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CRYPTOEXPLOSION STRUCTURES CAUSED FROM WITHOUT OR FROM WITHIN THE EARTH? ("ASTROBLEMES" OR "GEOBLEMES?")

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ABSTRACT. Roughly circular structures with elevated centers consisting of materials forced up from below in disordered fashion were called "cryptovolcanic" by Branco and Fraas in 1905. In the last decades it was realized that the impact of a giant meteorite may have caused the explosion. Dietz's term "cryptoexplosion structures" is useful; it leaves the cause unspecified. For the same reason, open craters surrounded by a low wall of ejected bedrock fragments should be called "explosion craters", not "meteor craters". The presence of shatter cones in most cryptoexplosion structures, and especially the discovery of coesite, a heavy phase of silica, in two cryptoexplosion and two explosion structures seemed to provide evidence of impact from above. Moreover, some puzzling aspects of cryptovolcanic structures are simply explained by meteorite impact.

If meteorites caused these structures, they must be distributed randomly, i.e., they must not bear a systematic relation to structures of terrestrial origin nor to magmatic activity. In this paper this test is applied to the largest cryptoexplosion structures in Europe, North America, and Africa. This impartial selection includes the most quoted examples of coesite occurrence and of shatter cones.

Maps and detailed descriptions show that the European and American examples lie on large anticlinal flexures and that they and so-called satellite structures are aligned along these flexures with structures of demonstrably deep-seated magmatic origin. The Ries Basin lies, in fact, at a unique point where a broad anticlinal axis joins the flexure. Moreover, they are essentially contemporaneous with the magmatic activity. The Vredefort Dome is one of a whole string of basic and ultrabasic intrusions, in a part of the continent where such intrusions are widely distributed.

These test cases are decidedly not randomly distributed, neither in space nor in time. The meteorite impact hypothesis is therefore rejected. The writer suggests the release of vast quantities of water vapor through sudden crystallization of supercooled molten rock near the base of the crust as source of energy, carried rapidly into porous rocks near the earth's surface under an impervious cover. Rapid arrival of the vapor results in an explosion crater, with coesite, but without shatter cones. The energy required to form coesite may have been kinetic, transmitted as the pulverized material was forced through narrow and crooked passages toward the surface.

The presence of shatter cones in cryptovolcanic structures suggests that the presence of vapor under high pressure in the pores of the rock favored their formation. The pressure of the intergranular water vapor would increase its brittleness. Typical shatter cones from brittle bituminous coal lend credibility to this suggestion. Simple experiments show that the direction in which a cone points can not be used to "prove" impact from above.

Finally two other "evidences" frequently mentioned to "prove" meteoritic origin are criticized: the presence of nickeliferous iron among the ejecta of explosion craters and the remoteness from centers of volcanic activity of cryptovolcanic structures. Nickeliferous iron is habitually associated with basic and ultrabasic rocks. It is not the presence, but the high percentage of nickel in the original mineral that is diagnostic of meteoritic origin. If it is the release of water vapor from sudden crystallization of supercooled magma near the base of the crust below stable continental platforms that causes the explosion, then it is not "volcanic" activity we must look for, but the evidence of transport to or near the land

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surface of ultrabasic rock materials. Actually, ultrabasic breccia pipes and dikes are distributed over the central United States in the same manner and in comparable numbers as the cryptoexplosion structures.

INTRODUCTION

The face of the moon is pockmarked with pits and craters. Astronomers, who habitually think in terms of solid bodies traveling through space, prefer to interpret these marks as scars of meteorite impact (e.g., Baldwin, 1949). Geologists, who are accustomed to pay close attention to observable detail of structure and topography, prefer to view the pits and craters as part of the whole structure pattern of the moon's surface, as lunar counterparts of the earth's complex volcanic phenomena. They interpret them as evidence of the defluidization of the moon (e.g., Green and Poldervaart, 1960), the process to which the earth probably owes all the water above and within its crust, besides the vast quantities of volcanic ejecta that cover the ocean floors and sizeable portions of the continental platforms.

Until the closing decade of the last century, geologists had not found features of any kind on the surface of the earth or in the assembled geologic record, which suggested meteorite impact. Since then, an increasing number of roughly circular depressions on the present surface of the earth and older structures brought to light by erosion are being interpreted as products of meteorite impact. The first of these was Arizona's much-advertised "meteor crater", better called the Barringer Crater. When the mineralogist Foote (1892) first described the masses of iron meteorite found nearby, Gilbert proposed "a new hypothesis" that "the shower of falling iron masses included one larger than the rest, and that this greater mass, by the violence of its collision, produced the crater" (Gilbert, 1896, p. 4). In the paper just quoted, Gilbert rejected his meteorite impact hypothesis. This careful analysis of closely observed facts is still worthwhile reading today—65 years after publication. The presence of great masses of meteoric iron, lying east of a north-south line passing through the middle of the crater and (chiefly) within two miles of its rim was held to be accidental. Since then, an increasing number of craters which, like the Barringer Crater, are morphologically indistinguishable from explosion craters, "Maare", (plural of "Maar"), are being called "meteor craters", because no igneous rock is associated with them and because nickeliferous iron is found associated with them in quantities which range from hand specimens to small limonitic residues containing nickel.

In 1905, Branco and Fraas gave a detailed description of the strange, essentially circular structure of the Steinheim Basin in southern Germany, which originally must have looked like a lunar crater. Since no volcanic rocks are found associated with it, they called it a "cryptovolcanic" structure. Later, I mapped and described three areas (and discussed several others) which exhibit essentially the same features and were accordingly termed "cryptovolcanic" (Bucher, 1925, 1933b, 1936). Soon after, Boon and Albritton (1936, 1937, 1938) suggested that the so-called "cryptovolcanic" structures were due to the *impact* of large meteorites. They suggested a similar origin for the Vredefort Dome in South Africa. Daly (1947) accepted and elaborated this interpretation of the Vredefort structure.

The hypothesis of meteorite impact explains many puzzling features of "cryptovolcanic" structures, so that most geologists received it with a sense of grateful relief. By systematically hunting for them, Dietz (1947, 1959, 1960, 1961a) could demonstrate that "shatter cones" are virtually always found in the disordered central portion of "cryptovolcanic" structures. They had already been recognized as evidence of violent shock by Branco and Fraas (1905, p. 36-38). Since the formation of "cryptovolcanic" structures may not have been of a volcanic nature, but the reaction to meteorite impact, Dietz has proposed the neutral term "cryptoexplosion" structures in place of "cryptovolcanic". It will be used in this paper for roughly circular structures from which relatively little or nothing was ejected, but within the center of which rock materials from deeper down have been forced upward in disordered fashion, while a ring-shaped marginal belt has been depressed. Correspondingly, open craters without central uplift, from which no volcanic rocks have been ejected, should be called "explosion craters" (e.g., the Barringer Crater), to keep the reader's mind open to the possibility that they may not be the product of meteorite impact after all.

No shatter cones have been found associated with explosion craters, with the exception of quartzite shatter cones reported by Rohleder from the great Ashanti Crater in Ghana (Rohleder, 1934).[1]

The discovery of coesite, the high-pressure form of silica, at Barringer Crater associated with fused silica, has provided independent powerful proof of violent shock connected with the formation of explosion craters (Chao, Shoemaker, and Madsen, 1960). The same material was formed by the impact of an atomic blast at the Nevada Proving Grounds (Dietz, 1961a, p. 56). When Shoemaker and Chao looked for, and found, coesite in the tuff-like material from the second largest known cryptoexplosion structure, the Ries Basin in southern Germany (Shoemaker and Chao, 1961, p. 3371), the basic problem of all these structures seemed solved. Stated explicitly, the solution takes this form:

> Coesite requires pressure exceeding 20,000 atmospheres, corresponding to the pressure at a depth of over 75 km. (45 mi). Such pressures can be produced near the earth's surface only by impact greater than that attained by ordinary volcanic steam explosions; they have been attained in atomic explosions and could easily be produced by the impact of giant meteorites, i.e., meteorites large enough not to be appreciably slowed down by passage through the atmosphere.
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> Shatter cones have been found (so far) at only one explosion crater, interpreted as due to meteor impact, because of the presence of nickel-bearing iron at the site.
>
> Shatter cones have been found in the central portions of almost all known cryptoexplosion structures. They are almost certainly the products of special strain conditions, such as might be created by violent shock.

Therefore, explosion craters (with nickel-iron) and cryptoexplosion structures (without nickel-iron) must be due to the fall of giant meteorites. Being

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[1] Chao found one small fragment of sandstone among the fallout debris of the Barringer Crater which Dietz considers a shatter cone (Dietz, 1961a, p. 55). Chao told the writer that he doubts this interpretation.

distinctive, they deserve being called by the general term "astrobleme" from the Greek words for "star" and "wound" (Dietz, 1960, p. 1781).

This explanation further accounts for the following properties of the cryptoexplosion structures:

> The highly disordered structure of the central uplift consisting of rocks carried above their original positions (and the limitation of the shatter cones to these central uplifts).
>
> The corresponding downward displacement of a ring-shaped belt of rock concentric with the central uplift.
>
> In some cases, the development of a seemingly wave-like up-and-down movement in one or two rings surrounding the first rim syncline.
>
> The relatively shallow depth to which these cryptoexplosion structures seem to extend, judging from the few drill holes the results of which have become available.

This impressive list of items favorable to the astrobleme hypothesis was recently presented to the general scientific public by Dietz in an impressive paper published in the "Scientific American" (Dietz, 1961a). It produces in the reader an euphoria of expanding insight such as prompts gratitude and congratulations to the enthusiastic team of research workers who contributed to the hypothesis.

But the soundness of a hypothesis is not proved by the emotions it produces, but rather by its capacity to explain all essential facts within its range. If meteorite impact has produced the cryptoexplosion structures they must be:

(1) Randomly distributed, e.g., not demonstrably related to structures of purely terrestrial origin;

(2) Independent of magmatic activity in the region;

(3) Structurally of a nature that is comprehensible in terms of instantaneous impact and its immediate consequences.

In the following, we shall apply these criteria to the three largest known cryptoexplosion structures:

(1) The Ries Basin, the largest cryptoexplosion structure of Europe and its much smaller neighbor, the Steinheim Basin, the impact product of a "twin meteorite", acording to the meteorite hypothesis.

(2) The Wells Creek Basin, the largest well-exposed cryptoexplosion structure of North America and three minute craterlets just outside it, interpreted as produced by fragments of the master meteorite.

(3) The Vredefort Dome, the largest cryptoexplosion structure of Africa, concerning which Dietz has written: "If this is not an impact scar, then it would seem that there are none this side of the moon" (Dietz, 1961b, p. 500).

Between them, they exhibit all the criteria by which "astroblemes" are identified. Being the largest in each continent, they may be expected to offer the most convincing evidence.

THE RIES, STEINHEIM, AND URACH AREAS OF EXPLOSIVE ACTIVITY IN SOUTHERN GERMANY

The Ries Basin, the largest explosion structure of Europe, is aligned with a small cryptoexplosion structure, the Steinheim Basin, and the largest area of explosion pipes of undoubted volcanic nature, the Urach area of breccia pipes. This alignment parallels the axis of a sharp crustal flexure, the Danube flexure (fig. 1). The considerable topographic relief on the crystalline basement beneath the sedimentary cover is reflected in the discontinuous pattern of geomagnetic anomalies shown on the map. Moreover, the Ries Basin lies at the point of junction of the Danube flexure and the axis of a broad crustal fold, the Tauber-Ries axis (fig. 7). A description of these structures follows.

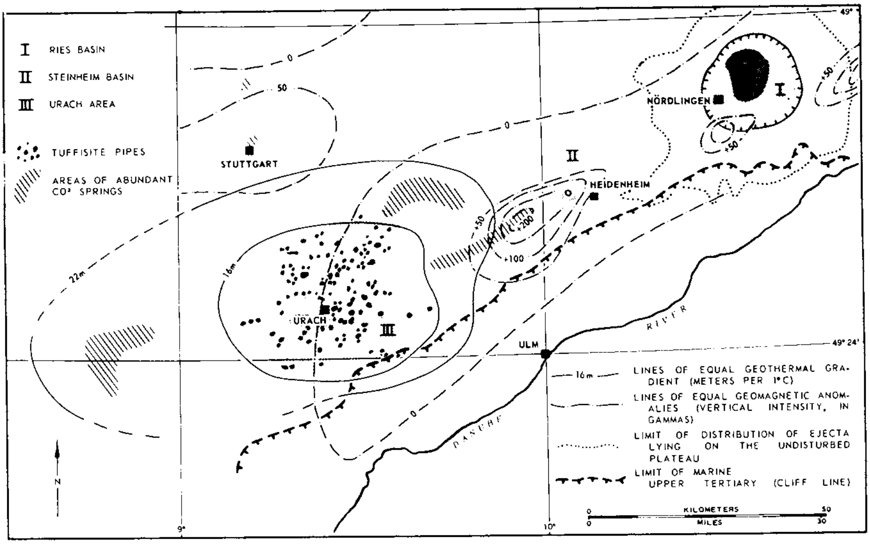

Fig. 1. Map of the structural axis on which lie the Ries Basin, Steinheim Basin and the Urach area of breccia pipes (data from Georg Wagner, 1960; Gerold Wagner, personal communication; Neumann, 1939; Reich and Horrix, 1955; Carlé, 1958). (This figure appeared in Nature, v. 197, p. 1243, and is reprinted by permission.)

Since the Ries has become an outstanding example of the successful application of the meteorite impact hypothesis and most of the literature concerning the Ries is not readily accessible to American geologists, a fuller account of the significant observations is given below than for the other structures discussed.

A. The Ries Basin.[2]—Figure 2 shows the major structural elements of the environment within which the nearly circular Ries plain appears as a foreign topographic element. Its southern half cuts into the conspicuous escarpment, capped by massive limestones of the Upper Jurassic, which faces north and

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[2] Since 1919, when he became interested in cryptoexplosion structures, the writer has kept in touch with the literature on the Ries and Steinheim basins and has corresponded with those then most actively pushing their investigation. He visited both areas in 1937. In the summer of 1962, he spent four most valuable days in the Ries Basin under the guidance of Professors Georg Wagner and Richard Löffler and Drs. Gerold Wagner and Rudolf Hüttner, to whom he wishes to express his gratitude. The writer owes special thanks to Professor Georg Wagner for permission to use three illustrations from his concise up-to-date account of the essential facts in the Ries problem (1960, p. 596-603), and to Dr. Gerold Wagner for many invaluable comments and for providing him with an insight into the advanced state of geologic mapping in the Ries and environments (reproduced here in Appendix A). For a concise review of the history of the Ries studies, see Hölder, 1962.

runs in an irregular front east-northeastward. It rises 100 to 150 m (300 to 490 ft) above the lowland to the northwest, in which first Middle and Lower Jurassic strata and then successively older formations come to the surface.

Southeast of this escarpment, the massive limestones of the Upper Jurassic dip gently in the direction of the Danube, north of which they disappear under the Miocene beds of the Molasse Basin, along the "Danube flexure". When the sea spread over the Molasse Basin in Middle Miocene (Burdigalian) time, it produced a well-defined shoreline ("cliffline") in the Upper Jurassic limestones, which can be traced by the boulders along its base, the layers built up largely from fragments of *Balanus*, by the boreholes of pholadid pelecypods, etc. (See figs. 1 and 2.) This cliff line can be traced for some 120 km (72 mi) into the "Vor-ries," i.e., the belt around the Ries, where it lies partly buried under the

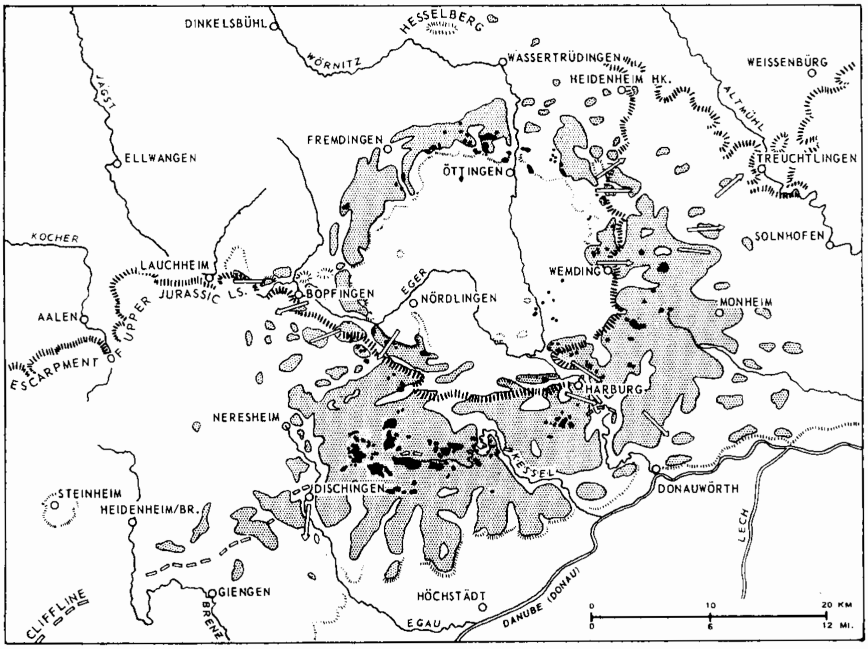

Fig. 2. Map of the Ries Basin in its regional setting (redrawn from Georg Wagner, 1960, p. 599, fig. 527).

