The lunar near-side crater, Tycho, an example of a fresh crater with well-developed central uplift. Tycho is approximately 85 km across and the central peak is estimated to rise to a height of 1.9 km above the crater floor. The structure and form of this lunar crater is believed to be analogous to terrestrial craters in the size range 3.5-30 km, including the Kentland structure. Lunar Orbiter Photo, NASA SP-200.

A Structural and Petrographic
Study of the
Kentland, Indiana Impact Site

by

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Professor in Charge

For the Department

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ABSTRACT

The structurally disturbed area near Kentland, Indiana is a typical example of a so-called 'cryptoexplosion' structure which can be attributed to a large natural impact event. The structure includes a central uplifted area approximately 4 km in diameter, the most intense deformation being confined to a core slightly greater than 1 km in diameter. Stratigraphic uplift in the core region is probably greater than 600 m. The central uplifted area is surrounded by a ring depression 1.5 to 2.0 km wide, situated 3.2 km from the center of the uplifted area, and within which are preserved soft Pennsylvanian coals. At a radius of approximately 6.2 km from the center of the site, a subdued structural high is present and is believed to be the limit of the disturbance.

Although most of the site is covered with a thin veneer of glacial till, a large quarry (0.4 km^2 in area, 70-80 m deep) located on the northern flank of the central uplift exposes in detail some of the complexities which occur as a result of structural modifications of an original transient cavity. Quarry exposures are dominated by a large NNW plunging synclinal fold and numerous high angle normal and reverse faults. Megabreccia zones containing blocks 100 m or more long bound this synclinal fold on three sides. These zones are structurally very complex and characteristically seem to involve the more mobile sandstone and shale formations along with the competent carbonates. Recent drilling indicates that this pattern of large carbonate

blocks and megabreccia zones also characterizes the structural pattern of the remaining covered portions surrounding the core of the central uplift.

Shock deformational features produced by the impact event, including monomict and polymict breccias and shatter cones, are exposed in the quarry. Petrographic studies of quartz grains from the breccias and other sandy units show that brittle failure was common with irregular fractures, microfaulting, and cleavage the dominant features in almost all grains. Less than one percent of the grains studied contained basal deformation lamellae; multiple sets of other planar features in quartz grains have not been observed. These results suggest shock pressures in the range of 50 kb for the material in the quarry.

Information gathered in this study indicates that the probable mechanism producing central uplift formation in impact craters in sedimentary rock is some type of rebound of the impact-compressed material. Most terrestrial impact structures in sedimentary rock are in various states of degradation, and information on the structural details at deeper levels in these impact sites is generally lacking. Nonetheless, comparison of similar-sized impact sites indicates that various factors, including target characteris~~t~~tics, projectile characteristics, and basement depth, could play important roles in determining final crater morphology.

INTRODUCTION

A significant development in the geological sciences within the last two decades has been the application of geological methods of investigation to the study of the nearby planetary bodies and their moons. To augment the gathering of this basic information and to aid in the interpretation of the data, certain aspects of terrestrial geology have received intensive investigation. Most notable has been the research into impact cratering phenomena. During the era immediately preceeding man's first landing on the Moon, investigations were underway that dealt with the structures produced by hypervelocity impact and, on a smaller scale, the mineralogical changes which accompany such catastrophic events. It was felt such information was necessary to interpret correctly the geologic history of the returned lunar samples. Scientific interest in impact cratering has continued to the present. Photographic missions to Mercury, Venus, and Mars have shown that each planet has undergone periods during which impact cratering was a significant factor in the evolution of their surfaces. The realization that exogenetic factors could play vital roles in the evolution of a planetary body is a new facet in geologic thinking and one that will probably receive more attention as the exploration of the solar system continues. One result of this interest in planetology has been an increase in the number of suspected impact structures discovered on the

Earth. During the first part of the 20th century only those craters associated with meteorite fragments were assigned an impact origin. Other larger circular anomalies that displayed highly disrupted and shattered rock, but had no associated meteoritic material, were believed to be due to some sort of hidden, violent explosive activity or 'cryptovolcanism' (Bucher, 1936). Explanations involving endogenetic origins for these structures were usually weak, and, as these structures were investigated more closely, many similarities among them became apparent. Most of the structures were roughly circular in plan view and possessed a central high area usually surrounded by a ring depression. Unusual conical fracture surfaces, termed shatter cones, were present at most of these sites. Dietz (1946) proposed the non-genetic name 'cryptoexplosion structure' to designate these geological curiosities, many of which he believed to be of true impact origin. During this time microscopic study of the rocks from cryptoexplosion sites and from laboratory shock wave experiments was preceeding. From these studies it was discovered that some minerals underwent certain phase changes and that mineral grains displayed some structures which were non-existent in grains from normal tectonic environments. These 'shock metamorphic features' have become generally accepted as valid criteria to be used in assigning an impact origin to any suspected terrestrial site. On this basis the number of suspected impact sites has risen to almost 80 (Kinsler, 1977); approximately 70 more sites are possible candidates, but at present these have not been fully investigated.

Most of the suspected impact structures in the United States occur in well-stratified sedimentary rock sequences and range in diameter from 3.5 to 30 km (Fig. 1). These 'cryptoexplosion' or suspected impact sites display many similar features such as those listed by Boon and Albritton (1937) and Bucher (1936). Although cases have been made relating some of these structures to regional faults, lineaments, or other tectonic features, no conclusive proof of an endogenetic origin for any of these sites has been forthcoming (Bucher, 1933, 1963, 1965; Jamieson, 1963; Snyder and Gerdemann, 1965). On the other hand, evidence supporting an impact origin for these structures is overwhelming (the reader is referred to volumes by French and Short, 1968; Horz, 1971; Roddy, Pepin, and Merrill, 1977 and the references cited within as an introduction to impact cratering studies). Indeed, the burden of proof must be placed on those who still propose endogenetic origins for these structures.

Most of the impact structures located in the United States are morphologically very similar. However impact craters on the terrestrial planets and their moons can, as a whole, be broadly grouped into three catagories (Fig. 2). On the Earth those craters developed in sedimentary rock and having diameters less than two km (approximately four km for those developed in crystalline rock) display a simple steep-walled, bowl-shaped form. A typical example is the 1.2 km diameter Barringer Crater in Arizona (Fig. 2a). Larger

Figure 1.

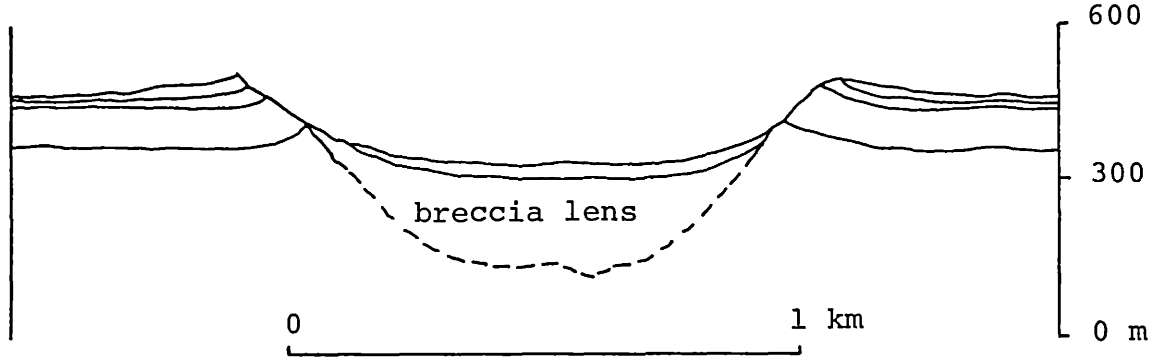
Map of the eastern half of the United States showing the location of 'cryptoexplosion' or suspected impact structures. Open circles denote that shock metamorphic features have not been confirmed from the site. Dark circles indicate shock metamorphic features have been identified. These structures all occur in sedimentary rock sequences and range in age from Lower Paleozoic to Cenozoic. Diameters range from 3.5 km (Flynn Creek) to 30 km (Manson).


Glover Bluff
Manson
Kentland
Glasford
Serpent Mound
Jeptha Knob
Versailles
Decaturville
Crooked Creek
Middleboro
Dycus
Flynn Creek
Wells Creek
Howell
Kilmichael
Sierra Madera

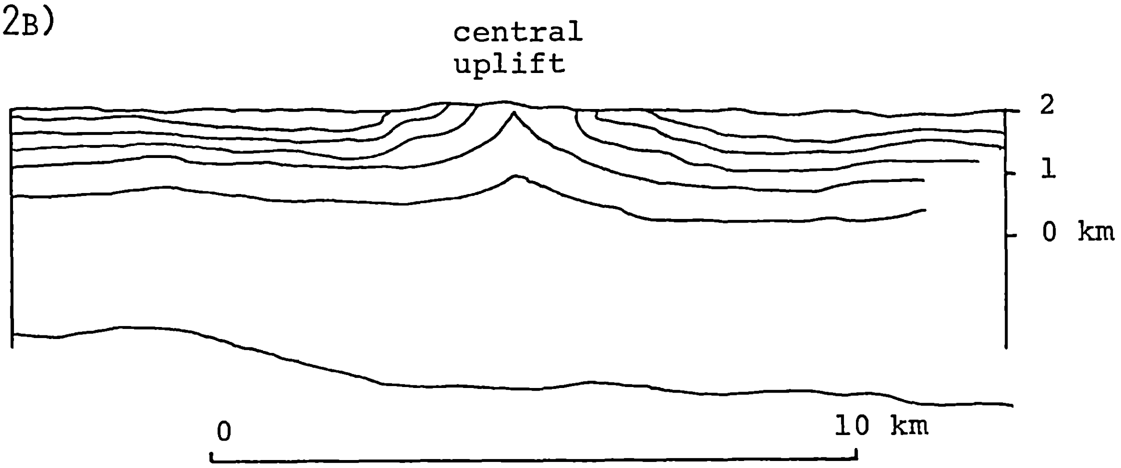
Figure 2.

a) Barringer Crater, Arizona. Classic example of a steep-walled, bowl-shaped crater that formed less than 30,000 yr. ago (Roddy, 1977a). b) Sierra Madera, Texas. Example of a suspected impact structure showing well-developed central uplift. Strata near the center of the structure have been uplifted over 1200 m (Wilshire et al., 1972). c) Profile of the Orientale Basin, Moon. Similar multi-ring structures are believed to occur on all the terrestrial planets (Roddy, 1977a). The three crater forms illustrated presumably are transitional, the determining factor being the mass and velocity of the projectile.

2A)


600
300
0 m
breccia lens
0
1 km

2B)


central uplift
2
1
0 km
0
10 km

2c)


ring 1
ring 2
Cordillera Mtns.
Rook Mtns.
40
0 km
0
500 km

craters, between three and 30 km in diameter, include a transition to forms characterized by shallow, flat floors and poorly to well-formed centralized uplifts. Structures of this type have been termed complex craters and an example has been illustrated in Fig. 2b, the 14 km diameter Sierra Madera, Texas structure. Still larger craters, those over 30 km in diameter, begin to display concentric, topographically high internal rings. A terrestrial example is the 100 km diameter Popigia, USSR structure (Dence et al., 1977). Presumably analogous impact structures developed on the Moon and Mercury occur as basins hundreds of kilometers across (Fig. 2c).

This study is concerned with an example of a complex crater with central uplift (as in Fig. 2b). Throughout this investigation, certain aspects of impact crater structure will be discussed and so a diagrammatic representation of the basic elements of a complex crater is presented in Fig. 3. This idealized crater represents an uneroded impact structure (i.e., a freshly produced crater). A central uplift has been defined as, "... a local feature that is topographically high, physically near the center of the crater, and consists of material that was displaced upward during the cratering event. This term is applicable to a definite structural feature, and is not meant to include the possibility that material ejected from the crater may subsequently fall into the crater and form a hill at the center" (Ullrich et al., 1977). These uplifts typically occupy a

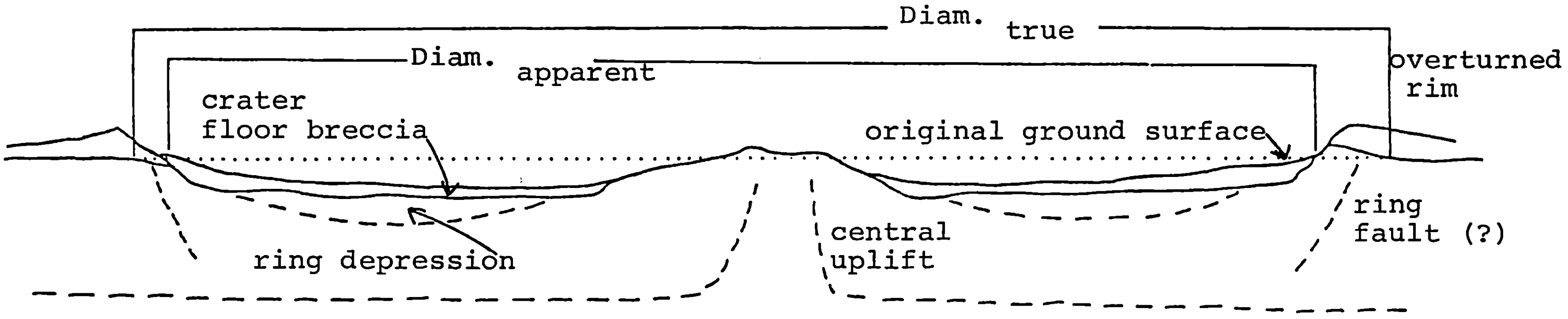


Figure 3. Cross section of an idealized complex crater, based on the Flynn Creek structure (Roddy, 1977c). All the features illustrated normally do not occur at every impact site. The location of the limit of disturbance for those structures eroded below the original ground surface is believed to lie somewhere between the true and apparent diameter. In most cases the diameter of disturbance is taken as representative of the apparent diameter for comparitive purposes. The lower dashed line represents strata that occur at a depth approximately 1/9 of the apparent crater diameter.

a large part of the interior of the crater. However, since most terrestrial sites have undergone extensive erosion, the topographic expression of the uplifts are commonly subdued. Usually surrounding the central uplift is a ring depression or ring syncline. These depressions are believed to be genetically related to the formation of the central uplift and this point will be discussed in detail below. As stated previously, most terrestrial impact sites are in various states of erosional degradation and so features such as fall-back breccia on the crater floor and overturned material on the rim have usually been removed by erosion. At many of the impact structures in the United States, the erosional level is believed to be below the original crater floor, and, as such, the structures exposed are those associated with deformations which occur at moderate to deep levels below the original floor (e.g., Wilshire et al., 1972). Due to our incomplete understanding of cratering processes, it is usually difficult, when dealing with deeply eroded impact sites, to relate the features present to the original crater dimensions. As indicated in Fig. 3, it is still not certain how the lateral limit of the subsurface disturbance at any specific depth is related to the true diameter of the crater. This information becomes important when trying to reconstruct the original crater shape. Most parametric cratering studies deal with crater dimensions as a function of crater diameter. Therefore an accurate value for the original crater diameter is needed, but in most cases this value is only an estimate.

A simplification of one of the deformational styles that occur in some central uplifts is also indicated in Fig. 3. The presence of this steeply inclined, abrupt uplift of deep material which occurred during central uplift formation has been revealed by intensive investigation of several high-explosive experimental craters and one typical cryptoexplosion site (Roddy, 1968, 1976, 1877a). Since most other impact structures in sedimentary rock have not received as intensive investigations as Flynn Creek (Roddy, 1968), details of the structures at deep levels in the central uplifts of most of these sites are not available. However, field studies of terrestrial impact sites occuring in sedimentary rock indicate that generally the ratio of upward displacement to the diameter of the disturbance (which may be closely related to the apparent crater diameter) is approximately 1:10 (Offield and Pohn, 1977). For impacts occuring in crystalline rock this ratio is believed to be smaller. The actual sequence of events leading to central uplift formation is still only poorly known. The purpose of this study has been to examine in detail a portion of the central uplift of one impact crater in an effort to shed some light on this matter.

THE KENTLAND IMPACT SITE

The area of disturbed rock known as the Kentland, Indiana structure is the fourth largest impact site in the United States. Quarry operations over the last 70 years have exposed a complex assemblage of Ordovician and Silurian rocks near the center of the disturbance. Though quarry operations have accelerated recently, only about 0.3 percent of the entire structure has been exposed. For almost 100 years geologists who have visited Kentland have speculated as to the origin of this disturbance, which is in an area that is otherwise regionally tectonically stable. Only within the last 15 years has more intensive investigation brought to light the extent and nature of the structure (e.g., Gutschick, 1976; Tudor, 1971). Although various endogenetic origins have been proposed to account for the disturbance (Shrock, 1937; Gutschick, 1976 Tudor, 1971) these hypotheses still encounter the same objections as when they were applied to explain other similar impact sites (e.g., Roddy, 1968; Wilshire and Howard, 1972; French, 1968). On the other hand, interpretation and integration of available geophysical data, along with information gathered from quarry exposures and core drilling, allow for a consistent picture to be drawn of the Kentland site that compares favorably with other well-studied impact sites, such as Flynn Creek (Roddy, 1968, 1977b), Sierra Madera (Wilshire et al., 1972), Wells Creek (Wilson and Stearns, 1968), and

Decaturville (Offield and Pohn, 1977).

GEOLOGIC SETTING

The Kentland structure lies approximately four km east of the town of Kentland, Newton County, Indiana (Fig. 4). More than 700 m of Lower Ordovician through Pennsylvanian strata are known to be involved in the 12.5 km diameter disturbance. Almost all of the bedrock in this region is veneered with Pleistocene glacial till, which reaches a thickness of over 40 m in the ring depression. Several minor structural sags occur in the Kentland region (Tudor, 1971) but, for the most part, the regional bedrock is essentially flat-lying and consists of Lower Mississippian and Upper Devonian strata which dip gently to the southwest, toward the Illinois Basin. Figure 5, a tectonic map of the region surrounding the Kentland area, shows some of the basement features and other structures that are believed to be present. The Kentland area lies approximately 30 km SW of the crest of the Wisconsin (Kankakee) Arch, and the nearest known basement fault occurs approximately 80 km to the east. From this map it can be seen that with the presently available information the Kentland structure does not appear to be intimately associated with any known major tectonic feature, either in the sedimentary section or in the basement rocks.

