

MANNER AND RATE OF
PLANT INVASION OF
SUNSET CRATER

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A very significant part of the United States is mantled with recently erupted volcanic materials. Areas with such materials are located in several of the Rocky Mountain and Pacific Coast states, and in Alaska and Hawaii. About 3000 square miles in the northern part of Arizona are covered with lava, ash, and cinders of recent age. The highest mountains in the state, the San Francisco Peaks, rising to 12,600 ft, are remnants of old volcanoes which began erupting in either Miocene time (Sabals, 1959), or in Pliocene time (Robinson, 1913).

In several directions from the San Francisco Peaks are hundreds of others, as well as lava flows. Many of them appear to be quite young. The two which are said to be the youngest are S. P. and Sunset Cones. Sunset, the subject of this report, lies 16 miles north from Flagstaff, Arizona, and 3 miles east from U. S. Highway 89. This cone and its several associated lava flows lie within Sunset Crater National Monument. (As used in the report the term Sunset Crater will refer to the complex of the cone and lava flows.)

The date of the eruption of Sunset Cone has been set at 1064 A.D., by Smiley (1958) who applied dendrochronology techniques to timbers found within the area of ashfall from the cone. The climatic conditions which resulted in the preservation of timbers for 900 years, included scanty rainfall, low atmospheric humidity, and short summers, and were responsible for the slow invasion of vegetation to the lava flows, the cinder cone, and surrounding ash fields.

Geologic History

The main feature of Sunset Crater is the large cinder cone; but the lava flows form an important part of the complex also. It is probable that the eruption occurred over a period of several months, or a few years. Varying thicknesses of ash on different flows indicate that the flows were extruded at different times in relation to cone building, and hence to ash fall. Two volcanoes comparable to Sunset in size of cones and extent of flows are Parícutin and Jorullo in Mexico. They were active for approximately nine and sixteen years and their eruption pattern suggests that Sunset could have been active for several years. (Eggler, 1959).

Sunset Cone is about a mile in diameter. Its base is at an elevation of about 7000 ft and the summit is 1000 ft higher. The cone is formed of a mixture of cinders, ash, and lava blocks, with a few volcanic bombs. Ash, the finest-textured of the ejecta mentioned is the size of medium and fine sand, silt, and clay. Cinders have the texture of gravel and are over 2 mm in diameter. Lava blocks on the cone may be several inches in diameter. Most of the exposed surface of the cone consists of ash and cinders but there are areas, particularly toward the summit and around the crater rim, where coarse rubble predominates.

According to Hodges (1962) the diameter of the crater which lies within the cone is 1700 ft by 2250 ft; its depth is about 400 ft. Hodges reported the slope of the flanks of the cone to be fairly constant, between 25 and 28 degrees.

Wind-borne Ash

Colton (1945) reported that wind-carried ash from the Sunset eruption originally mantled an area of about 800 square miles, but that erosion has removed it from all but about 100 square miles. Colton also reported that

more ash was transported in a northeasterly direction than in any other because prevailing winds blew in that direction at the time of the eruption.

At least 8 to 10 small cinder cones, all older than Sunset, are located within 2 miles of the base of Sunset Cone. An accumulation of Sunset ash upon them apparently destroyed much of their vegetation. Most of the cones have not regained a complete vegetation cover and ash is still bare, particularly on the south-facing slopes. Some intercone areas are also not yet completely vegetated.

I have found it difficult to distinguish Sunset ash near its outer margin from that of the other cinder cones. Lennox Crater appeared to have a mantle of ash from Sunset; Cone 48, where some quantitative vegetation studies were made, appeared not to have. The present margin of Sunset ash in a WSW direction appears to lie between Lennox Cone and Cone 48, or approximately 1 mile from the base of Sunset (see Fig. 1). In a northeasterly direction the depth of ash was measured at several points near the loop road between Sunset Cone and Wupatki National Monument. At 3 miles distance the ash was $1\frac{1}{2}$ ft thick; at 7 miles it appeared to end but traces of ash were found at even greater distances.

Ash depths today cannot do more than suggest what they may have been 900 years ago. The ash is not consolidated and vegetation which might fix it in place is sparse. Wind and water have surely moved the ash a great deal.

The typically near-black color of basaltic ash and cinders has been altered to red in several places. The rim of the crater in Sunset Cone has a reddish color. Immediately northwest of the main crater is a hummocky ash and cinder mantle on lava, in which the hummocks or small mounds are quite red (called Red Hills in Fig. 1). Again about a half mile east of the main

cone is a red cinder ridge. It is probable that fumarolic activity, during which hot gases emanated from the hot lava beneath, caused oxidation of iron in the material to give the red color.

Lava Flows

Lava flows, which Hodges (1962) stated emerged from the base of the cone, moved away from Sunset in two directions. A flow known as Kana-a moved in a northeasterly direction, as a narrow tongue, for a distance of about 6 miles. The Kana-a flow is ash-covered, to varying degrees, throughout its length. The loop road to Wupatki Monument runs on or beside it.

* Road construction and timber-cutting had greatly altered the vegetation on the flow so no attempt was made in the present study to consider invasion of plants to the Kana-a Flow. West and northwest from Sunset Cone lies a complex of flows known as the Bonito Flow (Fig. 1). It occupies an intercone basin and extends for almost 2 miles in its greatest extremity north and south by about $1\frac{1}{2}$ miles east and west. Almost all studies of vegetation on lava were made on the Bonito Flow.

The lava from Sunset is basaltic, and usually dark in color. Most of it is fragmental and broken, and hence may be called aa; but in places there isropy pahoehoe. Again there are large, massive blocks of lava many feet in diameter. The lava is much broken in many places as the result of fracturing and faulting which occurred after the eruption ceased. Fault lines can be traced for long distances across the flows. Again, some early flows were apparently disrupted by subsequent flows. Hodges (1962) believes flows moved under earlier ones, and caused them to dome and often break.

There is great variability in the amount and kind of plant growth on the flows. A few inches distance may show several different ecological forms of plants. The flow cannot be described as a unit or single type of habitat.

Rather, it consists of innumerable microhabitats. Every fissure, crevice, or bit of exposed surface is a separate one. The lava by itself would support only lichens under the climatic conditions. Hence, wind-borne material on the lava is extremely important for plants. The aeolian material is usually ash from Sunset Cone, transported during or after the eruption, but old soil and bits of debris may be transported also. More than anywhere else on the lava flows vascular plants get started along the margins of aeolian deposits, that is, at the contact of lava and wind-borne material.

Climate

The climate of the Sunset Crater area is characterized by low atmospheric humidity much of the time, a great number of days with sunshine, and with precipitation coming mostly in the winter and late summer (Kearney and Peebles, 1960). The same authors state that there are great differences in amount of precipitation from year to year. Hodges (1962) reported precipitation at Sunset Crater to be between 17 and 20 in. per year. Colton (1959) gave precipitation data for 17 stations near the San Francisco Peaks. Records for four of the stations with altitudes comparable to that of Sunset Crater are presented.

Station	Altitude (feet)	Max. annual ppt in.	Min. annual ppt in.	Season with greatest ppt
Coconino Divide	7282	31.46	10.54	Summer
Black Bill Park	6800	24.33	9.74	Summer
Doney Park	6700	31.24	11.43	Summer
Deadman's Wash Upper Terrace	6275	19.32	8.01	Summer

These data emphasize the great difference between maximum and minimum annual precipitation. The years with low precipitation, 8 to 12 in., must be the most difficult times for tree and shrub seedlings, and for herbaceous

plants, especially annuals which must grow from seeds. Large established trees, and shrubs, apparently do not suffer very much in a dry year other than in reduced growth. It is probable that it is the dry years which retard the rate of vegetation migration in such places as Sunset Crater. Only on the lower half of the north slope of Sunset Cone is there what can be called soil, with a forest which is well established and in no danger of succumbing because of lack of water. Elsewhere on the cone there are numerous scattered trees which appear to be quite healthy but there is usually no reproduction and the future of the species in those areas is precarious. There are areas where the shrub Fallugia is well established. Trees on the lava usually occur singly, in microhabitats of small size, such as a crevice or other depression. Reproduction is usually absent.

Vegetation of Sunset Crater and Adjacent Areas

There is general agreement between several different reports as to the kind of vegetation which occupies areas in northern Arizona with the altitude of Sunset Crater but not much agreement as to a name for it. Merriam (1890) called it the Neutral Zone, with ponderosa pine. Shelford (1926) referred to the zone starting at 7000 ft altitude as a Mountain Coniferous forest. Pearson (1931) called it the western Yellow Pine zone. He described the climate as cool, and said precipitation was 18 to 25 in. annually, with much coming as snow. Merriam (1890) said a pinon-pine zone extended from about 6000 ft to 7000 ft. The south-facing slopes of several old cones in the area supported pinon-juniper forest in 1964. Even though the altitudes are more than 7000 ft the greater insolation on the south slopes reduced the water balance below that required by ponderosa pine but tolerated by pinon and juniper.

Since Sunset Crater lies at 7000 ft elevation, or above, it should

potentially support the ponderosa pine forest, but soil conditions are unfavorable over most of it. The ash, cinders, lava, and rubble have not weathered enough in most places to form good soil. As stated above established true forest is limited in area; widely scattered trees are over all the main cone except on the south side, and on most of the flows. Shrubs occur in scattered clumps on both cone and flows. Herbs grow very scatteredly and are often limited in time of growth to the short rainy season.

The presentation of information on the vegetation of the area will be in part general and in part quite specific, with quantitative data for 2 cones, Sunset and Cone 48, and for parts of several different flows of the Bonito series. The first presentation will be that for 6 cinder cones, then for several intercone areas, finally for the lava flows. The cones are Sunset, #82, #83, #141, Lennox, and #48 (Fig. 1). The last 5 are all older than Sunset and they undoubtedly received ash cover from Sunset. All but #141 and #48 still retain recognizable amounts.

SUNSET CONE

The vegetation on Sunset Cone varies with the sides. On the south slope the cone has very few trees although there are some at the summit on the south rim of the crater (Fig. 2A). Even the seemingly bare south slope is not completely devoid of plant life, at least not in all seasons. A few kinds of herbaceous plants grow in the ash and cinders. Figure 2B shows Physaria, one of the more common ones.

On the lower north side is an open forest, in which Pinus ponderosa Lawson is the dominant tree (Fig. 2C). There are some quite old and large trees in the forest. The present timber line on the north slope lies about midway between the base and the summit; above the tree zone is a grass and shrub zone.

