PETROLOGY OF O'LEARY PEAK VOLCANICS,
COCONINO COUNTY,
ARIZONA

by

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STATEMENT BY AUTHOR

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PREFACE

O'Leary Peak is named for Dan O'Leary who was a scout for General Crook during the Indian campaigns of the late nineteenth century in northern Arizona. The first mention of O'Leary in Arizona was in 1864 when he prospected in the Bradshaw Mountains. In 1867 he was a scout in the campaigns against the Walapais. In 1868 he worked for the Palmer Railroad surveying crew. He scouted for Crook in 1872 during Crook's march on the Date Creek Reservation. The only mention of O'Leary's association with the San Francisco Mountains is that of his hunting there in 1873. He died January 20, 1900 at Needles, California.

Henry Hollister Robinson in 1913 published a paper in which O'Leary Peak and the flows northwest of O'Leary Peak were mapped as pyroxene dacite. He mapped the dome southeast of O'Leary Peak and the flows north of O'Leary Peak as rhyolite. However, in discussing the petrography, Robinson described O'Leary Peak as a hornblende dacite and the dome as a biotite dacite. Robinson, in his discussion of the silicic centers of the San Francisco Volcanic Field, proposed that Elden Mountain (southwest of the thesis area) formed through a combination of "...laccolithic intrusion with volcanic extrusion." He supported magmatic differentiation of a parent basalt or andesite as the source of silicic centers such as O'Leary Peak and Elden Mountain.

The purpose of this investigation is to determine the volcanic history of the O'Leary Peak area and more clearly define the rock types. This information is then used to determine if O'Leary Peak formed by the mechanism proposed for Elden Mountain. Chemical analyses are plotted to indicate trends and are then compared with San Francisco Mountain and the San Francisco Volcanic Field.

Mapping was done on a topographic base map enlarged to a scale of 1:12000 from the 7½ minute U.S.G.S. topographic map of O'Leary Peak Quadrangle, Coconino County. Forest Service air photos at a scale of 1:15840 were also used and, in areas where prominent topography made the air photos more helpful, locations were later transferred to the base map.

Reconnaissance mapping was done in the area west of O'Leary Peak between Robinson Crater and the Strawberry Crater road. Samples were taken in this area from morphologically or lithologically distinct units for thin section comparison with units within the mapped area.

105 thin sections were examined and modal analyses of selected sections using 500 to 1000 points were used. One purpose was to determine if O'Leary Peak and the dome

to the southeast are as different petrographically as Robinson suggested. Another purpose was to compare the O'Leary Porphyry with the flow material to the north. Chemical analyses of volcanic units distinguished in the field augmented the petrographic comparisons.

I wish to thank Dr. D. Smouse (previously of Northern Arizona University) for suggesting the area. I wish to express gratitude to my thesis director Dr. B. Nordlie for direction during the course of the investigation. Discussions with Professors E. Mayo and P. Damon of The University of Arizona and Professor R. Eastwood of Northern Arizona University were most helpful. Conversations with Mrs. E. Holm (U.S. Geol. Survey, Tucson) concerning the Kaibab Formation were also helpful. Written communications with Mr. E. Gaffney of California Institute of Technology (who did graduate work on O'Leary Peak), Dr. B. Kudo of The University of New Mexico, and Mrs. K. Verbeek of Pennsylvania State University (who did graduate work on the White Horse Hills) were most informative.

I would like to express appreciation to the Research Center of the Museum of Northern Arizona which allowed me to use their library facilities and to Mr. W. Breed of the Museum of Northern Arizona for discussions concerning nomenclature. Special thanks go to Mr. D. Lynch (graduate student of The University of Arizona) for repelling down the eastern lobe cliff of the Banded Flow.

I would like to thank "Red" MacGraw of Mountain State Telephone who pulled my "field vehicle" out of the cinder.

Sincere thanks go to Mr. E. Wolfe and G. Ulrich of the Astrogeology Center, U.S. Geol. Survey, Flagstaff, and Mr. R. Moore (graduate student of The University of New Mexico). I am indebted to them not only for their comments on the thesis area, but also to Mr. Wolfe for nine chemical analyses which I was able to obtain through him.

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ABSTRACT

O'Leary Peak and Darton Dome, within the San Francisco Volcanic Field, are breached and unbreached volcanic domes composed of porphyritic rhyodacite. Sanidine crystals mantled with continuous rims and oriented phenocrysts of oligoclase are common within the porphyry of O'Leary Peak. Basic volcanic inclusions (oxyhornblende, andesine-labradorite, and olivine) within the porphyry show resorption in localities where mantled sanidine is present. They are unresorbed where the mantled sanidine is absent.

Non-porphyritic rhyodacite flows north of O'Leary Peak appear to have source areas which delineate a north-northeast lineation. Levees appear to have channeled some of this flow material to form Deadman Mesa.

Sedimentary xenoliths are present on the eastern side of O'Leary Peak, but the lack of upturning of sedimentary beds argues against a laccolithic theory of emplacement for the domes. Emplacement formed a brecciated zone on the eastern side of O'Leary Peak dome. Late basalt flows, spatter, and cinder deposits occur on the eastern and southern sides of O'Leary Peak.

The mantled sanidine is analogous to rapakivi texture. Addition of calcium and sodium from the basic volcanic

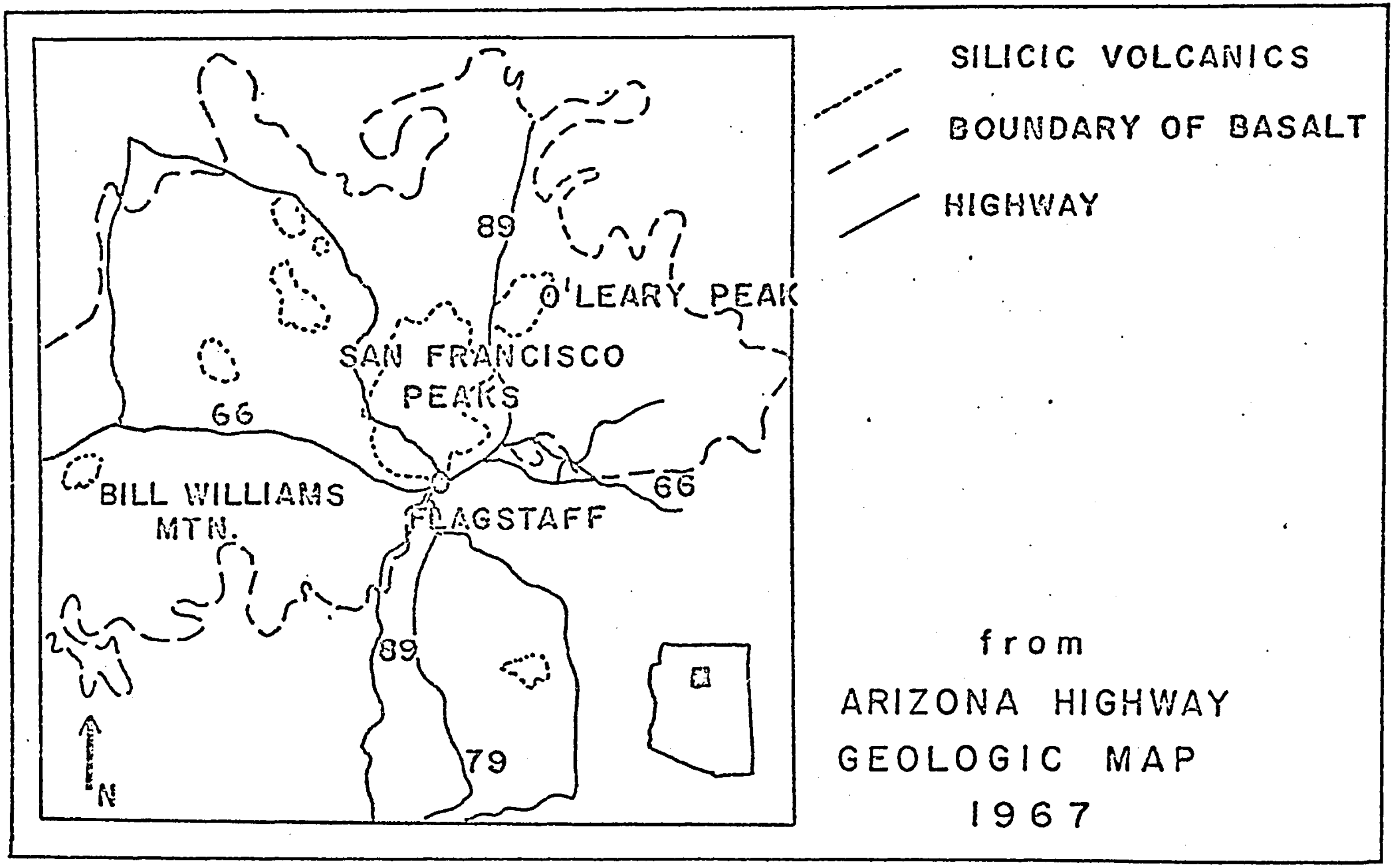
inclusions ("basification") and variation of water pressure are probable causes of the texture. O'Leary Peak Volcanics Major element analyses show the O'Leary Peak Volcanics to be alkalic and higher in Na_2O and lower in K_2O than units from the San Francisco Mountain. Trace elements show no clear differentiation trend.

INTRODUCTION

Location and Accessibility

O'Leary Peak is located within the central part of the San Francisco Volcanic Field approximately fifteen miles northeast of Flagstaff, Arizona. The San Francisco Volcanic Field makes up about 3000 square miles in the north-central part of Arizona. O'Leary Peak, located in the SE ½ of section 3, T. 23 N., R. 8 E. is approximately the center of the investigated area (figure 1, in pocket). The area is bordered on the south by the boundary of Sunset Crater National Monument (figure 2).

U.S. Highway 89 north from Flagstaff passes approximately three miles to the west of the area. Access from the south is by means of this road and the Sunset Crater National Monument turn-off. O'Leary Peak is reached by means of a Forest Service dirt road which connects the Sunset Crater road to the tower on O'Leary Peak. Access from the north is by means of a Forest Service road called the Strawberry Crater road which originates at Highway 89. This road extends to the northeast part of the area where a fork leads southward to Sunset Crater, thus encircling the O'Leary Peak Volcanics.



from ARIZONA HIGHWAY GEOLOGIC MAP 1967

Figure 2: San Francisco Volcanic Field.

This location map shows the extent of the basalt flows and the silicic centers which make up the San Francisco Volcanic Field. O'Leary Peak is located to the northeast of Flagstaff.

Topography, Physiography, and Climate

O'Leary Peak is dome-shaped with a slope of approximately 22°. It has a semi-circular ridge (varying in elevation between 8916 and 8938 feet) which outlines a depression on the north. Except for ravines cut into the northwest side, O'Leary Peak is relatively undissected. Darton Dome, on the southeast side of O'Leary Peak, is elongate in a north-northeast--south-southwest direction and is dissected on the south by one large ravine. This dome is asymmetrical due to a lobe extending from its eastern side. These two domes are shown in figure 3. Protrusions from the side of O'Leary Peak include a flat-topped one on the eastern side referred to as the Eastern Flat, and a dome-shaped one on the southwestern slope referred to as the Southwestern Lobe.

North of O'Leary Peak three ridges radiate at an elevation of 7800 feet from a circular feature. The middle ridge extends about 2.0 km almost directly north; the eastern and western ridges are shorter, extending about 1.0 km, and are rounded at their distal ends. The western ridge is made up of two discontinuous ridges approximately 0.5 km apart. Between the middle and eastern ridges is a 4.0 km square area of hummocky topography. To the north of the three ridges the topography flattens forming Deadman Mesa, the gradient of which is about 100 m per km.

West of O'Leary Peak and north of Robinson Crater is a "plateau", somewhat centrally sunken, covering an area of

Figure 3: O'Leary Peak.

O'Leary Peak (left), Darton Dome, and Sunset Crater (right) as seen looking north from Highway 89.

of about 5.0 square km. This plateau is bordered by steep margins some 100 m in height. Superimposed on this plateau is a basaltic cone (#47) rising to 7309 feet in elevation. The cone is slightly crescent-shaped in plan-view and opens on the western side.

Drainage of the entire area is by several ephemeral streams which do not join to any main drainage but, rather, end blindly probably due to the permeability of the cinder cover.

Flagstaff, fifteen miles southwest of the thesis area, has a mean annual rainfall of 18-19 inches, a mean annual snowfall of 76-77 inches, and a mean annual temperature of 46° F. (Smith 1956). The O'Leary Peak area is situated approximately at the junction between two climatic zones--that of the upper Sonoran juniper-Pinyon pine grassland which continues to the north and that of the Transition Zone Ponderosa pine-covered mountains of the San Francisco Peaks area. Higher on O'Leary Peak the Canadian Zone is represented by aspen and Douglas fir.

Geologic Setting

The sedimentary section present in the San Francisco Volcanic Field includes the Redwall Limestone of Mississippian age through the Triassic Moenkopi Formation. The volcanics generally lie on the erosional surface of the Kaibab Formation.

Verbeek (personal communication 1971) describes the Redwall Limestone as a light gray, light tan, or white coarsely crystalline fossiliferous limestone with dolomite and oölitic limestone.

The basal unit of the overlying Supai Formation, according to Verbeek (personal communication 1971) is composed of reddish-brown fine-grained limestone which is occasionally interbedded with shale layers. The middle member is reddish-brown to orange siltstone and the upper member is a red to brown massive cross-laminated fine-grained sandstone.

The Coconino Formation which overlies the Supai Formation is a fine-grained quartz sandstone showing pitting and frosting of the sand grains. This sandstone is usually buff to white in color but has been reported to be red due to iron staining (Verbeek, personal communication 1971). Massive cross-bedding is described within the Coconino by Robinson (1913).

The Kaibab Formation is described by Gilman (1965) as "...a series of calcareous sandstones and limestones. The very fine-grained limestones are usually dolomitic and partly sandy or cherty. They are yellowish to tannish gray..." The sand grains, according to Lehner (1958) are subrounded to subangular and are predominately quartz. At Walnut Canyon National Monument the Kaibab Formation is very fossiliferous and contains cavities lined with quartz crystals. Within the White Horse Hills the Kaibab Limestone is light tan in color and contains quartz-lined cavities and one to two inch thick beds of chert (Verbeek, personal communication 1971). Robinson (1913) described the Kaibab Formation as forming a "...very flat anticline" which strikes N30W, dips less than one degree, and dies out northward. Recent evidence suggests that block faulting on the Kaibab Formation may have caused erosion to remove differing amounts of the formation in various areas (Holm, personal communication 1970). Major structural trends within the area are shown in figure 4.

Upon this Kaibab surface are developed the cones and flows of the San Francisco Volcanic Field. Robinson divided the activity within the field into three periods; the first and third periods are basaltic and the second is silicic. The basalts of the first period covered an area larger than the field itself producing a volume of some 30 cubic miles of material made up almost entirely of flows. The flows have a thickness of 25 to 75 feet, according to Robinson, and nowhere exceed 200 feet in thickness. Second period silicics compose San Francisco Mountain, Elden Mountain, and O'Leary Peak. The third period basalts erupted from scattered vents within two stages producing volcanics which cover an area of approximately 1,200 square miles.

Colton (1967) divides the activity of the field into five stages with the second including the silicic centers and the other four consisting of basalt. His first stage

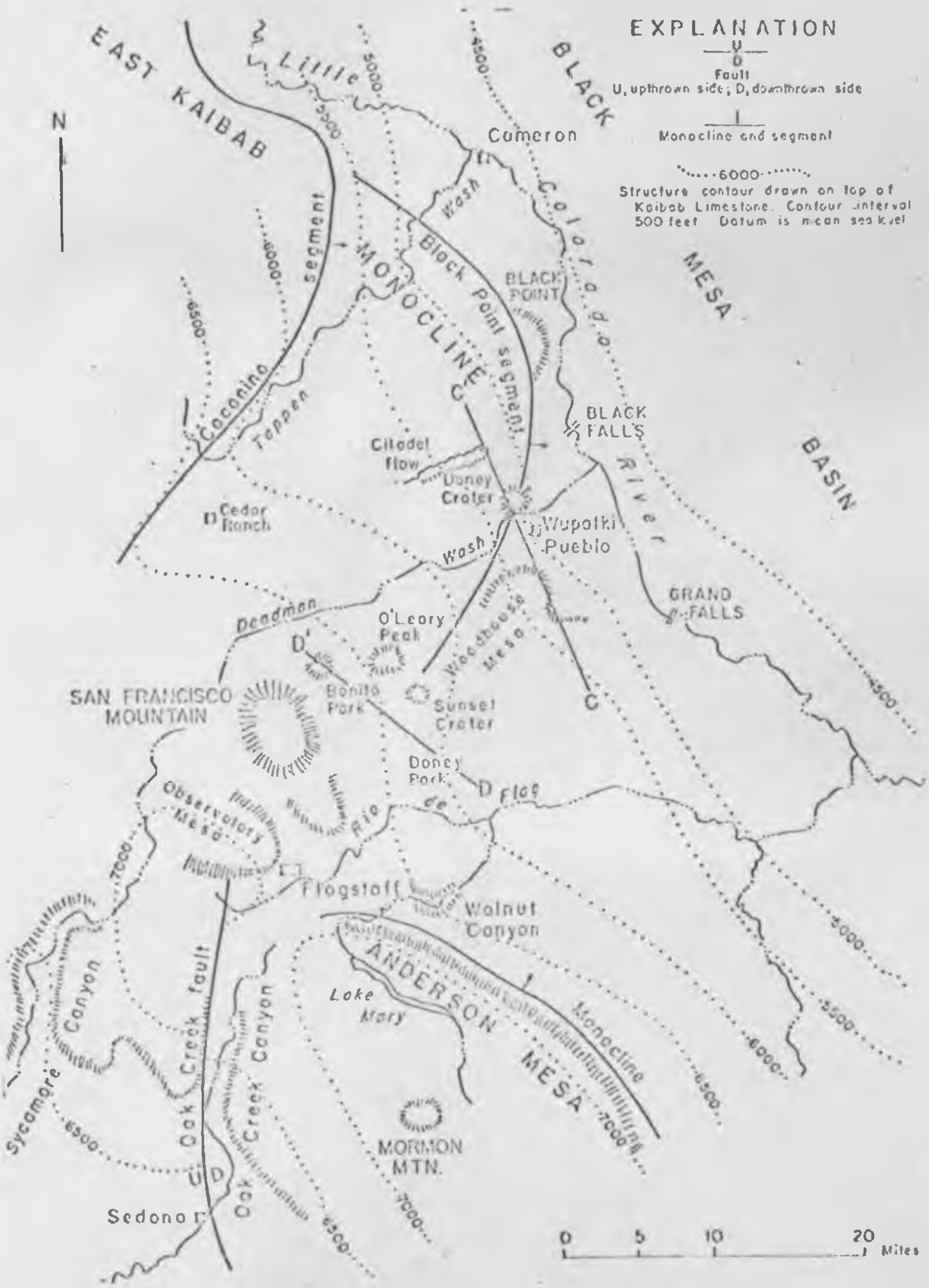


Figure 4: Structure map of San Francisco Mountain area.

Structure contours are on the top of the Kaibab Formation. The map is taken from Cooley (1962, p. 105).

consists of basaltic flows which are older than the San Francisco Peaks including Switzer's Mesa north of Flagstaff, Black Point Flow, the flows of upper Oak Creek, and a flow upturned on the flank of Elden Mountain. Stage II basaltic flows can not be traced back to their craters as they are covered by later flows. While Stage III flows occurred much later than the acidic centers, Colton is not certain whether Stage II basaltic flows are younger or older than the acidic centers. Stage III activity resulted in North and South Sheba, O'Neil Crater, and Crater 160. Four basaltic centers are placed by Colton into Stage IV: S.P. Crater, Merriam Crater, Strawberry Crater, and Janus Crater. Stave V is represented by Sunset Crater. Stage I and II flows are quite thin while those of Stage III and IV show considerable variation in thickness. Cooley (1962, p. 104) shows "intermediate" rock types (San Francisco Peaks, Elden Mountain, and O'Leary Peak areas) as spanning the time from late Stage I through Stage III.

Sabels (1960) does not confine silicic activity to a short interval. He states that drill cores show alternation between basaltic and rhyolitic activity. Acidic lavas within the field and within the Verde Valley range between 14 and 2-3 million years in age (Sabels 1960, p. 200). He states:

> The difficulty to explain early, pre-basaltic rhyolitic activity did not exist in the past...According to Robinson, volcanism commenced with basaltic activity, and then, in the intermediate to acidic period, the magma evolved nicely through a latitic,

dacitic and rhyolitic stadium, strictly in keeping with ideas of differentiation. Then, after an andesitic interval, basaltic activity was resumed.