Line of delicate hachures (in northern part of map): Low, south-facing escarpment bounding the basin in the north.

Line of heavy hachures: The high, northwest-facing escarpment formed by the massive limestone members of the Upper Jurassic which form the southeast-sloping plateau of the "Alb". The southern half of the Ries Basin is cut into this plateau, with the high escarpment forming a conspicuous border around the southern half of its outline. The surface of the flat Ries Basin floor is formed largely by young alluvial deposits and freshwater limestones, with scattered outcrops of crystalline basement.

Stippled areas: Rock debris derived from the Basin, thrust onto the rim and far beyond, especially on the east and south sides.

Hollow arrows: Trend of striations on the thrust plane, the arrowhead giving the direction of movement (left off where not determined) (from Gerold Wagner, 1957a).

Black dots and areas: Suevite tuffs in pipes ("Schlote") or sheets occupying local depressions ("Wannen").

debris from the Ries catastrophe (e.g., Hüttner, 1961, p. 78-83). Opposite the center of the Ries, the cliff line bends sharply southeast.

The Ries Basin (Kranz, 1922) is nearly circular, 21 to 24 km (12 to 14 mi) wide. Its southern half, which cuts into the plateau, is bounded by a prominent escarpment. The northern half is rimmed by a low, south-facing escarpment ± 50 m (165 ft) high (fig. 2). The surface of the Ries Basin is a plain covered by young, largely alluvial sediments, underlain by later Miocene limestones and clastic sediments of the Ries lake, from which emerge here and there rocks of the crystalline basement to form low hills, capped by freshwater limestone. The structural relations of the rocks within the basins will be described later.

Outside the basin, the autochthonous rocks lie practically undisturbed, exposed in numerous quarries. But plastered against the rim and far beyond in all directions, especially on the high plateau, heterogeneous masses of rock debris lie strewn as allochthonous masses as far as 20 to 25 km (12 to 15 mi) from the basin rim. They are shown on the map (fig. 2) as stippled areas.

Sections 3A to 3C (fig. 3) illustrate the structure of such allochthonous masses as they appear plastered against the very rim of the Ries Basin. In Sections 3A and 3C, as almost everywhere, a spectacular breccia, called "Bunte Breccie", is intimately associated with larger blocks derived from most diverse stratigraphic units. In figure 3C, these include a large slice of crystalline basement (chiefly granite and gneiss); a smaller block of basal Lower Jurassic and Upper Triassic marls with sandstone at the base in original sequence with strong westward dip; and large bodies of white Upper Jurassic limestone shattered throughout to look like a breccia of small (0.1 to 1 cm, i.e., grit-sized) fragments, recemented (called "Gries"[3] = grit). All these disjoined units are inclusions in the "Bunte Breccie" which emerges at the base of the overthrust mass and at many points within it. This breccia consists of angular fragments of the harder rocks of the region in a wildly kneaded and contorted matrix of many-colored shales (from the red of Triassic shales to pink, greenish, and all shades of gray from light to black from higher formations). Subangular to rounded pebbles from the gravels of the pre-Ries surface occur widely. They are generally polished and scratched and resemble glacial pebbles. The pebbles are especially abundant along the base of the allochthonous rock shown in Section 3 B[4] and are therefore referred to as "Buchberg pebbles" in the Ries literature. Note that here seven members of the Middle and Upper Jurassic have maintained their original sequence in what appears to be a wedge-shaped slice sheared off obliquely from its original position and shoved westward with the thin edge in front.

In Section 3A, the "Bunte Breccie" lies near, but not at, the base of the allochthonous body. On the east side, Upper Miocene freshwater limestone faces basinward with a characteristic reef-like front.

The surface over which these rock masses moved is generally uneven, polished and grooved, forming a veritable pseudo-glaciated surface. Branca and

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[3] The process by which originally massive limestones were transformed thoroughly into "Gries" is called "Vergriesung" = gritification.

[4] The thrust nature of the Buchberg and its pebble-bearing base lying on the striated thrust plane were explored by means of a shaft (Branco and Fraas, 1901).

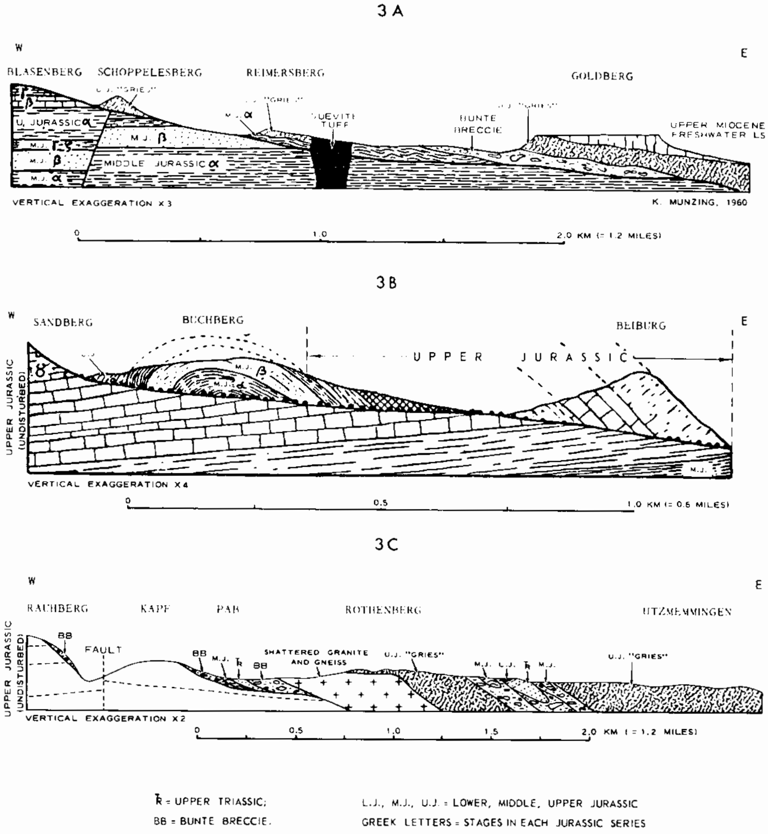


Fig. 3. Three cross sections illustrating the position of allochthonous materials ejected ("overthrust") from the Ries Basin on the undisturbed autochthonous strata of the rim.

All three sections lie on the west side of the Basin, in the region around Bopfingen (legends, names, symbols have been made uniform and anglicized).

A. East-northeast of Bopfingen. Badly crushed Middle and Upper Jurassic strata with a wedge of explosion breccia ("Bunte Breccie") thrust on rim of Ries Basin (after K. Münzing, reproduced from Georg Wagner, 1960, p. 598, fig. 526).

B. Near Bopfingen. Eroded sequence of Middle and Upper Jurassic strata cut off obliquely to the original bedding and thrust onto rim, with scratched pebbles ("Buchberg pebbles") on rim of basin now forming the striated thrust plane (after Fraas and Löffler, reproduced from Georg Wagner, 1960, p. 597, fig. 525.

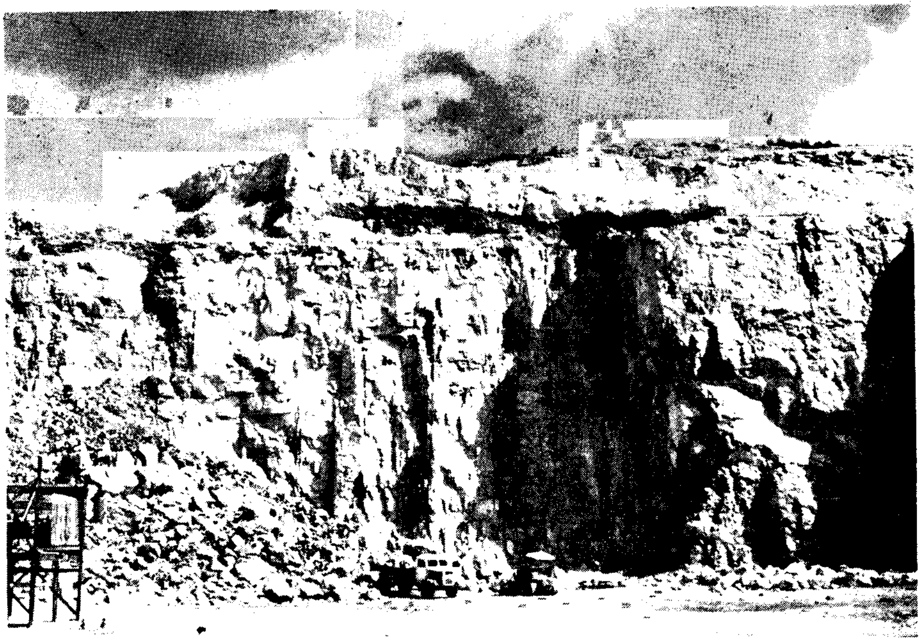
C. About 3 km southeast of Bopfingen. Thrust mass of intensely shattered granite and overlying Triassic and Jurassic sediments with thin layer of scratched pebbles between it and the striated thrust plane (after Bentz, 1928, p. 422, fig. 4).

Fig. 4.

A. Quarry 1.5 km northeast of Harburg about 3 km southeast of the rim of the Ries Basin.

Main part of quarry: Undisturbed autochthonous limestone of the Upper Jurassic (zone δ), with vertical joint systems typical of the Jura plateau; cut off on top by grooved and striated thrust surface. On it lies a thin slice of the same limestone into which is intruded a wedge of typical "Bunte Breccie" (dark interval), looking like ground moraine (shown in close-up in figure 4B). Above the wedge lies a lighter zone of the Upper Jurassic (upper right of picture), dipping to the right (photograph by Bucher in 1962).

B. Close-up of the "Bunte Breccie" shown in figure 4A looking along quarry front (*because* of narrowness of ledge) (photograph by Bucher in 1962).



A

B

Fraas (1907, p. 5, 51) recognized that the grooves are directed outward and that this observation combined with the nature and wide distribution of the "Bunte Breccie" practically proves the explosive origin of the Ries phenomena. Gerold Wagner (1957a) has studied all known localities and plotted the direction of movement (arrows in fig. 2), which does indeed everywhere point outward from the central part of the basin.

Figure 4A illustrates the appearance of the "Bunte Breccie" as seen in the field on the southeast side of the Basin and over 3 km (2 mi) outside the rim. Most of the quarry walls show the typical undisturbed (autochthonous) Upper Jura (zone δ) with the simple system of vertical joints characteristic of the Jura plateau all around (Gerold Wagner, 1957b). It is cut off on top by a slickensided bedding plane along which the uppermost part of the quarry beds was moved an unknown distance. "Bunte Breccie" (dark in photograph) has wedged into the allochthonous limestones, bending up the higher members of the moved block (far right side of picture). It looks as if the explosion breccia had wedged into the basal part of a zone that was detached and pushed outward from the basin by the force of the explosion. Figure 4B shows a close-up of the "Bunte Breccie" at this locality. In the allochthonous masses, fragments of granite and gneiss grow fewer and smaller away from the rim.[5]

Inside the basin, such explosion breccias consist almost entirely of angular and rounded blocks of rocks from the crystalline basement. Figure 5 gives a close-up of a fine exposure (about 30 m long), some 5.5 km (3 mi) northwest of Harburg (fig. 2), 2 km (1.2 mi) inside the rim. Narrow dikes of finely ground granitic explosion products are seen cutting across most basement exposures within the Ries. The same materials are found cutting limestone masses pushed out from the inside of the rim (fig. 6).

These granitic explosion products are remarkable for the complete absence of any signs of heat action, such as partial melting resulting in the formation of glass, which is so conspicuous a feature of the suevite tuff and the fragments in it (to be described presently). The fine rock powder is the result of pulverization ("fluidization") of rock material. This pulverized material was blown into the network of fractures that opened in the top of the basement and in the overlying sediments as they bent up under the pressure of the explosion. We shall encounter corresponding tuffisites associated with explosion features in many of the structures discussed in this paper.

The entrenched valley by which the Wörnitz River used to run and still runs southward through the Upper Jurassic limestone plateau (south of the present town of Harburg) was completely blocked by a wall of ejecta. The remnants of this wall still lie plastered against the valley walls to a height of over 60 m (almost 200 ft) above the grooved and striated pre-Ries stream bed which lay only about 5 m above the present valley floor. A lake quickly developed behind this explosion-made dam in which freshwater limestones and

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[5] In rare cases, the direction of transport is indicated by fragments of peculiar rock type, such as, e.g., a pinkish granite which is seen in the occasional outcrops of bedrock within the basin at one point only, near Lierheim, about 3 km (1.8 mi) inside the south rim of the basin. Dr. Löffler found fragments of the same granite at a number of localities in the "Bunte Breccie" on top of the plateau at a number of localities, 4 to 7 km (2.5 to 4.2 mi) south of the rim and nowhere else. (Dr. Löffler, oral communication.)

Fig. 5. A close-up view of a body of explosion breccia consisting chiefly of ground-up crystalline basement rock including angular blocks of diverse rocks, ranging from granite and migmatite to basic rock types. None of the rocks show any heat effect, such as partial melting and formation of glass. Fragments of Triassic red shale and white sandstone make up only a small percentage (Gerold Wagner has estimated them at not much more than one percent of the total). "Tieferweg" near Appetshofen, about 5.5 km northwest of Harburg (fig. 2) (photograph by Bucher in 1962).

muds were deposited, the limestones taking the form of masses of calcareous tufa along the margin, suggesting algal growth.

Locally hot springs must have contributed to the formation of tufa. This is indicated by the presence of aragonite and by very rare finds of pitticite (hydrous ferric sulfate-arsenate), lazurite, and malachite in the freshwater limestones,[6] and by the presence of a zeolite (probably heulandite) in cavities of limestone overlying the basement, found in a drill core in Nördlingen (Nathan, 1957, p. 140-141).

The lake sediments and later alluvial deposits conceal most of the structural conditions within the basin.

Reich's seismic refraction studies (Reich and Horrix, 1955) shed light on the structural conditions that lie concealed below the lake sediments in the Ries Basin. Compared with the normal velocities of seismic waves in the crystalline basement and the different sediments above, those within the Basin are greatly reduced; this is consistent with the shattered condition of all rocks exposed within and along the margin of the basin. Three major structural units stand out clearly in the record within the basin:

(1) An inner, caldera-like roughly circular depression, about 8 km (5 mi) in diameter. It is shown on figure 1 by denser stippling. Its bottom is remarkably flat, about 700 m (2300 ft) below the present surface. Lake deposits occupy the upper 250 to 320 m (800 to 1000 ft) of this section (Reich and Horrix, 1955, p. 47). Explosion products of an unspecified nature occupy the remainder down to the solid basement. The existence of such an "inner basin" was deduced over 30 years ago by A. Bentz (Bentz and Jung, 1931, p. 5-6) on the basis of earlier torsion balance studies.

(2) A horseshoe-shaped ring wall, open at the north, 1 to 2 kms wide. It consists of piled-up units of basement rock which are separated from the normal rock below by "elastically weaker" materials, possibly explosion products. Most of the more conspicuous exposures of basement rocks in the basin are projecting high points in this ring wall.

(3) The ring-shaped area between the ring-wall and the basin rim which is clearly underlain by a jumble of large and small bodies, probably like those shown in the cross sections of figure 3. Here the seismic velocities change abruptly over short distances so as to defy detailed analysis. At two localities within this area, the depth to the solid basement is almost as great as the central "caldera" (2 km = 1.2 mi northwest, and 7 km = 4.2 mi southeast of Nördlingen) forming what seem to be subsidiary "craters" (Reich and Horrix, 1955, p. 49, fig. 22). Within these "craters" the thickness of the lake sediments is two to three times as great as over the surrounding surface and two-thirds as great as it is in the central depression (Reich and Horrix, 1955, p. 48, fig. 21). Such local depressions deserve special attention, and we shall refer to them again.

The last major event in the development of the Ries structure introduces an entirely new element, the appearance of tuff-like materials, especially in the "Vor-ries" (Branco, 1903; for a map and detailed description of all occurrences, see Schnell, 1926). Sauer (1901) gave the name "suevite" to a hypo-

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[6] Specimens in Museum of Nördlingen, collected by Löffler.

thetical magma at depth from which the tuff was derived. The product is therefore best called suevite tuff. This tuff (called "Trass" in the cement industry) consists of comminuted mineral fragments derived from the crystalline basement (comparable to the fine-grained "granitic explosion products"), intermixed with varying amounts of glass droplets and splinters, but never lapilli or crystals of primary magmatic origin (Schuster, 1922). In this fine-grained matrix, there are variable amounts of small and large angular fragments of all kinds of basement rocks known in this region. These show varying degrees of melting. Ahrens (1929) has shown that the angular fragments consist of basement rocks more or less fused along their borders. In their more acid phases, the ferromagnesian mineral components are unaltered, whereas the surrounding quartz and feldspar grains have changed into a glass, often maintaining their crystal outlines, contrary to "normal" melting order. Where melting has gone farther, the fragments are surrounded by a more or less glassy streaky envelope with relicts of the original rock in the center.

