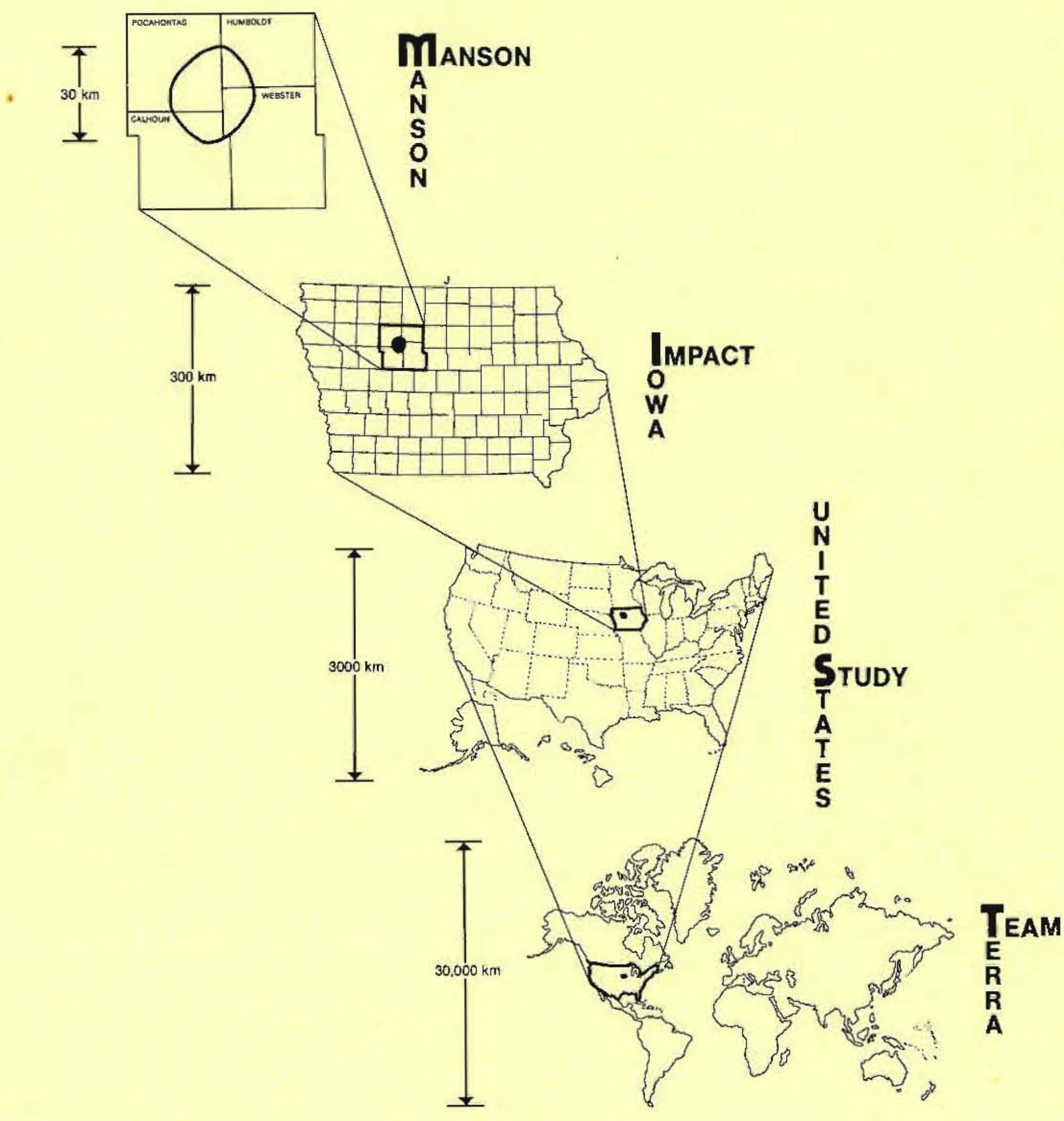
A COMPILATION OF INFORMATION AND DATA ON THE MANSON IMPACT STRUCTURE



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A COMPILATION OF INFORMATION AND DATA ON THE MANSON IMPACT STRUCTURE

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A Compilation of Information and Data on the Manson Impact Structure

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A problem for the impact hypothesis for the Cretaceous-Tertiary (K-T) mass extinction is the apparent absence of an identifiable impact site. The Manson Impact Structure is a candidate impact site because it is large (the largest recognized in the U.S.); it is relatively close to the largest and most abundant shocked quartz grains found at the K-T boundary; and its age is indistinguishable from that of the K-T boundary based on paleontological evidence, fission track dates, and preliminary $^{40}Ar/^{39}Ar$ measurements. The region of northwest central Iowa that contains the Manson Impact Structure is covered by Quaternary glacial deposits that are underlain by Phanerozoic sedimentary rocks (mostly flat-lying carbonates) and Proterozoic red clastic, metamorphic, volcanic, and plutonic rocks. In a circular area about 22 miles (35 km) in diameter around Manson, Iowa, this normal sequence is absent or "disturbed," and near the center of the "disturbed" area granitic basement rocks have been uplifted about 20,000 ft (6000 m). Attention was drawn to Manson initially by the unusual quality of the groundwater there. Within the structure three roughly concentric zones of rock associations have been identified: (1) displaced strata, (2) completely disrupted strata, and (3) igneous and metamorphic rocks. Manson was established as an impact structure based on its circular shape, its central uplift, and the presence of shocked quartz within the granitic central uplift. A gravity survey identified locations of low-density brecciated rocks and high-density uplifted crystalline rocks, but the outer boundary of the structure could not be established. Aeromagnetic and ground magnetic surveys indicated locations and depths of shallowly buried crystalline rock and the locations of faults. A refraction seismic survey identified the crystalline central uplift, determined that the average elevation of bedrock is 70 ft (20 m) higher outside the structure than within, and was used to map the bedrock topography within the structure. A connection between the Manson impact and the K-T boundary may be established or refuted through study of the impact energy, the impact time, and compositions of host rock, possible impactors, and impact melts.

INTRODUCTION

The end of the Mesozoic era is marked by the extinction of up to half of the species then on the Earth. Based on anomalously high iridium abundances in Mesozoic-Cenozoic (Cretaceous-Tertiary or K-T) boundary clay, *Alvarez et al.* (1980) concluded that a large extraterrestrial object (about 10 km in diameter) had collided with the Earth and produced a thick, globally dispersed cloud of dust that blocked light from the sun and ultimately caused wholesale loss of life on the Earth.

A problem for this impact or collision hypothesis is the apparent absence of a large crater, perhaps 200 km in diameter, to mark the site where the postulated impact occurred. The presence of larger and more abundant shocked quartz grains at North American K-T boundary sites indicates a North American continental impact site is more likely than one in an ocean basin or on another continent (*French*, 1984). While the absence of a known large crater associated with the K-T boundary does not disprove the impact hypothesis, the positive identification of such a crater would greatly strengthen it. Therefore, it is appropriate to study thoroughly all craters that may be related to the K-T boundary, especially those on the North American continent.

It was known over 20 years ago that rocks underlying and surrounding the town of Manson, Iowa, had been affected by a large impact (*Short*, 1966; *Bunch*, 1968). But vigorous study of the structure was not undertaken because it is entirely covered by Pleistocene glacial deposits. However, nearly identical ages for the Manson Impact Structure and the K-T boundary have recently stimulated considerable interest in the structure. This interest has resulted in the formation of the Manson Impact Study Team (MIST) and the preparation of this report.

The Manson Impact Structure is only 22 miles (35 km) in diameter and may be too small to account for all of the effects related to the K-T boundary, but it may account for some of them and remains the best candidate for an impact structure related to the K-T boundary for the following reasons: (1) It is the largest impact structure recognized in the U.S.; (2) it is relatively close to the largest and most abundant shocked quartz grains found at the K-T boundary; and (3) recent preliminary $^{40}Ar/^{39}Ar$ age measurements have narrowed the time of the Manson impact to an interval of about 4 million years, which includes the time of the K-T boundary, about 66 million years ago.

The objective of this report is to summarize what has been learned about the Manson impact up until the present time. The report consists of a summary of the pre-Pleistocene geology of northwest central Iowa, a description of the geology of the "disturbed" area surrounding Manson, Iowa, the results of geophysical studies that include the Manson structure, a presentation of age data for the Manson impact, and a discussion

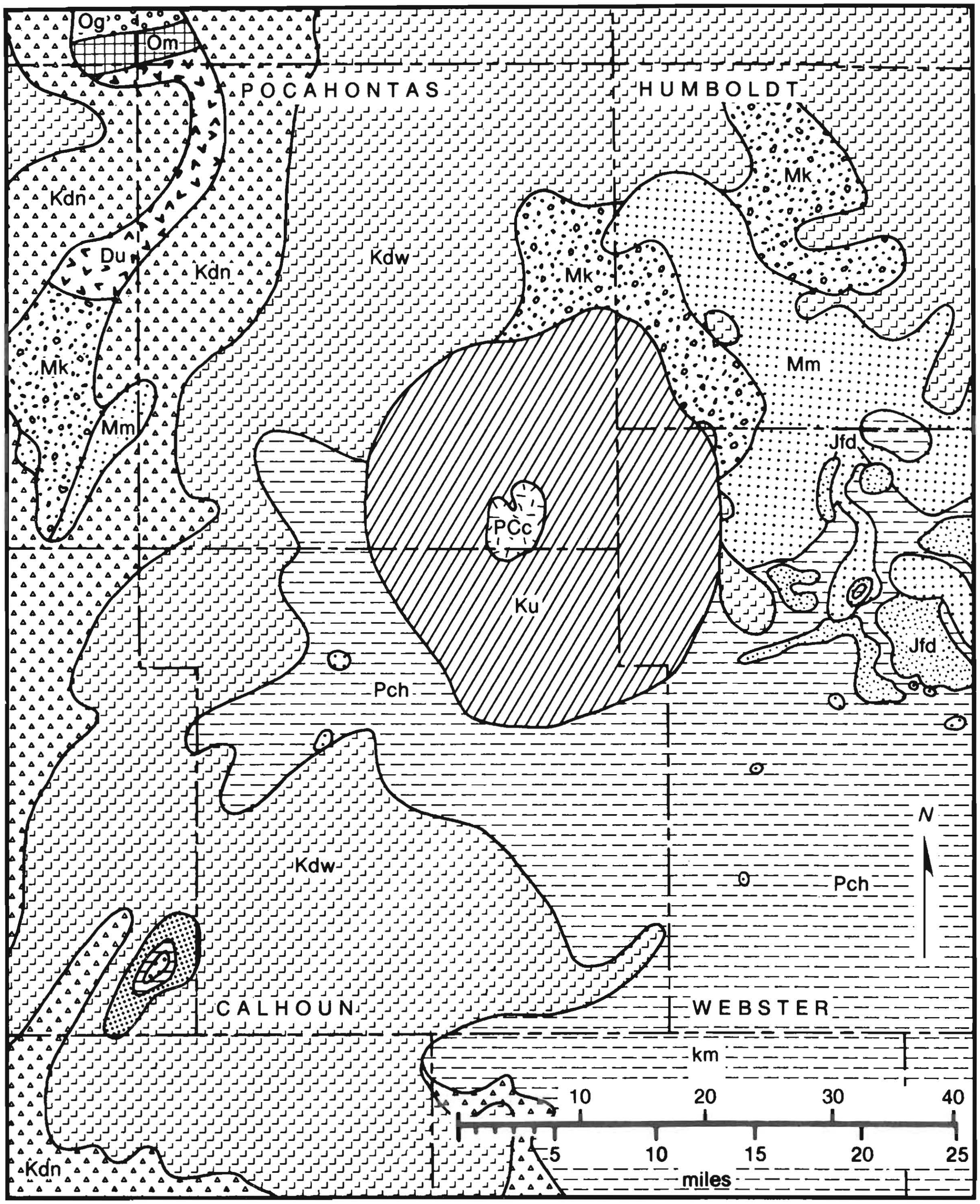

Fig. 1. Geological map of the bedrock in the area of northwest central Iowa that includes the Manson Impact Structure (modified from *Hershey*, 1969, and *Munter et al.*, 1983). Most of the region, and all of the Manson Impact Structure, is covered by Quaternary glacial deposits, so most of the information shown on the map was obtained through study of water well cuttings.

emphasizing the possible relationship between the Manson impact and the K-T boundary mass extinction.

GEOLOGY OF NORTHWEST CENTRAL IOWA

Stratigraphy

The region of northwest central Iowa that contains the Manson Impact Structure is covered by a thick sequence of Quaternary sediments. Mesozoic, Paleozoic, and Middle Proterozoic sediments and sedimentary rocks overlie a basement of Proterozoic metamorphic and plutonic rocks (Figs. 1–3). The basement sequence includes garnetiferous oligoclase-biotite-quartz gneiss that was apparently part of an island arc sequence accreted to the Superior craton during the Penokean orogeny about 1850 Ma ago. This gneiss was invaded by migmatitic, intrusive pink-to-leuco granite, sometimes displaying lit-par-lit structure, and magnetite metasomatism, which probably occurred during a continent-wide felsic igneous event about 1450 Ma ago. These rocks were cut by diabase dikes, probably intruded during Keweenawan rifting, about 1000 Ma ago. All of these basement lithologies can be observed in the central uplift of the Manson Impact Structure (*Dryden*, 1955). The general ages of the Penokean gneiss and subsequent granite plutonism in this area were determined by Z. Peterman (personal communication, 1987).

With the waning of rifting and volcanism during formation of the Midcontinent Rift System about 1000 Ma ago, a period of regional subsidence led to the deposition of a thick sequence of fluvial sediments dominated by red shales, siltstones, and sandstones informally called "red clastics" in Iowa. The "red clastics" probably consist of an older sequence of immature sandstones, conglomerates, and shales equivalent to the Oronto group of the Great Lakes area overlain by a sequence of more mature feldspathic sandstones and quartz arenites similar to the Bayfield group of Wisconsin. Gravity modeling suggests that the "red clastics" range from about 18,000 to 24,000 ft (5500–7400 m) in thickness in the area of the Manson Impact Structure (*Anderson*, 1986a,b). Cores and cuttings from within the structure contain rocks tentatively identified as "red clastics."

Above the "red clastics" a similar fluvial sequence, presently interpreted as Middle Cambrian, is preserved just beneath the rounded, frosted quartz arenites of the Mt. Simon formation, the first unit of a sequence of dozens of marine transgressive-regressive cycles that occurred in the central midcontinent during the Paleozoic. The rocks deposited during these cycles are dominated by marine carbonates, shales, siltstones, and sandstones, but include minor continental sandstones, siltstones, shales, and coals, which are especially thick in Middle Pennsylvanian strata.

During the Mesozoic Jurassic shale, sandstone, and gypsum, called the Fort Dodge beds, were deposited and preserved in structures east of the Manson structure. Cretaceous fluvial sediments of the sandstone-dominated Nishnabotna member and the more shaley Woodbury member of the Dakota formation are overlain by Graneros shale, Greenhorn limestone, and Carlile shale, which occur as rare, locally preserved outliers. A map of the bedrock geology around the Manson structure is shown in Fig. 1. Rocks of the Mississippian Kinderhookian and Osagean series and overlying Cretaceous Woodbury member are found north of the structure and Pennsylvanian Cherokee group rocks to the south.

The bedrock is overlain by 100 to 300 ft (30–90 m) of Quaternary glacial deposits. The basal, pre-Illinoian Alburnett formation is probably Pleistocene and is overlain by pre-Illinoian Wolf Creek and Wisconsinan Sheldon and Dows formations. A summary of the stratigraphy in the area around the Manson Impact Structure is given in Fig. 2.

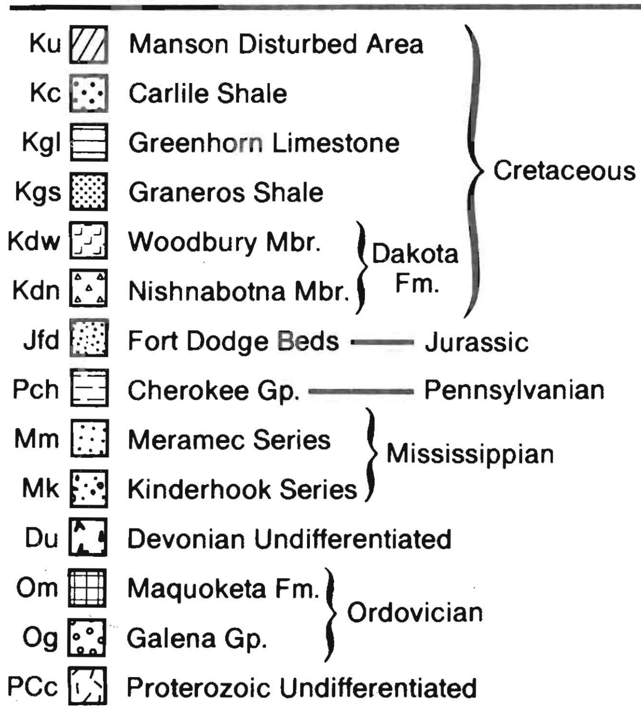

Fig. 1. Legend

Depth (ft)	System	Series	Group	Formation	Member	Lithologies
0	Quaternary	Pleistocene	Wisconsinan	Dows		diamicton
				Sheldon		diamicton
			Prelllinoian	Wolf Creek	Hickory Hills Till	diamicton
					Aurora Till	diamicton
					Winthrop Till	diamicton
		Pleistocene?		Alburnett	"unnamed till"	diamicton
200	Cretaceous			Dakota	Woodbury	sandstone, shale
					Nishnabotna	sandstone
350	Jurassic			Fort Dodge beds		gypsum, shale
400	Pennsylvanian	Desmoinesian		Floris		
			Cherokee	Kalo		shale, sandstone, coal
		Atokan		Kilbourn		
550	Mississippian	Meramecian		Pella		limestone, shale
				St. Louis		sandstone
				Warsaw		shale
		Osagean		Keokuk		dolomite
				Burlington		dolomite
				Gilmore City		limestone
		Kinderhookian		Hampton	Iowa Falls	limestone
					Eagle City	dolomite, limestone
					Maynes Creek	dolomite
			North Hill	Chapin		limestone
				Prospect Hill		siltstone
1050	Devonian	Upper	Yellow Spring	Maple Mill		shale
				Aplington		dolomite
				Sheffield		shale
				Lime Creek		dolomite
			Cedar Valley	Shell Rock		dolomite
				Lithograph City	Idlewild	dolomite
					Osage Springs	dolomite
		Middle		Coralville	Iowa City	dolomite
					Gizzard Creek	dolomite
				Little Cedar	Hinkle	limestone
					Bassett	dolomite
1600	Ordovician	Upper		Maquoketa	Clermont	dolomite
					Elgin	dolomite
			Galena	Dubuque		dolomite
				Wise Lake		dolomite
		Middle		Dunleith		dolomite
				Decorah	Ion	
					Guttenberg	shale
					Spechts Ferry	
				Platteville	McGregor	dolomite
					Pecatonica	
			Ancell	Glenwood	Harmony Hill	shale
				St. Peter		sandstone
		Lower	Prairie du Chien	Shakopee	Willow River	
					New Richmond	dolomite
				Oneota		dolomite
2300	Cambrian	Upper	Trempealeau	Jordan		sandstone
				St. Lawrence		dolomite
			Tunnel City	Lone Rock		dolomite
			Elk Mound	Wonewoc		sandstone
				Bonneterre		dolomite
				Mt. Simon		sandstone
2600	Middle Proterozoic	Keeweenawan Super Group	"Bayfield"			shale, siltstone,
			"Oronto"			sandstone
			"unnamed volcanic and plutonic rocks"			
			"Central Iowa Arch"	"unnamed granite" (ca. 1450 Ma)		granite
22000	Lower Proterozoic		"unnamed Penokean island arc-related rocks" (ca. 1850 Ma)			gneiss

Fig. 2. Representative stratigraphic section in the area of northwest central Iowa that includes the Manson Impact Structure.

