lifts in experimental craters are significantly smaller in diameter than the craters themselves, so the originial crater at Sierra Madera, now destroyed by erosion, was probably larger than 5 km in diameter. Similarly the Vredefort crater must have been larger than 60 km (*23*), rather than 40 km as proposed by Daly and Dietz (*24*).

H. G. WILSHIRE
KEITH A. HOWARD
U.S. Geological Survey, Menlo Park, California 94025

References and Notes

1. The term cryptoexplosion structure was introduced by R. S. Dietz [*J. Geol.* **67**, 496 (1959)] to denote formation by some violent event without bias toward terrestrial or extraterrestrial cause; it describes the same structures as does Bucher's term cryptovolcanic structure.
2. W. H. Bucher, *Int. Geol. Congr. 16th* (1936), vol. **2**, p. 1055; *Amer. J. Sci.* **261**, 597 (1963).
3. J. D. Boon and C. C. Albritton, Jr., *Field Lab.* **5**, 1 (1936).
4. R. S. Dietz, *Trans. Lunar Geol. Field Conf. Bend, Oregon* (1966), p. 25.
5. N. M. Short, *J. Geol. Educ.* **14**, 149 (1966).
6. Sierra Madera is being studied in detail jointly by us, D. Cummings (Occidental College), and T. W. Offield (U.S. Geological Survey). The generalized geologic map includes also work by E. M. Shoemaker, R. E. Eggleton, and L. C. Rowan (U.S. Geological Survey).
7. R. E. Eggleton and E. M. Shoemaker, *U.S. Geol. Surv. Profess. Paper 424-D* (1961), p. 151.
8. P. B. King, *Univ. Texas Bull. 3038* (1930), pp. 1–167; H. G. Wilshire, D. Cummings, T. W. Offield, K. A. Howard, in *Program Geol. Soc. Amer. 1967 Ann. Meeting* (1967), p. 239.
9. P. B. King (*8*) originally thought that the tightly folded Permian rocks were overlain by gently domed Lower Cretaceous rocks, and hence that Sierra Madera was formed by two distinct periods of deformation, one earlier than Cretaceous and one after early Cretaceous time. It was later shown [E. M. Shoemaker and R. E. Eggleton, in *U.S. Geol. Surv. Astrogeol. Stud. Ann. Progr. Rep. 25 August 1962 to 1 July 1963* (1964), p. 98] that Permian and Lower Cretaceous rocks are similarly deformed, and that Sierra Madera formed some time after deposition of Lower Cretaceous rocks.
10. K. A. Howard and T. W. Offield, *Science*, this issue.
11. W. I. Manton, *Ann. N.Y. Acad. Sci.* **123**, 1017 (1965); J. G. Ramsay, discussion of paper by R. B. Hargraves, *Trans. Geol. Soc. S. Africa* **64**, 147 (1961).
12. C. W. Wilson, Jr., and R. G. Stearns, "Geology of the Wells Creek structure, Tennessee," *Tenn. Div. Geol.*, in press; R. G. Stearns, H. A. Tiedemann, C. W. Wilson, Jr., *Tenn. Dept. Conserv. Geol. Map Erin Quad. GM 38-SW* (1967).
13. D. J. Milton and P. R. Brett, in *Program Geol. Soc. Amer. Ann. Meeting Cordilleran Sect. Tucson* (1968), p. 82.
14. F. G. Snyder and P. E. Gerdemann, *Amer. J. Sci.* **263**, 465 (1965).
15. G. C. Amstutz, *Eclogae Geol. Helv.* **52**, 904 (1960).
16. E. B. Bailey, *Geol. Mag.* **63**, 481 (1962); L. T. Nel, *The Geology of the Country around Vredefort* (South Africa Department of Mines Industry, Pretoria, 1927), pp. 9–130; P. B. King, *Univ. Texas Bull. 3038* (1930), pp. 1–167; E. W. Bishopp, *Trans. Geol. Soc. S. Africa* **44**, 1 (1942); K. L. Currie, *Ann. N.Y. Acad. Sci.* **123**, 915 (1965); P. D. Lowman, Jr., *ibid.*, p. 1182.
17. C. E. Prichard and T. Quinlan, *Bur. Mineral Res. Australia Rep. 61* (1962), pp. 1–39; P. D. Lowman, Jr., *Ann. N.Y. Acad. Sci.* **123**, 1182 (1965).
18. D. J. Milton and P. R. Brett noted that centripetal movement rules out formation by explosion with a focus at depth [in *U.S. Geol. Surv. Astrogeol. Studies Ann. Progr. Rep. 1 July 1966 to 1 October 1967* (1967), p. 33].
19. G. C. Amstutz, *Trans. Kansas Acad. Sci.* **67**, 343 (1965); *Ann. N.Y. Acad. Sci.* **123**, 876 (1965); R. H. Zimmermann and G. C. Amstutz, *Neues Jahrb. Mineral. Monatsh.* **1965**, 9, 288 (1965).
20. "Central uplift" is restricted to materials uplifted from beneath the crater floor; the more general term central peak includes also mounds formed of materials derived from above the crater floor.
21. A. D. Rooke, Jr., and T. D. Chew, *U.S. Army Corps Eng. Waterways Sta. Misc. Paper I-764* (1965), pp. 1–61; C. H. Diehl and G. H. S. Jones, *Suffield Exp. Sta. Tech. Note 187* (1967), pp. 1–23; D. J. Roddy, *Trans. Amer. Geophys. Union* **49**, 272 (1968).
22. W. S. Partridge and H. B. VanFleet, *Astrophys. J.* **127**, 416 (1959); O. G. Engel, *Director Mater. Processes U.S. Air Force Systems Command Tech. Rep. WADD-TR-60-475* (*2*) (1962), pp. 1–51; A. M. Worthington, *A Study of Splashes* (Macmillan, New York, 1963); F. H. Harlow and J. P. Shannon, *J. Appl. Phys.* **38**, 3855 (1967); F. H. Harlow and J. P. Shannon, *Science* **157**, 547 (1967).
23. That the Vredefort dome is the central uplift of a structural basin some 160 km across is implied by D. W. Bishopp, *J. Geol.* **70**, 500 (1962); R. B. Hargraves, *Trans. Geol. Soc. S. Africa* **64**, 158 (1961); R. D. C. Gallant, *Nature* **197**, 38 (1963).
24. R. A. Daly, *J. Geol.* **55**, 125 (1947); R. S. Dietz, *ibid.* **69**, 499 (1961).
25. Publication authorized by the Director, U.S. Geological Survey. We thank Warren Hamilton, P. B. King, D. E. Stuart-Alexander, and D. E. Wilhelms, U.S. Geological Survey, for critical review of the manuscript.

