3.90	5.67	2.76	2.90	3.33	1.50	2.79	2.43	3.15	5.09
hm----------	0	0.64	2.22	0	0	0	0	0	0	0	0	0	0	0
il----------	3.98	2.04	1.95	1.56	3.71	3.50	4.65	2.15	1.66	0.88	4.66	3.90	4.52	2.47
ap----------	1.72	1.07	1.18	0.77	0.65	0.63	1.01	0.63	0.41	0.15	0.86	0.89	1.07	0.43
cc----------	0.51	0.07	0.07	0.12	0.39	0.14	0.07	0.12	0.07	0.07	0.18	0.09	0.30	0.48

is at the intersection of this lineament and the north-northwest trending belt of faults, previously described, that extends northward from Duck Valley. An additional east-trending fault intersects the northwest set at the Flint district south of De Lamar. In both the De Lamar and Flint districts, Piper and Laney (1926) deduced that some lateral slip had occurred along the east-trending fault zones. These faults with their probable oblique slips are inferred to be surface expressions of major east-west trending crustal discontinuities. As such, they appear to be the same type of structures as those described in central Nevada by Ekren and others (1976), and in Utah and eastern Nevada by Rowley and others (1978), and they probably have a long and varied history.

SILICIC VOLCANISM AND THE SNAKE RIVER PLAIN

Several investigators, including Bonnichsen and others (1975), have recognized that the western and eastern segments of the Snake River Plain are best treated as separate entities. The western plain is about half as wide as the eastern, and, over most of its length, is rather sharply separated from the bordering highlands by fault zones. The fault zone that forms the northeastern margin of the western plain is narrow and abrupt; the zone on the southwest is broad, and no single fault exhibits major displacement. The eastern plain, in contrast, is broad, and its borders with the surrounding highlands are not marked by visible faults

TABLE 1.—*Chemical analyses and CIPW norms for mafic and intermediate volcanic rocks, Owyhee Mountains, Idaho*—Continued

SAMPLE DESCRIPTIONS AND LOCALITIES

[Listed by sample number. (Field number in parentheses)]

1 (OM–53). Oligocene K-rich basalt with prominent olivine phenocrysts at base of predominantly andesitic sequence on upper Salmon Creek near northwest corner of sec. 4, T. 2 S., R. 4 W. Matrix is trachytic, contains plagioclase, clinopyroxene, brown "brittle mica" with small axial angle (2V) and apatite(?) needles. Reverse magnetic polarity.

2 (OM–57). Oligocene andesite; lowest platy flow of predominantly andesitic sequence of upper Salmon Creek; rests on basalt flow of sample 1 (above) on spur in northeast corner of sec. 5, T. 2 S., R. 4 W. Contains brown olivine microphenocryst pseudomorphs and clinopyroxene microphenocrysts in a very fine trachytic matrix of plagioclase, clinopyroxene, opaque oxides, and apatite(?) needles. Probable weak reverse magnetic polarity.

3 (OM–62). Oligocene andesite; part of highest exposed flow sequence in predominantly andesitic sequence of upper Salmon Creek; on east-facing slope of ridge in NE¼SE¼ sec. 6, T. 2 S., R. 4 W. Contains prominent quartz xenocrysts, opaque pseudomorphs of mafic phenocrysts, and clinopyroxene microphenocrysts in a very fine trachytic matrix of plagioclase, clinopyroxene, opaque oxides, and brown "brittle mica." Probable weak reverse magnetic polarity.

4 (OM–69). Oligocene andesite; prominent plug exposed on Hardtrigger Creek east of Shares Basin, near southwest corner of sec. 3, T. 1 S., R. 4 W. Abundant finely granular opaque pseudomorphs after pyroxene plus a few grains relict clinopyroxene in very fine trachytic matrix of plagioclase, clinopyroxene, opaque oxides, and minor interstitial glass alteration-product.

5 (HN–1). Basalt; part of Hoot Nanny Olivine Basalt of McIntyre (1972) exposed in bottom of dry wash 1,006 m N. 59° E. from the southwest corner of sec. 32, T. 2 S., R. 3 W. Ophitic, with plagioclase, clinopyroxene, olivine, opaque oxides, and minor interstitial glass and glass alteration-products. Sample locality near top of unit and near a polarity transition; basalts lower in unit have reverse polarity. Sample locality has remanent component too weak for field measurement; overlying latitic rocks and Toll Gate Olivine Basalt exposed elsewhere (underlies latitic rocks) have normal polarity.

6 (OM–59). Basalt; part of the Soldier Cap Olivine Basalt of McIntyre (1972) exposed on Wilson Peak in SW¼ sec. 30, T. 1 S., R. 3 W. Porphyritic, containing zoned olivine phenocrysts with iddingsite cores or intermediate zones and plagioclase laths in slightly flow-alined matrix of plagioclase microlites, granular clinopyroxene, and opaque oxides. Reverse magnetic polarity.

7 (OM–61). Andesite; part of Toll Gate Olivine Basalt of McIntyre (1972). Collected from exposures on east side of Reynolds Creek south of stream gaging station in SW¼ sec. 24, T. 3 S., R. 4 W. Fine blocky jointed, glassy; opaque oxide-charged glass (nearly opaque in thin section) contains sparse quench-crystallized plagioclase, olivine, and clinopyroxene. Normal magnetic polarity.

8 (OM–60). Andesite; part of Toll Gate Olivine Basalt of McIntyre (1972). Collected from exposures at gaging station in south-central sec. 13, T. 4 S., R. 4 W. Intersertal, with pale-brown glass between grains of plagioclase, clinopyroxene, orthopyroxene, opaque oxides, and clinopyroxene coronas after completely resorbed quartz xenocrysts. Normal magnetic polarity.

9 (OM–43–B). Quartz latite; part of lower latite unit of McIntyre (1972). Black, glassy portion of hogback-forming flow north of Reynolds-Murphy road in SW¼ sec. 32, T. 2 S., R. 3 W. Rests on friable vitric tuff; toward north replaced laterally by devitrified rock that rests on fused, bedded vitric tuff. Contains 5–10 percent phenocrysts as large as 1 mm, most of which consist of plagioclase-pigeonite clusters, but clusters of orthopyroxene jacketed by clinopyroxene and single crystals of clinopyroxene with large 2V also are present. Some clusters have glassy interstitial matrix different from rock matrix, which contains glass, plagioclase, clinopyroxene, and opaque oxides. Normal magnetic polarity.

10 (OM–54). Quartz latite; part of upper latite unit of McIntyre (1972). Black, glassy, blocky to fine columnar lava at Coal Bank, near southwest corner of sec. 18, T. 2 S., R. 4 W. that contains round quartz and plagioclase xenocrysts, clinopyroxene and orthopyroxene microphenocrysts, and irregular clots (white on the outcrop) that are very fine intergrowths of clinopyroxene, plagioclase, and brown glass. Matrix is very pale brown glass filled with random network of plagioclase and clinopyroxene prisms. Opaque oxides are nearly absent. Apparent normal magnetic polarity.

11 (OM–12). Basalt; intrusion into basalt breccia exposed in dry wash northwest of Murphy in SW¼NW¼ sec. 19, T. 2 S., R. 2 W. Ophitic, intersertal; crystals of plagioclase, clinopyroxene, olivine, with interstitial opaque oxides and altered brown glass.

12 (OM–30). Basalt; in dike in feeder complex for mesa-capping pillow breccia north of Murphy northeast of triangulation station 3555; sample from SE¼NE¼ sec. 6, T. 2 S., R. 2 W. Pilotaxitic, intersertal; random plagioclase laths with adhering clinopyroxene granules; scrattered grains of altered olivine; interstices filled with opaque-charged altered glass.

13 (OM–39–B). Basalt; blocky weathering, diktytaxitic mesa-capping flow immediately north of Reynolds-Murphy road, in NW¼SE¼ sec. 1, T. 3 S., R. 3 W.; contains plagioclase, clinopyroxene, olivine, and opaque oxides, with local relict interstitial altered glass.

14 (BE–2). Banbury Basalt; lower of two flows at headwaters of Battle Creek in sec. 36, T. 9 S., R. 1 E.; intergranular. Plagioclase, 54 percent; clinopyroxene, 24 percent; olivine, 10 percent; opaque oxides, 2 percent; interstitial matrix, 10 percent.

TABLE 2.—*Potassium-argon ages and analytical data on rocks from Owyhee County, Idaho, and Malheur County, Oregon*

[Avg., average; mol/g, moles per gram; m.y., million years. Constants: $^{40}K\lambda_{\epsilon}$ 0.581×10^{-10}/yr; $^{40}K\lambda_{\beta}$=4.962×10^{-10}/yr. Atomic abundance: K^{40}=1.167×10^{-4}. Sample OC–77–BE–96 analyzed by G. Brent Dalrymple; all others by R. F. Marvin, H. H. Mehnert, and V. M. Merritt]

Lab. No.	Field No.	Material dated	K_2O percent (average weight percent)	$^{40}Ar_{rad}$ (10^{-10} mol/g)	$^{40}Ar_{rad}$ (percent)	Age (m.y. ± 2)
D2767S	BE-27	Sanidine-----	4.14 (2 analyses)-----	0.8263	80	13.8±0.5
D2768S	BE-574	Sanidine-----	5.55 (2 analyses)-----	1.113	87	13.9±0.5
D2769P1	OM-5	Plagioclase--	1.57 (2 analyses)-----	0.3571	63	15.7±0.5
D2770S	LG-2	Sanidine-----	6.61 (2 analyses)-----	1.515	82	15.8±0.6
D2771P1	OM-12	Plagioclase--	0.23 (4 analyses)-----	0.0269	30	8.1±1.3
D2773R	OM-57	Whole rock---	1.71 (2 analyses)-----	0.7591	85	30.6±1.0
7A231	OC-77-BE-96	Obsidian-----	5.18±0.01 (4 analyses)	1.19	84.3	16.0±0.3
7A232				1.20	51.4	

SAMPLE DESCRIPTIONS AND LOCALITIES

[Listed by field number]

BE–27. Sanidine from hydrated basal vitrophyre of lower-lobes tuff of Juniper Mountain; contains 27 percent phenocrysts that consist of 18 percent quartz, 66 percent sanidine, 10 percent plagioclase, 4 percent pigeonite, and 1 percent opaque oxides. Sample site is at lat 42°34′39″ N., long 116°39′12″ W. (NE¼ sec. 11, T. 10 S., R. 3 W.), Owyhee County, Idaho.

BE–574. Sanidine from hydrated vitrophyre at base of flow-layered part of upper-lobes tuff of Juniper Mountain; contains 17 percent phenocrysts that consist of 45 percent quartz, 44 percent sanidine, 3 percent plagioclase, 6 percent altered mafic minerals, and 1 percent opaque oxides. Sample site is at lat 42°27′ N., long 116°49′ W. (SW¼ sec. 21, T. 11 S., R. 4 W.), Owyhee County, Idaho.

OM–5. Plagioclase from flow-banded rhyolite of Black Mountain; contains 7 percent phenocrysts that consist of plagioclase and hypersthene. Sample site is at lat 43°07′55″ N., long 116°39′51″ W., (NE¼SW¼ sec. 26, T. 3 S., R. 3 W.) on saddle of ridge west of Brunzell Spring, Owyhee County, Idaho.

LG–2. Sanidine from hydrated basal vitrophyre of Leslie Gulch Tuff Member; contains 21 percent phenocrysts that consist of quartz, sanidine, and clinopyroxene. Sample site is at lat 43°26′ N., long 117°08′ W.; first west-side canyon south of the mouth of Succor Creek canyon, Malheur County, Oreg.

OM–12. Plagioclase from ophitic basalt of Murphy area. Sample site is at lat 43°14′01″ N., long 116°37′43″ W. (SW¼NW¼ sec. 19, T. 2 S., R. 2 W.), Silver City 15-minute topographic quadrangle, Owyhee County, Idaho.

OM–57. Trachytic andesite that contains tiny phenocrysts of clinopyroxene and olivine pseudomorphs in a fine-grained holocrystalline groundmass of plagioclase, clinopyroxene, and opaque oxides. Andesite is part of the Salmon Creek Volcanics of McIntyre (1972). Sample site is at lat 43°17′05″ N., long 116°49′43″ W. (NE¼ sec. 5, T. 2 S., R. 4 W.), Sands Basin 15-minute topographic quadrangle, Owyhee County, Idaho.

OC–77–BE–96. Obsidian Apache tears from basal part of nearly aphyric rhyolite of the Silver City Range. Sample site is at Toy Pass on road between Oreana and Triangle at lat 42°54′10 N., long 116°32′45″ W., Owyhee County, Idaho.

(Armstrong, Leeman and Malde, 1975). Moreover, the eastern plain is coincident with a linear structural trend that extends beyond the plain itself, into Montana on the northeast and Nevada on the southwest (Christiansen and Lipman, 1972; Mabey and others, 1978). We designate informally the southwestern segment of this linear feature that includes the Silver City Range and Owyhee Plateau within Idaho, Oregon, and northern Nevada as the "eastern Snake River Plain trend." This zone is expressed clearly both on Landsat images and on the regional aeromagnetic map. On both images and map, there is no discontinuity where the topographic lowland of the eastern plain gently rises to become the highlands of the Owyhee Plateau. Landsat images, the geologic map of Elko County, Nev. by Hope and Coats (1976), and our mapping show that the highlands are a volcanic plateau, underlain chiefly by rhyolitic rocks, but veneered by widespread flows of basalt. The plateau is only slightly modified by basin-range faulting. The basalt, called Banbury Basalt by several authors, including Ekren and others (1978a; 1981), is an olivine tholeiite whose major-element chemistry closely resembles that of basalt within the Snake River Plain lowland. Both the Landsat image and the aeromagnetic

TABLE 3.—*Potassium-argon ages for rocks from Owyhee region, Idaho, recalculated using constants in table 2*

[Data from Armstrong (1975). cm³/g, cubic centimeters per gram; m.y., million years]

Sample No.	Material dated	Unit	Latitude north	Longitude west	Potassium (weight percent)	$^{40}Ar_{rad}$ (10^{-6} cm^3/g)	Age reported (m.y.)	Recalculated age (m.y.)
YU-PZ(A325)	Sanidine--	Rhyolite of--- Silver City Range.	43°01'05"	116°51'35"	4.21, 4.18	2.64	15.7±0.3	16.1±0.3
YU-PZ(A98)	--do------	----do--------	42°58'55"	116°45'05"	7.32, 7.36	4.58	15.6±0.3	16.0±0.3
YU-PZ(A26)	Whole rock	----do--------	43°00'15"	116°47'55"	3.89, 3.87	2.41, 2.44	15.6±0.2	16.0±0.2
YU-PZ(A345)	Biotite---	----do--------	43°00'05"	116°45'00"	6.73, 6.81	4.25, 4.33	15.8±0.3	16.2±0.3
YU-PZ(A45)	Whole rock	----do--------	43°00'30"	116°46'45"	4.09, 3.99	2.43, 2.62	15.6±0.3	16.0±0.3
YU-PZ(A34)	Biotite---	----do--------	42°59'30"	116°48'20"	6.06, 6.04	4.20, 4.18	17.3±0.3	17.8±0.3
YU-WT268	--do------	Granitic rocks of South Mountain.	42°47'10"	116°55'40"	7.00, 7.06	12.85	45.2±1.4	46.5±1.4
YU-WT268	Hornblende	----do--------	42°47'10"	116°55'40"	0.905, 0.956	1.873	49.7±1.5	51.1±1.5
YU-PZ(A56)	Muscovite-	Granitic rock-	43°00'50"	116°43'00"	8.44, 8.41	22.88	66.8±1.3	68.6±1.3
YU-PZ(A346)	--do------	----do--------	43°01'30"	116°42'10"	8.29, 8.32	20.94	62.1±1.2	63.8±1.2

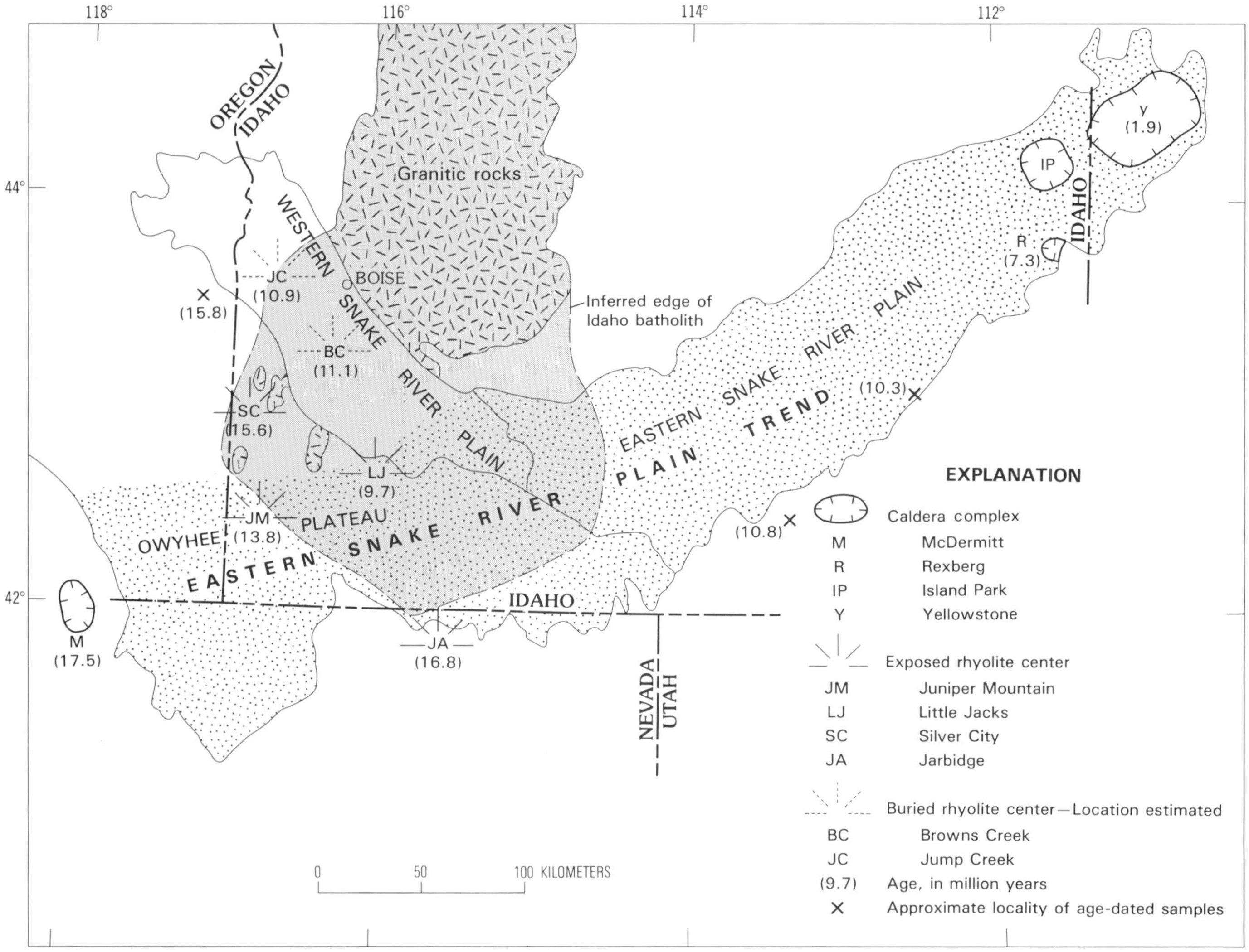


FIGURE 3.—Tectonic diagram showing eastern Snake River Plain trend (stippled) and locations of rhyolite volcanic centers. Modified from King and Beikman (1974). Inferred edge of Idaho batholith modified from Taubeneck (1971).

map show that the eastern Snake River Plain trend is sharply truncated toward the southwest by a northwest-trending lineament that, farther northwest, joins the Brothers fault zone of central Oregon.

The ages of inception of the two segments of the plain, as inferred from the ages of onset of silicic volcanism, differ significantly. A K-Ar age for the rhyolitic Leslie Gulch Tuff Member of the Sucker Creek Formation of Kittleman and others (1965), probably erupted from a source within the western plain, is 15.8±0.6 m.y. (table 2). About 35 km farther southeast, another rhyolitic unit exposed in the highlands bordering the plain, informally termed the rhyolite of Black Mountain in the present report, gave a K-Ar age of 15.7±0.5 m.y. (table 2). The rhyolites of the Silver City Range have yielded several K-Ar ages of about 16 m.y. (Armstrong, 1975; present report, tables 2 and 3). As mentioned previously, one of the rhyolitic units in the Silver City Range flowed down a northeast-trending paleocanyon cut in granitic rocks at the plain margin, demonstrating that, at about 16 m.y. ago, a lowland was present at the site of the present-day western Snake River Plain.

Silicic volcanism in the southwestern part of the eastern Snake River Plain trend (fig. 3) was taking place at least as early as 17.5 m.y. ago in the McDermitt volcanic center, Nevada (Rytuba and Glanzman, 1978; Laursen and Hammond, 1978, p. 18) and on the Owyhee Plateau within Idaho at about 14 m.y. at the Juniper Mountain volcanic center. However, silicic volcanism that appears to be related to or at least coincident with the subsidence of the eastern plain did not take place until about 11–10 m.y. ago. Silicic volcanism of this age, as shown in figure 3, took place over most of the length of the plain, including both eastern and western segments. This silicic volcanism appears to have been triggered by a rifting event that affected both segments simultaneously, reactivating the already formed western segment and beginning the rifting and subsidence in the eastern segment.

The presently known distribution of ages of onset of silicic volcanism within the eastern Snake River Plain does not support the hypothesis of progressive migration of activity from southwest to northeast, as earlier proposed by Armstrong, Leeman, and Malde (1975). An age of 7.5 m.y. for the onset of silicic volcanism at the Rexburg caldera complex (Glenn Embree, oral commun., 1978), which is about 70 km southwest of the Yellowstone Park caldera complex (Christiansen and Blank, 1972), is much older than would be predicted by any of the proposed progressive migration models (Armstrong, Leeman, and Malde, 1975; Suppe and others, 1975; Minster and others, 1974). These facts, together with the essential simultaneity of activity in both eastern and western segments of the plain at about 11–10 m.y., shows that the progressive migration model is not in harmony with available data. Neill (1975) and Citron (1976) also have argued that the age data do not support the progressive migration model.

Taubeneck (1971) inferred, from characteristics of scattered remnants of granitic rocks in southwestern Idaho and northern Nevada, that granitic rocks of the Idaho batholith underlie nearly all of southwestern Idaho. The thick mass of granitic rock that underlies the Silver City Range and the highlands to the north, and the isolated mass of granitic rock and gabbro at South Mountain are the best exposed and most convincing evidence in support of Taubeneck's thesis. Whether such rocks also are present in more or less undisrupted fashion beneath the Owyhee Plateau, in the area crossed by the eastern Snake River Plain trend, is conjectural. A seismic profile by Hill and Pakiser (1967, fig. 13) shows an abrupt thickening, to more than 30 km, of lower crust beneath the eastern Snake River Plain trend (fig. 3), but does not give any information about fine-scale changes in the upper crust. Magma chambers for two rhyolitic ash-flow tuff units exposed on the Owyhee Plateau were, by all indications, within this thick lower crust.

Hill and Pakiser (1967) and Hamilton and Myers (1966) inferred that granitic rocks are totally absent beneath the western Snake River Plain. As mentioned earlier, one deep drill hole has confirmed the local presence of granitic rock under the plain. How broad an area is underlain by that granitic rock is unknown; surely such rock that may be present has been highly disrupted by rifting and Tertiary intrusive activity.

STRATIGRAPHY AND PETROGRAPHY OF PRINCIPAL RHYOLITES

The principal rhyolitic rock units exposed in the Owyhee Mountains and Plateau were erupted at irregular intervals, from about 16 m.y. to about 10 m.y. ago, probably all at temperatures of at least 1000°C, from widely spaced vent areas within the Owyhee Mountains and Plateau and the western Snake River Plain. Despite this time span, the long distances between eruptive centers, and variations in composition from unit to unit, all the rhyolitic rocks have one characteristic in common—namely, features indicating high fluidity during emplacement together with internal characteristics indicating en-masse viscous lavalike flowage. The degree to which these characteristics are developed is extraordinary and may be unique to the region in which these rocks are found. Our descriptions of rock units in the sections that follow focus attention on these unique features.

RHYOLITES OF THE SILVER CITY RANGE AND ADJACENT AREAS

Flow-layered rhyolites that, for the most part, contain only a few percent small phenocrysts (table 4), form the backbone of the Silver City Range and large parts of the downdropped eastern and western flanks of the range. These rocks are the principal hosts for the silver-gold veins of the Silver City district. Age data (Armstrong, 1975; Pansze, 1975; G. B. Dalrymple, written commun., 1977; our tables 2, 3) indicate that the rocks are about 16 m.y. old and that the associated silver-gold mineralization is on the order of 16.6–15.2 m.y. old (Armstrong and others, 1980).

Field relations indicate that some of the Silver City rhyolite units grade laterally within a distance of a few kilometers from classic densely welded tuffs at or near their distal ends(?) into rocks, nearer the sources, that are flow layered from base to top; and some of these last have flow-brecciated basal vitrophyres. Most units probably were erupted from vents in and adjacent to the present Silver City Range, which is characterized by numerous feeder dikes, plugs, and extrusive domes of rhyolite (Pansze, 1975; Piper and Laney, 1926; and Bennett and Galbraith, 1975). Of interest to the present report is the fact that many of the dikes were intruded after extensive north- to northwest-trending normal faulting—especially in the De Lamar area—had occurred, thereby dating the start of normal faulting of that trend as pre-16 m.y. ago.

One of the baffling results of this study is that so few of the rhyolites in the Silver City Range can be correlated from the western flank of the mountains to the eastern flank. This lack of correlation could be due to a topographic barrier that coincided with the present topographically high outcrops of granitic rocks and basalt-latite lavas. However, there is no present indication that such a topographic barrier could have existed, because the rhyolites south of Silver City form the highest outcrops in the range; these rocks are present on the downdropped eastern flank, and they should have been capable of flowing down the western flank. Our thin-section studies show that, with the possible exception of the highest cooling unit of the tuff of Flint Creek, none of the rhyolite units in the De Lamar–Flint Creek areas are present at the top or the east flank of the Silver City Range. These rocks will be described by geographic area in four sections of the report.

ROCKS OF DE LAMAR AND FLINT CREEK

TUFF OF FLINT CREEK

Two genetically related purple and brownish-gray ash-flow tuff cooling units that are each from 30 m to as much as 90 m thick are exposed in the canyon of Flint Creek (pl. 1; tuff of Flint Creek included in map unit Tsc) in the central part of T. 6 S., R. 4 W. In these canyon exposures, the tuff rests on basaltic rocks of the basalt-latite sequence. Pansze (1975) included the upper cooling unit in his upper rhyolite map unit, and he included the lower in his quartz latite map unit.

Both units grade upward from partially welded gray vitric tuff at the base into basal vitrophyre that contains well-flattened pumice clasts, and thence upward into flow-layered purplish-gray tuff at the top in which pumice clasts are so flattened and stretched that they resemble laminations in a rhyolite lava. To the north of Flint Creek canyon, the tuff of Flint Creek is overlain by the rhyolite of the millsite, and there, only one thick cooling unit could be recognized with certainty. To the south and west, the tuff of Flint Creek is overlain by the Swisher Mountain Tuff and its close relative—the tuff of Mill Creek (see later pages). The two cooling units of the tuff of Flint Creek apparently were deeply eroded prior to extrusion of the overlying strata because both cooling units locally are missing and the Swisher Mountain Tuff rests directly on the pre-rhyolite basalt-latite sequence in outcrops west of the junction of Flint Creek and Jordan Creek. In outcrops to the north, near De Lamar, the rhyolite of the millsite rests directly on the lower cooling unit of the tuff of Flint Creek and the upper cooling unit is absent. A few kilometers still farther north, the rhyolite of the millsite rests directly on the basalt-latite lavas.

The lower quartz latite tuff of Flint Creek contains 4–7 percent phenocrysts that consist of 37–47 percent quartz; 36–53 percent plagioclase; 0–3 percent alkali feldspar; and 2–8 percent pigeonite, hypersthene, and opaque oxides (in order of decreasing abundance). All the phenocrysts are small: quartz, 1–2 mm; plagioclase, 1–3 mm; and pyroxene, 1 mm. Apatite and zircon are fairly common accessory minerals.

The upper rhyolite cooling unit (fig. 4) contains virtually the same size and abundance of phenocrysts in its basal part as does the underlying cooling unit, but its alkali feldspar content is higher and the alkali feldspar increases upward within the cooling unit. A sample taken about 20 m above the base contained 5 percent phenocrysts that consist of 44 percent quartz, 23 percent alkali feldspar, 27 percent plagioclase, 4 percent pseudomorphs after pyroxene, and trace amounts of biotite. In contrast to the lower cooling unit of the tuff of Flint Creek, the upper unit contains abundant small lithic fragments. These fragments are mostly basalt and latite but include a few clasts of granite. Where the tuff is intensely altered, the clasts are not easily recognized as such, and all the crystals in the clasts and enclosing tuff except quartz are altered.

The tuff of Flint Creek, whether consisting of one

TABLE 4.—*Chemical analyses and CIPW norms for rhyolitic rocks from the Silver City Range and vicinity, Idaho, and from Succor Creek canyon, Oregon*

[All analyses by X-ray fluorescence spectroscopy (analysts: D. Hopping, K. Wong; chemical determinations of FeO, H_2O+ H_2O^-, and CO_2 by S. Neil and P. Klock). All values in weight percent; nd, not determined]

Sample No.--	1	2	3	4	5	6	7	8	9	10
Field No.---	LG-2	BE-190	BE-683	OM-2	BE-180	OM-5	OM-42	OM-55	OM-33	BE-160C
					Chemical composition					
SiO_2--------	72.77	70.44	77.02	76.78	75.70	74.98	68.89	74.02	75.95	74.26
Al_2O_3-------	12.84	13.75	12.77	12.86	12.50	12.80	13.82	11.99	12.23	11.58
Fe_2O_3-------	0.86	2.49	0.42	0.62	1.02	1.24	1.28	1.17	1.17	1.15
FeO---------	0.67	0.79	0.76	0.23	0.10	0.54	1.67	0.13	0.10	0.76
MgO---------	0.31	0.29	<0.02	0.00	<0.02	0.03	0.33	0.13	<0.02	0.12
CaO---------	0.50	1.94	0.72	0.74	0.56	1.40	1.77	0.90	0.74	0.85
Na_2O--------	4.25	3.75	3.14	2.90	3.26	3.11	3.32	3.46	3.29	2.63
K_2O---------	3.98	4.05	5.09	5.25	5.15	4.97	4.89	5.01	5.57	5.05
H_2O^+--------	2.94	0.45	0.20	0.36	0.34	0.16	2.86	0.54	0.44	2.25
H_2O^---------	0.34	0.54	0.06	0.32	0.32	0.34	0.16	0.44	0.18	0.36
TiO_2--------	0.16	0.70	0.11	0.27	0.26	0.33	0.53	0.11	0.17	0.23
P_2O_5--------	0.02	0.18	0.04	0.04	0.03	0.06	0.13	0.04	0.05	0.06
MnO---------	0.00	0.046	0.021	0.10	0.007	0.03	0.10	0.00	0.01	0.028
CO_2---------	0.04	0.03	0.05	0.11	0.07	0.06	0.01	1.18	0.35	0.08
Sum-------	99.68	99.44	100.40	100.58	99.31	100.06	99.76	99.13	100.25	99.40
					Normative composition					
Q-----------	32.50	29.59	37.52	38.70	36.61	35.32	27.26	nd	35.13	39.22
C-----------	0.80	0.17	1.00	1.41	0.79	0.04	0.19	nd	0.38	0.59
or----------	24.40	24.31	30.04	31.05	30.85	29.50	29.87	nd	33.04	30.83
ab----------	37.30	32.22	26.53	24.56	27.96	26.43	29.04	nd	27.94	22.99
an----------	2.18	8.39	2.99	2.72	2.17	6.20	8.13	nd	1.14	3.43
hy-en-------	0.80	0.73	0.00	0.00	0.00	0.08	0.85	nd	0.00	0.31
hy-fs-------	0.27	0.00	0.90	0.00	0.00	0.00	1.36	nd	0.00	0.12
mt----------	1.29	0.68	0.61	0.29	0.41	0.89	1.92	nd	0.14	1.72
hm----------	0.00	2.06	0.00	0.42	0.75	0.63	0.00	nd	1.08	0.00
il----------	0.32	1.35	0.21	0.51	0.23	0.63	1.04	nd	0.23	0.45
ap----------	0.05	0.43	0.09	0.09	0.07	0.14	0.32	nd	0.12	0.15
cc----------	0.09	0.07	0.11	0.25	0.16	0.14	0.02	nd	0.80	0.19

or two cooling units, gradually loses its pyroclastic texture northward from Flint Creek. It becomes conspicuously flow laminated and layered and the flow-layered rock tends to weather to thin plates. In exposures 3 km south of De Lamar, where only one thick cooling unit was recognized with certainty, the devitrified rock is finely laminated where relatively unaltered, and the basal vitrophyre is also flow laminated. Where intensely altered, the rock still weathers to thin plates but the fine laminations are no longer apparent. The altered rock is bluish gray or medium gray and is not easily distinguished from the underlying gray latite lava. Distinction in the field is made on the presence of the sparse fine (mostly 1 mm) grains of quartz in the rhyolite and the lack of quartz in the latite. The tuff of Flint Creek was not recognized north of Jordan Creek.

RHYOLITE OF THE MILLSITE

Flow-layered rhyolite that is relatively rich in phenocrysts compared with other rhyolites of the Silver City–De Lamar area is exposed at the millsite of the De Lamar open-pit mine. We infer that the rock is present also in the open pit (map unit Tsc, pl. 1) but because

TABLE 4.—*Chemical analyses and CIPW norms for rhyolitic rocks from the Silver City Range and vicinity, Idaho, and from Succor Creek canyon, Oregon*—Continued

SAMPLE DESCRIPTIONS AND LOCALITIES

[Listed by sample number. (Field number in parentheses)]

1 (LG–2). Vitrophyre at base of ash-flow tuff (Leslie Gulch Tuff Member of Kittleman and others, 1965, 1967) near mouth of Succor Creek canyon, Oreg.; from first side canyon south of the mouth of canyon that joins main canyon from west at picnic ground (lat 43°26′ N., long 117°08′ W.). The vitrophyre forms a 3-m-thick ledge that crops out about 50 m above the valley floor northwest of apex of an alluvial fan. The vitrophyre here is irregularly devitrified and contains evidence of local incipient spherulitic crystallization and chalcedonic vug-filling; the vitrophyre grades laterally into devitrified rock. Perlitic, dark gray, contains 21 percent phenocrysts as much as 3 mm long that consist of 30 percent slightly rounded, embayed quartz, 67 percent sanidine, 3 percent green clinopyroxene with large 2V, and a trace of opaque oxides. Reversed magnetic polarity.

2 (BE–190). Quartz-latite breccia—probable basal part of tuff of Flint Creek in Idaho, about 7 km east of Jordan Valley, Oreg.; just above road level on county road between Jordan Valley and De Lamar at lat 42°57′54″ N., long 116°58′42″ W. Consists of devitrified "rhyolite" breccia that contains about 2 percent small (less than 3 mm long) phenocrysts of quartz and feldspar. Believed to be the same rock that includes a fresh vitrophyre in an outcrop 1.6 km southeast. The vitrophyre contains 4.3 percent phenocrysts that consist of 49 percent quartz, 37 percent plagioclase, 7 percent alkali feldspar, 7 percent pigeonite, and a trace of hypersthene. Mode is typical of lower unit of tuff of Flint Creek.

3 (BE–683). Apache tears from aphyric rhyolite at Toy Pass along the road between Oreana and Triangle, at lat 42°54′10″ N., long 116°32′45″ W. (same outcrop as age-dated sample, BE–96). Nearby devitrified rock is flow layered and contains fewer than 1 percent phenocrysts, less than 2 mm long, of quartz, sanidine, plagioclase, altered pyroxene, and scattered tiny flakes of biotite. Despite the fact that the sample locality is considerably higher than the base of the rhyolite section as exposed to the south and east, the Apache tears appear to have weathered out of the basal part of the rhyolite unit as exposed on the pass; therefore, considerable relief on the basal contact of the rhyolite is indicated.

4 (OM–2). Finely flow laminated, devitrified rhyolite a few meters above the base of cooling unit at Tiddie Spring in SE¼ sec. 33, T. 3 S., R. 3 W.; lat 43°07′ N., long 116°42′ W. Correlated with rhyolite of the Silver City Range. Grayish-red to grayish-purple rhyolite contains 2–6 percent phenocrysts as much as 1 mm long that consist of plagioclase, quartz, alkali feldspar, pyroxene pseudomorphs, and minor biotite and zircon. Upper two-thirds of cooling unit is blocky, lithophysal, and contains larger and more abundant quartz and biotite than does lower one-third. Reversed magnetic polarity.

5 (BE–180). Rhyolite of Silver City Range about 11 km southwest of State Highway 45 in tributary of Sinker Creek along county road to Silver City from Murphy, at lat 43°06′ N., long 116°36′ W. Devitrified aphyric rhyolite thought to be part of same cooling unit whose basal vitrophyre contains 6 percent phenocrysts as much as 1.5 mm long that consist of 49 percent quartz, 31 percent alkali feldspar, 19 percent plagioclase, and a trace of biotite.

6 (OM–5). Rhyolite of Black Mountain exposed on ridge crest west of Brunzell Spring in NE¼ SW¼ sec. 26, T. 3 S., R. 3 W.; lat 43°08′ N., long 116°40′ W. Grayish-purple flow-layered rhyolite contains 4–7 percent phenocrysts as much as 3 mm long that consist of 75–85 percent plagioclase, 13–24 percent hypersthene, 0–1.5 percent quartz, and traces of opaque oxides and zircon.

7 (OM–42). Quartz latite in Jump Creek Rhyolite of Kittleman and others (1965, 1967). Basal vitrophyre breccia exposed on northeastern rim of Shares Basin in NE¼ sec. 32, T. 1 N., R. 4 W.; lat 43°23′ N., long 116°50′ W. Contains 20 percent phenocrysts as much as 4 mm long that consist of 73 percent plagioclase, 16 percent alkali feldspar, 9 percent hypersthene, 2 percent quartz, and traces of opaque oxides, apatite, and zircon.

8 (OM–55). Tuff of Wilson Creek in SW¼ sec. 6, T. 1 S., R. 3 W.; lat 43°22′ N., long 116°45′ W. Grayish-red purple lithophysal rhyolite contains less than 5 percent phenocrysts as much as 2 mm long that consist of alkali feldspar, quartz, and hematitic pseudomorphs after clinopyroxene. Norm not computable because molecular amount of CO_2 is greater than molecular amounts of CaO and MgO. Extremely thin carbonate films lining some lithophysae account for the high CO_2 content, but not for the low CaO and MgO content.

9 (OM–33). Tuff of Browns Creek; sample from near Reynolds Creek, in NW¼ sec. 26, T. 1 S., R. 3 W.; lat 43°19′ N., long 116°40′ W.; red-purple and white, slightly lithophysal rhyolite that contains quartz and alkali feldspar phenocrysts as much as 2 mm long, and pseudomorphs after pyroxene.

