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THE RELATIONSHIP OF LARGE SCALE SURFACE MORPHOLOGY TO
LAVA FLOW DIRECTION, WAPI LAVA FIELD, SOUTHEASTERN IDAHO

WAPI LAVA FIELD

by

Duane Edwin Champion

L-3000

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NOTE: Also included in original copy were illustrations of common formations and 2 maps showing:

1) SURFACE Feature MAP of Eastern LOBE WAPI of Cow

2) MAJOR SURFACE Feature MAP of Entire WAPI Flow including indication of

MAJOR SCARPS

MINOR SCARPS

MAJOR & MINOR Flow Ridges

collapse depressions

VENT CRATERS

RIFT Faults

Internal Drainage Areas

Reveled Channels

Subsidence Faults

Rootless vents

Intermittent Streams

Kipukas

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ANDREW D. GIBBS
U. of MONTANA
ET. RIFT Primitive
STUDY

current Address:

Duane Champion
CAL. TECH
Division of Geology & Planetary Sciences
Pasadena, California
91109

Home address:

345 Middlefield Rd.
Menlo Park, California

Abstract

It is proposed that the direction of movement of a lava flow can be determined by a photogeologic analysis of the large scale morphologic features such as pressure ridges, pressure plateaus and collapse depressions. The Wapi Lava Field, in southeastern Idaho, was chosen for this study because it is a relatively ^{young} field and because it is situated on the Snake River Plain, an area which is somewhat ^{analogous} to lunar maria surfaces. The Wapi Field is a large, 415 sq. km. area of alkali olivine basaltic lava which is slightly elongate in a N-S direction. The flows have an average thickness of about 35 m. The slope of the Field is less than one degree, which accounts for a dominance of pahoehoe type lava.

This paper describes the large scale morphologic features as well as the distribution of various small scale surface types of the Field. The paper also defines a primary-secondary dichotomy between two fundamental surface aspects of the Field. Pillar Butte, the vent complex on the Field is described and its relation to the Field explained. The literature on the origins of pressure ridges is reviewed and a system of classification is proposed. Two maps are included, one is a large scale map of a small portion of the Field which was prepared to support the interpretation of the larger photogeologic map of the entire field. Conclusions reached from the maps and field work include: 1) flow ridges parallel the direction of flow and may be distinguished from pressure ridges; 2) collapse depressions are localized at distal ends of flows and usually occur in groups that indicate flow direction, and 3) Nichol's model of the domical formation of pressure ridges is acceptable but needs to be related to fluid dynamics.

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TABLE OF CONTENTS

Illustrations	1
Introduction and Methodology	2
Previous Work	3
Geologic Setting	4
General Description of the Wapi Field	7
Wapi Field	9
Pillar Butte Vent Area	13
Small Scale Surface Features	
General Description	14
Primary-Secondary Dichotomy	19
Pressure Ridges	22
Collapse Depressions	26
Detailed Field Map	30
General Photogeologic Map	34
Conclusions	38
Future Work	40
Appendix	
Map Legend Description	41
Bibliography	43

INTRODUCTION AND METHODOLOGY

Within the last decade, a new branch of geology dealing with the surface and the interiors of other planetary bodies in the vicinity of the Earth has come into being. In the United States this science called astrogeology, has concerned itself most specifically with the Moon and Mars. It is apparent from the results of the Surveyor, Orbiter, Apollo and Mariner missions, that the surfaces of the extraterrestrial bodies so far studied are often covered with large accumulations of basaltic lavas. At this time, Apollo is the last scheduled series of manned missions to any of these planetary surfaces and at least for awhile, astrogeologists will have only remote sensing data to use in their research. This remote sensing data will be comprised mainly of aerial photography of the planetary surfaces. It is necessary therefore that remote sensing criteria be established, so that extraterrestrial surfaces can be evaluated.

This study was undertaken to examine closely and document the Wapi Lava Field which is a large, flat accumulation of basaltic lava on the Snake River Plain of Idaho. By its size alone, the Wapi Lava Field is a reasonable analog to the immense accumulations of basaltic lava evident from aerial photography of the Moon and Mars. This study will document the large scale features of the Wapi Field as well as specific interpretations that can be made about large fields of lava. Lava flow direction is significant and carries implications concerning the internal characteristic and genesis of the flow. For any field made up of a number of flows, flow direction can relate to many of the properties of accumulation of that field. Due to erosion or impact cratering only the largest morphologic features of a flow will survive on a planet's surface

and these large scale features should be related to flow direction.

These are the only features that can be resolved at the scale of the photos of these planets. This thesis relates flow direction of a lava flow to the large morphologic features commonly exhibited on the surface of the flow.

The text is organized so that the Wapi Field is put into its regional geologic setting first. Then the Field itself is described from a viewpoint which starts from a high aerial view of the entire field and extends down to detail of the small features on the surface. These small features are then described and their relation to flow direction explained. Pressure ridges and collapse depressions are described and previous ideas concerning their formation are discussed. Finally a small detailed field map illustrating the relationships of large features to flow direction as well as a large photomap of the entire field are explained and conclusions drawn based on the criteria developed in this study.

PREVIOUS WORK

Much work has been done on the Snake River Plain and most of it pertains at least peripherally to the Wapi Lava Field. Russell (1902) made an early survey of the Plain and documented and explained many of the geologic and volcanic features. Stearns (1938) updated the 1902 survey and included a description of the area within the present Craters of the Moon National Monument. Stearns also reported on the ground water aquifer conditions beneath the plain. Both the reports of Russell and of Stearns refer to the Wapi Lava Field but do not consider it in any great detail. The Snake River Aquifer was again studied and greatly clarified by Mundorff, Crosthwaite and Kilburn (1964). Malde (1960) studied the tectonics of the Plain, and LaFeur and Pakiser (1962) have done a grav-

ity survey of the east half of the Plain in an attempt to delineate the structure of that region.