22 May 1968; revised 9 August 1968

Shatter Cones at Sierra Madera, Texas

Abstract. *Shatter cones abound in the central uplift of Sierra Madera and they occur as far as 6.5 kilometers from the center. Apical angles average near 90 degrees. Whole cones and full cones represented by diversely oriented cone segments in any structural block show relatively uniform orientations of axes and a dominant direction of point. The cones predate faulting and folding in the central uplift, and, when beds are restored to horizontal, most cones point inward and upward, a pattern that supports the hypothesis of an impact origin.*

Shatter cones (*1–3*), recognized in at least 18 cryptoexplosion structures, have been considered presumptive evidence of shock resulting from meteoritic impact. In the Sierra Madera structure (*4*) they are well developed in slightly to highly deformed Permian sedimentary rocks (*2, 4, 5*). These and deformed Cretaceous rocks form a pronounced central uplift surrounded by an alluviated structural depression that is bounded by a circumferential system of normal faults upthrown on the outside. This fault system defines a circular structure 12 km across, outside of which are only mildly deformed Cretaceous rocks of Edwards Plateau. Deformation and upward stratigraphic displacement increase markedly inward, from the structural depression, toward a central zone in the uplift where dips are steep or overturned and Permian rocks have been uplifted as much as 1200 m (*4, 5*). Figure 1a shows the generalized geology of the hill exposing the central uplift; a rock column is shown in Fig. 2.

The shatter cones at Sierra Madera as elsewhere are conical fracture surfaces with characteristic striae that fan outward from the apex in "horsetail" fashion (Fig. 3). The striae are sharp grooves between intervening rounded and broader ridges; they are straightest, most regular, and best developed in fine-grained rocks; in coarser rocks they are coarser and less detailed. Away from the apex, the surface of a cone is built up by parasitic cone segments successively overlapping like shingles. Whole cones, and clusters of whole cones having a common axial orientation, are found in places (Fig. 3a), but segments or partial cones (Fig. 3b), which may intersect at high angles, are more common. Cone segments may have any orientation relative to bedding; in several places, particularly in aphanitic dolomite, they are preferentially developed on joint and bedding surfaces so that in outcrop they may be developed almost exclusively on two or three sets of such subplanar surfaces. Some whole cones are asymmetric, having one side longer than the other.