10 (BE–160C). Upper unit of sample from rhyolite of Browns Creek; sample from just east of narrow gorge where Hart Creek has cut through a horst of crystal-poor (lower unit) rhyolite of Browns Creek at lat 43°01′ N., long 116°28′30″ W. Sample of glassy rhyolite contains 24–40 percent phenocrysts that consist of 55 percent quartz, 34 percent alkali feldspar, 9 percent plagioclase, and 1 percent altered mafic minerals.

of intense alteration there only the quartz phenocrysts remain intact. Flow layering in the rock in the vicinity of the millsite, as seen on aerial photographs, defines a broad circular whorl that is about 1.6 km in diameter. A water well drilled to a depth of about 610 m near the millsite whorl bottomed in rhyolite (William Crowl, Earth Resources Corporation, oral commun., 1978). Inasmuch as the thickness drilled exceeds the combined

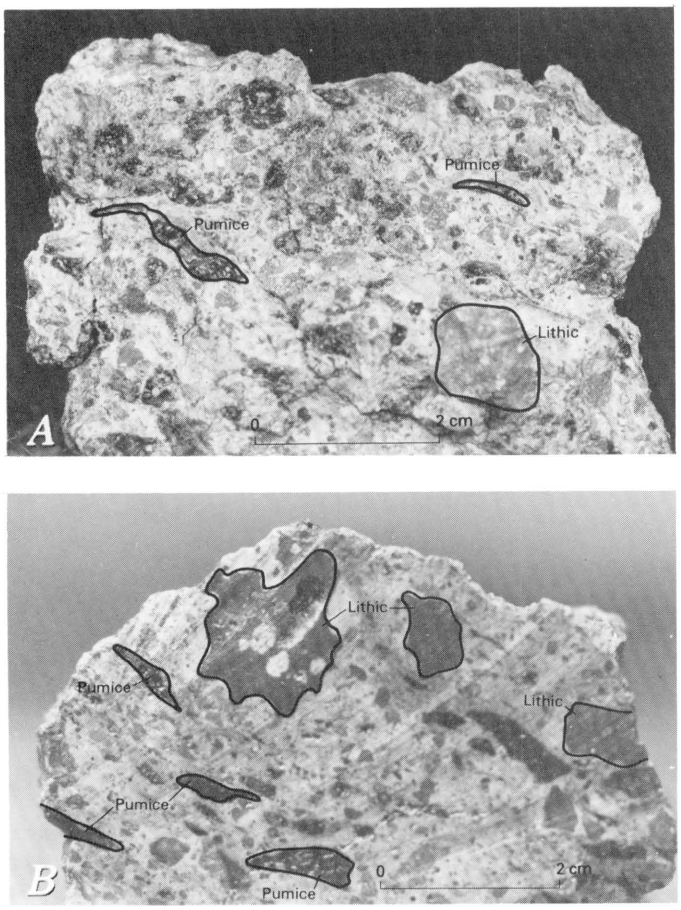


FIGURE 4.—Hand specimens of upper tuff of Flint Creek. Note black glassy pumice fragments and numerous lithic fragments.

thicknesses of all the extrusive rhyolites that occur in the area, presumably the hole was drilled into an intrusive mass that was quite probably the feeder for the rhyolite. Exclusive of the whorl, the rhyolite is at least 50 m thick.

The rhyolite of the millsite, like the tuff of Flint Creek, grades upward from a basal part that contains little or no alkali feldspar to an upper part that is rich in alkali-feldspar phenocrysts that commonly are as large as 3 mm and that locally are as large as 4 or 5 mm. The rock is pinkish gray and white and is characterized by abundant vapor-phase crystals throughout. In places, large (<15 cm) spherulites are scattered through the rock and are abundant on weathered slopes. The rhyolite typically contains 6–10 percent phenocrysts, that in the lower part consist of plagioclase and about 4 percent pigeonite and hypersthene. In the upper part, in contrast, they consist of 50 percent quartz, 40–50 percent sanidine, 0–10 percent plagioclase, and about 3 percent pigeonite, hypersthene, and altered biotite, in order of decreasing abundance. In an outcrop just south of the millsite in a zone of intense vapor phase crystallization, oxidized biotite phenocrysts as large as 3 mm were observed in small cavities in freshly broken rock. These crystals give the general impression of having crystallized in the cavity. Conceivably, they could represent an unusual product of vapor-phase crystallization. Zircon and apatite are fairly common accessories, and one thin section contained a grain of allanite.

No conclusive evidence was found during the course of this study to indicate that the rhyolite is a welded tuff. In exposures just south of the Flint Creek mining district, the unit is separated from the underlying upper cooling unit of the tuff of Flint Creek by a zone of nonwelded, soft, yellowish-gray tuff several meters thick. The soft tuff is overlain by flow-layered rhyolite that is so highly altered that no phenocrysts remain intact. No pumice was observed in the flow-layered rhyolite there, which we mapped as rhyolite of the millsite, nor in any other locality as far north as the northernmost outcrops, which are about 6.4 km northwest of De Lamar and Jordan Creek. The distribution of the rhyolite, therefore, is known with reasonable certainty to extend from about 6.4 km northwest of Jordan Creek on the north to Flint Creek on the south, a distance of about 21 km. This distribution suggests that the rhyolite of the millsite is an ash-flow tuff.

RHYOLITES ON THE WESTERN FLANK NORTH OF DE LAMAR

In addition to the rhyolite of the millsite, which we infer extends 6.4 km northwest of De Lamar, other rhyolites (commonly silicified) are present north of De Lamar that occupy the same stratigraphic position there—namely, on top of the basalt-latite sequence. The most persistent of these rhyolites forms a rugged cliff in sec. 36, T. 3 S., R. 5 W. (pl. 1, map unit Tsc). In the cliff exposures, the unit is 90–120 m thick. The lower part (about 30 m) is nearly aphyric and contains only about 1–2 percent of small plagioclase phenocrysts and sparse, altered pyroxene phenocrysts. This zone is flow layered throughout; it grades upward to flow-layered rock that contains 5–10 percent phenocrysts of plagioclase and altered pyroxene. The upper 30–40 m consists of flow-layered rhyolite that contains 5–10 percent phenocrysts that have subequal amounts of quartz (<2 mm), alkali feldspar (2–3 mm), and plagioclase (2–5 mm). In most places, the entire 90- to 120-m-thick unit appears to be a single cooling unit; locally, the upper, quartz-bearing zone is separated from the underlying plagioclase rhyolite by a thin black vitrophyre.

The possibility exists that the cliff-forming rhyolite is equivalent to the rhyolite of the millsite. The units are similar modally and in megascopic appearance. The correlation was precluded on the basis of the abundance of, and persistence of plagioclase in the upper part, that, in the rhyolite of the millsite, was never found to compose more than about 10 percent of total phenocrysts.

At several localities, especially in sec. 36, T. 3 S., R. 5 W., a perlitic vitrophyre crops out at the top of the rhyolite sequence. This vitrophyre, like the underlying devitrified rock, is conspicuously flow layered and contains subequal amounts of quartz, alkali feldspar, and plagioclase. It also contains small phenocrysts of fresh pyroxene that consists of subequal pigeonite and hypersthene.

The rhyolite described in the preceding paragraphs, with a lower part that contains only plagioclase and an upper part that contains quartz, alkali feldspar, and plagioclase, was considered to be welded tuff by Asher (1968). Despite the overall flow-layered, lavalike appearance of the rock, we concur with Asher's classification because of the local preservation of shards in both the lower part of the sequence (plagioclase only) and in the upper part. Surprisingly, these shards are visible with a hand lens—especially in the highly silicified rock. We disagree, however, with Asher's classification and with our own earlier interpretation (Ekren, McIntyre, and Bennett, 1978b) of strata in secs. 21, 22, 27, and 28, T. 3 S., R. 5 W. Highly vesiculated and silicified latite or quartz latite is exposed there that was erroneously mapped as rhyolite. The similarity to rhyolite is due to intense silicification and the partial replacement of plagioclase by alkali feldspar. The latite, whose vesicles are commonly filled with opaline silica, is overlain by olivine basalt that locally is a pillow basalt and much altered to palagonite. The olivine basalt, in turn, is overlain by the plagioclase rhyolite. Asher (1968) pointed to this locality as one at which basalt was interbedded with rhyolite; this is definitely not true.

Farther north in NW¼ T. 2 S., R. 5 W., a rhyolite dome or circular vent crops out on the west edge of the mountain front. This rhyolite has concentric flow layering parallel to the outer edge of the mass, and it stands in high relief with respect to the soft sedimentary rocks that bound the rhyolite on the north and west. The sedimentary rocks, which are part of the Sucker Creek Formation, are clearly younger than the rhyolite because they contain conglomerate beds that have angular clasts derived from the domical rhyolite mass. The rhyolite has been silicified, and the alkali feldspar phenocrysts (and some quartz phenocrysts as well) are surrounded by finely crystalline micrographic haloes that consist of quartz and potassium feldspar, or albite, or both. Some phenocrysts have been entirely replaced by the micrographic material. We presume that the rhyolite was altered by the same type of siliceous fluids that intensely altered the opal-bearing latite described previously that crops out about 13 km to the south. Two thin sections from relatively unaltered rhyolite lava that crops out about 2 km southeast of the domical rhyolite mass contain 6 percent phenocrysts that consist of 35–40 percent quartz (<2 mm), 45–50 percent alkali feldspar (<2 mm), 4–7 percent plagioclase (<2 mm), 2–5 percent altered pyroxene, and 3 percent hypersthene. This rhyolite, although similar to that in the dome, appears to have been fed from a small feeder at the northwest end of the lava outcrops and not from the dome of altered rhyolite.

RHYOLITES OF THE CENTRAL SILVER CITY RANGE

Flow-layered and, for the most part, hydrothermally altered white and light-gray rhyolites cap the Silver City Range on Florida Mountain and a broad area south of War Eagle Mountain (pl. 1). In places these capping rhyolites are at least 300 m thick. Nearly all the exposed rocks contain only 1–2 percent phenocrysts of quartz, alkali feldspar, and plagioclase that rarely exceed 1 mm in length. Three locally preserved vitrophyres in the range south of Silver City, which occur at the base, middle, and near the top of the rhyolite section, provided most of the thin sections for this study and indicate breaks or partial breaks in cooling. Stated another way, the vitrophyres indicate that there were significant pauses during the massive rhyolite eruptions. Whether or not the pauses were of sufficient duration to cause complete cooling breaks is unknown. Modally, the three vitrophyres show only slight variations. The lowest vitrophyre, which rests on an uneven surface developed on the latite-basalt sequence and locally on granite, contains 2 percent phenocrysts that consist of 27 percent quartz, 20 percent plagioclase, and nearly 50 percent alkali feldspar—a mode that differs from the cooling units of the tuff of Flint Creek, exposed along the western flank of the range. The small size and amount of phenocrysts also precludes correlation with the rhyolite of the millsite. The middle rhyolite vitrophyre contains 1.6 percent phenocrysts that consist of 44 percent quartz, 32 percent alkali feldspar, and 19 percent plagioclase; mafic pseudomorphs constitute about 5 percent of the phenocrysts and appear to be after pyroxene and biotite. The third vitrophyre contains 1 percent phenocrysts that consist of subequal amounts of quartz, alkali feldspar, and plagioclase. The three vitrophyres appear to be representative of the bulk of the rhyolite section—at least we found no rocks in our reconnaissance mapping that were obviously different. A single sample, for example, from devitrified rhyolite low in the section on Cinnabar Mountain yielded a mode that is a good match for the lowest rhyolite vitrophyre just described. No samples were collected from the mostly highly altered rhyolite on

Florida Mountain, which, according to Pansze (1975, p. 30), includes welded tuff breccia.

Although the phenocryst content and the mineralogy of the capping rhyolites in the Silver City Range do not match those of any of the rocks sampled along the western flank, they do match the lower strata exposed on the eastern flank.

All rhyolites capping the Silver City Range appear to have normal magnetic polarity.

RHYOLITES ON THE EASTERN FLANK

Phenocryst-poor, extensively flow-layered rhyolite crops out along the eastern flank of the Silver City Range from the south township line of T. 6 S. to the north township line of T. 4 S. This sequence, which is at least 250 m thick, was not sampled in its entirety but various thin sections, mostly from exposures along creek beds, strongly suggest that most of the rocks are the same as those that cap the Silver City Range. In contrast to the rocks exposed in the central part of the range, however, those along the eastern flank are mostly fresh and pale red, brownish gray, or reddish gray. In several exposures the rocks are virtually aphyric, and ferromagnesian minerals appear to be extremely sparse throughout; rarely, a few tiny flakes of biotite are visible in hand specimen. In the vicinity of Pickett Creek and southward along the county road from Triangle to Oreana, the rhyolite section includes several zones of mostly thin (2–3 m) vitrophyre. A thin section from one of these zones, from near the base of the sequence near Toy Pass (pl. 1), contained 1 percent phenocrysts that consisted of 36 percent quartz, 46 percent alkali feldspar, 15 percent plagioclase, and 2 percent altered biotite(?). This mode is essentially the same as the modes obtained from rhyolites at the base of the sequence on Cinnabar Mountain and in exposures south of Silver City. Apache tears weather out of the rhyolite at Toy Pass and vicinity, and these yielded a K-Ar age of 16.0 ± 0.3 m.y. (table 2; G. B. Dalrymple, written commun., 1979). This age indicates that the rocks along the eastern flank are, in part at least, coeval with those on the western flank and at Silver City (Pansze, 1975; Armstrong and others, 1975; our table 3). A single chemical analysis (table 4, sample 3, field No. BE-683) indicates that the rock is a silicic rhyolite. All the phenocryst-poor rocks in the vicinity of Toy Pass appear to have normal magnetic polarity.

Along the county road from Triangle to Oreana in sec. 12, T. 6 S., R. 2 W., a magnetically reversed sequence of rhyolite crops out that probably consists either of two thin ($20 \pm$m) virtually identical cooling units, or of a single compound cooling unit; these rocks contain conspicuous flakes of biotite. The lowest unit is locally separated from the magnetically normal, phenocryst-poor rhyolite described earlier by a thin, poorly exposed zone of nonwelded and partially welded tuff. Except for the abundance of biotite, as well as of larger and more abundant phenocrysts, the modes of these magnetically reversed rhyolites are similar to those of the underlying magnetically normal rhyolite; all these rhyolites probably were erupted from the same general source. The lower of the two cooling units contains 6–11 percent phenocrysts as large as 2 mm that consist of 37 percent quartz, 45–48 percent alkali feldspar, 9–13 percent plagioclase, 1.6–3.5 percent biotite, and a grain or two of hypersthene. The upper unit contains 9 percent phenocrysts as large as 3 mm that consist of 47 percent quartz, 31 percent alkali feldspar, 15 percent plagioclase, 3.4 percent biotite, and 1 percent altered pyroxene. The biotite-bearing rhyolites were traced northwestward for about 3 km along the flank of the range. They were not recognized north of Browns Creek.

In the Pickett Creek drainage (pl. 1) in sec. 16, T. 5 S., R. 2 W., an interesting sequence of rhyolite crops out that seemingly occupies the same stratigraphic position as the biotite rhyolite described earlier—namely just above the phenocryst-poor rock. The sequence consists of nonwelded ash at creek level overlain by a brown, densely welded, vitric ash-flow tuff about 2 m thick that contains well-flattened black pumice fragments. The ash-flow tuff, in turn, is overlain by thin-bedded black and brown glassy agglutinate (welded air-fall bedded tuff). The welded bedded tuff, 10–15 m thick, is overlain by flow-layered and laminated, partly devitrified rhyolite, that looks like typical lava. A thin section of the lower part of the flow-layered rock, however, shows a matrix of strung-out shards. Modal analyses of a thin section of this rock and of a thin section of welded bedded tuff are very similar, and furthermore they are acceptable for the upper cooling unit of the tuff of Flint Creek. Sparse magnetic data, however, suggest that the unit at Pickett Creek is magnetically reversed, whereas the tuff of Flint Creek is probably magnetically normal.

The thin sections of welded bedded tuff and flow-layered tuff contain 3.3–5.3 percent phenocrysts about 1 mm in size that consist of 50–57 percent quartz, 10–15 percent alkali feldspar, 24–33 percent plagioclase, 3 percent pigeonite, and a trace of biotite. The flow-layered tuff probably extends northward as far as Sinker Creek, because at Sinker Creek, near an old abandoned homestead in sec. 15, T. 4 S., R. 2 W., nearly identical rhyolite is exposed. The rhyolite at Sinker Creek rests directly on granite, and a single thin section shows that it contains virtually the same volume of phenocrysts and similar proportions of quartz, alkali feldspar, and plagioclase as the rocks at Pickett Creek. Despite the presence of fine laminations in the thin section from Sinker Creek, strung-out shards are preserved in some laminae; they also are preserved in hollows around the phenocrysts (fig. 5).

Rhyolite that is mostly phenocryst-poor crops out just above Sinker Creek on the road to Silver City from Murphy. We inferred, during the course of mapping, that this unit was part of the same sequence that caps the Silver City Range. Although this inference still may be correct, the rhyolite along the Sinker Creek road contains abundant lithic fragments that were not observed in the rhyolite on the top of the range. In addition, the two rhyolites contain slightly different phenocryst assemblages. The rhyolite along the Silver City–Murphy road, on the basis of pyroclastic textures still preserved in the basal vitrophyre, is definitely a welded tuff (fig. 6). Rhyolite shown in figure 6*A* is from the vitrophyre just above the contact with granite. Eutaxitic foliation is nearly vertical here because of the steep contact with the granite. The vitrophyre contains a few clasts of granite, and, in addition, contains abundant hydrothermally altered fragments of crystal-rich rhyolite and crystal-poor intermediate lavas. Neither of the two latter fragments could have been picked up locally. They either were torn from the throat of the vent or were picked up at considerable distance from the outcrop area.

The rhyolite of the Sinker Creek area above the basal vitrophyre just described is conspicously flow layered—some layers are aphyric; others contain as much as 2 percent phenocrysts (1–2 mm) of quartz and alkali feldspar. Near the base, the phenocrysts are generally more abundant than they are in the higher exposures, and the locally preserved basal vitrophyre (fig. 6) contains 7 percent phenocrysts. The decrease in volume of phenocrysts upward was not observed in the rhyolite section on the top of the range nor in the exposures southward in the vicinity of Pickett Creek and the

FIGURE 5.—Thin section of finely laminated rhyolite showing preserved shards in a single lamination. Shards in adjacent laminae have been completely destroyed. Sample taken a few meters above contact with granite along Sinker Creek.

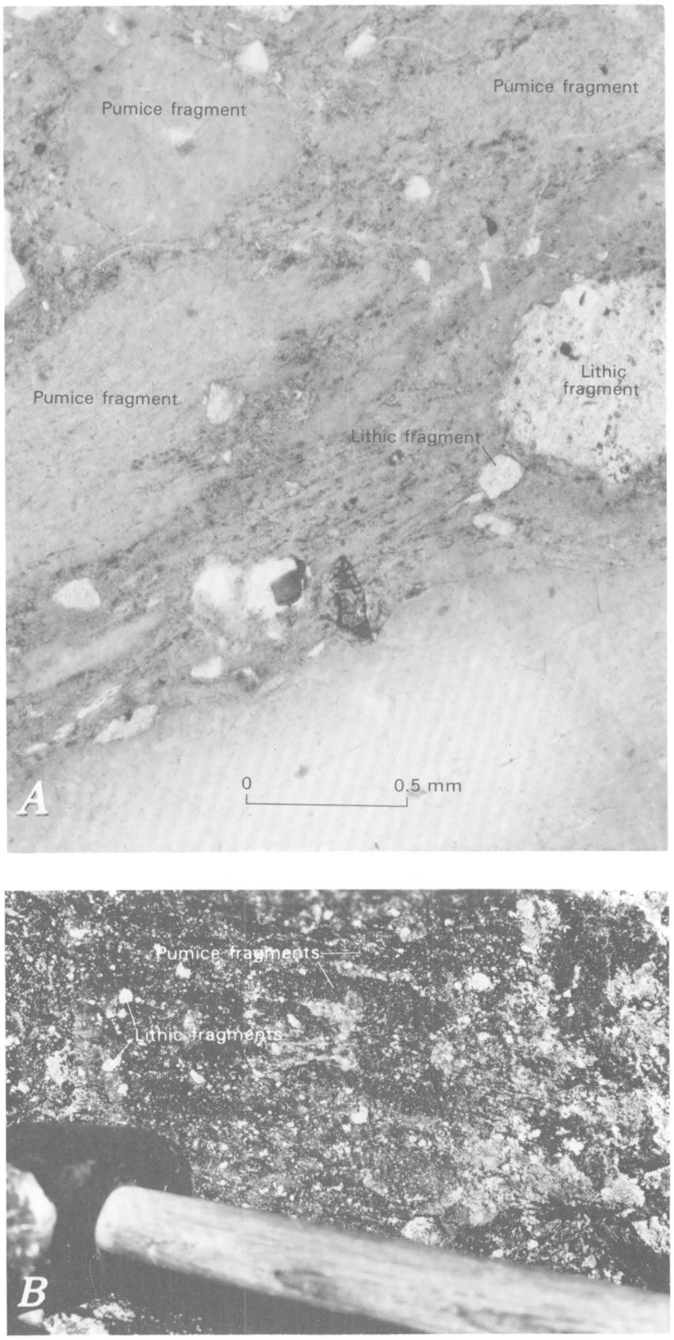


FIGURE 6.—Pumice in basal vitrophyre of rhyolite exposed along road from Murphy to Silver City. White lithic fragments in thin section (*A*), and abundant small white lithic fragments in outcrop (*B*) are altered, moderately crystal-rich rhyolite. Tiny phenocrysts of alkali feldspar and quartz, and two altered grains of pyroxene(?) are visible in thin section. Pumice fragments are lighter than matrix in thin section (plane light) and appear as dark lenticles in outcrop. Hammer handle in *B* is about 25 cm long.

Oreana-Triangle road. This characteristic and the differences in relative proportions of phenocrysts (see following discussion) strongly suggest that at least three separate cooling units of rhyolite are present in this area and that they are probably nowhere juxtaposed.

The thin section (fig. 6 contains 6.7 percent phenocrysts as large as 1.5 mm that consist of 50 percent quartz, 31 percent alkali feldspar, 19 percent plagioclase, and a trace of biotite and altered pyroxene(?)). The volume of phenocrysts and the relative abundance of quartz rules out correlation with the rock at Toy Pass, and the overall abundance of phenocrysts appears to rule out correlation with any of the units that were sampled in the central part of the Silver City Range. We infer that the various rhyolites in the Sinker Creek and Pickett Creek drainages were locally derived, were never too extensive, and were confined to areas that were topographically low at the time of their eruptions.

RHYOLITE OF BLACK MOUNTAIN

A distinctive plagioclase- and hypersthene-bearing rhyolite occurs on Black Mountain, at several localities southeast of Reynolds Basin on the divide overlooking the Snake River Plain, at scattered localities several kilometers farther southeast along the plain margin, and also southwest of Reynolds Basin in the highlands overlooking the drainage basin of Succor[1] Creek and its tributaries. This rhyolite does not have internal features that would indicate an ash-flow tuff origin, but its widespread extent suggests either that it actually was emplaced as an ash-flow tuff or that several widely separated vents erupted lavas of nearly identical composition at about the same time.

The rhyolite of Black Mountain (pl. 1) is gray to grayish purple and contains as much as 7 percent crystals of plagioclase, green hypersthene, and minor opaque oxides and zircon. Minor amounts of quartz were noted in a few samples, and rocks near Pickett and Hart Creeks contain, in addition to quartz, as much as 2 percent oxidized biotite. A chemical analysis of rock containing only plagioclase and hypersthene as major constituents show it to be rhyolite (table 4, sample 6, field No. OM-5).

Most of the rhyolite of Black Mountain is finely flow laminated. Exposures of the base show unbrecciated, laminated vitrophyre (NE¼ sec. 34 and SE¼ sec. 22, T. 3 S., R. 3 W.); unbrecciated, lithophysal, devitrified rock (SE¼ sec. 25, T. 3 S., R. 3 W.); and brecciated, devitrified rock (SW¼ sec. 29, T. 3 S., R. 3 W.).

A K-Ar age for a sample collected near Brunzell Spring, east of Black Mountain, yielded a K-Ar age of 15.7±0.5 m.y. (middle Miocene), close to, but younger than, the age of rhyolite volcanism and mineralization in the Silver City Range to the south. North and west of Black Mountain, the rhyolite of Black Mountain is underlain by gravels that contain rhyolite of the Silver City Range and detrital gold, indicating that at least a short erosional interval separated the Black Mountain rocks from those of the Silver City Range. The rhyolite of Black Mountain has reversed magnetic polarity.

The best exposures of the rhyolite of Black Mountain are adjacent to Black Mountain itself, where about 120 m of the unit is exposed, and to the east and northeast, where remnants of the unit are discontinuously preserved in a zone that extends to the margin of the Snake River Plain. The unit in various exposures throughout the area rests locally on granitic rock, or basalt, or on rhyolite of the Silver City Range. Age relations between rhyolite and younger basaltic rocks near the plain margin are, in places, difficult to interpret. For example, poor exposures along the upper reaches of Rabbit Creek in sec. 11, T. 3 S., R. 3 W. show an upper Miocene basaltic tuff that crops out well within the narrow, steep-walled canyon cut into the rhyolite. In the absence of clean exposures of the contact, a reasonable interpretation of the field relations would be that the basaltic tuff underlies or is interbedded with the rhyolite. Available K-Ar ages and contact relations elsewhere, however, show that this sequence cannot be so. Instead, the present canyon is a re-excavation of an older one that was cut into the rhyolite and that was once more or less filled with the basaltic tuff; outcrops of basaltic tuff now seen against the canyon walls evidently represent remnants of this canyon fill.

On the western slope of the Silver City Range southwest of Black Mountain and about 4 km east of Twin Peaks (pl. 1), rhyolite occurs at the top of the rhyolite sequence exposed there that, although not contiguous with the rocks in the Reynolds watershed, is typical of the rhyolite of Black Mountain. This rock contains only plagioclase (<3 mm) and tiny prisms of hypersthene that, on the average, are considerably less than 1 mm long. A few clots or clusters that consist of hypersthene and small plagioclase are as much as 3 mm in diameter. Between Twin Peaks and De Lamar (pl. 1) the hypersthene rhyolite is preserved locally in a few fault slivers where it apparently rests directly on the rhyolite of the millsite. In the vicinity of Twin Peaks, it rests on the plagioclase-pyroxene-biotite rhyolite described on previous pages.

In several places along the road from De Lamar, Idaho, to Jordan Valley, Oreg., rhyolite crops out in isolated blocks that rest on the latite-basalt sequence. Many of these blocks of rhyolite are brecciated throughout and appear to have slid over the weathered, clay-al-

[1]Spelled Sucker on some maps and signposts; Sucker is also an accepted spelling for the geologic name Sucker Creek Formation (Kittleman and others, 1965, 1967).

tered basalt and latite prior to the deposition of the Sucker Creek Formation. These blocks were mapped by Ekren and others (1981) as rhyolite of Silver City Range undivided. At several localities, however, the blocks include, at the top, hypersthene rhyolite that closely resembles the rhyolite of Black Mountain, except that the rocks contain small percentages of quartz and alkali feldspar phenocrysts. The overall similarity of this rock to the rhyolite of Black Mountain, coupled with its stratigraphic position at the top of the rhyolite sequence, suggest that it is probably about the same age as the Black Mountain, and that possibly it was derived from the same volcanic center.

On the east flank of the Silver City Range, in the Pickett Creek and Hart Creek drainages along the margin of the Snake River Plain, rhyolite crops out at the ultimate top of the rhyolite section that superficially resembles the rhyolite of Black Mountain. This rhyolite, like the rhyolites at the top of the blocks on the western flank, also contains minor amounts of quartz, or alkali feldspar, or both. Along Pickett Creek, the rhyolite has a conspicuous basal vitrophyre about 6 m thick that consists of 3–4 m of massive dark-gray vitrophyre at the base, grading upward to 2 m of spherulitic vitrophyre, and thence upward to flow-laminated, devitrified, gray rhyolite. The vitrophyre contains 13 percent phenocrysts that consist of 5 percent quartz, 82 percent plagioclase, 12 percent hypersthene, and 1 percent opaque oxides. This same vitrophyre crops out also along Hart Creek, where its lower part is massive but its upper part is conspicuously flow layered. The overlying devitrified rock contains flattened lithophysae that could have formed from altered pumice fragments.

LESLIE GULCH TUFF MEMBER OF THE SUCKER CREEK FORMATION

An important rhyolite unit that appears to be the same general type of rhyolite as those previously described, but that occurs in Leslie Gulch, T. 26 S., Rs. 44 and 45 E., Malheur Co., Oreg., west of the area shown in plate 1, is the Leslie Gulch Tuff Member of the Sucker Creek Formation of Kittleman and others (1965, 1967). Our interest in this unit derives from the possibility that its source was within the Snake River Plain. Our reconnaissance suggests that the rhyolite at Succor Creek canyon mapped by Kittleman and others (1965, 1967) as Sucker Creek Formation may best be treated as a separate unit from other rocks included in the Leslie Gulch Tuff Member as a map unit. A K-Ar age of 15.8±0.6 m.y. on sanidine was obtained from outcrops at Succor Creek canyon (table 2).

The Leslie Gulch Tuff Member at Succor Creek is a crystal-rich rhyolite as indicated by sample 1 (LG-2, table 4) that contains quartz and sanidine phenocrysts as long as 4 mm. The devitrified tuff is grayish red and grayish red purple and commonly lithophysal. The few samples examined showed no pyroclastic textures, but the unit still may have originated as an ash-flow tuff rather than as a lava because the basal vitrophyre, where seen in two localities, is not flow-brecciated—an unlikely possibility if the rock originated as a rhyolite lava flow.

The Leslie Gulch Tuff Member in the Succor Creek canyon area is a remnant of a paleocanyon fill. The marginal contact is best seen on the west side of the remnant in the SE¼, T. 24 S., R. 45 E., where flow foliation steepens as the contact is approached, and unbrecciated vitrophyre can be found at the steep contact with older, flat-lying volcanic rocks. Relations along the east side of the remnant are complicated by faulting. On the east side of Smith Butte, in sec. 20, T. 25 S., R. 46 E., the rocks show overfolding toward the south, suggesting that transport was from the north—from a source within the Snake River Plain.

ROCKS OF JUNIPER MOUNTAIN VOLCANIC CENTER

At least five rhyolite tuffs were erupted within a short time interval from a buried vent complex centered near Juniper Mountain, in the southwestern part of the map area (pl. 1; fig. 7). The Juniper Mountain area is the approximate center of distribution of at least four of the five tuffs, and two of the sequences form flow lobes that radiate from a center near Juniper Mountain.

No fault-bounded collapsed caldera is present in the Juniper Mountain area, although small, locally subsided areas lacking sharply defined margins are present north and northeast of Juniper Mountain (Ekren and others, 1981). Instead of a caldera, the area is a poorly defined structural low with a dome about 30 km in diameter rising from the low. Juniper Mountain is near the center of the dome that is defined by dips of less than 10°. The lack of a caldera can be explained by eruption from a magma chamber at unusually great depth, perhaps 15 km or more below the surface. That some volcano-related subsidence may have occurred, however, is indicated by the fact that Juniper Mountain rocks more or less fill a broad, probably east-northeast-striking structural depression (see isopachs, pl. 2, in pocket). Using the elevations of the rhyolite and Banbury Basalt contact as a structural datum, and subtracting the thickness of the Little Jacks Tuff east of Juniper Mountain, we infer that the depression probably extends from Oregon (about 65 km west of Juniper Mountain, Idaho) to the Snake River Plain east of the mapped area (pl. 2). The depression, in turn, lies within the linear, west-southwest-trending rifted region that we

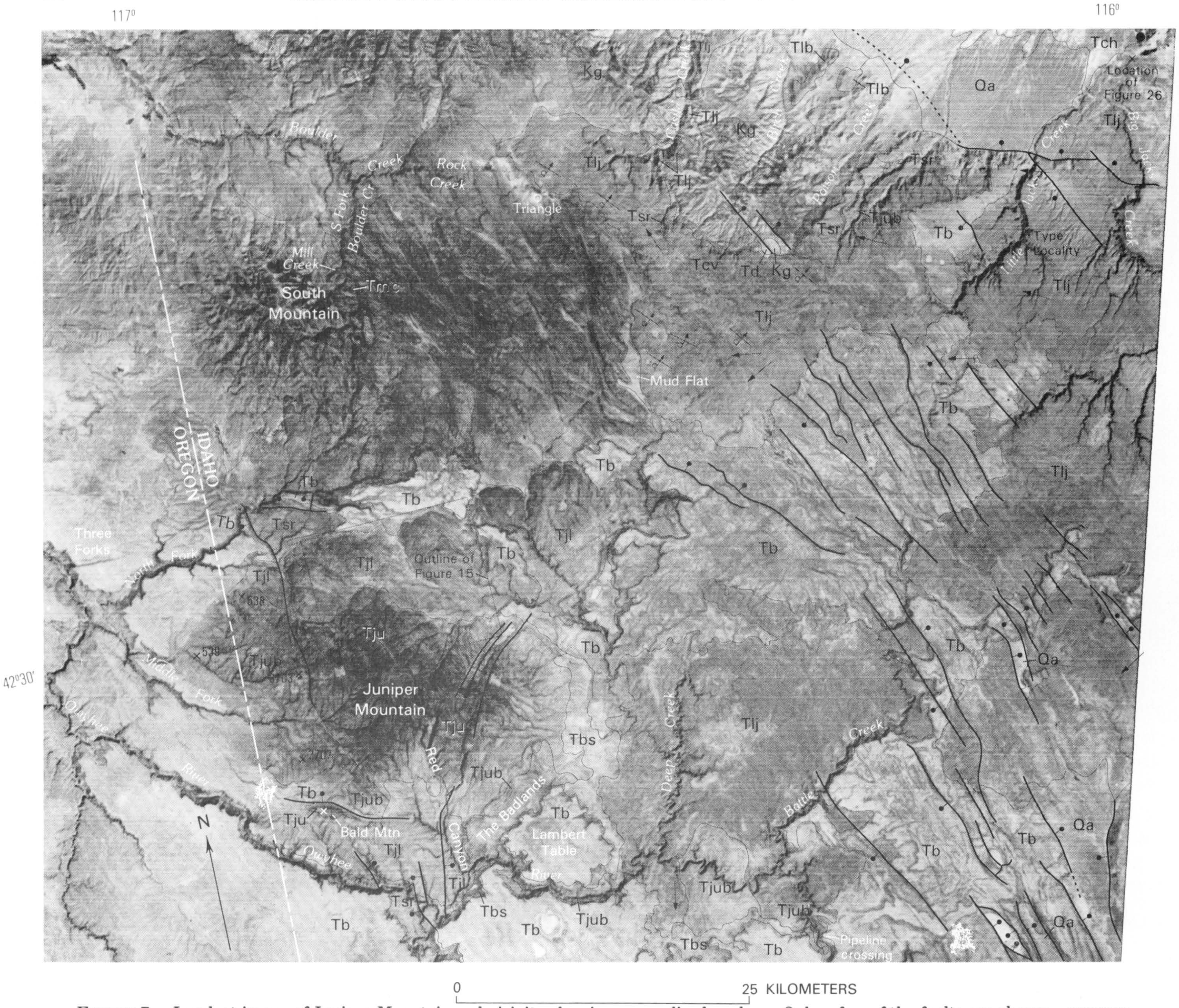


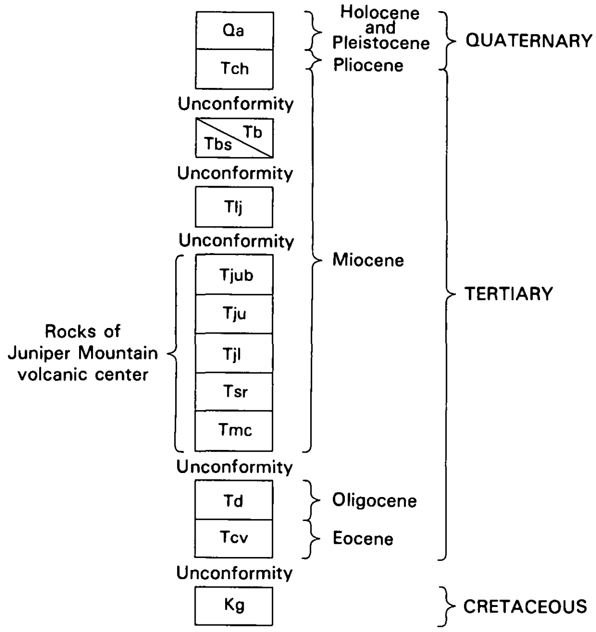
FIGURE 7.—Landsat image of Juniper Mountain and vicinity showing generalized geology. Only a few of the faults are shown—compare with Ekren and others (1981). Note lobate pattern of lower lobes of Juniper Mountain (Tjl).

have termed "the eastern Snake River Plain trend" (see Introduction, this report).

The structural depression accommodated at least 650 m (2,400 ft) of tuffs of Juniper Mountain and similar thicknesses of Little Jacks Tuff (see later pages). These thicknesses suggest that subsidence and tuff eruptions were concomitant. The problem is: was the subsidence due to magma withdrawal, or was it due to rifting along the southwest-striking eastern Snake River Plain trend? We infer that it was due to both, but that rifting along the eastern Snake River Plain trend was the principle cause. We infer this because of the breadth of the subsided ground. If directly related to magma withdrawal, such breadths would imply magma chambers that were nearly as broad as the sheets they gave rise to. That this is unlikely is indicated by numerous tuff terranes in western United States where the subsided source areas are generally less than one-third the diameter of the extruded sheets.

The rocks erupted from buried vents in the Juniper Mountain area include from oldest to youngest: tuff of Mill Creek, Swisher Mountain Tuff, two tuff units called informally the lower lobes and the upper lobes of Juniper Mountain, and the tuff of The Badlands. Several of the units show a general increase from base to top in the abundance of alkali feldspar and quartz, and, with the exception of the tuff of The Badlands, the units become more rhyolitic in composition with decreasing

CORRELATION OF MAP UNITS



LIST OF MAP UNITS

Qa	Alluvium and eolian deposits
Tch	Chalk Hills Formation
Tb	Banbury Basalt
Tbs	Sedimentary rocks
Tlj	Little Jacks Tuff
Tjub	Tuff of The Badlands
Tju	Upper lobes of Juniper Mountain
Tjl	Lower lobes of Juniper Mountain
Tsr	Swisher Mountain Tuff
Tmc	Tuff of Mill Creek
Td	Dacite dike rock
Tcv	Challis Volcanics
Kg	Granitic rocks

Contact

Fault—Dotted where concealed. Bar and ball on downthrown side

Bearing of flow lineation and direction of inferred flowage

Strike of dunelike feature in Little Jacks Tuff—Arrow points down steep (lee) side

× Sample locality

age (table 5). The oldest unit, the tuff of Mill Creek, is a plagioclase tuff without quartz and virtually without alkali feldspar. The next youngest, the Swisher Mountain Tuff, contains much alkali feldspar, although plagioclase is the dominant feldspar; in places, especially at its top, it contains a few crystals of quartz. The next youngest unit, the lower-lobes tuff, contains more alkali feldspar than plagioclase and contains significant amounts of quartz; the overlying upper-lobes tuff is rich in both quartz and alkali feldspar and is virtually without plagioclase. These units, therefore, show a general tendency to become more rhyolitic with decreasing age. The tuff of The Badlands, however, shows a reversal of this tendency; in its lower part it has a phenocryst assemblage that is similar to that of the lower-lobes tuff; in its upper part it has an assemblage that is virtually identical to that of the upper-lobes tuff.

All the rocks are flow layered and flow folded; locally they are flow brecciated, but they all show, at one locality or another, unequivocal pyroclastic textures.

TUFF OF MILL CREEK

The oldest unit that we infer was erupted from the Juniper Mountain volcanic center is called informally the tuff of Mill Creek. The name is derived from exposures in Mill Creek, a tributary of South Fork Boulder Creek (fig. 7), in sec. 6, T. 8 S., R. 4 W. (pl. 1). The tuff in this area is well exposed and forms a distinct rim beneath the Swisher Mountain Tuff that overlies the unit with slight angular unconformity. In this area, the tuff of Mill Creek rests unconformably on basalt that has been dated at about 17 m.y. (Pansze, 1975). Elsewhere, as in the Flint Creek and Jordan Creek area (pl. 1), the tuff rests locally on rhyolites of the De Lamar area. The tuff of Mill Creek probably is exposed in the deeper parts of Boulder Creek and Rock Creek canyons, which were not traversed during this study, and it probably is buried beneath the Swisher Mountain Tuff over broad areas. The two units possibly had similar distribution patterns (pl. 2).