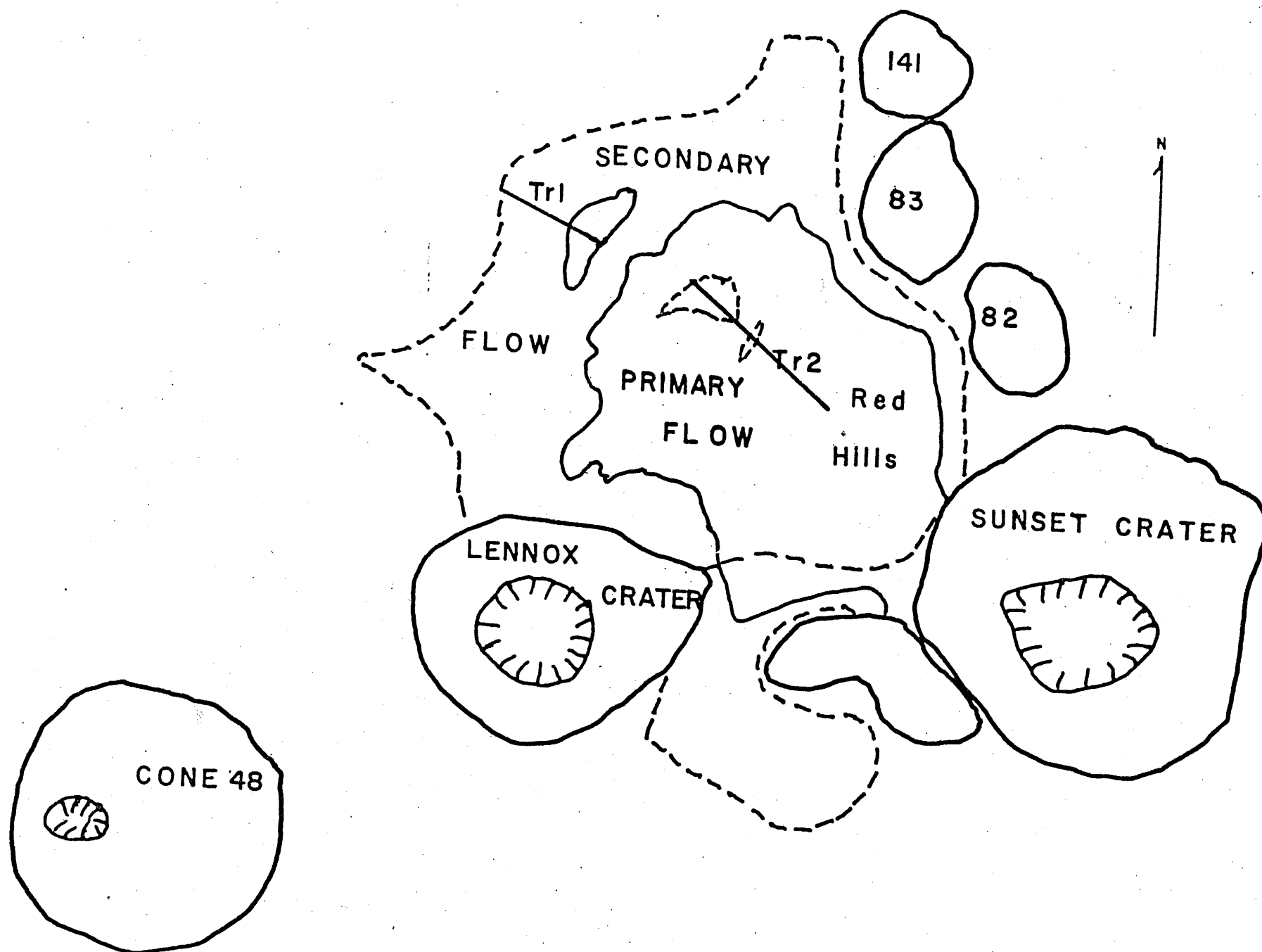


FIG. 1

The forest is continuous from the north to the east and around to the southeast (Fig. 2D). It actually extends a little higher on the cone on the southeast side than on the east, because the angle of slope is less (Fig. 2E). On the west side trees are widely, but rather evenly, spaced from the base to the summit (Fig. 2F). Some shrubs, chiefly Fallugia, are intermixed.

The crater in Sunset Cone has a small ponderosa pine forest growing in the bottom at the deep western end, but not elsewhere. The apparent reason is the western wall of the crater is very steep and the influence of drying winds would be less at its base than in the shallower and more exposed middle and eastern end of the crater. It is also probable that snow and rain water accumulate on the western end.

To make a quantitative comparison of vegetation on the north and south sides of the cone a transect was run across, from base to base. Trees and shrubs were tabulated in a 10 m wide transect and herbs in a 2 m wide transect run along one side of and included in the wider transect. In the field every tree and shrub was located on a chart. Herbs were counted by units. For presentation results for all classes of vegetation have been combined into 10 m units.

North Slope

Trees

In Table 1 is presented information on trees in the 10 m wide transect on the north side of Sunset Cone. The transect was begun on the flat interconal area at the north base of the cone and plots 12 to 18 are on it; number 19 is the first on the cone itself. One to 11 were little different from 12 to 18 and are not given. The number 29 was inadvertently not used. Plot 90 was at the summit of the cone. Hence there were actually 70 plots on the north slope for a total length of 700 meters. The tree zone occupied the lower 39 plots, 19 to 58, or 390 meters. Diameters were all taken at breast height, referred to hereafter as d.b.h.

Table I shows several things. One is that the forest is not an even stand; some plots have only one or two, or a few trees, and some have several. A striking thing is that trees tend to become smaller from the base of the cone upward. Trees in the diameter classes 10" to 16" and over 16" are most numerous in plots 19 to 26. The upper plots have fewer large trees. Actually, they do not have many small ones either. Total basal area is the best measure of the abundance of a species in a particular plot, and a comparison of total basal areas, in square inches, shows the lower cone, plots 19 to 31, to have the greatest abundance.

Another striking thing is that Pinus flexilis James, limber pine, is present in the middle part of the forested zone, plots 27 to 45, and Pinus edulis Engelm. is present in three of the upper plots. The positions of these two species must be controlled largely by moisture, limber pine growing in small numbers where moisture is greatest and pinon coming in near the tree line where moisture is less abundant.

The greatest number of pine seedlings present at the time the field work was done on the cone, late June and early July, 1964, were in plots 40 through 56. Two seedlings were limber pine and all others were ponderosa pine. There were no seedlings in the first 10 plots above the base, the section with most of the large trees. The greatest concentration of seedlings was at the level where the forest stand was open, probably because trees were small and few, but moisture was available for germination (Fig. 3A). Seedlings were almost absent near the upper limit of trees.

Unless 1964 was an unusual year it is extremely unlikely that any of the seedlings survived past the first year. The paucity of small trees in the upper plots indicates that seedlings seldom survive, and the few which grow into small trees must not live very long. Some of those present in

TABLE 1. Density and total basal area of trees in consecutive 10 m X 10 m plots (divisions of transect) on the north side and base of Sunset Cone. Cone slope begins with plot 19; 90 is on summit; fl = *Pinus flexilis*.

Plot number	Seedlings	Diameter size classes						Total basal area in.²		
		<1"	1"-3"	3"-6"	6"-10"	10"-16"	≥16"	<i>P. ponderosa</i>	<i>P. edulis</i>	<i>P. flexilis</i>
90										
58	-	-	1	-	-	-	-	.85	-	-
57	-	1	-	-	-	-	-	.78	-	-
56	1	-	2	-	1	-	-	3.0	52.8	-
55	-	-	-	-	-	-	-	-	-	-
54	-	-	1	1	1	-	-	57.0	3.2	-
53	-	1	1	-	-	-	-	.2	7.0	-
52	1	-	-	-	-	-	-	-	-	-
51	-	1	-	-	1	-	-	50.5	-	-
50	1	1	3	1	-	-	-	26.1	-	-
49	-	2	-	-	-	-	-	0.4	-	-
48	10	1	1	-	-	-	-	3.16	-	-
47	31	-	-	-	-	-	-	-	-	-
46	-	1	1	-	-	-	-	3.6	-	-
45	1 fl	-	-	-	2	1	-	263.0	-	-
44	2	-	2	-	-	-	-	1.8	-	-
43	-	-	2	-	-	-	-	4.3	-	-
42	-	-	-	-	-	-	1	985.2	-	-
41	1 fl	2	3	1	-	-	-	11.4	-	15.1
40	4	2	4	2	1	-	-	62.0	-	0.8
39	-	-	2	-	-	1	-	108.0	-	0.78
38	-	1	1	-	-	-	-	0.7	-	0.8
37	-	-	-	1	-	-	-	12.0	-	-
36	-	1	-	-	-	-	-	0.5	-	-
35	-	-	-	-	-	-	1	415.0	-	-
34	-	-	-	1	-	-	-	19.0	-	-
33	-	2	1	-	-	-	-	0.4	-	0.8
32	1	2	4	1	-	-	-	9.7	-	10.0
31	3	1	4	-	1	-	1	353.9	-	50.0
30	2	1	-	-	-	1	1	380.1	-	154.0
28	-	-	-	1	1	-	1	274.8	-	-
27	-	2	3	3	-	-	-	47.7	-	0.5
26	-	8	5	4	-	-	-	56.7	-	-
25	-	-	-	-	-	-	1	255.0	-	-
24	-	-	-	-	-	4	2	1792.0	-	-
23	-	1	-	2	1	3	2	852.0	-	-
22	-	-	-	-	1	4	1	797.0	-	-
21	-	-	-	-	-	2	1	524.5	-	-
20	-	-	1	-	-	2	1	413.0	-	-
19	-	-	-	-	-	-	1	491.0	-	-
18	1	-	-	-	-	1	1	372.0	-	-
17	-	-	-	-	-	-	-	-	-	-
16	2	-	-	-	-	-	1	314.0	-	-
15	-	-	-	-	-	1	-	115.0	-	-
14	-	-	-	-	-	1	1	314.0	-	-
13	-	-	-	-	-	2	-	187.0	-	-
12	-	-	3	-	-	-	-	8.8	-	-

9586.59

1964 had many dead branches and many leaves were brown. There were dead trees also.

It appears that pine seeds germinate in almost all parts of the tree zone. Shade from the tree canopy in the lower forest probably prevents most seedlings from photosynthesizing enough to survive. In the middle forest level is the largest number of small trees. Close to tree line inadequate water is probably the force which kills seedlings and small trees and has fixed the timber line in its present position.

