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Gosses Bluff Impact Structure, Australia

Geological and geophysical techniques establish the origin of an analog of lunar craters.

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Craters are the dominant surface feature on the Moon and on Mars. Some resemble terrestrial volcanic craters but most appear to have their analogs on Earth among the cryptoexplosion structures (*1*), of which only some sixty are known. A complex of shared features clearly defines cryptoexplosion structures as a class, although no one feature by itself can be relied on as an unfailing index. These features include severe deformation localized within a roughly circular perimeter, an open crater or one filled with undisturbed sediments (unless erosion has reached a level beneath the crater floor), uplifted bedrock in the center, shatter cones, breccias of melted rock fragments, unusual deformation features and anomalous optical properties in mineral grains, and minerals that are formed only at extreme pressures (*2*). Cryptoexplosion structures occur in a wide variety of geologic environments; the apparent randomness of their occurrence may be considered an additional characteristic. It is generally agreed that cryptoexplosion structures were produced by violent events involving intense shock (*3*). It is hotly debated, however, whether the cause is to be sought among processes entirely within the Earth or whether hypervelocity impact of objects from space—meteorites, asteroidal fragments, or comets—is responsible.

The Gosses Bluff structure in central Australia, 160 km west of Alice Springs, is a typical cryptoexplosion structure. In the little over a decade since it was recognized as a geologic anomaly a variety of explanations have been advanced: igneous intrusion (*4*), salt diapirism (*5*), cryptovolcanism (*6*), impact (*6, 7*), and mud volcano activity (*8*). Gosses Bluff is unusually amenable to study for several reasons. It lies in a sequence of nearly flat-lying strata, which simplifies reconstruction of the pre-event geology. Erosion has cut down to just beneath the crater floor and has laid bare the central uplift, and exposures in the semiarid environment are generally good. We have carried out a comprehensive study that includes detailed geologic mapping, and seismic reflection and refraction, gravity, aeromagnetic and ground magnetic surveys. Our conclusion is that the Gosses Bluff structure is indeed an eroded crater formed by a single nearly instantaneous shock event, and that the event can be explained only by impact.

Geologic Setting

A photograph taken by the Gemini V astronauts (Fig. 1) shows Gosses Bluff as an isolated circular ridge about 5 km in diameter in Missionary Plain. Rings of slightly differing topography and vegetation show that the structure is larger than the Bluff itself; on the ground, marked structural effects are found as far as 11 km from the center. Missionary Plain, at the northern edge of the Amadeus Basin, is underlain by a flat-floored syncline of Proterozoic and Paleozoic strata which crop out in the MacDonnell Ranges to the north and the James Ranges to the south. Seismic reflection surveys indicate that the sedimentary section in the vicinity of Gosses Bluff is about 8000 meters thick. Although dips near the axis of the Missionary Plain syncline are generally low, a subsurface cross fold, the Gardiner-Tyler anticline (*9*) with dips on the flanks as high as 15° runs northeast-southwest beneath the bluff.

Geologic Structure

The Gosses Bluff structure may be divided into two zones: a lower zone of systematic displacements and an upper zone, now largely stripped by erosion, of more chaotic deformation. The basic pattern of the lower zone at the surface is one of upturned strata facing outward, so that the Brewer Conglomerate, the unit ordinarily at the surface in Missionary Plain, forms an outer ring and increasingly older strata crop out in sequence inward, until at the center strata normally 3000 meters below the plain are exposed.

The resemblance of the hollow ring of Gosses Bluff to a crater is an accident; the form is an expression of lithology. Resistant sandstones of the uppermost unit of the Larapinta Group, the Mereenie Sandstone, and a sandstone member of the Parke Siltstone stand high, rising to about 200 meters above the plains. Outside the bluff are soft siltstones of the Parke, and then poorly lithified Hermannsburg Sand-

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Fig. 1. Gosses Bluff (center) in Missionary Plain, between the MacDonnell Ranges to the north and the James Ranges to the south. Area approximately 60 by 80 km. [Photographed from Earth orbit by G. Cooper and C. Conrad, Jr., Gemini V Spacecraft]

stone and Brewer Conglomerate. Inside the bluff, the lower slopes are underlain by sandstone and siltstone of the Carmichael Sandstone, a low-lying interval with very little outcrop is underlain by Stokes Siltstone, and the low hills in the center are underlain by sandstone beds in the lowermost Stokes and the uppermost Stairway Sandstone.

The map pattern shows that successive strata do not describe continuous belts but occur in discrete plates, each a few hundred meters long (Fig. 3). Some open folding and minor faulting occur within individual plates, but major changes of attitude correspond to the faults which separate plates. Few faults can be traced for long distances; most terminate against another or curve into parallelism with the bedding. En echelon overlapping of plates and lateral wedging between pairs of convergent faults indicate crowding that results from displacement not only upward but inward as well, so that the outcrop band of any stratum is on a perimeter shorter than that which the rocks occupied at depth. Such centripetal displacement is characteristic of the central uplifts of cryptoexplosion structures (*10*). In contrast, around and above diapirs outward displacement is indicated by the characteristic through-going radial fractures (*11*).

The map pattern of the high bluff is a pentagon with a north-south line of symmetry. In the central hills the two shorter sides of the pentagon are suppressed, leaving a triangular pattern. On each side the bedrock plates (or more obviously the faults) are oblique and tend to have one set of orientations in the Stairway-lower Stokes, another in the Carmichael-Mereenie, and yet a third (more or less parallel to the first) in the Parke. The core of the structure, a tight anticline in the Stairway Sandstone, is found on the northwest side of the central triangle. The adjustment to a decreased perimeter requires some systematic pattern, but we offer no explanation why this particular pattern developed rather than any of the multitude of conceivable alternatives. It does not appear to reflect structural predisposition. The north-south line of bilateral symmetry appears to have no relation to the regional geology. One may speculate with no supporting evidence that it marks the direction of entry of the impacting bolide.

Subsurface Structure from Seismic Reflection

An exploratory well drilled for oil in the center of the bluff indicates that steep dips are maintained to a depth of at least 1380 meters. All other subsurface information has been obtained by geophysical techniques.

Two main seismic reflection traverses were run, each 25 km long, crossing at right angles at the center of the bluff (Fig. 4). Reflection quality, normally excellent in the Amadeus Basin, deteriorates markedly within the perimeter of the disturbance. Shot hole and geophone patterns were therefore designed to minimize both coherent and random noise. Multiple coverage, common depth point recording was used within the disturbance, for the most part 3-fold coverage, but as much as 24-fold coverage, inside the bluff. Continuous multiple coverage was obtained under the inaccessible high bluff by offset shooting. Earlier seismic surveys extend the coverage and allow identification of reflectors with horizons penetrated by exploratory wells.