The tuff of Mill Creek resembles the Swisher Mountain Tuff so closely in outcrop and thin section that its genetic affinity with the Swisher Mountain and other rocks of the Juniper Mountain volcanic center seems certain. It differs from the Swisher Mountain in having different magnetic polarity and having slightly smaller and fewer phenocrysts, and it consistently has less alkali feldspar. The two tuffs, however, have the same colors in both the basal vitrophyres and the devitrified rocks. The basal vitrophyres in both units commonly show distinct flow banding in shades of black and gray—a feature that is rare in the Little Jacks Tuff, for example. The devitrified rocks are reddish gray or brown and locally are orange and brick red. The basal vitrophyre of the tuff of Mill Creek in the Mill Creek area is conspicuously columnar jointed. The columns are small—rarely exceeding 40 cm in diameter. Where the underlying topography was extremely irregular, the

TABLE 5.—*Chemical analyses and CIPW norms for rhyolitic rocks from the Juniper Mountain volcanic center, Idaho*

[All analyses by X-ray fluorescence spectroscopy (analyst: S. Morgan; chemical determinations of FeO, H_2O^+, H_2O^-, and CO_2 by P. Klock). All values in weight percent]

Sample No.--	1	2	3	4	5	6	7	8	9	10
Field No.---	BE-511A	BE-33	BE-25	BE-27	BE-548	BE-546	BE-531	BE-547	BE-487	BE-488
					Chemical composition					
SiO_2--------	71.27	70.40	71.13	72.50	72.63	73.79	75.87	76.66	75.22	74.78
Al_2O_3-------	13.94	12.81	13.37	12.69	12.44	12.56	11.66	11.89	12.65	12.71
Fe_2O_3-------	2.33	0.97	2.90	1.39	1.50	2.48	1.29	1.55	1.85	1.40
FeO---------	0.12	1.65	0.49	0.43	0.62	0.16	0.19	0.12	0.17	0.66
MgO---------	<0.02	0.29	0.19	<0.02	<0.02	<0.02	0.10	<0.02	0.04	0.04
CaO---------	1.28	1.24	1.16	0.56	0.69	0.65	0.88	0.33	0.74	0.83
Na_2O--------	3.44	2.69	3.26	2.41	2.93	3.06	3.18	3.06	3.02	2.86
K_2O---------	5.06	5.80	5.22	6.46	5.99	5.58	5.31	5.38	5.48	5.73
H_2O^+--------	0.31	2.85	0.54	2.46	1.97	0.28	0.34	0.25	0.27	1.53
H_2O^---------	0.57	0.30	0.57	0.65	0.55	0.52	0.45	0.29	0.38	0.38
TiO_2--------	0.58	0.47	0.56	0.30	0.32	0.34	0.18	0.19	0.29	0.27
P_2O_5--------	0.10	0.07	0.10	0.04	0.05	0.06	0.26	0.05	0.08	0.06
MnO---------	0.016	0.041	0.037	0.016	0.027	0.039	0.026	0.019	0.026	0.034
CO_2---------	0.07	0.04	0.02	0.05	0.03	0.06	0.32	0.09	0.27	0.46
Sum-------	99.09	99.62	99.55	99.96	99.75	99.58	100.06	99.88	100.49	101.74
Na_2O+K_2O----	8.50	8.49	8.48	8.87	8.92	8.64	8.49	8.44	8.50	8.59
Na_2O/K_2O----	0.68	0.46	0.62	0.37	0.49	0.55	0.60	0.57	0.55	0.50
Na_2O/CaO----	2.69	2.17	2.81	4.30	4.25	4.71	3.61	9.27	4.08	3.45
					Normative composition					
Q-----------	30.18	30.14	30.23	33.87	32.30	34.03	36.89	38.19	36.05	35.85
C-----------	0.89	0.12	0.54	0.96	0.07	0.60	0.45	0.77	1.22	1.51
or----------	30.46	35.53	31.33	39.41	36.41	33.42	31.60	32.00	32.44	33.92
ab----------	29.65	23.59	28.02	21.06	25.50	26.24	27.11	26.07	25.60	24.24
an----------	5.36	5.64	5.05	2.27	2.99	2.49	0.65	0.75	1.44	0.82
hy-en-------	0.00	0.75	0.48	0.00	0.00	0.00	0.25	0.00	0.10	0.10
hy-fs-------	0.00	1.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
mt----------	1.26	1.46	0.08	0.59	1.19	0.00	0.18	0.10	0.21	1.46
hm----------	1.51	0.00	2.89	1.03	0.72	2.51	1.18	1.49	1.71	0.40
il----------	0.29	0.93	1.08	0.59	0.63	0.43	0.34	0.30	0.42	0.51
ap----------	0.24	0.17	0.24	0.10	0.12	0.14	0.62	0.12	0.19	0.14
cc----------	0.16	0.09	0.05	0.12	0.07	0.14	0.73	0.21	0.62	1.05

columns dip at diverse angles; commonly they are horizontal, and in many places nearly vertical flow banding is visible in the horizontal columns. In a few places, well-flattened pumice fragments are visible in the basal glass, but these fragments have been totally destroyed in the overlying flow-layered devitrified rock.

A thin section from an outcrop in the Mill Creek area that has horizontal columnar jointing (fig. 8) contained 17 percent phenocrysts of which 80 percent are plagioclase, 12 percent are pigeonite, 2 percent are alkali feldspar, and 6 percent are opaque oxides. The tuff of Mill Creek has reversed magnetic polarity.

SWISHER MOUNTAIN TUFF

The Swisher Mountain Tuff is named herein for an exposure at Swisher Mountain, Idaho, near the Oregon

TABLE 5.—*Chemical analyses and CIPW norms for rhyolitic rocks from the Juniper Mountain volcanic center, Idaho*—Continued

SAMPLE DESCRIPTIONS AND LOCALITIES

[Listed by sample number. (Field number in parentheses)]

1 (BE–511A). Devitrified tuff of Mill Creek; from Mill Creek just east of road to Indian Meadows, at lat 42°42'30" N., long 116°50'30" W. Flow-layered ash-flow tuff contains 17 percent phenocrysts as much as 3 mm long that consist of 77 percent plagioclase, 18 percent altered pyroxene, 3 percent alkali feldspar, and 2 percent opaque oxides. Sparse accessory zircon.

2 (BE–33). Basal vitrophyre of Swisher Mountain Tuff (lower part); 1.6 km southeast of Poison Creek and the Mud Flat Road and 1.6 km northwest of the west fork of Perjue Canyon; lat 42°44'24" N., long 116°18'24" W. Contains 14 percent phenocrysts that consist of 76 percent plagioclase, 16 percent pigeonite, 7 percent alkali feldspar, 0.7 percent opaque oxides, a trace of hypersthene, and numerous accessory zircon.

3 (BE–25). Devitrified Swisher Mountain Tuff (upper part); about 0.8 km west of Bureau of Land Management camp at Mud Flat and west of road to Juniper Mountain at lat 42°36' N., long 116°33'36" W. Rhyolite contains 24 percent phenocrysts that consist of 54 percent plagioclase, 33 percent alkali feldspar; 11 percent altered pigeonite, 2 percent opaque oxides, and numerous accessory zircon.

4 (BE–27). Black basal vitrophyre of lower-lobes tuff (lower part); about 11 km west of Bureau of Land Management camp at Mud Flat and 1.6 km south of road to Juniper Mountain at lat 42°34'39" N., long 116°39'12" W. Contains 27 percent phenocrysts as much as 4 mm long that consist of 66 percent alkali feldspar, 18 percent quartz, 10 percent plagioclase, 4 percent pigeonite, 1 percent opaque oxides, and numerous accessory zircon.

5 (BE–548). Gray basal vitrophyre of lower-lobes tuff (lower part); same outcrop as sample 4 (BE–27); numerous accessory zircon.

6 (BE–546). Devitrified lower-lobes tuff (upper part); about 3.2 km above mouth of Red Canyon on mesa east of canyon at lat 42°18'45" N., long 116°51' W. Contains 24 percent phenocrysts that consist of 50 percent alkali feldspar, 26 percent quartz, 18 percent plagioclase, 4 percent altered pyroxene, 0.8 percent opaque oxides, and numerous accessory zircon.

7 (BE–531). Devitrified upper-lobes tuff; just south of road to Brace Brothers ranch on northeastern flank of Juniper Mountain at lat 42°28'32" N., long 116°50' W. Flow-layered ash-flow tuff, strong vapor-phase crystallization, with tridymite and alkali feldspar; contains 8 percent phenocrysts that consist of 56 percent quartz, 41 percent alkali feldspar, 2 percent plagioclase, 1 percent altered mafic minerals, and sparse accessory zircon.

8 (BE–547). Devitrified upper-lobes tuff on road between Trout Spring and Bull Basin at lat 42°24' N., long 116°48'20" W. Flow-layered, ash-flow tuff, strong vapor-phase crystallization, with tridymite and alkali feldspar and with incipient microlites that show weak flow alinement; contains 15 percent phenocrysts that consist of 60 percent alkali feldspar, 39 percent quartz, 1 percent opaque oxides and altered mafic minerals, and sparse accessory zircon.

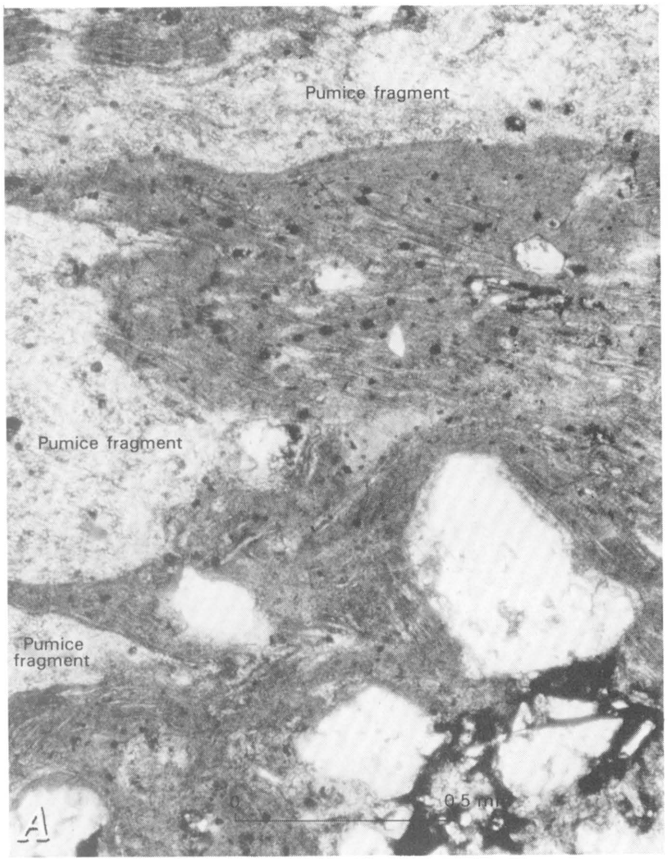
9 (BE–487). Devitrified tuff of The Badlands (phenocryst-rich lower part); Owyhee River canyon south of Lambert Table at lat 42°15' N., long 116°45' W. Flow-layered welded tuff contains 29 percent large phenocrysts that consist of 38.2 percent alkali feldspar, 37.5 percent plagioclase, 19.4 percent quartz as much as 5 mm long, 4.9 percent altered mafic, one grain allanite, and numerous accessory zircon and apatite.

10 (BE–488). Vitrophyre of tuff of The Badlands (top of phenocryst-rich lower part); same locality as sample 9. Top of rhyolite exposure contains 32 percent phenocrysts that consist of 44 percent alkali feldspar, 31 percent plagioclase, 21 percent quartz, 2.6 percent altered mafic minerals, 1 percent hypersthene, trace of opaque oxides, and numerous accessory zircon and apatite. One alkali feldspar (6 mm) with reaction rim of tiny plagioclase crystals.

State line on the road between the De Lamar open-pit silver mine, Idaho, and the village of Jordan Valley, Oreg. The type locality is designated as the northern wall of Wood Canyon in the SE¼ sec. 29, T. 5 S., R. 5 W. (pl. 1, fig. 9). In this vicinity, the tuff is as much as 50 m thick (including benches above cliff exposure) and rests on tuffaceous sedimentary rocks of the Sucker Creek Formation of Kittleman and others (1965). The tuff is overlain in this area by fan gravels and fanglomerate of late Pliocene or Quaternary age. The Swisher Mountain Tuff is the same as welded tuff no. 1 of Bennett (1976) and the same as the informally named rhyolite of Poison Creek of Neill (1975) who obtained K-Ar ages on sanidine of 13.5±0.2 m.y. and 14.2±0.4 m.y. (Armstrong and others, 1980). The average of these two dates (13.85 m.y.) is virtually the same as the K-Ar dates on the overlying, informally named lower-lobes and upper-lobes tuffs (see later pages).

The Swisher Mountain Tuff was deposited on a surface of considerable relief at the type locality, as expressed by abrupt changes in the elevation of the basal vitrophyre. The vitrophyre at the type locality shows minor brecciation; this may be due to incipient landsliding after emplacement on a sloping surface rather than to flowage at the time of emplacement. Farther north, however, in the Cow Creek drainage, the base of the tuff has true flow brecciation, and in a few places at the extreme north end of Swisher Mountain the unit consists entirely of flow breccia.

Despite the overall abundance of breccia, the unit



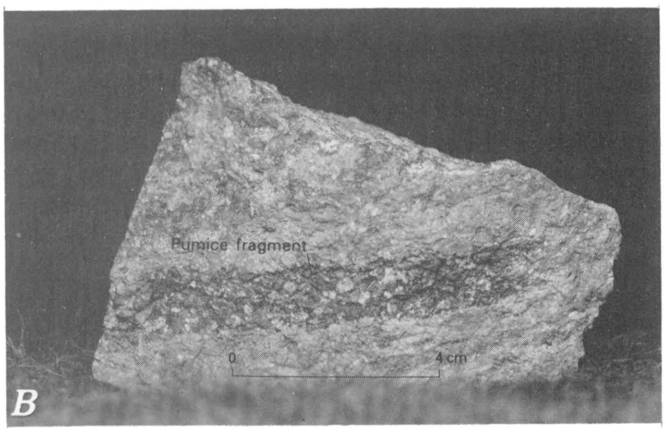


FIGURE 8.—Thin section (*A*) and hand specimen (*B*) of basal vitrophyre of tuff of Mill Creek. Note large pumice fragment in hand specimen. In thin section, pumice appears lighter than matrix; all crystals in this view are plagioclase; dark zone in lower right is altered volcanic lithic fragment.

does, nevertheless, exhibit well-flattened pumice fragments in a few local outcrops. One of these outcrops is about 9.6 km northeast of the type locality along the county road that follows the Cow Creek drainage between De Lamar and U.S. Highway 95 (pl. 1). A thin section of this rock shows that the flattened pumice fragments contain incipient feldspar microlites but that

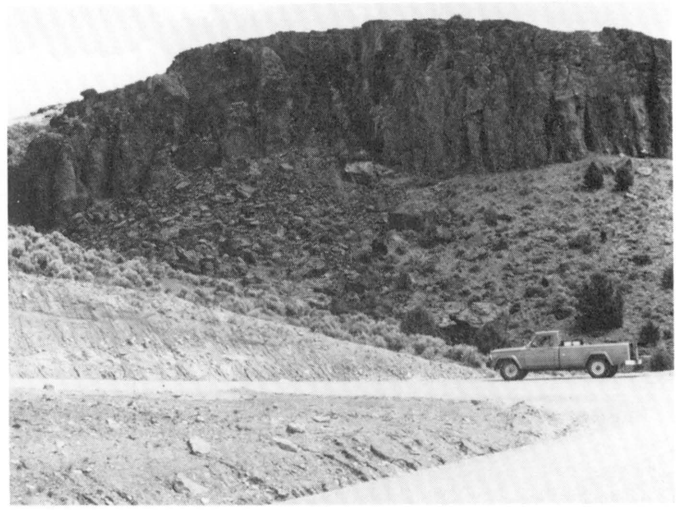
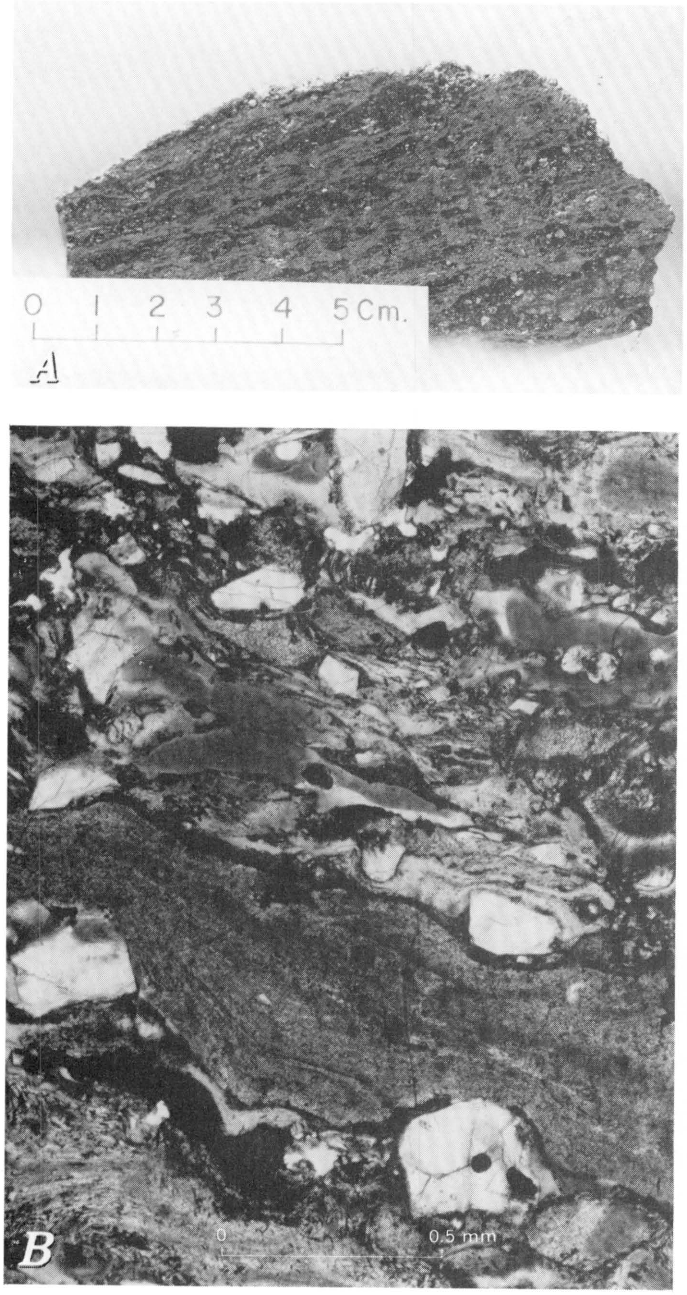


FIGURE 9.—View to the east of Swisher Mountain Tuff at type locality. Sedimentary rocks of Sucker Creek Formation are exposed in roadcut.

the shard matrix does not (fig. 10). We interpret this thin section as indicating that the rock in the basal part of this roadside exposure retained enough heat after final emplacement to liquify the volatile-rich pumice but not the shard matrix. The abundance of crystal fragments indicates that there was considerable crystal fragmentation during movement of this extremely hot ash flow. Broken crystals, however, are rare in outcrops of vitrophyre and in devitrified Swisher Mountain Tuff that show no preserved pyroclastic texture, and that we infer formed from completely liquified ash. In several places, such rock contains abundant tiny feldspar microlites (fig. 10). The vitrophyre from which this thin section was cut is homogeneous glass that shows only vague suggestions of outlines of former pumice.

At the type locality, the Swisher Mountain Tuff appears to be a densely welded, simple cooling unit. Southward toward the source area at or near Juniper Mountain, the unit is a compound cooling unit, and westward in Oregon, as will be explained on later pages, it appears to comprise two or more separate cooling units. In the Idaho exposures near Juniper Mountain, the Swisher Mountain Tuff is about 200 m thick and there are several vitrophyres within the sheet. Some of these are flow brecciated; others are massive. Several show only partly flattened pumice lapilli in shard matrices. The vitrophyres undoubtedly mark pauses and limited cooling between the eruptions of various ash flows, but whether or not any represent complete cooling breaks is unclear. None of the vitrophyre zones that were examined were accompanied by subjacent bedded tuff or nonwelded tuff. The lack of such material, as well as a lack of any indication of erosion beneath the vitrophyres, suggested to us



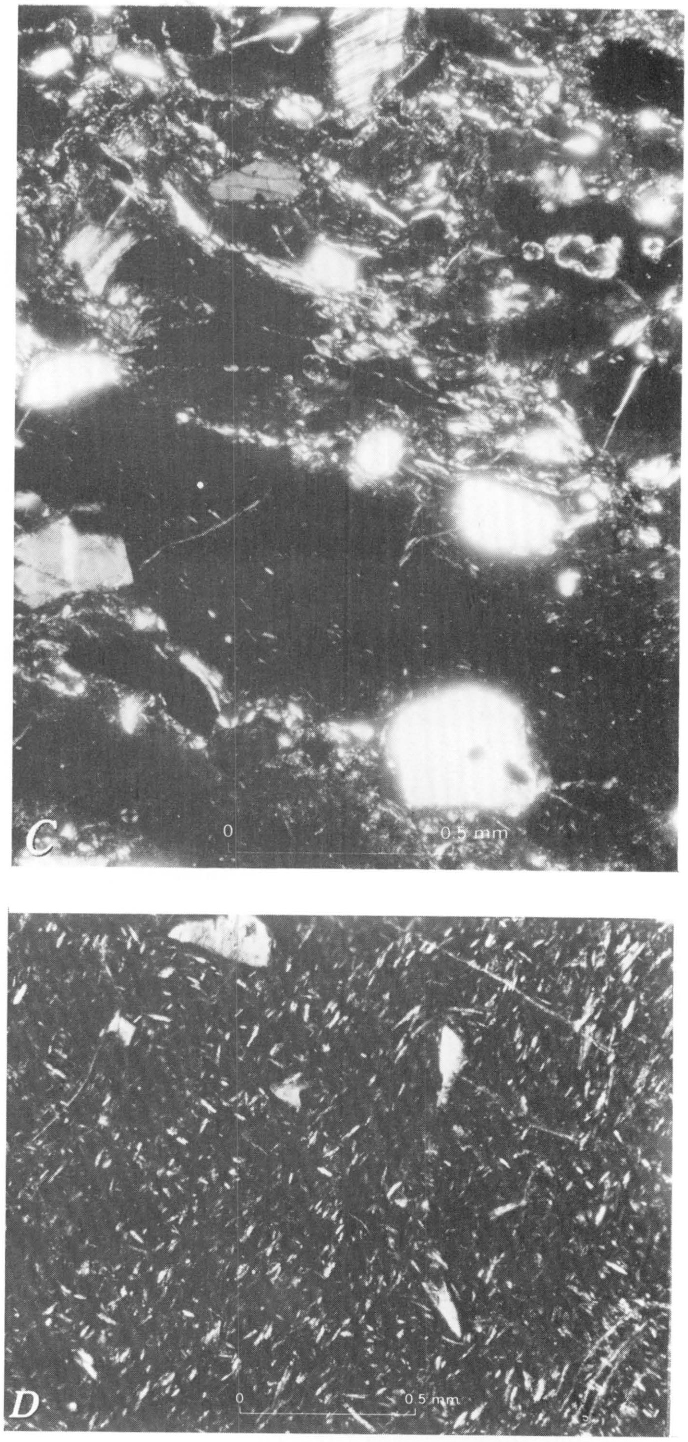


FIGURE 10.—Basal vitrophyre of Swisher Mountain Tuff. *A*, Hand specimen from outcrop 9.6 km northeast of type locality. *B* and *C*, Thin sections from hand specimen in *A* showing shards and pumice—note incipient feldspar microlites in pumice fragments. *B*, Plane light; *C*, crossed nicols. *D*, Thin section in crossed nicols of homogenous basal vitrophyre at type locality—note swarm of microlites.

(Ekren, McIntyre, and Bennett, 1978a) that most of the vitrophyres merely represent partial cooling breaks between ash flows. The presence of two or more cooling units in Oregon west of Juniper Mountain, however, suggests that the vitrophyres in Idaho mark significant cooling intervals.

Evidence that the Swisher Mountain Tuff is indeed a welded ash-flow tuff and not an unusually widespread rhyolite lava is not confined to a few local outcrops of basal and internal vitrophyres. The uppermost part in several exposures shows abundant pumice, and thin sections show that these pumice-bearing rocks have shard matrices. Figure 11 is a view of an outcrop and thin-section locality along the Mud Flat Road between

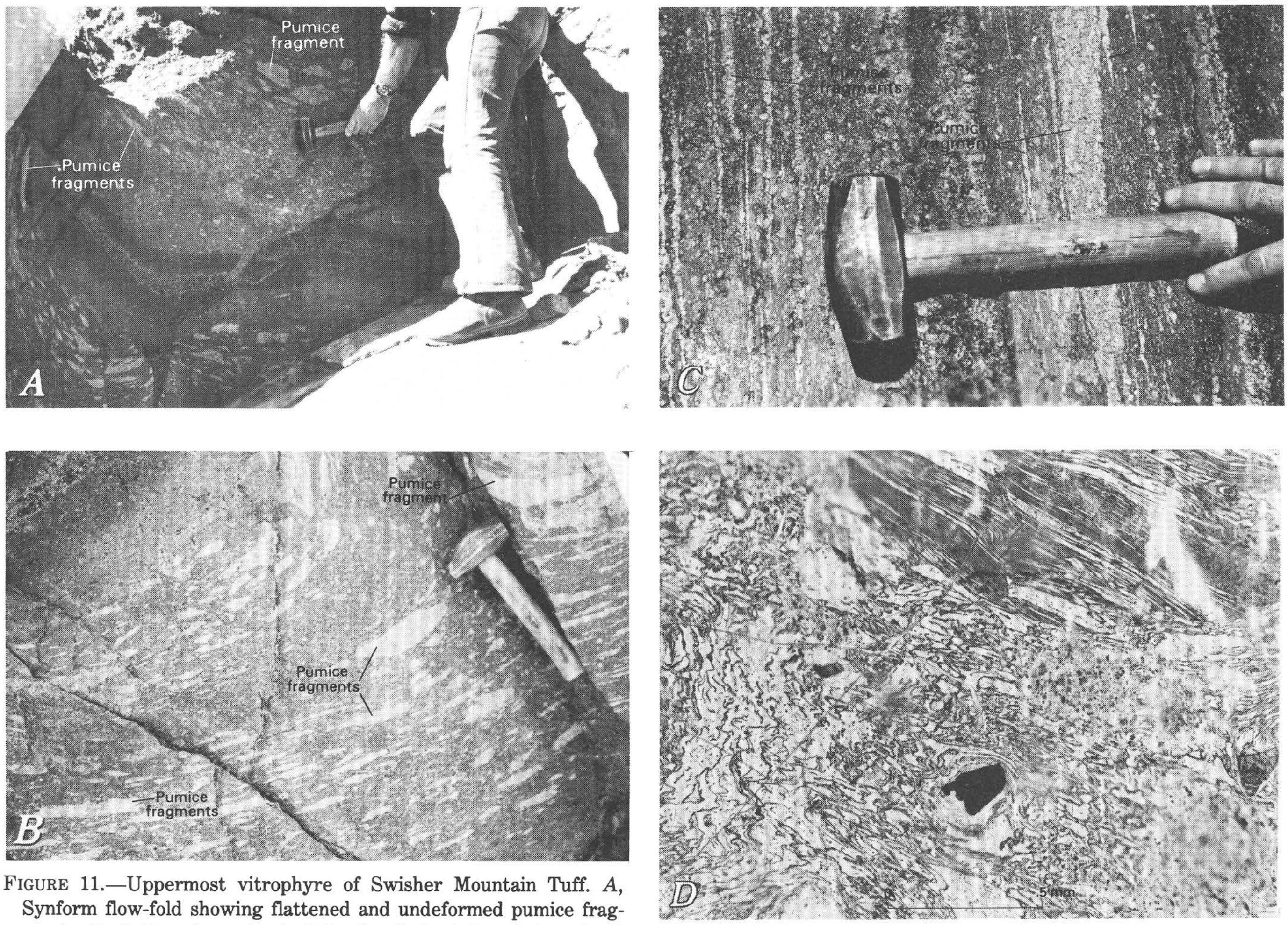


FIGURE 11.—Uppermost vitrophyre of Swisher Mountain Tuff. *A*, Synform flow-fold showing flattened and undeformed pumice fragments; *B*, flattened pumice to left of and about 1 m below *A*; *C*, stretched pumice from just below *B*; *D*, photomicrograph showing shards and cognate fragment in groundmass of vitrophyre viewed in *A*.

Grand View and Juniper Mountain. Figures 11*A* and 11*B* show flattened and undeformed pumice fragments in outcrop, and figure 11*D* shows unequivocal shards in thin section. The tuff beneath this upper part is mostly devitrified and is conspicuously flow layered. Pyroclastic textures have been completely destroyed, except where other vitrophyre zones mark partial or complete cooling breaks. The preservation of pumice in this uppermost part of the sheet and locally also in the basal and interior vitrophyres, is due to rapid cooling that effectively checked the coalescence of the ash to form liquid.

The Swisher Mountain Tuff is light gray, bluish gray, or brownish gray on fresh surface and weathers reddish gray and light brown; locally it weathers red and orange. With the exception of the thick Swisher Mountain Tuff exposed in the Owyhee River canyon south of Juniper Mountain (see later pages), the tuff shows a general upward increase in the abundance and size of phenocrysts and in the abundance of alkali feldspar. In the basal vitrophyre in exposures north of Juniper Mountain, the tuff contains about 15 percent phenocrysts that consist of 65–85 percent strongly and incipiently resorbed plagioclase about An_{30} in composition (table 6), 13–20 percent intermediate pigeonite, and only 5–15 percent alkali feldspar. Both feldspars rarely are larger than 4 mm. In contrast, the top of the Swisher Mountain Tuff in many localities, both north and south of Juniper Mountain, contains as much as 23 modal percent of phenocrysts; plagioclase constitutes only about 50 percent; alkali feldspar 35 percent or more; and quartz, as much as 3 percent. The plagioclase is as long as 6 mm and the alkali feldspar, 8 mm. Locally, the upper part is characterized by layers rich in phenocrysts of both plagioclase and alkali feldspar that alternate with layers low in phenocrysts, most of which are plagioclase.

The general tendency toward larger and more abundant phenocrysts of alkali feldspar upward and a corresponding decrease in plagioclase also is accompanied by

TABLE 6.—*Electron probe microanalyses (in weight percent) of plagioclase and pyroxene in the Swisher Mountain Tuff, the Jump Creek Rhyolite of Kittleman and others (1965), and the Little Jacks Tuff, Idaho*

[Analyst: C. R. Knowles, Idaho Bureau of Mines and Geology. nd, not determined]

	Swisher Mountain Tuff (Sample BE-29A)		Jump Creek Rhyolite (Sample BE-289)		Little Jacks Tuff (Sample BE-55A)	
	Plagioclase	Pyroxene	Plagioclase	Pyroxene	Plagioclase	Pyroxene
SiO_2----	61.22	50.23	62.79	50.25	60.80	49.83
Al_2O_3---	24.78	0.75	23.22	0.93	24.32	0.70
FeO-----	nd	33.74	nd	35.76	nd	37.83
MgO-----	nd	11.74	nd	11.62	nd	7.02
CaO-----	5.87	3.69	5.15	1.23	6.64	4.47
Na_2O----	6.97	nd	7.44	nd	6.73	nd
K_2O-----	1.14	nd	1.40	nd	1.51	nd
TiO_2----	nd	0.24	nd	0.18	nd	0.27

SAMPLE DESCRIPTIONS AND LOCALITIES

Sample BE-29A, oligoclase and intermediate pigeonite, collected from cuesta overlooking Poison Creek in NE¼ sec. 29, T. 8 S., R. 1 E., (lat 42°42′26″ N., long 116°21′25″ W.). See also table 7.

Sample BE-289, oligoclase and intermediate pigeonite, collected about 9.7 km southwest of French John Hill in SE¼ sec. 6, T. 1 S., R. 5 W. (lat 43°22′ N., long 116°58′05″W.). See also table 7.

Sample BE-55A, andesine and ferriferous pigeonite, collected from Perjue Canyon in NW¼ sec. 9, T. 8 S., R. 2 E. (lat 42°44′55″ N., long 116°13′40″ W.). See also table 7.

a slight decrease in amount of mafic constituents. As mentioned previously, pyroxene constitutes from 13 to as much as 23 percent of the total phenocrysts in the lower part; in the upper part, mafic constituents generally constitute less than 10 percent of the total phenocrysts. The pyroxene is principally intermediate pigeonite (table 6), but some thin sections contain a few grains of clinopyroxene that have a fairly large axial angle and also a few grains of ferrohypersthene. A few thin sections show hypersthene mantled with pigeonite.

A common feature of the Swisher Mountain Tuff is the presence of combined grains of alkali feldspar and plagioclase. Another common feature is the presence of alkali feldspar phenocrysts with reaction rims that consist of many tiny crystals of plagioclase. Less commonly, the plagioclase is rimmed with alkali feldspar. The alkali feldspar, whether occurring as discrete phenocrysts or as part of a duo with an attached crystal of plagioclase, shows considerable variation in axial angle, from 0° to at least 20°.

The Swisher Mountain Tuff has normal magnetic polarity and lies between two magnetically reversed units—the tuff of Mill Creek below and the lower-lobes tuff of Juniper Mountain above.

AREAL DISTRIBUTION OF THE SWISHER MOUNTAIN TUFF AND DESCRIPTIONS OF CONTIGUOUS ROCKS IN NEVADA AND OREGON

The inferred distribution pattern of the Swisher Mountain Tuff is shown in plate 2. The reasoning behind the various inferences that led to this pattern of distribution will be enumerated in a clockwise succession from southeast to northwest.

At locality 257 (pl. 2) in the Duck Valley Indian Reservation, flow-layered ash-flow tuff is exposed in a fault slice surrounded by basalt. The tuff contains plagioclase and alkali feldspar phenocrysts, both as long as 1 cm. Modes of this tuff indicate that it is either the lower-lobes tuff or the tuff of The Badlands. In isolated outcrop, the two units cannot be distinguished with certainty without magnetic measurements, and magnetic polarity was not determined here. The large phenocrysts strongly favor the tuff of The Badlands, but whichever unit it is, we infer that the Swisher Mountain Tuff probably is present at depth beneath the exposed rock because of the much wider distribution of the Swisher Mountain in areas where all three units (Swisher Mountain, lower lobes, tuff of The Badlands) are preserved. The reasoning, therefore, is as follows: If one of the younger tuffs of Juniper Mountain is present, almost certainly the Swisher Mountain is present also beneath the younger outcrops. None of the three units extend too far into Nevada in this area, however, because just southeast of Owyhee, Nev. (pl. 2), excellent exposures show that the pre-Tertiary strata there are directly overlain by the Cougar Point Welded Tuff, and thence by the Banbury Basalt (Coats, 1971).

South of Juniper Mountain, the unit is nearly continuously exposed from the junction of the South Fork Owyhee River and the main Owyhee River in Idaho, southward across the State line for about 9 mi (14.5 km) into Nevada (fig. 12). In this area, the tuff forms a gentle southeast-sloping ridge flanked by Banbury Basalt. The ridge is actually a plunging horst controlled by faults that, for the most part, predate the basalt (fig. 12). The base of the tuff is not exposed and the full thickness in this southern extremity, therefore, is unknown. The ridge in Nevada has about 75 m of relief, which indicates a minimum thickness for the unit. The tuff is covered by basalt south of the plunging horst-ridge, but the exposed thickness suggests the likelihood that the tuff continues southward at depth for a considerable distance beyond the southernmost outcrops (pl. 2).

Farther west in Nevada, just south of the Oregon State line and about 25 km east of McDermitt (fig. 12), the Swisher Mountain Tuff forms the highest rimrock along the southern margin of the Owyhee Plateau overlooking the East Fork Quinn River. The tuff is only a few meters thick in this area, so we presume the outcrop to be at or near the distal edge of the sheet. Two thin sections from the East Fork outcrop averaged 19 percent phenocrysts that consist of 59 percent plagioclase, 25 percent alkali feldspar, 12 percent pigeonite, 3 percent magnetite, and traces of ferrohypersthene and clinopyroxene that has a large axial angle.

The Swisher Mountain Tuff in the East Fork Quinn

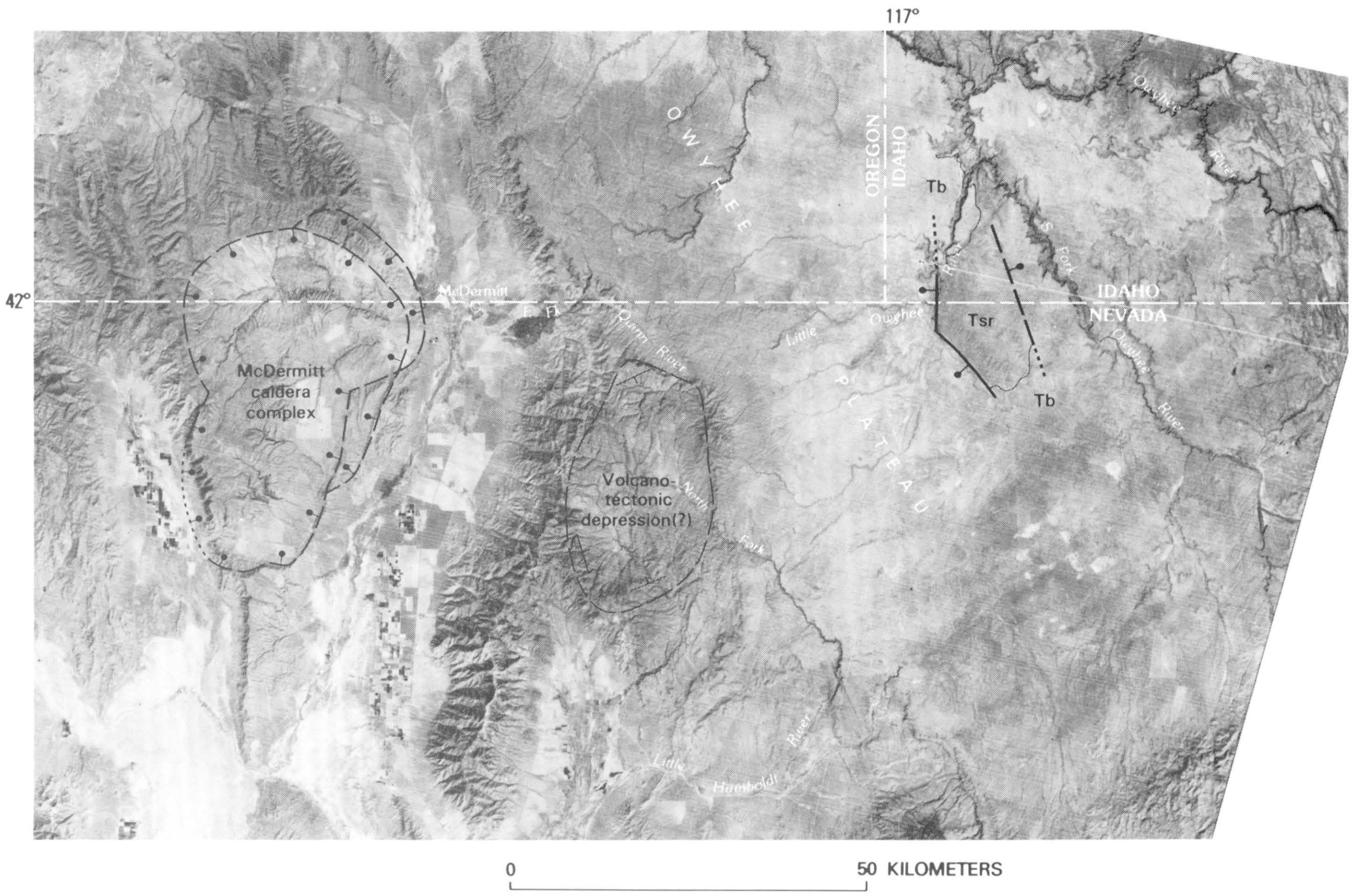


FIGURE 12.—Landsat image showing the southwestern edge of the Owyhee Plateau in Oregon and Nevada. The McDermitt caldera complex (Rytuba and Glanzman, 1978) and a saucer-shaped structure that may be a volcano-tectonic depression or caldera are indicated. Tb, basalt; Tsr, Swisher Mountain Tuff in horst block referred to in text. Faults and boundaries of volcano-tectonic structures are dashed where approximately located and dotted where concealed. Bar and ball on downthrown side of fault.