In discussing the possibility of endogenetic origins for the Kentland site the writer does not go as far as Dietz (1963) in dismissing arguments involving regional tectonic

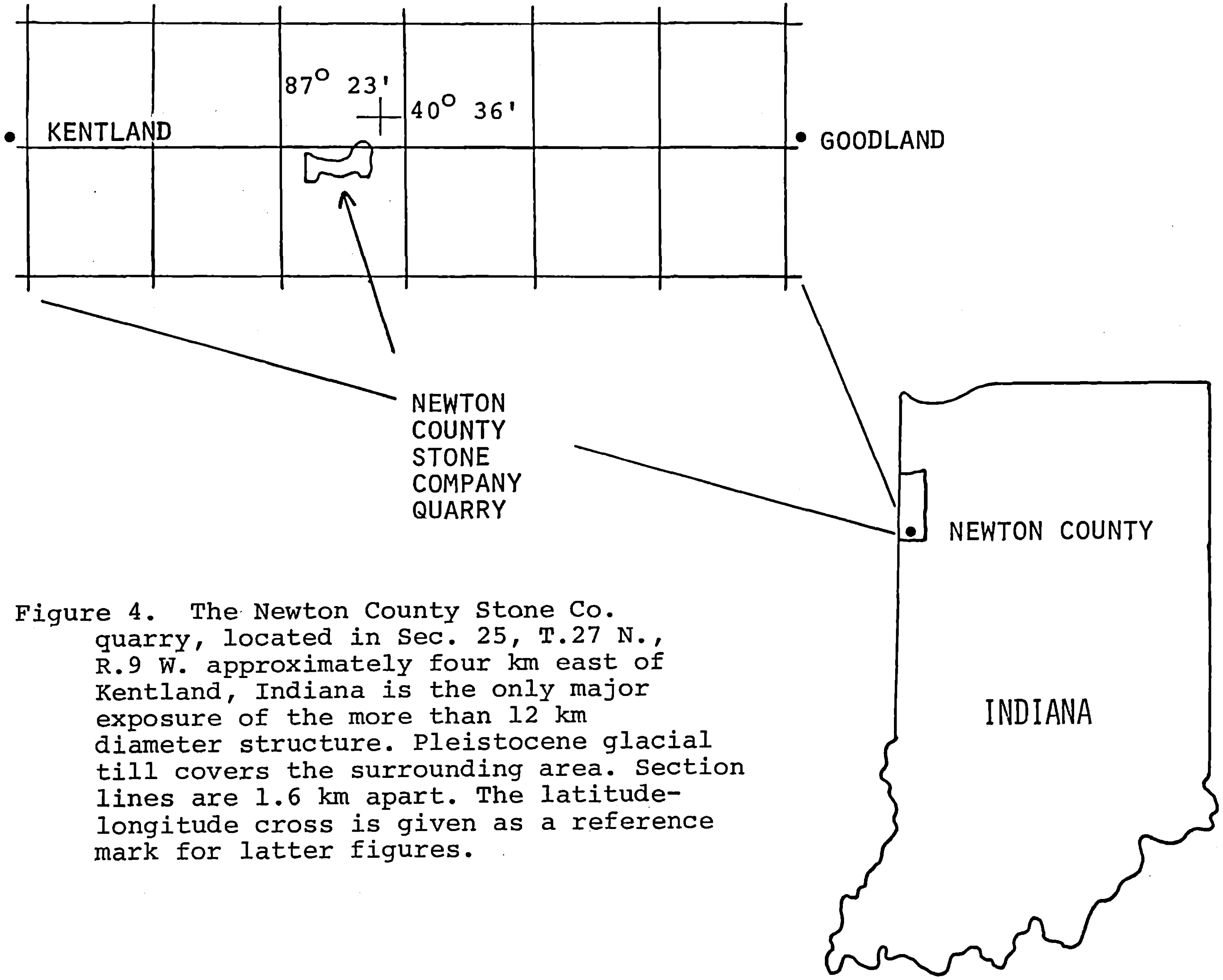
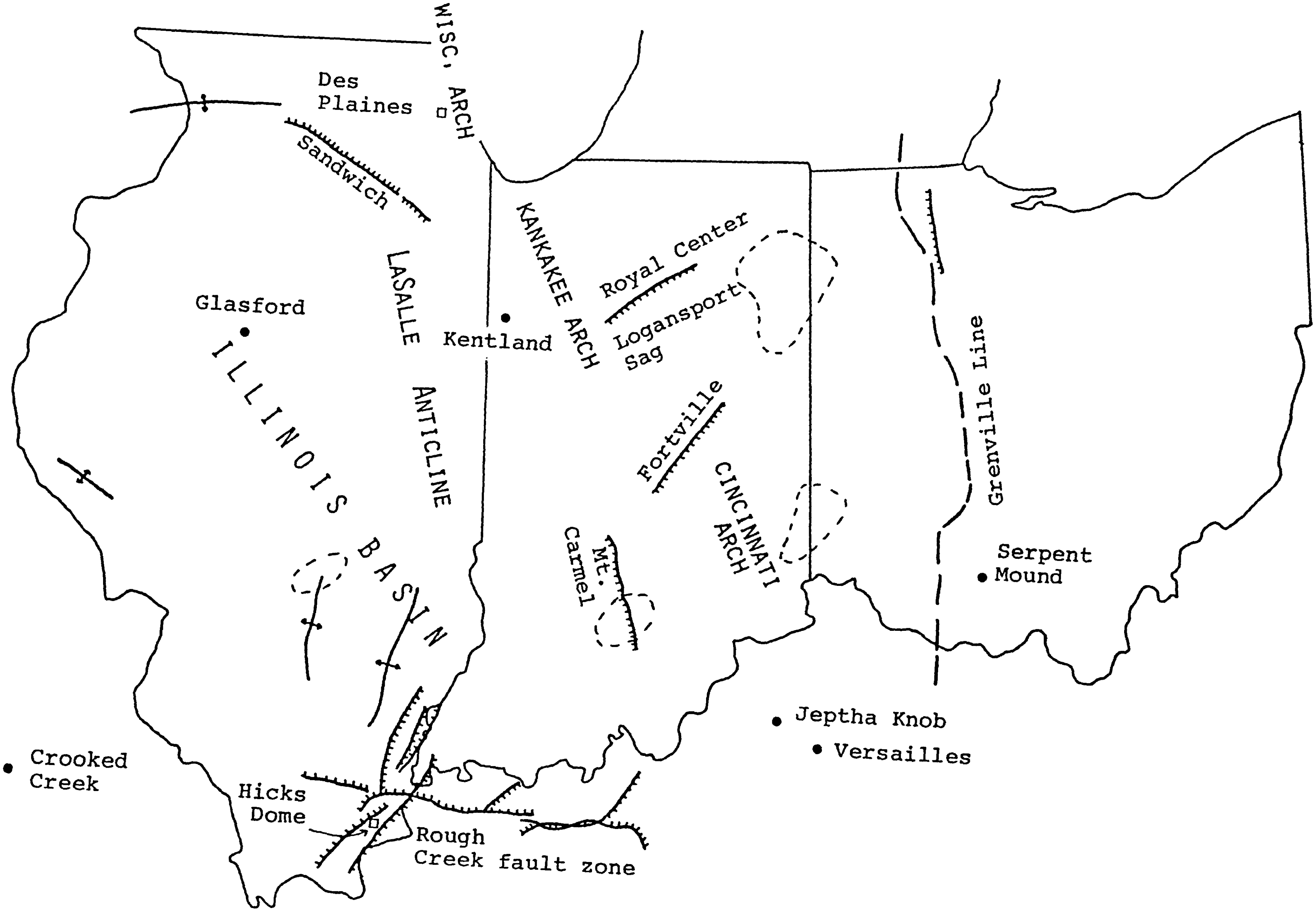


Figure 4. The Newton County Stone Co. quarry, located in Sec. 25, T.27 N., R.9 W. approximately four km east of Kentland, Indiana is the only major exposure of the more than 12 km diameter structure. Pleistocene glacial till covers the surrounding area. Section lines are 1.6 km apart. The latitude-longitude cross is given as a reference mark for latter figures.

Figure 5.

Map showing the location of several suspected impact sites and also the Des Plaines and Hicks Dome structures. Also shown are the major tectonic features of the region. Dashed areas indicate suspected occurrences of basaltic rock in the granite-rhyolite basement rock terrain. Modified from the Tectonic Map of the United States, 1962 and A.A.P.G. Mem. 15, 1971.


WISC. ARCH
Des Plaines
Sandwich
LASALLE
ANTICLINE
Glasford
ILLINOIS BASIN
Kentland
KANKAKEE ARCH
Royal Center
Logansport Sag
Fortville
CINCINNATI ARCH
Mt. Carmel
Grenville Line
Serpent Mound
Jeptha Knob
Versailles
Crooked Creek
Hicks Dome
Rough Creek fault zone

trends as when he stated, "What, for example, could be more lonesome than the Kentland disturbance. There is a great geologic literature about lineaments and trends, but often the points correlated seem as random as the stars in the sky". On the other hand, it is hard to reconcile arguments such as those presented by Tudor (1971) which involve the intersection of the Sandwich and Mt. Carmel faults, the alignment of the contours and structural trends of the Illinois Basin and the Logansport Sag, and a series of east-west magnetic highs as being a possible cause of the Kentland structure. Since the Kentland site shares many of the same features that are present at other 'cryptoexplosion sites' throughout the world, the chance that all of these structures owe their origin to similar sets of fortuitous tectonic circumstances is indeed slim. Many of the problems encountered in arguing for endogenetic origins for these structures can be solved by employing the impact hypothesis.

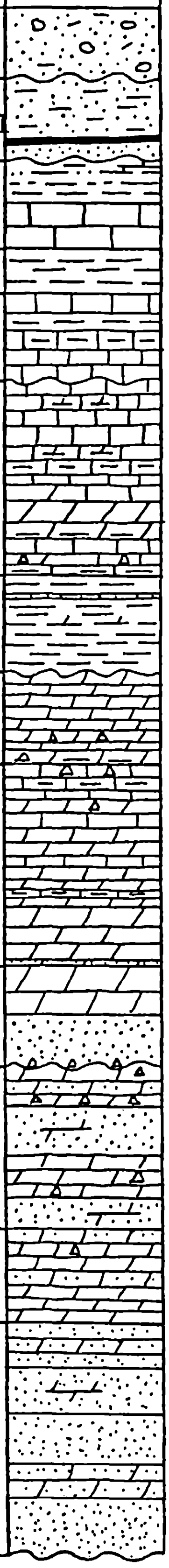
STRATIGRAPHY

In the vicinity of the Kentland structure, the Precambrian basement occurs at a depth of approximately 1680 m, 1460 m below sea level (Bond et al., 1971). Unconformably overlying this terrain of granite and rhyolite is a 1645 m thick succession of Paleozoic marine sandstone, carbonate, and shale formations which make up the local stratigraphic sequence (Fig. 6). The majority of the Cambrian sediments are represented by the 1015 m thick Potsdam Sandstone

Figure 6.

Stratigraphic sequence in the vicinity of Kentland. Maximum thickness of a Group or Formation recognized to date in the Newton County Stone Co. quarry is given (taken from Gutschick, 1976) along with its regional thickness (taken from Bond et al., 1971).

System	Series	Mega-group	Stage or Group	Thick-ness m	Symbol	Formation
Pleis.			Wisc.	53		Wisconsin till
PEN		KNOBS			P	Mansfield Sh.,Ss.,coal
MIS.			Bord.	60	Mb	New Providence Sh.
						Rockford Ls.
DEV.				46	DM	New Albany Sh.
		HUNTON		11	D	Traverse
						Detroit River
SILURIAN	NIAG					Kokomo Ls.
						Wabash Ls.
						Louisville Ls.
	ALEX			76/91	Ss	Salamonie Dol.
					Sb	Brassfield Ls.
ORDOVICIAN	CINN		Maquo-keta	24/91	Om	Brainard Sh.
						Scales Sh.
	CHAMPLANIAN	OTTOWA	Gal-ena	56/56	Og	Wise Lake Dol.
						Dunleith Dol.
			Platte-ville	72/72	Op	Quimsby Mill Ls.
						Nachusa Dol., Ls.
						Grand Detour Dol.,Ls.
						Mifflin Ls., Dol.
						Pecatonica Dol.
			Ancell	19/30	Oj	Joachim Dol.
				24/38	Osp	St. Peter Sandstone
	CANADIAN	KNOX	Prairie du Chien	38/61	Osh	Shakopee Dol.
				70		New Richmond Ss.
						Oneta Dol.
						Gunter Ss.
UPPER CAMBRIAN	CROIXAN			130		Eminence Formation
						Potosi Dol.
		POTSDAM		1015		Franconia Formation
						Ironton Ss.
						Galesville Ss.
						Eau Clare Formation
						Mt. Simon Ss.
Precambrian						



Megagroup. The Cambrian-Ordovician Knox Dolomite Megagroup is composed of 266 m of dolomite and sandstone which confomably overlie the Potsdam Megagroup. The upper member of the Knox, the Shakopee Dolomite, is the oldest unit exposed in the quarry. Unconformably overlying the Knox are 123 m of the Ordovician Ottawa Limestone Megagroup. The relatively pure Platteville and Galena carbonates that comprise this Megagroup are the rocks presently being quarried for crushed stone purposes. Eighty m of Upper Ordovician Maquoketa shale disconformably overlie the Middle Ordovician carbonates and conformably underlie 146 m of Silurian dolomite. Approximately 50-60 m of limestone and shale of Devonian and Mississippian age comprise the bedrock in the Kentland area. Disturbed sandstone, shale, and coal of presumably Early Pennsylvanian age are preserved in the ring syncline of the Kentland disturbance. Unconformable and undisturbed Pennsylvanian sediments occur in structural lows elsewhere in the surrounding region (Gutschick, 1976).

The age of the Kentland disturbance has so far been bracketed only between post-Early-Pennsylvanian and pre-Pleistocene. Several periods of erosion and deposition of sediments have occured in the mid-continent during late Paleozoic, Mesozoic, and Cenozoic time (Wilman et al., 1975) making it difficult to estimate the thickness of sediments at Kentland at the time of impact. For example, the St. Peter sandstone outside the area of disturbance has a present regional depth of 450 m. Assuming that the maximum amount of known post-Mississippian sediments found in the Midwest was present at the time of impact, the St. Peter Sandstone could have been at a maximum depth of 2400 m below the surface (Damberger, 1975). The possible presence of an additional 1950 m of overlying sediments at the time of impact should be considered an upper limit only. By scaling from other impact sites, such as Flynn Creek, the presence of an additional two km of overlying sediments would not produce the types of deformation seen at Kentland. Such deformations would have been confined to the overlying sedimentary rock, which has been eroded away. At the present erosional level, little deformation should be seen. It therefore appears probable that most of these overlying sediments were already eroded away at the time of impact and that post-event erosion has been on the order of 300 m or less. However this point is still a matter of contention and more field data will be needed in order to resolve this question.

Presented below are descriptions of the formations present in the Kentland quarry. The stratigraphic nomenclature follows that used in the state of Illinois and by Gutschick (1976).

Shakopee Dolomite

The oldest unit exposed in the quarry, with a recognized thickness of about 38 m. The dolomite is a light gray, argillaceous to pure and very fine grained. Also present are thin beds of medium grained sandstone, buff siltstone and green shale partings. Oolitic chert nodules and algal stromatolites are also found. The layers are usually irregular and thin-to-medium-bedded.

St. Peter Sandstone

The St. Peter Sandstone rests on a surface that is a result of karst topography developed on the underlying Shakopee Dolomite. The Kress Member, the basal unit of the St. Peter Sandstone, consists of an accumulation of residual materials, mainly green shale, chert nodules, oolites, and sand grains (Wilman et al., 1975). The St. Peter consists of fine-to-medium-grained, well-rounded, frosted quartz grains. The sandstone is only weakly cemented. In quarry exposures, bedding is difficult to recognize. Gutschick (1976) estimates about 24 m of this sandstone is present in the quarry.

Joachim Dolomite

This unit consists of light gray, very fined grain to aphanitic dolomite. Some silty to sandy dolomite is also present. The layers are medium-to-thick-bedded with some very thin shale partings in between. Approximately 19 m of this unit have been identified in the quarry.

Platteville Group

This dominately carbonate unit consists of five formations with a total thickness of about 72 m. The Hennepin Member of the basal Pecatonica Formation consists of white dolomitic sandstone with interbedded green shale. This unit is distinctive because weathering of pyrite-marcasite concretions produces rusty limonite streaks

(Gutschick, 1976). The rest of the Pecatonica is mainly brown, medium-to-thick-bedded, vuggy dolomite. Thin wavy discontinuous shale partings and some chert are also present. The Pecatonica is separated from the overlying Mifflin by a sharp contact, that is probably a regional diastem (Wilman et al., 1975). The Mifflin is a gray, very-fined grained, thin-bedded limestone with some dolomite. Gray to green shale partings are present. The Grand Detour consists of slightly argillaceous to pure, very fine grained, dolomite mottled limestone with brown shale partings. The overlying Nachusa is similar in appearance and consists of fine-grained, vuggy dolomite which is thick bedded. The top of the Platteville is made up of the Quimbys Mill dolomite and limestone, which are light brown, very fine grained with brown shale partings. The Platteville Group is transitional into the overlying Galena Dolomite.

Galena Dolomite

Approximately 56 m of this unit have been recognized in quarry exposures. The dolomite and dolomitic limestone making up this unit are dominately light brown, pure to argillaceous, medium-to thick-bedded. Some chert nodules are present near the base of the unit. The contact with the overlying Maquoketa Shale is a sharp disconformity, marked by a ferruginous, pitted surface.

Maquoketa Shale

This shale unit has a regional thickness of approximately 91 m, however only about 24 m, consisting of the lower and upper portions have been recognized in the quarry.

The lower portion consists of dark gray to dark brown, silty shale with interbedded siltsone. The upper portions are argillaceous, partly dolomitic and lighter in color than the lower portion.

Brassfield Limestone

The basal portions of this unit consist of wavy, thin-bedded, cherty dolomite. Also present is thick-bedded, glauconitic dolomite, and crinodial limestone with green shale partings.

Salamonie Dolomite

The Salamonie Dolomite lies transitionally above the Brassfield Limestone and is an off-white, dolomitic limestone with green shale partings. The total thickness of the Silurian rocks in the quarry is estimated at about 76 m (Gutschick, 1976).

New Albany Shale

No Devonian strata have been recognized in quarry exposures, but Gutschick (1976) has found New Albany Shale clasts in isolated fault breccia occurences.

PREVIOUS GEOLOGICAL STUDIES

Geologic interest in the disturbed rocks at Kentland began with the discovery of limited outcrops by J. Collet and G. K. Greene in 1881 (Collet, 1883). Quarry operations apparently commenced soon after this, as the first reference to open pit quarries was made by Gorby in 1886. Although Greene correctly identified recovered fossils as being of

Ordovician age, controversy about the age of the rocks continued until 1921 when Foerste confirmed Greene's original fossil age assignments. This confusion resulted from the mistaken belief that the Kentland structure was one of a series of 'quaquaversal domes' or reefs of Silurian age which occur in northern Indiana. Work by Cumings and Shrock (1928) identified more Ordovician fossils and put to rest speculation that the Kentland structure had the same origin as other 'domes' in Indiana by indicating the structural dissimilarities between the Silurian reefs and the Kentland disturbance. They stated that the rocks showed "...considerable faulting and crumpling..." and as such the origin of the structure may be the result of cryptovolcanic action". Two more reports by Shrock and Malott (1930, 1933) gave additional accounts of the quarry structure, stratigraphy, and paleontology. Studies by Shrock (1937) and Shrock and Raasch (1937) were the most detailed accounts to that time of the Kentland site.

Shrock (1937) lists seven possible hypotheses concerning the origin of the structure, including the meteorite impact hypothesis. Shrock ruled out the impact possibility by stating that no meteorite fragments had been located, no indication of any thermal metamorphism presumably associated with the impact could be found, and he felt that the magnitude of the disruption was too large to be the result of an impact event. Instead he opted for Bucher's (1936) 'cryptovolcanic' explanation citing that at Kentland, "The shattered rocks indicate that the deforming stresses were probably created by the sudden release of pent-up forces, perhaps by explosion". Also the absence of any volcanic material or thermal activity was in accord with Bucher's list of 'cryptovolcanic' features.

The next substantial geologic studies were conducted by Gutschick (1961, 1971, 1972, 1976). These reports have firmly established quarry stratigraphy and structure, and since Gutschick has been actively mapping new exposures as quarrying activity continues, much valuable information concerning the geometry of the quarry structures has been gathered. Gutschicks' studies have laid the groundwork for a large part of this investigation.

Gutschick (1976) lists several hypotheses concerning the origin of the Kentland site including, a) the 'cryptovolcanic' theory, b) the intersecting fault hypothesis, c) diapirism, d) a solution collapse of an evaporite dome, and e) the impact hypothesis. While Gutschick apparently wants to continue using the 'crypto-explosion' label for the structure, he states, "While geological confirmation is equivical, structural and mineralogic evidence as reported favors meteorite impact as the cause;

GEOPHYSICAL STUDIES

Several geophysical studies of the Kentland disturbance have been conducted and these have shed considerable light on the form and areal extent of the structure. An aeromagnetic survey flown in 1948 by the U. S. Geological Survey in the vicinity of the Kentland site showed that no unusual susceptibility contrast is associated with the structure (Joesting and Henderson, 1948) and this finding was confirmed by a later localized ground magnetic survey (Lucas, 1952). However the 1952 survey indicated that a positive gravity anomaly did coincide with the disturbance and this finding was the basis for the more thorough and detailed geophysical study undertaken by Tudor (1971).

This latter geophysical survey consisted of shallow seismic reflection and refraction studies, a shallow bedrock drilling program in conjunction with the seismic survey, and a detailed gravity study involving 2600 metered stations covering an area of about 184 km^2 (approximately a square 13.5 km on a side). The results of the refraction survey and drilling program provided information on the bedrock topography and geology which will be presented in a later figure. Although Tudor's drilling program brought to light much new geologic information, the compilation of a detailed bedrock geology map of the whole structure must await further drilling. The best geologic control exists for the Silurian and Ordovician strata on the flanks of the central uplift due to quarry exposures and more drilling information.

The gravity survey and subsequent modelling done by Tudor (1971) provides information on the extent and form of the total disturbed area. The Bouger gravity map for the Kentland area is presented in Fig. 7. A 3.5 to 4.0 milligal positive gravity anomaly is centered near the middle of the disturbance. An encircling 1.0 negative anomaly, at a radius of 3.2 km from the center of the structure, is believed to represent a ring depression or moat fault system within which Pennsylvanian strata are preserved. Two-dimensional gravity modelling suggests that where the negative anomaly is the greatest, up to 90 m of Pennsylvanian rock could be present (Tudor, 1971). An outer encircling positive gravity anomaly of 0.5 milligals occurs at a radius of 6.2 km and is thought to be a low relief, structurally high area that is a ring anticline and which represents the outer limit of the disturbance. These gravity features are better displayed on the map of the residuals from the 6th degree surface (Fig. 8).

