interaction profile. The fact that the half-widths of the experimental interaction profiles at 20°C were 70 to 360 oersteds showed that interactions are important in all samples.

Theoretical ARM magnetization curves were obtained by numerical integration of the experimental H_i distributions and normalization to the saturation remanence. A good match to the observations resulted (Fig. 2). Magnetization and a-c demagnetization curves of saturation IRM were well predicted from the Preisach diagram, as shown by the theoretical and experimental coercivity spectra of Fig. 3.

The TRM magnetization curve was recalculated; again I used the equations of simple Néel theory, but now took into account the fact that the total field acting on a grain, at its blocking temperature, T_B, is $H_{d\text{-}c} + H_i(T_B)$. The spectrum of H_i at T_B was taken as the 20°C interaction profile suitably contracted by the thermal decrease of spontaneous magnetization between 20°C and T_B. Improvement in agreement between theoretical and experimental TRM curves was spectacular (Fig. 2).

The TRM calculation is important for three reasons. It demonstrates that the properties of the monodomain grains in these samples are markedly modified by magnetostatic grain interactions. Thus it follows that two published estimates of grain size (*1, 4*), based on the untenable assumption that the shape of the TRM magnetization curve follows directly from Néel theory, are unreliable. Most important is the fact that the interaction spectrum, derived from the Preisach diagram, can be successfully used in calculations depending on the Néel equations; this provides a general method of analyzing the thermal properties of interacting monodomain grains.

Thus, the results of many experiments, insensitive to the interaction state of a sample, are quantitatively well predicted by the Néel theory of independent monodomain grains. Interactions are significant in some real rocks, however, and produce deviations from simple Néel theory in experiments involving the magnetization and demagnetization of remanences. Quantitative analysis in the presence of interactions can be performed by Preisach theory (isothermal processes only) or more generally by an extended form of Néel theory that takes account of interactions.

The properties of my two natural rocks agreed as well with monodomain theory as did those of the four synthetic "rocks" containing grains known to be of single-domain size. This fact strongly suggests that the natural remanence of paleomagnetic materials similar to those studied here is carried largely by high-stability, single-domain grains or regions. While problems such as development of a physically adequate model of monodomain-like regions in large grains are of great fundamental interest, it is equally important to gain further insight into the properties of monodomain assemblies and to discover what classes of rocks display such properties.

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Structural Pattern in Central Uplifts of Cryptoexplosion Structures as Typified by Sierra Madera

Abstract. *The pattern of deformation in central uplifts of Sierra Madera and other well-known cryptoexplosion structures indicates that inward as well as upward movement of strata formed the uplifts. This kind of movement is incompatible with structures not of impact origin with which they have been compared. The structural style of cryptoexplosion structures, together with features that suggest shock deformation, supports the belief that they are the eroded roots of impact craters.*

The debate concerning whether cryptoexplosion structures (*1*) are of terrestrial or extraterrestrial orgin began three decades ago (*2, 3*) and continues. As shown (*2*), they are roughly circular structures, with a ring depression surrounding a central uplift of disordered and brecciated rocks. The gross structure, as well as the common occurrence of shatter cones (*4*) and of unusual mineral deformation (*5*), indicates an origin by explosive release of energy, either from impact (*3*) or from volcanic gas (*2*).

Most published explanations of the origin of these structures have been based on inadequate information about their geometry, and give undue weight to the disorder of the central uplifts. Our detailed examination (*6*) of the Sierra Madera cryptoexplosion structure shows that, despite extensive brecciation and small-scale structural complexity (*7*), the rocks of the central uplift have a coherent structure and are so arranged that the strata must have moved both inward and upward to reach their present positions. A similar style of deformation is found in other well-studied cryptoexplosion structures, and casts doubt on a nonimpact origin.

Sierra Madera (*8*) is a circular body of intensely deformed rocks about 12 km in diameter, 5 km northeast of the Glass Mountains in west Texas. Its intense deformation of rocks is unique in a region where the rocks are otherwise slightly deformed; there is no apparent relation between Sierra Madera and any regional or other local feature. The deformed rocks are Permian limestones and dolomites, like those exposed in a more orderly sequence in the nearby Glass Mountains (Leonard Series, Word, Gilliam, and Tessey formations), and Lower Cretaceous limestones and marls, with a conspicuous basal sandstone (Trinity and Fredericksburg groups, and the lower part of the Washita Group). Records of deep holes drilled for oil and gas show little if any deformation below 2 to 2.5 km under the center of the exposed structure, although the thickness of the

Permian and pre-Permian sedimentary rocks above the crystalline basement is about 6 km. The bedrock of the area is covered in places by thin, undeformed Quaternary deposits. The age of the Sierra Madera structure is post-Lower Cretaceous (*9*) and pre-Quaternary.