River area overlies a sequence of red, densely welded tuffs and lava flows(?) that is more or less continuously exposed from the road intersection with the Nevada State line to the Fort McDermitt Indian Reservation headquarters—a distance of about 25 km (road trending southwest from sample localities 271 through 272, pl. 2). The exposed sequence, in places 250 or more meters thick, consists of at least three cooling units. The lowest unit could be either a lava flow or a tuff; it lacks pyroclastic textures and contains myriad poorly alined feldspar microlites in the groundmass and abundant small, nearly circular vesicles filled with tridymite and alkali feldspar. The rock contains 6 percent phenocrysts that consist of 92 percent plagioclase as large as 3 mm and 8 percent altered mafic minerals. This unit is overlain by a similar unit that is indeed a densely welded ash-flow tuff that contains well-flattened pumice and that is characterized by a thick lithophysal zone at the top. The ash-flow tuff is also crystal-poor, containing principally plagioclase, but has sparse grains of vaguely twinned feldspar that we infer to be plagioclase partly replaced by alkali feldspar. The third unit is also an ash-flow tuff, and is characterized by alternating phenocryst-poor and phenocryst-rich (as much as 30 percent) layers. Some of the layers possibly constitute beds of welded air-fall tuff (agglutinate). This tuff closely resembles the Swisher Mountain Tuff in outcrop, and it has a mode that is extremely similar to that of the Swisher Mountain Tuff. It differs, however, in several ways. The unit contains numerous lithic fragments that have not been observed elsewhere in the Swisher Mountain. It also contains more phenocrysts than are common in the Swisher Mountain, and these include more grains of clinopyroxene that have a larger axial angle (2V) than generally is found in the Swisher Mountain. Some of these grains are zoned and have cores that yield larger axial angles than do the outer rims. This rock also contains plagioclase phenocrysts that are partly replaced by alkali feldspar, which suggests the possibility that it is genetically related to the underlying tuff. The feldspar grains that appear to be nearly wholly replaced show vague grid-twinning and have axial angles of about 50°, thereby suggesting that the replacement alkali feldspar is anorthoclase.

The three-unit (and certainly incomplete) sequence is not outflow from the nearby McDermitt caldera because outflow rocks from the McDermitt are all peralkaline and are characterized by phenocrysts of alkali feldspar and soda amphibole in a granophyric groundmass (Rytuba and Glanzman, 1978). Instead, the sequence is inferred to overlie the McDermitt rocks that have been dated at 15.8–17.9 m.y. (Rytuba and Glanzman, 1978). The possibility exists that the three-unit sequence and any buried genetically related rocks were erupted from a center just south of the East Fork Quinn River in the headwaters area of the North Fork of the Humboldt River. This area, when viewed from the southern edge of the Owyhee Plateau overlooking the East Fork has the appearance of a giant saucer-shaped depression with steep rims. The depression also is an outstanding feature on a Landsat image (fig. 12). It measures about 28 km north to south and about 19 km east to west. The geologic map of Humboldt County (Willden, 1961) partly outlines a structural basin on the western and southern flanks of this saucer-shaped feature.

In Oregon, west of the immediate vicinity of Juniper Mountain (pl. 2), rocks mapped as "partly to densely welded tuff and rhyolite or dacite flows" by Walker and Repenning (1966) include in many areas two red or reddish-gray cooling units of flow-layered welded tuff. The upper of these units we infer correlates with the middle and upper parts of the flow-layered Swisher Mountain Tuff as mapped in exposures north of Juniper Mountain, and the lower cooling unit correlates with the plagioclase-rich basal part of the Swisher Mountain Tuff as mapped in exposures north of Juniper Mountain. The upper cooling unit in Oregon, exclusive of the lobate lower-lobes tuff and tuff of The Badlands (pl. 1), correlates directly with the 200-m-thick Swisher Mountain Tuff exposed in the Owyhee River canyon south of Juniper Mountain along the Idaho-Oregon State line (the lower plagioclase-rich part is missing there, possibly because of high paleotopography—see later pages).

These correlations are based on the overall similarity of the units in outcrop, and the fact that thin sections from Oregon have the same features as thin sections in Idaho. If the correlations are valid, they indicate that the Swisher Mountain Tuff probably is a composite sheet (Smith, 1960; Christiansen, 1979). The sheet consists of a single compound cooling unit near the source area at Juniper Mountain and vicinity and at least two cooling units in Oregon. That a complete cooling break separates the two units in Oregon is indicated by numerous Owyhee River canyon exposures between the Idaho State line and Three Forks, Oreg. (pl. 2, loc. 638). In several of these exposures, bedded tuff, breccia, and soft nonwelded ash-flow tuff(?), that together are a few meters to several tens of meters thick, separate the two densely welded ash-flow tuff cooling units.

The mineralogic similarity of the upper and lower sequences of the Swisher Mountain Tuff in Idaho and Oregon is marked. For example, in the near vicinity of the Idaho-Oregon State line, the single exposed cooling unit of the Swisher Mountain Tuff, about 200 m thick, is characterized there, as it is also at Three Forks, Oreg., by numerous alkali-feldspar phenocrysts as long as 6 mm and occasionally 8 mm. A thin section taken from the lower outcrops in the river canyon about 2 km east of the Idaho-Oregon State line contained 20.2

percent phenocrysts that consisted of 48.1 percent plagioclase, 42.2 percent alkali feldspar, 7.4 percent pigeonite, 2.5 percent opaque oxides, and a trace of quartz. A sample from Three Forks in Oregon, where the unit is estimated to be about 170 m thick, contained 20.5 percent phenocrysts that consisted of 46.2 percent plagioclase, 42.8 percent alkali feldspar, 8.3 percent altered pyroxene, 2.5 percent opaque oxides, and a trace of quartz. These modes are similar to many that were obtained from the upper part of the Swisher Mountain Tuff in exposures north of Juniper Mountain. A thin section from the top of the tuff at the type locality, for example, contained 23 percent phenocrysts that consisted of 51 percent plagioclase, 29 percent alkali feldspar, 17 percent pigeonite, 3.5 percent opaque oxides, and trace amounts of quartz and hypersthene. The amount of pigeonite in this last sample is unusually high for the upper part of the Swisher Mountain Tuff. The average pigeonite content of five samples from other widely separated outcrops north of Juniper Mountain is only 8.3 percent. The overall phenocryst content of these same thin sections averaged 20.9 percent, and, in addition to 8.3 percent pigeonite, included 54.4 percent plagioclase, 34.6 percent alkali feldspar, and 2.6 percent opaque oxides. Three of the five samples contained trace amounts of quartz. Thus, the mineralogy of the upper part of the Swisher Mountain Tuff, including the thick, flow-layered upper cooling unit at Three Forks, Oreg., is remarkably consistent over broad areas.

The phenocryst mineralogy of the lower cooling unit in Oregon also is more or less repeated in several outcrops in Idaho where the lower part of the Swisher Mountain compound cooling unit is exposed. Two thin sections from outcrops several kilometers apart in the Owyhee River canyon south of Three Forks, Oreg., yielded an average phenocryst content of 16.7 percent consisting of 65 percent plagioclase, 12 percent alkali feldspar, 20 percent pigeonite, 2.7 percent opaque oxides, and trace amounts of ferrohypersthene. Two thin sections from Idaho—one from the basal vitrophyre at the type locality and another from Cow Creek near Swisher Mountain—yielded an average phenocryst content of 15 percent consisting of 70 percent plagioclase, 11 percent alkali feldspar, 14 percent pigeonite, 4 percent opaque oxides, and trace amounts of ferrohypersthene. The degree of resorption of the feldspar phenocrysts in the four thin sections is similar, and, in addition, one thin section from Idaho and one from Oregon each contained a phenocryst of alkali feldspar thinly mantled with plagioclase—a feature that is extremely common in the Swisher Mountain Tuff.

Between localities 637 and 638 in Oregon (pl. 2), the lower cooling unit just described is an extremely permeable rock judging from the abundance of warm springs that pour into the eastern side of the canyon from the densely welded interior of the unit. The amount of water from these abundant springs becomes an increasingly significant fraction of the Owyhee River northward from locality 637 toward the stream junctions at Three Forks, Oreg. (locality 638).

In the Owyhee River canyon at the Oregon-Idaho State line (pl. 2), a single exposure suggests that the lower cooling unit just described may be absent there. Two samples were taken of rocks at the State line that crop out directly beneath the massive cliff-forming cooling unit of the Swisher Mountain Tuff that contains the large alkali-feldspar phenocrysts. The two sampled rocks included a glassy flow breccia a few meters thick at the top and an underlying partly exposed red rock that could be either a flow-layered ash-flow tuff or a lava flow. The rocks are mineralogically similar, and, in general, are similar to rocks of the Juniper Mountain volcanic center, but they do not correspond to the plagioclase-rich lower cooling unit. They differ from the latter in having too much alkali feldspar, and both thin sections contain quartz. The upper sample contained 18 percent phenocrysts, of which 10 percent were quartz; the lower sample contained 16 percent phenocrysts, of which 13 percent were quartz. Both rocks contained subequal amounts of alkali feldspar and plagioclase, and both contained pigeonite as the principal mafic mineral. Because the phenocryst mineralogy is similar to that of other rocks of the Juniper Mountain volcanic center, a reasonable hypothesis is that the rocks are part of the Juniper Mountain volcanic sequence. A moot question, however, is where they fit into that sequence. Conceivably, they could be part of a local pile that was erupted during the hiatus between the lower and upper cooling units of the Swisher Mountain Tuff described earlier, or they could be part of a local pile that accummulated prior to the eruptions of both the lower and upper cooling units.

LOWER LOBES OF JUNIPER MOUNTAIN

Juniper Mountain and surrounding benches are formed of two rhyolite cooling units that on high-altitude infrared photographs and Landsat images have the appearance of two congealed masses of viscous molasses (figs. 7 and 13). Flowage of both units resulted in the formation of concentrically ridged flow lobes; as a consequence, the two units are informally called the lower lobes and upper lobes of Juniper Mountain. A startling feature of both units is the fact that without the lobate appearance of the units and the well-defined flowage structures that are visible on aerial photographs, an experienced volcanologist would not hesitate to call both units ash-flow tuffs on the basis of sparse occurrences of well-flattened pumice fragments within

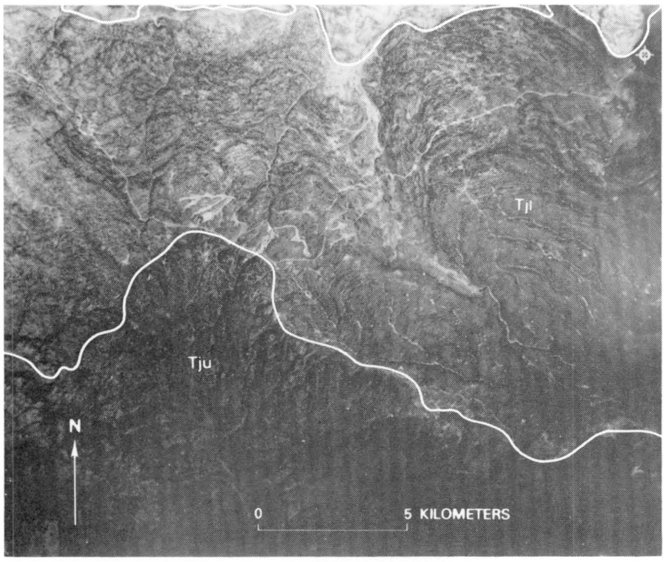


FIGURE 13.—High-altitude photograph of northern flank of Juniper Mountain showing upper and lower lobes. Tb, Banbury Basalt; Tju, upper-lobes tuff; Tjl, lower-lobes tuff. Photograph of infrared imagery by National Aeronautics and Space Administration. For location, see figure 7.

and at the bases of both units. We infer that both units are ash-flow tuffs that coalesced to form viscous liquids.

The lower lobes of Juniper Mountain form a series of irregular benches that are more or less concentrically arranged around the flanks of the mountain. The satellite image, however, shows an orientation of the lobes and a pattern of flowage-structures within the lobes that suggest a source area that is centered a few kilometers to the east and south of the mountain—an area that is now covered with basalt (fig. 7). The base of the lobate rhyolite mass is poorly exposed in and adjacent to Juniper Mountain, but the few good exposures indicate that the rhyolite rests directly on Swisher Mountain Tuff without intervening bedded air-fall tuff or nonwelded ash-flow tuff. Its basal vitrophyre is locally brecciated, and, on both the north and south flanks of the mountain, this vitrophyre rests directly on the flow-contorted uppermost vitrophyre of the Swisher Mountain Tuff. The two vitrophyres are not easily distinguished from one another because they both contain a similar assemblage of phenocrysts, and the phenocrysts are as large as 8 mm. The lower-lobes tuff, however, is magnetically reversed and the Swisher Mountain Tuff is normal. In addition to opposite magnetic polarities, the units are separable on the basis of relative abundance of quartz. The Swisher Mountain, even in its upper part, contains only a grain or two of quartz per fist-size hand specimen and the lower-lobes tuff, in contrast, contains 20 or more. Both vitrophyres have well-flattened pumice fragments, even where the vitrophyre of the lower-lobes tuff is brecciated. Boulder-size fragments as large as 30 cm in diameter in the breccia commonly contain several flattened pumice clasts. The presence of these clasts suggests that the brecciation occurred after the lower part of the mass had come to rest and after the basal vitrophyre had chilled. The basal brecciated vitrophyre, which is only a few meters thick, grades upward into flow-contorted vitrophyre, and thence upward into flow-contorted partly devitrified rock that is red gray on fresh surface and weathers red. The entire sequence is as much as 150 m thick in the exposures north of Juniper Mountain and 200 m thick in exposures south of the mountain. Within the sheet, well-flattened, and, for the most part, strung-out pumice fragments are visible in several zones.

The occurrence and abundance of flattened pumice in outcrops of the lower lobes are similar to that in outcrops of the upper part of the Swisher Mountain Tuff (fig. 11), thin sections of which show a matrix of shards. The upper vitrophyre of the Swisher Mountain also shows, albeit to a lesser degree, concentric flowage patterns with about the same orientations as the patterns in the lower-lobes tuff. We believe that the near-duplication of flowage patterns is highly significant and supports the inference that the two units were erupted from the same general source area. The well-preserved, viscous flow pattern of the lower- lobes tuff may, in fact, be somewhat misleading. Other units, including the Swisher Mountain Tuff, may have had much sharper flowage patterns prior to deep erosion, and their distal ends may have been lobate. Quick burial and recent exhumation account for the excellent preservation of the structures in the lower-lobes tuff. Nevertheless, the extremely lobate pattern probably indicates that the remobilized liquid of the lower-lobes tuff was more viscous than that of the Swisher Mountain Tuff and of other units as well (see discussion of Little Jacks Tuff).

The lower-lobes tuff typically contains about 25 percent phenocrysts that consist of 12–36 percent quartz, 50–66 percent alkali feldspar, 3–22 percent plagioclase, 2–7 percent pyroxene (principally the same intermediate pigeonite that characterized the Swisher Mountain Tuff), and 1–2 percent opaque oxides. Both the feldspars and the quartz are intensely resorbed; "sieve" grains are common. The degree of resorption contrasts strongly with that in the "typical" upper-lobes tuff (see later pages), and to a lesser degree with that in the underlying Swisher Mountain Tuff. The groundmass is mostly homogeneous—either entirely glass or weakly devitrified glass. Zones of vapor-phase crystallization are a common feature of the tuff, but the zones are not as strongly developed in the lower-lobes tuff as they are in the upper-lobes tuff. Two thin sections of basal glass from the lower-lobes tuff from outcrops that show stretched pumice clasts show a few clear-glass laminae in thin section that we interpret as stretched shards (fig. 14).

The lower-lobes tuff is magnetically reversed, and it is 13.8±0.5 m.y. old based on K-Ar analysis of sanidine from exposures south of Hurry Back Creek (pl. 1; table 2).

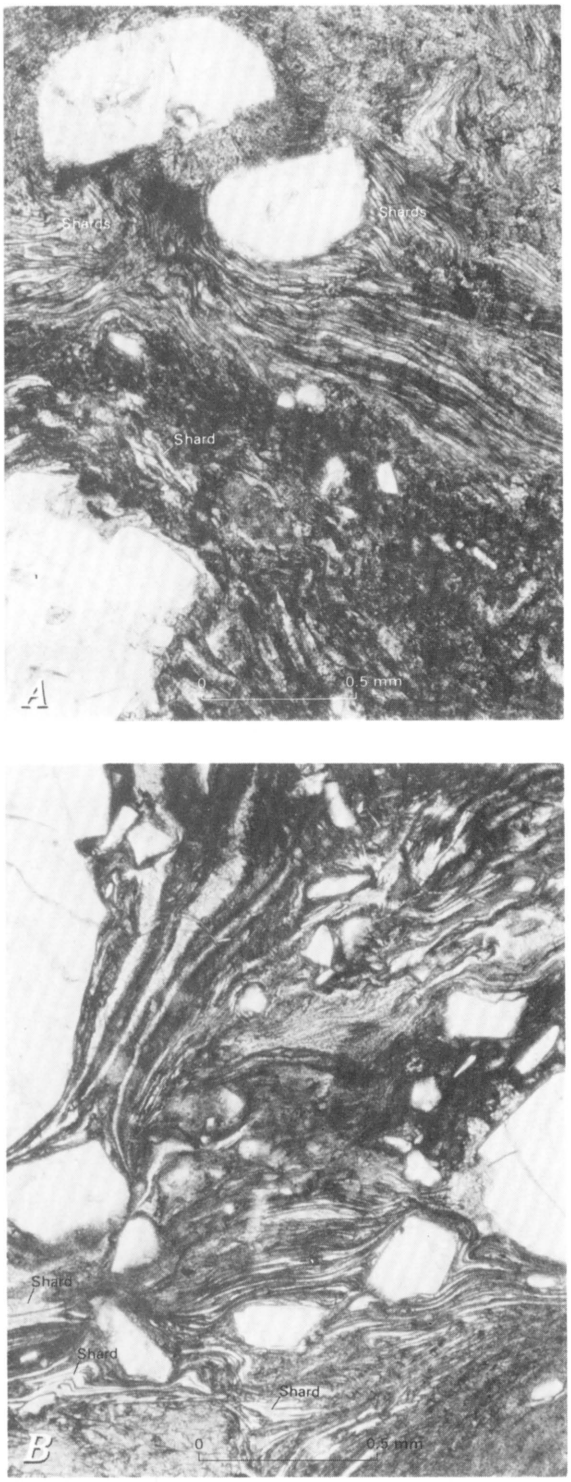


FIGURE 14.—Photomicrographs of the basal vitrophyre of the lower-lobes tuff showing contorted shards. *A*, From vitrophyre at southernmost outcrop of lower lobes south of Juniper Mountain; *B*, from vitrophyre at northernmost outcrop north of Juniper Mountain.

UPPER LOBES OF JUNIPER MOUNTAIN

The upper-lobes tuff forms the crest and a series of high benches that are more or less radially arranged around the summit of Juniper Mountain (pl. 1; fig. 7). The present-day radial pattern, however, probably is not due to Juniper Mountain being the exact center of eruption of the upper lobes, although this could well be true, but is due to gentle post-eruption doming that was centered on the present-day mountain. The juxtaposition of two flow-contorted rhyolites on the dome and the development of radial drainage give a false overall impression of the mountain being an incipiently dissected stratovolcano.

Concentric flow layering is not as well defined or as well preserved in the upper lobes as in the lower lobes and this fact, as well as the radial dissection, make it difficult to pinpoint the source area using the orientation of flow lobes and flow configurations as guides. We infer that the upper-lobes tuff and the lower-lobes tuff had a common source that was somewhat to the east and south of the present-day mountain, based on the aforementioned configuration of the radial pattern of the lower-lobes tuff.

Although Juniper Mountain does not appear to coincide precisely with the inferred source area, it is sufficiently close that the doming of Juniper Mountain must represent upward movement of the magma that gave rise to all the rhyolite units. Had the eruption of the various units caused a fault-bounded caldera-complex to form, Juniper Mountain would constitute a resurgent dome as defined by Smith and Bailey (1968). As such, it probably would be more or less centered over the magma chamber.

There is no brecciated vitrophyre at the base of the upper-lobes tuff. The basal part locally consists of alternating partially welded and moderately welded tuff that grades upward into densely welded tuff, and thence upward into flow-layered tuff in which nearly all pyroclastic textures have been destroyed. Exposures of partially welded tuff at the base are confined to the eastern and southeastern flanks of Juniper Mountain. The partially welded tuff apparently thins northward and westward and possibly pinches out entirely in those directions. In the northern and western exposures, the contact between the upper lobes and lower lobes is everywhere covered by thick talus or it is hidden by the overlapping tuff of The Badlands (pl. 1; fig. 7). In several places along the north flank, however, the covered interval is so thin that any hidden, partially welded tuff that is not flow layered would necessarily be correspondingly thin or absent.

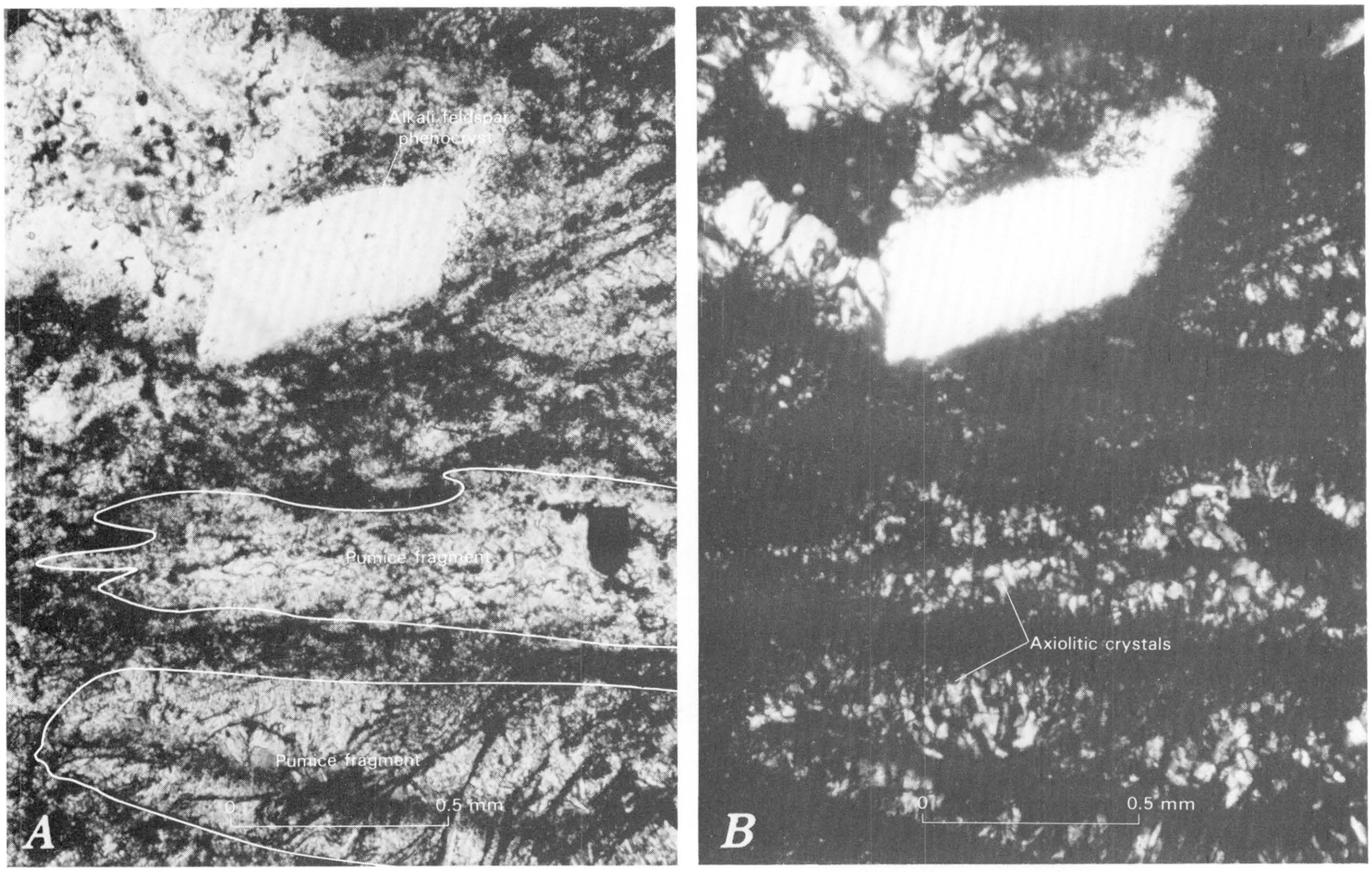


FIGURE 15.—Photomicrographs of partly devitrified tuff from the lower part of the upper-lobes tuff. *A*, Plane light showing flattened pumice (light tone); *B*, crossed nicols. In hand specimen, pumice fragments in this lower part are darker colored than the matrix.

On the east flank, the partially welded tuff is at least 100 m thick and consists of alternating weakly welded and moderately welded pink, red, and reddish-brown tuff that contains abundant, conspicuous pumice lapilli (fig. 15) that are, in general, darker than the enclosing matrix. We infer that this interval comprises a number of ash flows that were emplaced with sufficient time lapses between eruptions to at least have caused compound cooling. The moderately welded rock forms thin ledges, and the weakly welded rock forms slopes beneath and above. In most places there are two conspicuous ledges, and in a few places three or more are present; in a few localities the partially welded tuff at the top of the highest ledge can be seen to grade upward into densely welded tuff in which the pumice clasts show increasing degrees of flattening upward until, in a vertical distance of about 10 m, they become so stretched as to be nearly unrecognizable as pumice (fig. 16). Above this zone, the rock becomes flow layered and contorted, and stretched pumice fragments are preserved only locally. The flow-layered rocks form the lobate masses that are so conspicuous on aerial photographs.

The gradational nature of the contact between unequivocal welded tuff and the flow-layered rock that gave rise to flow lobes completely precludes the possibility that the rock is hybrid, formed in part from ash flows and in part from liquid lava. Had the eruptive material being spewed changed from ash to liquid, there necessarily would have been a time lapse between the rapidly emplaced ash flows and the slowly emplaced viscous lava flows, and there surely would have been some disruption of the underlying ash. No disruption is evident. In all likelihood, the slow moving viscous lava would have formed a flow breccia and none is evident. We infer instead that the evidence of denser welding upward in the upper-lobes tuff is due to gradually increasing emplacement temperatures as eruptions proceeded, and that the last flows were emplaced at such high temperatures that the extremely hot ash coalesced to form a liquid.

The outcrops just described can be regarded as the key to understanding the nature of the high-temperature rhyolites of southwestern Idaho. The outcrops show that the welded tuff did not simply become flow layered at the top because of laminar flowage (Walker

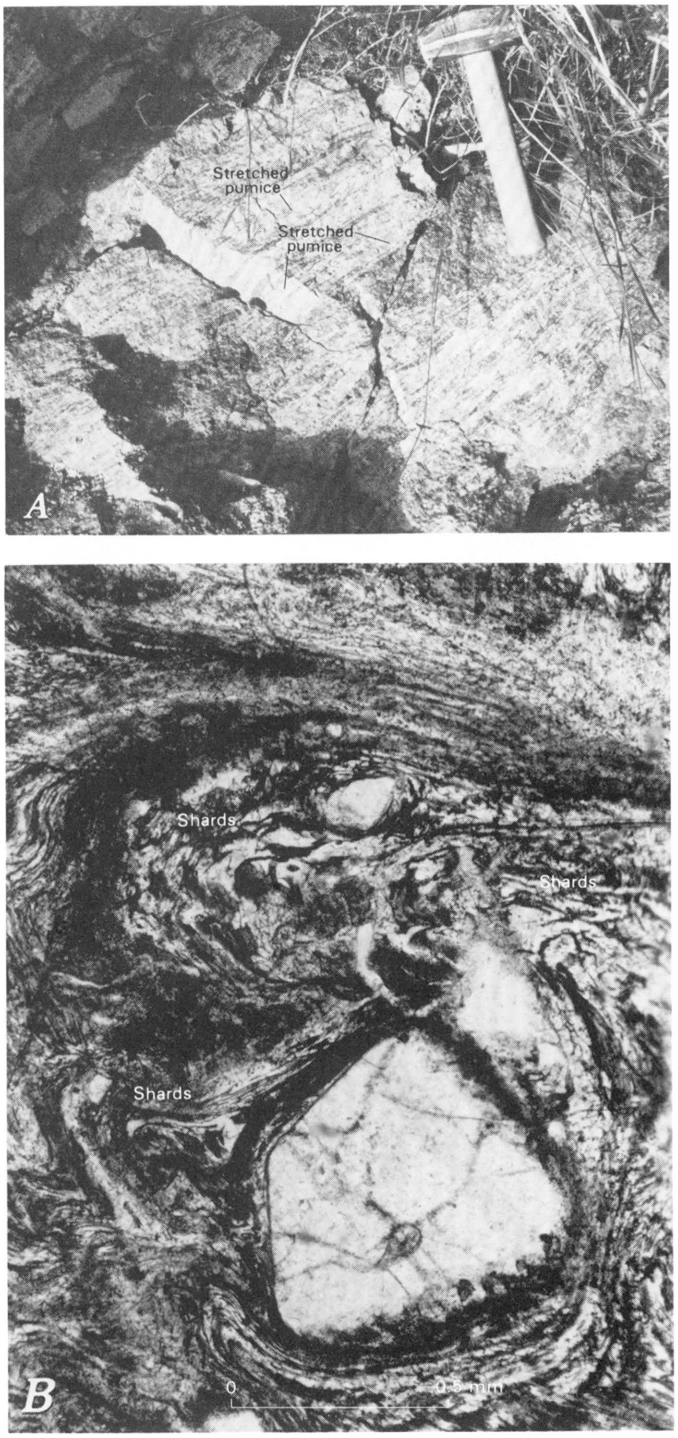


FIGURE 16.—Upper-lobes tuff in transitional zone below highly flow-contorted rock and above welded tuff that has well-flattened but not stretched pumice. *A*, View of outcrop showing stretched pumice; compare with fig. 11*C*. *B*, Thin section showing contorted shards and pumice.

and Swanson, 1968); the flow lobes indicate that the extremely hot ash coalesced to form a viscous liquid. The difference between the lower lobes and the upper lobes is merely that the initial ash flows of the upper lobes were colder. The last flows of the upper lobes, however, may have been hotter than the corresponding flows in the lower lobes because they apparently were less viscous, as suggested by less definition of concentric flow layering in the lobate masses of the upper lobes compared with the lower.

The relatively restricted areas of distribution of both the upper and lower lobes (compared with the distribution area of the Swisher Mountain Tuff) suggest that their eruption columns were not nearly as high as the column that gave rise to the Swisher Mountain. The smaller columns may have been somewhat analogous to fire fountains—a possibility that was first suggested by R. L. Christiansen (oral commun., 1977). If this is true, the columns nevertheless were at least sufficiently high to give rise to avalanches of hot particles (see "Nature of eruption column," this report) in order to account for the considerable diameters of distribution; for example, 56 km for the lower lobes.

The upper-lobes tuff typically contains 7–10 percent phenocrysts in the lower partially welded basal part and as much as 26 percent in the upper flow-layered part. Except for a few sparse and poorly exposed layers at and near the top of Juniper Mountain that contain phenocrysts as large as those in the tuff of The Badlands, the relative proportions and sizes of phenocrysts remain virtually the same from base to top. For the most part, the phenocrysts are smaller and less resorbed than are those in the underlying lower-lobes tuff, and they are also smaller and less resorbed than are those in the immediately overlying tuff of The Badlands (quartz, 2 mm in the upper-lobes tuff versus 4–6 mm in the adjacent rocks; feldspars, 3–4 mm versus 5–10 mm). The phenocrysts consist of 40–50 percent quartz, 40–50 percent alkali feldspar, and 0–3 percent plagioclase; mafic minerals constitute less than 1 percent of the phenocrysts and consist principally of completely altered pyroxene. The quartz grains are bipyramidal.

The few zones or layers at and near the top of Juniper Mountain that do not conform to the typical mineralogy just cited have modes that are virtually identical to those of the basal part of the tuff of The Badlands, and they are characterized by large quartz and feldspar phenocrysts, both of which are considerably resorbed. Exposures are poor in the areas where the large-phenocryst rocks were found, and although we were unable to determine conclusively that the rocks were interlayered with small-phenocryst tuff typical of the upper lobes, the evidence greatly favored that interpretation. Other interpretations that were considered include (1) the rocks are erosional remnants of tuff of The Badlands, and (2) they are discordant intrusive masses. If the rock with large phenocrysts is indeed part of the upper lobes tuff, then it follows that the magma supplying those layers came from the same part of the magma chamber that was later tapped to form the initial ash flows of the tuff of The Badlands. Furthermore, the final ash-flow eruptions of the tuff of The Badlands (see later pages) tapped the same part of the chamber that had earlier supplied most of the material for the upper-lobes tuff. In places, in fact, there may not be a cooling break between the upper-lobes tuff and the tuff of The Badlands.

The upper-lobes tuff has normal magnetic polarity and is 13.9±0.5 m.y. old based on analyses of sanidine from outcrops on the northeast flank of Juniper Mountain (table 2).

TUFF OF THE BADLANDS

Tuff of The Badlands is the name that we informally apply to the youngest cooling unit of the Juniper Mountain volcanic center. It forms the rugged topography at The Badlands (fig. 7) where its flow-brecciated black basal vitrophyre rests directly on red welded tuff of the upper-lobes tuff. The tuff of The Badlands was distributed over a broader area than that of the upper-lobes tuff. On the southern and western flanks, for example, the tuff of The Badlands rests directly on the lower-lobes tuff, and at Poison Creek at the extreme northeastern edge of its distribution pattern, it rests directly on the Swisher Mountain Tuff (fig. 7).

The tuff of The Badlands shows more extreme mineralogic variations internally than do the other units of the Juniper Mountain center among themselves. The basal part (as much as 200 m thick) locally contains the largest phenocrysts found in any of the Juniper Mountain rocks, and the upper part (also as much as 200 m thick) contains perhaps the smallest. The unit bridges the lithologies of the lower- and upper-lobes tuffs: the lower part of the tuff of The Badlands is a virtual repetition of the lower-lobes tuff, and the upper part is a repetition of the upper-lobes tuff. The lower part of the tuff of The Badlands sampled at localities 538 and 539 on the western flank of Juniper Mountain (fig. 7) is reddish gray and weathers brown or reddish brown, and the upper part at localities 3703 and 2707 (fig. 7) is pink or reddish gray. Sample 538 contains 24 percent phenocrysts that consist of 9 percent quartz, 53 percent alkali feldspar, 32 percent plagioclase, 6 percent altered pyroxene, and a trace of opaque oxides. The rock sampled at locality 539 contains 18 percent phenocrysts that consist of 28 percent quartz, 37 percent alkali feldspar, 28 percent plagioclase, 5 percent altered pyroxene, and 2 percent opaque oxides. The feldspar phenocrysts at these localities are as large as 1 cm. The modes, although typical of the lower part of the tuff of The Badlands, are also typical of the lower-lobes tuff. In contrast, the rocks at localities 3703 and 2707 (fig. 7) are modally indistinguishable from the upper-lobes tuff, and they contain a distinctively more rhyolitic phenocryst assemblage than do the rocks at localities 538 and 539. The samples contain 12 percent phenocrysts at locality 3703 and 18 percent at 2707; both contain 50 percent quartz, 50 percent alkali feldspar, and only trace amounts of plagioclase, altered pyroxene, and opaque oxides—modes that typify the upper-lobes tuff. The phenocrysts are mostly less than 3 mm long and they show only slight resorption effects.

The interval between localities 3703 and 2707 and localities 538 and 539 was not carefully traversed, but the exposures that were observed suggest that the contact between the mineralogically different zones is not abrupt. Zones of small-crystal tuff appear to be interlayered with zones of large-crystal tuff, and the former gradually becomes the dominant lithology upward.

In exposures on The Badlands and in the Owyhee River canyon (fig. 17) as far eastward as the pipeline crossing (fig. 7), the tuff of The Badlands, except for the large mass of rock exposed between Deep Creek and Battle Creek (fig. 7), consists only of the large-phenocryst lower part. In places in the canyon south of Lambert Table, the large-phenocryst rock has a vitrophyre at the base and also one at the top. The presence of the vitrophyre at the top, which is directly overlain by sedimentary rocks associated with the Banbury Basalt, indicates that the lower, large-phenocryst part of the tuff of The Badlands and the upper, small-phenocryst part are not a continuous simple cooling unit. Instead, the two parts are at least separated by a partial cooling break, and in the canyon exposures south of Lambert Table the upper part either was removed by erosion prior to the deposition of Banbury Basalt and related sedimentary rocks or it was never deposited there.

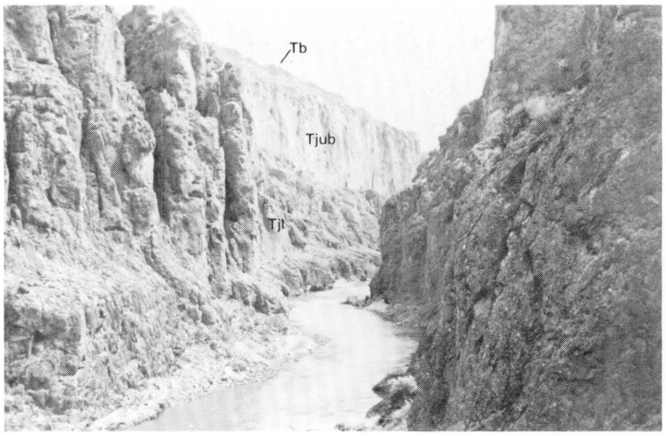


FIGURE 17.—Owyhee River canyon looking upstream showing tuff of The Badlands overlying the lower-lobes tuff. Tb, basalt; Tjub, tuff of The Badlands; Tjl, lower-lobes tuff.

The tuff of The Badlands in several places contains quartz phenocrysts as large as 8 mm. If these phenocrysts were consistently present throughout the unit they would provide a useful criterion to distinguish the unit from the lower-lobes tuff; unfortunately they are not. Where the large grains are present, however, they are spectacular because they have been so extensively resorbed. Commonly they are completely riddled with holes and show as virtual sieves in thin section. Alkali feldspar and plagioclase are similarly extensively resorbed. The degree of resorption of the crystals, however, is nearly matched by the crystals in the lower-lobes tuff.

Between Deep Creek and Battle Creek, the large outcrops labeled Tjub (fig. 7) consist entirely of the upper lithology of the tuff of The Badlands. The contact with the lower lithology (the large-phenocryst tuff) is not exposed. The exposed rock has modes that are virtually identical to those at localities 3703 and 2707 on the west flank of Juniper Mountain. The rock is flow layered and is characterized by intense vapor-phase crystallization, but, nevertheless, stretched pumice fragments are obvious in nearly all exposures. The rock in these exposures is as much as 200 m thick.

Elsewhere, the tuff of The Badlands is typically flow layered from base to top, and the basal vitrophyre commonly is extensively flow brecciated. In most exposures, however, the lower part as well as the upper, displays unequivocal stretched pumice, and thin sections from widely separated localities display highly deformed shards. If the correlation of the unit as far to the east as the Duck Valley Indian Reservation and to the west as far as Tent Creek in Oregon is correct, the unit is second only to the Swisher Mountain Tuff in areal extent of units erupted from the Juniper Mountain center.

Both parts of the tuff of The Badlands are magnetically normal. Armstrong and others (1980) reported a K-Ar age of 12.0 ± 0.2 m.y. on sanidine from an outcrop sampled by Neill (1975) at Poison Creek (fig. 7).

JUMP CREEK RHYOLITE

The Jump Creek Rhyolite of Kittleman and others (1965), defined from exposures in Jump Creek Canyon, northwest of French John Hill, (pl. 1), occurs as a widespread, sheetlike mass in the highlands adjacent to the Snake River Plain margin in the vicinity of the Idaho-Oregon State line. The Jump Creek Rhyolite, in places, rests on Miocene andesite and basalt, and in other places on sediments of the Miocene Sucker Creek Formation. It is overlain to the southeast by the tuff of Wilson Creek. The Jump Creek has a K-Ar age of 11.1 ± 0.2 m.y. (Armstrong and others, 1980); it has reversed magnetic polarity; and, on the basis of iron-titanium oxide data (table 7), it was erupted at a temperature of at least 1100°C.

The Jump Creek Rhyolite is grayish red to brownish gray, and contains 12 to 23 percent phenocrysts that consist mostly of conspicuous crystals of plagioclase as large as 15 mm. Quartz is present sporadically; locally it constitutes as much as 8 percent of the phenocrysts and the grains are as large as 4 mm. Also present, but readily seen only in thin section, are very fine (<1 mm) crystals of ferrohypersthene (table 6), sanidine (1–2 mm, rarely as large as 6 mm), clinopyroxene, apatite, and zircon; sparse olivine was observed in one thin section. The unit usually is conspicuously flow layered and tends to form bold bluffs. Individual ledge-formers that possibly constitute separate ash flows in these bluffs tend to be discontinuous, although some can be traced for several kilometers. Several ledges are markedly irregular in profile, and, in places, they thicken abruptly to form lobate masses that have flow layering parallel to the margins. The base of the Jump Creek commonly is marked by flow breccia as much as 20 m thick that consists of a rubble of vitrophyre blocks. At the mouth of Jump Creek Canyon is a well-indurated breccia of devitrified blocks that, toward the west, is overlapped by massive, flow-layered rock that forms the ledge at Jump Creek Falls. The breccia of devitrified blocks probably is tectonic having formed during a period of low-angle faulting. Numerous caves near the mouth of the canyon occur at the intersections of low-angle and high-angle faults. The rock at the intersections is brecciated and locally is iron-stained.