Work on the extrusive volcanism of the Snake River Plain is somewhat limited. Prinz' (1970) work on the Idaho Rift System, Stearns' (1963) and Murtaugh's (1961) work on the Craters of the Moon event, and Malde and Power's (1972) mapping of the geology of the Glenn's Ferry-Hagerman Area comprise most of the few studies which deal with it. In the recent past, attention has turned to the Snake River itself through the work of Malde (1968) who investigated the geomorphic effects of the Pleistocene Lake Bonneville Flood down the present valley of the Snake River. To the best of the present author's knowledge, no specific study on the Wapi Lava Field has ever been carried out.

GEOLOGIC SETTING

The Wapi Lava Field is located in south-central Idaho in a physiographic province known as the Snake River Plain. The Plain is partly surrounded by highlands of the Northern Rockies. These highlands are composed of folded Paleozoic sedimentary rocks and granite of the Idaho Batholith as well as faulted Cenozoic volcanics. The Snake River Plain is so named because the Snake River cuts across it and forms its southern margin. The Plain is a flat accumulation of Quaternary lava flows containing occasional eruptive centers. While it appears quite flat, there is actually a predominant surface dip to the south and west involving a difference in elevation from 2000 m. in the east to 700 m. in the west. The Snake River Plain is commonly associated with the Columbia Plateau of Oregon and Washington because they are generally contiguous and both have large accumulations of lava. However, the two areas differ significantly in that they are governed by different structures, their lavas

appear to be different chemically, and they have very different geologic ages. The Snake River Plain is Pleistocene in age while the Columbia Plateau dates from the Eocene-Pliocene.

It is convenient to divide the eastern and western parts of the Plain at the $114^{\circ} 30' W$ meridian, which passes approximately through Twin Falls. The Wapi Lava Field is located at the southwestern end of the eastern half of the Snake River Plain. The eastern half of the Plain is composed of a large accumulation of flood basalts which derived from a number of local vents. The eastern surface is covered with late Pleistocene and Recent basalts which are almost totally undissected and all drainage is internal. Tectonically, the eastern half of the Snake River Plain is controlled by a late Tertiary downwarp, with some minor marginal faulting. The fault block mountains north and south of the east half appear to plunge beneath the surface of the lava (Malde, 1966). In contrast, the western part of the Plain has a much narrower areal accumulation of basalts, the exposed upper flows of which generally have an age of early to middle Pleistocene. The Plain is heavily dissected in places by the Snake River and its tributaries. Tectonically the western half of the Plain is a graben 50 kilometers across, formed by northwest trending bounding faults.

The late lavas of the eastern half, including those of the Wapi Field, are known as the Snake River Group. It is evident that their accumulation has gradually forced the Snake River to its present south marginal position. The aggregate thickness of the lava of the eastern half is not known as there is no well data through the pile. Seismic data between Craters of the Moon and Idaho Falls indicate at least 1,300 meters of lava, and electrical resistivity data indicate a 2000 meter

maximum for a profile from Arco to Blackfoot (Zohdy and Stanley, 1972). The lava of the Wapi Field is the most recent veneer of fresh basaltic lava on the accumulation.

Structurally, most of the vents in the eastern half of the Snake River Plain are controlled by rifting. These rifts trend either in a northwesterly or northeasterly orientation. Most likely these directions are derived from the structural trend of the buried Paleozoics, or from the trend of the downwarp to the east half of the Plain. The Wapi Lava Field is spatially related to a Recent rift system, called the Idaho Rift System which was named and described by Prinz (1970). The Idaho Rift System accounts for and controls two of the four largest Recent Fields which cover the surface of the eastern Snake River Plain. These two fields are the Craters of the Moon Field and the Wapi Field. From north to south the Idaho Rift System follows a general southeasterly course but gradually changes to a south-southeasterly direction. The Idaho Rift System is composed of 4 sets of rifts: (1) the Great Rift Set which is located within the Craters of the Moon Field, (2) an Open Crack Rift Set, (3) the King's Bowl Rift Set and (4) the Wapi Rift Set. The strikes of the various rift sets vary along the system, but the sets are contiguous to one another. The proximity of the sets and the correlation of the overall surface weathering similarity between the separate lava fields are the main arguments for the sets to be related in time as well as in space (Prinz, 1970). This author does not agree with Prinz' hypothesis or analysis of the inferred Wapi Rift Set, but most of his analysis and conclusions pertaining to the entire Idaho Rift System seem well-established. Most probably as Prinz hypothesized, the rifting on the Plain is caused by the same extensional forces that produce block faulting in

lobes extend from the northwest corner of the Field to the north and to the west. The margin of the Field is generally smooth and continuous on the northern and eastern sides, but on the south and west the margin is broken up into long lingular flows occupying the drainages of small intermittent streams. The margin pattern is no doubt an effect of the regional slope to the southwest, such that flows to the north and east would be ponded while flows to the south and west would continue to move until their internal characteristics caused them to stop. Generally the flows of the Field have moved across the typical weathered lava and loessal mantled surface of the Snake River Plain, but in the southern region, they are superimposed on a field of sand dune blowouts, which trend ENE from the area around Lake Minidoka to the vicinity of American Falls.

