

RECONNAISSANCE GEOLOGY AND GEOPHYSICS OF  
THE PINACATE CRATERS, SONORA, MEXICO

by

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## ABSTRACT

The Pinacate volcanic field of northwest Sonora, Mexico, contains ten large craters remarkable for their number and fresh appearance. To test the applicability of geophysical methodology for investigation of crater substructures and to attempt to distinguish between maar and caldera origins, reconnaissance geophysical and geological surveys were made of the craters. Crater-form terminology and mechanisms are reviewed and synthesized to provide probable models of the subsurface structure of maars and calderas.

Magnetic surveys indicate the presence of a subsurface, cylindrical, basaltic plug associated with MacDougal Crater but not with Molina Crater or Cerro Colorado. The MacDougal plug is gravimetrically insignificant. The central peak of Moon Crater is morphologically and magnetically a cinder cone. Cinder cones generally have basaltic, highly magnetic plugs, whereas the major craters generally have tuffaceous plugs.

Most craters are characterized by raised tuff rims unconformably resting on flat-lying basaltic cliffs. It is suggested that diatreme activity led to the construction of tuff cones which collapsed following the eruption of the tuff. A multiphase eruptive and collapse history for each of the craters is evidenced by cinder cones exposed in cross section in crater rims, rim-breaking cinder cones, major eccentric vents, and coalescing craters. Basaltic intrusions occurred along ring fractures and in the center of MacDougal Crater. Circumstantial evidence

suggests that most craters be considered maars, although Cerro Colorado may best be described as a tuff ring and Moon crater as a ring dike.

## INTRODUCTION

Sierra Pinacate is a roughly circular volcanic shield about 30 miles in diameter in the Sonoran Desert of Mexico, east of the Gulf of California. In addition to cinder cones and malpais, which are commonplace in southwestern North America, the lava-flow and ash-deposit terrain of the Pinacate is penetrated by ten large well-preserved craters. The literature concerning the origin of these craters is sparse and not yet in accord. The craters may be analogous to the original surface expressions (i.e., explosion vents) of eroded volcanic necks exposed in Arizona, Scotland, and Germany; or perhaps the craters are small calderas. In an attempt to test the applicability of geophysical methodology to distinguish between these two basic crater-forming mechanisms and to improve understanding of the Pinacate craters, reconnaissance gravity and magnetic surveys, as well as geologic investigations, were made across MacDougal, a typical crater; for comparison, magnetic and geologic surveys were carried out in other craters with different morphologies.

### Previous and Concurrent Studies

Although artifacts of the Pinacatenos people indicate a continuous occupation of the Pinacate for nearly 2,000 years (Hayden, 1967), white men have generally avoided these volcanoes and the inhospitable surrounding desert. The first written descriptions of the Pinacate by the Jesuit priest Padre Kino and his companion, Captain Mateo Manje, in

the early 18th century (Bolton, 1919) were separated by a hiatus of 200 years from the first scientific reconnaissance expeditions reported by Hornaday (1908) and Lumholtz (1912). The historian and geologist Ives backpacked 30 miles from the nearest town to the Pinacate in 1931 to begin his long association with the region. The results of Ives's 35 years of exploration are summarized in his 1964 monograph.

Much of the geologic information reported here comes from a 1959 paper by Jahns, resulting from 28 days of mapping. Shoemaker, reported in Galbraith (1959), has also visited the Pinacate and offered an explanation of the origin of the craters. Extensive geological and geophysical studies of the area are now being completed by J. R. Sumner, M. F. Donnelly, and J. E. Gutman of Stanford University. Sumner's dissertation and Donnelly's geologic map of the Pinacate have been made available in advance of publication.

Travel in the Pinacate is still difficult and potentially dangerous. Hayden (1967, p. 335) praised "the woodcutters who have, with their dilapidated trucks, with a barrel of water, a sack of frijoles, and an abiding faith in God, laid down tracks where no sensible person would have driven an army tank." These tracks, which are frequently either deeply rutted or invisible, quickly become wheel-grabbing treacle during rainstorms. All needed water must be carried into the Pinacate, for the traditional natural water tanks were dry in 1971 and have been polluted by cattle. Heat normally prohibits travel from late April through October; the midday August temperature is as high as 130°F. The field work reported here started in August 1970 and continued intermittently to January 1972.

### Historical Notes

The Pinacate volcanic field nearly belonged to the United States. Originally the Gadsden Purchase was to include Baja California and parts of Sonora as far south as Guaymas so that the United States could have seaports on the Gulf of California, but the U.S. Senate, after heated debate, refused to appropriate the extra ten million dollars necessary to buy this land, and the present boundary was the compromise solution (Corle, 1951).

Although there have been few scientific ventures into the Pinacate until recently, Hayden (personal communication) recounted stories of U.S. Treasury agents patrolling the area trying to stop smuggling into the prohibition-dry United States. The Border Patrol today is equally vigilant about marijuana smuggling. In the 1950's, Hayden was stopped by poachers armed with machine guns. This may explain the near extinction of the pronghorn antelope so common in Hornaday's account of 1908.

Recently the Pinacate has been used as geology training sites for Apollo astronauts. And now the ancient desert pavement is being torn apart by the influx of weekend campers in dunebuggies and jeeps.

## SUMMARY GEOLOGY OF THE PINACATE REGION

Figure 1 shows the desert-surrounded Pinacate as photographed from the Gemini IV spacecraft at a height of 110 miles above the earth's surface. The mouth of the Gulf of California is in the southwest corner of the picture, and fault-block topography typical of the Basin and Range is shown, especially to the east (Fig. 2). Three of the north-northwest-trending pre-Tertiary crystalline ranges, Sierras Hornaday, Extrana, and Blanca, project up through the apparent edges of the lava flows. Basin and Range tectonic forces do not appear to have influenced the alignment of the craters. However, the proximity of the Pinacate to the Gulf of California and its series of transform faults linking the East Pacific Rise to the San Andreas fracture zone (Larson, Menard, and Smith, 1968) hints that the Pinacate magma may have derived from deep-seated sources activated by ocean-floor spreading.

The Pinacate shield is dominated by the twin peaks, Pinacate (4,235 feet) and Carnegie (4,180 feet), which are composed of inter-fingered lava flows and pyroclastic deposits (Ives, 1965). Hundreds of cinder cones, often sources of both ash falls and lava flows, complete the landscape, especially in the northern half of the field. Small lava tubes, hornitos, and other minor features of lava flows occur. The rough flows suggest T. E. Lawrence's (1926, p. 191) description of a volcanic terrain in the Arabian desert: ". . . lava-like scrambled eggs gone iron-blue, and very wrong."

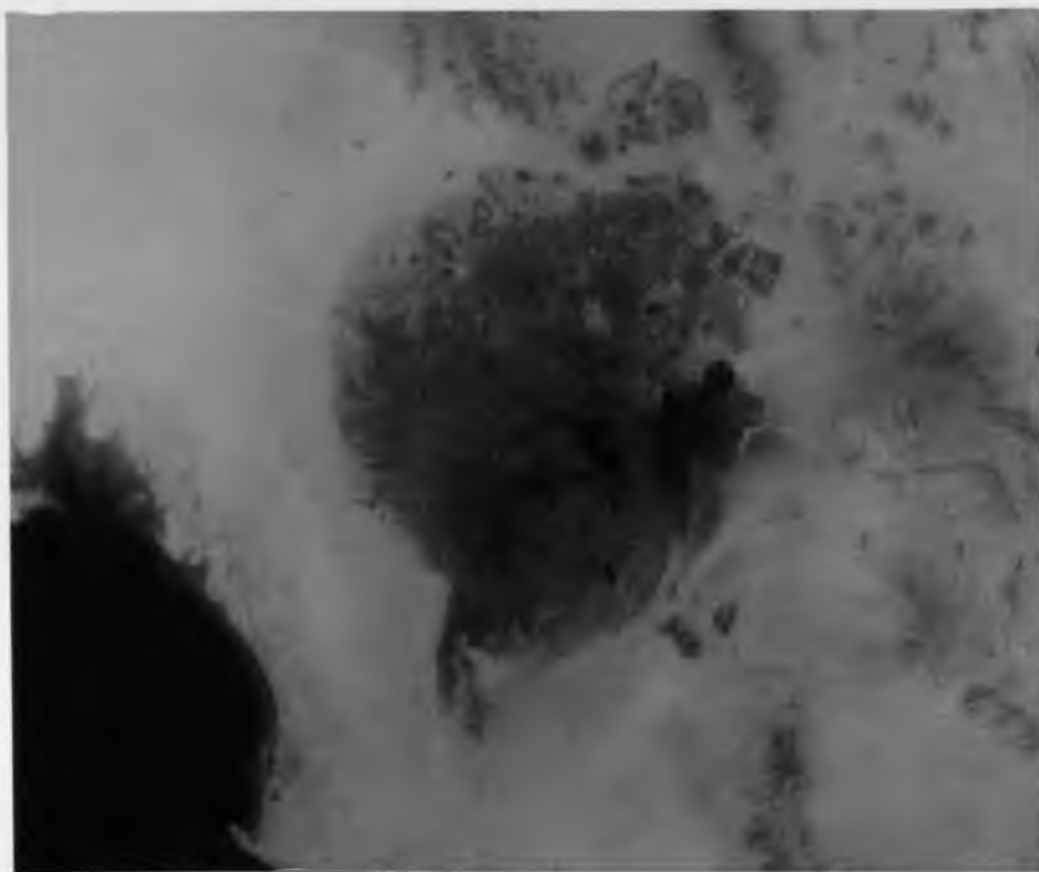


Figure 1. Pinacate Volcanic Field

Photographed from Gemini IV spacecraft at a height of 110 miles above the earth's surface. Photograph courtesy of NASA.



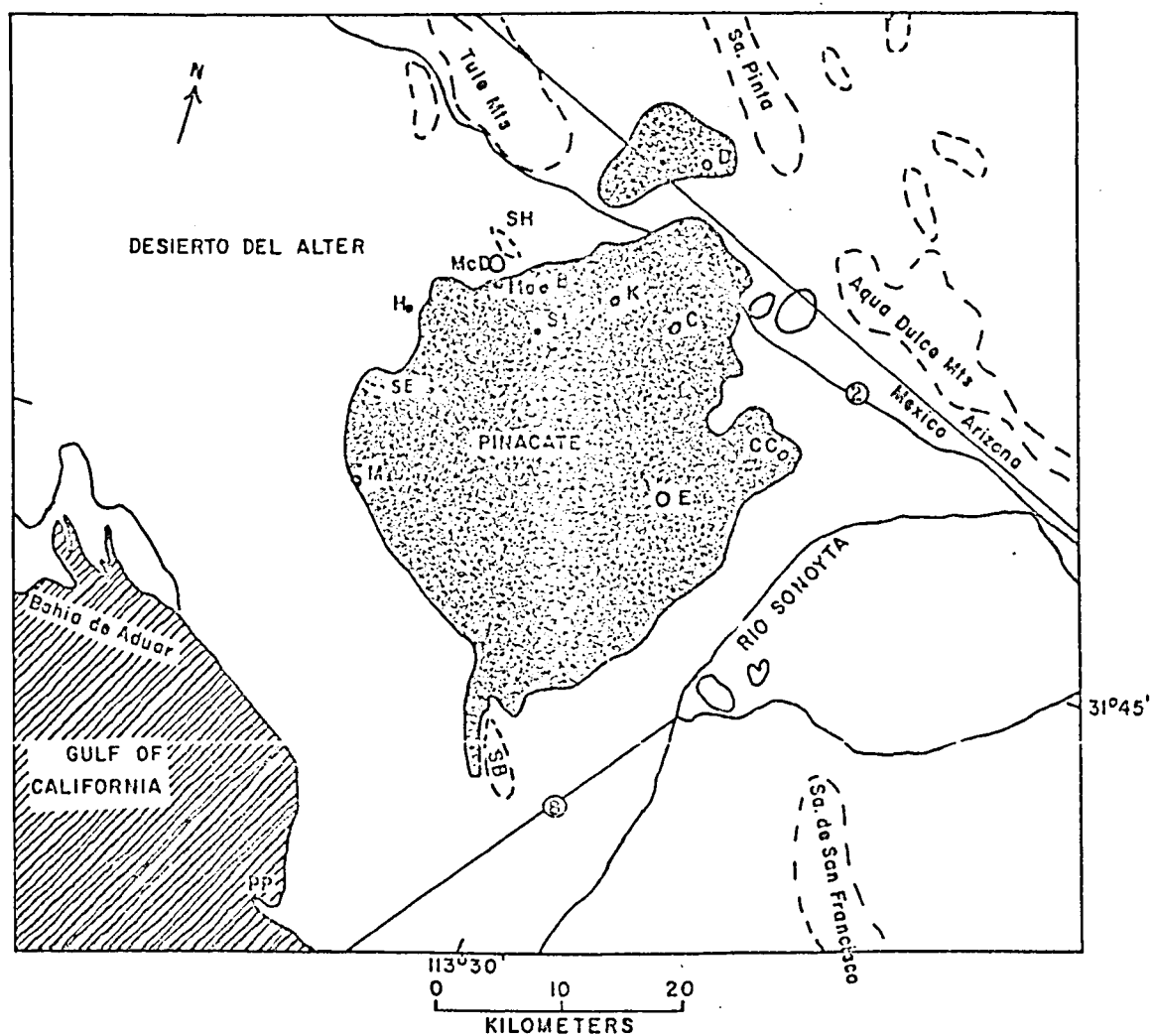


Figure 2. Index Map of Figure 1

Craters: B = Badillo, C = Celaya, CC = Cerro Colorado, D = Diaz, E = Elegante, H = Hayden, K = Kino, M = Moon, Ma = Molina, McD = MacDougal, S = Sykes. Mountain ranges (sierras): SB = Sa. Blanca, SE = Sa. Extrana, SH = Sa. Hornaday.

Jahns (1959, p. 27) describes the basalts as:

fine to medium grained, and many are both vesicular and porphyritic in various degrees. The characteristic minerals are plagioclase in the labradorite-bytownite range, greenish-brown to brown magnesium olivine, magnetite, and hypersthene. Sparse to very abundant phenocrysts of plagioclase and olivine commonly set in a pilotaxitic or fluidal ground-mass.

Most of the volcanic rocks are mapped by Donnelly (1970) as Quaternary with some Tertiary flows visible around the margins of the field.

Thicknesses of the three major units--lavas, sediments, and granitic basement--can be estimated. The basalts are laterally more extensive than presently revealed, being partially covered by encroaching desert sands (Ives, personal communication), and are at least 125 feet thick as far from the central peaks as Molina Crater. Thickness of alluvium in the region surrounding the Pinacate lavas varies from zero to 3 miles with values of 800 to 6,500 feet most common, according to modeling of aeromagnetic and gravity data by J. R. Sumner (1971). The granitic basement thickness is approximately 30 km (18 miles), extrapolating from the map of Noble (1970). This agrees with a crustal thickness of  $33.5 \pm 7$  km ( $\sim 21$  miles) calculated from Woollard's (1968) empirical relation between thickness  $M$  and Bouguer gravity anomalies  $\Delta g$ :

$$M = - (36 - 8.0 \Delta g) + 7 \text{ km.}$$

However, the depth to the mantle in the vicinity of Pinacate may be much less, inferred from the proximity to Gulf of California spreading centers. The basaltic Pinacate lavas are an exception to the "general rule for Arizona" that basalts occur in areas of thick continental crust

and silicic volcanics in areas of thin crust (Sheridan, Stuckless, and Fodor, 1971). The San Bernardino lava field in southeast Arizona is another exception, indicating the general rule is too great a simplification.

## GEOLOGIC RECONNAISSANCE OF PINACATE CRATERS

It is the craters that make Pinacate unique and provoked J. D. Milton of Tombstone to exclaim, "Hell boiled over at Pinacate" (Ives, 1964, p. 3).

From morphological considerations alone, four types of craters occur in the Pinacate. The most common type is exemplified by Elegante, with MacDougal, Sykes, Badillo, Celaya, and Kino apparently similar except for the degree of erosion. All of these craters are characterized by large tuff rims resting on top of cliff-forming basalts. Molina Crater is tentatively considered a second type because it is a complex of interlocking craters apparently with multiple eruptive centers. Cerro Colorado is the third type of crater, unique in being constructed entirely of tuff. The final crater type is represented by Moon and possibly Hayden Craters. Moon has a rim built up of basaltic boulders with no visible rim tuffs and a cinder cone central peak on the floor. Reconnaissance field studies of all Pinacate craters were made to provide a geologic background for interpretation of geophysical data. This chapter is based on the author's field observations and published literature. Crater dimensions are collected in Table 1.

### MacDougal Crater

Located on the northwestern edge of the Pinacate volcanic field, MacDougal (Fig. 3) is the largest of the craters, being approximately one mile in diameter. Prominent basaltic tuff rim beds project

Table 1. Dimensions of Pinacate Craters

Name	Diameter (feet)	Depth (feet)	Depth- Diameter Ratio	Rim Height <sup>a</sup> (feet)	Floor Elevation <sup>b</sup> (feet)	Rim Bed Thickness (feet)	Reference
MacDougal	5000-5700	430	1:13	50	50	65-90 140	Ives (1964) Jahns (1959) this report
Elegante	4800 4300-5500	796	1:6.1	120	200	150	Ives (1964) Jahns (1959)
Sykes	3200-3500	750 580	1:5.8		150	90-125	Ives (1964) Jahns (1959)
Celaya	3000	290	1:9.7	100	700	50-125	this report
Kino	2700	50	1:50	40	900	0-35	this report
Badillo	2050						this report
Molina	2000, 950	145, 200 250	1:7, 1:5			75	this report Ives (1964)
Cerro Colorado	2800-3500		1:9	50-350 350	<sup>c</sup> 50	50-350	Jahns (1959) Ives (1965)
Moon	2000	85	1:25	90	270	absent?	this report
Hayden	1200						this report

a. Above surroundings.

b. Above sea level.

c. Above outside playa (Ives, 1956).



Figure 3. North-looking Infrared Aerial View of MacDougal Crater

Hornaday Mountains appear beyond the crater. Photograph by W. K. Hartmann.

about 50 feet above 100-foot vertical walls of layered basalt (Fig. 4), which apparently extend out beneath the surrounding plain. The extent of the tuff apron of MacDougal and other craters can be judged from Donnelly's (1970) geologic map (Fig. 5). The yellow-brown tuff is well stratified into platy, coarse units dipping outward an average of  $10^{\circ}$  (Fig. 6). These tuff beds, like those of other Pinacate craters, exhibit cross bedding, reverse bedding, and bedding sags. Somewhat rounded basaltic boulders and granitic xenoliths are common in the tuff. Jahns (1959) also notes fragments of vesicular basalt, crystals of plagioclase and olivine, and schist, phyllite, and vein quartz. Lynch (private communication) has collected olivine nodules on the rim of MacDougal. Rounded, dense, basaltic boulders, split open upon impact, also litter the rim.