Opinion is still divided on the question of whether all suevite tuff was blasted out of the Ries "crater" as part of the Ries catastrophe or has reached the surface through numerous smaller vents. One of the chief objects of the writer's visit last year was to examine the evidence to decide between the two alternatives. His expert guides took him to localities that seemed to him to provide indisputable evidence of local origin from discrete vents (see brief report by Georg Wagner, 1962). In the old, classical quarry at Alte Bürg, about 5.5 km (3 mi) southwest of Nördlingen (fig. 2) about 1 km beyond, i.e., outside the Ries Basin, the tuff cuts on one side across the massive limestone of Upper Jurassic in a vertical wall (see Bentz, 1928, p. 430-438). At that point the tuff contains relatively few, but very broad and very flat cakes of partly melted rocks, some sharply bent back on themselves. Near the wall, they tend to be clearly aligned vertically, parallel to the contact. Here, half-melted slices of heated schistose or gneissic rock were carried upward with the tuff which must have been quite cool, since small angular fragments of the white limestone in the tuff show no signs of heating. The same wall effect is seen in the new quarry at Aumühle, diagonally across the Ries Basin from the Alte Bürg, 2.5 km (1.5 mi) northeast of Öttingen (fig. 2), about 1.5 km (0.9 mi) outside the rim of the Basin (see Löffler, 1927, p. 117). Here a large body of "Bunte Breccie" measuring many meters across (red clay shales and white sandstone of the Upper Triassic and fragments of Middle Jurassic) appears embedded in the tuff. Since this inclusion lies close to the border along which flat cakes of partly melted crystalline rock are aligned parallel to the steep border, vertical transport from below seems the only reasonable explanation of its presence. In two smaller quarries nearby, there is indisputable evidence of successive eruptions. A coarse bed of tuff, full of large and small flat cakes of partly melted crystalline rock is overlain, with a clearly defined boundary, by a finer-grained tuff practically without large fragments and flat cakes embedded in it. In one corner lies an angular block of layered fine-grained tuff, apparently broken from the adjacent wall. Such sudden variations in grain size are characteristic of ejection from local vents.

Fig. 6. Thin (10 to 30 cm wide) dike of somewhat altered greenish gray fine-grained explosion product derived from granitoid material. (Mica, quartz, feldspar, and one small fragment of crystalline rock, in inclined allochthonous thin-bedded Upper Jurassic limestones—zone β.) There is no trace of glass or any heat effect along the wall rock.

Schwalbenberg quarry, about 3 km east of the rim (6.5 km west of Monheim; see fig. 2) (photograph by Bucher in 1962).

Tuffs which were hurled from a vent and accumulated on the sides of the explosion crater and the surface beyond ("Wannentrass") always abound in fragments with a glass-rich. scoriaceous. slag-like crust. Larger, softer masses are apt to have the shape of volcanic bombs. rounded with twisted ends. or flat cakes with curled edges. Cracked surfaces. such as are characteristic of breadcrust bombs. are not found. because they form when the interior is still essentially molten; the typical bombs in the Ries. however. never had a molten core. In these ejected tuffs. even very perishable Tertiary sediments. such as freshwater limestones and fragments of lignites. are frequently found.

In tuffs which lie in vents, the basement fragments have little or no scoriaceous crust, though they may contain glass. The tuffs also contain varying amounts of bedrock fragments, from slivers of shale and small pieces of limestone to sizeable rock bodies. None of the sedimentary rocks. however. show any signs of melting, and even in the limestones there is little more than discoloration to suggest any heat effect. As is to be expected. all transitions exist between the two extremes where chance exposures range from surface deposits into the uppermost part of a vent and farther down into the explosion pipe.

From the glassy rinds of such bombs. from localities outside the Ries Basin. which were brought to the surface after the Ries explosion. the heavy mineral phase of silica (coesite) and perhaps the still heavier stishovite were obtained (Shoemaker and Chao. 1961). These will be discussed later.

The suevite tuff cuts across all allochthonous materials and is. therefore. definitely younger than the results of the major Ries catastrophe. In fact, the contrast between the tuff and the "granitic explosion products" and the vast mass of allochthonous debris scattered by the Ries catastrophe is striking and long recognized (Branco and Fraas. 1907. p. 12). No traces of glass or any heat effects have been found in the rock of the allochthonous masses, nor in the "Bunte Breccie" and associated products of the main explosion.[7]

The tuff eruptions must have begun soon after the main catastrophe and must have ended soon enough not to have pierced the upper portion of the freshwater lake sediments now exposed in the Ries Basin. On the east side of the Wörnitz valley. where the river enters the Ries plain (fig. 2) near the town of Hainsfarth. freshwater limestones lie on the tuff (Wagner. written communication) which nearby in the same valley locally lies on the pre-Ries valley floor. only a few meters above the present floor (Löffler. oral communication). Since considerable amounts of ejecta form an almost continuous cover east and west of the river in the north. enough time must have elapsed before the last tuff fell here to allow erosion to expose the valley floor locally.[8] This is further evidence that the suevite tuff is not the result of a single central explosion.

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[7] This evidence is wholly contrary to the thinking of the geochemists who accept the meteorite impact hypothesis and have merely collected suevite tuff specimens without regard to structural relations.

A picture such as that drawn by V. Vand (1963, p. 4) is incompatible with the geological facts: "The meteoric explosion must have produced a fireball several miles in diameter which, like a balloon, rose high up into the stratosphere, forming there the now too familiar mushroom cloud. This cloud must have sucked up the 7 Km^3 of molten granitic bombs and pulverized rock. Suevite resulted from the more or less vertical fall of this mass of debris . . . ".

[8] Note the contrast with the opposite side of the Basin where explosion debris still cling to the entrenched valley wall to a height of 60 m (200 ft) above the pre-Ries valley floor.

Horrix' geomagnetic observations (Reich and Horrix. 1955. p. 65-87) have brought to light another significant fact: He found a number of well-defined areas with negative magnetic anomalies below –200γ in the central, flat-bottomed explosion crater (inside the ring-wall).

One especially significant area lies near Wörnitzostheim. about 1 km outside the ringwall. (Compare Horrix' map. p. 85. fig. 35. with Reich's map. p. 49. fig. 22). Computation shows that this small area of intensive negative magnetic anomaly must be due to a cylindrical body. about 80 m (260 ft) in diameter. reversely magnetized. Its surface is estimated to lie about 80 m below the surface of the Basin. i.e.. it cuts through the overlying layer of explosion products (like the pipe shown in Section 3C) and lies buried beneath the Tertiary.

Similar high negative values (up to –261γ) were found by Horrix on a very small patch of suevite tuff on the Jurassic upland 11 km southwest of Harburg (fig. 2) and about 4.5 km (2.7 mi) south of the southern border of the Ries Basin. This patch of suevite tuff west of Frohnhofen (Reich and Horrix. 1955. p. 74) was described by Schnell (1926. p. 270) as lying in a "50 m (165 ft.)-wide fissure in massive Jura limestone". exposed by chance in a limestone quarry. The reversed polarity was determined in the quarry and in oriented hand specimens (Reich and Horrix, 1955. p. 74). Since most suevite tuff localities checked by Horrix show no significant remanent magnetism. the high values of this (and one other) locality are surprising. especially in such a sialic rock. It suggests influence of (and perhaps contributions from?) a basic rock at depth. The very much higher negative anomalies near Wörnitzostheim are of an order of magnitude known only from basic magmatic rocks. This suggests that components of basic magmatic materials. if not basic magma. reached higher levels along suevite vents. recalling Sauer's hypothesis that hot mafic magma ascending from lower parts of the crust was responsible for the partial melting of the basement.

Horrix considers it even possible that sheets of basic lava are responsible for the large areas of strong negative anomalies within the inner Ries "crater".

For the purposes of this discussion the presence of such pipes in the Ries Basin is important. We shall find a similar situation in the Urach explosion vents. where basalt reached the level of the present land surface in only a few of the over 250 pipes. An indication of similar local channels of lava ascent has been found associated with one of the explosion craters. "Maare". of the Eifel region (Frechen. 1960. p. 22).

It is not surprising in this light. that the thermal gradient found in a group of shallow wells drilled in and about Nördlingen is almost three times as high as in the surrounding parts of Europe: 1°C per 12.4 m (Nathan. 1957. p. 143). This just about equals the thermal gradient at Thermopolis. Wyoming. 145 km (90 mi) southeast of Yellowstone National Park (Van Orstrand. 1951). Horrix points out that reversed remanent magnetism is known from a number of German volcanic regions. most of them Miocene in age (Reich and Horrix. 1955, p. 75).

Fortunately. the Ries explosion is well dated. The fragments of Tertiary limestone found in the "Bunte Breccie" (at about 50 localities. chiefly east and

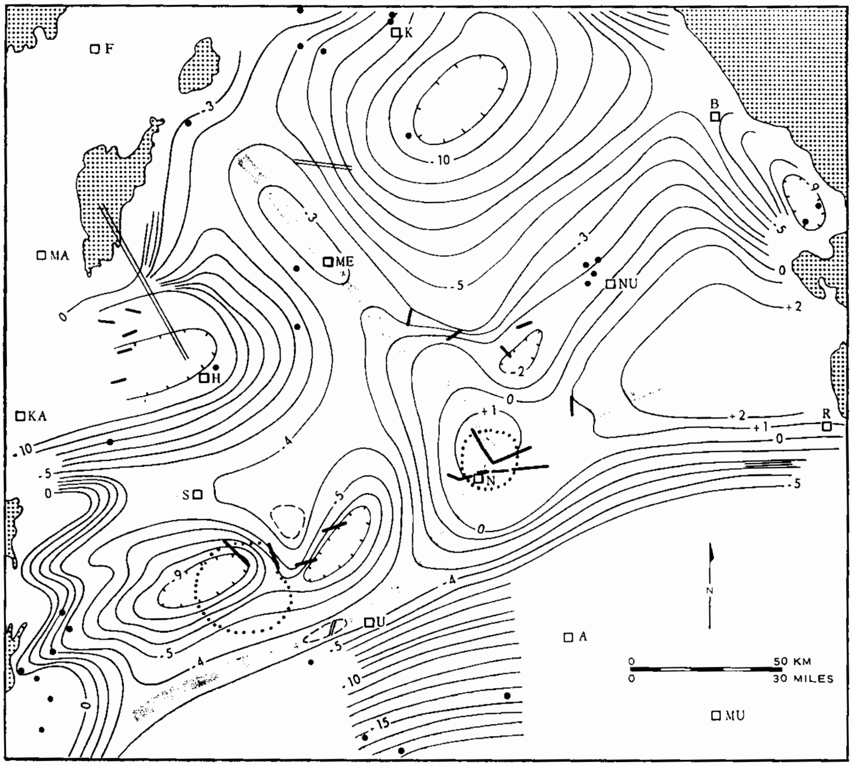

Fig. 7. Contour map of the surface of the crystalline basement (late Paleozoic) in southern Germany, based on boreholes (black dots), seismic refraction shotlines (short single lines), and seismic records of quarry blasts (long double lines).
Dark shaded areas = Outcrop of crystalline basement.
Light shaded bands = Axes of basement elevation.
Rings of small dots = Ries (eastern) and Urach (western) areas.
Cities and towns:
A = Augsburg; B = Bayreuth; F = Frankfurt a. M.; H = Heilbronn; K = Kissingen; KA = Karlsruhe; MA = Mannheim; ME = Mergentheim; MU = Munich; N = Nördlingen; NU = Nürnberg; R = Regensburg; S = Stuttgart; U = Ulm.
(Redrawn from Breyer, 1956, p. 33, fig. 6; marginal parts of the map on all but the south side omitted, the number of names reduced and shadings added.)

west of the Ries) contain Tortonian (lower Upper Miocene) fossils. In the samples from a deep borehole[9] near the center of the Ries Basin, Rein found pollen of Tortonian age at a depth of 250 m (820 ft) near the base of the Tertiary fill, but pollen of Sarmatian (upper Upper Miocene) age at 110 m (360 ft). (Dehm, 1962, p. 74; Rein, 1961, quoted by Dehm.) In a borehole in Nördlingen at a depth of 34.5 m (207 ft) Nathan (1957, p. 139-140) identified a 10-cm thick layer of bentonite. Similar bentonite is widespread in the Tertiary of the Molasse Basin immediately to the south, and there lies close to the base of the Sarmatian (Dehm, 1962, p. 76). The Ries explosion must have occurred close to the end of Tortonian time.

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[9] Deiningen I. No stratigraphic and petrographic record of this important drilling seems to have been published.

Some of the observations here recorded find a ready explanation in the hypothesis of meteorite impact, and none disprove it, though several suggest well-known results from volcanic activity. The decisive fact is that the position of the Ries within the structural framework of southwestern Germany is such that only a phenomenally rare chance would allow a giant meteorite to hit the precise spot. These are the facts:

(1) The Ries Basin, the Steinheim Basin, and the Urach area of explosion craters and breccia pipes lie on a line which is practically parallel to a prominent structural axis which antedates the Ries catastrophe. The map (fig. 1) shows three sets of data which delineate this axis, namely (a), the line of flexure along which the Upper Jurassic limestones of the plateau bend down beneath the Tertiary sediments of the pre-Alpine Molasse trough, here indicated by the sharply defined cliff line which marks the shore of the short-lived Miocene invasion by the sea; (b), the line of high positive magnetic anomalies which reflects a buried topographic axis, toward which most of the Lower and Middle Triassic and even higher beds pinch out or thin out from the northwest; (c), the axis of the isotherms of the geothermal gradient.

(2) The reality of the topographic axis indicated by the belt of geomagnetic highs in figure 1 is documented by Breyer's contour map of the surface of the crystalline basement, reproduced in figure 7 (Breyer, 1956, p. 33. fig. 6). Here the Ries Basin is seen to lie at the line of junction of (a), a narrow "hinge-line" which runs west-southwestward from Nördlingen (in the Ries Basin) past Ulm (less than –400 m (–1312 ft) below sea level); and (b), a broad ridge (less than –400 m and in fact less than –300 m (–985 ft) below sea level), along which thickness and especially facies changes were common throughout Mesozoic times, the so-called "Ries-Tauber" line. It would be difficult to find a more clearly defined position within the structural framework of southern Germany for a giant meteorite to hit. Pure chance could, of course, produce such an event. If this were a unique phenomenon, the argument involving chance would have little weight. But the meteorite hypothesis demands that the Ries giant had a small companion which is supposed to have produced the Steinheim Basin, and that it was placed neatly on the line connecting the Ries with the volcanic Urach area and, more remarkably still, almost exactly halfway between these two major structures.

B. The Steinheim Basin.—The Steinheim Basin is small (Kranz, 1924, 1936, 1938), with a diameter of about 3 km (1.8 mi), an outer ring depression lowered about 100 m (330 ft) and, in its center, a hill of highly disturbed strata forced up some 150 m (500 ft) above their original level. Apart from its round form and basin topography, it shares only three significant features with the Ries Basin:

(1) Along most of its periphery the thick-bedded, white, Upper Jurassic limestones of the rim, which look quite normal from a distance, at closer range appear shattered into grit-sized fragments to which the rock crumbles readily when struck by a hammer. This is the "Gries" so common along the rim of the Ries Basin and among the Upper Jurassic rock bodies ejected from it.

(2) Sedimentary explosion breccia, the equivalent of the "Bunte Breccie" of limited extent, is practically confined to the east and south slopes of the rim

and, in contrast to the Ries Basin, contains no fragments of formation lower than Lower Jurassic (Liassic) and, therefore, is not varicolored ("bunt"). Here, detailed studies have convinced most workers, as far as the writer knows, that the relative scarcity of explosion breccia over most of the rim of the Steinheim Basin and its absence beyond cannot be ascribed to later erosion, but indicates that no large quantities of sedimentary fragments were erupted.

(3) The ring-shaped depression in the then still largely unbroken plateau surface held a freshwater lake, long famous for its wealth of vertebrate and invertebrate fossils. In the Steinheim Basin, the highest freshwater sediments lie at an elevation of 624 m (1047 ft). the floor of the present basin surface lies 100 m (330 ft) lower (Kranz, 1924, p. 73). Drilling to the basin floor has cut over 100 m of freshwater sediments. It is safe to say that the Tertiary sediments, which lie on the slopes and bottom of the Steinheim Basin, reached well over 100 m thickness.

Freshwater limestone fringes the basin and caps the central hill which was an island in the lake. These calcareous tufa deposits are rather dolomitic, approximating a ratio of $3CaCO_3:2MgCO_3$. Associated with them is opaline silica which locally can be shown to have been deposited simultaneously with aragonitic sinter, suggesting hot springs action. The astonishing phenotypical form changes exhibited by the enormously abundant specimens of the freshwater gastropod formerly called "*Planorbis multiformis*" have been studied for more than a century. This instability of form is probably due to the variations in temperature and mineral content of the lake water (Kranz, 1924, p. 100-105). This implies long-lived hot springs activity.

Apart from its size, the Steinheim Basin differs from the Ries Basin in the nature and depth of the disturbance and in the abundance of shatter cones. No formations older than Lower Jurassic are involved in the structure. All Jurassic formations below those of the upper Jurassic are limited to a central hill, the Klosterberg-Steinhirt, in which the limestone horizons lie in wild confusion of disordered blocks between which the shale zones appear plastically squeezed and kneaded together. The lower horizons (Liassic and lower Dogger) have been carried up to 500 m (over 1600 ft) above their normal positions. The details of the structure within the central hill were studied in tunnels dug for this purpose (Branco and Fraas, 1905, p. 11-21, pl. II).