The slope of the Wapi Field can be determined from the 1:250,000 topographic map. Generally the contour lines on the surface of the Field scribe arcs to the south which roughly parallel the margin of the lava field. The degree by which they do not parallel the actual flow margin carries implications as to the thickness of the lava of the Field. The circular pattern of the contour lines that center on the topographic high near Pillar Butte seem to owe their circularity to portions of the surface of the Plain which were completely unaffected by the Wapi flows. When the contour line segments representing these unaffected portions are connected without the Wapi Field segments, they still form a circular pattern but it is no longer centered on Pillar Butte. Instead, the center is moved to the line of vents trending NNE known locally as Wapi Park. These vents are about 2 kilometers NW of Pillar Butte. This implies that the Wapi Field is underlain by an older field that centered and emanated from the Wapi Park Vent area. The older field occupies the

same general position as the Wapi Field and this is interpreted to mean that the Wapi Field probably has an average thickness of about 35 meters overall rather than having a thickness of 150 to 200 meters in the Pillar Butte area and thinning away from that point to the edge of the Field. In one locality, approximately 40 meters of local relief measured from the bottom of a collapse depression to the upper edge of a scarp was noted but this is believed to represent a maximum. Russell (1902) states the average thickness of flows of Snake River lavas to be 50 to 80 feet with large lateral extents. The large number of kipukas that are on the southern and western edges and the appearance of one kipuka within 4 kilometers of Pillar Butte also present evidence that the thickness of the lavas is not great. Using the figure of 35 meters for the thickness of the Wapi Field and 415 sq. km. as the area of the Field, the total volume of the Field is approximately 14.5×10^9 cubic meters.

The surface slope of the lavas on Snake River Plain is generally very low, and the Wapi Field is no exception to this. Four measurements were made from the 1:250,000 Pocatello topographic sheet and the slopes for the Field over distances of 10 to 20 kilometers were found to vary from 38 to 48 minutes of one degree. These slope figures agree well with the average figure of 1/2 to 1 degree. The exception to this slope is in the vicinity of Pillar Butte where there is a large, low mound of lava that has a slope of 5 to 7 degrees, which is much steeper than the rest of the Field.

Wapi Field

Local relief on the surface of the Wapi Field varies greatly from location to location. Large pressure ridges, pressure plateaus and collapse depressions are concentrated near the periphery of the Field and

define the greatest overall relief. However, the surface of these peripheral areas is nonetheless relatively smooth and use of a 4-wheel drive vehicle could be carefully undertaken.

Local relief away from the edges and toward the interior on the rest of the Field is not great, and is dominated by smaller pressure ridges and collapse depressions, which are surrounded by areas of pahoehoe toe flow of random orientation. These 3 to 5 meter low-relief interior areas have a rough irregular surface which makes them impassible to any form of vehicle. In summary, as one progresses into the Field from the margin, and especially from the ponded eastern side, one first passes over an area of smooth, high-relief lava, then gradually into areas of lava with less local relief but which in general are much more irregular. The difference between these two types of local relief is basically the primary-secondary dichotomy which will be discussed in the section on small-scale surface features.

The lava of the Wapi Field is dominantly filamented pahoehoe. There are small patches where the Field has been broken into slab pahoehoe and more rarely aa. The filamented pahoehoe varies in surficial relief from area to area and covers about 90% of the surface of the Field. Assuming a continuous series of variations from pahoehoe to aa, the Wapi lava type is best classified as pahoehoe which is locally transitional to aa.

In hand specimen, the Wapi lava appears to be a typical olivine basalt. Near the surface it is vesicular with large planar accumulations of vesicles arranged in horizontal layers every 5 to 15 centimeters. These vesicle layers are not found below 3 to 4 meters. In its interior as viewed through large cracks in the surface, the Wapi Flows are gener-

ally massive and dense and show columnar jointing at several scales. Different sets of columns penetrate into the flow to differing depths. Columns 5 to 8 centimeters wide are only 10 centimeters long; columns 15 to 20 centimeters wide are a meter and a half long; and large incipient columns 3 to 4 meters wide extend to greater depth, but this extent is not documented. All three of these groups of column sizes have some surface expression as polygonal cracks and these usually are not open. The deep, massive portions of these columns contain olivine phenocrysts and plagioclase laths and only rarely, some small round vesicles. By contrast, near surface specimens of the columns commonly contain irregular vesicles and occasionally brown phenocrysts of pyroxene as well as green phenocrysts of olivine. Occasionally the euhedral phenocrysts of olivine are very large, with the largest observed being 8 mm in length.

Petrographically, the Wapi Lava is an alkali olivine basalt. In thin section the Wapi Basalt is made up of a glassy matrix which surrounds euhedral phenocrysts of olivine, irregular brown pyroxene and laths of plagioclase feldspar. The feldspar varies in composition from labradorite to anorthite (Michel-Levy). Larger laths of plagioclase are occasionally observed to be zoned and olivine is commonly found adjacent to pyroxene with no evidence of reaction. The pyroxene was identified as augite and there was no orthopyroxene or pigeonite found.

The basalts of the Snake River Plain have a very distinctive chemical character. A partial averaged x-ray fluorescence analysis of 4 samples from the Wapi Field is shown in Table I and compared with: (1) a tholeiite, the Yakima Basalt (Washington, 1922); (2) an olivine basalt, the Ninole Basalt (Stearns and Clark, 1930); and (3) an Apollo 11 rock from Mare Tranquillitatis, 10020-23 (Peck and Smith, 1970).

Table 1 - Chemical Comparison of Wapi Basalt and other basalts

<u>Oxide</u>	<u>Yakima</u>	<u>Wapi</u>	<u>Ninole</u>	<u>10020-23</u>
SiO ₂	54.50	55.	48.60	39.95
Al ₂ O ₃	14.43	---	10.75	10.19
Fe ₂ O ₃	2.17	---	3.92	.03
FeO	8.80	14.5(total iron)	9.38	19.14
MgO	4.24	---	9.80	7.87
CaO	8.01	11.8	10.38	11.31
Na ₂ O	3.05	---	2.54	.39
K ₂ O	1.29	1.9	.34	.05
TiO ₂	1.69	2.7	3.37	10.52
MnO	<u>.10</u>	<u>---</u>	<u>.05</u>	<u>.27</u>
Total	98.28		99.13	99.72

The difference between an alkali olivine basalt and a tholeiitic basalt according to Poldervaart (1964, p. 229) is:

"In tholeiites, olivine generally shows evidence of a reaction relationship with orthopyroxene or pigeonite, the predominant pyroxene is a Ca-poor augite, and interstitial free silica is present as a silica mineral or siliceous glass. In alkali basalts, olivine shows parallel crystallization with pyroxene, orthopyroxene and pigeonite are absent or scarce, the predominant pyroxene is a Ca-rich augite that is commonly titaniferous, and interstitially there is albite, nepheline, analcite or equivalent mesostasis!"

