COLLAPSE DEPRESSIONS OF THE PINACATE VOLCANIC FIELD, SONORA, MEXICO*

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INTRODUCTION

The Pinacate region of northwestern Sonora, Mexico, is characterized by hundreds of cinder cones and basaltic lava flows. This volcanic field extends over an area of nearly 600 square miles between the Gulf of California and the International Boundary, and a small part of it projects northward into Arizona. Its northern half, though topographically irregular, lies at altitudes that exceed 1,000 feet in few places. Its southern half, in contrast, is dominated by the Sierra Pinacate, a great pile of lava flows and pyroclastic deposits that rises to a maximum altitude of 4,235 feet. So well preserved are the youngest parts of this pile that their volcanic origin was recognized by explorers as early as 1701 (Ives, 1942).

Contrasting strongly with the cinder cones and other volcanic forms of the area are seven calderas, long referred to as craters by the local residents, and a partially collapsed cone, known as Cerro Colorado, that appears to represent a diatreme. These features lie north of the Sierra Pinacate in a northwest- to west-trending arc about 20 miles long (fig. 60). Several of them have been briefly described by MacDougal (1908), Hornaday (1909), Lumholtz (1912), and others. Separate accounts of exploratory trips to Crater Elegante, largest of the calderas, have been published more recently (Henderson, 1951; Jahns and Fiedler, 1952; Kelley, 1952).

The substance of this brief paper has been drawn from the results of 28 days' field work and subsequent petrographic studies. The treatment is necessarily confined to generalizations and a few selected descriptions; fuller discussion of the collapse depressions, the rocks associated with them, their spatial and temporal relation-ships with adjacent features, and their genesis must await publication elsewhere.

GEOLOGIC SETTING

The Pinacate volcanic rocks occur within and upon a terrane of pre-Tertiary plutonic and metamorphic rocks. They also rest upon and interfinger with non-marine sediments of Quaternary age, extensively so in the northern parts of the field. A broad belt of dune sand borders the field on the west (fig. 34), and several other, more localized accumulations of such sand are present along its southern and eastern margins. Many ridges and small mountain masses of the older crystalline rocks buttress the volcanic section or project upward through it (figs. 34, 38), especially in the area north of the Sierra Pinacate, and it is clear that the pre-volcanic surface was one of considerable local relief.

Some of the volcanic section may date from late Tertiary time, but most is Quaternary in age. Eruptive activity apparently reached a maximum during the Pleistocene epoch, and continued at diminished levels thereafter. Eruptions have been observed since the region was first occupied by man, and a small outburst reportedly occurred as recently as January 1935 (Ives, 1935).

* Contribution No. 915, Division of the Geological Sciences, California Institute of Technology.

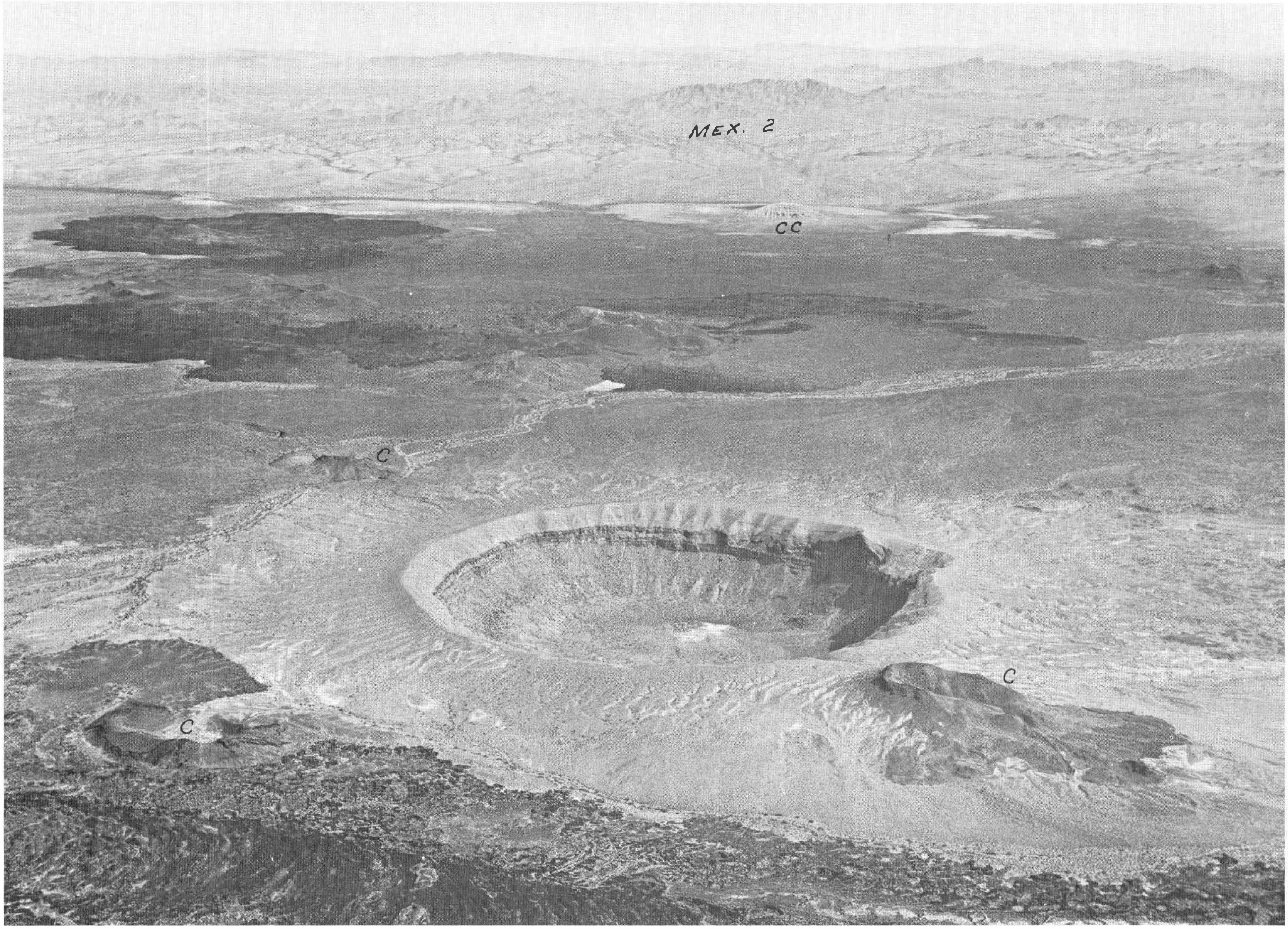

FIGURE 31. Northeastward aerial view of Crater Elegante and nearby remnants of breached cinder cones (C). Younger lava flows, very dark colored, are in foreground, middle distance, and farther distance to the left. Also in distance are Cerro Colorado (CC) and Mexico Route 2. Pacific Air Industries photo.

