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The Gravity Field and Tectonics of Illinois

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ABSTRACT

One-mile-grid gravity measurements made in Illinois from 1961 to 1973 define the gravity field over the state to within ±0.5 milligal. Configuration of the Bouguer gravity field is primarily a function of the density distribution in the earth's upper mantle and in the crust below the surface of the crystalline basement. It is also influenced to a lesser degree by relief on the basement surface and by differences in density within the sedimentary rocks. The differences in density are caused by structure, facies changes, and relief on unconformities, especially the unconformity beneath the glacial drift.

Bouguer gravity anomaly values range from about -45 milligals in northern Illinois to about +20 milligals in southern Illinois near the northern edge of the Mississippi Embayment. Low gravity-field intensities are also located between axes of major structural features. Moderately high gravity intensities are located in the center of the Illinois Basin and along the axes of the Kankakee Arch and the La Salle Anticlinal Belt.

It is speculated that the earth's crust beneath the areas now occupied by the Illinois, Black Warrior, and Reelfoot Basins was intruded late in Precambrian time by plutons of mafic magma during an episode of incipient rifting. During plutonism, uplift occurred at the rifts while regions flanking the rifts received a thick blanket of coarse-grained, arkosic clastic rocks similar to those deposited adjacent to the Keeweenawan rift system in Minnesota. Regions between incipient rifts were buried at depths sufficient to produce linear belts of low-grade metamorphism and accompanying increases in density of 1 or 2 percent. Upon termination of the rifting episode, the rift region collapsed under the load of the high-density plutons, sedimentation in the interrift regions abated as these regions bulged upward in response to the subsidence of the rifts, and a new phase of sedimentation began in the basins formed by the collapsed rifts.

As a consequence of rifting, heating, bending, and burial, the primordial continental crust increased in density (from 2.67 gm/cc). Areas in basin centers attained mean densities greater than 3.2 gm/cc, axes of present arches (interrift belts) increased to 2.75 to 2.80 gm/cc, and small intrusions flanking the axes of the interrifts reached 2.91 to 3.40 gm/cc. Isostatic adjustment and elastic bending provided further control on basin development.

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A disruptive event associated with continental breakup in Mesozoic time resulted in renewed rifting that extended from the southern edge of the continent northward to southern Illinois. Reactivation of plutonism further increased mean densities south of the Illinois Basin and contributed to development of the Mississippi Embayment. Gravity anomalies associated with plutonism in the embayment are second in intensity only to the Midcontinent Gravity High.

INTRODUCTION

The Illinois State Geological Survey has sponsored a 12-year program of gravity-field measurements in Illinois; the program was completed in April of 1973. This report describes Illinois' gravity field and explains its relationship to density distributions in the subsurface.

Gravity measurements in Illinois are described as "second generation" (McGinnis et al., 1972) because they permit both qualitative and quantitative analyses of broad regions (thousands of square miles) of the earth's crust. Heretofore analyses were restricted to regions of more limited areal extent (hundreds of square miles). In second-generation studies, many broad crustal anomalies are included within a region of high-precision coverage. The area of Illinois is 55,947 square miles. Within it, approximately 50,000 gravity stations were occupied, an average of one station every 1.1 square miles. Gravity readings within a 15-minute quadrangle are generally accurate to within ±0.5 milligal. The Bouguer Gravity Map of Illinois (plate 1) is contoured at a 5-milligal interval. A more detailed portrayal of the Bouguer gravity field of Illinois (contour interval = 0.5 milligal) will be available from the Survey later as a six-map set (scale = 1:250,000). Bouguer gravity anomaly values were calculated using mean sea level as the base elevation and 2.35 gm/cc as the density of the surficial rocks. Theoretical gravity values were determined using the 1930 International Formula (Nettleton, 1940).

