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MORPHOMETRIC ANALYSIS OF CINDER CONE DEGRADATION

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ABSTRACT

Wood, C.A., 1980. Morphometric analysis of cinder cone degradation. J. Volcanol. Geotherm. Res., 8: 137—160.

Measurements of the geometry of cinder cones can be used to determine the morphological effects and rates of degradation. Cinder cones in the San Francisco volcanic field, Arizona (where radiometric dates and stratigraphic studies have determined cone ages) decrease in height, height/width ratio and slope through time. The ratio of crater diameter to cone basal diameter does not appear to change with degradation, nor, as suggested previously, with chemical composition or particle size. Similar results obtained for cinder cones in Nevada, Oregon, Manchuria, Italy and Reunion suggest that the morphometric patterns of degradation are similar for all cinder cones. The rates of degradation vary tremendously, however, with rainfall and temperature being perhaps the most important factors. Since the initial geometrics of cinder cones are remarkably similar, degraded cones may be ideal gauges of long-term climatic change.

Degradation can be readily modelled for two cases: burial of cinder cone flanks by subsequent lava flows, and erosion and mass wasting. Although the former is locally important, degradation appears to occur principally by the second process: cinders weather to clay, which is gullied by rainfall, with the debris sliding downslope. Such erosion and mass wasting produces a degradation curve in general agreement with observations. Erosion rates can be accelerated orders of magnitude, however, by the mantling of old cones with easily eroded ash deposited during nearby eruptions. Comparison of cinder cone isopach radii and cone separation distances suggests it to be a common effect.

INTRODUCTION

Morphologic studies of volcanoes have had few adherents in recent decades, but the current need to decipher the origins of various conical structures seen on spacecraft images of the Moon, Mars, Venus and Io has led to a fresh appreciation of the relationships between magma composition, eruption style and volcano morphology. This revival of interest in morphology also reflects the realization that the life history of a volcano is preserved in its structure, stratigraphy and form, as well as in the chemistry of its lavas. Recent morpho-

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logical studies differ from typical previous investigations in the employment of quantitative measures of morphology and statistical comparisons of many volcanoes. The most ambitious statistical study of the morphometry of volcanoes is Pike's (1978) compilation and analysis of the dimensions of 655 volcanoes.

The present study examines the effects and processes of erosion of cinder cones, perhaps the simplest and most common volcanic landform. This investigation accepts a simple geometric model (Fig. 1) of fresh cinder cones (Porter, 1972) that appears to be a satisfactory description for a large number of cinder cones around the world (Wood, 1980). Aberations to this standard fresh cone morphology (e.g. elongate cones formed along fissures, craterless cones, collapsed cones) are thought to be relatively infrequent and are not considered.

Previous studies of cinder cone degradation include Colton's (1936, revised 1967) classic account of cone morphology in the San Francisco volcanic field, Arizona, and the quantitative assessments of cone erosion in New Mexico (Scott and Trask, 1971), Mexico (Bloomfield, 1975) and Papua New Guinea (Ollier and Brown, 1971). Additionally, studies of erosion processes and rates were reported for two Mexican cinder cones born in 1943 (Paricutin: Segerstrom, 1950, 1966) and 1952 (Barcena: Richards, 1965).

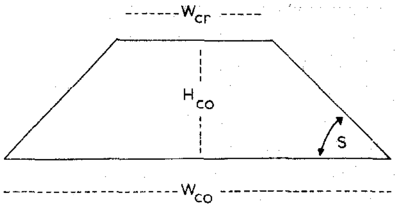

Fig. 1. Schematic diagram illustrating measured values for cinder cones: W_{cr} = crater diameter; W_{co} = cone basal diameter; H_{co} = cone height; S = average cone slope.

CINDER CONE DEGRADATION IN THE SAN FRANCISCO VOLCANIC FIELD

Although data on cinder cones from various regions of the Earth are used in the present study, a major focus is the cinder cones of the San Francisco volcanic field (SFVF) of northern Arizona (Fig. 2). This field is well suited for morphological investigations because it contains hundreds of cones of differing degradational states, with lava compositions ranging from basalt to basaltic andesite to benmoreite. More important, substantial amounts of geologic mapping, radiometric dating and chemical analyses, published and in progress, are available. I have supplemented this information with limited field observations.

Colton (1967) classified cinder cones in the SFVF into five degradation stages based on the intensity of erosional modifications. The youngest cones

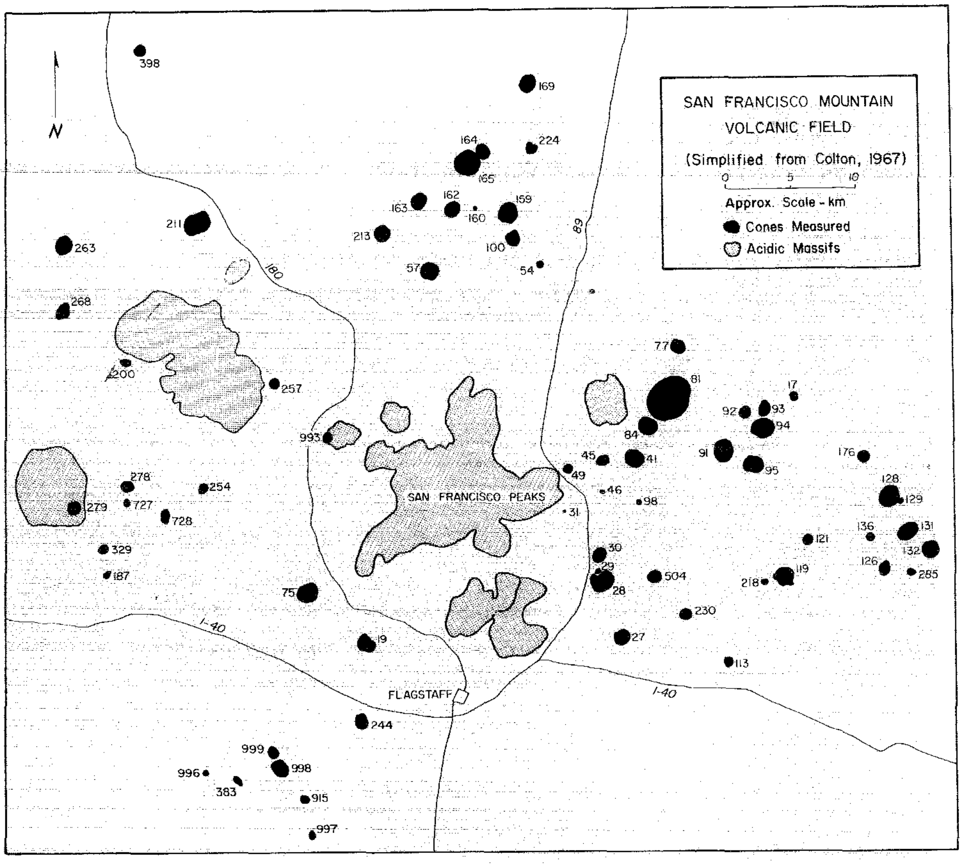

Fig. 2. Map of the major features of the San Francisco volcanic field, simplified from Colton (1967), identifying measured cinder cones.