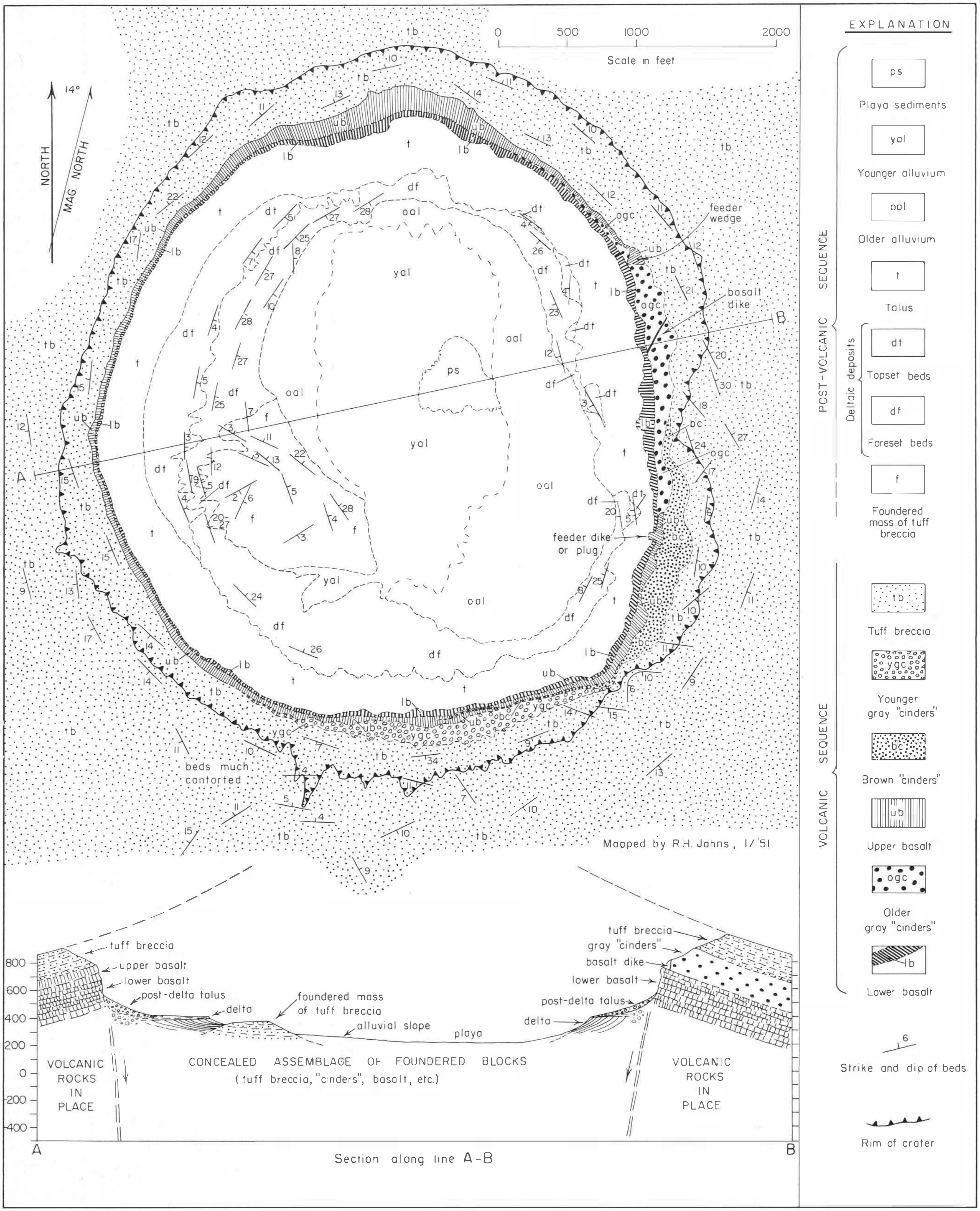

FIGURE 32. Geologic map and cross section of Crater Elegante.

The basalts occur chiefly as tongue- and sheet-like flows that range in average thickness from a few inches to as much as 30 feet. The average flow in the northern half of the field is 12 to 15 feet thick, is in part vesicular, includes some masses of flow breccia, and is dense to scoriaceous along its rough upper surface and irregular margins (figs. 31, 36, 38); departures from this average, however, are both considerable and common. Some flows are stacked, one upon another, to form sections many tens of feet thick. Others interfinger laterally, and still others are interlayered or intertongued with stratified sections of cindery ejecta in which pellets and bombs of juvenile material are very abundant. Both flow and pyroclastic sections are cut at many localities by plugs, dikes, and sills of basalt, breccia, and cindery material.

The basalts are holocrystalline to holohyaline, and crystalline types predominate. Most are 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 magnesian olivine, magnetite, and hypersthene. Sparse to very abundant phenocrysts of plagioclase and olivine commonly are set in a pilotaxitic or fluidal groundmass. Some spectacularly porphyritic flow and dike rocks are crowded with vesicles, pea-like crystals of olivine, and translucent to transparent tablets and thick chunks of plagioclase 1/4-inch to 5 inches long. Amygdaloidal calcite and epidote are moderately abundant in several of the lava flows.

Most of the pyroclastic material in the field is related to cinder cones, several hundred of which are prominent features of the present landscape. Their development represents a considerable span of time, and they show a wide range in degree of erosional modification (figs. 31, 34, 36, 38). Many are asymmetric, having been breached by columns of lava rising in their throats; most of the youngest exposed lava flows can be traced sourceward to cinder cones of this type.

The cinder cones are composed mainly of lapilli and bombs with rounded to clinkery surfaces. Both accessory and accidental ejecta also are present, and include scattered blocks of large size. Many of the essential and accessory fragments contain crystals of plagioclase, olivine, and magnetite in matrices of dense to highly vesicular glass. The cindery materials are loose-textured, even where appreciable amounts of interstitial ash are present. They form beds a fraction of an inch to about 20 feet thick; these range in gross color from medium to dark gray through greenish gray and buff to reddish brown.

COLLAPSE DEPRESSIONS

General features of the calderas

The principal calderas are steep-walled depressions with circular to broadly oval outlines, and from the air they appear as huge pock-marks on the rough face of the volcanic field. Each has a remarkably even rim from which the ground surface slopes moderately to gently outward, giving the impression of a low, flat-topped hill with wide and symmetrical shoulders when viewed from adjacent points on the ground. The depressions range in maximum diameter from 2, 500 to 5, 700 feet, in maximum depth from 120 to 800 feet, and in ratio of diameter to depth from 6:1 to nearly 25:1. Each marks the site of a volcanic cone that was considerably larger than any of the associated earlier cinder cones. Each has an almost flat floor, from the margins of which an essentially continuous apron of talus rises to the base of a cliffed wall; a moderate to steep slope extends upward from the top of this wall to the rim of the caldera (figs. 31, 34, 36).