Gravity studies completed during the course of the present program include those of Brahana (1968); Ervin and McGinnis (1974, 1975b); Georgiou (1970); Heigold (1970); Heigold, McGinnis, and Howard (1964); Langan and Speed (1973); McGinnis (1965a, 1965b, 1966a, 1966b, 1969, 1970, 1972); McGinnis and Ervin (1974); McGinnis et al. (1972); McGinnis, Kempton, and Heigold (1963); McGinnis and Leeds (1974); Schafersman (1973); and Segar (1965). These studies have provided a general knowledge of the association between the geology and the gravity field and have revealed significant differences in the earth's crust between southern and northern Illinois.

In Illinois, gravity measurements were initially made by exploration companies in search of hydrocarbons; however, these data were not available to the public. Measurements of the regional gravity field on a 10-mile grid were made in the late 1950's by G. P. Woollard and his students from the University of Wisconsin. These were incorporated and published in the Bouguer Gravity Map of the United States by Woollard and Joesting (1964). Subsequently, 1-mile-grid gravity surveys were established in search of gas storage structures by Jack Mack and Associates of Madison, Wisconsin; these data were contributed to the Illinois gravity project and have been incorporated in this and earlier reports.

Gravity studies by the Illinois State Geological Survey were begun in 1961. Earliest measurements were made in north-central Illinois (McGinnis, Kempton, and Heigold, 1963) in an attempt to define bedrock channels buried beneath low-density glacial sediments. It was found that gravity measurements made during this program were sufficiently precise to map buried bedrock valleys in northern Illinois in places where bedrock consists of high-density carbonate rocks. Later work, however, showed that where bedrock consists of Pennsylvanian strata, as in central Illinois, gravity techniques were not successful for mapping buried bedrock valleys, even where deep valleys such as the Mahomet-Teays Bedrock Valley were involved.

Early studies of the gravity field in northern Illinois (McGinnis, 1966a) showed an inverse relation between the gravity field and structure over the Sandwich Fault Zone (fig. 1). Such a relationship showed the applicability of gravity-field studies to analyses of tectonics and structure. Hence, it was decided to extend coverage to all of Illinois. Systematic annual surveys were made from 1961 through 1973 during summer months. In late 1973, approximately 300 gravity stations in the city of Chicago and its suburbs were provided to the program by Robert C. Speed of Northwestern University to essentially complete the state gravity survey.

Worden, World-Wide, and LaCoste-Romberg gravity meters were used in the course of the program. The Illinois base station network (McGinnis, 1966b) was established with LaCoste-Romberg meter G-4, which was lent to the Survey by the U.S. Army Map Service, Gravity Division, through the cooperation of Robert Iverson. To facilitate the tying of data to the base station network and to aid in reducing and interpreting the data, the data were sorted into subsets based upon the 289 fifteen-minute quadrangles covering Illinois.

The interpretations of observed gravity anomalies made in this paper are those which seemed most reasonable to the authors. Alternative interpretations are possible in some cases, but they are not discussed here.

Acknowledgments

The authors wish to thank the many individuals who have aided in this study, particularly Clifford C. Clark, who assembled most of the half-milligal contour maps; John C. Georgiou, who first modified the Talwani modeling program for Northern Illinois University computers; those who contributed large amounts of gravity data, such as Jack Mack, Robert C. Speed of Northwestern, Emil Mateker of Washington University, St. Louis, and Christopher Schmidt of Knox College, Galesburg, Illinois, who lent his World-Wide gravity meter; and the many students who spent their summers traversing every mile of Illinois roads. Some of the students are Thomas Jensen, Dale Pederson, J. V. Brahana, Brian Hirst, S. S. Tikrity, R. L. Segar, and Robert Ouellette. Our appreciation is finally extended to Northern Illinois University, at whose computer center a considerable amount of the data was processed.