Interpretation of records is complicated by an increase of velocities from

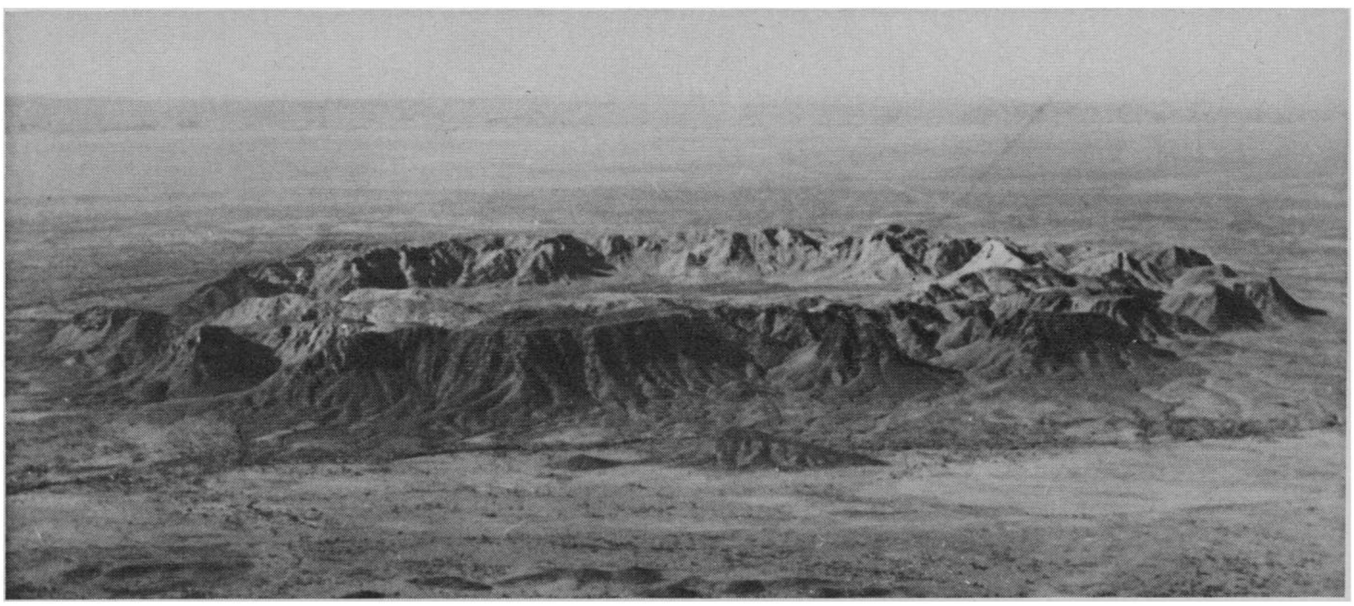


Fig. 2. Aerial view of Gosses Bluff from the north. [Photograph by C. Zawartko]

south to north, presumably caused by increasing silicification toward the MacDonnell Ranges, and by variable surface conditions close to the bluff which make elevation and weathering corrections deduced by normal methods very unreliable. The velocity in the section under Gosses Bluff does not seem to have been significantly affected by the disruption. The principal feature shown by the traverses is a bowl-shaped zone within which continuous reflections are absent. Migrated seismic horizons along the northwest-southeast traverse are shown in Fig. 5. The limits of disruption are difficult to located precisely. In the center of the structure the shallowest reflection event was recorded at 2.4 seconds after the shot indicating that disruption does not extend deeper than 5500 meters. On the cross section we have drawn the boundary of disruption as a hemisphere of radius 4.3 km inscribed within the end points to which reflecting horizons can be traced. This hemisphere is surmounted by a shallower saucer of disruption that can be defined by surface geology, the gravity field, the extent of the shallower seismic reflections, and by measurements of near-surface seismic velocity.

The Gardiner-Tyler anticline is evident in the deeper reflections along the northwest-southeast traverse (Fig. 5) and the northeast-southwest traverse shows that the Gosses Bluff disturbance lies above a domal high. This feature, suggested by earlier seismic surveys, led to the hypothesis (*5*) that the Grosses Bluff structure is a diapir with a core of salt rising from the upper Proterozoic Bitter Springs Formation at the crest of the anticline. The continuity of reflecting horizons in and above the Bitter Springs clearly rules out any diapirism. There is, however, an anomalous thickening of the lowest seismic interval (approximately equivalent to the Bitter Springs Formation) beneath the Gosses Bluff disturbance. If the thickening is a result of salt flowage completed in early Paleozoic time, as appears to be the case elsewhere along the anticline, the superposition of an impact structure must be simple coincidence. It is quite possible, however, that the Gosses Bluff event initiated renewed slow movement of salt. A third possibility, that the structure at depth is in some way an immediate response to impact, seems least likely, as the seismic coherence suggests slow deformation.

Shatter Cones

Shatter cones (Fig. 6) are conical fracture surfaces with divergent striations along the length of the cone. They have been found at about 20 cryptoexplosion structures (*12*) and have been produced in craters blasted in granite by multiton charges of TNT at shock pressures of 30 ± 5 kilobars (*13*). Shatter cones apparently form during the compressive phase of a shock event, with axes normal to the shock front and apices at points where the shock wave is diffracted by minor inhomogeneities in the rock (commonly bedding plane discontinuities but occasionally more unusual features; see Fig. 6, right) (*14*).

The orientation of shatter cones records the direction of advance of the shock front and the assemblage of cone axes should point to a focus that corresponds to the center of shock propagation. To use this record, however, displacements of the shatter-coned beds during the subsequent rarefaction phase must be taken into account. Analysis of cone orientation thus requires both finding the axes of the cones and restoring them to their original orientations and positions.

The axial orientation and apical angle of each cone were determined from about 20 measured striations (*15*). Because individual full cones are the exception rather than the rule at Gosses Bluff, striations from several cone segments usually had to be measured (Fig. 6, left). The axis and apical angle of the cone of best fit to the striations and the root mean square deviation of the striations from this cone were computed. Of 95 stations, 87 yielded a well-defined cone (root-mean-square deviation of striations $<9°$), belying the impression of multiple cones or even random orientations which the partial cone segments can give.