FIGURE 33. Typical exposure of tuff-breccia "rim beds," Crater Elegante. The layering, though locally undulatory, is remarkably continuous. The large surficial fragments are weathered-out accessory blocks of dense to highly vesicular basalt.

The rocks exposed within the depressions can be divided into two contrasting sections. The older section is dominated by flows of cliff-making basalt, separated and overlain in many places by thin intervals and thicker but more lenticular bodies of cindery ejecta. These rocks represent a complex sequence of eruptive activity at each locality, but are not significantly different from rock types exposed elsewhere in the Pinacate volcanic field.

Quite different, on the other hand, are the well-stratified tuff breccias that compose the younger, or upper, section. These "rim beds" are an essential feature of all the calderas and the diatreme cone, but have not been found in genetic association with any other volcanic form in the entire field. They lap up and butt against the sides of nearby cinder cones and basalt flows (figs. 31, 34, 36), and in turn are overlapped by several basalt flows of very recent appearance (fig. 31).

The tuff breccias are fine to extremely coarse grained, and form very continuous layers whose thickness ranges from a small fraction of an inch to nearly 20 feet. They consist chiefly of glassy ash and lapilli, with abundant crystals, crystal-bearing pellets of glass, and small bombs of juvenile origin. Both accessory and accidental ejecta, which in many beds are dominant, include older lapilli, crystals, and bombs, as well as blocks of basalt and pre-Tertiary rocks such as granite, pegmatite, gneiss, schist, phyllite, quartzite, and vein quartz. Fragments 1 to 3 feet in diameter are common, and a few 15- to 18-foot blocks are present within the "rim beds" of at least three calderas.

Most of the tuff breccias are distinctly platy (fig. 33). Typically they dip away from the caldera rims in gross accordance with the exterior surface slopes. Many structural features, such as graded bedding, slump marks, and local ripple marks and cross bedding, suggest a fluvial environment. However, these features must be of aeolian origin, as the "rim beds" plainly were laid down by direct fallout of volcanic ejecta. This is attested by the great extent of even the thinnest beds, which can be traced individually for hundreds of feet within areas of favorable exposure, by the continuity of beds across many preexisting surface irregularities attributable to erosion and slumping, by similar continuity at places where the section reverses its dip and laps against older cinder cones, and by sedimentary structures in the finer-grained debris surrounding numerous bombs and blocks.

The youngest deposits within the collapse depressions include talus, alluvium, playa sediments, and windblown sand. These materials, whose aggregate thickness probably is not great, rest upon various masses of volcanic rocks that were dropped downward and jostled about during caldera formation, and effectively conceal most of them.

Crater Elegante

General features

Crater Elegante, most spectacular and best known of the calderas, is almost circular in gross plan, 4,300 to 5,500 feet in diameter, and 796 feet in depth as measured from the highest point on its rim. The lowest point on its floor lies slightly more than 200 feet above sea level. The erosional remnants of three older cinder cones are surrounded by its "rim beds", and a fourth cone is exposed in cross-section along the southeastern part of its walls (fig. 31). A younger lava flow lies nearby on the west and southwest, and others are present at greater distances to the north.

Volcanic rocks

"Rim beds" about 150 feet in average thickness are exposed in the upper parts of the caldera, and undoubtedly were much thicker in the higher parts of Elegante volcano prior to its collapse. They are yellowish to pale greenish gray and typically platy (fig. 33). The ashy matrices, are rich in fragments of vesicular basalt with sparse to moderately abundant phenocrysts. Along the south side of the depression these beds rest upon a broad lens of gray, loose-textured ejecta that evidently represent the partly buried cinder cone to the south (fig. 31). Along the east side they lie upon two older units of cindery ejecta that are parts of the buried cone now visible in cross-section on the caldera wall. The crater of this cone was once occupied by a small lava lake as much as 50 feet deep; the congealed remnant of the lake appears beneath a section of reddish-brown "cinders" and against a lower section of gray "cinders," and extends vertically downward in the form of a feeder dike or plug about 60 feet thick (fig. 32).

Along the other sides of the caldera the "rim beds" lie upon an irregular layer of scoria and basalt breccia with taffy-like flow structure. This in turn is underlain by several flows of basalt and basaltic breccia, ranging in individual thickness from a few inches to 22 feet, that commonly are separated by much thinner intervals of cindery pyroclastic materials. These rocks together constitute the upper basalt unit shown in figure 32. Some of the flows stemmed from the vent occupied by the feeder dike or plug noted above, others from a source marked by a large, wedge-like mass of basalt that transects the older section of gray "cinders" on the north-eastern part of the caldera wall. Intertonguing of these two sets of flows can be observed along the southern cliffs, where the relationships are complicated by the presence of several thin sills and dikes of similar basalt.

The lower basalt unit, which antedates all major exposed sections of pyroclastic materials, comprises cliff-making flows, 3 to 25 feet thick, and at least two much thinner sills. It consists of basalt -- some is fine- to medium-grained and dense to scoriaceous, and some is vesicular and porphyritic. None of this section can be correlated with exposed vents. Both the upper and lower basalt units appear to dip very gently outward; their inclination may well be less than that of the overlying "rim beds," and hence the concordant relationships suggested in the cross-section of figure 32 probably are much oversimplified.

A remarkable composite dike of basalt porphyry, 28 inches in maximum thickness, appears as a vertical spine projecting from the wall of older gray "cinders" on the east side of the caldera (fig. 32). It extends only a few feet into the underlying basalt, and lies below the "rim-bed" section. The nearly horizontal attitude of its crest and keel suggests that it may have been formed by outward, rather than upward, injections of magma from a source to the south-southeast. Some upward movement, however, is evidenced by local flow structures within the dike. All parts of the intrusive mass are vesicular and porphyritic in various degrees, and all contain phenocrysts of olivine and plagioclase. Its thin crestal portions are the finest grained and most vesicular. In contrast, one unit near its center contains chunky phenocrysts of transparent plagioclase as much as 4-1/2 inches long.

Younger deposits

Deltaic deposits of material derived from the "rim beds" and older volcanic rocks form a distinct bench about 200 feet above the caldera floor. The deposits are ring-like in their distribution within the caldera, but much of the bench is con-

FIGURE 34. West-northwestward aerial view of MacDougal Crater (center) and Molina Crater (foreground). Hornaday Mountains at right beyond MacDougal Crater, edge of Gran Desierto at left, and Mexico Route 2 in middle and right distance. Note cinder cones (C) in various stages of degredation. Pacific Air Industries photo.