Most exposures of the Jump Creek Rhyolite show flow layering; locally, however, features are present that suggest well-flattened relict pumice and vague pyroclastic texture. Despite the occurrence of the irregular and commonly discontinuous ledge-forming units just described, the overall aspect of the Jump Creek is of a thick tabular sheet of broad areal extent. It covers a minimum area of about 270 km^2, with a possible additional 204 km^2 if the unit shown as Jump Creek Rhyolite by Kittleman and others (1967) south of the Mahogany Mountains, Oreg., is indeed part of the same unit. An unknown amount of the unit is buried beneath the Snake River Plain. This broad extent and the overall tabular shape of the Jump Creek suggest that the unit was emplaced as a series of hot ash flows with considerable flowage that followed initial emplacement in order to account for the general lack of pyroclastic textures and the thick flow breccia at the base.

Kittleman and others (1965) believed the Jump Creek Rhyolite to be of rhyolitic composition. Our one chemical analysis of a vitrophyre block from breccia at the base of the unit indicates that that particular basal part is of quartz latite composition (table 4). Based on the

TABLE 7.—*Electron probe microanalyses (in weight percent) of iron-titanium oxides in the Swisher Mountain Tuff, the Jump Creek Rhyolite of Kittleman and others (1965), and the Little Jacks Tuff, Idaho*

[Analysts: D. H. McIntyre and E. B. Ekren]

	Swisher Mountain Tuff (Sample BE-29A)		Jump Creek Rhyolite (Sample BE-289)		Little Jacks Tuff (Sample BE-55A)		Little Jacks Tuff (Sample BE-139A)	
	Magnetite	Ilmenite	Magnetite	Ilmenite	Magnetite	Ilmenite	Magnetite	Ilmenite
Fe------	59.05	38.77	56.70	38.21	55.40	37.57	53.23	33.23
Ti------	11.09	28.07	10.94	28.32	14.47	29.95	13.60	32.75
Al------	0.92	0.31	0.95	0.25	1.17	0.49	1.50	0.68
Mg------	0.42	0.72	0.39	0.63	0.27	0.40	0.48	0.56
Mn------	0.32	0.32	0.31	0.31	0.39	0.42	0.44	0.66

SAMPLE DESCRIPTIONS AND LOCALITIES

Sample BE–29A, collected from cuesta overlooking Poison Creek in NE¼ sec. 29, T. 8 S., R. 1 E.; lat 42°42′26″ N., long 116°21′25″ W.; same locality as age-dated sample NPS–1. Value for magnetite is average of three grains, and value for ilmenite is average of five grains.

Sample BE–289, collected about 9.7 km southwest of French John Hill in SE¼ sec. 6, T. 1 S., R. 5 W.; lat 43°22′ N., long 116°58′05″ W. Values for both magnetite and ilmenite are averages of five grains each.

Sample BE–55A, collected from Perjue Canyon in NW¼ sec. 9, T. 8 S., R. 2 E.; lat 42°44′57″ N., long 116°13′40″ W. Values for both magnetite and ilmenite are averages of three grains each.

Sample BE–139A, collected from Castle Creek in SW¼ sec. 26, T. 6 S., R. 1 W.; lat 42°52′16″ N., long 116°25′45″ W. Value for magnetite is average of five grains, and value for ilmenite is from one grain.

NOTE: All analyses are of grains from vitrophyres showing no evidence of post-emplacement oxidation. Of the more than 30 vitrophyre samples examined under the microscope, only the four reported here were judged to be suitable for microprobe analysis.

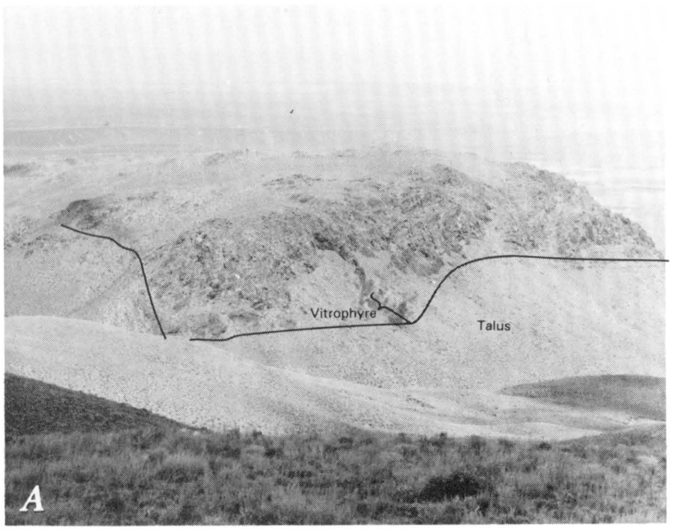
general tendency of rhyolites in southwestern Idaho to become more silicic upward, or, at least to contain a greater abundance of silicic phenocrysts upward, the possibility exists that analyses of rocks from the upper part of the Jump Creek would fall in the rhyolite field.

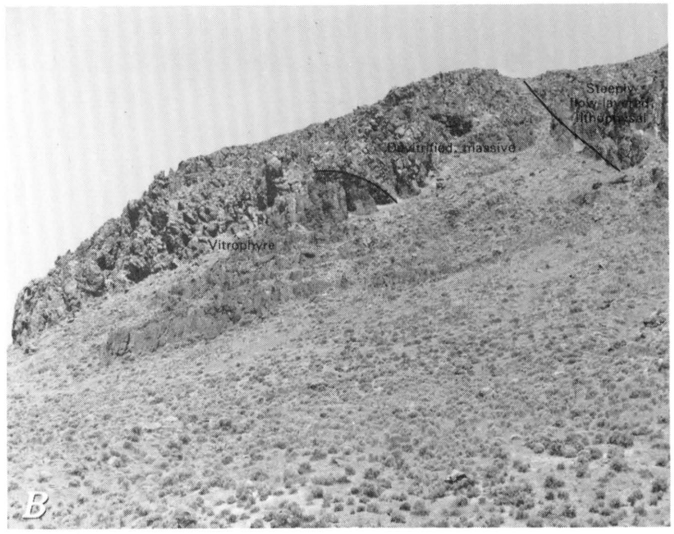
TUFF OF WILSON CREEK

The tuff of Wilson Creek occurs as a tabular sheet, much broken by minor faults, along the Snake River Plain margin and as a paleocanyon-filling tongue extending parallel to Wilson Creek. It is a simple cooling unit that locally is more than 170 m thick. Toward the northwest it overlies the Jump Creek Rhyolite, and toward the southeast it passes beneath the rhyolite of Browns Creek. The tuff of Wilson Creek is 11 m.y. old because K-Ar ages for both the underlying and overlying units are about 11 m.y. The unit has reversed magnetic polarity.

The tuff of Wilson Creek is chiefly grayish-red and grayish-red purple, crystal-poor, devitrified rhyolite containing less than 5 percent crystals (less than 2 mm in size) of quartz and sanidine in subequal amounts, together with seldom-seen clinopyroxene. The rare vitrophyric rocks in this unit contain a few crystals of biotite and plagioclase; the latter probably are xenocrysts. Lithic inclusions sparsely scattered throughout the unit are mostly of aphyric, trachytic-textured, plagioclase-rich andesite that occurs in the surrounding area, and, locally, beneath the tuff of Wilson Creek. Most outcrops of the tuff of Wilson Creek are devitrified, lithophysal, and finely flow layered. Along the canyon of Hardtrigger Creek near the Snake River Plain margin, the flow layering is thrown into broad folds. Toward the southwest, the folding disappears, and, at the southwesternmost end of the paleocanyon fill, flow layering is chiefly horizontal except where it steepens to meet the lateral margins of the paleocanyon.

The only known exposures of vitrophyre in the tuff of Wilson Creek are along the paleocanyon margins at the southwest end of the canyon fill. Some of this glassy material is as flow layered as the devitrified rock. However, exposures at Wilson Bluff, at the southwestern extremity of the paleocanyon fill (fig. 18), show abundant collapsed pumice fragments as much as 2×6 cm





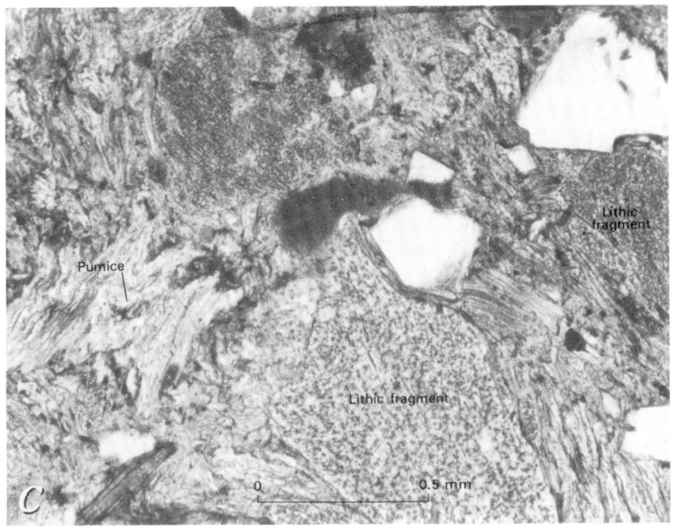


FIGURE 18.—Tuff of Wilson Creek—relations at southwest terminus of paleocanyon fill at Wilson Bluff. *A*, View toward northeast showing cross section of paleocanyon and location of pumice-bearing vitrophyre. *B*, View toward northwest showing pumice-bearing vitrophyre and devitrified, massive rhyolite that still shows fragmental character. The massive rhyolite grades abruptly into steeply flow-layered, lithophysal rhyolite in which all evidence of original fragmental character has been erased. *C*, Photomicrograph of vitrophyre showing pumice and lithic fragments and crystals of quartz, alkali feldspar, and biotite.

and similar-size lithic inclusions in a shard matrix in the marginal vitrophyre. Continuous exposures allow the vitrophyre to be traced upward and channelward into patchily devitrified rock that locally still preserves pumice outlines, and thence into steeply flow-layered lithophysal rock in which all traces of pyroclastic character have been erased. Continuing away from the margin, the steep flow layering flattens, merging with the layering in the inner part of the flow. No discontinuities interrupt the transition from pumice-rich vitrophyre at the paleocanyon margin to devitrified, flow-layered, lithophysal rock in the interior of the paleocanyon fill. These exposures provide firm evidence that the tuff of Wilson Creek is indeed a welded ash flow or flows whose fragmental texture has at most places been completely obliterated by flowage and the formation of lithophysae. Preservation of vitroclastic texture at the paleocanyon margins appears to be due to rapid chilling.

Geologic mapping shows that the paleocanyon occupied by the tuff of Wilson Creek could not have extended much farther southwest than where it is presently filled by the southwesternmost end of the tongue-like sheet. No possible source for the unit exists to the west or south; the tuff must have been extruded from a source to the northeast that is now buried beneath the Snake River Plain. Detailed study in the highlands to the southwest (McIntyre, 1972) showed that streams draining the highlands flowed toward the Snake River Plain during the time when the tuff of Wilson Creek was emplaced. Thus, the tuff of Wilson Creek must have flowed up-canyon during its emplacement, additional evidence that the unit moved as an ash flow and not as a viscous lava.

TUFF OF BROWNS CREEK

W. M. Neill (unpub. data, 1975) described a flow-layered rhyolite exposed in the vicinity of Browns

Creek in T. 5 S., R. 1 W. Neill did not designate a type locality, and, because of the limited distribution of the unit, we believe that a formal name is not warranted. Neill determined a K-Ar age of 11.0±0.7 m.y. reported in Armstrong and others (1980) for the unit, and noted its similarity to a rhyolite in the Reynolds Creek area for which he determined an age of 11.4±0.6 m.y. (Armstrong and others, 1980). On the basis of phenocryst mineralogy, the correlation appears to us to be reasonable, although the unit is not continuously exposed from Browns Creek on the south to Reynolds Creek on the north.

At Browns Creek and vicinity, the rhyolite tuff consists of two cooling units. The lowest unit appears to be magnetically normal and the highest probably is reversed. The remanent magnetization of the highest unit, however, is so weak (at least in the outcrops tested) that the measurements were inconclusive. The lowest unit contains 8–13 percent phenocrysts that rarely exceed about 3 mm in length. Quartz is generally the most abundant phenocryst, but alkali feldspar exceeds quartz in some thin sections. Plagioclase is much less common than either quartz or alkali feldspar in all outcrops examined. In thin section, plagioclase shows a range in volume from only 1 percent to a maximum of 18 percent of the total phenocrysts. The ferromagnesian minerals are extremely sparse and are completely altered. Vague crystal outlines suggest that these pseudomorphs are after pyroxene. The upper cooling unit is conspicuously porphyritic and contains alkali feldspar phenocrysts as large as 12 mm. This unit contains 25–39 percent phenocrysts that consist of 39–45 percent quartz, 39–50 percent alkali feldspar, 5–16 percent plagioclase, and trace amounts of altered ferromagnesian minerals.

Both units are flow laminated and flow layered, and in places they are extensively flow folded and flow brecciated. Both are gray on fresh surface and brownish gray and brown on weathered surface.

TUFF OF BROWNS CREEK AT REYNOLDS CREEK

The rhyolite tuff of Browns Creek in the Reynolds Creek area occurs as a single, narrow, northeast-trending tongue that, like the tuff of Wilson Creek, is also the erosional remnant of a paleocanyon fill. Margins of the paleocanyon, where preserved beneath the rhyolite of Browns Creek, are quite steep (fig. 19). The paleocanyon was carved chiefly in granitic rock by a stream flowing northeastward toward the Snake River Plain. Basaltic pyroclastic rocks locally are found beneath the rhyolite. Later streams were consequent on both marginal contacts of the rhyolite tongue; the stream following the northwest margin tapped drainage from the Reynolds Basin and cut a deep gorge along the northwest margin of the rhyolite tongue, forming the present Reynolds Creek. Near the plain margin, the tuff of Browns Creek overlies the tuff of Wilson Creek, and a K-Ar age of 11.4±0.6 m.y. was determined by Armstrong and others (1980) for the Browns Creek near the northeast divide of the Reynolds Basin. The unit has normal polarity, which suggests that it correlates with the lower of the two cooling units exposed in the Browns Creek area.

The basal rock of the tuff of Browns Creek in most outcrops in the Reynolds Creek area consists of massive devitrified rhyolite without obvious flow layering. A massive, flow-layered vitrophyre, 3 m or more thick, locally marks the base. Irregular basal zones of vitrophyre breccia are exposed only sporadically; these are not present beneath the westernmost 6 km of exposures. In a rock-walled draw in NW¼ sec. 3, T. 2 S., R. 3 W., however, a basal breccia is prominent. Several clasts in the breccia contain probable well-flattened pumice, and provide the only direct clue that this paleocanyon fill may have originated as an ash flow. As appears true for the rhyolite tuff of Wilson Creek, the rhyolite tuff of Browns Creek here flowed southwestward, upslope, away from the Snake River Plain,

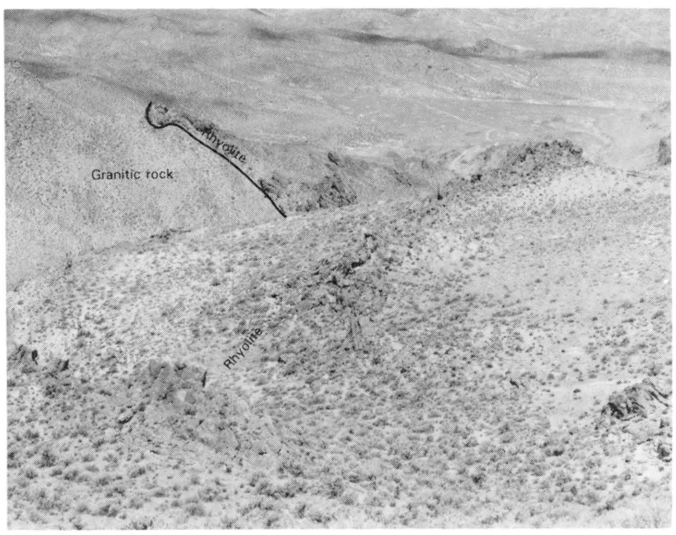


FIGURE 19.—View looking northward of steep irregular contact between the tuff of Browns Creek (rhyolite) and granite at margin of paleocanyon on lower Reynolds Creek.

TABLE 8.—*Chemical analyses and CIPW norms for the Little Jacks Tuff, Idaho*

[All analyses by X-ray fluorescence spectroscopy (analyses by: D. Hopping; chemical determinations of FeO, H_2O^+, H_2O^-, and CO_2 by P. Klock). All values in weight percent]

Sample No.--	1	2	3	4	5	6	7	8	9
Field No.---	BE-528	BE-530A	BE-530B	BE-529C	BE-529E	BE-16A	BE-16B	BE-205A	BE-205B
					Chemical composition				
SiO_2--------	69.65	70.66	72.05	73.32	73.03	71.45	71.99	74.09	72.10
Al_2O_3-------	12.89	12.61	12.60	12.50	12.33	12.13	12.47	12.09	11.90
Fe_2O_3-------	1.46	1.97	2.97	1.24	1.48	1.78	2.61	2.66	1.40
FeO---------	2.38	1.42	0.37	1.82	1.51	1.20	0.52	0.29	1.30
MgO---------	0.49	0.25	<0.02	<0.02	0.06	0.11	0.12	<0.02	0.13
CaO---------	2.03	1.46	1.19	1.15	1.14	0.94	0.92	0.56	0.99
Na_2O--------	2.80	2.39	3.00	2.89	2.94	2.67	3.15	2.91	2.42
K_2O---------	4.47	5.34	4.95	5.10	5.03	5.51	5.21	5.40	6.17
H_2O^+--------	1.59	2.64	0.42	0.13	0.28	1.96	0.47	0.58	2.44
H_2O^---------	0.41	0.36	0.74	0.18	0.39	0.62	0.45	0.43	0.45
TiO_2--------	0.63	0.49	0.49	0.42	0.42	0.35	0.37	0.37	0.37
P_2O_5--------	0.18	0.11	0.10	0.08	0.08	0.07	0.10	0.05	0.04
MnO---------	0.061	0.050	0.03	0.044	0.040	0.045	0.054	0.021	0.043
CO_2---------	0.10	0.05	0.08	0.04	0.11	0.16	0.53	0.12	0.02
Sum-------	99.141	99.80	99.01	99.934	98.84	98.995	98.964	99.591	99.773
Na_2O+K_2O----	7.29	7.73	7.95	7.99	7.97	8.18	8.36	8.31	8.59
Na_2O/K_2O----	0.63	0.45	0.61	0.57	0.58	0.48	0.60	0.54	0.39
Na_2O/CaO----	1.38	1.64	2.52	2.51	2.58	2.84	3.42	5.20	2.44
					Normative composition				
Q-----------	31.84	34.25	34.36	34.58	34.89	34.41	33.98	36.28	33.22
C-----------	0.43	0.64	0.58	0.42	0.43	0.63	1.47	0.85	0.00
or----------	27.19	32.60	29.90	30.56	30.28	33.77	31.40	32.38	37.62
ab----------	24.39	20.89	25.95	24.80	25.34	23.43	27.19	24.98	21.14
an----------	8.51	6.41	4.85	5.00	4.52	3.31	0.57	1.72	3.49
di-wo-------	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.49
di-en-------	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16
di-fs-------	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.35
hy-en-------	1.26	0.64	0.00	0.00	0.15	0.28	0.30	0.00	0.17
hy-fs-------	2.30	0.27	0.00	1.73	0.95	0.25	0.00	0.00	0.38
mt----------	2.18	2.95	0.13	1.82	2.19	2.68	0.83	0.07	2.10
hm----------	0.00	0.00	2.94	0.00	0.00	0.00	2.09	2.65	0.00
il----------	1.23	0.96	0.86	0.81	0.81	0.69	0.70	0.67	0.73
ap----------	0.44	0.27	0.24	0.19	0.19	0.17	0.24	0.12	0.10
cc----------	0.23	0.12	0.19	0.09	0.25	0.38	1.23	0.28	0.05

because no possible source for the unit exists toward the west.

LITTLE JACKS TUFF

A compositionally distinctive sequence of flow-layered and nonwelded rhyolite tuff that for the most part contains only plagioclase and ferriferous pigeonite phenocrysts (tables 6 and 8) is well exposed throughout a large part of the eastern Owyhee Plateau (fig. 7). The best exposures are in Little Jacks Creek canyon about 35 km south of Grand View, Idaho, where at least four cooling units are exposed. This sequence is

TABLE 8.—*Chemical analyses and CIPW norms for the Little Jacks Tuff, Idaho*—Continued

SAMPLE DESCRIPTIONS AND LOCALITIES

[Listed by sample number. (Field number in parentheses.) All samples contain accessory apatite and zircon, but the zircon is extremely sparse]

1 (BE–528).	Basal vitrophyre of unit of uncertain stratigraphic position exposed in horst about 3 km southeast of mouth of Little Jacks Creek canyon at lat 42°43′ N., long 116°04′ W.; contains 11.6 percent phenocrysts that consist of 76 percent plagioclase, 18 percent pigeonite, 6 percent opaque oxides. Normal magnetic polarity.
2 (BE–530A).	Basal vitrophyre of lowest exposed Little Jacks Tuff at type locality at lat 42°40′ N., long 116°08′10″ W.; contains 12.3 percent phenocrysts that consist of 78.2 percent plagioclase, 18.7 percent pigeonite, 3.2 percent opaque oxides. Reversed magnetic polarity.
3 (BE–530B).	Devitrified; same outcrop as sample 2 (BE–530A).
4 (BE–529C).	Basal vitrophyre of unit exposed just above creek level at mouth of Little Jacks Creek canyon at lat 42°43′10″ N., long 116°06′25″ W. Unit is inferred to correlate with unit 3 (counting from top of section downward) at the type locality. Contains 7.5 percent phenocrysts that consist of 81.3 percent plagioclase, 18.7 percent pigeonite, and trace of opaque oxides.
5 (BE–529E).	Devitrified; same outcrop as sample 4 (BE–529C).
6 (BE–16A).	Basal vitrophyre of highest cooling unit at type locality at lat 42°40′ N., long 116°08′10″ W.; contains 6.8 percent phenocrysts that consist of 82 percent plagioclase, 18 percent pigeonite, and a trace of opaque oxides. Reversed magnetic polarity.
7(BE–16B).	Devitrified; same outcrop as sample 6 (BE–16A).
8 (BE–205A).	Brecciated devitrified tuff exposed in road cut at Mud Flat at entrance to Bureau of Land Management camp at lat 42°36′18″ N., long 116°33′ W.; contains 5 percent phenocrysts that consist of 80 percent plagioclase, 18 percent pigeonite, and 2 percent opaque oxides. Reversed magnetic polarity; presumed to be part of unit 1.
9 (BE–205B).	Brecciated vitrophyre from same outcrop as sample 8 (BE–205A).

named herein Little Jacks Tuff, and the type locality is designated as the east wall of the canyon at the junction of a large tributary (Rattlesnake Creek of local usage) in SW¼ sec. 5, T. 9 S., R. 3 E. (pl. 1, fig. 7). The Little Jacks Tuff corresponds to the tuff of Antelope Ridge of Bennett (1976) and the rhyolite of Owyhee Plateau of Neill (1975) who obtained K-Ar ages of 9.6±2.0 m.y. and 10.0±1.5 m.y. on plagioclase (Armstrong and others, 1980).

The type locality of the Little Jacks Tuff can be reached via a dirt road that leaves the gas-pipeline road at elevation 5,025 ft (Ekren and others, 1981). Near the type locality, the canyon is about 275 m deep, and the tuff forms as many as six distinct rims that are each 15 m to as much as 100 m thick (fig. 20). Only four of the rims are traceable over long distances and these are separated from each other by slope-forming covered intervals that in places, at least, consist of nonwelded tuff. Because of the extensive covered zones, the number of individual cooling units present is not known with certainty. On the east side of the canyon, where there are only four distinct rims, the bases of the upper three rims all include black flow-banded vitrophyre in the lowest exposed parts. These vitrophyres are inferred to rest on soft, nonwelded shard tuff that is nearly completely covered at the type locality but that is only locally exposed in other areas (fig. 21). Despite the covered intervals, at least four cooling units certainly are present at the type locality on the east side of the canyon. On the west side of the canyon, in contrast, (fig. 20) there are locally six distinct rims. The second and third rims counted from the top are inferred to merge into a single thick rim about 90 m thick on the east side of the canyon; and the fourth and fifth rims actually merge into a single thick rim within the view of the photograph (fig. 20). All these rims possibly constitute separate cooling units, but, if they do, they are only locally separated by soft tuff because there is no nonwelded tuff within the two merging zones on the east side. Glassy zones do occur, however, in the approximate middle of each of the two thick rims, thereby suggesting the presence of at least partial cooling breaks. We conclude, therefore, that at least four cooling units are exposed in the vicinity of the type locality, and the possibility exists that as many as six are present. Magnetic polarity measurements indicate that the lowest rim whose base is not exposed (fig. 20) is reversed; the next higher rim (90–100 m thick) is normal; and the next higher rim (90 m thick), which probably comprises two separate cooling units, is weakly magnetic; the upper part possibly is reversed and the lower part possibly is normal; and the mesa-capping highest rim (about 15 m preserved thickness) is reversed.

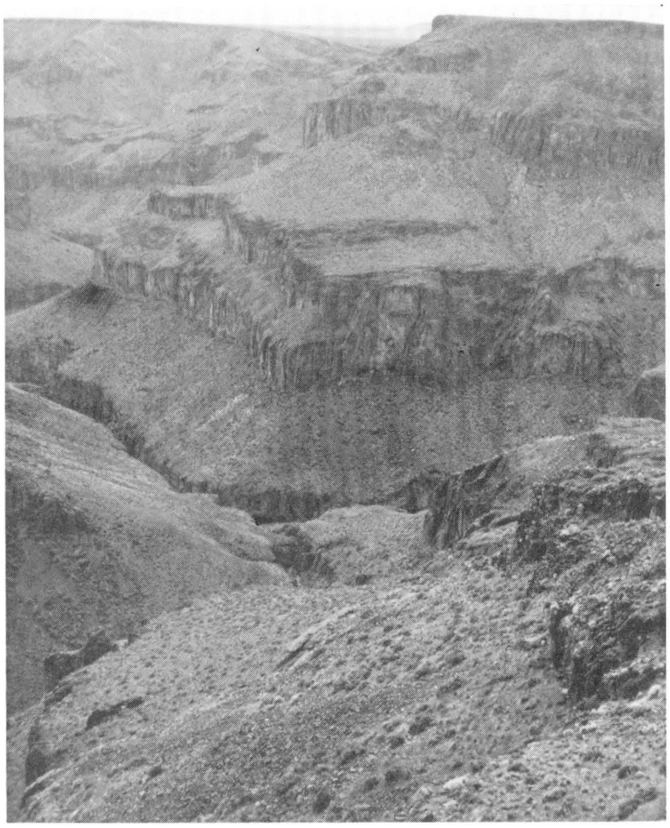


FIGURE 20.—West side of Little Jacks Creek canyon opposite type locality of Little Jacks Tuff. Here the tuff forms as many as six distinct rims, each of which possibly constitutes a separate cooling unit.

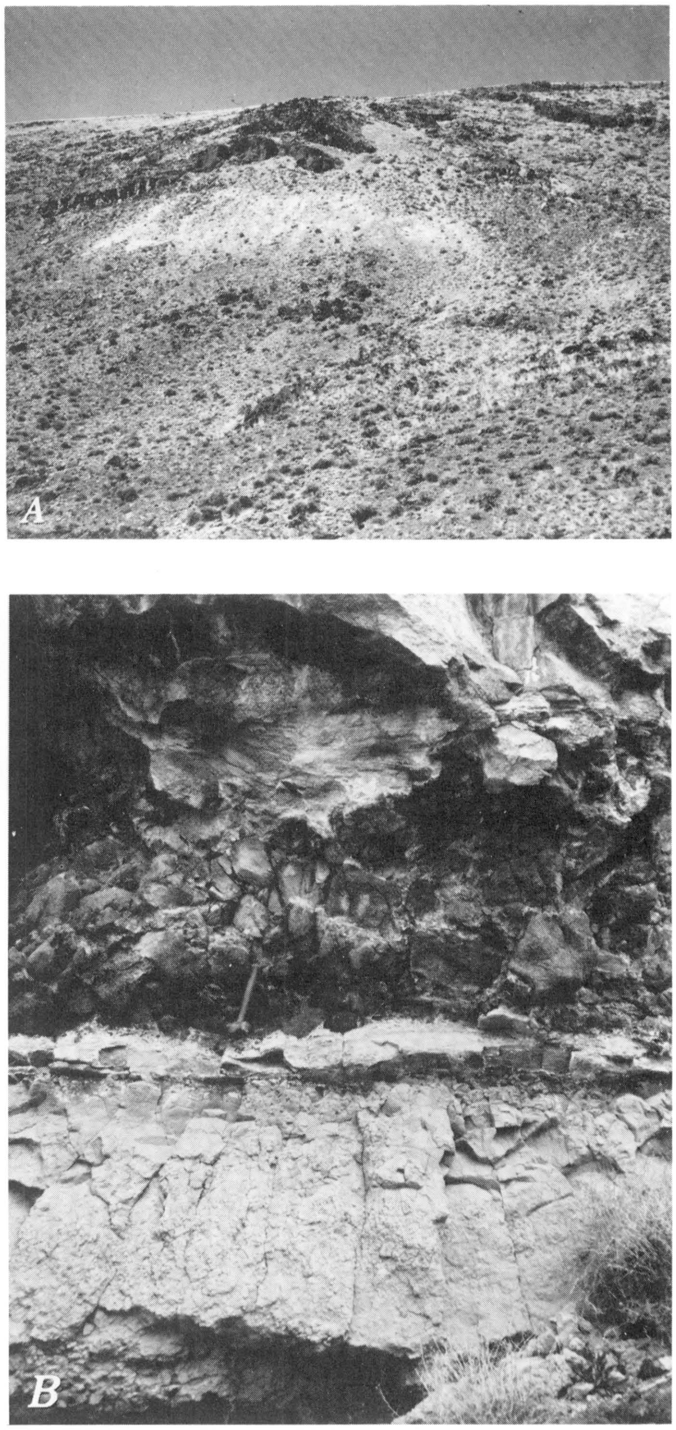
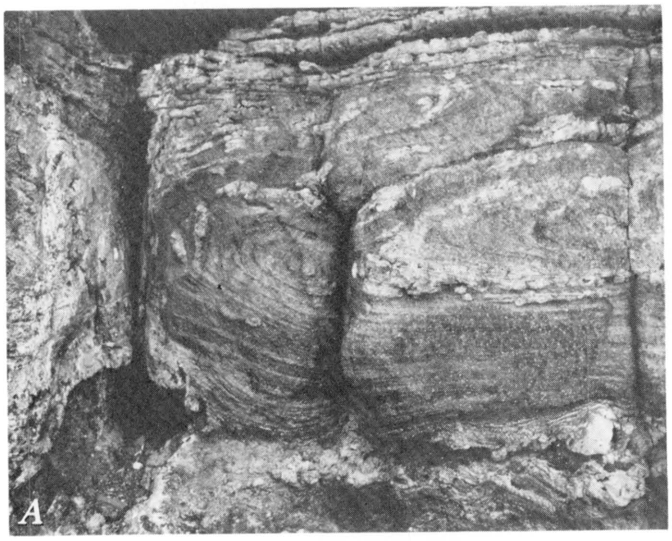


FIGURE 21.—Rarely exposed soft tuff zones beneath densely welded cooling units of Little Jacks Tuff. *A*, High cooling unit exposed a few kilometers east of Little Jacks Creek canyon; *B*, base of unit at locality of sample 1 (table 8) exposed a few kilometers east of Little Jacks canyon—note basal breccia.

The densely welded devitrified rock of the Little Jacks Tuff in all the four or more cooling units is medium gray to purplish gray on fresh surface, and is dark reddish brown or purple on weathered surfaces; rarely it weathers deep red. Because of its well-developed flow layering, the tuff weathers flaggy, and the flagstones in most areas completely cover underlying zones of soft tuff. The flagstone slabs commonly have surfaces with distinctive round, cup-and-saucer-shaped depressions. The soft tuff zones are so seldom observed that the overall properties of the zones and their relationships to overlying and underlying rim-forming densely welded tuffs are poorly known. In the few outcrops that were found (for example, fig. 21), the ash is mostly yellow brown and is virtually without crystals. The lack of crystals and local observations that the overlying rocks rest disconformably on the soft tuff indicate that the soft tuff probably is never part of the same cooling unit that includes the overlying cliff. Far more likely is the possibility that the nonwelded crystal-poor tuff is not genetically related to any of the densely welded units, or, if it is, it is related to the underlying cooling unit, possibly constituting coignimbrite ash as defined by Sparks and Walker (1977).

The densely welded rocks are extensively flow folded and flow layered (fig. 22), and in most exposures the



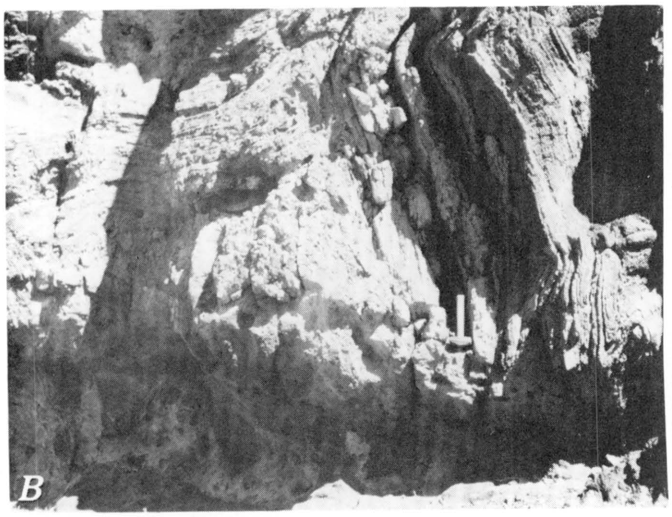


FIGURE 22.—Flow layering in units 2 and 3 of Little Jacks Tuff. *A* and *B*, Recumbent and steep flow layering at base of unit 3 exposed near mouth of Little Jacks Creek canyon (scale is the same in both photographs)—note flow breccia at base in photo *B*; *C*, flow layering in glassy zone within probable unit 2; *D*, flow layering in devitrified part of unit 2 in exposure a few kilometers east of Little Jacks Creek canyon.

basal vitrophyres of the various cooling units include 2–5 m of flow breccia (see for example fig. 21). The rocks, in fact, in at least 95 percent of all outcrops have all the features indicative of lava flows and none characteristic of ash-flow tuffs. In a few outcrops, and in a few thin sections from widely separated outcrops, however, the units do show preserved pumice (fig. 23). Shards are visible also in some thin sections as, for example, in a thin section from the basal vitrophyre of unit 3 (counting from the top) (fig. 24). The thin section cut from a sample taken nearest the base (fig. 24*A*) shows thick-walled shards; a thin section taken from the base of the same cooling unit exposed about 1 km upstream (fig. 24*B*) has a flow-textured glass matrix with shards nearly totally destroyed; and a thin section from a sample taken about 0.5 m above that in figure 24*B* shows a matrix of homogeneous perlitic

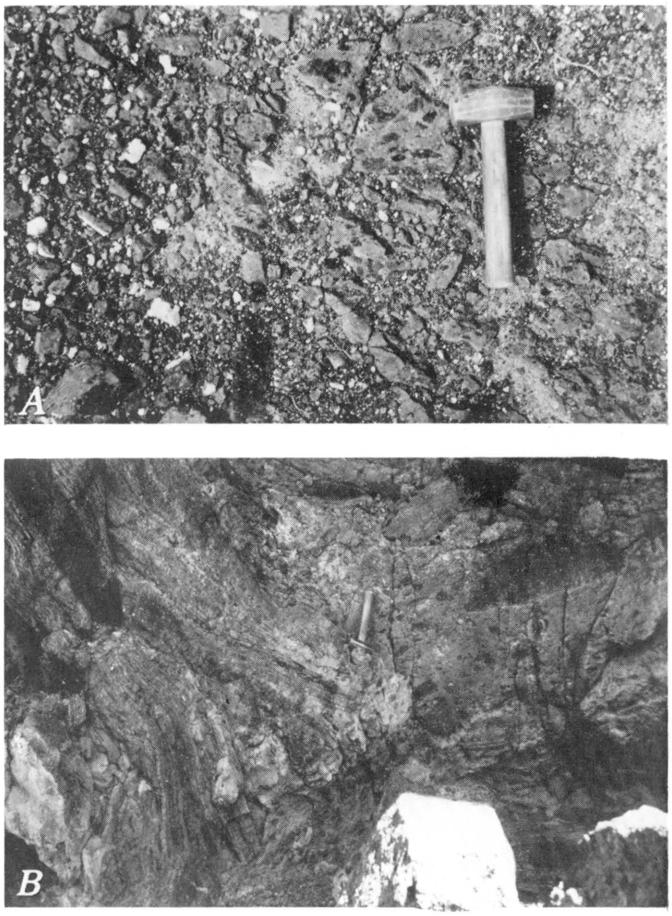


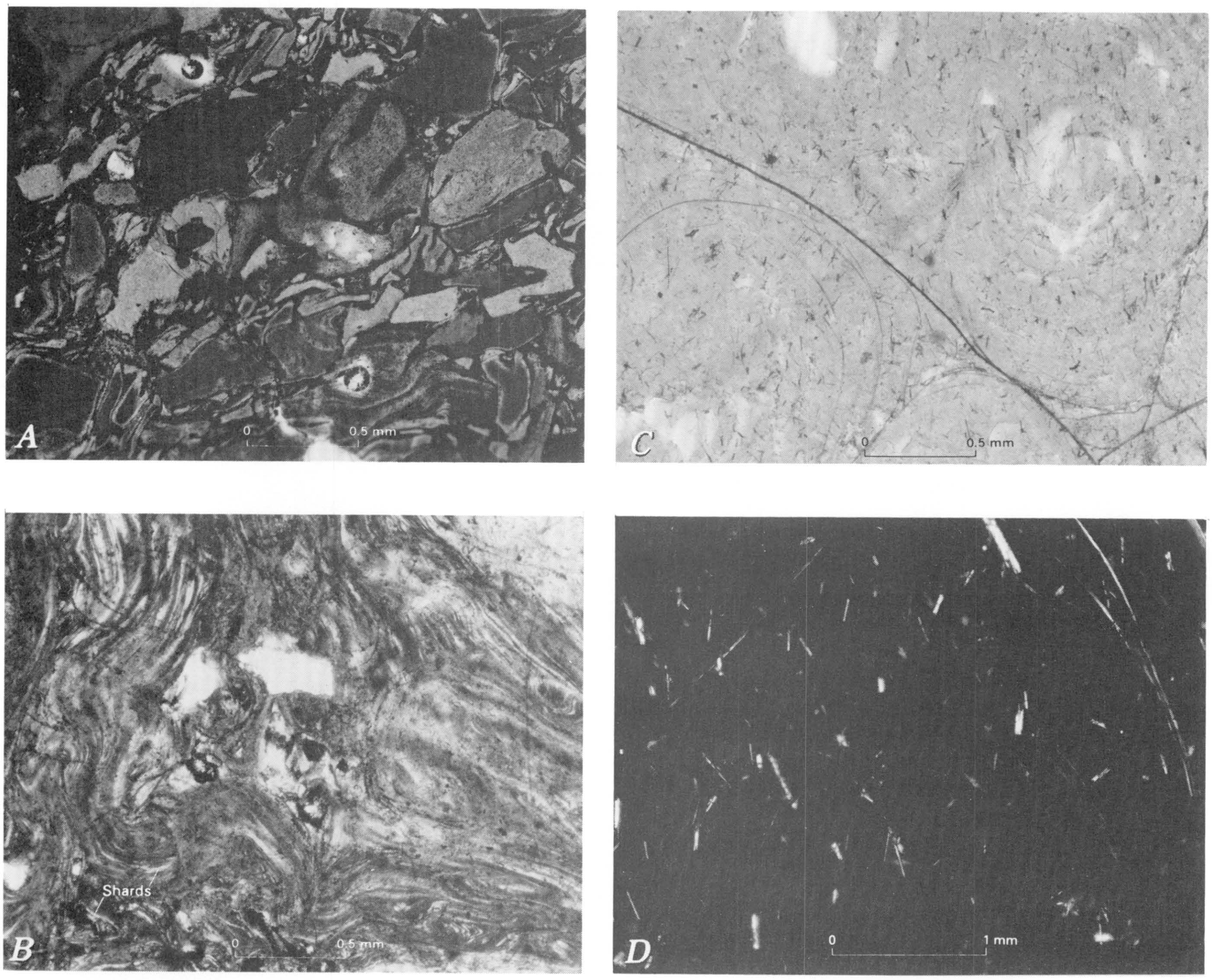
FIGURE 23.—Pumice in outcrops of Little Jacks Tuff. *A*, Partly flattened pumice at top of unit 3; *B*, basal flow-layered layered and brecciated unit 3 showing local zone of breccia with preserved pumice clasts; *C*, close-up view of pumice zone shown in *B*.

glass with crystallites and incipient microlites (fig. 24*C*,*D*).

