Caldera-like collapse at Kilbourne Hole maar, New Mexico

William R. Seager

New Mexico Geology, v. 9, n. 4 pp. 69-73, Print ISSN: 0196-948X, Online ISSN: 2837-6420.
https://doi.org/10.58799/NMG-v9n4.69

This page is intentionally left blank to maintain order of facing pages.

New Mexico GEOLOGY
• Science and Service
Volume 9, No. 4, November 1987

Caldera-like collapse at Kilbourne Hole maar, New Mexico

by *William R. Seager*, New Mexico State University, Las Cruces, NM 88003

Introduction

Kilbourne Hole, one of a group of Pleistocene volcanic craters collectively known as the Afton craters, is located about 20 mi southwest of Las Cruces in south-central New Mexico (Fig. 1). Perhaps best known for its wonderful array of mantle and lower crustal xenoliths, Kilbourne Hole has yielded considerable information about the mantle and deep crust of southern New Mexico (e.g., Carter, 1965, 1970; Padovani, 1977; Padovani and Carter, 1977; Reid, 1976; Reid and Woods, 1979).

Geologic studies focusing on the origin of the ejecta blanket as well as on the crater began in 1907. In that year Lee (1907) interpreted both Hunt's Hole and Kilbourne Hole as explosion craters caused by ground water flashing to steam as the ground water was invaded by basaltic dikes. Darton (1916) supported Lee's hypothesis and compared the Afton craters to similar craters in Germany, India, Mexico, and at Zuni Salt Lake, New Mexico. In 1935, Dunham (1935) described Kilbourne Hole and also seemed satisfied with the explosion hypothesis for the origin of the crater. In the most detailed study up to 1940, Reiche (1940) rejected the explosion hypothesis, suggesting instead that the craters were formed by subsidence. However, Reiche (1940) believed that subsidence greatly postdated explosive volcanic activity and was only vaguely related to it. In fact, Reiche (1940) suggested that subsidence was caused either by subsurface solution of limestone promoted by acidified volcanic waters, or by a vague "volcanic subsidence" that occurred at the site of an older volcanic vent but long after the vent had become inactive and buried by hundreds of feet of "fluvial" deposits.

Since Reiche's (1940) paper was published, little more has been said about the role of subsidence in the formation of Kilbourne Hole. Shoemaker (1957) recognized evidence for explosive volcanic activity in the ejecta blanket that forms the crater rim, and, in a later paper (Shoemaker, 1962), he noted "the Afton craters . . . exhibit downfaulting or collapse along the crater wall," an apparent reference to the evidence that led Reiche (1940) to his subsidence hypothesis. De Hon (1965a, b) studied Hunt's Hole and Kilbourne Hole and found evidence of subsidence lacking. "A collapse origin may be dismissed . . . (because) inward dips are absent at the holes as are ring dikes; (the) raised rims are not explainable by a collapse mechanism" (De Hon, 1965a). De Hon (1965a, b) and Reeves and De Hon (1965) believed that phreatomagmatic explosions were responsible for the craters, although they did recognize the role of "down faulting or slumping, accompanied by normal backwasting of the wall" as pro- ☞

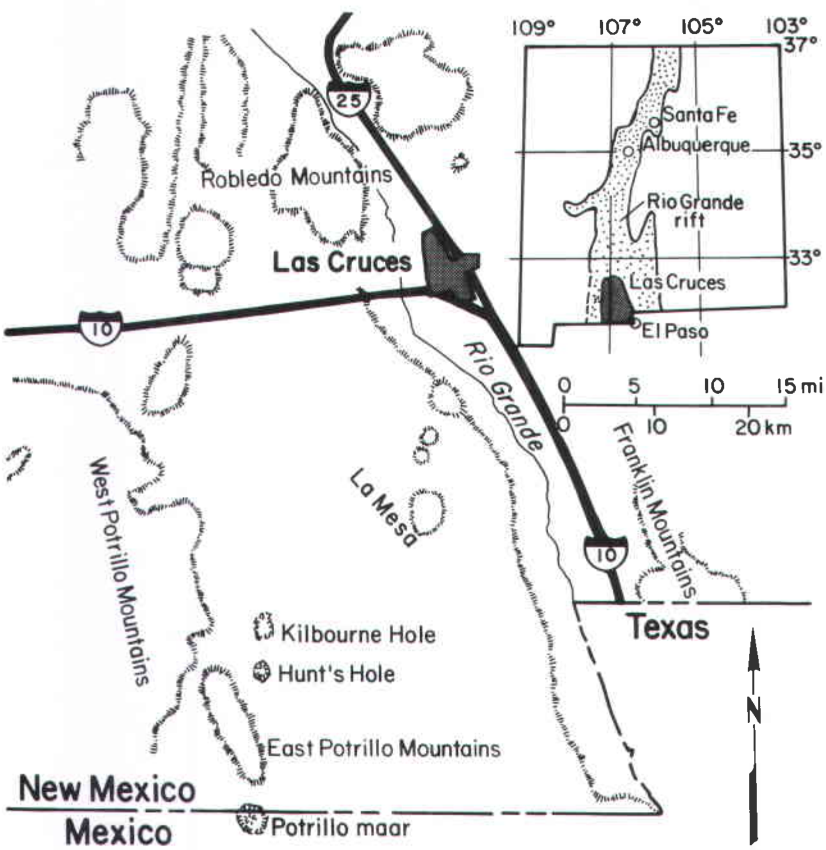

FIGURE 1—Location map of the Kilbourne Hole maar and vicinity.