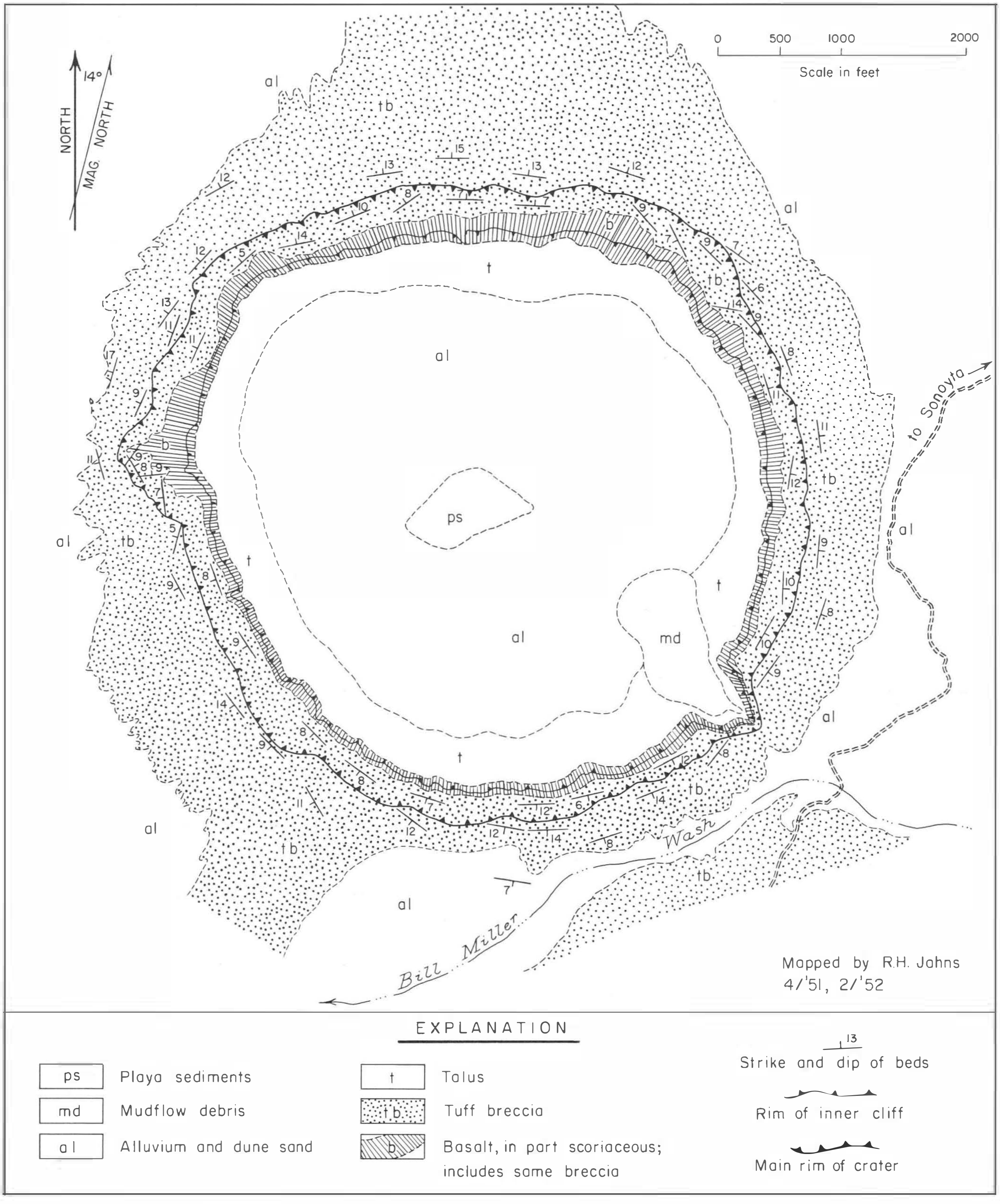

FIGURE 35. Geologic map of MacDougal Crater.

cealed by younger accumulations of talus. Its surface is uninterrupted along the western and northwestern sides of the depressions, where it is 120 to 200 feet wide. The deltaic foreset beds, which dip as much as 28 degrees toward the center of the caldera, are capped by very gently inclined and much coarser-grained topset beds. The entire assemblage consists of poorly lithified mudstone, fine- to coarse-grained sandstone, and gritty pebble conglomerate. Distributed throughout are irregular blocks of basalt derived from the nearby cliffs.

The delta evidently was developed along the margin of a lake that occupied the caldera soon after its collapse. The sediments appear to have been laid down upon foundered parts of Elegante Volcano and locally upon marginal aprons of talus; in most places they probably are in contact with down-dropped masses of "rim-bed" material. Erosion of foreset parts of the delta has exposed one of these masses on the southwestern side of the present floor (fig. 32). Occurrences of travertine and the consistent position of the deltaic deposits indicate that the lake must have been at a nearly constant level during most of its existence; in contrast, its recessional history probably was episodic, as suggested by the remnants of several narrow but well-defined topset benches at lower levels.

Post-lake erosion, chiefly of the lacustrine deposits, has been responsible for development of alluvial aprons and a thin section of playa sediments in the lowest parts of the depression. Alluvial accumulations of two ages can be distinguished, the younger having been derived in part from the older. The slight difference in their level may reflect minor readjustments among the underlying foundered masses, leading to some depression of the central part of the floor and subsequent trenching of the earlier post-lake alluvium. That readjustments and the progressive filling of voids are continuing at the present time is indicated by numerous shallow sink-holes and slump trenches on the floor of the playa. Some of these depressions are more than 100 feet long. Water penetrates so rapidly into the ground beneath the playa that ponding rarely persists for more than an hour or two, even after severe storms.

MacDougal Crater

MacDougal Crater, westernmost of the calderas, is 17 miles north-northwest of Pinacate Peak (fig. 60). It lies at the eastern margin of the Gran Desierto, a broad expanse of dune sand and isolated rock hills, and immediately south of the Hornaday Mountains, a small, elongate mass of pre-Tertiary crystalline rocks (fig. 34). The caldera is oval in plan, and ranges in diameter from 5,000 to 5,700 feet. The maximum depth of its almost flat floor is about 430 feet beneath the highest point on its east rim. Like Crater Elegante, it is flanked by the remnants of older cinder cones.

The yellowish-brown "rim beds" are platy to slabby, and in part are somewhat coarser and more gritty than those at Crater Elegante. They are rich in fragments of vesicular basalt and crystals of plagioclase and olivine. Also well represented among the rock constituents are granite, schist, phyllite, vein quartz, and friable aggregates of coarsely crystalline plagioclase, olivine, and magnetite. Separate crystals and crystal fragments of plagioclase constitute the bulk of some layers. The stratification of these tuff breccias is very continuous, and some of the layers are distinguished by aeolian cross bedding. Cut-and-fill structure is exposed on a small scale at many places.