Previous Work

Published investigations concerning the San Francisco Volcanic Field include those of Atwood (1905), Johnson (1907), Robinson (1913), Colton (1929, 1930, 1931, 1934, 1945, 1964, 1967), Mintz (1942), Sharp (1941, 1942, 1958), Feth (1952), Smiley (1958), Sabels (1959a, 1959b), Kelly and Clinton (1960), Babbitt (1964), Breed (1964), Breternitz (1967), Van Campen (1967), Cooley et al (1969), Smouse (1970), and Toll (1970). Unpublished investigations include those by Howell (1959), Sabels (1960), Hodges (1962), Gilman (1965), McLain (1965), Chase (1966), and Verbeek (personal communication 1970).

The only published investigation concerning O'Leary Peak is Robinson (1913). Unpublished work includes that of Gaffney (person communication 1970). Yet to be published is work by Wolfe (U.S.G.S.) and Moore (University of New Mexico).

Nomenclature

The dome lying on the southeast flank of O'Leary Peak has been named, by the author, Darton Dome after the geologist Nelson Horatio Darton (1865-1948) who did detailed work on the stratigraphy of northern Arizona and New Mexico. The proper forms have been filed with the U.S.G.S. Board on Geographic Names in order to have the name offically recognized.

Darton's publications on Arizona include the following: "A Reconnaissance of parts of Northwestern New Mexico and Northern Arizona" (U.S.G.S. Bulletin 435), "A Resume of Arizona Geology"(Arizona Bureau of Mines Bulletin 119), "The Permian of Arizona and New Mexico" (American Association of Petroleum Geologists V. 10, pp. 819-852), and "Crater Mound, Arizona"(Geological Society of America Bulletin V. 56, pp. 1154). The latter article stems from Darton's belief that Crater Mound (now called Meteor Crater) was a volcanic phenomenon and contained no meteorite.

GENERAL GEOLOGY

Units are presented in the order of extrusion as determined by the author. Field evidence for this stratigraphic sequence is discussed under Stratigraphic Relations.

O'Leary Porphyry

O'Leary Peak, the Eastern Flat (figure 15, in pocket), and the main part of Darton Dome are composed of porphyritic rhyodacite consisting of sanidine phenocrysts, oligoclase phenocrysts and cumulates (to 20 mm), and quartz phenocrysts (2-5 mm) in a lavender to tan (5 YR 6/1) matrix (figure 5). The porphyries of the Southwestern Lobe and of the eastern lobe of Darton Dome have similiar phenocrysts in a gray, glassy matrix showing well-developed flow structure. The porphyry exhibiting this glassy matrix is called the "gray porphyry" while that porphyry (as in O'Leary Peak) which contains a lavender matrix is referred to as "purple porphyry". Scattered mafics (to 2 mm in length) optically identified as oxyhornblende dot the matrix of both porphyry types. Common within both porphyry types are basic volcanic inclusions. Within the "purple porphyry" of O'Leary Peak these inclusions are red (5 R 4/2) and range from 2.5 to 5.0 cm in length; within the "gray porphyry" they are gray (N2) and range from 1.5 to 30 cm in length. Quartz and feldspar phenocrysts resembling those within the porphyry are common within the inclusions (figure 5). These phenocrysts are discussed under PETROGRAPHY.

Robinson (1913) states that O'Leary Peak is composed of hornblende dacite and Darton Dome of biotite dacite. No such distinction was apparent to the author in the field. Inclusions are larger and more abundant within Darton Dome than within O'Leary Peak and phenocrysts are smaller and less abundant than those phenocrysts within O'Leary Peak. This appears to be the only distinction. The dominant mafic in both areas is oxyhornblende.

O'Leary Peak

O'Leary Peak is a volcanic dome consisting of approximately 1.9 cubic km of rhyodacite porphyry. A semi-circular crest outlines a depression on the north which the author believes to be the vent of the dome. Two summits on the ridge are separated by a saddle which is approximately 200 feet lower in elevation than the summits. The northwestern summit is itself divided into a northern and a southern summit which are separated by a saddle approximately fifty feet lower in elevation. These irregularities are probably the result of autobrecciation and spine development on the top of the rising O'Leary Peak Dome. Erosion has apparently accentuated such original features.

Figure 5: O'Leary Porphyry.

This O'Leary Porphyry is exposed in a roadcut on the southern side of O'Leary Peak. Porphyry feldspar and quartz phenocrysts occur within the basic volcanic inclusions.

The Tower Summit. The Forest Service road to the tower on the eastern summit provides excellent exposures of the porphyry. The unsheared portions of this outcrop were mapped at a scale of 1:1200. At suitable places one square foot of outcrop face was outlined and the total area of inclusions within this outline was measured. It is assumed that the percent area of inclusions per square foot of porphyry is proportional to the percent volume of inclusions per cubic foot of porphyry. Thus, variations in inclusion volumes were noted. In order to determine any variations in grain size, the long axes of feldspar phenocrysts were also measured. A random sample of long axes was obtained by measuring those phenocrysts lying on the two diagonals of the square. The results appear in Table I.

The porphyry of the tower summit shows an increasing amount of shearing and alteration as the summit is approached. Red, purple, and brown coloration of the porphyry is common near the saddle between the two summits (see Emplacement of the Dome under VOLCANIC HISTORY).

The Western Summit. The southern part of the western summit consists of a chaotic mass of porphyry blocks. The phenocrysts are generally smaller and red inclusions are less numerous than on the tower summit. An outcrop of reddened porphyry suggests resorption of and streaking out of the red inclusions. This feature is also present on the eastern side of O'Leary Peak (figure 6). Farther to the north, outcrops

Figure 6: Red schlieren within the O'Leary Porphyry.

This association of schlieren and red inclusions occurs within the porphyry on the eastern side of O'Leary Peak.

Table I: Inclusion volume and phenocryst length.

Sample locations indicated begin near the O'Leary Porphyry-red cinder contact on the southern side of O'Leary Peak. Inclusions and phenocrysts within roadcuts in the O'Leary Porphyry (P31) were measured as described in the text. Locations are progressively closer to the tower along the road as their numbers increase.

Location	Percent volume of inclusions	Average porphyry feldspar length (mm)
1	1.13	
2	1.66 3.85	
3	0.22	5.8
4	1.36	4.64
5	0.79	
6	0.46	6.35
7	4.9	6.67
8	4.5	5.77

show various degrees of alteration of the porphyry matrix and replacement of the cores of the feldspar and quartz. Here also is a cliff showing nearly vertical flow banding delineated by vesicular layers and by alignment of inclusions and of phenocrysts. This may represent a spine.

The Central Depression. The semi-circular ridge joining the two summits of O'Leary Peak is bounded on the north by a depression referred to as the "central depression." This depression, considering the lack of extensive dissection of O'Leary Peak, appears to be an original feature. Within it are outcrops of pervasively fractured porphyry of unrotated fragments 1 to 4 cm in length. The porphyry contains gas cavities and has been stained shades of yellow, red, and brown suggesting the passage of fluids and/or gases. Mafics are almost totally replaced by hematite and magnetite. Veins of limonite are present.

Southwestern Lobe

The porphyry of the Southwestern Lobe (see figure 15) consists of phenocrysts 0.5-1.5 cm in length and of basic volcanic inclusions 1.5-30 cm in length within a red-yellow (5 YR 6/1) to gray (N5) matrix. The inclusions here are sometimes red but are usually gray (N3) and are larger than inclusions within the porphyry of O'Leary Peak. The matrix is glassy and shows prominent flow structure. Outcrops can be followed continuously westward to within 1500 feet of Robinson Crater (see figure 15) where they are covered by alluvium.

Porphyry outcrops are also present within the eastern wall of Robinson Crater. This porphyry is not identical to that of the Southwestern Lobe. Feldspar phenocrysts are to 1.1 cm in length and volcanic inclusions are to 18 cm in length. Both red and gray inclusions are present within a glassy, gray (N3) matrix. One brecciated outcrop contains porphyry fragments (2.5-22.5 cm) and fragments of various other rock types mixed in a porphyry matrix. This outcrop may represent a vent.

Darton Dome

Darton Dome southeast of O'Leary Peak (see figure 15) consists of approximately 0.5 cubic km of rhyodacite porphyry within an unbreached dome. Outcrops on the western side of Darton Dome are poorly exposed due to weathering and lichen cover; however, outcrops are good on the southern and northern sides. The asymmetrical profile of the dome appears to be due to a lobe of porphyry which flowed toward the northeast without rupturing the chilled shell of the dome (figure 7).

On the north side of Darton Dome the porphyry consists of feldspar phenocrysts to 1.9 cm (average 0.7 cm) in length in a gray, glassy matrix. Quartz is less obvious than at O'Leary Peak. Volcanic inclusions (usually red) range from 4 to 30 cm in length and make up about five percent of the rock (figure 8). Flow structure parallel to the elongation of the dome (northeast-southwest) can be seen. Inclusions are aligned parallel to this flow structure.

Figure 7: Eastern side of Darton Dome.

A protrusion out of the eastern side of Darton Dome is seen from the O'Leary Peak tower.

Figure 8: Basic volcanic inclusions within Darton Dome.

Abundant red volcanic inclusions occur within the "gray" porphyry of Darton Dome. The green lines are two inches in length. The outcrop is on the north side of the dome.

Volcanic inclusions on the east side of the dome are commonly 15 cm long. They are gray (N3) and show numerous acicular mafic phenocrysts (identified in thin section as oxyhornblende). Inclusions near the top of the dome on the eastern side are up to 25 cm (average 7.5 cm) in length and are gray (N3). Phenocrysts are to 2.5 cm (average 1.2 cm) in length; the matrix is gray.

The Eastern Flat

Protruding from the eastern side of O'Leary Peak (see figure 15) is a flat-toped lobate mass of rhyodacite porphyry with a volume of approximately 0.20 cubic km. This lobe appears to be an offshoot from the O'Leary Peak Dome which did not break through to form a flow. It is referred to as the Eastern Flat; its morphology resembles "terraces" described in northern California by Anderson (1933). The porphyry here is remarkably similar to that of O'Leary Peak in size of phenocrysts, size and color of volcanic inclusions, and color of matrix. The jumble of blocks covering the lobe probably represents a "carapace" of talus as described by Williams (1932b) and by Loney (1968) for volcanic domes and coulee tops.

Porphyry Structure

Primary flow structure within the O'Leary Peak porphyry is delineated by alignment of feldspar phenocrysts and of volcanic inclusions and by vesicular layers. The short axes of feldspar phenocrysts appear to be perpendicular to a common plane; however, lineation of the long axes within this plane was not found. Inclusions where not resorbed are oriented approximately parallel to the phenocrysts. Vesicular layers are the best planar structure within the porphyry. Alternation of color and texture also indicate flow banding. Red streaks within the porphyry (figure 6), possibly due to "streaking out" of volcanic inclusions, are present locally but are contorted. Flow structure was mapped along the southern side of O'Leary Peak at a scale of 1:1200; however, only enough fresh material was exposed to yield 24 measurements. Flow structure here strikes northeast and dips 39-73° to the northwest (towards the "central depression").

Several directions of jointing are common along the road on the southern side of O'Leary Peak, but not enough measurements were available to delineate any definate trends on a Schmidt net diagram. One area of prominent jointing is located between the summit saddle of O'Leary Peak and the curve in the road at an elevation of about 8400 feet. Here the joints have a red, indurated coating. In one outcrop where the plane of the joint was exposed, slickensides were present. These joints strike N12-32E and dip 42-68° to the southeast. How much movement has occurred along these joints is uncertain. They may actually be faults; however, no markers were available from which to determine displacement.

Description of O'Leary Peak Dome

Most of the volcanic domes cited in the literature occur within the craters of volcanoes. Several from Auvergne and New Zealand do not, however, and closely resemble the O'Leary Peak and Darton Domes. Most domes described, however, have a fine-grained to glassy lithology rather than a strongly porphyritic one similar to that of the O'Leary domes.

Basic inclusions are common within the domes described by Williams as they are within the O'Leary domes. According to Williams (1932a, p. 292) inclusions within Raker Peak of Lassen National Park decrease in size and number toward the top of the dome. No definite indication of this was discernable from detailed mapping along the southern side of O'Leary Peak.

Williams (1932b) describes volcanic domes as having a "carapace" of talus due to autobrecciation of the dome during growth. Much talus can be seen on Darton Dome, the Eastern Flat, and the summit of O'Leary Peak. One locality on O'Leary Peak may be a spine suggesting that more fluid material rose through the cracks of the dome shell. Such fissures in the brecciated shell according to Williams (1932b, p. 134) are passages for "solfataric emanations" and thus may be coated with opal, hematite, and sulphur. He states: "...steam ascending along joints, has converted the pale gray matrix to a brick red, an alteration that is most intense in the upper and marginal parts of the dome." (Williams 1932b, p.342).

This may explain the alteration at the top of the O'Leary Peak Dome. Williams also states (1932b, p. 134) that slickensides are common within domes indicating post-consolidation movement. These may be analogous to the slickensides on the southwestern side of O'Leary Peak already mentioned.

Flow banding within domes has been described by Verhoogen (1937), Williams (1932b), and Lewis (1968) as forming a fan being nearly vertical at the center and dipping inward at the margins. Williams (1932b) describes a possible mechanism to produce this: "...earliest lavas tend to spread from the vent at low angles and thus build up a kind of levee about the orifice. Hence, the later outlows [sic] are restricted and must rise at increasingly high angles as the levee grows in height...". Detailed mapping of the flow structure within O'Leary Peak Dome was possible only along the road where roadcuts provided fresh material. Within this area flow structure dips into the "central depression." This may suggest that a fan arrangement of flow structure is present within the O'Leary Peak Dome.

Banded Flow

Just north of the "central depression" of O'Leary Peak is a dome-shaped accumulation of volcanic material which is the focal point of three ridges. The eastern and western ridges consist of Banded Flow material (see figure 1). The two lobes of the Banded Flow together have a volume of about

1.4 cubic km. A chemical analysis of the Banded Flow (W_b17) appears in Table II. The norm (see Table III) of W_b17 classifies it as a rhyodacite.

A cliff on the southern side of the eastern lobe of the Banded Flow shows prominent obsidian flow bands up to 20 feet thick which alternate with pink to tan, contorted, frothy flow material (figure 9). The flow banding is nearly horizontal within the middle of the cliff but turns sharply upward toward the western end (nearer the source) as seen in figure 10. Toward the eastern end of the cliff (away from the source) the bands disappear as the flow material apparently becomes autobrecciated. Beneath the basal obsidian layer on the western end of the cliff there is a xenolith of Kaibab Limestone which measures approximately 65 feet by 30 feet. The obsidian shows contortion of flow bands suggesting that turbulent flow was produced around the xenolith within the obsidian. The dips within this lobe are generally inward but the outcrops do not indicate if the flow banding is arranged in a series of "nestled spoons." Overhangs and vertical exposures above the examined outcrop show continuous asymmetrical folds, detached synforms and antiforms, and rotated bodies similar to those described by Christiansen and Lipman (1966, p. 677). Due to the vertical nature of the cliffs, detailed study could only be made at the base. Flow banding is not well developed on the north side of this lobe.

Table II: Chemical analyses of O'Leary Peak rhyodacites

Samples listed are located in figure 15. Numbers given are in weight percent. Analyses were supplied by the U.S. Geol. Survey, Astrogeology Center, Flagstaff, Arizona.

	P31[a]	W_b17[b]	W_r16[c]	DM1[d]	DM2[d]	W_f19[e]	X4[f]	X13[f]	X2[f]
Ba	950	1200	750	1100	1050	1250	500	750	1050
Sr	190	250	250	410	390	170	370	530	520
Cu	10	7	7	7	8	7	85	78	40
Ni	15	15	15	10	10	15	300	65	25
Co	30	20	25	20	20	15	80	75	65
Cr	25	25	25	25	25	25	675	50	50
Li	15	5	5	5	5	15	5	5	5

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a. P31 is from the O'Leary Porphyry.

b. W_b17 is from the Banded Flow.

c. W_r16 is from the Red Flow.

d. DM1 and DM2 are from Deadman Mesa outcrops.

e. W_f19 is from the Frothy Flow.

f. X4, X13, and X2 are from basalt outcrops on the eastern and southern sides of O'Leary Peak.

Table III: Norms of O'Leary Peak rhyodacites

Norms were calculated according to the method of Barth (1962). Samples used to calculate norms are those of Table II. Locations of these samples appear in figure 15. The chemical analysis of P31 appears in Table V.

	P31	W_b17	W_r16	DM1	DM2	W_f19
Ap	0.27	0.24	0.37	0.43	0.37	0.16
Ilm	0.08	0.34	0.44	0.60	0.56	0.18
Or	22.50	18.25	17.70	18.70	16.50	23.50
Ab	44.75	50.00	51.00	44.00	51.00	45.75
An	5.63	8.20	9.15	11.32	10.50	6.00
Cor	----	0.37	----	0.63	----	0.15
Magn	----	1.65	2.40	1.49	1.20	1.81
Fs	----	1.96	1.04	2.74	3.44	----
En	1.12	1.10	1.12	2.22	1.60	0.40
Qtz	22.76	17.89	16.52	17.87	14.55	21.95
Wo	0.08	----	0.26	----	0.28	----
Sph	0.45	----	----	----	----	----

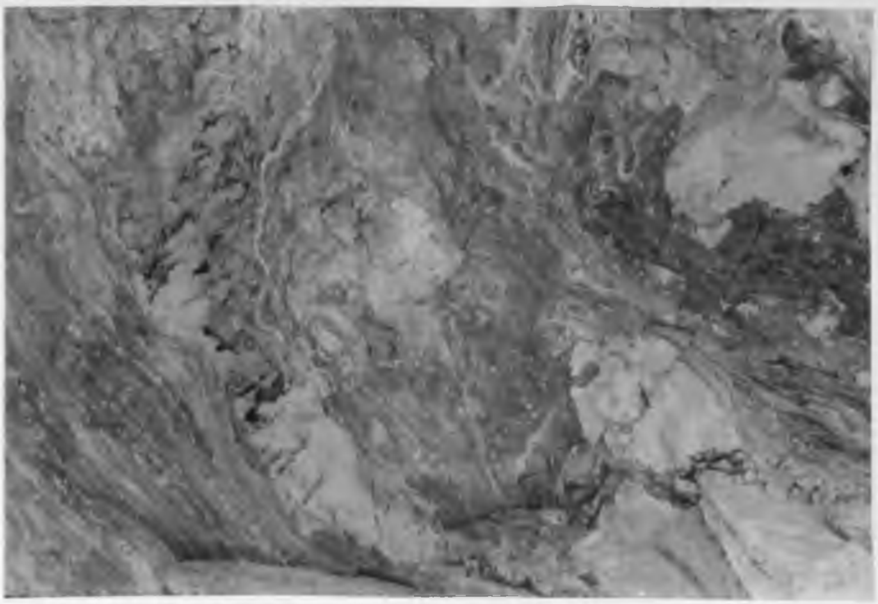

Figure 9: Flow structure within the Banded Flow.

This contorted flow banding occurs within an overhang of the cliff developed on the southern side of the eastern lobe of the Banded Flow (near W_b17 of figure 15).

Figure 10: Obsidian flow banding within the Banded Flow.

The southern edge of the eastern lobe of the Banded Flow is seen from the southeast.

A typical sample from the western lobe contains obsidian flow bands 5-15 mm wide separated by frothy purplish material (5 RP 4/2-7/2) in lenses 15-20 mm wide. A few feldspar phenocrysts 2-5 mm in length are present and are aligned approximately parallel to the bands.

Red Flow

Flowing over the sides of the distal end of the western lobe of the Banded Flow are curtains of the Red Flow (W_r16). It is so named because of its red (8 R 4/2) color. Similar material is present to the north and northeast of here. The red material within the western side of the area (see figures 1 and 15) consists of, from south to north, 1) material which forms curtains over the Banded Flow, 2) a "narrow ridge" beginning about 0.6 km northwest of the curtains and trending toward the northwest, and 3) a lobate ridge at the western edge of Deadman Mesa northwest of the "narrow ridge." The red material within the eastern side of the area consists of, from south to north, 1) the "wide ridge" extending northward from the Amphitheater (see figure 15), 2) a "narrow ridge" which at its southern end connects with the "wide ridge" and 3) a lobate ridge trending northeast from the northern end of the "narrow ridge." The latter shows a series of pressure ridges convex toward the northeast along which hornitos have been developed. The volume of Red Flow material present south of the Strawberry Crater road is approximately 0.2 cubic km.