REGIONAL GEOLOGY

Aspects of Illinois geology especially pertinent to an understanding of the gravity field are briefly reviewed below. For a complete bibliography and index of Illinois geology through 1965, see Willman et al. (1968). Swann (1968) and

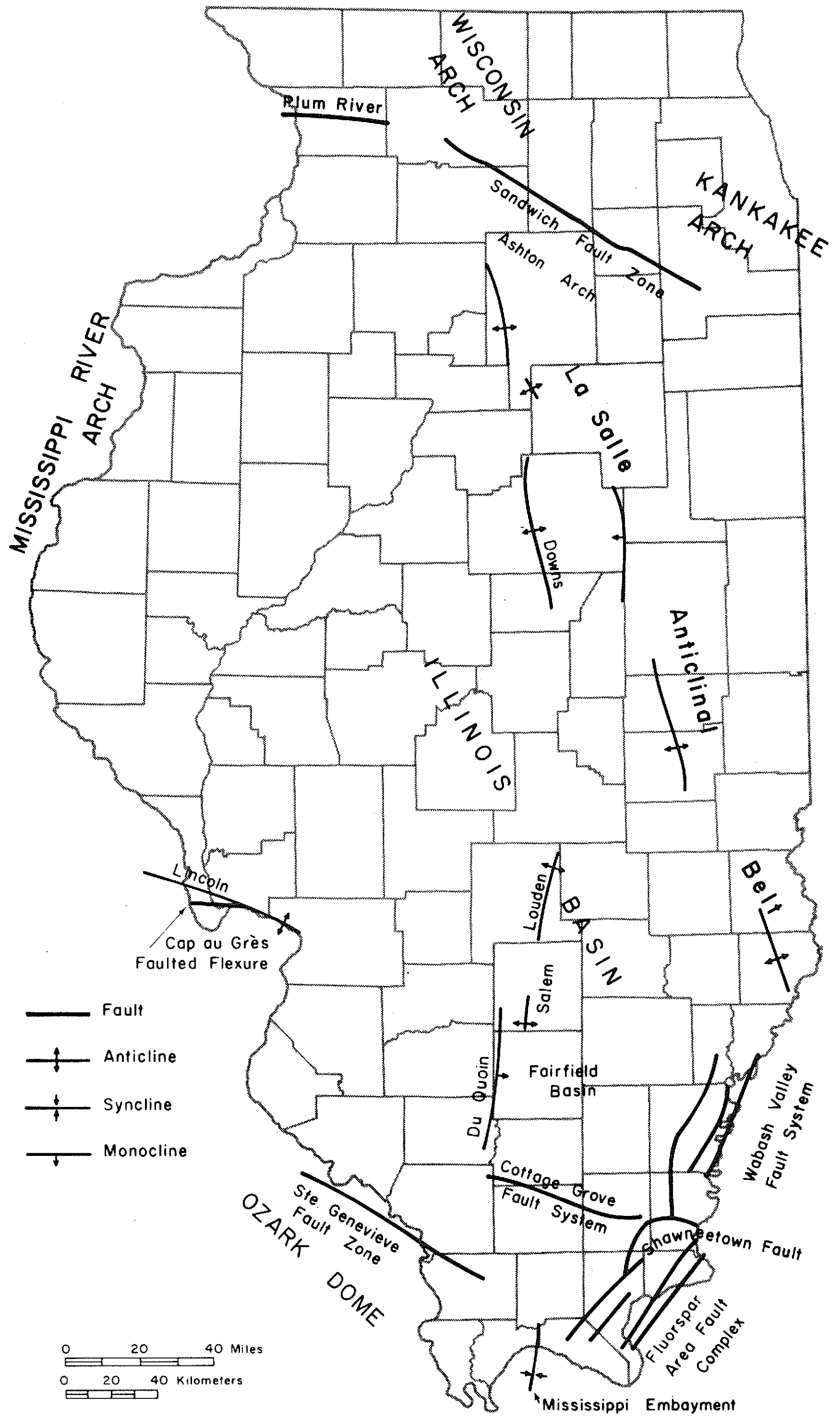

Fig. 1a - Major geologic structures in Illinois (modified from Smith, 1975).