The "rim-bed" section is 65 to 90 feet thick, and slopes gently outward from the edge of the caldera. It is covered to the west by dune sand, but is exposed over a wide, nearly flat area for at least a mile to the east and northeast. To the north and south the beds lap onto the shoulders of cinder cones, and elsewhere they are locally concealed beneath patches of alluvium and wind-blown sand.

No well-defined section of "cinders" is exposed within the depression. Instead, the "rim beds" lie upon a very rough surface that appears as a bench above a continuous series of basalt cliffs (fig. 34). Forming this surface is highly vesicular basalt, intimately associated with breccia and with lenses of cindery and clinkery material. These rocks are transected by numerous irregular, steeply-dipping dikes of fairly dense, porphyritic basalt. The dikes are a few inches to 12 feet thick, and their average exposed breadth is about 4 feet. Most are plainly composite. Their arch-like tops commonly project upward into basal parts of the "rim-bed" section. Thin stringers and tongues of reddish-brown "cinders" also transect the vesicular basalt and immediately overlying "rim beds."

The cliff-making parts of the basalt section resemble the corresponding units in Crater Elegante, except that sills, feeder dikes, and pyroclastic elements are less abundant. On the southeast wall of the caldera the basalt is shattered, much altered along both vertical and subhorizontal fractures, and locally mixed with reddish-brown cindery material. Some has been brecciated and cemented by anastomosing stringers of fine-grained basalt. These features suggest proximity to an old vent.

The floor of the depression, which is ringed by a steeply-sloping apron of coarse talus, consists of yellowish, sandy material derived mainly from the "rim beds," along with subordinate amounts of wind-blown sand. A small patch of playa sediments is present near the center of the floor. The brecciated and jointed basalts on the southeastern part of the caldera wall have yielded readily to erosion, and their position is marked by a distinct reentrant in the cliffs (fig. 35). Below this reentrant is a composite tongue of mudflow debris that lies upon the talus and alluvium of the floor. The crescentic, moraine-like terminations of two large debris flows mark the upper surface of the tongue.

Crater Grande (Sykes Crater)

Crater Grande, also known as Sykes Crater, is 3 miles east-northeast of Papago Tanks and about 13 miles north-northwest of Pinacate Peak (fig. 60). The depression lies in relatively high ground at the north end of the Rainbow Hills, a cluster of reddish-brown cinder cones, and it appears as a deep puncture between two of these cones (fig. 36). It is 3, 200 to 3, 500 feet in diameter, and 580 feet in maximum depth.

The "rim-bed" section is 90 to 125 feet thick. Lithologically it is much like that at MacDougal Crater, except that fragments of pre-Tertiary rocks are less abundant. The tuff breccias are unusually coarse grained along and near the rim, where they dip outward at angles as high as 30 to 38 degrees, and it seems clear that caldera formation spared a much larger portion of the pre-existing cone than at MacDougal Crater.

On the north and northwest sides of the depression, the "rim beds" rest upon two thick wedges of reddish-brown cindery ejecta that represent a cone whose crater, rim, and flanks are now exposed in cross-section (fig. 37). The pyroclastic material in turn overlies a continuous section, 8 to 45 feet thick, comprising 2- to 10-foot

FIGURE 36. Westward aerial view of Crater Grande (Sykes Crater) and the two cinder cones that flank it. The buried sides and crater of a third cinder cone (C) are exposed on the right-hand side of the main depression. Pacific Air Industries photo.

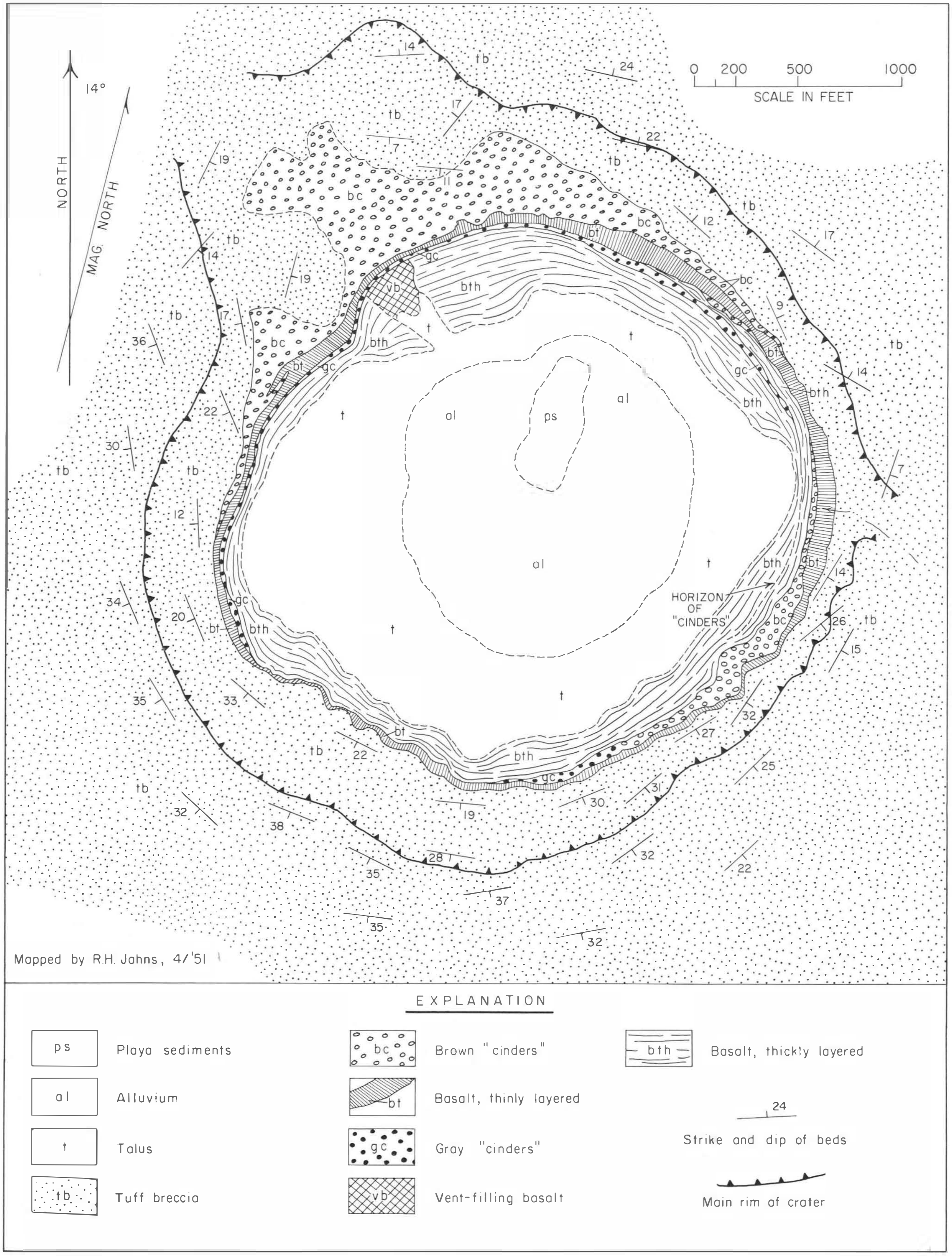

FIGURE 37. Geologic map of Crater Grande (Sykes Crater).

layers of vesicular basalt. This section, which appears to slope gently west-southwest, lies immediately beneath the "rim beds" along the southwestern, southern, and eastern sides of the depression. Below it is a lens of reddish-brown "cinders" that can be correlated with a cone nearby on the southeast, as well as a thinner layer of gray "cinders" whose source has not been established.