The lithology of this red material varies slightly with locality. The material of the "narrow ridges" and the lobes contains contorted obsidian flow bands and large gas cavities suggesting that the material rolled over itself as it moved downhill. Feldspar phenocrysts are small (4-5 mm) and rare. No inclusions of other rock types were seen. The "wide ridge" on the east consists of a frothy purplish-red material in which flow banding is represented by vesicular bands and by color variations. Obsidian bands are absent. This lithology continues westward from the "wide ridge" making up a steep cliff, the Amphitheater Wall (see figure 15), which is just east of the Red Flow "curtains" on the Banded Flow's western lobe. The Amphitheater Wall is made up of a series of knobs, probably representing vents, showing flow structure some of which dips toward the south but most of which dips northward. To the south of the Amphitheater Wall (on either side of the line separating sections 2 and 3) is a depression which marks the "focal point" where the Banded Flow lobes join each other. The eastern and western rims of this depression have been built up of frothy material similar to that of the "wide ridge" and the Amphitheater Wall.

On the eastern side of the western ridge and on the western side of the eastern ridge are outcrops of obsidian-banded material and glassy, gray material. One such outcrop occurring where the "wide ridge" bulges to the west (SE ¼ of the NE ¼ of section 34) weathers in a slaty manner.

Scattered outcrops of both the flow-banded and glassy, gray types are present along the periphery of the distal end of the eastern "lobe."

Amphitheater Flow

The Amphitheater Flow (see figure 1) consists of three lithologies, each one lying in a roughly north-south linear zone within the Amphitheater (see figure 15). These three will be referred to as, from west to east, the W9, W12, and flow-banded units.

The most westerly lithology within the W9 unit contains contorted obsidian flow bands. This layer appears, projecting eastward, to dip beneath the next outcrop which contains similar continuous obsidian flow bands 3-8 mm thick. This material grades into a vesicular layer lying about 15 feet to the east which, in turn, grades into a reddish frothy layer. Unit W9 is expressed as a prominent rib forming the western wall of the Amphitheater. Its eastern slope is covered.

Below the W9 outcrops are scattered outcrops of the W12 unit which occur on the floor of the Amphitheater. This unit contains quartz and feldspar phenocrysts 2-13 mm in length in a gray (N3), aphanitic matrix. One boulder shows 3-5% phenocrysts, all of which are anhedral. Flow banding is represented by alternation of red and purple layers and a rough parallelism of the phenocrysts. Since outcrops of this unit are randomly oriented blocks, no readings of the flow banding were taken. Outcrops are not continuous so no information on the contact between this unit and the flow-banded unit was obtained.

The banded unit crops out on the eastern wall of the Amphitheater. Here a few feldspar phenocrysts 2-3 mm in length are present within a gray, aphanitic matrix which weathers into platy fragments. Obsidian flow banding (3-8 mm wide) within a purplish matrix is also present. An isolated outcrop farther north resembles the W9 unit. Here quartz and feldspar phenocrysts (2-10 mm in length) are present within a gray (N4), aphanitic matrix.

Mesa Flow

To the north of the Strawberry Crater road, Deadman Mesa continues for about 5 km and has a volume of about 0.5 cubic km. The mesa is outlined on the west by Red Flow material. Mesa material continues to the east out of the mapped area. The northern end of the mesa is made up of obsidian flow-banded material the bands of which are 1-4 mm wide and are continuous and straight but somewhat lenticular. The bands are separated by bands 2-10 mm wide of compact, blue to purple (N5-5 PB 3/2) material. A very few feldspar phenocrysts (1-2 mm in length) are present and are aligned parallel to the flow banding.

Just north of the Strawberry Crater road, material (DM 1 of Table II) similar to but not identical with that of the Amphitheater Flow material is present. The outcrops here are blocks of material rising only a few feet above the top of the mesa. These blocks may be representative of the material of the mesa or may be rafted blocks. The size and percentage of feldspar phenocrysts varies between outcrops; otherwise, outcrops north of the road are quite similar to one another. Quartz phenocrysts range from 2-6 mm in diameter and feldspar phenocrysts from 2-6 mm in length. This matrix of this material (DM1 of Table II) although a rhyodacite (see Table III) resembles that of the X2 basalt.

Frothy Flow

Between the eastern ridge of the Red Flow and the eastern lobe of the Banded Flow is a rhyodacite flow (W_f19) covering an area of about 4 square km and with a volume of about 0.7 cubic km (see Table II, figure 1). Due to its cover of pumiceous blocks it has been called the Frothy Flow. The top surface of the flow consists of randomly-oriented, pumiceous gray (N5) to tan blocks and minor obsidian float. The air photos show obvious flow structure consisting of ridges convex toward the northeast. These ridges are covered with blocks and grass while the areas between are covered with late black cinder and thus constitute the material mapped in figure 1. The chaotic arrangement of the blocks made only general flow directions discernible. The blocky nature of the surface is probably a primary feature caused by brecciation of the top of the flow. The fact that these blocks remain suggests that this unit is young.

Traversing the flow from north to south, obsidian float increases, outcrops of alternating red and gray layers are more common, and the flow layers are more obvious (figure 11). This suggests that the frothy cover was either thinner toward the south or that erosion has been more active here.

At the southern edge of the flow a cross-section is exposed in a cliff. Here the top unit is a gray to tan, laminar rhyodacite which is commonly complexly folded. Beneath this unit is a spherulitic obsidian unit containing pink (5 R 4/4) spherulites (to 30 mm in diameter) and lenses.

Within outcrops near the end of this cliff the obsidian occurs as rounded fragments (1.2-5.0 cm in diameter) within the laminar unit (figure 12). The laminar unit, however, shows no brecciation. Farther toward the east along the face of the cliff brecciation is not as intense and the obsidian forms lenses which are intercalcated with the laminar material. This suggests that the brecciation occurred within one flow rather than being a surface accumulation of blocks which was incorporated into a later flow as it moved over the surface. The author suggests that autobrecciation may have occurred where more viscous obsidian could not flow as readily as the plastic laminar unit and thus brecciated while it flowed down the steep slope of the Red Flow ridge. Such an accumulation of material at the base of the slope would then fill the

Figure 11: Flow layers within the Frothy Flow.

Folded flow layers occur near the surface of the Frothy Flow at its southern end.

Figure 12: Brecciation within the Frothy Flow.

Fragments of the basal spherulitic obsidian of the Frothy Flow are incorporated into the upper laminar unit. This is located within the cliff at the southern end of the flow.

depression lessening the gradient. Later material could then flow downhill more smoothly without brecciation.

DM2 Outcrops

On Deadman Mesa northeast of the Frothy Flow (W_f19) and just northeast of the Strawberry Crater road, a rhyodacite crops out (DM2 of Table II). This flow dips toward the northeast. It is doubtful if this represents the lower part of the Frothy Flow since it is distinctive lithologically and chemically. It was not mapped. This flow is discussed under VOLCANIC HISTORY where it is suggested that it may be part of the mesa-forming flow.

Basalts

Eastern Slope of O'Leary Peak

On the eastern slope of the Eastern Flat (see figure 15) and of the Banded Flow are outcrops of basalt and olivine basalt which appear to be related to the complex. The northern of the two outcrops is located in the NE $\frac{1}{4}$ of section 2. Here only the basalt X2 (see Table IV) is present. Although the outcrop consists of variously oriented blocks, its area outlines a flow which appears to have partially filled the crater of a cinder cone. The cinder cone is essentially undissected; an accumulation of bombs is present on the cinder cone's southern side. Since an unconsolidated unit such as a cinder cone would probably erode rapidly, the flow which filled its crater must be quite young.

Table IV: Chemical analyses of O'Leary Peak basalts

Samples listed are located in figure 15. Numbers given are in weight percent. Analyses were supplied by U.S. Geol. Survey, Astrogeology Center, Flagstaff, Arizona.

	X2	X13	X4
SiO_2	51.10	48.50	47.50
Al_2O_3	17.70	16.80	14.20
Fe_2O_3	3.70	5.30	2.10
FeO	7.38	5.58	8.51
MgO	4.30	6.70	11.30
CaO	7.20	10.80	10.70
Na_2O	4.10	3.30	3.00
K_2O	1.20	0.90	0.70
TiO_2	1.94	1.31	1.49
P_2O_5	0.90	0.74	0.48
MnO	0.20	0.20	0.19
$+H_2O$	0.10	0.13	0.12
$-H_2O$	0.30	0.15	0.15
CO_2	< 0.05	< 0.05	< 0.05
Total	100.17	100.46	100.49

The southern outcrop within the SE ¼ of section 2 and the SW ¼ of section 1 contains both basalt (X2) and olivine basalt (X4). Most of the outcrop is covered by recent cinder but it appears that the olivine basalt (X4) crops out at a lower elevation than the basalt (X2). The outcrop consists of randomly-oriented blocks; thus, no information on the overall orientation of the flows could be determined.

Wolfe (personal communication 1970) considers these outcrops to be "...east-dipping hogbacks of older (first period of Robinson) basalts resting on the top of a Paleozoic sequence disrupted by extrusion of the dome [O'Leary Peak Dome]." The age relationship with the cinder cone suggests to the author that the basalts are younger than the O'Leary Peak rhyodacite.

Southern Slope of O'Leary Peak

Several red cinder deposits are present on the southern slope of O'Leary Peak (figure 13) as well as on the Southwestern Lobe (see figure 1). Red cinder float, but no outcrop, is found in the depression at the top of Darton Dome, on the southwestern side of the Eastern Flat and in the saddle separating the northern and southern knobs of the western summit of O'Leary Peak.

On the Southwestern Lobe a linear vent about 150 feet long is exposed. Crude bedding dips into the hillside (to the north) at about 21°. Cinder particles up to 2 cm

Figure 13: Stratified red cinder.

The cinder contains O'Leary Porphyry and X12 Obsidian blocks. The outcrop is located on the southern side of O'Leary Peak where the road crosses the 8250 foot contour.

in length constitute the red (10 R 4/6) matrix although in some localities the matrix is massive. Blocks of "purple" and of "gray" porphyry and of obsidian (maximum diameter of 140 cm) are included in the matrix. Resorption of the "purple" porphyry is extensive.

Along the O'Leary Peak road there are several small vents. The cinder closely resembles that of the linear vent on the Southwestern Lobe. Porphyry blocks up to 40 cm (average 23 cm) are common within the matrix. In one cinder deposit, blocks of sandstone and obsidian are also common. The matrix of the red cinder, in certain areas, contains abundant quartz xenocrysts apparently derived from disintegration and/or resorption of the porphyry fragments. No chemical analyses of the red cinder were made due to this apparent contamination; however, an analysis of purple-black spatter (X13 of Table IV) located near two of the red cinder deposits is basaltic. Shoemaker and Gaffney (personal communications, 1970) believe this red cinder to be silicic based upon one thin section. Thin section evidence (see PETROGRAPHY) and field evidence of resorption of the porphyry inclusions suggest to the author, however, that the cinder is basaltic. Both red cinder and the purple-black spatter are only slightly eroded and appear to be among the most recent materials in the complex.

The stratigraphic order of the recent basaltic material is difficult to determine, but the red cinder is apparently covered by stratified black cinder indigenous to O'Leary Peak. This cinder dips toward the south and grades laterally and vertically into a purple cinder related to the overlying spatter X13. On top of the black cinder a soil horizon is developed. Above the soil horizon there is a blanket of air-transported black cinder which is probably from one of the cones near Sunset Crater. This cinder is the youngest unit within the mapped area.

Xenoliths

O'Leary Peak Tower

Beneath the O'Leary Peak tower there are several nearly horizontal blocks of non-calcareous, buff (10 YR 8/2) sandstone which are poorly exposed due to construction beneath the tower. Thin red (5 R 5/4-5 R 6/2) to purple silty laminae are present within the sandstone in some samples (figure 14). No cross-bedding was observed. Sandstones similar to this occur within the Kaibab Formation (Holm, personal communication 1970), the Supai Formation (Verbeek, personal communication 1970), and the Coconino Formation (Ulrich, personal communication 1970). The author believes that it is more likely that these blocks are of Coconino Sandstone.

These sandstone blocks may represent the "roof" of the O'Leary Peak Dome which was subsequently uplifted and isolated. They may also represent a xenolith which has been

Figure 14: Sandstone xenolith beneath the O'Leary Peak tower.

This xenolith's (Coconino Sandstone ?) red-purple lamination is well-developed.

incorporated and fragmented within the rising dome. The outcrops are not adequate to choose between the two possibilities.

Eastern Slope of O'Leary Peak

A large accumulation of xenoliths occurs beneath and on the talus slope of the eastern lobe of the Banded Flow (see figure 1). Here three blocks of Kaibab Limestone are present. The largest is beneath the flow and measures about 65 feet in length and 25-30 feet in height. The block appears to have been altered and its color varies between cream (5 YR 7/2) and salmon (5 R 6/4). This may represent staining by interbedded red shales which are present in the alpha zone of the Kaibab Formation (Holm, personal communication 1970).

The second largest block is on the talus slope. It measures about 20 by 25 by 40 feet and varies in color from 5 YR 4/4 to N8 and also appears to have been altered. On the western side of the block there is a contact with porphyry suggesting that beneath the talus the xenoliths are anchored in porphyry. The smallest of the blocks rests on the talus slope between the other two. It is about 15 feet in height and is coated with porphyry.

Xenoliths of Kaibab Limestone are present on the tops of the basalt outcrops of both the NE $\frac{1}{4}$ and the SE $\frac{1}{4}$ of section 2. The largest of the Kaibab blocks on the northern basalt outcrop is about two feet square. Most fragments are cobble sized. Kaibab fragments on the southern basalt are generally cobble sized but three blocks measuring 12 feet by 15 feet are present on top of the flow just west of the 7025 bench mark. These three blocks strike N48E and dip 84°SE.

The southern basalt outcrop (SE $\frac{1}{4}$) also contains crinoidal limestone, red sandstone, and red siltstone as float fragments of cobble size. The crinoidal limestone is considered to be Redwall Limestone (Ulrich, personal communication 1970). The red sandstone and siltstone are likely Supai or Moenkopi Formation.

Stratigraphic Relations

The two lobes of the Banded Flow (W_b17) originate from a dome-shaped accumulation of flow material (NE $\frac{1}{4}$ of section 3 and NW $\frac{1}{4}$ of section 2). The central depression within this accumulation is, unfortunately, covered with late air-fall black cinder. However, the location of this depression at the origin of the two lobes suggests that it is the source area of the lobe material. The cliff exposed on the southern side of the eastern lobe of the Banded Flow (see figure 1) shows obsidian flow banding which turns upward toward the source (toward the west). These flow bands strongly suggest flow from the source and over the northern slope of the O'Leary Dome. Gaffney (person communication 1970) suggests that the dome is younger than this flow and that the flow banding is upturned by emplacement of the dome. If this were the case, it would appear that fracturing should be present along this contact; however, none was observed by the author. Kaibab Limestone xenoliths lie on the talus slope of the southern cliff on the eastern lobe of the flow. As mentioned under Xenoliths, these are anchored in the O'Leary Porphyry beneath the talus. The xenolith highest on the slope is overlain by the Banded Flow obsidian which shows contortion as if the xenolith caused turbulence within the flow. This relationship indicates that the Banded Flow moved across O'Leary Porphyry and is thus younger.

The Red Flow (W_r16) contains two distinct lithologies. The typical red lithology ("1" of figure 1) with contorted obsidian flow banding, as mentioned, overlies the Banded Flow material of the western lobe. Here then the typical red Red Flow material is younger than the Banded Flow. This material is not continuous with the red lithology of the "narrow ridges" or "lobes". However, the similar lithology of these red lithology outcrops suggests that they were extruded nearly contemporaneously.

The pink frothy lithology ("2" of figure 1) occurs along the Amphitheater Wall, along the rims of the central depression of the Banded Flow, and in the "wide ridge" (see figure 1). Foliations measured on the southern end of the "wide ridge" (see figure 1) indicate a vent here. Similar foliation suggesting vents is less well-developed in the Amphitheater Wall and the eastern rim of the Banded Flow depression. Contortion of flow banding is common in these two areas. Hornitos built around the vents are characteristic of this subunit while they are not well-developed within the red lithology (except on the eastern "lobe"). The pink, frothy lithology overlies the eastern lobe of the Banded Flow. The "wide ridge" shows a bulge (NE $\frac{1}{4}$ of section 34) as if it were ponded by the "narrow ridge" (see figure 1). Microprobe work (see MICROPROBE WORK) suggests that the frothy lithology is younger than the red lithology.

Outcrops of the Amphitheater Flow occur within the Amphitheater and near the northern end of the "wide ridge" (see figure 1). This material may represent the top of a flow of which the Red Flow ridges are levees or it may be later. Thus, from the morphology it would appear that this unit is as young or younger than the Red Flow. Similar lithology (the Mesa Flow which may be essentially contemporaneous with the Amphitheater Flow) occurs just north of the Strawberry Crater road (as described). The relationship, however, is not clear since outcrop is not continuous.

The Frothy Flow (W_f19) appears on photos to "lap" up onto the Red Flow. The Frothy Flow shows autobrecciation near its southwestern end which, as described, suggests flow down the side of the Red Flow ridge. Thus, the Frothy Flow appears to be younger than the Red Flow. Youth of the Frothy Flow is also suggested by its original cover of pumiceous blocks and preservation of pressure ridges. Lithologically the Frothy Flow does not resemble the nearby Banded Flow.

Thus, the author believes that there is no evidence to suggest that the Banded Flow and Frothy Flow are one. The stratigraphic sequence built up would, on the contrary, suggest that they represent the oldest and youngest (respectively) rhyodacite flows in the complex. The relationship between the rhyodacites so far discussed and the DM2 outcrops is uncertain.

The basalts on the eastern slope of the O'Leary Complex are believed by the author to be younger than the rhyodacites as discussed. The red cinder vents on the southern side of O'Leary Peak contain O'Leary Porphyry blocks and are thus younger than the porphyry. Their age relationship with other units can not be directly determined as they have contacts only with the porphyry; however, they are relatively undissected and thus appear to be quite young.

RECONNAISSANCE OF THE ROBINSON CRATER AREA

Reconnaissance mapping and sampling was done within the area north of Robinson Crater and west of O'Leary Peak. Samples from which thin sections were made (see PETROGRAPHY) are located on figure 15. The major portion of the area north of Robinson Crater consists of a series of silicic porphyritic flows or coulees. These were assigned Roman numbers on the basis of superposition indicated on air photos. Coulee II has the closest relationship to O'Leary Peak since it appears to originate from the western end of the Southwestern Lobe.

The O'Leary Coulees

Coulee II

The Southwestern Lobe (see figure 15) appears to grade northward into a flow (Coulee II) which covers an area of about 5 square km west of O'Leary Peak and north of Robinson Crater. One lobe of this coulee may either extend into or have a source in Robinson Crater where porphyry is exposed in the wall.

Eastern Edge. The eastern edge of Coulee II extends northward from the Southwestern Lobe. The porphyry at the southern end contains feldspar phenocrysts (to one cm in length) and gray volcanic inclusions (to 5 cm in length) in a gray (N6) matrix.

Somewhat north of this outcrop the porphyry contains feldspar phenocrysts 0.2-1.8 cm (average 0.8 cm) in length and gray volcanic inclusions 1.2-18 cm (average 8 cm) in length in a gray (N6½) matrix. At the distal end of this edge the porphyry contains feldspar phenocrysts up to 1.2 cm in length and both red and gray volcanic inclusions (to 38 cm in length) in a purplish (5 PB 6/2-5 P 6/2) matrix.

Northern Edge. The eastern edge ends, but to the north of it are isolated knobs of porphyry rising to a height of about 200 feet above the elevation of the distal end of the eastern edge. Followed westward this front is lost beneath the later basalt cone (#47) but similar material reappears southeast of that cone and forms the western edge of the coulee.

The porphyry at the northern front of the coulee varies from outcrop to outcrop. Feldspar phenocrysts are 2-15 mm in length. Volcanic inclusions are usually gray (N2) and are 2.5-45 cm (average 8-13 cm) in length; they constitute up to 20% of the total rock. The matrix varies in color from gray (N6) to yellow-red (10 YR 6/2) to red (10 R 4/2). The porphyry appears to dip toward the south (inward toward the center of the coulee).