To reconstruct the original orientation and location of the shatter cones, it was assumed that bedding was horizontal when shatter coning occurred and that the cones formed directly beneath their present locations at depths corresponding to their stratigraphic positions. The orientation within the horizontal plane must also be specified. Alternate computer programs were run in which (i) the bedding at each station was either simply rotated about the line of strike to be horizontal, or (ii) the bedding was first rotated about a vertical axis to put the strike at right angles to a radius from the center of the structure and then rotated to horizontal. A focus, defined as the point closest to the extended axes of all the cones, was found by least squares anal-

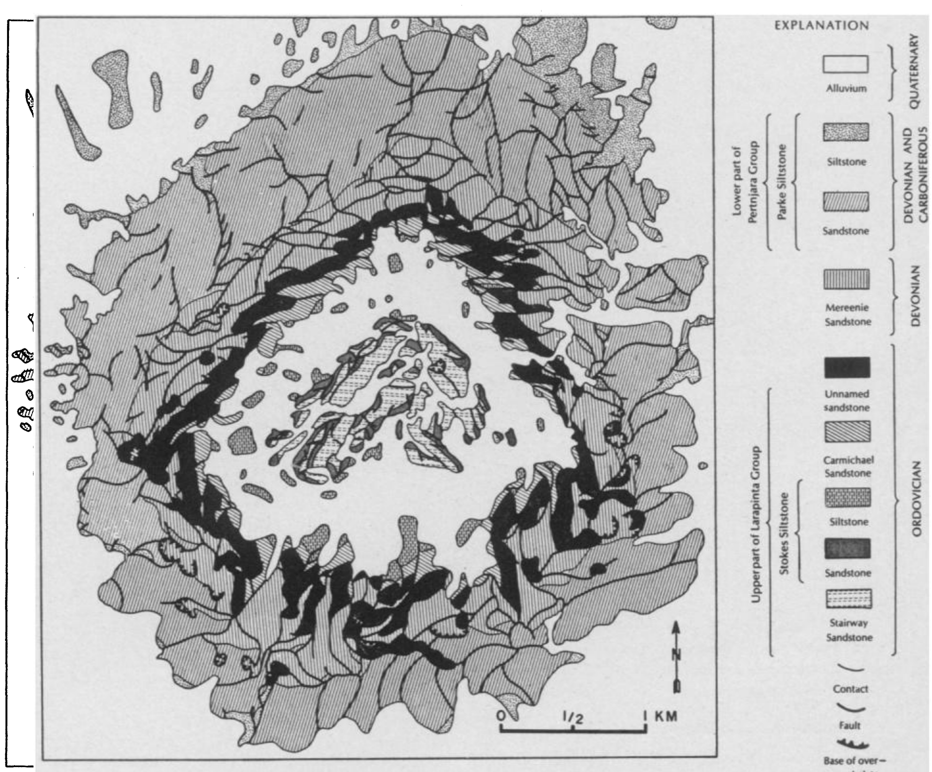


Fig. 3. Geologic map of the central uplift area, Gosses Bluff.

ysis. Foci found by the two methods of reorientation are very close; the simpler method (i) yields a focus with less variance. The map location of this focus is no more than a hundred meters from the center of the bluff.

The deviation of individual cone axes from the direction of the common focus reflects the history of particular rock masses. Stations in the south of the bluff, for example, show less deviation when reoriented by program (i) than (ii), indicating that the plates, despite their marked obliquity to the broader structure, were only rotated about their lines of strike (and translated) during emplacement. Other plates, however, underwent more complex rotations, so in order to treat all stations uniformly, a third program was used in which all cones were rotated so that the bearing of their axes pointed to the center of the structure. This, of course, assumes the horizontal coordinates of the focus, but yields a better estimate of the vertical coordinate.

An overall focus was found about 3000 meters stratigraphically above the lowest exposed bed. More significantly, however, the separate foci obtained when cones in different stratigraphic units are treated separately are spread through a vertical span of 1900 meters in which foci from higher units are progressively higher. A possible interpretation of this spread is that it reflects some nonhemispherical shape of the advancing shock front. We believe, however, that it results from the neglect in our model of the inward displacement that occurred during formation of the central uplift. If the radial distances to the cone stations were greater, the foci would be higher. We assume that the outermost cone stations, in the Hermannsburg Sandstone at about half the radius of the structure, have not moved horizontally. If so, then the foci for the lower units are brought into coincidence with the Hermannsburg focus if the mean horizontal radial distances to the stations have been reduced by the following percentages of the original radial distances: Parke Siltstone, 20 to 30 percent; Mereenie Sandstone, 24 to 37 percent; Carmichael Sandstone, 25 to 38 percent; Stairway and Stokes Formations, 33 to 52 percent. The range of values arises from uncertainties in the stratigraphic thicknesses. We believe that these decreases in radius are the best measure of the centripetal displacement. The Hermannsburg focus is 1500 meters above the mean stratigraphic elevation of the stations in this unit. Neither the stratigraphic thickness in the higher units nor the position of the ground surface at the time of the event are known precisely, but it appears that the focus of energy responsible for the shatter coning at Gosses Bluff was at most 600 meters below the pre-event ground surface and probably much shallower.

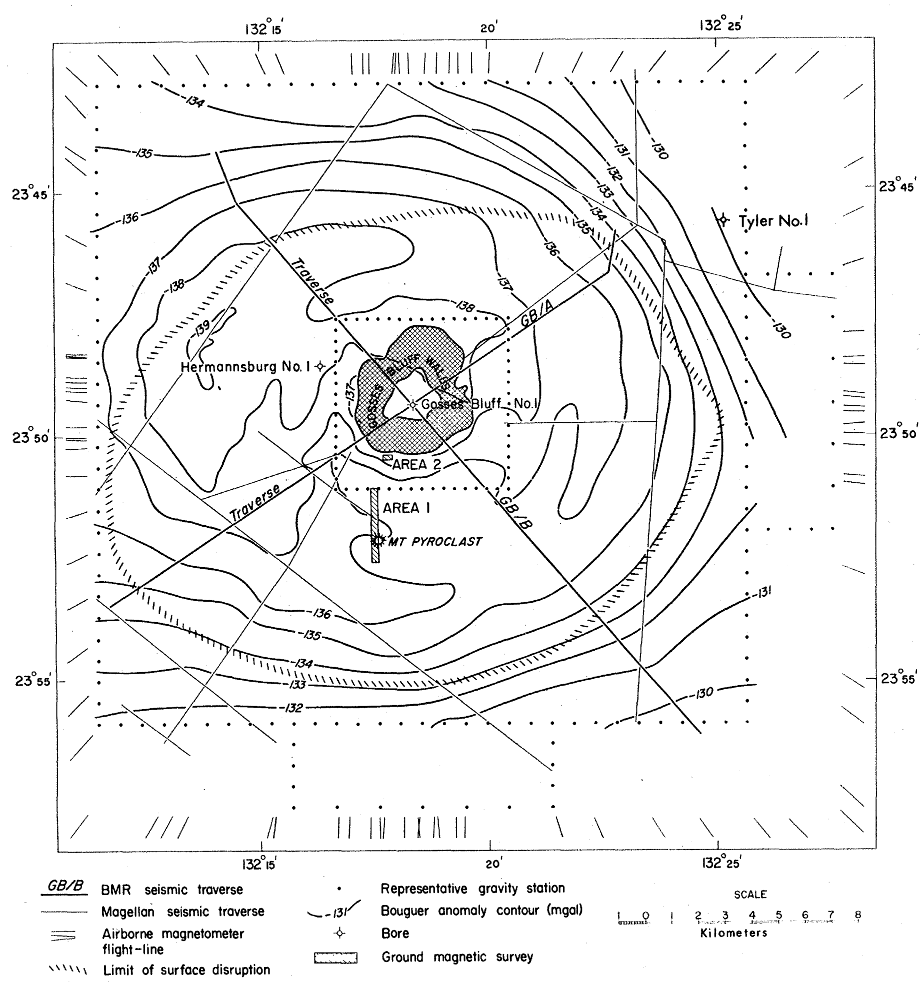


Fig. 4. Geophysical operations and preliminary Bouguer anomalies. Contour interval, 1 mgal.