The rim beds of the northern half of the crater are especially eroded back, with a tuff cliff face, revealing a bench zone of basalt, the surface of the basaltic cliffs. Nearly vertical to slightly inward-dipping ring dikes (?) penetrate the bench surface and thin tuff (Fig. 7). Some of these basaltic dikes are split open along their crests similar to pressure ridges with thin extruded spines scarred with slickensides. Associated with the dikes are subrounded pebbles of granite, basalt, and quartz coated with red-brown spatter rich with plagioclase, magnetite, and hornblende crystals. On the west side of the rim, two mounds of reddish vesicular basalt occur in a slight trough. Exceedingly fine, millimeter-scale flow marks attest to a considerably more recent emplacement of these mounds than any other basalt seen in the crater.



Figure 4. Rim of MacDougal Crater with Hornaday Mountains in the Background

Dark basalt cliffs are topped by light-hued, layered, basaltic tuffs.





Figure 5. Distribution of Tuff around Pinacate Craters.--  
Modified from Donnelly (1970)



Figure 6. Rim Tuff of MacDougal Crater



Figure 7. MacDougal Basalt Bench Perforated by Inward-dipping Ring Dikes

The basaltic cliffs are nearly vertical, and the flow units which compose the cliffs are approximately horizontal. This differs from Jahns's (1959) interpretation that the basaltic cliffs of Elegante dip very gently outward. A reentrant on the southeastern wall of MacDougal is considered by Jahns to be a product of erosion of locally shattered and jointed wall basalts, although it has the appearance of a sectioned secondary crater, as observed in other Pinacate craters. Reddish-brown cinders cemented by stringers of fine-grained basalt suggest proximity to an old vent. Morainelike mounds of talus and mudflow debris mark two separate debris flows enlarging the reentrant. Talus ramparts extend in some places nearly to the top of the basalt units, indicating a long period of erosion. Alluvium and windblown sand provide a nearly flat floor with a central playa dense with saguaro, palo verde, and a central reedlike thicket. The thickness of alluvium and sand fill can be estimated by noting that the depth-to-diameter ratio for MacDougal is 1:13 as compared with 1:6.1 for Elegante and 1:5.8 for Sykes (Table 1), both of which are fresher and further from the sand dunes than MacDougal. If 1:6 were an average ratio for fresh, unfilled craters, MacDougal would have been originally about 900 feet deep. Thus, approximately 500 feet of filling may have occurred.

#### Elegante and Sykes Craters

These craters have been visited by the author but were not studied in detail by him. The following points, perhaps helpful to the interpretation of Elegante-type craters, are from the literature and study of aerial photographs.

Elegante (Fig. 8) and Sykes (Fig. 9) are very similar in appearance, but Elegante is probably slightly older, judged by somewhat deeper gullying of the outer rim beds. This idea is reinforced by Sykes's marginally smaller depth-to-diameter ratio (1:5.8 vs 1:6.1) and its sharper, steeper rim beds. Ives (1964) characterized Sykes as a mountain with a hole in the top, and although there are no measurements, its rim crest certainly appears higher above the surrounding terrain than does Elegante's. The tuff rim beds of Sykes dip outward as steeply as  $38^{\circ}$ , and clearly a larger portion of the original cone has been preserved than at the other craters (Jahns, 1959). Lynch (personal communication) has found pisoliths in Elegante tuff beds.

Jahns (1959) reports the following. Rim beds of both Sykes and Elegante rest upon reddish-brown cinders from sectioned cinder cones revealed resting on the tops of basalt cliffs. Also exposed in Elegante is a cinder cone lava lake with a feeder dike of basalt. A basalt unit 8 to 45 feet thick in Sykes appears to have its origin away from the crater because it systematically dips gently to the west-southwest rather than radially away from the crater. Thick and thin basalt layers alternate with pyroclastics in the cliff basalts of both craters. Elegante's lowest basalt unit has no pyroclastics or noticeable vents.

Elegante contains deltaic beds derived from the tuff rim, travertine deposits, and a gastropod fauna, showing clearly that a lake occupied the crater floor at one time (Ives, 1964). Two samples of carbonates from the deltaic beds have been dated at  $12,970 \pm 560$  and  $17,200 \pm 200$  years ago (Long, personal communication). This shows that the crater was formed at least before the later part of the Wisconsin



Figure 8. Aerial View of Elegante Crater

Sheer basaltic cliffs and deltaic deposits are well shown in this photograph by S. Larson.

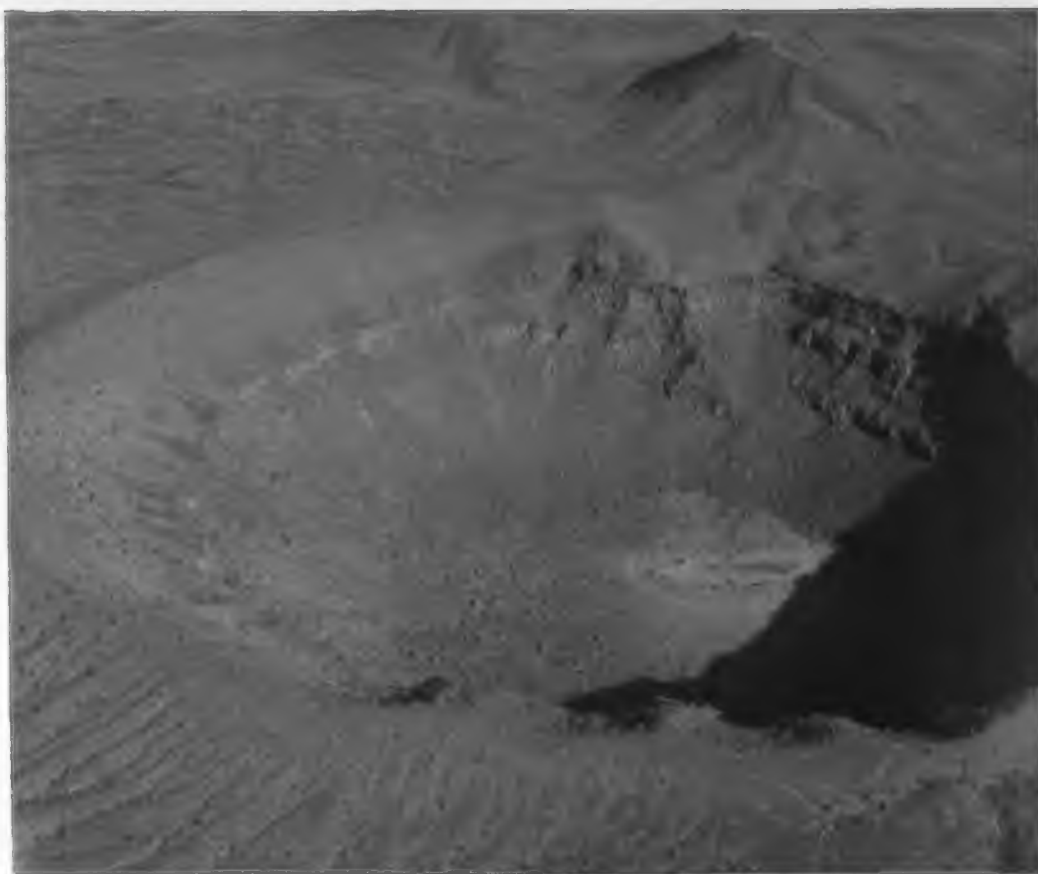


Figure 9. Aerial View of Sykes Crater

Compare the degree of gullying on the rims of Sykes and Elegante (Fig. 8). Opposite wall of Sykes includes buried and sectioned cinder cone. Photograph by S. Larson.

glaciation. It is peculiar that no other crater shows evidence of possessing a lake. And it is surprising that Elegante ever did, for today Elegante's substructure is so porous that even after severe rains flood the floor 6 inches deep, the "lake" drains totally away in one day (Ives, personal communication). A large foundered mass of the tuff bed is exposed in an eroded section of the deltaic beds.

### Celaya, Kino, and Badillo Craters

These craters are smaller, shallower versions of Elegante and Sykes. Celaya (Figs. 10 and 11) is actually two interlocking craters, the southern being considerably smaller than the northern. The rounded tuff rim is similar to Elegante's, and scarps reveal a sequence of rhythmic beds with basaltic and granitic inclusions (Fig. 12). A layer of highly vesiculated red scoria, approximately 3 feet thick, separates the tuff from the massive basaltic cliffs. A small vesiculated basaltic tableland, similar to the basaltic bench of MacDougal, shows slickensides and clinker blocks. Most basalt blocks on the rim of Celaya, as around most of the other craters, are dense and nonvesicular. Celaya is easily reached by a good cinder road turning off Mexico Highway 2 at Los Vidrios Cafe.

Kino is a broad, shallow crater with low, where present, rim beds (Fig. 13). On the south-southwest rim a vent has built high, scarped cliffs of tuff and red spatter in which erosion has produced many caves, and Thomson (personal communication) reports finding pottery shards in one cave. Comparison of the high tuff rim of the secondary vent to the very low tuff rim of the main crater indicates that a





Figure 10. Aerial View of Celaya Crater

Notice interlocking crater at upper left. Photograph by S. Larson.



Figure 11. Boulder-strewn Rim of Celaya Crater



Figure 12. Variation in Tuff Bedding in Rim of Celaya Crater

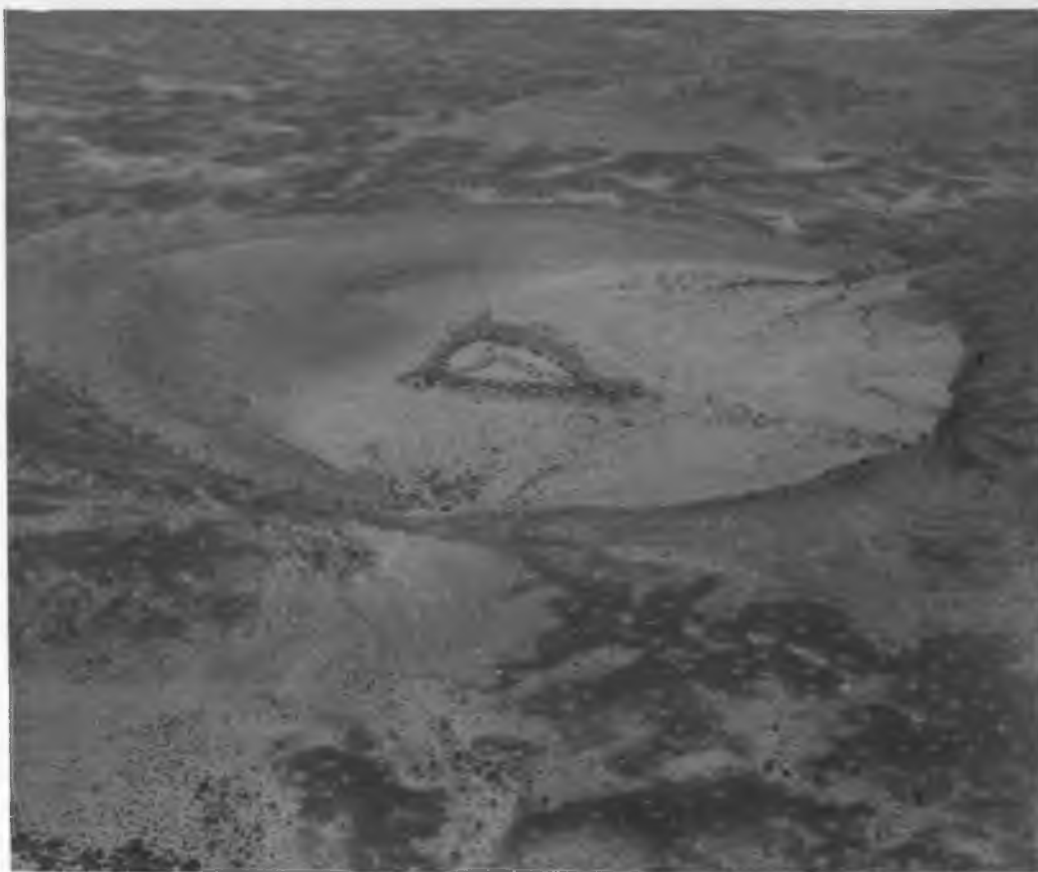


Figure 13. Aerial View of Kino Crater

Secondary vent has built up high tuff rim on west (left) side of crater, whereas tuff rim on the east side of the crater nearly eroded away. Line of vegetation in wash on left side of crater marks fault which has caused double rim. Photograph by S. Larson.

significant period of erosion occurred before the rim-vent eruption. A fault trending subparallel to the crater walls has created a double south rim.

Badillo is another broad, shallow crater with a rounded tuff rim (Fig. 14). Notice that a large, breached, reddish cinder cone has broken through Badillo's south wall; this cone was formed after Badillo. Three cinder cones revealed in section along the crater's wall are reported by Jahns (1959).

### Molina Crater

Molina Crater is a cluster of coalescing depressions (Fig. 15). The writer has found only one small exposure of tuff beds, the rim being peppered with subangular basalt blocks on a desert pavementlike rocky rubble with yellow dust under the rubble. Donnelly (1970) maps a broad tuff apron around the crater, and Jahns (1959) comments on the coarseness and lack of ashy materials compared to rim beds of the other craters.

The northernmost crater is deepest (200 feet below the rim crest) and has two sheer basalt cliffs, the lower one about 75 feet high and the upper about 50 feet high, according to altimeter measurements made with W. K. Hartmann of The University of Arizona. The top of the lower basalt cliffs is at an altitude of 625 feet compared to an altitude of 635 feet for the top of the MacDougal basaltic cliffs. Within the probable errors of measurement, these two altitudes are nearly equal and possibly represent a widespread lava surface penetrated by both MacDougal and Molina.



Figure 14. Aerial View of Badillo with MacDougal Crater in the Background

A cinder cone has broken the left rim of Badillo.



Figure 15. Aerial View of Molina Crater (Cloverleaf Crater)

On right margin is shallow, sand-filled, suspected crater.

Figure 16 shows how slumping and rubble falls tend to build up a talus ramp covering the sheer basalt faces. The southern crater complex has all of its lower basaltic cliffs hidden by talus and hence is probably older than the northern crater. This hypothesis is strengthened by the greater depth of the north crater and the fact that it has obviously cut into the rim of the southern craters.

### Moon Crater

On the south-southwest edge of the Pinacate lies Moon Crater (Figs. 17 and 18), with desert sands nearly lapping against its west rim. Although Glenton G. Sykes is credited with discovering this crater in 1956 (Ives, 1964), Hayden (personal communication) points out that it has long been known to local Mexicans as Vulcan di Chichi. As this crater has only been mentioned but not yet described in the published literature, space is taken here to record its unusual features, which were observed by the author in 1971.

Moon Crater is conspicuously unlike all the other major Pinacate craters in that it has a large central mountain (Fig. 19). Indeed, the peak is 40 feet higher than the rim. Apparently simply a large cinder cone constructed principally of scoracious red cinders, the peak has some dark, dense basalt exposed in a partial breach on the south side (Fig. 19). On the east side of the peak the red-brown cinders are overlain by fresh-appearing dark cinders from the last eruptive phase.

The crater rim is not circular but is cusped north-northwest of the central peak. A remnant of a second cinder cone occurs at the cusp. Exposed on the north-northwest wall of this vent are the only detected





Figure 16. Rim View into Molina Crater

Note the decrease in amount of talus from far left to far right to center depressions, presumably reflecting age differences.



Figure 17. Oblique Aerial View of Moon Crater

Photograph by S. Larson.

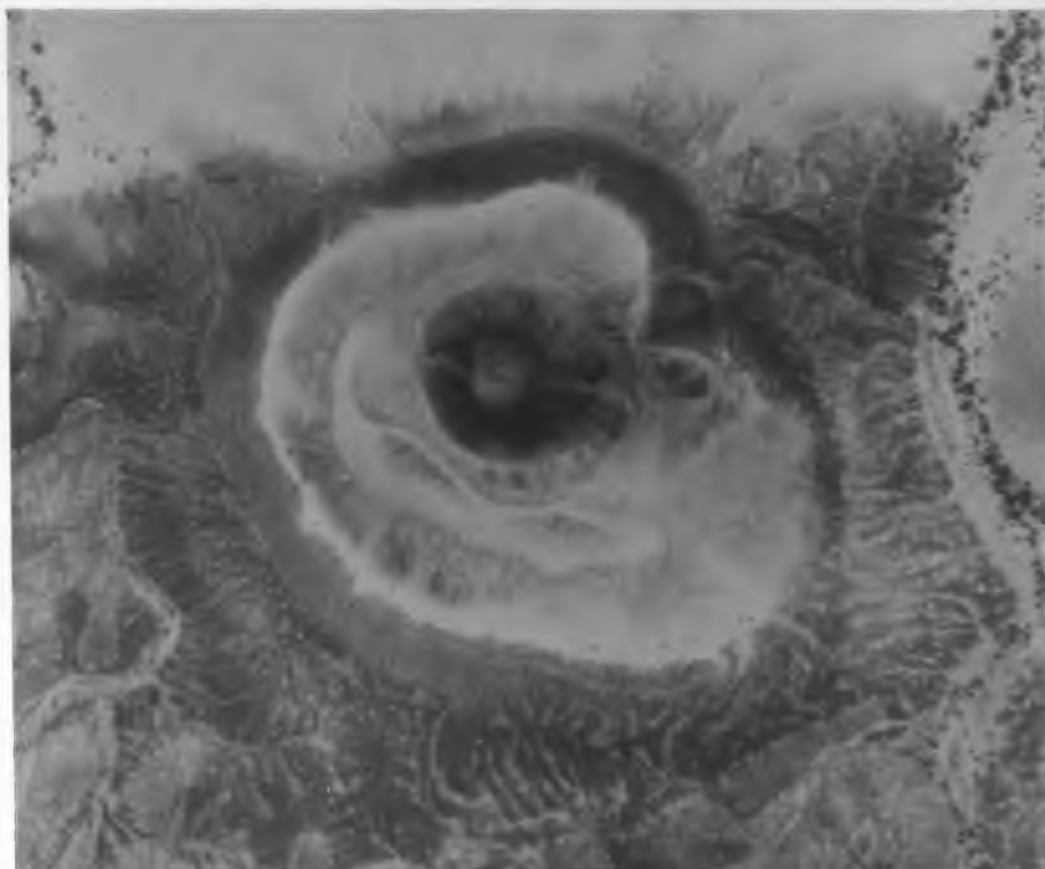


Figure 18. Plan Aerial View of Moon Crater

Note vent at cusp and immediately to its right a drainage irregularity. Photograph by R. A. Laidley.