Some porphyry of the northern edge consists of feldspar phenocrysts 3-5 mm in length with red volcanic inclusions 0.8-2.5 cm in length in a gray, glassy matrix. One outcrop shows red material which has apparently incorporated the earlier porphyry. This may be a vent comparable to the red cinder vents on O'Leary Peak.

Western Edge. The western edge of Coulee II is a steep cliff 200-250 feet high. At its southern edge it is lost beneath the material of Robinson Crater. One location (#66) shows feldspar phenocrysts 2-24 mm (average 2 mm) in length and volcanic inclusions (predominantly gray) 2.5-30 cm (average 8 cm) in length. The morphology here suggests that another coulee may underlie Coulee II or that a toe may have broken out of the front of Coulee II.

Coulee I

On air photos a remnant of a coulee front appears northeast of cone #47; this is labeled as Coulee I (see figure 15). The morphology here suggests that either two coulees are present or that a toe broke out of the front of this coulee. Coulee II appears to overlie Coulee I.

Coulee III

The relationship of Coulee III with Coulee II (see figure 15) is not certain because its southern end is obscured beneath O'Leary Peak alluvium. Flow structure is obvious on the air photos.

Coulee IV

Coulee IV overlies Coulee III (see figure 15) and may have flowed toward the northeast from a source located beneath cone #47. The history of this unit may be more complex than that of a simple coulee. Samples IV_1, IV_2, and IV_3 show that it consists of porphyry similar to that of Coulee II. The feldspar phenocrysts are 2-18 mm (average 4-5 mm) in length. The volcanic inclusions are 1.8-23 cm (average 4 cm) in length and are generally gray although some are red. The matrix is red (5 R 4/2).

Lavender Flow

Flooding the depression in the center of Coulee II and thus surrounding the knobs at the coulee's northern front, is a pumiceous lavender flow (R_1 of figure 15). Bulldozer cuts within the area expose fragments of this unit but are not deep enough to expose the solid interior of the flow. The direction of flow is uncertain, but the lithology of this flow resembles some of the flow material which is in the core of the volcanics of Robinson Crater. In thin section this flow shows hematite-rich bands alternating with purple bands. This color banding and the alignment of microlites is an excellent flow structure which wraps around the phenocrysts. Both resorbed plagioclase and magnetite phenocrysts are present.

Robinson Crater Complex

Robinson Crater is a nearly circular depression within a volcanic accumulation (figure 16). The crater is interpreted to be a late stage explosive phenomenon which covered much of Coulee II with pyroclastics and built a rim of graded pyroclastics

Figure 16: Robinson Crater.

Robinson Crater (foreground) is viewed from the O'Leary Peak road (looking west toward the San Francisco Peaks).

on the northern side of the crater. The rim of pyroclastics was likely deposited where the dome had previously been breached during the extrusion of the Lavender Flow. The dome is composed of spherulitic obsidian and laminar flow material (R_{rc} of figure 15).

Spherulitic Obsidian

The spherulites of this obsidian (figure 17) are pink (5 R 6/2) and are 2-6 cm (average 4-4.5 cm) in diameter. Radial structure is poorly to well developed. The obsidian contains a few minute feldspar phenocrysts 1-5 mm in length. Obsidian bands are 1.2-4.5 cm thick and alternate with pink (5 R 6/2) layers (about 0.5 cm thick) which resemble the material of the spherulites. These layers are folded, and in places the material is isolated in a boudinage manner. Thus, it appears that the lenses are gradational into spherulites. The fold axes of these lenses trend N10W. Tension cracks striking N80E are developed on the crests of the folds. The obsidian is, in places, fractured and the fractures are filled with the pumiceous pink material. It appears that the pink material was injected into cracks within the already chilled obsidian. Simons (1962) describes a locality in Arizona where potassium-rich fluids moved along fractures producing devitrification.

In thin section this rock shows well-developed flow banding due to an alignment of microlites, biotite, and

Figure 17: Spherulitic obsidian from Robinson Crater. This outcrop is within the wall of Robinson Crater.

magnetite in a glass matrix. Plagioclase, olivine, and zircon are present. Crystallites are present within the glass.

Laminar Volcanics

Pumiceous gray (N5) to tan volcanic material crops out both within the crater wall and northwest of the crater. This material is layered (1-3 cm thick) and alternates in color on the weathered surface from red (5 R 2/4) to yellowish red (5 YR 7/1). Phenocrysts are not common and are less than 1 mm in length.

In thin section flow banding is produced by an alignment of microlites and biotite. Plagioclase makes up slightly less than one percent of the rock. Five phenocrysts of olivine with iddingsite were seen as well as a trace of magnetite and hematite and apatite. A pseudo-spherulitic structure is observed under crossed nichols.

Pyroclastics

The sand pit on the northern rim of Robinson Crater contains cinder-sized pyroclastic particles deposited in graded bedding. The pit on the western rim contains obsidian breccia.

PETROGRAPHY

O'Leary Porphyry

The rocks of O'Leary Peak, Darton Dome, the Eastern Flat, the Southwestern Lobe, and the O'Leary Coulees are rhyodacite porphyry some of which contains large sanidine phenocrysts mantled with oligoclase. Two types of porphyry have been distinguished--the "purple" and the "gray".

Purple Porphyry

The "purple" porphyry in thin section contains 3-9% quartz although quartz is obvious in hand samples in amounts greater than 10%. Sanidine varies from a trace to 8%, and plagioclase (An_{23}-An_{37}) from 15-33%. The matrix consists of a fine-grained mosaic of interlocking quartzo-feldspathic material including occasional small plagioclase crystals which stand out in relief. Oxyhornblende ranges from a trace to 11%, and is usually replaced by magnetite and/or hematite. Some oxyhornblendes have rims of iron oxides; others are totally replaced by dactylitic intergrowths of hematite and magnetite. Apatite and zircon are ubiquitous.

The "purple" porphyry of Darton Dome varies from other "purple" porphyry outcrops in that it contains up to 2% hypersthene and a trace of green hornblende. Olivine is sometimes present and is obviously xenocrystic as shown by its close proximity to or presence within the volcanic inclusions. Altered and replaced oxyhornblende resembles biotite without bird's eye texture and the two are difficult to distinguish in sections showing only one direction of cleavage. Thus, some grains identified as oxyhornblende may actually be biotite.

Robinson (1913) describes Darton Dome and the flows to the north as either rhyolite (his map) or biotite dacite (his discussion of petrography). He describes O'Leary Peak as pyroxene dacite (map) or hornblende dacite (discussion). These distinctions are not supported by the present petrographic study. Oxyhornblende is the major mafic of both Darton Dome and O'Leary Peak porphyries. Pyroxene (hypersthene) is present in Darton Dome but was not found at O'Leary Peak as suggested by Robinson.

Gray Porphyry

Where the porphyry has flowed, the matrix is gray due to its high glass content and is thus called "gray" porphyry. It makes up the eastern lobe of Darton Dome, the entire Southwestern Lobe, and parts of the wall of Robinson Crater and Coulee II.

No section were made of samples of the "gray" porphyry on the eastern lobe of Darton Dome. Two thin sections of the porphyry matrix from the Southwestern Lobe were examined. These contain 5-14% quartz, 15-27% oligoclase (approximately

An_{30}), 3-8% oxyhornblende, and 0-2% pigeonite. The remainder is glass. Mantled sanidine is present in one section. A trace of hypersthene (?) is present. Xenocrystic olivine (1%) occurs in both samples. Hematite is not present but magnetite is common. Apatite and zircon are present. The matrix is fine-grained in contrast to the mosaic-matrix characteristic of "purple" porphyry.

Seven samples of the porphyry were taken along the eastern edge of Coulee II (see figure 15). Quartz ranges from 1-5%. Sanidine is rarely present and no mantled texture was seen. Plagioclase (An_{23}-An_{54}) ranges from 9-19%. Oxyhornblende ranges from 2-6% and is rimmed with magnetite. Hematite is sometimes present, but magnetite is dominant. All sections contain a trace to 2% hypersthene and/or augite. Xenocrystic olivine is present. The remainder is vesicular glass which shows poorly to well developed flow structure. Vesicles are common and are lined with a silica mineral which is probably tridymite and/or cristobalite.

The porphyry of Darton Dome, the Southwestern Lobe, and Coulee II are slightly different petrographically from the porphyry on O'Leary Peak--especially in pyroxene content. However, this distinction is minor (2%). A chemical analysis of "gray" porphyry may show more distinct differences but the evidence presently available indicates that the differences are minor and result from flow in some areas with local concentrations of pyroxene.

Other Porphyry Units

Coulee II "toe". Three thin sections (II_{54}, II_{56}, and II_{66}) were examined of the porphyry matrix on the western "toe" of Coulee II. Quartz varies from 1-3%. Sanidine is present in trace amounts but no mantled texture was seen. Plagioclase (An_{30}-An_{58}) showing resorption makes up 12-16% of the rock. Oxyhornblende varies from 2-7%. Hypersthene and xenocrystic olivine are present in trace amounts. Both hematite and magnetite are present but magnetite is dominant. Apatite and zircon are present. The matrix which comprises the remainder of the rock is glassy and shows flow structure.

Coulee III. One sample was taken from Coulee III. This thin section (III_{34}) shows 2% quartz, 8% andesine (An_{48}) and 3% magnetite-rimmed oxyhornblende in a glass matrix. Magnetite is common; traces of hypersthene and xenocrystic olivine are present.

Coulee IV. Three samples (IV_1, IV_2, and IV_3) were taken from Coulee IV. They contain 2-3% quartz, 14-20% oligoclase (An_{28}) and 1-2% oxyhornblende in a glass matrix which shows flow structure. Magnetite is common; traces of hypersthene and augite (?) are present. Oligoclase is present as cumulates and as single crystals, both of which show resorption.

Robinson Crater Wall. Two sections (Rb2, and Rb3) of the porphyry within the wall of Robinson Crater show approximately 5% quartz, 15% oligoclase (An_{25}) and 4%

oxyhornblende in a glass matrix. Both hematite and magnettite are present. The matrix is reddened by hematite.

Porphyry Variations

The abundances of all the mineral components of the western and eastern sides of O'Leary Peak are similar. Hematite and magnetite are present in both areas. The porphyry within the Eastern Flat very closely resembles that of O'Leary Peak but it contains traces of green hornblende and biotite (?).

The Southwestern Lobe samples are richer in quartz than O'Leary Peak ones. Conversely, Darton Dome samples are lower in quartz. These differences are probably due to variations in random sampling. The coulees contain 2-3% quartz while the outcrops within the wall of Robinson Crater contain 5% quartz.

Hypersthene is present within the Southwestern Lobe, Darton Dome, Coulee II, Coulee III, and Coulee IV. Biotite (??) is present within the Darton Dome and Robinson Crater outcrops. Xenocrystic olivine, while common in the surrounding porphyry, is rare within the porphyry of O'Leary Peak and the Eastern Flat. Mantled sanidine is absent or rare within the "gray" porphyry of the Southwestern Lobe and the coulees. The plagioclase of the coulees is slightly more basic than that of O'Leary Peak.

Plagioclase within the Porphyry

Glomeroporphyritic to equidimensional cumulates of oligoclase and/or andesine are common throughout the porphyry. They range from 2.8-6.0 mm (average 4 mm) in diameter. Plagioclase also occurs in single crystals dispersed throughout the matrix. Some plagioclase crystals show poorly developed zoning with the twinning continuing across zone boundaries. Most of the plagioclase shows resorption by the matrix. Twinning is usually after the albite law, but complex twins are sometimes present.

Developed within some plagioclase crystals is a "sponge" texture which honeycombs either the core, the rim, or the entire crystal (figure 18). It sometimes appears to be related to zoning within the crystal. Included within the crystals, along cleavage planes and apparently replacing them, are glass or opaque "blebs." A discussion of theories of formation of this texture is presented under PETROLOGY.

Mantled Sanidine

The mantling of sanidine with continuous rims or aligned phenocrysts of oligoclase resembles the texture called "rapakivi." The term "rapakivi" has been applied to granites in which plagioclase (usually oligoclase) mantles microcline or orthoclase ovoids. The texture within the O'Leary Peak Porphyry varies from cited references of "rapakivi" in several important distinctions. The O'Leary

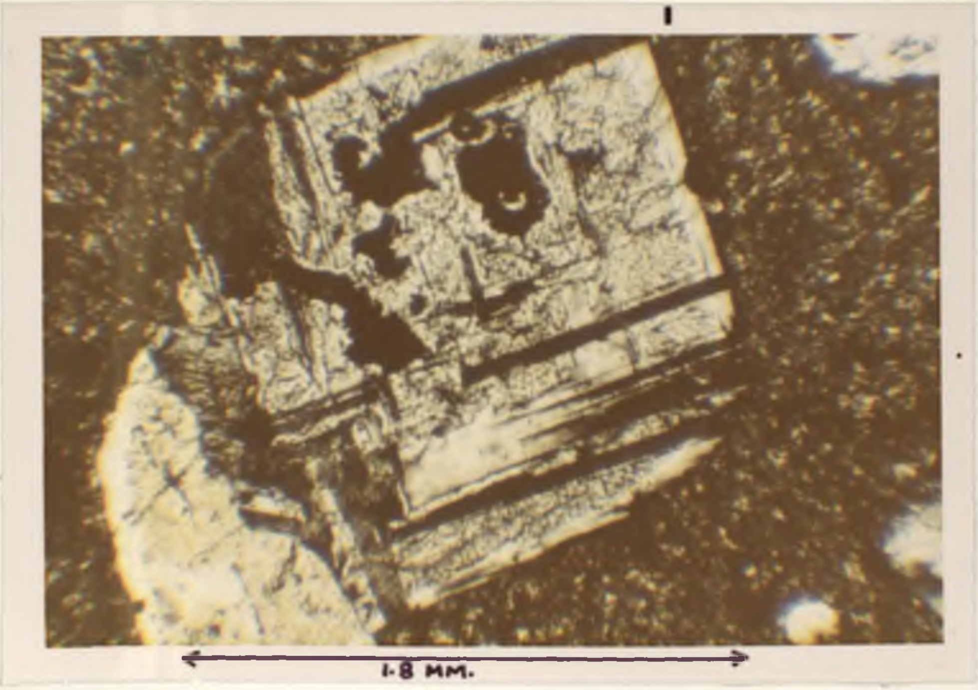

Figure 18: Photomicrograph of "sponge" texture.

This texture occurs within the O'Leary Porphyry and here appears to be related to zoning within the plagioclase phenocryst in thin section P19 (crossed nochols).

Porphyry is a rhyodacite rather than a granite and to use the term "rapakivi" for this volcanic texture would require modification of the term to refer to the plagioclase-potash feldspar relationship without regard to rock type. Although the rhyodacite plagioclase is oligoclase, the potash feldspar which it mantles is sanidine. The mantled texture is poorly developed. Usually, oligoclase rims are not present; instead, oligoclase phenocrysts are oriented with their long axes more or less parallel to the edge of the sanidine crystal forming a "string of beads" rim (figure 19). The alternation of sanidine or perthite and oligoclase usually occurs only once; however, it does occur up to three times within a single crystal with each successive cycle being less well developed than the previous one. Despite its departure from the classic "rapakivi", this texture probably results from a mechanism in common with "rapakivi."

The mantled crystals range in size from 3-10 mm (average 6 mm). They compose only a small percentage of the porphyry, but, where present, are especially obvious due to their glassy core and cloudy rim. The sanidine core is usually twinned and may be zoned. Zonation probably reflects a varying sodium content of the magma producing a slight variation in composition of the sanidine. The sanidine crystals can be irregular in shape but are often rectangular or have the original shape somewhat rounded; they do not show the "ovoid" outline characteristic of classic "rapakivi."

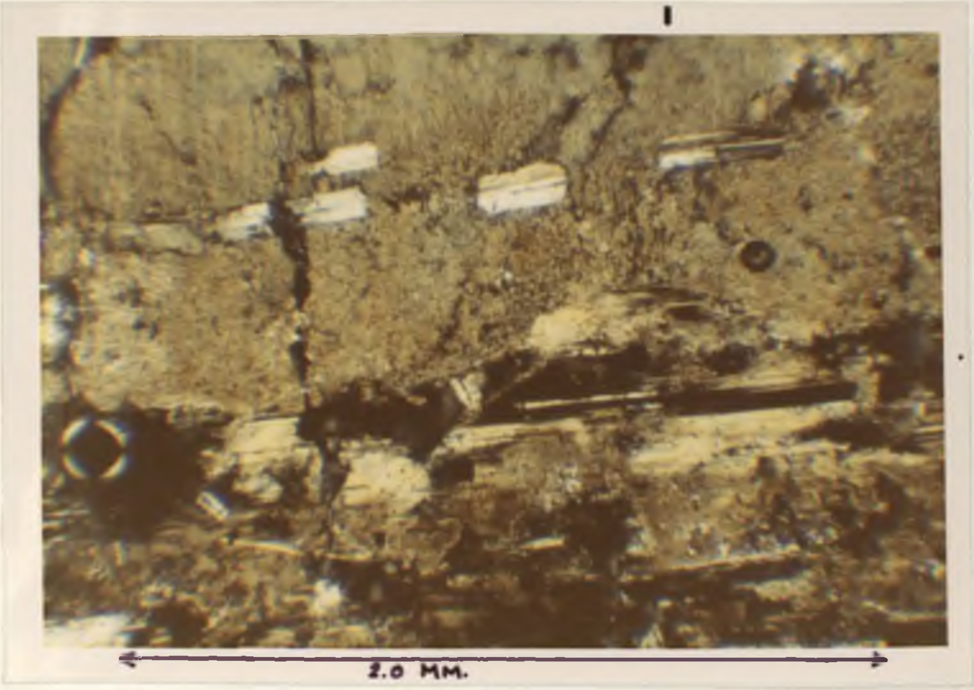

Figure 19: Photomicrograph of mantled sanidine.

A "string of beads" of oligoclase are oriented within the perthite rim on sanidine. A continuous rim is present farther outward from the center of the sanidine crystal (toward the bottom). Picture is taken from thin section P18 (crossed nichols).

One sample shows quartz "blebs" within the sanidine core forming a graphic intergrowth. Such quartz "blebs" are also present within the oligoclase rims. Perthite is present at various locations within the crystals although some crystals have no perthite at all. One crystal rim shows perthite in two directions (possibly related to cleavage) as shown in figure 20. Perthite on the edge of sanidine cores often appears to be due to replacement and resorption from without (figure 21).

The best developed mantled crystal shows the following zones from the sanidine core outward:

1. core of sanidine
2. perthite rim zone
   - a. perthite showing replacement of core
   - b. oriented oligoclase phenocrysts varying laterally with discontinuous rim of oligoclase
   - c. perthite without oligoclase
   - d. oriented oligoclase phenocrysts forming rim
3. continuous oligoclase rim
4. perthite zone which is gradational with (3) as perthite replacement is more dominant outward
   - a. perthite with oriented oligoclase at boundary with continuous rim (3)
   - b. perthite without oligoclase
   - c. oriented oligoclase rim
   - d. perthite without oligoclase

This series of zones is best developed on the ends of the crystals; some zones merge on the sides and some appear to have been partially removed. The general pattern exhibited in the mantled sanidine of the O'Leary Porphyry is that of sanidine core, oriented oligoclase and/or oligoclase rim, and perthite rim. This may be repeated several times.

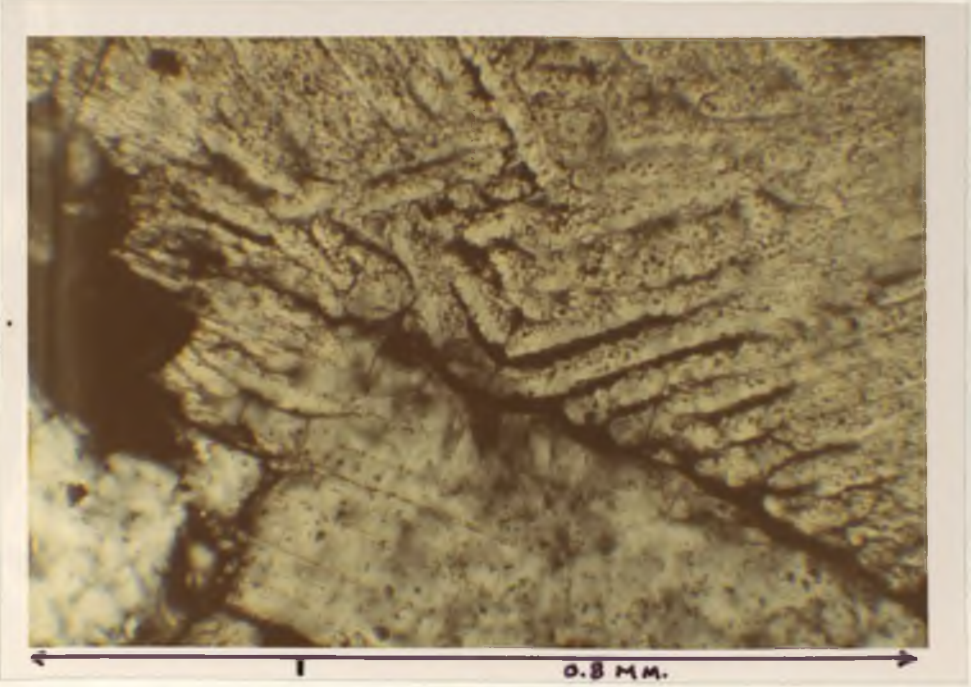

Figure 20: Photomicrograph of perthite.