Increment cores were taken from all trees more than $2\frac{1}{2}$ in. d.b.h., and from the cores ages of the trees were determined. Figure 5 locates the trees by age in the several plots. Plots 1 to 18 were on the cinder flat * north of the cone where several trees had been cut at some time, and hence the density of trees in these plots was unnaturally low. Whether any trees which were cut were older than those remaining could not be determined.

The oldest tree in the transect, 433 years, was in plot 18, very near the north base of the cone, which fell in plot 19. The greatest concentration of trees in any age range occurred in plots 20 to 25, where 25 trees were between 130 years and 268 years. The most striking thing the figure shows is that the maximum age of trees decreased with increasing altitude. The last tree which was bored was a pinon pine (Pinus edulis) in plot 56. It was 7.6" in diameter, and 46 years old. Two ponderosa pines in plot 54 were 4.2" and 7.3" in diameter and 25 and 21 years of age respectively. Table 1 showed that trees were smaller higher up on the cone and Fig. 5 indicates that they are younger. Hence it must be concluded that trees are smaller higher upon the north side of Sunset Cone, not because they have grown less rapidly than lower down, but because they are younger. Are then, the trees at higher levels on the north side of Sunset Cone small and

young because they have only recently migrated to that area? Or is it because they do not live to become old? I believe the second explanation is the correct one, even though there is no strong evidence to support it. There does appear to be a high mortality rate among trees, as has already been stated.

Shrubs

The number of kinds of shrubs on the north side of Sunset Cone was hardly larger than the number of kinds of trees (Table 2). Two species of shrubs, Fallugia paradoxa (D. Don.) Endl. (Apache-plume), and Eriogonum aureum Jones were the only important ones. Apache-plume was restricted to what might be called open-woods and apparently it requires quite high light intensity. It was present in large numbers on the nearly-level interconal area at the base of the cone, plots 12 to 19, where some trees had been cut and where light intensity was greater than on the north facing slope. The numbers of this shrub decreased sharply with plot 19 and was absent or nearly so, in plots 19 to 40, in heaviest tree growth. As trees became smaller up the cone there was more Apache-plume, but it ended where pines ended.

Eriogonum must be more drought resistant than Apache-plume. There were a few Eriogonum plants, beginning in plot 28, but they did not become abundant until Apache-plume decreased. Eriogonum had its greatest density above plot 60, where there were neither trees nor Apache-plumes. It continued to the summit of the cone.

Lygodesmia spinosa and Ribes cereum (currant) were minor members of the shrub population.

Herbs

Herbs, which were present in the 2 m wide transect on the north side of Sunset Cone in late June and early July, 1964, are given in Table 3. Because

TABLE 2. Density of shrubs in consecutive 10 m X 10 m plots (divisions of transect) on north side and base of Sunset Cone. Cone slope begins with plot 19

Plot number	<u>Eriogonum aureum</u>	<u>Fallugia paradoxa</u>	<u>Lygodesmia spinosa Nutt.</u>	<u>Ribes cereum Dougl.</u>	Plot number	<u>Eriogonum aureum</u>	<u>Fallugia paradoxa</u>	<u>Lygodesmia spinosa Nutt.</u>	<u>Ribes cereum Dougl.</u>
90 Summit of cone									
89	191	-	-	-	50	4	25	-	-
88	136	-	-	-	49	1	-	-	-
87	72	-	-	-	48	1	-	-	-
86	32	-	-	-	47	-	-	-	-
85	12	-	-	-	46	-	-	-	-
84	8	-	-	-	45	1	2	-	-
83	7	-	-	-	44	1	4	-	-
82	39	-	-	-	43	6	2	-	-
81	36	-	-	-	42	5	5	-	-
80	43	-	-	-	41	12	10	1	-
79	5	-	-	-	40	3	8	26	-
78	2	-	-	-	39	2	-	-	-
77	5	-	-	-	38	1	-	-	-
76	2	-	-	-	37	2	1	-	-
75	13	-	-	-	36	1	-	-	-
74	59	-	-	-	35	2	1	-	-
73	96	-	-	-	34	7	-	-	-
72	73	-	-	-	33	4	-	-	1
71	71	-	-	-	32	3	3	-	-
70	95	-	-	-	31	2	-	-	-
69	153	-	-	-	30	5	2	-	-
68	130	-	26	-	28	1	3	-	-
67	129	-	1	-	27	-	-	-	4
66	116	-	-	-	26	-	1	-	-
65	95	-	-	-	25	-	-	-	-
64	105	-	-	-	24	-	-	-	1
63	90	-	-	-	23	-	-	-	-
62	88	-	-	-	22	-	-	-	-
61	111	-	-	-	21	-	-	-	-
60	101	-	-	-	20	-	-	-	-
59	63	20	-	-	19	-	3	-	-
58	66	1	-	-	18	-	74	-	-
57	42	23	-	-	17	-	135	-	-
56	24	18	-	-	16	-	164	-	-
55	26	-	-	-	15	-	159	-	-
54	20	-	2	-	14	-	133	-	-
53	13	-	2	-	13	-	115	-	-
52	5	3	1	-	12	-	48	-	-
51	2	17	-	-					

the entire transect is reported in one table density values for herbs in 10 m segments were combined as indicated.

No single species of herb was present in all parts of the transect. There did seem to be some relationship between the ranges of some herbs and trees and shrubs. To provide reference points the transect is here considered in four segments. Plots 1 through 18 are in the interconal forest at the north base of the cone; 19 through 45 include the most nearly-closed pine forest and will be referred to as forest; 46 to 58 is the area with smaller pine trees and will be referred to as open woodland. Plots 59 to 90 are in the shrub-herb zone.

Andropogon hallii Hack., a grass, occurred throughout the three lower parts of the transect, interconal forest, cone forest, and cone woodland, and was coextensive with pine. This grass did not extend into the shrub-herb zone. Artemisia (sage) includes two species and a variety, as indicated in Table 3. It was not possible to distinguish between the three at the time the field work was done. Later in the summer it was. Sage was restricted to the two lower forest zones, interconal, and the forest on the lower cone. Bouteloua gracilis (H.B.K.) Lag. (blue grama) was limited to the interconal forest. Euphorbia fendleri Torr. and Gray. was present with a few individuals in the interconal forest and also in the pine forest, but became abundant in the open woodland and in the shrub-herb zone above. Euphorbia lurida Engelm. was largely confined to the interconal and pine forest. Galium rotrockii Gray. grew in the forest and the open woodland. Gilia aggregata (Pursh.) Spreng. occurred in open woodland and in the shrub-herb zone. Monardella odoratissima Benth. had a few individuals in the pine forest, many in the open woodland, and it continued 50 meters into the shrub-herb zone. Oenothera caespitosa Nutt. was scantily represented in the cone

TABLE 3. Density of herbs in 2 m wide transect, north side and base of Sunset Cone; each value is sum of two 10 m plots. Cone slope begins with plot 19. *Artemisia* includes *A. caruthii* Wood, *A. caruthii* var. *wrightii* (A. Gray) Blake, and *A. pacifica* Nutt. 6/29-7/10/64.

Plot number	<i>Andropogon nervosus</i>	<i>Artemisia</i>	<i>Bouteloua gracilis</i>	<i>Euphorbia fendleri</i>	<i>Euphorbia lurida</i>	<i>Galium rothrockii</i>	<i>Gilia aggregata</i>	<i>Monardella odoratissima</i>	<i>Oenothera caespitosa</i>	<i>Orobancha fasciculata</i>	<i>Oryzopsis hymenoides</i>	<i>Pentstemon barbatus</i>	<i>Pentstemon clutei</i>	<i>Phacelia integrifolia</i>	<i>Physaria newberryi</i>	<i>Poa fendleriana</i>	<i>Silene hystrix</i>
9-90	-	-	-	5	-	-	-	-	-	-	-	-	-	-	-	-	-
7-88	-	-	-	3	-	-	-	-	-	-	-	-	-	2	2	-	-
5-86	-	-	-	-	-	-	-	-	-	-	-	-	-	5	2	-	-
3-84	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-
1-82	-	-	-	-	-	-	-	-	-	-	-	-	-	6	-	-	-
9-80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7-78	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5-76	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-74	-	-	-	10	-	-	4	-	-	-	7	-	-	25	6	-	-
1-72	-	-	-	33	-	-	2	-	-	-	48	-	-	18	5	-	-
9-70	-	-	-	28	-	-	3	-	-	-	63	-	-	19	5	-	-
7-68	-	-	-	27	-	-	6	-	-	-	54	-	-	19	10	-	-
5-66	2	-	-	30	-	-	9	-	-	-	65	-	9	19	8	-	-
3-64	15	-	-	22	-	-	13	-	-	1	50	-	7	15	8	-	-
1-62	-	-	-	19	-	-	18	21	1	2	47	-	6	36	11	-	-
9-60	4	-	-	14	-	-	30	87	2	1	35	-	5	23	12	-	-
7-58	107	-	-	8	-	8	21	138	1	3	7	-	5	34	14	-	-
5-56	60	-	-	3	-	21	16	92	-	-	3	1	7	1	12	-	-
3-54	81	-	1	1	-	17	10	145	2	-	-	2	28	-	25	-	-
1-52	52	-	-	-	-	3	10	97	-	-	-	3	2	-	13	18	-
9-50	18	-	2	1	-	6	8	123	-	-	4	7	1	-	6	6	-
7-48	54	-	-	-	-	9	1	190	-	-	-	6	-	-	7	24	-
5-46	5	-	-	-	-	2	1	78	-	-	-	4	-	1	6	11	-
3-44	13	-	-	-	-	3	-	38	-	-	-	-	-	-	4	-	-
1-42	-	-	-	-	-	4	-	53	1	-	-	7	-	10	1	1	-
9-40	19	-	1	-	-	1	-	38	-	-	-	7	-	-	-	-	-
7-38	-	-	-	-	-	1	-	43	-	-	-	3	-	-	2	40	-
5-36	-	-	-	-	-	1	1	44	-	-	-	4	-	-	-	7	-
3-34	2	-	-	2	2	-	-	51	3	-	-	-	5	-	-	2	-
1-32	2	-	-	-	-	1	-	26	-	-	-	-	4	-	-	2	-
9-30	-	-	-	-	-	-	-	6	-	-	-	-	3	-	-	-	-
7-28	13	15	-	4	-	1	-	56	2	-	-	7	-	-	-	-	-
5-26	5	1	-	-	-	1	-	2	1	-	-	9	-	-	-	-	-
3-24	9	-	-	-	-	-	-	-	-	-	-	13	-	-	-	-	-
1-22	9	2	-	1	1	1	-	7	1	-	-	11	-	-	-	-	-
9-20	6	2	43	-	1	1	-	23	-	-	-	12	-	-	-	-	-
7-18	9	2	5	-	10	-	-	1	2	-	-	6	-	-	-	-	-
5-16	7	22	22	7	9	-	1	3	6	-	-	9	-	-	-	-	-
3-14	-	14	15	-	2	-	-	-	1	-	-	1	-	-	1	-	3
1-12	15	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9-10	18	4	10	-	-	-	-	-	-	-	-	2	-	-	-	-	-
7-8	4	5	12	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5-6	8	-	1	-	-	1	-	-	-	-	-	-	-	-	-	-	-
3-4	2	1	1	-	-	-	1	-	-	-	-	-	-	-	-	-	-
1-2	-	24	57	-	-	-	-	-	4	-	-	-	3	-	-	-	-

