Proc. Lunar Planet. Sci. Conf. 10th (1979), p. 2815–2840.
Printed in the United States of America

Monogenetic volcanoes of the terrestrial planets

Charles A. Wood

NHB—Stop 119, Smithsonian Institution, Washington, D.C. 20560

Abstract—Small volcanoes formed by single eruptions of a few days to a few years durations are common on the Earth. Such monogenetic volcanoes constructed mainly of pyroclastic deposits include spatter cones, cinder cones, pseudocraters and maars—the latter two types resulting from explosive interaction of magma and water. Eruptions of lava flows from central vents form small shield volcanoes, already classified by Pike (1978) into three subclasses according to diameter and flank slope. Average volumes range from 0.02 to 40 × $10^6 m^3$ for the pyroclastic cones, and from 50 to 9000 × $10^6 m^3$ for the lava cones. Relations between cone and summit crater diameters define general fields of occurrence for each volcano type, allowing geometric distinctions between pyroclastic and lava cones, and rough subdivision of individual cone types. Spatial densities also tend to differ for various volcano types, and thus are an additional clue to remote identification of cone origins.

Based on morphology, morphometry and geologic setting, possible cinder cones and small shields have been identified on Mars and the Moon. Median volumes of the extraterrestrial cinder cones average only 25% of typical volumes for Earth cones, implying smaller and shallower (1 km vs. 3 km) magma chambers for lunar and martian pyroclastic cones. Estimated minimum eruption velocities were also only 1/3 to 1/10 typical values for terrestrial cinder cones of equal volumes, suggesting that the volatile/solid ratio was less for the alien cones. Small shields on Mars and the Moon have dimensions comparable to similar volcano types on Earth, except that the craters of the former are 2–5 times larger—an effect that may be related to planetary differences in gravitational acceleration.

INTRODUCTION

One of the most common results of a volcanic eruption on Earth is the construction of a small, crater-topped cone. These cones are monogenetic, representing a single eruption lasting a few days to a few years. Different cone morphologies are due to differences in eruption style, which is determined by magma volume and extrusion rate, eruption energy, and other extraneous factors (e.g., availability of ground water). Grossly similar cones have been detected on the Moon and Mars, and correct interpretation of their modes of origin can provide clues to magmatic processes on those planets. The present paper presents brief characterizations of the different morphologies and eruption mechanisms for the main types of small volcanic cones on Earth, and new morphometric data for selected cones on the Moon and Mars. Interpretation of the extraterrestrial cones in light of understanding of eruption processes for terrestrial cones leads to estimates of their eruption velocities, rates, and magma source depths. In this study only relatively well defined, symmetrical cones are considered; aberrations due to elongated vents, strong winds, etc. confuse basic morphological relations.

Fig. 1. Spatter and cinder cone on the floor of Mokuaweoweo Caldera, Mauna Loa. The cone, formed in 1940 and cut by a fissure in 1949, is about 200 m wide at the base (W_{co}) and roughly 50 m high (H_{co}). Aerial photograph by R. Fiske.

TYPES OF TERRESTRIAL VOLCANIC CONES

When magma rises to the Earth's surface, it can either quietly flow away from the vent as a lava flow, explosively fragment and ballistically eject ash and cinders, or do both simultaneously. The resulting landform depends on which process predominates, but two major morphologic subdivisions are possible: 1) cones built by lava flows (small shields) and 2) cones formed by the accumulation of pyroclastic deposits. Recently, Pike (1977, 1978) and Head and Gifford (1979) have provided new quantitative data for lava cones/small shields, and compared examples on the Earth and the Moon. Pyroclastic cones have been quantitatively investigated by Head (1975), McGetchin and Head (1973), McGetchin *et al.* (1974), Head and Wilson (1979), Wilson and Head (1979), and Wood (1977, 1979a, 1979b).

Pyroclastic cones

There is a progression in morphology of pyroclastic cones depending on explosivity and volume of magma. Kennedy (1955) has suggested that these two variables are closely related, and Wood (1979a) has demonstrated that explosivity (and presumably volatile content) increases with magma volume. Weak eruptions of pasty magma often build a spatter cone (Fig. 1) over the eruption vent and commonly feed a relatively small volume lava flow. Spatter cones are generally too small to be depicted on topographic maps, but data (Peter Mouginis-Mark, pers. comm.) for cones within the caldera of Piton de la Fournaise, Reunion illustrate that this type of cone typically has a base diameter of tens to hundreds of meters and a volume of $10^4 - 10^5 m^3$ (Table 1). Spatter forms when centimeter to decimeter size blebs of magma are ejected only a short distance above their vent and are still hot enough to deform and weld to the cone's surface on landing.

Table 1. Average dimensions of terrestrial monogenetic volcanoes.

Volcano Type	Volume[b] (10^6 m^3)	W_{co} (km)	W_{cr}/W_{co}	H_{co}/W_{co}	SD[b] (#/km^2)
Pyroclastic Cones					
Spattercone[a]	0.06	0.08	0.36	0.22	2
Cinder Cone[b]	40	0.80	0.40	0.18	0.03–0.5
Pseudocrater[b]	0.02	0.08	0.42[b,c]	0.10[c]	200
Maar[c]	25	1.38	0.60	0.02	0.006–0.03
Lava Cones[c]					
Icelandic Shield	9200	8.6	0.06	0.06	0.001
Steep Shields	50	1.6	0.12	0.04	?
Low Shields	450	4.8	0.08	0.02	?

W_{co} = cone basal diameter; W_{cr} = crater diameter; H_{co} = cone height; SD = cone spatial density. Data from (a) Mouginis-Mark (pers. comm.); (b) Wood (1979a and unpublished data); and (c) Pike (1978).

More explosive eruptions (due to higher gas content or more viscous magma) fragment erupting magma into millimeter to centimeter size ash and cinders that follow ballistic trajectories, fall onto cone flanks and roll downslope until reaching the angle of repose. McGetchin *et al.* (1974) and Chouet *et al.* (1974) have closely studied such eruptions for Etna and Stromboli. Cones built by this type of eruption are called cinder or tephra cones (Fig. 2) and are the most common type of subaerial volcanic edifice on Earth. Based on measurements of 910 cinder cones (Settle, 1979; pers. comm.) the basal diameters range from 0.25 to 2.5 km with a mean of 0.8 km and a typical volume of about $4.0 \times 10^7 m^3$ (Wood, 1979a).

If a rising column of magma intersects near surface water, the additional thermal energy generated by vaporization dramatically increases the explosivity of the eruption (Peckover *et al.*, 1973) and the magma is comminuted to smaller particles and ejected higher and further than in typical cinder cone eruptions, building a broad cone. After the eruption the central part of the cone normally collapses, producing a wide, deep crater bounded by a low rim. These craters are known as maars (Fig. 3) and average about 1.4 km in basal diameter, with typical volumes of $2–3 \times 10^7 m^3$. Maars were previously considered as rare phenomena,

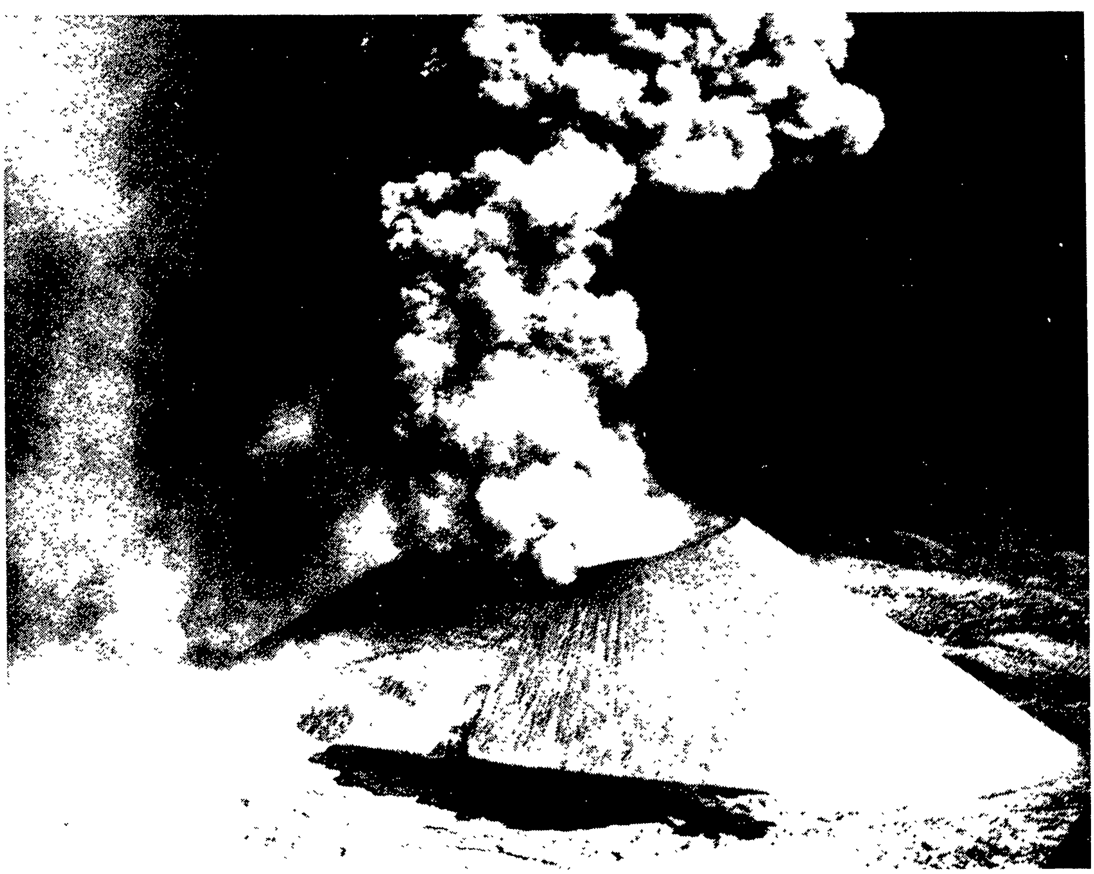

Fig. 2. Eruption of Paricutin, November, 1944, a cinder cone in central Mexico. At this time the cone was about 310 m high and about 950 m wide at the base. Aerial photograph by Frank Zierer, from the archives of the Smithsonian Institution.