From his study, Tudor (1971) was not convinced of an exogenetic origin for the Kentland structure. He was concerned with the problem of explaining the origin of the 3.5 to 4.0 milligal anomaly coincident with the central uplift. He considered that the structure did not conform to the geophysical model of simple meteorite impact craters, such as Canadian structures described by Innes (1961). Instead he invoked a "...subterranean source for the

Figure 7.

Bouger gravity map of the Kentland region. The Newton County Stone Co. quarry is indicated by the blackened area near the center of the figure. Contour interval is 0.5 milligals. Modified from Tudor (1971). Section lines are 1.6 km apart.

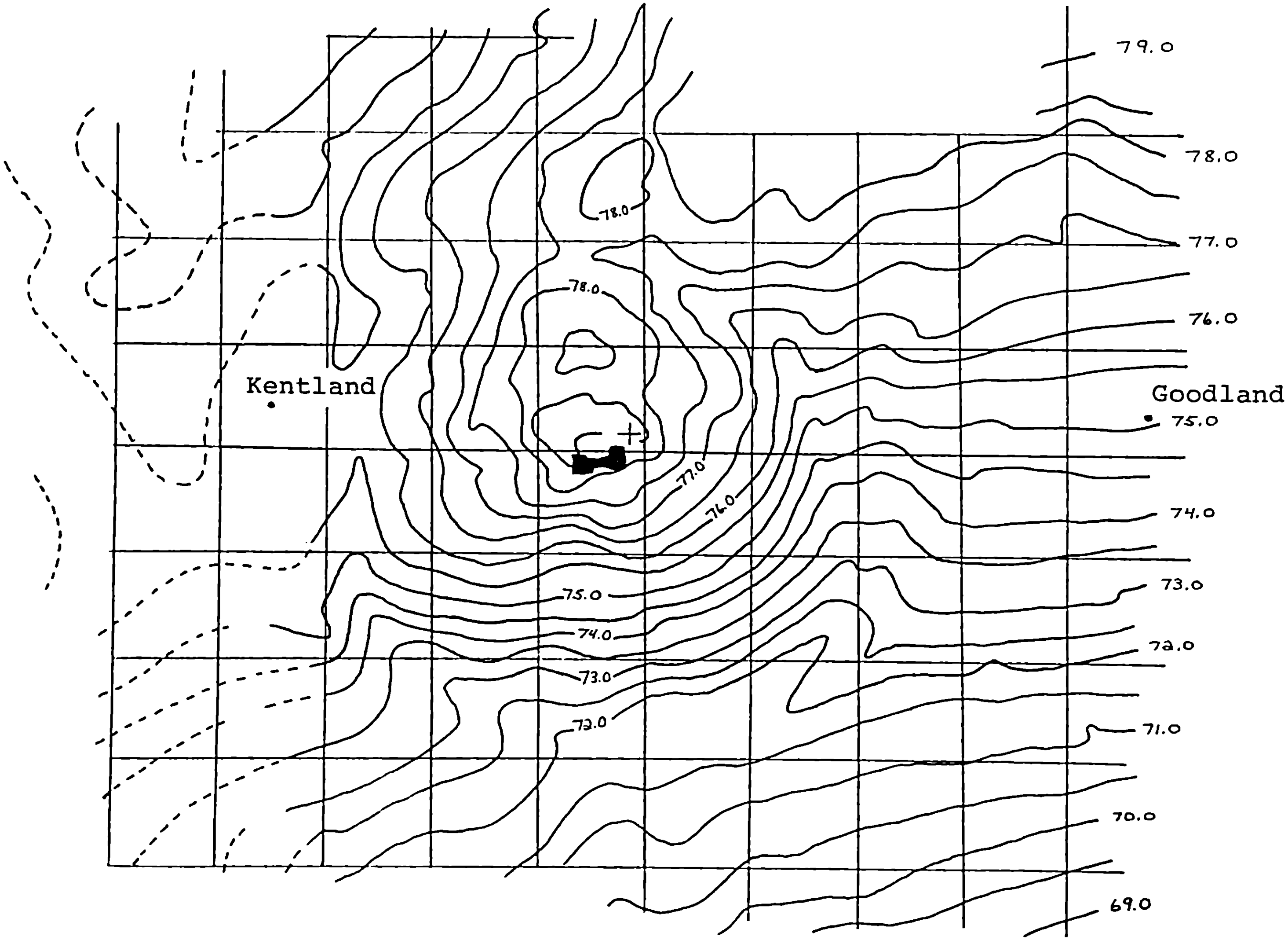
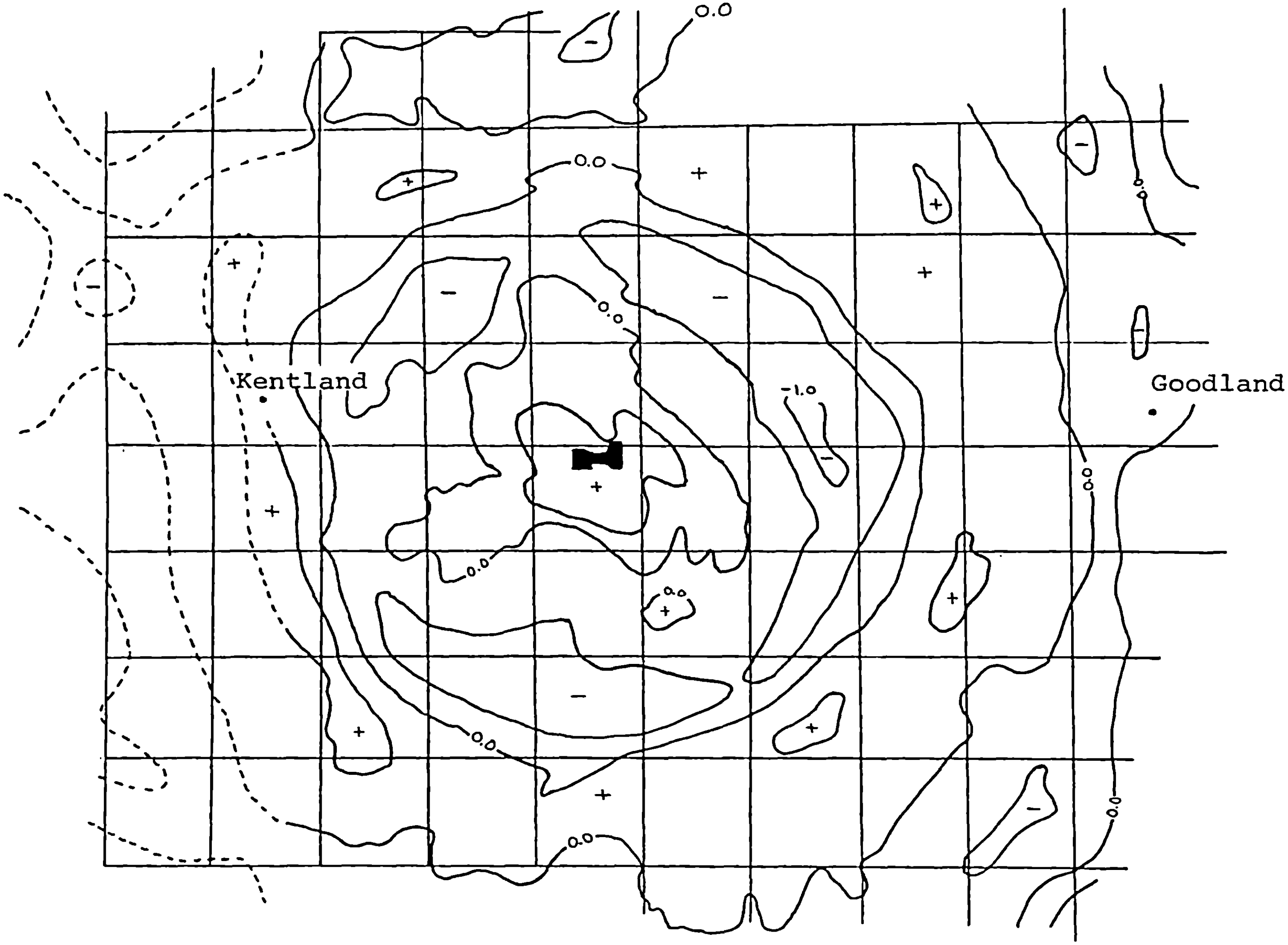

79.0
78.0
77.0
76.0
Kentland
Goodland
75.0
74.0
73.0
72.0
71.0
70.0
69.0
78.0
78.0
77.0
76.0
75.0
74.0
73.0
72.0

Figure 8.

Contours of the residuals from the 6th degree surface. Major gravity features are apparent in this representation. Central gravity positive is surrounded by a negative gravity anomaly caused by the ring depression which is in turn surrounded by a small gravity positive at a radius of 6.2 km from the center of the structure. Contour interval is 0.5 milligals. Modified from Tudor (1971).


Kentland
Goodland
0.0
-1.0
+
−

deformation..." involving the uplift of 600 to 900 m of basement rock (Tudor, 1971). Presumably this elevator-type uplift would have affected the overlying 1680 m of Paleozoic cover and produced the 550 to 600 m uplift that is present at the center of the Kentland structure. The mechanism to produce such an uplift was not stated but instead the reader was referred to Jamieson's (1963) work on natural analogues that could produce local pressures of tens of kilobars.

Apparently Tudor was not aware that small positive gravity anomalies exist at other suspected impact sites in sedimentary rock (e.g., Wells Creek: Wilson and Stearns, 1968) and basement uplift is not indicated at this structure. A comparison of the gravity signatures of a Canadian crater, which displays a negative gravity anomaly, and the Wells Creek structure shows the marked dissimilarity in the gravity anomalies due to different target rock and crater structures at each site (Fig. 9). The Canadian crater (Deep Bay, Saskatchewan) is one of the craters discussed by Innes (1961). One of the major arguments Tudor uses in supporting his conclusion of an endogenetic origin for Kentland comes from Innes' article, which dealt exclusively with craters developed in crystalline rocks of the Canadian Shield. According to Tudor (1971), "The gravity positive is an obstacle to interpretations which attribute the cause of the Kentland deformation to meteorite impact. The mass excess implied by the gravity is opposite to what would be expected from meteorite impact in an area of limited

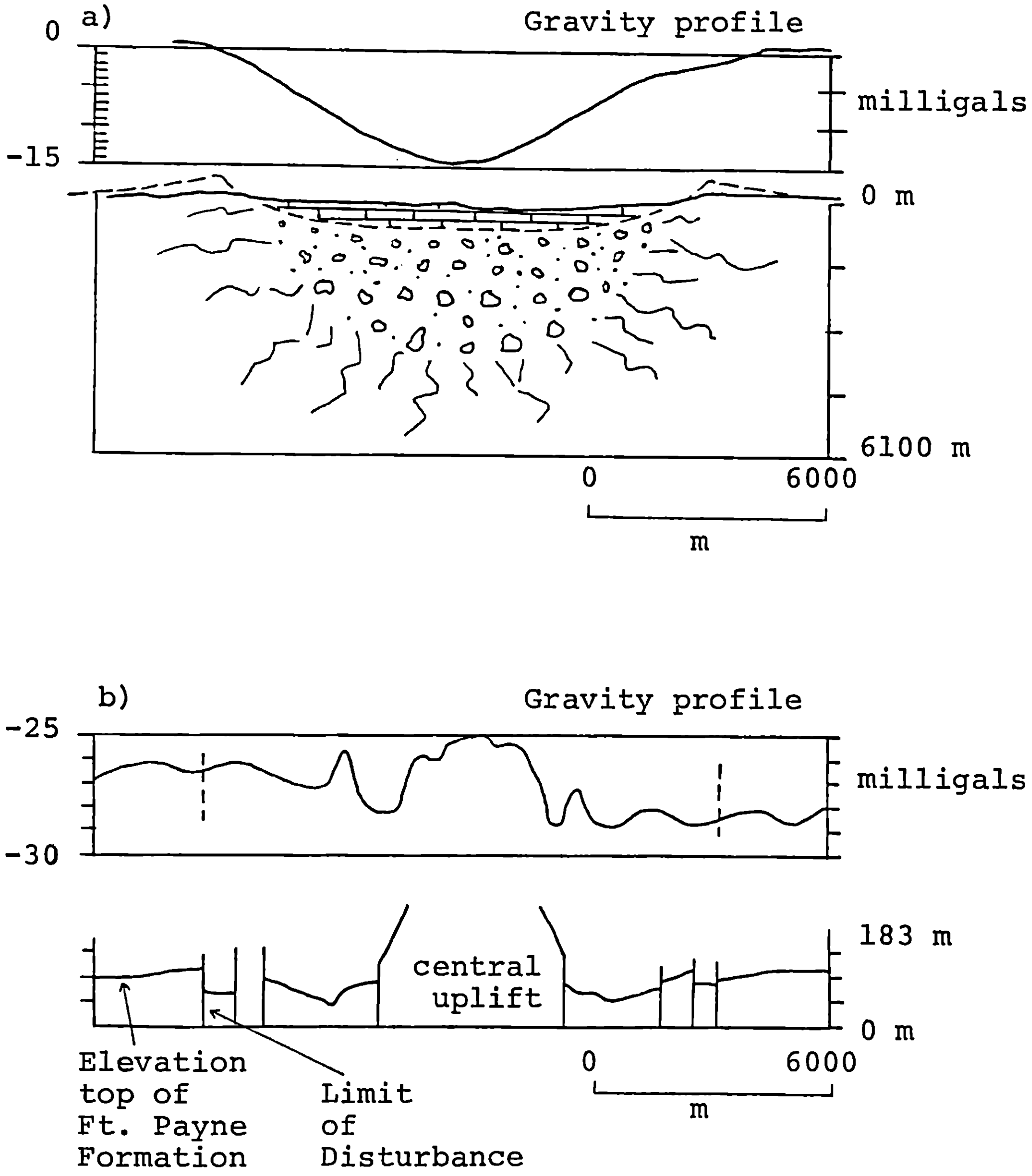


Figure 9. Gravity features of two suspected impact structures. a) Deep Bay, Saskatchewan, a crater developed in crystalline rocks. Crater filling sediments and brecciated, fractures rock beneath the floor of the crater combine to produce the negative 15 milligal anomaly centered in the middle of the structure (from Innes, 1961). b) Wells Creek, Tennessee. Impact structure developed in sedimentary rock. Uplift of dense Ordovician and Cambrian carbonates into the center produced a positive 3.0 milligal gravity anomaly, similar to the anomaly found at Kentland (from Wilson and Stearns, 1968).

deformation". However, approximately 500 km south of Kentland lies the Wells Creek structure which displays many of the same features found at Kentland. A geophysical study of Wells Creek has shown that a similar positve gravity anomaly of 3.0 milligals is associated with the central uplift (Wilson and Stearns, 1968). Furthermore, several geophysical investigations of other suspected impact sites in sedimentary rock have shown that small positive gravity anomalies are associated with the central uplifted regions (Milton et al., 1972; Seeger, 1966). Therefore, one of Tudor's main objections to an impact origin can be resolved by confining such comparisons to structures which are developed in similar geologic environments (i.e., sedimentary rocks). Gravity characteristics of craters formed solely in crystalline rocks are governed by a different set of conditions and so arguments based on comparisons such as Tudor's are generally not valid.

The gravity study conducted by Tudor led him to believe that the basement was involved with the Kentland structure. Because of this Tudor states, "The interpretation of basement uplift of a magnitude similar to or larger than the uplift visible at the surface does not support the impact hypothesis". Since no deep drilling has ever been done to either refute or confirm the presence of uplifted basement rock, and because of the general ambiguity involved in the modelling of gravity features, alternatives to Tudor's uplifted basement hypothesis can be reasonably developed. Assuming possibly more realistic density contrasts, the 3.5 to 4.0 milligal positive anomaly can be accounted for in the sedimentary section alone without postulating basement involvement. Thus, the positive gravity feature described by Tudor (1971) could be explained by the uplift of the more dense Upper Cambrian to Middle Ordovician carbonates into the core of the structure.

Apparently no in situ or laboratory density measurements of bedrock samples were made during Tudor's study. Instead Tudor reports that he used density values derived from gamma-gamma density logs published by McGinnis (1966). Tudor averaged the different density determinations reported by McGinnis, which encompassed more than 1500 m of sedimentary rock. Another factor which Tudor took into account in his density assumption was a point taken from Innes' (1961) study of Canadian craters. Innes stated that beneath the floors of several Canadian craters, fractured and brecciated rock occurred which accounted for some of the low density material that produced the negative gravity anomalies. Tudor felt that similar fracturing occurred at Kentland and this would lead to lower density values for the rock in the central uplifted column. Combining this assumption with a lump-sum average of the density values derived from the logs (McGinnis, 1966), Tudor arrived at a value of 2.5 cgs units which he used to represent the entire sedimentary section at Kentland (excluding the glacial till).

Later on in this study the writer proposes that near the middle of the Kentland uplift a megabreccia core is present, which grades into more coherent structural blocks proceeding radially away from the center. From the writer's field work in the quarry much evidence of faultying, brecciation, and fracturing of the rock was noted. However, it does not appear that a large-scale increase in the porosity of the rocks (which would have a major affect on densities) has taken place as postulated by Tudor. Where brecciation has occurred, the fragments are in most cases well cemented by recrystallized carbonate material. The rocks that have been fractured in situ (monomict breccias) are also still coherent, with mylonitic matrix firmly cementing the clasts. Although no direct observations of the assumed megabreccia core have been made, it is the writers' feeling that this material, which is probably in a jumbled chaotic arrangement, is also firmly bonded together by carbonate cement. Studies of other impact sites in sedimentary rock give no indication of any major decrease in the densities of rock in the central uplifted column (e.g., Wilson and Stearns, 1968).

Laboratory density measurements were made on 15 samples of the Shakopee, Joachim, Platteville, and Galena carbonates and on seven samples of the monomict and polymict breccias. Values for the carbonates ranged from 2.61 to 2.76 cgs units with the average at about 2.72. The breccias averaged slightly less, at 2.58-2.60 cgs units. Although no samples were available of the Lower Ordovician or Upper Cambrian carbonates (mainly dolomites), their densities are believed to be in the range 2.70 or greater. At Wells Creek, the Knox Group has a density approaching 2.77 (Wilson and Stearns, 1968). Using these measured densities, a simplified calculation was carried out to determine the gravity effect caused by the uplift of these denser rocks. An idealized diagram of the mass distribution of the rocks in the central uplift at Kentland is presented in Fig. 10. Arguments supporting such a subsurface structure are presented later. The Middle Ordovician to Upper Cambrian carbonates in the central uplift are divided into a series of thin horizontal disks. The density contrast used for each disk is indicated in the figure. The gravity effect caused by each disk is calculated using the formulas given by Nettleton (1942) and others. The effects for all the disks are summed to give the gravity anomaly in milligals for the particular mass distribution chosen. Several different models were tried and the gravity effects ranged from a positive 2.97 to 3.40 milligals. Since much information is still lacking about the subsurface shape of the central uplift, these simplified calculations should be viewed as first approximations only.

Although models such as the one presented in Fig. 10 produce gravity anomalies similar to what is observed, attempts to fit the observed Bouger gravity profiles to profiles calculated by the proposed models has not met with the same success. Such calculated profiles tend to drop off in value more rapidly away from the center of the structure than do the observed profiles. Better mass

Figure 10.

Diagrammatic representation of the mass distribution in the central uplift at Kentland. Ordovician and Cambrian carbonates are divided into a series of thin horizontal disks, with a density contrast indicated for each disk. The model density chosen for the carbonate rocks in the central uplift is 2.7 cgs units. The glacial drift is approximated at 2.0. The Cambrian sandstones and Precambrian basement rocks are not considered in this model. A calculation using the illustrated mass distribution and density contrasts results in a positive 3.2 milligal gravity anomaly.