Also in this issue

Coming soon

Castile and Salado Formations, Delaware Basin
Lower Cretaceous strata under southern High Plains
Mineral paragenesis and structure at the U.S. Treasury mine
Mineral Symposium abstracts

cesses that "enlarge the diameter and filled the craters" (De Hon, 1965b). Hoffer (1973, 1976, 1986) summarized the results of his and previous workers' studies of Kilbourne Hole and Hunt's Hole. Like others before him, except Reiche and probably Shoemaker, Hoffer apparently accepted the craters as products of phreatomagmatic explosions, with "normal backwasting and slumpage enlarging the crater to its present shape and size" (Hoffer, 1976). By evaluating De Hon's (1965a) alternative hypotheses for formation of Hunt's Hole, Stuart (1981) also concluded that volcanic explosion was most likely ("blasting during eruption could have pulverized rock, forming the crater"). Both Stuart (1981) and De Hon (1965a) visualized Hunt's Hole (and the other craters) as developing "passively," the result of "some form of coring or rasping by jets of sediment-laden stream (which) gradually formed the crater" (Stuart, 1981, p. 71).

Evidence presented in this paper supports the interpretation that major subsidence was an important process in the formation of Kilbourne Hole, and that the crater is therefore a maar in the sense of Lorenz (1973). The subsidence immediately or closely followed phreatomagmatic explosive activity and involved caldera-like collapse, along a ring fracture, of the tuff ring that had accumulated above and around the vent. The present dimensions of Kilbourne Hole are not so much a result of explosive excavation, slumping, landslides, and erosion as they are a product of large-scale subsidence of the tuff ring. Such caldera-like subsidence along ring fractures is an important part of the evolution of maars and diatremes in Mexico, France, Germany, Montana, and elsewhere (e.g., Jahns, 1959; Lorenz, 1973; Gutman, 1976).

General features

Kilbourne Hole is a roughly elliptical crater approximately 1.7 mi long along the major axis and a little more than 1 mi wide (Fig. 2). It is surrounded on all sides except the south by a prominent rim of ejecta that rises as much as 150 ft above the surrounding La Mesa plains and nearly 450 ft above the playa at the center of the crater floor. Although rim ejecta slopes moderately to gently outward away from the crater, the inner walls of the crater are generally steep or even vertical.

Figure 3 shows the stratigraphy exposed in the inner walls of the crater. Pre-explosion rocks form the lower half of the crater walls and include the Camp Rice Formation (Qcr) of early to middle Pleistocene age (Gile et al., 1981) overlain by Afton Basalt (Qb). Exposed Camp Rice strata consist of basin-floor bolson sediments and minor fluvial gravel containing multiple paleosols, including conspicuous caliche. The upper surface of the Camp Rice strata is the constructional La Mesa surface upon which the paleosols evolved since the surface stabilized approximately 0.5 Ma. (Gile et al., 1981). The Afton Basalt, as much as 15 ft thick, locally buried the La Mesa surface and Camp Rice For-

