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**A STUDY OF THE ASH RINGS OF SPLIT BUTTE,
A MAAR CRATER OF THE SOUTH-CENTRAL
SNAKE RIVER PLAIN, IDAHO**

by

MICHAEL B. WOMER

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A MAAR CRATER OF THE SOUTH-CENTRAL SNAKE RIVER PLAIN, IDAHO

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Michael B. Womer

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ABSTRACT:

Split Butte is a volcanic crater of recent origin which consists of a tephra ring which at one time retained a lava lake. The tephra, which consists of partially palagonitized sideromelane and lithic fragments, is thinly bedded and dips radially away from the center of the Butte.

The tephra ring is believed to be the result of phreatomagmatic eruptions caused by the interaction of slowly rising basaltic magma with abundant groundwater. Evidence of this is given by the glassy and granulated nature of the pyroclastic debris, the presence of palagonite and other secondary minerals, abundant accretionary lapilli in the ash, and plastically deformed ash layers below ejecta blocks. Statistical parameters derived from grain size analysis provide further evidence of the phreatomagmatic nature of the Split Butte tephra. Further analysis of the grain size distribution reveals that the lower ash layers were deposited by base surge mechanisms while the upper ash layers, which comprise the bulk of the ring, were deposited by air fall mechanisms. The ash layers lack dune forms and cross bedding, which indicates air fall was the primary mechanism of emplacement.

The inner lava lake was formed when phreatomagmatic activity at the vent suddenly ceased. This abrupt change in eruptive style was caused by an increase in the rate of extrusion of the lava, as is evidenced by the high level of the lava lake.

Erosion of the ash, deposition of eolian sediments, and encroachment of the Butte by surficial lava flows followed the volcanic activity and have completed the development of Split Butte.

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STATEMENT OF PROBLEM:

Split Butte is a volcanic construct which was formed during Late Pleistocene or Early Holocene times. It is located in the south-central Snake River Plain and consists of a tephra ring 550 m in diameter which has a maximum relief of approximately 50 m relative to the surrounding plain. The tephra lies in disconformable contact with the basalt of a lava lake, which the ring confined.

The objectives of this study were to determine the specific processes and environmental conditions which interacted to generate the present day feature, and to evaluate the applicability of Split Butte as a planetary geologic analog study.

The above objectives were accomplished through detailed field investigations, photo analysis, grain size analysis of the tephra, and petrographic observations of prepared samples of the geologic units at Split Butte.

PREVIOUS WORK:

Although very little information has been published concerning the geology of Split Butte, an excellent summary of the local geologic and physiographic setting is provided by Greeley and King (1975). These investigators offer a concise description of the structure of the crater and the composition and texture of the lithologic units present. The interaction of rising basaltic magma with groundwater to produce the tephra ring and the subsequent reduction of this interaction to form the inner lava lake were suggested as possible mechanisms of formation by these workers.

REGIONAL GEOLOGIC SETTING:

The Snake River Plain is a curvate structural and topographic low approximately 650 km long which extends across the southern section of Idaho from the Oregon boundary to the base of the Yellowstone Plateau. It is concave to the north and ranges in width from 80 to 200 km with the greater width occurring in the east. The relief is low, and the elevation varies from approximately 1800 m in the east to 700 m in the west. The Snake River Plain is bounded by highlands to the north and south. Miocene Columbia River basalts bound the province to the west and the silicic Tertiary volcanics of the Yellowstone Plateau lie to the east.

The Snake River Plain is divided into two sections at approximately $114^{\circ} 30'$ W longitude due to marked structural and geophysical differences between east and west sections of the plain (Hill, 1963). The western section is characterized as a graben bounded by Lower Pliocene volcanics and the Cretaceous Idaho Batholith. The graben has been down-dropped along northwest trending high-angle faults. Malde (1965) states that at least 2700 m of displacement has taken place along these faults since early Pliocene time.

The eastern Snake River Plain, where Split Butte is located, is characterized by low gravity relief and an apparent absence of bounding faults, although Malde (1965) states that the truncation of mountain fronts on the northern boundary does suggest faults. Older rhyolitic and sedimentary deposits which border the plain to the north and south gently dip toward the axis of the plain. The dip, which increases in older rocks, is greatest along the borders of the

plain and tends to flatten at its axis (Greeley and King, 1975; Schoen, 1974). It has been tentatively concluded that gentle downwarping, rather than structural control, has been responsible for the formation of the eastern Snake River Plain (LaFehr and Pakiser, 1962; Kirkham, 1931). Studies by Eaton et. al. (1975), however, suggest that the eastern plain may be the result of a mantle plume migrating along a structure in the precambrian basement.

Lithologically, the Snake River Plain consists of a sequence of interlayered basalt flows and sediments which probably averages over 1500 m in thickness in the eastern plain (LaFehr and Pakiser, 1962) and over 2900 m in thickness in the western section (Hill, 1963). Resistivity studies by Zohdy and Stanley (1973), however, indicate an average thickness of approximately 3600 m of basalt in the eastern plain. The basalts are divided into two major groups, the Idaho Group in the western section and the Snake River Group which covers the eastern section of the plain. The age of the Idaho Group ranges from Lower Pliocene to Middle Pleistocene while the Snake River Group is Upper Pleistocene to Holocene in age (Stone, 1967).

LOCAL GEOLOGIC SETTING:

Split Butte is a volcanic feature of recent origin located in the south-central Snake River Plain at latitude 43° N, longitude $113^{\circ} 20'$ W. It lies approximately 13.5 km west of King's Bowl and 12.5 km south of the Craters of the Moon lava field (Fig. 1). The Butte overlies basalt flows of the undifferentiated Snake River Group, which are Pleistocene in age.

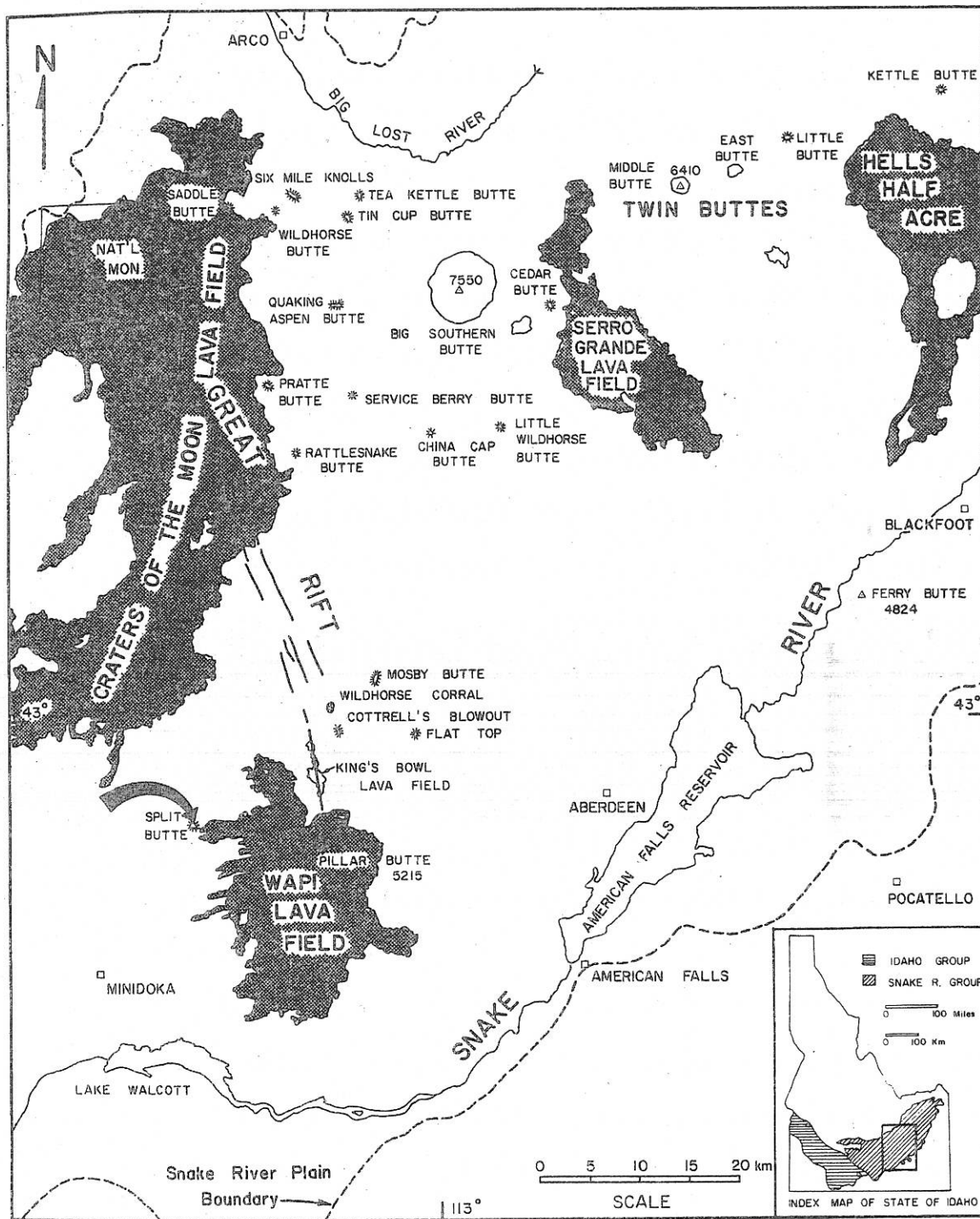


FIGURE 1: LOCATION MAP — CENTRAL SNAKE RIVER PLAIN, IDAHO

The surface of the flows in the south-central plain are typically of low relief and generally slope about 6.0 m per km from northeast to southwest. The lavas are believed to have been very fluid because of the low slopes and large areas covered by the flows. A single flow may cover several hundred km² of the plain (Stearns, Grandall and Steward, 1938). The individual flows are thin, with average thicknesses ranging from 50 to 80 m (Russell, 1902).

The nearby Wapi lava field basalts flow over fissures of the King's Bowl fracture set (Champion, 1973) which infers that they are among the most recent flows in the area. The recent origin of the King's Bowl fracture set is inferred from the age of the first flow to emanate from it, which has been dated at 2130 years $\pm$ 130 years (Prinz, 1970). The young Wapi flows slightly overlap Split Butte, indicating that the Butte predates the Wapi.

A veneer of loess mantles the most recent flows of the Snake River Group, but many of the prominences on the lava surface remain uncovered.