Figure 19. Panorama of Moon Crater from Rim Crest

Photograph by F. L. Herbert

tuff layers associated with the crater. Around this vent, dense basalt bombs and other smoothed projectiles were also found. About 150 feet north-northwest of this rim-crest vent are two low rises and a drainage irregularity hinting at a third eroded vent.

The rim of Moon Crater is unlike those of other Pinacate craters in that it possesses no tuff beds, other than those associated with the rim vent, although Donnelly (1970) maps a tuff apron around the crater. The rim is covered with blocks, less than 2 feet in diameter, of dense, poorly vesiculated basalt.

The only good exposure of in-place rim basalts, on the north-east interior of the rim, reveals another major difference between Moon Crater and other Pinacate craters: the basalts are not layered but are massive, dense, and unstructured (Fig. 20). Note that the massive basalt of the rim projects above the outside terrain. Furthermore, the alluvium-covered floor of Moon Crater is marginally higher than the surrounding plains, reflecting either considerable infill or yet another basic difference in morphology compared to the other craters.

The outer rim of Moon Crater appears slightly less gullied than the other craters, supporting Ives's (1964) suggestion that Moon Crater may be younger than the other craters. Ives also proposes that Moon Crater was the source of a vast amount of ash which forms ramps banked against the east face of a granitic fault-block mountain at Pelican Point on the Gulf of California (Fig. 2) 28 miles south of Moon Crater. The ash ramps are truncated by shorelines estimated by Ives to have formed between 10,000 and 20,000 B.C., providing a lower limit for the age of the eruption. However, it seems unlikely that Moon Crater is the



Figure 20. Exposure of Rim Basalt in Moon Crater

Compare with Figs. 4 and 8. Photograph by Patricia Malchow.

source of the ash. It would be peculiar for a crater to deposit thick units of ash 28 miles away but not on its own rim.

### Hayden Crater

Figure 21 shows a crater vaguely similar to Moon Crater brought to my attention by Hayden (personal communication). This feature has not been visited by me, and the nature of the rim and peak are not known in detail, although Donnelly (1970) maps it as a cinder cone. It is, however, a large (1,200 feet in diameter), perhaps unique structure and is here designated "Hayden" after Julian Hayden, a Tucsonian well known for his studies of the history and archeology of the Pinacate. The crater Hayden is located approximately  $113^{\circ}42'$  E.,  $31^{\circ}53'$  N., 6 miles southwest of MacDougal and 5 miles north of Sierra Extrana.

### Cerro Colorado

This volcano (Fig. 22) is unique in the Pinacate. It is composed entirely of tuff breccia; there are no basalt cliffs. The floor is approximately 50 feet above the surrounding playa (Ives, 1956), showing the constructional nature of the crater. Jahns (1959) recognized three tuff units, ranging in color from pink to reddish brown to grey, which form the rim of Cerro Colorado. These tuff units are exposed as scarp faces inside the crater and the upper unit has been gullied. A smaller, elevated, second vent on the north-northwest side of the crater was the source of a fourth tuff breccia which was plastered over the previous crater. Thus, the high southern rim of Cerro Colorado, dipping both into and out of the crater, is the product of a later eruption from the

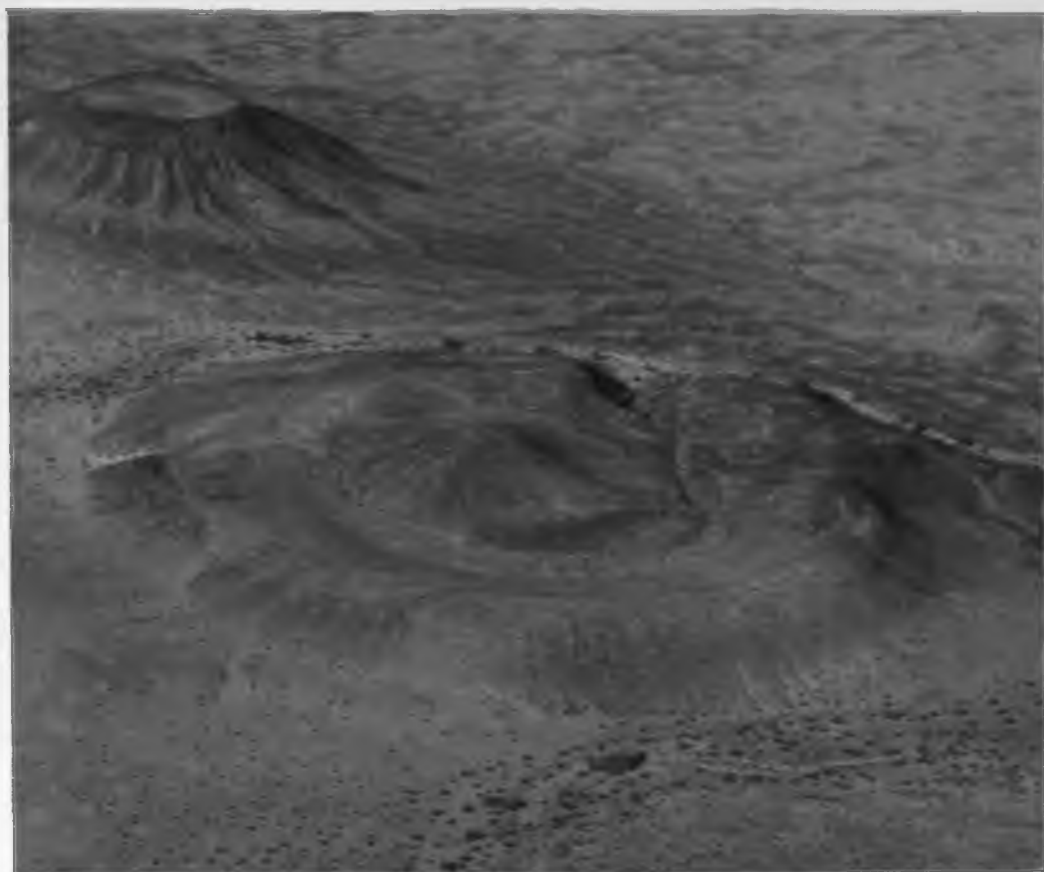


Figure 21. Aerial View of Hayden Crater

Is this a large, peculiar cinder cone or a small crater? Photograph by S. Larson.





Figure 22. Aerial View of Cerro Colorado.

The uneven height of the rim, scarped interior walls, and eccentric secondary vent are well shown in the photography by D. Roddy, reproduced from Green and Short (1971).

eccentric vent. This eruption did not build up a tuff cone but rather might have constructed a tuff ring if the ejecta trajectories were uninterrupted.

Waters and Fisher (1970) have found both pisoliths (accretionary lapilli) and sideromelane in Cerro Colorado tuffs. The sideromelane, resulting from a drastic cooling of basaltic magma as occurs in submarine eruptions, implies that the rising magma had access to water. Indeed, Ives (1964) has found evidence of at least three ash eruptions into the playa south of Cerro Colorado. The pisoliths result from the aerial movement of water drops through eruption clouds. The poor sorting of Cerro Colorado pisoliths could be due to formation in water sprayed upward from the vent, rather than in rain.

#### Diaz Crater(?)

Cruikshank and Hartmann (private communication) suggested that a circular patch of light-colored material surrounded by a darker ring, first noted in Gemini photograph (Fig. 1), in the extension of Pinacate lavas into the United States, was another crater. They named this feature "Diaz" in honor of Melchior Diaz, a Spanish conquistador who passed near the Pinacate in 1539 (Corle, 1951). On Donnelly's map (1970) Diaz is indicated as a tuff ring filled with alluvium, and J. R. Sumner (personal communication) stated it is a tuff mound. Hartmann did observe the structure from low altitude flights and noted only low nondiagnostic relief in a circular pattern. The feature is sufficiently intriguing for the name Diaz to be kept as a convenience until its true nature can be ascertained.

## TERMINOLOGY AND MECHANISMS OF CRATER FORMATION

To interpret the geophysical data, it is necessary to have a model of what the subsurface structure of a typical crater may be like. Since the Pinacate craters are so fresh that essentially the original surface expressions are preserved, it is necessary to investigate the mechanism of formation of older, dissected, and eroded structures. But first the following discussion of crater forms and origins attempts to synthesize a conflicting terminology in light of recent investigations and to define the terms used here.

### Calderas

Calderas are "large volcanic depressions, more or less circular or cirquelike in form, the diameters of which are many times greater than those of the included vent or vents no matter what the steepness of the walls or form of the floor" (William, 1941, p. 242). This definition is not entirely satisfactory because (1) vents may also be linear conduits or arcuate fissures, and (2) it neglects the word "collapse" which is the main process that produces calderas (Williams, 1941). The term "explosion caldera" is maintained by Williams and McBirney (1968) even though in this rare type of crater the depression is formed by a completely different process (steam blast). Similarly, "erosion calderas" are not products of volcanic activity. These terms, like Williams' (1941) "cryptovolcanic calderas" (now generally considered astroblemes), are confusing and should not be used.

Williams and McBirney's (1968) classification for calderas (Table 2) is based on the belief that often a single process dominates in caldera collapse. However, Johnson (1969, p. 409-410) takes a different view:

Processes that cause cauldron subsidence--like many geological phenomena--do not record themselves readily in the rocks and structures they produce; and coupled with the hindrances of observation, the problem of genetic interpretation becomes extremely difficult. . . . there are few calderas where one mode of origin can definitely be said to exclude, or dominate over, another, while there are many calderas in which alternative processes may be equally acceptable.

He prefers a flow diagram (reproduced as Fig. 23) of possible sequences leading to the formation of a caldera rather than a classification scheme.

In keeping with this opinion, a more permissive definition of a caldera is that given by Green (Green and Short, 1971, p. 463): A polygenetic, more or less circular volcanic depression over 1 km and less than 250 km in diameter formed by subsidence or engulfment with or without varying degrees of explosivity and localized by circular or polygonal fractures."

For the purposes of geophysical modeling, the major subsurface structure of a caldera is a magma reservoir at least as large as the caldera itself. Depending on the particular case history, the chamber may be filled with breccia, molten magma, crystallized magma, or a mixture of all these. There is no geologic evidence as to the shape or depth of the bottom of a magma chamber. It may taper, broaden, or become slablike.

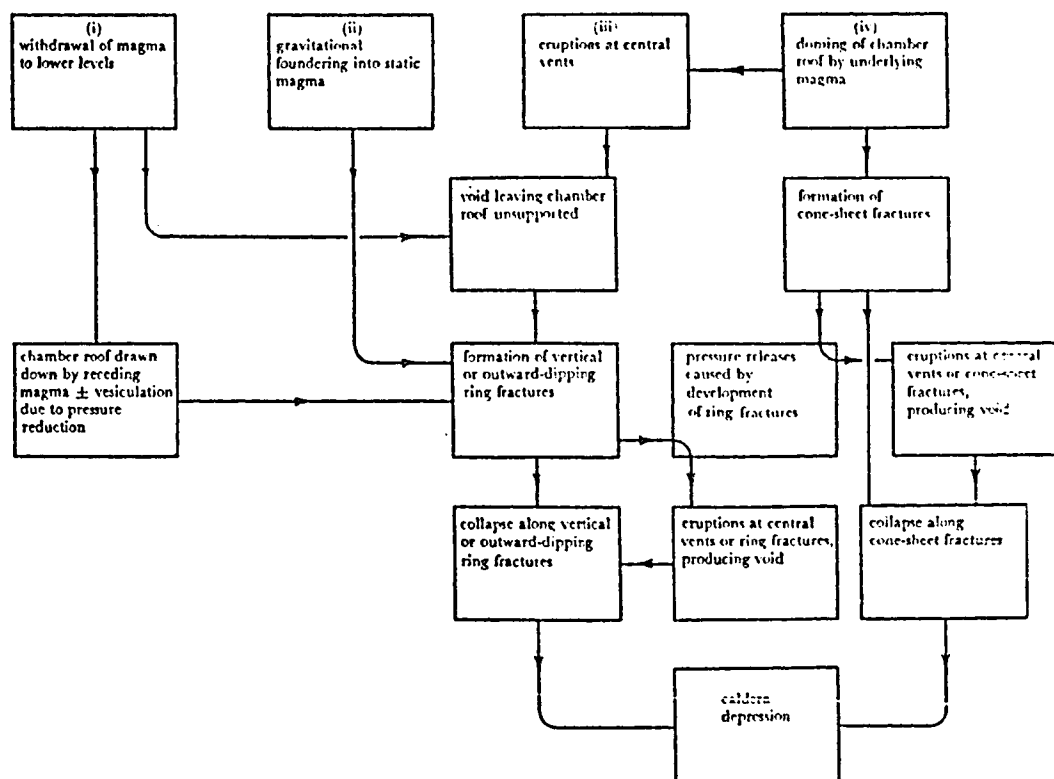
#### Diatremes

A diatreme is a pipelike vent of brecciated country rock and magmatic materials, formed by a rising fluidized mixture of gas and

Table 2. Summary of Williams' Caldera Classification\*

Type of Eruption	Reason for Collapse	Volcanic Products	Vent
<u>Silicic</u>			
Krakatoa	voluminous eruptions	pumice falls pumice flows	preexisting summit, vents, new flank fissures
Katmai	Drainage of vents through adjacent conduits	ash & pumice flows	eruptive vents in Valley of 10,000 Smokes
Valles	voluminous eruptions	ash & pumice flows	new arcuate fissures
<u>Basaltic</u>			
Masaya	magma migration	basalt flows	craters and cones
Hawaiian	drainage into rift zone	basalt flows	occasional flank eruptions
Galapagos	injection of sills, eruptions	basalt flows	circumferential near-summit fractures, lower radial fractures
<u>Mixed</u>			
Glencoe	long-continuing eruptions, gravitational settling	lava & pyroclastic ejecta	arcuate fissures
Suswa	magma withdrawal and settling	lavas, fragmental ejecta (after collapse)	ring fractures
<u>Silicic</u>			
Volcano-tectonic depressions	colossal eruptions	pyroclastic flows	tension fissures

\* In Williams and McBirney (1968).



(1969) Figure 23. Processes of Caldera Formation.--From Johnson

solids. Spalling and slumping of country rocks, abrasion and comminution of all rocks, subsidence along ring faults, and intrusion of plugs and dikes are common (Lorenz, McBirney, and Williams, 1970). If an erupting diatreme penetrates the surface, it produces an explosion crater. As suggested by Peterson and Groh (1963), the term diatreme should be restricted to eroded features where only the pipe or the pipe-filling breccia remains.

It is difficult to understand how gas-charged magma could rise through as much as thousands of feet of rock to the surface to form a maar. Lorenz et al. (1970) show that previous arguments concerning deep-seated gas-charged magma boring through rock to the surface are untenable--indeed even a nuclear explosion is incapable of rupturing the surface if the focus of the explosion is at a depth greater than a few hundred feet. Lorenz et al. (1970, p. 28) suggest that

An explosive eruption triggered at the surface by vaporization of heated groundwater could be propagated downward as pressure is released on progressively deeper gas-charged horizons. A decompressional wave could theoretically extend to great depth and tap a source of magma which would rise into the pipe along with fragments of the walls from the entire vertical section. . . . Salt Lake Crater, near Honolulu, Oahu, is an excellent example. The crater was originally formed by a steam eruption produced when magma rose into water-saturated beach sands and coral, but as the eruption continued, the focus of the explosions reached deeper and deeper levels bringing up fragments of ultramafic rocks and eclogites from depths well beneath the crust.

Fluidization also plays a part in diatreme evolution as seen by the mixing and rounding of entrained particles and the occurrence of particles both above and below their original stratigraphic level (Cloos, 1941).

And finally, there is extensive evidence from almost all diatremes investigated that subsidence along ring faults began at the end of eruptive activity when gas pressure was reduced and the weight of the cone and vent filling was greatest. The vent material of the Rödern structure of southwest Germany subsided 1,600 to 1,800 feet below its original position (Lorenz, 1970). Subsidence of 4,240 feet has been documented by Hearn (1968) for the Black Butte diatreme in Montana.

Diatremes exposed at various depths or mined (for example, the Kimberly pipe) often are not simple vertical pipes but are mildly sinuous conduits becoming dikelike at depth. Other vents can be traced to sills intruded at shallow depths.

It is commonly believed that volcanic necks are columns of basalt; this is a misconception. Shiprock is welded tuff (Shelton, 1968), as is Castle Rock near Pena Blanca, Arizona (Nelson, 1963). Hearn (1968), Francis (1971), and Shoemaker et al. (1962) reported bedded-tuff and breccia diatremes which were intruded by igneous rocks preferentially at the center and along ring faults. The cores of many Navajo-Hopi necks are igneous rocks surrounded by an igneous matrix containing finely brecciated wall rocks (McBirney, 1959). Thus, diatremes are complex structures.

### Explosion Craters

The uneroded surface expression of a diatreme is an explosion crater. Maar, gas maar, ubehebe, tuff cone, and tuff ring have been used to refer to these generally saucer-shaped explosion craters. The variety of terms exists because explosion craters have a wide range of



characteristics; some are deep, lake-filled, small, circular, flat-floored, and have ejecta rims of pyroclastics, and some explosion craters have none or even the opposite of these characteristics (Ollier, 1967).

Waters and Fisher (1970) examined more than 40 maars and tuff rings in western North America and found sideromelane or its decomposition product, palagonite, in the ejecta of each. This, and the locations of the maars and tuff rings in basins formerly occupied by lakes, near shorelines, or other water bodies, is strong evidence that these maars and tuff rings resulted from phreatic or phreatomagmatic eruptions where rising basaltic magma came in contact with ground water near the surface. Maars and diatremes not formed in areas of abundant ground water are often associated with "the rise of alkaline ultramafic (kimberlitic) and carbonatite magmas rich in juvenile gases, notably  $H_2O$  and  $CO_2$ " (Lorenz et al., 1970, p. 23).