Along the outer rim of the ring-shaped basin which surrounds the central hill, basinward dips, locally quite steep, are recorded from a number of places (Kranz, 1924, p. 82-86; 1936, p. 6-8). Since the Tertiary and younger sediments conceal the structure beneath the lowland, one must try to decide between two possibilities: either the ring depression is chiefly the result of collapse, as it is in the deeper eroded North American examples; or it is chiefly the result of a central explosion which created a very shallow funnel-shaped depression in the middle of which a second, weaker explosion forced the jumbled mass of Lower and Middle Jurassic horizons to the surface. The basinward dips observed along the outer rim and the presence of explosion breccia chiefly within the ring depression (and in minor amounts only) suggest that collapse with simultaneous upsurge in the center produced the Steinheim Basin.

The whole disturbance seems to have taken place above the top of the Triassic. The crystalline basement was certainly *not* involved, whereas in the Ries a large body of the crystalline rocks was removed and shoved and blown out of the "inner basin". The explosion was followed by prolonged outpouring of suevite tuffs, extending southward far beyond the Ries Basin itself.

This contrast is significant: The Ries Basin seems to be the product of the arrival of a large amount of heat carried by gases which, accumulating fast relatively near the surface, led to a major explosion that created the "inner basin" and the body of ejected materials. This was soon followed by the extended suevite tuff explosions. In the Steinheim Basin, the gases rose more slowly above the basement resulting in a largely unsuccessful explosion which produced only a minor amount of ejecta, no explosion crater, and no heat effects other than possibly a prolonged rise of thermal springs, chiefly in the center of the structure.

Shatter cones abound in the Steinheim Basin (cf. figs. 15A, B and 17A, B), from which they were introduced into the literature as distinctive results of explosive shock by Branco and Fraas (1905, p. 36-38). They are found abundantly in the limestone fragments of the jumbled formations of the central hill. There they occur in rocks ranging down to the lowest Middle Jurassic (Kranz, 1924, p. 56). but chiefly in limestones of the lower and middle Upper Jurassic (Malm α to γ, Kranz, 1924, p. 59-61). Remember that no shatter cones have been found in the Ries Basin. Could it be that only unsuccessful explosions produce shatter cones, that they are limited to cryptoexplosion structures? This question will be discussed in the last chapter.

The wealth of freshwater and land mollousks (and mammals) dates the bulk of the freshwater deposits in the Steinheim ring lake as upper Upper Miocene (Sarmatian). No definite evidence of slightly greater age (uppermost lower Upper Miocene, or Tortonian) has been found in its lowest stratigraphic unit such as was found in the Ries Basin (Dehm 1962, p. 76). So while the Steinheim Basin has formed in the same general time interval as the Ries Basin, it rather looks at present as if they had not formed at the same "instant". But this cannot be used as an argument until more detailed information becomes available.

C. The Urach Area.—This area contains the remarkable cluster of volcanic tuff pipes, made famous by Branco's monograph on Swabia's "125 Embryonic Volcanoes" (1894). Here, within a roughly circular area with a diameter of about 40 km (24 mi), over 250 volcanic pipes have now been identified perforating the plateau surface (Georg Wagner, 1956). Most of these (about seven out of eight) are filled with rock fragments and varying amounts of fine-grained tuff, much of it lapilli of olivine-bearing melilite-basalt (Gaiser, 1905). Only three consist of basalt and twenty-one contain basalt associated with tuff (Georg Wagner, 1956, p. 111).

Hans Cloos (1941)[10] studied the region and has given a graphic detailed picture of his structural and textural observations. The material of these tuffs consists of an intimate mixture of small and large fragments of bedrock from

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[10] Cloos points out that these tuffs resemble very closely those described by W. Rust from St. Genevieve County, Missouri (Rust, 1937).

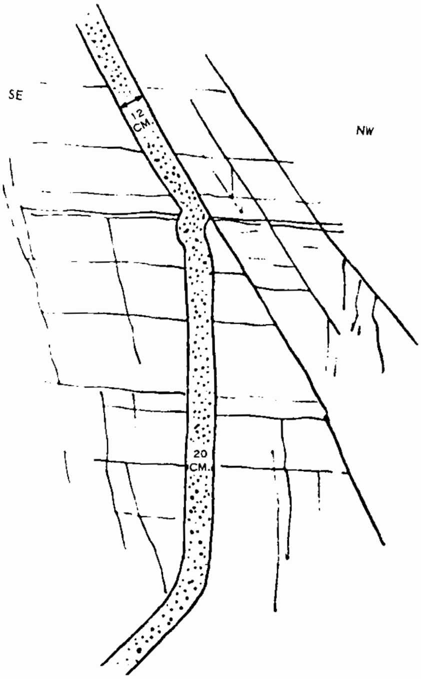

Fig. 8. Dikelet of tuffisite in Upper Jurassic limestone. It consists of minute grains of Triassic, Lower and Middle Jurassic rock fragments and basalt grains. The absence of fragments of the wall rock proves that the material was introduced from below into widening joints. The width varies between 12 and 20 cm (4.7 and 7.9 inches) (redrawn from Cloos, 1941, p. 732, fig. 17, with two minor omissions).

the crystalline basement through the overlying formations, with basalt crystals, fragments, and lapilli. This now poorly consolidated "tuffisite", as Cloos has called this mixture, was capable of carrying upward in the pipes blocks of granite weighing hundreds of pounds (p. 778), as well as of penetrating into narrow joints as a fine powder, forming dikelets only a few inches wide (fig. 8, reproduced from Cloos, 1941, p. 732). The swarms of such dikelets contain recognizable fragments only of rock formations lying below the beds in which they occur. This requires that rock fragments and gas traveled as a dry mixture under high pressure as a gas-tuffisite emulsion (Cloos, 1941, p. 778). D. L. Reynolds (1954) has applied the industrial term "fluidization" to the geological process by which solid or liquid particles are propelled under high gas pressure in a finely divided state. This is the same process which created the dikelets of fine-grained "explosion products" in the Ries.

Some of the larger pipes form relatively steep-sided hills on the slopes of which the contact of the tuffs with the walls and their internal structure can be studied. On the basis of carefully documented observations, Cloos concluded that the tuff pipes began by local, slight lifting of a column of jointed rocks, which caused the preexisting network of intersecting joints to open slightly, providing outlets for the dust-charged high-pressure gases. Where the center of a pipe was blown out, large, marginal blocks, bounded by tuff dikes, sank downward, while the central rock-gas emulsion flowed upward (Cloos, 1941, p. 785, fig. 35). Cloos has estimated that in one of the largest of the Swabian pipes, that of Mt. Jusi, probably not more than 50 percent of the crater surface was due to the upward expulsion of tuffisite materials, while the other half of the crater depression was caused by the sinking of marginal blocks. In some cases, marginal blocks were bent down in a way that suggests support was withdrawn from below, causing them to dip steeply towards the core of the tuff pipe. In the small Aichelberg pipe, e.g., all the Jurassic formations are bent down on the east side, with westward dips increasing to vertical where the red residual soil zone of Eocene age ("Bohnerz") is separated only by a thin wall of tuff from the normal extrusive tuff of the pipe center (Cloos, 1941, pl. 3, opposite p. 752). The white limestones of the upper part of the Upper Jurassic are intensely brecciated ("zerrüttet") away from the center and traversed by a multitude of dikelets of finest tuff near it ("tuffisiert"). The Tetriary red residual soil lies here 250 to 280 m (820 to 900 ft) below its original position (Cloos, 1941, p. 752). Note that beds dipping more or less steeply toward the basin center are general along the outer border of the ring depression of cryptoexplosion structures, as e.g., along the outer rim of the Steinheim Basin.

Cloos has pointed out that steeply dipping blocks of higher formations are similarly found in the South African kimberlite pipes which are of comparable, though somewhat smaller, dimensions. He (Cloos, 1941, p. 790, fig. 36) gives the outlines of representative examples of the two regions drawn on the same scale. According to Poldervaart (oral communication), the similarity between the Urach and kimberlite pipes is even closer than Cloos realized. The kimberlite pipes occur in clusters; in the same general region clusters of melilite basalt occur. The pipes must have fed large explosion craters, which have been removed by erosion in South Africa, but are still exposed in East Africa. The pipes contain blocks of overlying sediments, basement and mantle rocks. A peculiar gas-rich medium is characteristic of the kimberlite-alnoite rock suite. These gases must have been highly explosive, as shown by their geologic occurrence, though the reason for this behavior is as yet not understood.

The roughly circular outline of these denser clustered tuff pipes of the Urach area led Cloos to suggest that they were produced from a single, highly explosive, volcanic center, the gases of which perforated the surface like a sieve.

The geothermal gradient accords with this: It ranges from 1°C in 11.1 m (4.95°F in 100 ft), down to 1°C in 22 m (2.49°F in 100 ft). Its highest value is, therefore, essentially the same as that found at Nördlingen, in the Ries Basin. Its lowest value lies well below it. This difference agrees quite well with the field evidence of the heat effects in the two regions.

In the Ries Basin, enough heat reached the uppermost levels of the crystalline basement to cause partial melting of the most fusible silicates. The gases from the Urach area came from greater depths. They have carried basaltic melt products from below the sialic crust as dry, cold lapilli and crystal fragments through the sialic zone toward the surface of the covering sediments. Much more heat must have reached closer to the surface in the Ries Basin than in the

Urach region. To the writer this seems entirely consistent with the much higher magnetic anomaly over the Ries Basin than over the Urach area.

Those explosion craters ("Maare") in the Urach area which have suffered least erosion contain freshwater sediments with fossils of Upper Miocene age. The rich fauna of one "Maar" (Laichingen) contains only species found also in Steinheim (Dehm, 1962, p. 76).

All these facts fit into a coherent pattern: The probability that two of the three structures lined up in so striking a fashion are due to a chance impact of twin meteorites seems altogether too small to deserve confidence. Chance would have had to provide: (1) the alignment of the Urach area with the other two: (2) the coincidence of this line with that of a narrow belt of magnetic anomalies deriving from the basement; (3) the coincidence of this line with the Danube flexure, by which the Jurassic plateau bends down toward the Miocene basin of the Swiss foreland of the Alps; (4) the coincidence of the Ries Basin, the structure involving most expenditure of energy, with the point of junction of the Ries-Tauber structural axis with the Danube flexure; (5) similar high thermal gradients in the volcanic Urach area and the Ries Basin; (6) the creation of all three structures within a relatively short time interval, viz., in late Tortonian and early Sarmatian time.

THE WELLS CREEK BASIN, HICKS DOME, AND AVON AREA OF TUFFISITE PIPES

The Wells Creek Basin of western Tennessee (Houston and Stewart Counties), the largest well exposed cryptoexplosion structure of North America,[11] lies aligned with the Hicks Dome and a belt of breccia pipes and dikes containing ultrabasic rocks along a structural axis produced by a major flexure zone as well defined as that which bears the Ries and Steinheim Basins and the Urach area. This axis was produced when the upper end of the Mississippi embayment was depressed below sea level in Cretaceous time, reversing the gentle northeast dip of the Late Paleozoic formations into the southwest dip of the Cretaceous and Tertiary formations. The map (fig. 9) shows the broad structural relations as shown in the new edition of the Tectonic Map of the United States (U. S. Geol. Survey and Am. Assoc. Petroleum Geologists, 1961).

About 168 km (105 mi) west-northwest of the Hicks Dome lies the Avon area of explosion breccia pipes in Ste. Genevieve County, Missouri. It also lies along the same zone of flexure which curves around the head of the embayment but is not obviously connected with the other two structures.[12] It is the North American counterpart of the Urach region.

[11] The Manson "disturbed structure" of northwestern Iowa (Calhoun County) lies completely concealed beneath glacial drift and is known only from numerous shallow holes drilled for water. Its diameter seems to be about 20 miles (Hoppin and Dryden, 1958, p. 694-699).

[12] West of the Avon area, almost on a straight line with it, lie two much older cryptoexplosion structures: (1) The Crooked Creek structure, about 96 km (60 mi) to the west, in Crawford County, Missouri, which is younger than Lower Ordovician (Jefferson) time and older than the Middle Pennsylvanian (Desmoinesian) (Hendriks, 1954, p. 52-70); (2) The Decaturville structure in Camden and Laclede Counties, Missouri, about 216 km (135 mi) west of the Avon area, which is younger than the Upper Cambrian Eminence formation and older than the lower Ordovician Gasconade (Bucher, 1936, p. 1071; Krishnaswamy and Amstutz, 1960, p. 1960).

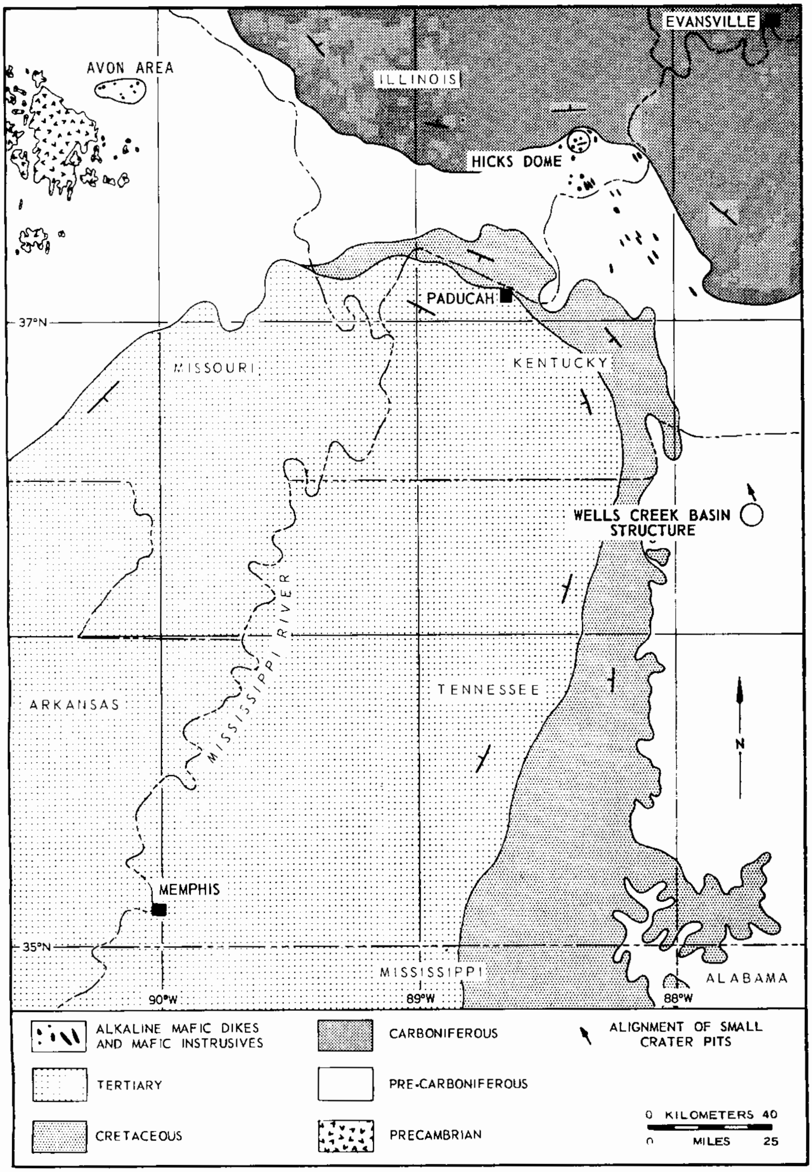

Fig. 9. Map of the structural axis on which lie the Wells Creek Basin, the Hicks Dome, and the Avon area of breccia pipes. Note: Only the location of the structures and of mafic alkaline dikes (exposed or cut in drill holes), breccia pipes, and the trend of three diminutive craterlike pits are shown. All structural details, especially the complex fault system of the Illinois-Kentucky mining district, are omitted (data from Heyl and Brock, 1961; Kidwell, 1947; and U. S. Geol. Survey and Am. Assoc. Petroleum Geologists, 1961, Tectonic Map of the United States, 2nd ed.). (This figure appeared in Nature, v. 197, p. 1244, and is reprinted by permission.)

As in the preceding chapter, important details of the geology of these three structures are given as a basis for a realistic appraisal of the processes that may have entered into their formation.

A. The Wells Creek Basin Structure.—The Wells Creek Basin, a somewhat oval topographic depression measuring 3.2 by 4.8 km (2 by 3 mi), was excavated by erosion of the central uplift. But the structure extends far beyond it, assuming a roughly circular shape with a diameter of about 13.7 km (8.5 mi). It comprises two concentric depressed zones separated by a discontinuous ring of upfaulted blocks and local uplifts along the outer border, suggesting a partial second anticlinal ring, raised, however, to a much lower elevation than that of the central area. The writer's map of the structure (Bucher, 1936, p. 1069, fig. 7) shows that "the northeastern third of the outcrop of the Silurian, Devonian, and Lower Mississippian formations in the central uplift appears offset along a line that cuts across the central uplift from north-northwest to south-southeast. Northeast of this line the central uplift is smaller than southwest of it. A similar asymmetry with reference to the same line is seen even in the two anticlinal rings" (Bucher, 1936, p. 1068).

In the central part, the Lower Ordovician "Wells limestone" lies exposed as a giant breccia, in blocks a hundred or more feet long, standing more or less on end and abutting against each other at all possible angles. The angular spaces between the individual blocks are occupied by finer-grained breccia made up of irregular fragments of dolomite and limestone ranging from blocks over two feet in diameter down to a granular matrix grading into a fine powder, practically identical with the matrix of the tuffisite pipes in the Avon area, described below.