Structure

An overall NE-SW structural grain in the basement rocks in the area of the Manson Impact Structure was produced by the accretion of a series of island arcs and associated rocks onto the northeast-trending margin of the Archean Superior Province, which lies about 60 miles northwest of the Manson structure. This grain is cut by the anomalous, north-trending Central Iowa Arch, apparently the product of a granitic pluton intruded about 1450 Ma ago. High-angle, normal faults associated with the formation of the Midcontinent Rift System followed the older northeasterly structural trend. These faults formed the walls of high-relief grabens that filled with mafic volcanics-dominated Keweenawan rocks. Volcanism and graben subsidence then apparently ceased, but isostatic subsidence of the area continued, leading to the deposition of thousands of feet of fluvial "red clastics" sequence rocks. A major regional compressive event followed shortly and reversed the sense of throw on the graben-bounding faults by lifting the Keweenawan volcanic rocks and forming the Iowa Horst (Fig. 3) about 6 miles (10 km) southeast of the Manson structure. Clastic sediments shed from the rising horst are a major component of the upper portion of the "red clastics" in the area. The region was subsequently subjected to about 500 Ma of erosion, which removed most of the sediments from the Iowa Horst and produced a low relief, deeply weathered terrain.

A map showing the relationships of the Precambrian rocks in the area of the Manson structure is given in Fig. 3. A map showing the elevation of the top of Precambrian crystalline rocks in the same area and one showing the elevation of the top of the "red clastic" sequence, or the top of the crystalline rocks where the "red clastics" are absent, are given in Figs. 4 and 5. The "difference" between the contours shown in these two maps is the thickness of the "red clastic" sequence.

The stratigraphic and structural relationships described are summarized schematically in the cross-section shown in Fig. 6. The section trends NW-SE across the state of Iowa. Because of extreme vertical exaggeration, the Manson structure appears as a narrow "finger" extending from just below Pleistocene sediments down to a depth of more than 4000 ft (1300 m). The transient cavity that existed momentarily while the structure was developing is shown to penetrate to a depth of about 20,000 ft (6000 m). (A schematic view of the impact structure not distorted by vertical exaggeration is shown in Fig. 17.)

Thinning of Lower Paleozoic marine shelf carbonates and clastics delineates a persistent, north-trending arch located at the northern end of a magnetic anomaly. *Bunker* (1981) named this structure the Central Iowa Arch. This thinning of sediments over the Central Iowa Arch is shown on isopach maps of *Sloss* (1963) Sauk sequence, Cambrian to Lower Ordovician (Fig. 7), and Tippecanoe sequence, Middle Ordovician to Silurian (Fig. 8). *Bunker* (1981) suggested that the Central Iowa Arch "stood in mild positive relief during the initial incursions of the Middle Devonian seas" as is suggested in his paleogeographic for the map pre-Kaskaskia sequence, pre-Devonian to Mississippian (Fig. 9). The Manson structure lies at the north end of the Central Iowa Arch (Figs. 7–9).

TABLE 1. Mineral content of water from Manson and other wells (parts per million; *Norton et al.*, 1912).

Element or Radical	Average of Nine Deep Wells	Manson
Silica (SiO_2)	16	10
Calcium (Ca)	210	16
Magnesium (Mg)	67	1
Sodium and potassium (Na+K)	181	221
Bicarbonate radical (HCO_3)	373	4*
Sulfate radical (SO_4)	719	162
Chlorine (Cl)	10	206
Total solids†	1425	651

*Carbonate radical (CO_3), 38 parts.
†Sum of the constituents minus one-half the bicarbonate radical.

Mesozoic structural features are also present in the area. One preserves economic thicknesses of Jurassic evaporites along the northern boundary fault zone of the Iowa Horst. Another is the Manson Impact Structure itself. The limits of the Manson Impact Structure were delineated by *Hershey* (1969) primarily on the basis of thick, structurally preserved shale units and other anomalous rock sequences seen in samples of drill cuttings. Surrounding the delineated limits is a ring 6 to 10 miles wide that is largely devoid of Cretaceous rocks, which suggests uplift and erosion of rock strata around the impact structure. This is illustrated by the isopach map for the Cretaceous Period shown in Fig. 10.

GEOLOGY OF THE MANSON IMPACT STRUCTURE

Early Work

Geologic structure in the Manson area was first recognized to be unusual because of the character of the local groundwater. In 1912 it was reported that "the well at Manson is the only deep well in the state whose water was found to contain normal carbonates; the magnesium and calcium in it are very low, the solids being mostly alkaline chlorides and sulfates. It may be questioned whether its comparatively soft water and its alkalinity may not be due to contamination by surface water owing to faulty casing" (*Norton et al.*, 1912, p. 174). The data that stimulated such skepticism are shown in Table 1.

A driller's log of the Manson city well reported "granite-like rock" at a depth of 1250 ft (380 m). According to *Norton et al.* (1912, p. 1017), "it is improbable that any deformation exists in this area sufficient to bring the floor of crystalline rocks so near the surface." We now know an improbable event did occur, and it did produce a central uplift or peak consisting of crystalline rock.

Other deformation probably related to the Manson impact was recognized early. "In Gilmore this limestone surface was found to drop 80 ft (24 m) between two wells 150 ft (46 m) apart, and other similar evidence suggests that in some localities there may be a buried limestone escarpment" (*Norton et al.*, 1912,

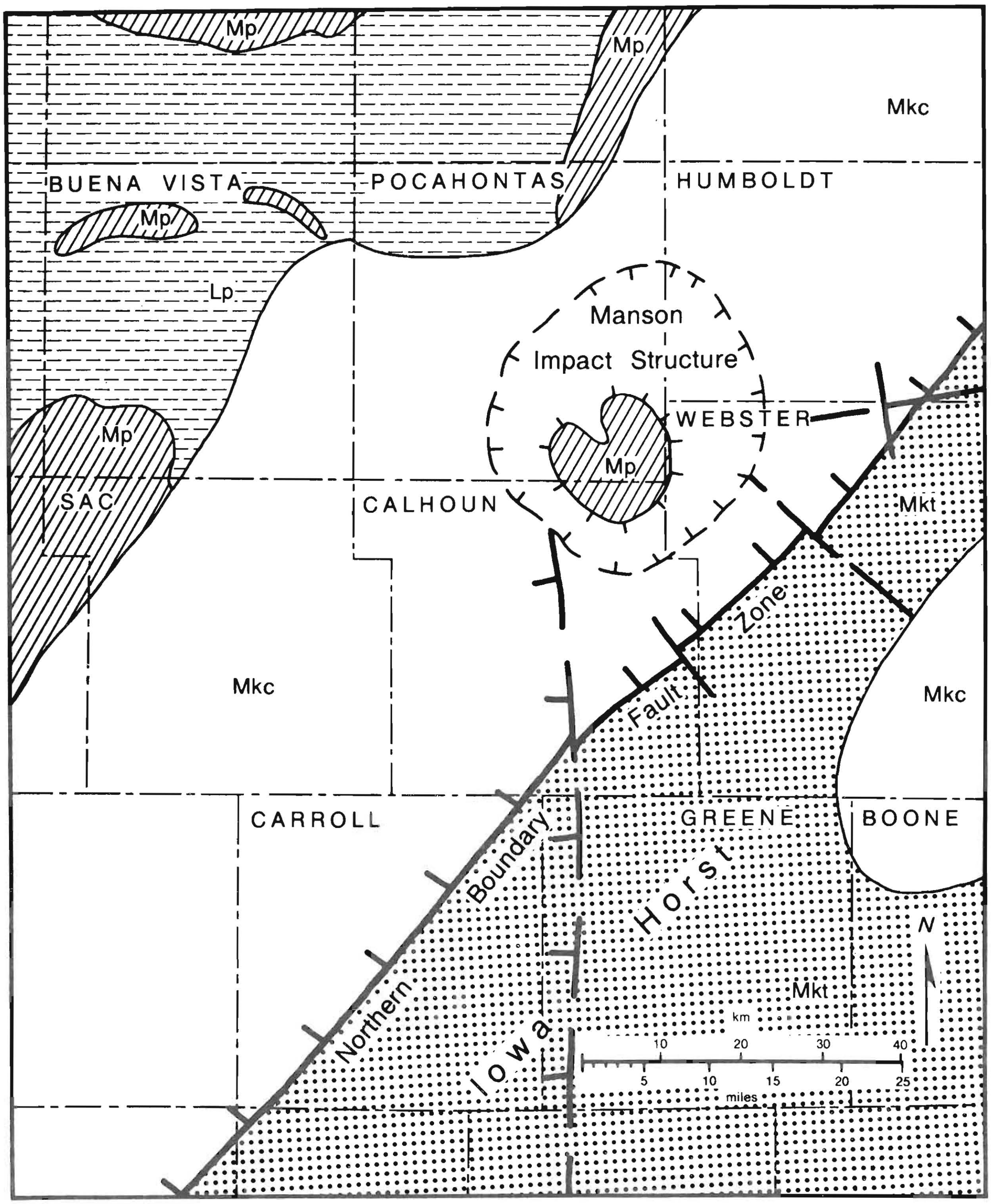

Fig. 3. Geological map of the Precambrian surface in the area of northwest central Iowa that includes the Manson Impact Structure (modified from *Anderson*, 1986a).

p. 1079). This "escarpment" is apparently a peripheral fault delineating the rim of the crater.

On May 1, 1928, the Manson city well #2 was completed and a description of the rocks encountered based on cuttings was obtained (*Norton*, 1928, pp. 246–254). The geologic section of this well, as well as Manson city well #1, were recognized as unique. Deep wells surrounding the Manson structure in all directions penetrate flat or gently dipping Paleozoic strata consisting mostly of carbonate rocks. At Manson, beneath 230 ft (70 m) of Pleistocene tills and gravel, is almost 800 ft (244 m) of material described as shale with occasional sandstone. The bottom 200 ft (61 m) was described as mostly arkose. Cuttings obtained while drilling through granite or granitic gneiss may have been thought to be derived from an arkose, because igneous and metamorphic rocks were not expected at this level.

Norton (1928) interpreted the absence of strata normally found in northwest Iowa and the presence of a thick sequence of marine shales underlain by "arkose" as being due to a large erosion channel filled first by continental sediments, arkose derived from granitic rocks to the north, and later by marine shales. The inadequacy of cuttings as a basis for interpretation is illustrated by *Norton's* (1928) observation that "the large content of crystalline rock in the lower cuttings of the Manson well indeed give rise to the question of whether the drill was working in decayed gneiss or granite," which, in fact, it was. Norton rejected this possibility, however, because the cuttings contained quartz, sand, and limestone pebbles that could not have come from gneiss or granite. It is likely that the sandstone and limestone pebbles washed into the borehole from overlying strata.

In addition, the thick section of shale itself was observed to have unusual characteristics. "The source of the coarse material in these shales is not determined" (*Norton*, 1928). A wide variety in texture and color of limestone fragments exists in the so-called shale, most of which have no counterpart as layers anywhere in the overlying strata already penetrated. Therefore, "it proves that these fragments were not broken by the drill from limestone beds in place," but were native to the strata ("shale") in which the drill was working." The presence in the so-called "shale" of fragments of various rocks and minerals that were not encountered in overlying strata may indicate penetration of a polymict breccia or suevite-like rock.

Drill Cores

Alvina Luebke core. The first known core drilling project within the Manson Impact Structure was on the Alvina Luebke farm at a location described as the NE 1/4 of the NE 1/4 of the NW 1/4 of section 25 of T89N R31W (NE, NE, NW, section 25, T89N, R31W) in Calhoun County. The well was drilled to a depth of 1223 ft (373 m) with a cable tool rig in late 1948 and early 1949. The drilling encountered about 450 ft (137 m) of sandstone and red Proterozoic shales at the bottom of the hole. In April 1950 the well was deepened. James Cooper, U.S. Geological Survey/Iowa Geological Survey geologist, was at the site, but the extent of federal government participation in the drilling project is not documented. A red Proterozoic shale was cored from 1223 to 1270 ft, then a poorly consolidated sandstone was drilled with a rock bit from 1270 to 1380 ft. Coring was resumed at a depth of 1380 ft and continued to 1428 ft through a Paleozoic dolomite. A fishtail bit was used to complete the drill hole, from 1428 to 1532 ft, penetrating Proterozoic red shales. The strata in this well are completely disrupted. Core and cutting samples are stored at the Iowa Department of Natural Resources, Geological Survey Bureau, however only about one-half of the core is preserved (the other half was apparently taken as souvenirs by local residents at the time of the drilling.)

In late 1953 a core drilling project was undertaken to recover uplifted granitic rock (Manson 2-A core) and surrounding "disturbed" bedrock (Manson 1-A core). The drilling was a cooperative effort between the Iowa Geological Survey (IGS) and the U.S. Geological Survey (USGS). According to *Hoppin and Dryden* (1958), the reasons for drilling were that the crystalline mass was geologically anomalous and an unusually good source of soft water.

Manson 1-A core. The Manson 1-A core was taken at NE, NW, NW section 30, T90N, R31W in Pocahontas County, Iowa. This location is about 4 miles (6.4 km) north and 3/4 of a mile (1.2 km) west of the center of Manson, Iowa. The drilling by C. L. Jennings and V. Balmer began on August 3, 1953, and was completed on September 18, 1953. The drill rig used is shown in Fig. 11. Only cuttings were obtained for the uppermost 187 ft (57 m). From that depth, which is just below the glacial drift, to the bottom of the hole [360 ft 4 in (109.8 m)], core was

M. Proterozoic

Mkc Keweenawan Clastic Rocks

Mkt Keweenawan Volcanic-dominated Rocks

Mp Plutons (ca. 1450 Ma)

L. Proterozoic

Lp Penokean (ca. 1850 Ma) Island Arc and associated rocks

Fig. 3. Legend

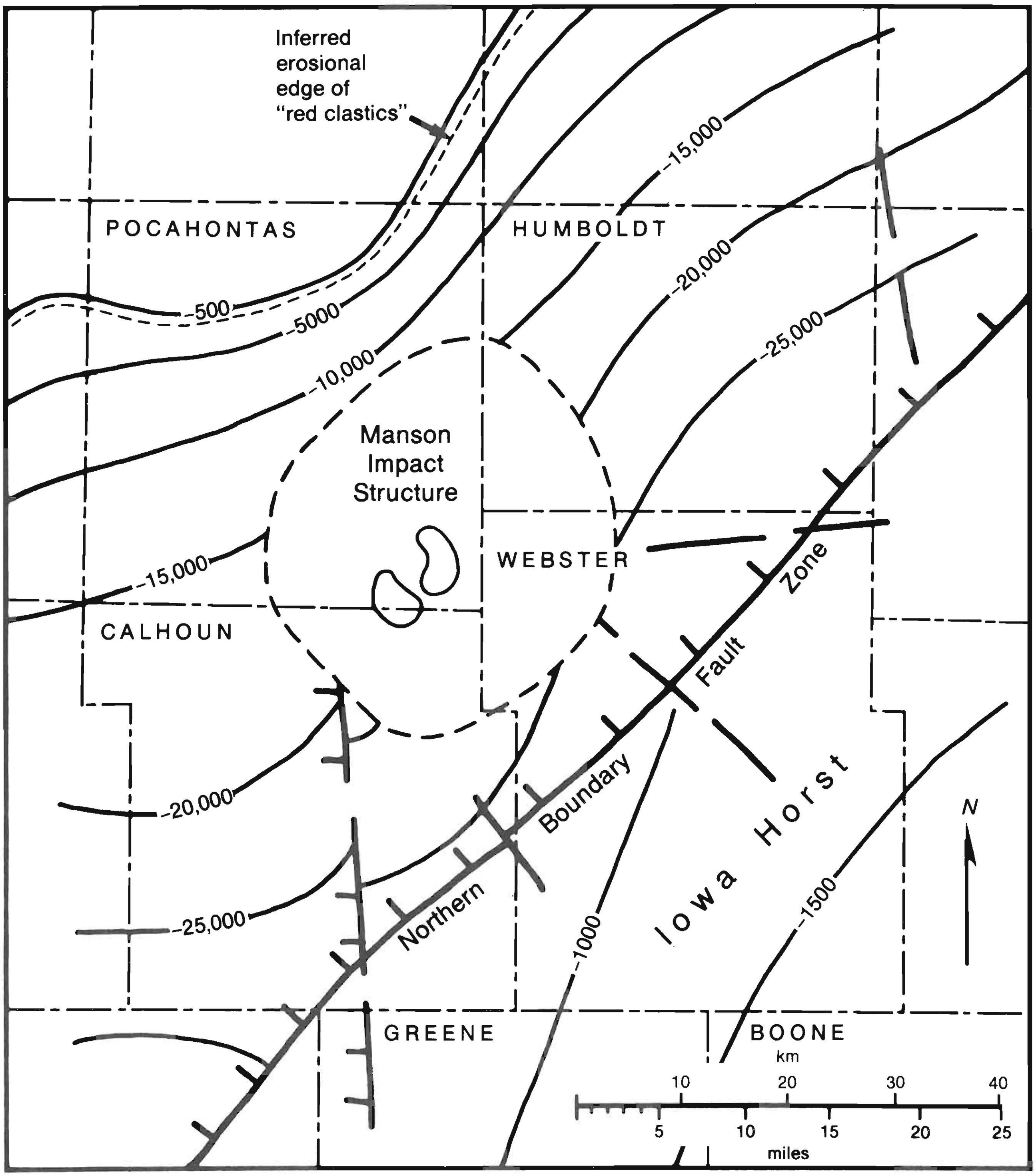

Fig. 4. Map showing elevation from sea level of the top of the Precambrian crystalline surface in the area of the Manson Impact Structure as determined by gravity modeling. Elevations are in feet and contour intervals are variable.