All features described as explosion craters have similar origins with variations caused as second order or modifying effects. Thus, it is not unreasonable for tuff ring and maar to be used interchangeably (Peterson and Groh, 1963) or for maar to be used for any explosion crater (Shoemaker, 1962). Nonetheless, Diamond Head, Hawaii, is never labelled a maar, and Mt. Gambier, Australia, could not be considered a tuff ring because it has no tuff ring (Ollier, 1967). Thus, there is a spectrum of morphologic forms all due to the same basic process. The various terms for explosion craters can be arranged in a sequence representing a decreasing volume of tuff compared to the volume of the crater: tuff cone, tuff ring, maar, ubehebe, gas maar.

If an explosive eruption occurs at depth, ejecta are erupted nearly vertically, falling back to form a tuff cone. Explosions nearer the surface result in a wider dispersal of ejecta producing a tuff ring (Heiken, 1971). Lorenz et al. (1970) note that the volume of a tuff-cone crater is small compared to the volume of the cone itself and that the volume of a tuff-ring crater is large compared to the volume of the rim. Heiken (1971) found that the height-to-width (= rim base diameter) ratio for Oregon tuff cones to average 1:10, whereas tuff rings vary from 1:10 to 1:30. As tuff cones and rings result from the same mechanism, it is proposed that a height-to-width ratio of 1:10 be the arbitrary division between the two. Diamond Head Crater in Hawaii is the most famous example of a tuff ring.

Tuff cones are either uncommon or unspectacular for they are infrequently mentioned in the literature; the only examples known to the writer are in Hawaii and Oregon. Tuff rings and cones are constructional features, hence their craters lie above the pre-eruption surface, although Lorenz et al. (1970) give examples of tuff rings deepened by collapse.

Maar originally referred to lake-filled volcanic craters in the Eifel region of Germany. The terms dry maar and ubehebe were introduced by Cotton (1969) to describe lake-free maars. They are unnecessary for the term maar has been extended by common usage to include similar volcanic craters without lakes. Lorenz et al. (1970, p. 6) slightly modified Noll's (1967) definition of maars as:

Volcanic craters cut into the "general ground" (pre-eruption surface) and having a shape intermediate between that of a funnel and a shallow dish. They are surrounded by a blanket of pyroclastic debris of very variable thickness, in some cases reaching the height of a tuff ring. The craters

originated mainly by abrasion and slumping or by collapse along ring faults. Late-stage eruptions may form a central tephra cone or even a lava lake.

This definition provides two means of distinguishing maars from tuff rings: (1) tuff rings have higher rims than typical maars (compare Diamond Head, Hawaii, with Hole-in-the-Ground, Oregon), and (2) maars penetrate the pre-eruption surface while typical tuff rings, which are constructional features, have floors elevated above or level with the pre-eruption surface.

Agas maar is a maar-like depression with no apparent ejecta (Ollier, 1967). Rittmann (1962) uses the term diatreme for a rimless maar; however, it is best to preserve the word diatreme to describe the conduit that results in an explosion crater at the surface.

Explosion craters are generally believed to be considerably larger than the actual vent; thus, a simple model of the subsurface structure of a maar or tuff ring is a smaller vertical cylinder filled with a variable mixture of brecciated tuff, country rock, and basaltic intrusive rocks.

## GEOPHYSICAL SURVEY TECHNIQUES

MacDougal was selected as a typical Elegante-type crater that is large, relatively accessible, and not dangerously difficult to carry equipment into and out of. The methodology reported here was followed at other craters for comparison purposes.

### MacDougal Gravity Survey

In August 1970, J. R. Sumner of Stanford University and the writer carried out reconnaissance gravity and magnetic surveys on the floor of MacDougal Crater. Twenty-six gravity observations were made by J. R. Sumner with a LaCoste and Romberg gravimeter, having a scale constant of 1.04950 milligals per division. The error of a single determination was estimated to be  $\pm 0.04$  milligals based on repeated observations at selected stations. Difficulty in transporting equipment into and out of the 400-foot-deep crater prohibited determining elevation by alidade and plane table; instead a Brunton compass was used as a clinometer. All elevations were measured relative to Jahns's (see below) value of 371 feet above sea level for the center of the floor. Stations were located by pacing and reference to cacti and palo verde trees identified on aerial photographs. The estimated maximum error in position is about 10 feet and in station elevation about 1.5 feet. The resulting error in milligals is zero and 0.1, respectively. The gravity observations are tied into the worldwide gravity net through comparison to station NQ83 along Mexico Highway 2 on the northern edge of the Pinacate field. The

absolute value of gravity for NC 83 is 979500.69 milligals. Details on this and other gravity stations in the Pinacate region are reported by J. R. Sumner (1971).

The simple Bouguer anomaly of each station was calculated using a density of 2.67 gm/cc, a value commonly assumed as an average density of crustal rocks. The density of underlying granite rocks, sampled as xenoliths in MacDougal tuff is 2.60 gm/cc. However, the gravity stations are located at various but close distances from towering crater walls so that a terrain correction is necessary. Unfortunately, the only topographic information is a series of spot elevations made available through the courtesy of Dr. R. Jahns of Stanford University. Terrain corrections were determined with a Hammer graticule (Dobrin, 1960) for (1) the crater center, (2) an intermediate point, and (3) a floor-edge point, extrapolating elevations from the spot measures on Jahns's map. This provided three terrain corrections, which were plotted against radial distance from the crater center. Corrections for the remaining 23 stations were interpolated from the graph. The maximum correction was 1.26 milligals. The resulting Bouguer anomalies are plotted on Figure 24.

#### MacDougal Magnetic Survey

Aeromagnetic surveys from elevations of 4,000 and 2,000 feet, plus a ground survey, have been made for MacDougal Crater. Survey techniques and data reduction are reported here; interpretation is considered in the following chapter.

A section of J. R. Sumner's (1971) aeromagnetic survey flown at a barometric altitude of 4,000 feet ( 3,630 feet above the floor of

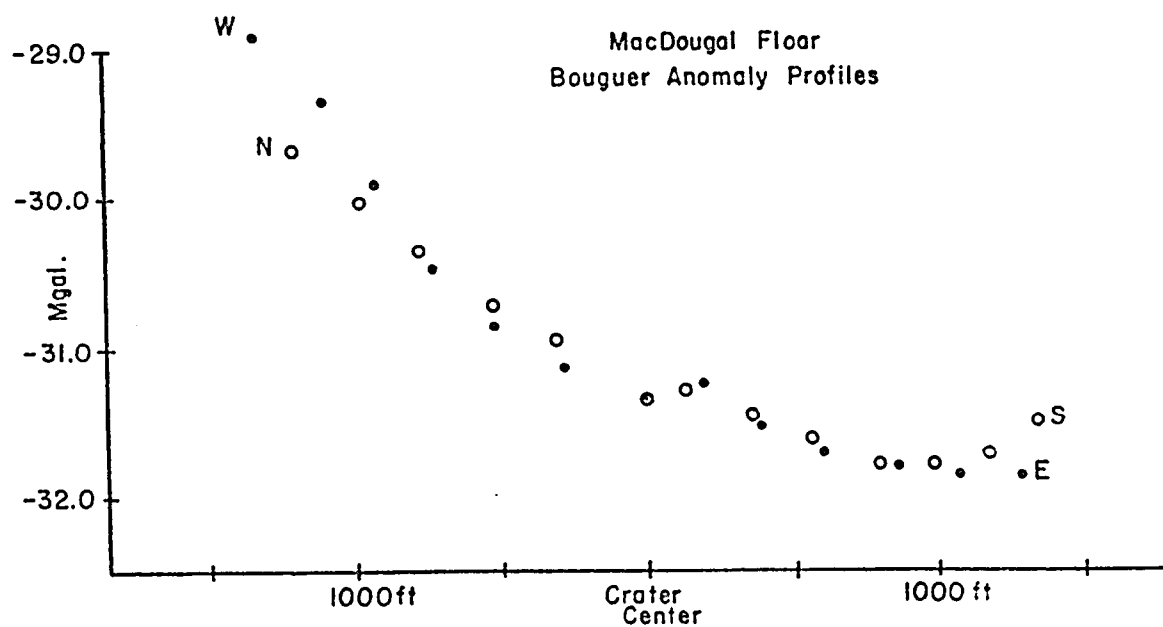


Figure 24. Bouguer Anomaly Profiles for the Floor of MacDougal Crater

Open circles are gravity stations on an east-west line; filled circles a north-south line.

MacDougal Crater), shows that neither MacDougal nor any of the other craters distort the magnetic field (Fig. 25). It is interesting, though, that cinder cones produce large anomalies.

Through the courtesy of J. S. Sumner and J. R. Sumner, an aeromagnetic survey of MacDougal Crater and environs was flown in August 1971, using a GeoMetrics Model G-806 portable proton magnetometer. Flight lines spaced approximately 2,000 feet apart were flown along a north-northeast trend, along with a south-southeast tie line at a barometric altitude of 2,000 feet. The digitized output of the magnetometer was correlated by clock to an automatic camera which took one photograph every five magnetometer readings. Following procedures outlined in Reford and Sumner (1964), the individual camera frames were located and mosaicked onto an enlarged photograph of MacDougal Crater. The total magnetic field measurements, plotted and contoured on an acetate overlay on the photograph, revealed sharp herringbone patterns pointing in the flight directions. This effect could have been produced if the plane flew nose tilted slightly up, allowing the camera to photograph an area significantly ahead of the area sampled by the trailed bird carrying the magnetic sensor. Or, the effect could be the result of a plotting error due to a misalignment of the photographic and magnetic data. Two corrections suggested by J. S. Sumner were made to bring the north-northeast lines into correspondence with the south-southeast tie line: each north-northeast line was shifted north or south a maximum of 350 feet to account for the fact that each magnetometer reading integrated over approximately two seconds of flying time and the air speed was 150 mph. After that, a constant value was algebraically added to each

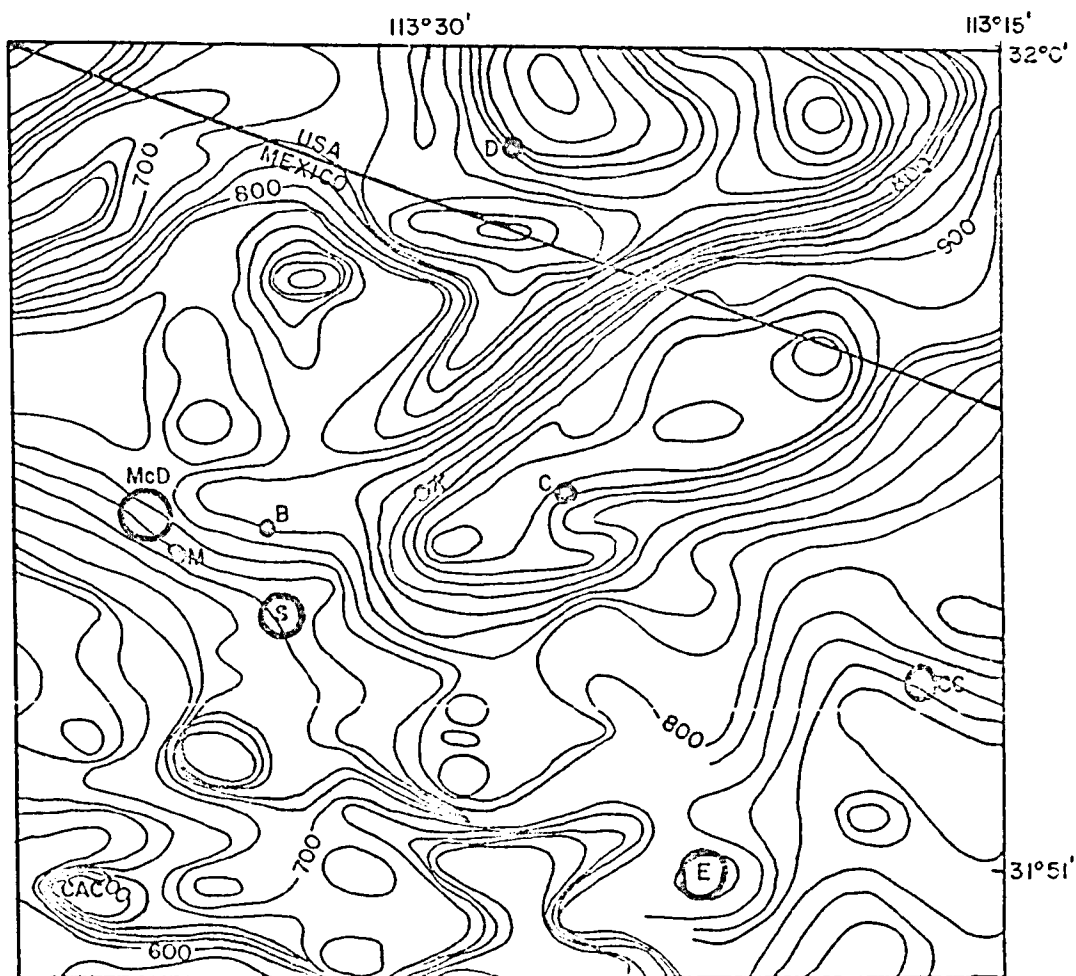


Figure 25. A Section of J. R. Sumner's (1971) Total Force Aeromagnetic Map over the Northern Part of Pinacate

Same abbreviations as Figure 2 with exceptions of CAC = cinder agglutinate cone, and M = Molina Crater. Contour interval is 20 gammas; flight elevation 4,000 feet barometric.



measurement in each north-northeast line to bring into coincidence the tie line and the shifted north-northeast lines. The resulting aeromagnetic map is shown in Figure 26. The subdued herringbone effect suggests caution in interpretation. The tie line magnetic profile of MacDougal (Fig. 27) shows that the crater rim produces an anomaly as large as +60 gammas, but a considerably smaller anomaly exists over the center of the crater. Diurnal changes in the earth's magnetic field should little affect the anomalies measured in a single flight line, as the plane covered the crater's diameter in approximately 25 seconds.

A short series of magnetic measurements were made on the floor of MacDougal Crater in August 1970, using a Jalander vertical field magnetometer. This revealed a strong central anomaly, and a more thorough mapping of the crater floor was undertaken in April 1971 with an Askania vertical field magnetometer with a scale constant of 243.6 gammas/degree. Repeated measurement at a selected station indicated the average error of a single observation was 0.036 degree, corresponding to about 8 gammas. This error is insignificant compared to the measured anomaly of nearly 1,000 gammas. Diurnal variation in the magnetic field was corrected by reoccupying a base station at intervals always less than one hour. At no time was the difference in readings greater than the average error of a single observation. It is unlikely that field variations lasting only a few minutes or seconds affected the readings, because the anomaly is smooth and regular. As for all surface magnetic surveys in Pinacate craters, station locations were determined with respect to cacti and palo verde trees identified on aerial photographs. Figure 28 shows the measured magnetic field.

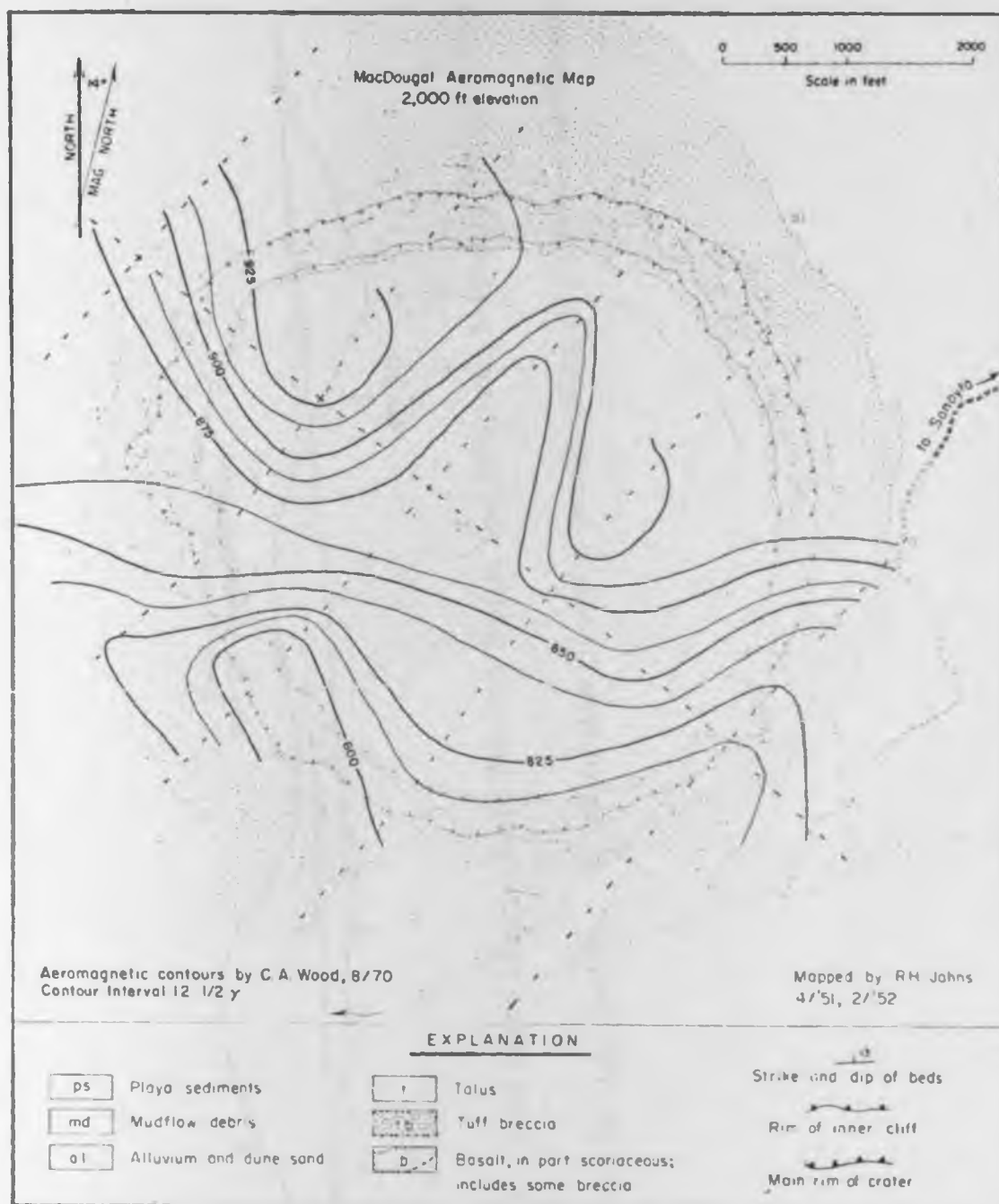


Figure 26. Total Force Aeromagnetic Map of MacDougal Crater

Contour interval 12.5 gammas; flight elevation 2,000 feet barometric. It is not clear how much of the central irregularity is anomaly and how much is an artifact of survey methods and reductions. Geologic map by Jahns (1959).