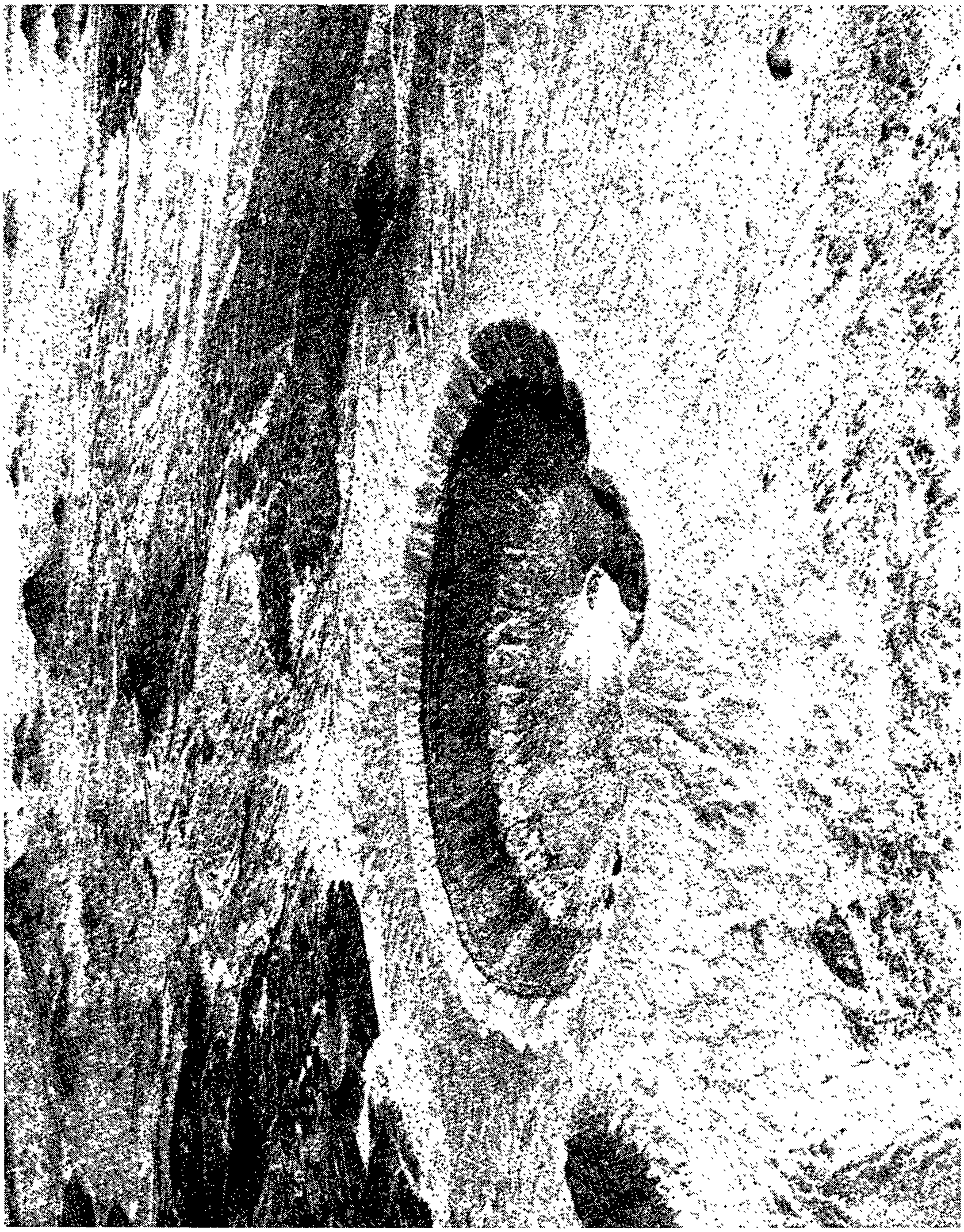

Fig. 3. Crater Elegante, a maar (W_{cr} = 1460 m; H_{co} = 37 m; Wood, 1974) in the Pinacate Volcanic Field, Sonora, Mexico. Photograph by P. Kresan.

Fig. 4. Pseudocraters of the Skutustadir crater group, Lake Myvatn, Iceland. Basal diameter is estimated at roughly 100 m.

but are now recognized as common volcanic landforms, being merely cinder cone eruptions modified (drastically) by the magma's interaction with water (Wood, 1979c). Maars have been studied by Ollier (1967, 1974), Lorenz (1973, 1975), Wood (1974) and others.

In Iceland an apparently unique style of water/magma interaction produces small features called pseudocraters (Thorarinsson, 1953). These craters (Fig. 4) are well-known from the Lake Myvatn region of northern Iceland where hundreds, with diameters of 2 to 300 m (Rittmann, 1938), occur on a 2500 year old lava flow (Thorarinsson, 1953). The restriction of the pseudocraters to areas where the lava flow crosses Lake Myvatn shows that the craters formed by explosions of steam trapped beneath the lava. Pseudocraters are rare features outside of Iceland. The only dimensional data presently available are for 10 pseudocraters measured by Pike (1978), for which the average diameter is 130 m. This value is biased towards large diameters because only the larger pseudocraters are readily measurable on maps and photographs. Perhaps a more representative average basal diameter is 80 m, averaged from measures of all 42 pseudocraters depicted in Rittmann's (1938) map of the Skútustathir crater group at Myvatn.

Lava cones/small shield volcanoes

Non-explosive extrusion of lava from a central vent can result in the formation of a lava cone or a minature shield volcano (Fig. 5). A well observed, but complex, example of this process is the birth and evolution of Mauna Ulu, a small

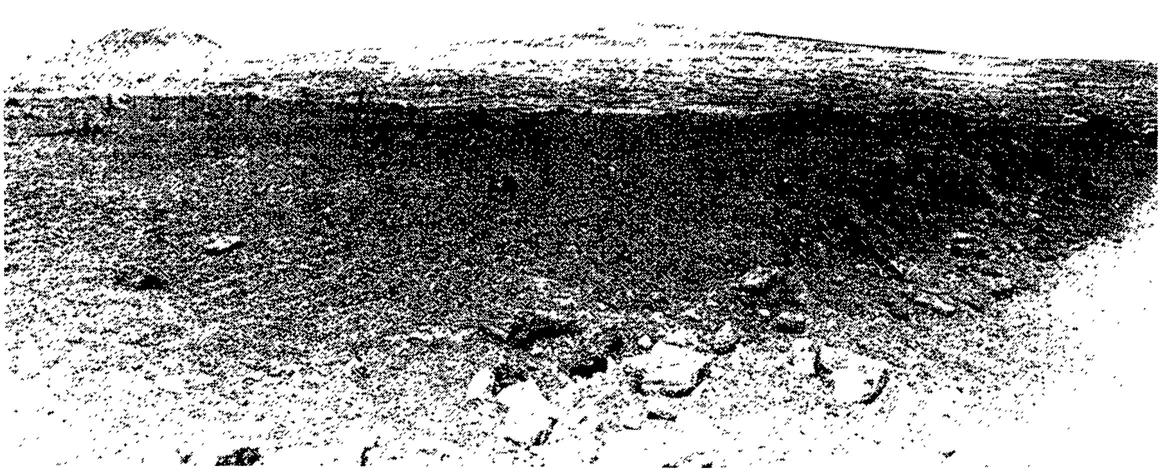

Fig. 5. The small shield volcano of Mauna Ulu in July, 1971 (W_{co} about 500 × 800 m; H_{co} about 80 m: Swanson *et al.*, 1979). Photograph by D. Cruikshank.

shield on the flank of Kilauea volcano, Hawaii (Peterson *et al.*, 1976; Swanson *et al.*, 1979). During a 5-year period of activity a shield 120 m high was built, with the total volume of all flows being about $3.5 \times 10^8 m^3$. Pike (1977, 1978) has classified small shields into three types depending on their size and steepness (Table 1).

Morphometric signatures

Since the purpose of this review of terrestrial monogenetic volcanic cones is to provide a basis for interpreting cratered cones of unknown origin on the Moon and Mars, it is necessary to be able to distinguish between the various morphological types of cones by a method applicable to the alien cones. Table 1 illustrates that this can be accomplished using only three measurements of cone geometry and derived quantities (Porter, 1972): cone height (H_{co}), cone basal diameter (W_{co}), and crater diameter (W_{cr}). It must be appreciated, however, that there is considerable variety in morphology within a single cone type, and that Table 1 presents average values (see Fig. 6 for distribution of data).