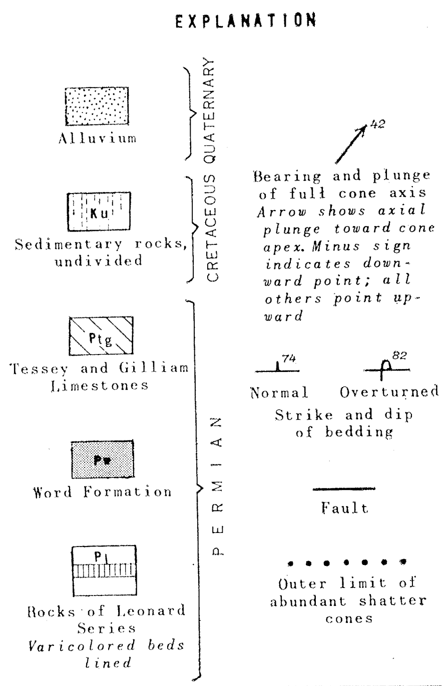
Shatter cones are found in all the exposed Permian formations; Fig. 1a shows their outer limit of abundance on the central hill. The distribution of cones inside that limit is very irregular, apparently because lithology is an important factor in their formation; fine-grained and brittle rocks appear to be most favorable. Thus cones are most common in aphanitic and dense marly dolomite (Fig. 3, a and b), are present in crystalline dolomite, siltstone, fine-grained sandstone, and calcareous chert, are least common in limestone, and do not occur in coarse-grained sandstone. They may, however, be abundant in a particular rock type at one place and not developed at all in virtually the same lithology at another place; they occur locally in shattered and finely brecciated dolomite.

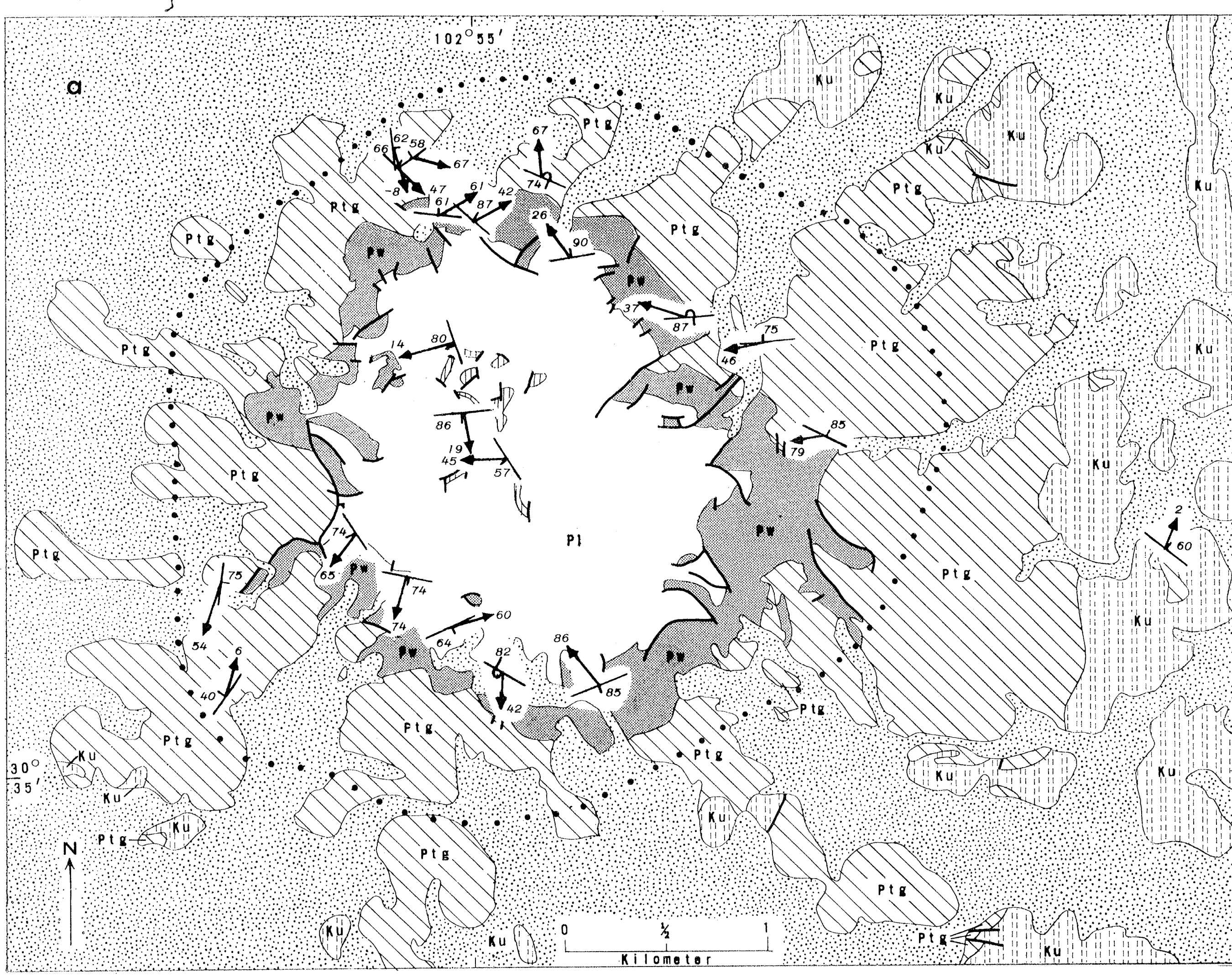
Whole cones vary in height from less than 2 mm to 12 cm, so that the sides are 2 mm to 17 cm long, but incomplete cone segments are typically larger and may be as long as 45 cm. Even in a single bed with 3-cm whole cones, cone segments reach 10 cm in length. For any given rock type, cones are more abundant toward the center of the structure but show no change in range of size. Along the outer limit of abundant shatter coning (Fig. 1a), the cone segments typically are 5 cm long in aphanitic dolomite, as long as 12 cm in marly dolomite, and as long as 20 cm in sandy siltstone; in like rocks near the center they are of comparable size.