This is basically a petrographic distinction and the chemical equivalent is somewhat more nebulous. Unfortunately the Snake River basalts fall into an area of questioned definition. In basalts of this type, the olivine shows no reaction with orthopyroxenes or pigeonite, the augite is relatively Ca-rich compared to other tholeiites, and the mesostasis has small amounts of albite. Normative calculations place the Wapi Basalt with the olivine tholeiites. This is apparent even from the limited chemical analysis carried out in this study. The Wapi Basalt has too much silica to be undersaturated, too much calcium to form a Ca-poor augite and the titanium content is transitional to the two major types of basaltic lava. The Wapi Basalt would seem therefore to be a typical Snake River Plain basalt as described by Poldervaart (1964).

Pillar Butte Vent Area

Pillar Butte is a sharp point on a low mound of lava about 25 km from the Snake River. Owing to its striking relief, it served as a landmark for travelers on the Oregon Trail. Pillar Butte is located within the Wapi Field, near the northern edge, and is the only large vent complex evident on the Field. It is a good example of the type of low accumulation of lava that Russell recognized as the sources of the Snake River lavas. On an aerial photograph it appears as a distinctive dark

albedo patch superimposed on the rest of the Field. Its darker albedo is due to the large amount of aa that cover the 5 to 7 degree slopes of the Pillar Butte area. The flow patterns near Pillar Butte are elongate to the southeast (Plate 2). This is because of a low depressed area to the southeast in the older lavas of the Field which the more recent lavas later filled. There are 10 major craters of varying sizes in the Pillar Butte area which are arranged in a NNW line and occupy the summit of that low mound. Most all flows in the Pillar Butte area clearly originated at one or another of these craters. Probably owing to the larger slope angle, many of the flows of Pillar Butte are of the aa type with prominent leeved channels although there are pahoehoe flows interbedded with them and, especially in proximity to the craters, the surface is largely mantled with shelly pahoehoe flows. Near the west side of the summit there are several short subsidence faults trending to the NNW and near the east side there are several small patches of lapilli. Plate 5, Fig. 1 is an aerial view of the Pillar Butte vent area, showing the craters, the aa flows to the southeast, the leeved channels, the subsidence faults on the west side of the craters, and the general aspect of the Field in total. The flows near Pillar Butte overly and are clearly younger than the large pahoehoe flows which compose the majority of the Field. However, the difference in age is probably a matter of weeks or months, rather than decades or centuries. Probably these later lavas are the products of vent activity at Pillar Butte after the major portion of the Wapi eruption had taken place.

SMALL SCALE SURFACE FEATURES

General Description

The usual pahoehoe flow shows a multiplicity of surface features,

some of which have very precise directional implications, Waters (1960) presents a compendium of these features, and rates their usefulness as directional indicators. These features include: 1) inclined columnar joints in the flow interiors caused by the down-flow shifting of the upper cooling cells, 2) spiracles in which the top is displaced in the direction of flow, 3) primary foreset bedding in palagonite breccias, 4) orientation of the streamlined horizontal cross sections of lava tree molds, 5) bending of the top of pipe vesicles and vesicle cylinders in the direction of flow, 6) trailing out of vesicles or foreign debris from spiracles or tree molds, 7) direction of curvature of ropes and wrinkles found on the pahoehoe crust, 8) direction of inclination of platy jointing near the snouts of some flows, and 9) direction of curvature of ridges on block lava flows where these are preserved.

The recency of the Wapi event precludes sufficient erosion to expose the cross-sectional indicators and reliance in this study was exclusively on surface markings. Although most all surface features are produced by lava motion, there is some ambiguity as to their interpretation. Waters (1960) ended his discussion on surface features by stating that:

"from limited observation the writer is of the opinion that measurements of the trend of stretched bubbles and pulled glass filaments on the common filamented pahoehoe will give the least ambiguous results of the many kinds of structures that occur on flow tops"

Filamented surfaces would seem then to be one of the best indicators with which to measure lava flow direction. During the course of the present mapping, filamented surfaces were subjectively grouped into three classes based on their degree of roughness. These low, medium, and high relief filamented surfaces were subdivided also because the common fila-

mented surface of the Field seemed to have three different affinities.

Low relief filamented surfaces are textbook examples with the parallel lineations of stretched vesicles very prominent and the relief of the surface less than 1/2 centimeter. Plate 4, Fig. 2 shows the general surface aspect of low relief filamented pahoehoe. Medium relief filamented surfaces are very similar to the low but the surface relief is greater, from 1 to 1 1/2 centimeters. Plate 3, Fig. 2 shows a medium filamented surface with the sense of lineation straight into the picture. High relief filamented surfaces are much different than the low or the medium types. High relief filaments have from 2 to 5 centimeters of relief and a very knobby aspect that occasionally makes interpretation of directional features difficult. Plate 3, Fig. 1 shows a high relief filamented surface and its knobby aspect, although here the sense of lineation is very clear. High relief surfaces have the look of lumpy porridge. This combined with the usual occurrence of high relief filamented surfaces in the marginal and far distal portions of a flow lead one to associate them with cold, late-flow stages.

To these filamented directional indicators, the writer has added the common roped pahoehoe surface, which has an advantage over filamented surfaces in that its directional indication is unidirectional. Plate 4, Fig. 1 shows a large set of pahoehoe ropes curved toward the viewer indicating motion out of the picture toward the viewer. Another surface designated "filaments and ropes" was recognized and differentiated for the purpose of thesis. Plate 4, Fig. 2 shows this kind of a surface with a filamented surface passing laterally into a small set of ropes. This is dominantly a filamented pahoehoe surface, on which small ropes have begun to form. It can be used to determine a unidirectional arrow

of motion for a particular locality.