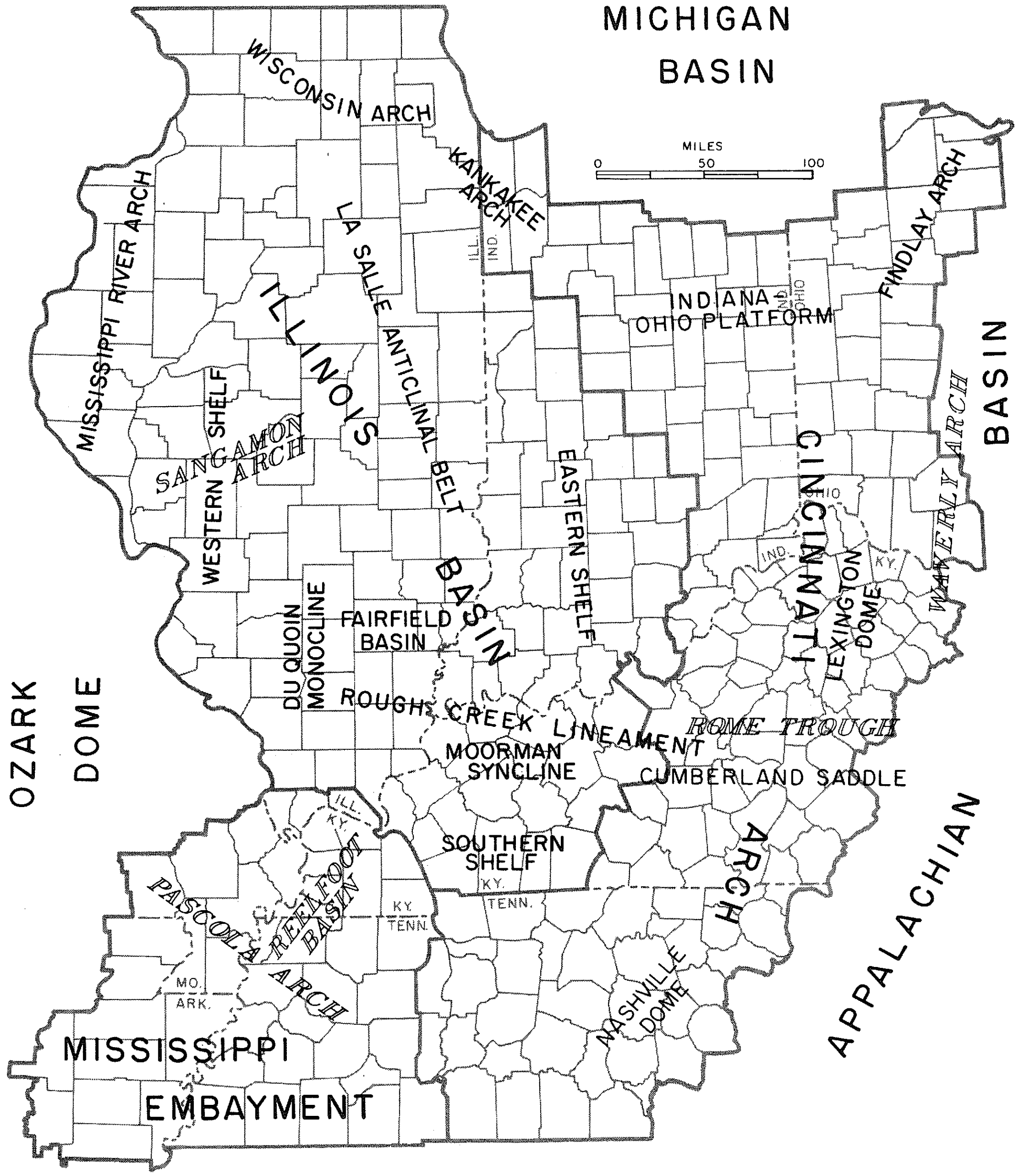

Fig. 1b - Structural features of the Eastern Interior Region of the United States. Features obscured by later structural movements are shown in italics. Modified from a figure prepared by H. M. Bristol and T. C. Buschbach in cooperation with Elwood Atherton, L. E. Becker, T. A. Dawson, Howard Schwalb, E. N. Wilson, A. T. Statler, and J. H. Buehner for publication in AAPG Memoir 15 (Bond et al., 1971). Used with permission of the American Association of Petroleum Geologists.

Atherton (1971) describe the tectonic evolution of the Illinois region as interpreted from stratigraphic evidence. See also the Geologic Map of Illinois by Willman and others (1967).

Illinois is located on the craton of the continental interior. The earth's crust underlying the state is typical of continental crust worldwide. The Precambrian surface in Illinois is composed mainly of granitic and rhyolitic rocks older than 1.2×10^9 years (Lidiak et al., 1966). The basement is overlain by 2,000 to 15,000 feet of Paleozoic sediments, which are in turn overlain by thin wedges of Cretaceous and Tertiary sediments in the extreme south, and by Cretaceous deposits that are locally preserved in western Illinois (Willman and others, 1967). Throughout most of the state, from the Wisconsin border in the north to Carbondale in the south, the Paleozoic rocks are covered by Pleistocene drift.

Stratigraphy

In Illinois, basement rocks of Precambrian age consist of red, coarse-grained granites and reddish rhyolites. Only 21 boreholes have reached basement (Bristol, 1971). The earth's crust is approximately 35 kilometers thick in northern Illinois, whereas it is more than 45 kilometers thick in the south, where the lower crust is more mafic (Ervin and McGinnis, 1974).