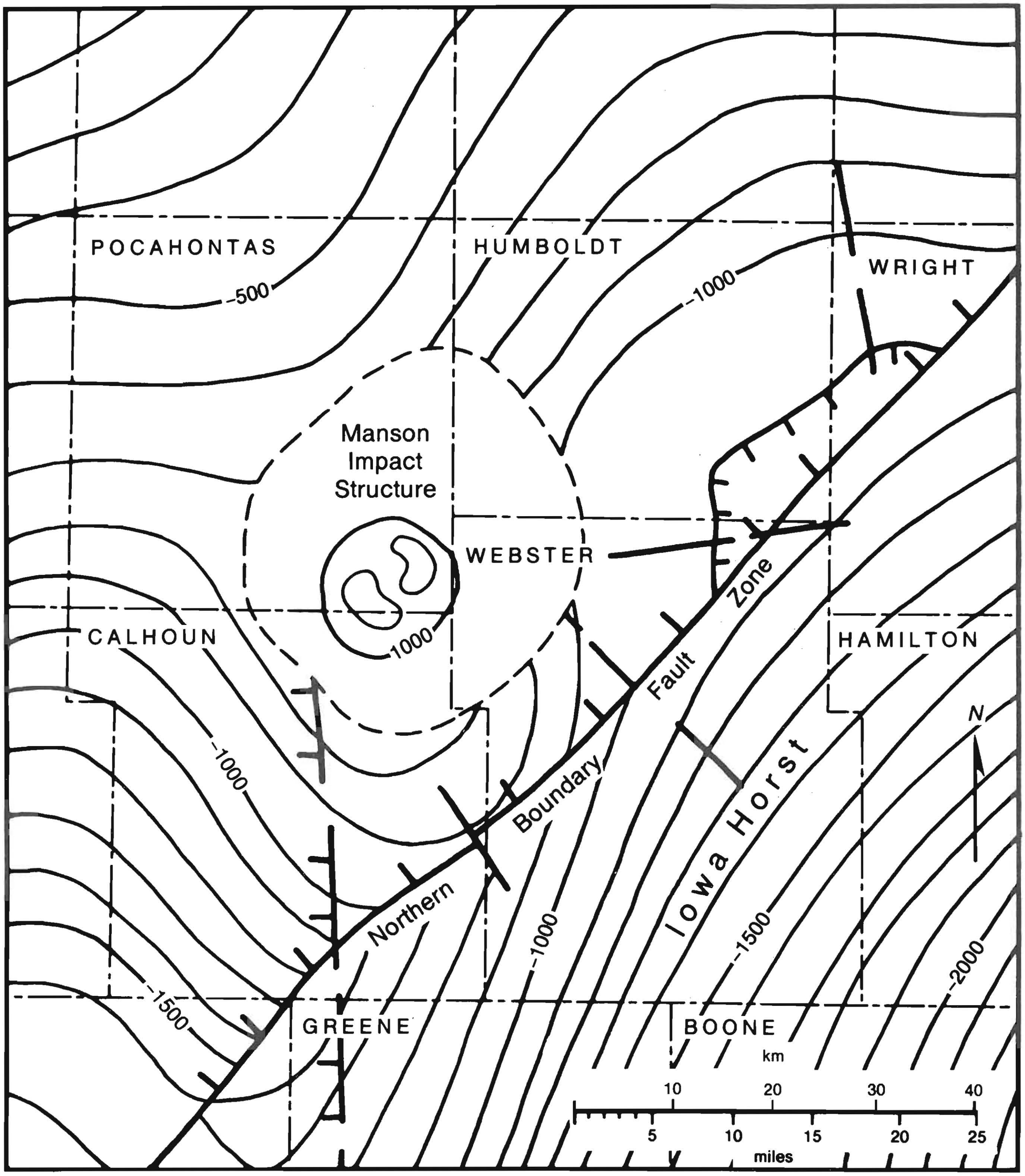

Fig. 5. Map showing the elevation from sea level to the top of the Precambrian, which displays crystalline rocks to the southeast and sedimentary rocks to the northwest of the Northern Boundary Fault Zone (modified from *Anderson*, 1986b). The contour interval is 500 ft.

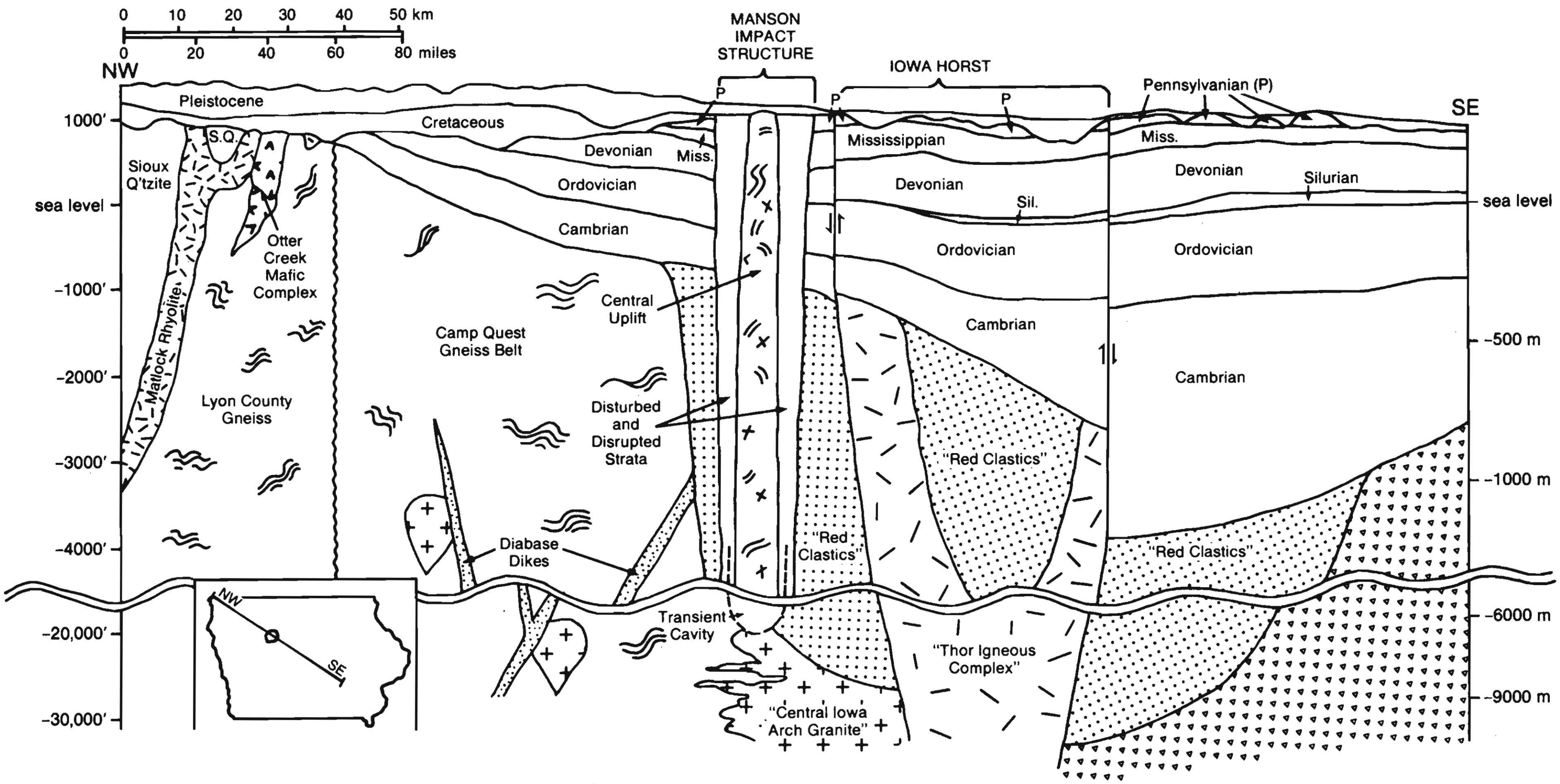

Fig. 6. Schematic structural cross-section across the state of Iowa. A large vertical exaggeration is required to show relationships between relatively thin units that extend for long distances. The Manson Impact Structure appears as a vertical finger consisting of uplifted granitic basement rocks surrounded by disturbed or disrupted sedimentary units. The location of the transient cavity present during the formation of the structure is indicated.

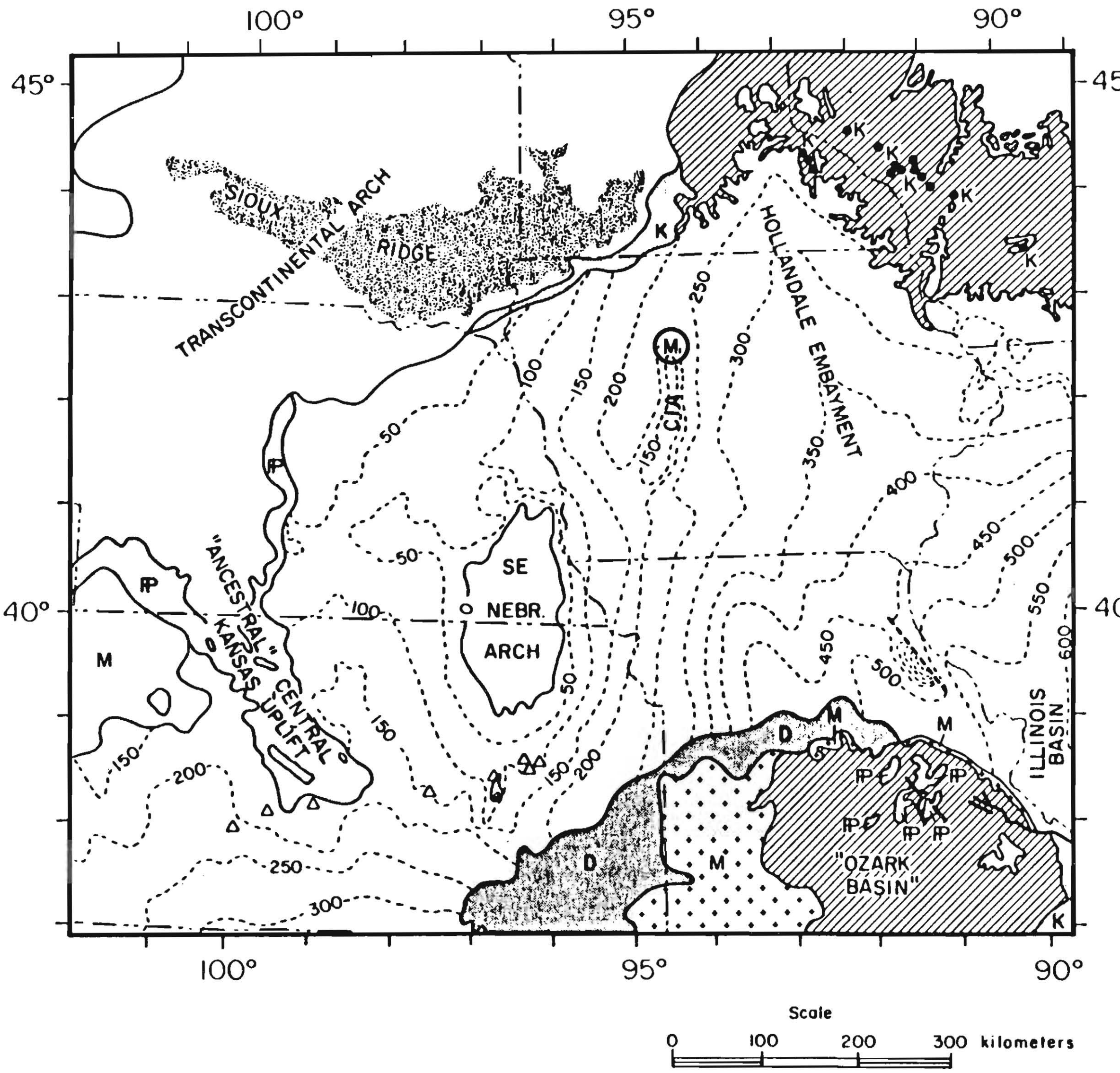

Fig. 7. Isopach map of Sauk sequence rocks (Cambrian to Lower Ordovician) in the central midcontinent (modified from *Bunker et al.*, in press, Fig. 2). The location of the Manson Impact Structure is indicated by M and the Central Iowa Arch by CIA. The contour interval is 50 m.

obtained. The dominant lithology displayed in the core is shale, with minor limestone. Considerable evidence for deformation was also observed. An abbreviated description of that core is presented in Table 2. Although the 1-A core "was drilled so as to penetrate the disturbed sedimentary rocks and the contact between these rocks and the crystalline mass, drilling difficulties caused abandonment of the operation before the contact was reached" (*Hoppin and Dryden*, 1958).

Manson 2-A core. The Manson 2-A core was taken at SW, SW, SW, section 29, T90N, R31W, a point approximately 3 miles (4.8 km) north of the center of Manson, Iowa. Core was obtained beginning just below glacial drift, 93 ft (28 m) below the surface, and ending at the bottom of the hole, 479 ft (146 m) below the surface. The drilling began on September 23 and was completed on October 17, 1953. The entire core was described by J. E. Dryden, a graduate student at the University of Iowa, as a part of a master's thesis (*Dryden*, 1955, pp. 11–18). That description is summarized in Table 3. The core displays abundant evidence of extreme deformation, extensive hydrothermal alteration and weathering. Photographs of the more abundant rock types present in the core are shown in Figs. 12a–d. "A chloritized breccia is one of the more common rocks present. It appears to be confined to the upper 260 ft (79 m) of the core. Less important in the upper part, but increasingly important with depth, is dark gray gneiss, which is the oldest rock. Distributed irregularly throughout the core are coarse to medium-grained pink granite, pink gneissoid

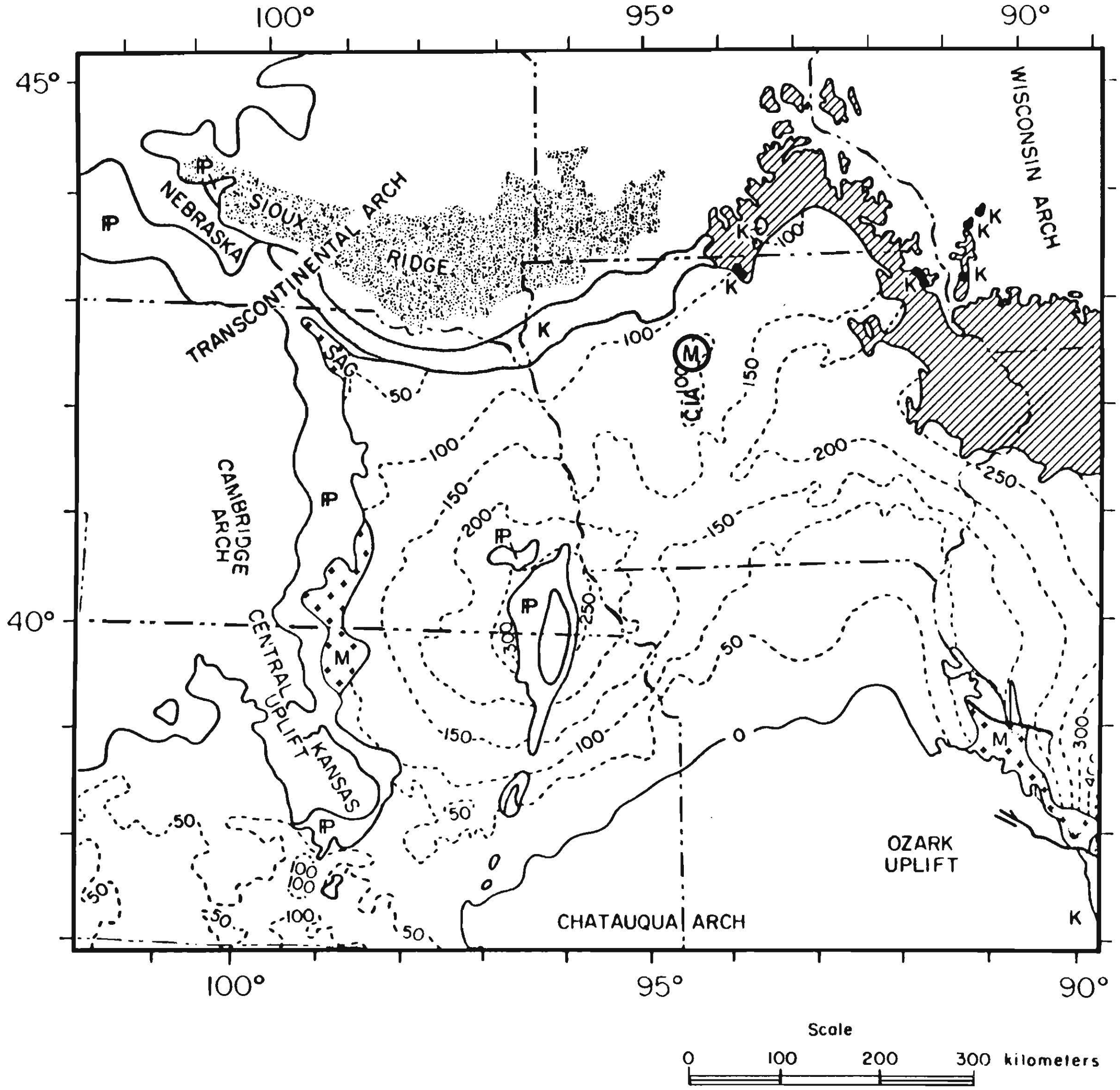

Fig. 8. Isopach map of Tippecanoe sequence rocks (Middle Ordovician-to-Silurian) in the central midcontinent (modified from *Bunker et al.*, in press, Fig. 3). The location of the Manson Impact Structure is indicated by M, and the Central Iowa Arch by CIA. The contour interval is 50 m.

granite, and small amounts of phyllonite, syenite, and diabase. All of these rock types are found as fragments in the breccia" (*Dryden*, 1955).

Detailed descriptions of the minerals that make up these rocks and their textural relationships are given by *Dryden* (1955) and *Hoppin and Dryden* (1958). Photographs of hand specimens and descriptions of 57 thin sections are given by *Dryden* (1955). (Note: Thin sections Dryden used and the cores described in this section are maintained in the laboratories of the Iowa Department of Natural Resources, Geological Survey Bureau, 123 North Capitol Street, Iowa City, Iowa 52242.)