The rocks in which shatter cones are most abundant also have generally the smallest cones. This lithologic control of size of shatter cones is illustrated in the Gilliam Limestone where sandy layers with 20-cm cone segments and finely crystalline dolomite beds with 5-cm cone segments are in direct contact. Another example is an outcrop of Word Formation, a few meters across, where fine sandy dolomite contains a few cone segments 9 cm long; marly dolomite layers contain abundant well-developed cone segments 5 cm long, but crystalline dolomite, limestone, and medium-grained sandstone contain no cones. Aphanitic marly dolomite of the Gilliam contains cones as small as 2 mm; the longest cone segments are in sandy dolomite of Word Formation (up to 35 cm) and limestone of the Leonard Series (up to 45 cm).

Shatter cones are not present in Cretaceous rocks at Sierra Madera, even where they are in contact with marly dolomite of Tessey Limestone containing abundant cones. Unfavorable lithology, combined with distance from the center, may explain the lack of cones in aphanitic-to-medium-grained Cretaceous limestone, and lithologic control is a reasonable explanation of the absence of cones from the basal Cretaceous sandstone, for similar medium-to-coarse-grained sandstones in the Permian Word Formation and Leonard Series also lack cones.

Most shatter cones are found within 2 to 4 km of the center of the structure (Fig. 1a). Outside the distribution limit shown, however, are several occur-





rences in uppermost Tessey dolomite near the east and south margins of the map. The most distal locality is in Tessey dolomite that was driven upward as a small slice into Cretaceous strata along a fault beyond the field of the map, on the outer perimeter of the structure, 6.5 km southeast of its center.

Cones also occur at depth. Cuttings from a well drilled within 0.5 km of the center of the structure reveal undoubted cone segments to a depth of 1600 m—1300 m stratigraphically below the top of the Permian. Possible cone segments are found from lower cuttings throughout the rest of the hole to 3600 m—3100 m stratigraphically below the top of the Permian.

Axes of whole cones in clusters have a nearly common orientation in any outcrop (Fig. 3a). In exposures showing only segments of cones (Fig. 3b), measurement of many striae shows that the segments are incomplete parts of cones having a common orientation, and that they define a common cone axis, even though the segments themselves are at large angles to one another (*3*).

Each measured striation at an outcrop was plotted (*3*) on a lower-hemisphere stereographic projection with the direction of point indicated (Fig. 4). Most plots resulted in a circular pattern corresponding to a conical arrangement of striae. A small circle was drawn through the points, and from this the cone axis and apical angle were determined. Where the cone axis plunged gently, the points were rotated so that the estimated axis of the cone lay in the center of the plot, and the arc defined by the striae was not broken by the edge of the projection. Figure 4a shows a typical plot from cone segments, in comparison with striations measured on a single whole cone (from a different locality) (Fig. 4b).

On average, 26 striae per locality were measured [far fewer than Manton used (*3*)], except for three localities in which whole cones were measured directly; we found that cone geometry could be reasonably estimated from as few as eight striae. The data were considered usable if the points defined an arc greater than 200 degrees and if 60 percent or more of the points lay within 10 degrees of the selected circle (that is, defining apical angles within 20 degrees of that selected). In only one-fourth of the instances were the arcs less than 270 degrees; in two-thirds, 80 percent of the points lay within 10 degrees of the selected circle, and, in one-third, all points lay within 10 degrees.