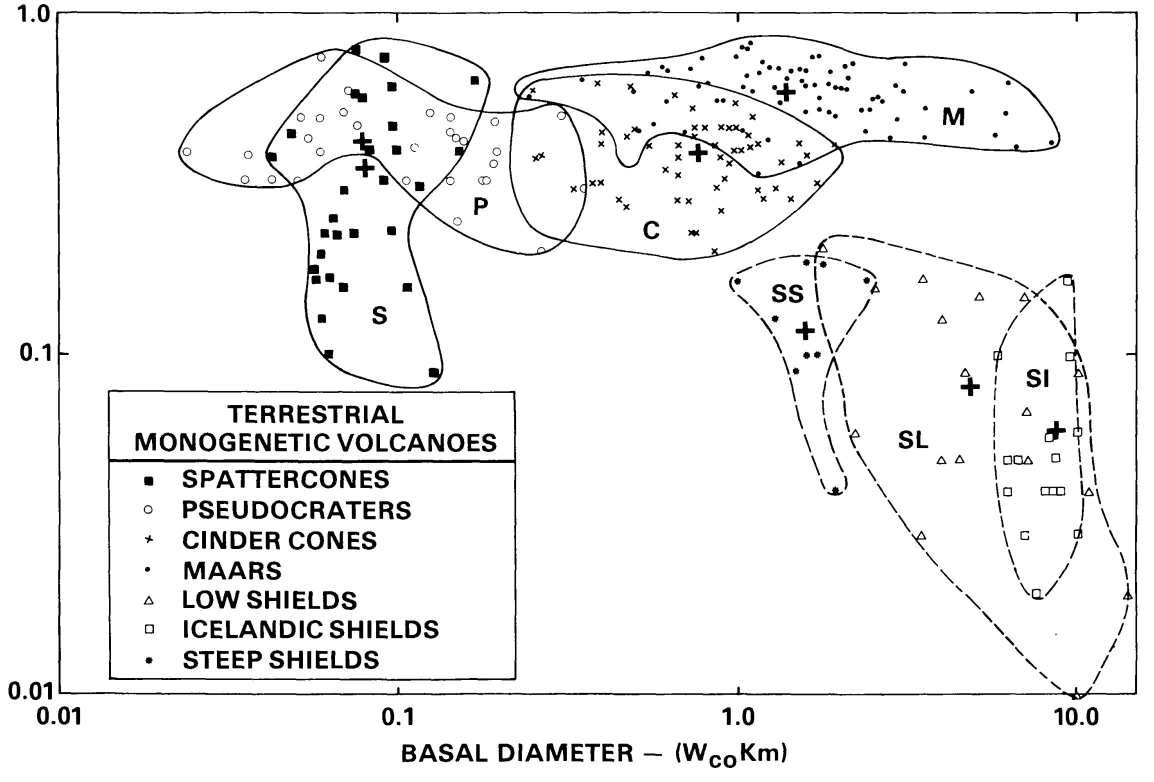

Fig. 6. Terrestrial monogenetic volcano groups as defined by measurements of cone basal diameter (W_{co}) and crater diameter (W_{cr}). P = pseudocrater, S = spattercone, C = cinder cone, M = maar, SS = steep shield volcano, SL = low shield, SI = Icelandic shield. All data from Pike (1978) except for S (Mouginis-Mark, pers. comm.), P (unpublished measures by Wood) and C (Wood, 1979b). The crosses mark average values.

Terrestrial cones constructed of lava flows (small shields) are statistically distinct from pyroclastic cones in morphometry as well as in eruption style. The shields have larger diameters (W_{co} = 1.5 to 9 km vs. <1.5 km for cones), larger volumes (10^7–$10^9 m^3$ vs. 10^4–10^7), lower slopes (1°–10° vs. 25°–35°), smaller craters (5–12% of W_{co} vs. 35–60%), and lower heights (2–6% of W_{co} vs. cone values generally between 10–20% of W_{co}). Differentiation between shield types is best based on cone diameters, although since it is unclear what causes the differences in shield morphology, little insight into eruption mechanism results. The pyroclastic cones cannot be separated by any single factor, but are distinct if two quantities are used. For example, spatter cones and pseudocraters have the same average diameters, but the latter are generally only half as tall as the former. Pseudocraters, cinder cones, and spatter cones all have W_{cr}/W_{co} ratios of about 0.4 but H_{co} and W_{co} values distinguish them. Unfortunately, the heights of lunar and martian cones are seldom known and thus identification of cone origins should be based mainly on measurements of horizontal dimensions—W_{cr} and W_{co}. These two quantities distinguish pyroclastic cones from lava shields (Fig. 6), and generally subdivide the various types of pyroclastic cones, although there is substantial overlap of the spatter cone and pseudocrater fields. The use of W_{cr} and W_{co} to distinguish cone origins is also favored by the observation (Wood, 1979a) that erosion and differences in petrology do not appear to strongly effect W_{cr}/W_{co} for pyroclastic cones, whereas the H_{co}/W_{co} ratio is significantly decreased by erosion.

Spatial distributions

An additional clue to cone origins comes from their spatial distributions, a generally neglected topic. Spatter cones commonly occur along fissures (e.g., the early stages of Mauna Ulu; Swanson *et al.,* 1979) and thus commonly are closely spaced in straight lines. According to Mouginis-Mark (1977), the spatter cones within the caldera of Piton de la Fournaise, Reunion are aligned along fissures that radiate from the central vent, and based upon the number of cones mapped within the caldera have a spatial density of about 2 cones/km^2.

Cinder cones occur in nearly all volcanic environments, and Settle (1979) has documented systematic differences for cone distributions in the two most common settings. Cinder cones on the flanks of pre-existing volcanoes (e.g., Etna, Mauna Kea, Kilimanjaro) are typically aligned along radial fracture zones (Nakamura, 1977) and are smaller and more closely spaced than cones in flat-lying volcanic fields (e.g., San Francisco Volcanic Field, Nunivak Island, Pinacates). Frequently, cones in these latter fields are randomly distributed, with separation distances of 1–1.5 km. Spatial densities for cinder cones measured by Settle (1979) range from 3–11 cones/100 km^2.

Pseudocraters are tightly clustered, often overlap, and are randomly aligned (Rittmann, 1938). They are confined within the boundaries of a single lava flow at each site in Iceland and are further localized by pre-existing ground water concentrations. The tiny island of Mikley in Lake Myvatn is said to contain more than 100 pseudocraters (Barth, 1950), yielding a spatial density of about 200 cones/km^2!

Maars are not randomly distributed, but rather are concentrated near sources of abundant water. Lorenz (1973) has shown that the maars of the Eifel region of Germany and of the Massif Central of France occur almost exclusively in river valley floors. The spatial density of maars in the regions he has mapped range from 0.6–3 cones/100 km^2. Stearns and Vaksvik (1935) pointed out that Diamond Head and the other tuff rings/maars (see Wood, 1979c for the distinction) on Oahu, Hawaii only occur near the sea, providing evidence for their phreatomagmatic origin.

The distributions of small shield volcanoes is completely unstudied. Based upon the number of shields mapped (Kjartansson, 1962) in a 750 km^2 area near Skjaldbreithur (Fig. 5) these Icelandic shields have a spatial density of 1.0 cone/100 km^2, but this is likely to be an overestimate because an area with numerous shields was selected to determine the density. The Icelandic shields appear to be randomly distributed within the island's axial rift zones.

The spatial distribution data (summarized in Table 1) show that there is a wide range of cone spacings, implying that this parameter might be of use for remotely diagnosing cone origins. For example, pseudocraters have a spatial density that argues against each cone being a separate eruption vent with an independent source, consistent with their proposed origin (Thorarinsson, 1953). The somewhat overlapping spatial densities for cinder cones and shields disguises a significant difference—the cinder cones are commonly isolated, having diameters much less than their spacing separations, whereas shields often butt up against each other.

Magma chamber depths

Classification of a cone as a maar, shield, etc. immediately implies general eruption characteristics and processes. Recent investigations (Wood, 1979a) of the dynamics of cinder and spatter cone eruptions suggest that measurements of cone morphology can also yield estimates of eruption rates and magma chamber depths. Wood (1979a) observed that the final volume (V in $10^6 m^3$) of a spatter or cinder cone is proportional to the average construction rate (R in $10^6 m^3$/day) for the cone:

$$V = 12.1(R)^{1.08}. \quad (1)$$

This result parallels Walker's (1973) conclusion that lava flow lengths are proportional to their extrusion rates.

Fedotov (1976) demonstrated that the minimum dike propagation and magma intrusion rates necessary for magma to reach the surface before freezing are directly proportional to magma chamber depth. Thus, wedding equation (1) to Fedotov's model yields a relation between cinder cone volume and magma chamber depth (Fig. 7). As an example, magmas that rise to the surface at 5 ×

$10^6 m^3/d$ come from depths of about 5 km, and produce cones with volumes of about $70 \times 10^6 m^3$ (similar to Monte Nuovo, near Vesuvius). It is interesting to note that the average volume for pseudocraters implies a magma source of 1–10 m, in accord with an origin by steam explosions under a hot lava flow. Figure 7 also implies that spatter cones have shallow sources, and indeed, some are fed from crusted-over lava lakes and lava tubes (although it is admitted that others have deeper sources).