The Shallow Zone of the Central Uplift

Closer to the focus and the ground surface, where the shock was less attenuated and the rock less constrained, stresses behind the rarefaction front were sufficient not only to break apart and move rock in large plates but to break rock into small fragments and to hurl them upward to fall back as breccia deposits. Erosion has removed much of the breccia but little coherent bedrock, so that the original bedrock-breccia contact is closely approximated by the present ground surface, including the abrupt outer (and probably inner) walls of the bluff and the deep valleys that dissect it. Nevertheless, breccia remnants are found at the summit surface of the bluff, in the valleys, and at the base of the outer wall, as well as on the surrounding plain. Fragmentation is often extreme and clasts are unsorted and randomly oriented, but mixing of clasts from different units is very uncommon.

The depth to which brecciation occurred depended on the strength of the rock, so that resistant strata remained in coherent plates while adjacent weaker strata were brecciated. During the few seconds before the breccia settled, vertical plates of harder strata stood against empty space. In many places the unsupported upper ends toppled outward to lie as overturned plates or detached blocks on the truncated edge of stratigraphically higher units. Some large blocks lie so far from the parent plates that outward propulsion rather than simple toppling must have oc-

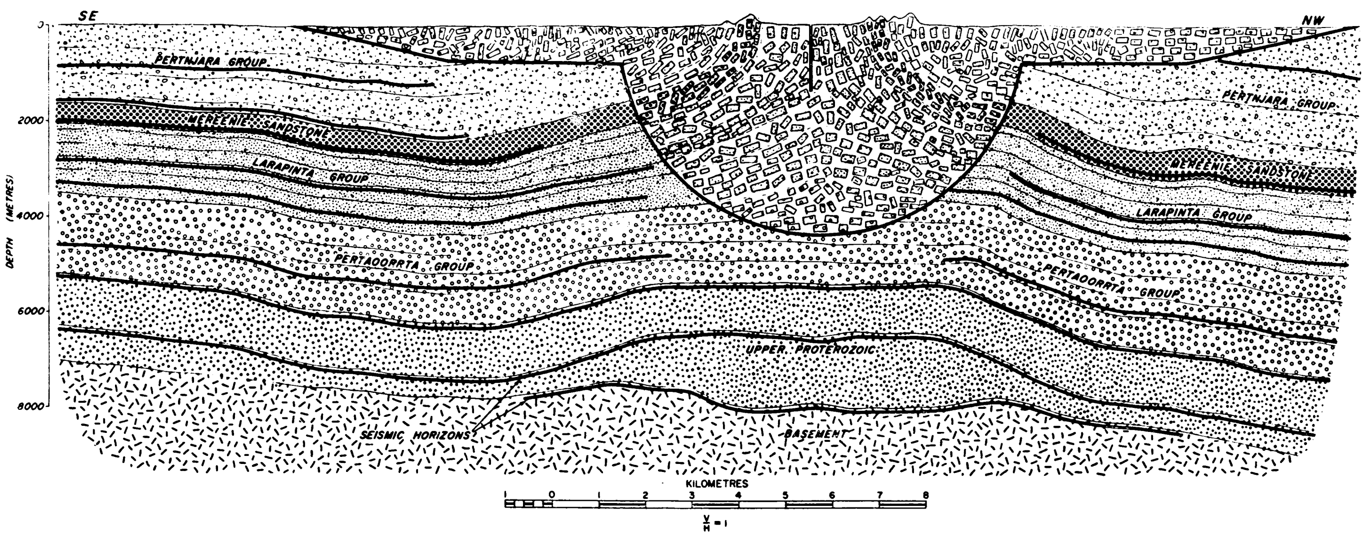


Fig. 5. Migrated seismic horizons and generalized geologic cross section through the Gosses Bluff structure.

curred. Hundred-meter-long blocks of the uppermost Larapinta sandstone lie 350 meters from the Larapinta outcrop; others lie within the narrow valley at the base of the Parke, on edge and facing inward after a 270° rotation from the original horizontal. Breccia is commonly thin or absent beneath overturned blocks, indicating that they were emplaced before the bulk of ejecta settled.

All the displacements observed in the central uplift, as well as the ejection of material that created the topographic crater itself, appear to reflect the flow field established as an immediate response to the rarefaction wave: accelerations dominantly upward, with an inward component at depth and an outward component near the surface. This concept differs significantly from current ideas, which view central uplift as a late phenomenon in an impact event induced by slumping of the crater walls (*16*).

Outer Zones and Gravity

The structural pattern of the bluff continues on the plains outside: steeply dipping, outward-facing bedrock plates, with some plates overturned outward to nearly horizontal downward-facing attitudes; and zones of breccia, both ordinary breccias in which clasts range from meter size to powder, and megabreccias, chaotic assemblages of blocks characteristically tens of meters to a hundred meters in size.

Geophysical data, especially gravity results, partly compensate for the relative lack of outcrop on the plains. Preliminary simple Bouguer anomaly contours (not including terrain corrections) from measurements at about 1550 stations are shown in Fig. 4. The extremely low values are typical of the Amadeus Basin. Removal of the regional gravity field (*17*) and correction for terrain effects indicate a residual gravity low, reasonably circular and centered on the bluff (Fig. 7). The anomaly shows an irregular but basically flat bottom with an average value of about -3 mgal extending to 8 km from the center and a persistent gradient between 8 and 13 km. Gravity models, based on concentric cylinders centered on the bluff, demonstrate that the mass deficiency is not distributed throughout the volume of disturbance as indicated by the seismic data but is primarily due to a near surface disk. A disk of radius 11 km, thickness 2 km, and density contrast -0.04 g/cm^3 gives a reasonable fit to the average gravity profile and is not only the simplest model but also that which gives the estimate of maximum thickness. Figure 5 shows a geologically more acceptable model which also gives a good fit to the profile if a density contrast of -0.1 g/cm^3 is taken for the near surface material. The fine structure of the gravity field is thought to arise from local density contrasts up to 0.1 g/cm^3. Some of this fine structure arises from the different densities of stratigraphic units—for example, the