(Stage 5) are steep and lack gullies, and scoria fragments are little oxidized. Stage 4 cones are similar to those of Stage 5 in terms of the general lack of large-scale erosion, but oxidation has sufficiently decomposed cinders to form clay and to support sparse vegetation. Gullies are characteristic of Colton's Stage 3 cones, while Stage 2 examples have suffered more severe erosion that reveals inner dikes and ridges, subdues the rim, and provides soil for mature vegetation. Complete stripping away of a cone's fragmental material leaves a plug, Colton's Stage 1 cone. These degradation stages are similar to the sequence developed by Kear (1957) for larger volcanic cones (composite volcanoes) in New Zealand.

On the basis of detailed stratigraphic mapping and petrological studies, Moore et al. (1976) redefined Colton's SFVF sequence, and Damon et al. (1974) have anchored this new sequence to a series of radiometric dates on associated lava flows; Table 1 compares Colton's stages with the newer, dated sequence and Fig. 3 illustrates the main cone types. The grouping of


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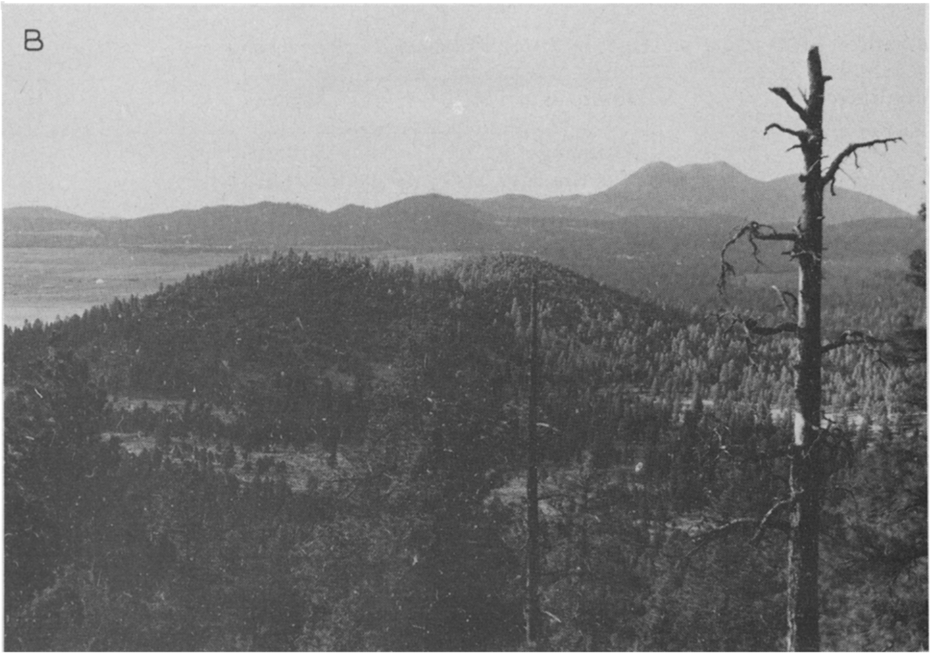


Fig. 3. Three stages in the degradation of cinder cones in the San Francisco volcanic field. A. Fresh cone: S.P. Crater of Merriam age; photograph by D.P. Cruikshank. B. Moderately degraded cone: Cone V30 of Tappan age. C. Severely degraded cone of probable Rim Basalt or Woodhouse age.

TABLE 1

Comparison of degradation stages in the San Francisco volcanic field

Colton stage	Moore et al. (1976)	Age (m.y.)
5	Sunset age	0.001
4	Merriam age	0.05
3, 2	Tappan age	0.2–0.7
2	Woodhouse age	0.8–3.0
1	Rim Basalts age	3 –4
1	Cedar Ranch age	5.5–6

volcanic activity into approximately discrete episodes (10^3, 5×10^4, 5×10^5, 2×10^6 years ago) is perhaps an artifact of incomplete sampling, but permits statistical study of cinder cone erosion, always assuming that the older cones had initial geometries identical to the young fresh cones (Fig. 1).

In Fig. 4 variations in cone heights (H_{co}) with basal diameters (W_{co}) are compared for SFVF cones of different age groups, as mapped by Moore and Wolfe (1976). The dimensions of these and other cones discussed below

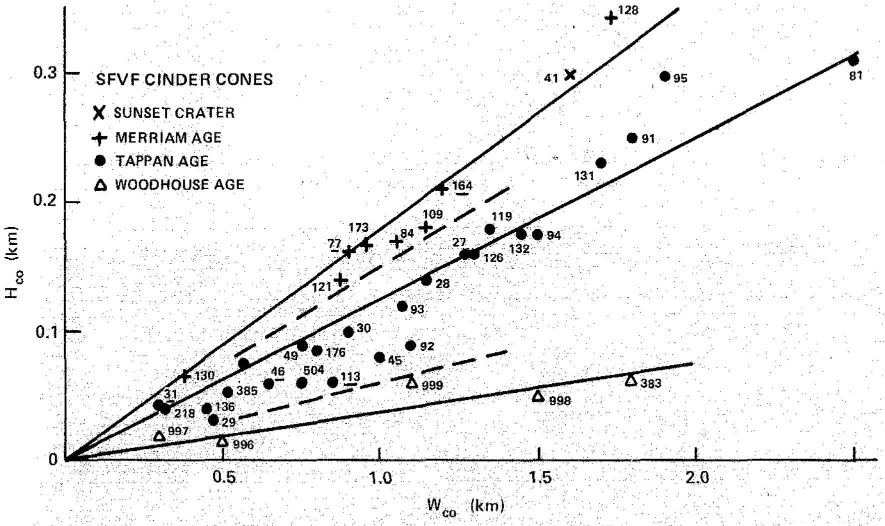


Fig. 4. Cone height (H_{co}) vs. basal width (W_{co}) for 38 cones of assigned stratigraphic ages (Moore and Wolfe, 1976) in the eastern portion of the San Francisco volcanic field. The solid lines are least squares fits to Sunset plus Merriam, Tappan, and Woodhouse age cones., and the dashed lines are proposed as critical values that divide San Francisco volcanic field cones into different age groups. Cone 95 appears unusually well preserved for a Tappan age cone. Underlined cone numbers are basaltic-andesite to benmorite composition cones, the remainder are basaltic. Cone numbers are from Colton (1967) except for numbers greater than 900 which were assigned informally.

are listed in appendices in Wood (1979a). Cones classified as Sunset and Merrian age (< 100,000 years) have H_{co}/W_{co} relations that are virtually identical to those of fresh cinder cones on Mauna Kea, Hawaii (Fig. 1, and Porter, 1972):

$$H_{co} = 0.179W_{co} \qquad (N = 9; r = 0.98) \tag{1}$$

Tappan age cones (0.2—0.7 m.y.) are significantly lower:

$$H_{co} = 0.125W_{co} \qquad (N = 24; r = 0.97) \tag{2}$$

and the few Woodhouse age cones (0.8—3.0 m.y.) measured are lower yet:

$$H_{co} = 0.038W_{co} \qquad (N = 5; r = 0.90) \tag{3}$$

No cones of Cedar Ranch age (about 5.5. m.y.) have been measured.

The systematic differences in H_{co}/W_{co} ratios for cones of different ages offer the opportunity of classifying cones into age groups in areas of the SFVF not yet mapped. Thus, Fig. 4 includes not only least squares fits (solid lines) to cone data, but also dashed lines that separate cones into the three age groups. Merriam and Sunset age cones have H_{co}/W_{co} ratios greater than 0.15, Woodhouse cones have ratios less than 0.06, and Tappan age cones occupy the intermediate field.