The relation between cone volume and magma chamber depth predicts that

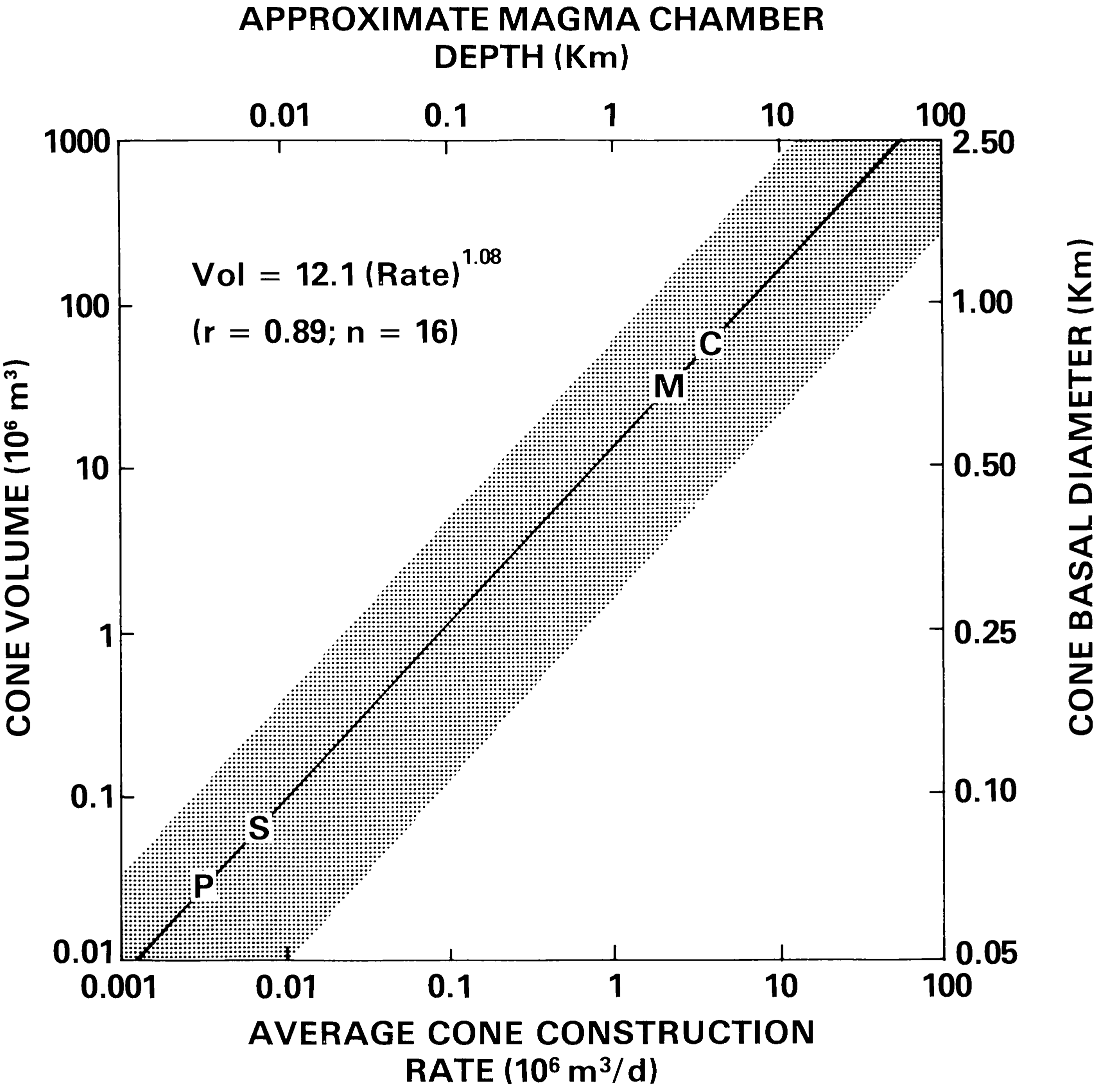

Fig. 7. Least-squares relationship between average cinder cone construction rate and final cone volume determined by analysis of 16 pyroclastic cone-forming eruptions (Wood, 1979a). The range of scatter in the original data indicated by pattern; r = correlation coefficient; P,S,M,C as defined in Fig. 6 and plotted by average cone volume. Nominal cone diameter determined from Equation (6) and $H_{co} = 0.18 W_{co}$ from Porter (1972) and Wood (1979a). The approximate relationship between cone construction rate and magma chamber depth is developed in Wood (1979a).

average terrestrial cinder cones (W_{co} = 0.8 km) have magma chambers at about 3 km depths, and that the largest cinder cones (W_{co} about 2–2.5 km) have magma sources at depths of 35–40 km, the average thickness of the Earth's crust. Clearly, Icelandic shields and larger volcanoes generally do not have chambers at greater depths than this, implying that the relation only holds for spatter and cinder cones.

EXTRATERRESTRIAL CONES

Because monogenetic volcanic cones are common on the Earth, it should be anticipated that they also occur on the Moon and Mars, two other planets with globally significant volcanic deposits. Indeed, lunar domes have been recognized as likely volcanoes for many years (e.g., Pickering, 1908), and numerous other possible volcanic cones have been detected on Orbiter and Apollo photography. Similarly, with the advent of Mariner and especially Viking images of Mars various crater-topped cones have been described.

Interpretation of these extra-terrestrial cones as volcanic, and further as specific types of volcanoes (shields, pseudocraters, etc.) is hampered by uncertainty as to (1) the effects of different gravitational fields and atmospheric regimes on eruptive processes, and also (2) the possibility of non-volcanic processes that could produce similar landforms. The restriction of lunar cones to known volcanic regions (the maria), and the absence of other credible processes for producing crater-topped cones argues forcefully for volcanic origins. Additionally, McGetchin and Head (1973) and McGetchin *et al.* (1974) have modeled the effects of the Moon's (and Mars') gravitational field and negligible atmosphere on eruption processes to predict the morphology of lunar (and martian) cinder cones. There is less certainty that the various martian cones are volcanic, for although some cones formed on obvious lava flows on the flanks of large shield volcanoes (Carr *et al.,* 1977), other cones with somewhat different morphologies occur in areas that may represent strongly eroded surfaces (Underwood and Trask, 1978). Thus, some martian cones may be erosion modified impact craters, or perhaps pingos (ice-cored hills found in permafrost regions of the Earth; Holmes *et al.*, 1968) or other non-volcanic landforms. At the present time interpretations of extraterrestrial cone origins must be based on general geologic setting, morphology and morphometry. The lunar and martian cones described below are among the best examples known, but the listing (Table 2) is not exhaustive, especially for Mars.

Lunar cones

Telescopic observers of the Moon had mapped various lunar domes that were suggested to be of volcanic origin (summarized by Wilhelms, 1970). Following the acquisition of high resolution Orbiter and Apollo photography, a number of small, crater-topped conical hills were suggested to be lunar cinder cones (e.g., Hartmann, 1968; Green, 1971; Scott and Trask, 1971; El Baz, 1972; Scott, 1973; McGetchin and Head, 1973). Head (1975) classified possible lunar pyroclastic cones into three types: dark-halo craters, small cones, and large cones. The prime examples of dark-halo craters are those on the floor of Alphonsus (Head, 1975; Peterfreund, 1976; Head and Wilson, 1979). These structures are low craters having rims about 40 m high, diameters of 1–3 km, and depths of 200–300 m. It is impossible to determine accurate H_{co}/W_{co} and W_{cr}/W_{co} ratios, but the former are roughly 0.03 and the latter are near unity.

Head's small pyroclastic cones are best exemplified by Osiris and Isis (Fig. 8), two crater-topped cones on a fissure in Mare Serenitatis (Scott, 1973; Head, 1975). Osiris is 2.1 km wide with an irregular crater about 0.7 km across on a summit 90 m above the surrounding mare surface. Isis is a smaller (W_{co} = 1.6 km, W_{cr} = 0.65 km, H_{co} = 0.06 km) breached cone with a short sinuous rille disappearing into the mare.

Head's large cones are larger and steeper than the small cones; most of the known examples are in the Marius Hills. Three of these cones have been measured; average values are W_{co} = 1.9 km and W_{cr} = 0.5 km. Numerous other volcanic edifices occur in the Marius Hills, but domes and uncratered cones predominate (Whitford-Stark and Head, 1977).

A number of crater-topped cones occur on the floor of the crater Copernicus. Originally these structures were thought to be lunar cinder cones (Hartmann, 1968; Green, 1971), but more recently they have been re-interpreted as random impacts on impact melt floor hummocks (Howard, 1975). These cones are included in the present data set (Table 2) for comparison with the other cones, which are undoubtedly volcanic.

Martian cones

A small cone occurs on the summit of Pavonis Mons, the middle of the three giant Tharsis shield volcanoes on Mars. The cone has a basal diameter of 1.1 km and its summit crater is about 0.45 km wide; the height is roughly estimated at 0.07 km based on apparent grazing illumination in Mariner 9 frame DAS 05563953. The morphology and setting of this cone leave little doubt that it is volcanic.

The origins of many other martian cones are uncertain (West, 1974). Carr *et al.* (1977, Fig. 25) illustrated several rounded cones with summit craters on the flank of the volcano Alba-Patera, and suggested that they may be volcanic domes (caption, Fig. 25) or cinder cones (p. 4007). Several of these rounded cones were measured (Table 2); their diameters range from about 1–5 km.

Another field of cratered cones occurs in Cydonia Mensae, a transitional region between the southern cratered highlands of Mars and the smoother, northern lowlands. This is a region of apparent scarp retreat, and residual hills and mountains abound (Underwood and Trask, 1978). However, there are also mare ridges,

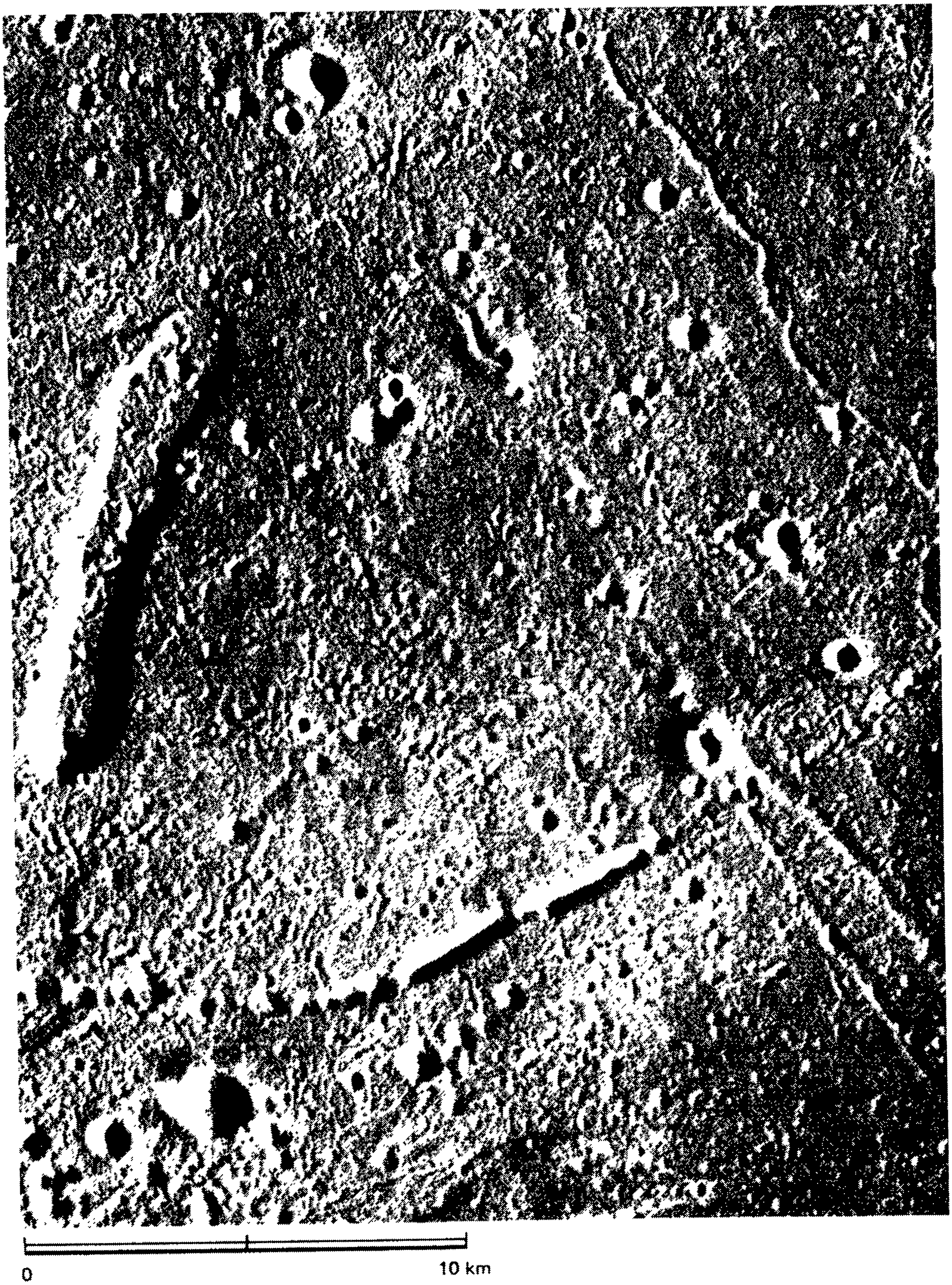

Fig. 8. Lunar cones Isis (A) diameter 1.35 km and Osiris (B) diameter 2.1 km. Apollo 17–2317 photograph from Masursky *et al.* (1978).