Borehole Cuttings

Hale (1955) used several sets of well cuttings to define what was thought then to be a "volcanic basin" surrounding Manson. Control available at that time suggested a roughly elliptical basin whose length in a northeastward direction was about 25 miles (40 km) and whose width was about 18 miles (29 km). It was recognized that Manson was "possibly a cryptovolcanic structure." [The following acknowledgment is made by Hale in his report on the geology and groundwater resources of Webster County, Iowa (*Hale*, 1955). "The theory expressed as to the origin of

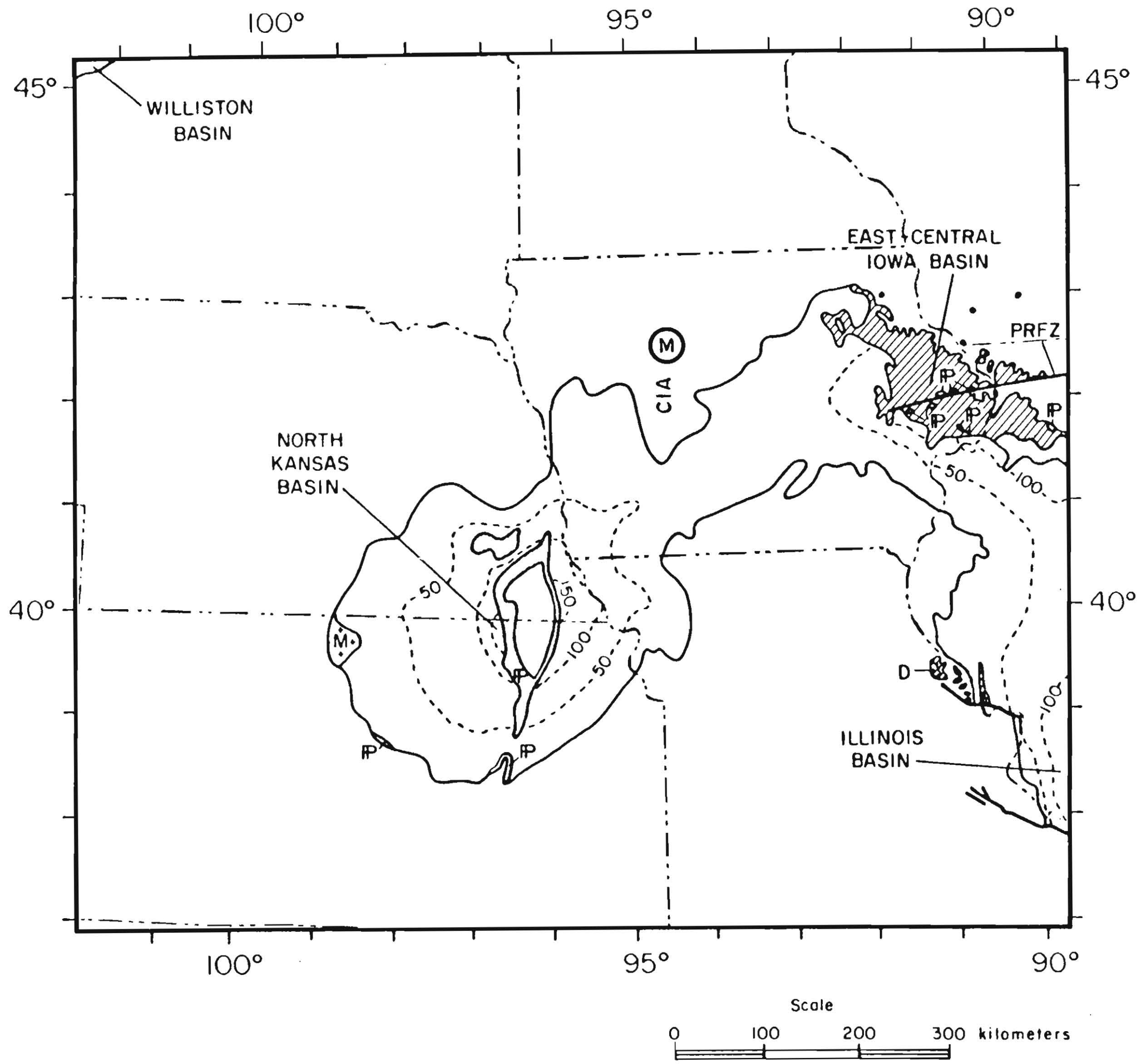

Fig. 9. Isopach and paleogeographic map of pre-Kaskaskia sequence rocks (pre-Devonian to Mississippian) in the central midcontinent (modified from *Bunker et al.*, in press, Fig. 4). The location of the Manson Impact Structure is indicated by M and the Central Iowa Arch by CIA. The contour interval is 50 m.

the structural features of the Manson area was developed by C. R. Murray of the U.S. Geological Survey and the description of it in this report is based on discussions with him." C. R. Murray was a geologist at the USGS Water Resources Division office in Iowa City in the early 1950s and was apparently responsible for obtaining the two Manson drill cores.]

"Details of the structure have not been worked out because the area is covered by glacial drift. Well cuttings indicate that the regional structure is abruptly broken by faulting, which has produced a roughly circular structural basin. Outside the basin, the section penetrated by wells generally consists of Pleistocene drift and Paleozoic strata. Within the basin, wells penetrate the Pleistocene drift and then apparently continue in Cretaceous strata to about 600 ft (180 m). Below this the deeper wells penetrate about 900 ft (270 m) of red arkosic sandstone, siltstone, shale, and an occasional dolomite of undetermined age. Near the center of the structure, however, wells encounter igneous rock consisting largely of microcline feldspar or basic tuffaceous rock at a depth of a few hundred feet and in places less than 100 ft (30 m). That the crystalline rock continues to considerable depth is shown by a well. . . . which entered it at 389 ft (119 m) and finished in it at 874 ft (266.4 m)" (*Hale,* 1955).

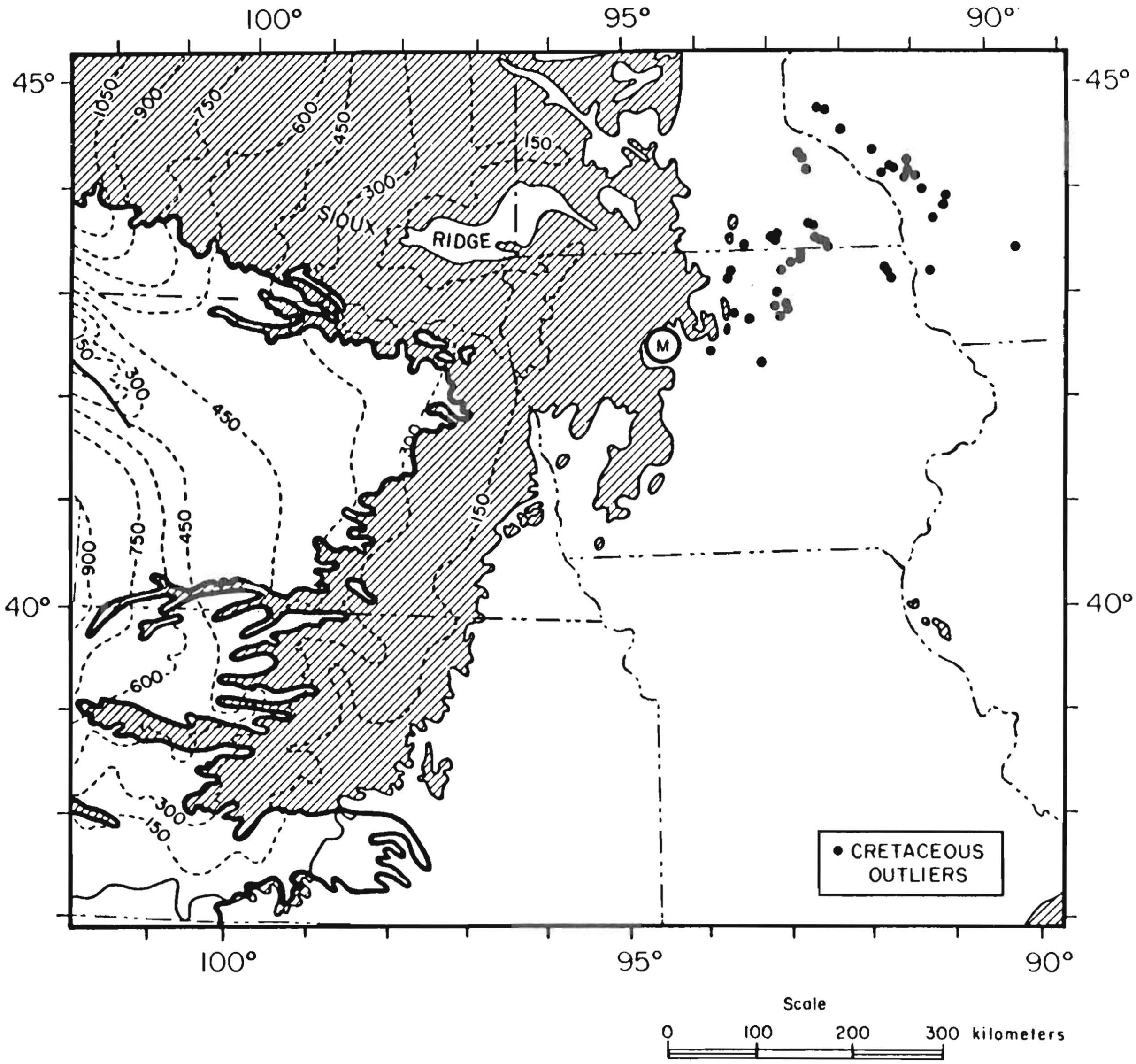

Fig. 10. Isopach map of Cretaceous rocks in the central midcontinent (modified from *Bunker et al.*, 1988, Fig. 12). The location of the Manson Impact Structure is indicated by M. Cretaceous rocks have been uplifted and eroded around most of the Manson structure. The contour interval is 150 m.

Shown in Fig. 13 are the locations of water wells in the area of the Manson structure from *Hale* (1955). Filled circles correspond to wells that penetrate the normal Paleozoic section (mostly near flat-lying carbonates) in that part of Iowa. Open circles correspond to wells that lack the normal Paleozoic section.

As more wells have been drilled in the Manson area, the boundary of the structure has been established more accurately. Furthermore, Anderson and coworkers at the Iowa Geological Survey Bureau have identified four general stratigraphic associations using logs of wells in the Manson area. These associations are described below, and wells penetrating the different associations are located on the map in Fig. 14.

1. *Normal Phanerozoic strata.* Rocks immediately underlying glacial till may be Cretaceous, Mississippian, or Pennsylvanian, depending on the location around the structure. In any case, the strata present beneath glacial till are easily correlated throughout the region. Wells that penetrate normal Phanerozoic strata are indicated on the map by filled circles. As an example, an abbreviated description of cuttings from a well in normal Phanerozoic strata is given in Table 4.

2. *Displaced strata.* Includes Cretaceous shales preserved on down-dropped blocks and Keweenawan shales on uplifted blocks encountered at or near the bedrock surface. Strata are in their original depositional sequence, although evidence for faulting may

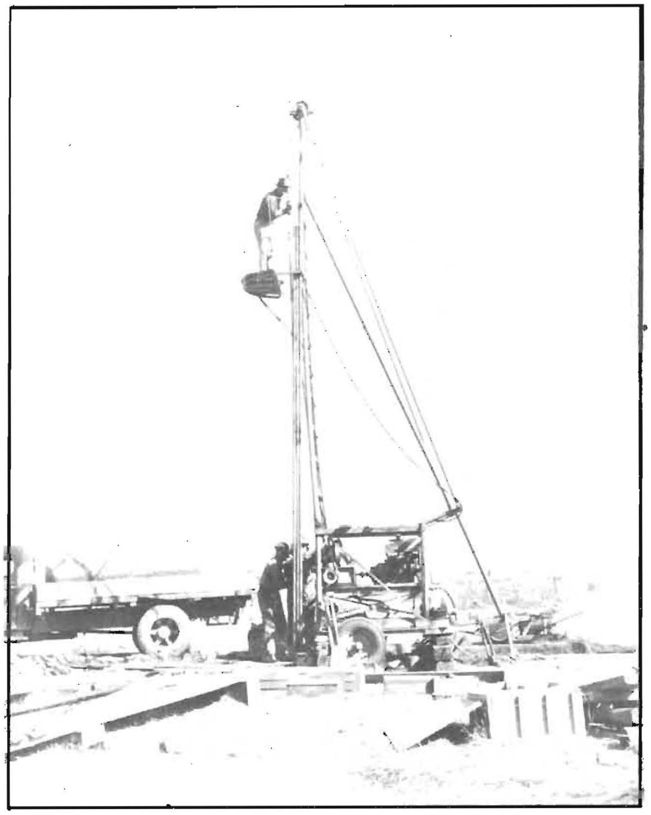

Fig. 11. Drill rig used to obtain Manson USGS #1-A and #2-A cores between August 3 and October 17, 1953.

TABLE 2. Abbreviated description of the Manson 1-A core.

Depth in Feet	Rock Type
0–170	Quaternary drift, medium grained, sand, gravel, and some till, poor quality
170–187	Dark green laminated shale
187–189	Brecciated dolomitic limestone
198–220	Dark green, calcareous shale, some with embedded sand; green (probably Cretaceous) marine shale
220–230	Black, waxy fissile shale
230–250	Medium to dark green calcareous shale with fragments of brecciated limestone and steeply dipping fracture planes
250–295	Medium to dark green calcareous shale with "carbonaceous specks"
295–315	Interbedded dark green shale, siltstone, and very fine-grained micaceous sandstone (probably upper Dakota formation)
315–360.4	Dark green lumpy shale, contorted, 3–in calcareous sandstone at 352.6 ft (probably upper Dakota formation)
360.4 T.D.	

IGS W-6133 (C-113). Location: NE, NW, NW, section 30, T90N, R31N. Adapted from original description done in 1953 by D. Northup (an example of completely disrupted strata). Appears to be section of Cretaceous rocks including marine shales and some upper Dakota formation (Woodbury member) lithologies. Possible admixture of some Paleozoic carbonates at 187–189 ft.

be observed. Other Phanerozoic units may yet be discovered as displaced strata. Wells containing displaced strata are indicated on the map by open circles. As an example, an abbreviated description of cuttings from a well in displaced strata is given in Table 5.

3. *Completely disrupted strata.* Exotic lithologies are present, units are not in the normal stratigraphic sequence, and evidence for severe deformation is present. These rocks are poorly bedded, if at all, and often include mixtures of sedimentary, igneous, and metamorphic rocks, and some display glassy material. Wells that penetrate completely disrupted strata are indicated on the map by open squares. The Manson 1-A core penetrates completely disrupted strata dominated by Phanerozoic rocks. An abbreviated description of this core is given in Table 2. Other wells displaying especially unusual strata, described as tuff, are also considered in this category.

4. *Igneous and metamorphic rocks.* Rocks are mainly granites and granitic gneisses, apparently uplifted from the Precambrian basement and commonly brecciated. Igneous and metamorphic rocks are indicated on the map by open triangles. The Manson 2-A core penetrates igneous and metamorphic rocks and is described in detail by *Dryden* (1955). His description is summarized in Table 3.

Also shown in Fig. 14 are the locations of the Alvina Luebke and Manson 1-A and 2-A core holes.

The abnormal strata underlying the area around Manson were "known to crop out only in the NE 1/4 of the NE 1/4 of the SE 1/4 of section 11, T89N, R30W," along the right bank of the Lizard Creek immediately upstream from the bridge over the stream. The outcrop was "a few feet of gray micaceous (marine) shale" exposed at low-water level (*Hale,* 1955). (The authors have attempted, without success, to rediscover this outcrop. It may have been destroyed by road and bridge construction completed in the intervening years.)

Impact Hypothesis

By the early 1950s the area around Manson was recognized, based mainly on well cuttings, to be anomalous for several reasons: (1) granitic rocks are about 20,000 ft (6000 m) too high in the section near Manson; (2) the sedimentary rocks near Manson range from being somewhat out of place stratigraphically to being totally disrupted and mixed, in contrast to orderly sequences of rocks found 20 miles away in all directions; (3) well water from Manson is remarkably soft; and (4) both granitic and nearby sedimentary rocks show evidence of violent deformation.

The first publication to deal exclusively with the Manson structure was a note by *Hoppin and Dryden* (1958). They considered the available information about the rocks in the Manson area and presented a map similar to the one shown in Fig. 13 and

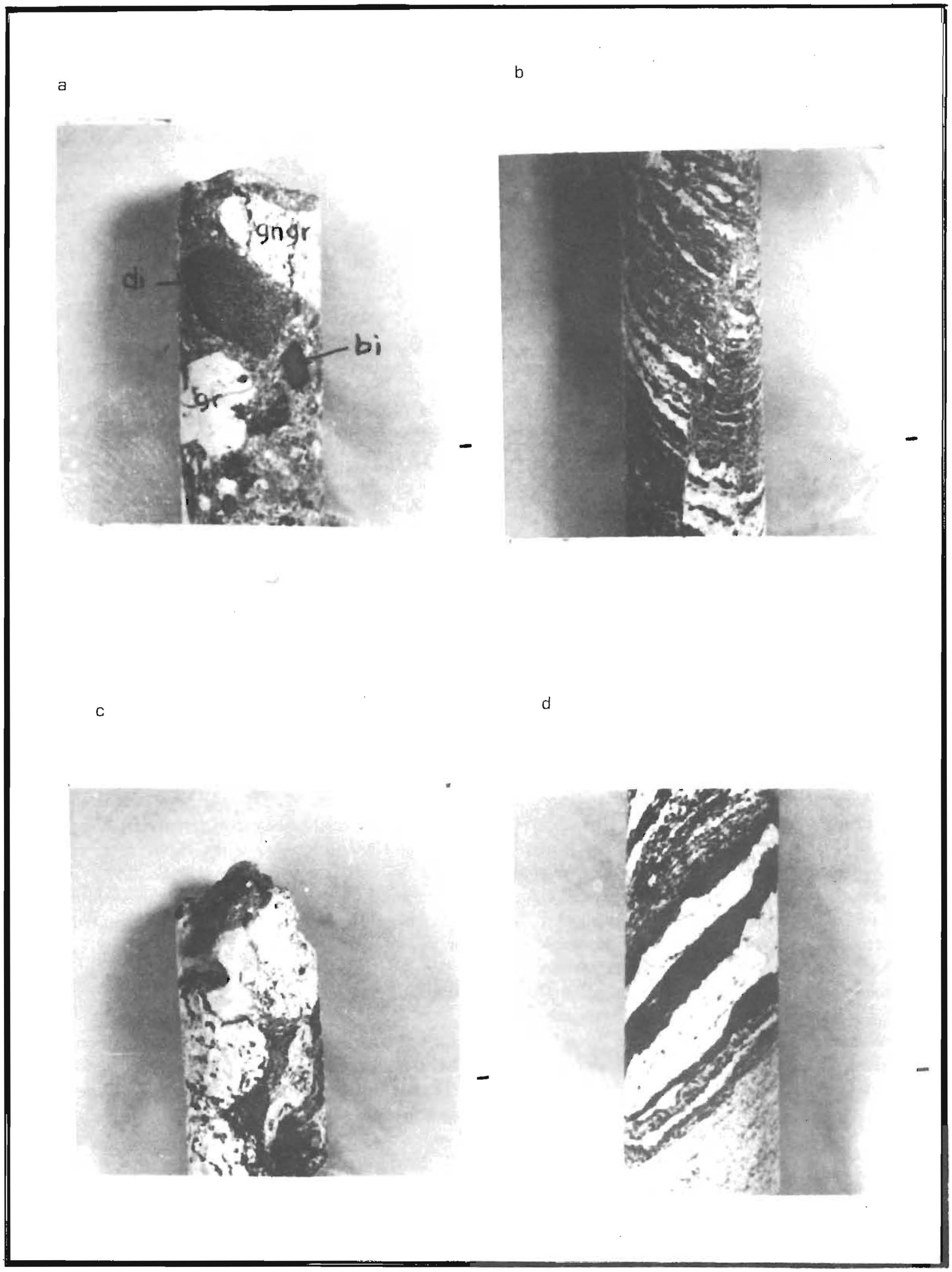

Fig. 12. Samples of Manson 2-A core. Core diameters are 1.6 inches (4 cm). From *Dryden* (1955). (**a**) Chloritized microbreccia. Depth, 195 ft (59 m); di = diabase, gr = granite, bi = biotite schist, and gngr = gneissoid granite. (**b**) Dark gray gneiss. Depth, 335 ft (108 m). Note small fault perpendicular to foliation. (**c**) Depth 235.5 ft (72 m). Brecciated granite. (**d**) Depth, 352 ft (107 m). Granite and gneissoid granite with biotite schist.