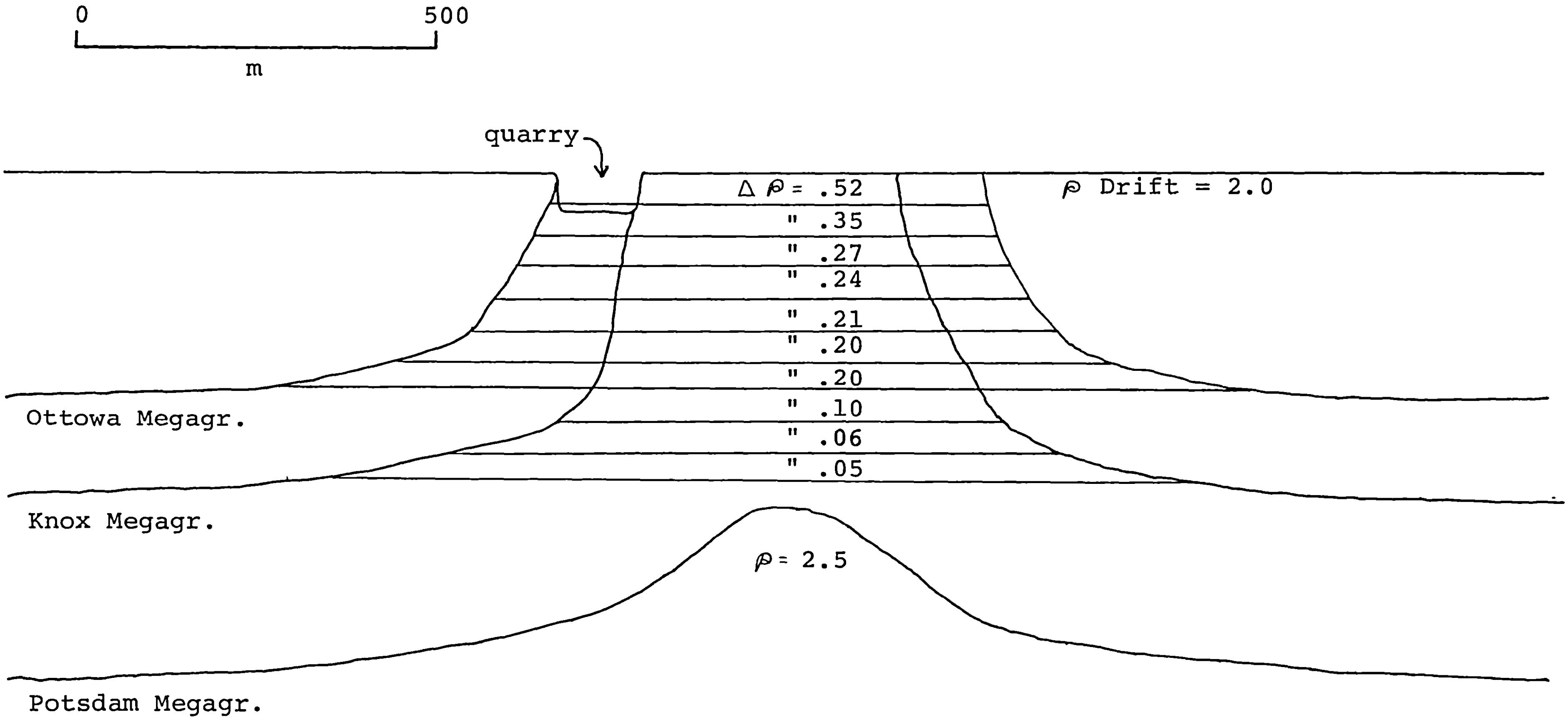
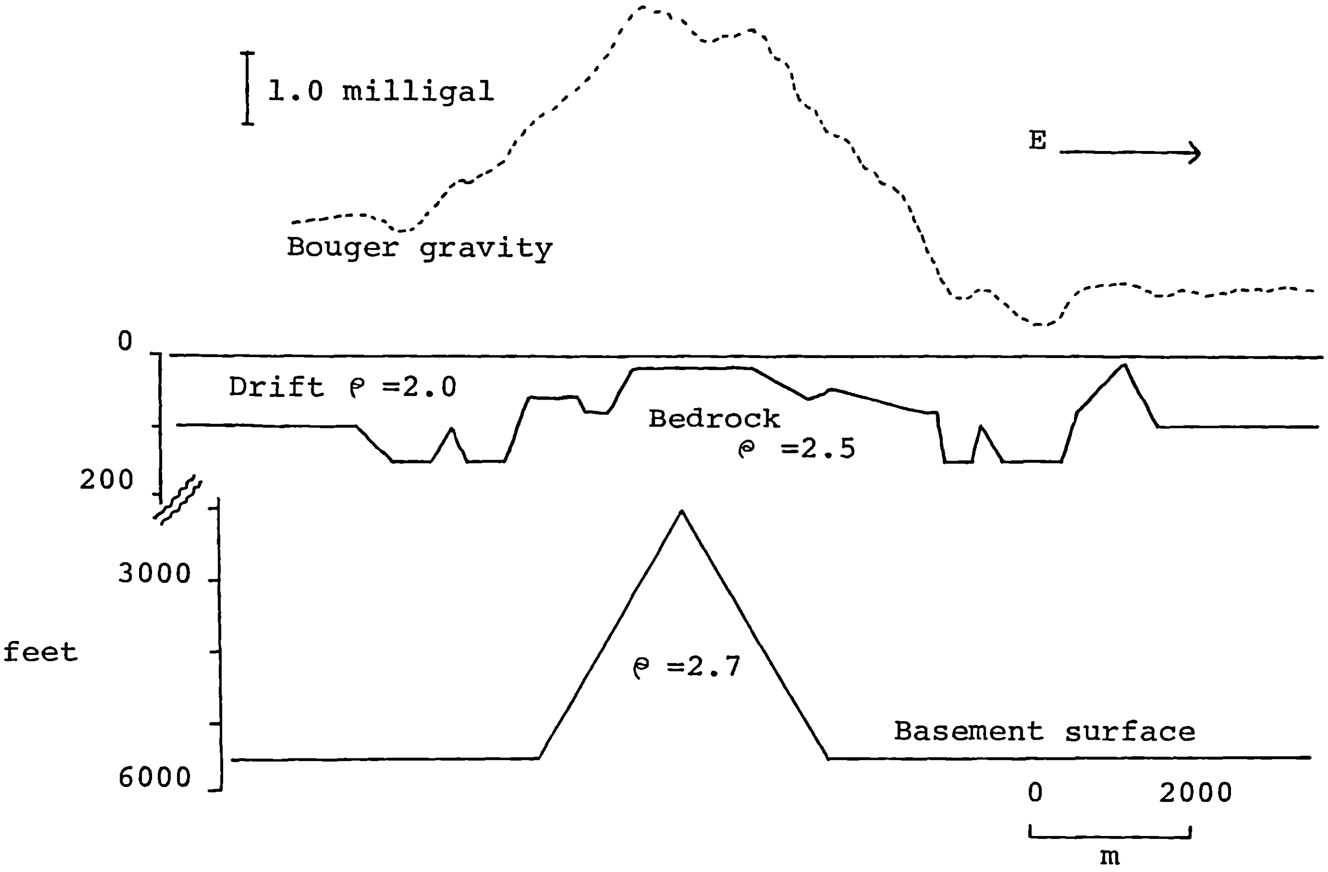

0
500
m
quarry
Δ ρ = .52
" .35
" .27
" .24
" .21
" .20
" .20
" .10
" .06
" .05
ρ Drift = 2.0
Ottowa Megagr.
Knox Megagr.
ρ = 2.5
Potsdam Megagr.

Figure 11.

Mass distribution and densities used by Tudor in his study. The +3.5 gravity anomaly is postulated as being the result of 600-900 m of uplift of basement rock (taken from Tudor, 1971).


1.0 milligal
E
Bouger gravity
0
Drift ρ =2.0
Bedrock
ρ =2.5
200
3000
feet
ρ =2.7
Basement surface
6000
0
2000
m

distribution models must await further deep drilling in the central uplift. However, the writer still believes that the gravity anomaly described by Tudor can be accounted for solely due to the uplift of denser sedimentary rocks into the middle of the Kentland structure; there is no a priori reason to involve the basement rocks.

A consideration of the results from other impact sites also indicates that little, if any, basement involvement need be present at Kentland. At the 6.0 km diameter Decaturville, Missouri structure, Offield and Pohn (1977) have postulated that the transient cavity penetrated approximately 550 m of Paleozoic cover to briefly expose the basement surface. They note that isolated Precambrian ejecta blocks lying on the present ground surface and other structural evidence support this hypothesis. However deep drilling near the center of the structure indicates little (50 m or less) general uplift of the basement surface. At Kentland, where the Paleozoic cover is some three times thicker, it seems improbable that the transient cavity would have excavated down to the level of the Precambrian basement. This is consistent with the writer's contention that the positive gravity anomaly at Kentland did not originate due to 600-900 m of basement uplift as proposed by Tudor (1971).

STRUCTURE

A) Ring Anticline

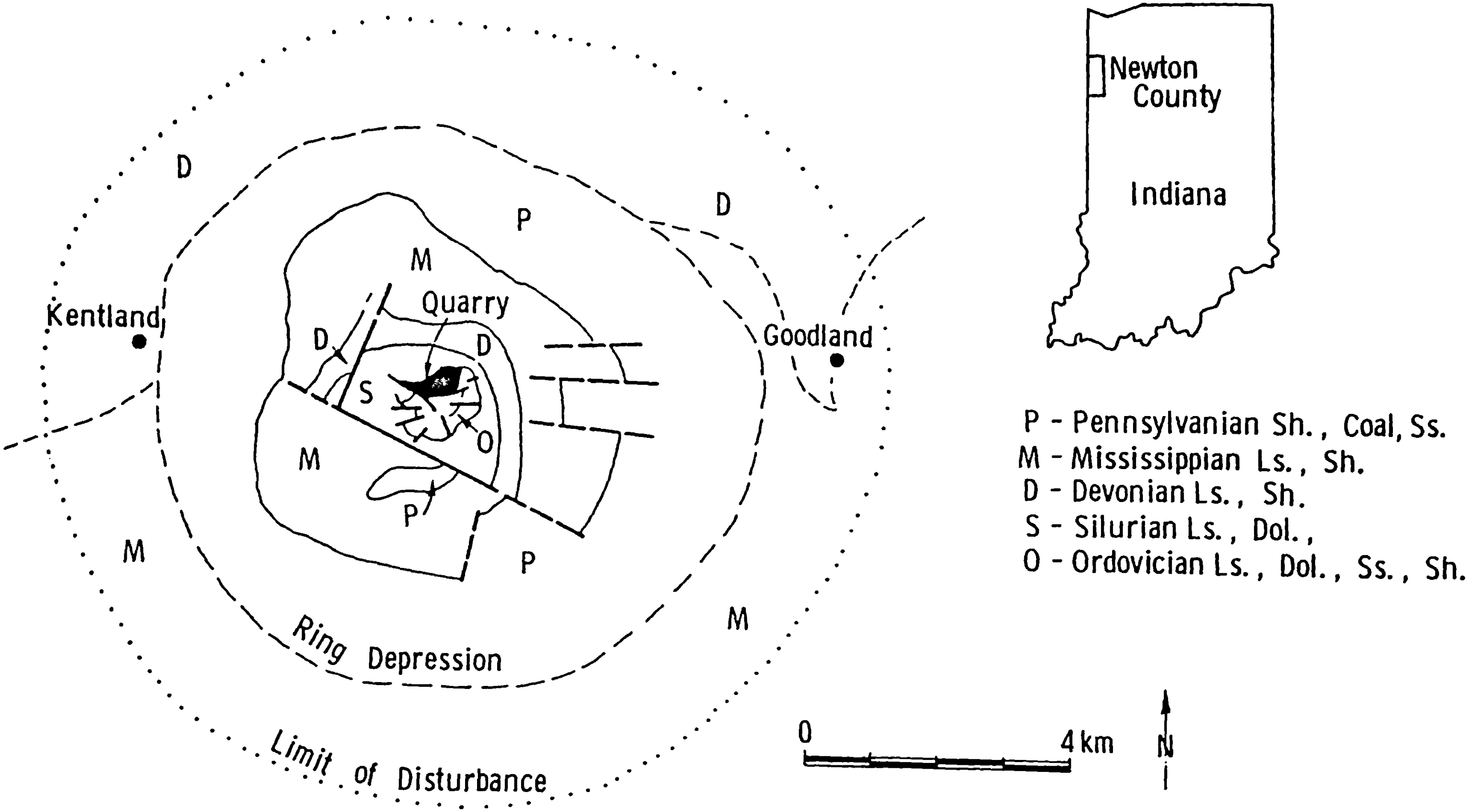
Very limited information exists for this part of the Kentland structure. Two water wells (total depth, 72 and 328 m) near the townsite of Goodland, Indiana indicate a structurally high area (approximately 15 m). This area is coincident with the small positive (0.5) milligal anomaly determined from Tudor's (1971) gravity survey. Presumable a structural high of this type surrounds the Kentland disturbance at a radius of 6.2 km from the center of the structure, and separates the disturbed area from the surrounding flat-lying regional bedrock (Fig. 12).

B) Ring Depression

Most of the information derived from geologic studies about the overall configuration of this element of the Kentland structure has been presented above. This information was derived from several deep holes (total depth, 73, 93, and 158 m) drilled by the Indiana Geological Survey in the area surrounding the central uplift (Gutschick, 1976) and the shallow (generally 10-25 m) bedrock drilling and gravity survey of Tudor (1971). Compared to better exposed impact sites (e.g., Sierra Madera and Wells Creek), the bedrock geology map presented in Fig. 12 is lacking in detail, particularly for the area surrounding the Ordovician core. A hint of the possible true complexity of the area comes from the negative results of Tudor's seismic reflection study. Continuous reflection profiles were

Figure 12.

Bedrock geology map of the Kentland, Indiana impact site. Inset indicates location of the disturbance. Quarry site is indicated by blackened section near the center of the structure. Diagram is based on the work of Tudor (1971), Gutschick (1976), and this study.


Newton County
Indiana
Kentland
Goodland
Quarry
D
P
D
M
D
D
S
O
M
P
P
M
M
Ring Depression
Limit of Disturbance
P - Pennsylvanian Sh., Coal, Ss.
M - Mississippian Ls., Sh.
D - Devonian Ls., Sh.
S - Silurian Ls., Dol.,
O - Ordovician Ls., Dol., Ss., Sh.
0
4 km
N

attempted along four lines at distances up to 3 km from the center of the structure. No useable seismic information was recorded, indicating that faulting and other subsurface complexities are more abundant than indicated on the bedrock map (Tudor, 1971). A more comprehensive drilling program would be needed to bring to light additional information about the area surrounding the central uplift.

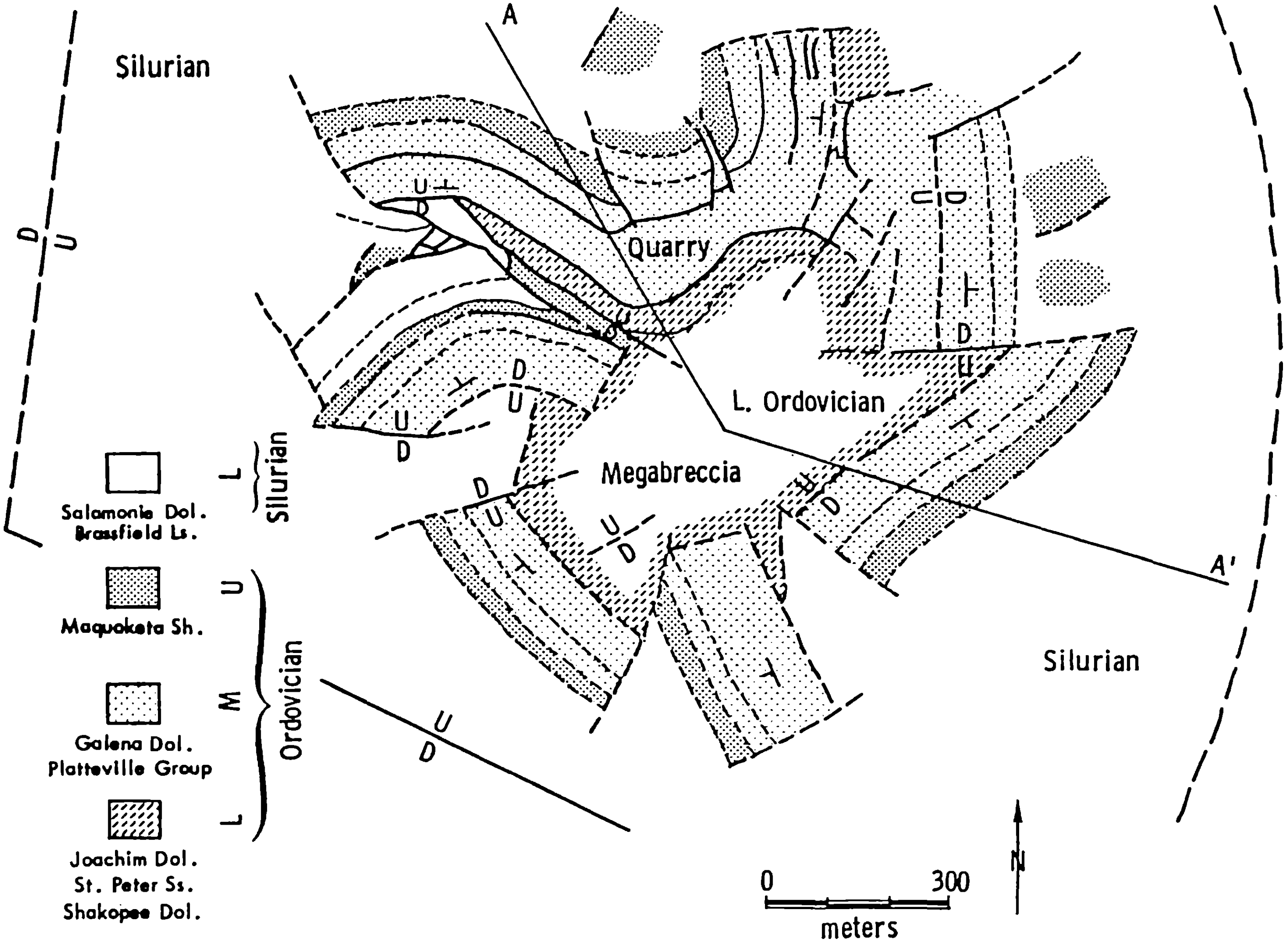
The origin of the structural depression is believed to be the result of inward displacement of deeper material during central uplift formation. Structural depressions surrounding central uplifts have been reported at many suspected impact sites in the U. S. (Wilshire and Howard, 1972; Wilson and Stearns, 1968; Offield and Pohn, 1977; Hendriks, 1965; Black,1964). Such depressions also occur in large-scale, high-explosive cratering experiments (Roddy, 1976). Although no calculation has been made for Kentland, at other sites it has been shown that the amount of material brought into the center of the structure is approximately accounted for by the amount of material downfaulted into the ring depression (e.g., at Decaturville: Offield and Pohn, 1977). Roddy (1976, 1977 a, b) argues that this inward flow beaneath crater floors is common at both flat-floored impact (e.g., Flynn Creek) and flat-floored experimental explosion craters with central uplifts.

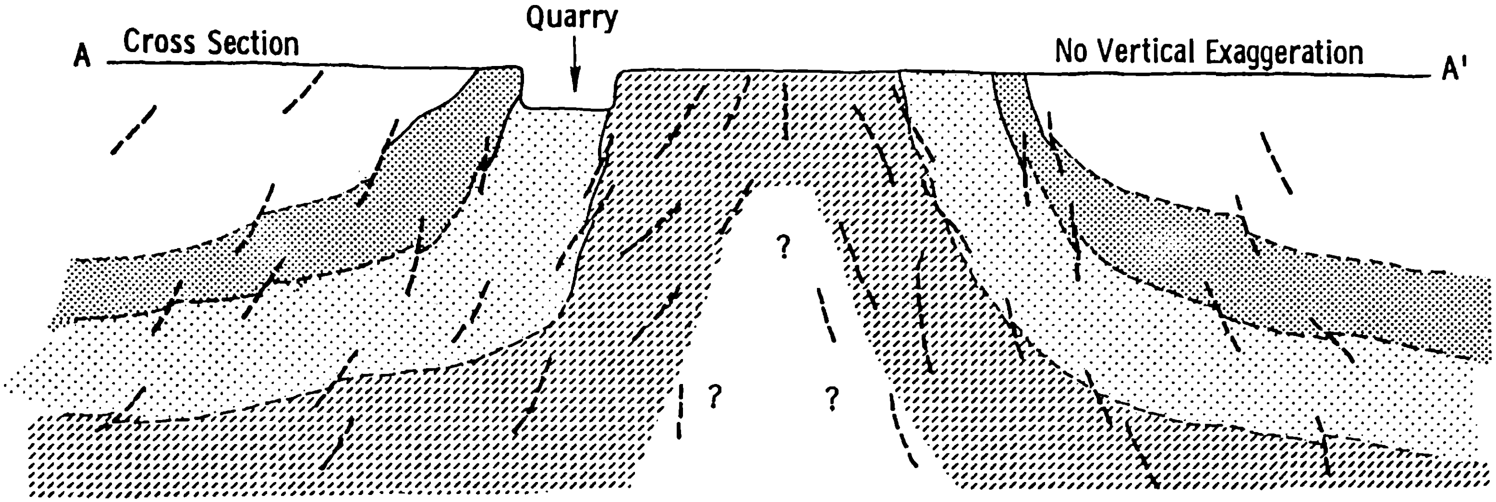
C) Central Uplift

A somewhat simplified bedrock geology map and cross section of the Kentland central uplift are presented in Fig. 13 a and b. A more detailed bedrock geology map of the

Figure 13.