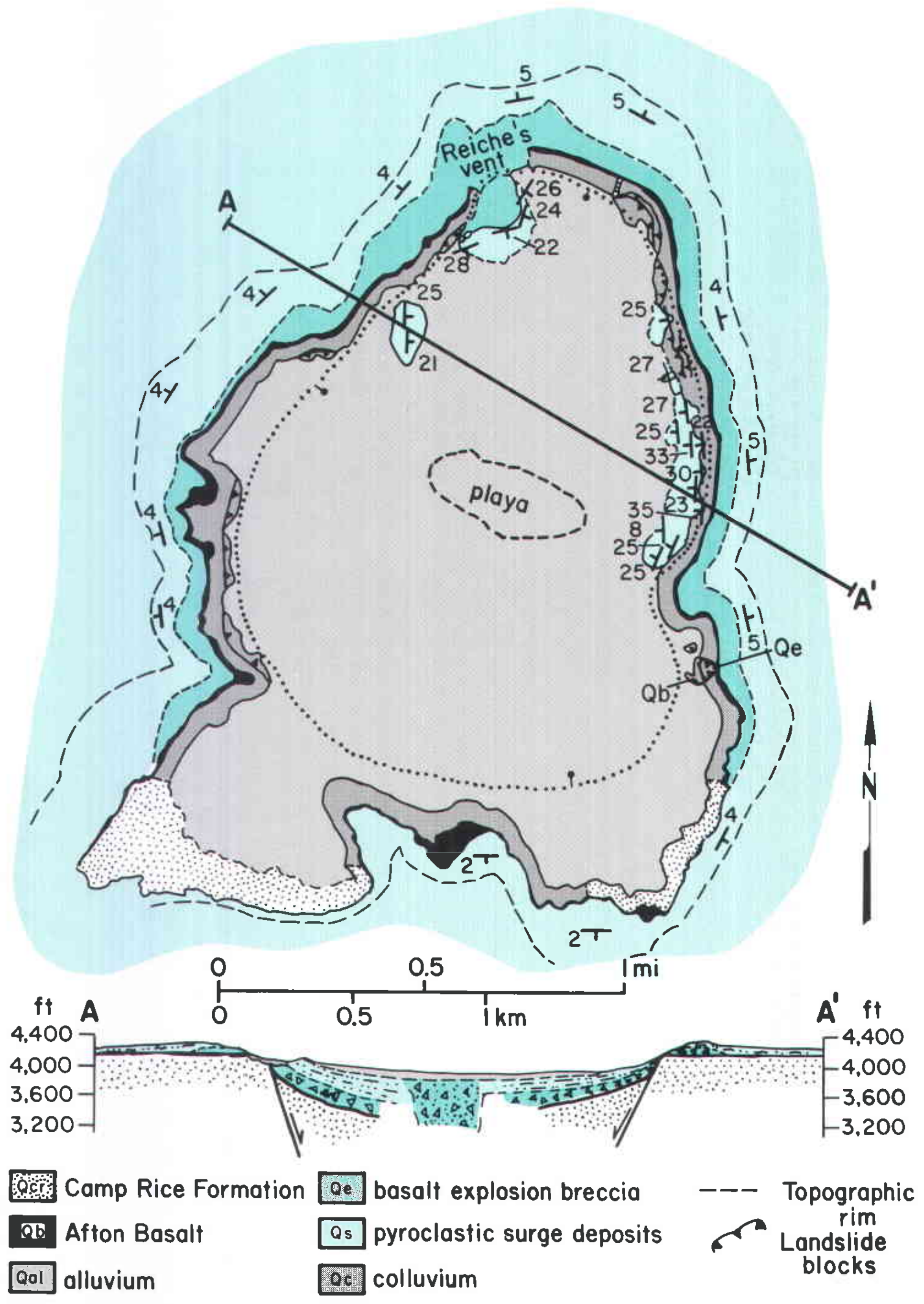

FIGURE 2—Geologic map and cross section of Kilbourne Hole. All units are Quaternary.

New Mexico GEOLOGY

• Science and Service

Volume 9, No. 4, November 1987

Editor: Deborah A. Shaw
Drafter: Monte M. Brown
Published quarterly by
New Mexico Bureau of Mines and Mineral Resources
a division of New Mexico Institute of Mining & Technology

Subscriptions: Issued quarterly, February, May, August, November; subscription price $6.00/calendar year.

Editorial matter: Articles submitted for publication should be in the editor's hands a minimum of five (5) months before date of publication (February, May, August, or November) and should be no longer than 20 typewritten, double-spaced pages. All scientific papers will be reviewed by at least two people in the appropriate field of study. Address inquiries to Deborah A. Shaw, Editor of *New Mexico Geology*, New Mexico Bureau of Mines & Mineral Resources, Socorro, NM 87801

Circulation: 1,600

Printer: University of New Mexico Printing Plant

mation before formation of Kilbourne Hole. The basalt has yielded radiometric dates ranging from 0.5 m.y. to about 0.1 m.y. (Seager et al., 1984; Hoffer, 1976; Hawley and Kottlowski, 1969). Based on soil development, Gile (1987) believes the basalt is approximately 0.1 m.y. old.

Tuff-ring ejecta overlies the Afton Basalt and forms the upper half of the crater wall, as well as the rim and back slopes. De Hon (195b), Hoffer (1976), Brenner (1979), Stuart and Brenner (1979), and Stuart (1981), give detailed descriptions of the stratigraphy, and Wohletz and Sheridan (1983) provide an excellent summary. In general, the rim ejecta can be divided into two units. The basal unit, first described by Reiche (1940), is an explosion breccia that varies in thickness from 0 to 150 ft, averaging 70 ft thick. The breccia consists of angular blocks of basalt up to 5 ft in diameter in a matrix of essentially unbedded, chaotic pyroclastic-fall deposits. The basalt blocks are fragments of the Afton Basalt disrupted by the eruption. Other accidental clasts in the breccia include mantle and lower and upper crustal xenoliths up to 1.5 ft in diameter. Much of the breccia matrix appears to be disaggregated sand and gravel from underlying bolson deposits. Minor pyroclastic-fall deposits with graded bedding have also been described within or at the base of the explosion breccia (Hoffer, 1976; Stuart, 1981; Wohletz and Sheridan, 1983).

The upper part of the rim ejecta consists largely of much finer grained, thinly bedded pyroclastic-surge and fall deposits that are 100 ft thick or more on the east rim. Reiche (1940) interpreted these strata to be fluvial in origin, but Shoemaker (1957), Hoffer (1976), Brenner (1979), Stuart and Brenner (1979), and Stuart (1981) have shown them to be the deposits of base surges and air fall. The strata exhibit beautiful sandwave structures and "repeated alternations in bedding from seams of coarse air-fall juvenile basaltic lapilli" to finely bedded sandwaves to massive beds with abundant accretionary lapilli (Wohletz and Sheridan, 1983). The abundance of juvenile lapilli increases upward. Occasional basalt blocks or xenolith bombs are associated with sag structures in the section. The uppermost 10 ft of rim deposits are unstratified, slightly palagonitized fine ash that De Hon (1965b) interpreted to be lahar deposits, but which Stuart (1981) recognized, at least at Hunt's Hole, as bioturbated, massive tuff.