TABLE 3. Abbreviated description of the Manson 2-A core.

Depth in Feet	Rock Types
0–93.5	Glacial drift, undescribed
93.5–102	Deeply weathered mixture of granite, phyllite, diabase, and polymictic microbreccia, with intense staining by ferric oxides
102–103	No recovery
103–107	Phyllite with fractures filled by microbreccia
107–113	No recovery
113–116	Granite, medium grained, weathered
116–117	Granitic gneiss, medium grained
117–122	No recovery
122–124	Granitic gneiss, medium grained
124–129	Pink, medium-grained granite
129–135	No recovery
135–136	Pink, medium-grained granite
136–140	Light gray, fine-grained biotite-oligoclase-quartz gneiss
140–142.5	No recovery
142.5–144	Granitic gneiss, medium grained
144–150	As in 136–140
150–154	Granitic gneiss, medium grained
154–156	No recovery
156–157	Granitic gneiss, medium grained
157–159	Dark gray gneiss
159–162	Pink, medium-grained granitic gneiss
162–165	No recovery
165–184	Microbreccia with chloritic matrix, fragments of granite, light gray gneiss, diabase, coarse-grained biotite schist, and coarse pink syenite
184–191	Gray quartz-oligoclase-biotite gneiss, cut by veins of microbreccia
191–195	Microbreccia with fragments of gneiss, solution cavities with calcite crystals
195–203	Pink, medium-grained granite
203–225	Microbreccia with fragments of granite, biotite schist, gneiss, and diabase
225–228	Pink, medium-grained granite
228–232	Pink, medium-grained granitic gneiss
232–242	Breccia with solution cavities lined with chlorite and calcite
242–252	Brecciated granite, with large masses of biotite and chlorite
252–252.5	Dark green weathered diabase
252.5–253	Microbreccia
253–254	Phyllite with cavity fillings of zeolite (?) minerals
254–280	Microbreccia with fragments of coarse-grained granite and biotite schist, solution cavities filled by calcite
280–298	Light gray gneiss cut by veins of microbreccia
326–352	Dark gray, fine-grained gneiss, cut by small-scale faults and veins of microbreccia
352–365	Pink medium-grained granite
365–377	Garnetiferous oligoclase-biotite-quartz gneiss, dark gray
377–390	Alternating bands of pink, medium-grained granite, microbreccia, and dark gray fine-grained gneiss
390–402	Dark green-white, fine-grained augen gneiss, augen up to 3 mm with magnetite at center
402–404	Pink, medium-grained granite
404–410.5	Augen gneiss as above
410.5–411	Brecciated granite
411–427	Augen gneiss, cut by small-scale faults
427–435	Pink, medium-grained granite
435–439	Dark gray fine-grained gneiss
439–442	Pink medium-grained brecciated granite
442–449	Alternating bands of granitic gneiss and augen gneiss
449–461	Dark gray, fine-grained augen gneiss
461–462	Pink, medium-grained granitic gneiss
462–470	Pink, medium-grained granitic gneiss
470–479	Alternating granitic gneiss and dark green gneiss
479 T.D.	

IGS-W-27271. Location: SW, SW, SW, section 29, T90N, R31W. Adapted from original description done by *Dryden*, 1955, pp. 11–18 (an example of granite and granitic gneiss rocks).

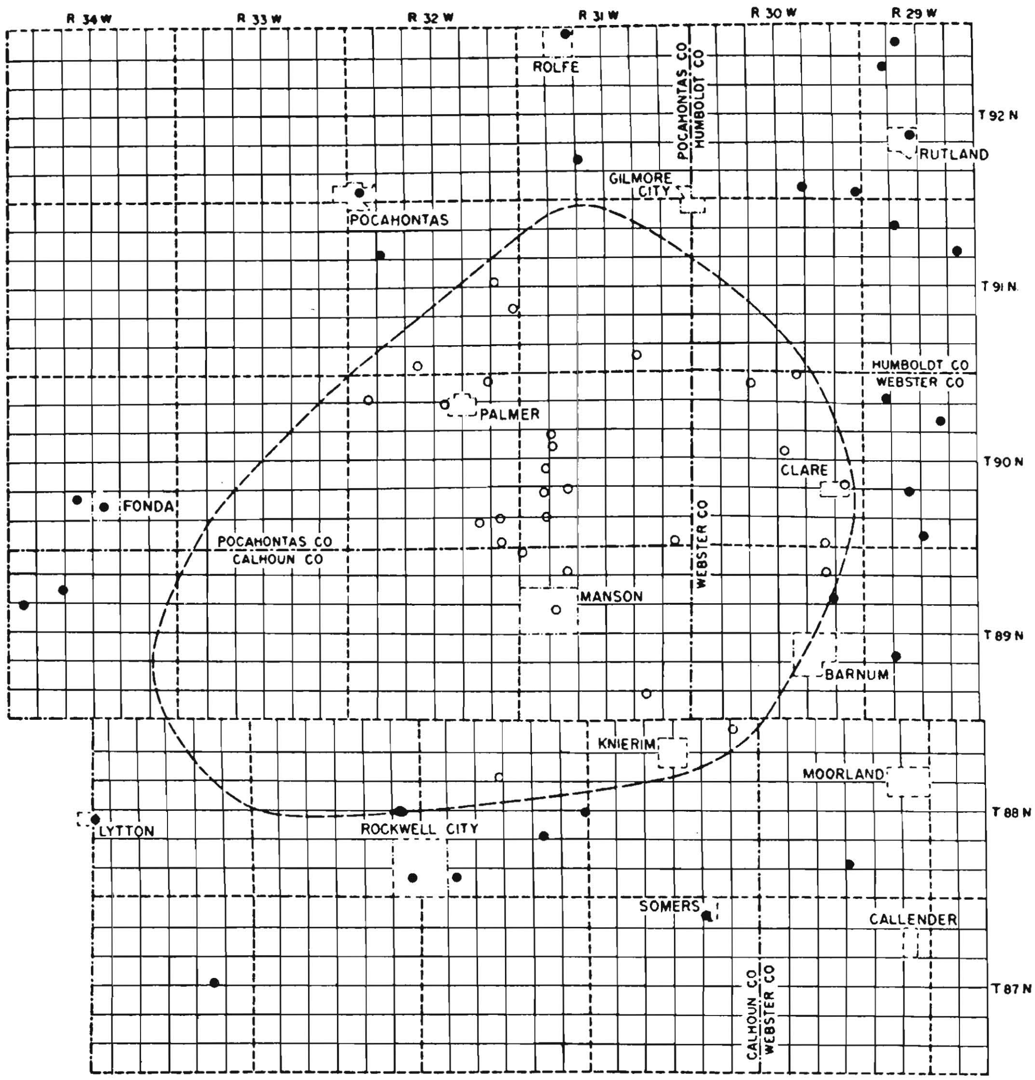

Fig. 13. Map of the area around Manson, Iowa, showing the locations of wells that penetrated a normal Paleozoic section (•) and those that did not (O) (from *Hale,* 1955). The dashed line indicates Hales' estimate of the boundary of the Manson "disturbed" area.

a cross-section similar to the one shown in Fig. 15. They noted the similarity of Manson to other large circular structures with central uplifts and evidence for explosive deformation and concluded that "the mechanism of intrusion is believed to be the same as that which caused the formation of the cryptovolcanic structures described by Bucher" (1933).

During the following year R. Dietz gave a lecture at the University of Iowa and suggested to Hoppin, who raised no objection, that "cryptoexplosion" might better describe the Manson structure, thereby allowing an impact origin for Manson. In the 1960s several investigators visited the Iowa Geological Survey and acquired samples from core 2-A. Ted Bunch and A. Cohen (R. A. Hoppin, personal communication, 1987) attempted unsuccessfully to identify coesite or stishovite in quartz grains. *Short* (1966) first reported the presence of planar features in quartz grains from Manson core samples. A photograph of such a quartz grain from the Manson 2-A core is shown in Fig. 16. The multiple sets of planar features were judged to have been produced during a shock event. Their presence strengthened the case for an impact origin for Manson. These findings were confirmed by *Bunch* (1968), *Short and Bunch* (1968), and *Carrigy and Short* (1968). During this period one of the authors (J.H.) and Fred Hörz also tried unsuccessfully to identify coesite and stishovite.

Samples from cores and cuttings from nearby water wells were examined by *Yoho* (1967), who noted the abundance of cataclastic

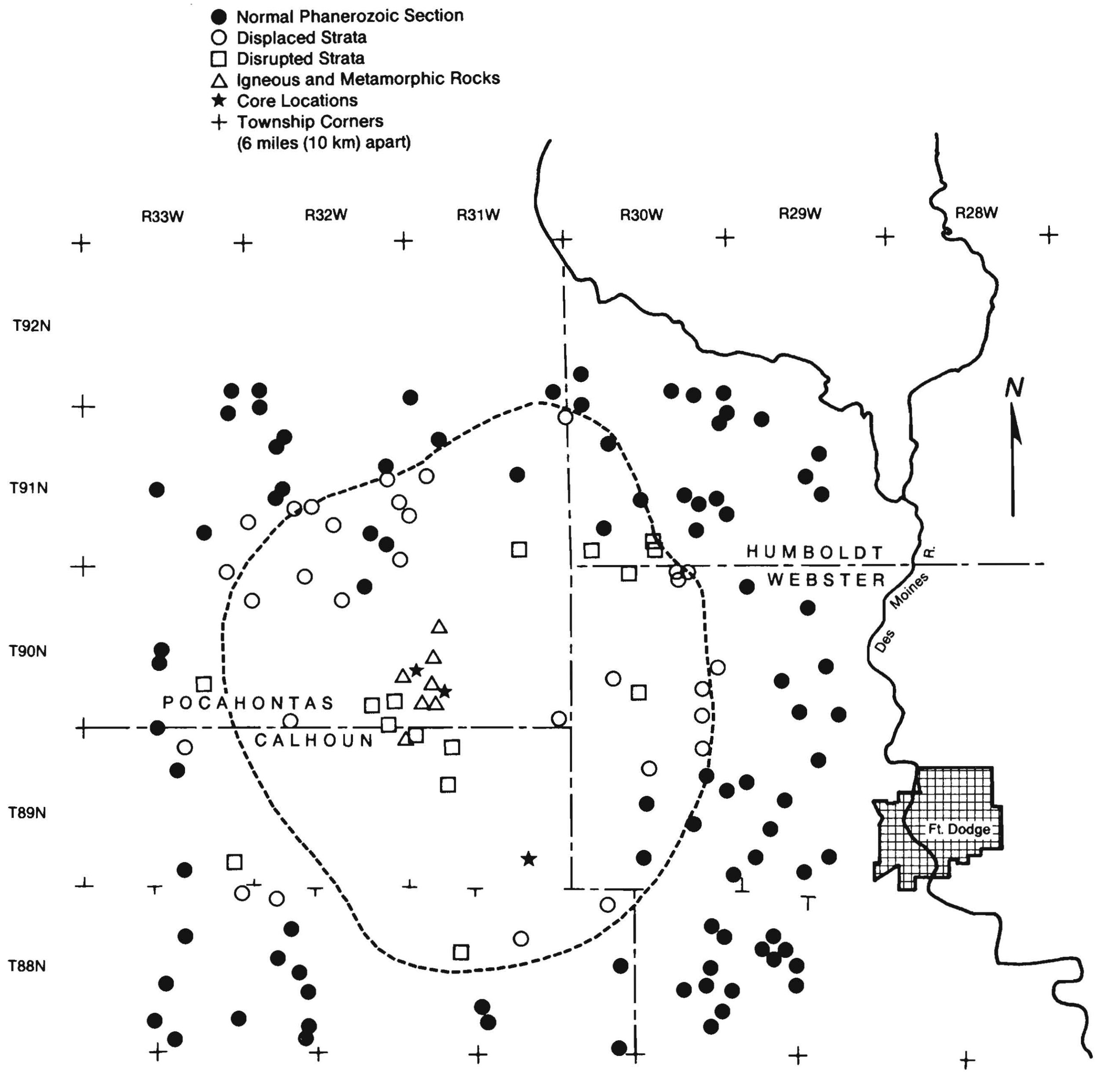

Fig. 14. Map of the area around Manson, Iowa, showing the locations of wells that penetrate a normal Phanerozoic section (•), displaced strata (○), completely disrupted strata (□), and igneous and metamorphic rocks (△). Data were collected by Anderson and coworkers. Locations where cores have been obtained are also indicated (★). The symbols (+) are township corners and are 6 miles (10 km) apart. The dashed line is from *Hershey* (1969) and is for reference only. It reflects the limits of the structure based on data available in 1969. The data shown are those available in 1987.

TABLE 4. Abbreviated description of the Rockwell city well #3.

Unit	Depth in Feet	Rock Type
Pennsylvanian	0–180	Dark gray carbonaceous shales, pyritic, with interbedded thin sandstones and variegated mudstones
Mississippian	360–640	Interbedded limestones and cherty dolomites
"Sheffield" shale	640–665	Green dolomitic shale
Devonian	665–1165	Dolomites with interbedded thin shales, siltstones, and sandstones
Upper-Middle Ordovician	1135–1365	Cherty dolomites
Decorah	1365–1385	Green pyritic shale
Platteville	1385–1400	Dolomite
Interval	1400–1485	Interbedded dolomites with phosphate nodules and green shales
St. Peter sandstone	1485–1530	White sandstone, medium grained
Shakopee formation	1530–1700	Interbedded sandy dolomite and sandstone
Oneota formation	1700–1800	Sandy dolomite with thin interbedded shale and chert
Jordan formation	1800–1865	Sandstone, fine grained
St. Lawrence formation*	1865–1960	Silty dolomite, glauconite at base

IGS-W-4094. Locations: NW, SE, NE, section 36, T88N, R33W. Adapted from original description done in 1950 by M. Parker (an example of normal Phanerozoic strata).

*Probably older Cambrian units as well.

TABLE 5. Abbreviated description of the Erling Malmin well, Clare, Iowa.

Depth in Feet	Rock Type
0–80	Quaternary, till (granite at 80–85 ft probably from tills)
80–155	Probably Cretaceous shale (Pierre?), inoceramid at 85–90 ft (contains till and till-derived igneous caving to 175 ft)
155–205	Shale with some sandy limestone, needs restudy, might be Niobrara facies(?)
205–255	Shale, some ironstone (probably Cretaceous)
255–385	Shale, calcareous, with "white specks" (forams), fish material, common Inoceramus (Cretaceous marine shale, probably Niobrara and/or Carlile)
385–420	Shale as above and Inoceramus-rich limestone (probably Greenhorn)
420–500	Shale as above with Inoceramus, marine shale (probably Greenhorn and Graneros)
500–680	Mixed gray shale (noncalcareous), siltstone-sandstone, ironstone, carbonaceous shale + lignite, common siderite—probably disturbed)
680–710	Sand, sounds like Lower Dakota sand, probably disturbed

Probable Stratigraphy

Unit	Depth in Feet
Quaternary	0–80
Pierre?	80–155
Niobrara?	155–~250
Carlile	~250–385
Greenhorn	385–420
Graneros	420–495
Dakota	
Woodbury	495–680
Nishnabotna	680–710

IGS-W-3270. Location: SW, SW, SE, section 35, T90N, R30W (an example of disturbed strata).

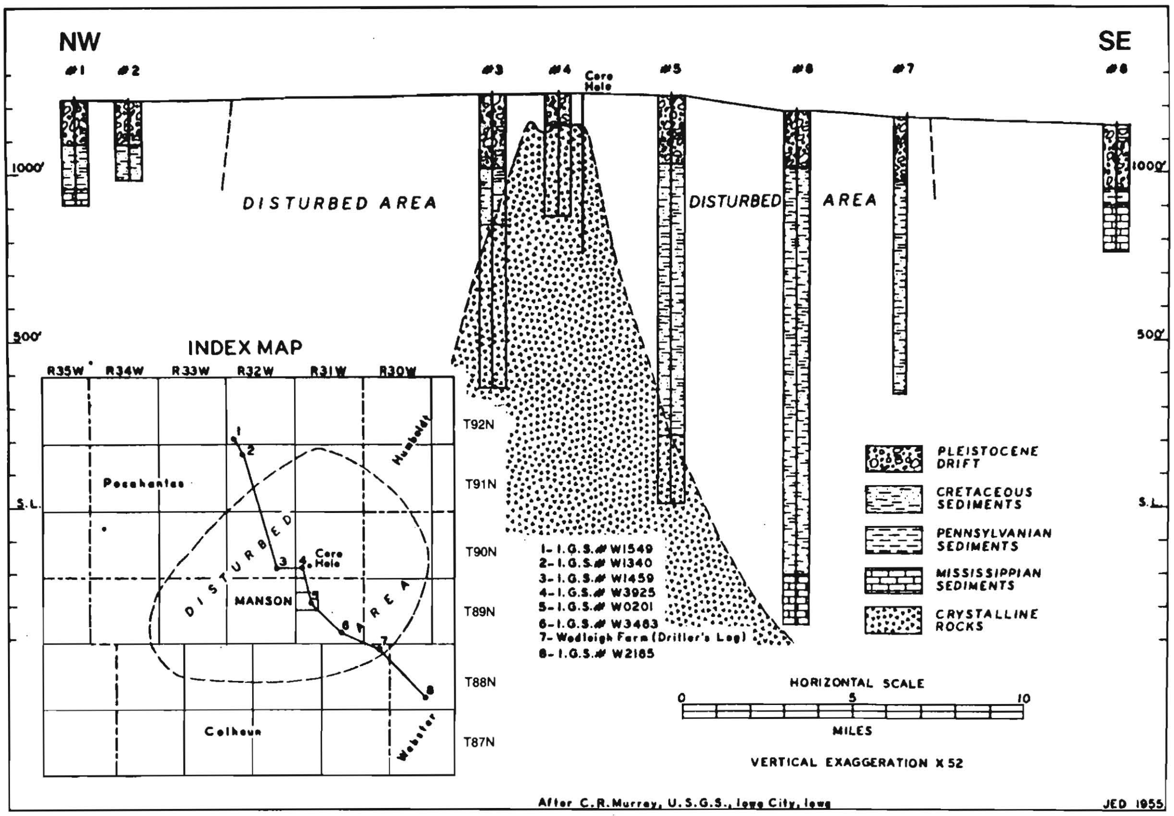

Fig. 15. Schematic cross-section through the Manson Impact Structure from *Dryden* (1955), based on earlier work by C. R. Murray.