In Fig. 5, 28 cones from the northern and western portions of the SFVF

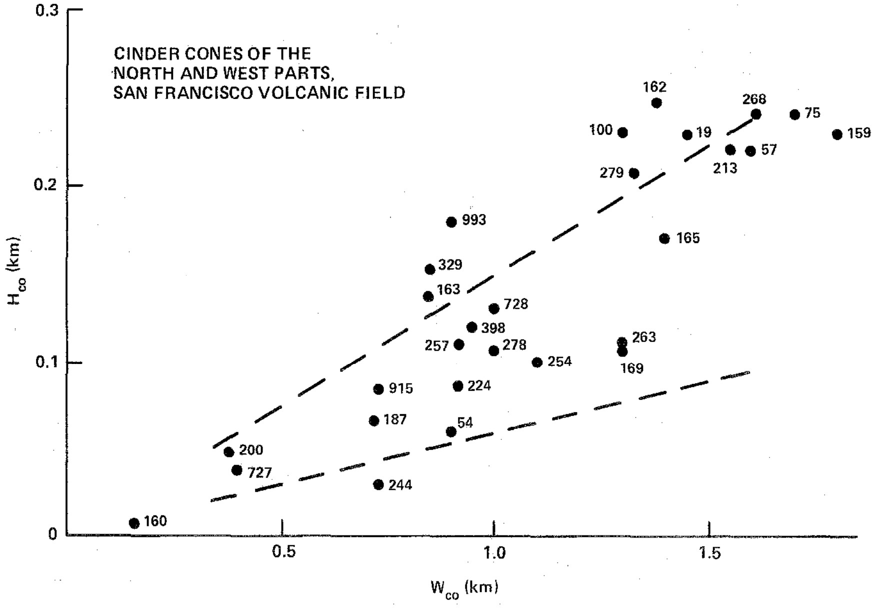


Fig. 5. Cone height vs. basal diameter for 28 cones of unknown stratigraphic ages in the northern and western portions of the San Francisco volcanic field, with the critical H_{co}/W_{co} lines that separate age groups in the mapped eastern portion of the field (see Fig. 4). Most of the cones are morphologically similar to Tappan age cones, but some are as fresh as Merriam age.

(for which geologic maps have not yet been published) are plotted as well as the H_{co}/W_{co} lines that divide the mapped cones according to age groups. As for the eastern part of the field, most of the cones appear to be Tappan age. Three of the cones in Fig. 5 that are considered Tappan age on the basis of morphometry have ages (P.E. Damon and E.H. McKee, unpublished) of 0.44 (V75), 0.46 (V254) and 0.53 m.y. (V257), in agreement with dated Tappan cones in the eastern part of the field. Possible Merriam age cones north and west of Flagstaff have greater vegetation cover than Merriam age cones in the eastern portion of the SFVF. This may be due to the greater (present day) rainfall (500—640 mm) in the north and west compared to the east (380—500 mm; Sellers and Hill, 1974). Radiometric dates (P.E. Damon and E.H. McKee, unpublished) for two cones of possible Merriam age in the western SFVF (0.33 m.y. for cone V19, and 0.35 m.y. for V993) are greater than for dated Merriam cones in the eastern part of the field, and are typical of Tappan age cones. A third date of 1.15 m.y. for V279, a cone of Merriam age according to morphometry, is perplexing; such an age normally corresponds to Woodhouse age cones in the eastern SFVF (Table 1). V279

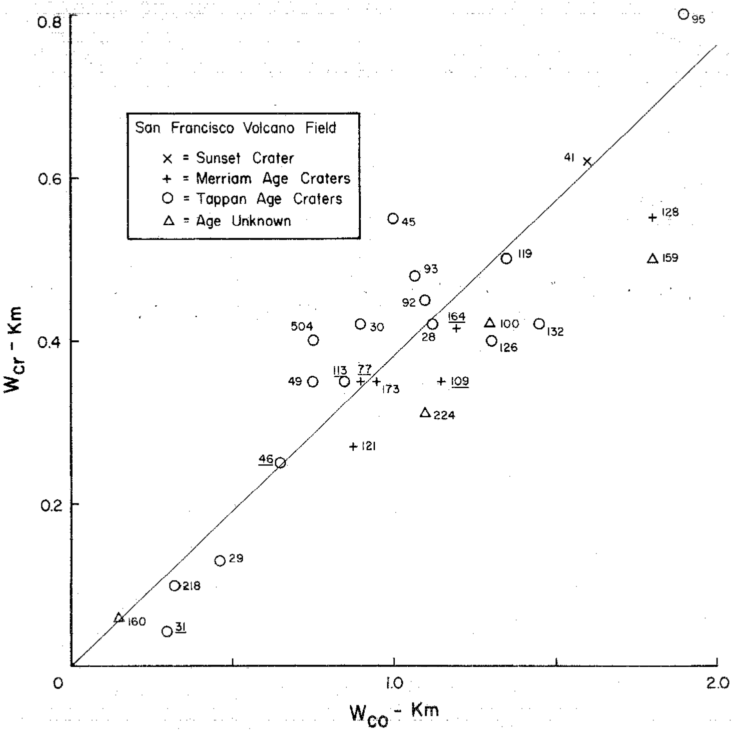


Fig. 6. Crater diameter (W_{cr}) vs. basal diameter (W_{co}) for 27 cones of various ages in the San Francisco volcanic field. There is no obvious difference in the W_{cr}/W_{co} ratios for these cones despite their age differences, except for a tendency for greater scatter for the older cones. Underlined cone numbers are non-basaltic cones. This diagram suggests that W_{cr}/W_{co} ratios are largely independent of degradation and magma composition.

is difficult to measure because it is on the flank of an older silicic massif, but it is unlikely that measuring errors totally account for the discrepancy.

In summary, the transference of age assessment morphometry criteria, established in one part of the SFVF, to the remainer of the field is useful but somewhat uncertain. Tappan age cones have similar ages and morphometry in all parts of the SFVF, whereas some apparently young cones in the north and west are considerably older than their morphometric twins to the east.

In contrast to the dramatic decrease in cone height with degradation, the ratio of crater diameter to cone basal diameter (W_{cr}/W_{co}) does not change appreciably from Sunset to Tappan age cones (Fig. 6). Thus, W_{cr}/W_{co} is relatively constant for numerous cinder cones in various geologic environments (e.g. fig. 4b. in Wood, 1980), and over a moderate range of degradation states. The data in Figs. 4 and 6 further suggest that differences in chemistry of the SFVF cones (basalts vs. basaltic andesites to benmoreites — underlined in the figures) do not strongly alter their morphometry.

DEGRADATION TRENDS IN OTHER CINDER CONE FIELDS

In order to test whether trends of degradation observed in the SFVF are representative of cinder cones in general, measurements of height, basal diameter and crater diameter were made for cones in five other cinder cone fields. Crater diameters are generally not measureable with accuracy on topographic maps, and, being the least consistent of cinder cone parameters (Wood, 1980), are insensitive measures of degradation. Thus, crater diameter variations are not analysed here; least-squares fits to cone heights and diameters are summarized in Table 2. For many of the cone fields insufficient geologic mapping and radiometric dating have been done to segregate cones into differing age groups.

TABLE 2

Least-squares fits of cinder cone height/diameter ratios

Cone field	Subgroup	H_{co}/W_{co}	r	N
Mauna Kea	all	0.188	0.938	30
SFVF	Merriam + Sunset	0.179	0.985	9
SFVF	Tappan	0.125	0.970	24
SFVF	Woodhouse	0.038	0.902	5
LCVF	all	0.123	0.836	22
Newberry	all	0.147	0.723	28
Wu-ta-lien-chi	all	0.132	0.913	13
Etna	A.D. 1535–1928	0.176	0.925	27
Etna	pre-1535	0.152	0.805	100
Reunion	all	0.220	0.812	43

SFVF = San Francisco volcanic field, Arizona; LCVF = Lunar Crater volcanic field, Nevada; r = correlation coefficient; N = number of cones.