Generalized geologic map and inferred cross section of the Kentland central uplift. Note that at the present erosional level most of the intense structural dislocations are confined to a relatively small area (1.0-1.2 km^2) compared to the area occupied by the total disturbance (123 km^2). Information for these diagrams comes from quarry exposures and drilling by Tudor (1971) and the Newton County Stone Company (pers. comm.).


Silurian
A
Quarry
L. Ordovician
Megabreccia
A'
Silurian
U
D
U
D
0
300
meters
N
L
Silurian
U
M
L
Ordovician
Salamonie Dol.
Brassfield Ls.
Maquoketa Sh.
Galena Dol.
Platteville Group
Joachim Dol.
St. Peter Ss.
Shakopee Dol.


A
Cross Section
Quarry
No Vertical Exaggeration
A'
?
?
?

uplift is presented in Plate 1 (in pocket). These maps are based on information from quarry exposures and core drilling by the Newton County Stone Company (pers. comm. 1978), the Indiana Geological Survey, and work by Tudor (1971) and Gutschick (1976). Although field data are limited for the southern half of the uplift, the interpretation presented in Fig. 13 a is consistent with the presently available geologic information. The writer believes this interpretation represents at least the gross structure of the central uplift. The inferred structure presented in the cross section of the uplift is based on more limited data. Additional drilling information will greatly improve our knowledge about the structural details of the uplift and may require modifications of the contacts inferred.

In overall form, the central uplift displays a crude domical arrangement of Silurian and Ordovician strata, caused by normal faulting during uplift formation. Proceeding from the outer Silurian strata inward successively older formations are exposed and the outward dips of the beds and structural complexity increase toward the center. Silurian dolomites have been uplifted approximately 275 m above their regional stratigraphic level, whereas the Ordovician Shakopee Dolomite (the oldest unit exposed in the quarry) is some 550 m above its normal position. Dips on the Silurian strata are about $20-30^{\circ}$ and increase abruptly to $75-90^{\circ}$ for the Middle Ordovician carbonates.

Intensity of faulting and folding also increase from the flanks of the central uplift towards the center, where large-scale structure is still recognizable, inward to an area of about 0.25 km^2 which is thought to be composed of blocks of lower Ordovician units in a complex structural arrangement or megabreccia. This megabreccia core is inferred from recent drilling (pers. comm., Newton County Stone Co.) which indicates that patches of Maquoketa Shale are present bounding small blocks of carbonate rock. Where this relationship occurs in quarry exposures, the structure is usually very complex (e.g., in the SW quarry section, discussed below).

For the area outside of the quarry, core drilling is the main source of information. It appears from the presently available data that relationships similar to those in the quarry characterize the remaining portion of the flanks of the uplift. There also appears to be a correlation between lithology and deformational style, with the Middle Ordovician carbonates deforming as competent blocks 400-900 m in length, whereas the more mobile sandstone and shale units are involved in complex faulting between these blocks. Circumferential faulting, presumably dip-slip or closely sub-parallel to bedding, separates these blocks from the inferred megabreccia core, and radial faults cut these blocks perpendicular to their strike (Fig. 13 a). An example of this structural pattern is present in the quarry area. The Middle Ordovician carbonates occur as a more or less coherent block with a total strike length approaching 1000 m. Faulting has broken the block and duplicated sections of it, but essentially the carbonate rock comprising the block deformed as a single unit. Immediately bounding this block on at least three sides are areas of little structural uniformity. In the southwest quarry section, Silurian dolomites have been broken into at least four blocks with Ordovician Maquoketa Shale occuring as slivers and small blocks faulted and wedged in between the dolomites (Figs. 13 a and 15). On the east side of the quarry, Middle Ordovician carbonates are again present, but as isolated blocks again fault bounded by Maquoketa Shale. A quarry reentrant in the extreme SE corner once exposed a small block consisting of Joachim, Platteville, and Galena carbonates, but was not quarried and has since been back-filled (Gutschick, 1961). The carbonates were not of the same quality as those in the quarry, apparently because of intense shattering during uplift and subsequent weakening by groundwater percolation (pers. comm., Newton County Stone Co. staff). This is also the situation for the small block of Galena immediately to the north. This rock weathers into a yellowish, gritty powder with bands of well-formed dogs-tooth calcite occuring throughout the block. Secondary calcite occurs also as layers cementing nearby Maquoketa Shale. These features apparently are the result of dissolution and recrystallization of fine carbonate rock powder formed by intense granulation during uplift formation.

A cross section for the Kentland central uplift is given in Fig. 13 b. The steeply dipping attitude of the strata adjacent to the inferred megabreccia core is indicated from drilling in the quarry by the Indiana Survey. A drill hole placed near the Kentland Quarry fault (Fig. 16 d) has shown that the steeply dipping fault surface extends at least 280 m below the present ground surface. It is not certain what strata are present deeper in the megabreccia core, but Cambrian carbonates could be at a relatively shallow depth below the ground surface. Drilling in the core will be needed to clarify this.

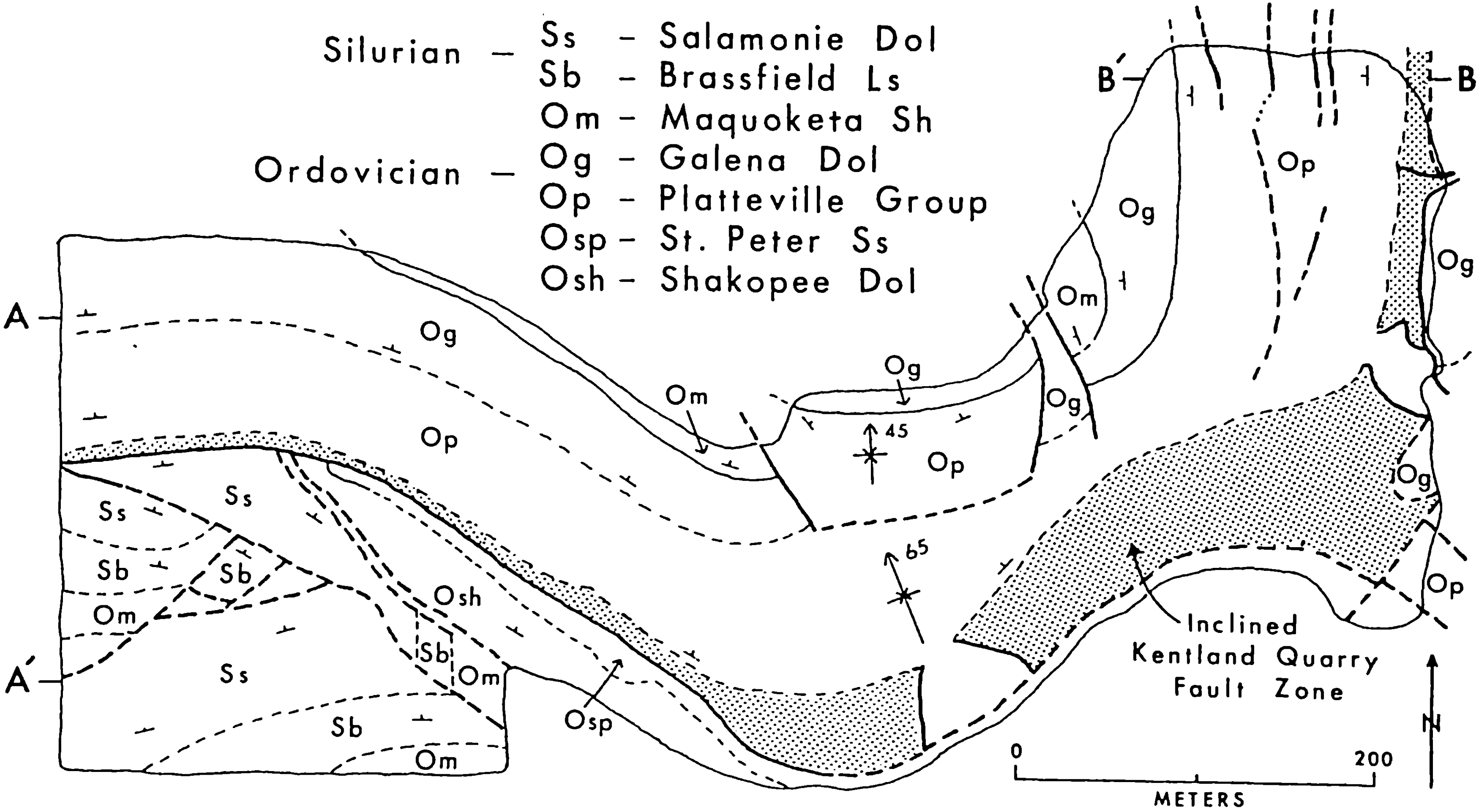
In the sequence of rocks at the Kentland site several good marker beds are present, and these allow eludication of detailed structural relationships. This has been done at the quarry site located on the northern flank of the central uplift. Fig. 14 is an air photo of the quarry, courtesy of the Indiana State Highway Commission, and Fig. 15 illustrates details of the quarry geology. The Newton County Stone Company has been quarrying continuously at this site since 1906 (Gutschick, 1976), and their recently increased activity has exposed much new information concerning structural relationships. The main quarry is about 70 m deep and quarry extraction has followed the Platteville and Galena carbonates westward. This has dramatically exposed the main structure of the quarry, in which the Middle Ordovician carbonates are synclinally folded with the axis of the fold plunging about 65° NNW

Figure 14.

Air photo of the Newton County Stone Co. quarry, Kentland, Indiana. Quarry expansion over the years has resulted in a broad U-shaped pattern, following the strike of the Platteville and Galena carbonates. Notice the brilliant white outcrops of St. Peter Sandstone along the south wall of the quarry. U.S. Highway 24 runs east-west, just north of the quarry. Courtesy of the Indiana State Highway Commission.

Figure 15.

Plan map of the Kentland quarry. Major structure present is a NNW plunging synclinal fold. Stippled pattern indicates where quarry extraction has excavated down to the surface of the Kentland quarry fault zone. Cross sections along lines A-A' and B-B' are given in Figs. 16 b and d, respectively. Map modified after Gutschick (1976).


Silurian – Ss – Salamonie Dol
Sb – Brassfield Ls
Om – Maquoketa Sh
Ordovician – Og – Galena Dol
Op – Platteville Group
Osp – St. Peter Ss
Osh – Shakopee Dol
A
A′
B′
B
Og
Op
Ss
Sb
Om
Osh
Osp
45
65
Inclined Kentland Quarry Fault Zone
0
200
METERS
N

and oriented radially to the center of the structure (Fig. 15). The westward limb of this synclinal fold appears to begin to take on an anticlinal aspect, but is broken by a fault as is the east limb. A major fault, the Kentland Quarry fault (KQF) dips steeply northward and bounds this synclinal fold throughout the quarry on the south. This fault involves the friable St. Peter Sandstone and the massive Joachim Dolomite. As pointed out by Gutschick (1976), this fault is actually a wide zone of deformation (i.e., a fault zone). Strata on the hanging wall are severely distorted and broken up by many smaller faults up to 15 m or more from the main fault surface. Movement along the main fault has been essentially dip-slip near the axis, whereas hanging wall material farther out on the limbs of the fold has moved obliquely toward the axis. Mullion, mylonite, and slickensides are well displayed where quarrying has exposed the main fault surface. Intimately associated with this fault are monomict and polymict breccias.

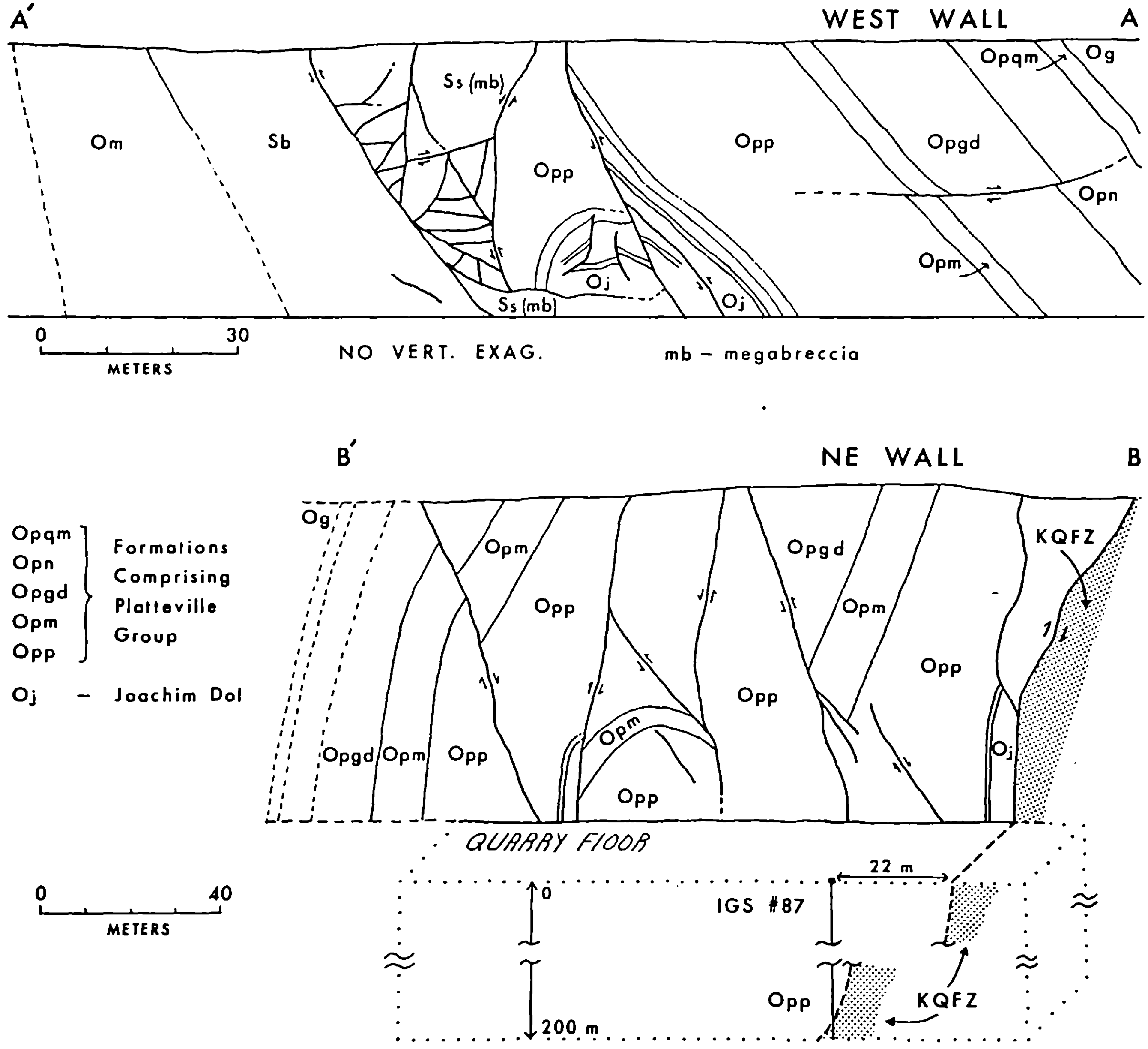
The west wall of the quarry (Figs. 16a and c) displays a steep reverse fault that has placed Middle Ordovician carbonates over younger Silurian dolomites, with a zone approximately 30-40 m wide of Silurian strata that has been jumbled into a megabreccia. Other structures present in the quarry include a small nested syncline involving Middle Ordovician carbonates near the axis of the main synclinal fold, and several high angle faults have duplicated sections of the Platteville group in the NE section of the

Figure 16.

a) Photo of west wall of quarry. b) Geologic profile of the west wall of quarry. Center portion indicates steep reverse fault that has placed the Ordovician Platteville Group (Op) over younger Silurian strata (Ss) that have been jumbled into a complex megabreccia. c) Photo of the NE wall of the quarry. d) Geologic profile of the NE wall of the quarry. IGS #87 denotes Indiana Geological Survey drill hole #87. Drilling started on the level of the quarry floor (approximately 68 m below the present ground surface) and continued for a total depth of 198 m. At about 190 m in the drilling, the Kentland Quarry Fault zone (KQFZ) was encountered, indicating the steeply dipping nature of the fault plane.

A

C


A′
WEST WALL
A
Opqm
Og
Om
Sb
Ss (mb)
Opp
Opp
Opgd
Opn
Opm
Oj
Oj
Ss (mb)
0
30
METERS
NO VERT. EXAG.
mb – megabreccia
B′
NE WALL
B
Og
Opm
Opgd
KQFZ
Opp
Opm
Opp
Opp
Opgd
Opm
Opp
Opm
Opp
Oj
QUARRY FLOOR
22 m
0
IGS #87
Opp
KQFZ
200 m
Opqm
Opn
Opgd
Opm
Opp
Formations Comprising Platteville Group
Oj – Joachim Dol
0
40
METERS

quarry (Figs. 16 b and d). These faults, along with several others present in the quarry, appear to be clean separations with no breccia, while others (e.g., the Kentland Quarry fault) are associated with polymict injection breccias or intensely shattered rock near the fault surface.

SHOCK DEFORMATION AT KENTLAND

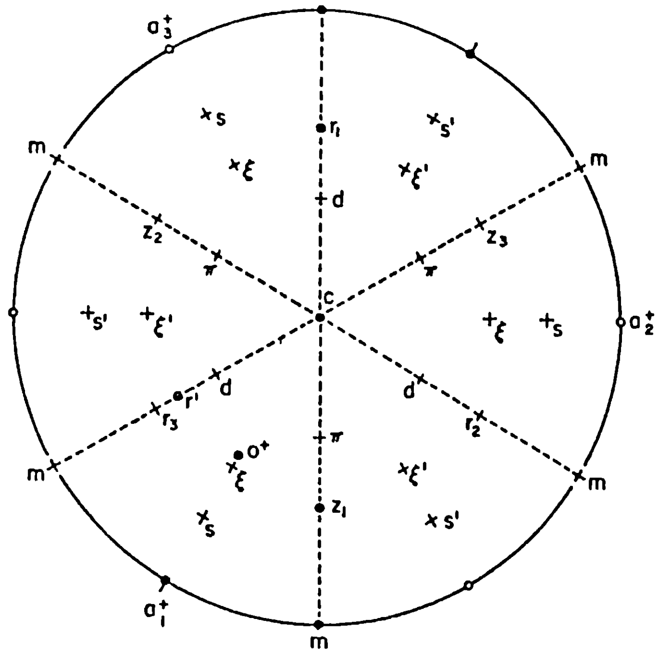
Perhaps the most persuasive arguments supporting an impact origin for structures such as Kentland are recorded in the rocks themselves. Features such as shock-deformed mineral grains, deformational breccias, and shatter cones have been noted to occur at almost all suspected impact sites and an extensive literature exists on these subjects (e.g., French and Short, 1968; Roddy et al., 1977). Similar features occur at Kentland and these will be discussed below.

A) Shocked Quartz

A petrographic study of quartz grains from the Kentland quarry was undertaken in order to determine the approximate peak shock pressures experienced by the grains. Similar studies of quartz grains from other impact sites have shown that the grains exhibit features that are rare or less well developed in quartz from normal tectonic environments (Bunch, 1968; Carter, 1968). Unshocked quartz grains form the St. Peter Sandstone are shown in Fig. 18a. When this information is compared to data on experimentally shocked quartz, approximate ranges of shock pressures at various levels in the impact structure can be determined (Dence, 1968; Stoffler, 1966; Engelhardt and Bertsch, 1969).

Data were obtained from universal stage measurements on 21 thin sections of rock from mixed breccias and from sandstone and sandy dolomite units, namely the basal Platteville, St. Peter, and Joachim units which are situated approximately 50 m apart stratigraphically. Cleavage and microfaults are the most common shock features in these grains. Cleavage as used in this study conforms to the definition of Carter (1968) as being fairly wide (2 to 10 μ) planar elements that form as the result of brittle fracturing along crystallographic planes of low indices (Fig. 17). A typical grain displaying rhombohedral cleavage is shown in Fig. 18b. Microfaulting may be related to crystallographically controlled cleavage, but offsets along the plane of discontinuity are visible.