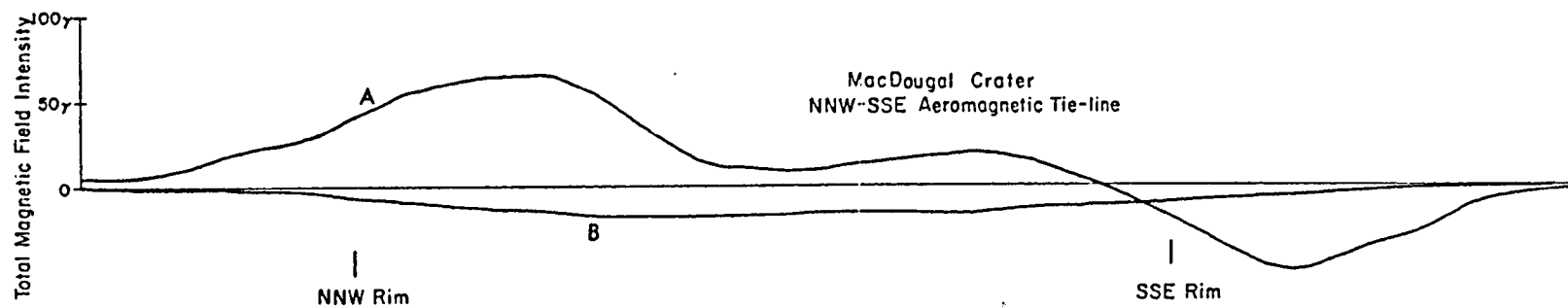


Figure 27. Total Force Aeromagnetic Tie-line Profile and Computed Magnetic Terrain Effect, MacDougal Crater

A. Observed tie-line profile. B. Computed magnetic terrain effect at 2000-foot barometric altitude.

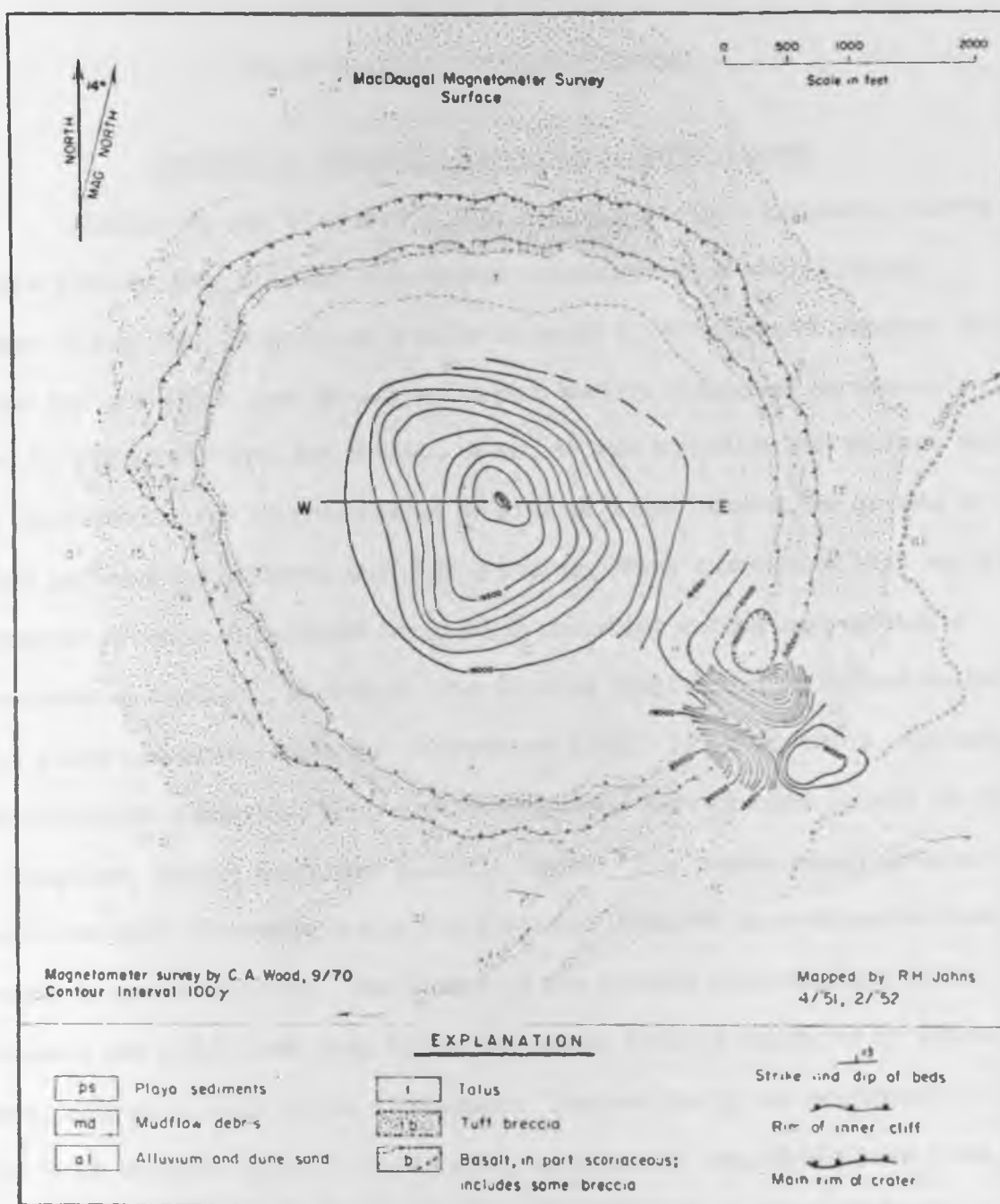


Figure 28. Surface Vertical Field Magnetic Map of MacDougal Crater

Contour interval 100 gammas. The line W-E marks the position of the cross section shown in Figure 31. Geologic map by Jahns (1959).

## GEOPHYSICAL INTERPRETATION

### Validity of Magnetic Surveys on Crater Floors

Malahoff and Woollard (1966) report a surface magnetic survey across Kilauea Iki, a small side crater interconnected with Kilauea Crater in Hawaii. They found a difference of 5,100 gammas between the crater rim and floor, yet an aeromagnetic survey indicated an anomaly of only 60 gammas within the crater. Also, it was noted in the surface survey that raising the magnetometer head from 4 feet above the ground to 5 feet produced a difference of 300 gammas. They concluded that surface magnetic surveys should not be used to interpret subsurface geologic structures of craters. However, the floor of Kilauea Iki is pahoehoe lava lake slabs remaining from the eruption of 1959. In other words, Malahoff and Woollard conducted their ground magnetic survey immediately on top of irregular, highly magnetic basaltic rocks. The pronounced variation of field intensity depending upon the distance between magnetometer and ground is not surprising. The floors of the craters investigated in the Pinacate are not frozen lava lakes but rather smooth surfaces of inblown sand, alluvium, and playa sediments. Susceptibility measurements of this floor material gave 0.00058 cgs, an order of magnitude less than dense basaltic rocks. Thus, it does not appear that spurious high magnetic intensities are introduced in the ground surveys across alluvium-filled crater floors. In fact, it appears that the magnetometer might be a means to reveal hidden local concentrations of basaltic lava buried not too far beneath the alluvium.

### Magnetic Terrain Effects for Craters

Marsh (1971) and other workers have shown that a magnetic response is produced between an irregularity in the surface of a homogeneous lithology and the atmosphere. This magnetic terrain effect can contribute significantly to an observed anomaly and lead to incorrect interpretation. The nature of terrain effects due to a crater was investigated, using a two-dimensional modeling program derived from that of Talwani and Heirtzler (1964). Modeling of the magnetic field due to a particular surface feature takes advantage of the zero field produced by any infinite slab. Thus, the terrain correction for a crater uses a model extending both laterally and in depth toward infinity to eliminate edge effects.

Compensation for magnetic terrain effects has been considered for large volcanic mountain masses, such as the island of Hawaii (Malahoff, 1969), but not for individual craters. As a guide to the nature and magnitude of terrain effects due to craters, Figure 29 shows the topography and resultant magnetic terrain effects (surface survey and 2,000-foot flight elevation) for two different craters. The shape of the effect is dependent on the topography, but the intensity of the magnetic anomaly, once the shape is established, varies directly with susceptibility. The terrain effects in Figure 29 were calculated using a susceptibility of 0.001 cgs; for any other susceptibility the intensities shown must be multiplied by that susceptibility. Note that a crater formed of only tuff (negligible susceptibility) produces no terrain effect.

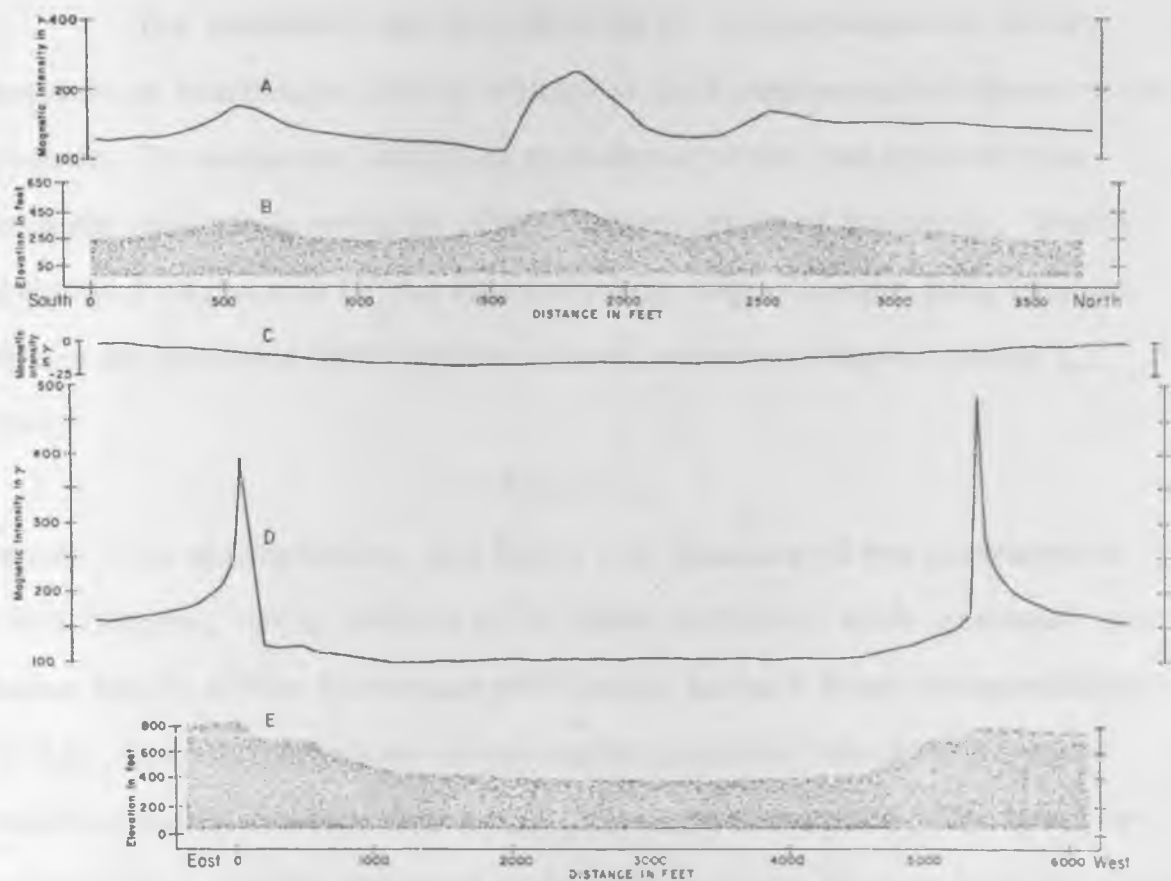


Figure 29. Magnetic Terrain Effects Due to Craters

Vertical magnetic response (A) 4 feet above ground due to crater with central peak (B). Total magnetic field (C) at approximately 1,600 feet above surface and vertical magnetic field (D) at 4 feet above ground for a simple crater (E). Assumed susceptibility = 0.001 cgs.

### MacDougal Magnetic Interpretation

The steepness and amplitude of the ground magnetic survey anomaly at MacDougal Crater indicate a high magnetization close to the surface. To calculate particular geometries which can produce this anomaly requires knowledge of the magnetization of the rocks. Magnetization  $J$  is the sum of the susceptibility magnetization  $KH_0$  induced by the geomagnetic field and the natural remanent magnetization  $J_n$ ; thus,

$$J = KH_0 + J_n$$

where  $K$  is susceptibility and  $H_0$  is the intensity of the geomagnetic field (Nagata, 1969). Values of  $K$  listed in Table 3 were measured with Bruce Marsh of The University of Arizona, using a Bison Susceptibility Bridge. Possible errors in volume corrections and variability among samples indicate errors may be as large as a factor of 2. The low susceptibilities of tuffs compared to basalts (perhaps derived from the same parent magma) reflect the fact that basalts retain magnetite, whereas magnetite in basaltic tuffs (the explosive result of contact of magma with abundant water) is oxidized to the weakly magnetic mineral hematite. The susceptibilities show that basalts are an order of magnitude more magnetic than any of the other rocks, and therefore the magnetic contours will show the general distribution of this rock.

Measurements of remanent magnetization and susceptibility magnetization for two Pinacate basalts show that  $J_n \approx 4KH_0$  (Sumner, 1971). For comparison,  $J_n \approx 5KH_0$  for Hawaiian basalts (Malahoff and Woollard, 1966). Thus, with  $K = 0.0052$  (from Table 3),  $J = 0.016$  for Pinacate basalts. Sumner also found that directions of remanent



Table 3. Wet Densities and Susceptibilities

	No. of Samples	Range of Measured Densities (gm/cc)	Average Density (gm/cc)	Suscep- tibilities (cgs)
MacDougal basalts	3	2.73 - 2.98	2.90	0.00520
MacDougal tuffs	2	2.12 - 2.33	2.23	.00093
MacDougal granitic xenoliths	3	2.57 - 2.63	2.60	.00004
Hornaday Mts. (granitic and gneissic)	2	2.62 - 2.68	2.63	
Cerro Colorado tuff	3	2.18 - 2.31	2.24	.00018
Moon Crater dense basalts	3	2.87 - 2.94	2.91	.00400
Moon Crater central peak red cinders	3	1.37 - 1.75	1.69	.00062
Alluvium and surface deposits (J. R. Sumner, 1971)	3	2.02 - 2.31	2.13	.00058

magnetization are within 30 degrees of present values, indicating that Pinacate basalts are not reversely magnetized. This conclusion is strengthened by the observation that the anomalies are positive maxima.

Nettleton (1942) published a series of formulas for calculating the magnetic and gravitational anomalies produced by generalized geometric solids, assuming that the magnetic polarization is normal to the surface. J. S. Sumner (personal communication) suggests that this assumption leads to less than 15 percent error in curve fitting, and therefore is appropriate for first order approximations. Modeling with these equations demonstrates that a spherical body, representing a magma chamber, could not produce the observed anomaly. The best fit to the observed data is a vertical cylinder of radius 440 feet and a depth of burial of 525 feet (Fig. 30), using a magnetization of 0.016 cgs and a value of 43,700 gammas for the vertical component of the earth's field. The lack of a negative portion of the anomaly is due to the essentially infinite depth assumed to the lower surface; the magnetic effect of the pole at the bottom of the body is negligible in this instance. Note also that the anomaly is entirely on the floor of the crater and is probably not greatly affected by terrain-induced anomalies. The depth of 525 feet to the top of the basaltic cylinder is approximately equal to the depth to the pre-sand fill floor of the crater, implying that the cylinder is an intrusive plug rather than a buried central peak.

Continuing to use the three-dimensional modeling equations of Nettleton and the geometry for the basaltic cylinder deduced from the ground magnetic survey, the theoretical magnetic fields at 2,000 and 4,000 feet flight elevations were calculated. At 4,000 feet an anomaly

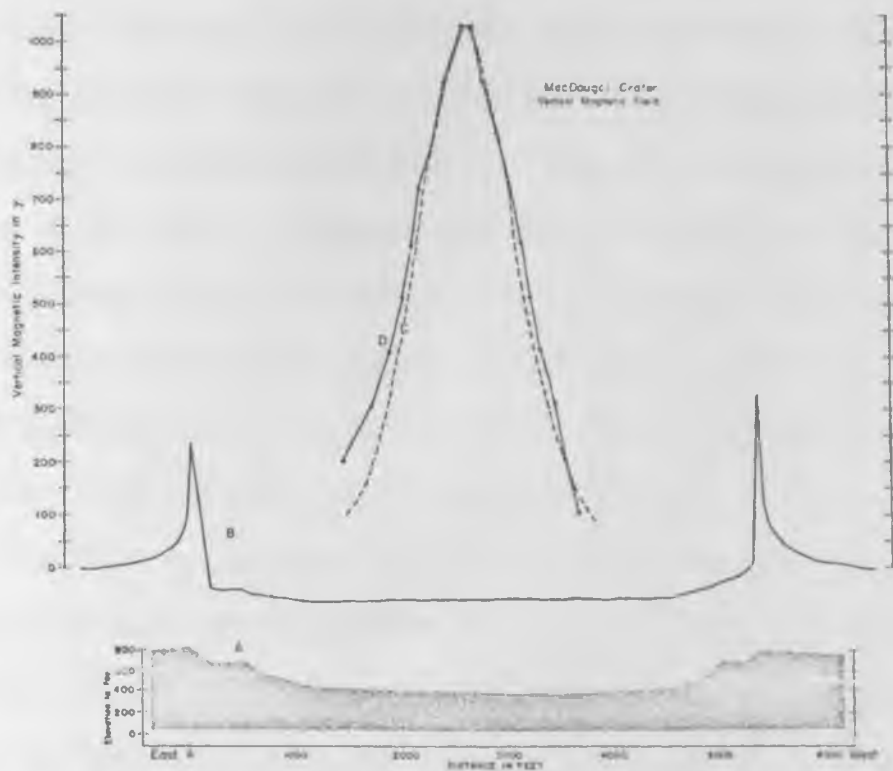


Figure 30. Vertical Magnetic Field Cross Section on the Floor of MacDougal Crater

A = topography; B = magnetic terrain effects; C = theoretical anomaly; D = observed anomaly.

of 35 gammas should have been observed, but Figure 25, contoured at 20-gamma intervals, reveals no break in the regional field over Macdougall Crater. However, J. R. Sumner's (1971) survey was flown with a flight-line spacing of about 3 miles since he was investigating basement structure, and the nearest flight line was more than one mile from the center of the crater. As reported by Dobrin (1960), the probability of detecting a meaningful anomaly increases as the spacing is decreased. In general, a quarter-mile spacing is necessary for estimating the size of a body with reasonable precision. Thus, the 4,000-foot aeromagnetic data do not contradict the above interpretation.