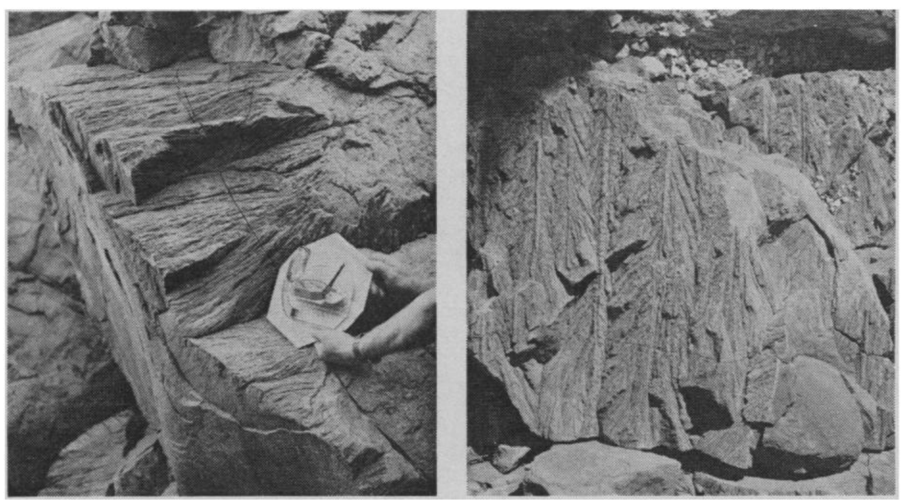


Fig. 6. (Left) Shatter cone measurement in Mereenie Sandstone. The cone segments near the instrument describe two-thirds of the complete cone; striations on segments in the upper right corner complete the cone. (Right) Shatter-coned "pipe rock" in Mereenie Sandstone. Coning was initiated along Scolithus tubes, casts of burrows normal to the bedding made by organisms dwelling in the sand.

steep-sided annular gravity low apparently associated with the lower density sandstones that underlie the high bluff (Fig. 4). The arcuate gravity lows on the outer plains, however, together with surface geology and shallow seismic refraction, appear to indicate troughs of breccia, one of which has a depth of at least 160 meters at the Hermannsburg No. 1 drill hole.

The maximum gravity gradient suggests a limit to the disturbance at a radius of about 11 km in all directions, and the most remote highly deformed and overturned beds and megabreccia are found at about this radius. In some sectors, however, beds dipping outward at low angles and interrupted at widely spaced intervals by faults or small sharp folds are found out as far as 13 km, while in other sectors flat-lying bedrock crops out as close as 7.5 km to the center. The irregular map pattern and the sharpness of the contact between highly deformed and gently tilted or undeformed rock, together with the general lack of significant associated distortions of the residual gravity field, suggest that these disturbances extend only to shallow depths. It would appear that there is an uptilted crater wall on which lie remnants of the basal part of a structurally complex rim zone, corresponding to the zone of thrust slices and overturned folds mapped at the Ries crater (*18*) or the Henbury craters (*19*). Correlation of structural and topographic features of the crater is difficult, but an original crest to crest diameter of about 20 km seems reasonable. The partial preservation of the rim zone suggests that the present ground level is not far below the pre-crater ground level.

Shock Metamorphism and Melt Breccia

The response to shock of a mineral grain or a rock depends on the entire extremely complicated history during the shock pulse and the relaxation period. Nevertheless, effects can be ranked in a sequence of increasing shock metamorphism (*20*), and the peak pressures associated with these can be determined experimentally (*21*). Quartz is one of the best indicators of progressive shock. The lowest grade of shock metamorphism in quartz—irregular fracturing—is widespread at Gosses Bluff. "Cleavage," widely spaced open fractures along rational planes, most commonly $\{10\bar{1}1\}$, is well developed in many specimens, particularly in the sandstones from the center of the bluff. In the laboratory cleavage begins to develop at shock pressures of about 50 kilobars (*21*). "Planar features" in quartz, sets of many parallel closely spaced, very narrow closed planes, are perhaps the most diagnostic and widely recognized indicator of shock in rock. Experimentally, they are produced at shock pressures above about 100 kb. They are common at Gosses Bluff (Fig. 8, left); where they are few, $\{0001\}$ planes dominate; where more abundant, $\{10\bar{1}3\}$. Planar features are more abundant in heavily silicified sandstone than in adjacent more porous sandstone, suggesting that development is favored by lower rock compressibility. They are also more abundant in breccia fragments than in nearby bedrock outcrops of the same units. Differences in peak shock pressure could not have been great; it may be that confinement during decompression partially suppresses the development of planar features.

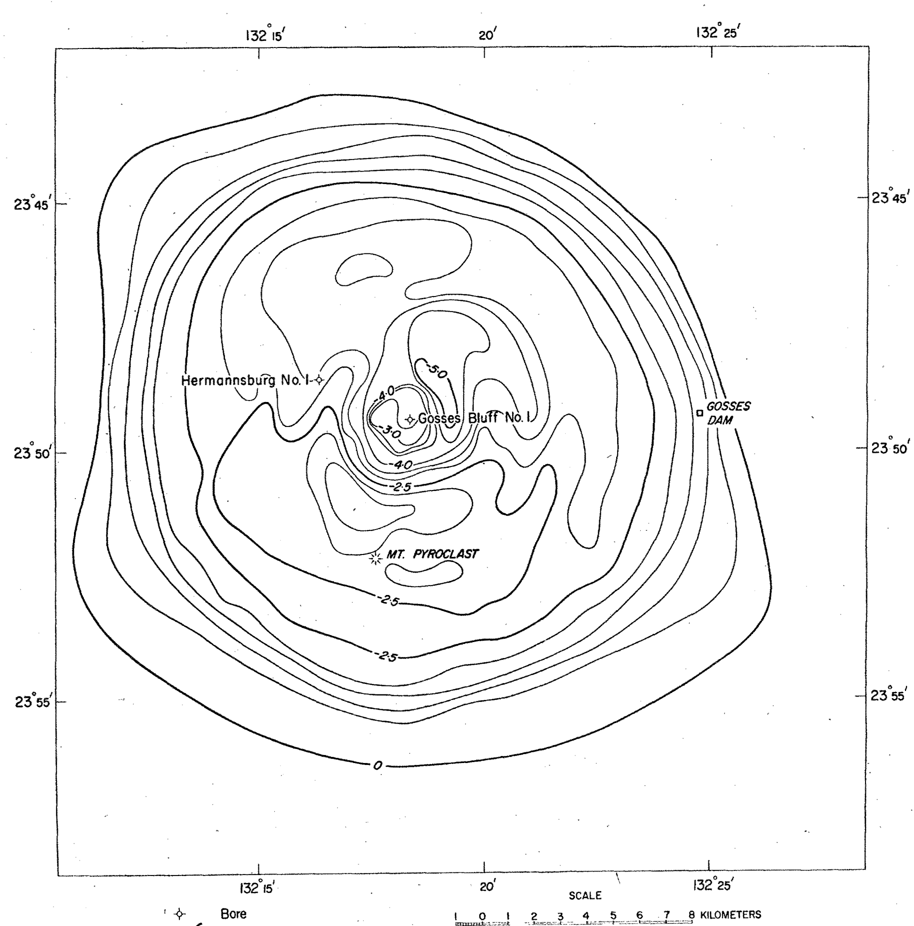


Fig. 7. Bouguer gravity anomaly contours, corrected for regional gradient and terrain effects. Contour interval, 0.5 mgal.