Split Butte (Fig. 2) is a volcanic crater consisting primarily of a tephra ring 550 m in diameter which at one time retained a lava lake. The tephra ring has a maximum relief of approximately 50 m relative to the surrounding plain. It is moderately asymmetrical, and shows a greater accumulation of ash on the northeast, the result of prevailing southwesterly winds during the eruption. The tephra, which consists of partially palagonitized sideromelane and lithic fragments, is thinly bedded and dips radially away from the center of the Butte. A large split 150 m wide occurs in the eastern section

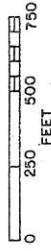
Fig. 2 -

GEOLOGIC MAP OF SPLIT BUTTE, BLAINE COUNTY, IDAHO

MICHAEL B. WOMER

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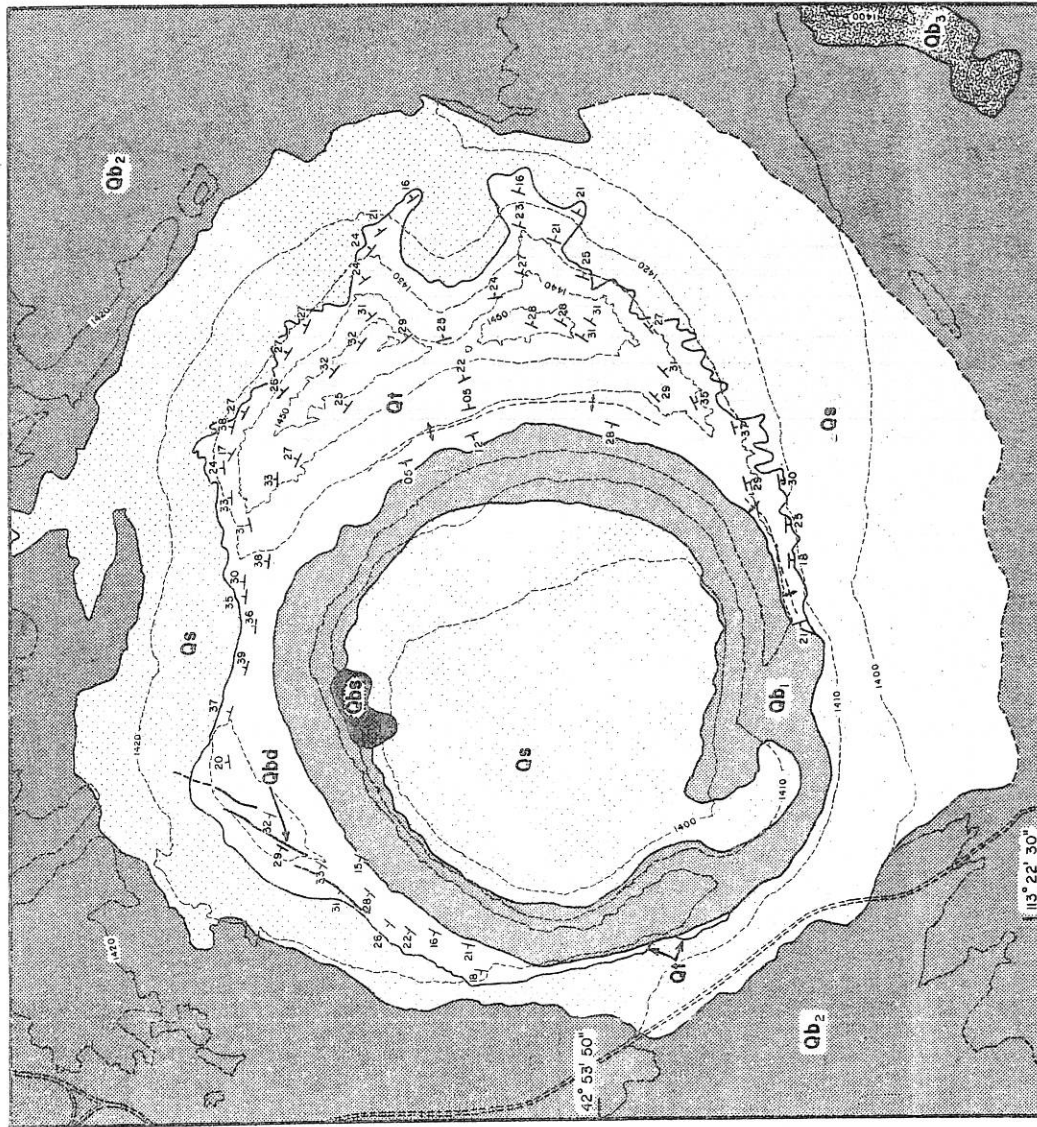
Elevations Expressed in Meters Above Mean Sea Level. Topographic Base Prepared by U.S. Geological Survey



EXPLANATION

- Qs Surficial Deposits -
Eolian Sediments and Colluvium
- Qb₃ Wapi Lava Field Flow
Basalts
- Qb₂ Snake River Plain
Undiff. Flow Basalts
- Qb₁ Split Butte Spatter
Basalts
- Qbd Split Butte Dike
Basalts
- Qb₁ Split Butte Lava
Lake Basalts
- Qt Split Butte Tephra -
Bedded Fine Grained Vitric Tuff

- Contact, Dashed where
Inferred
- Dike, Dashed where
Inferred
- Contour Line
- Strike and Dip of
Bedding
- Anticlinal Axis
- Jeep Road



of the tephra ring. The ring is in disconformable contact with the basalt of the lava lake, and is discontinuous, as the lake basalt appears to have overflowed a section of the tephra on the southwest. The lake crusted and solidified to an unknown depth, after which the central portion of the lake subsided due to withdrawal in the subsurface. This resulted in an inner pit crater 420 m in diameter and approximately 20 m deep. A small cluster of spatter cones lies on the circular fracture along which collapse occurred, and colluvium from the fracture scarp along with unconsolidated loessal sediments cover the pit crater floor. Three parallel basalt dikes tangentially cut the tephra ring along the northwest rim of Split Butte. The thin, nearly vertical dikes are traceable for nearly 200 m before disappearing beneath unconsolidated sedimentary cover.

DETAILED GEOLOGY OF SPLIT BUTTE

Tephra Ring:

Outcrop Description:

The Split Butte tephra forms a low, asymmetrical ring which has a greater accumulation on the northeast. The ring is also slightly elliptical, with the major axis oriented southwest-northeast. This reflects the prevailing wind direction during the eruption.

The tephra, which ranges in color from black to reddish-brown, occurs in two basic types: thickly bedded to massive basal layers which are poorly sorted and extensively palagonitized; and, above this, thin planar beds of well sorted ash. The thinly bedded tephra, which comprises the bulk of the ring, dips 20° to 40°

radially outward from the center of the Butte. Individual layers are from 2 to 10 cm thick and are the result of variations in grain size, sorting and color of constituent materials. The thin layers also vary in resistance and this accentuates the bedding. Erosion of less resistant layers results in low ridges and shelf-like projections of resistant material. The individual beds vary somewhat in thickness, but lack dune forms and cross bedding. Numerous lithic fragments up to 1.25 m in diameter are found in the tephra, and cause bedding sags in the layers below them.

Reversal of dip of the ash occurs close to the lava lake contact, with the tephra layers changing their outward dip and dipping 25° to 35° toward the center of the Butte. The tephra layers form an anticlinal structure, the axis of which is visible at several points around the ring (Greeley and King, 1975). This dip reversal is depositional and represents the opposing primary dips of the eruption rampart.

The Split Butte tephra is very porous and typically quite friable. Erosion of the outer dip slopes of the tephra ring has produced a very irregular dissected topography which is most fully developed in the thick eastern deposits. A large split also occurs in the eastern section of the tephra ring at the point of greatest accumulation of the tephra, and is the result of removal of a large volume of tephra from the ring.

Petrographic Description:

In thin section the tephra consists of round glass grains

which lie in a matrix of angular glass fragments and very finely divided dark brown material. The glass grains, which comprise 30% to 45% of the tephra, range in size from 0.5 to 4.0 mm with an average size of approximately 2.0 mm. The glass grains are extremely vesicular and generally round, but may have an irregular outline due to the intersection of vesicles with the grain boundary. The vesicles, which are 0.05 to 0.4 mm in diameter, are generally spherical to ovoid but may locally be stretched or flattened. Plastic deformation of the light brown isotropic glass is also indicated by flow banding and trains of opaque inclusions. The grains frequently contain inclusions of plagioclase and olivine, which comprise 3-5% of the tephra.

The vesicular grains lie in a matrix composed of smaller angular glass clasts which constitute 20% to 30% of the tephra, and very finely divided glass which is rich in opaque minerals. The angular clasts range in size from 0.05 to 0.5 mm and are composed of light to medium brown glass which has an average refractive index of 1.612. The SiO_2 content of the glass is estimated at 47%, based on the relationship of refractive index of natural glasses versus % SiO_2 (Williams, Turner and Gilbert, 1954) (Fig. 3). The clasts are much less vesicular than the larger grains, with the vesicles, where present, typically spherical and generally less than 0.1 mm in diameter.

A thin layer of yellow to orange palagonite is found rimming the clasts and grains in several of the samples studied. The palagonite, which is slightly birefringent, is found only in the

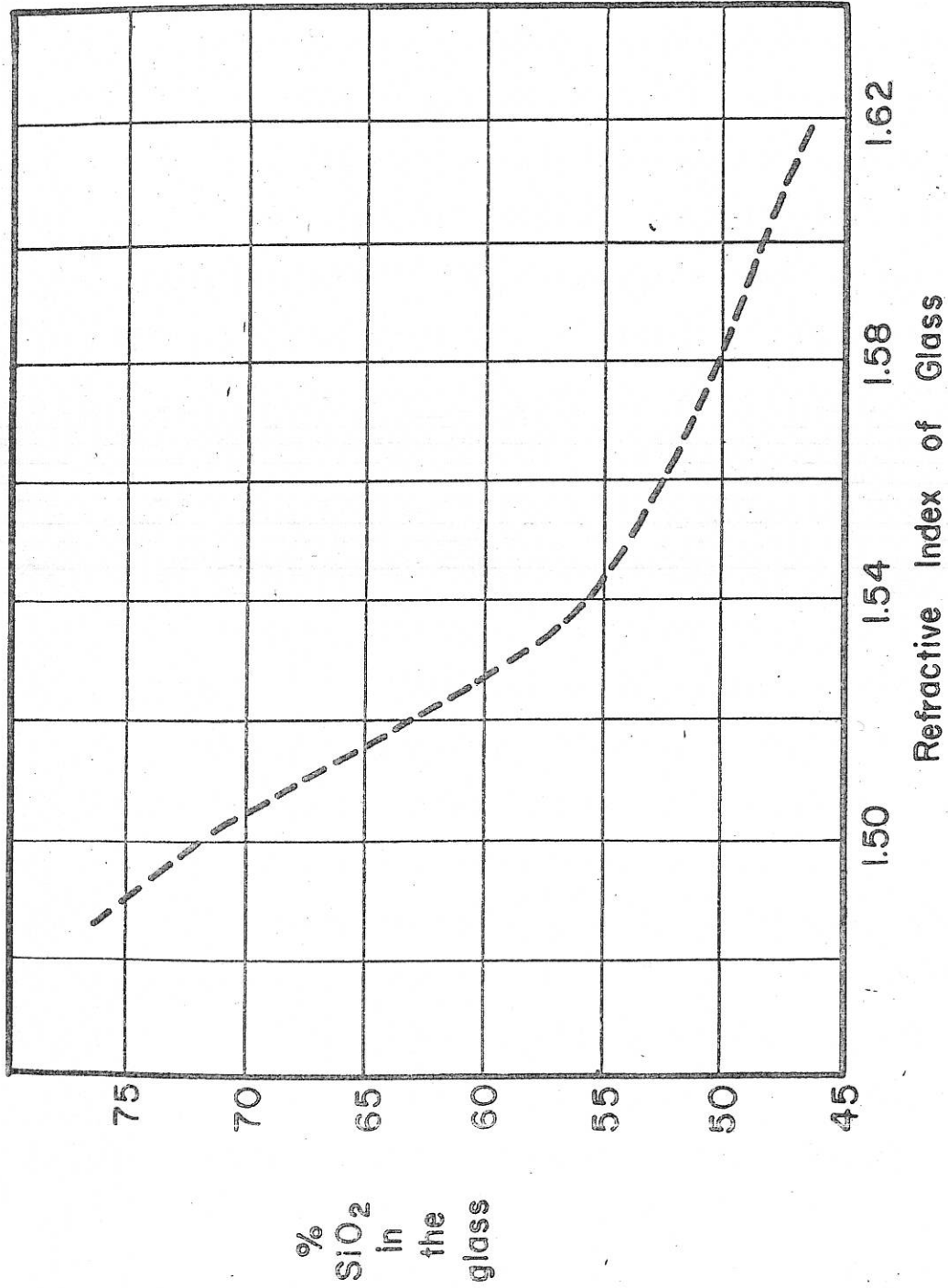


Figure 3. Relationship Between Silica Content and Refractive Indices of Volcanic Glasses Modified from Williams, Turner and Gilbert, 1954

reddish-brown tephra which also contain secondary calcite or quartz. The palagonite has a refractive index of approximately 1.580, which is significantly lower than the glass.

The very fine matrix material which fills the interstices between the clasts consists of very finely divided volcanic glass and birefringent crystallites. It is dark brown in color due to a high concentration of minute opaque inclusions. Very small birefringent crystallites are common throughout the matrix, and very faint and spotty birefringence indicates partial palagonitization and devitrification in some of the samples. The matrix constitutes from 10% to 40% of the tephra with an average of approximately 20%.