In order to check the accuracy of use of relatively few striae, about one-third of the points were selected at random from two localities and plotted, and the results were compared with results from more complete data. Thus it was estimated that discrepancies between our apical angles and cone axes, and those yielded by many more measurements,

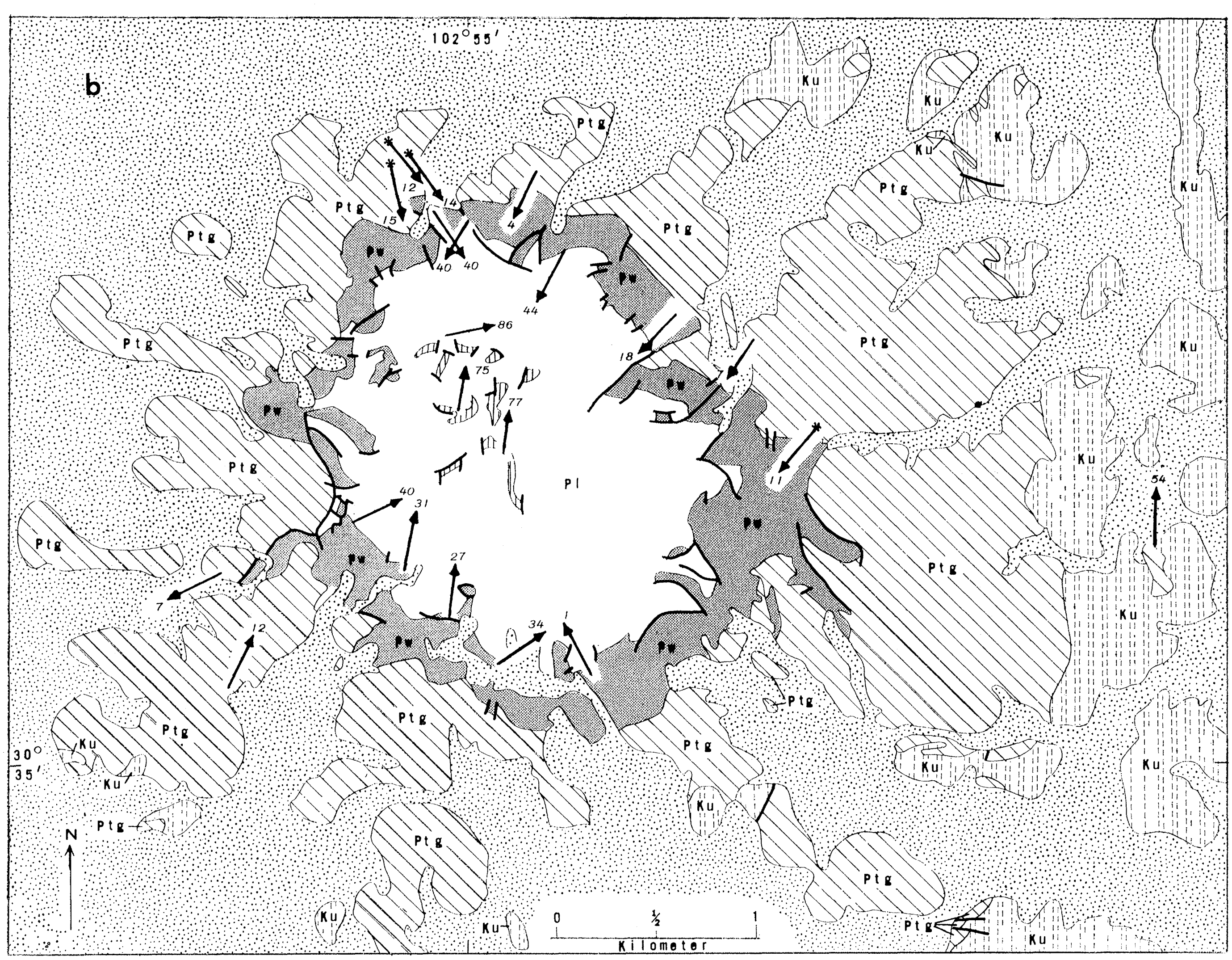


Fig. 1 (pages 262 and 263). Generalized geologic map of central hill. (a) Orientation of shatter cones *in situ*. (b) Orientation after restoration of beds to horizontal.