The Sierra Madera structure (Figs. 1 and 2) consists of a complex central uplift about 5 km in diameter, a surrounding synclinal depression 1 to 3 km wide, and an outer rim where the rocks are locally folded and cut by concentric fractures and normal faults downthrown toward the center. Pods and dikes of basal Cretaceous sandstone and shatter-coned masses of Permian dolomites were injected upward into the Cretaceous limestones along some of these faults and fractures. The sandstone and dolomite intrusions into overlying strata suggest a violent origin, so that the concentric normal faults and the rim syncline are not simply a passive response to uplift in the center, as they might be in a diapiric structure.

Permian rocks in the central uplift are extensively shatter-coned and brecciated. Shatter cones pointing inward and upward, if the beds containing them are restored to horizontal, indicate a central source of energy for their formation (*10*). Some Permian rocks show extensive shattering, generally without associated faulting or mixing of beds. Dikelike bodies of mixed breccia, composed of fragments from several formations, also are present. Drill holes show that the breccias do not persist downward (*7*). Other features possibly of shock-deformation origin are multiple sets of planar features in quartz, and intense twinning of carbonate minerals in the mixed breccias and locally in unbrecciated rock.

The lowest strata exposed in the central uplift (Fig. 3) are approximately 300 m below the top of the Leonard Series and are raised about 1200 m above their normal position (Fig. 2). The outward dips and fold plunges steepen from the flanks toward the central uplift, becoming vertical or overturned in the center. The rocks are cut by many generally steep faults. Individual beds, such as the conglomerate at the top of the Leonard Series (Fig. 3), are imbricated across subradial faults and are folded so that the total strike length of the beds is greater than the length of the perimeter on which they lie. The perimeter at the stratigraphic level of the conglomerate was evidently shortened about 25 percent by the inward movement during doming; moreover, the section in the center is thickened by duplication, so that a central area with a minimum width of 1500 m is filled by near-vertical beds consisting of only 300 m of the Leonard Series (Fig. 3). A hole drilled near the center of the uplift (Fig. 2) shows that the thickening persists about 1 km below the surface and is thus more than superficial, so that the rocks have been squeezed or drawn inward during uplift.

The central uplifts of some other cryptoexplosion structures also had both inward and upward movement as in the Vredefort ring in South Africa (*11*), the Wells Creek Basin in Tennessee (*12*), and the Gosses Bluff structure in Australia (*13*). Rocks in the collar of the large Vredefort structure are overturned and uplifted for about 30 km from the center; the lowest Witwatersrand sedimentary rocks, uplifted at least 16 km, lie on a perimeter that is shortened about 7 percent (*11*).

In the center of the Wells Creek structure (*12*), which is about the same size as Sierra Madera, steep dips across a wide belt of the oldest rocks suggest they were thickened by inward movement of rock. Segments of individual