Void space occurs as vesicles in the glass fragments and as irregular voids in the matrix. The voids have an average size of 0.4 mm to 0.8 mm and control the permeability of the tephra as shown by the presence of secondary minerals in the voids compared with the absence of these same minerals in vesicles.

Plagioclase is present as inclusions in the glass fragments of the tephra as well as scattered anhedral grains in the matrix. The volume of the plagioclase is estimated at approximately 2%. The inclusions occur as elongate laths which are typically subhedral, with lengths ranging up to 0.7 mm. The average length of the crystals is approximately 0.3 mm. Oscillatory zoning is common and the crystals are intergrown with each other as well as with olivine. The plagioclase laths are frequently fractured or broken, but show no sign of resorption. The composition of the plagioclase, as estimated by the Michel-Levy optical method, is An 54-64%.

As indicated, subhedral to euhedral equant crystals of olivine frequently occur intergrown with plagioclase in the glass grains. The olivine crystals, which have an average size of approximately 0.2 mm, make up from 1 to 2% of the tephra. Highly fractured olivine crystals are abundant, and numerous small broken fragments are common in the groundmass. The composition of the olivine, as estimated from 2V measurements, is Fo 77-88%. The olivine is unaltered, but a slight brown discoloration around crystal boundaries is present in some samples.

Opaque minerals occur as a heavy charge of minute inclusions in the fine matrix and as equant anhedral to subhedral grains associated with olivine. The average size is approximately 0.05 mm. The opaques, which consist primarily of magnetite, also rarely occur as spongy grains and networks up to 1.0 mm across.

Secondary minerals are found in the inter-grain void spaces in several of the palagonitized samples. Microcrystalline calcite forms irregular banded deposits lining void spaces, and light brown fine grained material is found filling many pore spaces. Radiating clusters of elongate quartz crystals occur growing inward from the walls of void spaces in palagonitized samples.

Grain Size Analysis:

Grain size analyses were performed on 51 randomly selected samples of tephra using an Allen-Bradley LP3 Sonic Sifter. The friable tephra was first disaggregated by soaking overnight in a 1N solution of HCl, rinsing several times, soaking in hexametaphosphate solution, rinsing again, and gently breaking apart the softened ash.

The disaggregated samples were then oven-dried preparatory to sieving. Sample sizes of approximately 20 g were run, and sieve fractions from -1 to +5 phi were determined. The resulting data were analyzed using a modified statistical computer program developed at Syracuse University. The calculated statistical parameters are summarized in Table 1.

Overall, the tephra is moderately fine grained, having a mean grain size of 0.475 phi and a median of 0.142 phi. The tephra is poorly sorted, having an average variance of 2.369 phi and a standard deviation of 1.539 phi. The size distribution is rather strongly negatively skewed, which is the result of the high concentrations of coarse material found near the vent. The coarse material also causes the distribution to be moderately leptokurtic. The strong displacement of the median from the mean grain size results from the asymmetry of the distribution.

In an attempt to relate variations in resistance of the tephra to grain size fluctuations, statistical parameters for resistant, intermediate and soft beds were compiled and compared. The results are summarized in Table 2, and indicate that there are no systematic variations in average grain size or sorting which may be related to bed resistance.

However, visual estimates of void space in thin section reveal that the resistant tephras are consistently less porous than the soft layers. There tends to be a higher frequency of grain-to-grain contacts in samples taken from resistant ridges which results in a more compact, resistant structure. There are no

Calculated Moment Statistics			
	Red Type	Green Type	Total
No. of samples	24	27	51
Mean ϕ	0.930	0.016	0.475
Median ϕ	0.607	-0.410	0.142
Variance ϕ	2.967	1.948	2.369
Standard Dev. ϕ	1.721	1.425	1.539
Skewness	-0.561	-1.169	-0.841
Kurtosis	-0.612	1.798	0.507

Table 1. Size Distribution Parameters of Split Butte Tephra

	Resistant	Intermediate	Soft
No. of Samples	22	13	16
Mean ϕ	0.518	0.229	0.589
Median ϕ	0.206	-0.206	0.176
Variance ϕ	2.570	2.357	2.548
Standard Deviation ϕ	1.603	1.535	1.596

Table 2. Grain Size versus Resistance

compositional variations visible between ash layers.

Inner Lava Lake:

Outcrop Description:

A lava lake consisting of an undetermined thickness of layered basalts was confined by the tephra ring (Fig. 2). The lake appears to have overflowed a section on the southwest, causing the ring to be discontinuous (Greeley and King, 1975). The lava lake is preserved as a continuous shelf of basalt which is covered by float and eolian and colluvial sediments. The central portion of the lake has subsided, forming a flat-bottomed pit crater 20 m deep and 420 m in diameter. The pit crater is roughly circular, and is bounded by the nearly vertical walls of the fracture scarp. Talus covers the base of the scarp, but the upper 10 m of the lake stratigraphy is exposed in most areas.

The upper 10 m of the lava lake is composed of a series of horizontal layers of basalt, ranging in thickness from 0.2 to 3.0 m, with an average of approximately 2.0 m. These layers are generally fairly planar, but may locally thin or thicken and be contorted. Each layer appears to be a sheet of lava which spread over the surface of the lava lake, as the upper and lower margins appear chilled. The centers of the layers are slightly more vesicular than the margins and in some cases show flow structure which consists of stretched, flattened and banded vesicles.

Petrology and Petrography:

In hand sample the basalts are medium gray, fine grained and vesicular. The porosity is variable, ranging from 1-2% in the massive flows to about 30% near the tephra contact. The size and shape of the vesicles is also quite variable, ranging from 0.5 to 15.0 mm, with most being irregularly shaped. White to tan, very fine grained material is found lining and partially filling the vesicles in all layers sampled. The basalts are unaltered, but exposed surfaces are coated with dark reddish-brown oxide.

In thin section the basalts are hypocrystalline with intersertal textures common. The plagioclase occurs as subhedral elongate laths ranging in size from 0.1 to 2.5 mm, with an average length of approximately 0.5 mm. Many of the laths are fractured or broken, and corroded and embayed crystals are also common. Minute birefringent and opaque inclusions occur in many laths, which are normally zoned and often intergrown with olivine crystals. The plagioclase, which comprises approximately 30% of the lava lake basalt, has a composition of An 55-65% as determined by the Michel-Levy optical method. Abundant microlites in the groundmass have approximately the same composition as the larger phenocryst phase.

Olivine occurs as subhedral equant grains ranging in size from 0.05 mm crystallites to phenocrysts 2.0 mm in diameter. The crystals, which have an average size of 0.3 mm, are colorless and unaltered, although some show brown staining. They tend to occur in clusters up to 2.5 mm across and are often intergrown with plagioclase. The olivine contains inclusions of subhedral opaque grains less

than 0.1 mm in size, or spongy networks of opaques in the cores of corroded crystals. The olivine, which comprises approximately 15% of the lava lake basalts, has a composition of Fo 78-88%, as estimated by 2V measurements.

Interstitial clinopyroxene occurs as anhedral moderately elongate to irregular crystals having an average size of 0.25 mm. The medium brown, non-pleochroic crystals are intimately associated with glass in the groundmass and appear to have been the last crystals to form. The clinopyroxene, which comprises approximately 10% of the basalt, is biaxial (+) with a 2V of approximately 60° and an extinction angle of about 45° .

Dark brown intersertal glass comprises 5 to 15% of the basalt. The glass is iron-rich and contains numerous opaque inclusions.

Dike Basalts:

Outcrop Description:

Three parallel basalt dikes tangentially cut the tephra ring along the northwest section (Greeley and King, 1975) (Fig. 2). The nearly vertical, curvilinear dikes are 20-30 cm thick and are traceable for over 200 m before disappearing under a cover of unconsolidated sediments. The dikes are more resistant than the tephra which they cut and form ridges standing 30-45 cm above the tephra. The dikes have chilled margins 5 cm thick which are dense and glassy. The central portions of the dikes are vesicular, and locally show flow structure consisting of stretched vesicles. The tephra in contact with the dikes exhibits a baked zone approximately

8 cm thick which consists of a black friable tephra which has been altered to a cindery layer.

Petrographic Description:

In thin section the dike basalts are hypohyaline, with glassy matrix enclosing phenocrysts of plagioclase and olivine. The plagioclase comprises approximately 5% of the dike, but may locally occur in concentrations of up to 25%. It occurs as elongate euhedral to subhedral laths which are often intergrown with olivine, and as abundant microlites within the groundmass. The intratelluric laths range in size from 0.2 mm to 1.5 mm and have an average length of 0.5 mm. Oscillatory zoning is common in the crystals, which are unaltered. There is little evidence of magmatic transport, as very few of the crystals are fractured or broken. The microlites are very elongate and have an average length of 0.1 mm. A composition of An 54-60% is inferred on the basis of extinction angle data determined by the Michel-Levy method.

Olivine occurs as euhedral crystals which range in size from 0.1 to 2.0 mm and have an average size of approximately 0.3 mm. Highly fractured and broken crystals are common, and often occur in clusters up to 2.5 mm across, where they may be intergrown with plagioclase. The composition of the olivine, which comprises 2% of the dike basalts, is Fo 86-90% as determined by 2V measurements.

Anhedral interstitial clinopyroxene is present in well-crystallized sections of the dikes. It is medium brown, non-pleochroic, and is intimately associated with the glassy groundmass.

The clinopyroxene is unaltered and may locally comprise up to 20% of the dike basalt.

Opaque glass forms the groundmass which encloses the phenocrysts of plagioclase and olivine. It constitutes up to 90% of the basalt in the chilled margins and 15-30% in the interior of the dikes.

Opagues are found as a heavy concentration of minute inclusions in the glassy matrix and as subhedral to anhedral equant grains less than 0.1 mm in diameter which are associated with olivine.

Traces of secondary calcite are found lining some vesicles.

Spatter Basalts:

Outcrop Description:

Two coalescing spatter cones outcrop along the pit crater fracture in the north (Fig. 2). The basalts of these spatter cones form a low mound and consist of highly oxidized scoria. They are very glassy and hematite-rich, and are extremely vesicular, having up to 50% void space.

Petrology and Petrography:

In thin section the spatter cone basalts are hypohyaline, with opaque hematite-rich glass enclosing crystals of plagioclase and olivine. The plagioclase is subhedral to euhedral, and ranges in size from 0.1 to 1.2 mm with an average length of approximately 0.5 mm. Normal and oscillatory zoning is visible, and many of the laths have cores which contain swarms of opaque inclusions. The plagioclase, which is unaltered, is frequently intergrown with

olivine. The composition ranges from An 45% to An 50% as determined by the Michel-Levy method.

Crystals of olivine occur as typically anhedral to subhedral equant grains which have an average size of approximately 0.25 mm. The highly fractured crystals commonly occur in discrete clusters, where they are intergrown with plagioclase and contain inclusions of subhedral opaque grains. These opaques also form sponge-like networks in the crystal cores and may occupy up to 40% of the crystal. The composition of the olivine ranges from Fo 84-90%.

Opaque glass encloses the crystals and forms the groundmass of this quickly chilled basalt. Magnetite and hematite are abundant accessories.

Snake River Group, Surface Flows:

Outcrop Description:

Surface flows of the undifferentiated Snake River Group encroach upon Split Butte from all directions. The advancing lava stopped where it encountered the outer slopes of the Butte, and formed a ring-like depression 2-5 m deep around the Butte. The Snake River Group flows are thinly covered by eolian sediments, but prominences on the surface remain exposed. Numerous small pressure ridges up to 5 m high are aligned with their axes perpendicular to the flow direction.

Petrology and Petrography:

In hand sample the Snake River Group basalts are light gray,

fine grained and vesicular. The vesicles are irregular, 6-7 mm in size and may locally be stretched and flattened. The basalt is unaltered but may show a reddish-brown oxide coating on exposed surfaces.