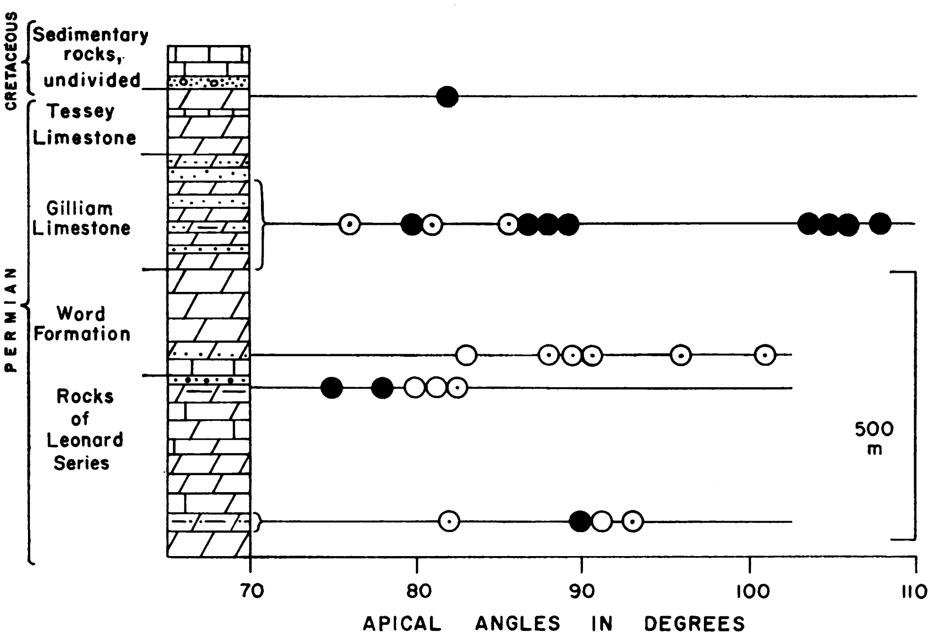


Fig. 2. Apical angles of shatter cones, measured at various stratigraphic levels. Each measured apical angle is represented by a symbol showing rock type: dotted circles, siltstone or sandstone; solid circles, aphanitic or marly dolomite; open circles, crystalline dolomite. Rock-column symbols: rectangular brick, limestone; slanted brick, dolomite; circles, conglomerate; dots, sandy or sandstone; dashes, shaly or marly.

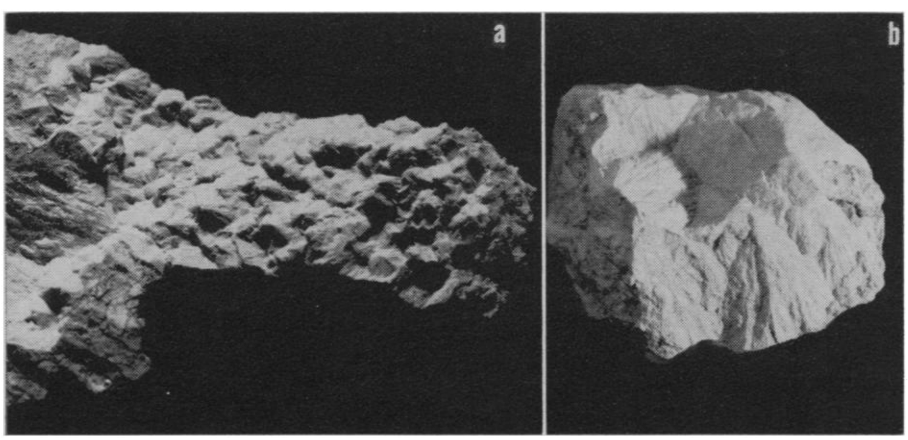
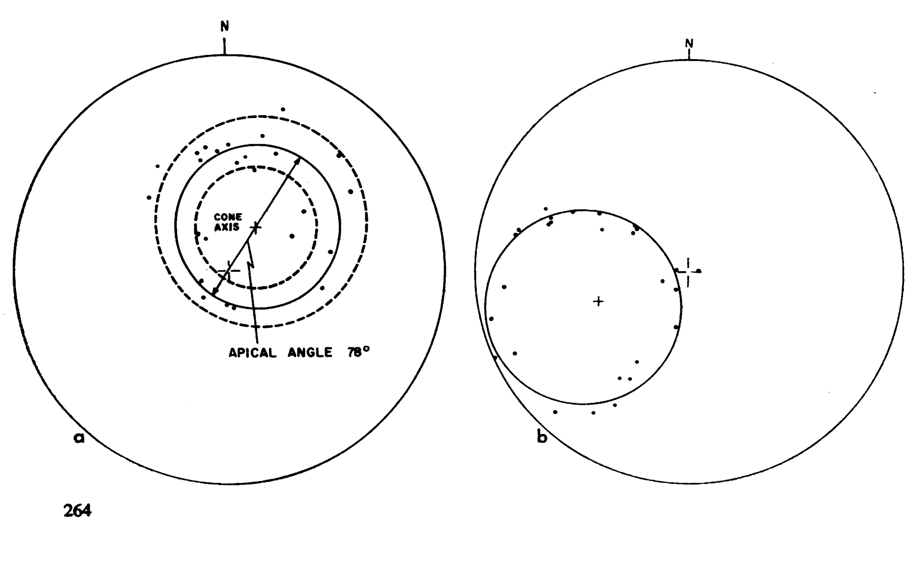


Fig. 3. (a) Whole shatter cones, 2 to 10 mm high, in marly dolomite (Gilliam Limestone). Length of specimen, 11 cm. (b) Variously oriented shatter-cone segments in marly dolomite (Gilliam Limestone). Surfaces in foreground and background are parallel and have similarly oriented cone segments. Note shingle-like overlap of parasitic cone segments. Specimen measures 6.5 by 5.5 cm.



never exceed 15 degrees and are generally much less. Such discrepancies do not materially affect our conclusions, since axial orientations of cones vary somewhat within any exposure (*6*).