According to Wohletz and Sheridan (1983), the stratigraphy suggests that "opening eruptions were dominantly low-energy strombolian ones that distributed fragments of the capping basalt flow and juvenile material toward the north and east. Subsequent eruptions became Surtseyan and ejected dominantly reworked alluvial material from the underlying Santa Fe Group (Camp Rice and older formations) in highly inflated surges. These opening Surtseyan eruptions cleared the vent and excavated the large crater. As eruptions progressed, the proportion of juvenile material in them increased. Final eruptions were weakly Surtseyan, producing wet, massive beds of ash that moved downslope as lahars."

The age of Kilbourne Hole is late Pleistocene. It is clearly younger than the Afton Basalt, which has yielded conflicting age estimates between 0.5 and 0.1 Ma. If Kilbourne Hole is approximately the same age as Potrillo maar, a very similar structure located on the Mexico–USA border 14 mi south–southwest of Kilbourne Hole, then an age of 180,000 years is indicated. This date is based on a radiometric date from a late-stage basaltic flow on the floor of Potrillo maar (Seager et al., 1984). On the other hand, Gile (1987) estimates the age of Kilbourne Hole to be approximately 24,000 years, based on the extent of pedogenic carbonate development in soils of the rim ejecta.

Evidence for caldera-like collapse

Although most previous workers (except Reiche and perhaps Shoemaker) visualized Kilbourne Hole crater being "excavated" by Surtseyan-type explosive blasts, there are two lines of evidence that favor caldera-like collapse as the most important process in forming the present crater. The first is the presence of large downfaulted masses of tuff-ring material located at the base of the inner crater wall and beneath the crater floor. The second is the small volume of pyroclastic material in the maar rim and on the La Mesa plains compared to the volume of the crater.

Perhaps the most compelling evidence for subsidence of the tuff ring is the downfaulted pyroclastic strata within the crater. These downfaulted strata were also recognized by Reiche (1940) and constituted his basis for emphasizing the subsidence origin for Kilbourne Hole. The downfaulted tuff-ring strata are exposed along the northwestern, northern, and northeastern inner walls of the crater (Figs. 2 and 4), through an arc of nearly 180°. Elsewhere the subsided mass presumably underlies the crater floor but is hidden by alluvium.

The subsided beds are mostly correlative with the thinly bedded surge and fall deposits that compose the upper part of the rim ejecta, although basal explosion breccia constitutes part of the subsided mass at the northern edge of the crater. Relative to the same strata in the maar rim, the downfaulted pyroclastic deposits have subsided a minimum of 350 ft. This has resulted in the crater floor being 200 to 300 ft lower than the surrounding La Mesa plains, clear evidence for subsidence (Cas and Wright, 1987).

Observed dips of strata in the sunken block range from 8 to 35°, and all dips are centroclinal, toward the center of the crater (Figs. 2 and 4). Steepest observed dips are at the edges of the subsided mass at the crater wall, becoming flatter toward the center of the crater. Thus, available strike and dip data suggest that the subsided block is saucer-shaped in three dimensions. There is no evidence that stratal dips are the product of draping of pyroclastic debris across a pre-existing crater wall. Rather, faulting and tectonic rotation are indicated by the upbending and especially by the truncation of strata at the lower crater wall.

The ring fault that presumably borders the subsided mass is nowhere visible because of the thick colluvial apron of basalt blocks that mantle the lower slopes of the crater wall. In the northern part of the crater, however, the fault can be confidently placed in the lower part of the crater wall beneath the Afton Basalt (Figs. 2 and 4). In this area it is clear that the fault is a simple fracture rather than a wide, complex zone. No fault, except the ring fracture, disrupts the continuity of either the Afton Basalt or the downfaulted pyroclastic beds. In fact, along the eastern margin of the crater, nearly continuous outcrops of in- ☞

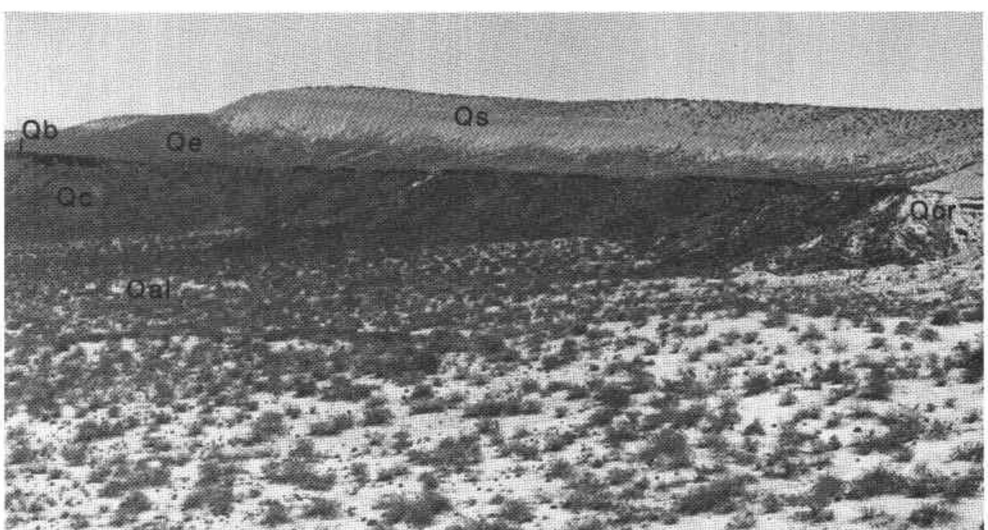

FIGURE 3—Eastern part of crater wall and rim of Kilbourn Hole looking north. **Qcr,** Camp Rice Formation; **Qc,** colluvium; **Qb,** Afton Basalt; **Qe,** basalt explosion breccia; **Qs,** pyroclastic surge deposits; **Qal,** alluvium.