Primary-Secondary Dichotomy

During the course of the first summer's field work spent on the eastern lobe of the Field, a dichotomy was noticed in the general character of the surfaces of the various flows which make up the Field. Certain areas of the Field are quite flat, and the dominant surface type is medium filamented, which is generally a reliable direction indicator for any particular locality where it is found. These flat areas also commonly exhibit large sections of pahoehoe ropes up to 50 meters long and 15 meters wide. Because of the clarity of the directional indicators of these areas, the mapping favored them and directional readings were taken on them wherever these features could be found. These areas, made up of medium filamented pahoehoe with occasional large sets of pahoehoe ropes, were designated Primary, as it became apparent that they would have a significant influence on the flow directional map.

In contrast to the primary flow areas were areas designated as Secondary. The dominant surface types for these areas were much rougher and made up of low and high relief filamented pahoehoe. Pahoehoe ropes are common but their total areal extent is quite small and the largest sets of ropes are less than 3 meters in length. In general the secondary surfaces are composed of large accumulations of pahoehoe toes which have flowed one on top of another. Interpreting the directional indicators on these surfaces is very difficult, as any filaments exposed vary widely in their directional orientation. The directional indicators exhibit considerable ambiguity and in some instances it is impossible to determine the local flow direction. These differences however were sufficiently constant to define the primary-secondary dichotomy.

During the second field season, a detailed map of the same area of the Wapi Field was produced (Plate 1), and while this was being done, the same dichotomy between primary and secondary surface types was apparent but this time differences in distribution as well as surface form was noted. Mapping proved that areas covered by primary surfaces were large through-flows that constitute the vast bulk of the Field. Through-flows represent pulses of lava that flowed unobstructed from the vent, rather than flows that are readjustments of these pulses to the small scale local topography. Primary surface flow direction is in response to the large scale topography and to the position of the last through-flow of the Field. These large through-flows have such a volume that a topographic feature must be several meters in size to cause any change in direction of the flow, and thus the through-flows have consistent directions of flow. The secondary flows by contrast appear to be of a smaller scale, and are commonly breakouts from the crust of the large primary flows. Thus the flow directions of the secondary flows are determined by the morphology of the nearest primary or in some cases secondary flow that they move against or across. This results in a flow direction lacking a consistent pattern. Plate 5, Fig. 2 shows secondary pahoehoe toe flow moving onto a surface of flat smooth primary lava, and gives a good feeling of the difference in the fundamental aspect of the two lava types.

Thus there is a dichotomy between two fundamental aspects of the Field's surface, that is between major primary flows and secondary flows which are derived from them. This generalization is not without exception, but it proved very useful in mapping the various flows of the detailed map area (Plate 1). As a suggestion, other workers might keep it in mind in similar areas to test its general applicability.

PRESSURE RIDGES

Pressure ridges are a common feature of the lavas of the Snake River Plain. They were first described by Bradley of the Hayden Survey and later more thoroughly by Russell (1902). Russell (1902, p. 95) described them as:

"... dome-like ridges, commonly from 10 to 30 feet high, 20 to 70 feet wide, and from 50 to possibly 500 feet long, which are usually cracked open at the top throughout their length, the cracks being open fissures usually 3 to 4 feet wide but sometimes as much as 10 feet. The fissures referred to narrow downward, and the basalt forming their walls is frequently columnar, the columns being at right angles to the outer surfaces of the ridges"

He also noted that these cracked ridges frequently occur in groups with their long axes subparallel. His projected mechanism (Russell, 1902, p. 95) for the formation of these features was:

"The similarity between the large ridges on the surfaces of the older sheets of the Snake River lava and the hollow folds, corrugations, etc., observed at the Cinder Buttes, leaves no room for doubting that the former, like the latter, were produced by lateral pressure in the surface portion of a lava flow"

Russell attributed the size of the features to the fact that the parent flow had to move such a great distance over such a relatively flat surface. Russell does not specifically state the relationship between the orientation of the long axes of the pressure ridges to the flow direction, but it generally has been assumed that it is transverse to the principal direction of flow such that frictional drag of the flow underneath causes the crust of the flow to compress up into a ridge. Wentworth and MacDonald (1953, p. 49) state that:

"Many of them (tumuli), particularly those of highly elongate form, and the great majority of pressure ridges, apparently were formed by the horizontal thrusting and buckling of the flow crust caused by the pressure of fluid lava"

Wentworth and MacDonald cite an actual observation in Waesche (1940, p. 8) of the formation of a pressure ridge by this mechanism in Mokuaweoweo, the summit caldera of Mauna Loa in the eruption of 1940. The occurrence was in the thick ponded lavas and seemed to be a product of the force of convection against the crust of the lavas of the crater. This occurrence would be very similar to the formation of pressure ridges in sea ice and the mechanism as postulated by Russell is plausible.

Probably the most detailed work on the formation of pressure ridges was carried out on the McCartys Basalt Flow in New Mexico (Nichols, 1946). In Nichols' study the relationships between large morphologic features such as pressure ridges and collapse depressions are carefully described over the area of the last 6 miles of the flow. Several models based on mechanical studies were advanced to explain the relationships actually found. Among the most interesting of Nichols' observations and interpretations that pertain to the Wapi Field are: (1) there are two kinds of cracks in the flow, one is wedge-shaped and is caused by stretching of the lava crust by uplift while another kind is parallel-sided and is caused by thermal contraction of the cooling of the lava; (2) cracks formed in a slowly uplifting and thickening crust would be wedge-shaped as the upper crust would be stretched more than the bottom part of the crust which would have been liquid during all except the last stages of the uplift; (3) pressure ridges can be divided into two types, longitudinal ridges with axes parallel to flow direction and transverse ridges with axes across the direction of flow; (4) the medial cracks in the pressure ridges are empty although some are filled with "squeeze-ups"; and (5) Nichols' rejected the viscous drag model for the formation of the pressure ridges on the McCartys Flow and instead proposed a domical coll-

apse theory to account for them. Nichols' observations are excellent and many support interpretations of pressure ridges made by the author on the Wapi Field.