Table 2. Proposed extra-terrestrial monogenetic volcanoes

Name	Location	W_{co}	W_{cr}	H_{co}	Reference
Pyroclastic Cones					
Falcon	Taurus Littrow	0.35	0.10	0.01	McGetchin and Head (1973)
	Taurus Littrow	0.90	0.30		McGetchin and Head (1973)
Osiris	Serenitatis	2.10	0.75	0.09	LTO 42C3S2
Isis	Serenitatis	1.60	0.65	0.06	LTO 42C3S1
	Copernicus	0.78	0.25	0.03	V-H154,H155
	Copernicus	1.35	0.46		V-H154,H155
	Copernicus	0.91	0.41		V-H154,H155
	Copernicus	0.77	0.27		V-H154,H155
	Pavonis Mons	1.10	0.45	0.07?	DAS 05563953
	Cydonia Mensae	0.51	0.20		V72AO2
	Cydonia Mensae	0.76	0.30		V72AO2
	Cydonia Mensae	0.69	0.35		V72AO2
	Cydonia Mensae	0.50	0.20		V72AO2
	Cydonia Mensae	0.55	0.25		V72AO2
	Cydonia Mensae	0.45	0.17		V72AO2
	Cydonia Mensae	0.70	0.30		V72AO2
	Cydonia Mensae	0.55	0.25		V72AO1
	Cydonia Mensae	0.75	0.30		V72AO1
	Cydonia Mensae	0.80	0.40		V72AO1
	Cydonia Mensae	0.70	0.30		V72AO1
	Cydonia Mensae	0.75	0.25		V72AO1
	Cydonia Mensae	0.75	0.30		V72AO4
	Cydonia Mensae	0.85	0.35		V72AO4
	Cydonia Mensae	0.55	0.20		V72AO5
	Cydonia Mensae	0.40	0.15		V72AO6
	Cydonia Mensae	0.40	0.15		V72AO6
	Cydonia Mensae	0.65	0.25		V72AO6
	Cydonia Mensae	0.75	0.30		V72AO6
	Cydonia Mensae	1.35	0.50		V72A11
Lava Cone/Shield					
	Marius Hills	1.94	0.60		IV-157 H2
	Marius Hills	1.87	0.45		IV-157 H2
	Marius Hills	2.00	0.60		IV-157 H2
	Alba Patera	2.91	0.73		V7B21
	Alba Patera	4.86	1.20		V7B21
	Alba Patera	2.70	0.75		V7B24
	Alba Patera	2.00	0.68		V7B24
	Alba Patera	2.36	0.75		V7B24
	Alba Patera	4.00	1.20		V7B25
	Alba Patera	1.36	0.54		V7B16
	Alba Patera	3.22	0.97		V7B15
	Alba Patera	1.67	0.51		V7B15
	Alba Patera	2.76	0.66		V7B14
	Alba Patera	1.25	0.47		V7B14
	Alba Patera	2.48	0.68		V7B12

W_{cr} = crater diameter; W_{co} = cone basal diameter; H_{co} = cone height (all in km). LTO = Lunar Topographic Orthophotomap; IV- and V- refer to Lunar Orbiter 4 and 5 photographs. The remaining cones are on Mars and were measured on Mariner 9 (DAS) and Viking (V) photographs.

flow fronts, occasional sinuous rilles, and hundreds of small crater-topped cones. Although the origin of these cones is somewhat uncertain, their association with volcanic features (the cone in Fig. 9 is the source of a sinuous rille) strongly supports a volcanic origin. Frey *et al.* (1979) also consider the Cydonia cones to be volcanic, favoring a phreatic origin (similar to Icelandic pseudocraters), the cones having formed when lava flows covered ground ice.

Fig. 9. A possible cinder cone (arrow) of basal diameter 1.35 km in the Cydonia Mensae region of Mars. The cone is the apparent source of a sinuous rille that is interrupted by a superposed impact crater.

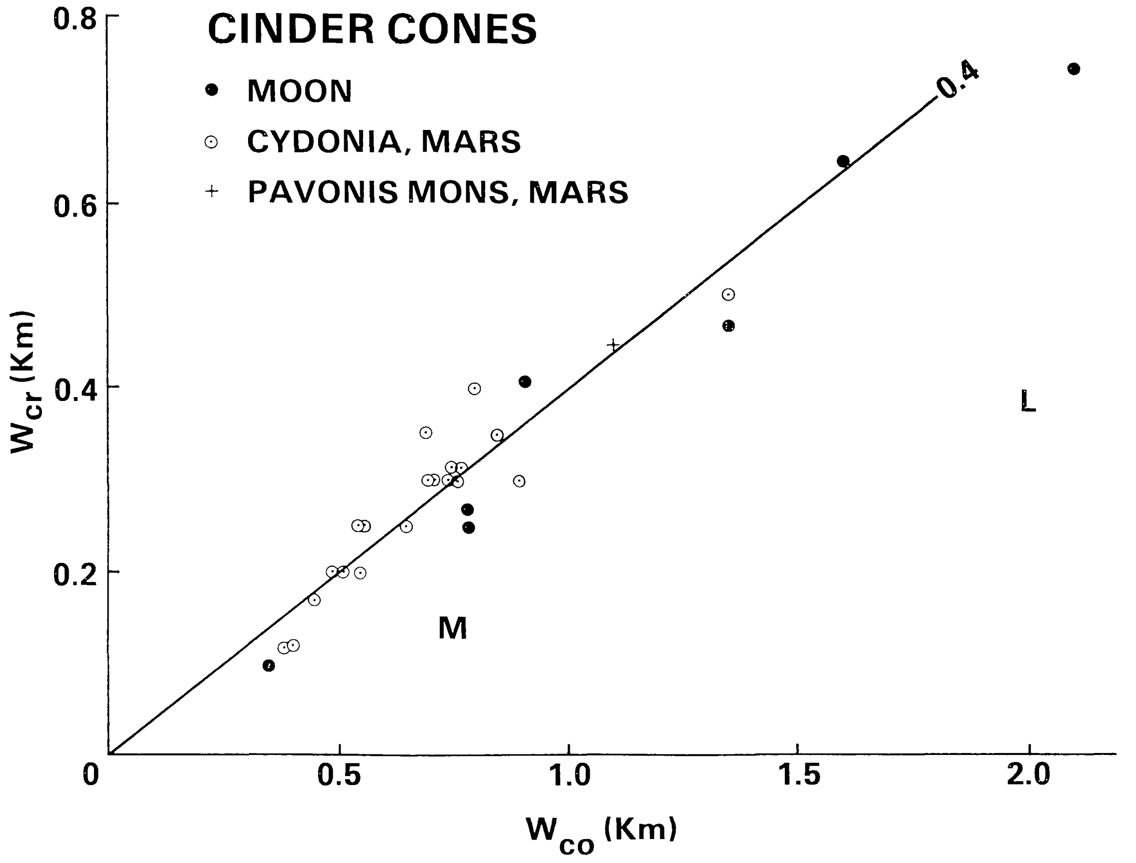

Fig. 10. Comparison of cone basal diameter (W_{co}) and crater diameter (W_{cr}) for possible cinder cones on the Moon and Mars. These cones closely follow the relation (W_{cr}/W_{co} = 0.4) defined by terrestrial cinder cones (Porter, 1972 and Wood, 1979a). The geometry of martian (M) and lunar (L) cones predicted by McGetchin *et al*. (1974) are indicated.

Morphometric relations of pyroclastic cones

Preliminary inspection of the W_{cr}/W_{co} data for the martian and lunar cones suggests that there may be at least two different cone populations, and thus the two groups are considered separately. The first group appears most similar to terrestrial pyroclastic cones and the second may be equivalent to small shields. In Fig. 10 the W_{cr}/W_{co} ratios for the possible pyroclastic cones (all of the lunar cones except the three from the Marius Hills, plus the martian cones in Cydonia Mensae and the Pavonis Mons cone) are compared with the least squares fit to similar data for terrestrial cinder cones (Porter, 1972; Wood, 1979a):

$$W_{cr} = 0.40 W_{co} \, (r = 0.94). \quad (2)$$

For 21 martian cones:

$$W_{cr} = 0.41 W_{co} \, (r = 0.93) \quad (3)$$

and for 8 lunar cones:

$$W_{cr} = 0.37W_{co} \; (r = 0.98). \quad (4)$$

On the basis of these morphometric results, morphology, and geologic settings these lunar and martian cones are considered to be cinder cones, in agreement with similar conclusions (Head, 1975; Scott, 1973; West, 1974; etc).