forest and the open woodland. Orobanche fasciculata Nutt. is a root parasite and a number of individuals associated with Eriogonum aureum were in flower on July 13, 1964. Oryzopsis hymenoides (Roem. and Schult.) Ricker (Indian rice grass) was abundant above the open woodland zone but it stopped quite sharply in plot 73. Pentstemon barbatus (Cav.) Roth. was present in the interconal forest, pine forest, and open woodland. Pentstemon clutei A. Nels. grew in the upper part of the open woodland and continued a short way into the shrub-herb zone. Phacelia integrifolia Torr. was present in small numbers in the upper part of the open woodland and it continued on into the shrub-herb zone nearly to the summit of the cone. Physaria newberryi Gray. occurred in the upper part of the pine forest, in the open woodland, and some in the shrub-herb zone. Poa fendleriana (Steud.) Vasey (mutton grass) was present in the upper part of the cone forest and the lower part of the open woodland. Sitanion hystrix (Nutt.) J. G. Smith (squirrel tail) was in the upper open woodland and in the shrub-herb zone.

South Slope

The aspect of Sunset Cone from the south side can be seen in Fig. 2A. The base of the cone, seen in the foreground, is a cinder flat supporting a rather poor forest in which ponderosa pine is predominant. There were a few pinon pine also. Lumbering had removed the largest trees from the flat some time prior to the date of field work.

When viewed from below the south slope of the cone appears to be devoid of vegetation, except for a few widely dispersed trees, and a belt of trees high up on the rim of the crater. Ponderosa pine is predominant. Herbs do not become evident until the cone is climbed and they can be observed close-up.

Trees

A record of the trees in a 10 m wide transect, beginning 110 m from base of the cone on the cinder flat (Fig. 2A), and continuing to the rim of the crater, is given in Table 4. Trees were present in only 13 of the 68 10 m X 10 m plots, including only 5 plots on the body of the cone itself. Four trees were within the transect on the side of the cone, exclusive of the summit, a distance of 550 m. The four were in plots 14, 16, and 27. There was a relatively high density of trees on the south rim. Eleven trees were in two plots, numbers 67 and 68; and all but one were less than 6" d.b.h. Ten were ponderosa pine, and one was juniper.

There were not enough trees in the transect on the south side of Sunset Cone to justify the preparation of an age-plot record similar to Fig. 5. But it is believed an informal report on the ages of some trees is of value. The oldest and largest trees were on the cinder flat and in the first 40 m of slope. Twelve trees over 2.5" d.b.h. were in the 11 plots on the cinder flat and two trees were in plots 12 to 16. These 14 trees varied in age from 93 to 375 years. All but four were over 200 years. Only two trees large enough to bore were in plots above number 16 and below 67. They were 21 and 62 years old. Three trees near to, but not within, plots 62 to 64 were between 53 and 79 years of age. Cores were taken from 8 trees in plots 67 and 68. Seven between 2.0" and 4.15" d.b.h. ranged in age from 18 to 26 years. The eighth was 70 years old and 15.0" d.b.h. All trees mentioned above were ponderosa pine.

Cores were taken from 19 other trees on the south rim, all ponderosa pine, close to but not within the transect. Sixteen of the trees were under 100 years of age. They were in the following age and diameter classes: 6 trees, 26 to 50 years old, 2.7" to 5.7" d.b.h.; 4 trees, 51 to 75 years, 9.0" to 12.3" d.b.h.; 6 trees, 76 to 100 years, 5.9" to 19.8" d.b.h.

One tree 7.0" d.b.h. was 123 years old; one 14.0" was 134 years of age; and one 14.3" was 209 years old.

The 14 trees at the south base of the cone were quite like those at the north base, discussed earlier. They were quite old and large in diameter, and had grown rapidly enough so growth layers were thick enough to distinguish easily. The two trees on the side of the cone were small and young, as had been the trees at middle elevations on the north side. The trees on the south rim had also grown quite rapidly; most of them were between 26 and 100 years old.

The general aspect of many of the trees on the crater rim was that of timberline trees. Many had branches asymmetrically arranged due to wind-training or wind-pruning. All trees were short in stature. (Almost all ponderosa pine trees in the Sunset Crater area, on the cone, on flows, and ash fields, have a very low height to stem diameter ratio. This feature will be discussed further under a later section on autecology of ponderosa pine.) One might expect to find that trees with the timber-line aspect had grown very slowly, but such was not the case. The rate of diameter increase suggested that moisture conditions were quite mesic, for the two trees on the south slope as well as those on the summit.

A summary of facts about the trees on the slope and summit is as follows. Most of the trees are small and under 100 years old. There are a few older, but none is as old as most at the base of the cone. Trees are short in stature; they are widely spaced; and there is almost no reproduction. Diameter growth has been quite rapid. Nearly all trees are ponderosa pine; juniper and pinon pine, which are the most abundant trees on south slopes of old cones in the area, are few in number.

Two questions are relevant at this point. Why are there more trees on the crater rim than on the south slope? Has ponderosa pine as a species begun

TABLE 4. Density of trees and total basal area of trees in 10 m X 10 m plots (divisions of transect) on south side and base of Sunset Cone. Cone slope begins with plot 12; 68 is at summit. No trees present in omitted numbers.

Plot number	Diameter size classes						Total basal area in. ²		
	<1"	1"-3"	3"-6"	6"-10"	10"-16"	>16"	<u>Pinus ponderosa</u>	<u>Pinus edulis</u>	<u>Juniperus deppeana</u> Steud.
68	-	2	1	-	1	-	197.5	-	-
67	2	1	4	-	-	-	43.2	-	0.7
27	-	-	-	-	1	-	140	-	-
16	1	-	-	-	-	1	700	0.2	-
14	-	-	-	-	-	1	346	-	-
9	-	-	1	1	-	-	-	52.5	-
8	-	-	-	1	-	-	-	29	-
6	-	-	-	-	-	1	210	-	-
5	-	-	-	-	-	1	283	-	-
4	-	1	-	-	-	-	-	0.78	-
3	-	-	-	-	1	1	426	-	-
2	-	-	-	-	1	-	113	-	-
1	-	-	-	-	3	-	371	-	-

begun to invade the south slope and rim during the last century or two, or has it been there longer? The answer to the first question appears to be simple. The south rim is nearly level, hence insolation with resulting heat and evaporation would be less than on the south slope. There would also be less run-off of rainwater, and probably snow is not blown away as easily as on the slope. All of these conditions would tend to make a more favorable water balance. In addition the rim has a more stable surface than the slope.

There is little evidence to substantiate my answer to the second question which is that there have probably been trees on the rim and south slope much longer than the life span of the oldest, presently-living tree, 209 years. One type of evidence is the presence of a few dead and broken rather large ponderosa pine trees on the south slope of the cone. They were larger than the two living trees in the transect. There were also dead trees on the summit. Also, there is apparently no minimum time requirement necessary after a volcanic eruption before trees can begin to grow on a cinder cone. At Paricutin, for example, small pine trees were found on the cinder cone and on lava flows six years after eruption ceased (Eggler, 1963). Unless there was less precipitation in the past than now at Sunset there is no reason to think that it would have been more difficult for trees to become established on the cone soon after activity ceased, than now, unless seeds were not available. The cinders and ash have not been altered significantly, on the summit and south slope, and are not now a soil.

Soil formation and plant invasion and establishment take place simultaneously and cooperatively. As soil forms plants have more success. Without plants volcanic material does not become soil, at least not under climatic conditions of Sunset Crater.

The paucity of pine seedlings and small trees indicates that only rarely

does a combination of conditions necessary to produce a tree occur. They are: a viable seed in a favorable germination site where moisture is adequate, plus enough relatively wet seasons to enable the seedling to develop an extensive root system. With an adequate root system trees seem to grow successfully and quite rapidly in diameter but not much in height. Why they do not live to be older will be considered in the section on autecology of ponderosa pine.

Shrubs

Shrubs were confined to the cinder flat and to the bottom 9 and top 9 plots on the cone slope. In between was a distance of 390 meters without shrubs. Where shrubs were present Fallugia was dominant. Eriogonum (buckwheat), Chrysothamnus (rabbit-brush), and currant were present in low densities.

Herbs

A survey of herbs on the south slope of Sunset Cone was made in a manner similar to that on the north side. A 2 m wide transect was run from the cinder flat at the base of the cone to the summit, and herbs in the transect were counted and recorded by 10 m segments. To reduce the length of the table the densities of herbs are reported in Table 6 as the sum of pairs of plots. As stated above the cinder flat at the base of the cone, plots 1 to 12, supported a sparse pine forest, with a considerable population of the shrub Fallugia. Herbs in this forest (Fig. 2A) included two grasses, Andropogon and Bouteloua, which were also present up the incline of the cone for a distance of about 50 meters. The main expanse of the south-facing slope where trees and shrubs were nearly absent, plots 21 to 60, was populated mainly by the herbs Physaria, Phacelia, Mentzelia, Gilia, and Euphorbia fendleri. They thinned out appreciably in plots 42 to 60 but increased in number in the final 50 m at the summit, which was also a zone of

TABLE 5. Density of shrubs in consecutive 10 m X 10 m plots (divisions of transect) on south side and base of Sunset Cone. Cone slope begins with plot 12. No shrubs present in omitted numbers.