The oldest rocks on the caldera walls are dense to vesicular basalts, mainly thick flows intertongued with several thinner flows and still thinner layers of pyroclastic materials. One thick layer of gray "cinders," exposed on the northeast wall of the hole, also lies within this section. Some of the flows butt sharply against others, and the assemblage is further complicated by several feeder dikes and by one large, cross-cutting mass of vent-filling basalt (fig. 37).

The post-collapse deposits, in the lower parts of the caldera, include talus, alluvium, and playa sediments whose gross relationships are relatively simple.

Other calderas

The other four major calderas are shallower and in general smaller than Elegante, MacDougal, and Grande (fig. 60). Descriptions cannot be included in this paper, and a few notes on their most distinctive features are offered instead.

Molina Crater, a short distance southeast of MacDougal Crater, has a cloverleaf outline and evidently represents collapse about three closely related centers (fig. 34). Its "rim beds" are thick and in part very coarse grained. Fragments more than an inch in diameter constitute the bulk of some layers, and blocks more than 6 feet long are very abundant. These explosion breccias, whose coarser constituents are almost wholly accidental and accessory, contain much less ashy material than the "rim beds" at any other locality. They lie upon basalt, which is best exposed in the relatively small and deep northwestern hole within the cluster. Here are prominent cliffs, some of whose faces may be fault surfaces related to collapse of the former cone.

Badillo Crater is relatively shallow, with a relatively thin section of coarse-grained "rim beds." Its formation was preceded by a complex sequence of volcanic activity, involving development and breaching of at least three cinder cones revealed in section along its walls. Many alternations of effusive and pyroclastic activity are indicated in an exposed section less than 150 feet thick.

Kino Crater, least accessible of the larger depressions, is shallow and asymmetric in terms of wall height. A few exposures of earlier basaltic rocks appear beneath its "rim beds." This caldera provides unusually good evidence concerning the nature of collapse, thanks chiefly to the presence of recognizable faults that trend subparallel to its walls.

Celaya Crater, in relatively low ground approximately 8 miles west-northwest of Cerro Colorado (fig. 38), exposes about 100 feet of "rim beds" and an equal thickness of underlying basalts. It appears to represent preferential collapse about the more northerly of two closely-spaced centers of explosive activity. Its present floor is being aggraded by drainage from a broad area outside its rim.

Cerro Colorado

Cerro Colorado is a light reddish-brown hill that rises above a broad, nearly flat surface 15 miles northeast of Pinacate Peak. It is clearly visible from Mexico Route 2 about 5 miles to the north, and is accessible from this highway over 7 miles of unimproved road (fig. 60). The hill, about a mile in diameter at its base, actually is an asymmetric shell surrounding a moderately deep, flat-floored depression 2, 800 to 3, 500 feet in diameter (fig. 38). The gullied outer surface of this shell rises 50 to 360 feet above a wide, gently sloping circumferential apron of alluvium that merges with a playa surface along most of its outer margin.

The oldest rocks within the depression are exposed only along the western edge of its floor (fig. 39). They comprise ash, cindery ejecta, and fine-grained, highly vesicular basalt, in general crudely interlayered. This section may be correlative with a series of lava flows exposed a short distance west of the hill, or it may be somewhat older.

A younger volcanic sequence, consisting solely of tuff breccias, forms the entire hill. Its lowest unit, a pinkish, thinly-layered ash with scattered lapilli and bombs, is 35 feet in maximum known thickness. Above is a gravelly tuff breccia, about 45 feet in average thickness, whose distinctively flat gray color is due to a predominance of granitic and metamorphic rock types among its very abundant fragments. This unit is well exposed along the steep west, north, and northeast walls of the depression, where it is overlain by a thicker section of regularly and continuously stratified tuff breccia of light reddish-brown color. This material is much like that forming the "rim beds" of Crater Elegante, though somewhat finer grained. It is extensively exposed both inside the depression and on the relatively high southwest, south, and southeast exterior slopes of the hill, and is overlain unconformably by 25 to 40 feet of lithologically similar tuff breccia, the youngest unit of the volcanic sequence.

The youngest tuff breccia clearly was laid down after an episode of gully cutting on the exterior slopes and major collapse about one or more interior vents. On the south side of the hill, where the rim of the crater is preserved, these beds extend continuously over the top with an accompanying reversal of dip. Evidently they were plastered over the walls and irregular floor of an interior depression almost as large as the present one, with inclinations approaching the angle of repose. The depression had been formed by sloughing and downward movement of the older tuff breccias from the walls of an earlier crater, and no inward-dipping parts of this older section have been preserved at the levels of present exposure.

Following deposition of the youngest tuff breccia, additional collapse occurred within the earlier depression, deepening it and enlarging it slightly in northeastward and southwestward directions. Large parts of the inward-dipping blanket of youngest beds have survived on the northwestern and southeastern sides; where they lie with pronounced angular unconformity upon the older beds (fig. 40). The same horizon of unconformity, with numerous but highly localized angular relationships that reflect the filling of gullies, is exposed on the southerly exterior slopes of the hill, where the upper and lower tuff breccias have not been distinguished separately on the map (fig. 39).