From this central part of the Wells Creek Dome, the writer described the occurrence of abundant shatter cones and pointed out that "the axes of the cones run obliquely across the bedding planes and traverse several layers with a continuity entirely impossible in true cone-in-cone structure. That they are due to mechanical shattering . . . is evident, especially when they are studied in the field". The writer pointed out that Kranz (1924, p. 100) has suggested "that gases under high pressure may be essential to their formation . . . " and emphasized that the fact that the shatter cones in the Wells Creek Basin are found only in the lowest beds exposed looks "as if they had been formed only close to the seat of the force that produced the disturbance" (Kranz. 1924, p. 1070).

Large shatter cones were common in the upper 200 ft of the drill core to be described presently, "at many horizons, particularly well developed at depths of 48 feet and 90-100 feet. The great majority have their long axes horizontal and parallel to each other. Occasionally, the apex may point obliquely up the core". Only "small, poorly defined and incomplete cones were found at greater depth, with the exception of one at a depth of 1237 feet" (Wilson, 1953, p. 766; for good photographs of some of these cones, see Dietz, 1959, pls. 7, 8).

Wilson (1953, p. 765-768) studied the core of a 2000-ft well drilled in 1947 in the center of the dome by the Ordman Company in search of salt. He writes: "The examination of this core was an unusual privilege and in a way an eerie experience. The deep fingers of grotesque injection dikes and the intense, bizarre, ever-changing patterns of brecciation and deformation are awe-inspiring" (p. 767). "The injected breccia consists of a matrix of pulverized rock containing fragments of chert, limestone, and dolomite of great variety and usually less than half an inch in maximum dimension. It is much darker than the rock into which it was injected. Calcite veins and vugs, dolomitization, silification, occurrence of pyrite, manganese dendrites, chalcedony rings around nuclei abound" (p. 766). The writer visited the site of the drill hole some five years later and was surprised by the abundance of well-rounded sand which had been used for grouting the hole. Most of the samples of the core Dr. Wilson had in his office showed the same sand filling cavities apparently well down in the drill hole. Wilson speaks of the vicinity of the drill holes as "a local area of highly porous rock" and ascribes the porosity to groundwater action.

The main path which the explosion took must have been very crooked. That seems to the writer the simplest explanation of the fact that between the levels 1067 ft and 1743 ft, "the frequence and thickness of the dikes are greatly reduced . . . with several intervals of as much as 100 feet having no dikes", and "the great majority of those present are ¼ to ½ inch thick" (Wilson, 1953, p. 767). From 1743 ft to 1930 ft depth brecciation recurs, with many dikes between 1786 ft and 1799 ft. The lowest dike was cut 11 ft above the bottom of the hole which lies in "sheared, but unbrecciated bedrock" (p. 767). These dikes recall those of fine-grained explosion products in the Ries Basin and of tuffisite in the Urach area.

B. The Hicks Dome and associated belt of mafic dikes and breccia pipes. —As early as 1954, Brown, Emery, and Mayer suggested that the Hicks Dome in southern Illinois "is an incipient or uncompleted example of a cryptovolcanic structure" (Brown, Emery, and Mayer, 1954, p. 897). This dome is a rounded uplift, slightly elongated in a northwest-southeast direction, with a diameter of over nine miles. "The core of the dome, where the rocks dip 10-15 degrees, includes limestone, chert, and black shale of Devonian age in which there are a few tabular and possibly oval-shaped pipelike masses of breccia, some radioactive areas, and an altered mafic dike" (Trace, 1960, p. 63). The geologic map of the Hicks Dome area (Brown, Emery, and Meyer, 1954, p. 894, fig. 1) shows that it is cut into fault blocks by some of the numerous northeast-trending faults that characterize the fluorite district at the head of the Mississippi embayment. It must, therefore, have formed earlier than, and independent of, that fault system.

From the map in a recent paper by Heyl and Brock (1961, p. 5), the writer has reproduced in figure 10 only the elements that enter into this discussion; all faults are omitted, even those concentric with, and therefore part of, the Hicks Dome. To their map, he has added information pertinent to the following discussion.

Note first the clustering of explosion breccia pipes near the center of the dome and the presence of others and of eight peridotite dikes "having alkaline affinities" within the confines of the structure. No igneous or metamorphic rocks have been identified in the breccia from the center of the dome (Trace, 1960, p. 63).

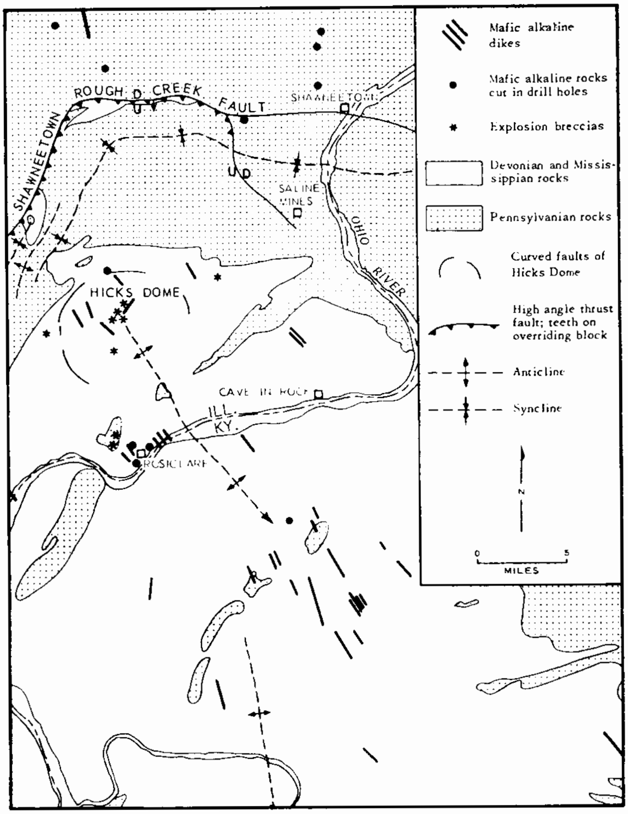

Fig. 10. Map of the Illinois-Kentucky mining district reproduced from Heyl and Brock (1961, p. 5) to show the distribution of mafic alkaline rocks and of explosion breccia pipes, the Shawneetown Rough Creek Fault with associated fold axes, and the few curved faults of the Hicks Dome (redrawn from Heyl and Brock, 1961, p. D-5, fig. 294.2). Note: All the very numerous younger, north-northeast- to east-northeast-trending faults, the ore bodies, and locations of mines are omitted.

A 2944-ft test well, the Hamp hole, drilled in the approximate center of the dome found the sedimentary rocks below a depth of 1605 ft strongly brecciated This suggested to Brown, Emery and Meyer (1954, p. 895, fig. 2) that the hole had cut an inclined[13] breccia dike. The hole ended in intensely brecciated Ordovician rocks. Fluorspar was found "in virtually every sample cut in the Henry Hamp (well), either as breccia filling, veins, incipient veinlets or replacement" (Brown, Emery, and Meyer, 1954, p. 897). The breccia in the lower 1600 ft of the hole is strongly mineralized "containing a matrix of 2 to 10 percent fluorite, much barite, quartz, calcite, and a little pyrite, sphalerite, galena. biotite, and apatite. Thorium, rare earths, beryllium, zirconium, and niobium are intimately associated with the fluorite and barite and increase in amount with these minerals" (Heyl and Brock, 1961, p. 6). In a radioactive breccia dike, about 10 ft wide, traced for a horizontal distance of over 260 ft

[13] Or rather, in the writer's opinion, one of an irregularly crooked shape.

and (by drilling) to a depth of over 100 ft, Trace (1960, p. 63) identified an unusual yttrium-thorium monazite of the type that is most likely to have been formed at great depth in the earth's crust (Heyl and Brock, 1961, p. 6). This monazite gave a lead-alpha age of 90 to 100 million years, or "middle" Cretaceous (Heyl and Brock, 1961, p. 61).

Figure 10 shows that beyond the Hicks Dome there is a broad belt of scattered mafic alkaline dikes which trends southeast to south-southeastward. Most of these dikes consist of sedimentary breccias within a mafic alkaline matrix, like those within the dome. A line drawn from the center of Hicks Dome to that of the Wells Creek Basin, 90 miles away, lies well within this belt of mafic breccia dikes.

This relationship recalls the line that connects the Ries Basin with the Urach area of explosion pipes. Here again we find evidence of heat effects at one end (the Hicks Dome) and a cryptoexplosion structure at the other (the Wells Creek Basin).

But this is not all. North of the Wells Creek Basin there lie three small shallow crater-like depressions described by Wilson in 1953, which are filled with clays and sands, the largest containing beds of lignite. From south to north their dimensions are: (1) Cove Spring Hollow depression, perhaps a mile across, depth unknown, the area inferred from the extent of augur borings: (2) Indian Mound depression, about 2000 ft in diameter and more than 263 ft deep, the depression having a low central hill; (3) Austin depression, no larger than 375 ft in diameter and at least 40 ft deep.

The nature of the rocks through which the best explored of these pits are cut rules out the possibility that they are giant sinkholes (see Wilson, 1953. p. 765, and p. 759, fig. 3). Wilson concludes that the Indian Mound depression "represents a doughnut-shaped explosion crater with a central hill" and that the other two craters are "small meteoric pits, or craters, without known central hills". He concludes "that a swarm of meteors (sic) approached the earth's surface from the south, or a single meteor fragmented into at least four pieces before striking the surface" (p. 765).

But a line drawn through these three minor "craters" trends north-northwest, i.e., in the same direction as the mafic dikes southeast of Hicks Dome. These three separate meteorites (or fragments of one original one) did a neat job in falling in a line, which conforms to the trend of the regional structure.[14]

These craterlets near the Wells Creek Basin structure have, moreover, a special significance. The careful analysis of the sediments, especially of their flora, narrows the time interval within which they were formed to the post-Eutaw, pre-Wilcox interval (Wilson, 1953, p. 764). This compares favorably with the age of the Hicks Dome, indicated as 90 to 100 million years. This is not as close a time determination as is possible in the case of the Urach-Ries axis. The two events in the United States took place after the middle of the

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[14] A fourth craterlet, the Little Elk Creek depression, lies within the Wells Creek Basin, in the northwest quadrant, four miles west of Cumberland City. It is interpreted by Wilson as being the product of a smaller fragment that trailed behind and fell inside the larger crater (Wilson, 1953, p. 765). Remember that similar small "craters" exist in the floor of the Ries Basin.

Cretaceous and before Early Eocene time. They may very well have been as closely connected as their German counterparts.

C. The Avon Area of tuffisite (breccia) pipes.—The presence of ultrabasic rocks associated with breccia "dikes" in St. Genevieve County, Missouri, has been known for half a century (for earlier reference, see Kidwell, 1947, p. 6) ; but its significance was not realized until Rust (1937) published his paper on "Explosion volcanism in southeastern Missouri". He recognized the volcanic nature of the peculiarly localized patches of "breccia", which had been first described as "conglomerates", and very properly applied Daubrée's term "diatremes"[15] to the pipes that contain them. He found 71 of them. In a more detailed account of this area, Kidwell (1947) brought the total number of pipes up to 78, scattered in clusters within an oval area of 192 sq km (75 square mi), with the long axis measuring about 17.6 km (11 mi) and trending east-west (Kidwell, 1947, map, p. 13). All the pipes are small. Some of the larger ones measure 180 to 300 m (300 to 500 ft) in diameter. (See magnetic intensity maps in Kidwell, 1947, pls. 8, 9.)

More than half of the pipes studied by Kidwell consist of abundant breccia fragments in a tuffisite matrix, i.e., a fine-grained groundmass of pulverized rock with volcanic material mixed in, chiefly in the form of lapilli (up to 3 cm in diaemter). The others belong to the two extremes: breccia with no volcanic materials on the one hand, and others (in dikes rather than pipes) consisting chiefly of lava, with little or no rock fragments and almost no lapilli (except in the marginal contacts of some). All the truly igneous rock bodies consist of more or less altered ultrabasic materials. The characteristic concentric arrangement of small melilite crystals in the lapilli is identical to that seen in the lapilli of the Urach region (Cloos, 1941, p. 718; Rust, 1937, p. 48). The presence of quantities of these lapilli in the tuffisite is eloquent evidence of the gaseous dispersion of the residual liquid at depth through the explosion which pulverized the materials of the higher part of the crust.

The turbulence that resulted from the explosive action of the gases is evident from the degree to which materials ranging through a vertical stratigraphic section of about 4000 ft have been intermixed (Kidwell, 1947, p. 30). Fragments of granite and other basement rocks are found at most surface exposures brought up from below, while fossiliferous fragments of Devonian limestone have been carried down from an original level well above the present surface (p. 30-31).[16] It is probable that the presence of materials drawn down from above indicates pipes which never blew out at the surface.

Recently, during a brief visit with Dr. Frank G. Snyder, chief geologist for the St. Joseph Lead Company, the writer saw a drill core which had penetrated to the basement, a coarse-grained pink granite. Above the granite, the

[15] In this paper, the writer is not using this term (which has been generally used in Europe since the publication of Daubree's [1879] "Études synthetiques de géologie expérimentale"), because most American geologists do not know it, or distrust it because they are uncertain of its meaning. A spot check shows that it appears in none of the indices of four leading textbooks on "general geology" and in only one of three textbooks on "structural geology".

[16] The nearest Devonian rocks lie today some five miles northeast of the Avon area, as narrow slivers along the eastward-trending end of a major fault zone which enters the St. Genevieve fault zone from the northwest (McCracken, 1961, Geol. Map of Missouri).

drill core had cut into the tuffisite pipe which here consists of granite fragments averaging perhaps 1/4 inch in chance section, with some as large as 3 inches. all lying in a greenish-gray fine-grained matrix full of dark green grains. probably lapilli. Higher up the drill had missed the pipe, the core consisting of well-stratified sediments. Still nearer the surface, the breccia was cut again. consisting here chiefly of sedimentary fragments with pieces of granite scattered among them. Again missing the explosion pipe, the drill core was made up of the undisturbed Bonneterre formation in which the drilling had started. The contact between tuffisite material and the undisturbed beds through which it is cut is sharp and clean. In this, and in the irregularly curved shape which permitted the drill to pass into and out of it repeatedly, this pipe conforms to the well-known character of the kimberlite pipes of South Africa and the tuffisite pipes of the Urach region.

The breccia pipes of the Avon area must have come into existence after the Devonian and before the complete removal of Devonian rocks from the northeastern flank of the Ozark uplift. The presence of peridotitic rocks of post-Permian age in eastern Kansas and of petrographically similar rocks of Cretaceous age in central Arkansas suggest a Cretaceous epoch of explosive. deep-seated activity for the whole region (Kidwell. 1947. p. 34).

Here then, we have:

(1) A cryptoexplosion structure at the south end of a belt marked by minor craterlets in the south and by alkaline mafic breccia dikes in the north. leading up to the Hicks Dome with its explosion breccia pipes. Still along the same, now curving. belt lies the Avon area of 78 volcanic breccia pipes, recalling the Urach area at the far end of the Steinheim-Ries Basin axis.

(2) They were both formed within a relatively narrow time interval and may well have been "penecontemporaneous".

(3) The belt defined by these end structures bears a demonstrable relation to the regional structure, a hingeline produced by the sinking of a basin, as in the Ries-Steinheim-Urach axis.

THE VREDEFORT DOME AND ITS POSITION WITHIN THE BELT OF MAFIC INTRUSIVES BETWEEN THE ZAMBESI AND ORANGE RIVERS IN SOUTHERN AFRICA[17]

A. The belt of basic intrusives.—Like the largest cryptoexplosion structures of Europe and America, the Vredefort Dome lies on a major structural axis, but one of a wholly different nature. Figure 11 (Cousins, 1960, p. 187, fig. 3) shows that it is one of four roughly circular areas in the Orange Free State which lie on a straight line over 430 km (270 mi) long, trending toward the center of the vast Buchveld area, in a north-northeasterly direction (about N 27° E). In Southern Rhodesia a second structural axis trends a little more northerly (N 17° E), also toward the center of the Buchveld intrusive center. This is the Great Dyke, one of the great ultramafic terranes of the earth's surface. The total distance from the northern end of the Great Dyke to the Trompsburg structure is more than 1450 km (900 mi).

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[17] The writer thanks his friend and colleague, Arie Poldervaart, for literature references. liberal loans from his personal library, and much invaluable advice.

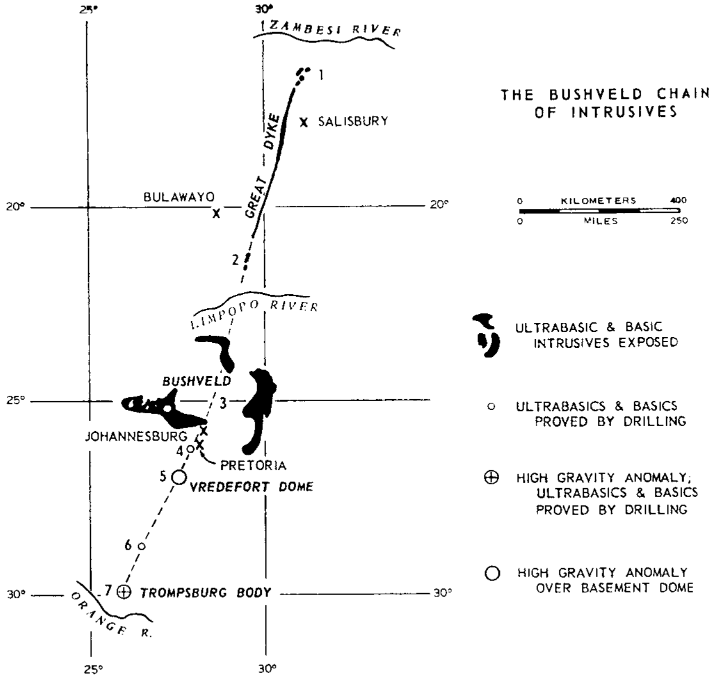


Fig. 11. Map of the Bushveld chain of intrusives (redrawn from Cousins, 1960, p. 187, fig. 3, with changes in symbols and omission of some names). (This figure appeared in Nature, v. 197, p. 1245, and is reprinted by permission.)