Paleozoic strata range in age from Cambrian to Pennsylvanian. Thick, massive, arkosic Cambrian sandstone (Mt. Simon) rests on basement rocks in northeastern Illinois. The Mt. Simon thins in all directions from its depocenter in northeastern Illinois. In general, coarse-grained sandstones and dolomites of early Paleozoic time give way to fine-grained clastic sediments, carbonates, and sediments rich in organic matter of late Paleozoic time. The younger sediments form the bedrock surface in central and southern Illinois, whereas the older Paleozoic strata underlie the glacial drift in northern and parts of western Illinois.

Structure

Geologic structure in Illinois is dominated by the broad intracratonic depression known as the Illinois Basin (Bell et al., 1964). When the basin formed, it was located on a continental shelf that subsided differentially under the load of basinal sediments. The Illinois Basin, as observed today (fig. 1), is centered in southeastern Illinois and, in regional terms, is bordered by the Wisconsin Arch on the north, the Mississippi River Arch on the northwest, the Ozark Dome on the southwest, the Pascola Arch on the south, the Cincinnati Arch on the east, and the Kankakee Arch on the northeast.

A major structural lineament in the basin is the La Salle Anticlinal Belt, which extends from La Salle County in north-central Illinois southeastward to southeastern Lawrence County near Vincennes, Indiana, on the Wabash River. The anticlines in the belt are asymmetrical, dipping steeply (locally up to 1,000 ft/mi) to the west and gently (~100 ft/mi) to the east. The Fairfield Basin, the deepest part of the Illinois Basin in Illinois, lies to the west. The Du Quoin Monocline, a steeply eastward-dipping structural feature having a north-south axis marks the western boundary of the Fairfield Basin. All of these structural features are reflected by anomalies in the gravity field.

In the Illinois Basin, four large faults with vertical displacements greater than 500 feet have been observed. Some strike-slip motion in southern and western

Illinois has been suggested by Cole (1966) and Heyl (1972). However, Gibbons (1972) asserts that interpretations of strike-slip are erroneous and that all motion on faults can be explained by vertical displacements.