The phenocrysts throughout the Little Jacks Tuff (fig. 25) rarely are crushed or shattered, thereby suggesting that the conversion from ash to homogeneous glass (figs. 22 through 25) is almost completely a function of temperature. Had the ash been compacted into homogeneous glass (figs. 22 through 25) primarily as a function of lithostatic loading and flowage, many of the fragile, extensively resorbed plagioclase crystals surely would have been shattered.

The basal vitrophyre that yielded the thin sections (fig. 24) is as much as 10 m thick in the vicinity of the sample localities, and weathers to massive outcrops without visible layering, partings, or flow brecciation. In many other areas, however, this vitrophyre is extensively flow layered, is locally flow brecciated, and commonly is flow folded (fig. 22). We believe that the extensive flow layering of the various units, as well as their local flow-brecciated bases, constitute ample evidence that the ash flows coalesced to liquids before final emplacement and cooling. Furthermore, several thin sections of Little Jacks Tuff from various localities throughout the mapped area (pl. 1) show the development of incipient tiny feldspar microlites like those shown in fig. 24*D*. A few thin sections show a virtual felt of the tiny microlites, and many thin sections show a pronounced flow alinement of the tiny microlites. The microlites must have formed after liquefaction of the ash and before the mass had come to rest.

Along the edge of the Snake River Plain near the confluence of Little Jacks and Big Jacks Creeks (pl. 1, fig. 7), the Little Jacks Tuff consists entirely of flow breccia (fig. 26). Unknown is whether this breccia comprises parts of several cooling units or of a single unit. The degree of brecciation diminishes gradually upstream along both creeks from the confluence southward toward the plateau. Within the plateau, where both creeks have carved deep canyons into the Little Jacks Tuff, flow breccia is confined to thin zones (a few meters or less thick) at the bases of the various cooling



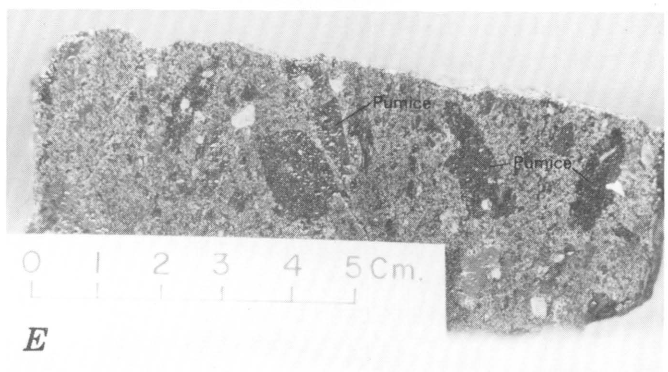


FIGURE 24.—Basal vitrophyre of unit 3 of Little Jacks Tuff in Little Jacks Creek canyon. *A-D*, photomicrographs. *A*, Lowest exposed part of massive-weathering basal vitrophyre showing virtually undeformed thick-walled shards. *B*, Sample at base of unit 3 exposed about 1 km upstream from locality of sample *A* showing highly deformed shards. *C*, Sample about 0.5 m above that in *B* showing homogeneous perlitic glass with incipient crystallites; shards are totally destroyed; plane light. *D*, View of same field as *C* but with higher magnification showing incipient feldspar microlites, crossed nicols. *E*, Photograph of hand specimen from which sample in *A* was cut.

units. The abundance of breccia at the confluence is extremely puzzling. The area of outcrop is complexly faulted (fig. 7), and the faults strike parallel to the edge of the Snake River Plain. Perhaps the breccia formed when partly solidified rock cascaded down pre-tuff fault scarps; conceivably the rock was further brecciated by contemporaneous fault movements before final cooling. The latter fault movements could have been triggered by major earth tremors that undoubtedly accompanied the massive eruptions of the Little Jacks Tuff, which we infer was erupted from a center only about 20 km southeast of the confluence of the two creeks. In Big Jacks Creek, especially just above the junction with Little Jacks Creek, the flow breccia is cut by several steeply layered dikelike masses that have the same mineralogy as the breccia. These masses were thought

FIGURE 25.—Photomicrograph of 4-mm-long plagioclase phenocryst in basal vitrophyre of unit 3, Little Jacks Tuff. From same thin section as that in figures 24*C* and *D*. Dark haloes are inked circles on cover glass; circle above phenocryst is field of figures 24*C* and *D*.

FIGURE 26.—Flow breccia of Little Jacks Tuff exposed along Big Jacks Creek just above junction with Little Jacks Creek. Largest blocks in breccia in this view are about 50–70 cm long.

by Littleton and Crosthwaite (1957, p. 160) to be possible feeder dikes. We believe that the dikelike masses are best explained as remobilized liquid fractions that ascended from the base of the pile into tensional fractures.

The Little Jacks Tuff in the northwestern part of its outcrop area, near Mud Flat (fig. 7), weathers to a peculiar wavelike or dunelike pattern that is distinctive on aerial photographs (fig. 27). This pattern was noted first by Bennett (1976, p. 22, fig. 9). The "waves" consist of bedrock; they strike northwest, and, like current-ripple marks, they are asymmetric. The "waves" have their steep faces toward the northeast (fig. 27) and their gentle faces toward the southwest. The wave or dunelike features do not represent ash-flow movements during emplacement because they do not conform to flow-lineation trends (fig. 7) and they are not controlled by flowage structures. For example, the tuff moved generally westward or southwestward when it was emplaced in the vicinity of Mud Flat because the source area lay to the east, and this movement is confirmed in two localities by observable flow lineation. Furthermore, in the narrow outcrop belt southeast of Triangle (fig. 7) the tuff moved northwestward between the flanking higher outcrops of Swisher Mountain Tuff on the west and granite on the northeast. Beyond this stricture, the tuff flowed down the paleocanyon of Castle Creek (fig. 7). The dunelike features strike consistently northwest in both the Mud Flat and Triangle areas despite the direction of emplacement flowage.

Because the prevailing wind direction is from the southwest, approximately perpendicular to the strike of the dunelike features, we have considered the rather implausible possibility that waves formed on the tuff after it had come to rest but while it was still a hot, highly vesiculating liquid. We reject this possibility because of probable inherent difficulties with viscosity, lack of conformity between flow layering and the

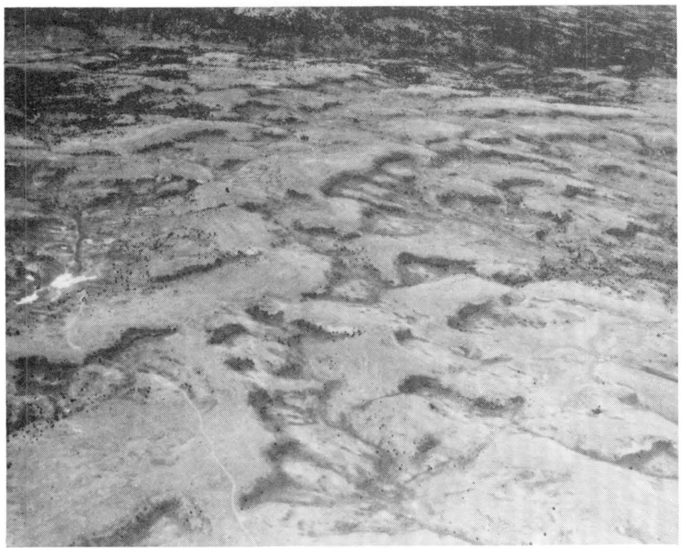


FIGURE 27.—Dunelike pattern developed on top of Little Jacks Tuff near its western edge. Dark outcrops in far background are Swisher Mountain Tuff. Steep faces on "dunes" are marked by dark brush and face toward northeast (see area near Mud Flat, fig. 7). Scale is given by county road visible in lower left.

"dunes", and the fact that in several areas north of the locale of figure 27 the "dunes" occur in a series of steps with as many as four "dunes" in a stepped sequence. The highest "dune" in places is as much as 40 m above the lowest. We conclude that the features are erosional and are controlled primarily by structure and insolation. The long axes of the "dunes" are parallel to northwest-striking joints and to a few northwest-striking faults that have minor normal displacements. As erosion proceeded along the fractures and small gullies developed there, moisture tended to last longer on more shaded northeast-facing slopes. Frost action caused the jointed rock to calve off parallel to the northwest-striking joints and to weather much more rapidly than on the southwest-facing (sunny) slopes. Once this process started, it was accentuated by the prevailing southwest wind that tends to sweep the southwest slopes clean of snow during the winter and to pile it into drifts on the lee (northeast slopes). In places, snow remains on the lee slopes well into late spring. As the steep northeast-facing slope retreats, the ground at the base of the retreating slope becomes littered with flagstones. This litter shields the underlying bedrock and greatly slows the erosion of the southwest-facing slope. The adjacent Swisher Mountain Tuff, which is also cut by many northwest-striking fractures, does not show this weathering habit—presumably because in most outcrops it has less tendency to weather to flagstones.

The Little Jacks Tuff has a remarkably consistent mineralogy from base to top. The tuff contains from 3 to 15 percent phenocrysts that consist of 75–85 percent plagioclase An_{35} (flat-stage extinction angles) that are 2–4 mm long; 10–20 percent of pale-brown ferriferous pigeonite (table 6) 1 mm and smaller; and from 2 to as much as 9 percent small opaque-oxide crystals that are <1 mm in diameter. The plagioclase crystals include many that are considerably resorbed, and a few that are poikilitic that contain very fine grains of pigeonite and opaque oxides. Several thin sections of Little Jacks Tuff contain a few crystals of ferrohypersthene, and a few thin sections contain an occasional grain of clinopyroxene that has a large axial angle.

Near the headwaters of Big Jacks Creek (pl. 2, localities 64, 66; also see fig. 28) the highest exposed rhyolite contains a few tiny crystals of quartz and alkali feldspar per thin section. This rock resembles the Little Jacks Tuff so closely in outcrop and thin section that genetic affinity to the Little Jacks plagioclase-only tuff seems to be a valid assumption (see later pages).

DISTRIBUTION OF THE LITTLE JACKS TUFF EAST OF THE MAPPED AREA AND DESCRIPTIONS OF OVERLYING ROCKS

Various normally and reversely polarized rhyolite cooling units that we infer are genetically part of the Little Jacks Tuff are exposed in canyons and erosional windows cut into the Banbury Basalt and related sedimentary rocks in eastern Owyhee County (pl. 2). In a few of these canyon and window exposures, the highest rhyolite, like that at localities 64 and 66 (pl. 2), contains a few small phenocrysts of quartz per thin section, or, less commonly, a few small phenocrysts of both quartz and alkali feldspar per thin section. In all these rocks, plagioclase is by far the predominant phenocryst, and thin sections are necessary to see the sparse, tiny <1-mm crystals of quartz or alkali feldspar.

The quartz-bearing rhyolite is sporadically present throughout these eastern exposures and we do not know if it comprises the erosional remnants of a single, locally thick cooling unit, parts of several cooling units, or, in some places, zones or lenses at the top of a principally nonquartzose cooling unit. Rocks containing quartz or both quartz and alkali feldspar were found at the top of the rhyolite exposures at localities 64, 66, 118, 119, 474, 549, 550, 556, 557, 859, 882 (pl. 2). This broad distribution suggests the former presence of a continuous stratum. That this stratum is no longer continuous is indicated by the following examples (pl. 2). Sample 474 was quartz bearing, but 857, 858, and 881 from nearby outcrops were not. Although 859 contained a few small phenocrysts of quartz, 860 through 865 did not. Samples 64, 66, 556, and 557 contained, in addition to quartz, sparse phenocrysts of alkali feldspar, but the others listed above contained only quartz.

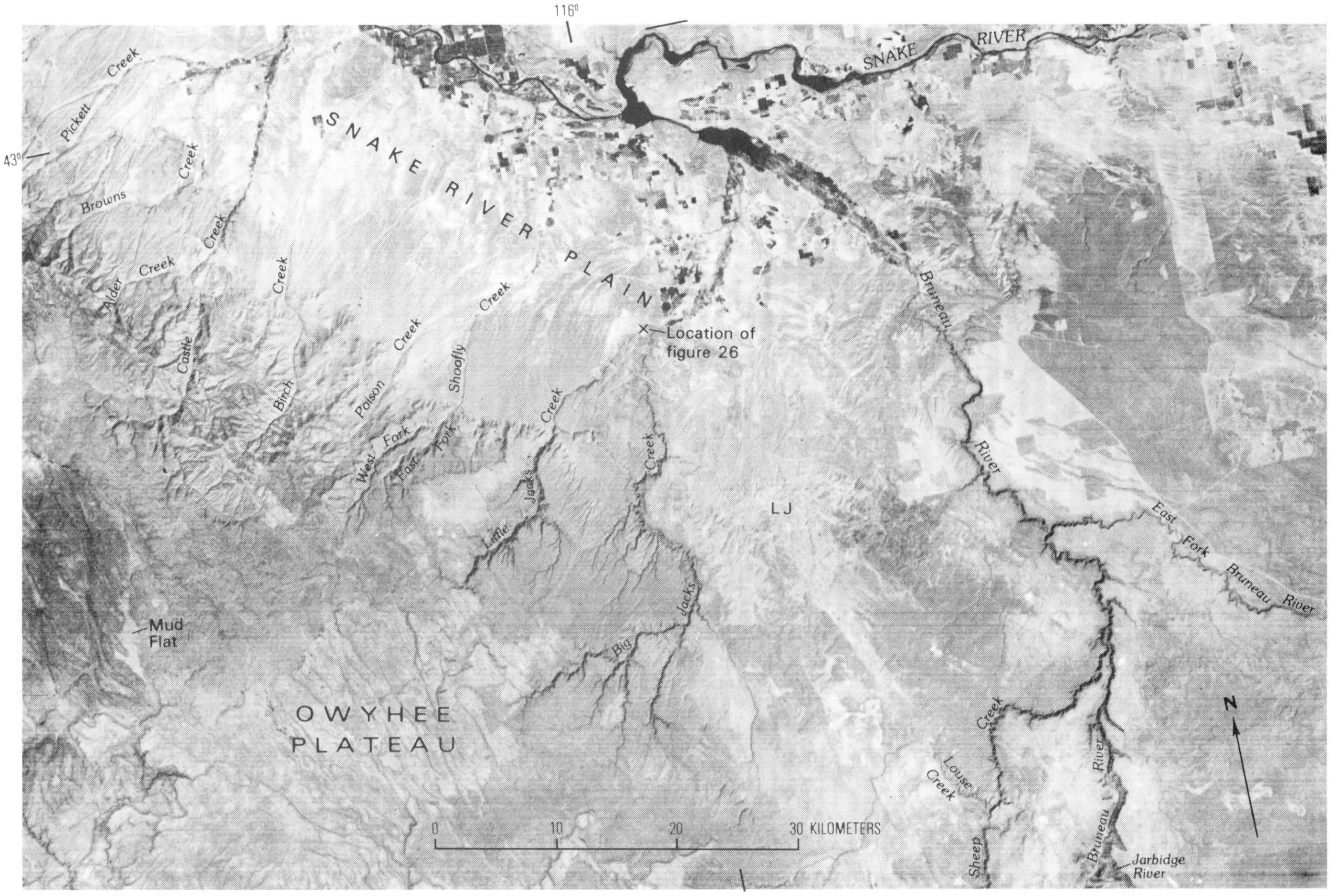


FIGURE 28.—Landsat image of part of Owyhee Plateau and Snake River Plain, showing domical area inferred to be source area of Little Jacks Tuff (LJ). Light tones in inferred source area are caused by extensive sagebrush removal and regrowth to grass. Note lack of any indication of caldera development.

The quartz-bearing (and locally alkali-feldspar-bearing) rhyolite that, on the basis of megascopic appearance and overall mineralogy, we consider to be part of the Little Jacks Tuff, crops out as far to the southeast as Murphy Hot Springs where it pinches out (pl. 2). It rests there on the Cougar Point Welded Tuff (B. Bonnichsen, oral commun., 1978) and is overlain by Banbury Basalt. At the confluence of the Jarbidge and Bruneau Rivers (locality 882), the topmost rhyolite probably is the same cooling unit as that at Murphy Hot Springs, and it is separated at the confluence from an underlying nonquartzose Little Jacks Tuff cooling unit by a thin (20-m-thick) ledge of olivine basalt (fig. 29) that is intercalated in several tens of meters of flat-stratified tuffaceous sedimentary rocks. These occurrences suggest the possibility that this particular Little Jacks rhyolite—namely the unit at Murphy Hot Springs and locality 882—is separated from the bulk of the Little Jacks pile by a significant erosional and depositional interval. This cooling unit is locally as much as 300 m thick in exposures in the Jarbidge River canyon according to B. Bonnichsen (oral commun., 1980).

At Murphy Hot Springs, three thin sections of the quartz-bearing cooling unit each contained a total 12 percent phenocrysts. These samples were collected from the base, middle, and top of a ±50-m-thick outcrop, and the three thin sections contained from 68 to as much as 80 percent plagioclase, from 10 to as much as 20 percent ferriferous pigeonite, 4 percent iron-titanium oxides, and 3 percent quartz. At locality 882, the brecciated basal vitrophyre of the cooling unit above the basalt sandwich contained 12 percent phenocrysts, as at Murphy Hot Springs, and these consisted of 83 percent plagioclase, 9 percent pigeonite, 2 percent iron-titanium oxides, 1 percent hypersthene, and 5 percent quartz. The overlying devitrified rock at locality 882 contained fewer phenocrysts overall than did the brecciated basal vitrophyre (9 percent versus 12 percent), but it contained relatively more quartz (11 percent versus 5 percent).

Whether or not the outcrops of quartz-bearing rhyolite at the top of the Little Jacks Tuff in eastern Owyhee County comprise a single cooling unit or parts of several, they provide, nevertheless, a useful marker

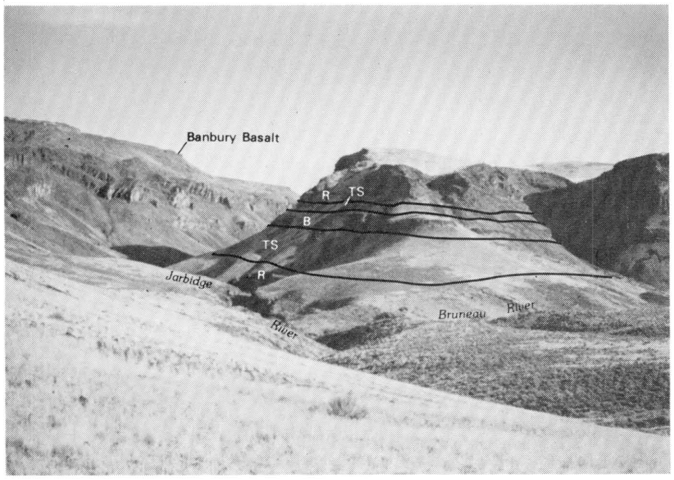


FIGURE 29.—View to south of two rhyolite (R) cooling units separated by basalt (B) and tuffaceous sedimentary rocks (TS) at confluence of Jarbidge and Bruneau Rivers (pl. 2, locality 882). Both cooling units are flow-layered, plagioclase-pigeonite rhyolites inferred to be part of Little Jacks Tuff. Upper unit (as much as 100+ m thick) contains sparse phenocrysts of quartz about 1 mm in diameter; lower unit (about 30 m exposed) contains none. Both rhyolites are magnetically normal; basalt is reversed. Tuffaceous sedimentary rocks form slopes above and below 20-m-thick basalt.

zone. At sample locality 556 (pl. 2), for example, a quartz- and alkali-feldspar-bearing rhyolite is exposed in the highest parts of an upthrown fault block[1] (see Malde, Powers, and Marshall 1963). On relatively downthrown blocks east of 556 and adjacent to the Snake River Plain, a distinctly different sequence of rhyolite is exposed that contains neither quartz nor alkali feldspar. This rhyolite crops out in the vicinity of Balanced Rock State Park (localities 551 through 557, pl. 2) and superficially resembles the Little Jacks Tuff. On the basis of the structural relationship described, we infer that these rocks are younger than the Little Jacks Tuff, although we have not seen the two units juxtaposed.

The rhyolite that we infer is younger than the Little Jacks Tuff and that superficially resembles the Little Jacks is best exposed at Balanced Rock State Park and vicinity (pl. 2) where at least three and possibly four or more cooling units form a series of cliffs and benches. All these units are flow layered throughout, are locally flow brecciated, and in a few places they have streaked-out vesicles or lithophysae that possibly are after pumice fragments. The rocks are gray, purplish gray, and brownish gray. They differ from the Little Jacks Tuff in that they contain more phenocrysts overall, more hypersthene, and more clinopyroxene that has an axial angle too large for pigeonite. Typically, the tuffs of Balanced Rock contain 22 percent phenocrysts that consist of 80 percent plagioclase, 10–12 percent pigeonite, 2–4 percent hypersthene, a trace to 6 percent augite, and 2–6 percent iron-titanium oxides. Of eight thin sections of samples collected from various localities from the base to the top of the exposed sequence, none contained quartz or alkali feldspar, and the volume of phenocrysts ranged from 18 to 26 percent. In contrast, the Little Jacks Tuff typically contains 10–12 percent phenocrysts, and commonly it contains as few as 5 percent total phenocrysts; of more than 60 thin sections counted or scanned from samples at widely separated outcrops, none were found that contained more than about 17 percent phenocrysts. Another difference that possibly is significant in distinguishing between the Little Jacks Tuff and the rocks at Balanced Rock State Park is a slight contrast in the degree of resorption of the plagioclase phenocrysts. Most of the plagioclase in the Little Jacks shows some resorption, and sieve (fig. 25) and skeletal (due to resorption) grains are common. The plagioclase phenocrysts in the tuffs of Balanced Rock on the other hand, although showing some resorption effects, rarely show sieve or skeletal grains; clear euhedral, nonresorbed grains are fairly common. The anorthite content of the plagioclase crystals in the two tuff sequences, however, as deduced from flat-stage extinction angles are extremely close—about An_{35}.

The Little Jacks Tuff is more than 350 m thick at the mouth of Little Jacks Creek canyon, at the southern margin of the Snake River Plain. Presumably, therefore, it is a thick major unit at depth beneath the plain. In the Mount Bennett Hills north of the plain it is only a few meters thick and was recognized with certainty only at sample locality 256 (pl. 2). A sample from this locality was collected from the lowest exposed rock in Rattlesnake Creek along State Highway 68. In hand specimen, the rock is identical in color, size, and distribution of phenocrysts to hand specimens from at or near the type locality of the Little Jacks Tuff. Although flow layered, the rock at locality 256 is clearly an ash-flow welded tuff that has strung-out pumice visible in outcrop and shards visible in thin section; it has a typical Little Jacks mode: 13 percent phenocrysts that consist of 77 percent plagioclase, 15 percent pigeonite, and 7 percent opaque oxides. This rock is overlain by several cooling units that are unrelated to the Little Jacks Tuff; they are mineralogically similar, and they probably comprise a genetic sequence. All the sampled rocks contain both quartz and alkali feldspar, and at some outcrops they show well-flattened pumice. The rock at the microwave-relay station above sample locality 256, for example, shows flattened and strung-out pumice in outcrop and shards in thin section (fig. 30). It contains

[1]Another possibility is that the rhyolite in the upthrown block at locality 556 is part of the same sequence that overlies the Little Jacks Tuff in the Mount Bennett Hills (see later pages). Even if this is true, however, the conclusion that the rock in the downthrown fault block is younger than the Little Jacks Tuff is sound because the rhyolites at Mount Bennett overlie the Little Jacks Tuff.

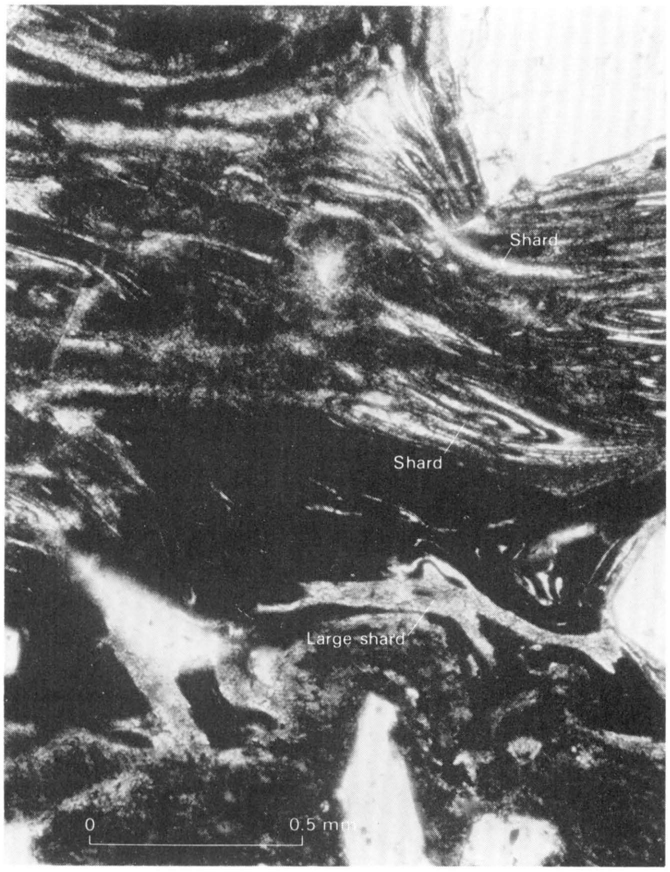


FIGURE 30.—Photomicrograph of flow-layered tuff at microwave-relay station in Mount Bennett Hills. Shards in upper half of field are highly deformed, but one large shard is intact in lower half of field. Plane light.

9–16 percent phenocrysts that consist of 68–74 percent plagioclase, 2–23 percent alkali feldspar, and 9–12 percent pigeonite. The flow-contorted tuff at the microwave-relay station overlies slope-forming tuffaceous sedimentary rocks, 20–30 m thick, that include beds of white rhyolite ash and beds of rusty basaltic-looking ash.

Samples 255 through 251 (pl. 2) contain on the average about 5 percent phenocrysts that consist of 34–58 percent plagioclase, 25–46 percent alkali feldspar, 7–14 percent altered pyroxene, 4–8 percent intensely resorbed quartz, and trace amounts of opaque oxides. The thin section from sample locality 252 (pl. 2) shows deformed shards and incipient microlites (fig. 31).

A plagioclase-pigeonite rhyolite that is locally exposed at the base of the Tertiary section on the northern flank of the Mount Bennett Hills near locality 596 (pl. 2) has a basal vitrophyre that has a strong tendency to weather to a white or light-gray rind. Because of this tendency, perhaps we convinced ourselves in the field that the rock was an unlikely candidate for Little Jacks Tuff. The thin section, however, shows about 9 percent phenocrysts that consist of 85 percent plagioclase, 17 percent pigeonite, and 3 percent iron-titanium oxides. This mode is typical of the Little Jacks Tuff, and a sample collected by Neill (1975) yielded a K-Ar age of 11.0 ± 0.6 m.y. on plagioclase (Armstrong and others, 1980). This date indicates that the rhyolite cannot be separated from the Little Jacks on the basis of age; therefore, we included this outcrop in the distribution field of Little Jacks Tuff (pl. 2).

INFERRED SOURCE AREA

The source areas of nearly all widespread ash-flow sheets that have been mapped in the Western United States coincide closely with the centers of distribution of the sheets. Examples include the Valles caldera and its Bandelier Tuff of New Mexico (Smith and Bailey, 1968); the Timber Mountain caldera and its Timber Mountain Tuff of southern Nevada (Byers and others, 1976); Black Mountain caldera and its Thirsty Canyon Tuff, also of southern Nevada (Christiansen, 1979; Noble and others, 1964); and Lunar Lake caldera and its tuff of Lunar Cuesta of central Nevada (Ekren and others, 1974). Assuming that the source of the Little Jacks Tuff also coincides closely with its center of distribution, and using flow-lineation trends observed within the mapped area, the Little Jacks center lies just east of the mapped area (fig. 28) within the area mapped in reconnaissance by Malde, Powers, and Marshall (1963). From their map and from the Landsat image (fig. 28), obviously no caldera complex is present in the inferred source area. Nevertheless, several features in this area suggest that the center of distribution does indeed coincide with the source area. The central area is a flat-topped, northeast-tilted topographic dome that is similar to the Juniper Mountain dome. It stands in gentle relief and has the configuration of an inverted saucer when viewed from vantage points in the Snake River Plain (fig. 28); it has little relief, however, on its southern and southwestern flanks. This contrasting relief of northeastern flank versus southwestern flank is due both to northeastward-tilting toward the plain and to a series of northwest-trending faults that drop the strata consistently down toward the plain (Malde, Powers, and Marshall, 1963). The flat-topped domical area is characterized by irregular hummocky topography thinly veneered with loess, and it includes some rhyolite outcrops that contain sparse phenocrysts of quartz (see previous discussion). Reconnaissance traverses suggest that most of the highly flow-contorted rhyolite in the topographically high area is part of a single, principally quartz-free, compound cooling unit that is magnetically normal. This unit does not appear to be present at the type locality of Little Jacks

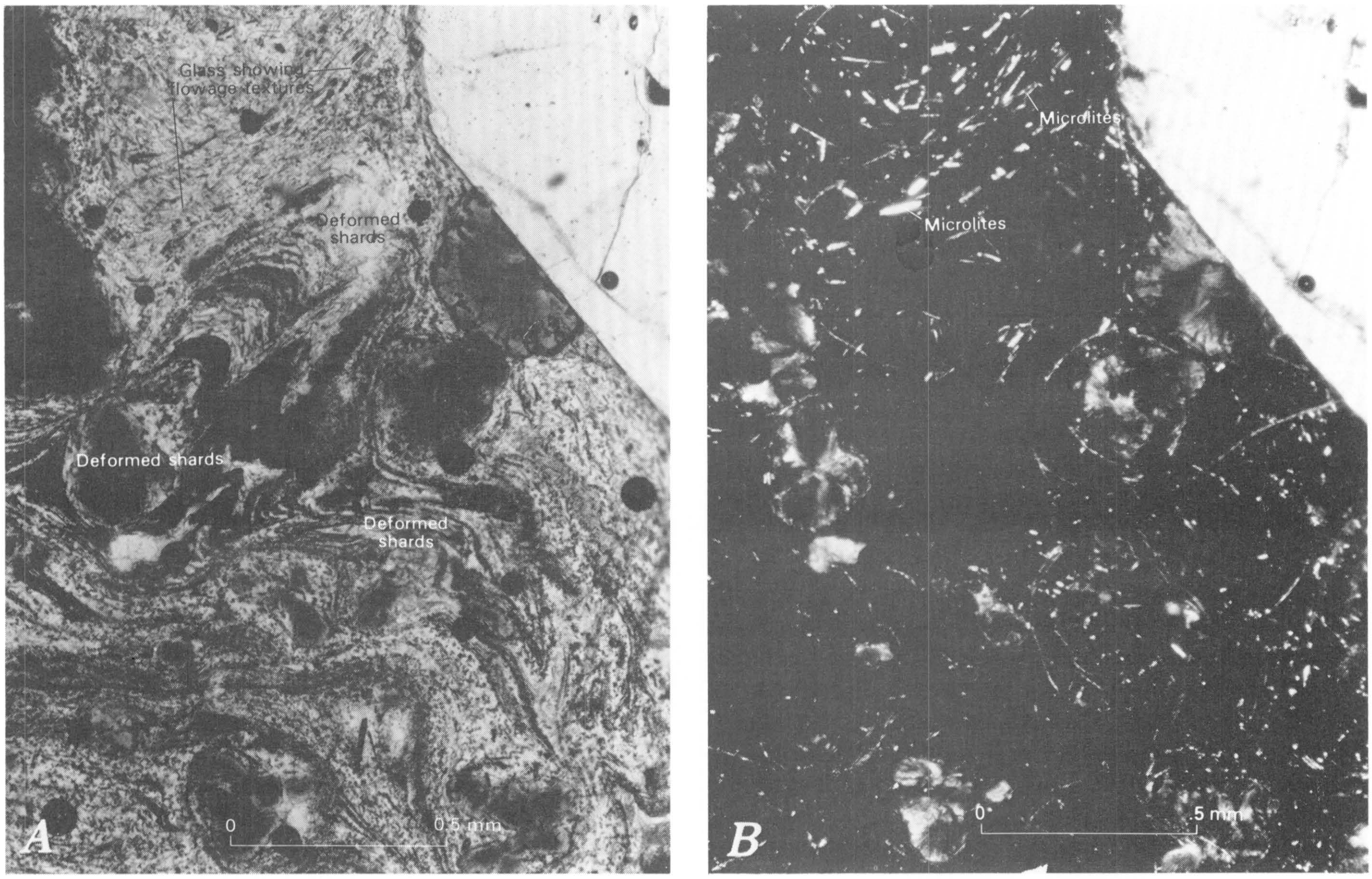


FIGURE 31.—Photomicrographs of flow-layered tuff at locality 252 (pl. 2) in Mount Bennett Hills. *A*, Plane light; *B*, crossed nicols. Note that zone containing deformed but recognizable shards in central part of field shows no microlites under crossed nicols, but that zones with strong flowage textures do show microlites, especially in upper half of field.

Tuff in Little Jacks Creek canyon where the uppermost cooling unit is magnetically reversed. Instead, the unit appears to be restricted to an area close to the inferred source. This area measures about 20 km in diameter and it is centered on locality 119 (pl. 2).

The best exposures of the flow-contorted, magnetically normal rhyolite are in road cuts along State Highway 51, which crosses the crest of the dome near the 1,480-m bench mark (pl. 2). The outcrops include several zones of possibly ramp-structured vitrophyres that dip at diverse attitudes. Some vitrophyres are flow brecciated. No pumice was observed with certainty, and no shards were observed in three thin sections from rocks at outcrops along the northern flank and from near the crest. The rocks contain, on the average, about 15 percent phenocrysts that consist of 78–82 percent plagioclase (as much as 4 mm long), 14–18 percent pale-brown or brownish-green pigeonite (0.2–10 mm long), and 3–6 percent opaque oxides. One thin section contains a single grain of hypersthene. All the thin sections from the outcrops along Highway 51 have incipient feldspar microlites in their groundmasses. The microlites are larger and more abundant than those in rocks at the type locality (fig. 24*D*) and in other outcrops far removed from the source area. We infer that the more abundant and larger microlites in outcrops along Highway 51 represent extreme heat retention in the ash flows or lavas at the source area.

ESTIMATES OF VOLUME OF SWISHER MOUNTAIN TUFF AND LITTLE JACKS TUFF

Estimates of volume of the two most widespread ash-flow sequences were made without regard for the number of individual cooling units present. In most places, canyon exposures were not deep enough to reveal total thicknesses of either sequence. Fortunately, thicknesses of the Swisher Mountain Tuff at a few key localities, together with knowledge of its total extent, allowed approximate isopachs to be drawn (pl. 2). Similar kinds of data, supplemented by data from a single drill hole (Anschutz Federal No. 1), were sufficient to permit approximate isopachs to be drawn for the Little Jacks Tuff in the western part of its area of distribution.

The best method for determining volume of deposits for which isopachs have been drawn is that described by Rose and others (1973). The method involves plotting the area within each isopach (determined by planimeter) against the thickness for each isopach, and integrating to determine the area under the resulting curve. This area represents the volume of the deposit. In practice, the log of the area within each isopach is plotted against the log of the isopach value. The resulting curve can be treated as a series of straight-line segments. Determining an empirical equation for each segment, and integrating to determine the area beneath each, is quickly and easily done using a programmable calculator. An additional advantage to this method, aside from its convenience and theoretical rigor, is that reasonably accurate extrapolation of thicknesses can be made, for limited distances, beyond the areas covered by measured thickness values.

A second method, less satisfactory than the first, is one commonly used to determine ash-flow tuff volumes. The procedure is to determine the total area of the deposit and multiply by the average thickness to arrive at a value for the volume. Comparing the cone with the cylinder in figure 32 shows that determining the volume by the "average thickness method" results in values that are at least 33 percent too large for deposits of subcircular outline that originate from a point near the center of distribution—that is, deposits whose distribution approximates a cone. In actual examples of ash-flow deposits for which isopach data are available, including some with irregular outlines, the "average thickness method" exceeds volumes determined by the method of Rose and others (1973) by between 33 and 40 percent (D. H. McIntyre, unpub. data).

It should be emphasized that the method of Rose and others (1973) is of general application—not restricted to deposits of subcircular outline.

Application of the method of Rose and others (1973) to the isopach map for the Swisher Mountain Tuff (pl. 2, fig. 33) gave a result of about 1,400 km^3 for the part of the unit that is 200 m thick, the greatest thickness measured. If the thickness of the unit, where concealed near its center of distribution, were to be 300 m, a reasonable assumption, the total volume becomes about 1,430 km^3.

A similar procedure was followed for estimating volume of the Little Jacks Tuff, but the isopachs are not as well controlled. The reason is that the streams draining the Little Jacks outcrops on the Owyhee Plateau have not cut completely through the tuff sheet except at or near the western edges of the sheet. For example, in exposures west of the granite high at Birch Creek (pl. 2), the base of the tuff is exposed and at least 100 m of Little Jacks is preserved. Farther south along the

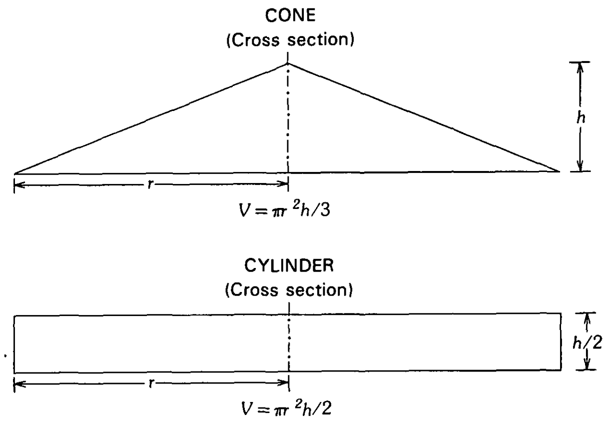


FIGURE 32.—Idealized analysis of "average thickness method" for determining volumes of ash-flow deposits. Deposit with maximum thickness h and circular outline, with radius r, has volume of cone. "Average thickness method" determines volume of deposit with radius r and average thickness, or one-half total thickness h, h/2:cylinder. Comparison of the two volumes, $r^2h/2$ for cylinder and $r^2h/3$ for cone, shows that "average thickness method" (cylinder) overestimates true volume (cone) by one-third. In actual practice, the results of the method overestimate volume by amounts between 33 and 40 percent. Examples may be found where the overestimate is greater than this amount.