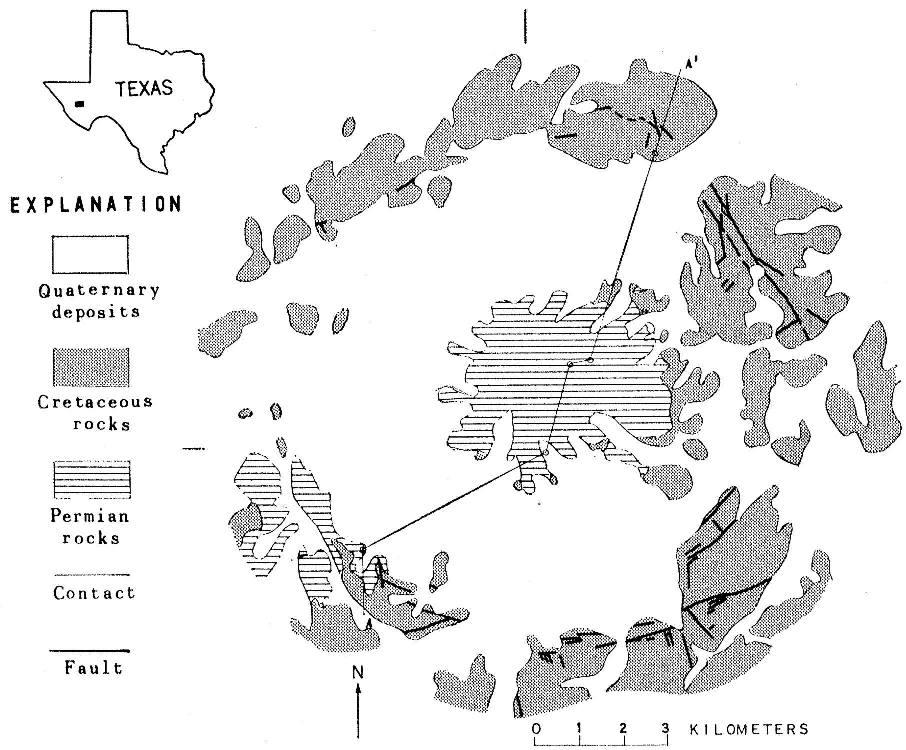

Fig. 1. Generalized geologic map of the Sierra Madera structure. Line A-A′ is line of cross section shown in Fig. 2.

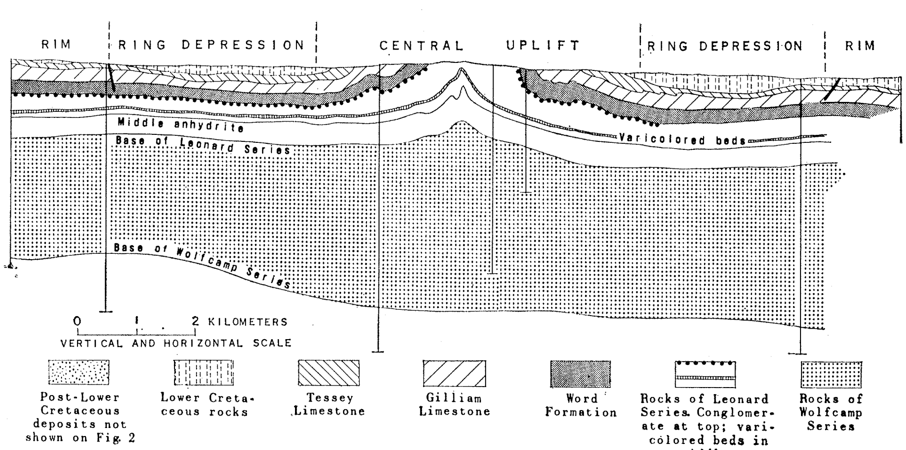

Fig. 2. Generalized cross section of Sierra Madera structure. Vertical lines are drill holes.

thin formations on the steep flanks of the uplift lie on a shortened perimeter as a result of imbrication across subradial faults; the section is further duplicated by tangential, outward-dipping faults along which the displacement is inward and upward toward the center of the structure. Wilson and Stearns concluded (*12*) that the rocks in the central uplift moved inward about 110 m and upward at least 750 m.

At Gosses Bluff, which is about twice the size of Sierra Madera, the central uplift consists of steeply dipping bedrock plates separated by faults (*13*). The plates overlap and indicate tangential fault movements; for this reason and because of other details of the structure, Milton and Brett (*13*) conclude that the plates moved inward and upward on a shortened perimeter from their original flat-lying positions.

Hypotheses of terrestrial origins for cryptoexplosion structures include explosive release of energy from a subterranean igneous source (*2, 14*), reactivated or primary basement structures (*15*), unexposed igneous intrusions (*16*), and unexposed diapiric intrusions (*17*). Drilling at Sierra Madera disproves schemes involving basement structures and igneous intrusions. Furthermore, all these proposals imply that the rocks in the central uplift were pushed upward from below, which idea is contrary to the geometry of the exposed structures (*18*). Deformation by uplift could produce a circular pattern of steeply dipping beds, but would require distension, and individual beds would either form a larger perimeter than before uplift (as a result of faulting) or be thinned. Because Sierra Madera and the other structures cited do not have such features, we conclude that they could not have originated by this kind of uplift.

Structures of terrestrial origin that do resemble the centers of cryptoexplosion structures are salt or shale diapirs, and a diapiric origin has in fact been proposed for the cryptoexplosion structures (*19*). Although inward and upward movement of rock occurs in diapirs, they lack shatter cones, pervasively shattered rocks, and multiple sets of planar features in quartz that were probably caused by shock deformation. No piercing or intrusion of the central uplift into surrounding rock has been observed in cryptoexplosion structures, and there are no density contrasts in the stratigraphic sequence at Sierra Madera, or in other cryptoexplosion structures, of the kinds that motivate emplacement of many diapirs.