These faults (fig. 1a) were reviewed by McGinnis and Heigold (1961) and are briefly described as follows:

1. Sandwich Fault Zone — This fault zone, southwest of the Kankakee Arch, extends for 150 miles from south of Joliet to near Oregon. It is downthrown to the northeast with maximum vertical displacement of more than 900 feet near its center. The fault has been recognized by many investigators on the basis of both geological and geophysical data (Willman and Payne, 1942; Willman and Templeton, 1951). Movement along the Sandwich Fault Zone did not occur until after the Silurian and was perhaps coincidental with movement along the La Salle Anticline. Major movements along the La Salle Anticline occurred during early Pennsylvanian time and after the Pennsylvanian (Cady, 1920; Payne, 1939; Clegg, 1965; Atherton, 1971).

2. Cap au Grès Faulted Flexure — This structural feature, which is located in eastern Missouri and in western Illinois, north of St. Louis, marks the southern boundary of the highly asymmetrical Lincoln Fold, which reaches its maximum development in Lincoln County, Missouri (Krey, 1924). In Illinois this structural feature has been mapped as a faulted flexure whose vertical displacement has been estimated to be as much as 1,000 feet. Cole (1966) has suggested that there is a component of strike-slip on this fault.

3. Rough Creek Lineament — This lineament consists of three component parts: the Rough Creek Fault Zone (Kentucky), the east-west portion of the Shawneetown Fault Zone (Illinois), and the Cottage Grove Fault System (Illinois). Heyl (1972) refers to this lineament as the 38th parallel lineament. Displacement along these systems is vertical, although portions of the Shawneetown Fault are dominated by high-angle thrust faulting. On the Shawneetown Fault throw is as great as 3,000 feet, down to the north. Heyl (1972) suggests right-lateral movement as much as 30 miles along the 38th parallel lineament; however, data presented here do not indicate such displacement. If anything, offsets in gravity lineaments in southern Illinois would suggest left-lateral displacement. Slickensides in the Rough Creek Fault Zone of Kentucky do not show lateral movement (James Palmer, personal communication, 1975). Vertical displacements on the Shawneetown Fault probably occurred late in Paleozoic time.

4. Ste. Genevieve Fault — This fault extends northwestward across Union County, Illinois, and crosses the Mississippi River just north of Grand Tower in southwestern Jackson County, Illinois (Meents and Swann, 1965). Vertical displacement is greater than 1,000 feet, and the downthrown side is to the north. Movement on the fault probably began as early as Devonian time (Tikrity, 1968).

Other fault systems in Illinois include some small faults with minor displacements and some with displacements as great as those of the major faults mentioned above. These fault systems include:

1. Fluorspar Area Fault Complex — In general, the faults in this area trend northeast from the Cretaceous cover to the Shawneetown Fault. The faults are normal, with displacements ranging from a few feet to more than a thousand feet. Structural features, such as the Rock Creek Graben, show characteristics generally associated with a tensional stress field. Present stresses probably remain tensional (Street, Herrmann, and Nuttli, 1974). McGinnis (1970) suggests the existence of a large vertical component of stress on the basis of a regional +20 milligal free-air gravity anomaly. The faulting appears to extend under the Cretaceous cover, roughly paralleling the axis of the embayment.

2. Wabash Valley Fault System — These high-angle normal faults have maximum vertical displacements of several hundred feet (Harrison, 1951; Bristol, 1968). The present-day stress field (Street, Herrmann, and Nuttli, 1974) suggests that the Wabash system is subject to stresses different from those in the Mississippi Embayment.

3. The presence of other major faults in Paleozoic strata has been suggested, but remains undocumented. Paleozoic strata in some parts of Illinois are capable of enduring considerable flexure without fracture (Bristol and Buschbach, 1973),and some subsurface structural features have been misinterpreted as faults because of steep dips. In the crystalline basement there may be faults associated with such steeply dipping strata.