Pressure ridges are the most ubiquitous large-scale feature on the Wapi Field and occur in a continuous series of sizes and shapes. They range in length from a nearly continuous 8 km length to those as short as 10 meters. They vary in height from 1 to 15 meters. Some of the ridges have a rounded domical form, but the vast majority of them are relatively flat-sided with the sides dipping at 30 to 40 degrees. Plate 6, Fig. 1 shows a large slab pahoehoe covered pressure ridge trending back into the picture and curving off to the right. The mound in the right background is the Pillar Butte vent area, and the flatness of the horizon shows the lack of relief on the surface of the Snake River Plain. The medial cracks of the pressure ridges are wedge-shaped and from 1 to 3 meters wide. Plate 6, Fig. 2 shows the medial crack of a small pressure ridge, and the columnar jointing that is common to the interior of the Field. It is also interesting to note that the pahoehoe ropes of the surface of the Field are broken perpendicular to their width by the longitudinal crack of the pressure ridge. The best formed and largest pressure ridges occur on primary surfaces on the eastern side of the Field. The medial cracks of the major pressure ridges invariably lack flowouts and generally are 6 to 10 meters deep indicating that cracking occurred late in the history of the flow.

In summary, there seems to be contradictory information relating to pressure ridge formation and a dual system such as Nichols' longitudinal and transverse classifications must be accepted.

The long continuous pressure ridges in the Wapi Field pass laterally

into what I have called pressure plateaus. Pressure plateaus as defined in the AGI glossary are:

"A broad area of lava, generally pahoehoe, that has been bodily elevated by the intrusion of new lava into the lower, still congealed part of a flow without the addition of any new lava at the surface"

The pressure plateaus of the Wapi Field are flat plateaus bordered by scarps. The edges of the plateau dip 30 to 40 degrees, the same as the sides of the pressure ridges. Plate 7, Fig. 1 shows the outside scarp of a large pressure plateau and all its characteristics. Plate 7, Fig. 2 shows the inside scarp of the same pressure plateau and on the right side of the picture, an area of chaotic secondary flow. The pressure plateaus vary in width from 15 meters up to 200 meters and because they are continuous with pressure ridges, any explanation of the ridges must also accomodate the plateaus.

COLLAPSE DEPRESSIONS

Collapse depressions are another large morphologic feature which are found in certain areas of the Wapi Field in great profusion. The depressions vary in size from 1 to 35 meters across and from 2 to 10 meters deep. The largest and best-formed of the collapse depressions are on primary surfaces and are particularly well-developed on the eastern side of the Field. Plate 8, Fig. 1 shows the lip of a typical collapse depression, with the characteristic overhang, layered interior and block jumbles. Plate 8, Fig. 2 is of a large elongate collapse depression in a typical primary flow area. although depressions can and do occur anywhere on the Field, secondary surfaces usually exhibit only very small ones.

The best description of collapse depressions is again in Nichols' (1946) work on the McCartys Flow. Many of his observations on collapse

depressions on the McCartys Flow coincide with those found on the Wapi Field. These observations include: 1) the long axes of the collapse depressions invariably parallel the direction of the flow, and the surface of the flow between the depressions is relatively flat; 2) the long axes of the collapse depressions parallel flow direction, but their arrangement does not indicate the number, position or direction of the lava tubes which should have formed them; 3) fluid lava and a steep gradient favor the production of a central lava tube but the gradient could not be too flat or the tubes would not drain the lava; 4) the cliff that faces in toward a collapse depression often overhangs the depression and the lower lip of the opening is grooved and striated, a phenomenon probably caused at the time of collapse when the lava is still soft and plastic; and 5) collapse depressions commonly have squeeze-ups within them, which are extruded after collapse occurs.

Nichols (1946, p. 1064) states concerning collapse depressions that, "These depressions and others are formed by the collapse of the roofs of lava tunnels." The McCartys Flow is located in the valley of the Rio San Jose, and the bottoms of collapse depressions are commonly filled with water and alluvium. These conditions prevent detailed study of the floors and interiors of the depressions. In comparison, the collapse depressions on the Wapi Field are completely unaltered and can be examined in detail. Of the 100 or so collapses which were studied, not one was found with any connection to a tunnel (tube) system of any kind at either the upstream or downstream end of the depression. If these are truly collapsed segments of lava tubes, and this collapse is not continuous, then the uncollapsed segments of the tunnel should still exist, but in fact they do not. The author has visited the McCartys Flow and the collapse

depressions there are very similar to those of the Wapi Field. The author believes that if the collapse depressions of the McCartys Flow could be explored, it would be found that there too, there is no connection to any uncollapsed lava tube. From their shape and position it is apparent that the collapse depressions are intimately related to the flow system, but apparently they are not simply collapsed roofs of lava tubes. From the observation of striations, and squeeze-outs it is believed that the failure of these features occurs relatively early in the flow history, while there is still heat and liquid lava present. The author believes that some configuration of gas bubbles and partially drained tubes while the surrounding lava is still plastic, causes the collapse depression complexes that one sees on the Wapi Field. Upon cooling and contraction these features collapse as the surrounding lava becomes brittle and fractures.

DETAILED FIELD MAP

A map was prepared in the field of the surface types, flow direction, and the large and small morphologic features of a 1.3 sq. km. area within the Wapi Field. This area is representative of the 2 to 4 km wide band around the edge of the Field, but probably not of the deeper interior portions of the Field. The extent that this area has been influenced by its position in the Field, such that it might not be completely representative is not known, but it is thought not to be too great. The flow features of the eastern lobe are controlled by a low valley which drained to the west as revealed by the remnant drainage pattern in that area. Thus any flow moving up the valley eventually would be ponded by the slope of the valley bottom.