The theoretical anomaly at a 2,000-foot elevation is 120 gammas for the 880-foot-wide cylinder whose top is 525 feet below the crater floor. But Figure 27 shows that the observed anomalies are about one-half the theoretical anomaly and are centered on the crater rim rather than the floor. This discrepancy cannot be explained by flight-line spacing (the spacing was approximately 1,500 feet, and the lines were centered on MacDougall) or uncertainties in data reduction. The remaining possibility is that the model based on the surface magnetic survey is incorrect. If the magnetization of the basaltic cylinder were 0.006 instead of 0.016 cgs, the cylinder would have to be wider and within 50 feet of the surface to satisfy the surface survey. The anomaly at 2,000 feet resulting from this body would be of much larger amplitude and a different shape than the anomaly actually observed. Also for this model the closeness of the cylinder to the surface is more difficult to explain than a burial depth of 525 feet, and a significant positive gravity anomaly would be expected. The original model appears geologically

more reasonable and in better agreement with the gravity data than the model based on lower magnetization.

J. R. Sumner (1971) discussed the major anomaly patterns shown on his aeromagnetic map but did not interpret the small circular anomalies occurring over the Pinacate lava field. Correlation of the aeromagnetic map and aerial photographs shows that these more concentrated anomalies are associated with major cinder cone masses; for example, the feature labelled "C.A.C." on Figure 25 is a 100-gamma anomaly spread over a distance of about 2 miles. This is a massive cinder-agglutinate cone of basal diameter of approximately 4,000 feet. A calculation using Nettleton's (1942) formulas shows a maximum anomaly of 100 gammas would be expected at 4,000-foot barometric altitude, if the core and feeder vent of the cone are represented as a cylinder of radius 500 feet and magnetization 0.016, extending to the Curie depth. Thus, cinder cones in the Pinacate appear to be massive plugs of basalt, as is the feeder vent exposed in the wall of Elegante.

#### MacDougal Gravity Interpretation

The Bouguer gravity profiles of Figure 24 apparently show no significant irregularities. The smooth increase in the gravitational field from southeast to northwest reflects either the regional trend or large-scale features of the basement rather than structures related to MacDougal Crater. This lack of a gravimetric anomaly appears to contradict the interpretation deduced from the ground magnetic data. However, the gravitational effect  $G$  of a basaltic cylinder 880 feet wide extending from 525 feet below the surface to the Curie depth can be calculated

from:

$$G = 2.03 \omega \rho t$$

where  $\rho$  is the density contrast,  $t$  the thickness of the cylinder, and  $\omega$  the solid angle subtended at the point of observation by the cylinder ( Nettleton, 1942). With the reasonable assumption that the field lava at MacDougal is less than 525 feet thick, the basaltic cylinder is surrounded by basement granites and  $\rho = 0.30$  gm/cc (Table 3). Under these conditions, the maximum value of  $G$  is 0.24 mgal. Such a small anomaly would not be expected to be detectable with the precision obtained on the gravity survey, but, perhaps coincidentally, an irregularity of the correct magnitude does appear. Thus, the magnetic and gravimetric data agree.

### Geophysical Interpretations for Other Craters

#### Molina Crater

Figure 31 presents the distribution of magnetometer stations and the resulting magnetic field at Molina Crater. A large centered magnetic anomaly, such as observed at MacDougal Crater, is missing; the gentle increase in field strength from south to north mimics the trend shown on the 4,000-foot aeromagnetic map of J. R. Sumner (Fig. 24). Figure 33, the measured magnetic field plotted against altimeter station elevations shows a clear altitude dependence of the field strength. The large variability at 740 feet is simply the regional spread from south to north. Presumably a magnetic elevation correction term would eliminate the elevation dependence.



Figure 31. Vertical Magnetic Field, Molina Crater

Contour interval 2.5 gammas. Surface survey. The dots mark magnetometer stations. The north arrow is within a suspected crater.

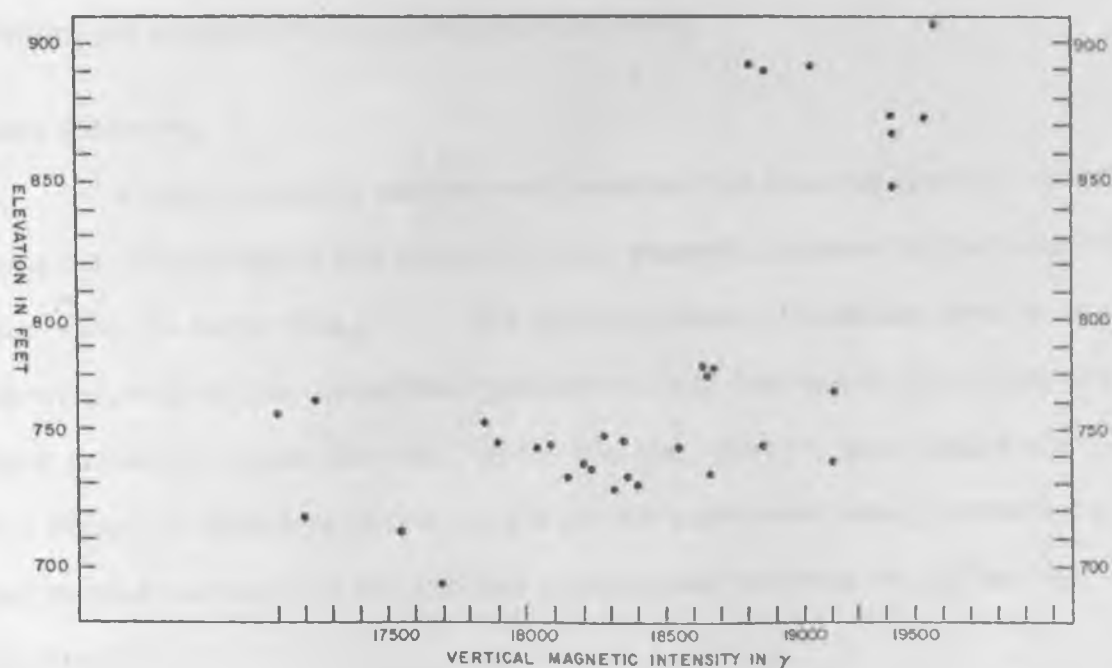


Figure 32. Magnetic Elevation Effect for Molina Crater



The lack of anomalies on the floor of Molina Crater implies the absence of a basaltic plug feeding each vent.

#### Cerro Colorado

A magnetometer survey over most of the floor of Cerro Colorado revealed no anomalies but rather a semi-smooth increase in field strength from south to north (Fig. 33). The concentration of contour lines along the west wall of the crater floor indicates that the basalt flow exposed there probably continues north under the rim. Only a very slight elevation effect is detected associated with the northwest vent, confirming that terrain corrections for craters constructed entirely of tuff are not important.

The lack of a strong anomaly implies that the vent of Cerro Colorado is a tuff pipe with few significant basaltic inclusions. A gravity survey of Cerro Colorado by J. R. Sumner (personal communication) showed a small negative anomaly due to the low-mass playa sediments and crater fill. The gravity data do not allow the existence of a basaltic plug, which is in agreement with the magnetic findings.

#### Diamond Head Crater, Oahu, Hawaii

The morphology and tephra lithology of Cerro Colorado led Shoemaker (Galbraith, 1959) and Jahns (1959) to consider it a diatrema, although in the terminology used here the crater would be considered a maar or tuff ring. Diamond Head Crater (Fig. 34) is the best known example of a tuff ring, a crater formed by hydromagmatic explosions. The water which caused the steam eruptions was probably concentrated in permeable, saturated limestones and was quickly superheated by



Figure 33. Vertical Magnetic Field, Cerro Colorado  
Contour interval 25 gammas. Surface survey.



Figure 34. Aerial View of Diamond Head Crater, Oahu, Hawaii  
Photograph by Hawaii Army National Guard.

rising magma until increasing pressure blasted a vent (Sterns and Vaksvik, 1935).

As the origin and substructure of Diamond Head are better known than they are for Cerro Colorado, a reconnaissance magnetic survey was made across Diamond Head for comparison. On July 5, 1971, Dr. D. P. Cruikshank of The University of Hawaii and the author made 45 measurements in north-south and east-west lines with a Jalander magnetometer. Military buildings prohibited measurements in the northern one-third of the crater. The observed magnetic field is so remarkably uniform over the crater that no magnetic map is necessary. No anomaly was detected associated with the floor or rim. A large piece of the rim tuff caused no deflection when held directly below the magnetometer, showing the negligible magnetic susceptibility of the tuff. Therefore, it appears that the entire crater, like Cerro Colorado, is composed of tuff and that the vent filled rather than containing basalt.

A cross section of Diamond Head (Fig. 35) based upon an adjacent well log, and inclusions of abundant reef limestone and fragments of basement basalt in the tuff show that the focus of the explosion was in the basalt, at least 1,178 feet below the surface (Sterns and Vaksvik, 1935).

#### Moon Crater

Approximate north-south and east-west magnetometer and altimeter traverses were made across Moon Crater in April 1971 (Fig. 36). The terrain-induced field computed for a susceptibility of 0.001 cgs is approximately one-fiftieth of the maximum magnetic field observed on

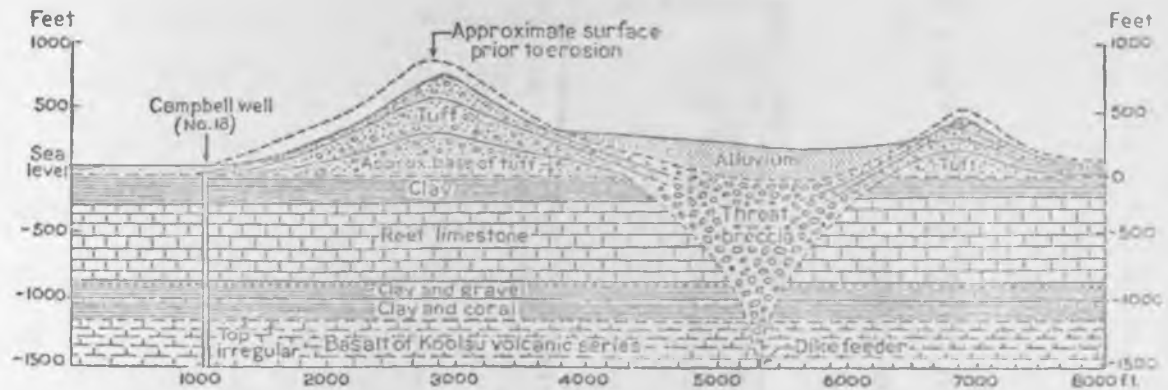


Figure 35. Geologic Cross Section of Diamond Head Crater.--  
From Sterns and Vaksvik (1935)

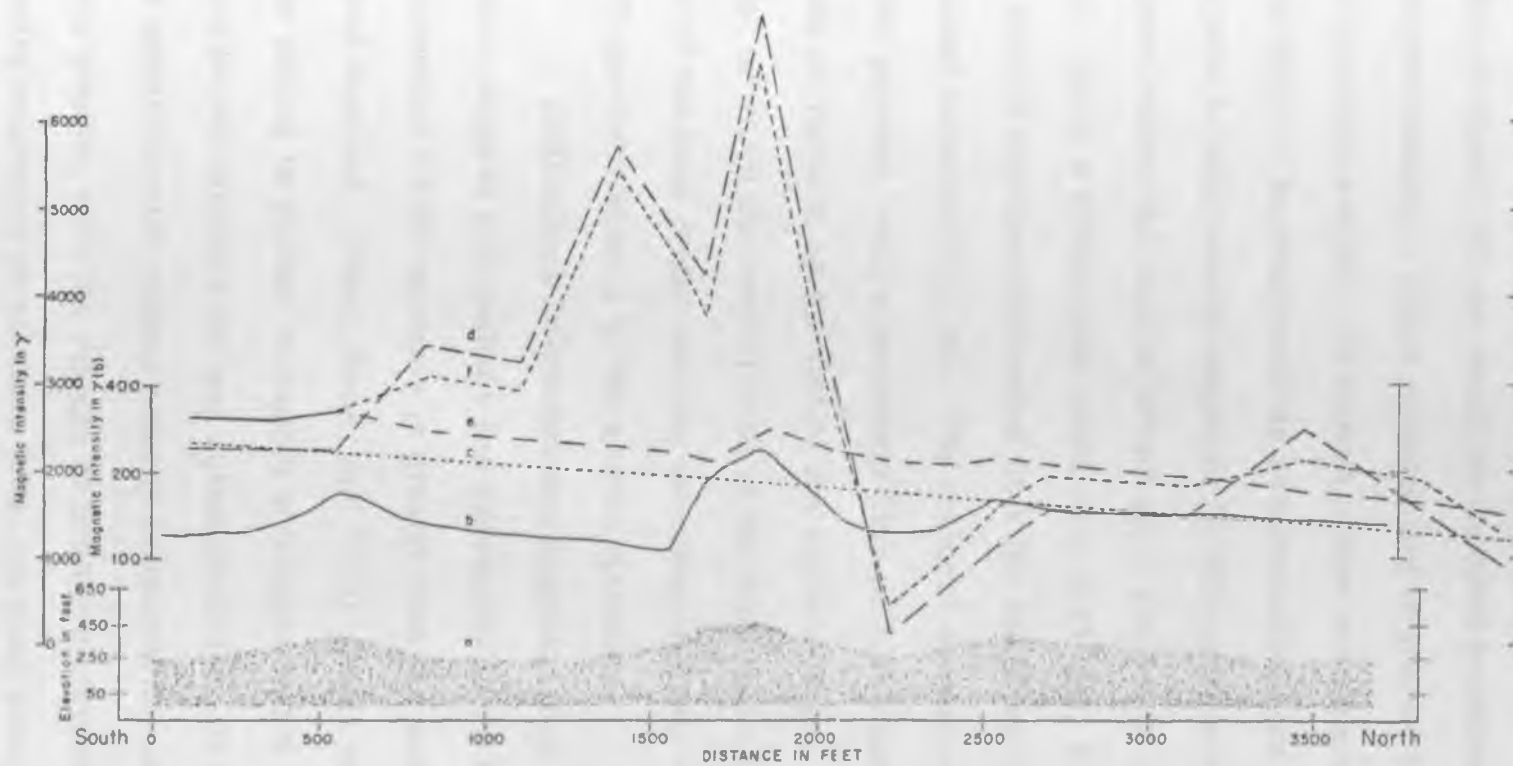


Figure 36. Vertical Magnetic Field Cross Section of Moon Crater

a = topography; b = terrain effect; c = assumed regional trend; d = observed anomaly; e = terrain effect adjusted to regional trend; f = residual anomaly.

the crater's central peak. Although the observed magnetic field associated with the peak is similar to a terrain anomaly signature, a susceptibility of about 0.05 cgs would be required to account totally for the observed anomaly. This susceptibility is greater by a factor of 12 than any measured sample. To make a proper terrain correction for the central peak requires knowledge of its susceptibility, but spatter collected on the peak is only weakly magnetic (0.0006 cgs) whereas dense basalt exposed where the peak is breached is similar to rim basalts (0.004 cgs). Using a compromise value of 0.0025 cgs, a terrain anomaly was calculated and then subtracted from the observed anomaly to obtain the residual anomaly (Fig. 36). The residual anomaly of the central peak is 4,760 gammas, with a secondary high of 3,950 gammas immediately south of the peak on the flat of the crater's floor. Modeling of a basaltic plug, of which the central peak is the top, limited in width by the diameter of the peak crater requires an unrealistically high magnetization of 0.03 cgs to produce a 4,760-gamma maximum.

Difficulties in interpreting magnetic data for Moon and other craters suggest that perhaps the susceptibility of the subsurface rocks responsible for the anomaly is greater than the susceptibility of collected samples. Stone, Amna, and Tribble (1971) reached this conclusion after failing to explain measured anomalies in the Valley of 10,000 Smokes using known thicknesses and susceptibilities. This could possibly occur if a magnetite-rich magma came in contact with water, oxidizing the rising magma, with the escape of hydrogen preventing equilibrium, and altering magnetite to hematite (Sill, personal communication). Malahoff (1969) speculates that Hawaiian intrusive rocks have a greater

magnetization than surface basalts due to higher density, greater physical stability, and a slower rate of cooling. Weathering can also reduce susceptibilities. Taylor and Reno (1948) found that unweathered granite and quartz monzonite have susceptibilities 20 times greater than weathered examples of the same rocks. Equivocal observations such as these reinforce the statement of Sterns and Vaksvik (1935, p. 137) that "volcanoes have many habits not subject to mathematical analysis."



## ORIGIN OF PINACATE CRATERS

### Summary of Observations

The following observations are considered relevant to the origin of the craters of the Pinacate:

1. The depth of the crust near the Pinacate is about 18 miles.
2. Ultramafic nodules have been found on MacDougal's rim.
3. Large plagioclase crystals are common in the lavas.
4. Except for Moon Crater, the basalt cliffs exposed in crater walls are below the level of the surrounding desert.
5. Cliff basalts are approximately flat lying and apparently continuous around the crater walls.
6. If MacDougal Crater was originally a flat-topped tuff mound, the volume of the crater is about 48 times greater than the volume of rim deposits.
7. Sykes, Elegante, MacDougal, Celaya, and Badillo have cinder cones exposed on their rims in cross section on top of cliff-forming basalts.
8. Celaya and Molina Craters are composed of at least two coalescing depressions.
9. Moon Crater has one or more remnants of cinder cones on its rim. A cinder cone breaks the rim of Badillo.
10. Cerro Colorado and Molina had major off-center vent eruptions significantly after the initial crater-forming activity.