Although Cerro Colorado is probably a very young feature, antedating only a few lava flows in this part of the volcanic field, it has been modified appreciably by erosion. The soft tuff breccias are being vigorously dissected on its outer slopes, and are contributing to aprons of talus and alluvium through gullying and cliff retreat inside the depression. One large mass of upper and lower tuff breccias, detached from the steep lower wall on the southeast side of the depression (fig. 39), has

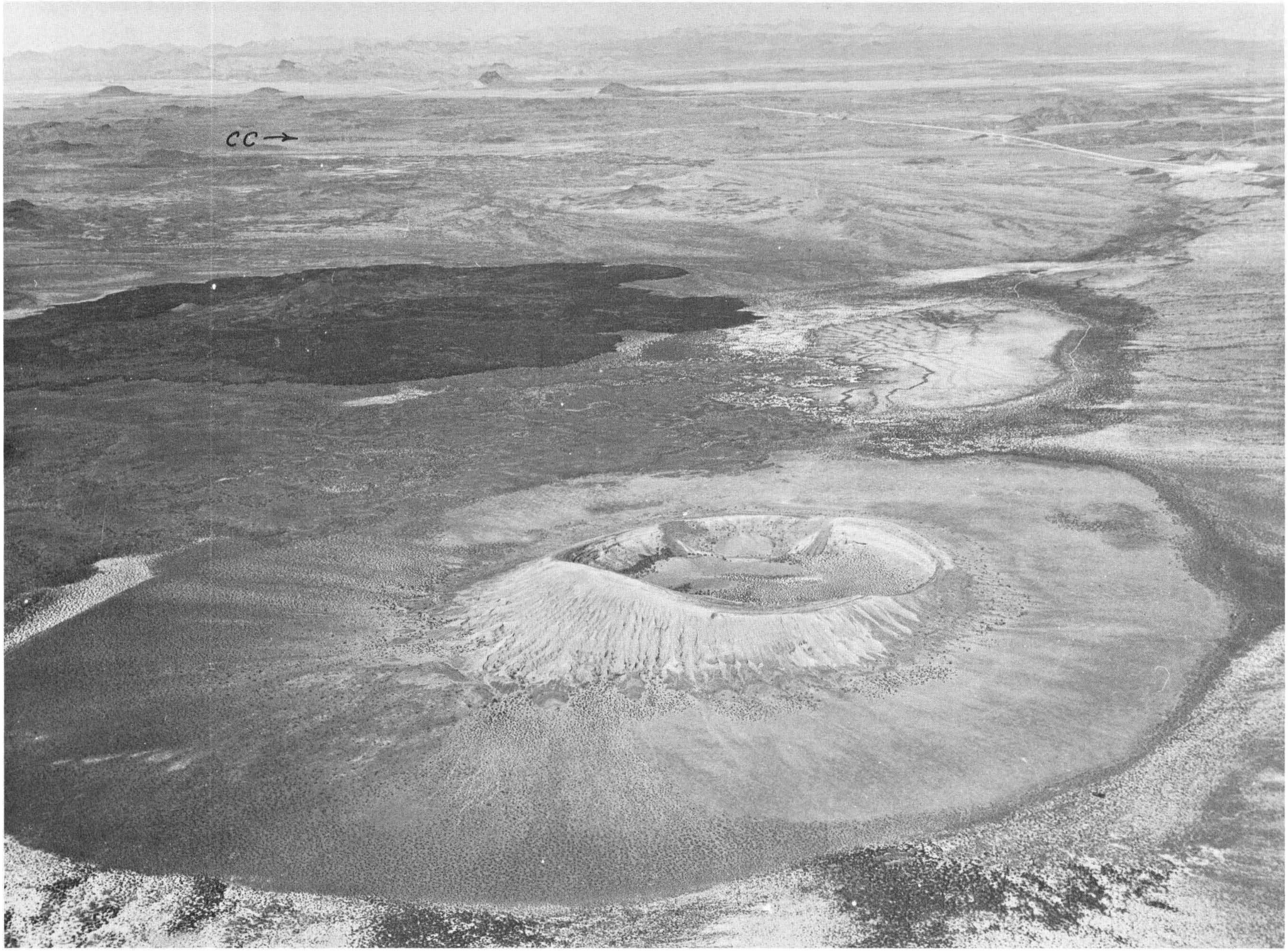

FIGURE 38. Northwestward aerial view of Cerro Colorado, its interior depression, and its broad circumferential apron of alluvium. A playa surface is encroached by dark-colored tongues of Recent basalt in middle distance. Celaya Crater (CC) in left distance. Pacific Air Industries photo.

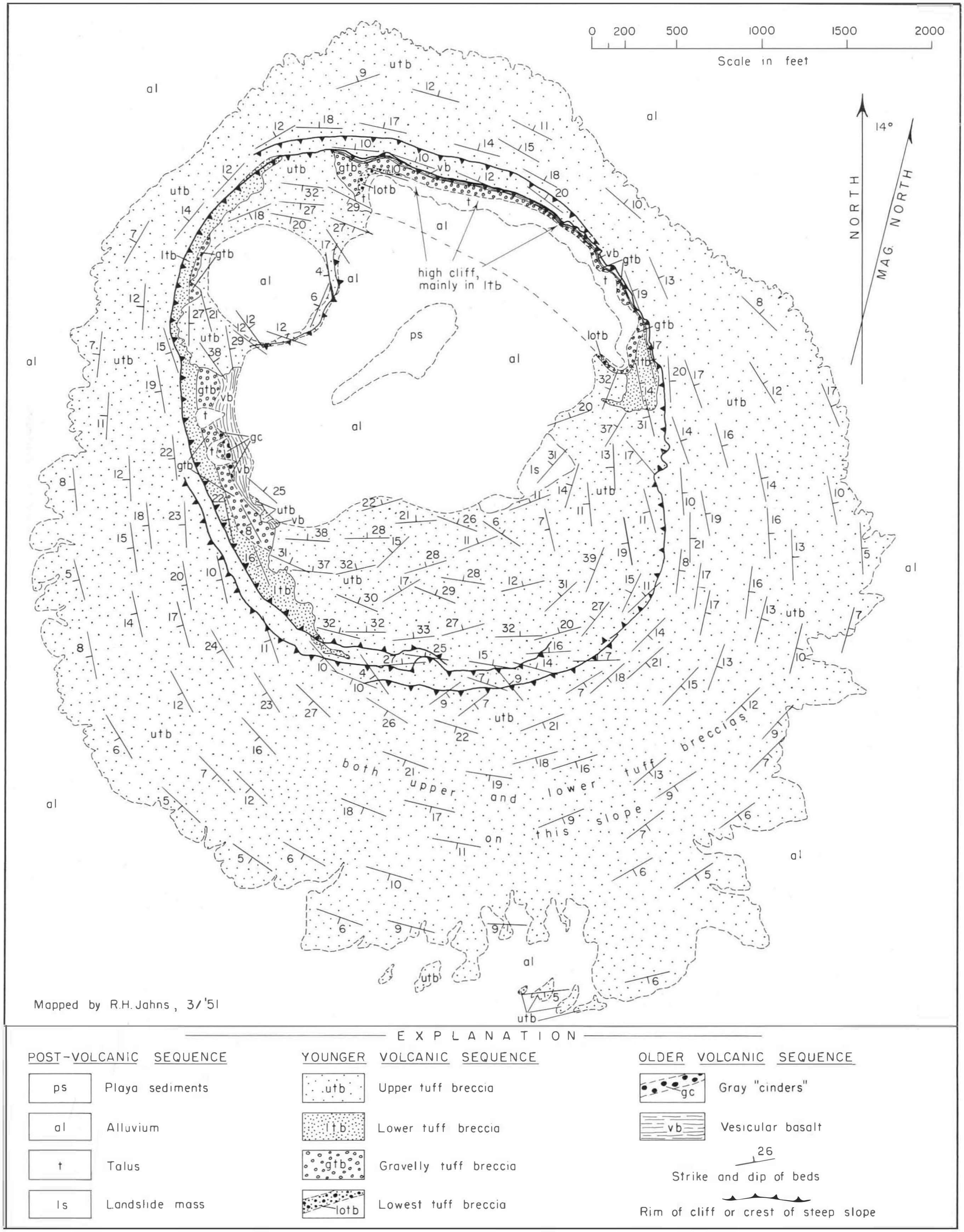

FIGURE 39. Geologic map of Cerro Colorado.