Formation of central uplifts (*20*) by chemical-explosive cratering in Canada (*21*) and in diverse experimental impact cratering studies elsewhere (*22*), together with the structural geometry and possible indications of shock deformation in cryptoexplosion structures, support the idea that such structures are eroded roots of impact craters. The central up-

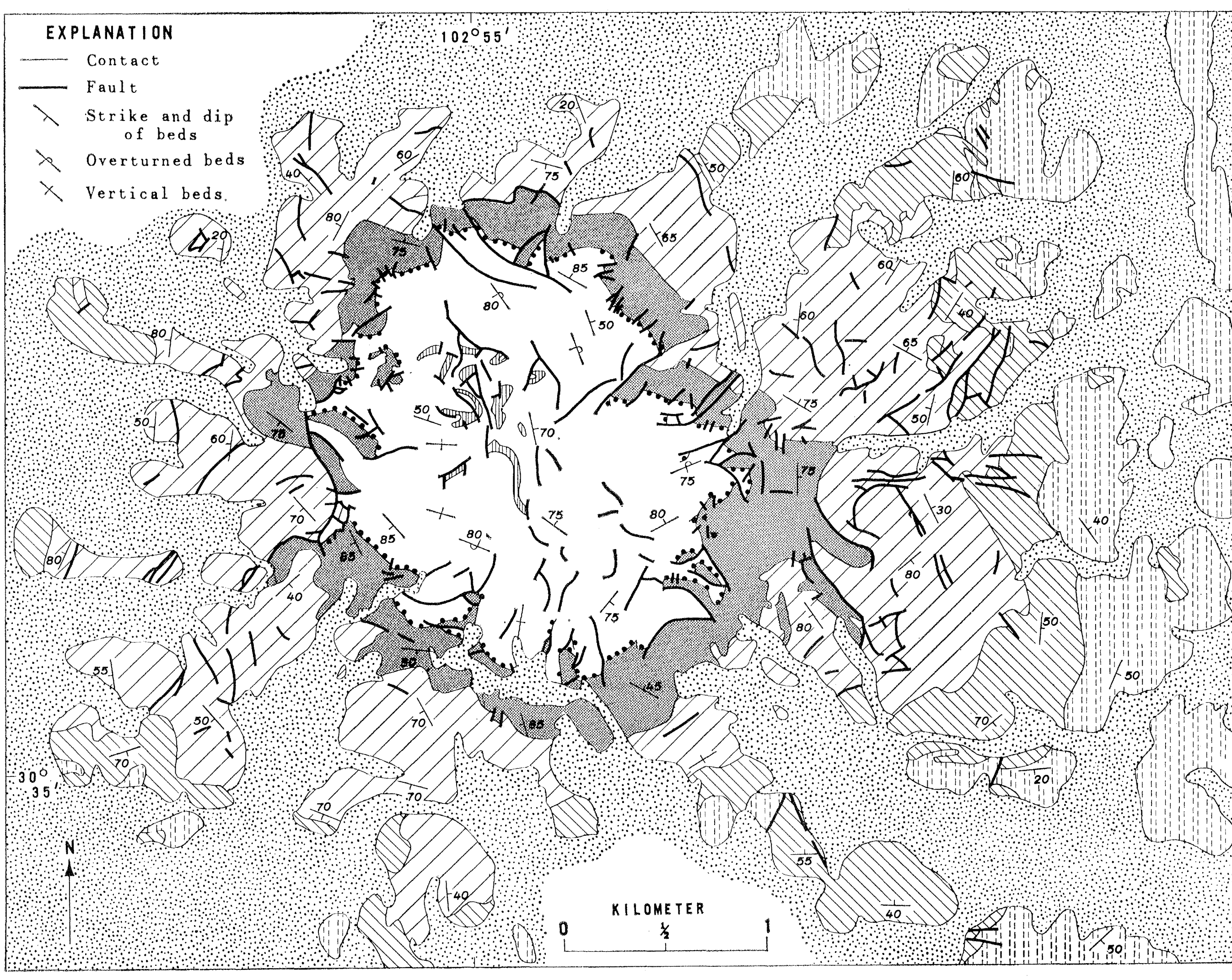

Fig. 3. Generalized geologic map of the central uplift of Sierra Madera. Rock units are defined in Fig. 2.

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

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Shatter Cones at Sierra Madera, Texas

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

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

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

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

Whole cones vary in height from less than 2 mm to 12 cm, so that the sides