Lunar Crater volcanic field, Nevada (LCVF)

This small volcanic field in east-central Nevada consists of a 30-km-long alignment of 70 cinder cones, 2 maars, and numerous lava flows of probable Quaternary to Holocene age (Scott and Trask, 1971). The lavas are all alkalic basalt with SiO_2 ranging from 44.4% to 49.6%, and alkalies of 4—6%. For 10 cones Scott and Trask measured accurate profiles and classified the cones according to degree of erosion, stratigraphic position, and ejecta albedo. They found that the ratio of cone radius to height increased, and average slope decreased, with increasing cone age.

New measurements have been made for 24 cones in the LCVF (Fig. 7A). The majority of the cones fall into the Tappan field of H_{co}/W_{co} ratios as defined by the SFVF cones; i.e. the Nevada cones have geometries similar to cones 0.2—0.7 m.y. old in Arizona. Whereas this age may be appropriate

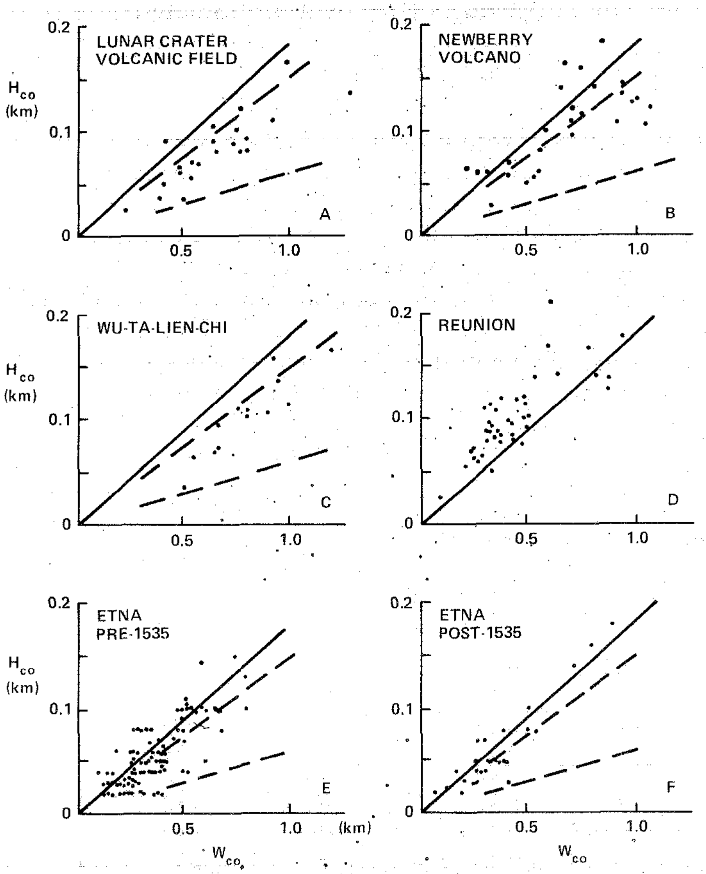


Fig. 7. H_{co}/W_{co} diagrams for different cinder cone fields; the solid line is Porter's (1972) relationship for fresh Mauna Kea cones and the dashed lines separate age groups in the San Francisco volcanic field (see Fig. 4).

for some of the older LCVF cones, ejecta from the youngest cones are intercalated with sediments younger than 9500—18,000 years B.P. (Scott and Trask, 1971). The morphometrically young cones ($H_{co}/W_{co} > 0.15$) may very well be as young as this.

There is little correlation between the relative ages of the cones as deduced by Scott and Trask and from the H_{co}/W_{co} data. It appears that cones with differing degrees of surface erosion can have very similar height/diameter ratios. This implies that cone morphology can be used to distinguish finer degradation stages than can morphometry.

Newberry volcano, Oregon

Previously considered to be a basaltic shield volcano (Williams, 1935; Higgins, 1973) because of its low slopes and basaltic surface lava flows, recent investigations (MacLeod, 1978) suggest that Newberry volcano is dominated by rhyolitic and dacitic deposits, and thus may be a silicious shield volcano (cf. Wood, 1977). The volcano is about 35 km across at the base and the 700-m-high summit contains an 8 km-wide caldera. The most recent eruptions include more than 200 basaltic to basaltic andesite cinder cones on the northern and southern flanks of the shield. Measurements of 28 cones on the northern flank (Fig. 7B) show that about half of the cones have H_{co}/W_{co} values > 0.15; this distribution is consistent with the variety of ages for the cones. Some cones are partially submerged by more recent shield-building lavas (ages of perhaps 100,000 years), whereas other cones are younger than the most recent pumice eruptions (1720 years B.P.: Higgins, 1969). Two of the cones (Lava Butte and Mokst Butte) show morphometric effects possibly due to their being surrounded by lava flows. Lava Top Butte is said to be made largely of basaltic lava flows (Williams, 1935), and it has the largest H_{co}/W_{co} ratio of any of the Newberry cones measured.

Wu-ta-lien-chi volcano, Manchuria

Remarkably complete dimensional data exist for cinder cones on and around Wu-ta-lien-chi, a small shield volcano in northern Manchuria (Ogura, 1969). All but one of the cones are apparently breached, but otherwise said to be little modified by erosion. The cones have slopes of 28—32° and are composed of fist-size fragments of trachybasalt.

Two cones, Lao-hei-shan and Huo-shao-shan, were formed in A.D. 1720. Three additional cones probably formed in the previous thousand years, for the traditional name for the area is Uyunhordongi, which means "9 mounts", yet there are currently 14 "mounts". Despite the youthfulness of at least one-third of the cones, only one plots near the H_{co}/W_{co} line for fresh Hawaiian cones (Fig. 7C); indeed the two cones formed in A.D. 1720 are morphometrically older than the older cones. Apparently, however, neither of these cones had simple cone geometries when they were formed. Lao-hei-shan has three vents on its summit, an 80-m-wide explosion on its ENE slopes, and the northern flank is cut by two fissures 300 m long and 40 m wide. The second young cone, Huo-shao-shan, is "badly broken" with a giant crater 60% as wide as the cone's base.

Etna, Italy

More cinder cones (25) have formed on the flanks of Etna during the last 450 years than in any other volcanic region known to me. Unfortunately, there is no modern, detailed discussion of Etna's cones, although Wadge (1977) has recently summarized his own estimates of volumes for cones and associated lava flows. The detectable cones are probably no more than a few thousand years old, and a 50-m-high cone was formed as recently as May, 1978 (SEAN, 1978).

The distribution of cone heights and diameters is shown in Fig. 7E,F from data supplied by G. Wadge (personal communication). Cones formed since A.D. 1535 follow the trend for fresh cones on Mauna Kea, and there is no detectable morphometric difference among the oldest and youngest of these cones. Considerable scatter characterizes the H_{co}/W_{co} distribution for the pre-A.D. 1535 cones (Fig. 7E); some cones are as morphometrically young as any of the more recent cones, but a considerable number have H_{co}/W_{co} ratios less than 0.15.