In thin section these basalts are hypocrystalline, with a glassy groundmass enclosing phenocrysts of plagioclase and olivine. The plagioclase occurs as elongate laths up to 2.0 mm long which have an average length of approximately 0.6 mm. They are anhedral, being broken and fractured by extensive transport. The plagioclase also occurs as abundant microlites and comprises up to 30-40% of these basalts. The composition ranges from An 62-66%.

Crystals of olivine account for 5-15% of the basalts and are generally anhedral to subhedral. Small fragments are common, and the size ranges from 0.05 to 0.6 mm with an average of approximately 0.2 mm. The equant crystals tend to occur in clusters up to 1.5 mm across where they may be associated with plagioclase. The olivine, which is unaltered, contains inclusions of anhedral equant opaque grains. The composition is estimated at Fo 86-90% on the basis of 2V angles.

Minor amounts of dark brown anhedral interstitial clinopyroxene are found associated with the glass in the matrix. The irregular crystals have an average size of approximately 0.15 mm. The glass with which it is associated is black due to a heavy concentration of opaques, and forms a groundmass which encloses the crystalline material. The glass is fresh and shows no signs of devitrification. Opaques are ubiquitous as inclusions within the groundmass and as

scattered small grains which consist primarily of magnetite.

Wapi Flow Basalts:

Outcrop Description:

A lobe of the Wapi flow basalts encroaches upon Split Butte in the southeast (Fig. 2). These young basalts overlie Snake River Group basalts and are free of sediment cover. The Wapi flow surface is irregular and has well-developed ropy pahoehoe texture.

Petrology and Petrography:

In hand sample the basalt is dark gray, fine grained and moderately vesicular. The vesicles are ovoid to irregular and have an average size of approximately 5.0 mm. No secondary minerals are present in the void spaces. Occasional laths of plagioclase are visible to the naked eye, and a slight silvery weathering rim is present on exposed surfaces.

In thin section the basalt is hypocrystalline, with interstitial glass forming a groundmass which encloses the phenocrysts of plagioclase and olivine. Plagioclase is present in two generations, large phenocrysts and abundant microlites in the groundmass. The phenocrysts are typically subhedral laths 0.2 to 1.5 mm long and have an average length of approximately 0.6 mm. They are frequently fractured and broken and have also been partially resorbed. The laths occur in discrete clusters where they are intergrown with each other and with crystals of olivine. The phenocrysts of plagioclase are normally zoned and contain numerous birefringent

and opaque inclusions. The microlites are very thin elongate crystals which have an average length of approximately 0.15 mm. Both generations of crystals have the composition An 56-58%.

Olivine occurs as equant crystals which range from anhedral to subhedral. The average size of the highly fractured crystals is 0.4 mm. The olivine, which has the composition Fo 86-88%, is unaltered.

Interstitial brown clinopyroxene, glass and opaques are also present.

Loessal Deposits:

A thin layer of eolian material mantles all but the youngest flows of the Snake River Plain. The sediment tends to fill hollows in the surface topography and to leave prominences exposed. Thicknesses of 1.5 m are average in many areas, but thicknesses of up to 3 m have been recorded (Stearns, Crandall and Steward, 1938).

The sediments at Split Butte are composed primarily of silt-sized fractions with minor amounts of clay and fine sand-sized fractions present. X-ray analysis of this material reveals high concentrations of quartz and amorphous material, with some plagioclase also present. A determination of possible weathering patterns in the tephra was attempted, but quantitative analysis proved unreliable. It is not known whether the sediment originated at Split Butte or at a more distal location.

PROCESSES AND CONDITIONS OF FORMATION:

Based on field studies and subsequent petrographic observation and grain size analysis of its tephra, Split Butte is believed to be a maar-type crater resulting from the phreatomagmatic eruption of basaltic magma.

There is little agreement on the definition of maars. Lorenz (1973) defines maars as large volcanic craters cut into country rock below general ground level which are defined by a low rim composed of pyroclastic debris. The Glossary of Geology (1972) states that a maar is a low relief, coneless volcanic crater ring, and is commonly filled by water. Ollier (1967) proposes the following definition of maars: maars are landforms caused by volcanic explosion, and consist of a crater, which reaches or extends below general ground level and is considerably wider than deep, and a surrounding rim constructed of material ejected from the crater.

Maars are commonly attributed to phreatomagmatic eruptions, which are defined as explosions resulting from the generation of steam from groundwater interacting with erupting magma (Walker and Croasdale, 1971). Ollier (1974) adds the restriction that juvenile magmatic material must be present in the ejecta.

The phreatomagmatic nature of the eruption which formed Split Butte is indicated by the following observations:

The major component of the tephra is clear, light to medium brown sideromelane, which occurs as fragments containing 3-5% crystalline material. Conversion of magma to such a glassy deposit

suggests extremely rapid cooling, as would be achieved by quenching in water.

The glassy fragments in the magma occur in two forms, large vesicular grains and small dense clasts. The small clasts have few vesicles which tend to be spherical and rarely show flow stretching. This is due to the rapid arresting of bubble growth in the magma as it was quenched (Heiken, 1971). Stretched vesicles are diagnostic of cinder cone pyroclastics, which Walker and Croasdale (1971) term Strombolian type deposits.

The clasts, which are shattered fragments of glass formed by quenching magma in water, are blocky and commonly have straight to slightly curved edges. In contrast, the ejecta from cinder cones, which are non-phreatomagmatic, is composed primarily of achneliths-particles whose form is controlled by surface tension rather than fracture planes (Walker and Croasdale, 1971) and have shapes ranging from spherical to filamentous. No such particles were seen among the clasts in the Split Butte tephra.

The tephra also contains numerous glassy grains which range in size from 0.5 to 4.0 mm and have an average diameter of approximately 2.0 mm. These grains have a distinctly different morphology, being moderately rounded and highly vesicular. Although fractured surfaces are present, giving the grains an irregular aspect where they intersect vesicles, most surfaces appear to be fluid boundaries. Many of the vesicles appear to be somewhat flattened, and well developed flow structure is common in these grains. The evidence indicates that the larger grains were chilled less quickly than the

clasts and therefore originated under conditions of limited water interaction.

Numerous crude accretionary lapilli are present in the tephra and consist of a nucleus which is typically a glass grain which is coated with a thin layer of fine ash. Accretionary lapilli have been known to form during volcanic eruptions as the result of several processes: (1) absorption of the fresh ash by the water of a raindrop; (2) accretion of ash around a nucleus rolling down a slope; and (3) the accretion of moist ash in an eruption cloud (Stearns, 1925). The accretionary lapilli at Split Butte appear to have formed by the accretion of ash around a nucleus in an eruption cloud.

Moore and Peck (1962) indicate that water rich ash clouds are primarily associated with phreatomagmatic eruptions of basaltic magma. As glass fragments fall through the wet ash cloud, an outer coating of fine ash sticking to the moistened surface of the nucleus is accreted.

The presence of accretionary lapilli in the tephra of Split Butte therefore provides additional evidence of a phreatomagmatic phase of activity.

Blocks of basalt ejecta up to 1.25 m in diameter are common in the tephra, and have caused bedding sags in the layers below them. The beds appear to have deformed plastically where impacted, as the beds below the blocks are bent downward and compacted, and the beds in front of the blocks may be slightly thicker than the undisturbed beds. No microfaulting or fracturing is visible. This

plastic behavior of the ash indicates that abundant water was associated with the eruption (Heiken, 1971).

The tephra at Split Butte occurs as two basic types: (1) basal ash layers which are typically poorly sorted red beds and are extensively palagonitized; and (2) planar beds 2 to 10 cm thick consisting of olive green, well sorted ash.

There are several indications that the red color and massive nature of the basal ash layers is the result of an extremely high water content as they were deposited. The lack of bedding is typical in basal ash layers of this type (Heiken, 1971) and indicates water-rich conditions. The lack of accretionary lapilli in these layers is also diagnostic, as the lapilli disintegrate in an extremely water-rich environment. Palagonitization is more widespread in the lower beds, and causes the distinctive red color of these ash layers. The presence of palagonite, secondary calcite, quartz, and in some cases possibly zeolite filling void spaces in these beds also indicates fluid-rich conditions. Finally, the paucity of vesicular, round, glassy grains in the basal ash layers is believed to indicate the extreme abundance of water during this phase of eruption.

Stratigraphically above the basal zone is a 3 m thick sequence of interlayered olive green and red beds which are from 5 to 10 cm thick. The thin red beds strongly resemble the basal tephras, and indicate that primary control of the tephra type is water content of the individual eruptive surges rather than a secondary percolation of groundwater. Therefore all of the red ash is believed to result

from a period of free water access to the vent which formed very wet ash deposits, rather than a collection of moisture in the lower ash layers. The interlayered zone represents a transition phase in the eruption, during which water was partially restricted from the vent.

Studies by Heiken (1971) indicate systematic variations in height-width ratios of tephra rings with the amount and depth of water-magma interaction. Cinder cones, which are non-phreatomagmatic in origin, have the lowest height-width ratios, while tephra rings located in areas of abundant groundwater have ratios ranging from 1:10 to 1:30.

The shapes of tephra rings also seem to be dependent upon the depth of water-magma interaction. In cases of deep explosions, the ejecta are guided into nearly vertical trajectories by the conduit walls and fall back near the vent to form a cone with a low height-width ratio. Shallow explosions would result in lower ejecta trajectories which would form a cone with a high height-width ratio.

Allowing for the effects of erosion, Split Butte had an original height-width ratio of approximately 1:10. This indicates that the ring is phreatomagmatic in origin and that the water-magma interaction occurred at moderate depth. It should be noted that the extremities of the ramparts have been concealed by recent basalt flows and an accurate determination of the height-width ratio is impossible.

It is also possible to differentiate phreatomagmatic and

non-phreatomagmatic basaltic ashes on the basis of their grain size parameters. Previously published data (Walker and Croasdale, 1971; Sheridan, 1971; Walker, 1971; Buller and MacManus, 1973; Fisher, 1964) indicates that basaltic pyroclastics generally are distributed log-normally with slight positive skewness and are approximately mesokurtic. Walker and Croasdale (1971) have demonstrated that phreatomagmatic ashes are typically finer grained and more poorly sorted than non-phreatomagmatic ashes.

Plotting median grain size versus variance reveals that Split Butte ash falls in a distinctly different field than that occupied by known non-phreatomagmatic ash in a similar plot (Fig. 4). Tephra from Split Butte have consistently higher variances and finer medians than non-phreatomagmatic ash. Comparison of plots of Split Butte tephra with plots of known phreatomagmatic ash reveals a much greater amount of correlation (Fig. 5). Further analysis reveals that the red tephra lie within the phreatomagmatic ash field while the green tephra appear to be a mixture of both types of ash (Fig. 6).

There are two basic mechanisms which form pyroclastic deposits: air fall or flow processes (Walker, 1971). Base surge is one type of flow process, and is often associated with phreatomagmatic eruptions (Moore, 1967; Lorenz, 1973). It is defined as a basal cloud of pyroclastic debris spreading radially outwards from a crater as a density flow (Lorenz, 1973).