It may appear surprising that cones formed by ballistic deposition of cinders have essentially identical W_{cr}/W_{co} relations despite differences in gravity and atmospheric conditions. However, for a given ejecta volume, martian and lunar cones do have greater diameters (see below), but the lower gravity and more tenuous atmospheres compared to the Earth allow wider dispersal of the ejecta that forms crater rim crests as well as that which forms cone edges. The W_{cr}/W_{co} ratio is thus independent of gravity or atmospheric effects.

Cone heights are more difficult to determine than cone diameters for extraterrestrial cones, and heights could be measured for only 4 lunar cones and estimated for 1 martian cone (Table 2). The lunar data are remarkably consistent (Fig. 11):

$$H_{co} = 0.04W_{co} \; (r = 0.995). \quad (5)$$

The single estimate for a martian cone suggests that $H_{co}/W_{co} = 0.06$ on that planet. Thus, lunar cinder cones are only 22% as high as their terrestrial counterparts ($H_{co}W_{co} = 0.18$; Porter, 1972; Wood, 1979a), and martian cones are only 1/3 as high. With these geometric relations it is possible to compare volumes of cinder cones. Because $W_{cr} = 0.4W_{co}$ for all three planets, cone volume can be expressed as:

$$V = 0.408(H_{co})(W_{co})^2. \quad (6)$$

Using equation 4-6 the relation between basal diameter for cones of equal volume are readily found:

$$W^{L}_{co} = 1.65W^{E}_{co} \quad (7)$$

$$W^{M}_{co} = 1.45W^{E}_{co} \quad (8)$$

where L = lunar cones, M = martian cones, and E = terrestrial cones.

The diameter distribution (converted to diameters of equal volume terrestrial cones) of the lunar cones spans nearly the entire range of terrestrial cone volumes, but the median equivalent W_{co} is 0.55 km, vs. 0.8 km for cones on Earth. The martian cones also cluster around $W_{co} = 0.5$ km; thus the volumes of the median size martian and lunar cinder cones are only about 25% of the median terrestrial cone. If eruption conditions were similar for cones on all three planets, the smaller volumes for martian and lunar cones imply that their construction rates were low (Fig. 7), and thus (Fedotov, 1976) that their magma chambers were smaller and at shallower depths (about 1 km) than is typical for the Earth (about 3 km; Wood, 1979a).

Eruption energetics

The observed dimensions of martian and lunar cinder cones can be used to estimate minimum eruption velocities for the explosions that deposited material at the edges of the cones (McGetchin *et al.,* 1974; Head, 1975). The velocities required to form the smallest and largest observed extraterrestrial cones, assuming (a) 45° and (b) 75° ejection angles are presented in Table 3. The range of velocities for lunar cones is 16 to 57 m/s, and for martian cones is 27 to 70 m/s. No account was taken of the reduced range due to the tenuous martian atmosphere; however, the calculations by McGetchin *et al.* (1974) suggest that drag-corrected martian velocities would be only about 10% higher. Terrestrial velocities (drag corrected) are 3 to 10 times greater than lunar and martian velocities for equal volume eruptions. This implies that the volatile/solid ratio is lower for lunar and martian magmas than for terrestrial magmas. The low eruptive velocities are consistent with the smaller average cone volumes, and presumably shallower and drier sources of magma for the extra-terrestrial cones.

Housley (1978) has modelled the rise of magma to the lunar surface, using hydraulic engineering data for turbulent flow through a 10 m wide conduit. He finds that a mass eruption rate of $1.9 \times 10^6 m^3/hr$ would produce fire fountaining to a height of 1 km, but he did not calculate the dimensions of the resulting cones. This mass eruption rate corresponds with that expected for the largest terrestrial cinder cones. Equal volume lunar cones would have diameters of about 3.5 km; larger than any observed. If Housley's model is correct, for a given magma volume, lunar eruptions were characterized by higher eruption rates than on Earth. Osiris, the largest lunar cone listed in Table 2, could have been built entirely in 38 hours, compared to 12 days for typical terrestrial cone-building eruptions (Wood, 1979a). Such brief lunar eruptions may result from the low viscosities (about 10 poise; Murase and McBirney, 1970) of lunar lavas, which would allow rapid segregation of the volatiles from the magma. This may explain why most lunar cones appear to lack associated lava flows (a major difference from terrestrial cinder cones), for the degassed magma (epimagma of Jaggar, 1947) would not rise to the surface.

McGetchin *et al.* (1974) predicted that if the same volume of pyroclastic ma-

Table 3. Ballistic velocities for pyroclastic cones.

	Min-Max Diameter	Velocity @ 45°–75°	Diameter Equal Vol Earth Cone	Velocity @ 45°–75°	Velocity Ratio
Moon	0.35 KM	16–23 M/S	0.21 KM	55–80 M/S	3.4
	2.10	40–57	1.27	400+	7–10+
Mars	0.40	27–39	0.28	65–120	2.4–3.1
	1.35	50–70	0.93	450+	6.4–9+

terial that comprises NE Crater, Etna were erupted on Mars or the Moon with the same exit conditions they determined for one eruption of NE Crater, the resulting cones would be very low and wide. The calculated cone dimensions given by McGetchin *et al.* (1974) (plotted on Figs. 10 and 11) are not in agreement with the geometry of proposed extraterrestrial cinder cones. The model cones are too low and too wide. Perhaps the most questionable assumptions for interplanetary modeling of volcanic eruptions are that terrestrial ejecta volumes, angles and velocities are typical of Mars or the Moon. Ejection velocities depend upon volatile abundance and species (Blackburn *et al.,* 1976), and ejection angles depend, in part, on the depth of explosion (Heiken, 1971) which is related to bubble pressure and thus gravity. On the Moon, the depletion of volatiles and low gravity imply that ejection conditions would be much different than for terrestrial volcanoes. Indeed, as documented above, lunar and martian cones had considerably smaller volumes and velocities than typical for terrestrial cinder cones.

Morphometric relations of lava cones

Three cones in the lunar Marius Hills and a dozen more on the martian shield volcano Alba Patera have geometrical relations unlike the proposed cinder cones discussed above. Cones of this second group have smaller craters for a given basal diameter, and a larger range of diameters than the pyroclastic cones. Preliminary evidence suggest that these large cones are equivalent to terrestrial shield volcanoes. Compared to the Cydonia Mensae cones, the Alba type structures

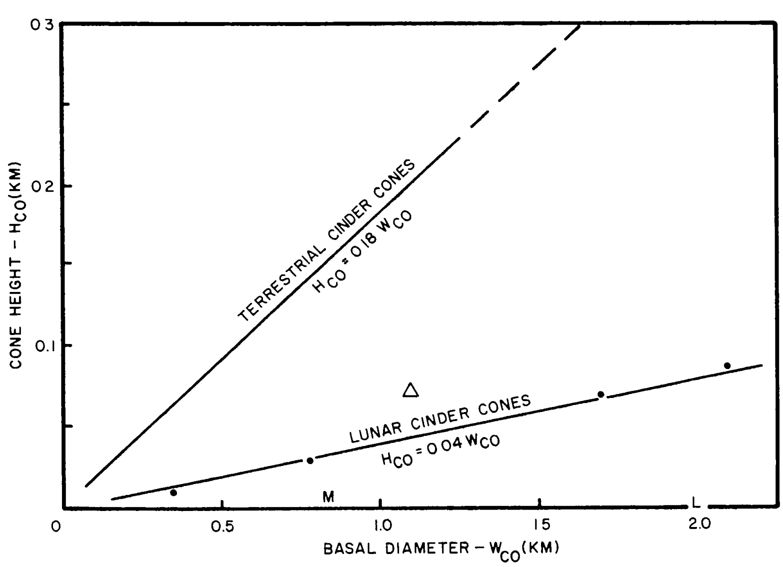

Fig. 11. Only a few heights are measurable for extraterrestrial cones, but the four lunar data points (Table 2) sharply define a H_{co}/W_{co} relation considerably different from terrestrial cones. The triangle represents the estimated position of a martian cone on the summit of Pavonis Mons. "M" and "L" are the predicted geometries of martian and lunar cones according to McGetchin *et al.* (1974).

have small craters. Morphometric data (Table 1) demonstrate that terrestrial cinder cones have larger craters (W_{cr} = 40%W_{co}) than do small basaltic shields (W_{cr} = 6–12%W_{co}). The Alba structures are also considerably larger (median W_{co} = 2.5 km) than the Cydonia cones (0.75 km). Similarly, terrestrial small shields (average W_{co} = 4–9 km) are much larger than terrestrial cinder cones (0.8 km). Thus, since both broad-cratered cones (Cydonia types) and small-cratered cones (Alba types) exist on Earth, Mars and the Moon, it is proposed that the former are cinder cones and the latter are lava cones or small shields. Additionally, the Alba cones are intimately associated with broad flows and lava channels, a volcanic style that, on Earth, is associated with quiet effusion of lava and shield-building, rather than explosive, cone-building activity.

If the Alba structures are small martian shield volcanoes, they have considerably larger craters (W_{cr} = 28%W_{co}) than terrestrial shields (W_{cr} = 6–12%W_{co}). The martian shield craters have sizes similar to the lunar domes, which from the data of Head and Gifford (1979) average W_{cr} = 24%W_{co}. The lunar domes are interpreted as small shields by Head and Gifford (1979) and others. Pike (1978) rejected the hypothesis that lunar domes were formed by the same process as terrestrial shields because the craters of the former are larger than those of the latter. This objection may be minimized if the size of shield craters is partially controlled by the value of the gravitational acceleration, for example by collapse of an unsupported roof. If lava density and strength are equal on the Earth, Moon and Mars, then lunar craters might be 6 times larger, and martian shield craters 2.7 times larger, than shield craters on Earth. Actually, craters on the proposed martian shields are 2.3 to 4.7 times larger, and the lunar dome craters are 2 to 4 times larger than terrestrial small shield craters. The agreement is satisfactory considering the uncertainties. Thus, it is proposed, on the basis of general geologic settings, analogy with the Earth, morphology and morphometry, that the cones in the Marius Hills and on Alba Patera (Table 2) are small shield volcanoes, as are the lunar domes.