Geologic History

The decipherable geologic history of Illinois began late in Precambrian time with crystallization of the granitic basement. Fractionation of continental crust through convective processes resulted in a heterogeneous crust, which was later modified by tectonism. Broad epeirogenic differential uplift of the crust and active marine erosion resulted in deep truncation of the Precambrian rocks.

Broad and gentle differential downwarp of the crust probably began late in Precambrian time in basin areas of Illinois, resulting in the deposition of a thick blanket of arkosic nearshore marine sandstones. The Kankakee Arch separating the Illinois Basin from the Michigan Basin rose in northern Indiana at the close of Canadian time (early Ordovician) (Atherton, 1971).

In addition to broad vertical displacements on a basinwide scale, there is some geophysical evidence that differential vertical movements of crustal blocks within the larger features also occurred (McGinnis, 1966a). Block faulting of the crust, accompanied by gentle draping and folding, probably was involved in these displacements, apparently without faulting in the overlying sediments.

Late in Paleozoic time important tectonic events in the Illinois Basin occurred in response to the deformation taking place in the southern Appalachians and in the Ouachitas along the continental edges. Notable examples are activities along the La Salle Anticlinal Belt and the Du Quoin Monocline (Atherton, 1971). By the end of Paleozoic time, compressive stresses acting on the Appalachians and Ouachitas had ceased, and the rifting and continental separation of Triassic time began. As the Gulf of Mexico widened and the fracture zone separating the southern Appalachians from the Ouachitas was eroded by drainage from the continental interior, erosion continued in Illinois.

In the complexly faulted and mineralized area of Hardin, Pope, and Johnson Counties in southern Illinois, the faults cut Pennsylvanian strata and are covered by Gulfian (upper Cretaceous) strata. Events that occurred during this interval cannot be dated more closely by stratigraphic evidence in the area.

However, early Permian rock may also have covered the region, as Permian marine sediments in southeastern Ohio and bordering states probably represent a brief invasion of the western seas during Permian time. The absence of early Mesozoic, Triassic, and Jurassic sediments in the Mississippi Valley indicates that the region was emergent and subject to erosion during those times. The erosion of a surface with low relief—the sub-Cretaceous peneplain with a local thick soil (the Little Bear Soil)—across several thousand feet of strata on the flanks of structural features, particularly the La Salle Anticlinal Belt, and the degree of carbonization of Pennsylvanian coals, which indicates erosion and complete removal of a mile or more of sediment, would seem to have required the major part, if not all, of Mesozoic time before late Cretaceous. Therefore, the major deformation probably occurred at the end of the Paleozoic Era, a time of major deformation in the Appalachian Region (Willman et al., 1975).

Mafic dikes and sills in southern Illinois have an average early Permian age of 265±15 million years, based on radioisotope studies (Zartman et al., 1967). Extensive faulting in southern Illinois followed intrusion of the dikes and preceded mineral deposition. The age of the Pascola Arch is obscure, but there is no evidence for the presence of the arch before Pennsylvanian time. The arch rose at about the close of Paleozoic time and was deeply truncated; more than 8,000 feet of strata had been eroded from its crest by the beginning of Tuscaloosa (late Cretaceous) time (Marcher, 1961), with the result that beds as old as Cambrian were exposed. Downwarping of the Mississippi Embayment has since depressed the Pascola Arch, and it now lies buried under Gulfian (upper Cretaceous) and Cenozoic deposits, which are as much as 3,000 feet thick in western Tennessee (Schwalb, 1969). A lead-alpha age determination on a monazite from a breccia on Hicks Dome (Trace, 1960) gave an early late Cretaceous age of 90 million to 100 million years, suggesting some activity at this relatively late date.

In middle to late Mesozoic time, mafic intrusions were injected at right angles to the edge of the continent into what is now the Mississippi Embayment. Subsidence of the Mississippi Embayment, possibly induced by the weight of the mafic intrusives, began in Cretaceous time (Ervin and McGinnis, 1975a). There is no conclusive evidence to suggest a common history of the intrusives in Illinois and those farther south in the embayment.