Studies by Walker (1971) and Sheridan (1971) indicate that

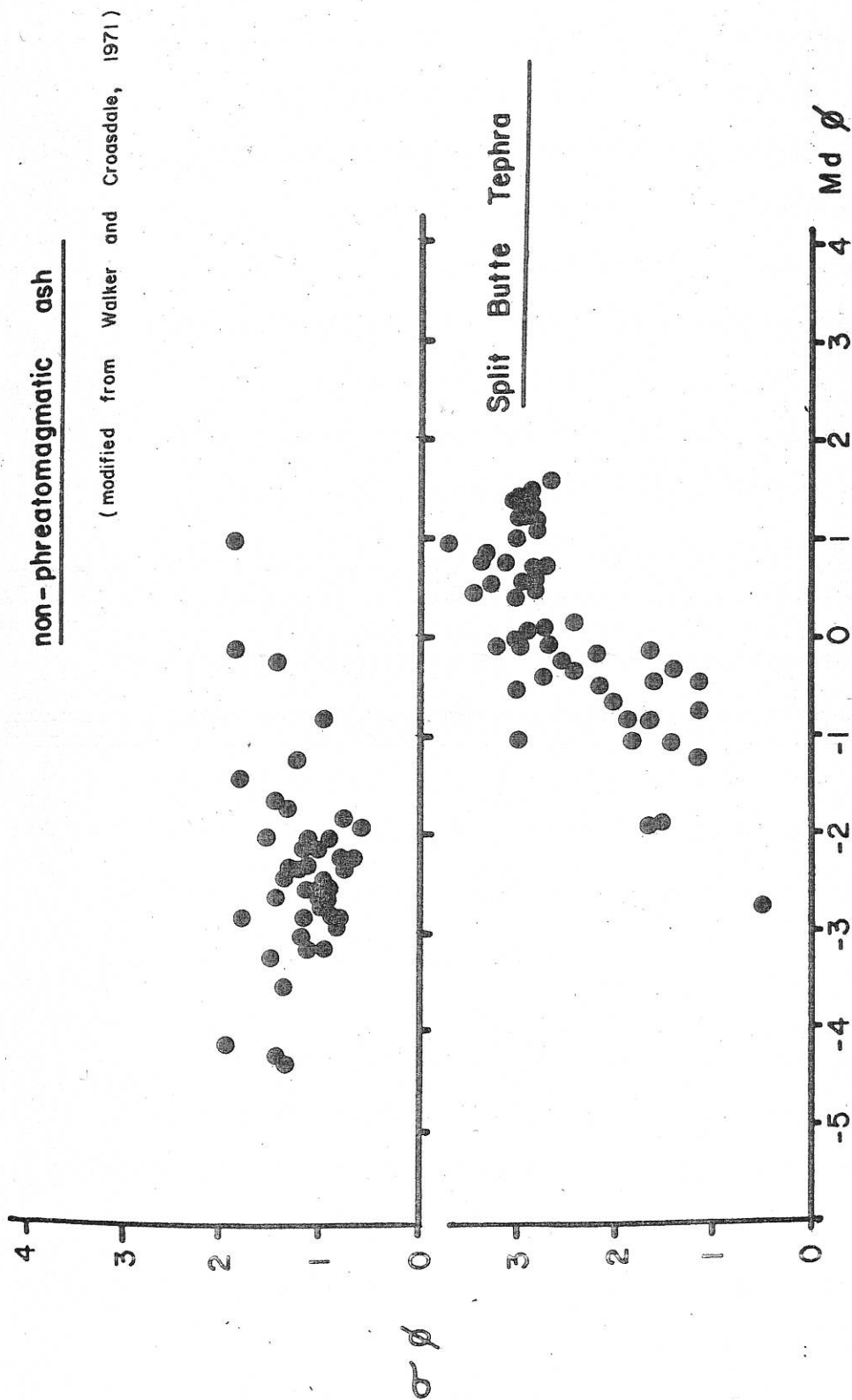


Fig 4. Plots of $\sigma \phi$ versus $Md \phi$ for known non-phreatomagmatic ash and Split Butte tephra.

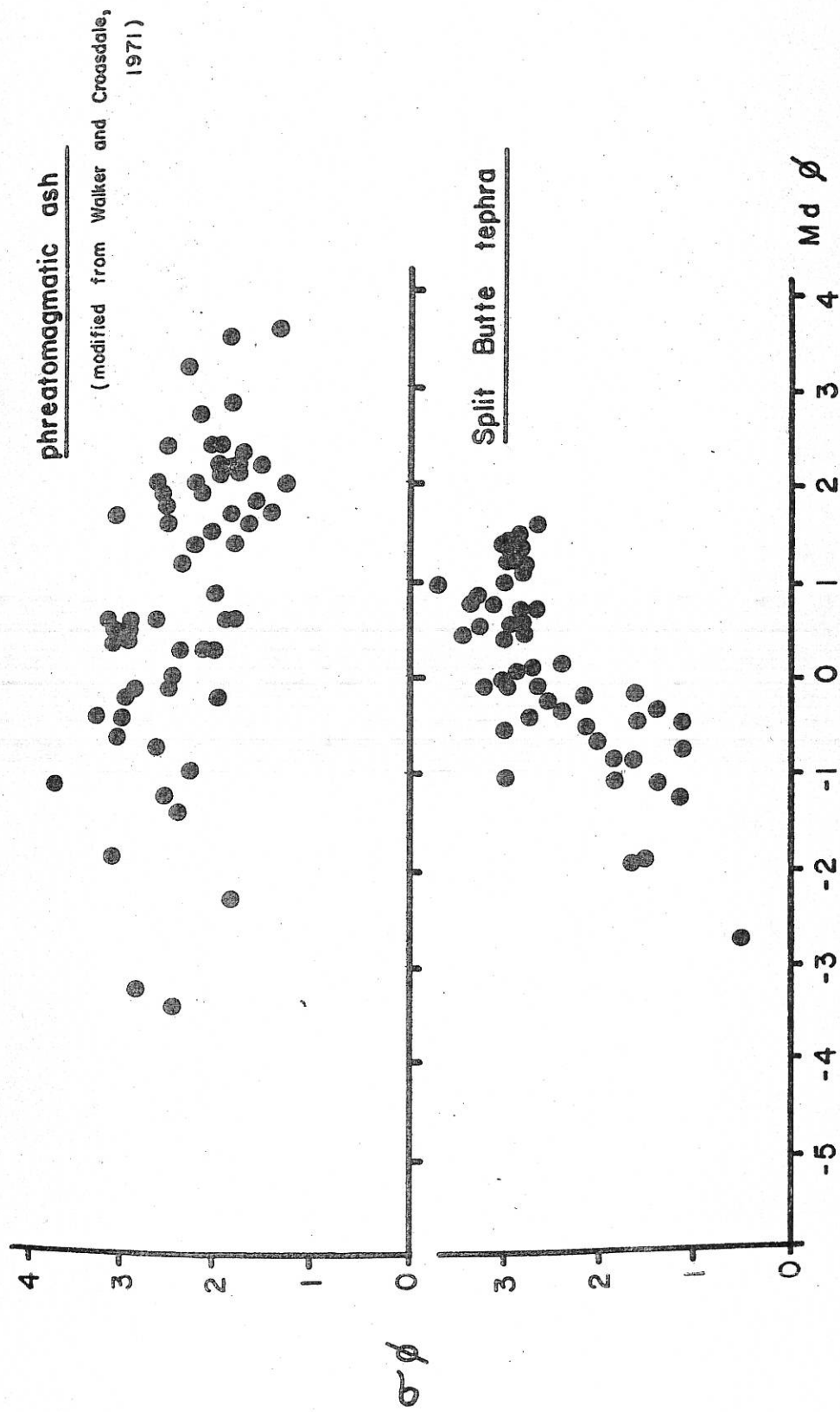


Fig. 5. Plots of $\sigma\phi$ versus $Md \phi$ for known phreatomagmatic ash and Split Butte tephra.

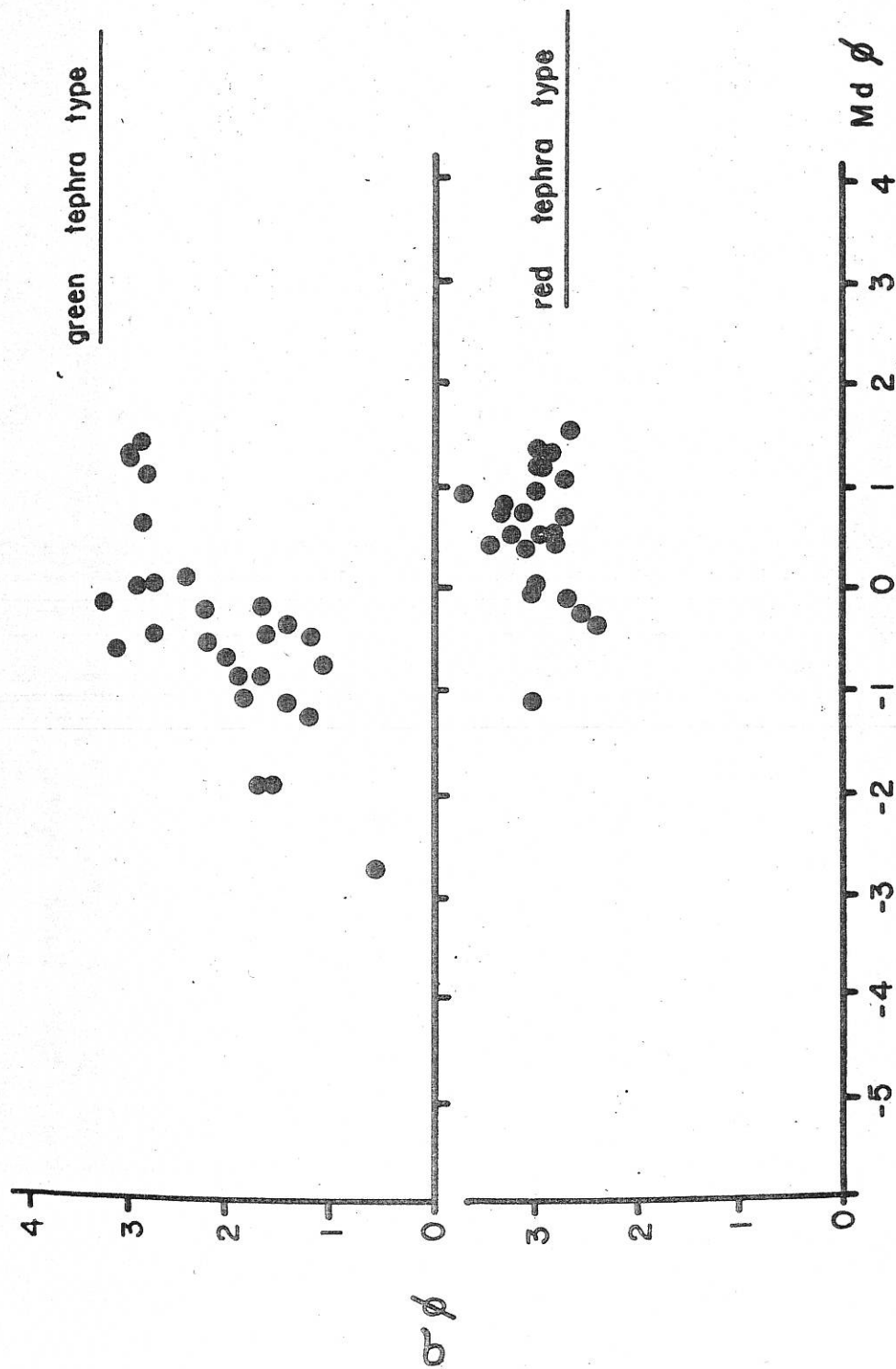


Fig 6. Plots of $\sigma\phi$ versus Md ϕ for green and red types of Split Butte tephra.

statistical parameters may be used to differentiate air fall pyroclastics from flow deposits. Their data indicates that air fall deposits are coarse grained and well sorted while flow deposits are fine grained and poorly sorted.

Comparison of the distribution parameters of ash from Split Butte with Walker's data (Fig. 7) indicates that the tephra corresponds to neither type of deposit, but appears to fall between the two types. The variances of ash from Split Butte seem to correlate fairly well with the variances of flow deposits, however, and may indicate the presence of base surge during the phreatomagmatic phase of the Split Butte eruption.

Consideration of the statistical parameters of only red tephras indicates that this ash resembles base surge deposits while the green tephras more strongly resemble air fall deposits (Fig. 8). Logically one would expect the more violent water interaction which produced the red beds to produce base surge deposits, while the restricted water interaction associated with the green tephra type would produce air fall deposits. However the evidence is too inconclusive to prove or disprove this hypothesis.

Air fall pyroclastics may also be differentiated from flow deposits on the basis of depositional structures. Waters (1971) states that base surge deposits usually consist of ash accumulated in cross bedded dunes which are poorly sorted. Accretionary lapilli are often absent from base surge beds, which frequently show reverse graded bedding. Channelways in the ash are also common in base surge deposits.