DISCUSSION

Explosive and effusive eruptions have constructed distinctive volcanic cones on the Earth and apparently on Mars and the Moon. On Earth this two-fold classification is complicated by the common availability of copious near surface water that can impart additional xplosiveness to pyroclastic eruptions and severely alter cone morphology. This factor is lacking on the Moon, and uncertain for Mars. As an aid to classification of origins of extra-terrestrial monogenetic volcanoes, terrestrial cones of generally known origins have been plotted (Fig. 6) using only two measurements of horizontal dimensions—W_{cr} and W_{co}. This classification scheme is less sophisticated than the multi-component factor analysis used by Pike (1978), but insufficient data are available to plot more than a few extra-terrestrial monogenetic cones using his method. Although there is considerable overlap in parts of Fig. 6, terrestrial pyroclastic and lava cones fall in separate parts of the diagram, and it is generally possible to subdivide these major cone types into subtypes representing different eruption processes.

Lunar and martian cones are compared in Fig. 12 with terrestrial volcano types as defined by the fields established in Fig. 6. The cone diameters (W_{co}) plotted for proposed lunar and martian cinder cones are the diameters of equal volume terrestrial cones. Distributions of the proposed extra-terrestrial pyroclastic cones and lava shields do not overlap significantly, but are not as clearly separated as terrestrial cones. This may be due to the enlargement of the summit craters of the lunar and martian shields because of their planets' lower gravitational fields. Lunar domes—long suspected to be shield volcanoes—plot in the same general field as the other proposed shields. There is a rough inverse relation between W_{cr}/W_{co} and W_{co} for lunar and martian shields; a similar, but more poorly defined tendency is indicated for terrestrial low shields in Fig. 6.

Proposed alien pyroclastic cones plot entirely within the terrestrial cinder cone field, although some cones fall in the overlap zones with maars and pseudocraters. Frey *et al.* (1979) have interpreted the martian Cydonia Mensae cones as pseudocraters. This interpretation is not supported here because (1) the cones' diameters are significantly larger than those of terrestrial pseudocraters; (2) the

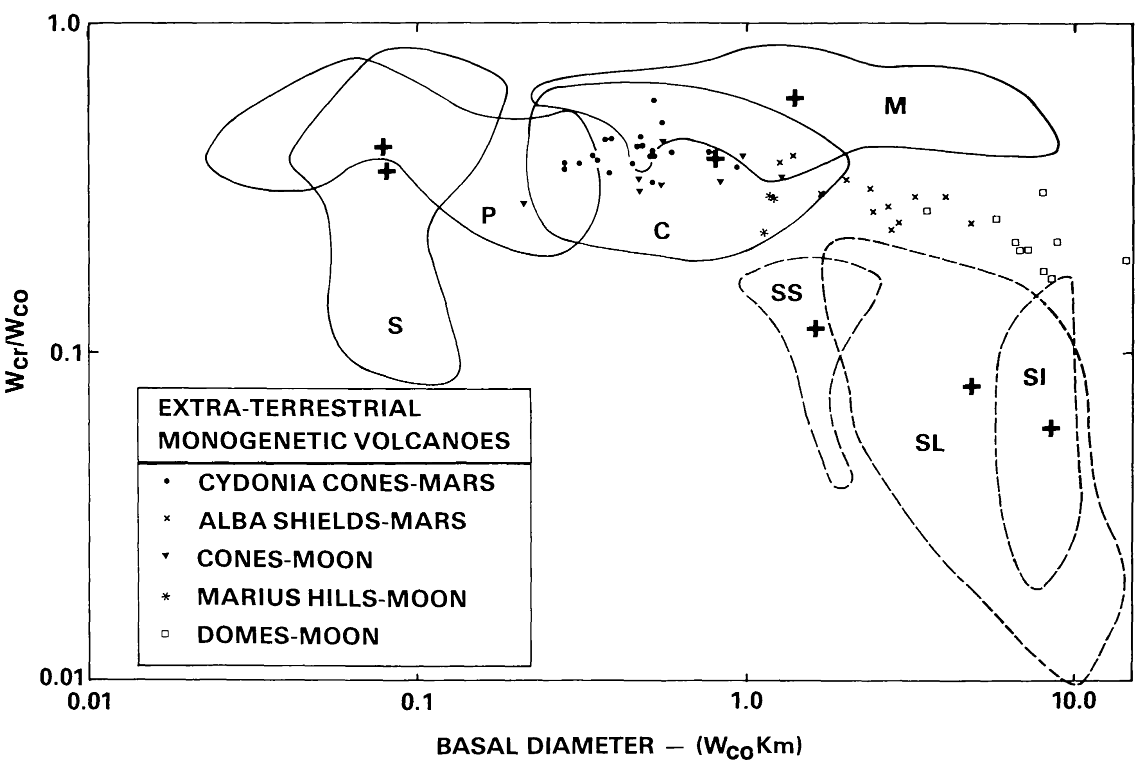

Fig. 12. Comparison of the geometry of extraterrestial cones and terrestrial monogenetic cones as defined in Fig. 6. The alien cones appear to fall into two groups: cinder cones (C field) and crater-widened (see text) shields (SS, SL and SI fields).

cones' volumes imply magma chamber depths of about 1 km, not surface magma sources; (3) the spatial density of the Cydonia cones is high, but not like the closely spaced and overlapping Icelandic pseudocraters; and (4) lunar pyroclastic cones—that definitely are not pseudocraters—plot in the same areas.

The possibility that the martian cones in Cydonia are pingos cannot be strongly supported, nor completely rejected. Pingos on Earth tend to be an order of magnitude smaller than the Cydonia cones; the average dimensions of 140 pingos on Prince Patrick Island, Canada are W_{cr} = 58 m and H_{co} = 3.3 m, with the largest being 250 m in diameter (Pissart and French, 1977). The W_{cr}/W_{co} ratio for pingos is unknown, but based on measures of a few photographs, pingos may have ratios of 0.55–0.70, considerably larger than the martian cones. Pingos are not well understood, however, and giant pingos could exist on Mars.

None of the observed extraterrestrial cones plot in the spatter cone field of Fig. 12, but spatter cones should be expected on Mars and the Moon. A typical terrestrial spatter cone with diameter of 80 m would have a rim only 5–10 m high on the Moon, too low to be conspicuous.

Some of the cones in Fig. 12 plot in the overlap zone for maars and cinder cones. All of the cones in the pyroclastic field are very similar and probably all have the same origin. The only extraterrestrial cones that would plot in the maar field are the dark halo craters of Alphonsus which have diameters of 1–2 km and W_{cr}/W_{co} ratios near unity. These cones are unique and appear to represent a style of volcanism unlike normal cinder cones or shield volcanoes.

If the cones on the floor of Copernicus are cinder cones, as implied by their morphometry, volcanic activity has occurred on the Moon since the formation of Copernicus about 1–2 billion years ago (Silver, 1971; Eberhardt *et al.,* 1973). As the youngest dated rocks on the Moon are about 3.2 billion years old (Taylor, 1975) and crater count estimated ages of unsampled maria yield ages no younger than 2 billion years (Boyce, 1975), evidence for volcanism in Copernicus would imply that lunar igneous activity was not restricted to the epoch of mare emplacement.

The importance of this possibility warrants further investigation: from systematic discrepancies in the central peak height and crater depth, Wood (1973) deduced that the floor of Copernicus has a volcanic fill 1 km thick. Hartmann (1968) identified rimless collapse pits similar to Hawaiian pit craters on Copernicus' floor, and Howard (1975) mapped patches of subdued topography which may represent a veneer of volcanic ash. Additionally, crater counts indicate that smooth ponds on the inner wall terraces and on the floor of Copernicus postdate the formation of the crater by a significant amount of time and thus may be volcanic (Greeley and Gault, 1971). Note that this diverse but consistent evidence for volcanism in Copernicus refers only to minor modifications of a crater formed by impact (Shoemaker, 1962; Howard, 1975). A fundamental question for the thermal history of the Moon is whether this post-impact volcanic activity resulted from normal igneous processes (generation of magma by internal heating) or from impact-related melting (French, 1970; Hulme, 1974).

CONCLUSIONS

Monogenetic volcanic activity has produced cinder cones and small shield volcanoes on Earth, Moon and Mars. Extraterrestrial cinder cones have median volumes only 25% as large as average cinder cones on Earth, implying that their magma chambers are smaller and shallower (1 km depth vs. 3 km) than those of terrestrial cinder cones. Ejection velocities for lunar and martian cinder cones ranged from about 20–70 m/s, only 1/3 to 1/10 as high as for equal volume terrestrial eruptions. These low velocities imply low volatile contents for both martian and lunar magmas.

Small shield volcanoes on Earth, Mars and Moon have similar diameters (and probably volumes), but summit craters on the alien shields are 2–5 times larger than those on Earth. This may simply represent a gravitational acceleration control on crater formation, perhaps through collapse of an unsupported roof.

Possible cinder cones on the floor of the young crater Copernicus provoke the question of whether the volcanism that formed them resulted from internal heating or from impact heating.

Acknowledgments—I thank M. Settle, P. Mouginis-Mark and R. Pike for data in advance of publication and for discussions of planetary volcanism. Helpful reviews were received from J. King and M. Grolier. L. Wilson provided considerable insight, and he and J. Head offered continuing support. This research was performed largely at Brown University under NASA grants NGR-40-002-088 and NGR-40-002-116.

REFERENCES

Barth T. F. W. (1950) Volcanic geology, hot springs and geysers of Iceland. Carnegie Inst. Washington, Publ. 587.

Blackburn E. A., Wilson L., and Sparks R. S. J. (1976) Mechanisms and dynamics of strombolian activity. *J. Geol. Soc. Lond.* **132,** 429–440.

Boyce J. M. (1975) Chronology of the major flow units in the western nearside maria (abstract). In *Papers Presented to the Conference on Origins of Mare Basalts,* p. 11–14. The Lunar Science Institute, Houston.