Experimentally, the refractive indices and birefringence of quartz are progressively reduced by higher shock pressures until at pressures between about 200 and 300 kilobars quartz is transformed to an isotropic glass. At about 400 or 500 kilobars the relaxation temperature in shocked sandstone is high enough to melt quartz. These stages of shock metamorphism were not reached in unfragmented bedrock or in the breccia now remaining on the bluff itself. Breccia composed largely of sintered shock-melted fragments ("suevite") is found, however, in isolated occurrences on the exterior plain, remnants of the basal layer of the crater fill. At Mount Pyroclast, a hill 40 m high and 5 km south of the center, a vertical gradation of shock effects is evident. At the base, quartz in breccia fragments shows abundant planar elements, but no evidence of phase change. In sandstone clasts higher on the hill destruction or at least severe disruption of the quartz lattice is indicated by sand grains which retain their outlines but have recrystallized in a diffuse, fine-grained texture. Still higher, actual melting is indicated by flowage features, at first barely detectable but more prominent upward until the breccia at the top is a mass of twisted ropy folds up to several meters long. Much of the quartz in this material recrystallized as felted aggregates of tridymite, the high temperature polymorph of silica, which have since completely reinverted to quartz (Fig. 8, right) (*22*).

Coesite and stishovite, the high-pressure polymorphs of silica, form at shock pressures of several hundred kilobars. Neither has been found at Gosses Bluff, despite extensive search. Their apparent absence, and the absence of any unrecrystallized glass, may be due to reequilibration during slow cooling near the base of the crater fill.

Shale and siltstone clasts in the melt breccia contain zeolites (mostly heulandite and some stilbite and chabazite) and sanidine. In general, no significant change of chemical composition of clasts is evident. Some pumiceous clasts composed largely of fine-grained potassium-rich high sanidine, however, contain 12.6 percent K_2O, more than any possible precursor. These are apparently shock-melted shale fragments enriched in potassium during an essentially hydrothermal stage in the cooling suevite (*23*).

Insofar as can be determined from clasts so highly altered, all material at Mount Pyroclast is Parke Siltstone, bedrock plates of which crop out nearby. The continuous vertical gradation of shock effects contrasts with the sharply marked base of suevite at the Ries Crater (*24*) but resembles the profiles in some Canadian craters (*16*). The clasts are unsorted; the larger ones tend to dip steeply rather than lie flat, although with no consistent strikes. There is no evidence that the material is fallback that was thrown a significant distance upward; it may have been packed against the crater wall after rather slight, largely horizontal transport.

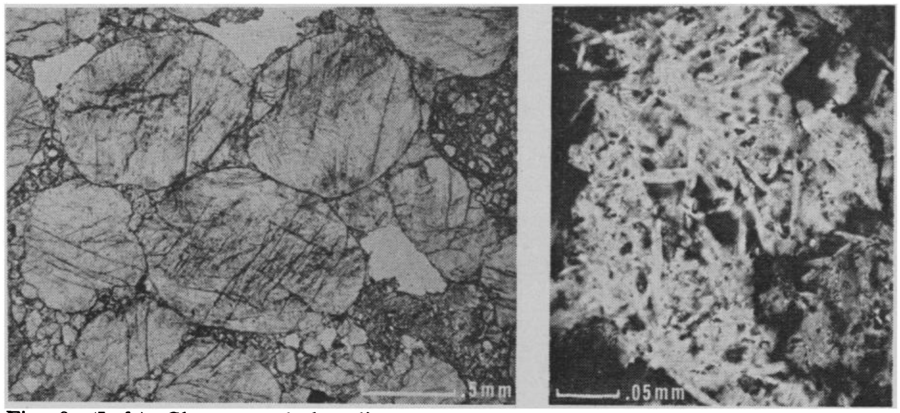


Fig. 8. (Left) Cleavage (darker lines) and planar features (fainter, closely spaced sets) in quartz grains in the basal sandstone of the Stokes Siltstone near the center of Gosses Bluff. (Right) Quartz paramorphous after tridymite in melt breccia, Mount Pyroclast. Crossed nicols.

Age of the Event

An earliest Cretaceous age is indicated by two dating methods. A potassium/argon age of 133 ± 3 million years was measured on the sanidine-rich rock from Mount Pyroclast. Zircon grains from thermally affected sandstones at the bottom of drill holes from beneath Mount Pyroclast have abundant fission tracks indicating Precambrian ages, as would be expected from the provenance of the detritus in the Paleozoic sediments. In zircon grains from the baked zone just beneath the melt breccia the older tracks have been annealed out and the number present would have developed in 130 ± 6 million years.

Magnetic Effects

An earlier regional aeromagnetic survey, flown at 300 meters above ground, showed no anomaly for Gosses Bluff. A survey at about 100 meters, with closely spaced flight lines (Fig. 4), however, showed a local anomaly of -75 gammas at Mount Pyroclast and smaller anomalies south, east, and west of the Bluff. Each of these is associated with an occurrence of highly shocked and thermally affected breccia. Many are nearly concealed by surficial deposits and were found only after being located magnetically. The anomalies are of short wavelength and reduce the intensity of the field; this indicates that they have very shallow sources whose main component of magnetization is in opposition to the Earth's present field, presumably, thermo-remanent magnetization in the direction of the Earth's magnetic field at the time of the Gosses Bluff event (*25*). From the aeromagnetic data alone, the Mount Pyroclast anomaly can be modeled by a dipole inclined at $+85°$ in the magnetic meridian at a depth of 100 meters. The true source of the anomaly, as indicated by drilling, is shallower than calculated.