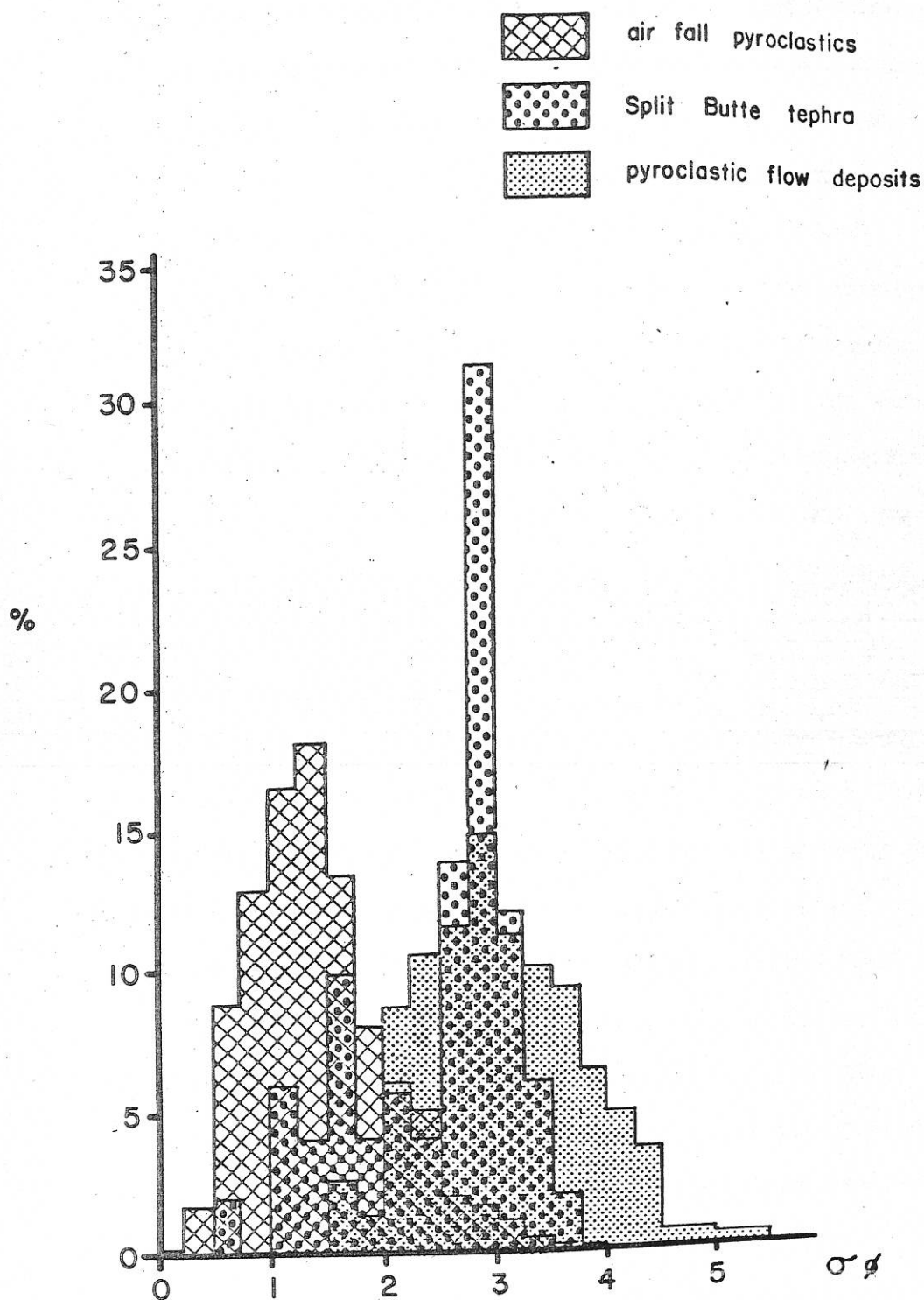


Fig 7. Range in $\sigma \phi$ shown by air fall pyroclastics, pyroclastic flow deposits, and Split Butte tephra.

(modified from Walker, 1971)

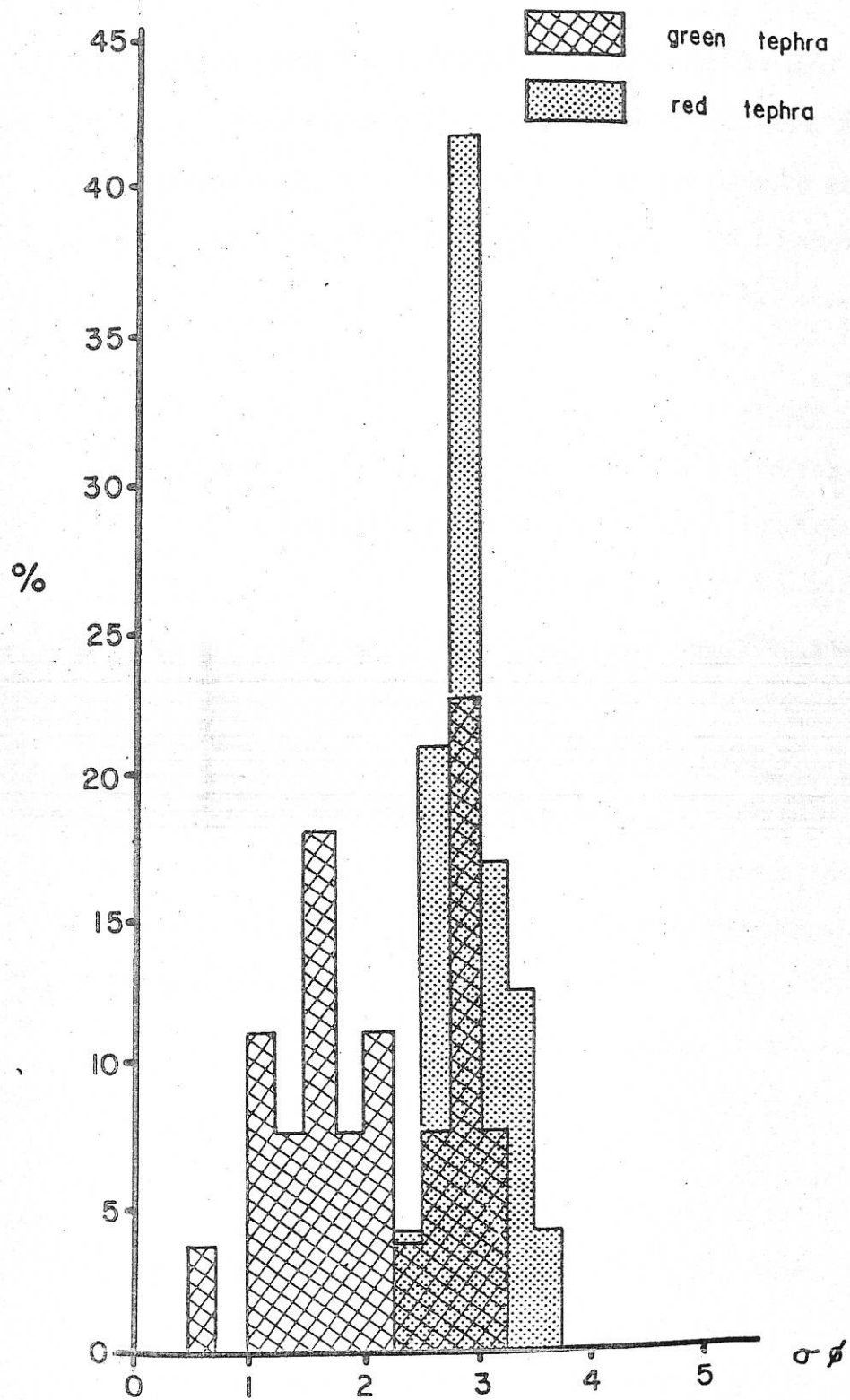


Fig 8. Range in $\sigma\phi$ shown by green and red types of Split Butte tephra.

The lack of dune forms, channelways and cross bedding, and the presence of accretionary lapilli therefore suggest air fall as the primary mode of emplacement of the tephra. Since reverse graded bedding occurs in both air fall and base surge deposits, its presence at Split Butte is not diagnostic.

SEQUENCE OF EVENTS:

The following sequence of events is hypothesized to have produced Split Butte and is summarized in Figure 9:

STAGE 1: Production of the tephra ring

During Late Pleistocene or early Holocene, rising basaltic magma erupted at Split Butte as part of the widespread effusive activity of the eastern Snake River Plain. The rising basaltic magma encountered abundant near-surface groundwater, causing the phreatomagmatic explosions which produced the tephra ring. The tephra was deposited primarily by air fall, with some early base surge possibly active as well. Prevailing southwesterly winds during the eruption formed thicker deposits of tephra on the northeast section of the ring.

STAGE 2: Emplacement of the lava lake

The second stage in the development of Split Butte was the emplacement of a lava lake which overflowed a section of the tephra ring on the southwest. This sudden shift in eruptive style was caused by the cessation of phreatomagmatic activity at the vent.

Phreatomagmatic activity is frequently observed to be followed

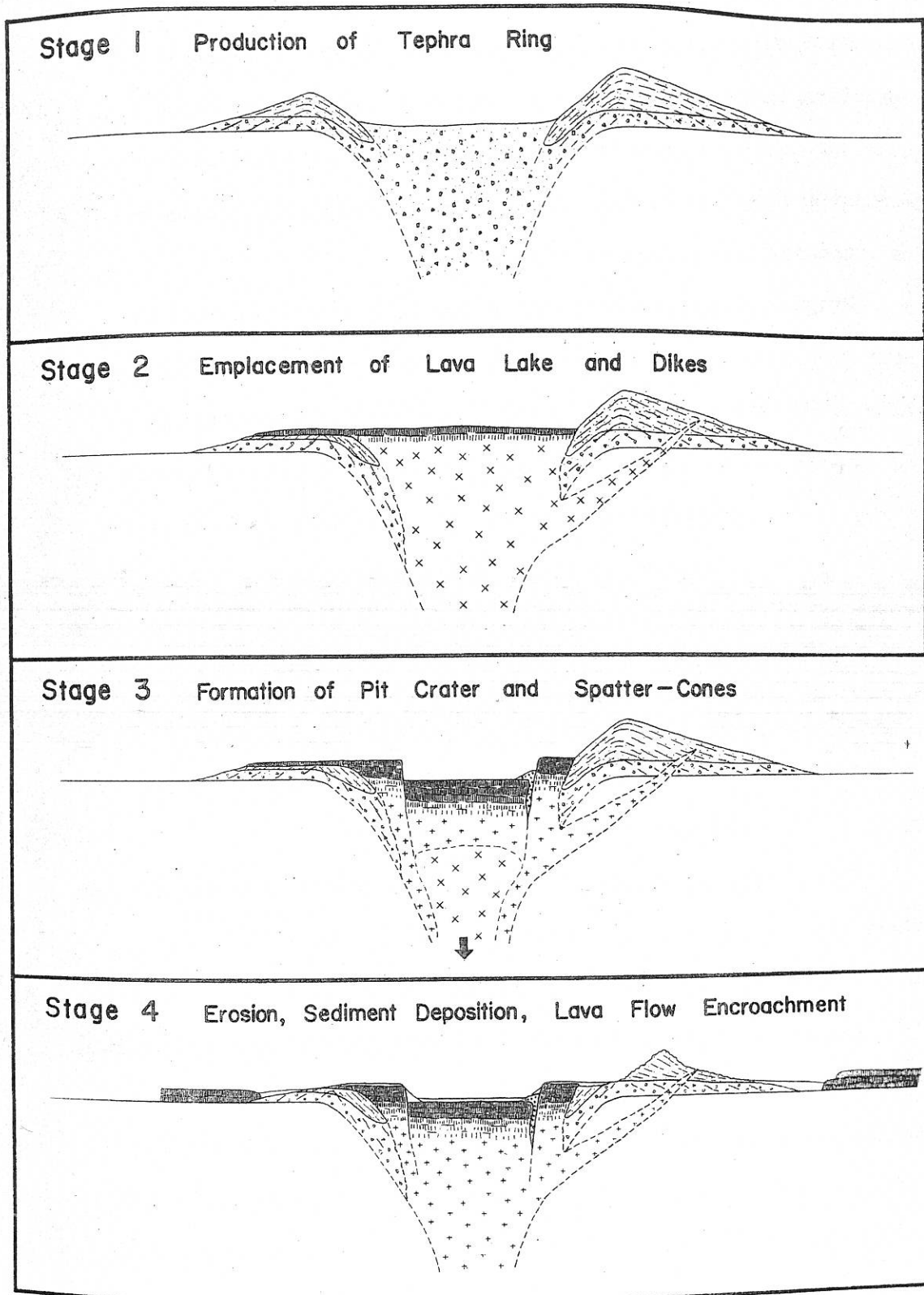


FIGURE 9. SEQUENCE OF EVENTS

by a period of eruption during which there is no magma-water interaction (Heiken, 1971). This lessening interaction may be caused by the removal of access of water to the vent, consumption of groundwater supplies by the eruption, or a greatly increased eruption rate lessening the effect of the water.