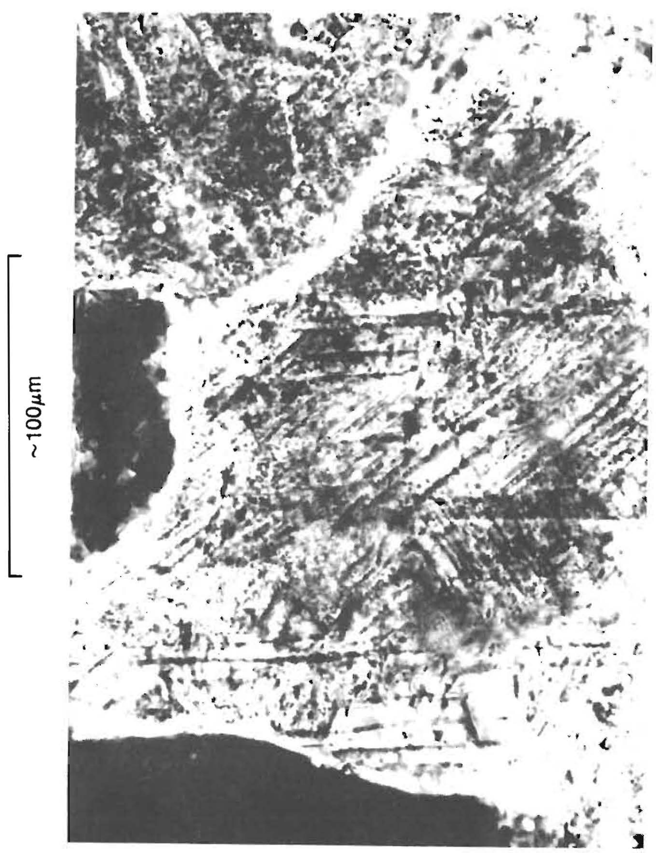

Fig. 16. Shocked quartz grain from granitic rock from Manson 2-A core. Three sets of decorated planar features are present. Grain is approximately 100 μm across.

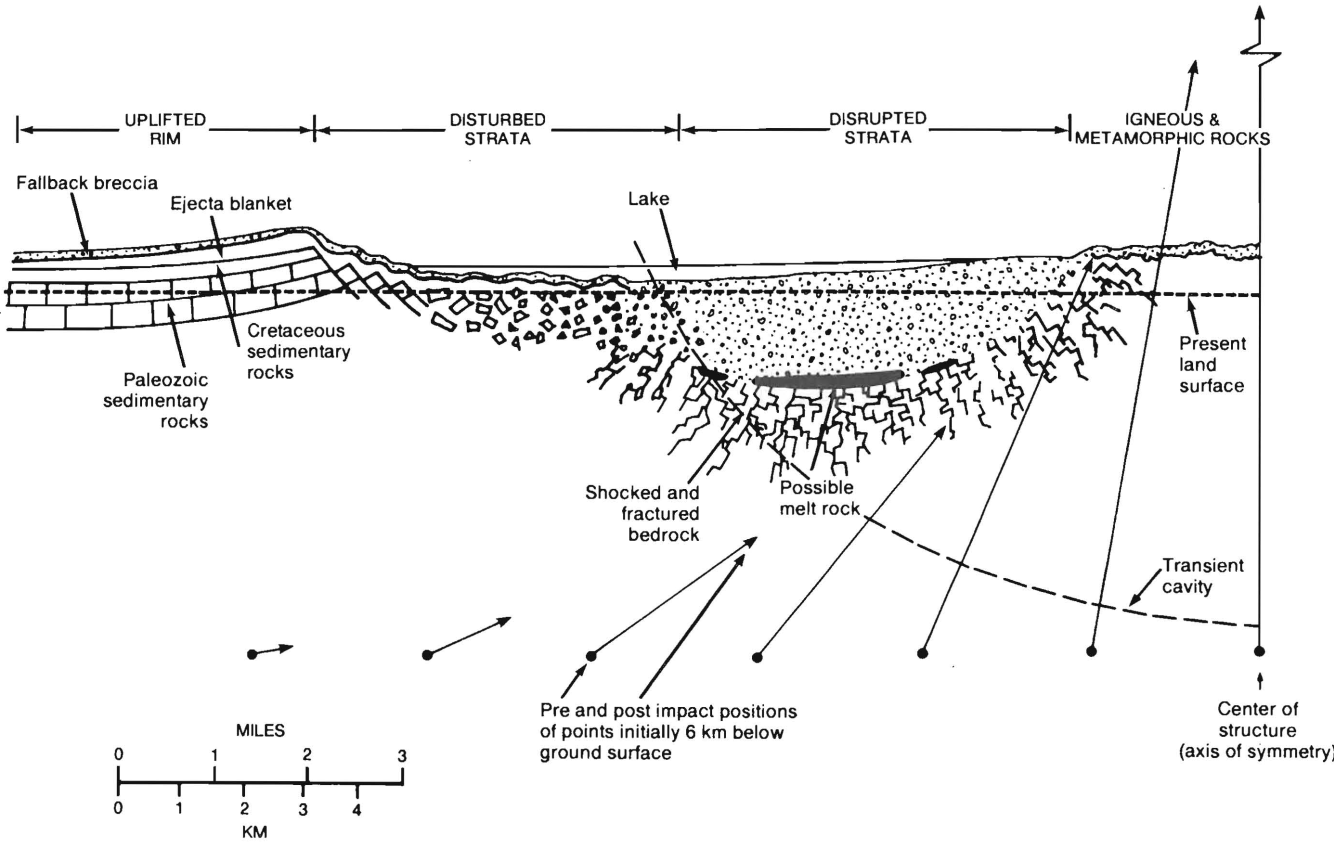

Fig. 17. Interpretive cross-section of the Manson Impact Structure. The structure is considered to be symmetric about its center, so only one half is shown. The position of the transient cavity present during formation of the structure is indicated by the curved dashed line. Rough estimates of the movement of material required to fill the transient cavity and produce the central peak are indicated by the arrows. Arrows extending above the ground surface suggest some material in the rising central peak may have been "airborne" for a short time before crashing back to Earth and producing an impact breccia. An estimate of the present level of erosion is indicated by the straight dashed line.

rocks and suggested the possibility of an impact origin for the Manson structure. Yoho also identified a sample of "chloritized devitrified basaltic glass" in one well. *Yaghubpur* (1979) identified deformed biotite and possible silica glass with recrystallized quartz among samples related to the Manson structure.

Our present interpretation of the geology and structures within the Manson Impact Structure is indicated schematically by the cross-section in Fig. 17. The major zone of disruption due to the impact is contained generally within the limits of a nearly circular feature 22 miles (35 km) in diameter centered at the location of the Manson 2-A core hole (see Figs. 12a–d). An area 6 to 10 miles (10 to 16 km) wide surrounding this limit has apparently been slightly uplifted. An area up to about 4 miles (6 km) wide within this limit is dominated by displaced or disturbed strata. The major stratigraphic units present in this zone are thick Cretaceous marine shales. These units have been preserved on down-faulted blocks within the structure, but are erosionally removed outside the structure. Today those units are found only up to several hundred miles west of the structure. Preliminary examination by B. Witzke, Iowa Geological Survey Bureau, suggests the presence of the Cretaceous Niobrara Formation and Pierre Shale strata inside the structure (Fig. 2); these units are not

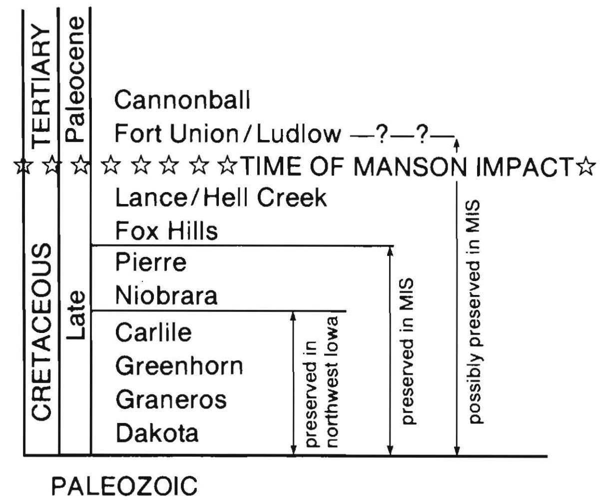

Fig. 18. Late Cretaceous and early Tertiary formations involved with the Manson Impact Structure (MIS). Lowermost late Cretaceous units are preserved generally in northwest Iowa and within the Manson structure. The overlying Pierre and Niobrara formations are preserved only within the Manson structure. Uppermost Cretaceous units may yet be found in the structure, as well as lowermost Tertiary units, such as post-impact lake or basin sediments.

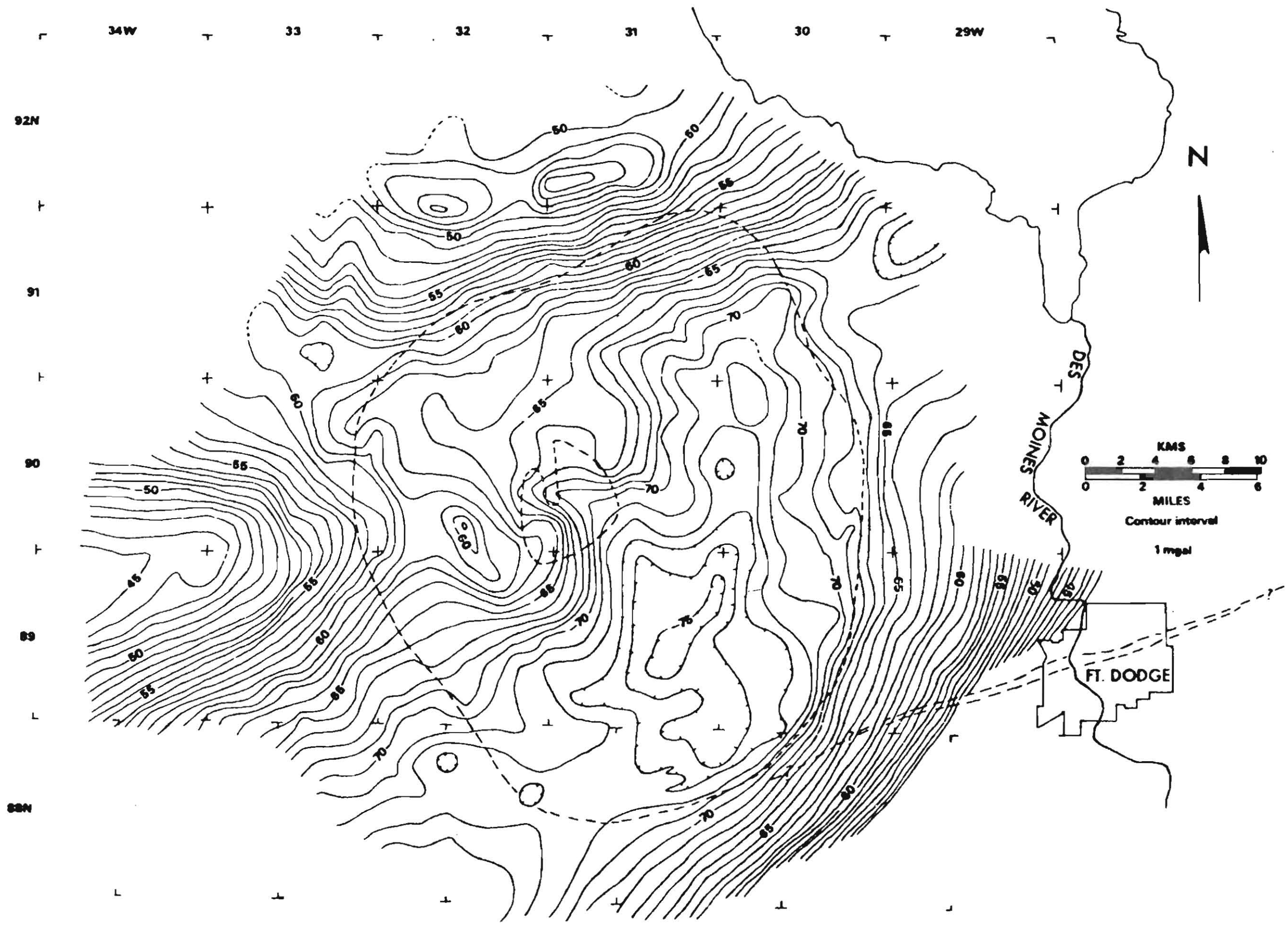

Fig. 19. Map showing Bouguer gravity contours for the area around Manson, Iowa. Data are from *Holtzman* (1970). The figure is from *Smith* (1971). The dashed lines indicate the boundaries of the "disturbed" area and the central "peak" of granitic bedrock, from *Hershey* (1969). The contour interval is 1 mgal.

preserved elsewhere in Iowa. The Cretaceous section possibly preserved in the Manson Impact Structure is shown in Fig. 18. These strata appear to be intact stratigraphically, but may show fault displacement. Several wells also in this zone have encountered what appears to be Proterozoic "red clastics" immediately underlying Quaternary glacial deposits.

Inside the zone of displaced or disturbed strata is a zone of completely disrupted strata possibly 5 miles (8 km) wide. This zone includes rocks such as those penetrated by the Manson 1-A core (Table 2) and mixtures of Proterozoic, Paleozoic, and Mesozoic rocks, which probably represent fall-back or slump breccias and fanglomerates that immediately began to fill the crater after its formation. Some of this material is highly deformed and fractured. Glass, tuff, and rhyolite reported in several wells in this area may represent impact melt.

The central area of the Manson Impact Structure is a zone of brecciated and altered gneiss, granite, and diabase uplifted shortly after the impact from a depth estimated to be over 20,000 ft (6000 m) below the surface. This lithology was encountered in the Manson 2-A core and a number of water wells near the center of the structure.

The interpretive cross-section shown in Fig. 17 has no vertical exaggeration. The structure is shown as it would appear soon after its formation. The rim is uplifted and stands about 0.6 miles (1 km) above the floor of the crater. The central peak is shown to have been uplifted at least 4 miles (6 km). The arrows indicate rough estimates of pre- and post-event positions of material originally about 4 miles (6 km) beneath the ground surface. Material beneath the center of the transient cavity may have been lofted above the ground surface as the structure developed. The location of the maximum limit of the transient cavity is indicated by the dashed line. A lake is shown to fill the crater, although no direct evidence for such a lake has been found. We estimate that about 1500 ft (460 m) of erosion has removed all lake sediments and fallback breccia, although it is possible that cuttings from water wells may contain material not yet recognized to be from these units. The expected location of impact melt rock, a little less than half way from the center to the rim, is also indicated. See *Stöffler* (1981) for a more complete description of impact crater formation and post-impact modification of craters.

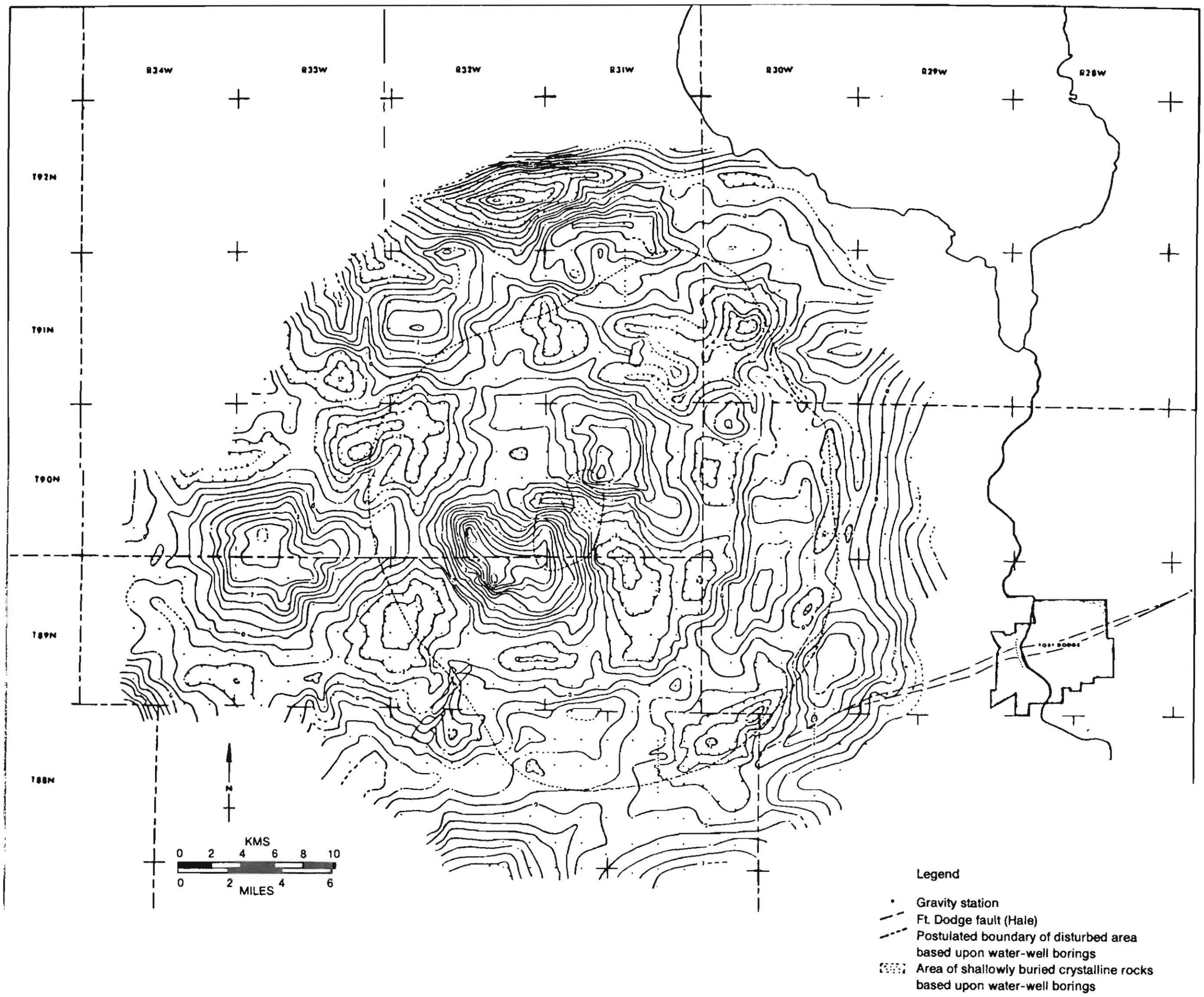

Fig. 20. Map for the area around Manson, Iowa, showing contours of the difference between a 6th degree surface fit to gravity data and the Bouguer gravity intensities, from *Holtzman* (1970). The roughly concentric dotted lines indicate the boundaries of the "disturbed" area and the central "peak" of granitic bedrock, from *Hershey* (1969). The contour interval is 0.5 mgal.