Plot number	<i>Chrysothamnus nauseosus</i> var. <i>graveolens</i> (Nutt.) Hall.	<i>Eriogonum aureum</i>	<i>Palladia paradoxa</i>	<i>Ribes cereum</i>
68	-	11	98	-
67	-	4	171	-
66	-	3	20	-
65	-	-	45	-
64	-	1	157	-
63	-	-	176	-
62	-	-	127	-
61	-	1	333	-
60	-	-	130	-
59	-	-	-	-
58	-	-	-	-
21	-	-	46	-
20	-	-	168	-
19	-	-	32	-
18	-	-	175	-
17	-	-	16	-
16	-	-	79	1
15	3	-	53	-
14	2	-	21	-
13	2	-	-	-
12	-	-	-	-
11	-	-	-	-
10	-	-	86	-
9	-	-	330	-
8	-	-	434	-
7	-	-	296	-
6	-	-	216	-
5	-	-	271	-
4	-	-	138	-
3	-	-	173	-
2	-	-	259	-
1	-	-	209	-

TABLE 6. Density of herbs in 2 m wide transect, south side and base of Sunset Cone; each value is sum of two 2 m X 10 m plots. Cone slope begins with plot 12. 6/29-7/10/64.

Plot number	<u>Andropogon hallii</u>	<u>Aster canescens</u> Pursh.	<u>Bouteloua gracilis</u>	<u>Brickellia californica</u> (Torr. and Gray) Gray	<u>Eriogonum capitatum</u> (Dougl.) Greene	<u>Euphorbia fendleri</u>	<u>Euphorbia lurida</u>	<u>Gallium rothrockii</u>	<u>Gilia aggregata</u>	<u>Kuhnia rosmarinifolia</u> Vent.	<u>Mentzelia pumila</u> (Nutt.) Torr. and Gray	<u>Oenothera caespitosa</u>	<u>Opuntia compressa</u> var. <u>macrorhiza</u>	<u>Pentstemon barbatus</u>	<u>Pentstemon clutei</u>	<u>Phacelia integrifolia</u>	<u>Physaria newberryi</u>	<u>Senecio spartioides</u> Torr. and Gray	<u>Sitanion hystrix</u>	<u>Verbascum thapsus</u> L.
67-68	7	-	-	-	7	14	-	-	5	-	-	-	-	3	-	6	5	-	16	-
65-66	-	-	-	-	-	18	-	-	6	-	3	-	-	-	-	15	28	-	-	-
63-64	-	-	-	-	1	2	-	-	3	-	1	4	-	-	-	6	21	-	-	-
6-2	-	-	-	-	-	-	-	-	3	-	1	-	-	-	-	1	33	1	-	-
59-60	-	-	-	-	-	11	-	1	5	-	-	4	-	-	-	3	28	-	-	-
57-58	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8	-	-	-
55-56	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6	-	-	-
53-54	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	4	-	-	-
51-52	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7	-	-	-
49-50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	4	-	-	-
47-48	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	20	18	-	-	-
45-46	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	36	16	-	-	-
43-44	-	-	-	-	-	-	-	-	4	-	-	-	-	-	-	19	13	-	-	-
41-42	-	-	-	-	-	-	-	-	14	-	19	2	-	-	-	41	10	-	-	-
39-40	-	-	-	-	-	-	-	-	10	-	59	5	-	-	-	130	18	-	-	-
37-38	-	-	-	-	-	-	-	-	-	-	9	-	-	-	-	13	11	-	-	1
35-36	-	-	-	-	-	-	-	-	-	-	4	-	-	-	-	18	28	-	-	-
33-34	-	-	-	-	-	15	-	-	3	-	11	-	-	-	-	307	26	-	-	8
31-32	-	-	-	-	-	28	-	-	2	-	31	4	-	-	-	189	18	-	4	-
29-30	-	2	-	1	-	20	-	-	2	-	15	2	-	-	-	68	24	-	10	1
27-28	-	-	-	-	-	22	-	1	5	-	5	-	-	-	-	58	23	-	6	-
25-26	-	-	-	-	-	-	-	-	-	-	18	-	-	-	-	-	11	-	-	-
23-24	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	5	-	-	-
21-22	-	-	-	-	-	-	-	-	-	-	7	-	-	-	-	-	1	-	-	-
19-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17-18	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	2	-	-	-
15-16	2	-	12	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13-14	30	-	88	2	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-
11-12	94	-	12	5	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9-10	4	-	69	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7-8	-	-	22	1	-	-	-	-	-	-	-	1	1	2	-	-	-	-	-	-
5-6	-	-	71	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-4	-	-	14	-	1	-	-	-	-	1	-	7	-	2	2	-	-	-	-	-
1-2	-	-	5	-	-	-	7	-	-	2	-	-	-	4	-	-	-	-	-	-

greater density of shrubs. Fig. 2B illustrates the density of herbs in one part of the south slope of the cone, but not within the transect.

Old Cones Near Sunset

There is an old, rather low, unnamed cone (or cones) SSE from Sunset Cone on which a thick mantle of Sunset ash and cinders still lies. The present condition of its vegetation is evident in Fig. 3E. There are no trees on the peaks, where plants are chiefly herbs, similar to those on Sunset. Trees are confined to depressions between the peaks, where moisture conditions are more favorable than on the summit. The lighter color of the surface under trees, as seen in the figure, compared with that on treeless peaks, denotes the presence of a layer of litter, mostly pine needles. The litter aids in soil formation and in water retention, serves as food for microorganisms, and results in the production of organic acids which further the weathering of ash and cinders.

Three other old cones lie in a row NW from Sunset Cone, between it and O'Leary Peak. The three cinder cones can be seen in Fig. 3B, with taller O'Leary Peak in the distance. Cone 82 lies just beyond the highway; 83 is next, and the top of 141 is visible just beyond. Their positions are given also in Fig. 1.

Cones 82 and 83 are almost treeless; 82 has a forest of ponderosa pine on the northeast, which is its steepest side. The forest reaches just to the summit, as can be noted in Fig. 3B. Fig. 3C shows outcrops of old lava on the south side of cone 82. Grasses and shrubs grow at the contact of the cinders (from Sunset Cone) and the older lava, but do not grow elsewhere. Conditions in the contact zone are apparently more favorable for plants than on lava alone or on ash or cinders alone. The following seems to be a reasonable assumption. Water and snow would concentrate in the zone; disseminules would lodge there; and the lava outcrop would act as a wind-break

to reduce evaporation. The fact of more favorable conditions at the juncture of lava and ash or cinders was also observed repeatedly on the Sunset lava flows.

Cone 83 has ponderosa pine at its north base and ponderosa and pinon pine at the summit where the Sunset ash has been eroded away, exposing older soil. Fig. 3D shows some wind-bent pines at the summit. The edge of the shrubs, in the foreground and at the left, coincides almost precisely with the contact of old soil at the right and Sunset ash at the left. This demonstrates the superiority of older, weathered ash and cinders over the younger, less-weathered Sunset cinders as a soil for plants.

Cone 141 was observed only superficially. Being farther from Sunset Cone than 82 and 83 it had a thinner layer of ash, which may explain why it had more vegetation than either of the other two. The south slope supported only herbs but other sides, up to the summit, were forested.

Lennox Crater (Fig. 1) was still completely mantled by Sunset ash but the layer must have been thin because the cone was forested everywhere in 1964, except in its crater.

CONE 48

Cone 48 lies SW from Lennox and is far enough from Sunset Cone so that any influence which the eruption may have had is no longer evident. It is smaller than Sunset Cone, 650 feet high compared with 1000 for Sunset; it is symmetrical and the angle of its slope is about the same as that of Sunset. Its crater is toward the west side,

The cone was completely forested in 1964. A ponderosa pine forest covered the north half, from base to summit, and continued on the east to 35 degrees south of east. The southwest quadrant plus 55 degrees of the southeast, was covered with pinon-juniper forest. Some lumbering had been done on the

flat at the north base of the cone, and at the extreme lower north slope. For that reason the transect was begun 60 feet above the base.

Nearly every ponderosa pine tree on the north slope had a fire scar at its base on the up-cone side, but no trees were killed. There was a thick mantle of litter in the ponderosa pine forest and the fire-scars resulted from litter-burning. It is not known what started the fires but lightning is suspected. There was almost no litter on the south slope in the pinon-juniper forest, and almost no signs of burning were seen.

Many of the ponderosa pine trees were larger than any of those on Sunset Cone. They were taller, and the trunks were longer and freer of branches, and they more nearly approached the form of the normal ponderosa tree than did those on Sunset Cone. A comparison of basal areas for ponderosa pine in Tables 1 and 7 shows that in fewer plots on Cone 48 there was greater basal area.

Vegetation on Cone 48 was analyzed in a transect running from the north base, over the cone, to the south base. This was similar to the analyses of Sunset Cone, except that the ages of trees were not determined.

It is believed that the vegetation type on Cone 48 is the type which will in time come to occupy Sunset Cone, if the climate does not change and cause it to develop to some other. Cone 48 has developed to a condition of physiographic climax and, barring some change in environmental conditions, it can be expected to continue in its present vegetation type. Because the cone presages the future vegetation of Sunset Cone, and illustrates physiographic climax for the region, it seemed important enough to describe its vegetation in a quantitative manner.

The densities of trees in the 10 m X 10 m plots on the north side of Cone 48 are recorded by diameter size-classes in Table 7. The data show that there was good representation in nearly all size-classes, with the smaller

sizes having the greatest population. This shows that the forest was reproducing and maintaining itself. The upper part of the cone showed an increase in the number of trees under 10" diameter, and fewer in the large classes. This is presumably a result of less favorable water balance toward the top of the cone. It is interesting that there was no increase in pinon pine in the upper levels of the cone. Not a single tree seedling of any kind (1964 plant in cotyledon stage) was found on Cone 48. But the numbers of small trees on the cone indicates there is seed germination and seedling survival in some years. Pinon pine was a minor constituent of the forest as is indicated by the small basal area of that species.

The south side of Cone 48 was earlier described as a pinon-juniper forest but Table 3 indicates that juniper was a minor member; there were only two juniper trees in the transect. One was nearly 40" diameter. There was actually more ponderosa pine in the forest than juniper, both in numbers of trees and basal area. Pinon pine is the dominant tree, and has good distribution in several size-classes.

There was not one shrub in the transect on the north side of Cone 48. From the summit to the south base there was a considerable growth of Fallugia, and lesser amounts of five other shrub species. There was some skunk-bush (Rhus trilobata Nutt.), as well as currant, rabbit-brush, horse-brush (Tetradymia canescens Dc. var. inermis (Nutt.) A. Gray), and Menodora scabra.