Singleton and Joyce (1969) propose a hypothesis which may account for such shifts in activity. These investigators postulate a three stage process, which is summarized as follows (Fig. 10):

Stage 1: The initial vent is formed and lava may be extruded, groundwater is unable to enter the vent, as it is converted to steam as it approaches the hot magma.

Stage 2: The lava withdraws slightly, allowing groundwater to enter the vent; phreatomagmatic eruptions result.

Stage 3: The lava column rises again, groundwater is driven off and a lava lake is produced.

This mechanism applies to areas where groundwater rather than surface water is of primary importance, and is believed to have been the operative formational mechanism at Split Butte.

Several factors indicate an increased rate of magma extrusion caused the emplacement of the lava lake. Since groundwater rather than surface water caused the phreatomagmatic phase of activity, building a tephra ring would have no effect in removing the water's access to the vent. Also, the vesicular and fractured Snake River Group basalts which underlie Split Butte are highly permeable and provide very high groundwater flow rates (Stearns, Crandall and

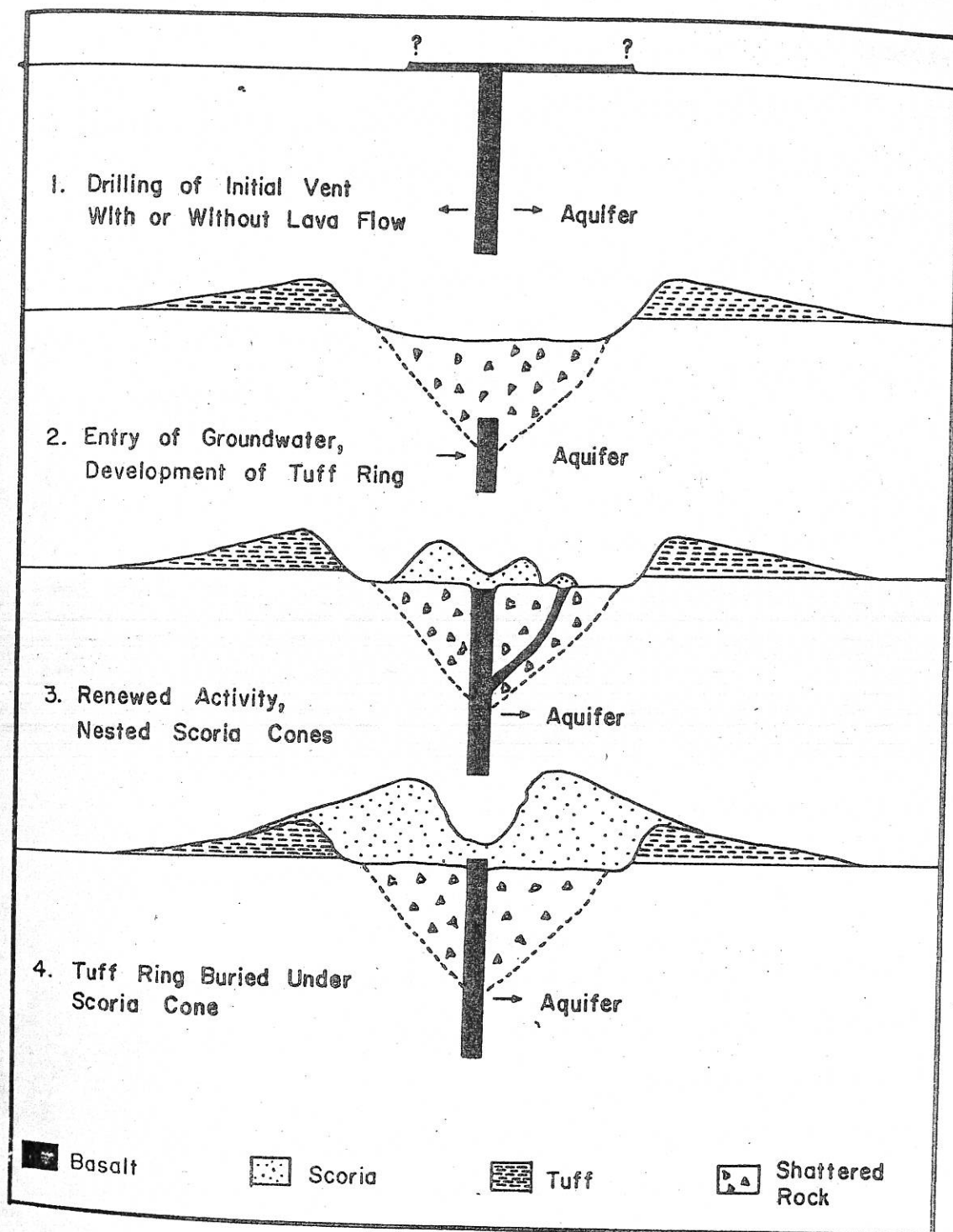


Fig. 10. Diagrammatic Evolution of Maars According to Singleton and Joyce (1969).

Modified from Ollier (1974)

steward, 1938). The very sudden depletion of groundwater in the Split Butte area is therefore highly unlikely, since it was obviously present in great abundance during the phreatomagmatic phase of activity.

The Singleton and Joyce hypothesis is also favored by the high level of the lava lake, which was maintained at a level approximately 15 m above the surrounding plain. This level was sufficiently high to cause the lake to overflow a section of the tephra ring.

Although the lava was largely degassed, as evidenced by the lack of spatter, the lake was turbulent enough to erode much of the inward dipping tephra. The result is a disconformable contact between the tephra and the lava lake which is found along the thick ash deposits in the east. The disconformable contacts were probably caused by the slumping of ash into the lava lake. Conformable contacts are prevalent along the lower sections of the ring in the west.

The level of the lake remained fairly stable, as evidenced by the solidification of at least the upper 20 meters of the lake before subsidence occurred.

Emplacement of three basalt dikes in the tephra ring is believed to have occurred during this stage of activity. The three parallel dikes tangentially cut the ring in the north and could have been propagated along slump fractures caused by the emplacement of the lava lake. Although the relation of the dikes to the lake remains unclear, petrographic comparison reveals strong

compositional and textural similarities between the two. The presence of glass and the absence of clinopyroxene from dike basalts is the result of rapid chilling of the magma. The dikes are slightly enriched in phenocryst phases as compared to the basalts of the lava lake, which probably results from the different emplacement mechanisms. Lacking conclusive proof, it is tentatively assumed that the dikes were fed from the lava lake at depth, and are contemporaneous with it. It is not known whether the dikes cut only the tephra or also transect country rock.

STAGE 3: Withdrawal of magma

Following partial solidification of the lava lake, the magma withdrew down the conduit. Removal of support resulted in the subsidence of the central portion of the lava lake. A block 420 m in diameter was down-dropped approximately 20 m along a circular fracture and formed a flat-bottomed pit crater.

At least 20 m of the crust had formed before subsidence took place, as the vertical fracture scarp was preserved when the movement occurred. The length of time necessary to form a 20 m thick crust on a basalt lava lake would indicate the minimum length of time between emplacement and subsidence of the lava lake.

Rates of thickening of crust on Hawaiian basalt lava lakes have been measured and are presented in figure 11 (MacDonald, 1972). The temperature of extrusion of these lavas was 1120° - 1190° C., which correlates closely with the temperatures of Snake River Plain basalts (Leeman, 1974). Assuming similar cooling rates for the

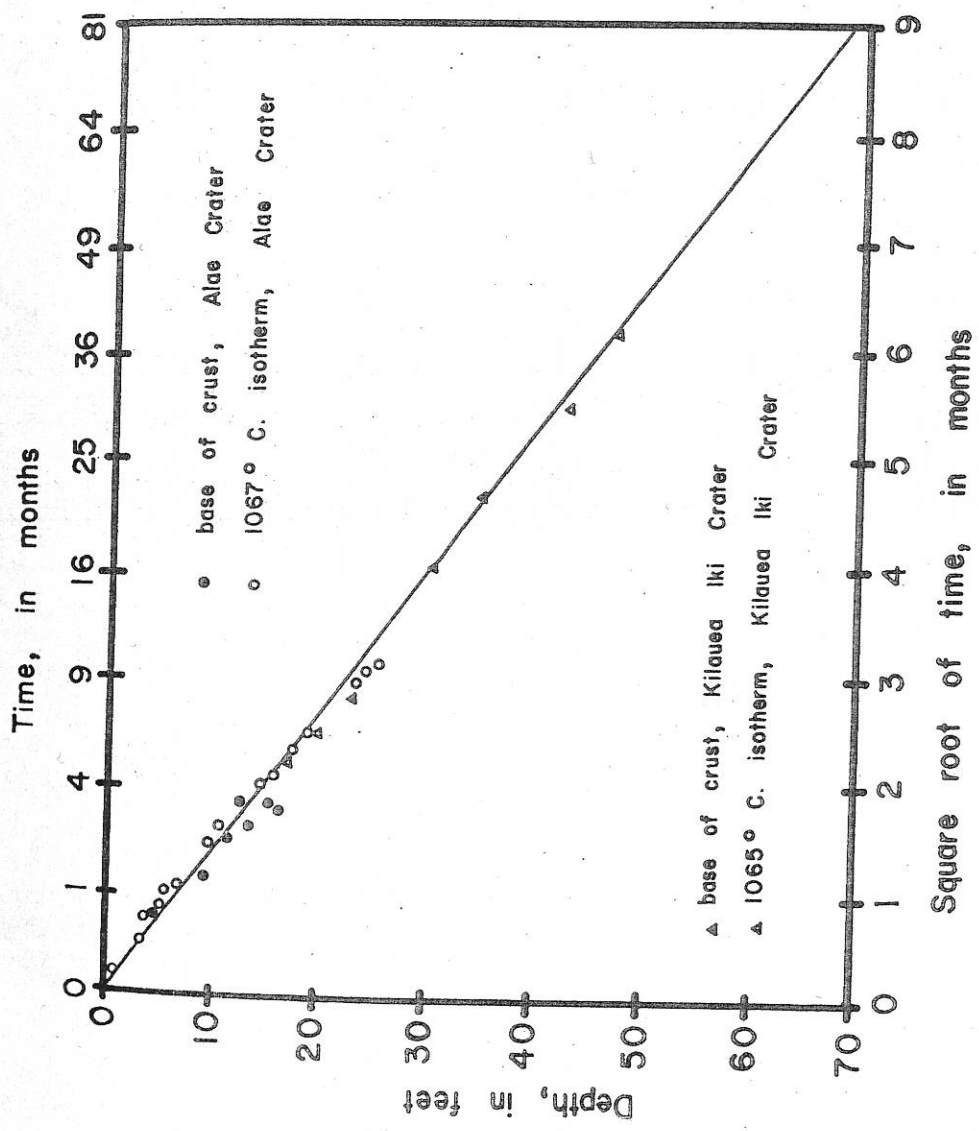


Fig 11. Rate of thickening of the crust on Alae and Kilauea Iki lava lakes, Kilauea Volcano, Hawaii.