The Great Dyke (Worst, 1960) is a relatively straight layered body of mafic and ultramafic rocks, over 530 km (330 mi) long and between 5 and 11 km (3 and 7 mi) wide. It was intruded into a terrane of crystalline rocks. chiefly granite, with occasional zones of metamorphic schists. Intrusion proceeded from four centers, each producing a sequence of similar structure and component rock types, but differing from each other in the number of layers. their thickness, and distribution. In each complex, the component layers maintain a remarkably constant average thickness. All dip toward the center of the Great Dyke from their borders. while longitudinally they plunge toward each center of eruption within each complex.

Where seen in a few good exposures and confirmed by inclined drill holes that passed from the rocks of the Dyke at the surface into the granite at depth. the borders of the Great Dyke are fault contacts dipping inward at angles varying from 25° to 70°. On either side. the Great Dyke is paralleled by a long quartz gabbro dike which disappears where the central portion of the Dyke is most depressed. These companion dikes seem to be the last phase in the regional differentiation process.

In length, width, and even in the northerly direction, the Great Dyke resembles the complex young grabens of the East African graben belt. These young grabens are, of course. much wider at the surface. But with border faults converging downward toward the base of the crust at angles averaging 45°, perhaps to a depth of 5 km or more in earlier Precambrian time, the border faults of the Great Dyke would converge to something like 4 km from a possible surface width of 14 km. Near the base of the crust, where the faults would tend to become merely boundaries between plastically moving rock masses, the ultramafic rocks of the subcrust would tend to rise isostatically in response to the lowering of the surface of the graben. Repeated intrusions of ultramafic materials into the base of the sinking graben block seem feasible in view of the plastic rather than the viscous conditions of the rock in moderate depth. The ultimate synclinal structure may be the result of final compaction and settling of the cooling rock body, perhaps combined with a last sagging of the graben.

The coarse grain of the ultramafic rocks requires the presence of a roof covering. Remnants of such a roof are preserved in bodies of schists measuring up to three miles across, where the Dyke cuts belts of metamorphosed sediments.

Recently a comparable complex was discovered (Worst, 1960, p. 12) in the Zambesi valley about 128 km (80 mi) west of the Great Dyke. It is some 40 km (25 mi) long and consists of rocks similar to those in the upper layers of the Great Dyke.

The Bushveld complex (Hamilton and Cooke, 1960, p. 238) of intrusive sheets and connecting dikes which lies at the center of this vast alignment of mafic and ultramafic rocks, is about 400 km (250 mi) wide east to west, and has nearly the same dimension in a north-south direction. The combined thicknesses of these intrusions amount to 6 to 8 km (4 to 5 mi), wedged between layers of the thick Transvaal system (15,000 to 28,000 ft); the lower horizons carry the same concentrations of platinum and chromium that are found in the Great Dyke.

The Trompsburg structure in the Orange Free State at the far end of the southern line of intrusives is roughly circular, and, from the size of the gravity anomaly, its diameter is estimated to be 48 km (30 mi) (Cousins, 1960, p. 286). It was first discovered by the high gravity and magnetic anomalies above it. Drilling showed that it contains the same mafic and ultramafic rocks that characterize the whole belt; the same was proved for the minor intrusions marked 4 and 6 on figure 11. The Vredefort Dome lies neatly in line with the whole belt of deep-seated intrusions (Dietz, 1961a, b, 1962; Bishopp, 1962).

B. The Vredefort Dome.—The Vredefort Dome (fig. 11) lies almost halfway between the center of the Bushveld area and the Trompsburg structure. It produces a strong gravity anomaly which must reflect the presence at depth of a body of rock not less mafic than gabbro (Maree, 1945). The uparching of the Early Precambrian granitic basement in the center of the Vredefort structure must. therefore, be related to the emplacement of such a mafic intrusive body. The exposed portion of this dome has a diameter of 40 km (26 mi), suggesting the presence of a substantial body of mafic rock below similar to that at Trompsburg. There. geophysical interpretation of the gravity anomalies indicates a "gigantic mushroom-shaped body some 30 miles (48 km) in diameter" (Cousins. 1960, p. 186).

These two major centers of intrusive activity of comparable dimensions are thus aligned along a structurally prescribed direction. In this respect they resemble the Ries-Urach centers of explosive activity which, together with the Steinheim Basin, line up in a direction parallel to the Danube flexure.

In the Vredefort Dome, the granitic basement was uparched to an elevation greater than the total thickness of the sediments of the overturned rim, i.e., at least 13.000 m (42.600 ft). There is abundant reason to think that the strength of crystalline rocks is insufficient, probably by orders of magnitude, to hold the shape of a plug of 12.8 km (8 mi) high and 20 km (12.5 mi) radius. It would have to flatten under its own weight as soon as its height became greater than could be supported; this would lead to overturning at least on the steepest side, i.e., on the north and northwest flank of the Vredefort Dome to which overturning is limited. (See cross sections in Daly, 1947, p. 128, fig. 2, after Maree, 1945.)

Such local plastic yielding along steep flanks of more or less oval crystalline uplifts of mountainous proportions is not uncommon (Bucher, 1933b, p. 169-173). The Bighorn Mountains of Wyoming, for example, are about 160 km long (100 mi) and up to 70 km (40 mi) wide. The southern two-thirds of the Bighorn uplift is steepest on the northeast side; the northern third is steepest on the west side. In the northern third, the crystalline basement has been exposed by erosion, some 1525 m (5000 ft) above the surface of the adjoining Bighorn Basin, in an area almost 40 km (25 mi) long and up to 16 km (10 mi) wide on the west side of the mountains (Love, Weitz, and Hose, 1955). For a distance of almost 15 km (10 mi) along that front, the normal basinward dip of 20° to 30° of the sedimentary cover becomes oversteepened and overturned, so that for some distance the beds dip about 30° upside down into the mountainside. A minor thrust cuts off a small part of the section. Over 1800 m (6000 ft) of Paleozoic and Mesozoic formations are involved in this overturn. The total difference in the elevation of the basement surface from the top of the uplift to the floor of the adjoining basin amounts to about 10 km (6 mi), but less than half of this distance is involved in the overturning. The difference between this structure and the overturning on the northwest flank of the Vredefort Dome is solely one of scale.

Such plastic behavior is entirely consistent with the elasticoviscous properties of the rock materials, so long as the deformation takes place on a time scale commensurate with their high coefficient of viscosity (Bucher, 1956, p. 1298-1301). The writer cannot comprehend in terms of the physics of materials how instantaneous impact could produce the picture which Dietz paints: "The explosion pulse centrifugally impels the sedimentary beds outward, peeling them back and overturning them like a gigantic flower opening its petals to the sun". To the writer, this "analysis . . . seems more intuitive than theoretically rigorous", to use Dietz's own comment on someone else's words (Dietz, 1961a, p. 506).

That the uparching of the Vredefort Dome went on simultaneously with the emplacement of the mafic core appears probable. The dolerite intrusions ("epidiorites") in the collar resemble the Bushveld dolerites petrographically and chemically (Poldervaart, in press) and were emplaced much before the alkalic granites, which, by their position with reference to the axis of symmetry of the Vredefort Dome, show their genetic relation to the uplift. Seen in this light, the whole structural complex of the Vredefort Dome must have been essentially completed before explosion phenomena appeared. This view is, of course, the exact opposite of Dietz's (1961a, b, 1962). It claims only to be consistent with observations elsewhere and with the little that is known about the inelastic behavior of rock materials.

Poldervaart (in press, especially figs. 1, 2) has provided field data which test the rival interpretations. He secured statistically significant measurements of joint patterns in the exposed surface of the Archean granite. This pattern should be radically different for the dynamic conditions implied in the two hypotheses: Hypervelocity meteorite impact on the one hand, which caused the sedimentary cover, 13,000 ft thick, to recoil like the "petals of an opening flower", and the unspectacular ("conventional") slow-motion uparching of a crystalline dome on the other.

Poldervaart found that vertical and near-vertical joints predominate, as is common on uparched rock surfaces. The joint patterns differ considerably at the nine well distributed localities where he obtained his measurements. In most cases, the influence of observable structural conditions was recognizable. At five localities within one to three miles from the edge of the sedimentary cover, two sets of joints intersecting at right angles are clearly determined by the (by no means circular) outline of the exposed area, one being parallel, the other normal to the border. In the northern part of the area, the "Bushveld trend" (NNE) shows up clearly at three localities lying within 8, 11, and 18 miles respectively from the southern end of an alkaline dike of the same trend which cuts the outer part of the rim (Poldervaart, in press, fig. 1). When the joint patterns are plotted on the map at their proper locations, the lack of a pronounced radial arrangement with reference to the center of the Dome becomes apparent.

All this follows as a matter of course from "conventional" tectonics, according to which the differential movements in the granite core are guided by overall form changes of the core and zones of weakness. The writer does not know what the fracture pattern resulting from a meteoric trauma should be, but he suspects that it would differ violently from the "normal" picture presented.

Two kinds of "shock" phenomena are well developed in the Vredefort Dome: shatter cones and dikes of pseudotachylites.

Shatter cones are present in all rocks that antedate the explosive phase, from basic schist inclusions in the Archean granite to the Bushveld dolerites and the (relatively fine-grained) alkali granites and all sediments, especially quartzites of the Vredefort "ring" (Hargraves, 1961, p. 2). No shatter cones have been recognized in the relatively coarse-grained Archean granites, nor in the pseudotachylite dikes.

Wherever shatter cones have been found *in situ* in sediments, their axes lie parallel to the bedding planes and their apices point upward. From this one would conclude that the beds were already dipping strongly and therefore parted more easily parallel to the bedding under the vertical impact which produced the shatter cones. But Dietz and Hargraves assert that the shatter cones were produced in horizontal beds by vertical meteorite impact, with their axes parallel to the horizontal beds, and carried to their present positions when the 13.000 feet of sediments recoiled into their present positions. How the cones could maintain their shape while the beds were bent through 120° to 150° is not clear to the writer.

Pseudotachylite is the name for a dark rock that traverses all the rocks of the Vredefort Dome in the form of anastomosing and interlacing dikelets and dikes which form a wholly irregular three-dimensional pattern. The material resembles the black basaltic glass called tachylite. It is not a glass at all, but a structureless microbreccia made up of thoroughly pulverized rock material (Willemse, 1938, p. 101-111). The comminuted rock material must have entered the rock fissures as fine, very dry powder. As such, it seems to be an extreme type of tuffisite as suggested by Reynolds (1954) and must have been injected with great force, much like the tuffisites of the Urach and Avon areas and of the Wells Creek Basin.

The development of pseudotachylite dikes in the huge Vredefort Dome should lead one to expect coesite and stishovite to be well developed. But none have been found so far.

The coincidence of supposed "astroblemes" with purely terrestrial structures associated with evidence of deep-seated volcanism seen in the European and North American structures described in the first two chapters appears to the writer sufficient reason to reject the hypothesis of meteorite impact. The assumption that a giant meteorite happened to strike a point precisely in line with structures produced by such large-scale deep-seated intrusive activity within the same general (earlier Precambrian) time interval, producing a structure of similar dimensions 35 km (22 mi) away, seems to the writer to carry the original hypothesis *ad absurdum*.

As three of the four cryptoexplosion structures discussed in this paper contain shatter cones and one carries much coesite and possibly stishovite, neither the presence of one nor the other can be used as evidence of meteorite impact.

OBSERVATIONS USED TO PROVE METEORITE IMPACT

The sudden shift in favor of meteorite impact as the explanation of cryptoexplosion structures was brought about by the thought that shatter cones and the high-density phases of silica, coesite, and stishovite, require for their formation the enormous energies delivered by the impact of giant meteorites, i.e., meteorites large enough not to be slowed down significantly by the earth's atmosphere. In view of the negative evidence of the historical record set forth in the preceding pages, it is necessary to scrutinize the factual and logical basis of these and other features which are thought to demand meteorite impact for their origin.

A. Shatter cones as evidence of meteorite impact.—Shatter cones are generally interpreted as conical fracture surfaces produced under a system of stresses so disposed that the maximum principal stress (compressive) acted parallel to the cone's axis, while the other two principal stresses were equal and represented a minimum value, producing equal tension in all directions at right angles to the axis. The apical angle, accordingly, is the angle of shear which depends on the physical properties of the material. at given conditions of confining pressure and temperature. and on the rate of application of the axial differential stress.

The surface of a shatter cone is typically covered with (partial) subsidiary cones. their apices all pointing upward. This characteristic pattern is poorly developed in some cones. but in many it is striking and highly ornamental. It will be discussed more fully below.

In three papers. Dietz (1947. 1959. 1960.) has given excellent descriptions and pictures of shatter cones from a number of American cryptoexplosion structures. as well as from the Steinheim Basin and the Vredefort Dome; he has developed arguments designed to prove that the speed of meteorite impact is required to produce shatter cones in solid rock. Dietz was so convinced of this that. when he found no shatter cones on Jeptha Knob (Kentucky) he concluded "that this structure is probably not of the same type as the others" (Dietz. 1960. p. 1782). meaning apparently that it is not a meteorite scar. Yet the Jeptha Knob structure exhibits all features characteristic of a cryptoexplosion structure (Bucher, 1925; 1936. p. 1056-1061).

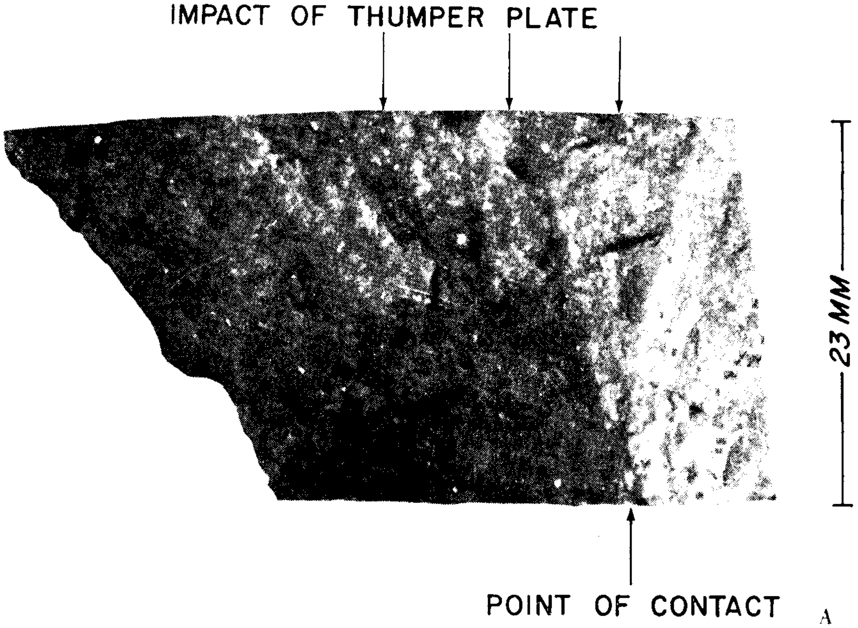
Shoemaker. Gault. and Lugn (1961) have demonstrated that a sharp blow is necessary to produce shatter cones in solid rock. At the Hypervelocity Ballistic Range at the Ames Research Center. they fired a small (4.76 mm) aluminum sphere from a light gas gun at a block of fine-grained sandy dolomite rock. The sphere struck the machined surface of the target at a perpendicular incidence with a speed of 5.61 km (18.400 ft) per second. Three minute but perfect shatter cones were formed, with basal diameters of 2.0 to 7.5 mm and apical angles of 45°. These cones pointed upward because the free surface surrounding the point of impact permitted the material to spread laterally at right angles to the axis of compression and thereby provided the stress distribution required for the formation of the conical fracture surfaces.