The perthite is developed in two directions within the rim on the sanidine. The picture is from thin section P29 (crossed nichols).

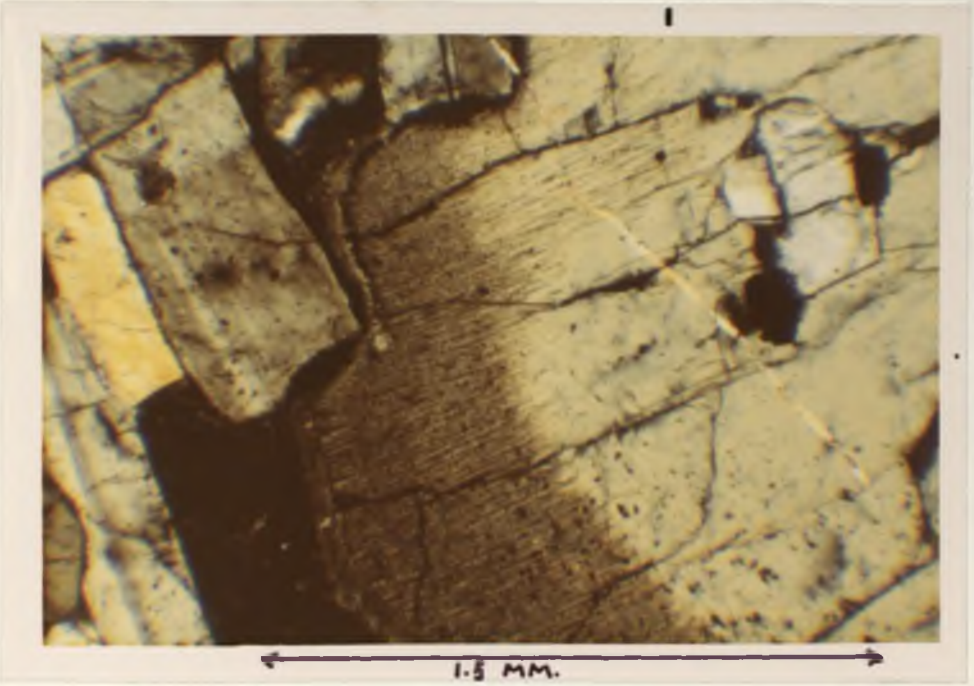

Figure 21: Photomicrograph of replacement perthite.

This perthite appears to be the result of replacement of the sanidine core by material from the matrix. The picture is taken from thin section P6 (crossed nichols).

Variations on this theme are common. For example, oriented oligoclase may occur within the sanidine core. The perthite often begins where the oriented oligoclase rim begins. Thus, oligoclase may be poikilitic with perthite. The perthite rim may be absent altogether. The oligoclase rim in one instance shows overprinting at the corner where two directions of twinning (one parallel to the end and one parallel to the side) intersect.

O'Leary Porphyry Inclusions

The basic volcanic inclusions within the O'Leary Porphyry vary in their size, the size of their constituent grains, and in their color; however, in thin section they are very similar. Red inclusions contain hematite replacing oxyhornblende while black inclusions contain magnetite replacing oxyhornblende.

The inclusions are composed of acicular needles of oxyhornblende alternating with andesine. The needles often form glomeroporphyritic groups with needles radiating in a sunbeam texture. The matrix shows an intergranular to intersertal texture.

Within the oxyhornblende-andesine mesh there are local clusters of coarse crystals. Any combination of the following four minerals may be found: olivine, oxyhornblende, magnetite, labradorite. The clusters average 2.0 mm in diameter; the olivine ranges from 0.5-1.25 mm, the oxyhornblende

0.5-1.0 mm, and the plagioclase 0.75-2.25 mm in length. Olivines often have magnetite rims.

Outside of the clusters the oxyhornblende ranges in content from 17-58%, olivine from 0-4%. Some olivine shows oxyhornblende rims which suggests a water-rich environment. Both andesine and labradorite are present--the latter is probably related to the coarse clusters but sometimes occurs some distance from them. Andesine ranges from 12-25%; labradorite from 5-52%. Hypersthene (?) is present in trace amounts in the inclusions of Darton Dome and Coulee II. Hematite is present with magnetite within the inclusions of O'Leary Peak, Coulee II, and Coulee IV. Magnetite alone is present in the Southwestern Lobe, Darton Dome, and the outcrops within Robinson Crater.

Quartz, plagioclase, and mantled sanidine phenocrysts occur commonly within the inclusions. Resorption of quartz forming an ocellar reaction rim of inwardly projecting augite is present in several sections. Resorbed oligoclase cumulates show "sponge" texture and zoning. In one section only a ghost of a plagioclase crystal is left. A schiller-like structure of opaque needles within plagioclase is sometimes present. These phenocrysts appear to have been incorporated from the porphyry matrix. They are common within the inclusions of Darton Dome, the Southwestern Lobe, the Eastern Flat, and O'Leary Peak.

Inclusions are sometimes very vesicular. Vesicles are about 4-8 mm in diameter and constitute up to 40% of the rock. Elongation of vesicles indicating flow structure is sometimes developed. Amygdules of devitrified glass, calcite, or zeolites (?) fill some of the vesicles.

X12 Obsidian

Obsidian float is found on the Eastern Flat; similar blocks are found beneath the tower on O'Leary Peak, within the red cinder deposits on O'Leary Peak (X12), and in the linear vent on the Southwestern Lobe. No outcrop of this obsidian was found.

The groundmass is shown in thin section to be glass with flow-oriented microlites of andesine. Larger labradorite phenocrysts with "sponge" texture constitute up to 14% of the rock. Less than 1% quartz is present and reaction with the matrix has produced ocellar rims of inwardly radiating augite crystals. Some quartz phenocrysts show no reaction. Since the quartz is usually reacted, this rock type is considered to be a distinct unit rather than being part of the "gray" porphyry where quartz is unreacted.

Up to 5% hornblende is present within this unit. Extinction of the hornblende is less than 10° suggesting that it is oxyhornblende; however, it does not have the red-brown color characteristic of the oxyhornblende of the O'Leary Porphyry. A trace of olivine is present. Basic volcanic inclusions occur within the obsidian. Olivine is probably the result of incorporation of these inclusions. Up to 3% of both magnetite and hematite are present. Some pyroxene, probably augite, is present in trace amounts. Apatite is ubiquitous.

The Rhyodacite Flows

Banded Flow

The Banded Flow (W_b17) consists of feldspar microlites in a glassy groundmass. Flow structure is extremely well developed and is represented by color bands and by alignment of microlites which form a trachytic texture around larger phenocrysts. In this matrix are set phenocrysts of oxyhornblende, pyroxene (?), magnetite, biotite (?), olivine, apatite, and plagioclase. Some of the plagioclase contains "sponge" texture.

Red Flow

Three samples were taken along the western red ridge in order to note any changes away from the source. Two samples (W_r5 and W_r6) were taken along the Amphitheater Wall. One ($W_{rm}17$) was taken from the marginal material at the northern end of the eastern red ridge (see figure 15).

Of the three samples on the western ridge, one crystal of quartz was observed in the sample closest to the source. Olivine is present in all three. Farthest from the source the olivine appeared resorbed. Hypersthene is present except in the sample nearest the source. Zircon is present farthest from the source. The matrix and flow characteristics of the three rocks are very similar. Plagioclase and magnetite phenocrysts occur within a matrix of magnetite, hematite, plagioclase microlites, and glass. The plagioclase shows "sponge" texture and appears to be rounded due to resorption. In the most northerly section hematite flakes are localized in bands which are related to olivine concentration. The olivine has hematite rims.

W_r5, from the eastern end of the Amphitheater Wall, and W_r6, from the western end, show magnetite and spongy plagioclase in a vesicular matrix of microlites and glass.

The marginal material ($W_{rm}17$) is glassy and, from field relations, appears, possibly, to be a chilled margin. In thin section it has spongy, resorbed plagioclase phenocrysts as well as magnetite, augite (?), and one quartz phenocryst in a matrix of magnetite, microlites, and glass.

No clear-cut distinction away from the source or between the two ridges can be determined in thin section.

Amphitheater Flow

Samples W9, W11, W12, and W13 (figure 15) are taken from the Amphitheater between the two red ridges. They may represent either the interior of a leveed flow (the red ridges being the levees) or a separate later flow. In hand sample this material varies in appearance and size of phenocrysts.

However, these are probably vertical variations within a flow with W9 being the topmost layer.

Magnetite and spongy oligoclase (sometimes in cumulates) are present in a matrix of microlites and glass. Hornblende (?) is present in the W9 layer. Hypersthene is present in all lower layers. Quartz phenocrysts are present in W12, and have been identified in W13 by oil immersion. Apatite and zircon are sporadic. Vesicles are lined with tridymite and/or cristobalite.

Mesa Flow

Outcrops of a gray aphanitic material are present on Deadman Mesa just north of the Strawberry Crater road (DM1 of Table II). Although this material resembles the outcrops within the Amphitheater, the two have not been correlated due to the lack of outcrops in the area between the samples.

DM3 contains quartz phenocrysts in hand sample. In thin section it contains a "spongy" plagioclase, oxyhornblende, hypersthene (?), olivine, and magnetite phenocrysts in a matrix of microlites, apatite, and glass. DM1 shows "spongy" plagioclase, hypersthene, and magnetite phenocrysts.

DM2 represents a rhyodacite outcrop located on the northern side of the Strawberry Crater road. In thin section magnetite, "spongy" plagioclase, and olivine (?) appear in a vesicular matrix of microlites, apatite, and glass. Flow structure is prominent.

Frothy Flow

The upper frothy, pumiceous layer of the Frothy Flow (W_f19 of Table II) in thin section shows oxyhornblende and/or biotite, magnetite, olivine, and plagioclase phenocrysts in a vesicular matrix of microlites and glass with flow banding.

The glassy lower part of the Frothy Flow (W_f20) in thin section shows small grains of magnetite, biotite, zircon, pyroxene (?), and olivine (??) in a matrix of aligned microlites and glass. Spherulites are abundant but were not studied in thin section.

Basalts

Eastern Side

Basalt X2 crops out on the eastern side of O'Leary Peak near the eastern lobe of the Banded Flow. In thin section 8% olivine, 9% labradorite, 5% magnetite, and 1% vesicles appear in a fine-grained matrix of glass, plagioclase, olivine, and magnetite. Olivine ($2V=75-85^\circ$) ranges in size from 0.1-1.25 mm; zoned plagioclase ranges from 0.3-0.6 mm. There is a slight flow structure due to alignment of microlites.

The olivine basalt (X4) of figure 15 in thin section contains 61% olivine ($2V=45-85^\circ$), 31% labradorite, 7% magnetite, and 1% vesicles. The plagioclase is wrapped around the olivine producing a trachytic texture.

Southern Side

The black-purple spatter (X13) of figure 15 contains 6% olivine (2V=70-75°), 35% microlites, 10% magnetite, and 9% vesicles set in a slightly pilotaxitic matrix of glass and granular iron oxides.

Sample V1 represents the red cinder vents of the southern side of O'Leary Peak (see figure 15). A trace of olivine and of labradorite with one grain of reacted (to augite) quartz are set in a very vesicular (to 40%) matrix of microlites and glass. Shoemaker and Gaffney (personal communications, 1970), as previously mentioned, believe that these red cinder deposits are silicic. Sample V1, however, shows reaction of quartz with the matrix. The evidence suggests that the quartz is xenocrystic and comes from disintegrated porphyry blocks.

Xenoliths

Kaibab Formation

Thin sections of the xenoliths beneath the Banded Flow and of the blocks associated with the basalt on the eastern side of O'Leary Peak show them to be sandy micrites. They contain from 15-30% quartz sand grains in a matrix of fine-grained calcite. Traces of plagioclase and muscovite are present. Maximum porosity is 25%. Calcite veins cut the matrix and cavities lined with silica minerals and collophane (??) are present. The nature of these xenoliths in thin section suggests that they are from the Kaibab Formation.

Other Calcareous Xenoliths

One xenolith (S5) is a marble made up entirely of interlocking calcite grains 1.25-1.75 mm in diameter. It has lost most of its original character, but in hand samples crinoids appear to be present. This rock may represent the crinoid-rich Redwall Formation.

Another xenolith (S6) has been metamorphosed to a diopside (?)-forsterite (?)-tremolite hornfels. Calcite is still present suggesting that not enough silica was present within the xenolith to react with the remaining calcite.

MICROPROBE WORK

Microprobe work on W_r5 taken from the pink frothy lithology of the Amphitheater Wall shows its plagioclase microlites to be deficient in calcium compared with those of W_r22 of the red lithology. 534 counts (on the average) per ten seconds were obtained from W_r22 while only 431 counts were obtained from similarly sized microlites (35-42 microns) from W_r5. Sodium was not analysed as it is easily vaporized from feldspars. However, such a decrease in calcium in W_r5 suggests that the Amphitheater Wall vents are, as suggested by field evidence, of a slightly different time of extrusion than the western "narrow ridge." An enrichment in soda often occurs with differentiation; thus, this data may suggest that the more calcium-rich W_r22 represents an earlier flow.

PETROLOGY

Discussion of Textures

Mantled Sanidine

In considering the mantled sanidine texture of the O'Leary Porphyry a consideration of "rapakivi" is believed to be informative. According to Volborth (1962, p. 816) Hjarne first used the term "rapakivi" in 1694. The term is Finnish for "crumbling stone" and was used to describe the granite which weathered rapidly. Wahl (1925) defined two characteristic types of "rapakivi": 1) wiborgite in which the potassium feldspar was present as ovoids within plagioclase rims and, 2) pyterlite in which ovoids were unrimmed.

The only two occurences of "rapakivi" volcanics which have been cited are 1) that cited by Raguin (1965, p.70) who states that Fennoscandanavian "rapakivi" granite massifs are associated with rhyolites containing "rapakivi" ovoids, and 2) that cited by Maucher (in Schermerhorn 1956, p. 103) who states that oriented plagioclase inclusions occur within certain sanidine phenocrysts of a Turkish syenite porphyry.

The classical "rapakivi" is a granite containing microcline, orthoclase, or perthite ovoids rimmed with oligoclase mantles. Some occurences outside of the classical ones contain plagioclase phenocrysts rather than mantles similar to the "string of beads" rims described from the O'Leary Porphyry. Emmons (1953, p. 68) states that occupying the mantle is "...merely a group of irregularly oriented crystals surrounding the potash feldspar core." Erickson (1969, p. 80) states that rims may be "...internal rings of closely spaced but generally unconnected plagioclase crystals." He also describes perthite but believes, in the case of the "rapakivi" granite of the Dos Cabezas, that this in association with microcline patches suggests inversion of orthoclase. Perthite in the O'Leary Porphyry appears to be due to replacement by the matrix.

The classical "rapakivi" has been explained by a theory of metasomatism. Backlund (1938) suggests that "rapakivi" granite may have been formed by metasomatism of sediments. Emmons (1953) suggests sodium metasomatism for certain "rapakivi" granites of Wisconsin.

Popoff suggested that potash feldspar "kernels" repeatedly moved into new environments within the magma producing new coatings of material (in Read 1957, p. 137). Vogt (1906) suggests that "rapakivi" is due to "...oscillation of the composition of the magma about the 'eutectic' (field boundary), first the oligoclase becoming supersaturated and then the potash feldspar." (in Terzaghi 1940, p. 120). Harker suggests that supersaturation of the magma alternated between orthoclase and oligoclase (in Read 1957, p. 137). Wahl (1925) states that potash feldspar reformed into drops of liquid due to release of pressure and crystallization produced the secondary generation of quartz and feldspar (Tuttle and Bowen 1958, p. 94). Holmqvist (1899) suggested that liquid immiscibility formed droplets which crystallized into feldspar (in Tuttle and Bowen 1958, p. 93). Sederholm (1928) "...postulates that a limited zone immediately surrounding the potash feldspar ovoids may have become supersaturated with the components of the plagioclase..." (in Terzaghi 1940, p. 120).

The two modern igneous theories of "rapakivi" formation are that of "basification" and that of high water pressure. The "basification" is due to an introduction into the system of sodium and calcium from xenoliths. Two theories concerning high water pressure are that of Tuttle and Bowen (1958) and that of Terzaghi (1935, 1940).

Several authors point out the relationship between "rapakivi" texture and the occurence of basic xenoliths. Backlund (1938) although suggesting metsomatism as a mechanism mentioned that basic inclusions are "strongly digested." Sylvester (1962) mentions the abundance of basic rocks within his area and suggested that the oligoclase mantles are "reaction mantles" produced in order to maintain equilibrium with the environment due to the introduction of the basic rocks. Thomas and Smith (1932, p. 291) suggested that "basification" of the liquid phase has been produced due to the introduction of basic xenoliths. With the production of biotite, potash is taken out of the system thus plagioclase is crystallized on the microcline nuclei.

This idea of "basification" was used by Erickson (1969) in the discussion of the Dos Cabezas "rapakivi" granite. He suggests that in a magma where plagioclase and potassium feldspar are crystallizing simultaneously, biotite and epidote are formed from hornblende thus reducing the potash content of the melt. Thus, there is a shift from the potash feldspar-plagioclase cotectic into the plagioclase field so that potash feldspar no longer crystallizes. As crystallization proceeds with decreasing temperature, the cotectic is again reached and potash feldspar again begins to crystallize with plagioclase. In such a model some hornblende remains (Erickson 1969, p. 97) and epidote is formed. Neither of these minerals was found within the O'Leary Porphyry.

The simultaneous crystallization of plagioclase and potassium feldspar necessary for this model may explain why "rapakivi" is not present in every porphyry which is silicic. Potassium feldspar crystals, naturally, must be present before enrichment of sodium and calcium occurs to produce mantling. However, Erickson admits that "rapakivi" may be more common than previously thought (Erickson 1969, p. 101). The author has come to a similar conclusion after finding many obscure references to "rapakivi" within the literature (see Selected Bibliography, with annotations).

To explain a "rapakivi" crystal of more than one cycle with Erickson's theory would require some additional mechanism since in the "normal" sequence only one cycle would be expected to occur. However, if basic xenoliths are introduced this might upset the equilibrium of a system such that fluctuations might occur until equilibrium is again reached. There appears to be some relationship within the O'Leary Porphyry between digestion of basic volcanic inclusions and occurence of mantled sanidine. Within O'Leary Peak the red inclusions show a high degree of resorption and disintegration; here also mantled sanidine is common. However, elsewhere (as Darton Dome and Coulee II) where the inclusions are dark, more common, larger, and show no signs of resorption, mantled sanidine is either not present or is so rare that it is not observed in thin section. Insufficient sampling was done to make a quantitative correlation between inclusion resorption and mantled sanidine.

Terzaghi (1940, p. 121) suggests that the solubility of orthoclase within the melt may change depending upon the water content of the system. She believes that with an increase in water the field boundary is shifted into the orthoclase field so that orthoclase no longer crystallizes.

Tuttle and Bowen (1958) present a detailed graphic explanation of the relationship of increased water pressure to crystallization within the $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O system. As an alkali feldspar (albite-orthoclase solid solution) crystallizes from the melt, the liquid moves toward the quartz-alkali feldspar field boundary. Upon reaching this boundary, at about 770°C., quartz begins to crystallize. As quartz and alkali feldspar are crystallized, under increasing water pressure, the melt moves toward the albite apex since the quartz-alkali feldspar field boundary moves toward the albite-orthoclase sideline. At about 660° C. (and 4 kilobars pressure) the top of the albite-orthoclase solvus is intersected (figure 22). At this intersection the two crystallizing feldspars are very similar in composition, but as the temperature decreases further, the solvus is followed producing two feldspars, one rich in albite and one rich in orthoclase. Then, "...the already present alkali feldspar will zone in such a way that the two feldspars will both be accommodated by the zoning...some of the alkali feldspar will zone toward oligoclase, and others toward orthoclase." This requires, of course, maintainance of 4 kilobars of water pressure in a magma chamber with an unfractured roof and non-porous walls.