ward-dipping, but unbroken, tuff-ring strata can be traced for 0.5 mi (Fig. 4). Seemingly, very large parts, if not all of the crater floor, subsided as an unbroken, saucer- or cone-shaped unit along a ring fracture (Fig. 2, cross section). The inward dips of strata suggest insufficient room at depth to accomodate the subsiding mass, which indicates that the ring fracture dips inward, having the geometry of a downward-tapering cone.

Although the hypothesis of subsidence of a large, cone-shaped block is consistent with outcrop data in the northern part of the crater, the extensive alluvial cover in the central and southern part of the crater may hide evidence of a much more complex mode of subsidence. Furthermore, the position of the ring fault in the southern part of the crater is speculative (Fig. 2).

A second, less certain line of evidence favoring subsidence at Kilbourne Hole is the small volume of ejecta compared to the volume of the crater. If the crater were excavated by explosions, the volume of accidental material in the ejecta should approximately equal the volume of the crater. Lorenz (1973) suggests that because of the juvenile component of the ejecta apron, the volume of material erupted from maars (before collapse) normally exceeds that of the crater. Calculations from Kilbourne Hole indicate that the volume of the crater below the pyroclastic-fall deposits is on the order of 6×10^{-2} mi^3 and the volume of the pyroclastic rim deposits is approximately 1.5×10^{-2} mi^3. If one assumes another 1.5×10^{-2} mi^3 of pyroclastic debris was blown away to the northeast (pyroclastic deposits are thicker and more widespread on the northeastern side of the crater, presumably because of dispersal by northeasterly blowing winds) and dispersed across the La Mesa plains, then a total of 3.0×10^{-2} mi^3 of pyroclastic material was ejected during the explosive phase of the volcano. Much of this was juvenile material from a deep source and not a result of excavation of the crater. Consequently, the volume of the ejecta, especially accidental ejecta, seemingly falls far short of filling the crater as it must if the crater is to be excavated entirely by phreatomagmatic explosions. Subsidence must have played a major role in the formation of the crater.

Summary and discussion

The evidence favors the evolution of Kilbourne Hole first as a typical phreatomagmatic tuff ring (Lorenz, 1973; Wohletz and Sheridan, 1983) and finally as a small caldera—a maar (Lorenz, 1973). The Kilbourne Hole rim deposits, as well as pyroclastic strata in the subsided block, all exhibit characteristics typical of a tuff ring rather than a tuff cone (Wohletz and Sheridan, 1983). Consequently, it seems likely that phreatomagmatic explosions initially constructed a low, broad ring of ejecta. The size of the vent associated with the tuff ring must have been considerably smaller than the modern crater, and presumably now lies buried beneath the central crater floor (Fig. 2, cross section). Caldera-like subsidence followed all explosive activity at the vent; presumably the subsidence was caused by loss of support for the tuff ring. At this point, typical development of maar structure was complete (Fig. 5). Toreva-style slumping of the inner crater wall is obvious in many places (Fig. 2), and the southern wall, where it is unprotected by the Afton Basalt (Qb), may have been eroded back from its original position. These processes of "normal backwasting," however, have been minor in the formation of the crater compared to caldera-like collapse.

Kilbourne Hole is not unique in exhibiting subsidence as a part of the evolution of a phreatomagmatic eruption. Craters in the Eifel district of Germany are thought to be true maars produced by caldera-like subsidence because in most craters the volume of the existing ejecta does not equal the volume of the crater (Frechen, 1951, 1962; Noll, 1967; Lorenz, 1973). Maars of Seneze, France, also show evidence of prolonged subsidence by their ring faults and thick lake deposits encountered by the drill beneath the crater floor (Lorenz, 1973). In the Pinacate field of northwestern Sonora, Mexico, Cerro Colorado and Kino Crater and particularly Crater Elegante are wonderful examples of the role large-scale subsidence plays in the formation of maars (Jahns, 1959; Gutman, 1976). Arcuate, concentric faults and fault blocks, exposed along the perimeter of Zuni Salt Lake maar, New Mexico, indicate subsidence was also important in the development of that structure (Shoemaker, 1962; Bradbury, 1967; Cummings, 1968; Wohletz and Sheridan, 1983). Hearn (1968) has shown that subsidence of 330 to 3,300 ft characterize the kimberlitic diatremes of Montana. Lorenz (1973) observed that "this clearly indicates that surface expression (of the diatremes) must have been wide craters formed by subsidence. These craters must have appeared as maars or tuff rings modified by caldera-like collapse (Francis, 1970)."