Mapping traverses followed the marginal positions of the separate

flows and directions of motion of each particular area were noted along with positions of collapse depressions, crests of pressure ridges, edges of scarps associated with marginal positions of pressure plateaus, and points of extrusion of secondary flows. Reference to Plate I is helpful in reading the following section as well as the appendix on map description.

The surface of the detailed map area consists of a sequence of primary flows, (numbered 1-7), three large secondary flows (numbered 8-10) and many more small secondary flows which occur between the primary flows and are not numbered. From the field relationships it is apparent that the sequence of relative ages of the separate primary flows is 1 to 7 in numerical order with flow 1 the oldest; that is, flow 2 overlaps flow 1 and flow 3 overlaps flow 2, etc. This combined with the observation that flows 8 to 10 are large secondary flows from flow 1 indicates that flow 1 was probably the initial flow to invade the valley within this area. Each succeeding primary flow is usually separated from the older adjacent flow by an area of secondary lava which for the most part comes from the younger primary flow. This relationship can be seen on Plate I in several localities. The scarps that usually form the margins of the primary flows define moats in which the secondary lava may flow. These moats occasionally extend for several hundred meters. In certain areas the moats are filled with secondary outpourings so complex and contradictory that they were impossible to map completely.

Secondary flows 8 to 10 have smaller flowouts of their own that are secondary to them. This, together with the fact that flows 8 to 10 have many primary characteristics owing to their large size, makes the dichotomy between the primary and secondary flows somewhat imprecise and gener-

alized here. The author feels the distinction is valid, however in this instance it must be qualified. Upstream each of the primary surfaces becomes more secondary in nature; that is they develop more secondary characteristics while at the same time they have been overflowed by more and more secondary flows. On the east side of the map area, almost all flows encountered are secondary flows. This progressive change from primary to secondary in an upstream sense is common elsewhere.

An interesting feature is that the secondary flows are controlled by the morphology of the primary flows which they overlie and the flow directions of the secondary flows thus commonly parallel the flows which they partly cover. Even where the older lavas are completely covered, the surface made up of a younger flow reflects the direction in which the underlying lava moved. Thus a statistical analysis of the secondary areas, even with all their chaotic flow direction behavior, should reveal much about the principal flow direction of the Field as a whole.

Collapse depressions occur in greater profusion in the detailed map area than anywhere else in the Field. They occur on all of the flows, but the largest and best-formed of these collapse depressions occur on flows 1, 2 and 5. Their occurrence is usually in groups and in any group, collapse depressions are all about the same average size. This size is apparently governed by the size of the flow on which they are situated. An example of this is found in the smaller group of collapses that occur on flow 9. As a general rule these collapse groups are aligned or elongate with flow direction. This relation is more apparent on Plate 2 than on Plate 1. The collapse depressions are commonly elongate in plan view, and this elongation, as in the McCartys Flow is parallel to flow direction. This can be checked with almost any of the depress-

ions on Plate 1. These collapse depressions tell very little by their surface distribution except that they commonly are in the mainstream of a flow.

The most interesting aspect of the detailed map is the relationship between flow direction and pressure ridges and between flow direction and scarps that border pressure plateaus. The largest of these features occur on the largest of the primary flows: 1, 2 and 5. Flow 5 was the only flow with a large pressure ridge on it within the detailed map area although minor pressure ridges occur on several of the flows. From the map of flow direction, it is apparent that the large ridge of flow 5 parallels the flow flow direction and that the crest of the ridge changes direction with changes in flow direction. This was also found to be the case with the small pressure ridges in the map area and other traverses confirmed the relationship throughout the field. In no instance was the orientation of a pressure ridge crest found to deviate more than 15 degrees from the direction of flow at any point as indicated by the filamentation or roped character of the surface. The orientation of these features makes the theory of fluid drag formation untenable and although these ridges share the same general shape as pressure ridges, they are a separate and distinct type. I suggest that these ridges be called flow ridges to emphasize their association with flow direction. Flow ridges are the result of pressure as are pressure ridges, but the pressure comes from collapse shortening rather than from fluid drag. Therefore it is important to make a distinction between them. It is evident from a study of flow 5 that the flow ridge bifurcates and becomes two scarps which move to more marginal positions on that flow. This flat-topped flow ridge is referred to in this paper as a flow plateau. It is evident that the scarps of a

flow plateau again strongly parallel flow direction. I have called these plateaus, flow plateaus so as to express their association with flow direction and flow ridges.

There are scarps in the map area that definitely do no parallel flow direction, because they merely mark the marginal position of that particular flow. In general it can be said that if any flat area is bounded by scarps and is elongate, then there is a good possibility that the principal direction of flow in that area is parallel to the sense of elongation, and the greater the sense of elongation, the greater the possibility.

Commonly both flow ridges and flow plateaus appear sequentially in the course of a single flow, but their distribution is not understood. The author feels that flow plateaus are an expression of the dome in Nichols' domical theory of the formation of pressure ridges, and that in contradistinction, flow ridges are either collapsed domes or perhaps incompletely formed domes. These features can probably be theoretically modeled and understood with the aid of fluid dynamics.

The detailed map of Plate 1 and the observation made on general traverses provide keys to the understanding of the photomap of the entire field.

GENERAL PHOTOGEOLOGIC MAP

Plate 2 is a small scale map of the entire Wapi Field, which covers an area in excess of 6 townships. It was created by making a mosaic of 100 separate 1:20,000 United States Department of Agriculture photographs on a single sheet. All map detail is based on photomapping, although many specific localities were examined in the field. The only topographic control of the area is the 1:250,000 Pocatello map and it

did not prove satisfactory as a map base. It lacked sufficient identifiable control points and it would have had to be enlarged 10 times. Plate 2 is thus an uncontrolled mosaic. Absolute position may be incorrect by as much as 2.5 mm although relative position will have much less error. Pattern may be somewhat distorted and the orientation may be slightly incorrect but probably by less than 5 degrees.