GEOPHYSICAL STUDIES OF THE MANSON IMPACT STRUCTURE

Gravity Surveys

Woollard. Between 1949 and 1955, G. P. Woollard (University of Wisconsin) supervised the acquisition of gravity data throughout the upper Midwest. This included the state of Iowa, where a relatively complete data set of township-centered stations was acquired. A map of this data published by *Coons et al.* (1967), with a 10 mgal contour interval, did not display an anomaly in the area of the Manson Impact Structure.

Holtzman. During the summer of 1968 A. Holtzman, a graduate student at the University of Iowa, made a detailed gravity survey to more precisely delineate the concealed outer boundary of the disturbed area. In an area of about 620 square miles, a network of 725 field stations was occupied. The network extended at least 3 miles beyond the postulated limits of the structure. Bouguer gravity and 2nd, 4th, and 6th degree residual gravity maps were obtained. Maps showing Bouguer gravity contours and residuals from the 6th degree surface and Bouguer contours are shown in Figs. 19 and 20.

Holtzman (1970) drew the following conclusions from his survey of the Manson area.

1. The prominent midcontinent gravity high partially masks the gravity expression of the Manson structure.

2. The outer boundary of the structure cannot be established based on the gravity data obtained.

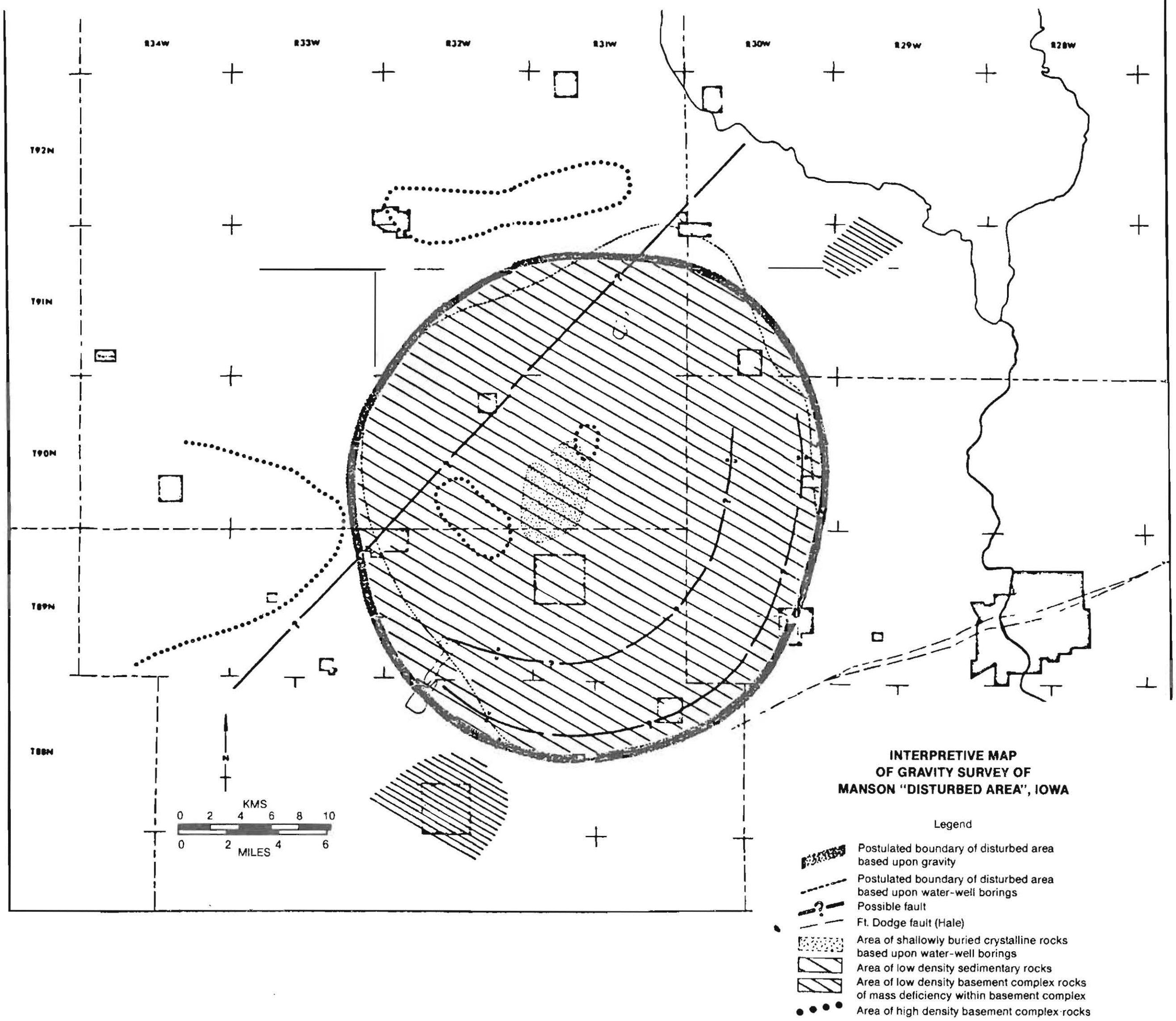

Fig. 21. Geologic interpretation of gravity data over the area of the Manson Impact Structure, from *Holtzman* (1970).

3. A large negative gravity anomaly within the disturbed area is interpreted to correspond to brecciated sedimentary rocks, and a subcentral "positive" is attributed to the uplifted crystalline core of the structure.

4. Other positive and negative features are attributed to differences in basement lithology or to the presence of faults confined to basement rocks.

5. The origin of the Manson structure cannot be clarified using the gravity data obtained.

An interpretation of some structures within the Manson Impact Structure based on gravity data is given in Fig. 21. An inner arcuate fault and a peripheral graben is suggested.

IGS Bouguer gravity anomaly map. The Iowa Geological Survey published a Bouguer gravity anomaly map of Iowa (*Anderson*, 1981) that included Woollard's gravity data and additional data, but still with a general 6-mile (10 km) station spacing. This map has a 5 mgal contour interval and shows some disturbances in the area of the Manson Impact Structure, but the crater cannot be resolved.

Magnetic Surveys

IGS/USGS. According to *Holtzman* (1970), in an effort to learn more about the basement complex underlying the Manson

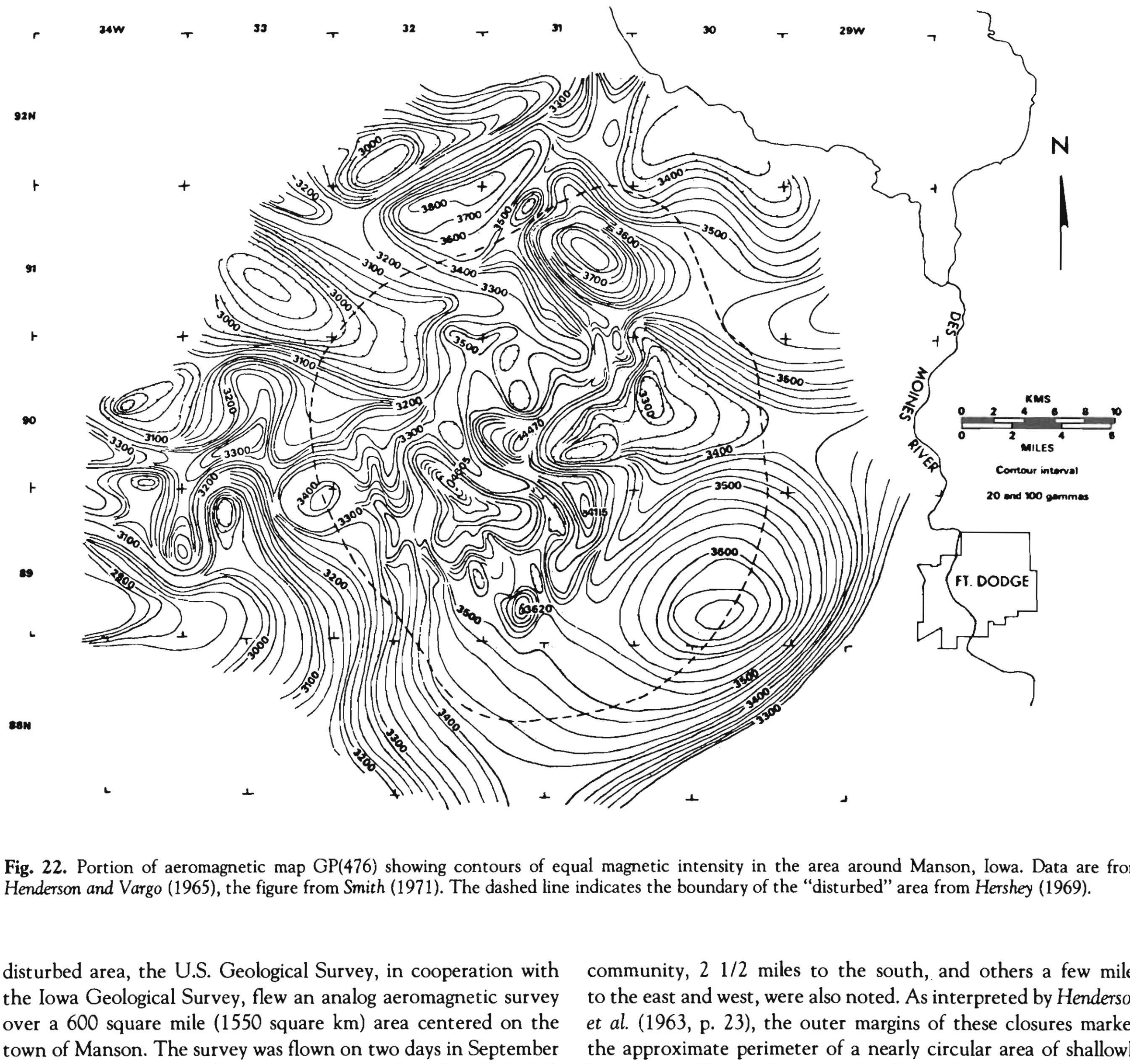

Fig. 22. Portion of aeromagnetic map GP(476) showing contours of equal magnetic intensity in the area around Manson, Iowa. Data are from *Henderson and Vargo* (1965), the figure from *Smith* (1971). The dashed line indicates the boundary of the "disturbed" area from *Hershey* (1969).

disturbed area, the U.S. Geological Survey, in cooperation with the Iowa Geological Survey, flew an analog aeromagnetic survey over a 600 square mile (1550 square km) area centered on the town of Manson. The survey was flown on two days in September and one day in November of 1953 at an altitude of 1000 ft (300 m) above ground level using a DC-3 aircraft equipped with an AN/ASQ-3A fluxgate magnetometer. Flight lines were east-west and spaced one mile (1.6 km) apart, with several north-south tie lines (*Henderson et al.*, 1963). The survey was flown in conjunction with the IGS/USGS coring program on the structure that produced the Manson 1-A and 2-A cores. A preliminary map of the magnetic anomaly in the survey area was prepared by J. L. Meuschke, L. A. Anderson, R. W. Bromery to aid groundwater geologists in their study of the Manson region (*Henderson et al.*, 1963). These data were incorporated into a more extensive aeromagnetic map of the Midcontinent Rift and published by the U.S. Geological Survey (*Henderson and Vargo*, 1965). The area of this map that includes the Manson Impact Structure is reproduced in Fig. 22.

The results of the survey showed an aeromagnetic high some 4 miles north of Manson. Positive anomalies northwest of this community, 2 1/2 miles to the south, and others a few miles to the east and west, were also noted. As interpreted by *Henderson et al.* (1963, p. 23), the outer margins of these closures marked the approximate perimeter of a nearly circular area of shallowly buried crystalline rocks, some 8 miles in diameter and centered about 1 mile northeast of Manson.

Warriner. According to *Holtzman* (1970), in an attempt to determine the depths to, and magnetic susceptibilities of, bodies within the basement complex that could be responsible for the positive aeromagnetic anomalies near Manson, two ground magnetic traverses were undertaken across the disturbed area in October of 1969 by J. Warriner of Iowa State University. These were oriented north-south [21 miles (34 km)] and east-west [24 miles (39 km)] and intersected at a point approximately 1 mile (1.6 km) north and 1 mile (1.6 km) west of the center of Manson. Measurements were made at intervals of half a mile (0.8 km) with a Schmidt Vertical Magnetic Force Variometer (T. Smith, written communication, 1969).

Warriner's analysis of the data, using *Peters*' (1948) half-slope method and the method of least squares, indicated an average depth of between 1250 and 1400 ft (381–427 m) to the postulated

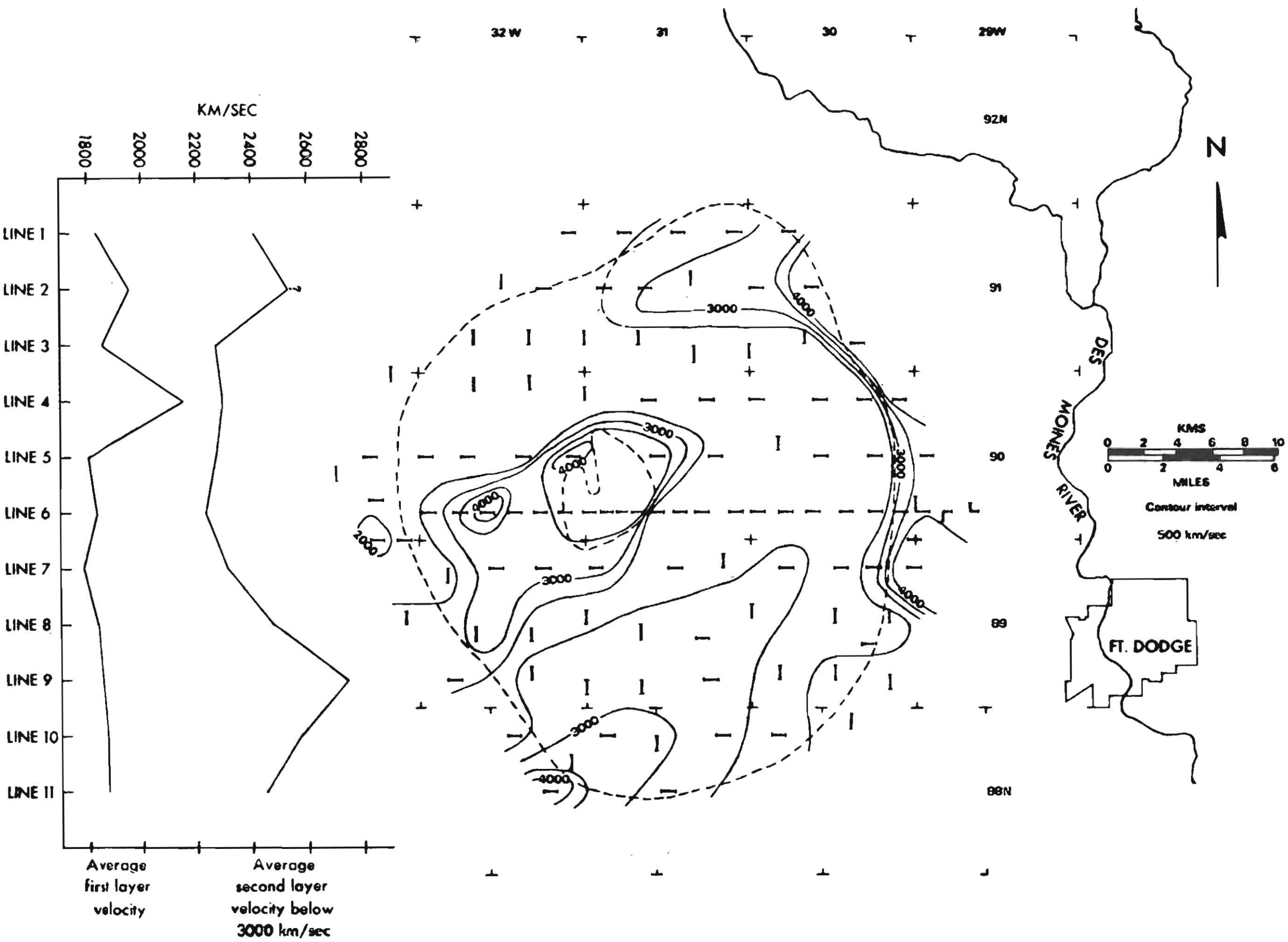

Fig. 23. Seismic wave propagation velocities in layers 1 and 2 averaged for 11 east-west lines and map of the area around Manson, Iowa, showing locations of geophone lines and contours of equal seismic velocity from *Smith* (1971), roughly concentric dashed lines indicate boundaries of "disturbed" area and the central "peak" of granitic bedrock, from *Hershey* (1969).

narrow and isolated sources of the sharp, central magnetic anomalies. Associated susceptibilities, computed using equations presented by Nettleton and Peters averaged 25×10^{-3}c.g.s. units (5% magnetite by volume). Surrounding anomalies were generally found to be deeper and with lower susceptibilities (on the order of 4×10^{-3}c.g.s. units), suggesting to Warriner that basic or ultrabasic rocks were "emplaced within" those of granitic lithology.