What causes foundering of large-scale blocks during the formation of a maar? Withdrawal of magma back down the plumbing system of the volcano is an obvious possibility as is evacuation of magma chambers during eruption (Jahns, 1959). Woolsley et al. (1975) have shown by model experiments that large-scale subsidence of vent wall rock can follow or proceed concurrently with maar formation and is a natural consequence of the gas-coring and vent-conduit enlarging process that opens eruption chambers at depth by attrition and spalling of wall rock. In the case of the Montana diatremes, where subsidence was repeated and obviously concurrent with a long interval of diatreme formation, the Woolsley et al. (1975) model applies nicely. The model also probably applies well to Kilbourne Hole and many other maars, although in scarcely eroded maars the cause of subsidence is hardly obvious. It may involve evacuation of a magma chamber by drainage or eruption as well as by the probable predominant mechanism of mechanical enlargement of the eruption chamber by gas coring, attrition, and spalling at depth.

ACKNOWLEDGEMENTS—I thank John Hawley, Bob Osburn, and Mike McCurry for their thoughtful and constructive reviews of this article. I am also grateful to Lee Gile for providing me with preprints of his papers on the soils and chronology of events at Kilbourne Hole.

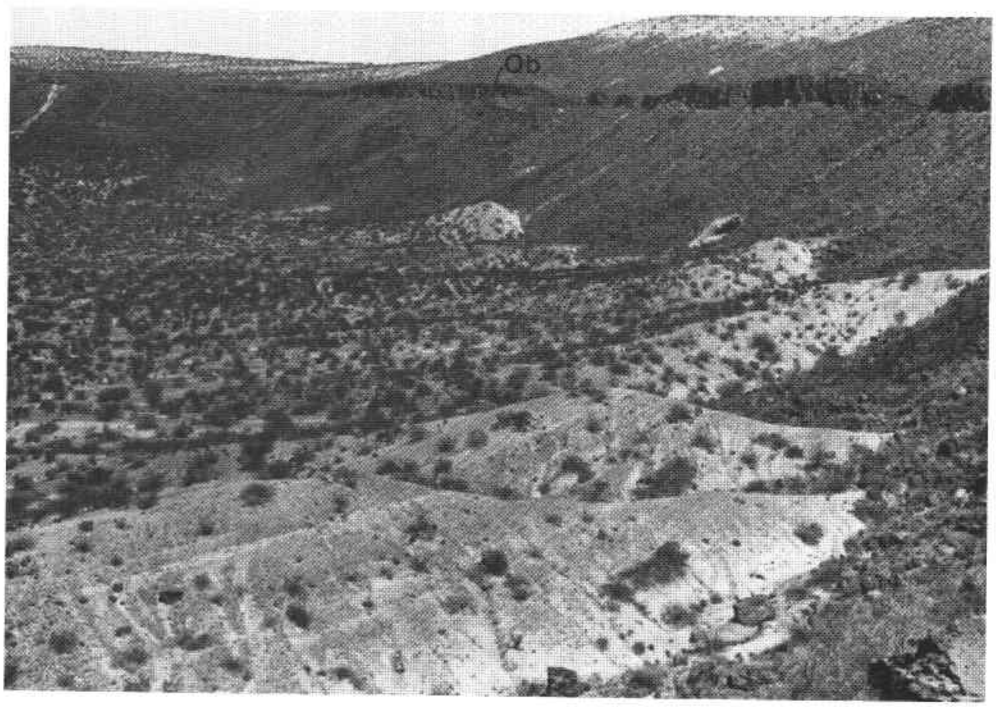

FIGURE 4—Downfaulted tuff-ring surge and fall deposits along base of northeast wall of Kilbourne Hole looking north. Ring fault occurs in basalt-strewn slope between Afton Basalt (**Qb**) and downfaulted, light-colored surge deposits. Note westward (left) dip of surge deposits toward center of crater.