Simple tests made by the writer demonstrate the rather self-evident postulate that the position of the free surface and the point of contact determine the direction in which a shatter cone points. not the direction of impact. The tests were made with a "thumper" device (used by seismologists) which drops a heavy steel plate (3 tons) from a height of 9 ft. In the first test. the thumper plate was dropped on a tabular plate of rather coarsely crystalline limestone resting on a layer of fist-sized rounded pebbles contained in a wooden box with low rim. Only a few reasonably good conical surfaces were obtained. one of which is shown in figure 12a. A few subsidiary apices show faintly on the cone. Here the impact came from above. the free surface and point of contact were on the underside. and the cone pointed accordingly away from the direction of impact. The same arrangement was used in a second test. but roller bearings of uniform size in a wooden box resting on a steel plate were used. the steel spheres projecting 1.5 mm above the rim. A used lithographic limestone

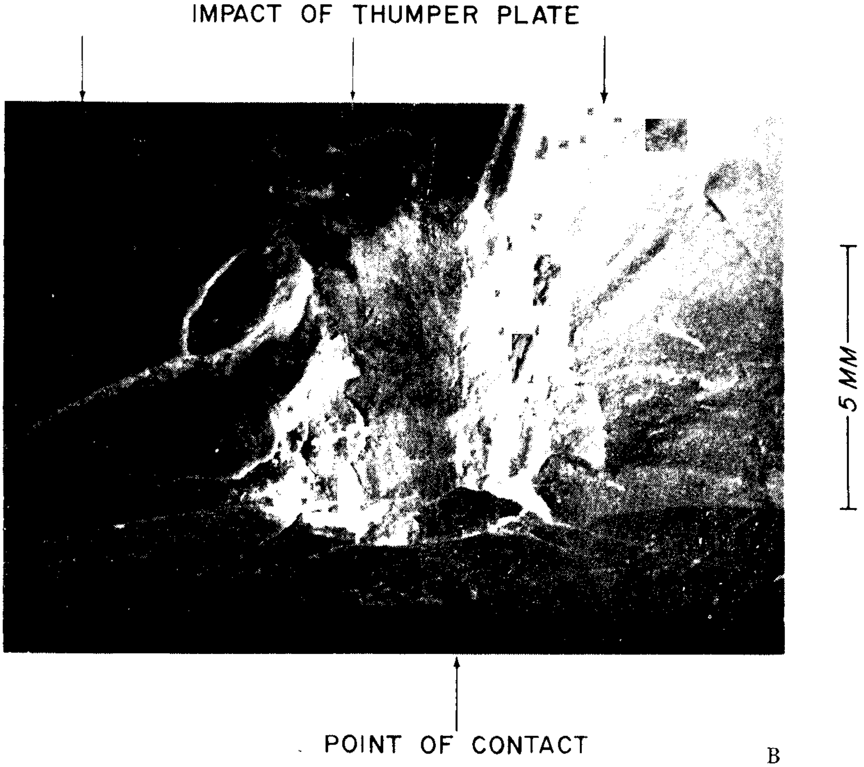
Fig. 12.

A. Primitive shatter cone produced in a plate of crinoidal limestone resting on an uneven layer of coarse, round pebbles, by impact from above of a 3-ton thumper plate (experiment by Bucher in 1961).

B. Primitive shatter cone produced in a plate of lithographic (Solnhofen) limestone resting on a layer of steel ball bearings, by impact from above of a 3-ton thumper plate (experiment by Bucher in 1961).


IMPACT OF THUMPER PLATE
23 MM
POINT OF CONTACT

A


IMPACT OF THUMPER PLATE
5 MM
POINT OF CONTACT

B

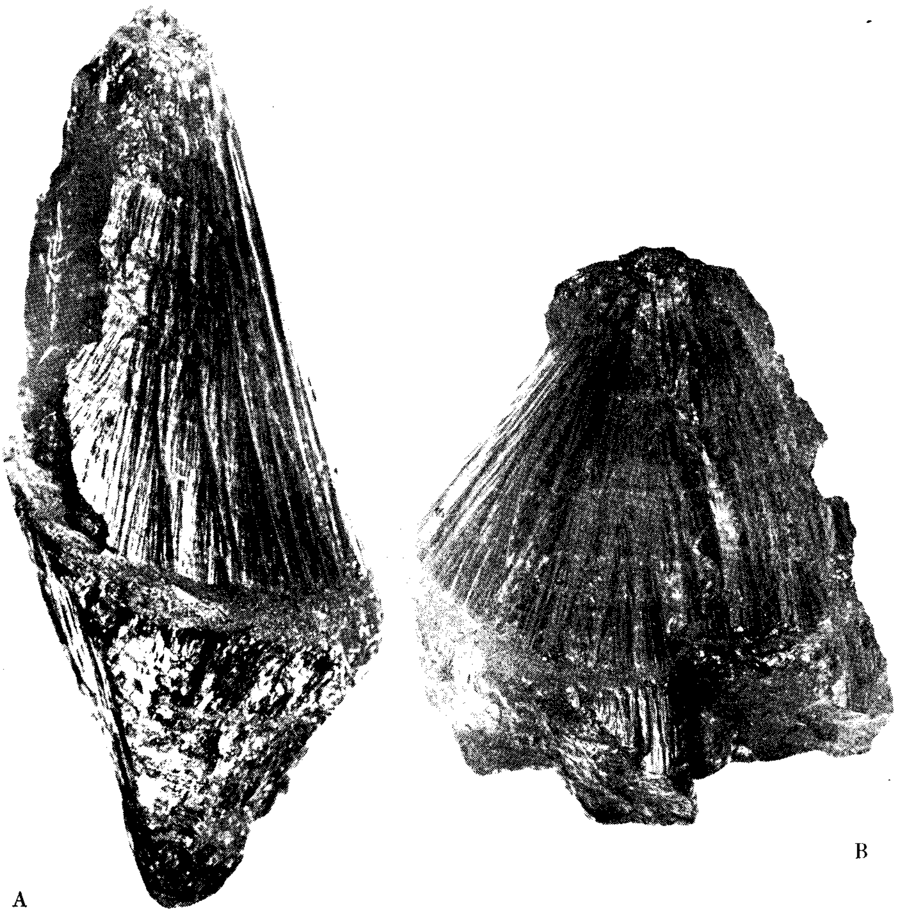


Fig. 13A and B. Double shatter cones in bituminous coal. Note: The transverse banding is stratification in the coal, not wrinkling. About ¾ natural size (in the collection of Dr. Paul H. Price, Director, West Virginia Geological Survey).

plate was laid on top of the spheres to be struck from above by the thumper plate. Figure 12b shows a typical result. The steel sphere was impressed into the limestone which was crushed to powder along the imperfect conical fracture surface. Even so, the tendency to develop subsidiary cones is recognizable.

These primitive tests demonstrate that hypervelocities are not required to produce shatter cones. This conclusion is borne out independently by the specimens shown in figure 13a and b, as fine examples of shatter cones as the writer has seen. But they consist of bituminous coal[18] and were presumably picked up

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[18] Note that the horizontal banding is the reflection from alternating layers of bright and dull coal (vitrain, fusein, etc.). The straight profile shows that they are not transverse corrugations such as are typical of cone-in-cone in limestones. The writer saw and examined these specimens in the collection of Dr. Paul H. Price, Director of the Geological Survey of West Virginia, to whom he is indebted for the photographs and for permission to publish them at this time.

from a coal car. It is not known where they came from, but it is safe to assume that they were not made by meteorite impact.

One aspect of these coal shatter cones deserves special attention: Both consist of two cones with apices pointing away from a common base in a shale parting such as is common in coal seams. Since the apices mark the points where fracturing started, they must lie where extension, parallel to the bedding, reached the breaking point first, i.e., in the midst of the clean coal. The fractures played out toward the impure coal. If the weight of the overburden fixed the position of the principal compressive stress, shrinkage of the clean coal may have provided the lateral extension. These shatter cones, like all fractures, started when the rate of extension exceeded the rate at which the coal substance could adjust itself plastically to permanent deformation. This inference leads to a conclusion of importance to this inquiry.

Substances with a minimum capacity to adjust to form changes by "creep" or plastic "flow" are called "brittle". When this capacity is very great, the substance is termed "ductile". It would be better to speak of ductile or brittle behavior under given conditions. One of these is the rate of application of stress. "Shoemaker's pitch" ("stitching wax") is highly ductile at room temperature. A cube of it will spread out into a thin layer under its own weight in a few hours. But when hit a sharp blow it splinters like glass;[19] if it were possible to increase the brittleness of a rock, less force would be required to produce fracturing in general and conical shattering in particular.

One way of making a rock more brittle would be to decrease its cohesion by filling its pores with gas under high pressure. This is precisely the condition widely postulated by geologists in their attempts to explain the localized violent phenomena associated with cryptoexplosion structures.[20] It may be visualized as follows: Gas, primarily water vapor, is introduced from below under high pressure into a series of relatively porous and permeable rocks sealed off on top by a relatively impervious formation. As the pressure rises in the pores, the whole rock undergoes strain which will lead to the formation of fractures that are small compared to the dimensions of the whole deforming rock body. With the rock made brittle by the expansive gas pressure, shatter cone fracturing may be expected to take place under far less pressure than would be required for the same rock in the laboratory. All this would take place before the overall pressure leads to the abortive attempt to blow off the roof which, according to this hypothesis, produces the cryptoexplosion structure. This line of thought leads to reasonable explanations of the peculiarities of form and distribution of shatter cones:

(1) Shatter cones can form in pairs, sharing a common base. Figure 14a shows one of the specimens collected during the summer of 1962 in the Steinheim Basin by our field party. It is a counterpart to the coal specimens shown in figure 13 and may indicate the same condition, viz., fracturing starting in

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[19] A cube of stitching wax will break along oblique shear planes like a rock under the impact of weight. For photographs illustrating this contrasting behavior of stitching wax, see Bucher, 1956, pl. 2, figs. 2, 3, opp. p. 1302.

[20] The thought that the presence of high pressure gas in the rock pores may have played a role in the formation of shatter cones was expressed by Kranz, 1924, p. 100.

Fig. 14.

A. Double shatter cone in Upper Jurassic limestone. Collected in 1962 in cellar excavation on Steinhirt, central hill in Steinheim Basin.

B. The same cone seen from above, to show characteristic curving pattern of radiating bifurcating ridges and grooves.

the (presumably) slightly more porous main part of the limestone layer and flaring out toward a slightly less porous zone.

(2) Shatter cones are found in all possible positions with reference to the bedding plane. At one extreme, the axes of the shatter cones stand approximately at right angles to the bedding planes as, e.g., those in Ordovician limestone at Kentland quarry (Indiana) which Dietz has illustrated (Dietz, 1960, p. 1782, fig. 1: the cones shown are "nearly one meter in length . . . oriented upward" with reference to the bedding planes).

At the other extreme are the shatter cones that lie nearly parallel to the bedding planes. In all cases of this kind known to the writer, the cones are only partially developed, only half or less of the cone surface having developed. This may be significant in itself, because the layering introduces an anisotropy into the rock causing it to break along bedding planes. A remarkable example of this type of shatter cone was shown to the writer by Messrs. G. E. Amstutz and Zimmermann during a visit to the Crooked Creek cryptoexplosion structure[21] in Crawford County, Missouri (Hendriks, 1954). Near the center of the structure in beds of little disturbed, fine-grained Upper Cambrian dolomite, small (2 to 3 in) shatter cones lie densely packed on the surfaces of successive beds. In the lowest bed (at the locality visited) the cones point N 34° E; in a bed only a few inches higher up, they point N 64° E and, in a still higher bed which outcrops some 100 ft away, they point N 8° W. In the lowest bed they are rather strongly inclined, but only slightly in the highest bed. All point upward away from the center of the structure. In one layer, however, cones were

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[21] The writer thanks Drs. Amstutz and Zimmermann for guidance on this valuable trip.

seen trending almost at right angles to each other. (More will be said about such occurrences below.)

Applying the inferred orientation of the principal stresses which produce the conical fracture, one arrives at the following conclusion: Cones with axes nearly parallel to the bedding planes indicate that extension was easiest upward. This would be the case during an early stage, when the upper layers of the permeable formation were filling with gas and the gently expanding column lengthened upward, while being constrained by the confining pressure all around. The cones with axes at right angles to the bedding would then arise later, when the major stage of the disturbance was beginning, when the center column was raised bodily from below and the surrounding ring of rock was settling downward, producing lateral tension while pressure from below imposed a maximum compression in the vertical direction. This resulted in cones with vertical axes. The two stages are parts of a single process and not separated by a large time interval. Furthermore, since the formation of the shatter cones depends on the local permeability and form changes, systematic or unsystematic variations in their attitude are to be expected, such as those seen in the Crooked Creek structure.

The formation of shatter cones with axes more or less parallel to the bedding has occurred on the largest scale known to the writer in all the thick sedimentary formations of the Vredefort Dome. As in the Crooked Creek structure, "in most cases their apices point away from the center of the uplift".[22] Shatter cones seem to be absent from the pseudotachylite dikes which have been brought into being by the "prodigious explosion" which Nel has inferred (Nel, 1927, p. 110, quoted from Hargraves, 1961, p. 6).

The assumption that all shatter cones with axes parallel to the bedding originated when the beds were still essentially horizontal is not justified. Because of the tendency to part along bedding planes, partial shatter cone surfaces may be expected to form whenever the direction of greatest elongation happens to be directed about at right angles to the bedding. This may apply, e.g., to the steeply dipping thin limestone beds intercalated between thicker shale zones in the central part of the Serpent Mound structure (Bucher, 1925a, p. 142; 1933a; 1936, p. 1062) where partial shatter cone surfaces were discovered by Dietz inside fragments of the thickest beds (up to 8 inches thick) by breaking them open with a hammer (Dietz, 1960, p. 1783). On a recent visit, the writer confirmed Dietz's observation that no shatter cone surfaces are seen on the upper and lower surfaces of the fragments, but only on the inside. This is readily explained in terms of the hypothesis here set forth.

(3) The concept of local control of "brittleness" through the action of high-pressure gases filling the pores of permeable rocks under an impervious cover provides for the variations and abrupt changes in the position of cone axes mentioned above. Two specimens collected during the writer's trip to Steinheim illustrate the observations involved. Figure 15a shows a group of shatter cones with axes oriented vertically. Most of them point upwards, but

[22] " . . . although in an individual outcrop a preferred orientation of cones is usually apparent, cones pointing at angles opposite to or oblique to the major trend are frequently present. Interference and interlocking of cones often add to the complexity" (Hargraves, 1961, p. 2).

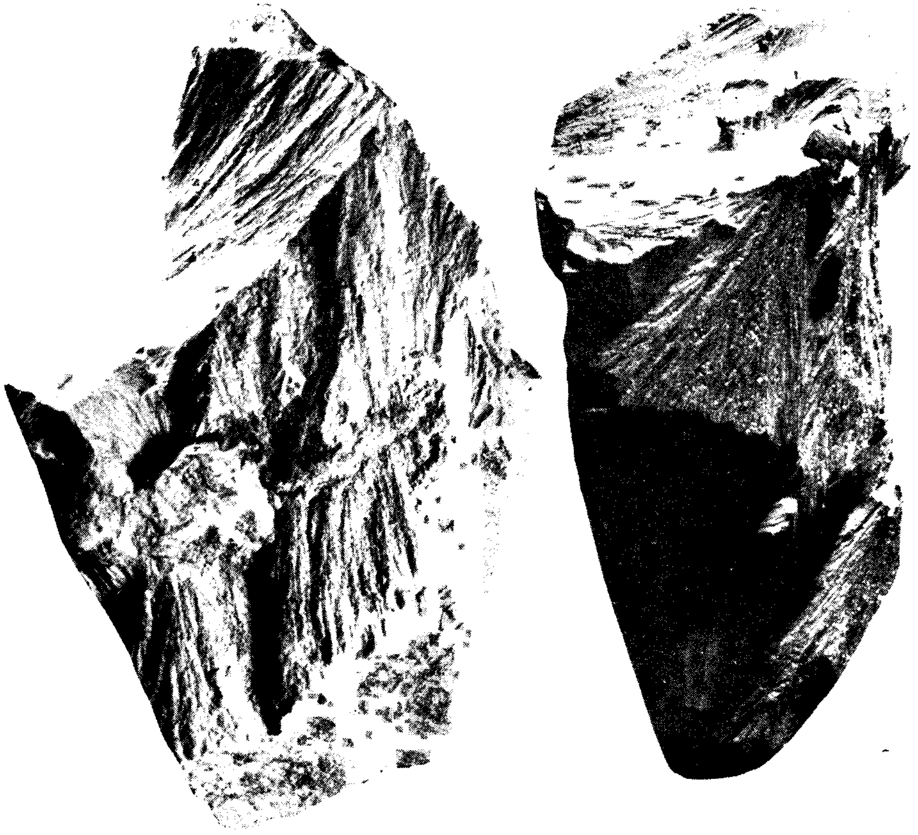

Fig. 15.

A. Shatter cones from the Steinheim Basin, showing a group of cones with vertical axes intersected by a single large cone with axis nearly at right angles (apex pointing to the left) (collected 1962).

B. Shatter cones from the Steinheim Basin showing intersection of two sets of cones, similar to 14A (collected 1962).

behind a small round concretion the upward diverging striations of the mould of one cone point downward. This system of cones with vertical axes appears cut off abruptly by the contours of a single large cone the axis of which trends at a high angle to that of the dominant pair. There is no evidence that the crosscutting cone is later than the others; its surface shows no traces of intercepted fracture planes. One gains the impression that they formed simultaneously. Figure 15b illustrates the same features.