The herbs which were present in the transect on Cone 48 at the time the field work was done are shown in Table 10. To permit compression of all 66 plots into a single table they have been combined, as indicated.

A comparison of herbs on Cone 48 with those on Sunset can be made from Tables 3, 6, and 10. There were 38 kinds of herbs on Cone 48, and 25 on Sunset. The herbs of first importance on the north slope of Cone 48 were

TABLE 9. Density of shrubs in consecutive 10 m X 10 m plots (divisions of transect) on south side of Cone 48. Plot 38 is at summit; 66 at base. Shrubs were absent from the north side of cone.

Plot number	<u>Chrysothamnus</u> <u>nauseosus</u> var. <u>inermis</u>	<u>Fallugia</u> <u>paradoxa</u>	<u>Menodora</u> <u>scabra</u> A. Gray	<u>Rhus</u> <u>trilobata</u>	<u>Ribes</u> <u>cereum</u>	<u>Tetradymia</u> <u>canescens</u> var. <u>inermis</u>
38	-	116	-	-	-	-
39	-	84	-	-	-	-
40	-	241	-	-	-	-
41	-	244	-	1	2	-
42	-	283	-	-	1	-
43	-	407	-	2	-	-
44	-	270	-	-	-	-
45	-	136	-	-	6	-
46	-	180	-	2	-	-
47	-	76	-	1	1	-
48	-	296	-	-	-	-
49	-	345	-	-	-	-
50	-	189	-	-	-	-
51	-	294	-	1	-	-
52	-	156	-	5	9	-
53	-	135	-	7	1	-
54	-	120	-	-	3	-
55	1	180	-	-	-	-
56	2	334	-	5	4	-
57	-	164	-	2	-	-
58	-	143	-	5	1	-
59	-	182	-	2	-	-
60	-	154	-	10	1	-
61	-	165	-	-	-	6
62	-	290	-	5	-	1
63	-	285	-	3	1	12
64	-	18	-	2	-	16
65	-	-	-	4	-	3
66	-	-	3	3	-	14

Androsace, Arabis, Brickellia, Commelina, Galium, Poa, Sitanion, and Thalictrum. Of these only Galium, Poa, and Sitanion were on the north slope of Sunset, but were not of great importance. Monardella had the highest density on Sunset but it did not occur at all on Cone 48. The presence of Thalictrum on Cone 48 indicated quite favorable moisture conditions.

Herbs with the highest densities on the south slope of Cone 48 included Euphorbia fendleri, Galium, Oxytropis, Phaseolus, and Sitanion. Of these only Euphorbia was important on Sunset. Oxytropis and Phaseolus were not present. The dominants on the north slope of Cone 48 were generally different from those on the south.

A comparison of Sunset Cone with Cone 48 indicates that the older cone supports more kinds of herbs, even though it is actually a smaller cone. Conditions of moisture on the north side of 48 appear to be more favorable than on the north side of Sunset. The greater age of Cone 48 has resulted in more weathering of ash and cinders producing a finer textured soil with greater water holding capacity. Nutrient supply in the older soil must also be more favorable.

Interconal Areas

"Interconal" here refers to the reasonably level areas around Sunset Cone, exclusive of Sunset lava flows, where ash and cinders still lie deep. The cinder flats at the base of Sunset are included; it is the area seen in the foreground in Fig. 3E. The photograph was taken from the side of Sunset Cone. Interconal areas are usually forested with ponderosa pine, but there may be an occasional pinon pine or juniper present.

No quantitative measurements were made of ponderosa pine trees growing in such areas but the following general description is given. Trees are short in relation to stem diameter; they are widely spaced so crowns do not meet,

and the forest is open. Since trees are widely spaced natural pruning of limbs is slight and the branch-free trunk is short. Roots are shallow but they extend far horizontally, so roots from adjacent trees meet, and all area at root level is occupied. This results in what has been called "root closure without crown closure." Wind-throw is common; whether this is because roots are shallow, or because volcanic cinders and ash offer little support, is not known.

Lava Flows

Hodges (1962) has separated the Bonito lava flows into two categories, primary and secondary, or before and after cinder cone eruption. Primary lava has considerable ash on it, secondary does not. I believe that if the full history of the flows were known it would be found that they are of more than two ages. The quantity of ash on different flows may differ considerably, and the amount of weathering seems to vary quite a bit. But because the lava flowed along such a maze of channels the result has been great confusion and it may never be possible to separate flows into more than two groups.

Plants on flows differ greatly in number and kind from place to place, much more than on cinder cones. The conditions influencing plants on lava are amount of aeolian material, the density or porosity of the lava, and the surface features--such as crevices, fissures, and folds. Lichens observed on Bonito flows were all crustose in character and were confined to lava rock surfaces. Some surfaces had almost no lichens; at the other extreme were some where lichens colored almost every bit of exposed lava and there was 100% lichen coverage.

The lava with the greatest density of shrubs and herbs was about 50% ash covered, that is, about half the lava was covered and half protruded above the ash. The most advantageous situation for plants to begin, as was stated earlier, is at the flow-ash contact, and flows with 50% coverage apparently

have the maximum contact area. Some plants which became established along the flow-ash contact were able to advance further into the ash area. Fallugia was most successful of all plants observed in that respect. Fig. 3F illustrates it.

Two transects, each 2 m wide, but of different lengths, were laid out in the locations identified as Tr 1 and Tr 2 on Fig. 1. A summary of the vegetation in them, with comments on the habitats, will show the great variation in microhabitats and in plants occupying them.

Transect 1

Transect 1 was begun at the extreme western edge of the Bonito Flow, on secondary lava, and continued eastward for 335 m, to an island of primary lava, or a kipuka; it continued across the kipuka for 130 m. Hence, on the younger, or secondary, lava the area of the transect was 670 m^2 , and on primary, or older lava, 260 m^2 . The two parts of the transect will be discussed separately, the younger first.

Secondary Flows

Notes were made in the field of the estimated coverage of lava by crustose lichens and the following percentages were recorded: 5%, 50%, 2%, 1%, 3%, 25%, 1%, 10%, in that order along the transect. This shows the great difference in lichen growth from place to place, on the same flow. Mosses were quite unimportant in the transect. Ten clumps were noted as being present, with an aggregate coverage of about 290 in.^2 . The only species of moss identified was Ceratodon purpureus (Heder.) Brid.

Any aeolian material on this younger flow had filtered down into crevices and it would be difficult to assign a percentage to the ash-covered portion. It would be only 1 or 2%.

Two species of ferns were in the transect, Dryopteris filix-mas (L.) Schott., shield fern, and Chellanthus feel Moore, the lip fern. Two plants of the first species were present in a crevice at the base of a 45 degree lava

wall where run-off water collected. Ten individuals of lip fern were present, distributed in three groups, all in crevices in walls of fissures 1 to 10 ft in depth. Such fissures have temperatures lower in the summer than lava surfaces and moisture relations are better.

Ten species of seed plants, with only a few individuals of each, were present on the secondary lava. Nine species were restricted to fissures, usually deep enough so little, or none, of the plant reached to the general lava surface. The nine species, with number of each, were: Andropogon hallii - 20; Arabis fendleri - 2; Brickellia californica - 2; Forestiera neomexicana Gray - 2; Heuchera parviflora var. flavescens (Rydb.) Rosendahl et al - 1; Holodiscus dumosus (Nutt.) Heller - 7; Paricome caudata Gray - 4; Phacelia integrifolia - 6; Verbascum thapsus - 5. Among these 9 species Heuchera and Holodiscus were restricted to the deepest fissures and appeared to be the most water demanding of the group. Fallugia was present in small numbers, only 6 individuals, and grew in narrow, shallow crevices, so the entire plants were exposed above the lava. This position seems to be in keeping with the situations where it was found on cinder cones, open areas with high light intensity.

Primary Flows

Looking casually across the secondary lava flow just discussed the only plants one would see would be an occasional pine tree. The shrubs and herbs were below the general lava surface and were seen only at close range. In contrast, the primary lava covered by transect 1, the kipuka or island, was quite different. As may be seen in Fig. 4A there were numerous trees and shrubs; closer observation would reveal herbs and lichens.

The surface exposure was about 50% ash and 50% lava, the optimum combination for seed plants on lava. As stated above the usual site for seed germination is at the juncture of ash and the lava outcrop. The ash supplies anchorage for root systems; the lava must supply water run-off, and possibly

may be effective in reducing wind velocity and evaporation.

The exposed lava here had almost complete coverage by lichens and 100% coverage was recorded for some parts.

Fallugia was by far the most abundant plant in this part of the transect; there were 188 in the 260 m² area. Other shrubs were: rabbit-brush - 2; and Holodiscus - 1. There were 3 species of trees: 1 Pinus ponderosa - 9" d.b.h.; 1 Juniperus monosperma (Engelm.) Sarg. - 1" d.b.h.; and 5 trembling aspen (Populus tremuloides Michx.), all 1 in., or less, in diam. Special mention will be made of aspen in Sunset Crater in a later section.

There were a few individuals of each of 3 species of herbaceous seed plants; Andropogon hallii - 7; Aster canescens - 1; Bahia dissecta - 2; Brickellia californica - 1; Echinocereus fendleri (Engler) Rumpel - 4; Senecio multilobatus Torr. and Gray - 1; Sitanion - 7; and Verbascum - 1.

The presence of the mesophyte, aspen, and the xerophyte, Echinocereus, in the same transect and only a few meters apart, points up the great diversity in water relations in different parts of the flow.

Mosses were again a minor constituent of the plant community. There were 5 clumps of Ceratodon, each about 10 cm across.

To give more information on the trees on lava flows, in this case the primary flow, a square plot, 64 m on a side, was laid out on the kipuka. This was the area shown in Fig. 4A. In it trees were counted and diameters measured. The ages of most ponderosa pines was determined. In the plot were 16 ponderosa pine, 7 piñon pine, 1 douglas fir (Pseudotsuga menziesii var. glauca Mayr. Sud.), and 1 Juniperus monosperma. A summary of the diameters and ages of 15 ponderosa pine follows: 1 tree 3.5" diam, 44 yrs; 8 trees 5"-6" diam, 28 to 102 yrs; 1 tree 8.25" diam, 73 yrs old; 4 trees 9.5" to 11.5" diam, 78 to 189 yrs; 1 tree 16" diam, 190 yrs old.