In such a system there is the possibility of exsolution of the albite from the alkali feldspar. Indeed, if "rapakivi" rims have an anorthite component rather than an orthoclase one, then some sort of exsolution of the albite from the alkali feldspar must have occurred. The anorthite component is not considered by Tuttle and Bowen. To form oligoclase rims, the exsolved albite would then have had to

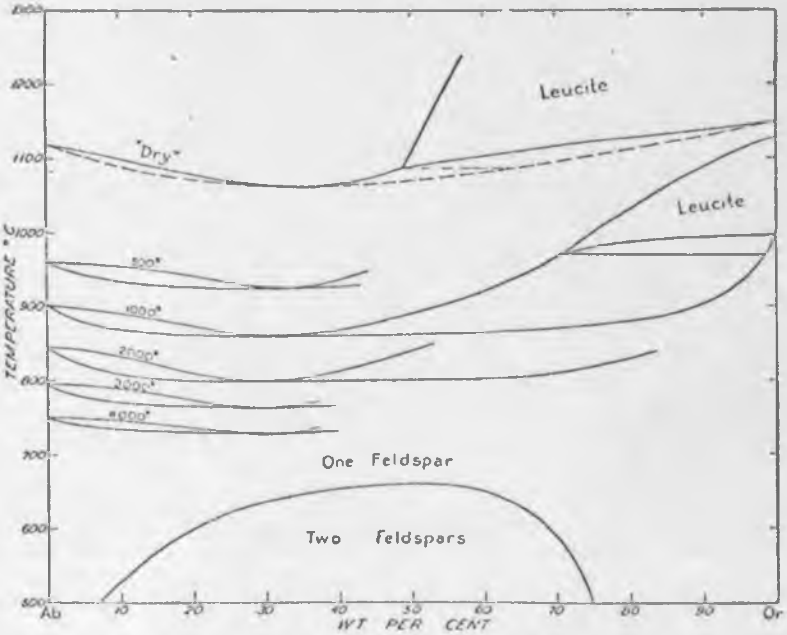

Figure 22: Isobaric equilibrium relations in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-H_2O.

Relations have been projected onto the Ab-Or face of the temperature-composition prism. Isobars are indicated in kg/cm^2. The solvus separating one and two feldspars is shown. The diagram is taken from Tuttle and Bowen (1958, p. 40).

migrate and accumulate. It may be that exsolution and migration do occur; indeed, this is the mechanism called upon by Buddington and Leonard (1962, p. 54) to explain "rapakivi."

The main difficulty with the Tuttle and Bowen theory is that 4 kilobars of water pressure must accumulate rather rapidly and then be maintained. If a magma is assumed to be present at a depth where such water pressure equals lithostatic pressure, then about 12-15 km of depth is required. This, then, must be maintained at some shallow depth where heat, but no volatiles, is lost from the system until the large "rapakivi" crystals are formed. Several cycles would require loss and rebuilding of water pressure. Fluctuations of the necessary magnitude seem unreasonable.

Probably several mechanism are responsible for the mantled sanidine texture of the O'Leary Porphyry. "Basification" due to the basic volcanic inclusions may have worked with fluctuating water pressure in producing the texture. These inclusions appear to have been present long enough within the magma to, in some cases, have been greatly resorbed. The mantled sanidine, oligoclase, and quartz phenocrysts within the inclusions suggest that the inclusions were within the magma a sufficient amount of time to become open enough to allow entire phenocrysts from the porphyry to migrate within them.

Sponge Texture

"Sponge" texture within plagioclase has been described under PETROGRAPHY. Similar textures have been described by Powers (1932, p. 263), Williams (1932b, p. 370), MacGregor (1938, p. 50), G. Baker (1949, p. 258), Kuno (1950, p. 967-8), Aoki (1959, p. 286-7), Chesterman (1963, p. 346), P. E. Baker (1968, p. 127), Smith and Carmichael (1968, p. 223), and Lowder (1970, p. 325).

Several types of "sponge" texture are present within the O'Leary Peak Volcanics. The plagioclase usually occurs as cumulates of variously oriented crystals. Both the crystal cumulates and single crystals show "sponge" texture along the edge of the crystal, within the center, or throughout the entire crystal. Those crystals consisting entirely of "sponge" texture are also embayed or rounded by the matrix suggesting that the texture here is possibly due to reaction with the matrix. Other crystals show a relationship between zoning within the crystal and localization of "sponge" texture (figure 18). More than one zone of "sponge" texture may be present.

Kuno (1950, p. 967-8) described xenocrystic plagioclase cumulates which are partially melted along cleavages due to suspension in a part of the magma of differing composition or due to detachment from cognate inclusions. An extreme degree of this results in a "honeycomb" structure (figure 23) which resembles some of the phenocrysts within the O'Leary Porphyry.

Where "sponge" texture is related to zoning, several explanations may be considered. Lowder (1970, p. 325) states that the glass inclusions within the feldspar of his area are anorthite-rich. He cites MacDonald and Katsura (1965) who suggest that this anorthite-rich material is due to incomplete resorption of earlier-formed phenocrysts which break down into a more calcic feldspar and glass. MacGregor (1938, p. 50) suggests that "sponginess" within phenocrysts of Montserrat rocks is due to corrosion causing the outlines to be rounded and the penetration of matrix into the interior along crystallographic directions of weakness (figure 24). Powers (1932, p. 263) suggests, on the other hand, that these "blebs" are magma which was trapped during the growth of the phenocrysts. The glass may also represent zones which, being richer in sodium, began to melt first.

Those spongy plagioclase within the O'Leary Porphyry which are related to zoning show rounded spongy zones which are ragged as would be expected if MacGregor's theory is correct. The glass inclusions may also be original inclusions of the melt as Powers suggests since microprobe work by Gaffney (personal communication 1970) has shown them to be potash-rich. This would suggest that the glass was the melt left after the sodium and calcium were removed in forming the plagioclase.

Figure 23: Honeycomb structure in plagioclase.

Inclusions are monoclinic pyroxene, glass, and iron ore. The drawing is taken from Kuno (1950, p. 968).

Figure 24: Corroded phenocryst of zoned plagioclase.

The "sponge" texture here occurs within a zone. The drawing is taken from MacGregor (1938, p. 50).

Oxyhornblende Occurrence

The most common mafic within the O'Leary Porphyry is oxyhornblende. This oxyhornblende is pleochroic from red to brown. Its extinction angle is less than 10° and generally is nearly parallel. The main difference, it appears, between hornblende and oxyhornblende is that the latter is poorer in volatiles--especially water. Experimentally, oxyhornblende has been produced by a loss of water due to heating of green hornblende to 750° (Kozu, Yoshiki, and Kani 1927). Kuno (1950, p. 981) states that this transition may occur in natural circumstances if magma is kept at an appropriate temperature under conditions where volatiles escape. Mathews (1957, p. 406) suggests that hornblende may transform to oxyhornblende under reduced confining pressure. Thus, the presence of oxyhornblende would suggest that the magma originally containing the oxyhornblende remained at a shallow depth for some time before emplacement.

The oxyhornblende, however, appears to be derived from the volcanic inclusions. These inclusions within the porphyry of O'Leary Peak show extensive resorption. In thin section oxyhornblende phenocrysts are obviously contributed to the matrix by the oxyhornblende-rich volcanic inclusions.

Petrochemistry

Major Elements

Nine chemical analyses of O'Leary Peak Volcanics were supplied by the U.S. Geological Survey (Tables II, IV, and V).

Table V: Chemical analyses of O'Leary Porphyry

	1[a]	2[b]	3[c]
SiO_2	71.2	66.98	62.34
Al_2O_3	14.4	16.47	16.40
Fe_2O_3	3.4	2.31	2.87
FeO	0.05	2.14	3.32
MgO	0.4	0.52	2.10
CaO	1.5	2.02	3.83
Na_2O	5.0	5.05	4.26
K_2O	3.8	3.32	3.25
TiO_2	0.27	0.35	0.96
P_2O_5	0.13	0.13	0.20
MnO	0.09	trace	----
$+H_2O$	0.07	0.59	0.62
$-H_2O$	0.07	0.12	0.08
CO_2	0.05	----	-----
Cl	----	trace	trace
Total	100.43	100.00	100.23

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a. Column 1 is from sample P31 of the O'Leary Porphyry taken by the author from a roadcut on the southern side of O'Leary Peak (see figure 15). The analysis was supplied by the U.S. Geol. Survey, Astrogeology Center, Flagstaff, Arizona.

b. Column 2 is "biotite dacite" from Darton Dome and the flows to the north (Robinson 1913).

c. Column 3 is "hornblende dacite" from O'Leary Peak (Robinson 1913).

The oxides versus the Larsen index have been plotted in figure 25. Plotting of percentage Al_2O_3 versus percentage $Na_2O + K_2O$ for the three basalts analyzed show them to fall well within the "alkali" basalt field (figure 26). The nine chemical analyses were plotted on an AFM (Na_2O+K_2O-FeO+Fe_2O_3-MgO) diagram along with typical calc-alkaline, alkaline, and tholeiitic trends (figure 27). The O'Leary Peak Volcanics plot near the alkaline curves. O'Leary norms of the rhyodacites are plotted on a Q-Ab-Or diagram (figure 28). Norms are listed in Table III.

The rhyodacite flows are progressively more basic than the porphyry of O'Leary Peak (P31) until the late Frothy Flow (W_f19) which is chemically similar to the porphyry. Robinson (1913) states that O'Leary material became more basic with time. Except for the Frothy Flow this appears to be true.

Robinson (1913) lists different chemical analyses for O'Leary Peak and Darton Dome (Table V). As discussed under GENERAL GEOLOGY and PETROLOGY, basic volcanic inclusions are greatly resorbed within the porphyry of O'Leary Peak but show little or no resorption within the porphyry of Darton Dome. This difference may suggest that Darton Dome was emplaced before O'Leary Peak, thus before the inclusions could be resorbed. However, Coulee II and the Southwestern Lobe have unresorbed inclusions as does Darton

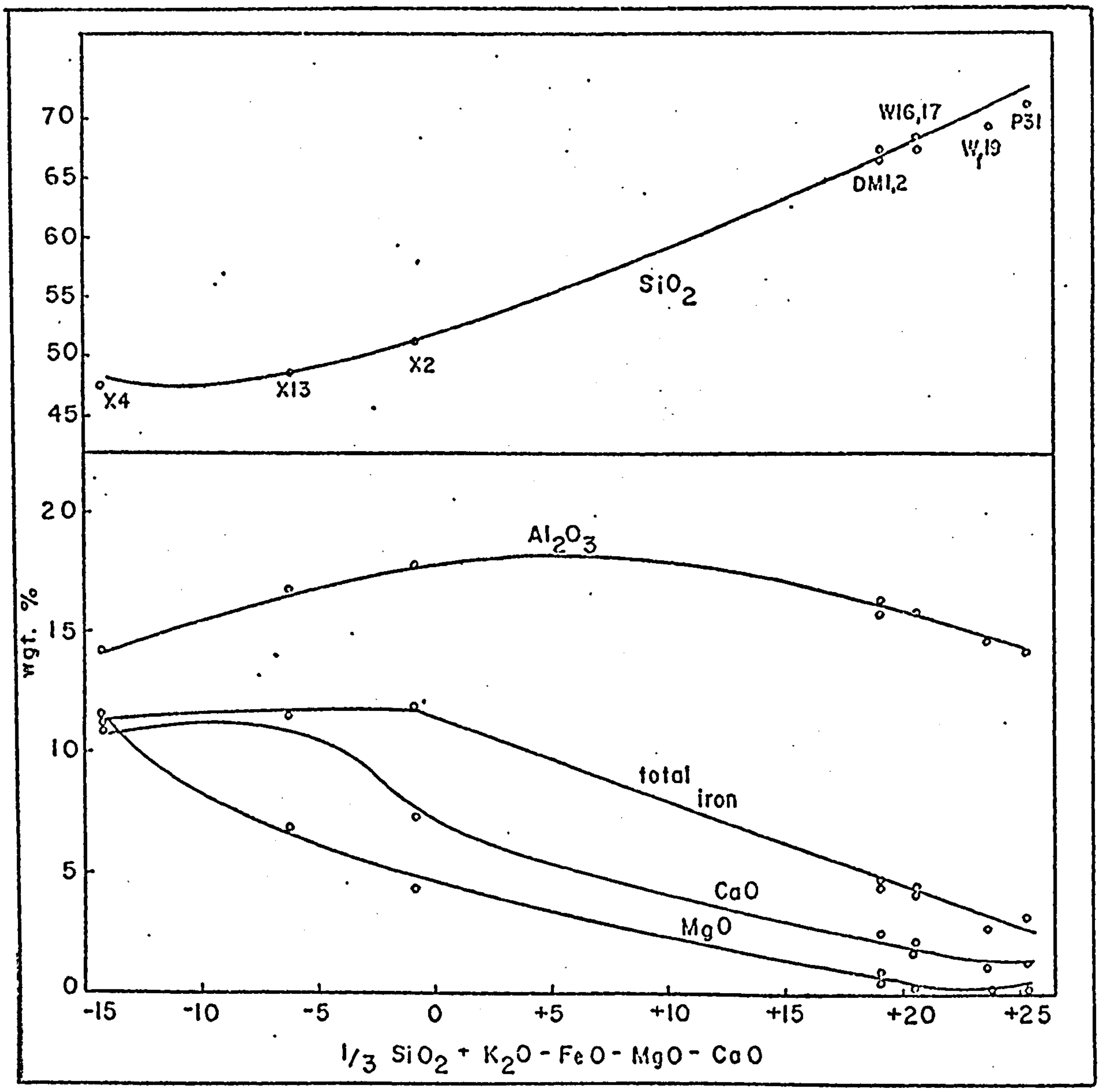

Figure 25: Oxide composition diagram for O'Leary Peak Volcanics.

Oxide values (from Tables II, IV) for O'Leary Peak Volcanics (in weight percent) are plotted against the Larsen Index (1/3 SiO_2 + K_2O - FeO - MgO - CaO).

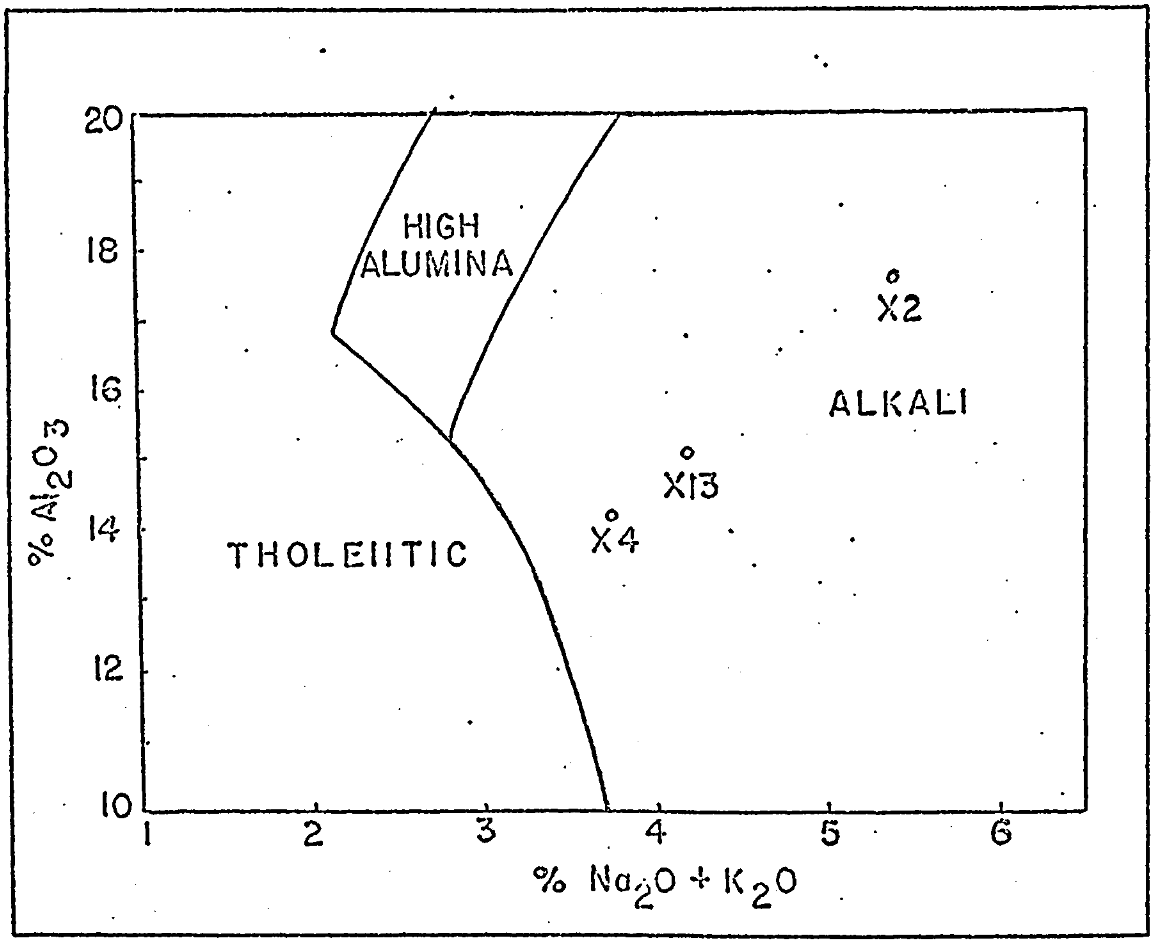

Figure 26: Classification of O'Leary Peak basalts.

O'Leary Peak basalts are plotted on an Al_2O_3 versus alkalis weight percent diagram. Oxide values are from Table IV. The classification is from Kuno (1960).

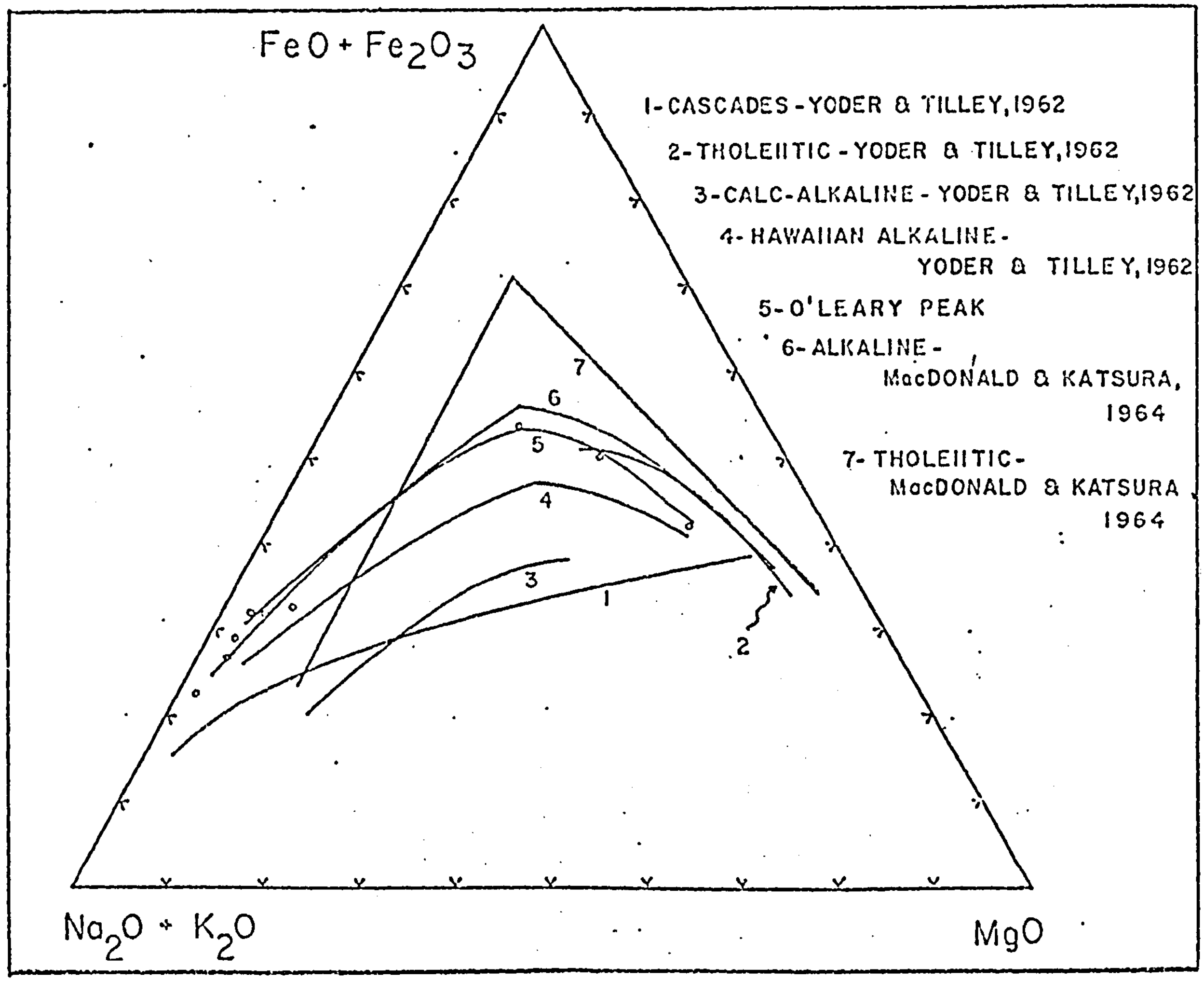

Figure 27: AFM diagram comparison of O'Leary Peak suite.