(4) Where typically developed, the pattern of radiating ridges and bifurcating grooves, which caused Branco and Fraas (1905) to give the name "Strahlenkalke" to the shatter cones from the Steinheim Basin, is a remarkable phenomenon. The writer has never seen anything remotely resembling this elegantly sculptured pattern of fractures produced in the laboratory by pressures rapidly applied on any rocks or rock-like materials. Note especially details of

this pattern as shown in figure 14b, which is the cone of figure 14a seen from above—the way the lines curve gracefully, actually running toward each other where they approach a deep groove. The pattern recalls the complicated designs that form occasionally in the paste on opposite surfaces of two sheets of paper peeled apart before the paste has begun to dry, or the comparable patterns that are apt to form on the imprint of a shoe when one walks on a sidewalk covered with a thin film of mud. The plumose designs which are apt to be well developed on the smooth sides of basalt columns and on tension fractures in brittle rocks (Roberts, 1961) may be analogous to those on shatter-cones. A close approach to the pattern seen on shatter cones is figured by Solomon and Hill (1962, opp. p. 494, pl. 1). Here delicate markings cover the curved surfaces of rib-marks, resembling symmetrical ripples, produced in tough, siliceous mudstones by explosion impact during blasting. These markings start in the troughs and diverge upward toward the crests of the "ripples". (See also Nadai, 1950, p. 196, figs. 15 to 21). Neither the opening of tensional cross fractures, the parting of cooling basalt walls, nor, of course, the explosives used in rock blasting involve speeds of deformation comparable to those of the impact of a giant meteorite.

(5) With one exception to be mentioned later, shatter cones have been found (in rocks other than coal) exclusively in cryptoexplosion structures, never among the ejecta of explosion craters. They abound in the center of the Wells Creek Basin, but are missing in the Ries Basin, and they are plentiful in the central hill of the small Steinheim Basin, but have not been found among the debris of the rim of any meteorite crater[23] or the explosion craters of the Eifel in northwest Germany of similar size. It does look as if the presence of shatter cones in the centers of unsuccessful "cryptoexplosion" structures offered a clue to their mode of formation. The hypothesis here advocated uses that clue to advantage: According to it, the difference between successful and unsuccessful explosions lies in the rate and manner in which gas under high pressure is introduced into the rocks from depth. When the gas finds numerous avenues of escape toward the surface, it will blow out a cluster of explosion pipes, like those at Urach and in the Avon area. On the other hand, the force that tore the sediments and even the uppermost levels of the crystalline basement into angular blocks and pulverized explosion products in the Ries was that of a mighty rush of gas which must have heaved up the rocks and blown them to pieces. From the start the manner of yielding was that of brecciation and fluidization, with no chance for the formation of shatter cones, which seems to have required introduction of the gases at a much slower rate, the gas producing slowly growing, variable strains in the sediments as it accumulated in the pores. Under such conditions, when the pressure finally reached the point where the central column could be lifted and the chaotic breakup and uprush began, with a ring of rock sagging down to replace the displaced rock volume, pressure was quickly dissipated and the explosion thwarted. In an exceptional case, a late speeding up of gas pressure may lead to the ultimate formation of an explosion crater.

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[23] In the course of prolonged search among the ejecta of the Barringer Crater, Chao found one tiny sandstone fragment that somewhat resembles a shatter cone. He told the writer that its nature is doubtful.

This would explain the one exception to the rule mentioned earlier, viz., the presence of shatter cones among the ejecta of the Ashanti crater (Rohleder, 1934).

B. The implications of the presence of coesite.—Coesite, the heavy phase of silica, provides the most potent argument for meteorite impact. It was first synthesized by Coes (1953) using an apparatus similar to the one with which Bridgman had transformed graphite into diamond. It is a mineral phase of silica, of density of 3.01 gm/cc, i.e., heavier than quartz (d = 2.67 gm/cc) and chemically much more inert.

In this original synthesis, dry sodium metasilicate mixed with a mineralizing agent such as diammonium phosphate, boric acid, or potassium fluoborate was sealed into a small iron capsule and placed under pressures above 35,000 atmospheres at temperatures between 500° and 800° C. No coesite formed below 35,000 atmospheres. At the end of the run, the pressure was released, the capsule removed and dissolved in hydrochloric acid. The residue was then treated with hot acids (nitric, chromic, and hydrofluoric). In one such experiment, 0.2 g of the first mixture listed above yielded "20-30 mg of dense silica in colorless tabular hexagonal crystals up to 50 μ in diameter". (Coes, 1953, p. 131)

These details are given here because subsequent geophysical studies concerned themselves quite naturally with the stability fields of quartz and coesite, and therefore used quartz and other forms of silica as starting materials in their experiments. (See reference in Chao, Shoemaker, and Madsen, 1960, p. 222.) This left the impression among geologists that natural coesite must have been produced from preexisting quartz or other solid forms of silica. Reading Coes' original paper, the writer was surprised that a 10 percent yield of good coesite crystals was obtained in relatively short runs from a mixture of a silicate and mineralizers containing such elements as boron and fluorine which the geologist associates at once with magmatic activity. (The resulting coesite could, of course, only form under pressures corresponding to a depth of 60 to 80 km[24] and at relatively high temperatures.)

Coesite has been identified so far in rocks from three cryptoexplosion structures: (1) the suevite tuff of the Ries Basin (Shoemaker and Chao, 1961): (2) the Kentland structure in Indiana, which abounds in large and small shatter cones—their apices typically pointing "normal to the bedding and toward the top of the beds" (Dietz, 1959, p. 503), where most of the coesite was found in "the finest fraction (–320 mesh) from St. Peter sandstone (about 98 percent silica)" (Cohen, Bunch, and Reid, 1961, p. 1624); (3) the Serpent Mound structure, Ohio, where the material was concentrated from the residue of solu-

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[24] It strikes the writer as strange to find himself making the statement that every submicron- or micron-sized crystal of coesite found in nature has to have formed at a depth of 60 to 80 km or something like that, when the best crystals he has seen figured have been produced at the earth's surface in the laboratory, by bringing high pressure to bear on very small surfaces in a confined space capable of withstanding such pressure (in such small space!) for the duration of the experiment. What proof is there that a similar, temporary concentration of force could not take place in the tortuous, often exceedingly narrow paths into which tuffisites are injected under forces that fractured a thickness of 8 to 10 km of rock, and in which not static, but kinetic energy, presumably at high velocities, was at work locally? Oral and written probing has brought conflicting opinions from colleagues who command the knowledge to give a definite answer if one were readily available.

tion in hydrochloric acid of a "shatter cone that weighed over 2 lbs by dissolving the carbonate in hydrochloric acid" (p. 1624). The material was collected near the center of the structure where large shatter cones—the only ones in the Serpent Mound structure—are found in float of the Upper Ordovician limestones[25] which are interbedded in shales.

The first noteworthy aspect of these occurrences is the very small yield of coesite in the two radically different chemical environments: 100 parts per million in the St. Peter sandstone. 10 parts per million in the limestone from the Serpent Mound structure. The St. Peter sandstone is about 98 percent silica (Cohen, Bunch, and Reed, p. 1624); the Cincinnatian limestone contains at best one to a very few precent of quartz. If impact from above created the coesite, the small yield from rocks of such radically different quartz content is puzzling, to say the least.

The second aspect is the fact that the appearance of coesite seems to be tied to the presence of shatter cones. Now this may not be essential. The coesite may be present in similar amounts throughout the St. Peter sandstone in the Kentland structure and in all the formations of the central part of the Serpent Mound structure. The fact is, it was looked for in these rocks and found. Nothing in the literature indicates that control tests were made on rocks of the same age outside the cryptoexplosion areas. The recitation of the steps taken in the original synthesis of coesite shows how time-consuming and taxing a job the search for coesite is. Yet, the investigators owe us the control tests—even though the probability is high that such tests will turn out to be negative.

Let us assume then, that the coesite is actually limited to the shatter cones and the shattered rocks around them. Is it foolish to suggest that in the opening of the fractures that define the shatter cones the kinetic energy of gases under high pressure was brought to bear in a highly confined space, probably in the presence of fluxing agents, on a very small portion of the silica present, not unlike that of the laboratory experiment by which coesite was synthesized? This may explain why only 10 times as much coesite was formed in a rock consisting almost entirely of silica as in one that contains almost none.

Poldervaart (oral communication) considers it possible that in the course of the action of gases under high pressure, coesite may form metastably, or as an impure phase along the upward path. He points out that coesite may possibly form metastably at a temperature as low as 200°C and a pressure of about 5000 bars from glass, or from colloidal silica or any colloidal silicate. Moreover, the purity of the coesite has never been established. Small traces of impurity may greatly lower the pressure and temperature from those required in the synthesis of pure coesite.

C. *Possible nature of a subterranean blast.*—What sort of blast could have been involved? Poldervaart has called the writer's attention to the great forces that are released when water-rich, supercooled magmas crystallize suddenly (Morey, 1922). Arthur Day has given a graphic picture of this process and its results in his paper on the last "eruption" of Mount Lassen (Day.

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[25] A thin section made from a sample of the material used in the tests (kindly supplied by Dr. Cohen) confirmed the age which was erroneously identified as "Middle Silurian" in the abstract of the short paper.

1922), where there was no lava, little heating, only a vast gas pressure at no great depth. If water-rich portions of magma were supercooled at great depth and then spurred to sudden crystallization, say, by earthquake shocks, enormous pressures would build up, penetrating into all fissures above the initial point of crystallization, crushing and partly pulverizing the rock in gouging out irregularly shaped pathways toward the surface, along which the comminuted rock fragments are driven upward as a highly fluid powder. This is what is meant by "fluidization". This explosive action may ultimately exhaust itself at depth, or end in an unsuccessful attempt to eject the rock material (a "cryptoexplosion structure"), or in a successful blowout, an explosion crater.[26]

This brings up a peculiar fact: Not one of the "bona fide" meteorite craters shows the least sign of a central uplift, whereas every one of the so-called cryptoexplosion structures has a central uplift and marginal collapse. Cryptoexplosion structures are known from a small size (less than 1 km–0.6 mi–diameter, as in the Flynn Creek structure) to more than eight km (4.8 mi) diameter (as in the Wells Creek Basin), i.e., through the same size range which is characteristic of most explosion craters. Yet consistently one shows no central uplift, the other no overall blowout. It looks suspiciously as if the two were produced by the same process: If there is a blowout, we call it "explosion crater"; if there is none, but only an attempt at one, we call it "cryptoexplosion structure".

Some of the so-called "meteor craters" may be the product of meteorite impact. But in most cases the evidence is subject to reasonable doubt.

D. Nickeliferous iron common in basic and ultrabasic rocks.—The presence of nickeliferous iron—often only as traces of nickel in limonitic crusts—is another argument used to "prove" the meteorite origin of explosion craters. Yet, that nickel iron, even displaying on polished sections features resembling Widmanstätten figures (Steenstrup, 1884; Carpenter, 1935; Lofquist and Benedicks, 1941), is an integral part of coarse-grained mafic inclusions in dolerite[27] has been known for more than a century, since Captain Ross discovered it at Ovifak on the island of Disko, on the west side of Greenland. Steenstrup and others have shown that this nickeliferous iron is not the result of a bullseye shot of a meteorite into a volcano, as Nordenskjöld still thought in the seventies of the last century, but is a regular component of the magma, not only at a single locality, but over the whole region. It must always be remem-

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[26] The description of an explosion crater in India, on the surface of the Deccan Trap, "parallels so closely the Arizona crater" that Blanford's old description (Medlicott and Blanford, 1879, p. 379-380) is here reprinted from Gilbert (1896, p. 11):

"The surrounding country for hundreds of miles consists entirely of Deccan Trap. In this rock, at Lonar, there is a nearly circular hollow about 300 to 400 feet deep and rather more than a mile in diameter, containing at the bottom a shallow lake of salt water without any outlet . . . the sides of the hollow to the north and northeast are absolutely level with the surrounding country, while in all other directions there is a raised rim, never exceeding 100 feet in height and frequently only 40 to 50, composed of blocks of basalt irregularly piled and precisely similar to the rock exposed on the sides of the hollow. The dip of the surrounding traps is away from the hollow, but very low".

[27] The writer is indebted to Dr. Jack Green, Space Sciences Laboratory, North American Aviation Company, for the references in the literature concerning the iron in the Disko basalt.

bered that it is not the presence of nickel associated with iron that is the hallmark of meteorite origin, but the high percentage of nickel: and that nickel is quite generally present in basic and ultrabasic rock bodies.

E. Alleged remoteness of cryptoexplosion structures from centers of magmatic activity.—Where neither shatter cones, coesite, nor nickeliferous iron can be found, the fact that an explosion crater lies far from "centers of magmatic activity" is thought to "prove" meteorite impact. "Centers of magmatic activity" recalls the freshman's idea of volcanic activity. But "pipes" and dikes of alkaline mafic materials occur just as unpredictably and wholly independently of what commonly is thought of as "volcanic activity" in the United States. Information on these occurrences is scattered in the literature, however, and known generally only to petrologists. One can hardly get farther away from traditional "volcanic activity" than South Dakota (Runner, 1957): Kansas (Moore and Haynes, 1920); Missouri (Rust, 1937; Kidwell, 1947); Illinois (Brown, Emery, and Mayer, 1954; Brock and Heyl, 1961); Tennessee (Gordon, 1927; Hall and Amick, 1944); Kentucky (Diller, 1892): Pennsylvania (Kemp and Ross, 1907; Honess and Graeber, 1926); New York (Martens, 1924). Most recently the occurrences of post-Cambrian igneous rocks east of the Rocky Mountains have been assembled on a most useful map by Brock and Heyl (1961). The map shows all sorts of igneous rocks, but distinguishes the "mafic rocks, mostly nepheline basalt, mica-peridotite, and lamprophyre" by a separate symbol. Looking at them alone will serve to bring out the "loneliness" of these occurrences in the region of the interior plains of North America. It does not, however, remind the reader that the absence of symbols in the northern state is, of course, due to the Pleistocene cover. The outcrops of alkaline mafic rocks are areally so insignificant that they could not be expected to be discovered below the drift sheets. A cryptoexplosion structure has a much better chance (e.g., Manson structure, Iowa: Kentland structure, Indiana).

Amidst the vast complexity of the Precambrian rocks of the Canadian shield, such small outcrops of post-Cambrian mafic activity would not be apt to attract attention. That they must be there is suggested by the discovery of diamonds in the glacial drift of the United States, in an area diverging southward and pointing to a source hidden somewhere beneath Hudson Bay, or covered by lake, forest, muskeg, or drift (Hobbs, 1899, 1902).

This does not mean, of course, that there are no impact scars of meteorites on the earth, but only that many features called by that name have no right to it. Before we look to the sky to solve our problems miraculously in one blow, we should consider the possibility that cryptoexplosion structures and explosion craters may hold important clues to processes going on at great depth below our feet, even if it threatens to lead us back to another "traditional" concept, that of cooling of the outer mantle. Distrust in traditional thinking should not deter us from looking hard at all aspects of the problem. Doing so will probably yield more useful results than computing possible velocities of imagined meteorites.

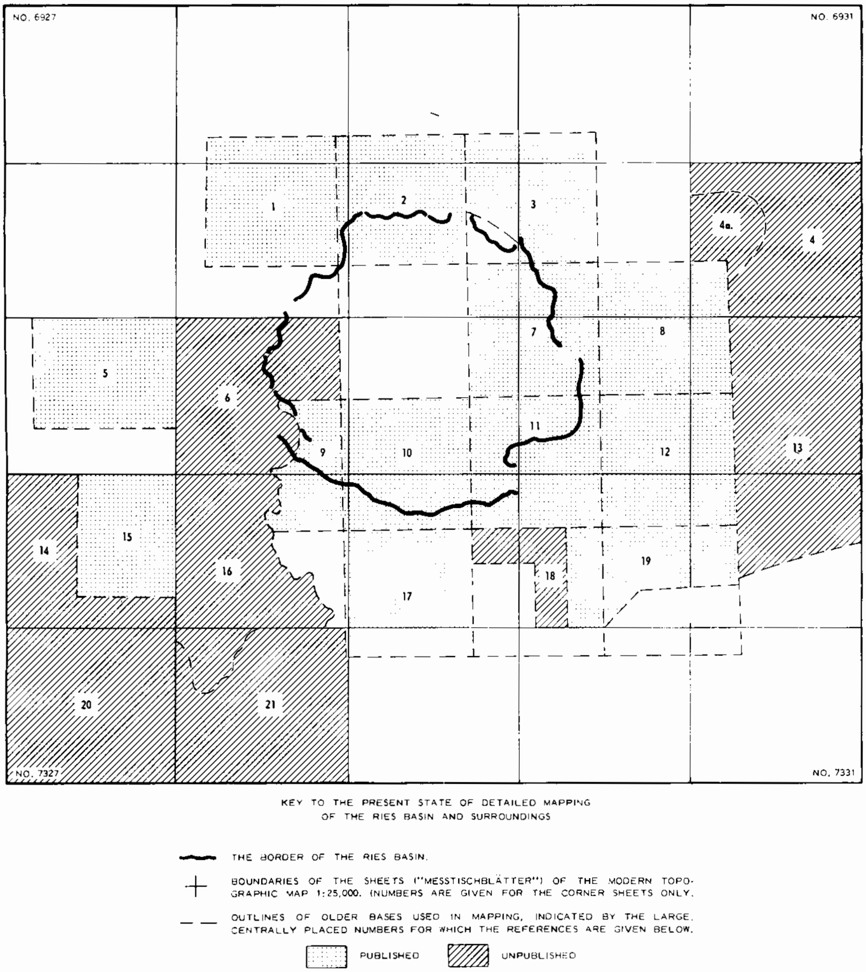

Fig. 16. Key to the present state of detailed mapping of the Ries Basin and surroundings.

APPENDIX I

Key to the map, Figure 16,
showing the present state of detailed mapping of the Ries Basin and surroundings.
(Prepared by G. H. Wagner, 1962.)

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1962. The small portion of the area indicated by the dotted line is also covered by:

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