The trees on this flow had the aspect which was earlier described for ponderosa pine in the Sunset Crater area; little height in relation to stem diameter, and limbs continuing close to the base. See Fig. 4A. These trees were uneven-aged, and ranged from 28 yrs to 190 yrs. They had not grown exceptionally slowly, just as trees on Sunset Cone had not. The trees are widely separated in space and age. It appears that the trees started over a considerable time, and never in quantity as is indicated by their uneven age. It is probable that there have been trees on this flow for much longer than 190 yrs, the age of the oldest one. It is also probable that the density of trees has not and will not change significantly, barring a change in climate.

Transect 2

The second transect, located as indicated in Fig. 1, was 690 m long, and cut across successive primary and secondary lava flows as indicated in Table II. The first segment, 446 m in length and consisting of approximately the eastern two-thirds of the transect, was on primary lava, with a deep mantle of ash and cinders. This segment of primary lava included a part of the Red Hills area. The eastern part of that area, but not any part of which was in the transect, is shown in Fig. 4C. This segment of transect had a surface composed of about 90% cinders and coarse ash, and 10% lava outcrops. The exposed lava was about 50% lichen-covered. The shrub Fallugia and the herb Mentzelia were the dominant plants on this portion of flow where ash was so deep. Mentzelia grew away from lava outcrops in open areas of ash and cinders. It is the herb seen in Fig. 4C. Elsewhere Mentzelia was abundant on the south slope of Sunset Cone. Fallugia was restricted largely to the edges of lava outcrops.

The other two sections of primary flow, 533 to 538 m and 639 to 644 m, were very short and totaled only 12 m. The ash cover on them was about 50%, rather than 90% as in the first part. In the area of the two segments, 24 m², there were 18 Fallugia, 10 Andropogon, and 25 Bouteloua.

TABLE II. Density of trees, shrubs, and herbs in different segments of transect 2. 1-446 m on primary lava; 447-532 m on secondary lava; 533-538 primary; 539-638 secondary; 639-644 primary; 645-690 secondary. S = seedlings.

	1-446 m Primary	447-532 m Secondary	533-538 m Primary	539-638 m Secondary	639-644 m Primary	645-690 m Secondary
Trees						
<u>Pinus ponderosa</u>	2 + 20	-	1 S	1 + 35	-	-
<u>Populus tremuloides</u>	4	-	-	-	-	-
Shrubs						
<u>Chrysothamnus</u>	1	-	-	-	-	-
<u>Fallugia</u>	182	10	5	3	13	-
<u>Holodiscus</u>	-	1	1	1	-	-
<u>Ribes</u>	1	-	-	-	-	-
Herbs						
<u>Andropogon hallii</u>	-	-	10	-	-	-
<u>Bahia dissecta</u>	19	-	-	-	-	-
<u>Bouteloua gracilis</u>	-	-	-	-	25	-
<u>Brickellia californica</u>	2	-	-	-	-	-
<u>Chellanthus faei</u>	-	3	-	-	-	-
<u>Galium</u>	-	-	-	1	-	-
<u>Gilia</u>	1	-	-	-	-	-
<u>Mentzelia</u>	677	-	1	-	-	-
<u>Muhlenbergia minutissima</u> (Steud.) Swallen	20	22	-	-	-	-
<u>Phacelia</u>	37	-	-	-	-	-
<u>Sitanion</u>	5	-	-	-	-	-
Moss						
(<u>Ceratodon</u>) Small clumps	1	6	-	5	2	-

The three segments of secondary flow had a total length of 232 m. Any aeolian material on them had sifted down into cracks and crevices and it was difficult to estimate ash coverage. It was probably not over 2 or 3%. Plants in the total area of 464 m^2 consisted of 13 Fallugia, 1 rabbit-brush, 2 Holodiscus, 1 Galium, 22 Muhlenbergia, and 11 small clumps of moss.

Thus 24 m^2 of primary flow had about as many plants as did 464 m^2 of secondary. There were a few ponderosa pine trees, plus some seedlings, on both primary and secondary flows, and a few aspens on the primary.

Age of Trees in Red Hills Area

A study of the ages of trees on lava with deep ash was made in the Red Hills area. Two figures illustrate. In Fig. 4C can be seen the eastern part where trees are few in number. The surface here is almost entirely red-colored clinders and there is little lava outcrop. The western part of it is shown in Fig. 4D. Here trees were more abundant and lava outcrops made up more of the surface area. Again there is pointed up the fact that the best conditions for most plants to become established, and this includes trees, were at the edges of lava outcrops. Most of the trees visible in Fig. 4D were located at the outcrops.

A rectangular area, $276 \text{ m} \times 455 \text{ m}$ ($125,580 \text{ m}^2$) was laid out, and trees in it were counted, diameters measured, and the ages of the larger ponderosa pine were determined. In the rectangle were 128 trees of all species and sizes. The average area occupied by each tree was 981 m^2 , or a square slightly over 31 m on a side. Actually trees were usually closer together than that because large areas had none. The areas seen in Figs. 4C and 4D were included in the rectangle.

The ages of 45 of the largest ponderosa pine trees are presented in 10-year age groups. The youngest tree was 10 years of age, the oldest was 189. Group 10-20 years: 4 trees; 21-30: 12 trees; 31-40: 6; 41-50: 3 trees;

51-60: 6 trees; 61-70: 1 tree; 71-80: 3 trees; 81-90: 1 tree; 91-100: 2 trees; 101-110: 1 tree; 111-120: 2 trees; 121-130: none; 131-140: none; 141-150: 1 tree; 151-160: 2 trees; 161-170: 1 tree; 171-180: none; 181-190: 1 tree.

The age distribution is well scattered, with the greatest number in the younger classes. There were fewer in older classes, and none as old as at the north and south bases of Sunset Cone. It appears that here, as was the case on the south side and summit of Sunset Cone and on the primary lava at the east end of transect 1, that the life expectancy of ponderosa pine is limited to not over 200 years.

Autecology of Certain Species of Plants in Sunset Crater

Autecology is the ecology of a single factor or a single species. In this report the second aspect will be considered, the ecology of a few important or interesting species. While no extensive quantitative studies were conducted on any species some observations were made which appear to be significant. These concerned three species of trees, ponderosa pine, Douglas fir, and aspen, and one shrub, Apache-plume (Fallugia). Ponderosa pine was the most abundant tree in the area and Fallugia the most abundant shrub.

Ponderosa pine

Two aspects of ponderosa pine in the Sunset Crater area are quite striking. One is the fact of its presence there, in the only slightly weathered volcanic ash and cinders, and on the lava flows. It is present in some places which would appear to be better suited to Pinus edulis, such as on the south slope of Sunset Cone, and again at altitudes below those normally occupied by ponderosa pine. A second interesting aspect is the physical form usually taken by ponderosa pine in the Sunset area, a short squatty tree with many branches and little natural pruning. The first aspect will be considered under

ecesis (germination and establishment) and one second under site quality.

Ecesis of ponderosa pine

Larson (1961) found that in northern Arizona ponderosa pine seeds may germinate in July and August, because it is then that a combination of adequate moisture and night-time temperatures above a certain minimum is most likely to occur. The fact that ponderosa pine was present on cone and flows is evidence that minimum requirements of moisture and temperature were met in certain times and places. I believe that water is the limiting factor for plants of most species growing in Sunset Crater, but it would seem to be easier to explain how water needs for trees are met than how temperature needs are met.

The north-facing slope of Sunset Cone has been described earlier as having the most favorable water relations of all sites on the Sunset Crater volcanics. Lowered insolation on the north slope was believed responsible for this. On the other slopes and at the summit of the cone trees were usually in slight depressions, or at least on level places. Most slopes of Sunset Cone, except where trees are most numerous on the north side, have developed a slight terrace-like profile, and that is where trees are. The terracing is usually the result of slumping and natural subsidence, but it is possible that animal trails helped cause some of the terraces. Such a level or slightly depressed surface would receive less insolation than a south slope and water would tend to run off less rapidly.

The very sparsity of trees on all slopes, except the north of Sunset, and on lava flows, must be a distinct advantage to the few that are there. There is little competition for water and nutrient, and probably none for light.

Colton (1945) called attention to the fact that ponderosa pine grows to lower altitudes near Sunset Crater than outside the influence of the volcano, and suggested that the Sunset ash acted as a mulch which improved moisture relations. I had little opportunity to study this problem but did use an

altimeter to determine the altitude of the last observed ponderosa pine tree along the road to Wupatki Monument, and found it to be at 6125 feet. At 6400 feet ponderosa and pinon pine were about equal in density. It appeared to me that proximity to lava rock outcrops, which would tend to concentrate rainwater and to hold snow, and a very sparse ground cover of herbs which offered little competition for water, could very well have been the reasons for the ability of ponderosa pine to grow at low altitudes.

It has been pointed out for two other basaltic lava areas that certain trees grow on lava when they do not grow on older soils adjacent to the lava. Lindsey (1951) stated that on basaltic lava near Grants, New Mexico, Douglas fir grows on lava and on the north slopes of cinder cones. It is absent on sites adjacent to the lava at comparable elevations, where ponderosa pine predominates. At lower elevations on lava ponderosa pine predominates. At Craters of the Moon in Idaho, limber pine (Pinus flexilis) grows on lava flows and on the north slopes of cinder cones. The densest growth on lava is on the roughest lava, where trees grow close to lava outcrops. It was concluded that moisture relations were improved close to lava outcrops. On older soils adjacent to the volcanic area limber pine was absent (Eggler, 1941).

Site Quality

The contrast in the form of ponderosa pine trees growing in Sunset Monument, with that of trees growing a few miles away, is striking. Sunset trees are not nearly as tall, the trunks have more branches, tops are often dead, and the rate of growth is less, particularly growth in height. The difference may be due to a difference in soil, or, it has been suggested verbally (none has published the opinion, to my knowledge), that the Sunset Crater ponderosa pine is genetically different, that it is a separate ecotype. Only transplant studies could determine if it is.

I have assumed that the Sunset Crater tree form is the result of poor

soil, inadequate water and nutrient. Acting on that assumption I have compared the height and age at $4\frac{1}{2}'$ for 64 trees in the transect on the north side and base of Sunset Cone with a standard Site Index developed by Professor Charles Minor of the Department of Forestry, Arizona State College.