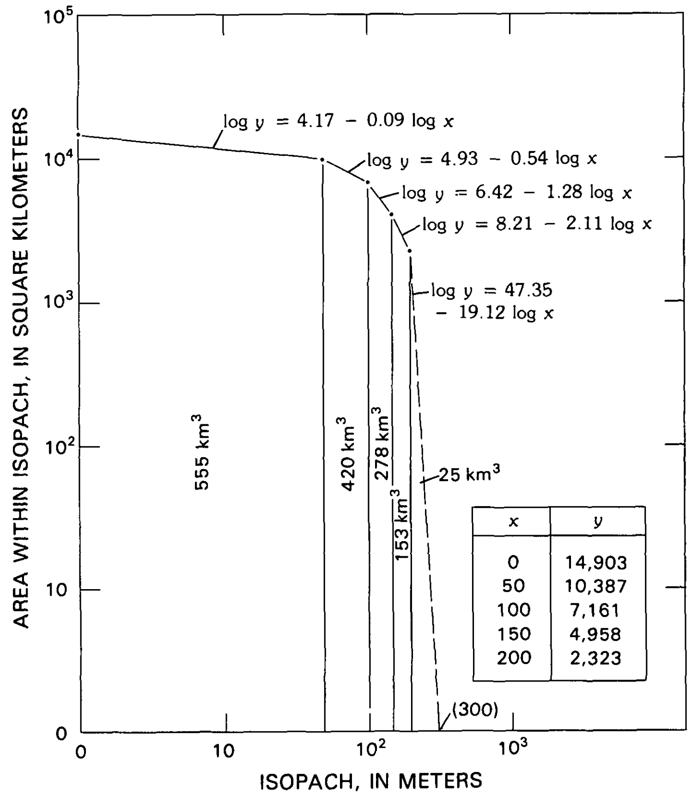


FIGURE 33.—Volume estimate for Swisher Mountain Tuff. The empirical equation for each segment of "curve" is integrated, using the end points of each segment as limits, to determine the area beneath each segment. This area $(km^2 \times m)/10^3$ equals the volume (in km^3) for that part of the isopach diagram (pl. 2). The total volume of the deposit is the sum of the segment volumes.

western distal edge, the onlap zone of Little Jacks Tuff is well controlled but the thickness of the tuff sheet is not because the streams east of the onlap zone have not cut all the way through the sheet. At the southwest nose of the sheet, where the Little Jacks onlaps a topographic high area underlain by tuff of The Badlands (Tjub, pl. 2), the base is exposed and a minimum of 150 m of tuff is exposed in the canyons of Deep Creek and Battle Creek near their junctions with the Owyhee River. These considerable (and minimum) thicknesses near the distal edge of the sheet, coupled with the configuration of the southwest-striking nose as defined by onlap relations, suggest to us that the Little Jacks fills a northeast-plunging structural low. That the tuff sheet thickens northeastward from the Deep Creek and Battle Creek outcrops is indicated by exposures at the type locality and at the mouths of Little Jacks Creek and Big Jacks Creek canyons (pls. 1, 2; Ekren and others, 1981). About 275 m is exposed at the type locality and 300 m or more at the canyon mouths, and the base of the sheet is not exposed in any of the three localities. A north-trending drainage divide separates the Jacks Creeks' drainage area from the Deep and Battle Creeks' areas and the canyons are not sufficiently deep to give firm control on the actual thickness of Little Jacks Tuff there except to indicate that the tuff is thicker than the canyon depths, which range from a few tens of meters near the drainage divide to more than 200 m at the canyon mouths on the west side and 300 m on the east side. Using these available thicknesses from outcrops and the thickness of about 350 m of Little Jacks Tuff as inferred from drill-hole cuttings in the Anschutz drill hole (McIntyre, 1979; pl. 2), the Little Jacks Tuff has a volume of 895 km^3 in the mapped area (pls. 1 and 2). The portion of Little Jacks Tuff for which isopachs have been drawn within the mapped area represents about 30 percent of the total inferred area of distribution. The total volume for the unit, including the portion of the unit concealed beneath the Snake River Plain, could be as much as 3,000 km^3. However, irregularities in the surface upon which the Little Jacks rests, such as the partially buried hills at Birch Creek (pl. 2), may also be present beneath the Snake River Plain. An accurate estimate of the total volume, thus, is not possible, but the approximate values we have derived do help give an appreciation for the enormous volume of rock within this unit. We must reiterate, however, that this volume is for the total sequence, an assemblage of many cooling units emplaced over a time span of, perhaps, several tens of thousands of years.

TABLE 9.—*Average rhyolite of Owyhee Mountains and Owyhee Plateau, Idaho, compared with Nockolds' (1954) "average calc-alkali rhyolite and rhyolite-obsidian," and average of Walker's (1966) "Icelandic acid rocks"*

[Leaders (—) indicate not determined]

	1	2	3
	Chemical composition (weight percent)		
SiO_2	74.05	73.66	71.6
Al_2O_3	12.50	13.45	12.9
Fe_2O_3	1.48	1.25	1.40
FeO	0.51	0.75	1.76
MgO	0.09	0.32	0.32
CaO	0.85	1.13	1.60
Na_2O	3.08	2.99	4.34
K_2O	5.33	5.35	2.95
H_2O^+	1.06	0.78	1.70
H_2O^-	0.39	---	0.71
TiO_2	0.30	0.22	0.30
P_2O_5	0.07	0.07	0.11
MnO	0.06	0.03	0.08
CO_2	0.12	---	
Sum	99.89	100.00	99.77
Na_2O/K_2O	0.58	0.56	1.47

1. Average of 20 analyses of rhyolitic rocks, Owyhee Mountains and Owyhee Plateau, Idaho.
2. Average of 22 analyses of calc-alkalic rhyolite (Nockolds, 1954, p. 1012, table 1, analysis II).
3. Average of 58 analyses of Icelandic acid rocks (Walker, 1966, p. 398, table 3).

CHEMISTRY AND PETROLOGY OF THE RHYOLITIC ROCKS

Chemical analyses of the principal rhyolitic rocks are shown in tables 4, 5, and 8. Comparison of an average of 20 of these analyses with the average of 24 calc-alkalic rhyolites compiled by Nockolds (1954) (table 9) indicates that the high fluidity of the Owyhee rocks is not a function of chemistry. The Owyhee rocks are simply "too normal" (see Summary discussion). The rocks from the Juniper Mountain volcanic center and the Little Jacks center (tables 5 and 8), however, are richer in iron than Nockolds' average and the rhyolites from the Silver City Range and vicinity (table 4). According to R. L. Smith and G. A. Izett (oral communs., 1978 and 1979), they are considerably richer in iron than are most rhyolites that have been described from Western United States. The abundance of that element in the Juniper Mountain and Little Jacks rocks, however, was obviously not a critical factor that accounted for high fluidity because several of the equally fluid, flow-layered rhyolite tuffs from the Silver City Range have relatively low iron values—values that are less than Nockolds' average (compare, for example sample 3 (BE–683), table 4, with table 9).

Sample 3 (BE–683) is nonhydrated glass "Apache tears" from the basal part at Toy Pass of the rhyolite of the Silver City Range. It is the only nonhydrated analyzed sample in the entire suite of rocks; therefore, presumably it is the most pristine. The total H_2O value of 0.26 percent for this rock, however, probably is representative of only a few of the units. This rock contains scattered tiny flakes of biotite, suggesting that there was more water in the Silver City magma chamber(s) than was available in the Juniper Mountain and Little Jacks centers. Presumably, H_2O contents of nonhydrated glasses from these last-mentioned centers would yield H_2O values of less than 0.26 percent.

Several paired samples of hydrated vitrophyre and devitrified rock from the same cooling unit were analyzed. These analyses confirm the conclusions of Lipman (1965) that Na_2O and K_2O are mobile components in hydrated glass. The vitrophyres, without exception, had lower Na_2O values and higher K_2O values than did the corresponding devitrified samples (see tables 5 and 8; especially compare sample 8 (BE–205A) with sample 9 (BE–205B), table 8). The vitrophyre samples in all the tables stand out because of their high H_2O^+ values (mostly 2 percent or greater), whereas the H_2O values of the devitrified samples are mostly less than 0.50 percent.

The rhyolites, whether erupted from the western Snake River Plain, the Silver City Range, Juniper Mountain, or the Little Jacks center are characterized by low Ca content and exceedingly low Mg content (tables 4, 5, and 8). According to D. C. Noble (1972, p. 143–144; and oral commun., 1979), rhyolites of this chemistry are fairly typical of areas of bimodal basalt-rhyolite volcanism, and the low Ca and extremely low Mg values represent their highly differentiated states. Several of the rocks from the Owyhee Mountains and Plateau actually have an Mg content that is less than the detection limits of the X-ray fluorescence spectroscopy method. Whether the low values represent end stages of a differentiation process or whether they represent early products of partial melting is a moot question.

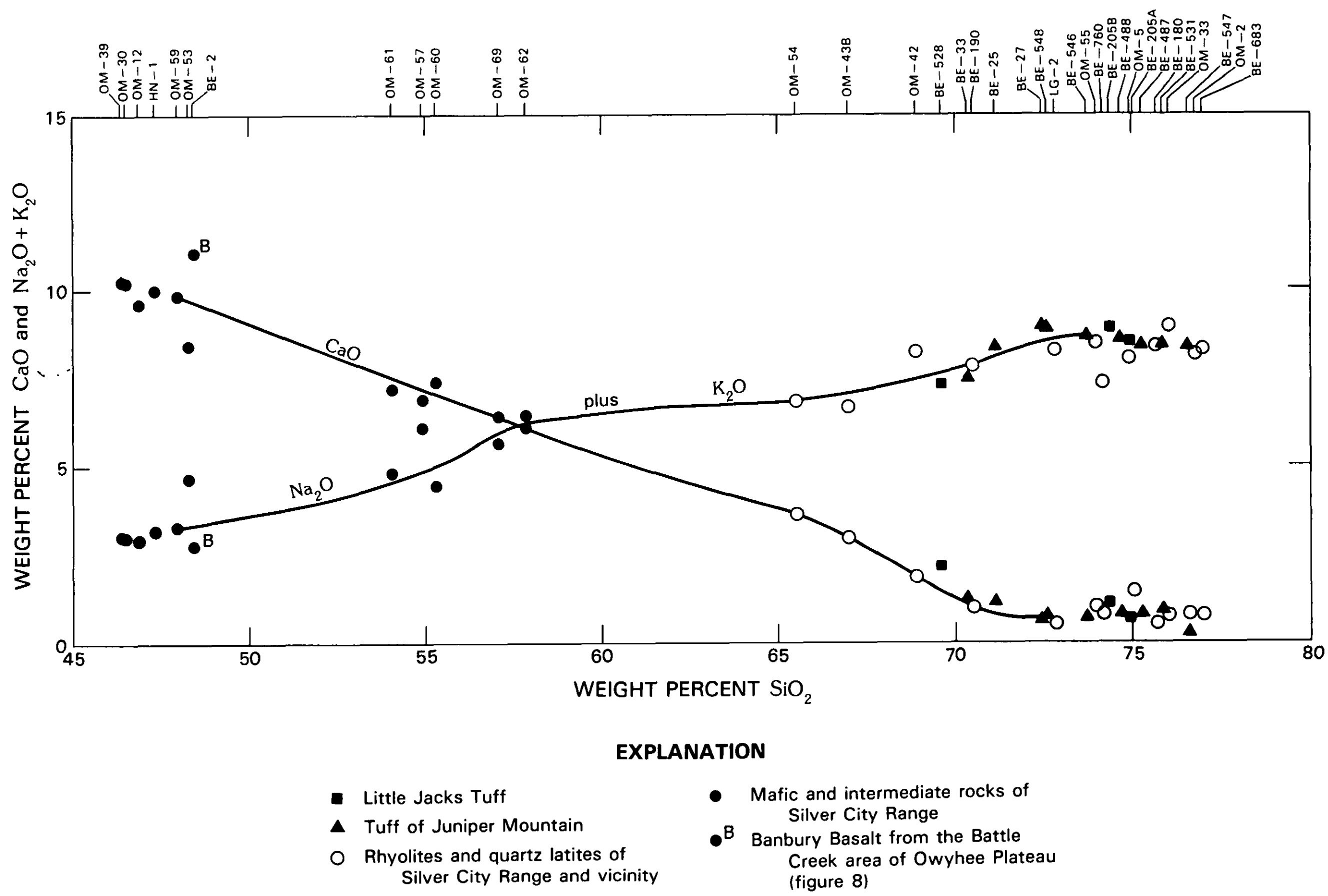


FIGURE 34.—Oxide weight percentages of alkali (Na_2O plus K_2O) and lime (CaO) plotted against SiO_2 for extrusive igneous rocks of the Owyhee Mountains and Plateau. The alkali-lime index (between 57 and 58) is within the calc-alkalic field of Peacock (1931). Numbers at top of graph are those of sample localities listed in tables 1, 4, 5, and 8.

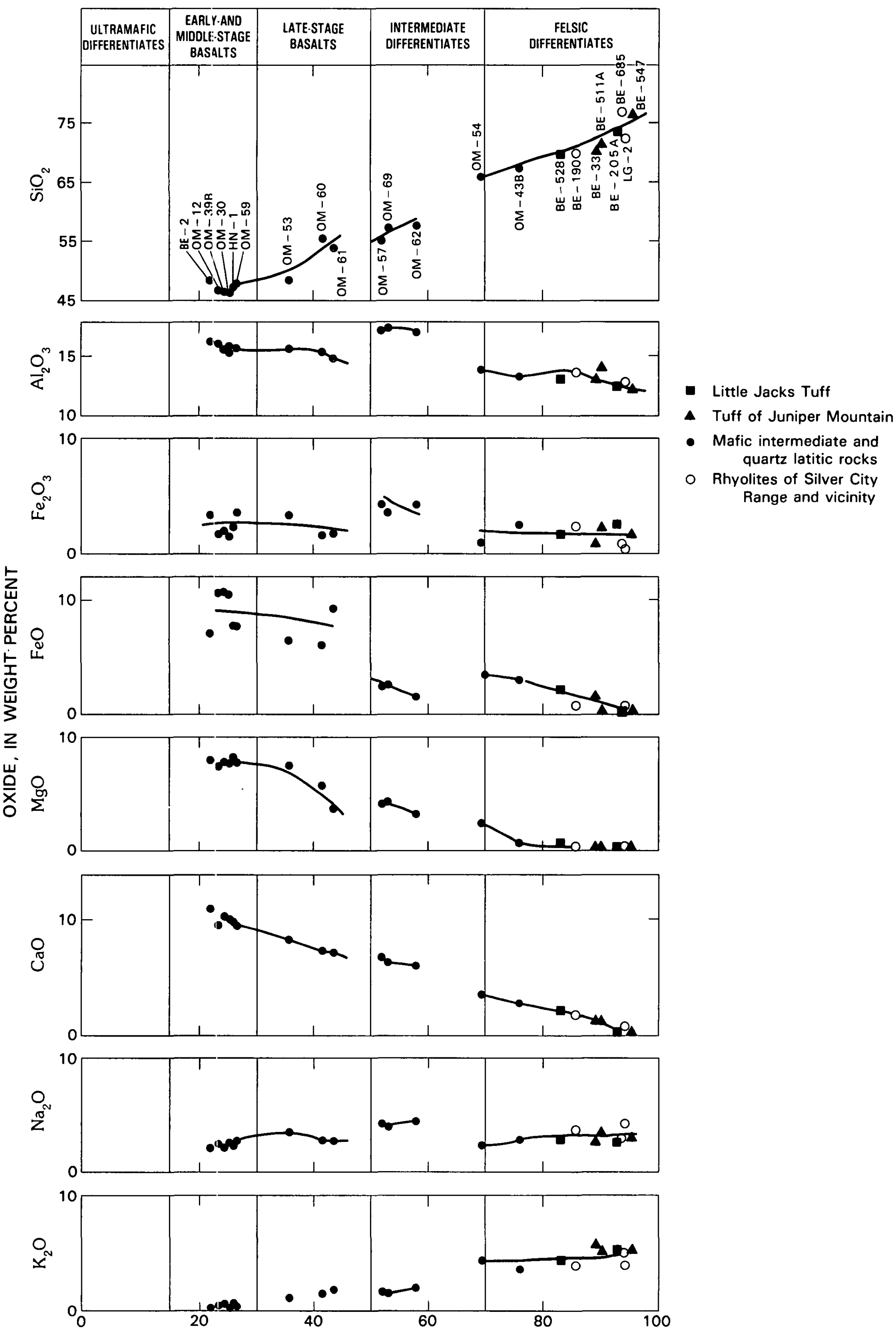


FIGURE 35.—Oxide weight percentages of extrusive igneous rocks from the Owyhee Mountains and Owyhee Plateau, plotted against sum of normative quartz, albite, and orthoclase (the differentiation index of Thornton and Tuttle, 1956); subdivision of differentiation index after Sukheswala and Poldervaart (1958). Symbols are same as in figure 34 except that quartz latites (samples OM-54 and 43B) are shown with solid circles. Note that sample BE-2, Banbury Basalt, is the most mafic rock in this plot. Numbers are those of sample localities listed in tables 1, 4, 5, and 8.

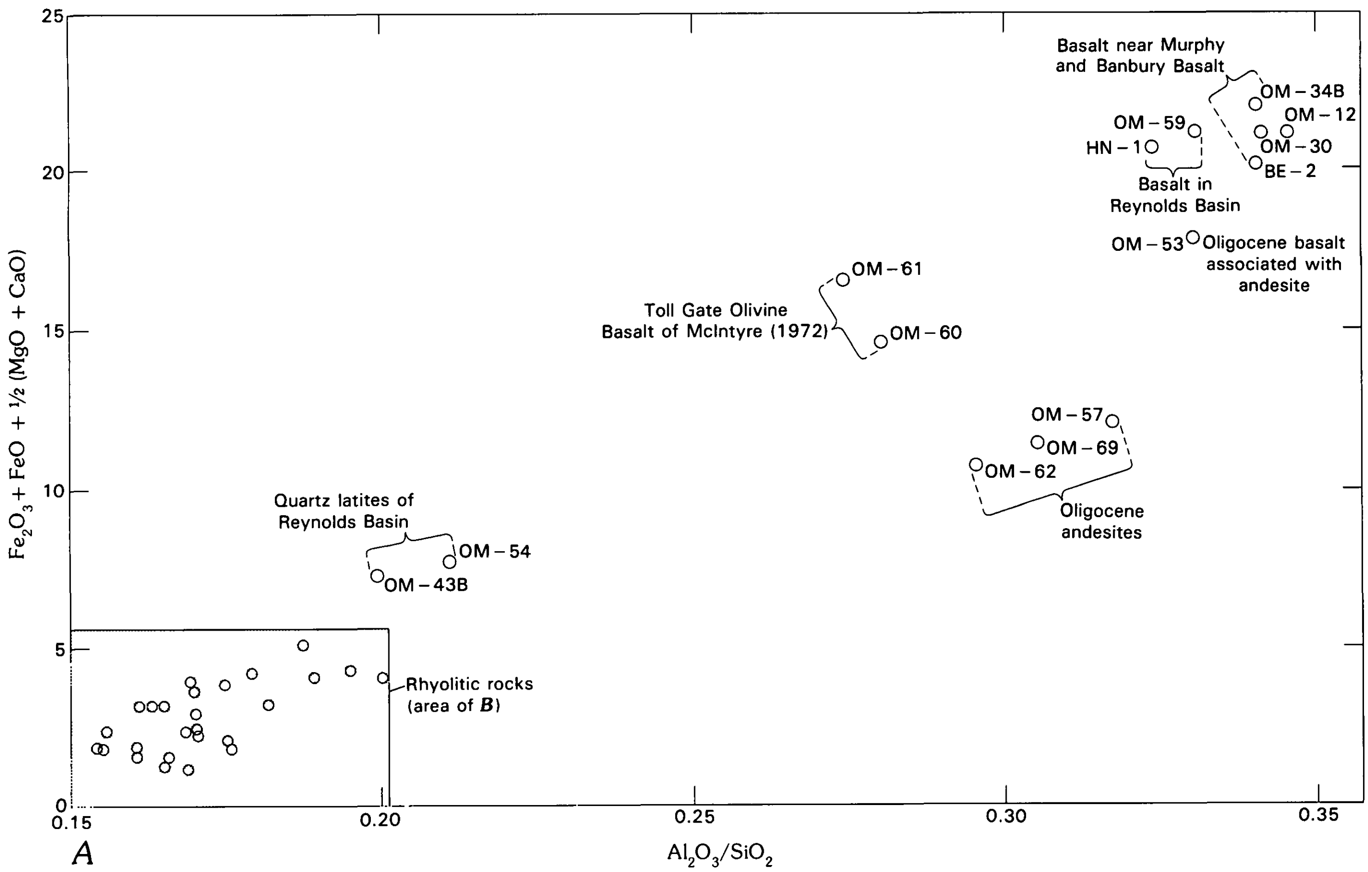
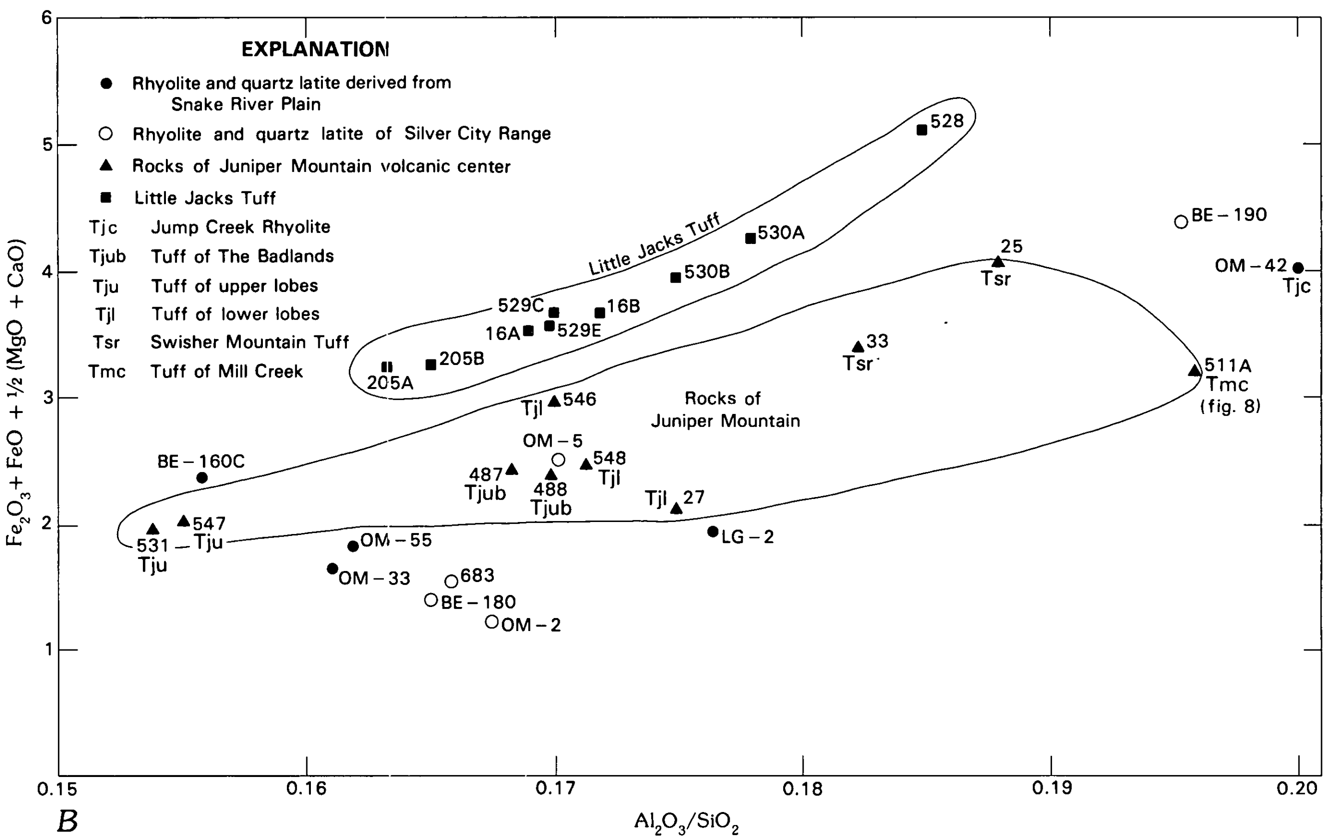


FIGURE 36.—Plots of sum of Fe_2O_3 plus FeO plus ½(MgO plus CaO) versus Al_2O_3/SiO_2 for extrusive rocks of Owyhee Mountains and Owyhee Plateau (diagram design from Church, 1971). *A*, All extrusive rocks; *B*, enlargement of plot of rhyolitic rocks (shaded area in *A*). Numbers are those of sample localities listed in tables 1, 4, 5, and 8.

COMPOSITIONAL TRENDS

Using representative rhyolites from the Silver City Range, Juniper Mountain, and Little Jacks center, and mafic rocks that are spatially and temporally associated with the rhyolites, the Owyhee suite of rocks has an alkali-lime index (Peacock, 1931) of about 57 (fig. 34). We regard this index as an approximation because there is no firm evidence that, aside from having been erupted from the same general areas during a time interval that bracketed the rhyolite eruptive interval, any direct genetic relationship existed between the mafic rocks and the intervening rhyolites. Certainly, the rhyolitic and mafic rocks are not part of a continuous igneous rock series. That they are not part of a continuous series is obvious in variation diagrams (figs. 35 and 36) that were designed by Sukheswala and Poldervaart (1958) and Church (1975). In the Sukheswala and Poldervaart diagram (fig. 35), the major oxides are plotted against the sum of normative quartz, albite, and orthoclase—"the differentiation index." On this diagram several compositional breaks are apparent. For example, the basalts of Miocene age, including some that are younger than the rhyolites and some that are older (samples BE–2 through OM–59), form a tight cluster that is not directly alined with Oligocene basaltic samples OM–53, 60, and 61 (Toll Gate Basalt of McIntyre (1972) and related(?) basalt), and these last are not alined with the Oligocene andesites (samples OM–57, 69, and 62). The latite and quartz latite of inferred Miocene age in Reynolds Basin (samples OM–54 and 43B) are more or less alined with the rhyolites in this diagram; but in the "Church Plot" (fig. 36) they cluster off any reasonable line that could be drawn through the rhyolite points. Compositional breaks between the other mafic rocks are even more pronounced in this diagram than they are in figure 35.

The rhyolite points of figure 36*A*, when replotted on an enlarged version of the "Church Plot" (fig. 36*B*), show that the Little Jacks Tuff is richer in total Fe, Mg, and Ca than the Juniper Mountain Tuff, and the points are more neatly alined. Based on what is known and inferred about their age relations, the Little Jacks samples show a general decrease in mafic constituents



B

and Al_2O_3/SiO_2 with decreasing age. For example, sample 530A (vitrophyre), which has the highest Al_2O_3/SiO_2 exclusive of sample 528, is of the lowest exposed unit at the type locality in Little Jacks Creek canyon; sample 530B is devitrified rock from outcrops a few meters above 530A; samples 529C,E are from the next overlying cooling unit exposed near the mouth of Little Jacks Creek canyon; samples 16A (vitrophyre) and 16B (devitrified) are from the basal parts of the highest cooling unit at the type locality; and samples 205A (devitrified) and 205B (vitrophyre) are from the highest unit exposed at Mud Flat. This last cooling unit, whose base is not exposed, was presumed during the course of field mapping to correlate with the unit sampled at 16A,B at the type locality. This could be a valid assumption and the Mud Flat samples, therefore, could correspond to stratigraphically higher parts of the same cooling unit as that at locality 16A,B. Sample 528 is from a horst block a few kilometers east of the type locality. Its age is uncertain, but it is not likely to be older than 530A. The phenocryst assemblages of the various Little Jacks Tuff plotted in this graph (fig. 36*B*) do not reflect the chemical changes that are suggested here. All the sampled units contain only plagioclase and ferriferous pigeonite and an occasional phenocryst of ferrohypersthene.

In contrast to the Little Jacks Tuff, the Juniper Mountain rocks (fig. 36*B*) show marked phenocryst differences between units, but these differences are not necessarily reflected in the chemical analyses. In addition, the rhyolites of Juniper Mountain (fig. 36*B*) show considerably more chemical variations than do the Little Jacks rocks. Although their total Fe, Mg, Ca, and Al contents generally decrease with decreasing age, some reversals are apparent in the Juniper Mountain rocks as they are also in the Little Jacks if sample 528 is not the oldest rock. For example, the tuff of Mill Creek (Tmc, sample 511A), the oldest rock in the sequence, has the highest Al_2O_3/SiO_2 but it has less Fe, Mg, and Ca than does the Swisher Mountain Tuff (Tsr, samples 25, 33). The top of the Swisher Mountain (sample 25) has higher Al_2O_3/SiO_2 and more mafic constituents than does the base (sample 33), despite the fact that modal analyses indicate that it has less plagioclase and much more alkali-feldspar phenocrysts at the top (table 5) than at the base. The upper-lobes tuff (fig. 36*B*, samples 531, 547) has the lowest Al_2O_3/SiO_2 and the least mafic constituents, and modal analyses indicate that it has the most rhyolitic phenocryst assemblage (table 5). The lower part of the tuff of The Badlands (Tjub, samples 488, 487), on the other hand, has virtually the same Al_2O_3/SiO_2 and mafic content as does the lower-lobes tuff (Tjl, samples 27, 548, 546), although it is considerably younger. In summary, the

Juniper Mountain rocks show a general decline in Al_2O_3/SiO_2 and total mafic constituents with decreasing age, but the decline is not systematic. Reversals occur within cooling units (for example, within the Swisher Mountain, Tsr), and also between cooling units (tuff of upper lobes, Tju, versus tuff of The Badlands, Tjub).

In contrast to the considerable variations in Al_2O_3/SiO_2 and mafic constituents shown by the Little Jacks Tuff and tuffs of Juniper Mountain, neither sequence shows much variation in Na_2O and K_2O. The Little Jacks Tuff (table 8) does show a slight increase in total alkalis with decreasing Al_2O_3/SiO_2, however, and, except for sample 1 (BE–528), shows a slight increase in alkalis with decreasing age—from about 7.73 percent in the oldest sample at the type locality (table 8, sample 2 (BE-530A) to as much as 8.36 percent in the youngest at the type locality (table 8, sample 7 (BE–16B). The total alkalis in the Juniper Mountain tuffs, in contrast, remain nearly constant from oldest to youngest despite changes in Al_2O_3/SiO_2 and variations in total Fe, Mg, and Ca content (table 5). For example, the tuff of Mill Creek and the Swisher Mountain Tuff have total alkali contents of 8.5 percent, which is the same as that in the upper-lobes tuff and in the tuff of The Badlands. The highest total alkali contents are actually in the middle unit, lower-lobes tuff—from 8.64 to 8.92 percent. The total alkali contents are consistently higher in the Juniper Mountain rocks than they are in the Little Jacks, but both sequences are characterized by low Na_2O/K_2O. The average ratio for the Little Jacks (excluding all vitrophyre samples) is 0.58 for four samples. The Na_2O/K_2O for the Juniper Mountain rocks (excluding all vitrophyre samples) is 0.59 for six samples. The Juniper Mountain rocks show a slight but systematic decrease in Na_2O from oldest to youngest—from 3.44 percent in the tuff of Mill Creek to 3.02 percent in the tuff of The Badlands; and they show a slight increase (excluding the lower-lobes tuff) in K_2O from oldest to youngest—from 5.06 percent in the tuff of Mill Creek to 5.48 percent in tuff of The Badlands. The Na_2O/K_2O for the tuffs of Juniper Mountain and Little Jacks Tuff are extremely close to Nockolds' (1954) average for calc-alkalic rhyolite (0.56, table 9), and they are completely unlike the Icelandic acid rocks (1.47, table 9).

The Na_2O/CaO values for the Little Jacks Tuff change little from base to top at the type locality. The lowest exposed devitrified rock (table 8, sample 3 (BE–530B) has a ratio of 2.52; the highest (table 8, sample 7 (BE–16B) has a ratio of 3.42. The Na_2O/CaO for the devitrified Juniper Mountain rocks range from 2.69 in the tuff of Mill Creek (table 5) to a high of 9.27 in one sample of upper-lobes tuff (table 5, sample 8 (BE–547). The tuff of The Badlands, however, and the lower lobes of Juniper Mountain have similar ratios (4.1 and 4.7, respectively).

The slight, albeit inconsistent, increases in silica and Na_2O/CaO, together with a general decrease in alumina, total Fe, Mg, and Ca from oldest to youngest cooling unit in both the Juniper Mountain and Little Jacks Tuffs indicate that there may have been some differentiation in both chambers during the time spans represented by the various cooling units. The time span could have been on the order of 2 m.y. for the Juniper Mountain rocks. More important than the evidence for slight differentiation in the two magma chambers, however, is the solid evidence that no high-silica rhyolitic roof zones characteristic of high-level magma chambers existed in either chamber. The earliest cooling units from both the Juniper Mountain and Little Jacks centers tend to be the least silicic and the most mafic. Furthermore, several of the individual cooling units from the Juniper Mountain center show a trend upward from plagioclase-rich basal parts to plagioclase-poor, alkali-feldspar-rich tops. The possible significance of these relationships is further evaluated in Summary Discussion.

Several rhyolites were analyzed for fluorine to determine approximately if the "anhydrous" Owyhee rocks had unusually high halogen contents. Analyzing for fluorine alone apparently provides some control for evaluating overall halogen content, because data compiled by Noble and Haffty (1969) suggested that most silicic glasses of both peralkaline and nonperalkaline chemistry appear to contain significantly more F than Cl. The Owyhee rocks (table 10) show a range in F from less than 0.02 percent to 0.15 percent. These values are close to the average for granites according to Parker (1967); they are generally less than the 0.15–0.30 percent F values reported for peralkaline oversaturated obsidians by MacDonald and Bailey (1973, p. N12); and they are virtually the same as the values for the comendite Grouse Canyon Member of the Belted Range Tuff of Nevada (Noble, 1970a).

The analyses of the rhyolites on the Owyhee Plateau and Owyhee Mountains (table 10) show that the devitrified rocks have the lowest contents of fluorine, and that the hydrated glasses have the highest. Sample 17 (BE–683) is the only nonhydrated glass in the group, and its value of 0.10 percent, being bracketed by the hydrated glasses (table 10, samples 3, 7, 10, 13, and 14), suggests that little fluorine was added to or subtracted from the glassy rocks during hydration. The most extreme example of fluorine loss during devitrification is shown by the sample pair 15–16 (BE–16A,B, table 10). The hydrated glass (15) contains 0.11 percent fluorine; the devitrified (stony) rock (16) contains less

TABLE 10.—*Fluorine content (in weight percent) of rhyolitic rocks, Owyhee Mountains and Owyhee Plateau, Idaho*

[Analysts: H. Neiman and P. Klock. For sample descriptions, see tables 4, 5, and 8]

Sample No.--	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Field No.---	OM-2	OM-5	BE-548 (glass)	BE-546	BE-531	BE-547	OM-42 (glass)	OM-55	OM-33	BE-528 (glass)	BE-529C	BE-529E	BE-530A (glass)	BE-530B	BE-16A (glass)	BE-16B	BE-683 (nonhydrated glass)
Fluorine----	0.04	0.06	0.15	0.04	0.03	0.06	0.11	0.03	0.02	0.08	0.08	0.04	0.09	0.03	0.11	<0.02	0.10

than 0.02 percent. In summary, the Owyhee rocks apparently contain normal amounts of fluorine for silicic rhyolites, which in turn, suggests that their overall halogen contents were not high.

STRONTIUM AND LEAD ISOTOPIC DATA

Strontium and lead isotopic data of W. P. Leeman (written commun., 1981) for rhyolitic rocks of the Owyhee region show that the rhyolitic rocks fall into two distinct groups. Initial $^{87}Sr/^{86}Sr$ values for the rhyolitic rocks fall into two ranges: 0.7094–0.7105 and 0.7055–0.7072. The Swisher Mountain Tuff, the tuff of Browns Creek, and the Little Jacks Tuff comprise the first group; the rhyolite of the Silver City Range, and the Jump Creek Rhyolite of Kittleman and others (1965) comprise the second.

A plot of $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ for the first group shows the values for the tuff of Browns Creek and the Little Jacks Tuff to be approximately colinear with values for rhyolitic rocks throughout the eastern Snake River Plain and Yellowstone area (W. P. Leeman, unpub. data). Our study suggests a source for the tuff of Browns Creek beneath the western Snake River Plain and a source for the Little Jacks Tuff near the plain margin. In contrast, the Swisher Mountain Tuff samples have distinctly higher $^{207}Pb/^{204}Pb$ values than the other samples, even though their Sr values are similar. The small differences in isotopic compositions of these tuffs probably reflect differences in the magma source rocks. The vent area for the Swisher Mountain Tuff (the Juniper Mountain volcanic center) is distant from the vent areas for the other tuffs and is outside the topographic depression marking the plain proper. However, the Juniper Mountain volcanic center is within the eastern Snake River Plain trend, which probably accounts for the isotopic similarity of rocks erupted there with those from sources in the eastern plain.

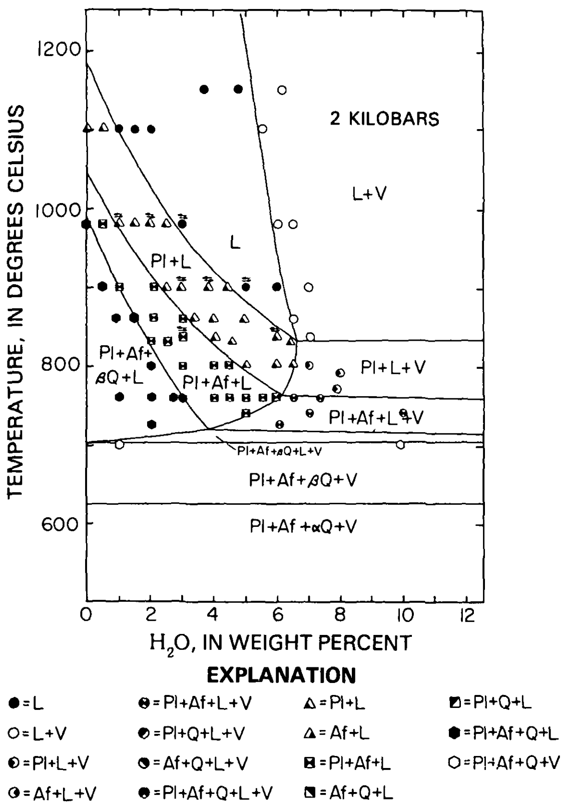
The second group of rhyolitic rocks distinguished by the Sr data, the rhyolite of the Silver City Range and the Jump Creek Rhyolite of Kittleman and others (1965), have lower $^{207}Pb/^{204}Pb$ values than do the rhyolites of the first group. Their isotopic compositions resemble those of rhyolites in eastern Oregon and the Cascades (W. P. Leeman, unpub. data).

CRYSTALLIZATION CONDITIONS AND MAGMA CHAMBER DEPTHS

As discussed earlier, mineral assemblages in the rhyolitic rocks of the Owyhee region are predominantly anhydrous. The only exceptions are some rocks in the rhyolite of the Silver City Range that contain sparse biotite. Even in these rocks, however, pyroxene commonly is the principal mafic constituent. Therefore, the rhyolitic magmas from which most of the rocks of the Owyhee region were formed seem likely to have been undersaturated with water during most of their crystallization history.

Most experiments on the system most applicable to rhyolitic rocks—Q-Or-Ab-An-H_2O—have been carried out under water- saturated conditions and at relatively low temperatures, so are of little use in explaining variations in the Owyhee magmas. Experimentation, fortunately, has begun on the relations in this system at low water contents and high temperatures (Whitney, 1975), and some of these initial results are applicable here. These experiments were conducted on materials that differed somewhat in composition from our rocks, but the experimental data suggest that the results are not highly sensitive to small compositional differences. The experimental data do provide some approximate limits to the conditions under which crystallization of the Owyhee rocks must have taken place.