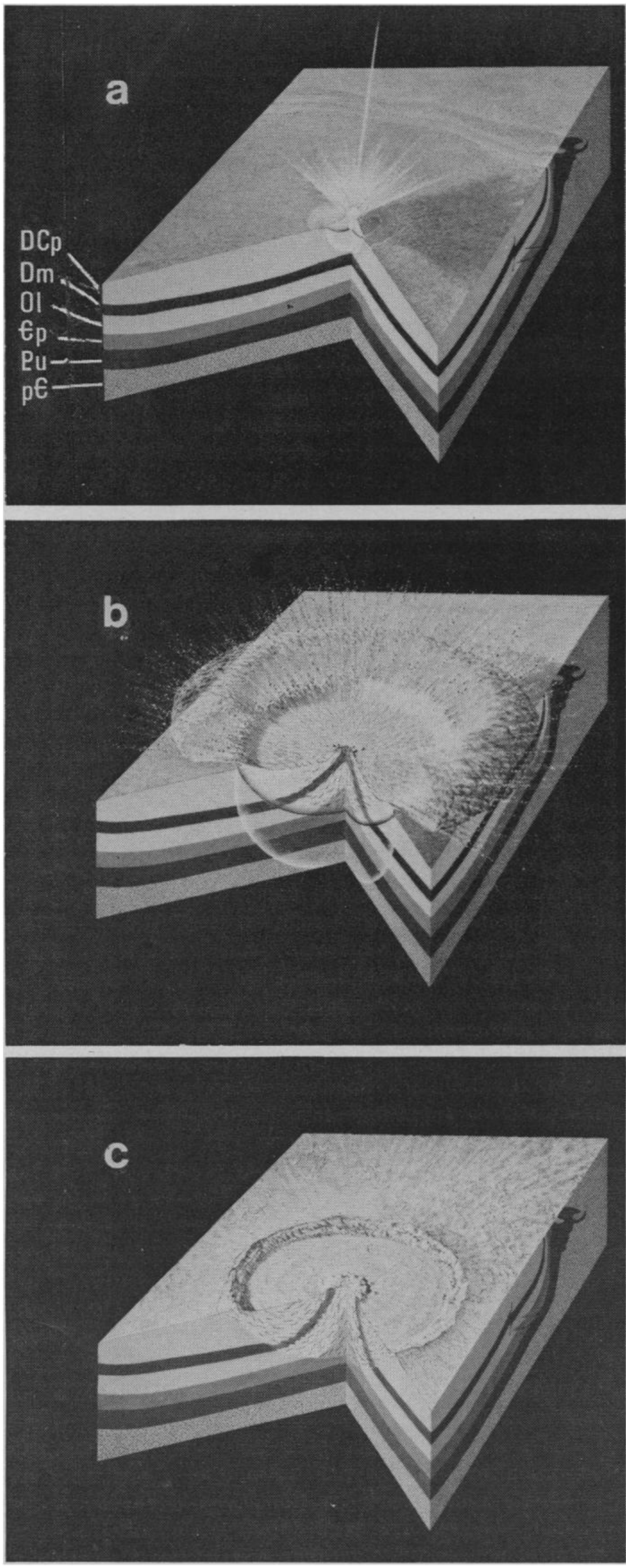
A detailed ground magnetic survey of the horizontal and vertical field over an area of thermal breccia at the base of the south wall of the Bluff revealed two anomalies which suggest sources similarly inclined at $+80°$. Measurement of the remanent magnetization of specimens confirmed the conclusions deduced from airborne and ground magnetic interpretation. The mean inclination is $+72° \pm 1°$, the declination 100°, intensities range up to 43×10^{-4} electromagnetic units per cubic centimeter and susceptibilities to 12×10^{-4} emu/cm^3. Australia was an unusually immobile continent during the Permian Period and Mesozoic Era, but the calculated pole position—170°E, 25°S—is satisfactory for an early Cretaceous date.

Origin

We may summarize the principal conclusions from the field evidence, which must be accounted for in any explanatory hypothesis: (i) Shatter cones were formed in undisplaced strata with their axes pointing to a focus near the ground surface. (ii) Displacement occurred after shatter coning, and so rapidly that large blocks were hurled through the air. (iii) Pressures in a large volume near the center of the disturbance reached at the least several hundred kilobars. (iv) Although the structure lies over an anticlinal axis, neither an igneous intrusion nor a salt diapir exists at depth.

The sequence of events accords with a shock process in which shatter coning occurred during the compression phase and displacement during the rarefaction phase. Loosely, the event could be called an "explosion," but this term can refer to processes of two quite distinct types, one exemplified by the deflagration of gunpowder and the other by the detonation of TNT. Deflagration is rapid but ordinary combustion. The pressures that are generated and the work that can be done depend on the thermal expansion of the hot gaseous products and the extent to which these are confined. Volcanic eruptions also operate by the adiabatic expansion of gases, particularly the flashing of water into steam, and are subject to the same limitations. Pressures in processes of these types cannot greatly exceed the 4.85-kilobar breech pressure of Big Bertha, which shelled Paris from 120 km (*26*), or the calculated 3-kilobar pressure of the 1956 eruption of the volcano Bezymianny, which hurled blocks 30 km (*27*).

By contrast, in a detonating explosive the combustion front advances at a supersonic velocity. The combustion front is then a shock front, behind which the energy, transiently in the form of the kinetic energy of motion rather than the potential energy of compression of the combustion products,