The area surrounding the Field on the eastern, northern and western sides is dominantly a loessal prairie covering lavas older than the Wapi Field. Some limited drainage has begun to develop on these surfaces but the dry climate prevents well-established patterns. On the northwestern side a fresh flow older than the Wapi Field, which is thought to emanate from the vents at Wapi Park, occupies the surface and therefore no drainage has begun to develop. On the southern edge of the Field, the northern boundary of the field of Quaternary sand dune blowouts is marked by two lines on either side of the Field trending ENE, and below this line the surface is more thickly mantled with sand.

It should be possible to evaluate the development of the Field, from the detailed map, using flow ridges, flow scarps and collapse depressions. In the first place, a lack of large features is noticeable the closer one gets to Pillar Butte. This relation is interpreted to be caused by proximity to the source vent where there are more lavas of a secondary nature which do not tend to form large morphological features. This "halo" of featureless terrain around Pillar Butte extends somewhat to the west and this reflects the fact that the slope was somewhat greater to the west favoring movement in that direction. Large features are generally confined to the peripheral areas of the Field and are especially common in the southern half of the Field which is a myriad of

distal ends of flows. . Collapse depressions are also almost totally absent from the region around Pillar Butte and are confined to the periphery and the lobe areas of the Field.

Based on the relationships obtained from the previous sections of this thesis, an analysis of the direction of flow in the Field is possible and arrows of general flow motion could be plotted for the entire Field. From Plate 2, it is apparent that flow from the Pillar Butte area moved east and southeast to the eastern lobe and west and northwest toward the western and northern lobes. The major portion of the Field owes its formation to flows coming from the west and southwest sides of Pillar Butte which moved west and southwest down the entire length of the Field. This flow was strongly controlled by the regional slope.

Study of the far southern end of the Field which overlies the sand dune blowout area is very interesting. The flows, upon encountering the northern edge of this sand blowout area, twist their dominant south and south-southeast flow pattern to a west-southwest-east-northeast direction which is prevalent in the elongate depressions of the sand dune blowout area. Thus sand dune blowouts exerted a strong control on flow direction.

There seems to be no expression of the north-south rift system that Prinz (1970) hypothesized for this Field. A more likely possibility in light of this work is that the King's Bowl Rift Set extends under the Wapi lavas. The last components of that set on its southwest side are orientated N22W and seem to be propagating en echelon southward. If one measures the subsidence faults of the Pillar Butte area they also have a N22W orientation. Based on the assumption that the Wapi Event is rift-controlled, it is quite likely that the orientation of late eruption

subsidence faults would be controlled by and related to the similar original rift orientation. Thus the subsidence faults could be taken as an indication of the original rift orientation.

That the King's Bowl Rift faults and the subsidence faults of Pillar Butte have identical orientations can be used to support the hypothesis that they originated from a single event. It is probable, therefore, that the rift zone for the King's Bowl event extended further south and that one of these rift segments became the source for a great deal of lava which created the Wapi Field. The superposition of the Wapi lavas on the rift faults of the King's Bowl event does not preclude this possibility. The vent which produced the lavas of the Wapi Field is now buried beneath the late accumulation of Pillar Butte lavas and removed from any possible surface study.

The occurrence of the rootless vent complexes to the west of Pillar Butte is simply an indication of a downward slope toward the rootless vents causing a flow to drain toward them and form the distinctive features. The rootless vents were recognized from the aerial photographs by small dome-like accumulations of aa lava and there is a good possibility of others in the area which were not mapped because they did not show this small surface difference. As a sidenote, these rootless vent complexes have dribble spires associated with them and this is the only known occurrence of these features in the continental United States, (Greeley, 1972).

CONCLUSIONS

The conclusions of this thesis can be summarized as follows:

- 1) The Wapi Lava Field is less than 2000 yrs old and virtually unaltered since the time of its extrusion.

2) The low slope of the Wapi Field, less than 1 degree, is a probable cause of its general flow characteristics.

3) The Wapi Lava Field is composed of alkali-olivine basalt which has a pahoehoe surface.

4) A primary-secondary dichotomy exists between two fundamental aspects of the Field, but the relationship is invalid in certain instances.

5) Collapse depressions occur mostly on primary surfaces, and are elongate in the flow direction.

6) Collapse depressions are scaled to the size flow that they occur on. On any particular flow the collapse depressions are of the same average size.

7) Groups of collapse depressions indicate flow direction by the elongation of the group as a whole.

8) Collapse depressions form early in the history of a flow and are related somehow to flow, but not necessarily to lava tube roof collapse.

9) Pressure ridges can in some instances parallel flow direction. Where this situation exists, the new term "flow ridge" is used to express this relation to flow.

10) Flow ridges are late phenomena in the history of a flow and any model of their formation must be in that context.

11) The high, flat areas, bordered by scarps, with some sense of elongation tend to parallel flow direction with this elongation.

12) The largest topographic features of the Wapi Field, are generally near the periphery of the Field and in the lobe areas.

13) Flow from the Pillar Butte area created the Wapi Lava Field and this flow was controlled by the regional slope as well as orientation of sand dune blowout elongation.

- 14) The King's Bowl Rift and Wapi Lava Field are part of a single event and their rift sets are unified.

FUTURE WORK

Lava flow morphology has not benefited from the trend in geology toward quantification, and lava flow phenomena have not even been adequately described. From this study the author sees a need for work in many areas. Pillar Butte's relation to the rest of the Wapi Field should be clarified, and the Recent eruptions on the Snake River Plain should be studied to see if any general relationships exist for the entire Plain. Also the leveed channels of the aa flows of Pillar Butte should be mapped and quantified to learn their characteristics and occurrence.

Flow morphology of other types of lava flow activity should be investigated to learn any general relations. Model studies could be carried out in an attempt to recreate the forms that are found in the field in order to understand their genesis. And finally fluid dynamics should be applied to the parameters of lava flow to understand the theoretical aspect of lava flow morphology.

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