The only other shock features noted in these quartz grains were deformation lamellae in the basal (0001) orientation (Fig. 18c). These lamellae are similar to those described by Carter (1968) as being sharp, narrow (1 to 2 μ wide) planar features that occur in sets of 5 or more individual lamellae. These lamellae generally do not extend across an entire grain in the Kentland material, but occur either in one section of the grain or are distributed in sets across the grain. Multiple sets of planar features in other crystallographic orientations as described by Carter (1968) have not been observed. However,

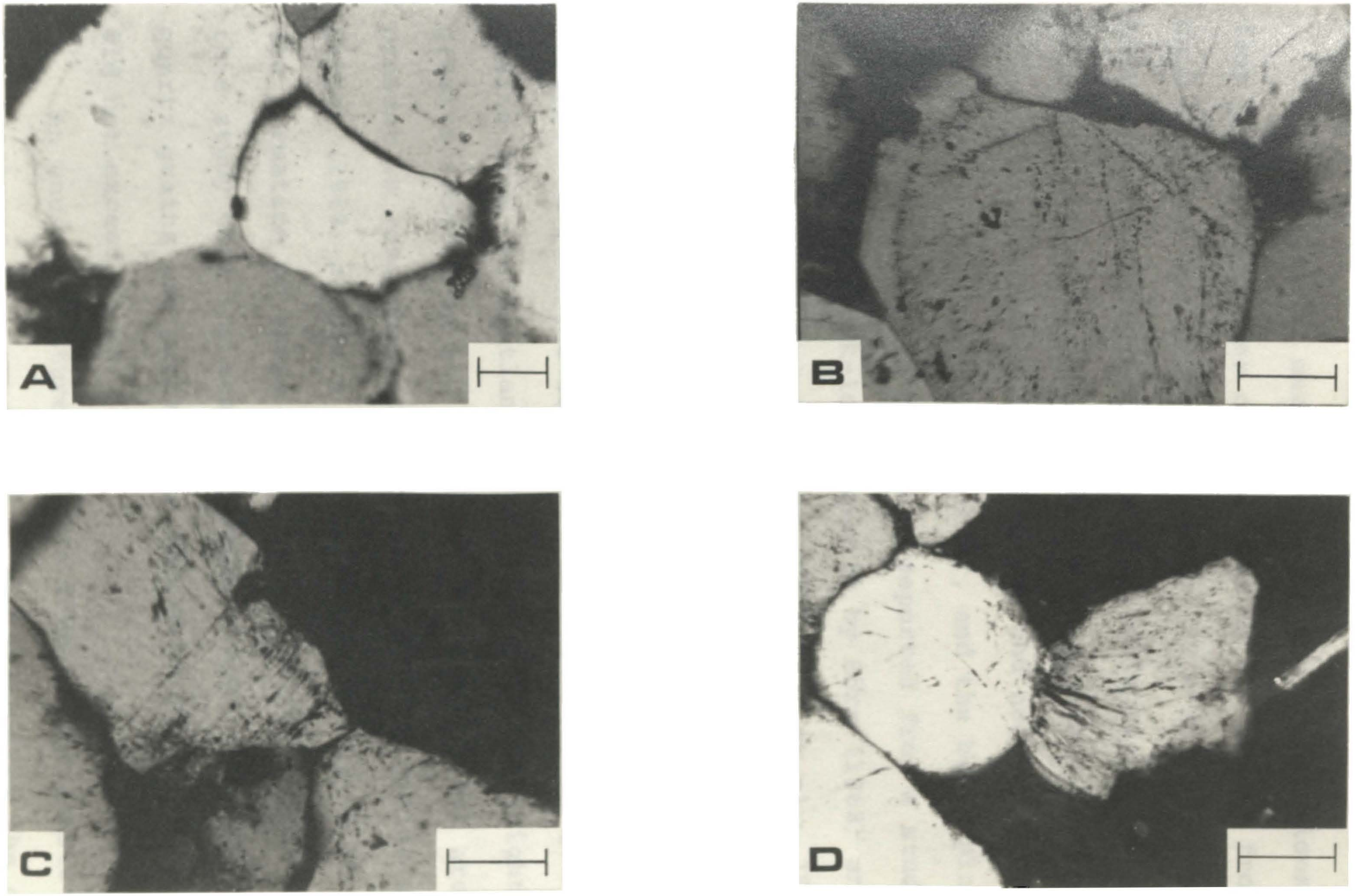


Common forms		C ∧ ⊥ form
c - {0001} - basal pinacoid		—
m - {$10\bar{1}0$} - first order prism		90°
a - {$11\bar{2}0$} - second order prism		90°
r - {$10\bar{1}1$} z - {$01\bar{1}1$}	unit rhombohedra	51° 47'
d - {$10\bar{1}2$} π - {$01\bar{1}2$}	rhombohedra	32° 25'
s - {$11\bar{2}1$}, s' - {$2\bar{1}\bar{1}1$} ξ - {$11\bar{2}2$}, ξ' - {$2\bar{1}\bar{1}2$}	trigonal bipyramids	65° 33' 47° 43½'

Figure 17. Equal area projection (lower hemisphere) showing the crystallographic orientations of poles to common crystal planes in quartz (right handed). Taken from Carter (1963).

Figure 18.

Examples of unshocked and shock-deformed quartz. a) Unshocked St.Peter Sandstone from the La Salle Anticline, Ill. b) Shocked quartz displaying rhombohedral cleavage. c) Deformation lamellae in the basal (0001) orientation. d) Concussion fractures developed as the result of neighboring grains colliding during shock compression. Scale bar represents 50 microns.


A
B
C
D

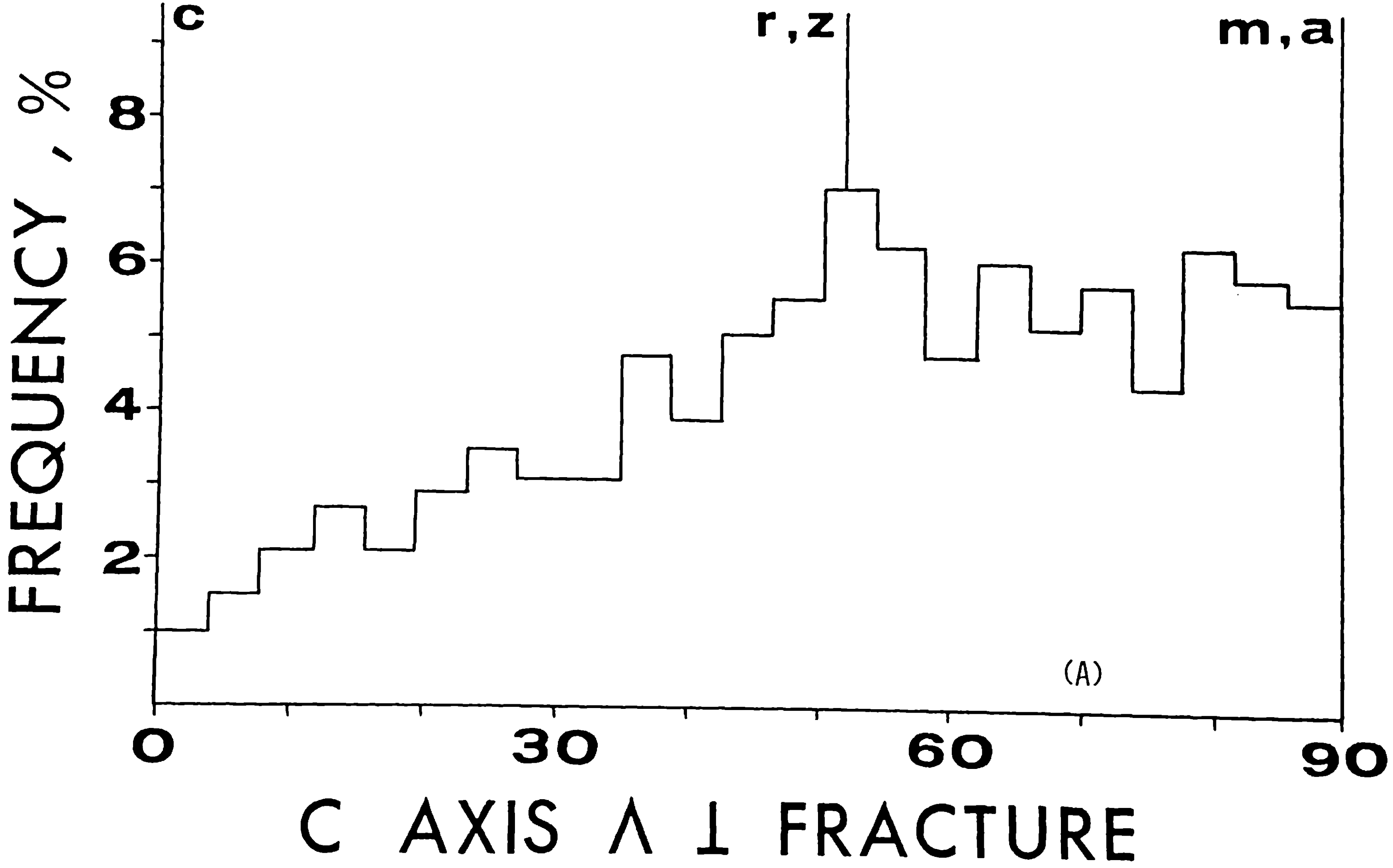
sampling is limited to the quarry area, which occupies only a small part of the total central uplift.

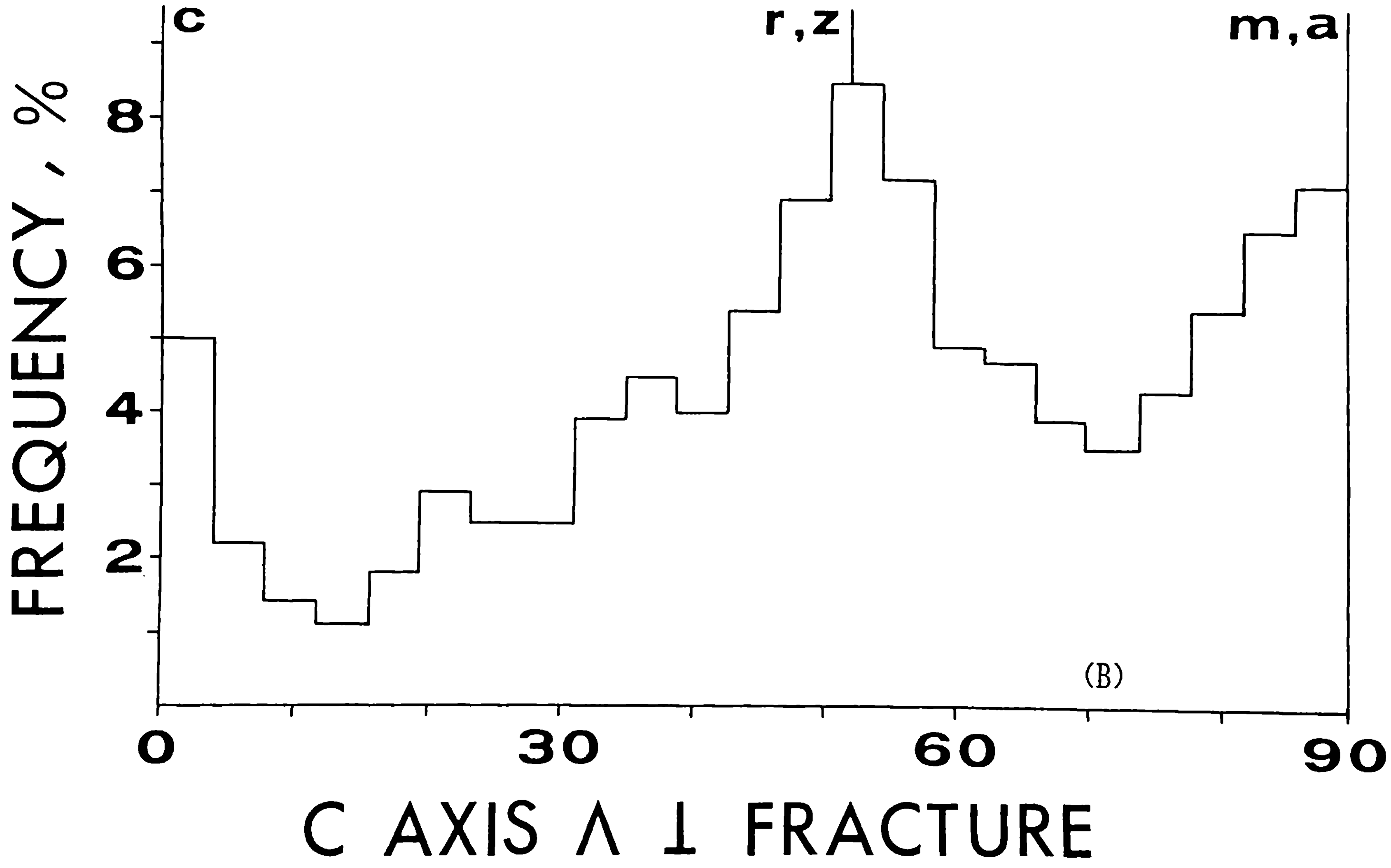
The results of measurements of the orientations of 2421 planar fractures or cleavages in 875 grains from 21 thin sections are presented in Fig. 19 a and b. From the histograms it is apparent that crystallographic control of some fracturing has occurred with the most frequent orientations involving the positive and negative rhombohedra (r,z), the unit prism (m,a), and the basal pinacoid (c). Similar results have been reported from a study of experimentally shock-loaded quartz by Hörz (1968) and of quartz from other impact sites (Robertson et al., 1968, 1975; Bunch, 1968). Hörz (1968) has shown that cleavage of this type usually begins to develop at about 50 kb and that microfaults begin to develop as low as 40 kb. Basal deformation lamellae occur very infrequently in quartz grains from the Kentland rocks. They occur in slightly greater numbers in the mixed breccia samples but are still present in less than one percent of all the grains surveyed. Carter (1968) places a shock range of from 23-76 kb for the formation of these lamellae. The writer concludes from this study that the shock pressures experienced by these quartz grains are probably in the range of 30-60 kb and did not exceed 80 kb.

An unusual feature noted in some of the quartz grains are fractures that appear to be radiating from the contact surfaces with other grains (Fig. 18d). These features

Figure 19.

a) Frequency histogram of the angles between the quartz optic axes and poles to cleavage fractures. Grains measured are from in situ sandstone formations (principally the St. Peter Sandstone). b) Frequency histogram for the cleavage and fracture orientations developed in quartz grains from polymict breccia occurrences in the quarry. These measurements suggest shock pressures in the range 30-60 kb.


c
r,z
m,a
FREQUENCY, %
8
6
4
2
(A)
0
30
60
90
C AXIS ∧ ⊥ FRACTURE


c
r,z
m,a
FREQUENCY , %
8
6
4
2
0
30
60
90
C AXIS ∧ ⊥ FRACTURE
(B)

appear to be almost exact analogues of the concussion fractures described by Kieffer (1971) and which occur in some quartz grains from the Coconino Sandstone at Meteor Crater, Arizona. These features are believed to be the result of tensile fracturing as neighboring grains collide during the passage of the initial compressional shock wave through the rock.

B) Breccias

Two types of breccias occur at the Kentland quarry: monomict breccias and the more commonly occurring polymict, or multiple lithology, breccias. The monomict breccias are generally recognizable in the carbonate units but may also be developed in some of the sandy units. In the carbonate rocks this type of breccia consists of angular to subangular clasts in an extremely fine-grained or mylonitic matrix. The clasts are variable in size (0.5-5.0 cm), and the larger ones are usually shattered. The matrix occurs as irregular veinlets or stringers variously oriented around the clasts; the clasts generally appear to have undergone little or no rotation. The lighter colored, mylonitic material contrasts with the darker clasts and these breccias can be easily recognized in the field (Fig. 20a). Presumably analogous brecciation has occurred in some of the sandy units, particularly in some outcrops of the St. Peter Sandstone. Granulation and pulverization has been intense enough to turn the well-rounded quartz grains into a fine-grained rock powder which is only weakly cemented by silica cement.

Monomict breccias in carbonate rocks described from other impact sites (Roddy, 1968; Wilson and Stearns, 1968; Wilshire et al., 1971; Offield and Pohn, 1977) are believed to form as the result of shattering, dilation, and subsequent recompaction of individual units with little or no mixing between units. A similar set of events is believed to have operated to produce the monomict breccias at the Kentland site.

Polymict breccias are abundantly exposed in the quarry. They usually occur as irregular to somewhat tabular bodies emplaced along fault surfaces and bedding planes, grouted into any available opening, or even injected as cross-cutting dikes into some sandstone beds (Fig. 20c). Clasts for these breccias are apparently derived from all lithologies present in the quarry and consist of quartz grains, stringers of quartz grains, chert, dolomite, calcite, shale, monomict breccia fragments, and even occasional shatter cone segments. Clast sizes typically range more or less continuously from a few millimeters up to blocks 0.5 m across; blocks tens of meters or more across have been observed in some of the megabreccia zones. The matrix of these breccias is usually light gray, fine grained carbonate material that is quite hard and dense (Fig. 20b). This material could have originally been finely communited carbonate rock powder that has been recrystallized to form the matrix. In some occurrences of this type breccia, material that was

Figure 20.

a) Example of a field occurrence of monomict brecciation from quarry. White stringers are of the same composition as the darker clasts, but have a mylonitic appearance due to intense granulation. b) Example of the fine-grained, light gray breccia that appears almost like grouting cement. Devoid of any sizeable clasts. c) Example of a polymict breccia 'injection dike' intruded into a St. Peter Sandstone bed. d) Close-up of the breccia shown in 18c. This sample displays excellent flow foliation texture.

A

B

C

D

originally separated 250 m stratigraphically can now be found as clasts occurring side-by-side. This indicates extensive mixing has occurred over relatively large distances during uplift formation. Some breccias are also flow-foliated, displaying preferred orientation of elongate clasts and distinct color banding of matrix material (Fig. 20d). This type of feature has been reported at other impact sites(e.g., Sierra Madera) and Wilshire et al. (1971) postulate that such breccias were emplaced '... as dense suspensions of clasts.. probably in CO_2-rich water or water vapor." This also implies that during rotational uplift of the strata there was transient dilation, presumably along bedding planes and faults. Roddy (1968) describes large sill-like injections of finely brecciated rock along the flanks of the central uplift at Flynn Creek and indicates that injection normally occurs during the rarefaction stage of the cratering event. During this stage much of the sub-crater floor and walls are in a tensional condition (Roddy, 1976), mixing of various lithologies took place, and subsequent settling and compaction of the strata forcibly injected the breccia material into available openings and spaces. Such a sequence of events would account for many of the features of the breccias described above.