moved downward in very recent times. Small-scale adjustments within the broken material underlying the present floor of the volcanic center are reflected by shallow sinks and troughs on the playa surface.

ORIGIN AND AGE OF COLLAPSE DEPRESSIONS

Vents

Each of the eight major depressions attributed to collapse corresponds in position to an eruptive center at which both ash and coarser debris were blown out upon the surface to form a cone much larger than the typical cinder cones of the region. Dimensions of the inferred vent or vents through which these materials escaped cannot be established directly, but it seems likely that such a vent was larger than those giving rise to earlier cinder cones nearby. On the other hand, it probably was of considerably lesser diameter than the depression now occupying the same general site. Were it as large or nearly so, the aggregate volume of older volcanic rocks occurring as accessory fragments in its pyroclastic contributions should be at least as great as the volume of the present depression. The "rim-bed" sections, in which relatively fine-grained juvenile ejecta are the dominant constituents, are quite inadequate to account for such a volume.

It might be argued that the vents were very large at the surface, but tapered markedly downward in funnel-like fashion. If such upward enlargement did exist in a reasonable geometric form, it could not be ascribed mainly to explosive action, which should have detached an abundance of tuff breccia from the higher parts of the associated cones and deposited the material in surrounding areas. The existing "rim-bed" sections do contain fragments of tuff breccia that could have been derived in this manner, but such fragments are very sparse. It seems more reasonable to view any marked upward enlargement of the vents as caused principally by slumping and insliding of materials from their walls, both during and after eruption.

Nature of collapse

The composition of the "rim-bed" sections denies the existence of cylindrial vents or explosion pipes comparable in diameter to the present depressions, and hence it is reasonable to infer the former presence of tuff-breccia cones whose lower slopes are now preserved outside the rims of the depressions. That these cones did not "blow their tops" at some late stage of activity also is indicated by the lithology of the "rim beds." Instead, the upper portions of the cones must have disappeared through inward collapse and wholesale foundering. The downward movements, amounting to hundreds of feet in most of the occurrences, probably were confined within cylindrical zones of near-vertical faults, as suggested by the very steep faces of hard, resistant rocks on the walls of the depressions, by exposures of such faults at Kino Crater, and by the position of a very large mass of typical "rim beds" on the floor of Crater Elegante.

The Pinacate "craters" thus appear to be small but otherwise typical collapse calderas as definitively discussed by Williams (1941). The depression at Cerro Colorado might best be called a diatreme, as the features at this locality resemble, in many respects, those described from numerous diatreme occurrences, notably those in the Navajo-Hopi country of Arizona and New Mexico (e.g., Appledorn and Wright, 1957; Hack, 1942; Williams, 1936). Recently Shoemaker (1953) has emphasized progressive subsidence or collapse as an important element in the complex history of these forms, which are characterized by thick sections of water-laid sediments that filled funnel-like depressions.

Collapse also was important at Cerro Colorado, but it occurred in only two recognizable late-stage episodes and created depressions with initially steep walls that subsequently were modified by slumping and sliding. Moreover, infilling sediments are not very abundant and include relatively little water-laid material. The present depression might be appropriately termed a miniature caldera, although little can be inferred concerning its structural relationships at depth.

Causes of collapse

Foundering of the tuff-breccia cones is most readily attributable to the elimination of magmatic support at depth. The critical sequence at each locality probably commenced with development of a diatreme through explosive drilling of a vent in the rocks overlying a chamber of partly crystallized magma. With reduction in confining pressure the magma began to vesiculate briskly, to rise in the vent, and to "flash-off" its dissolved volatile constituents with increasing violence as it rose. At the surface a cone grew rapidly in response to repeated contributions of juvenile crystals, pellets of lava, and abundant basaltic froth, along with numerous fragments of older rocks torn from the walls of the conduit. This ultra-vesiculation of basaltic magma was truly catastrophic, and marked the end of positive volcanic action at each locality. Rapid evacuation of the magma reservoirs effectively removed support from beneath the cones and the platforms on which they were built, and subsequent foundering was inevitable.

This explosion-collapse theory, which has been applied to many of the world's calderas, is fully compatible with all observed relationships in the Pinacate occurrences. But why were caldera-making processes confined to only a few localities and to only one part of the volcanic field? As suggested by H. T. Stearns (personal communication, 1952), the distribution of groundwater within rocks overlying the magma chambers may provide the answer to this query. Vaporization and explosive escape of near-surface waters could have drilled initial vents and triggered-off the paroxysmal expulsion of underlying magma through sudden reduction in confining pressure on the chambers. This notion is made attractive by a general correspondence between the position of the caldera arc and the distribution of water-bearing Quaternary sediments that probably represent an ancient course of the Rio Sonoyta. In the opinion of Ives (1936), this stream once flowed westward across the area north of the Sierra Pinacate, and thence southwestward to a mouth at Bahia de Adair, on the Gulf of California (fig. 60). Subsequent damming by volcanic rocks may well have deflected it to its present course east of the Sierra Pinacate. There is little evidence to suggest that comparable accumulations of groundwater were present in the other parts of the volcanic field.

Age

The collapse depressions are younger than the nearby cinder cones and older than the most recent lava flows in the region. Although they may have developed at different times, all are of essentially the same general age. The former existence of a lake in Crater Elegante suggests that this depression dates back to a pluvial climatic stage, perhaps corresponding to late Wisconsin glaciation in more northerly latitudes. Radiocarbon determinations on organic material collected from sediments laid down in this lake (F. W. Galbraith, oral communication, 1959) should settle the question. Meanwhile, a tentative assignment of the calderas to the upper Pleistocene seems compatible with the degree to which their walls and exterior slopes have been modified by erosion. Cerro Colorado might be somewhat younger, and its latest collapse may have occurred in early Recent time.