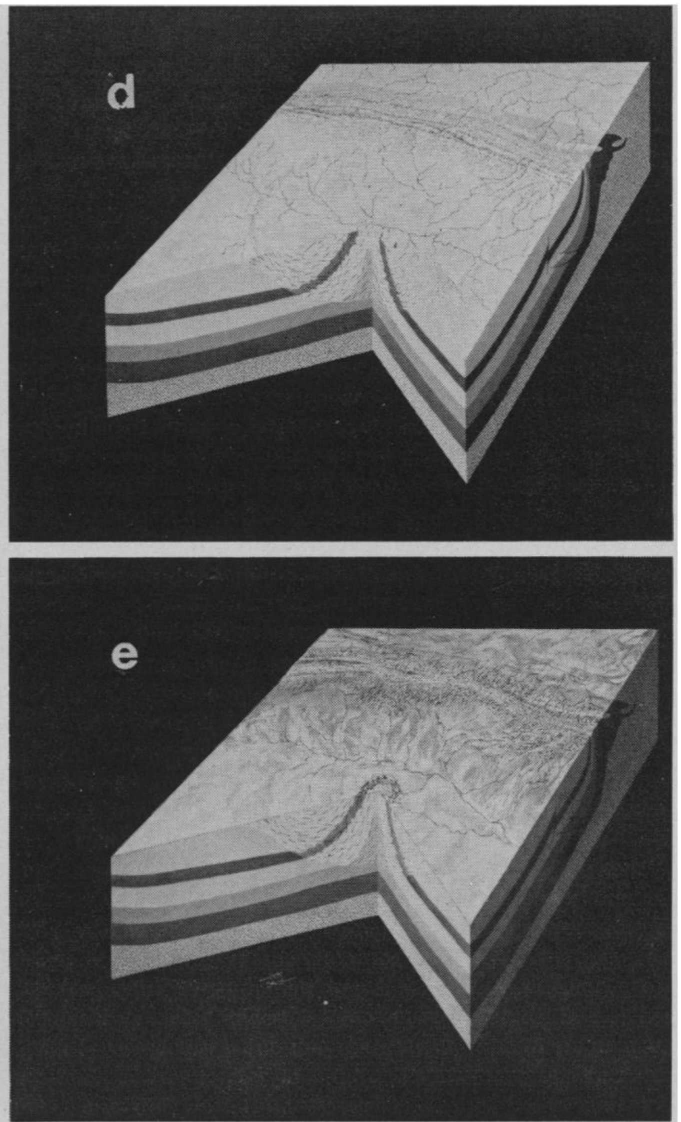


Fig. 9. Sequence of development of Gosses Bluff. *DCp*, Pertnjara Group; *Dm*, Mereenie Sandstone; *Ol*, Larapinta Group; *Cp*, Pertaoorrta Group; *PLu*, Upper Proterozoic; *pC*, basement [Paintings by Don Davis]. (a) Bolide enters ground. Shock wave (light surface) expands outward followed by the rarefaction front (dark surface) reflected from the ground surface. (b) Crater forms and central uplift is emplaced as rock moves behind the rarefaction front. (c) The ancestral Gosses Bluff stands as a central peak surrounded by suevite in the crater floor. (d) The crater rim has been destroyed by erosion and the crater filled by sediments. A plain extends from the present MacDonnell Ranges to the James Ranges (*31*). A stream flows across the site of Gosses Bluff, which is marked only by isolated sandstone hills less than 50 meters high. (e) Present state. Erosion has removed all postimpact sediments and most of the crater floor breccia. Beveled surfaces on the high bluff mark the former plains and notches mark the former watercourse.

can be extremely high. A massive detonation propagating a shock wave outward from the focus provides a model that fits the Gosses Bluff event closely. A large natural detonation seems impossible, but the impact of a bolide moving at many kilometers per second is a phenomenologically equivalent process (*28*) which would produce all the effects seen at Gosses Bluff.

Various scaling relations between crater diameter and energy (*29*) yield energies for the Gosses Bluff event spanning a range of about one order of magnitude with a mean about 10^{27} ergs or 2.4×10^4 megatons of TNT. This would be the kinetic energy of a low-density high-velocity comet (density = 1.3 g/cm^3, velocity = 40 km/sec) or a high-density low-velocity iron meteorite of asteroidal origin (density = 7.85 g/cm^3, velocity = 15 km/sec), each with a diameter of about 600 meters. Penetration of a bolide depends more on its density than on its velocity (*28*). The shallow depth of burst, indicated directly by the shatter cone data and indirectly by the presence of a central peak (*30*), suggests that the bolide was a comet. Whatever the material, it would have been melted or vaporized at impact and so dispersed that relicts are not likely to be found. Stages in the impact and in the subsequent development of Gosses Bluff are shown in Fig. 9.

Craters on Other Planets

Each cryptoexplosion structure that has been studied has its own individuality. Nevertheless, certain general patterns have emerged. Gosses Bluff is representative of its size class. Smaller craters, under about 2 km diameter [for example, Meteor Crater, Arizona (*28*)] have simple bowl-shaped profiles without central uplifts. Craters larger than Gosses Bluff may show multiple annular uplifts and depressions, and, unlike Gosses Bluff, contain igneous rock, either a product of crystallization of rock completely melted by shock [for example, Manicouagan, Quebec (*32*)] or of normal magma from depth, the intrusion of which was triggered by the impact [for example, Sudbury, Ontario (*33*)]. Each of these appears to have analogs on the Moon.

Techniques similar to those used at Gosses Bluff could some day be adapted to exploration of craters on the Moon and Mars. In the more foreseeable future, the findings at Gosses Bluff suggest critical observations that might be made on simpler and briefer missions such as the Apollo landings. The statement at the outset of this article that the terrestrial analogs of large lunar craters are cryptoexplosion structures is not universally accepted—an alternative hypothesis favored by many is that the proper analogs are volcanic calderas (*34*). The nature of the central peaks should be a critical test: Are they constructional volcanic forms contemporaneous with or younger than the floor material, or are they older rock rising from a floor of shock-melted breccia? If the lunar craters are indeed impact craters, the central peaks should furnish material uplifted from considerable depth. A first estimate of the depth could be based on simple analogy to Gosses Bluff and other terrestrial structures. A considerably more refined estimate should be possible, if only one or two orientable shatter cones could be recovered.

References and Notes

1. The term "cryptoexplosion structure" was introduced by R. S. Dietz [*J. Geol.* **67**, 496 (1959)] to avoid the genetic implication of the earlier "cryptovolcanic structure." One may conclude that certain, or all, cryptoexplosion structures are impact structures ("astroblemes") but a nongenetic term is still desirable.
2. B. M. French and N. M. Short, Eds., *Shock Metamorphism of Natural Materials* (Mono Book, Baltimore, 1968) compiles much recent research on cryptoexplosion structures.
3. A shock wave is a pulse of instantaneous compression that propagates away from the source at a supersonic velocity. The energy density or pressure decreases approximately in proportion to the mass of material engulfed by the shock wave. From each point at which the shock front reaches a free surface, a wave of decompression is generated and expands back into the compressed medium as a rarefaction front. Behind the rarefaction front material is accelerated toward the free surface. It is during the rarefaction rather than the compression phase that gross displacement of material may occur. If the solid body is the earth, material accelerated toward the ground surface may be ejected to produce a crater. During the brief duration of a shock pulse, either from a natural hypervelocity impact or in laboratory experiments, pressures may be in the range of hundreds of kilobars or even megabars, far beyond the range of ordinary metamorphism of rocks. Shock compression is essentially isentropic and decompression adiabatic, so that the final temperature of the shocked material is higher than the initial temperature.
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12. R. S. Dietz, in *Shock Metamorphism of Natural Materials*, B. M. French and N. M. Short, Eds. (Mono Book, Baltimore, 1968).
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14. Theories of shatter coning have been developed for ideal models [P. J. S. Gash, *Nature Phys. Sci.* **230**, 32 (1971)], but as yet have not been tested against actual occurrences. A fact that needs explanation, for example, is the differences in apical angle between cones at Gosses Bluff (mean 80.5°), Sierra Madera (mean 88.5°), and Vredefort (range 90° to 122°).
15. Techniques are basically those developed by Manton (*10*), adapted for computer plotting and calculation.
16. For example, M. R. Dence, in *Shock Metamorphism of Natural Materials*, B. M. French and N. M. Short, Eds. (Mono Book, Baltimore, 1968), p. 182.
17. Based on a regional Bouguer anomaly map compiled from unpublished gravity surveys, including a uniform 11-km grid of the Bureau of Mineral Resources and other data [see (9)].
18. E. Preuss, *Geol. Bavarica* **61**, 18 (1969).
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