Piton de la Fournaise, Reunion

Approximately once every two years (according to data compiled by Ludden, 1977) eruptions within the summit caldera of Piton de la Fournaise, Reunion, build a series of small cinder/spatter cones and associated flows. These cones are extremely small (the diameter of the largest — 190 m — is less than any of the 980 cones analysed by Wood, 1979a). Virtually all of the cones have formed within the present century.

Most of the cones within the caldera of Piton de la Fournaise are taller than predicted from Porter's (1972) relation for cinder cones on Mauna Kea (Fig. 7D), however, they are within the envelope of scatter for the Hawaiian cones. Similarly, W_{cr}/W_{co} values for Reunion cones tend to be somewhat larger than observed in Hawaii, but within the scatter. The slopes of the Reunion cones are steeper than normal for cinder cones, averaging 39°, according to data provided by Mouginis-Mark. These are spatter cones.

SYNTHESIS OF OBSERVATIONS OF CONE DEGRADATION

Cinder cones from five different volcanic fields have H_{co}/W_{co} relations similar to the spread of values for measured cones of various ages in the SFVF. Where sufficient information exists to separate cones into age groups (e.g. Etna) the older cones have lower H_{co}/W_{co} ratios than the younger cones, as is true in the SFVF. Where there is no detailed knowledge of cone ages the spread of H_{co}/W_{co} values is consistent with reasonable estimates of cone ages. In fact, the height/diameter ratio may be used for statistically segregating cones into relative age groups (e.g. northern and western portions of the SFVF, and Newberry volcano). The assessment of cone ages is only statistical, however, and does not apply to cones with initial abnormalities (birth defects) of geometry (e.g. the 1720 Manchurian cones). Furthermore, cone morphometry is a relatively coarse index of erosive modification (e.g. apparently no morphometric changes in about 50,000 years in the SFVF). The degradation sequence derived for the LCVF cones on the basis of stratigraphic and morphologic criteria is not reflected in the morphometry. For these cones the time scale of morphologic degradation is shorter than that for morphometric change. On the other hand, the differences in morphometry for pre- and post- A.D. 1535 Etna cones imply that both morphometric and morphologic changes there occur rapidly and together. Presumably climatic conditions are important in determining the rates of degradation; this topic is discussed below.

Finally, these results illustrate that cinder cone morphology is strongly dependent upon cone age, and thus, statistical studies of cinder cone morphology should not be based on random selection of cones (e.g. Pike, 1978; Settle, 1979), but must segregate them according to degradation classes.

MODELS OF CINDER CONE MODIFICATION

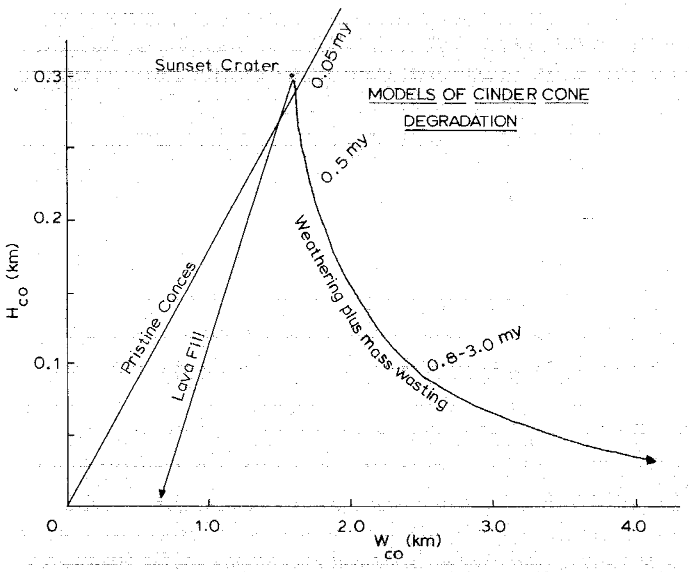
Although the actual processes of cone modification will be discussed in detail below, simple models of the resulting morphological changes are examined for the two most important degradation mechanisms: (1) burial of the cone flanks by subsequent lava flows, and (2) erosion and mass wasting of material from the cone flanks.

One possible explanation of the observation that old cones have lower height/diameter ratios than young cones is that the level of the surrounding terrain has been raised by emplacement of lava flows. This is a common occurrence — flows from Sunset Crater in the SFVF have partially surrounded the older Lenox Crater and cone V83 with flows up to about 10 m thick. Porter (1973) reports that some small cones on Mauna Kea have been completely covered by the buildup of successive lava flows. Additionally, Paricutin's own lavas buried the bottom half (by volume) of that cone.

Despite these examples of the increase of the burial of the flanks of cinder cones by lava flows, examination of the geologic map of Moore and Wolfe (1976) suggests that, in general, cones in the SFVF are not appreciably affected by later lava flows. An exception is that lava flows erupted from the base of a cone may form a substantial plateau around that cone. An extreme example of this is South Sheba Crater, SFVF, surrounded by flows up to 50 m thick. It is not known, however, if South Sheba were built upon the flow or if the flow post-dates the cone. If the latter is true the lava pile would account for only about one half of the difference between the height of

South Sheba and that of Merriam age craters of the same basal diameter. Thus, additional processes are probably required to explain the low rim heights of most old cones.

The morphometric effect of burial of cone bases by flows (assuming that no erosional processes act) is modelled in Fig. 8, using Sunset Crater as a test case ($W_{co} = 1.6$ km, $W_{cr} = 0.6$ km, $H_{co} = 0.3$ km). Submergence of the base by lava flows produces departures from the ideal H_{co}/W_{co} relation, with W_{co} approaching 0.6 km as H_{co} goes to zero. The concomitant decrease in H_{co}/W_{co} is shown in Fig. 9, which provides a nomogram for estimating lava flow thickness for partially buried, but otherwise fresh cones. An unusual circumstance provides a check on this calculation. The larger of two morphologically fresh cinder cones on the floor of Zuni Salt Lake Crater (a maar in New Mexico) has a H_{co}/W_{co} value of 0.13. Fig. 9 suggests that the bottom 94 m × 0.40 = 37.6 m of the cone must be covered, in excellent agreement with a cross-section by Bradbury (1967), who indicates that



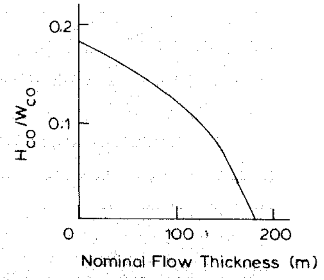


Fig. 8. Simple models of cinder cone degradation. Fresh cones (0—0.05 m.y. old in the San Francisco volcanic field) have $H_{co}/W_{co} = 0.18$. Lava fill around a cone's base would cause the cone geometry to change as marked and W_{co} would approach W_{cr}. If degradation is due to weathering of material from the summit of a cone and mass wasting redistributes the material around the flanks, the cone geometry evolution follows a different path. Mass wasting results in modified cones with W_{co} larger than initial values, whereas lava engulfment reduces W_{co}. The 0.5-m.y. and 0.8—3.0-m.y. tick marks show H_{co}/W_{co} values for San Francisco volcanic field cones of those ages.

Fig. 9. Nomogram for determining lava thickness around an otherwise fresh cinder cone that is assumed to follow the morphometric relations for fresh cones: $W_{cr} = 0.4W_{co}$ and $H_{co} = 0.18W_{co}$, as originally deduced by Porter (1972). Nominal flow thickness should be multiplied by W_{co} (in km) for estimate of actual flow thickness.

salt and other lake deposits rise 25–45 m above the covered base of the cone. If lava flooding — or salt deposition, as in this case — were the principal means of altering pristine cone geometry, the diameters of older cones should be smaller than for fresh cones; all other erosional processes increase W_{cr}.