11. Near-vertical dikes extend through MacDougal basalts and tuff beds.
12. Vertical faults are exposed subparallel to the walls of Kino. Molina has high, vertical, scarplike walls.
13. A block of Elegante tuff beds has foundered into the crater. Collapse of sections of the inner wall of Cerro Colorado has increased the crater diameter over the last 40 years.
14. Rim beds are apparently basaltic tuffs. Cerro Colorado is composed of sideromelane and palagonite.
15. Seven Pinacate craters are on a west to northwest-trending arc approximately 20 miles long.
16. The large, steep, magnetic anomaly at MacDougal Crater is best modelled by a subsurface cylinder of basalt. The lack of a gravity anomaly is expected from the basaltic plug's depth and small size.
17. Moon Crater's central peak is a strong magnetic anomaly. Magnetic and morphologic evidence indicates other vents in a north-south line.
18. Cinder cones are sources of a very large magnetic anomalies.
19. Molina and Cerro Colorado (and, for comparison, Diamond Head in Hawaii) have no magnetic expressions.

#### Origin of Cerro Colorado

The following reconstruction of Cerro Colorado's development accords with Shoemaker's (Shoemaker, Roach, and Byers, 1962, and in Galbraith, 1959) description of maar formation. The first eruptive stage

in the development of Cerro Colorado was probably similar to the vent opening, violent, gaseous discharges of Nilahue (Müller and Veyl, 1957). This gas phase may have derived from basaltic magmas rich in water and other volatiles (as at Hopi Buttes), or, as will be seen below, may have resulted from rising magma or its harbinger, heat "flashing" ground water into steam, as occurred at Diamond Head. At both Nilahue (Müller and Veyl, 1957) and Surtsey (Thorarinsson, 1967) the eruptions were staccato; one to three minutes of pressure increase would finally result in an explosive expulsion of steam and clouds black with tephra. A decompression wave propagated downward when the surface was breached. Rising gas bubbles expanded and coalesced, entraining fragments of degassed magma and creating a fluidized system in which spalled wall fragments and magma particles rose or sank, depending on the density and velocity of the system. Abrasion, spalling, and slumping enlarged the vent. Ultra-vesiculated magma was ejected to great heights with the heavier particles falling around the vent, constructing an ash rim. Rounded basaltic blocks embedded in the rim attest to extensive fluidization (Fig. 12). Both base-surge and air-fall deposition of ash occurred, building a sideromelane rim dipping inward and outward (Fig. 22; and Waters and Fisher, 1970). Presumably each of the staccato eruptions deposited a single, thin tuff layer on the rim.

Whether Cerro Colorado was a tuff cone or tuff ring at the end of this stage of activity is not known, but collapse occurred, truncating the inward-dipping tuffs and creating the shear cliffs still exposed on the northeast inner wall of the crater. This interpretation differs from Shoemaker's statement in Galbraith (1959) that subsidence did not occur

after the explosive activity. The collapse probably resulted from the evacuation of the magma chamber as the tuff was erupted, thus removing support from below the cone. But collapse did not occur simultaneously with the eruption for these early tuffs do not drape the collapse scarps.

Erosion gullied the crater rim and percolating rainwater began to alter sideromelane to palagonite, as investigated by Hay and Iijima (1970) in Hawaii. Then, northwest of Cerro Colorado's center a new vent resumed the eruption, spraying out more tuff breccias, perhaps as a base surge, which plastered the walls and talus of the collapsed crater, building up the high south side of the rim and blasting lower the crater's north wall. At Cerro Colorado, as at Diamond Head, a single wind direction dominated during the weeks or months of intermittent eruption, resulting in a high rim to the south (Figs. 22 and 34). Again collapse occurred at Cerro Colorado, and much of the tuff veneer slumped away from the earlier collapse cliffs. The new vent did not subside, but the approximately 20-foot-high scarp between it and the main floor shows that the main crater floor did and perhaps still is. Gullying resumed and continues, and slumping of the massive south wall has progressed noticeably since Ives's first visit to Cerro Colorado in 1931 (Ives, personal communication).

The lack of a magnetic anomaly implies that all of the available magma vesiculated, even that in the feeder pipe, which is therefore tuff filled. The gravity low is also explained by the alluvium and tuff breccia filling of the crater floor (J. R. Sumner, personal communication).

Jahns (1959) termed Cerro Colorado a "miniature caldera" because of the collapse which occurred. Waters and Fisher (1970) consider

the valcono a maar due to the bedding characteristics. Shoemaker (in Galbraith, 1959) called Cerro Colorado a diatrema. In view of the primarily constructional nature of Cerro Colorado--the floor is nearly 50 feet above the surrounding playa--and the fact that similar features in Oregon and Iceland have suffered collapse, I suggest that the present volcano is a tuff ring.

Ives (1935) reported that "violent eruptions" were audible to the people of Sonoyta, Sonora, in early January 1935, following a series of severe earthquakes centered in the Gulf of California on December 31, 1934. This is the basis for statements, such as those of Lorenz et al. (1970), that eruptions have recently occurred in the Pinacate. However, Ives (personal communication) commented that he and Glenton G. Sykes found small, fresh fault scarps in alluvium that were obviously new but no signs of recent volcanic activity on a Pinacate trip made soon after the 1934 earthquakes. Plumes of smoke near the Pinacate, reportedly seen in Sonoyta at the time of the earthquakes, presumably were clouds of dust thrown into the air by the sudden faulting. Hayden (personal communication) recounts a different origin for the "smoke" reported in 1935. Don Alberto Celaya, a respected resident of Sonoyta, told Hayden that his (Celaya's) father and some other people were exploring a Pinacate lava tube in the 1870's. A young boy dropped his torch igniting the floor-covering guano which burned for more than a year and sent up a column of black smoke which the people of Sonoyta still talked about in 1935.

The sequence of explosive eruption, cone building, and collapse that Jahns (1959) discusses for Pinacate craters fits all available

data and is similar to the processes postulated above to have formed Cerro Colorado.

### Origin of Elegante-type Craters

Elegante-type craters can be regarded as maars enlarged by collapse. The most important observation concerning MacDougal, the Elegante-type crater examined in this study, and Pinacate craters with similar morphologies is that the basalts exposed in the walls are apparently flat lying and continuous. This disagrees with Ives's (1964) suggestion that each vent was the source of effusive lava flows. The cliff-forming basalts are not derived from the crater-forming process but rather are penetrated by field basalts. Cerro Colorado, by contrast, was apparently formed at the edge of the lava field flows, and basalt is exposed only along the western inner wall.

A common feature of MacDougal and most other Pinacate craters is a boulder-strewn rim (Figs. 11, 16, and 19). It would be difficult to explain how these basalt boulders could have been ejected after the formation of the tuff. However, Figures 6 and 12 explain their presence. Boulders ejected from the vent at the same time the tuff was expelled were embedded in the tuff layers. As erosion proceeds, the tuff is broken down into dust which is carried away by the wind, while the basalt boulders accumulate on the current rim.

It is unlikely that the initial explosive vents were as large as the present craters; Krakatoa's original explosions came from a 100-foot orifice which was enlarged by engulfment and subsidence to 4 miles (Bullard, 1962). Because of MacDougal's boulder-strewn rim, one

interpretation is that a resurgence of explosive eruptivity enlarged MacDougal's original vent, producing the one-mile-diameter crater. This speculation was inspired by the large quantity and size of blocky ejecta blown out of Halemaumau, Hawaii, by the 1924 steam-blast eruption. However, 99 percent of the increase in the diameter of Halemaumau resulted not from the eruption but from simultaneous collapse triggered by the removal of magmatic support as magma migrated into the rift zone (MacDonald and Abbott, 1970).

Near-vertical basaltic cliffs, Kino's concentric fault, foundered tuff in Elegante, and the deficiency of rim tuffs as compared to MacDougal's crater volume indicate collapse also occurred in the Pinacate craters. Jahns (1959) and Ives (1964) consider Elegante-type craters typical collapse calderas in accordance to Williams' (1941) theory of collapse. This implies that the collapses occurred into laccolith-like magma chambers, as illustrated in Figure 37A. Díaz is especially intriguing, because it may be a tuff mound which never collapsed. But Kuno et al. (1971, p. 23) conclude from drilling cores and road-cut cross sections that Hakone, a Japanese caldera of the Krakatoa type, subsided

. . . along a complicated system of concentric faults combined with tilting of individual fault blocks toward the middle of the caldera. The magma reservoir into which the fault blocks sank probably had a shape of a cupola with a diameter comparable to or a little smaller than the diameter of the caldera.

(See Figure 37B.) This is not unlike the type of subsidence along ring fractures (or without them) detected in many maars (Francis, 1971). Therefore, collapse alone does not differentiate between calderas and maars.

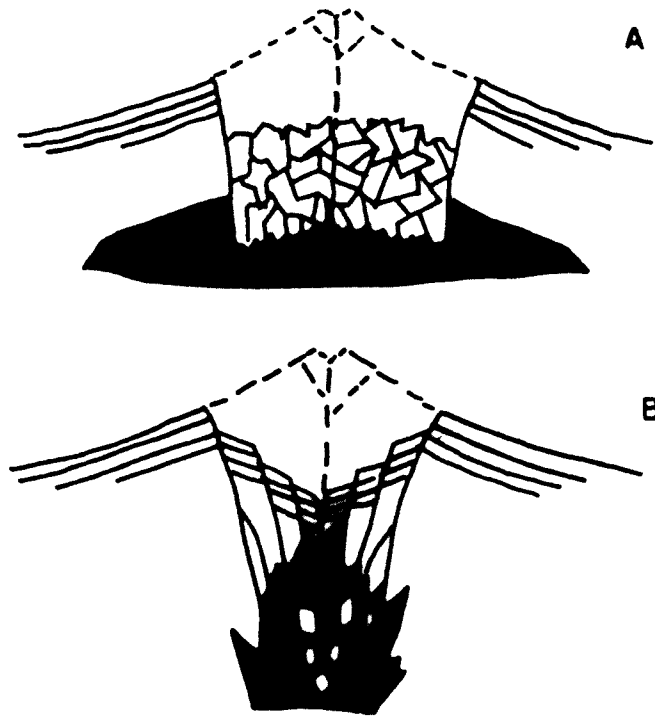


Figure 37. Models of Caldera Collapse

A: collapse into laccolith-like chamber as envisioned by Williams (1941). B: collapse along ring faults into cupolalike magma chamber (Kuno et al., 1971).



The geophysical surveys provide information concerning the subsurface of Pinacate craters and perhaps indicate whether they are maars or calderas. Table 4 presents gravity and magnetic anomalies of calderas, maars, and a meteor crater for comparison with Pinacate craters.

Three comments by Williams and McBirney (1968) should be stressed concerning these anomalies:

1. Negative gravity anomalies in Krakatoan calderas result from superficial filling of caldera floors with breccia rather than from major mass deficiencies in the subsurface structure. Crater Lake and Apoyo which do not have gravity lows have only a thin layer of sediments.
2. Gravity and magnetic anomalies associated with Hawaiian calderas are primarily due to the volcanic shields rather than to the calderas themselves.
3. Small, sharp magnetic anomalies not associated with gravity highs exist in some Japanese calderas; they are interpreted as gravimetrically insignificant buried cones or intrusions.

An additional comment by the author is that the large magnetic field of the Linhorka diatrema is due to a basaltic intrusion into the breccia pipe. Presence or absence of such intrusions may also explain the MacDougal magnetic high and the lack of magnetic anomalies (and presumably intrusions) in Cerro Colorado, Molina, and Diamond Head. Furthermore, MacDougal or any other crater conceivably could have a lava lake floor (similar to Halemaumau) covered with sediments, but such a continuous slab could not be detected geophysically. Such lava lakes occasionally occur in calderas and maars (Ollier, 1967).

Table 4. Gravity and Magnetic Anomalies of Craters

Name, Location	Size (km)	Gravity Anomaly (mgal)	Magnetic Anomaly (gamma)	Crater Type	Reference <sup>a</sup>
Towada, Japan	8 x 9	-10	<sup>b</sup> 1000	Krakatoan	1, 2
Hakone, Japan	10	-10	<sup>b</sup> 1000	Krakatoan	1, 2
Akan, Japan	13 x 24	-25			1
Kuttyaro, Japan	20 x 7	-16		Krakatoan	1
Toya, Japan	10	-14		Krakatoan	1
Aso, Japan	16 x 23	-20		Krakatoan	1
Aira, Japan	20	-30		Krakatoan	1
Skikotsu, Japan	15	-20		Krakatoan	1
Crater Lake, Oregon	8 x 15	0 to -5		Krakatoan	1
Mogollon Plateau, New Mexico	125	-60		Volcano- tectonic complex	3
Ambrym, New Hebrides	13	-12	<sup>b</sup> 600	Glencoe	4
Apoyo, Nicaragua	5 x 6	+30			1
O-Sima, Japan	3 x 4	+ 9	strong	Krakatoan	1, 5
Masaya, Nicaragua	11 x 6	+25	~0	Masayan	1
Mauna Loa, Hawaii	4 x 3	+100		Hawaiian	1
Kilauea, Hawaii	4 x 3	+60		Hawaiian	1
Lania, Hawaii	3 x 4	+40		Hawaiian	1
Kauai, Hawaii	16 x 20	+90		Hawaiian	1
Linhorka, Czechoslovakia	0.26	-0.25	1200	Diatreme	6

Table 4.--(Continued)

Name, Location	Size (km)	Gravity Anomaly (mgal)	Magnetic Anomaly (gamma)	Crater Type	Reference <sup>a</sup>
Nova Trubka, Czechoslovakia	0.11		30	Diatreme	6
Granatoryurch, Czechoslovakia	0.29	-0.3	120	Diatreme	6
Dreiser Weiher, Germany	1.4 x 1.2		190	Maar	6
MacDougal, Mexico	1.7	0	1000	Maar	7
Molina, Mexico	0.6, 0.3		~ 0	Maar	7
Moon, Mexico	0.6		4760	Ring dike(?)	7
Cerro Colorado, Mexico	1.0		~0	Tuff ring	7
Diamond Head Hawaii	1.1		~ 0	Tuff ring	7
Meteor Crater, Arizona	1.2	-0.75	30	Meteor crater	8

a. References: 1--Williams and McBirney (1968); 2--Malahoff (1969); 3--Elston (1971); 4--McCall et al. (1971); 5--Kuno (1962); 6--Lorenz et al. (1970); 7--this paper; 8--Van Lopik and Geyer (1963).

b. Denotes aeromagnetic data; all others surface measurements.

Some of the diatremes listed have gravity and magnetic anomalies similar to the Pinacate craters. This observation suggests the maar designation. The vertical ring dikes (?) observed around MacDougal may well be collapse fractures filled with magma. Additional circumstantial evidence indicates the Pinacate craters are maars rather than calderas. Figure 38, from Pike (1971), plots the relationship between rim height/crater depth and crater diameter for terrestrial and lunar craters. I have added to this diagram MacDougal and Moon, both of which fall into the maar field, considerably separated from the caldera field. And finally, considering that large maars and small calderas overlap in the diameter range 1 to 3 km and that subsidence occurs in both, I concur with Francis (1971) that the main basis for the classification of maars and calderas should be magmatic association--i.e. basic and acid respectively.

#### Origin of Molina Crater

Molina is similar to Elegante-type craters, except that there is no magnetic anomaly associated with its floor. Molina may be an end member of the sequence MacDougal, Sykes, Elegante (all with previous cinder cone vents exposed in their walls), Celaya (composed of two distinct coalescing craters), and Molina (composed of multiple coalescing collapses and a more recent overlapping collapse). Moon, Badillo, and Cerro Colorado erected cinder cones and vents after the main crater formation period ended. Fresh lava mounds on the west rim of MacDougal and loosely consolidated cinder deposits on Elegante's southeast rim

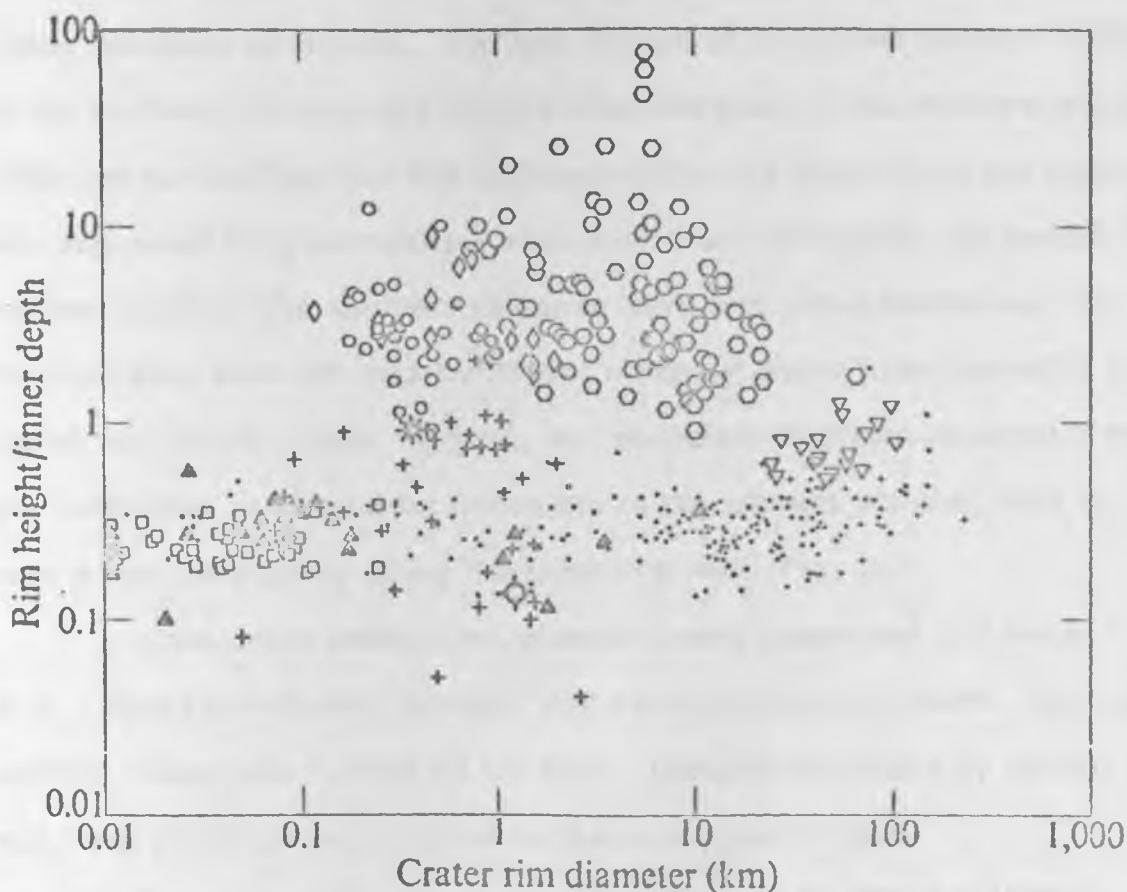


Figure 38. Morphometric Distinction between Explosion Craters and Calderas

Diagram from Pike (1971) with MacDougal ( $\diamond$ ) and Moon Craters ( $\circ$ ) plotted along with calderas ( $\circ$ ), maars ( $+$ ), cinder cones ( $\circ$ ), normal lunar craters ( $\cdot$ ), flooded lunar craters ( $\nabla$ ), lunar dome pits ( $\diamond$ ), experimental explosion craters ( $\square$ ), and meteorite craters ( $\triangle$ ).