The O'Leary Peak Volcanics are compared with various rock suites by means of an A (alkalis=Na_2O + K_2O)-F (FeO + Fe_2O_3)-M (MgO) diagram. Oxide values for the O'Leary Peak suite are from Tables II and IV.

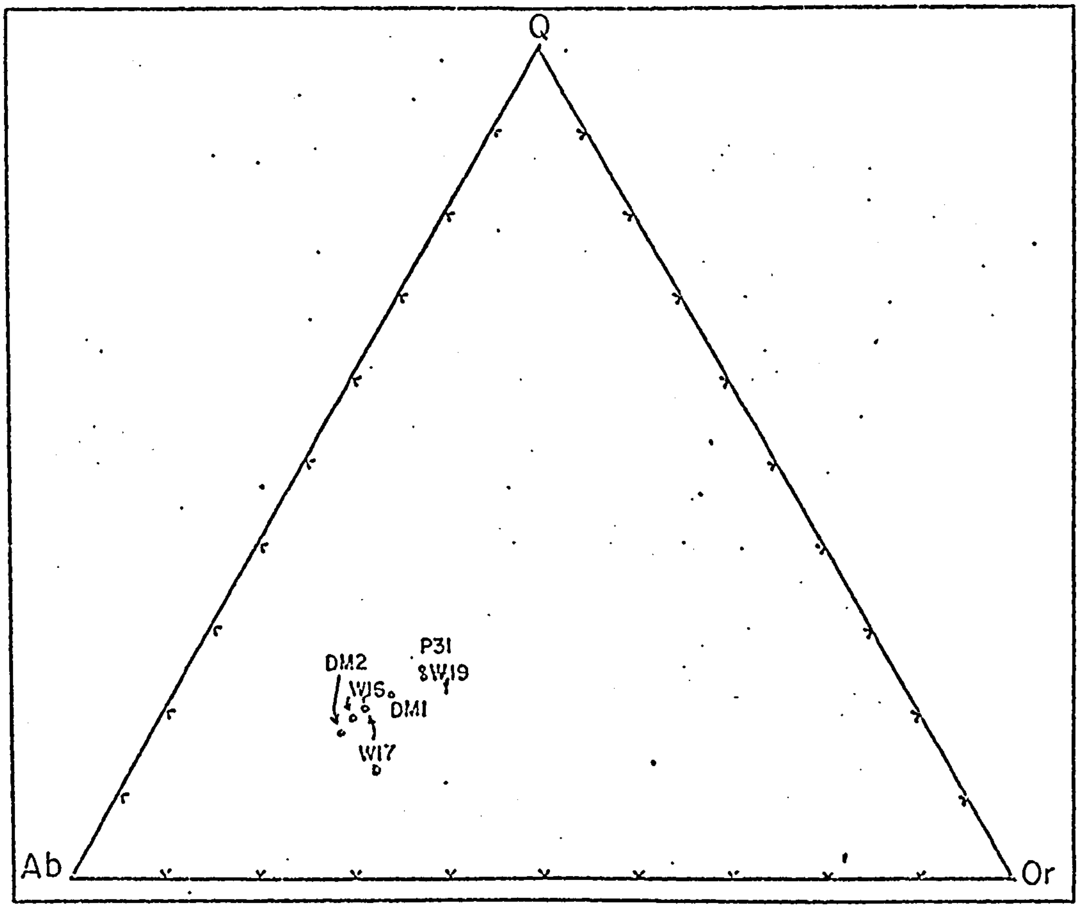

Figure 28: Rhyodacite norms plotted on a Q-Ab-Or diagram.

O'Leary Peak rhyodacite norms (Table III) are plotted on a Quartz-Albite-Orthoclase diagram.

Dome and these appear to be younger than O'Leary Peak. Thus, the difference may be due to a temperature difference, an elevation difference (related to inhomogeneities vertically within the chamber) or due to more than one magma chamber.

Such basic volcanic inclusions as described under PETROGRAPHY would be expected to be rich in CaO (labradorite), MgO and FeO (olivine), and poor in SiO_2 (ocellar reaction rims on quartz) and Na_2O (due to CaO-rich plagioclase). Thus, with resorption of these inclusions into the porphyry matrix, the chemical analysis of the porphyry of O'Leary Peak would be expected to show an increase in the components of the inclusions over the chemical analysis of Darton Dome. This is supported by Robinson's analyses which show the porphyry of O'Leary Peak to be richer in total iron, MgO, and CaO while being poorer in SiO_2 and Na_2O than Darton Dome. K_2O and Al_2O_3 remain approximately the same.

Only a few chemical analyses of silicics within the San Francisco Volcanic Field are available. Robinson (1913) stated that O'Leary Peak and Kendrick Peak are enriched in Al_2O_3, FeO, MgO, and CaO compared with the rest of the field while they are impoverished in SiO_2 and alkalis. Comparison between O'Leary Peak and San Francisco Mountain may be made with the aid of information from Deal (1969). Deal's curve for San Francisco Mountain is plotted in figure 29 for comparison with that of O'Leary Peak. Both San Francisco Mountain and O'Leary Peak show iron enrichment compared with the

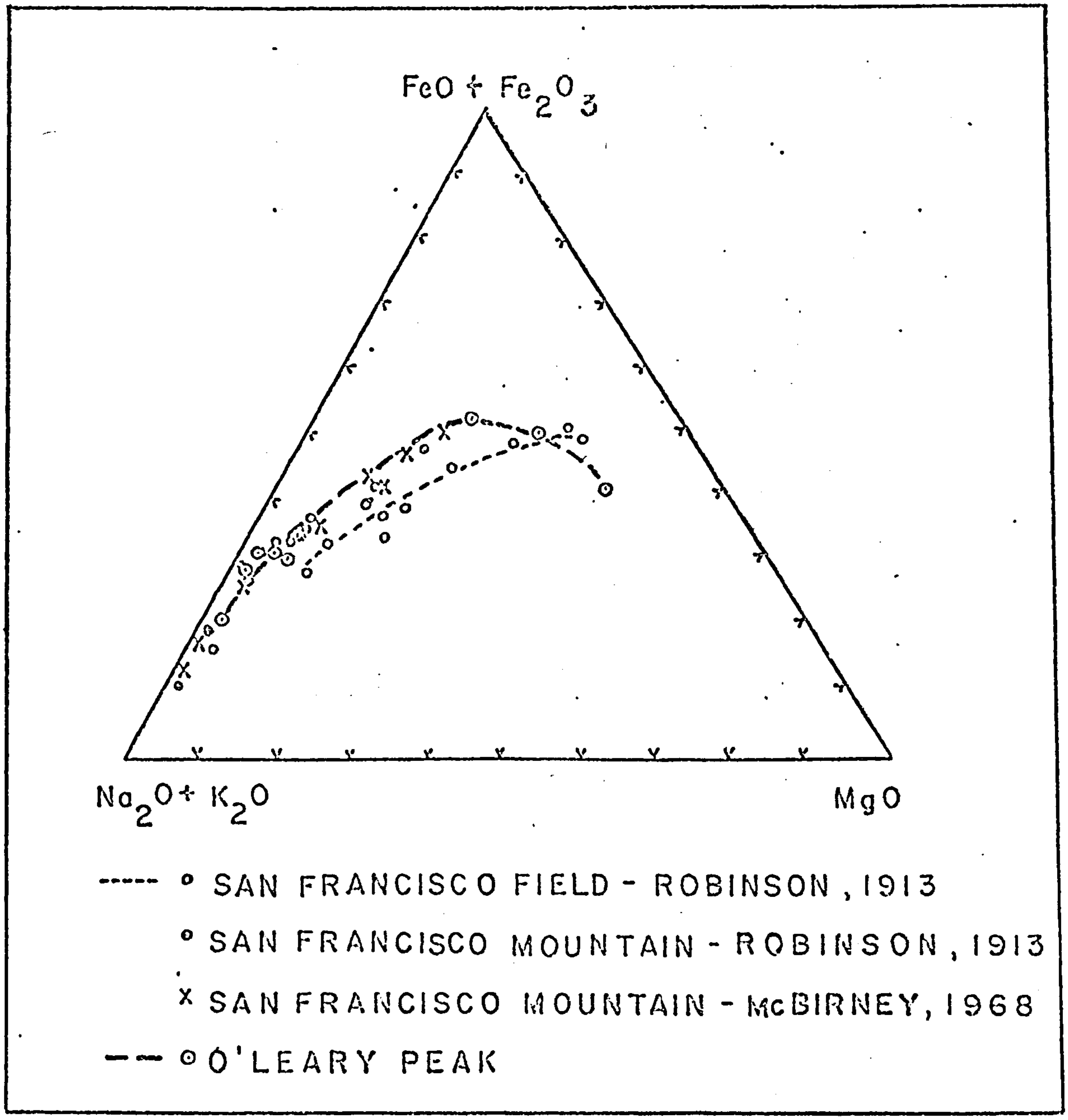

Figure 29: AFM diagram of O'Leary Peak Volcanics.

Analyses from the O'Leary Peak Volcanics, San Francisco Volcanic Field (Robinson 1913), and San Francisco Mountain (Deal 1969) are compared on an A (alkalis=$Na_2O + K_2O$)-F ($FeO + Fe_2O_3$)-M (MgO) diagram.

San Francisco Volcanic Field. Iron enrichment at O'Leary Peak doesn't appear to be greater than at San Francisco Mountain, however, as Robinson suggested.

Figure 30 shows Na_2O and K_2O curves for San Francisco Mountain and the San Francisco Volcanic Field compared with those of O'Leary Peak. Deal points out that San Francisco Mountain is enriched in Na_2O compared with the San Francisco Volcanic Field. O'Leary Peak has even more Na_2O than does San Francisco Mountain. K_2O of O'Leary Peak appears to be slightly less than at San Francisco Mountain. Thus, Robinson's statement that alkalis are less at O'Leary Peak than at San Francisco Mountain is not strictly true. Deal shows a figure illustrating the Na_2O/K_2O ratio of analyses of San Francisco Mountain. O'Leary analyses plotted on this diagram show this ratio to be even higher at O'Leary Peak than at San Francisco Mountain.

Trace Elements

Table VI shows the trace element analyses measured by the U.S. Geological Survey. Field relationships suggest to the author the following order of extrusion of the rhyodacites: P31, W_b17, W_r16, DM1 and DM2, W_f19. In the opinion of the author the three basalts (X2, X4, and X13) are essentially contemporaneous. Prinz (1967, p. 299) states that barium probably increases with fractionation of basaltic magma. Silicics within the San Francisco Volcanic Field

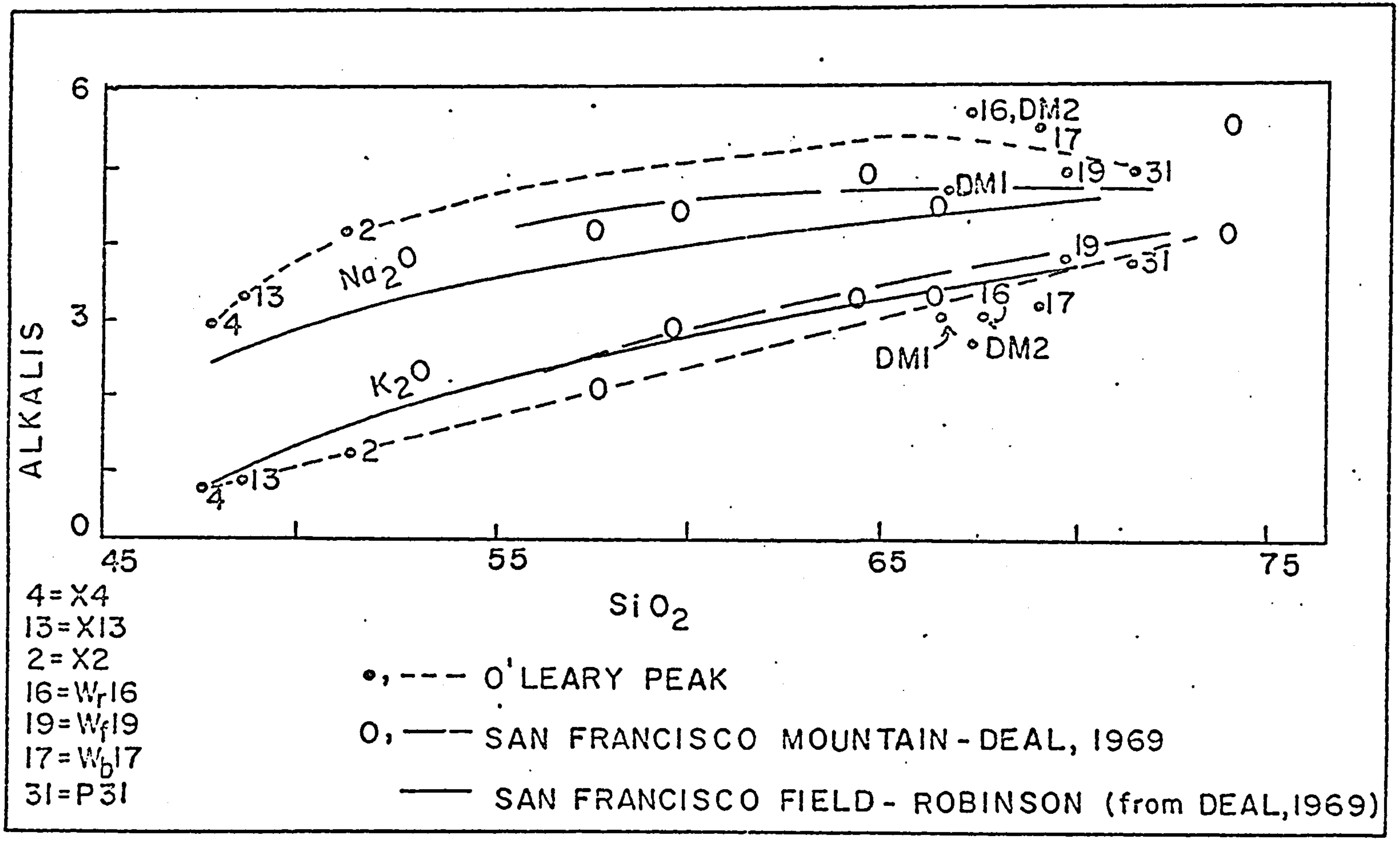

Figure 30: Na_2O and K_2O curves for the O'Leary Peak Volcanics.

Na_2O and K_2O curves for the O'Leary Peak Volcanics, San Francisco Volcanic Field (Robinson.1913), and San Francisco Mountain (Deal 1969) are compared. Oxide values for O'Leary Peak Volcanics are from Tables II and IV.

Table VI: Atomic absorption analysis of trace elements

Samples are taken from O'Leary Peak Volcanics (see figure 15). Units are parts per million. Analyses were supplied by the U.S. Geol. Survey, Astrogeology Center, Flagstaff, Arizona.

	W_b17[a]	W_r16[b]	DM1[c]	DM2[d]	W_f19[e]
SiO_2	68.80	67.50	66.40	67.30	69.70
Al_2O_3	15.90	15.90	15.90	16.30	14.70
Fe_2O_3	0.80	2.30	1.40	1.20	1.00
FeO	2.93	1.98	2.75	3.11	1.67
MgO	0.40	0.40	0.80	0.60	0.30
CaO	1.80	2.20	2.50	2.50	1.30
Na_2O	5.60	5.70	4.80	5.70	5.00
K_2O	3.10	3.00	3.10	2.80	3.90
TiO_2	0.25	0.32	0.42	0.41	0.13
P_2O_5	0.12	0.18	0.20	0.18	0.07
MnO	0.14	0.14	0.14	0.15	0.10
$+H_2O$	0.10	0.14	0.57	0.10	1.23
$-H_2O$	0.04	0.28	0.44	0.06	0.61
CO_2	<0.05	<0.05	<0.05	<0.05	<0.05
Total	100.03	100.09	99.47	100.46	99.76

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a. W_b17 is taken from the Banded Flow.

b. W_r16 is taken from the Red Flow.

c. DM1 is from outcrops on Deadman Mesa.

d. DM2 is from outcrops on Deadman Mesa.

e. W_f19 is taken from the Frothy Flow.

are considered by Damon (personal communication 1970) to be differentiated from mantle-derived material due to the low $^{87}Sr/^{86}Sr$ ratios (Damon 1969, p. 26). Thus it is reasonable to suppose that barium should increase with fractionation of the O'Leary Peak Volcanics being concentrated with potash feldspar due to its substitution for potassium. This trend does not appear to hold well for these rocks. Notably the barium content of X2 is as high as the rhyodacite DM2 and higher than W_r16 and P31. Prinz (1967, p. 311) and Wager and Mitchell (1951) state that strontium increases with differentiation. Of the basalts, on this criterion, X4 would be the earliest while X2 and X13 would be contemporaneous. Prinz (1967, p. 306) states that nickel is concentrated in early basalts. The olivine basalt X4 which is high in nickel would thus be the earliest and X2 the latest. Several trace elements, thus, suggest that the order of differentiation of basalts is X4, X13, and X2. This would suggest the contemporaneity of the basalts rather than X4 and X2 being Period One (of Robinson) basalts while X13 is post-O'Leary.

Conclusions Concerning Stratigraphy

Comparison of chemical analyses and of norms (Tables II and III) of the rhyodacites show that the O'Leary Porphyry (P31) and the Frothy Flow (W_f19) are very similar and distinct (more silicic) from the Red Flow (W_r16), Banded Flow (W_b17), and Mesa Flow (DM1). This difference between the Frothy Flow and Banded Flow supports the field evidence suggesting that they are distinct flows. The Banded Flow (W_b17), Red Flow (W_r16), and Mesa Flow (DM1) appear very similar chemically (especially in total iron) suggesting that they are nearly contemporaneous.

VOLCANIC HISTORY

Lineament Tectonics

Mayo (1958), in his discussion of lineament tectonics of the southwestern states, describes the San Francisco Volcanic Field as lying on the intersection of four dominant structural trends. These four are approximately north-south, east-west, northwest, and northeast. Other authors concerned with the San Francisco Volcanic Field have come to similar conclusions. Gilman (1965) lists four main structural trends from the Sitgreaves area: N10E, N80W, N30W, and N60E. McLain (1965) lists trends taken from photographic studies as N10W and N10E, E-W, N40-60W, and N40-50E. These trends are approximately those listed by Mayo. Breed (1964), however, states that the north-south direction is prevalent in the northern part of the field and the northwest direction in the southern part.

Within the O'Leary Complex it appears that northwest and northeast directions are best developed. O'Leary Peak lies on a northwest trending line connecting cone #47, O'Leary Peak, Darton Dome, Sunset Crater, and the cinder cones between Sunset Crater and Darton Dome (#141, 83, 82). A northeasterly trend connects basaltic cones #33, 35, and 36, Robinson Crater, and O'Leary Peak, the vents of the flows to the north, and Strawberry Crater (northeast of the area). It appears that migration has occurred along this northeasterly trend, probably along a major fissure running more nearly north-northeast than northeast. The vent was opened at what has been called the "central depression" of O'Leary Peak. When this conduit was plugged, new lava broke through to the northeast of it forming the lava accumulation which built the Banded Flow. This was then plugged and new lava was forced to escape farther to the northeast near the Amphitheater (see figure 15) forming the material which produced the Red Flow. Rittmann (1962, p. 132) shows migration along a fissure in Monte Rotaro (figure 31). This drawing is remarkably similar to the topography of the O'Leary Complex although it is of a different scale. The strato-volcano is analogous to O'Leary Peak; the secondary "endogenous dome" is analogous to the Banded Flow vent and the "eruptive cauldron" to the Amphitheater.