The second process of cone degradation that can be modelled simply is erosion and mass wasting of the cone itself. This process has been observed at Paricutin (Segerstrom, 1950), where fans of scoria became unstable due to rainfall and slid downslope. This must have affected many older cones which are ringed by talus aprons, and have craters that are filled or eroded away. Weathering breaks down cinder and ash into smaller particles that are no longer stable on their original slopes, leading to increased basal diameters, lower heights and decreased slopes.

Possible future morphometric changes at Sunset Crater are modelled as an example of the redistribution of material by weathering and mass wasting. It is assumed that erosion preferentially removes the top of the cone and deposits this material around the flanks. The basal diameter, crater diameter and slope are calculated for decrements of 10% of the initial height, assuming cone volume is conserved. Fig. 8 shows that for weathering and mass wasting cone height decreases rapidly with only slight increases in W_{co}, but beyond $H_{co}/W_{co} = 0.05$, W_{co} increases faster than H_{co} decreases.

The two processes of cone modification modelled in Fig. 8 have opposite effects on W_{co}: lava flooding around a cone reduces W_{co}, whereas redistribution of material from the top to the bottom results in enlargement of basal diameter. As an example, if the 300-m height of Sunset Crater is reduced by 1/3 (i.e. converted from Sunset/Merriam morphology to Tappan geometry) by engulfment by lava, W_{co} decreases from 1.6 km to 1.27 km (a 25% decrease), but if mass wasting is the principal agent of degradation. W_{co} will increase to 1.8 km (a 12% increase). Judging from a sample of only 8 Sunset/Merriam age cones and 22 Tappan age cones in the SFVF, the average W_{co} of the older cones is 5% larger than for the young cones, suggesting that mass wasting is the more significant degradation process in the SFVF.

Cone degradation due to mass wasting results in continual decrease in flank slope (Fig. 10), whereas modification by lava encirclement maintains a constant slope. Tappan age cones with $H_{co}/W_{co} = 0.12$ are predicted by Fig. 10 to have slopes of about 26°, compared to 30° to 31° for young cones. Field measurements of average slopes for 27 SFVF cones of differing morphological ages are:

Merriam age	$30.8 \pm 3.9^\circ$	$N = 7$
Tappan age	$23.1 \pm 2.0^\circ$	$N = 15$
Older cones	$14.1 \pm 4.2^\circ$	$N = 5$

A third mechanism of cone erosion has been observed following the Paricutin eruption. Segerstrom (1950) noted that erosion was accelerated

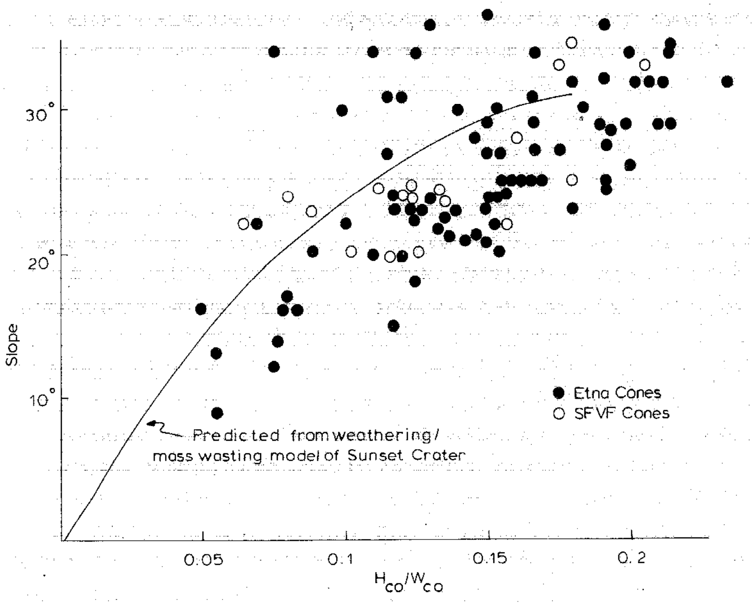


Fig. 10. Cone slope and H_{co}/W_{co} ratios for cinder cones on Etna and the San Francisco volcanic field, compared to predictions based on the weathering/mass wasting model of Fig. 8.

on cinder cones that were draped by Paricutin ash. As an example, Cerro de Cutzato, an older cone 6.3 km east of Paricutin was covered by 45 cm of ash that was quickly gullied by rainfall. Gullying of the Paricutin ash occurred more rapidly than gullying of the original surface of Cerro de Cutzato because (1) the protective vegetation had been stripped away, and (2) the heavier sediment load and larger grains resulted in greater cutting power for the Paricutin ash (Segerstrom, 1950). Additionally, the Paricutin ash surface was more susceptible to rill, channel and gully erosion because it was more friable than the somewhat consolidated surface of the underlying cone. As a consequence of all of these factors, channels that formed in the Paricutin ash continued cutting into the old surface. Segerstrom estimated that the erosion of the underlying cone, due to the Paricutin eruption, will accomplish as much degradation in a century as would normally have required thousands of years.

Paricutin ash also reduced the depths of crater floors. Four years of eruption by Paricutin had deposited so much ash on the floor of the Curitzeran cone (7.4 km north of Paricutin) that only 1.5 m of additional deposition (available through stripping of Paricutin ash from the inner walls of the crater) was required for runoff to flow over the lowest part of the crater's rim and cause rapid breaching of the cone (Segerstrom, 1950).

These examples illustrate that the rate of erosion may be accelerated by factors of 10 to 100 by eruptions of nearby cones. That similar "proximity erosion" is probably common can be demonstrated by comparison of average distances between cinder cones (Settle, 1979) and isopach radii. The data in Table 3 show that the average separation distance for cinder cones is about 1.5 km, and that the average radius of the 0.5 m isopach for the five cones listed is about 3 km. Thus, the typical cone should be effected by one or more nearby eruptions that accelerate erosion. Twenty-one cones occur within Paricutin's 0.5-m isopach, and roughly 40 cones are draped by the pyroclastic sheet of Sunset Crater (map unit Qsp of Moore and Wolfe, 1976). However, gully formation is uncommon in the SFVF, and thus enhanced erosion due to deposition of Sunset ash does not appear to have been important.

TABLE 3

Cinder cone separation distances and isopach radii

A. Separation distance (Settle, 1979)

Cone field	Median distance (km)
Etna	0.95
Mauna Kea	1.15
Paricutin	1.40
Kilimanjaro	1.45
San Francisco volcanic field	1.85
Nunivak Island	2.00
Average	1.47

B. Isopach radii

Cone	Radius of 0.5-m isopach (km)	Reference
W1974, Etna	0.13	Walker, 1975
Eldfell, Iceland	0.5 —0.7	Self et al., 1974
Mt. Rossi, Etna	1.7 —2.7	Walker, 1975
Cuautl, Mexico	4.7 —5.8	Bloomfield, 1975
Paricutin, Mexico	4.8 —7.1	Segerstrom, 1950
Average	2.8	

RATES OF EROSION

Regardless of which mechanisms account for the erosion of the SFVF cones, Fig. 4 illustrates that the rate of erosion is higher for large cones than for small ones. Consider two Sunset/Merriam age cones, one with W_{co} = 0.5 km and the other with W_{co} = 1.5 km. By the time (about 2 m.y.) the cones are eroded to Woodhouse age the height of the smaller cone is reduced from 90 to 20 m, whereas the larger cone shrinks from 270 to 60 m. Thus, over the same time interval the height of the large cone would be reduced by 210 m, versus 70 m for the small cone. The difference would be even greater if the changes in volume were considered.