Normal basement faults, inferred to be dipping steeply inward toward the center for the structure, were interpreted from three small asymmetrical anomalies approximately 4 1/2 miles (7.2 km) south, 6 1/2 miles (10.5 km) south, and 6 1/2 miles (10.5 km) east of the point of traverse intersection (T. Smith, written communication, 1969). Throws associated with the displacements to the south were estimated to be on the order of 100 ft (30 m). An east-west magnetic lineament was noted to underlie the disturbed area.

Seismic Refraction Survey

In 1971 a seismic refraction study was completed by T. Smith, a graduate student at Iowa State University. The purpose of the study was to determine the topographic relief of the bedrock surface, where bedrock refers to rocks that underlie glacial deposits (*Smith and Sendlein*, 1971).

Data were collected at 107 sites loosely fitting a 2 × 2 mile (3.2 × 3.2 km) grid using a truck-mounted, 24-channel, analog, seismic recorder. Single 14 Hz geophones were spaced 105 ft (30 m) apart along two 23-channel seismic lines. Five- to six-pound (2.3–2.7 kg) charges of 40% strength stick dynamite were buried about 10 ft (3 m) in the glacial drift and from 65 to 200 ft (20–60 m) from the nearest geophone along the seismic line and from 10 to 50 ft (3–15 m) perpendicular to the line. First arrival

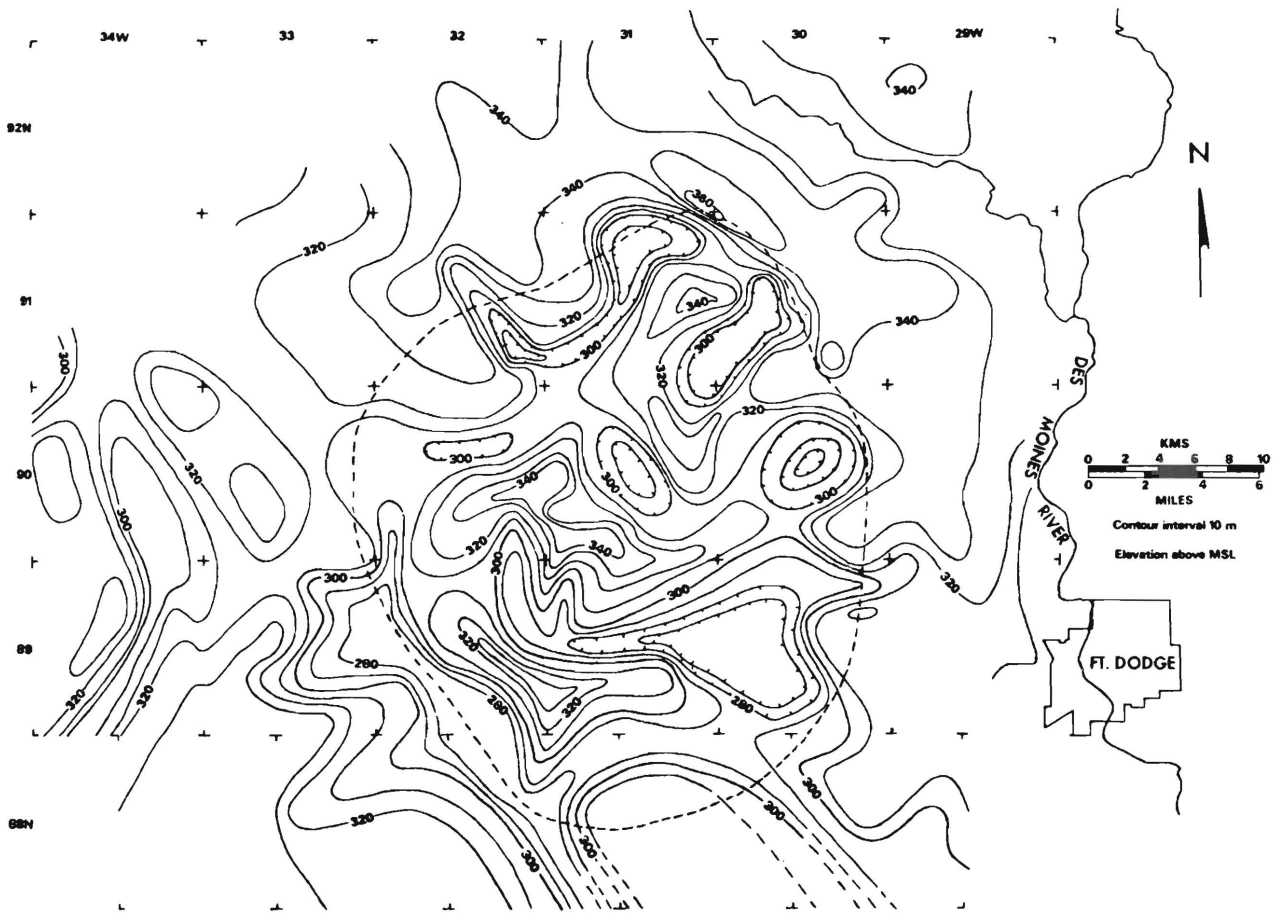

Fig. 24. Map of area around Manson, Iowa, showing the topography of bedrock inferred from seismic refraction data, from *Smith* (1971).

times and time breaks were picked using a 3X power microscope with a precision of ±0.002 sec (*Smith*, 1971).

Time-distance data were obtained and analyzed statistically to yield wave propagation velocities, usually for two layers of rocks. One layer corresponded to glacial till, which is about 100 ft (30 m) thick throughout the area, and the second layer was whatever was below the till. Average seismic velocities for these two layers for each traverse of the structure are given in Fig. 23. Also shown in Fig. 23 are contours of constant velocity in the second, or bedrock, layer. The area in the center of the figure bounded by the 12,000 ft/sec (3500 m/sec) contour roughly coincides with the area where crystalline rock immediately underlies glacial till, based on borehole cuttings. Another area of high bedrock velocity is located 10 km due west of the center of the structure. It may be that crystalline rock also subcrops in this area. Carbonates, which comprise the bedrock east of the disturbed area, are delineated quite well by the 13,000 ft/sec (4000 m/sec) contour (*Smith*, 1971).

Based on seismically determined depth values and bedrock elevations from boreholes, the bedrock topography was determined and is shown in Fig. 24. Observations by *Smith* (1971) based on these results are as follows.

1. The irregular surface within the Manson disturbed area contrasts sharply with the gentle slopes outside the area.

2. The average elevation of the bedrock is about 980 ft (300 m) inside the disturbed area and 1050 ft (320 m) just outside that area.

3. The central crystalline bedrock is a topographic high.

4. Hills of shale are present in the northeast and southwest parts of the disturbed area.

5. The drainage ways in the disturbed area are not well developed. Several valleys outside the disturbed area terminate in depressions inside the area, thus indicating the structure may be relatively young.

6. Two bedrock valleys in the southern portion trend northwest-southeast and their gradient is toward the southeast, away from the disturbed area.

7. The western bedrock valley follows the edge of the disturbed area for some distance. The zone between the disturbed and undisturbed bedrock must have been less resistant to erosion than either the disturbed or undisturbed bedrock. The shape of the western bedrock valley suggests that the disturbed bedrock was comparatively more erosionally resistant than the undisturbed Pennsylvanian shales to the southwest.

8. Mississippian carbonates to the northeast of the structure are more resistant to erosion than the Pennsylvanian shales and sandstones beyond the southwest rim.

The following are other results from this study.

1. Apparently, there is no mappable seismic refractor below the drift-shale interface, to a depth of 820 ft (250 m).

2. The rim structure is very complex. No model could be made of the geometric arrangement of the bedrock layers.

3. The seismic wave propagation velocity through the granite, gneiss, and diabase of the central crystalline mass averages near 13,000 ft/sec (4000 m/sec). Such an unusually low velocity for this rock type may indicate that it has an abnormally high porosity, which may be a result of the brecciation during the emplacement event.

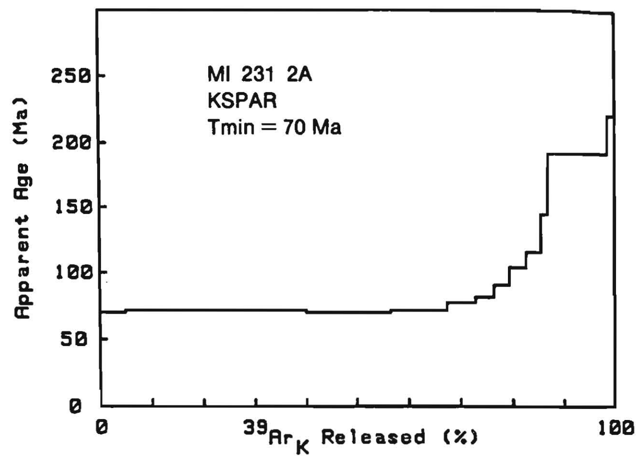

Fig. 25. The $^{40}Ar/^{39}Ar$ age spectrum for a microcline sample from the Manson 2-A core, 231 ft from the ground surface, from *Hartung et al.* (1986). The first 60–70% of ^{39}Ar released indicates an upper limit for the time of post-impact cooling of 70 Ma.

Seismic Reflection Survey

In September 1984, Western Geophysical (Englewood, Colorado) acquired about 350 miles (563 km) of speculative seismic reflection data over the Midcontinent Rift in Iowa in anticipation of petroleum industry activity in the area. Their line 3A is 23 miles (37 km) long and crosses the Manson Impact Structure in a north-south direction. They collected 20-fold, 120-channel data with 20 sec of recording time. (The results of this survey are available from Western Geophysical.)

AGES OF SAMPLES FROM THE MANSON IMPACT STRUCTURE

Precambrian Basement Metamorphism

Using biotites from gneiss at 367 ft (112 m) and 485 ft (140 m) in the Manson 2-A core *Lidiak et al.* (1966) obtained Rb-Sr ages of 1130 and 1070 Ma and K-Ar ages for the same samples of 970 and 720 Ma, respectively. They also reported a Rb-Sr age for a muscovite from a gneiss from cuttings from a nearby well of 1090 Ma. These ages represent regional metamorphic events that occurred during the Precambrian. Some mobilization of argon may have occurred as a result of the Manson impact, thereby producing somewhat lower ages.

Manson Impact Event

The age of the Manson Impact Structure is particularly important. The stratigraphic age of the upper part of the disturbed section was judged to be Cretaceous based on *Inoceramus* fragments found in limestone and shale cuttings and lignite and siderite pellets, which have been observed in Cretaceous sections elsewhere. Fish scales, no older than Mesozoic, and poorly preserved cephalopods suggestive of the Cretaceous were found at the single outcrop described previously (*Hale*, 1955, pp. 35 and 143). These rocks were deformed or disturbed by the impact event, therefore the impact must have occurred after middle to late Cretaceous time.

A fission track age of 61 ± 9 Ma (uncertainty 1 σ) was reported by *Hartung et al.* (1986) for apatite grains separated from Manson 2-A core material. This age corresponds to the time of cooling to below about 100°C, presumably subsequent to uplift with other rocks of the central region during crater formation.

An $^{40}Ar/^{39}Ar$ analysis of material thought to be shocked microcline, a mineral known to have a low blocking temperature, from a depth of 231 ft (70 m) along the Manson 2-A core produced an age less than, but not much less than, 70 Ma for a reheating event probably related to the Manson impact (*Hartung et al.*, 1986). The corresponding age spectrum is shown in Fig. 25. Subsequently, two additional $^{40}Ar/^{39}Ar$ age spectra for K-feldspar (probably microcline) separates from different levels within the same core were obtained. These spectra were similar to the first one and indicated a time of uplift of about 66 Ma ago, a time indistinguishable from the numerical age of the K-T boundary (*Kunk et al.*, 1987).

Paleomagnetic studies have been made using samples taken from the Manson 2-A core at depths of 317, 426, and 465 ft (97, 130, and 142 m). It is known that magnetization produced by a shock event is readily removed by alternating field demagnetization experiments. Such experiments on Manson rocks removed only positive or normal magnetization, thus indicating that the Manson impact occurred during a time when the Earth's magnetic field had a normal polarity. However, "*if* the K-T boundary is a global isochron occurring within polarity zone 29R," a time of reversed polarity, then the Manson impact cannot have been synchronous with the Cretaceous-Tertiary boundary (*Cisowski*, 1988). It must be noted that the basement rocks sampled in the Manson 2-A core had been violently uplifted over 20,000 ft from their original positions subsequent to the impact, and because there is no guarantee that they have not been rotated, this test may not be valid.

THE MANSON IMPACT STRUCTURE AND THE K-T BOUNDARY

The most important question related to the study of the Manson Impact Structure is whether or not it is related to the mass extinction that marks the K-T boundary. Properties of the Manson impact that may support, or refute, a link with K-T boundary mass extinctions are the following: (1) impact energy (impactor mass and velocity) or crater size; (2) impact time; and (3) compositions (mineral, chemical, and isotopic) of impactor, host rock, and impactite.

Impact Energy or Crater Size

As a first approximation, the kinetic energy of an impacting object is directly related to the size of the resulting crater. Based on extrapolations from impact experiments and nuclear explosions, the following relationship was obtained by *Dence et al.* (1977), for the impact energy, E, in joules, required to form a crater with a rim diameter, D, in km.

$$E = 1.0 \times 10^{16} D^{3.4} \quad (1)$$

Using this relationship and a diameter of 35 km for the Manson crater, an impacting energy for the Manson impactor would be 2×10^{21} joules. Perhaps more important is the distribution of that energy among its various sinks, such as heat, which produces ionization, vaporization, and melting of material, as well as an increase in its temperature, shock, and seismic waves, the motion of ejecta, and fracturing of target rock. Simplifying assumptions made to establish the amount of energy available and its partitioning relate to impactor and target densities, volatiles present, impact geometry, and extrapolation over orders of magnitude. Each assumption carries with it increased uncertainty in the final result. For example, an impact at a low angle of incidence will deposit disproportionately more energy into high velocity ejecta and less energy into low velocity ejecta, thus producing a smaller crater with more high-velocity ejecta (*Gault and Wedekind*, 1978). While a vertical impact producing a 35-km-diameter crater may not generate enough high-speed ejecta to cause a global dust cloud, it may be argued that a low angle impact could produce much larger amounts of high-speed ejecta for the same impact energy, so it may not be possible to rule out the Manson impact as the source of a globally dispersed dust cloud capable of causing a mass extinction (H. A. Zook, personal communication, 1987).

Based on initial estimates, to account for the worldwide abundance of iridium at the K-T boundary requires a carbonaceous chondrite composition impactor of about 10 km in diameter. Such an object would produce a crater about 200 km across. Therefore, to the first approximation, the Manson impact could not have been solely responsible for all of the events for which evidence exists at the K-T boundary. This leaves open the possibilities that (1) the Manson impact was responsible for some K-T boundary events (other unobserved properties of the impactor, such as an accompanying dust cloud, may have been the source of large amounts of iridium), or (2) the impact was partially responsible for all K-T boundary events [there may have been other similar impacts at nearly the same time (*Sharpton and Burke,* 1987)].

The two examples just cited illustrate the need for more comprehensive laboratory impact experiments and computer modeling, as well as more geological study of the structure itself.

Impact Time

A crucial test of the hypothesis that the Manson impact is related to K-T boundary extinctions is that the crater and the K-T boundary must have exactly the same ages. Three analyses of potassium feldspar, probably shocked microclines, a mineral known to have a low blocking temperature, from the Manson 2-A core yielded $^{40}Ar/^{39}Ar$ age spectra that do not possess good plateaux. The first spectrum can be interpreted to show that the maximum time for the crater formation was less than, but not much less than, 70 Ma ago (*Hartung et al.*, 1986). The other two spectra indicate a severe argon loss occurred about 66 Ma ago, an age that is indistinguishable from the age of the K-T boundary (*Kunk et al.*, 1987). These preliminary results show that the Manson impact and the K-T boundary could have the same age.

A more quantitative statement is that if an average production rate of known craters larger than 35 km in diameter, R_{35}, is given and a combined uncertainty in the ages of the K-T boundary and the Manson impact, Δt, is assumed, then the expression for the probability of the impact and boundary being coincident by chance is approximately

$$P = 1 - e^{-R_{35}\,\Delta t} \quad (2)$$

If the average production rate of known 35-km-diameter-and-larger craters on the North American continent is $2 \times 10^{-8} yr^{-1}$ (*Shoemaker*, 1977), and the combined uncertainty in the times of the Manson impact and the K-T boundary is assumed to be 2 Ma, then the probability of the two events being coincident by chance is approximately 0.03. If either the crater production rate or the analytical uncertainties in the age measurements were lower, this probability would be reduced. Because the production rate is a fact of nature, i.e., it is not subject to external control; no amount of effort can change its contribution to the probability of coincidence. However, the uncertainties related to the age measurements can be reduced by better sample selection and improved analytical procedures. Efforts made in this direction will have the effect of reducing the probability of coincidence by chance.

Three major efforts need to be undertaken in this connection. First, times of occurrence should be measured for all large terrestrial impact structures, the objectives being to establish a crater production rate with a minimum of uncertainty. Second, the absolute age of the K-T boundary should be determined as accurately and as precisely as possible. Finally, the time of the Manson impact should also be determined as accurately and precisely as possible. To accomplish this last objective probably will require acquisition of samples that were melted during the impact and subsequently retained argon quantitatively. This, in turn, will probably require drilling to recover such samples that remain within the structure as part of a melt sheet. No melt sheet of any kind has been definitively identified at Manson as a result of fairly shallow water well drilling in the area.

Establishing a low probability of coincidence by chance, unfortunately, cannot prove a relationship exists between the Manson impact and the K-T boundary. However, it is reasonable to expect that improved analyses will result in a probability of coincidence by chance of 0.01, which would be a strong argument for a Manson/K-T boundary connection.

Compositions

It may be possible to establish, or refute, a link between the Manson crater and the K-T boundary by studying the mineral, chemical, and isotopic content of crater host rocks, possible impacting objects, and impactites. Impactites may contain a mixture of impactor and host rocks.

Among the minerals found at the K-T boundary are quartz grains that have been shocked, presumably at the site of a large impact, and transported to distant locations. Shocked quartz grains have also been found in granitic rocks at Manson, but it has not yet been shown that the K-T boundary shocked quartz originated near Manson, Iowa. However, it has been shown that the largest shocked quartz grains have been found at North American K-T boundary sites, thus suggesting a North American source for these grains (*French*, 1984).

Iridium and other siderophile trace elements enriched in K-T boundary clays were apparently derived from extraterrestrial material, at least some of which could have produced the Manson Impact Structure. If so, then it is reasonable to expect that somewhere within or around the structure some of this material has survived, in glassy melt bombs, in a melt sheet, or in fallback breccia. Although some glassy material and "tuff" has been described among water well cuttings, no systematic study of this material in search of anomalously abundant siderophile trace elements has been made.

Once again, the search for such material at Manson will probably require drilling to recover melt rocks that have been shown at some other craters to contain a component derived from the impacting object.

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