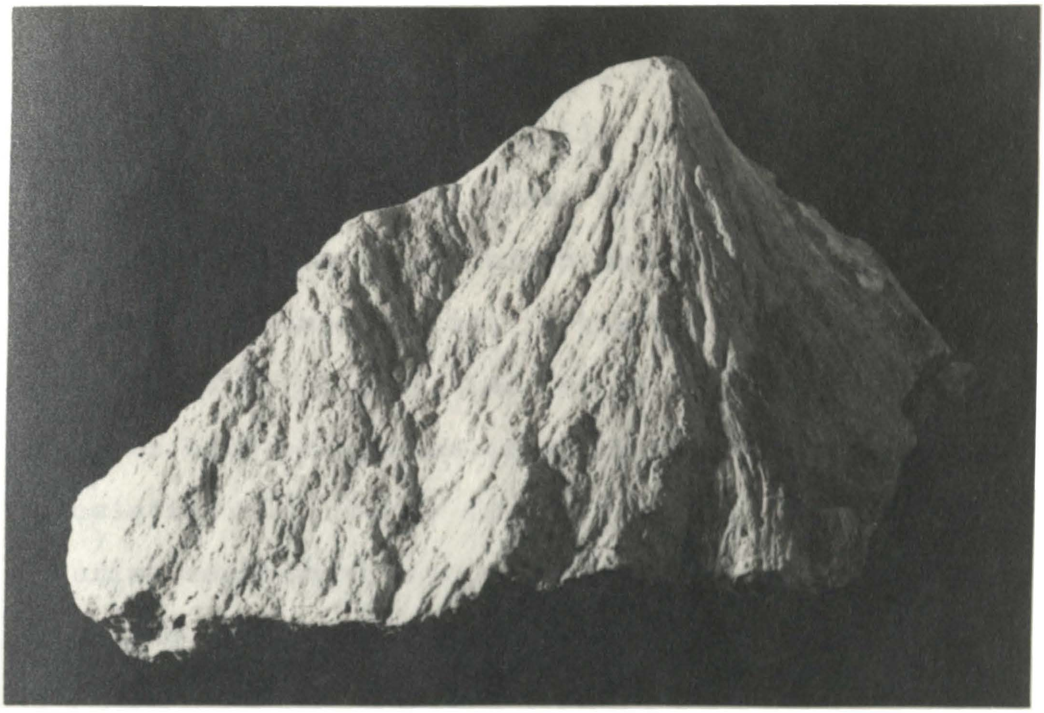
C) Shatter cones

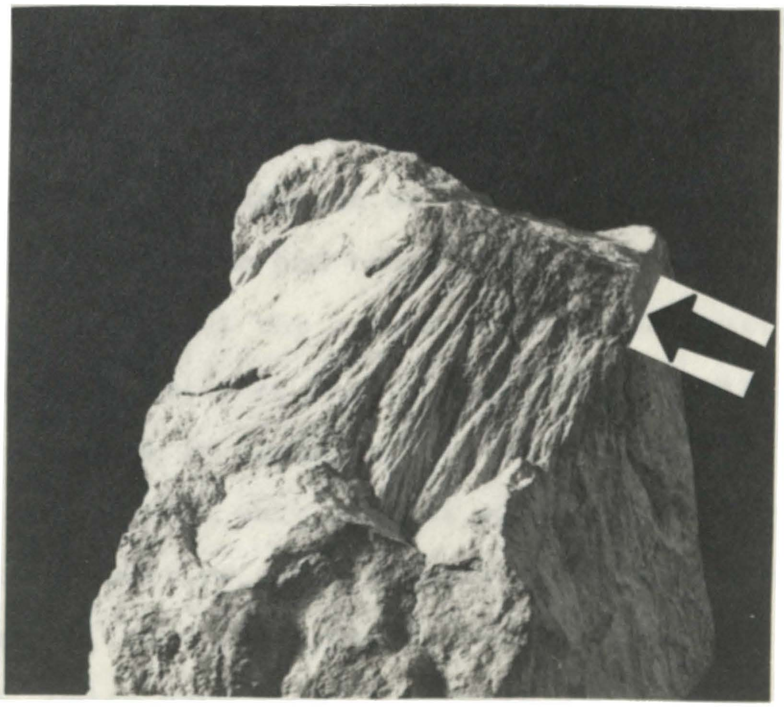
Shatter cones are an unusual type of mesoscopic shock deformational feature present at a large number of impact sites (Dietz, 1947, 1963, 1968, 1972). Shatter cones usually display a conical fracture surface with striae, grooves, and small parasitic half-cones radiating away from the master cone apex. Shatter cones have now been reported to occur at over 37 confirmed or suspected impact sites including several which are associated with meteoritic material (Dietz, 1963, 1968; Milton, 1977). True shatter cones have never been reported from structures which owe their origin to an endogenetic process (e.g., explosive volcanic eruptions). Recently, Roddy and Davis (1969, 1977) reported on a detailed study of shatter cones formed by several large-scale, high-explosive cratering experiments that firmly establish that shatter cones are formed by shock wave processes. This evidence strongly supports the contention that the presence of shatter cones is a valid criterion to be used in determining an impact origin for suspected structures. Formational pressures suggested by Roddy and Davis (1977) and from other studies (Dence et al., 1977; Hörz, 1971; Robertson, 1975) are in the range of 20-80 kb.

At Kentland, shatter cones apparently have formed in all lithologies; however, as is typical at other impact sites, they are most abundant in the denser carbonate rocks. Especially good development has been noted in Silurian dolomite in the south-west section of the quarry (Fig. 21a).

Figure 21.

a) Example of a complete shatter cone recovered from the south west quarry section. Shatter cone developed in the Silurian Salamonie Dolomite unit. Sample is approximately 23 cm across at base. b) Multiple shatter cone surfaces radiating away from a Silurian cephalopod shell (arrow). Approximately 14 cm across at base. Also recovered from the SW quarry section.





Kentland shatter cones generally range in size from 0.01 to 0.2 m, but Dietz (1963) has reported one gigantic cone surface that reached a length of 15 m. Apical angles for Kentland shatter cones generally range from 83° to 105°.

As noted by several other workers (Milton, 1977; Dietz, 1963), shatter cones are often developed in association with mesoscopic inhomogeneities in the rock (small clastic grains, voids, bedding planes). At Kentland, several excellent examples have been noted of shatter cones developing in association with fossil fragments. Fig. 21b shows a Silurian cephalopod with multiple shatter cone surfaces radiating away from the shell.

Orientations of shatter cone striations have been measured from quarry exposures and have been plotted stereographically in order to determine the orientation of the full cone axes (Fig. 22). These plots were then rotated to bring the host strata back to a horizontal attitude in order to determine the orientation of the cone axes before structural displacements had taken place (Manton, 1965). As can be seen, (Fig. 23) the orientations of the restored cone axes are generally at high angles to the horizontal. This orientation is in accord with a surface origin for the shock wave. Since only a small portion of the central uplift has shatter cones accessible for measurement, analyses similar to those preformed by Manton (1965) and Milton et al., (1972), which have shown a general convergence of all restored cone axes toward the center of the structure, was

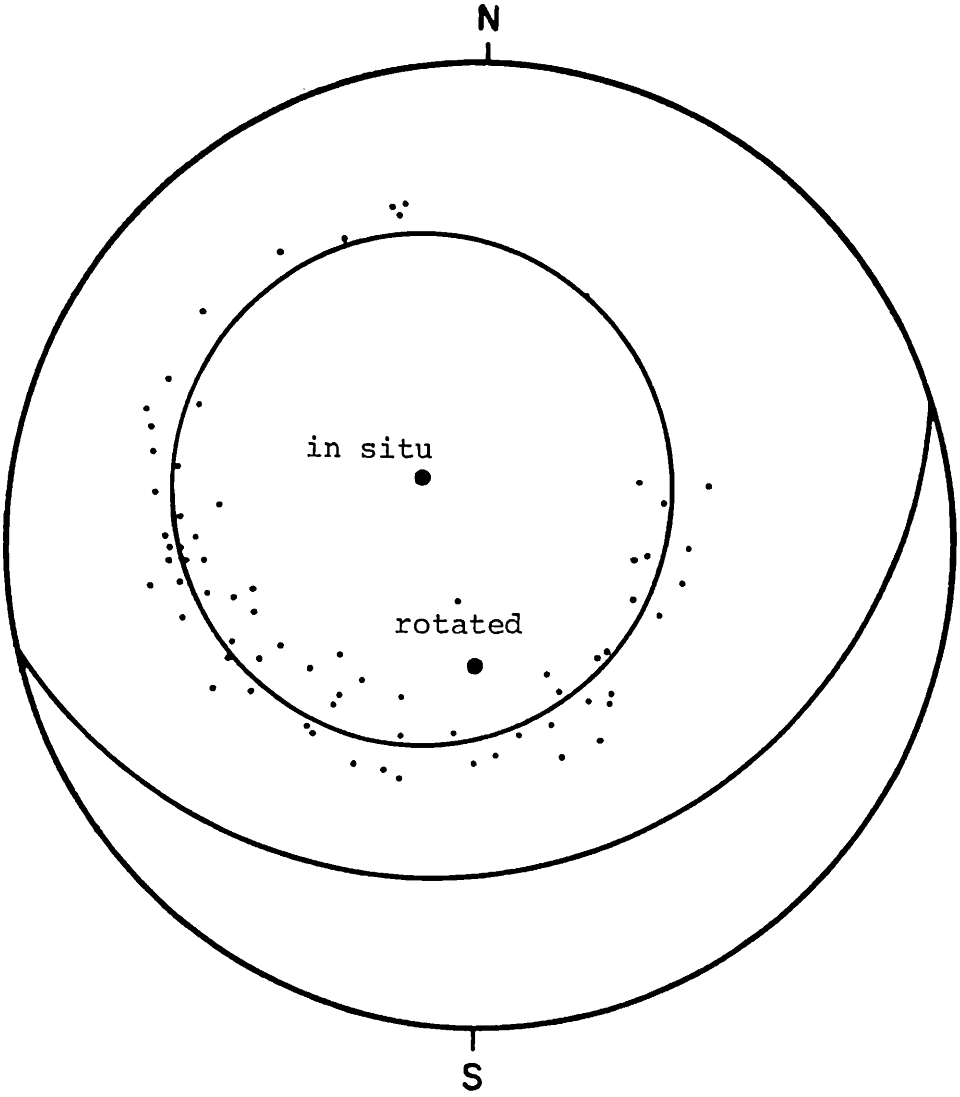
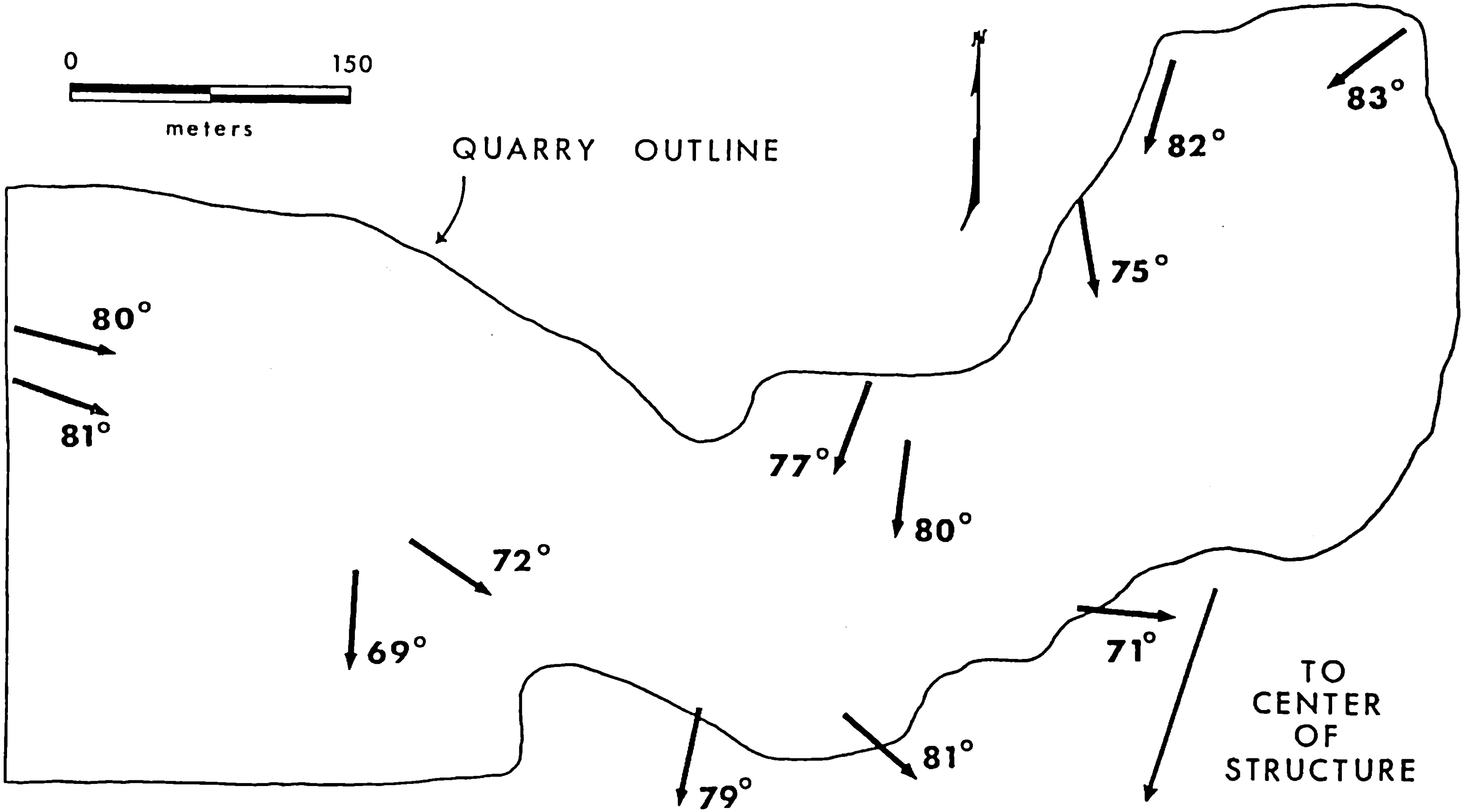


Figure 22. Stereogram (upper hemisphere) showing the plots of 71 shatter cone striae measured on shatter cone segments found in a block of Silurian strata in the SW quarry section. These measurements were taken from an outcrop area approximately one meter square. A best fit circle has been drawn through the points enabling the orientation of the in situ cone axis to be determined. The great circle shown represents the orientation of the host strata (N72E, 33N). When this plot is rotated so the strata assumes a horizontal attitude, the shatter cone axis points stratigraphically upward, 69° to the horizontal.

Figure 23.

Sketch of quarry limits and orientations of shatter cone axes restored to their position before major structural displacements had taken place. Note that most of the axes are oriented at high angles to the horizontal, in accord with a surface origin for the formational shock wave.


0
150
meters
QUARRY OUTLINE
N
83°
82°
75°
80°
81°
77°
80°
72°
69°
71°
TO CENTER OF STRUCTURE
79°
81°

not possible. As larger portions of the flanks of the central uplift are exposed by quarry operations, an analysis of this type may be feasible.

DISCUSSION

Much effort has been expended in recent years in an attempt to understand and characterize the mechanical factors which influence the formation of various structural features in impact craters (Dence, 1968; Dence et al., 1977; Milton and Roddy, 1972; Roddy, 1968, 1976, 1977 a,b; Roddy et al., 1977; Ullrich et al., 1977) Central uplifts are an example of one such structural feature and have been shown to occur in certain size ranges of craters on the terrestrial planets and their satellites (Pike, 1971; Cintala and Head, 1976; Wood, 1973; Cintala et al., 1977). On Earth, central uplifts commonly occur in impact structures with diameters ranging from 3.5 to 30 km (Dence et al., 1977). The apparent morphological evolution with increasing crater diameter, from simple bowl-shape craters, to flat floor-central peak craters, to multi-ring basins, implies that central uplift formation is an important phase in the repositioning of material during a medium-size impact cratering event. The detailed sequence of events and driving forces leading to central uplift formation in medium-sized craters, however, remains unclear (Roddy, 1976; Dence et al., 1977; Ullrich et al., 1977)

Central uplift formation resulting from some type of rebound mechanism was first proposed by Boon and Albritton (1937) and has been expounded on and modified by other workers (Short, 1965; Baldwin, 1963; Ullrich et al., 1977). Recently, numerical simulations of high explosive cratering experiments (Ullrich, 1976; Ullrich et al., 1977) have indicated that central uplift formation might be influenced by either a rebound mechanism following compressional shock or by late-stage gravitational collapse of the crater walls or by a combination of the two. An alternative mechanism involving gravitational deep sliding has also been proposed by Dence (1968), Gault et al. (1968), and Shoemaker (1963). Extensive photomorphometric studies by Cintala et al. (1977) and Wood (1973) suggest that a gravitational slumping mechanism for central uplift formation may play only a minor role at best.

Field studies of terrestrial impact structures with central uplifts (e.g., Wilshire and Howard, 1968; Wilson and Stearns, 1968; Milton et al., 1972; Offield and Pohn, 1977) have provided basic data on some of the structural relationships observed in the uplifted material at each of these sites. A common problem encountered in the field study of these impact structures, including the Kentland structure, is the lack of detailed surface exposures, a serious lack of adequate deep drilling information in the central uplifted region, and the different erosional level present at each site. However, there are several impact structures with central uplifts which exhibit very little erosion (e.g., Steinheim Basin, W. Germany and Flynn Creek crater, Tenn.) and from these important information regarding the form and extent of the central uplifted region has been obtained. Roddy's study of the Flynn Creek crater (1968,1976,1977 a, b,c) has shed considerable light on the processes and sequence of events leading to the formation of the central uplift at this structure. Roddy (1977b) argues that the Flynn Creek central uplift was formed as a late-stage material response to the initial compression and rarefaction phases of the impact event. The inferred configuration of the central uplift (a steeply conical, disrupted zone) resulted from a volumetric rebound phenomenon and inward displacement of sub-crater floor material (Fig. 24). The displacements of greatest extent were presumably confined to a relatively limited volume centered near the crater axis. Roddy states that due to the steeply conical subsurface shape of the central uplift, a large bowl-shaped transient cavity was probably not formed.

This study of the Kentland impact site also supports a model of abrupt inward and upward displacement of material to form the central uplift. However, it must be stated that exposures and drilling information are limited, much more so than, for example, at Flynn Creek. At the present erosional level of the Kentland site, the most intense structural dislocations are confined to an area approximately 1.2 km in diameter at the center of the uplift. In this region stratigraphic uplift of 600 m or more has occurred, with most of the fault planes dipping steeply outward and

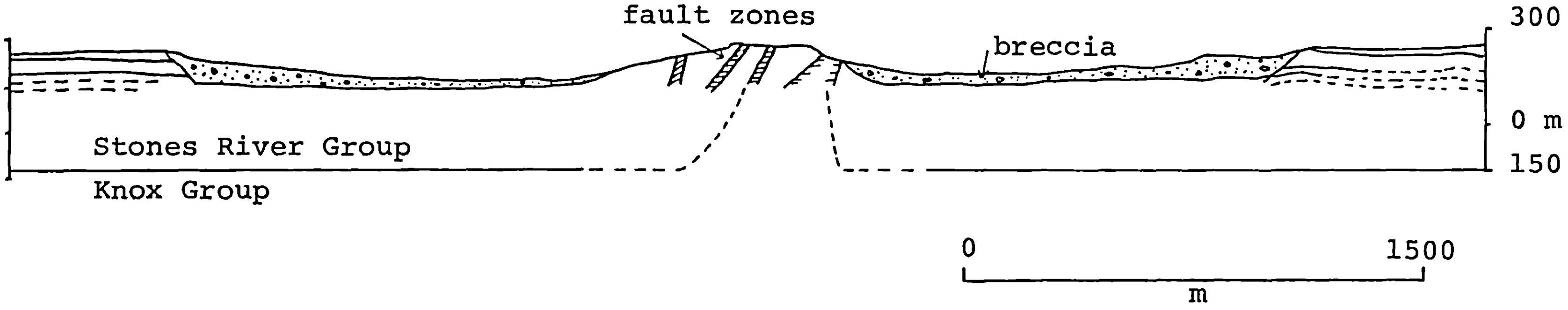


Figure 24. Generalized cross section of the Flynn Creek crater, Tennessee. Dashed lines indicate approximate location of the more intensely disrupted strata, as inferred from drill core data and central uplift exposures. Taken from Roddy (1968, 1977a).

interpreted to extend to relatively deep levels (e.g., the Kentland Quarry fault). From these relationships, observable only near the center of the structure, deep gravitational collapse and sliding of the crater walls seems to be an insufficient mechanism to produce the Kentland uplift.

During the early phases of uplift at Kentland it appears that, initially, steep, normal faulting occurred and was confined to a relatively limited area centered under the original cavity. Upward displacements continued with inward displacements at a deep level occurring to provide support for the uplifted material. Finally, late stage settling of this uplifted material occurred, accounting for some of the reverse fault relationships seen on the flanks of the uplift. Another possibility is that early inward movement dominated, producing thrust-reverse type faulting with lesser initial dips which were steepened during upward displacement. Later normal faults were produced as the rapidly rising core separated from the flanks of the uplift. Similar inward and upward displacements of both types have been reported from other impact sites and from craters produced by high-explosive devices (Wilshire et al., 1972; Wilson and Stearns, 1968; Milton et al., 1972; Roddy, 1968, 1976).

Evidence for inward displacements at Kentland is that the length of the segments of the Platteville Group (Plate 1) are approximately 10 percent longer than the perimeter of the area which they outline. This shortening of perimeter of the Platteville group at its pre-event stratigraphic level is an indication that inward movement took place as well as upward displacement. Similar horizontal movement has been reported from five other impact sites (Wilshire and Howard, 1968; Offield and Pohn, 1977). Inward crowding of material is also indicated by repeated faulting that duplicates portions of the Middle Ordovician carbonates in the quarry (for example, Fig. 16d). Table 1 gives a simplified version of the sequence of events which combined to produce the Kentland structure. Table 2 summarizes the main features found at the Kentland site. Many of these same features are found at other impact structures occurring in well-stratified sedimentary rock sequences.