The conclusion that large cones erode more rapidly than small ones is surprising, for as Scott and Trask (1971) point out, erosion should be most rapid for small cones with their large surface area to volume ratios. One possible explanation for the more rapid erosion of large cones could be related to changes in cone explosivity (E) with size. As discussed by Wood (1980) large cones appear to be associated with more volatile-rich magmas and thus have more intense explosive eruptions. Strongly explosive eruptions produce finer particles than less explosive activity and thus it may be speculated that more spatter and other large (and thus hot) fragments occur in small cones, welding them together and decreasing their susceptibility to erosion.

The potential for determining the rates of erosion of cones is great where there are numerous cones with historic activity (e.g. Etna) or where they have been dated radiometrically (e.g. SFVF). Paricutin had undergone very little erosion between its birth in 1943 and 1965, and Segerstrom (1966) suggested that another century may elapse before significant degradation is apparent. The cinder that comprises the cone is too permeable for surface flow of water and thus rill and gully formation will be delayed until weathering produces soil. This has already occurred at Jorullo, a cinder cone about 100 km southeast of Paricutin that formed in A.D. 1759 (Segerstrom, 1950). Within 90 years of the eruption sufficient soil had developed to support trees on the flanks of the cone, and by 1946 about half of the cone's circumference was fluted with gullies up to 7 m wide and 3 m deep. Nearer to Paricutin, the Cutzato cone, which may be about 1000 years old, is deeply scarred by ravines (Williams, 1950), although, as described earlier, erosion of these gullies was accelerated by the Paricutin eruption. Presumably Cutzato's relatively gentle slope (26.6°) compared to Paricutin (31—33°) is due to erosion rather than initial slope.

Erosion rates for longer intervals of time can be estimated where cone ages are known. For example, the average slopes of post-A.D. 1535 cones on Etna decreased from 32 to 21° in 450 years (Fig. 11). At this rate cone slope would be reduced to zero in 1264 years; but some of the Etna cones are believed to date from as long ago as 693 B.C. (Imbo, 1965), implying that the rate of erosion must decrease with increasing age.

Effects of erosion on the morphology of cones in the Massif Central of France have been studied by Kieffer (1971) who found that cones 10,000 years old have slopes 9° shallower than the most recent cones, and that slopes decreased another 11° for cones 1 m.y. old. Four-million-year-old cones are marked only by residual necks, the cinder cone itself being completely gone (Fig. 12).

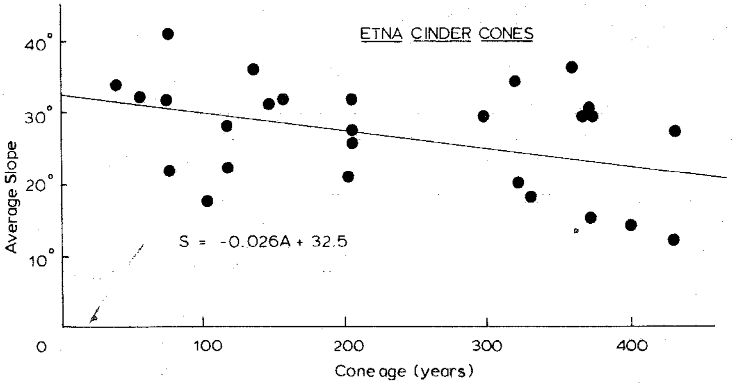


Fig. 11. Cinder cones on Etna have degraded at an approximately constant rate during the last 450 years.

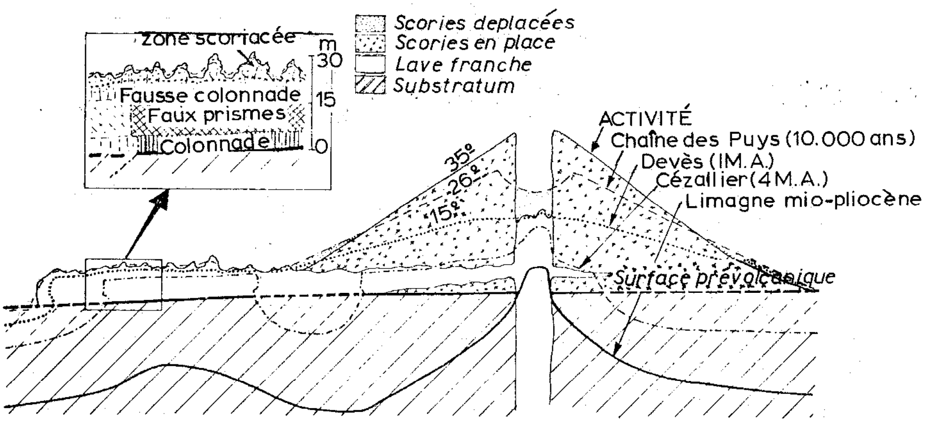


Fig. 12. Schematic cross-section illustrating changes in cone and flow morphology due to erosion. Example is from the Massif Central region of France (Kieffer, 1971).

Cones in the SFVF decrease in slope with age as discussed earlier. The average rate of change (accepting the nominal ages in Table 1) approximates $15^\circ/10^6$ years for Tappan age cones, and about $8^\circ/10^6$ years averaged over the last 2 m.y. (i.e. Woodhouse age cones).

The decrease in cone height through time in the SFVF permits estimations of the rate of degradation. Fig. 13 shows the future degradational history of Sunset Crater, assuming it slowly degrades through the Tappan and Woodhouse stage geometries defined by Fig. 3. For the next 50,000 years there will be little change in the dimensions of Sunset Crater, but between then and 0.5 m.y. from now the cone will decrease from a height of 305 m to 210 m, at an average rate of 210 m/10^6 years. For the following 2.5 m.y.

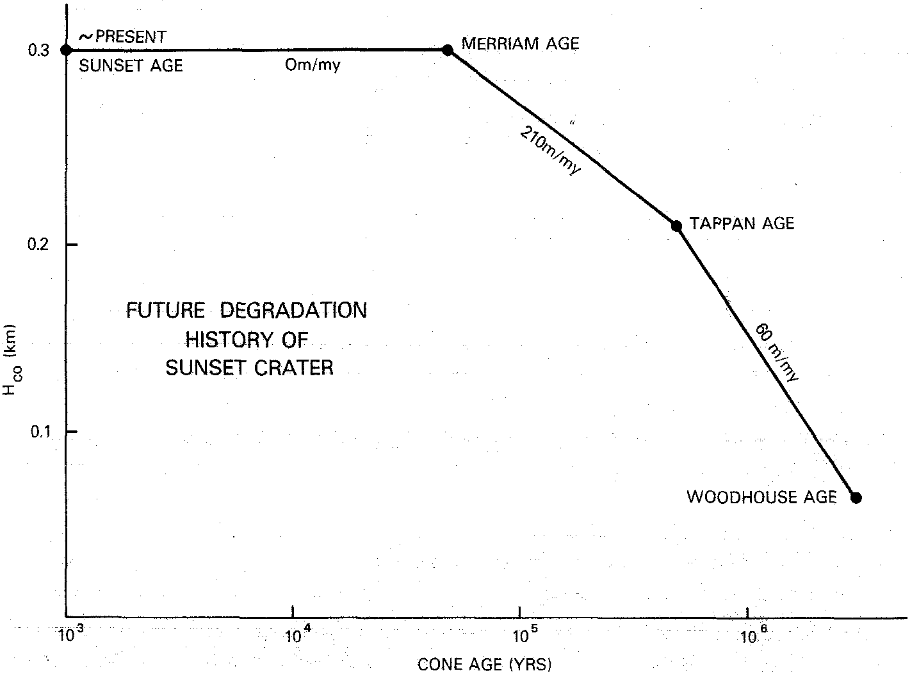


Fig. 13. A possible future degradation history for Sunset Crater can be derived from past degradation trends in the San Francisco volcanic field.

the rate of cone retreat will slow to 60 m/10^6 years, and Sunset Crater will appear as a 65-m-high Woodhouse stump. If degradation continues at the same rate for an additional million years (i.e. a total of 4 m.y.) the cone of Sunset Crater would disappear entirely, except for a possible residual spine.