In Fig. 6 the age at $4\frac{1}{2}'$ from the ground is designated on the horizontal axis, and the height in feet is indicated by the vertical. Professor Minor's lowest index values, 40 and 50, are drawn in for comparison. Because the Sunset trees are much older in relation to height than, apparently, were trees on which the site index curves were based the curves in Fig. 6 have a much steeper slope. Sixty of the 64 trees spotted in Fig. 6 show a site quality index below 40, the lowest on the index chart. Only one tree in the transect fell into the index range of 50. Hence if site is responsible for the slow growth in tree height, it is of very poor quality.

Other problems which also appear to be related to site quality are the cause for a timber line midway up the north side of Sunset Cone and the reason why ponderosa pine presently has a life expectancy not to exceed about 200 years on the south slope and summit of Sunset Cone and on all lava flows. There may be other factors involved, such as absence of an adequate amount of mycorrhizal fungus living symbiotically on and within the young roots of the pine. On the few small pine trees which I excavated fungi were present, so that did not seem to be a factor. Deficiency of water for prolonged periods of time, and nutrient deficiency are, I believe, the factors responsible for early death of most of the trees. On the north slope of Sunset Cone, near timber line, most pine trees fail to survive past the seedling stage; others die after a few years.

Douglas fir

Pearson (1931) stated that toward the upper limits of the yellow pine zone (7000'-8000') limber pine, Douglas fir, and white fir become associates.

Thus it may be a little unexpected to find an occasional Douglas fir tree on the Sunset lava flows, which are all at approximately 7000' altitude. The tree illustrated in Fig. 4B was the finest specimen seen. It grew at the edge of a secondary lava flow, at the base of an old cone. Water must concentrate in this depression. At least two smaller Douglas fir trees were seen on Sunset Cone.

Populus tremuloides

This tree which never grows to large size generally occurs in the Douglas fir zone. Again it was surprising to find it on the Sunset Cone volcanics. It was seen on Lennox Crater, on Cone 82, and on primary lava flows. It seemed to always follow the same pattern of growth, stem death, and sprouting anew from horizontal roots. No stem lives more than a few years, and then it dies, presumably from lack of water. But underground, horizontal roots remain alive and new stems grow up. Figs. 4E and 4F illustrate what happens.

Fallugia

Fallugia uses the same method as Populus for propagation and uses it much more successfully. On lava flows trees, shrubs, and many herbs can become started only at the contact of lava outcrop and ash deposit. Most species are permanently restricted to that habitat, but Fallugia sends out roots horizontally, about 2" beneath the ash surface, and stems sprout upward from the roots. Hence Fallugia is able to survive and spread on ash deposits.

Summary and Discussion

The Sunset Crater volcanic ejecta, in the form of a cinder cone approximately 1000 feet high, and two series of lava flows, were formed about 900 years ago. The material is all basaltic in character. The flows usually are broken and resemble aa, but occasionally they are more like pahoehoe.

The elevation of the flows is about 7000' and hence the cone rises to 8000'. The summers at the altitude and latitude are short and precipitation

Is usually under 20" per year, much of it falling as snow. The Sunset Crater area is in the ponderosa pine belt.

Vegetation has invaded the different volcanic materials at greatly different rates. The lower half of Sunset Cone on the north side has a ponderosa pine forest in which trees are up to 400 years old. The forest is more open than would be a "virgin" ponderosa pine forest on older soils elsewhere in northern Arizona. The trees grew less rapidly than they would have in average quality sites elsewhere. The ponderosa pine trees differ especially from those not on Sunset volcanics in their short stature. The forest on the north of Sunset Cone continues to the east side, but it is less dense. On the west trees are even more scattered but they are present from the base to the summit. The south slope has almost no trees; there is a zone of trees on the south rim of the crater; there are trees in the crater also.

Lava flows are of two ages. Some which are described as primary have a considerable mantle of ash; usually about 50% of the flow is covered. Secondary flows have little ash on them and are usually 1 to 2% covered. Herbs, shrubs, and trees are present on all flows but the primary flows generally have several times as many individuals as secondary. This is especially true of the shrub Fallugia which is relatively abundant on primary and almost absent from secondary. Otherwise there is not a significant difference between the species composition on the two ages of flows.

The differences between the two types of flows in regard to amount of ash and numbers of plants are not due to the greater age of the one kind of flow. The age difference might have been as little as a few months. The basic difference is that ash was wind-borne during the eruption of Sunset Cone and some flows were extruded before the cone eruption, and some after.

The question might be asked if a period of preparation and soil making of cinder cone and lava flow was necessary before plants could become

established? In some places, in more humid climates, lichens and mosses have been reported as pioneers on rock surfaces and prepare the way for vascular plants. Lichens and mosses are not now important on Sunset Cone and flows and there is no reason to believe they ever have been. Almost any taxonomic category of plant could be the first plant to grow in a particular microhabitat, provided moisture was adequate.

On the cinder cone the north slope received less insolation, and hence moisture relations were better than on the south slope and probably pine trees got started sooner there. On lava flows the best moisture relations are at the juncture of ash deposit and lava outcrop and that is where the plants have gotten started and have continued to be concentrated.

Under the present climatic regime the rate of soil making and of increase of plants is extremely slow. Several more centuries will elapse before Sunset Cone is completely forested. The forest on the north side will be dominated by ponderosa pine and that on the south by pinon pine and juniper. The rate of change on lava flows will be even slower than on the cinder cone. Under the present conditions of semi-aridity accumulation of organic matter from dead plant remains is extremely slow. The other possible source of soil material is for more aeolian material to be added to what is there. But the rate seems to be extremely slow. Mechanical and chemical disintegration of lava occurs at such a slow rate that it is relatively insignificant.

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Fig. 1. Sunset Crater and some adjacent old volcanic cones; four cones are designated by numbers only: 48, 82, 83, and 141. Sunset Cone is at right; primary flow and secondary flow comprise Bonito Flow from Sunset Cone. Tr 1 and Tr 2 locate 2 m wide transects on lava flows.

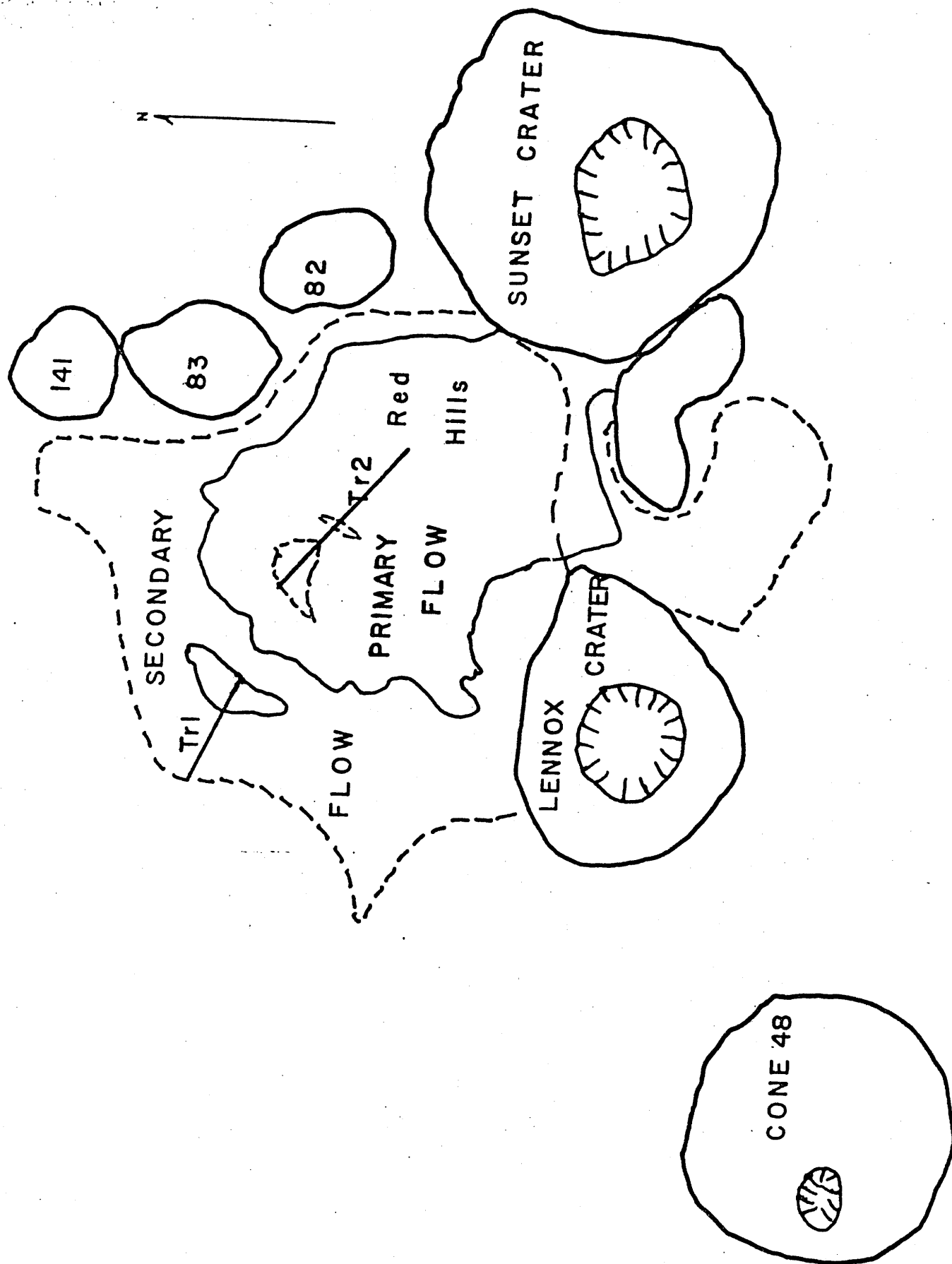


FIG. 1

Fig. 2.

- A. Sunset Cone from south base; ponderosa pine at base and summit and two or three trees on south slope. 7/6/64.
- B. Aspect of herbs on treeless part of SW slope of Sunset Cone; Physaria plants in foreground and left rear; Mentzelia left center beside pencil. Shrubs are Fallugia and Chrysothamnus. 7/6/64.
- C. North side of Sunset Cone in pine forest; plot 39; 3' tall limber pine in center. 7/17/64.
- D. Sunset Cone from east side; ponderosa pine forest extends about half way to summit; above forest are grasses and shrubs. 7/6/64.
- E. Sunset Cone from SE side. Densest ponderosa pine growth on level area. 7/6/64.
- F. Sunset Cone from west. Ponderosa pine trees grow scatteredly over whole side of cone but do not form a forest. Some trees show the influence of prevailing winds from SW, right, and have wind-trained branches bent toward the left. 7/6/64.