(modified from MacDonald, 1972)

Hawaiian and Idaho basalts, a minimum of 6.25 years $\pm$ 1 year is required for the formation of 20 m of crust on the lava lake. This represents the least possible time lapse between the emplacement of the lava lake and withdrawal of the magma, assuming subsidence occurred at the time of withdrawal. This figure is only a rough approximation, and the actual length of time was probably somewhat greater.

Two coalescing spatter cones formed when the lake subsided and represent the last volcanic activity at Split Butte. The spatter deposits are located on the ring fracture and may have been a degassing outlet for late stage liquids following subsidence.

STAGE 4: Erosion and encroachment of surface flows

The fourth stage in the development of Split Butte is erosion of the Butte and encroachment by surface flows. The soft, porous tephra has been extensively eroded since its deposition. The outer dip slopes of the tephra ramparts have been deeply dissected, producing a very irregular topography. The eroded ash has formed the soil which mantles the lower slopes of the tephra ring and covers the lava lake and pit crater.

Talus deposits covering the lower 8 to 10 m of the pit crater scarp have formed. These deposits consist of fine sediments and large blocks of basalt which have fallen from the crater wall. Eolian sediments fill depressions in the surrounding surface flows and form deposits within Split Butte, where they cover the pit crater floor to an unknown depth. These eolian sediments cannot be discriminated from the weathered ash.

A Snake River Group flow from an unknown source encroached Split Butte and completely surrounded it. The flow stopped where it encountered the increased gradient of the outer tephra flanks and formed a ring-like depression 2-5 m deep around the Butte. This flow is covered by a layer of eolian sediment, indicating that it is not a recent flow.

Split Butte is also encroached by a lobe of the Wapi flow, which overlies the Snake River Group basalts. The Wapi flow is less than 2130 years old $\pm$ 130 years (Champion, 1973; Prinz, 1970). This flow, which lacks sediment cover and vegetation, approaches to within 400 m of Split Butte in the southeast.

FORMATION OF THE SPLIT:

The formation of the large split in the eastern section of the tephra ring remains anomalous. The split represents the removal of a large volume of ash from the ring, and has developed in the outer dip slopes at the point of greatest tephra accumulation.

The split may be the result of erosion caused by the prevailing strong southwesterly winds of the area, as there is close correlation between orientation of the split and wind direction. The wind appears to be confined by the eastern section of the tephra ring and forced to pass over the rim at the split. The strong winds would notch the ash at the top of the rampart and continue to erode downward. However, the large volumes of ash which have been eroded are not visible beyond the tephra ramparts.

There is no indication that the split is the result of

volcanic activity, nor of the tephra being significantly finer grained or better sorted than at other sections of the ramparts.

EVALUATION OF SPLIT BUTTE AS AN ANALOG STUDY:

Split Butte provides excellent opportunities for comparison with similar extraterrestrial features. It displays nested circular structures which resulted from multi-stage volcanic processes and which strongly resemble surface features seen on other planets.

Split Butte is a recent feature which is very well preserved. The lack of vegetation cover also facilitates the study of Split Butte, both in the field and in aerial photo analysis.

The physiographic and geologic settings in which Split Butte is located also enhance its value as an analog study. The Snake River Plain is a structural depression of low relief which consists of thick sequences of interlayered basalts and sediments. The surface topography of the plain bears close resemblance to large areas of extraterrestrial bodies, and the geologic conditions may be the same as well. It seems likely that many of the geologic processes which acted to generate Split Butte may also have formed similar features on other planets.

SUMMARY AND CONCLUSIONS:

Split Butte is a maar-type crater which consists primarily of a moderately asymmetrical tephra ring with an approximate height-width ration of 1:10, an inner lava lake, and a pit crater. The tephra is composed primarily of partially palagonitized and

devitrified sideromelane glass fragments which have a silica content of approximately 47%. The glass contains numerous inclusions of plagioclase and olivine which have average compositions of An 54% and Fo 88%, respectively. There are two discrete types of particles present- small dense clasts and large vesicular grains. The small clasts show textural evidence of phreatomagmatic origin, while the large grains have characteristics typical of non-phreatomagmatic origin.

The basal ash layers tend to occur as massive red beds which are extensively palagonitized and frequently contain secondary minerals. On the basis of mineralogical and textural indications, these beds are believed to result from free water access to the vent. The upper ash sequences are composed of olive green tephtras which show evidence of limited water interaction during their formation. A short sequence of interlayered red and green beds lies between the two types which indicates a period of sporadic water access to the vent.

Analysis of grain size data provides additional evidence for the above conclusions, and indicates a high concentration of ejecta deposited near the vent. Green tephtras have characteristics which resemble air-fall pyroclastics, while red beds more closely resemble base surge deposits.

Removal of access of groundwater to the vent occurred before the end of eruptive activity at Split Butte. This resulted in a shift in activity from production of pyroclastics to the emplacement of a lava lake. The Singleton and Joyce hypothesis, which states

that water will interact with slowly erupting magma but cannot interact with rapidly erupting magma, is believed to be responsible for the end of the phreatomagmatic activity.

The basalt of the lava lake contains plagioclase (An 60%) and olivine (Fo 85%) in a fine grained matrix of clinopyroxene and glass. It is medium gray and moderately vesicular to massive in hand sample. Three basalt dikes which have compositions similar to the lava lake are believed to have been emplaced during this phase. The dikes are nearly vertical and from 20-30 cm thick. They have glassy chilled margins and vesicular cores.

Withdrawal of magma removed support from the partially solidified lava lake and caused the central portion of the lake to subside, forming a shallow pit crater. On the basis of the minimum thickness of the crust at the time of subsidence and known cooling rates for tholeiitic basalts, a minimum of 6.25 years is believed to have elapsed between emplacement of the lava lake and the withdrawal of magma. Two small spatter cones developed on the pit crater fracture at the time of subsidence, and were the last volcanic activity at Split Butte.

The last stage in the formation of Split Butte is the erosion of the tephra ring. This has been accompanied by the formation of talus slopes and deposition of eolian sediments at Split Butte. Two distinct surface flows have encroached the Butte since its formation, Snake River Group basalts and Wapi flow basalts.

The formation of the Split remains anomalous, although it appears to be caused by the prevailing strong southwesterly winds

of the area. Its formation cannot be associated with any volcanic activity, and no sign remains of the large quantities of ash which were removed.

Split Butte is highly applicable as an analog study due to its nested circular structures and known formational processes. Its well preserved condition and location within the Snake River Plain also enhance its value as an analog study.

REFERENCES CITED

- Buller, A.T., and MacManus, J., 1973, Distinction among pyroclastic deposits from their grain-size frequency distributions: Jour. Geology, v. 81, p. 97-106.
- Champion, D.E., 1973, The relationship of large scale surface morphology to lava flow direction, Wapi lava field, southeastern Idaho: Master's Thesis, State University of New York at Buffalo, Buffalo, New York, 44 p.
- Eaton, G.P., Christiansen, R.L., Iyer, H.M., Pitt, A.M., Mabey, D.R., Blank, H.R. Jr., Zietz, I., Gettings, M.E., 1975, Magma beneath Yellowstone National Park: Science, v. 188, n. 4190, p. 787-796.
- Fisher, R.V., 1964, Maximum size, median diameter, and sorting of tephra: Jour. Geophys. Research, v. 69, p. 341-355.
- Glossary of Geology, 1972, Gary, M., McAfee, R., and Wolf, C.L., eds., Am. Geol. Institute, Kingsport Press, 805 p.
- Greeley, R., and King, J.S., 1975, Geologic field guide to the Quaternary volcanics of the south-central Snake River Plain, Idaho: Idaho Bureau of Mines and Geology, Pamphlet n. 160, 49 p.
- Heiken, G.H., 1971, Tuff Rings: examples from the Fort Rock-Christmas Lake Valley basin, south-central Oregon: Jour. Geophys. Research, v. 76, n. 23, p. 5615-5626.
- Hill, D.P., 1963, Gravity and crustal structure in the western Snake River Plain, Idaho: Jour. Geophys. Research, v. 68,

p. 5807-5819.

Kirkham, V.R.D., 1931, Snake River Downwarp: Jour. Geology, v. 39,
p. 456-482.

LaFehr, T.R., and Pakiser, L.C., 1962, Gravity, volcanism, and
crustal deformation in the eastern Snake River Plain, Idaho:
U.S. Geol. Survey Prof. Paper 450-D, p. D76-D78.

Leeman, W.P., 1974, Part I. Petrology of basaltic lavas from the
Snake River Plain, Idaho and Part II. Experimental
determination of partitioning of divalent cations between
olivine and basaltic liquid: Doctoral dissertation, Univ.
of Oregon, 337 p.

Lorenz, V., 1973, On the formation of maars: Bull. Volc., v. 37,
p. 183-204.

MacDonald, G.A., 1972, Volcanoes, Prentice-Hall Pub. Co., 510 p.

Malde, H.E., 1965, The Snake River Plain; The Quaternary of the
United States, Wright, H.E., and Frey, D.G., eds., Princeton
Univ. Press, p. 255-263.

Moore, J.G., 1967, Base surge in recent volcanic eruptions: Bull.
Volc., v. 30, p. 337-363.

Moore, J.G., and Peck, D.L., 1962, Accretionary lapilli in volcanic
rocks of the western continental United States: Jour. of
Geol., v. 70, p. 182-193.

Ollier, C.D., 1967, Maars, their characteristics, varieties and
definition: Bull. Volc., v. 31, p. 45-73.

_____, 1974, Phreatic eruptions and maars, in Civetta, L.,
and others, eds., Physical Volcanology, Amsterdam, Elsevier

- Pub. Co., p. 289-310.
- Prinz, M., 1970, Idaho rift system, Snake River Plain, Idaho: Geol. Soc. America Bull., v. 81, p. 941-948.
- Russell, I.C., 1902, Geology and water resources of the Snake River Plains of Idaho: U.S. Geol. Survey Bull., n. 199, 192 p.
- Schoen, R., 1974, Influence of liquid waste disposal on the geochemistry at the National Reactor Testing Station, Idaho: 1952-1970: Robertson, J.B., Schoen, R., Barraclough, J.I., U.S. Geol. Survey Open-file report IDO-22053, 231 p.
- Sheridan, M.F., 1971, Particle size characteristics of pyroclastic tuffs: Jour. Geophys. Research, v. 76, n. 23, p. 5627-5634.
- Singleton, O.P., and Joyce, E.B., 1969, Cainozoic volcanicity in Victoria: Spec. Publ. Geol. Soc. Austr., 2: p. 145-154.
- Stearns, H.T., 1925, The explosive phase of Kilauea volcano, Hawaii in 1924: Bull. Volc., v. 5-6, p. 193-208.
- Stearns, H.T., Crandall, L., and Steward, W.G., 1938, Geology and groundwater resources of the Snake River Plain in southeastern Idaho: U.S. Geol. Survey Water Supply Paper #774, 268 p.
- Stone, G.T., 1967, Petrology of the Upper Cenozoic basalts of the western Snake River Plain, Idaho: Doctoral Thesis, Univ. of Colo., Boulder, Colo., 392 p.
- Walker, G.P., 1971, Grain size characteristics of pyroclastic tuffs: Jour. of Geology, v. 79, p. 696-714.
- Walker, G.P., and Croasdale, R., 1971, Characteristics of some basaltic pyroclastics: Bull. Volc., v. 35, p. 303-317.
- Waters, A.C., 1971, Base surges and their deposits: Capelinhos and

Taal Volcanoes: Jour. Geophys. Research, v. 76, p. 5596-5614.

Williams, H., Turner, F.J., and Gilbert, C.M., 1954, Petrography-

an introduction to the study of rocks in thin sections:

San Francisco, W.H. Freeman Pub. Co., p. 28.

Zohdy, A.A.R., and Stanley, W.D., 1973, Preliminary interpretation

of electrical sounding curves obtained across the Snake River

Plain from Blackfoot to Arco, Idaho: U.S. Geol. Survey Open

File Report, 3 p.