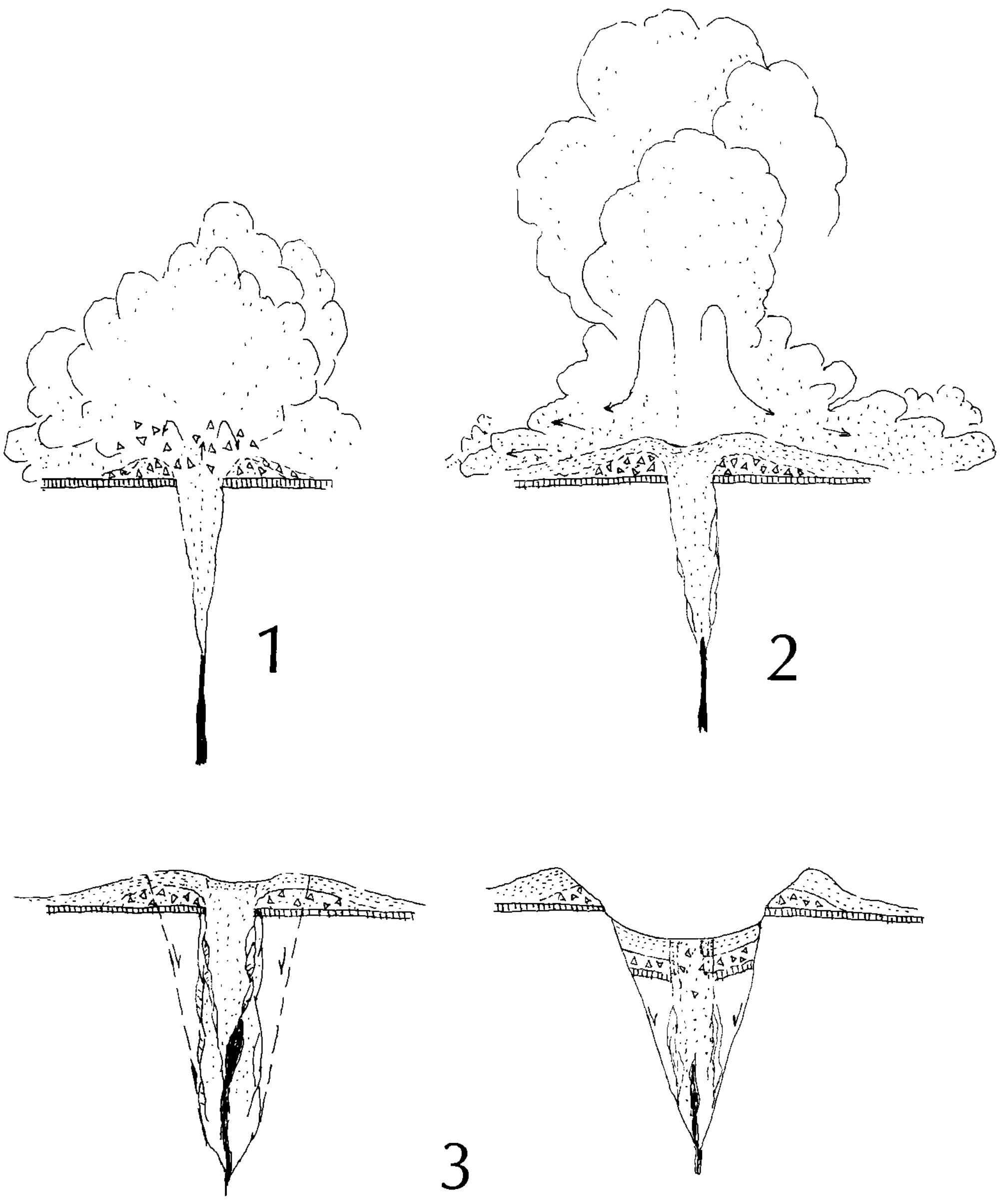

FIGURE 5—Diagrammatic evolution of Kilbourne Hole. **1)** Initial perforation of Camp Rice Formation and Afton Basalt and formation of basalt explosion breccia; **2)** formation of tuff-ring through accumulation of pyroclastic-surge deposits during Surtseyan-type eruptions; **3)** caldera-like collapse of part of tuff ring to produce the maar structure. The modern crater has been widened somewhat by slumping and erosion, and the crater floor has been buried to a great extent by alluvium.

References

Bradbury, J. P., 1967, Origin, paleolimnology, and limnology of Zuni Salt Lake maar, west-central New Mexico: Unpublished Ph.D. dissertation, University of New Mexico, Albuquerque, 247 pp.

Brenner, M. G., 1979, Sedimentary features in base surge tuffs, Kilbourne Hole, Potrillo Mountains, Doña Ana County, New Mexico (abs.): Geological Society of America, Abstracts with Programs, v. 11, no. 6, p. 267.

Carter, J. L., 1965, The origin of olivine bombs and related inclusions in basalts: Unpublished Ph.D. dissertation, Rice University, Houston, Texas, 264 pp.

Carter, J. L., 1970, Mineralogy and chemistry of the earth's upper mantle based on the partial-fusion partial-crystallization model: Geological Society of America Bulletin, v. 81, pp. 2021–2034.

Cas, R. A. F., and Wright, J. V., 1987, Volcanic successions, modern and ancient: Allen and Unwin, Boston, pp. 376–382.

Cummings, D., 1968, Geologic map of the Zuni Salt Lake volcanic crater, Catron County, New Mexico: U.S. Geological Survey, Miscellaneous Investigations Map I-544, scale 1:6000.

Darton, N. H., 1916, Explosion craters: Scientific Monthly, v. 3, pp. 417–430.

De Hon, R. A., 1965a, A maar origin for Hunt's Hole, Doña Ana County, New Mexico: Unpublished M.S. thesis, Texas Tech University, Lubbock, Texas, 70 pp.

De Hon, R. A., 1965b, Maare of La Mesa: New Mexico Geological Society, Guidebook to 15th Field Conference, pp. 204–209.

Dunham, K. C., 1935, The geology of the Organ Mountains with an account of Doña Ana County: New Mexico Bureau of Mines and Mineral Resources, Bulletin 11, 272 pp.

Francis, E. H., 1970, Bedding in Scottish (Fifeshire) tuff pipes and its relevance to maars and calderas: Bulletin Volcanologique, v. 34, pp. 697–712.