THE INFLUENCE OF CLIMATE

The change in cone height proposed in Fig. 13 is a history of erosion during the last 2—3 m.y. in the SFVF. It is remarkable that there appears to have been so little cone modification during the last 50,000 years, a time of two glaciations of the San Francisco Peaks (Updike and Pewe, 1974) and a general pluvial period in the American southwest (Hevly and Karlstrom, 1974). Strong cone erosion during Tappan time (between 0.05 and 0.5 m.y. ago) must reflect a more erosive and presumably wetter climate during that interval. This period coincides with an episode of intense degradation of the San Francisco Peaks (Sinagua of Updike and Pewe, 1974), but there is little detailed knowledge of that climate. Earlier still, there is even less climatic information because the San Francisco Peaks had not yet formed to accumulate glaciers (Wolfe, 1979), but Woodhouse age cones were probably being eroded at a rate intermediate to that of Merrian and Tappan times.

Although rain is apparently the main agent of cone erosion — wind is of little efficacy except perhaps on ash rings such as Barcena (Richards, 1965) — the colonization of cones by plants hastens the development of soil, and thus of rill and gully formation. Wurmli (1974) described how the 8-m-long roots of the broom species penetrate scoria and even crystalline lava to initiate soil formation. However, there must be competition between erosion enhancement resulting from plant growth and erosion retardation due to the plants' ability to anchor the soil. Perhaps the significance of plant colonization is that it helps develop soils that may be severely eroded during subsequent eruptions of nearby cones.

From the previous discussions it is clear that cone erosion depends strongly on rainfall, both directly and secondarily through plant growth. This suggests, not surprisingly, that climate is the ultimate governor of cone degradation

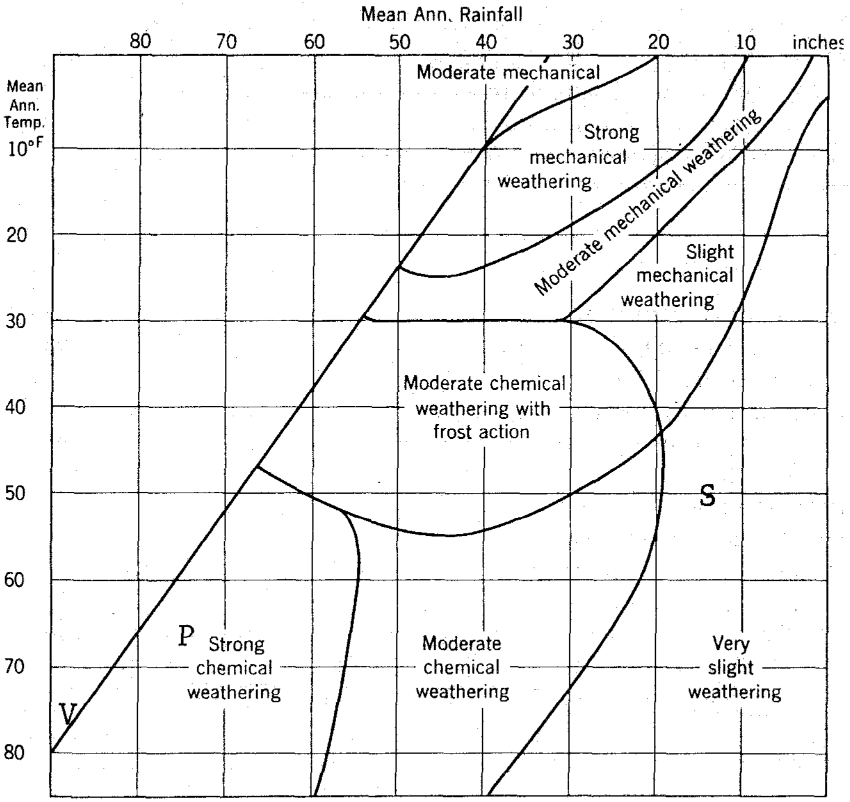


Fig. 14. Vulcan (*V*), a cone formed in 1937 in Papua New Guinea, is now deeply eroded, and cones in the Paricutin (*P*) region of Mexico show considerable gullying and other erosional modifications after 100 years, yet 10^3 to 10^5 years of weathering has caused little erosion of the San Francisco volcanic field (*S*) cones. These differences in erosion rates may be due largely to climatic differences between the three areas, as illustrated on this climate-process diagram of Peltier (1950).

rates, and that study of cone morphology may provide information on past climates. The influence of climate on degradation can be illustrated by comparison of three cones. Deep gullies and mature vegetation occur on the flanks of Vulcan (Papua New Guinea) which formed in 1937 (Ollier and Brown, 1971) and has received about 2260 mm of rain/year since then (Fig. 14). In the somewhat drier (about 1950 mm/year) and cooler climate near Paricutin, similar states of vegetation development and gullying require more than 100 years, whereas a cone of Merriam age in the SFVF harbors little plant life and no gullies despite about 50,000 years of rain and snow (currently about 400 mm/year; Wernstedt, 1972). The lack of significant erosion on young cones in the SFVF is remarkable for paleoclimate data indicate that the regional climate oscillates through wetter and drier stages (Euler et al., 1979) and that historic rainfall underestimates average rainfall for the last few millennia.

The effect of moderate differences in rainfall intensity on cone morphology in the SFVF was examined statistically by comparing H_{co}/W_{co} values for cones at different distances east of the San Francisco Peaks. Rainfall currently varies from 500 mm at U.S. Highway 89 near the peaks (Fig. 2) to 250 mm at the eastern edge of the SFVF (Sellers and Hill, 1974). For both Merriam and Tappan age cones the H_{co}/W_{co} ratios slightly increase to the east, however, the scatter is so large that neither result is statistically meaningful (r = 0.41 for Merriam cones, and r = 0.20 for Tappan cones).

CONCLUSIONS

(1) Cone heights, height/diameter ratios, and slopes systematically decrease as cones degrade, offering the possibility of roughly dating cones by simple measurements of morphology.

(2) Crater diameter/basal diameter ratios (W_{cr}/W_{co}) appear to be nearly independent of degradation, and thus may be a useful index of cone origin (see Wood, 1979b).

(3) Erosion and mass wasting can account for most observed changes of morphology as cinder cones degrade.

(4) Large cones degrade more rapidly than small ones, and the rate of degradation decreases with increasing cone age.

(5) Rates of erosion of cones vary tremendously and appear to be dominated by climate; measurements of cone morphology may be useful in assessing past climates over time spans up to a few million years.

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