Cone segments in a single structural block define an average cone orientation and an apical angle at most places at Sierra Madera. However, a few measured striae in one locality fall far off the circular plot, and data from three localities were discarded altogether, because striae orientations were scattered and no unidirectional cone axis was obvious. The discrepant orientations of cone segments may be attributable to effects of inhomogeneities in the rock.

Cones in a single structural block generally have a common direction of point as well as a common axial orientation. In a few localities, however, a few segments (as many as 31 percent) point toward the opposite apex on the same orientation of cone axis; in rare instances, some whole cones in a cluster point opposite the dominant direction of the cluster.

Apical angles vary from 75 to 108 degrees, averaging 88.5; thus they are significantly smaller than those reported from Vredefort, which range from 90 to 122 degrees (*3*). Figure 2 suggests that, as at Vredefort (*3*), each stratigraphic unit has a characteristic range of apical angles, and that apical angles may also be influenced by rock type.

The shatter-coned rocks have been faulted and folded, and no pattern is obvious when the average orientation of cones from each measured locality is plotted on a map (Fig. 1a). The fact that cones predate folding is shown by the three northwesternmost localities which were measured on both limbs and the trough of a syncline; the three have very different cone orientations, but, if the syncline is unrolled, the cones approach a common orientation. Likewise some broken cones found in faults show that the cones predate faulting.

The initial orientations of the cones may be estimated, but cannot be determined exactly. The paths through which they were deformed were undoubtedly complex; the initial attitudes of bedding

Fig. 4 (left, bottom). (a) Striae from shatter-cone segments from one locality, plotted on lower-hemisphere stereographic projection (all indicate upward-pointing cones). Dashed circles are drawn 10 degrees from small solid circle selected to represent cone. (b) Striae measured on a single upward-pointing whole cone.

also are unknown. Before the Sierra Madera event, Cretaceous strata lay nearly flat, but the sub-Cretaceous structure of Permian rocks of the area had a small northward regional dip and gentle undulations, with dips locally as high as 20 degrees.

Nevertheless, if the cones formed before the central uplift, their initial orientations can be approximated by assumption that the Permian beds were horizontal and that there were simple rotations. The facing direction of beds is known certainly for all but the three most central localities. For beds lying on recognizable folds (asterisks in Fig. 1b), the fold axes were first rotated to horizontal, then the beds unrolled to horizontal; for other localities, beds were rotated to horizontal simply about their strike lines.

The resultant pattern (Fig. 1b) clearly shows cones plotting inward and upward, as at other cryptoexplosion structures where shatter-cone orientations have been well studied (*3, 7*). When one considers the simplifying assumptions used for restoration of the beds to their initial positions, the in-and-up pattern is surprisingly good. One exception, the easternmost locality, lies in a chaotic sedimentary reef breccia having such high initial dips that the rotation assumption is not valid. A single location of outward point, in the southwest, is representative of the minority of cones that developed along the same axes but with points opposite those of the prevailing pattern (*8*). Apart from the easternmost locality, 13 percent of all striae used indicate cones pointing away from the center; 87 percent point toward the center.

Cone-axis plunges are steepest in the center and decrease outward. A very approximate central focus about 1 km above the lowest exposed Permian beds is suggested by restoration of the strata to a horizontal pile and by averaging of the upward projections of the cones. This focus lies approximately at the level of the youngest deformed rocks now exposed.

Our results generally confirm Manton's (*3*) at Vredefort. It is especially noteworthy that (i) variously oriented cone segments define an approximately common cone axis and a dominant direction of point in any structural block, (ii) cones predate the central uplift by whatever time elapsed (probably no more than seconds between explosion and the structural adjustment which followed), and (iii) cones restored to prefolding orientations point mainly inward and upward toward a crude central focus. The radial symmetry about this focus is consistent with suggestions (*3, 9*) that shatter cones are formed by an advancing shock wave emanating from a central source, and supports the hypothesis that shatter-coned cryptoexplosion structures are products of impact.