Frechen, J., 1951, Die Vulkane der Westeifel; *in* Hopmann, M., Frechen, J., and Knetsch, G. (eds.), Die Vulkanische Eifel: Georg Fisher Verlag, Wittlich, pp. 50–77.

Frechen, J., 1962, Führer zur Vulkanologisch-petrographischen Excursionen im Siebengebirge am Rhein, Laacher Vulcanarbeit, und Maargebiet der Westeifel: Schwartzbart, Stuttgart, 151 pp.

Gile, L. H., 1987, A pedogenic chronology for Kilbourne Hole, southern New Mexico—II. Time of the explosions and soil events before the explosions: Soil Society of America Journal, v. 51, pp. 746–760.

Gile, L., Hawley, J. W., and Grossman, R. B., 1981, Soils and geomorphology in the Basin and Range area of southern New Mexico—guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 pp.

Gutman, J. T., 1976, Geology of Crater Elegante, Sonora, Mexico: Geological Society of America Bulletin, v. 87, pp. 1718–1729.

Hawley, J. W., and Kottlowski, F. E., 1969, Quaternary geology of the south-central New Mexico border region; *in* Kottlowski, F. E., and LeMone, D. V. (eds.), Border stratigraphy symposium: New Mexico Bureau of Mines and Mineral Resources, Circular 104, pp. 89–115.

Hearn, C. B., Jr., 1968, Diatremes with Kimberlitic affinities in north-central Montana: Science, v. 159, pp. 622–625.

Hoffer, J. M., 1973, Kilbourne Hole: El Paso Geological Society, Guidebook 7, pp. 16–22.

Hoffer, J. M., 1976, Geology of Potrillo basalt field, south-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 149, 30 pp.

Hoffer, J. M., 1986, Hunts Hole; *in* Hoffer, J. M. (ed.), Geology of south-central New Mexico: El Paso Geological Society, Guidebook, pp. 9–10.

Jahns, R. H., 1959, Collapse depressions of the Pinacate volcanic field, Sonora, Mexico: Arizona Geological Society, Guidebook II, pp. 165–184.

Lee, W. T., 1907, Afton craters of New Mexico: Geological Society of America Bulletin, v. 18, pp. 211–220.

Lorenz, V., 1973, On the formation of maars: Bulletin Volcanologique, v. 37, pp. 183–204.

Noll, H. 1967, Maare und maar-ähnliche Explosionskrater in Island. Ein Vergleich mit dem Maarvulkanismus der Eifel: Sonderveroffentlichung des Geologisches Institut der Universität Köln, n. 11, pp. 1–117.

Padovani, E. R., 1977, Granulite facies xenoliths from Kilbourne Hole maar and their bearing on deep crustal evolution: Unpublished Ph.D. Dissertation, University of Texas (Dallas), Richardson, Texas, 172 pp.

Padovani, E. R., and Carter, J. L., 1977, Aspects of the deep crustal evolution beneath south-central New Mexico; *in* The earth's crust: American Geophysical Union, Geophysical Monograph 20, pp. 19–55.

Reeves, C. C., Jr., and De Hon, R. A., 1965, Geology of Potrillo maar, New Mexico and northern Chihuahua: American Journal of Science, v. 263, pp. 401–409.

Reiche, P., 1940, The origin of Kilbourne Hole, New Mexico: American Journal of Science, v. 238, pp. 212–225.

Reid, J. B., 1976, Upper and lower limits to the geothermal gradient beneath the southern Rio Grande rift (abs.): Geological Society of America, Abstracts with Programs, v. 8, no. 5, p. 621.

Reid, J. B., and Woods, G. A., 1979, Oceanic mantle beneath the southern Rio Grande rift: Earth and Planetary Science Letters, v. 41, pp. 303–316.

Seager, W. R., Shafiqullah, M., Hawley, J. W., and Marvin, R., 1984, New K–Ar dates from basalts and the evolution of the southern Rio Grande rift: Geological Society of America Bulletin, v. 95, pp. 87–99.

Shoemaker, E. M., 1957, Primary structures of maar rims and their bearing on the origin of Kilbourne Hole and Zuni Salt Lake, New Mexico (abs.): Geological Society of America Bulletin, v. 68, p. 1864.

Shoemaker, E. M., 1962, Interpretation of lunar craters; *in* Zdenck Kopal (ed.), Physics and astronomy of the moon: Academic Press, New York, 538 pp.

Stuart, C. J., 1981, Hunt's Hole maar volcano, Doña Ana County, south-central New Mexico; in Geology of the border, southern New Mexico–northern Chihuahua: El Paso Geological Society Guidebook, pp. 64–72.

Stuart, C. J., and Brenner, M. G., 1979, "Low regime" base surge dunes—an example from Kilbourne and Hunt's Holes, south-central New Mexico (abs.): Geological Society of America, Abstracts with Programs, v. 11, no. 7, p. 525.

Wohletz, K. H., and Sheridan, M. F., 1983, Hydrovolcanic explosions—II; *in* Evolution of basaltic tuff rings and tuff cones: American Journal of Science, v. 283, pp. 385–413.

Woolsley, T. S., McCallum, M. E., and Schumm, S. A., 1975, Modelling of diatreme emplacement by fluidization: Physics and Chemistry of the Earth, v. 9, pp. 29–42. □