Evidence for at least two phases of collapse activity in Molina Crater has been presented. The fact that all of the lower basaltic cliffs of the southern complex are talused over and most of the northern crater's cliffs are not implies that the collapse of the two sections of the crater was separated by a substantial amount of time. Similarly, the southwestern cliffs of the southern collapse have less talus blanketing than the northeast side and thus these two elongate crater forms probably occurred at different times. Indeed, the northeast structure apparently was two individual collapses for the stump of the missing common wall is seen as an irregularity along the northeast wall (Fig. 31).

Coalescent craters are common among maars and tuff rings (e.g., Salt Lake Crater, Hawaii, and Katwe explosion craters, Uganda) and the "composite" crater of Ale Bagu, Ethiopia described by Barberi and Varet (1970) is very similar to Elegante-type craters.

Does the lack of magnetic anomalies on the floor of Molina imply it is fundamentally different from MacDougal? Not necessarily for, as Francis (1971) has shown, clustered Scottish diatremes, presumably produced under similar conditions, may or may not have central igneous intrusions. If all of the magma in the chamber associated with Molina were expelled, none would remain to be intruded. Also, it is not yet known if other Elegante-type craters have large magnetic anomalies; perhaps MacDougal is unique in this respect.

There is an approximately 1000-foot-diameter depression near the north side of Molina Crater (Fig. 31, white patch under north arrow). This has a low rim made up of the same material as the blanket around

Molina. This may be an older collapse, almost filled in by desert sand and alluvium.

In summary, it appears that Elegante, Cerro Colorado, and Molina type craters have similar mechanisms of formation but have morphological differences due to variation in numbers of vents and collapse centers and degree of erosion and collapse.

#### Origin of Moon Crater

Unique among Pinacate craters, Moon has dense, unstructured rim basalts projecting above the surrounding terrain, a large cinder-cone central peak, and no exposed rim tuffs. The basalt rim cannot be penetrated field basalts, and its massive coherency argues against it being an ejecta pile from a central vent. The lack of rim tuffs and the presence of dense, vesicle-free lavas and bombs indicate Moon Crater was not a site of gas-charged eruptions nor did the rising magma apparently interact with the water table except perhaps during the rim-vent eruption when tuff was produced. As the crater's floor is slightly higher than the surrounding desert and there are no basaltic cliffs, collapse apparently did not occur. The cinder cone is only one of a series of four vents aligned approximately parallel to Basin and Range fractures. Moon Crater should not be considered a maar because the rim does not appear to have been produced by eruption from a central vent nor does the crater cut into the pre-eruption surface. Provisionally, Moon Crater is considered a ring dike with a cinder-cone central peak (Fig. 39).

## RING DIKE MODEL OF MOON CRATER

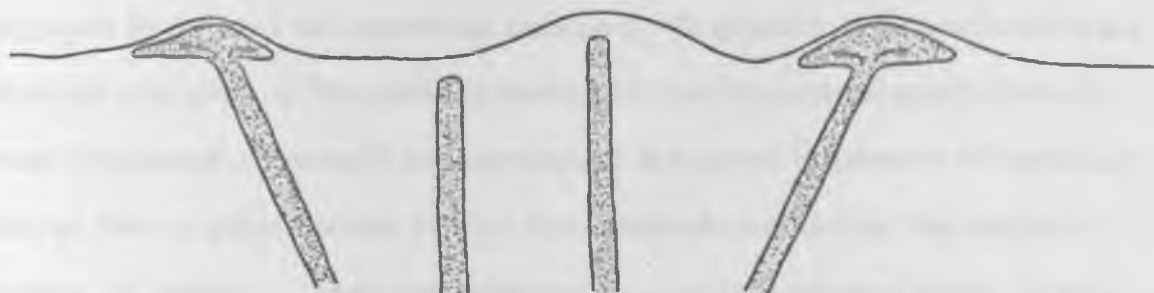


Figure 39. Ring-dike Model for Moon Crater

The central peak is a cinder cone built up of pyroclastic ejecta. The vent to the left did not reach the surface. Dikes feeding the rim did not result in a line of cinder cones but built up massive basalt walls, here shown covered with windblown sand and ash from the central peak.



### Tectonic Control of Pinacate Volcanism

Although there is disagreement whether vents in the Pinacate are aligned with trends of Basin and Range fracturing (J. R. Sumner, 1971; Green and Short, 1971). Ives (1935) pointed out that the seven northern craters define a west-northwest-trending arc approximately 20 miles long (Fig. 2). Ives (personal communication) suggested that the Sonoyta River had two previous courses. Originally it flowed westward through the area of the present center of the Pinacate massif; then it was displaced northward by eruption of the great thickness of lava filling in the original stream valley to a channel marked by the present string of craters. After the northern crater-forming eruptions, it was deflected southward to its present course. Although it is difficult to confirm the earlier paths of the Sonoyta in detail, Ives's suggestion is supported by two observations. The northern shoreline of the Bahia de Aduar (Fig. 1) is broken by an abandoned estuary in approximate alignment with the west-trending portion of the Sonoyta and the Pinacate crater arc. Secondly, a well dug at a ranch just beyond the edge of the surface lavas, along the track from Mexico 2 to MacDougal, penetrated 40 feet of silt and sediments, 40 feet of basalt, and 490 feet of river valley alluvium and a small amount of cinders (Hayden, personal communication). This alluvium apparently marks a previous course of the Sonoyta River.

Acceptance of Ives's theory implies that the northern Pinacate craters resulted from phreatomagmatic eruptions, as did nearly all maars and tuff rings in the western United States (Waters and Fisher, 1970) and Hawaii (Sterns and Vaksvik, 1935). This theory explains that

eruptions occurring after the crater-forming one produced cinder cones, such as the one breaking Badillo's rim, because the water table had been locally depleted, but it does not explain why previous eruptions in the area of each crater produced only cinder cones. Nor does it explain the origin of tuffs exposed on Pinacate Peak (Ives, 1964), the rim vent at Moon, nor the rim of Elegante, all south of the proposed former channel of the Sonoyta. As basaltic tuffs (sideromelane) are only produced by phreatomagmatic eruptions, the vents responsible for these tuffs must have intersected the water table or the magmas were rich in water. Neither of these alternatives explain why vents near the craters failed to produce tuffs, and additional evidence is not available.

The location of the entire Pinacate volcanic field is suggestively close to the Gulf of California and its spreading rises and transform faults. Recent evidence indicates that a subduction zone dipped under western America, giving rise to lower and middle Cenozoic andesitic volcanism and late Cenozoic basaltic volcanism (Lipman, Prostka, and Christiansen, 1971); the Sierra del Pinacate appears to be part of this basaltic sequence. A variation on the plate tectonics theory is the suggestion of Hey and Morgan (1971) that the Pinacate lava field is presently over a stationary mantle hot spot which previously produced volcanism at the San Juan Seamount and at the Southern California Continental Borderland Province as the North American plate moved westward. However, such speculation is more exotic than required, since J. R. Sumner (1971) has shown that the Pinacate field is located at the intersection of the northwest-trending Basin and Range faults and an east-northeast magnetic structure aligned with small graben near Bahia del

Aduar. Therefore, plate activity may be the source of the magma, and fractures of diverse origin responsible for providing a path to the surface for the magma.

## REFERENCES

- Barberi, F., and Varet, J., 1971, "The Erta Ale Volcanic Range (Danakil Depression, Northern Afar, Ethiopia)," Bull. volcanol., v. 34, p. 848.
- Bolton, H. E., 1919, Kino's Historical Memoir of Pimeria Alta, Glendale, Calif.: Arthur H. Clark Co. (Reprinted by University of California Press, Berkely, 1948.)
- Bullard, F., 1962, Volcanoes, in History, in Theory, in Eruption, Austin, Texas: University of Texas Press.
- Cloos, H., 1941, "Bau und Tätigkeit von Tuffschloten," Geol. Rdsch., v. 32, p. 705.
- Cotton, C. A., 1969, Volcanoes as Landscape Forms, New York: Hafner Publishing Company, Inc.
- Corle, E., 1951, The Gila, River of the Southwest, New York: Holt, Rinehart and Winston, Inc. (Reprinted by University of Nebraska Press, Lincoln, Neb., 1967.)
- Dobrin, M. B., 1960, Introduction to Geophysical Prospecting, New York: McGraw-Hill Book Company.
- Donnelly, M. F., 1970, Geologic Map: Sierra Pinacate Region, Sonora, Mexico-Arizona, U.S.A., unpublished map.
- Elston, W. E., 1971, "Evidence for Lunar Volcano-tectonic Features," J. Geophys. Res., v. 76, p. 5690.
- Francis, E. H., 1971, "Bedding in Scottish (Fifeshire) Tuff Pipes and Its Relevance to Maars and Calderas," Bull. volcanol., v. 34, p. 697.
- Galbraith, F. W., 1959, "Craters of the Pinacates," in Southern Arizona Guidebook II, Heindl, L. A. (ed.), Tucson, Arizona, Arizona Geological Society, p. 161-164.
- Green, J., and Short, N., 1971, Volcanic Landforms and Surface Features, New York: Springer-Verlag.
- Hay, R. L., and Iljima, A., 1970, "Nature and Origin of Palagonite Tuffs of the Honolulu Group on Oahu, Hawaii," in Studies in Volcanology, G.S.A. Mem. 116.

- Hayden, J., 1967, "A Summary Prehistory and History of the Sierra Pinacate, Sonora," American Antiquity, v. 32, p. 335.
- Hearn, B. C., Jr., 1968, "Diatremes with Kimberlitic Affinities in Northcentral Montana," Science, v. 159, p. 622.
- Heiken, G. H., 1971, "Tuff Rings: Examples from the Fort Rock-Christmas Lake Valley Basin, South-central Oregon," J. Geophys. Res., v. 76, p. 5615.
- Hey, R. N., and Morgan, W. J., 1971, "Parallel Seamount Chains in the Northeast Pacific," Eos, Trans. AGU, v. 52, p. 236.
- Hornaday, W. T., 1908, Camp-fires on Desert and Lava, New York: Charles Scribners Sons.
- Ives, R. L., 1935, "Recent Volcanism in Northwestern Mexico," Pan Am. Geol., v. 63, p. 335.
- Ives, R. L., 1956, "Age of Cerro Colorado Crater, Pinacate, Sonora, Mexico," Am. Geophys. Union Trans., v. 37, p. 221.
- Ives, R. L., 1964, "The Pinacate Region, Sonora, Mexico," California Academy of Sciences Occasional Paper No. 47.
- Ives, R. L., 1965, "The Lava Desert of Pinacate," Pacific Discovery, v. 18, p. 18.
- Jahns, R. H., 1959, "Collapse Depressions of the Pinacate Volcanic Field, Sonora, Mexico," in Southern Arizona Guidebook II, Heindl, L. A. (ed.), Tucson, Arizona: Arizona Geological Society, p. 165.
- Johnson, R. W., 1969, "Volcanic Geology of Mount Suswa, Kenya," Royal Soc. (London) Philos. Trans., v. 265, p. 383.
- Kuno, H., 1962, Catalogue of Active Volcanoes of the World Including Solfutara Fields; Pt. XI, Japan, Taiwan, and Marianas, Rome: Internat. Assoc. of Volcanology.
- Kuno, H., Oki, Y., Ogino, K., and Hirota, S., 1971, "Structure of Hakone Caldera as Revealed by Drilling," Bull. volcanol., v. 34, p. 713.
- Larson, R. L., Menard, H. W., and Smith, S. M., 1968, "Gulf of California: a Result of Ocean-floor Spreading and Transform Faulting," Science, v. 161, p. 781.
- Lawrence, T. E., 1926, Seven Pillars of Wisdom, London: Jonathan Cape.

- Lipman, P. W., Prostka, H. J., and Christiansen, R. L., 1971, "Evolving Subduction Zones in the Western United States, as Interpreted from Igneous Rocks," *Science*, v. 174, p. 821.
- Lorenz, V., 1970, "Collapse Structures in the Permian of the Saar-Nahe Area, Southwest Germany," *Geol. Rdsch.*, v. 60, p. 924.
- Lorenz, V., McBirney, A., and Williams, H., 1970, Maars, Tuff-rings, Tuff-cones, and Diatremes, Houston, Texas: NASA Progress Report.
- Lumholtz, C., 1912, New Trails in Mexico, London: Fisher Unwin.
- MacDonald, G., and Abbott, A. T., 1970, Volcanoes in the Sea, Honolulu, Hawaii: University of Hawaii Press.
- Malahoff, A., 1969, "Magnetic Studies over Volcanoes," in The Earth's Crust and Upper Mantle, Hart, P. J. (ed.), Washington, D.C.: American Geophysical Union, Geophysical Mon. 13, p. 436.
- Malahoff, A., and Wollard, G. P., 1966, "Magnetic Surveys over the Hawaiian Islands and Their Geologic Implications," *Pac. Sci.*, v. 20, p. 265.
- Marsh, B. D., 1971, "Aeromagnetic Terrain Effects," unpublished M.S. Thesis, University of Arizona.
- McBirney, A., 1959, "Factors Governing Emplacement of Volcanic Necks," *Am. Jour. Sci.*, v. 257, p. 431.
- McCall, G. J. H., LeMaitre, R. W., Malahoff, A., Robinson, G. P., and Stephenson, P. J., 1971, "The Geology and Geophysics of the Ambrym Caldera, New Hebrides," *Bull. volcanol.*, v. 34, p. 681.
- Muller, G., and Veyl, G., 1957, "The Birth of Nilahue, a New Maar Type Volcano at Rininalue, Chile," 20th Internat. Geol. Cong. Rept., Sec. 1, p. 375.
- Nagata, T., 1969, "Reduction of Geomagnetic Data and Interpretation of Anomalies," in The Earth's Crust and Upper Mantle, Hart, P. J. (ed.), Washington, D.C., American Geophysical Union, Geophysical Mon. 13, p. 391.
- Nelson, F. J., 1963, "Geology of Pena Blanca and Walker Canyon," unpublished M.S. Thesis, University of Arizona.
- Nettleton, L. L., 1942, "Gravity and Magnetic Calculations," Geophysics, v. 7, p. 293.

- Noble, J. A., 1970, "Metal Provinces in the Western United States," Geol. Soc. Am. Bull., v. 81, p. 1607.
- Noll, H., 1967, "Maare und Maar-ähnliche Explosionkrater in Island. Ein Vergleich mit dem Maarvulkanismus der Eifel," Geol. Inst. Univ. Köln Sonderveröff., v. 11, p. 1.
- Ollier, C. D., 1967, "Maars--Their Characteristics, Varieties, and Definition," Bull. volcanol., v. 31, p. 45.
- Peterson, N. V., and Groh, E. A., 1963, "Maars of South-central Oregon," The Ore Bin, v. 25, p. 73.
- Pike, R. J., 1971, "Height-depth Ratios of Lunar and Terrestrial Craters," Nature Physical Science, v. 234, p. 56.
- Reford, M. S., and Sumner, J. S., 1964, "Aeromagnetism," Geophysics, v. 29, p. 482.
- Rittmann, A., 1962, Volcanoes and Their Activity, trans. by E. A. Vincent, New York: Interscience.
- Shelton, J. S., 1968, Geology Illustrated, San Francisco: W. H. Freeman and Company.
- Sheriden, M. F., Stuckless, J. S., and Fodor, R. V., 1971, "A Tertiary Silicic Cauldron Complex at the Northern Margin of the Basin and Range Province, Central Arizona, U.S.A.," Bull. volcanol., v. 34, p. 649.
- Shoemaker, E. M., 1962, "Interpretation of Lunar Craters," in Physics and Astronomy of the Moon, Lopal, Z. (ed.), New York: Academic Press.
- Shoemaker, E. M., Roach, C. H., and Byers, F. M., Jr., 1962, "Diatremes and Uranium Deposits in the Hopi Buttes, Arizona," in Petrological Studies (Buddington Volume), New York: Geol. Soc. Am., p. 337.
- Sterns, H. T., and Vaksvik, K. N., 1935, "Geology and Ground Water Resources of the Island of Oahu," Hawaii Div. Hydrology, Bull. 1.
- Stone, D. B., Anna, K., and Tribble, M., 1971, "Magnetic Anomalies in the Valley of 10,000 Smokes," Eos, Trans. AGU, v. 52, p. 925.
- Sumner, J. R., 1971, "Tectonic Significance of Geophysical Investigations in Southwestern Arizona and Northwestern Sonora, Mexico, at the Head of the Gulf of California," unpublished Ph.D. Thesis, Stanford University.

- Talwani, M., and Heirtzler, J. R., 1964, "Computation of Magnetic Anomalies Caused by Two-dimensional Structures of Arbitrary Shape," Stanford University, Geological Sciences, v. 9, p. 464.
- Taylor, G. L., and Reno, D. H., 1948, "Magnetic Properties of Granite Wash and Unweathered Granite," Geophysics, v. 13, p. 163.
- Thorarinsson, S., 1967, Surtsey: the New Island in the North Atlantic, trans. by Sölvi Eysteinnsson, New York: The Viking Press.
- Van Lopik, J. R., and Geyer, R. A., 1963, "Gravity and Magnetic Anomalies of the Sierra Madre, Texas 'Dome'," Science, v. 142, p. 45.
- Waters, A. C., and Fisher, R. V., 1970, "Maar Volcanoes," in Proceedings of the Second Columbia River Basalt Symposium, 1969, Cheney, Washington: Eastern Washington State College Press, p. 157.
- Williams, H., 1941, "Calderas and Their Origin," University of California, Dept. of Geol. Sci. Bull., v. 25, p. 239.
- Williams, H., and McBirney, A., 1968, Geologic and Geophysical Features of Calderas, NASA Progress Report.
- Woollard, G. P., 1968, "The Interrelation of the Crust, the Upper Mantle, and Isostatic Gravity Anomalies in the United States," in Crust and Upper Mantle of the Pacific Area, Knopoff, Leon, Drake, Charles, and Hart, Pembroke (eds.), Washington, D.C., American Geophysical Union, p. 312