Carr M. H., Crumpler L. S., Cutts J. A., Greeley R., Guest J. E., and Masursky H. (1977) Martian impact craters and emplacement of ejecta by surface flow. *J. Geophys. Res.* **82,** 4055–4065.

Chouet B., Hamisevicz N., and McGetchin T. R. (1974) Photoballistics of volcanic jet activity at Stromboli, Italy. *J. Geophys. Res.* **79,** 4961–4976.

Eberhardt P., Geiss J., Grögler N., and Stettler A. (1973) How old is the crater Copernicus? *The Moon* **8,** 104–114.

El-Baz F. (1972) The cinder field of the Taurus Mountains. In *Apollo 15 Prelim. Sci. Rep.* NASA SP-289, p. 25–26 to 25–71.

Fedotov S. A. (1976) Ascent of basic magmas in the crust and the mechanism of basaltic fissure eruptions. *Internat. Geol. Rev.* **20,** 33–48.

French B. M. (1970) Possible relations between meteorite impact and igneous petrogenesis, as indicated by the Sudbury structure, Ontario, Canada. *Bull. Volcanol.* **34,** 466–517.

Frey H. V., Chase S. A., and Lowry B. (1979) Phreatic eruptions on Mars (abstract). In *Lunar and Planetary Science X,* p. 400–401. Lunar and Planetary Institute, Houston.

Greeley R. and Gault D. E. (1971) Endogenetic craters interpreted from crater counts on the inner wall of Copernicus. *Science* **171,** 477–479.

Green J. (1971) Copernicus as a lunar caldera. *J. Geophys. Res.* **76,** 5719–5731.

Hartmann W. K. (1968) Lunar crater counts. VI: the young craters Tycho, Aristarchus, and Copernicus. *Commun. Lunar and Planetary Lab., Univ. Arizona* **7,** 145–156.

Head J. W. (1975) Morphology of pyroclastic lunar volcanic deposits: implications for eruptive conditions and localized sources of volatiles (abstract). In *Lunar Science VI,* p. 349–351. The Lunar Science Institute, Houston.

Head J. W. and Gifford A. (1979) Lunar mare domes: classification and modes of origin. *Moon and Planets.* In press.

Head J. W. and Wilson L. (1979) Alphonsus type dark halo craters: morphology, morphometry and eruption conditions (abstract). In *Lunar and Planetary Science X,* p. 525–527. Lunar and Planetary Institute, Houston.

Heiken G. H. (1971) Tuff rings: examples from the Fort Rock-Christmas Lake valley basin, south-central Oregon. *J. Geophys. Res.* **76,** 5615–5626.

Holmes G. W., Hopkins D. M., and Foster H. L. (1968) Pingos in central Alaska. *U.S. Geol. Survey Bull.* **1241-H.** 40 pp.

Housley R. M. (1978) Modeling lunar volcanic eruptions. *Proc. Lunar Planet. Sci. Conf. 9th,* p. 1473–1484.

Howard K. A. (1975) Geologic map of the crater Copernicus. U.S. Geol. Survey Misc. Inv. Map I-840.

Hulme G. (1974) Generation of magma at lunar impact crater sites. *Nature* **252,** 556–558.

Jaggar T. A. (1947) The Origin and Development of Craters. *Geol. Soc. Amer. Mem. 21,* 508 pp.

Kennedy G. C. (1955) Some aspects of the role of water in rock melts. *Geol. Soc. Amer. Spec. Paper 62,* 489–504.

Kjartansson G. (1962) Geologic Map of Iceland, Sheet 6. Museum of Natural History, Reykjavik.

Lorenz V. (1973) On the formation of maars. *Bull. Volcanol.* **37,** 183–204.

Lorenz V. (1975) Formation of phreatomagmatic maar-diatreme volcanoes and its relevance to kimberlite diatremes. *Phys. Chem. Earth* **9,** 17–27.

Masursky H., Colton G. W., El-Baz F. (eds.) (1978) *Apollo Over the Moon: A View from Orbit.* NASA SP-362. 255 pp.

McGetchin T. R. and Head J. W. (1973) Lunar cinder cones. *Science* **180,** 68–71.

McGetchin T. R., Settle M., and Chouet B. A. (1974) Cinder cone growth modeled after Northeast Crater, Mount Etna, Sicily. *J. Geophys. Res.* **79,** 3257–3272.

Mouginis-Mark P. (1977) Morphology and mode of formation of martian rampart craters. Ph.D. thesis. Lancaster Univ., Lancaster, UK.

Murase T. and McBirney A. R. (1970) Viscosity of lunar lavas. *Science* **167,** 1491–1493.

Nakamura K. (1977) Volcanoes as possible indicators of tectonic stress orientation—principle and proposal. *J. Volcanol Geotherm. Res.* **2,** 1–16.

Ollier C. D. (1967) Maars. Their characteristics, varieties and definition. *Bull. Volcanol.* **32,** 45–73.

Ollier C. D. (1974) Phreatic eruptions and maars. In *Physical Volcanology* (L. Civetta, P. Gasparini, G. Luongo, and A. Rapolla, eds.), p. 289–311 Elsevier, Amsterdam.

Peckover R. S., Buchanan D. J., and Ashby D. E. T. F. (1973) Fuel-coolant interactions in submarine volcanism. *Nature* **245,** 307–308.

Peterfreund A. R. (1976) Alphonsus dark haoled craters: examples of isolated dark mantle sources. *EOS (Trans. Amer. Geophys. Union)* **57,** 275.

Peterson D. W., Christiansen W. A., Duffield W. A., Holcomb R. T., and Tilling R. I. (1976) Recent activity of Kilauea volcano, Hawaii. In *Proceedings of the Symposium on Andean and Antarctic volcanology problems* (O. G. Ferran, ed.), p. 646–656. IAVCEI Publication, Naples.

Pickering W. H. (1908) Lunar and Hawaiian physical features compared. *Mem. Amer. Acad. Arts Sci.* **13,** 173.

Pike R. J. (1977) Topography of small basalt shields. In *Abstracts for the Planetary Geology Field Conference on the Snake River Plain, Idaho* (R. Greeley and D. Black, eds.), p. 10–14. NASA TM-78436.

Pike R. J. (1978) Volcanoes on the inner planets: some preliminary comparisons of gross topography. *Proc. Lunar Planet. Sci. Conf. 9th,* p. 3239–3273.

Pissart A. and French H. M. (1977) The origin of pingos in regions of thick permafrost, western Canadian Arctic. *Quaestiones Geographicae* **4,** 149–160.

Porter S. C. (1972) Distribution, morphology, and size frequency of cinder cones on Mauna Kea Volcano, Hawaii. *Bull. Geol. Soc. Amer.* **83,** 3607–3612.

Rittman A. (1938) Die Vulkane am Myvatn in Nord-Island. *Bull. Volcanol.* **4,** 1–38.

Scott D. H. (1973) Mare Serenitatis cinder cones and terrestrial analogs. *Apollo 17 Prelim. Sci. Rep.* NASA SP-330, p. 30–7 to 30–8.

Scott D. H. and Trask N. J. (1971) Geology of the Lunar Crater Volcanic Field, Nye County, Nevada. *U.S. Geol. Survey Prof. Paper 599-I.* 22 pp.

Settle M. (1979) The structure and emplacement of cinder cone fields. *Amer. J. Sci.* In press.

Shoemaker E. M. (1962) Interpretation of lunar craters. In *Physics and Astronomy of the moon* (Z. Kopal, ed.), p. 283–359. Academic, London.

Silver L. T. (1971) U-Th-Pb isotopic system in Apollo 11 and Apollo 12 regolithic materials and a possible age for the Copernican event. *EOS (Trans. Amer. Geophys. Union)* **52,** 534.

Stearns H. T. and Vaksvik K. N. (1935) Geology and ground water resources of the island of Oahu. Hawaii Div. Hydrology Bull. 1.

Swanson D. A., Duffield W. A., Jackson D. B., and Peterson D. W. (1979) Chronological narrative of the 1969–71 Mauna Ulu eruption of Kilauea volcano, Hawaii. *U.S. Geol. Survey Prof. Paper 1056.* 55 pp.

Taylor S. R. (1975) *Lunar Science: A Post-Apollo View.* Pergamon, N.Y. 372 pp.

Thorarinsson S. (1953) Crater groups in Iceland. *Bull. Volcanol.* **14,** 1–44.

Underwood J. R. and Trask N. J. (1978) Geologic map of the Mare Acidalium quadrangle of Mars. U.S. Geol. Survey Misc. Inv. Map I-1048.

Walker G. P. L. (1973) Lengths of lava flows. *Phil. Trans. Roy. Soc. Lond.* **A274,** 107–118.

West M. (1974) Martian volcanism: additional observations and evidence for pyroclastic activity. *Icarus* **21,** 1–11.

Wilhelms D. E. (1970) Summary of Lunar Stratigraphy—Telescopic Observations. *U.S. Geol. Survey Prof. Paper 599-F.* 47 pp.

Wilson L. and Head J. W. (1979) Lunar cones and dark mantling deposits: consequences of patterns of volatile release (abstract). In *Lunar and Planetary Science X,* p. 1353–1355. Lunar and Planetary Institute, Houston.

Whitford-Stark J. L. and Head J. W. (1977). The Procellarum Volcanic complexes: contrasting styles of volcanism. *Proc. Lunar Sci. Conf. 8th,* p. 2705–2724.

Wood C. A. (1973) Moon: central peak heights and crater origins. *Icarus* **20,** 503–506.

Wood C. A. (1974) Reconnaissance geophysics and geology of the Pinacate Craters, Sonora, Mexico. *Bull. Volcanol.* **38,** 149–172.

Wood C. A. (1977) Cinder cones on Earth, Moon and Mars. *EOS (Trans. Amer. Geophys. Union)* **58,** 425.

Wood C. A. (1979a) Morphometric evolution of cinder cones. *J. Volcanol Geotherm. Res.* In press.

Wood C. A. (1979b) Morphometric studies of planetary landforms: impact craters and volcanoes. Ph.D. thesis, Brown Univ., Providence.

Wood C. A. (1979c) Maars. *Encyclopedia of Volcanology.* In press.