COMPARISON WITH OTHER IMPACT STRUCTURES

In recent years investigators have identified various factors which could influence impact crater morphology. These factors have included: a) properties of the projectile, such as velocity and strength; b) energy coupling to the target material; c) properties of the target material, such as strength and layering; and d) gravity effects (Baldwin, 1963; Oberbeck and Quaide, 1976; Gault et al., 1968; Cintala et al., 1977; Head, 1976; Roddy, 1968, 1977a,b). Since the Earth's surface preserves only the vestiges of an impact event, information concerning projectile type, mass and velocity, and the distribution of energy into the target rock is not usually available for study. However, recent work by

TABLE 1.

EVENT	STRUCTURAL RESPONSE
1) METEORITE IMPACT	
2) PASSAGE OF COMPRESSIONAL SHOCK WAVE	2) SHATTER CONING, SHOCK DAMAGE IN MINERALS
3) EXCAVATION, TRANSIENT CAVITY FORMED	3) VOID EITHER IN FORM OF BOWL-SHAPED CAVITY OR FLAT WITH STEEPLY CONICAL ZONE NEAR CENTER; UNSTABLE AND UNCOMPENSATED CONFIGURATION
4) VOLUMETRIC 'REBOUND' AND BULKING OF SUB-CRATER FLOOR MATERIAL. POSSIBLE COLLAPSE OF UNSTABLE WALLS OF TRANSIENT CAVITY	4) INWARD AND UPWARD MOVEMENT OF SUB-CRATER FLOOR MATERIAL BEGINS; NORMAL FAULTING AND POSSIBLY SHEAR GLIDING OR THRUSTING ALONG BEDDING PLANES
5) DILATION AND MIXING OF STRATA, ESPECIALLY INTENSE NEAR CENTER OF STRUCTURE	5) BRECCIA MATERIAL PRODUCTION
6) SETTLING AND COMPRESSION OF UPLIFTED MATERIAL	6) REVERSE FAULTING AND EMPLACEMENT OF INJECTION BRECCIAS; FORMATION OF MONOMICT BRECCIAS
7) EROSION	

Table 1. Postulated sequence of events that combined to produce the Kentland structure. Due to our incomplete understanding of cratering processes, this listing should be considered only as a simplified version of the actual sequence of events.

TABLE 2. FEATURES FOUND AT THE KENTLAND SITE
WHICH ARE USUALLY ASSOCIATED WITH OTHER
PRESUMED IMPACT SITES IN SEDIMENTARY ROCK.

1) INTENSE LOCALIZED DEFORMATION RESULTING FROM AN EXPLOSIVE EVENT WHICH PRODUCES A HYPERVELOCITY SHOCK WAVE.

2) SURROUNDING STRATA FLAT, UNDEFORMED.

3) LOCATED IN A REGION LITTLE AFFECTED BY OBSERVED TECTONIC OR VOLCANIC ACTIVITY. NO VOLCANIC MATERIALS OR SIGNS OF THERMAL ACTION LOCATED.

4) MAJOR STRUCTURAL FEATURES INCLUDE A CENTRAL UPLIFT SURROUNDED BY A CONCENTRIC RING DEPRESSION AND RING ANTICLINE.

5) SUB-CROP PATTERN APPROACHES CIRCULAR FORM.

6) MATERIAL IN CENTRAL UPLIFT RAISED APPROXIMATELY 550-600 METERS ABOVE NORMAL STRATIGRAPHIC LEVEL.

7) CENTRAL UPLIFT ASSOCIATED WITH SMALL POSITIVE GRAVITY ANOMALY CAUSED BY THE UPLIFT OF MORE DENSE SEDIMENTARY ROCKS INTO THE CORE OF THE STRUCTURE.

8) INTENSIVE BRECCIATION (BOTH LARGE AND SMALL SCALE) WITH DEVELOPMENT OF MONOMICT AND POLYMICT BRECCIAS.

9) DEVELOPMENT OF SHATTER CONES; ESTIMATED SHOCK PRESSURES IN THE RANGE 20-80 Kb. SHATTER CONE AXES ORIENTED STRATIGRAPHICALLY UPWARDS.

10) SHOCK DEFORMATION OF MINERAL GRAINS; PLANAR DEFORMATION FEATURES IN QUARTZ. ESTIMATED SHOCK PRESSURES IN THE RANGE 30-80 Kb.

Palme et al. (1978) has attempted to classify the chemical composition of the projectiles that produced several impact structures. This work has met with some success if impact-melted rock incorporating some traces of the original projectile still remains. Such impact melt is usually not present at most of the older sedimentary rock impact sites, including Kentland. On the other hand, if erosion has not been too severe, information regarding the nature of the target material is available and this allows for comparisons to be made of the possible variations in impact structures due to differences in the target rock, if such differences do indeed exist.

Gault et al. (1968) have shown that variations in target rock layering have influenced final crater shape during laboratory experimental impact studies. Interplanetary comparisons of fresh crater morphology by Cintala et al. (1977), Head (1976), and others, have indicated that substrate characteristics may play a role in determining initial diameters for various crater features, thus indicating that target properties may be a significant determining factor of final crater morphology. From studies of high-explosive produced craters (Roddy, 1976) and the numerical simulation of these events (Ullrich et al., 1977), it has been pointed out that: a) compactibility of target materials, b) strength of target materials, c) layering of the target, and d) the presence of a low strength or a fluid layer underlying a more competent, dry layer may significantly influence or enhance upward motions in the sub-crater floor region.

These motions ultimately combined to form the central uplifts of the experimental and numerically simulated craters.

It has been noted by Roddy (1977c), and others, that most terrestrial impact structures are in various stages of degradation, and if structural comparisons are to be meaningful the amount of erosion that has taken place at each impact site must be known. Cross sections are presented in Fig. 25 of the central uplifts of the Kentland and Wells Creek structures. Fig. 26 gives cross sections for the entire structure at the Kentland, Wells Creek, and Sierra Madera sites, which are all of comparable diameter. For each structure an estimated amount of erosional leveling has been given; these are based on estimates given by the various authors. However, recently Offield and Pohn (1977) have questioned the accuracy of the erosional estimate of 600 m given for the Sierra Madera structure. Based on their finding that relatively little erosion has occurred at the Decaturville structure, they argue that erosion at Sierra Madera may be much less than previously estimated (Wilshire et al., 1972). In fact, until more field evidence is available, the amount of erosion at Kentland is still a matter of conjecture (the same can probably also be said for Wells Creek). However, based on scaling from structures such as Flynn Creek (Roddy, 1977c) it appears that the relative amount of erosional leveling has been greatest at the Kentland structure (i,e., the Kentland site possibly displays material from a deeper level in the impact structure

Figure 25.

Simplified cross sections of the central uplifts of the Kentland and Wells Creek structures. Wells Creek diagram taken from Wilson and Stearns (1968). Although the two structures involve similar sedimentary rock sequences, the central uplift at Wells Creek covers an area some nine times larger than at Kentland. The erosional level is not thought to be drastically different for each structure, therefore the difference in the sizes of the uplifts is presumed to reflect some basic impact parameter possibly involving differences in target or projectile properties.

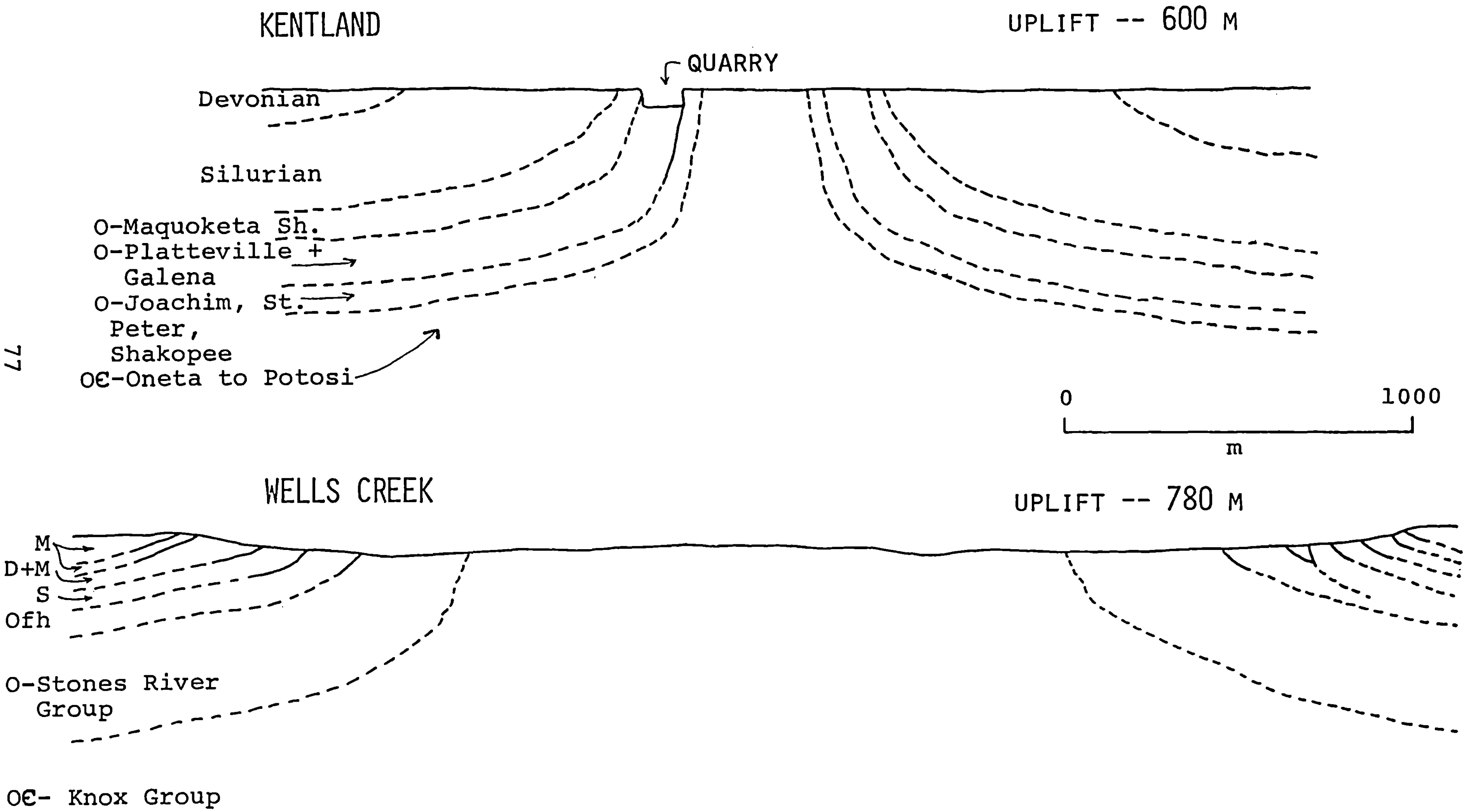
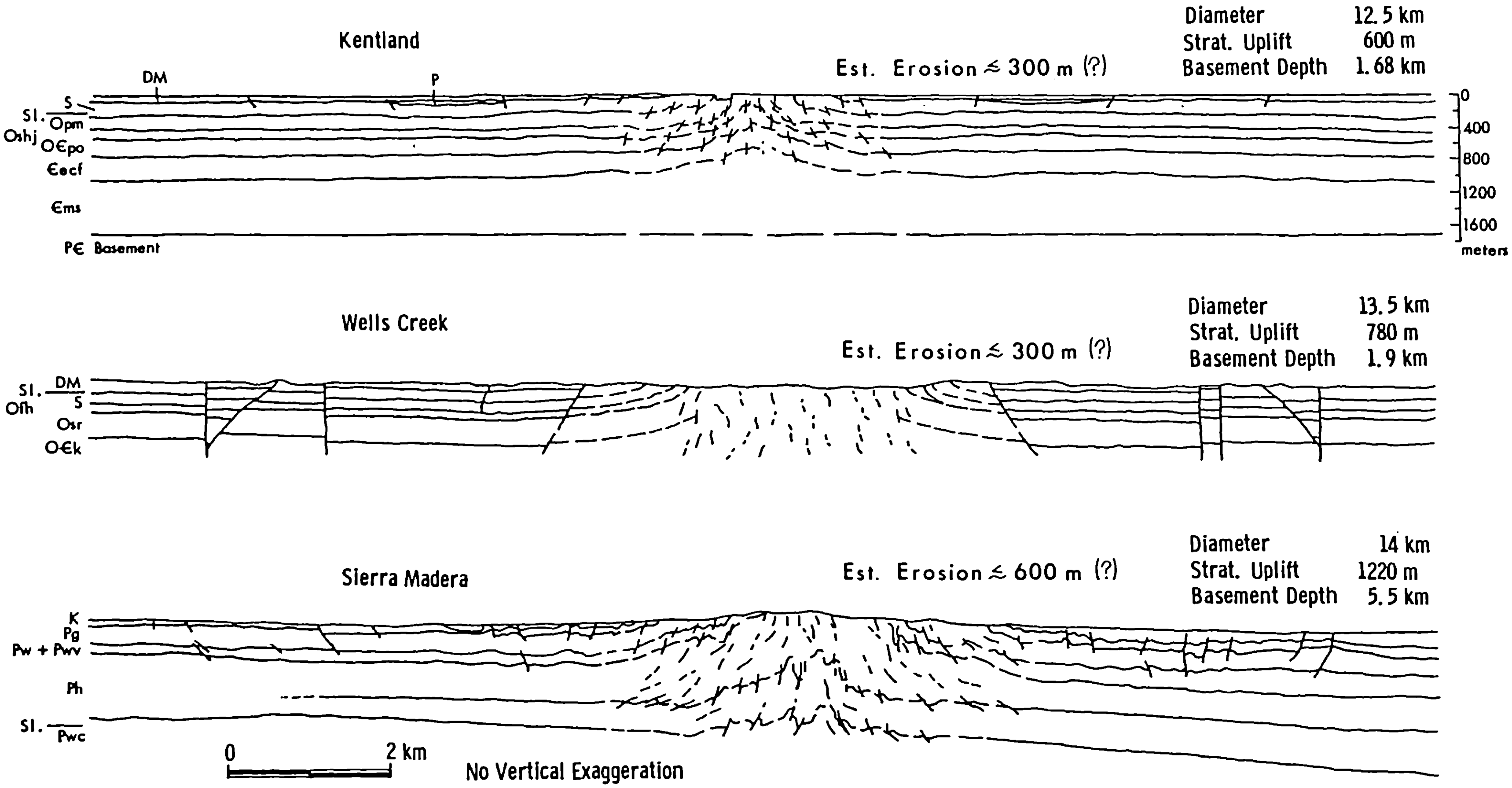

KENTLAND
UPLIFT -- 600 M
QUARRY
Devonian
Silurian
O-Maquoketa Sh.
O-Platteville +
Galena
O-Joachim, St.
Peter,
Shakopee
O€-Oneta to Potosi
0
1000
m
WELLS CREEK
UPLIFT -- 780 M
M
D+M
S
Ofh
O-Stones River
Group
O€- Knox Group

Figure 26.

Cross sections for three impact structures of approximately the same size developed in sedimentary rock. a) Kentland, Indiana: P-Pennsylvanian; DM-Devonian and Mississippian; S-Silurian; Opm-Ord. Platteville Group to Maquoketa Sh.; Oshj-Ord. Shakopee Dolomite to Joachim Dol.; OЄpo-Ord. and Cambrian Potosi Dol. to Oneota Dol.; Єecf-Cambrian Eau Claire to Franconia Ss.; Єms-Cambrian Mt. Simon Ss. b) Wells Creek: DM-Devonian and Mississippian; S-Silurian; Ofh-Ord. Fernvale Ls. and Hermitage Form.; Osr-Ord. Stones River Group; OЄk-Ord. Knox Dol. Diagram modified after Wilson and Stearns, 1968. c) Sierra Madera: K-Lower Cretaceous; Pg-Permian Gilliam Ls.; Pw + Pwv-Permian Word Form.; Ph-Permian Hess Form.; Pwc-Permian Wolfcamp Form. Diagram modified after Wilshire et al.,1972. Erosional estimates are uncertain but probably do not exceed the values listed. Details are not evident on these sections, but at their present erosional levels structural differences do occur in the central uplifts of each of these impact sites. Although erosional level could account for some of these differences, it appears that other impact parameters, such as target material properties, could play a role in determining impact crater structure.


Kentland
Diameter 12.5 km
Strat. Uplift 600 m
Basement Depth 1.68 km
Est. Erosion ≲ 300 m (?)
DM
P
S
Sl.
Opm
Oshj
O€po
€ecf
€ms
P€ Basement
0
400
800
1200
1600
meters
Wells Creek
Diameter 13.5 km
Strat. Uplift 780 m
Basement Depth 1.9 km
Est. Erosion ≲ 300 m (?)
Sl.
DM
S
Ofh
Osr
O€k
Sierra Madera
Diameter 14 km
Strat. Uplift 1220 m
Basement Depth 5.5 km
Est. Erosion ≲ 600 m (?)
K
Pg
Pw + Pwv
Ph
Sl.
Pwc
0
2 km
No Vertical Exaggeration

than either Wells Creek or Sierra Madera). The basis for this statement comes from a comparison of the known maximum amount of stratigraphic uplift versus the apparent diameter (or diameter of disturbance) for craters developed in sedimentary rock sequences (Table 3). The results from two experimental, high-explosive produced craters are also listed for comparison. It can be seen that although target characteristics may play a role in uplift formation (as discussed below), the uplift/diameter of disturbance ratios are very similar for those craters showing little erosion (generally ranging bewteen 1:7 - 1:9). The ratio for the Kentland structure is approximately 1:21, the highest of the tabulated values. Although the cause for such a high value could be due to some unrecognized basic cratering principle, the writer believes this ratio reflects only a greater degree of erosional leveling at Kentland as compared to most other sites.

Referring again to Fig. 26, it is to be noted that although these structures involve similar type sequences of carbonate, sandstone, and shaley units and have approximately the same overall diameter of disturbance, some structural differences do occur in the central uplifted regions of each. Very similar target rocks occur at the Kentland and Wells Creek sites, except for portions of the Upper Cambrian sequence (at Kentland it includes 1015 m of sandstone whereas at Wells Creek this portion of the Cambrian is composed of dolomite (Fig. 25). At

TABLE 3.

SITE	STRATIGRAPHIC UPLIFT: APPARENT DIAMETER (OR DIAMETER OF DISTURBANCE*)	PRINCIPAL LITHOLOGIES	EROSION (EST.)
a) KENTLAND	1:21*	carb.,ss.,sh.	300 m (?)
b) WELLS CREEK	1:17*	carbonates	300 m (?)
c) SIERRA MADERA	1:12*	carb., ss.	50-600 (?)
d) DECATURVILLE	1:11*	carb., ss.	50 m
e) STEINHEIM	1:9	carbonates	10 m
f) FLYNN CREEK	1:7.8	carbonates	15 m
g) GOSSES BLUFF	1:7*	sandstones	50-75 m
h) SNOWBALL	1:11	alluvium	negligible
i) DISTANT PLAIN 6	1:7	alluvium	negligible

their present erosional levels, stratigraphic uplifts at both sites are of the same order of magnitude, but the central uplift at Wells Creek occupies an area more than nine times larger than the equivalent one at Kentland. The area occupied by the uplifts at Wells Creek and Sierra Madera are similar, but the amount of uplift at Sierra Madera is significantly larger. The criteria used for determining the diameters of equivalent uplifted areas were points where the styles and intensity of deformation were similar in each structure.

The cause of these differences could be the result of differences in the properties of the layered substrate at each impact site. As the initial cavity expanded after impact, it encountered the differing sedimentary rock types (e.g., more mobile sand or shale units as compared to the more competent carbonates) at different levels in each structure. Alternatively, projectile characteristics, such as strength and impact velocity and the resulting changes in the energy imparted to the rock, could have been different at each site; however, this does not strictly conform to the ideas presented by Baldwin (1963) and others relating crater diameter to the energy of impact. Another factor which could have been an influence is the depth at which the shock wave encountered a significant physical (seismic) discontinuity (e.g., basement surface). This surface occurs at different levels for each of these structures. Various implications of physical discontinuities, large and small, have been discussed by Short (1965), Dence et al. (1965) and Ullrich (1975). The presence of an inland sea at the time of formation of the Kentland structure is a possibility. Depending on the depth of water at the time of impact, such a body of water could significantly affect the cratering process, as discussed by Roddy (1977a). Since no extensive work has been done on the consequences of impact into a shallow sea and because there is no evidence at present to argue either way for the presence of water, no conclusions can be made at this point. Due to the complex nature of the impact process, all of the above features could play a role in determining differences in the uplift structure. More work will be needed on the mechanics of central uplift formation before specific differences in projectile and target media properties can be related to differences in impact crater structures.

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