Emplacement of O'Leary Peak

Robinson (1913, p. 78) proposes that Elden Mountain was emplaced by "...laccolithic intrusion with volcanic extrusion" and that Marble Hill (White Horse Hills) is a small laccolith. In both localities the sedimentary cover has been turned up. One of the purposes of this investigation was to determine if O'Leary Peak was emplaced, in part, intrusively under a sedimentary cover. Robinson (1913, p. 76) lists a total thickness of 1900 feet of sediments of the Redwall through Kaibab interval present at Elden Mountain.

Figure 31: Monte Rotaro on the island of Ischia.

The main cone (right) is a strato-volcano. The large endogenous dome has grown within the volcano and a lava stream has broken out from an eruptive cauldron at its foot. The drawing is taken from Rittmann (1962, p. 132).

He lists a total of 1600 feet of sediments for the same interval as being present at Marble Hill. His cross-sections would indicate that the units in both localities are in-place beds; however, recent workers describe the outcrops as float-covered slopes (Ulrich, personal communication 1970).

Sedimentary material is present beneath the O'Leary Peak tower and on the northern and eastern sides of the Eastern Flat (see figure 1). An estimate by the author of the volume of sediments represented by these blocks and float is 1,260,000 cubic feet. Assuming that these blocks are from units turned up along the extent of the float occurrences the strike distance would be about 5000 feet. Assuming a width of outcrop of only 10 feet, then the stratigraphic thickness represented by these blocks would be only 25 feet. Even if this is a gross underestimation, it is obvious that very little stratigraphic section is represented within the O'Leary Peak area.

None of the sedimentary material from O'Leary Peak is in place. Thus, identification of units can not be made by stratigraphic order. Since several of the units have similar lithologies (as already mentioned), identification of formations is under some doubt. Wolfe and Ulrich (personal communications 1970) have suggested that the float on the eastern side of the Eastern Flat (SE $\frac{1}{4}$ of section 2) is situated in stratigraphic order from east to west: Kaibab, Supai, Redwall. They believe that further material is buried beneath the late black cinder which mantles the area. The author agrees that Kaibab Limestone occurs farthest east within this area. The red sandstone identified as Supai, however, could be Moenkopi. Limestone float identified as that of the Redwall occurs with the red sandstone float. A non-calcareous sandstone identified as Coconino is present beneath the O'Leary Peak tower. This is yet farther to the west than the Redwall occurrence (thus is out of stratigraphic order) yet being at a higher elevation may be an isolated remnant. However, no Supai or Redwall fragments were found beneath the tower. If this Coconino material is original cover on the O'Leary Peak Dome, then it would be expected that fragments of the underlying Supai and Redwall Formations would be found. If stoping occurred to the Coconino level then these fragments are somewhere in the unexposed interior of the dome. However, the late red cinder on the southern side did not bring any such fragments to the surface. The Coconino block (or blocks) beneath the tower is not more than 15 feet thick unless the outcrop is funnel shaped, for Coconino outcrop is present only on one side of the summit where it is about 15 feet thick. If Wolfe and Ulrich's theory is correct, then the Eastern Flat might be analogous to the horizontal part of a laccolith. However, no sedimentary debris is located on top of the Eastern Flat. It is the opinion of the author that the Eastern Flat is a lobe from the side of O'Leary Peak which had no cover and which did not break its solidified shell to form a flow (coulee).

A zone of breccia is present between the dacite of Elden Mountain and the upturned sedimentary units and faulting occurred within the sedimentary units (Robinson 1913, p. 77). A breccia also occurs within the White Horse Hills laccolith which is believed to be due to shearing; extensive faulting is suggested by missing parts of the stratigraphic section (Verbeek, personal communication 1971). It is the opinion of the author that the relationship of the O'Leary Peak Dome to the sedimentary cover more closely resembles a "punching through" the cover and carrying upward of blocks along a breccia zone rather than a laccolithic intrusion. Incorporation of these blocks within the porphyry resulted in the xenoliths beneath the Eastern Lobe of the Banded Flow which are surrounded by porphyry. There are no upturned beds on the northern or eastern sides of the Eastern Flat. The stratigraphic order proposed by Wolfe and Ulrich is, it is believed, unconfirmed. The only evidence which may support an upturning of sediments here, if present, is buried beneath the recent black cinder cover.

The sedimentary fragments discussed above occur between the Eastern Flat and the basalts of the eastern half of section 2. Wolfe and Ulrich (personal communications 1970) believe these are Period I (of Robinson) basalts which originally covered the Kaibab Formation. Emplacement of O'Leary

Peak Dome then turned up both the stratigraphic section and the basalts forming hogbacks. The two basalt types (X2 and X4) present on the southern basalt outcrops could be explained by two flows separated by some length of time which were then turned up during emplacement of the dome. The topography of the two outcrops of basalts, however, doesn't appear to be consistent with an eroded hogback. Some 3000 feet separates the two outcrops. This area is covered by late black cinder yet no mantled topography is apparent. If these outcrops were originally hogbacks, then 3000 feet of outcrop is missing--more basalt would have been eroded than retained. One of the lobes of the northern outcrop appears to have flowed into the crater of the cinder cone located there. The loose packing of the cinder cone is easily eroded yet the cone appears undissected indicating that it is a recent feature. This suggests that the flow is young. The area, however, is heavily mantled with recent black cinder so contact relations are not clear. An alternate theory is, of course, that an asymmetrical cinder cone was built upon the dissected hogback and that what cinder covered the basalt has been buried by recent black cinder or transported into the crater and buried. Chemistry of the basalts has been discussed under PETROCHEMISTRY.

Crater Formation

The southern rim of the O'Leary Peak Dome is intact; however, the northern rim has been destroyed. The author suggests that after emplacement of the dome a crater was formed by explosion and/or collapse due to withdrawal of magma beneath the dome. The source area of the flows lying to the north of O'Leary Peak Dome is just northeast of the breached dome. However, due to the marked differences in lithologies between the O'Leary Porphyry and the fine-grained rhyodacite flows, it is not believed that the lava which was extruded to form the flows once occupied the center of the O'Leary Peak Dome. After collapse, fluids rose through the fractured debris filling the conduit. Thus, the porphyry of the "central depression" was stained shades of red and yellow.

Banded Flow

The topography northeast of the "central depression" of O'Leary Peak Dome suggests that lava welled up here and flowed toward the northwest and the northeast forming the two lobes of the Banded Flow (W_b17). Flowage downhill toward the northeast resulted in flow structure (obsidian layers) which turn up toward the source. A circular depression now filled with recent black cinder is present where the two lobes join (NW $\frac{1}{4}$ of section 2). The author believes that this is a central depression within the dome of the Banded Flow material. It is probably due to explosion and/or collapse. After the two lobes of the Banded Flow were extruded, the flows of the Deadman Mesa Complex were extruded. The Deadman Mesa Complex consists of the Red Flow (W_r16), Amphitheater Flow, and Mesa

Flow (DM1) which are grouped together because of their genetic relationship although they are lithologically distinct.

Deadman Mesa Complex

The Red Flow (W_r16) is made up of three distinct topographic types: hornito accumulations, "narrow ridges", and "lobes." The first type consists of the pink frothy lithology of the Red Flow while the latter two consist of the red lithology which contains contorted obsidian flow bands (see figure 1, 15).

The narrowness of the "narrow ridges" may be due to two possible origins in the opinion of the author. If two flows of similar material had poured down the side of the already present Banded Flow, they would have followed the topographically lowest portion. This may have represented the head of a stream valley (or valleys) or any depression of sufficient depth (10-20 feet perhaps) to constrain the flows. As the flows became cooler and thus more viscous, they were likely to "pile up" and roll over themselves. When the change in gradient between the slope of O'Leary Peak and that of the plateau to the north was reached, the flows may have been "ponded" forming the lobes as extensions of the ridges. The obsidian flow banded and gray aphanitic outcrops may represent chilled margins on the Red Flow.

An alternative and preferred hypothesis is that the red lithology of the Red Flow represents levees of a flow (or flows) originating in the Amphitheater the center material of which has flowed to the north forming Deadman Mesa. The narrowness of the "narrow ridges" suggests this hypothesis. Lithologies of the "narrow ridges" and the "lobes" are identical suggesting that they are related. Both are marginal to the "main stream" of flow proposed for formation of Deadman Mesa. However, the eastern lobe bends to the northeast as if deflected by the "narrow ridge" thus suggesting that it may be somewhat later. Should the "narrow ridges" and the "lobes" have been contemporaneous, the different morphology between the ridges and the lobes may be related to the change in gradient here. In this case they would be different expressions of the same levee.

Pressure ridges convex toward the northeast within the eastern "lobe" indicate flow here. Bryan (1966) describes silicic levees (from an area in Mexico) as "jumbles of blocks". He makes no mention of flow within such levees.

The obsidian flow banded material on the inside wall of the red ridges may be interpreted as "high-water" marks of the flow. Some of these blocks must have been rafted out into the mesa, however, for one such block just north of the Strawberry Crater road and east of the western "narrow ridge" strikes about N80W (perpendicular to the length of the red ridge) and dips about 70° to the north (away from the Amphitheater).

The "wide ridge" on the east consists of pink frothy material which appears to have been ponded by the "narrow ridge" (see figure 15). The vents along the rims of the central depression on the Banded Flow (see figure 1) and those of the Amphitheater may also have been active at this time since the lithology of their material is similar to that of the "wide ridge." This frothy lithology appears to have been more viscous than the earlier red lithology. Rootless vents common within this lithology probably provided an escape for volatiles. A tendency toward increased viscosity would result from such a volatile loss.

The units mapped within the Amphitheater Flow may represent the remnants of the flow (or flows) which built Deadman Mesa or may represent a later flow. The author prefers the first explanation and suggests that the different units represent different levels within the flow. The eastward dip of unit W9 may represent either sagging inward due to withdrawal of lava (as Deadman Mesa was formed) or may represent "nestled spoon" flow structure typical of silicic flows.

Outcrops discussed previously under "Mesa Flow" may represent the interior portion of the flow forming Deadman Mesa. These outcrops resemble the material of the Amphitheater Flow. The DM2 outcrops are probably related to the the formation of Deadman Mesa. Although the Red Flow, Amphitheater Flow and the Mesa Flow have been mapped separately (on their different lithologies) it is believed that they are very closely related genetically.

Frothy Flow

After extrusion of the Deadman Mesa Complex, the Frothy Flow (W_f19) broke out from a vent near the contact of the terminus of the eastern lobe of the Banded Flow with the "wide ridge" of the Red Flow. The Frothy Flow poured down the side of the red ridge becoming autobrecciated. After reducing the gradient by piling up of autobrecciated blocks, the flow continued to the east and northeast.

Late Basalts

The late activity within the O'Leary Complex was that of the late stage basalts. Red cinder, black cinder, and purple spatter (X13) vents were opened along the southern side of O'Leary Peak. A cinder cone was developed on the eastern side near the Banded Flow. Olivine basalt (X4) and basalt (X2) poured out the eastern side of the complex. These basalts appear to have been viscous and of small volume thus resulting in short flows. One of these flows entered the crater of the cinder cone. Soil was developed upon the cinder on the southern side of O'Leary Peak; erosion occurred. Recent eruptions from the vicinity of Sunset Crater blanketed the area with black cinder.

APPENDIX A

GLOSSARY

Dome: a circular to elongate dome-shaped accumulation of volcanic material formed as magma welled up, usually beneath an autobrecciated crust of chilled lava. Such a dome may have a crater or be craterless.

Coulee: any short, stubby viscous flow, usually with very steep flow edges.

Flat: a flat-topped protrusion out of the side of a dome which has not broken through to form a coulee.

Levee: the chilled margin of a flow which is often left as a spiny ridge when the center of the flow breaks through at its front.

Pressure ridge: a ridge on a flow, usually convex away from the source, where material is topographically higher due to a buckling of the chilled surface of the flow by the more mobile underlying lava.

Hornito: a small vent through which gases have escaped. Hornitos developed on flows where the crust was broken may be called rootless vents. They are often aligned along pressure ridges. The term is not here restricted to basic lavas.

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*. Refers to works concerning volcanic features.

#. Refers to works concerning San Francisco Volcanic Field and/or northern Arizona.

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2 pieces
in pocket

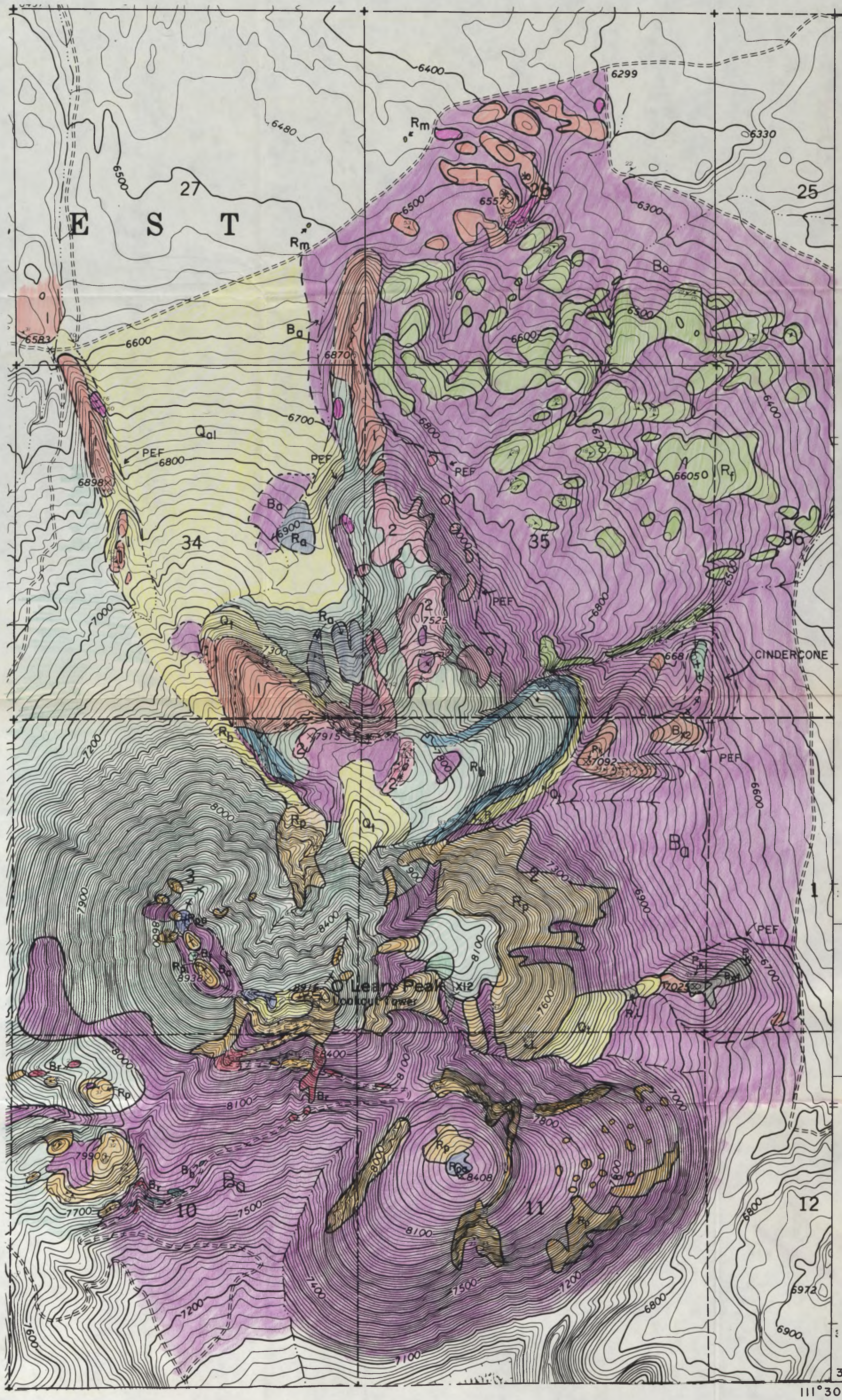

FIGURE I GEOLOGY OF O'LEARY PEAK VOLCANICS

COCONINO COUNTY, ARIZONA

EXPLANATION

Qt Qal	TALUS, ALLUVIUM
Ba	AIR-TRANSPORTED BLACK CINDER
Bb	STRATIFIED BLACK CINDER & PURPLE-BLACK SPATTER (cindercone on east side)
Br	STRATIFIED RED CINDER - contains blocks of O'Leary Porphyry, X12 Obsidian, and Coconino Ss.
Bf	RED CINDER FLOAT
Bx2	X2 BASALT - gray, aphanitic unit showing flow layering
Bx4	X4 BASALT - olivine phenocrysts (to 5 mm,) in a gray aphanitic matrix
Rf	FROTHY FLOW-(rhyodacite) pumaceous, laminar upper unit with spherulitic obsidian lower unit
Rm	MESA FLOW-(rhyodacite) Outcrops of blocks on surface of Deadman Mesa consisting of gray aphanitic material containing occasional quartz and feldspar phenocrysts
Ra	AMPHITHEATER FLOW- Material confined to Amphitheater. Lithology resembles Mesa Flow.
m 1 2	RED FLOW - (rhyodacite) m - Glossy gray material marginal to typical Red Flow material 1. Early typicial red flow material with contorted obsidian banding 2. Late pink-purple frothy material expressed as hornitos
Rb	BANDED FLOW-(rhyodacite) Alternating obsidian layers 10-20 feet thick with pink to purple frothy material.
Rpa Rp	O'LEARY PORPHYRY-(rhyodacite) Rpa - altered porphyry Sanidine and quartz porphyry containing red to grey basic volcanic inclusions.
▭	SEDIMENTARY XENOLITHS - P_k - Kaibab Limestone; R - Red siltstone and sandstone P_c - Coconino Sandstone; L - Metamorphosed Limestone
X12	X12 OBSIDIAN FLOAT - Age uncertain
▭	COVERED

PEF	probable extent of flow lithology
↙ ⌐	strike and dip of flow layers; fractures, bedding
*	vent, hornito
‐‐✱‐‐	line of vents
+++	crater rim
—	contact
— —	buried contact at change in slope
----	buried, inferred contact
↑	lineation
x	xenolith

Scale 1:12000 or 1 inch = 1000 feet

0 1000 2000

contour interval 20 feet

topography from U.S.G.S. O'Leary Peak Quadrangle

T.N.
M.N.
14 1/2°

Geology by K.M. Laing, 1970

LAING BLADH Thesis Geosciences 1971

Figure 15

Reconnaissance of O'Leary Peak-Robinson Crater Area, Arizona

EXPLANATION

Figure 15

O'LEARY VOLCANICS

Qal	TALUS, ALLUVIUM
Ba	AIR-TRANSPORTED CINDER
Bh	BLACK CINDER, SPATTER
Br	RED CINDER
Bx2	X2 BASALT
Bx4	X4 BASALT
Rf	FROTHY FLOW
Rm	MESA FLOW
Ra	AMPHITHEATER FLOW
Rr	RED FLOW
Rb	BANDED FLOW
Rp	O'LEARY PORPHYRY

AGE RELATIONSHIP UNCERTAIN

ROBINSON CRATER AREA

Qal	TALUS, ALLUVIUM
🟦	Cone 47 BASALT
Rl	LAVENDER FLOW
🟥	COULEE IV
🟩	COULEE III
🟥	COULEE II
🟪	COULEE I
Rrc	ROBINSON CR. VOLCANICS
Rp	O'LEARY PORPHYRY

Age relationship between Rb, Rrc, and I is uncertain

PEF	Probable extent of flow
⟋	Strike and dip of flow layers
+ + +	Crater rim
— — —	Contact-O'Leary Volcanics
····· · ·	Contact-Robinson Cr. area
------	Lineation from air photos
• W_{19}	Sample location

T.N.

M.N.

14 1/2°

SCALE: 1:2400 or 1 inch = 2000 feet

Contour interval = 20 feet
Topography from U.S.G.S. O'Leary Peak Quadrangle

Geology by K,Laing, 1970

LAING BLADH Thesis Geosciences 1971