The great bulk of the Little Jacks Tuff, although a rhyolite in chemical composition, contains only sparse phenocrysts of plagioclase, ferriferous pigeonite, and iron-titanium oxides. At a few localities, the highest cooling unit(s) contains a few small phenocrysts of quartz, and, less commonly, a few small phenocrysts of both quartz and alkali feldspar. Iron-titanium oxide compositions for the plagioclase-only Little Jacks Tuff indicate an equilibration temperature of about 1,090°C or higher (table 7). The data of Whitney (1975) for a synthetic granite melt (fig. 37) show that the crystallization sequence of plagioclase (Pl + L) to plagioclase plus quartz (Pl + βQ + L) occurs only at temperatures



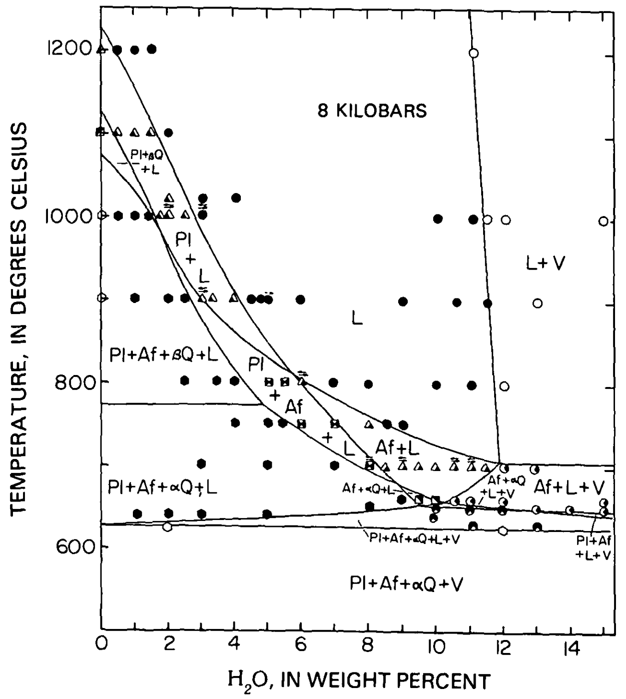


FIGURE 37.—Crystallization sequence at pressures of 2 and 8 kilobars in which temperature is plotted against weight-percent H_2O for the synthetic granite composition R-1, which approximates Nockolds' (1954) average biotite-hornblende granite. Modified from Whitney (1975, figs. 3 and 4; also see Luth, 1976, p. 380–386). Reprinted by permission of the University of Chicago Press from the Journal of Geology, v. 83, p. 1–31, "History of granodioritic and related magma systems—An experimental study" by James A. Whitney. ©1975 by The University of Chicago. All rights reserved.

greater than 1,000°C, at extremely high pressure (8 kilobars), and at extremely low water contents (<2 weight percent water). At lower pressures, probably not much lower than 8 kilobars, the field $Pl+\beta Q+L$ disappears. Those rocks in the highest unit of the Little Jacks Tuff that contain phenocrysts of plagioclase and quartz, and lack alkali feldspar, must have crystallized under conditions similar to those defined for the $Pl+\beta Q+L$ field by Whitney's experiments.

Crystallization conditions for the plagioclase-only rocks that make up the bulk of the Little Jacks Tuff are not as closely constrained. Crystallization temperatures of these rocks could have been considerably lower than 1,000°C, and the high temperatures indicated by the iron-titanium oxides (table 7) could merely reflect the temperatures that were briefly attained just prior to eruption (see later pages). Figure 37 shows that total pressure is not well defined for the plagioclase-only rocks, but it appears highly unlikely to have differed drastically from that indicated for the younger plagioclase- and quartz-bearing rocks. The pressure conditions indicated for the plagioclase-quartz tuff probably are a reliable indicator of the approximate crustal position of the Little Jacks magma chamber, and a reasonable conclusion is that pressures of 6–8 kilobars probably prevailed during the eruption of both the plagioclase-only and the plagioclase-plus-quartz magmas at water contents of much less than 2–3 percent. These pressures suggest a depth of about 20–25 km, within the lower crust as locally defined by the seismic data of Hill and Pakiser (1967). The magmas probably originated by partial melting of granulite-facies, lower crustal rocks. A source within the lower crust was proposed also by Citron (1976) for the Cougar Point Welded Tuff, exposed to the east and south of our area of study.

The Juniper Mountain volcanic center is similar to the Little Jacks center in showing no caldera development accompanying eruption of large-volume ash flows. Like the Little Jacks Tuff, the rocks derived from the Juniper Mountain center contain pyroxene (chiefly intermediate pigeonite) as the only mafic constituent. In contrast to the rocks derived from the Little Jacks center, however, those from the Juniper Mountain center have large variations in felsic phenocryst assemblages from unit to unit, and alkali feldspar is ubiquitous. The oldest unit, the tuff of Mill Creek, contains predominant plagioclase, trace amounts of alkali feldspar, and no quartz. The Swisher Mountain Tuff contains, in addition to plagioclase, considerable alkali feldspar, and quartz is present in some samples. Iron-titanium oxide compositions for the Swisher Mountain Tuff indicate equilibration temperatures of 1,090°C or higher (table 7), indistinguishable from temperatures for the Little Jacks Tuff. The anhydrous phenocryst assemblage in the Swisher Mountain suggests low water contents comparable to those of the Little Jacks, and, by inference, derivation of the magma from similar, water-deficient source materials. The marked differences in phenocryst assemblages between the Swisher Mountain Tuff and Little Jacks Tuff appear best explained by different pressure-temperature conditions at which crystallization took place, because the differences in bulk composition of the two units are not large.

Figure 37 shows, however, that the phenocryst assemblage of the Swisher Mountain Tuff cannot be used to determine magma-chamber pressure unless temperatures of more than 1,000°C are inferred to have prevailed there at the time the phenocrysts formed. Even if this inference is made, however, the available experimental data do not define a precise pressure for the Swisher Mountain Tuff or for any of the other Juniper Mountain rocks.

Rhyolitic magmas at temperatures in excess of 1,000°C could not have formed stable magma chambers because of melting and reaction with wall rocks. There are at least two possible ways to explain the relations seen for the Owyhee rocks:

1. The magmas were produced at or near temperatures above 1,000°C and were erupted just about as fast as they were produced.
2. The magmas resided in magma chambers at temperatures below 1,000°C and were heated to the higher temperatures only immediately prior to eruption.

A great deal more needs to be learned about rocks such as these before the conditions that produced them can be well understood. However, there are some features we already have described that do help define some broad limits to the conditions controlling their formation. The Little Jacks Tuff contains a phenocryst assemblage that would be in equilibrium with temperatures in excess of 1,100°C at pressures corresponding to a depth well within the lower crust. This magma erupted directly from the site where it was generated without pausing within a shallow-level magma chamber before appearing at the surface. It did so more than four times. The cooling units produced are nearly identical in bulk composition and phenocryst mineralogy, reflecting production under the same conditions, with no significant later modification. The Little Jacks Tuff, thus, probably is an example of magma that was erupted just about as fast as it was produced.

The tuffs erupted from the Juniper Mountain volcanic center show more variations in magma behavior than the Little Jacks Tuff, although the data needed to define well this variability are not available. The Swisher Mountain Tuff does resemble the Little Jacks Tuff in eruption temperature and areal extent, and there is little mineralogic or chemical variation between ash flows (cooling units?). It, too, may have been produced by eruption concurrent with magma generation. The tuff of the lower lobes, tuff of the upper lobes, and tuff of The Badlands, when considered together, however, exhibit a distinct compositional zonation, which implies that they were erupted from a stable magma chamber. As noted earlier, the tuff of The Badlands has about the same compositional zonation as the tuff of the lower lobes and the tuff of the upper lobes taken together, suggesting repeated tapping of the same zoned magma chamber. Worth re-emphasizing here is the fact that the zonation was the reverse of that common in shallow, caldera-related magma chambers; the first-erupted products were more mafic than the later products. Characteristics of this chamber differed in some as yet unknown way from those of caldera-related chambers.

We have no data on eruption temperatures for the tuff of the lower lobes, tuff of the upper lobes, and tuff of The Badlands. The flow phenomena exhibited by these units do indicate much higher temperatures than those usually found in ash-flow tuffs. The existence of a stable magma chamber, however, suggests that magma temperatures generally prevalent in the chamber were significantly lower than temperatures at times of eruption. Eruptions may have been triggered by sudden rises in temperature.

The resorbed condition of phenocrysts in the rocks of Juniper Mountain and to a lesser degree in the Little Jacks may support the hypothesis that eruptions were triggered by sudden rises in temperature. Noble (1970b), however, has pointed out that resorption also will take place if pressure is reduced when a magma is water-undersaturated, which is true for these magmas. Such resorption would, of course, take place during rise of the magma to the surface. If this rise were catastrophically rapid, however, little or no resorption could take place enroute, and the resorption we see could then be related to temperature rise in the magma chamber.

Many authors now believe that the most likely source of heat for producing rhyolite magmas in regions of crustal extension is basaltic magma (Smith and Shaw, 1975; Lachenbruch and Sass, 1978). Heat transfer from basaltic magma also is believed to be a common mechanism for triggering the eruption of rhyolitic rocks (Sparks and others, 1977). There appears to be little doubt that heat transfer from basalt was involved in generation and eruption of the Owyhee rocks, because we can imagine no other way to raise these rhyolitic magmas to eruption temperatures typical of basalt. Why this process should have operated in such a unique way in the Owyhee region remains a puzzle.

For example, our data indicate that the Little Jacks Tuff was erupted directly from a depth that may have been as great as 25 km. This may have been the depth at which the magma was generated. Normally, such a magma would rise quietly to a depth of say, less than 5 km, and stay there for some time in a magma chamber prior to eruption. Instead, some extraordinary event took place that stimulated rapid rise and eruption of the magma, in essence, directly from its site of generation within the lower crust. We surmise that the eruption was triggered by rapid temperature rise of the rhyolitic magma caused by a sudden, massive invasion of basaltic magma within or adjacent to the magma chamber. The superheated magma, then, rose rapidly and erupted.

What ultimately caused this sequence of events is conjectural. We suspect that the ultimate cause may have been an unusually sudden, rapid opening of a crustal rift. Such a rifting event not only would provide sudden access of the basaltic magma to the rhyolitic magma, but also would facilitate initial movement of the rhyolitic magma toward the surface.

The magmas that formed the Swisher Mountain Tuff and related rocks of the Juniper Mountain center and the Jump Creek Rhyolite of Kittleman and others (1965) were erupted at about the same temperature as was the Little Jacks Tuff. Development of flowage features in other rhyolitic units in the Owyhee region suggests similar eruption temperatures for them as well. The rocks of the Juniper Mountain center and most of the other units probably were erupted from depths considerably shallower than the depth of the Little Jacks Tuff. A probable sequence of events similar to that outlined for the Little Jacks Tuff probably accompanied eruption of all of them—namely, sudden, extreme temperature increase caused by massive invasion of the magma chambers by basalt.

A particularly interesting relationship among the rhyolitic rocks of the Owyhee region is that the rhyolites of the Silver City Range are highly mineralized, whereas other rhyolites in the same area are not. As mentioned earlier, some units of the rhyolites of the Silver City Range contain biotite, whereas none of the other rhyolites of the region contain primary hydrous mineral phases. This occurrence of biotite indicates higher water contents for the Silver City Range rocks during the period of time that phenocrysts were forming, and hence a magma chamber that was at shallower depths than those of the Little Jacks and Juniper Mountain centers. Magma chambers for the Little Jacks and Juniper Mountain sequences were for the most part below the level to which meteoric waters might descend. Although we cannot estimate with any degree of precision the depths of the Silver City magma chamber(s), perhaps it was sufficiently shallow to be within reach of meteoric waters. These two conditions (higher water content and magma chamber depth) might, of course, be the critical factors that enabled hydrothermal mineralization at Silver City and not at the Juniper Mountain or Little Jacks centers.

Mineralization at the McDermitt caldera (Rytuba and Glanzman, 1978) also might be explicable in these terms, plus an important third factor. Cauldron collapse there indicates a shallow magma chamber, well within reach of meteoric waters. In addition, the caldera complex is near or west of the western edge of Precambrian crust as defined by strontium isotope studies (Armstrong and others, 1977). The source rocks for the peralkaline rhyolites at McDermitt were relatively undepleted in incompatible elements, especially when compared to the Precambrian crust to the east. Rytuba and Glanzman (1978) have shown that even the unaltered silicic volcanic rocks at McDermitt are abnormally enriched in U, Li, Sn, and other incompatible elements. This enrichment strongly suggests that the McDermitt magmas originated from a substratum of decidedly different chemical composition than that that gave rise to the Owyhee magmas.

SUMMARY DISCUSSION

The three most important conclusions drawn in this report are: (1) large-volume ash-flow eruptions can take place without fault-controlled collapse of the source area, (2) extremely hot ash flows can coalesce to liquids during emplacement, and (3) ash-flow sequences like those of the Owyhee region commonly are "reversely zoned," that is, they are characterized by early eruptions of relatively mafic material followed by later eruptions of more felsic material—the opposite of the sequence commonly associated with caldera-forming eruptions. These conclusions are somewhat controversial, and as far as we know they have never been fully documented before. The purpose of this summary dicussion is to review the information and lines of reasoning that led to these conclusions.

SOURCE AREAS

Large-volume ash-flow tuffs that have been mapped in detail in many areas throughout the world have, in most places, been shown to have subsided source areas. As Smith (1960, p. 801) so aptly stated "***practically all the deposits of 'welded tuffs' or 'pumice flows' known to have a volume of more than a few cubic miles and that have been unequivocally related to their source areas are related to subsidence structures." Nevertheless, many large-volume ash-flow sheets in other parts of the Western United States, and especially in Nevada, have no known subsided source areas. Ekren and others (1980) described an area in west-central Nevada characterized by extremely large-volume, ash-flow tuffs in which mapping at scales of 1:48,000 and larger failed to disclose a cauldron complex. They ascribed the lack of caldera development in west-central Nevada to eruptions from depths that were too great to allow calderas to form, and, by analogy, compared caldera development to crater development caused by underground nuclear explosions at Nevada Test Site. Exploding a device at shallow depth at the test site invariably creates a surface subsidence crater (caldera) within minutes or hours after the explosion. At deeper levels no subsidence crater forms, although the underground cavity formed by the deeper explosion is in many examples larger than the more shallow-seated cavity. We believe that the lack of subsidence calderas at the source areas described in the present report, like the deeper cavities at the Nevada Test Site, are due to the magma chambers being at depths that were too great to allow calderas to form.

Have we correctly identified the source areas of the ash-flow tuffs of the Owyhee Plateau? If we have not, where are they? The distribution of the voluminous Swisher Mountain Tuff precludes eruption from the Snake River Plain. Our mapping, plus examination of the Landsat images reproduced in this report, preclude an "overlooked" caldera within the known area of distribution, although a broad depression may have formed in response to magma withdrawal. We believe the evidence is conclusive that the voluminous sheet was erupted from a source or sources near Juniper Mountain. The source area of the Little Jacks Tuff is sufficiently near the plain (fig. 28) that the argument can be made that the subsidence caldera is buried beneath the plain. Although this possibility cannot be completely discounted, it seems unreasonable to us because of flow-lineation trends in the mapped area, and because the center of distribution lies well within the Owyhee Plateau. Furthermore, if the eruption of the Little Jacks Tuff caused a caldera complex to form in what is now the Snake River Plain, quite probably this complex would have some present surface expression. The Island Park caldera at the northeastern end of the plain is well expressed. Other calderas have been tentatively identified and located in the plain on the basis of arcuate basalt dikes (Paul L. Williams, oral commun., 1977). No features suggestive of a partly buried caldera, including arcuate basalt ring dikes, are evident on the Landsat image (fig. 28) or on the geologic map of this part of the plain by Malde, Powers, and Marshall (1963), which is based there on detailed mapping at a scale of 1:48,000 or larger. To summarize this phase of the discussion, we believe that the source areas of the two extremely voluminous ash-flow sequences have been correctly identified and that no calderas exist in either vent area.

REVERSION FROM ASH FLOW TO LIQUID FLOW

The conclusion that the principal rhyolite rock units in southwestern Idaho were emplaced as extremely hot ash flows and that these ash flows coalesced in large part to form liquids before coming to rest seems to us, on the basis of evidence presented in this report, to be soundly based. The senior author has mapped a wide variety of welded ash-flow tuffs throughout a large part of Nevada. The tuffs in Nevada have such extreme variations in the degree of welding, ranging from formerly cold, thick ash-flow tuffs that are virtually nonwelded to formerly hot ash-flow tuffs that are densely welded from base to top and that have flowage features indicative of liquid flow, that it came as no surprise to see the tuffs in Idaho that probably were formed from the ultimate in hot ash flow.

Several ash-flow tuffs that have flowage features have been described in which the flow layers are ascribed to laminar flowage. In postulating the sequence of events that led to the development of the lava-like flowage features in the tuff of Wagontire Mountain in central Oregon, Walker and Swanson (1968, p. 44) pointed out, "The ash flow***advanced turbulently to almost its final position. Turbulence subsided, however, as the supply of upward-escaping gases was depleted and eventually the mass became so deflated that shards and pumice fragments came into contact with each other and welded into a coherent viscous fluid (glass). Flowage continued owing to momentum but the movement was laminar, not turbulent."

Flowage as a "coherent viscous fluid" is, to us, synonymous with flowage as a viscous liquid. Silicic lavas are coherent viscous fluids; flowage features in rocks such as ours, and in the laminated part of the ash-flow tuff described by Walker and Swanson (1968) are indistinguishable from the flowage features found in lavas. Walker and Swanson's example illustrates reversion of part of an otherwise normal ash-flow tuff to a viscous liquid during emplacement. Our examples show this process carried to an extreme, where commonly all of a given cooling unit has become a coherent viscous fluid—that is, a liquid.

Chemical composition has long been considered of prime importance in the development of flowage features in ash-flow tuffs (R. L. Smith, oral commun., 1967; Walker and Swanson, 1968; Hoover, 1964; Anderson, 1970; Noble and others, 1968). The chemical components believed to be of principal importance are Al_2O_3, the alkalis (especially Na_2O), total iron, and high volatile contents (principally water). Rocks with peralkaline composition (molecular $Na_2O + K_2O$ greater than molecular Al_2O_3) and those with high total iron have appeared more likely to develop flowage features than those with more or less normal subalkaline chemistry (figs. 38, 39).

Figure 38 shows that the ash-flow tuffs of the Owyhee region of Idaho do not have an unusually high ratio of Na_2O to K_2O compared to rocks with flowage features in Nevada and Oregon, and that the rocks from all three states have a wide range of total iron content. The amount of total iron is unrelated to degree of development of flowage features; such features are about equally developed in all the samples analyzed. Figure 39 shows that the ash-flow tuffs from Owyhee County do not have peralkaline compositions, therefore this aspect of chemical composition cannot be invoked to explain development of flowage features in these rocks. Totally anhydrous phenocryst assemblages, low water, and low fluorine content suggest strongly that the Owyhee magmas did not have unusually high volatile content. Nevertheless, the ash-flow tuffs from Owyhee County, with their low Na_2O/K_2O, their subalkaline compositions, variable iron content, and low water content, developed flowage features to a greater degree than did either the Nevada or Oregon rocks. Clearly, a factor or factors other than chemical composition must be called upon to explain the development of flowage features in the rocks of the Owyhee Mountains and Owyhee Plateau, and in several examples found in Nevada. We believe the critical factor, and perhaps the only important factor, that causes the development of flowage features in ash-flow tuffs is high eruption temperature.

As noted previously, temperatures for the Swisher Mountain and the Little Jacks Tuffs were on the order of 1,100°C (table 7). Smith (1960) has summarized evidence that indicates that there is almost no heat lost during transfer of an ash flow from its eruption-column source to its site of deposition. The eruption temperatures of the Swisher Mountain and the Little Jacks Tuffs are the temperatures, then, that could persist throughout the entire transport cycle of these ash flows. At these extreme temperatures, particles within the interiors of the ash flows may have more closely resembled liquid droplets than rigid, angular glass shards. Particles at the cooler margins of each ash flow may have been more shardlike; it may be these that we see locally preserved at the margins of, and, in some instances, within a cooling unit (containing several ash flows). In these instances, preservation of the shards really provides no firm clue concerning the nature of the particles within the main body of the ash flows.

If temperature is the overriding factor in determining development of flowage features in these rocks, a key "natural experiment" would be provided by an ash-flow unit that has a wide variation in degree of flowage-feature development, in which other factors affecting flow-

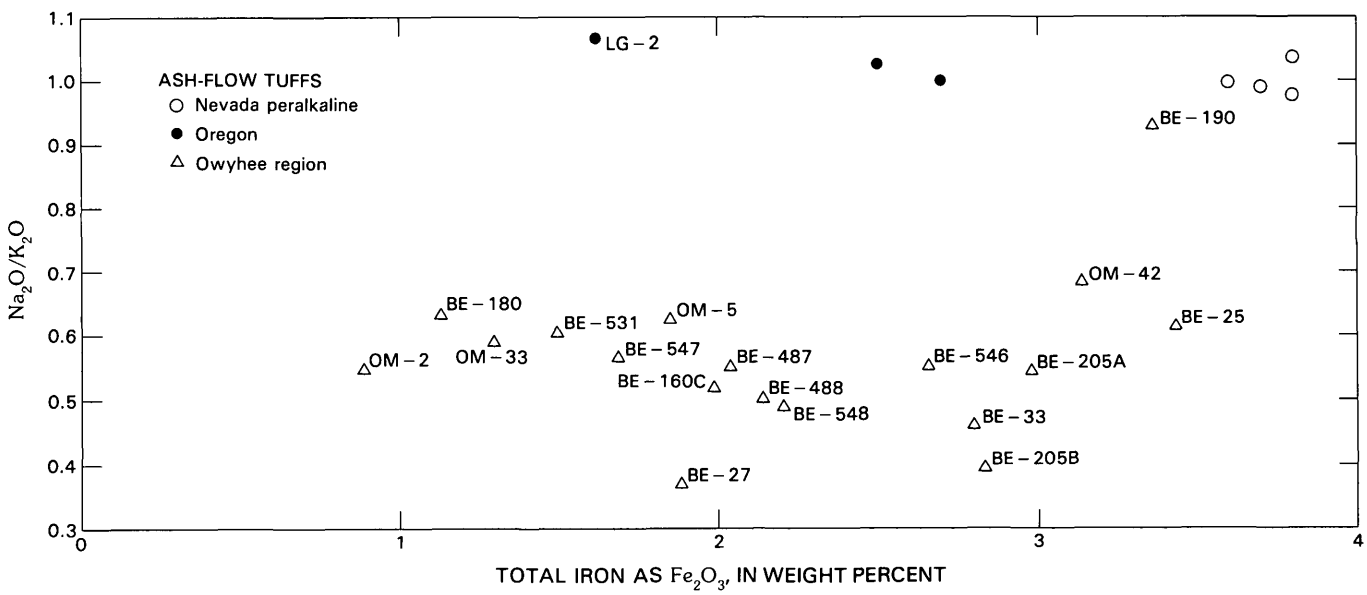


FIGURE 38.—Diagram comparing Na_2O/K_2O (based on weight percentages) versus weight percentage of total iron for ash-flow tuffs of southwestern Idaho with tuffs from Nevada and Oregon that show secondary flowage (Walker and Swanson, 1968; Noble and others, 1968). Numbers are those of sample localities listed in tables 4, 5, and 8.

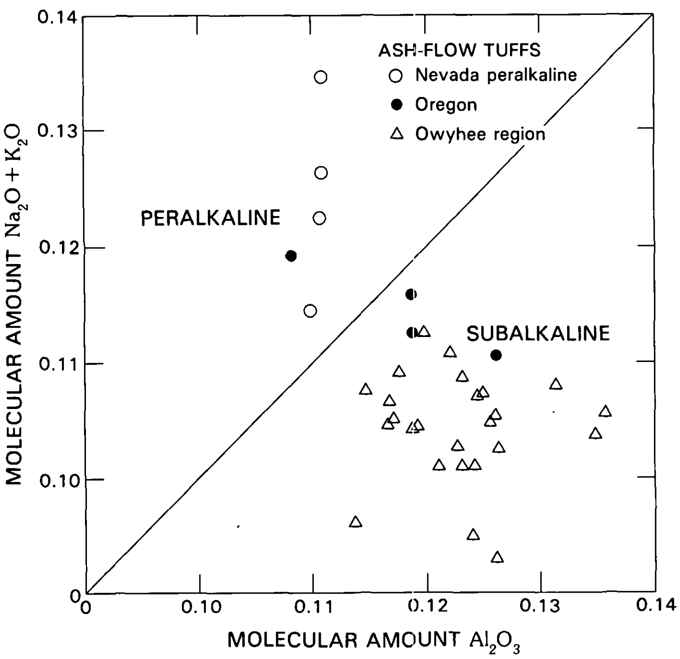


FIGURE 39.—Diagram comparing molecular amounts of Na_2O + K_2O versus molecular amounts of Al_2O_3 for ash-flow tuffs of southwestern Idaho with tuffs from Nevada and Oregon that show secondary flowage (Walker and Swanson, 1968; Noble and others, 1968).

age can be shown to be uniform, or not applicable. Such a unit is the upper-lobes tuff of Juniper Mountain. Chemical variation and phenocryst composition within the unit are small, and, as described earlier, the lower part of this 200-m-thick unit clearly shows features of a normal ash-flow tuff. This rock at the base passes upward into densely welded tuff with collapsed pumice that, in turn, passes upward into flow-layered rock in which nearly all pyroclastic textures have been destroyed. The surface of this upper zone has the large-scale, lobate flowage features that are prominent on aerial photographs. There is no chemical variation to produce this drastic variation in development of flowage features. Degree of compaction by load cannot be called upon because the flowage features are developed best at or near the *top* of the unit. The most plausible explanation for this variation in degree of development of flowage features is variation in temperature: relatively cool at the eruption's beginning, and becoming increasingly hotter as the eruption proceeded. The development of flow lobes in the upper part of the cooling unit clearly indicates that conversion from ash to liquid was virtually complete.

Is it misleading or inappropriate to call the Owyhee rocks "ash-flow tuffs" when a possibility exists that the particles in the flows were not glass fragments, but were, instead, liquid droplets? We think not, because of the small differences in physical properties of white-hot shards and liquid droplets, and the fact that the resulting sheetlike masses extending 50 km or more from their sources certainly must have been emplaced in much the same way as ordinary ash flows.

REVERSED COMPOSITIONAL ZONING

Most of the well-documented, caldera-producing, ash-flow tuffs are more rhyolitic at base than at top. Examples that show this "normal" compositional zoning are the Timber Mountain Tuff of southern Nevada (Byers and others, 1976; Lipman and others, 1966), Bandelier Tuff of New Mexico (Smith and Bailey, 1968), Windous Butte Formation of central Nevada (Ekren and others, 1974), and the Bishop Tuff of eastern California (Hildreth, 1979). Most of these tuffs show chemical variations from silicic rhyolite at the base to less silicic rhyolite, quartz latite, or even rhyodacite at the top. Commonly, the variations occur within a single cooling unit. Lipman and others (1966) stated that the sequence of compositional variation in each ash-flow sheet represents in inverted order the compositional zonation that existed in the magma chambers at the time of eruption. They noted also that simple crystal settling cannot account for this zonation.

A model to account for the common or normal type of zonation has recently been proposed by Shaw, Smith, and Hildreth (1976) that calls upon a combination of convection and liquid-state diffusion within the magma chamber. This concept has been further elaborated by Hildreth (1979) to explain the normal compositional zonation of the 0.7-m.y.-old Bishop Tuff. This study, which is based on a wealth of phenocryst and whole-rock major and trace-element data, showed that liquid-state thermogravitational processes probably were dominant in the Bishop Tuff magma chamber, and that crystal fractionation probably was an insignificant process.

The tuffs of the Owyhee region do not show normal chemical variation. They show, instead, virtually no variation at all, as for example, the Little Jacks Tuff, or they show a general *upward increase* in felsic material, as in the Juniper Mountain rocks. Although no drastic variations are apparent within a single cooling unit in any of the Owyhee rocks, considerable variations are apparent within the eruption interval represented by the Swisher Mountain Tuff, lower-lobes tuff, and upper-lobes tuff. All three of these units were erupted during a short time interval, as indicated by their identical K-Ar age of 13.8 m.y. They can be loosely regarded as a single compound cooling unit. Modal analyses of this "compound cooling unit" shows a general upward increase in the abundance of quartz and alkali feldspar phenocrysts and a corresponding decrease in the abundance of plagioclase. Chemical analyses (fig. 36*B*) show a general decline in total Fe, Ca, Mg, and Al with decreasing age, a corresponding increase in SiO_2, and decreasing Na_2O) values being systematically counterbalanced by increasing K_2O values, which resulted in nearly constant total alkali content for the Juniper Mountain rocks. These mineralogic and chemical trends (fig. 36*B*) are comparable to those of the extraordinary Guild Mine Member of the Mickey Pass Tuff in west-central Nevada (Proffett and Proffett, 1976; Ekren and others, 1980). This compound cooling unit has a range in composition from rhyodacite at the base to silicic rhyolite at the top. Analyses of the Guild Mine Member and other units in west-central Nevada that Ekren and others (1980) inferred to have been erupted without cauldron subsidence from deeply buried magma chambers show considerably more variations in phenocryst mineralogy and chemistry than are apparent in the Owyhee rocks. For example, the basal part of the Guild Mine Member, which is characterized by 30–40 percent phenocrysts that consist of 63–75 percent plagioclase, 9 percent biotite, 9 percent augite and hypersthene, and 3–10 percent alkali feldspar, has a silica content of only about 66 percent (analyses recalculated to 100 percent minus H_2O and CO_2). The top of the Guild Mine Member, in contrast, which contains about 27 percent phenocrysts that consist of 25–35 percent quartz, 45–55 percent alkali feldspar, 20–25 percent plagioclase, and less than 2 percent biotite, has as much as 77 percent silica (analyses recalculated to 100 percent from raw data that did not include an analysis for H_2O^+). Alumina, total iron, MgO, and CaO declined sharply from values typical of rhyodacite in the basal part to values typical of silicic rhyolite at the top (Ekren and others, 1980, table 3, p. 20; Proffett and Proffett, 1976, table 2, p. 18). These variations are much more extreme than any that are apparent in the Owyhee rocks, but the Guild Mine Member, like the Owyhee rocks, shows little variation in total alkali content from base to top. Na_2O declines from 4.10 at base to 3.16 at top, and K_2O increases slightly from 4.12 percent at base to 4.39 percent at top. These chemical variations strongly suggest that the compositional zonation in the Nevada magma chamber(s) must have been similar to the zonation in the Owyhee magma chambers, particularly in the Juniper Mountain chamber.

To account for the "reversed" zoning that characterized the Guild Mine Member and other west-central Nevada ash-flow tuffs, Ekren and others (1980) argued that the deeply seated magma chamber inferred there probably was shaped like a thick cylinder rather than a laccolith, which is a reasonable configuration for a shallow-seated chamber. They dismissed the possibility that the zoning was due to initial tapping of a deep level within the chamber because of the unlikelihood of this occurring repeatedly. They concluded that the early-formed crystals and the least siliceous magma must have been concentrated at the top of the chamber and at sides of the chamber near the top in a manner analogous to a zoned pluton. Whatever the actual shape of the deeply seated Juniper Mountain chamber in the Owyhee region, the early-formed crystals and the least siliceous magma must also have been concentrated at the top of the chamber and at the sides of the chamber near the top in order to account for the changing phenocryst assemblages and chemical variations during the eruption of the lower- and upper-lobes tuffs and, in particular, the tuff of The Badlands. This last tuff has an early phenocryst assemblage that consists of intensely resorbed quartz, plagioclase, and alkali feldspar, all as long as 1 cm, followed by an assemblage that consists of less plagioclase and much smaller and little-resorbed phenocrysts overall—an eruption sequence that exactly duplicated the earlier eruptions of the lower- and upper-lobes tuffs. The mechanism or combination of conditions that could consistently concentrate the least silicic liquids toward the top of the magma chamber is unknown.

NATURE OF ERUPTION COLUMN

Most geologists now accept the concept that ash flows move under the influence of gravity (Sparks, 1976). In addition to falling from whatever height the eruptive column reached, many large-volume ash flows moved downslope from structural domes that formed above shallow-seated magma chambers. An example of such doming is found in the Timber Mountain caldera of southern Nevada. According to Christiansen and others (1965, p. 44), "A broad domical swell developed in the Timber Mountain area before the climactic ash-flow eruptions and related collapse." Such doming could account for wide distribution of some ash flows without the ash having been lifted high in the air by high eruptive columns. In the deep-seated centers like those at Juniper Mountain and the Little Jacks center, there probably was little or no doming of the surface strata prior to ash-flow eruptions; at least there is no obvious thinning of strata in the vicinity of the inferred source areas. The thickest sections of both Swisher Mountain Tuff and Little Jacks Tuff are in close proximity to the source areas. To achieve the wide distribution of the Swisher Mountain Tuff and Little Jacks Tuff, the eruptive columns must have been extremely high, and, as will be explained later, of large diameter or width.

In considering the amount of mixing, the degree of cooling, and the nature of and the configuration of the eruption column, Sparks and Wilson (1976, p. 441) concluded that, "Eruption columns consist of two components. The lower gas-thrust component results from decompression of the gas phase, and decelerates rapidly to near zero velocity at heights of 1.5–4.5 km for initial gas velocities of 400–600 m/s. The upper convective-thrust component is due to the column having a lower density than the atmosphere, and can transport the column to heights of 30–40 km. At the base, the effective density of a column is considerably greater than that of the atmosphere and is very sensitive to changes of gas content. Fallout of clasts and incorporation and heating of air reduce the density substantially during the gas thrust part. Eruption columns formed from magmas with high water contents (5 percent) are likely to show convective motion. Magmas with low water

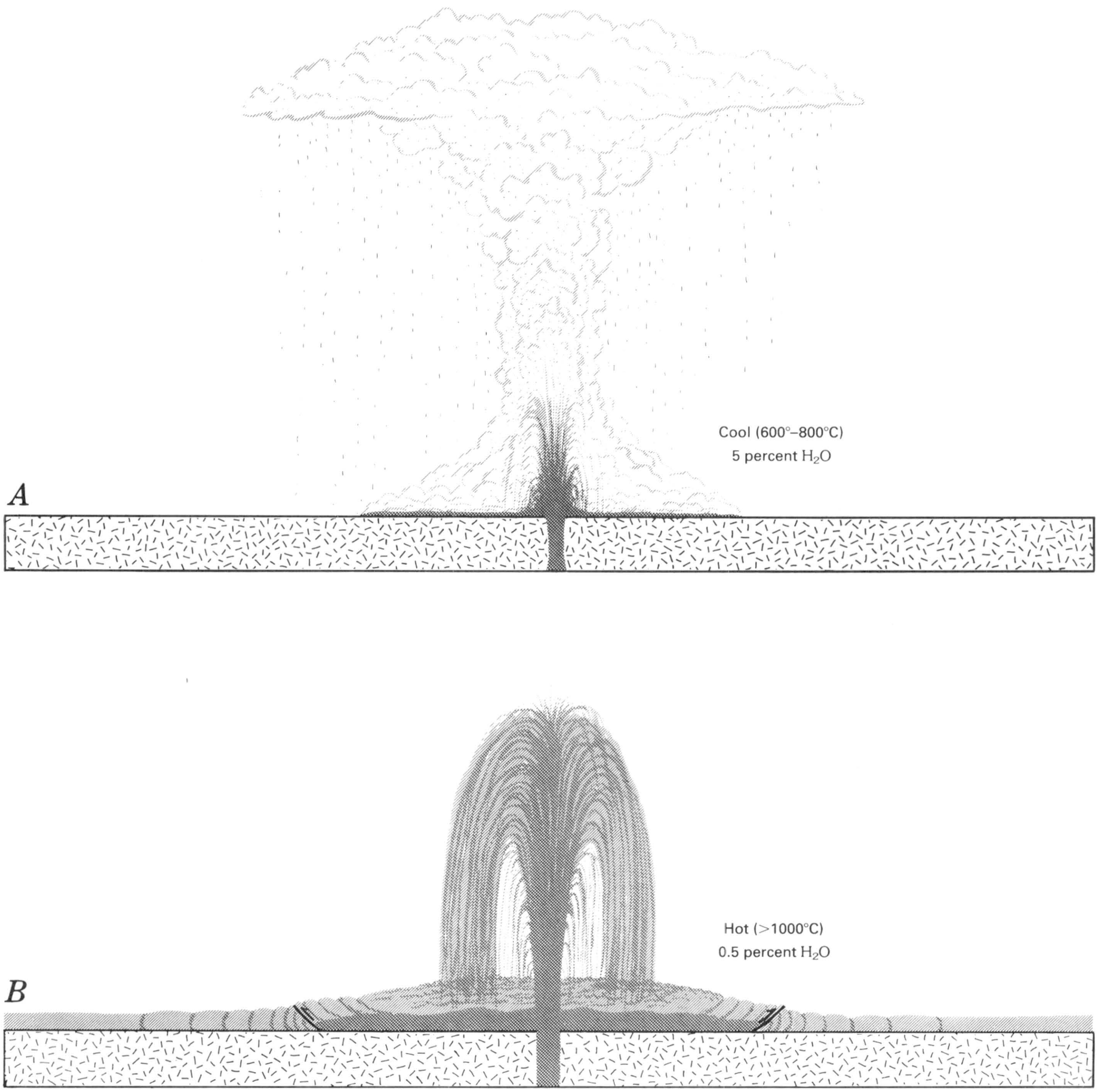


FIGURE 40.—Comparison of two types of eruption column. *A*, Plinian type with large convection component and small gas-thrust component (Sparks and Wilson, 1960). Type shown in *B*, is inferred to be the type that gives rise to large-volume ash flows such as those discussed in the present report. In *B*, convection component (not shown) is negligible because of high eruption temperature. Ramp structures, observed in field, may have formed at margins of thicker deposit that accumulated below eruption column. Figure drawn by Arthur Isom.

contents (½ percent) or high proportions of CO_2 will form a column with an effective density greater than the atmosphere, and gravitational column collapse can occur to generate ignimbrite-forming pyroclastic flows. In magmas with intermediate gas contents, the occurrence of convection (plinian case) or collapse (ignimbrite-forming) depends on vent radius, proportion of ash and gas content." Sparks and Wilson (1976) presented strong arguments for theorizing that a dry, hot magma will give rise to a dense eruptive column that will not mix with the atmosphere to any appreciable degree. This column will be comprised of virtually only the gas-thrust component because convective thrusting can occur only when the density of the column is much reduced by mixing with the atmosphere. We infer that the eruption columns that gave rise to the Swisher Mountain and Little Jacks Tuffs were primarily gas-thrust columns, in contrast to Strombolian and Plinian eruption columns, within which the convective part makes up more than 90 percent of the column's height. The tuffs of Idaho, in fact, show little evidence of Plinian phases, even at the start of the eruptions, because they generally lack air-fall deposits at their bases. This lack probably also indicates that the vent was of large diameter, inasmuch as a small-diameter circular vent or a small-width fissure vent would greatly favor extensive mixing of the earliest erupted material with the atmosphere, and, hence, cool initial ash flows (Sparks and Wilson, 1976). The tuffs of southwestern Idaho probably were erupted from centrally located circular vents rather than from arcuate or radial fissures because of a lack of any evidence of pre-eruption doming. Without such doming there would be no concomitant development of arcuate or radial fractures that could later serve as conduits for erupting magma. The inferred central vents gave rise to eruptive columns capped by mushroom-shaped clouds that spread ash flows in all directions like giant water fountains; each ash flow representing a renewed surge or pulse of erupting magma (fig. 40).

Because the firsthand knowledge of historical eruption columns and ash-flow eruptions, in general, is limited to the miniscule eruptions of Mount Pelée, Soufrière, and others, we are extremely handicapped in trying to envision the configuration and height of a column capable of giving rise to large-volume ash flows of magnitudes that are indicated by the Swisher Mountain Tuff and the various cooling units of the Little Jacks Tuff. A maximum height of 4.5 km for ignimbrite-producing columns as deduced by Sparks and Wilson (1976) probably constitutes a minimum for producing widespread ash flows. Such a height cannot account for a 100-km-diameter ash-flow sheet even if the ash flows traveled considerable distances by "riding on a cushion of air." Without extensive, pre-eruption doming the ash-flow producing columns must have been considerably higher than 4.5 km. That this is a distinct possibility is suggested by eruption columns on Jupiter's moon Io that were photographed by the Voyager I spacecraft. The columns on Io were found to be as much as 270 km high and had eruption velocities calculated to be 1 km/s (Smith and others, 1979, p. 961; L. Soderblom and S. Kieffer, oral communs., 1979). Because of Io's smaller size and density compared with those of the Earth (3,640 km diameter and 3.53 g/cm^3 according to Smith and others, 1979, p. 964) versus about 12,800 km diameter and 5.5 g/cm^3 for Earth, the eruption columns' heights on Io cannot be directly extrapolated to calculate potential heights on Earth. Nevertheless, even larger velocities than 1 km/s are now considered likely for Earth's prehistoric large-volume eruptions (S. Kieffer, oral commun., 1979). These velocities are double or triple the maximum considered by Sparks and Wilson (1976), and indicate that the eruption columns' heights calculated by Sparks and Wilson (1976) are too small. How high a column is necessary on Earth to produce ash-flow sheets of 100-km diameter? This question is difficult to answer principally because of the impossibility of determining the magnitude of the cushion-of-air effect. Intuitive reasoning suggests that heights on the order of 15 km may be necessary to distribute ash over a 50-km radius by gravity flowage from an eruption column. The Io eruptions indicate that such heights are in the realm of possibility.

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INDEX

[Italic page numbers indicate major references]

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Ekren, McIntyre, Bennett— LAVALIKE ASH-FLOW TUFFS WITHOUT CALDERAS IN SOUTHWESTERN IDAHO—Geological Survey Professional Paper 1272