KEITH A. HOWARD
TERRY W. OFFIELD

U.S. Geological Survey, Menlo Park, California 94025, and Flagstaff, Arizona 86001

References and Notes

1. R. S. Dietz, *J. Geol.* **67**, 496 (1959); in *Trans. Lunar Geol. Field Conf. Bend, Oregon* (1966), p. 25.
2. ———, *Science* **131**, 1781 (1960).
3. W. I. Manton, *Ann. N.Y. Acad. Sci.* **123**, 1017 (1965).
4. H. G. Wilshire and K. A. Howard, *Science*, this issue.
5. H. G. Wilshire, D. Cummings, T. W. Offield, K. A. Howard, in *Geol. Soc. Amer. Program 1967 Ann. Mtg.* (1967), p. 239.
6. For instance, eight whole cones measured directly in one locality show a spread of 30° in axial orientation, with a significant variation from bed to bed. Two comparisons were made between determinations from striae on single whole cones and on cone segments in the same outcrop. In one case, the discrepancies in axis and apical angle were less than 5°, approximately the limits of error of measurement. In the other, concordant results were obtained from two whole cones 20 feet apart, but cone segments in the same bed as one of the whole cones gave results that were different by 15° in axis and 19° in apical angle. Cone segments may, therefore, in some cases show even more dispersion than whole cones, and whole cones themselves are not perfectly circular (Fig. 4b). The localities in which we measured the most striae generally show the poorest fits of data to small circles on the stereonet. Axes differing by 17° and apical angles by 11° were determined on plots of cone segments from two commonly oriented beds 10 feet apart; plotting all the points together gave essentially the same orientation and angle as averaging the two, but with a poorer fit of data. Thus it appears that because of local variations in cones, measuring many striae from a large exposure will result in considerable data scatter, but a good average determination of cone axis and apical angle.
7. J. G. Bray *et al., J. Geol.* **74**, 242 (1966).
8. A nearby locality in this same structural block gave a plot suggesting a wholly different axis: very steeply plunging in beds restored to horizontal. However, this plot may be unreliable because a nearly equal number of striae point toward each apex on the apparent axis and because an unusally large apical angle was indicated.
9. R. S. Dietz, *Amer. J. Sci.* **261**, 650 (1963); R. B. Hargraves, *Geol. Soc. Africa Trans. Proc.* **64**, 147 (1961); J. P. Johnson and R. J. Talbot, *A Theoretical Study of the Shock Wave Origin of Shatter Cones* (U.S. Air Force Inst. Tech. School Eng., Wright-Patterson AFB, Ohio, 1964), p. 92; N. M. Short, *Lawrence Radiation Lab. Rep. 7787* (Univ. of California, Berkeley, 1964).
10. Publication authorized by the director, U.S. Geological Survey. We thank David Cummings and H. G. Wilshire for field measurements and studies of drill cuttings. J. L. Williams and C. J. Perusek of the Phillips Petroleum Co. made drill cuttings available and assisted in their interpretation. H. G. Wilshire, R. A. Loney, and D. J. Milton, all of the U.S. Geological Survey, improved the manuscript. Figure 1 is generalized from U.S. Geological Survey work by H. G. Wilshire, D. Cummings, L. C. Rowan, E. M. Shoemaker, R. E. Eggleton and us.

22 May 1968, revised 9 August 1968

Deep-Ocean Basalts: Inert Gas Content and Uncertainties in Age Dating

Abstract. *The radiogenic argon and helium contents of three basalts erupted into the deep ocean from an active volcano (Kilauea) have been measured. Ages calculated from these measurements increase with sample depth up to 22 million years for lavas deduced to be recent. Caution is urged in applying dates from deep-ocean basalts in studies on ocean-floor spreading.*

The radiogenic inert gas content of basalts from the deep ocean is used in the much favored potassium-argon method of dating these materials. Such dates are of great interest in correlating with other data to bolster the hypothesis of ocean-floor spreading (*1*). It has been suspected in certain cases that the ages obtained might be in error due to gas inherited from the magma from which the rocks were derived. Materials obtained from past and proposed (Mohole) deep-drilling programs also might suffer from this effect. We present data to show that in some instances volcanic rocks erupted into the deep ocean do in fact inherit radiogenic argon and helium, and when dated may yield unrealistic old ages.

Three samples of glassy, tholeiitic basalt dredged from the ocean bottom off the island of Hawaii on the submarine extension of the east rift zone of Kilauea volcano were examined (*2*). There is an evident lack of degassing of these samples, which thus can be used in magmatic gas studies. From the rate at which the subaerial extension of this rift zone has been covered by lavas in historical times, it is possible to deduce that these lavas are very young, probably less than 200 years old (*3*). The samples may, in fact, be very recent, as judged by their fresh appearance and the extreme thinness of the palagonite and manganese oxide layers on the surfaces. This relation of degree of palagonitization and manganese re-