During early Cenozoic time, the embayment continued to subside, collecting the debris washed from the continental surface.

In most of Illinois, a topographic surface having minor relief developed on the Paleozoic bedrock. During Cenozoic time the surface of Illinois was finally altered to its present form by erosion and deposition associated with continental ice sheets.

REGIONAL GRAVITY

Because of the limited topographic relief in the state, the Bouguer and free-air gravity fields are similar in general configuration. Gravity anomalies, for the most part, are distributed in a patchwork or mosaic pattern characteristic of the midcontinent, although the large positive anomaly associated with the

Mississippi Embayment extends northward into southern Illinois (see fig. 2). Bouguer gravity anomaly values range from less than -45 milligals in the north to more than +20 in the south, reflecting the changing character of the basement geology (plate 1). Although gravity values generally increase to the south, local gravity relief, both north and south, is about the same.

Mean elevation in Illinois is about 600 feet, which would produce mean Bouguer gravity anomaly values of approximately -20 milligals, if one assumes that the earth's crust is in isostatic equilibrium. In northern Illinois, this is essentially the case, whereas in southern Illinois, mean gravity values are approximately 18 milligals too high. The presence of excess crustal mass is especially apparent in the south because it is near the deepest part of the basin, which is filled with sediment less dense than the basement. Therefore, it is probable that the anomalous excess mass lies in the igneous rocks of the crust or of the upper mantle and not in the sedimentary column.

Bouguer gravity anomalies in Illinois have widths as great as 60 miles. Anomalies vary from high-gradient, circular features, obviously associated with deep-seated intrusions of plug-like form, to broad, low-gradient features that represent crust having little lateral inhomogeneity. In general, the smaller, high-gradient features occur in areas of known Paleozoic structure, such as along the Kankakee Arch and the La Salle Anticlinal Belt.

The Bouguer gravity anomaly map (plate 1) is contoured on the basis of readings from each gravity station. The free-air gravity field could have been contoured in a similar manner, but the result would essentially have been duplication of the Bouguer field in a region as flat as Illinois. In our study, mean free-air anomalies, on the other hand, provide information that cannot readily be obtained from Bouguer data; the mean free-air gravity values express the isostatic, or mean vertical, stress field over that portion of the crust covered by the gravity survey. The free-air maps of Illinois, then, are a measure of the vertical stress field.

Free-air gravity anomaly maps of Illinois, based on mean free-air gravity anomaly values of one, four, and twelve 15-minute quadrangles, are shown in plates 2, 3, and 4, respectively. All show essentially the same configuration; however, the absolute values derived by averaging larger areas are smaller in magnitude. Anomalies having wavelengths smaller than about 25 miles are filtered out of the maps shown on plates 3 and 4.

Inspection of the free-air gravity anomaly maps reveals the fundamental differences between the earth's crust in northern and southern Illinois. In Illinois, negative free-air gravity anomaly areas (plate 2) occupy 53.6 percent of the total area and positive areas occupy 46.4 percent. Positive and negative areas are not evenly distributed. Only positive values are present south of latitude 38°15' N. North of this line, negative values predominate. Negative free-air values in northern Illinois are as low as -30 milligals, whereas positive free-air values in southern Illinois approach +30 milligals.

If the earth's crust in Illinois were allowed to come to isostatic equilibrium, the region south of 38°15' N. would subside until the mean free-air gravity field reached zero when averaged over areas 60,000 km^2 or more. It is known from the abundance of shallow earthquakes in southern Illinois that the earth's crust is not unusually strong here. It follows then that either relatively rapid subsidence is taking place here and the positive free-air gravity field is being diminished, or that the free-air gravity field is being maintained by a dynamic contemporary stress field contained in the asthenosphere.

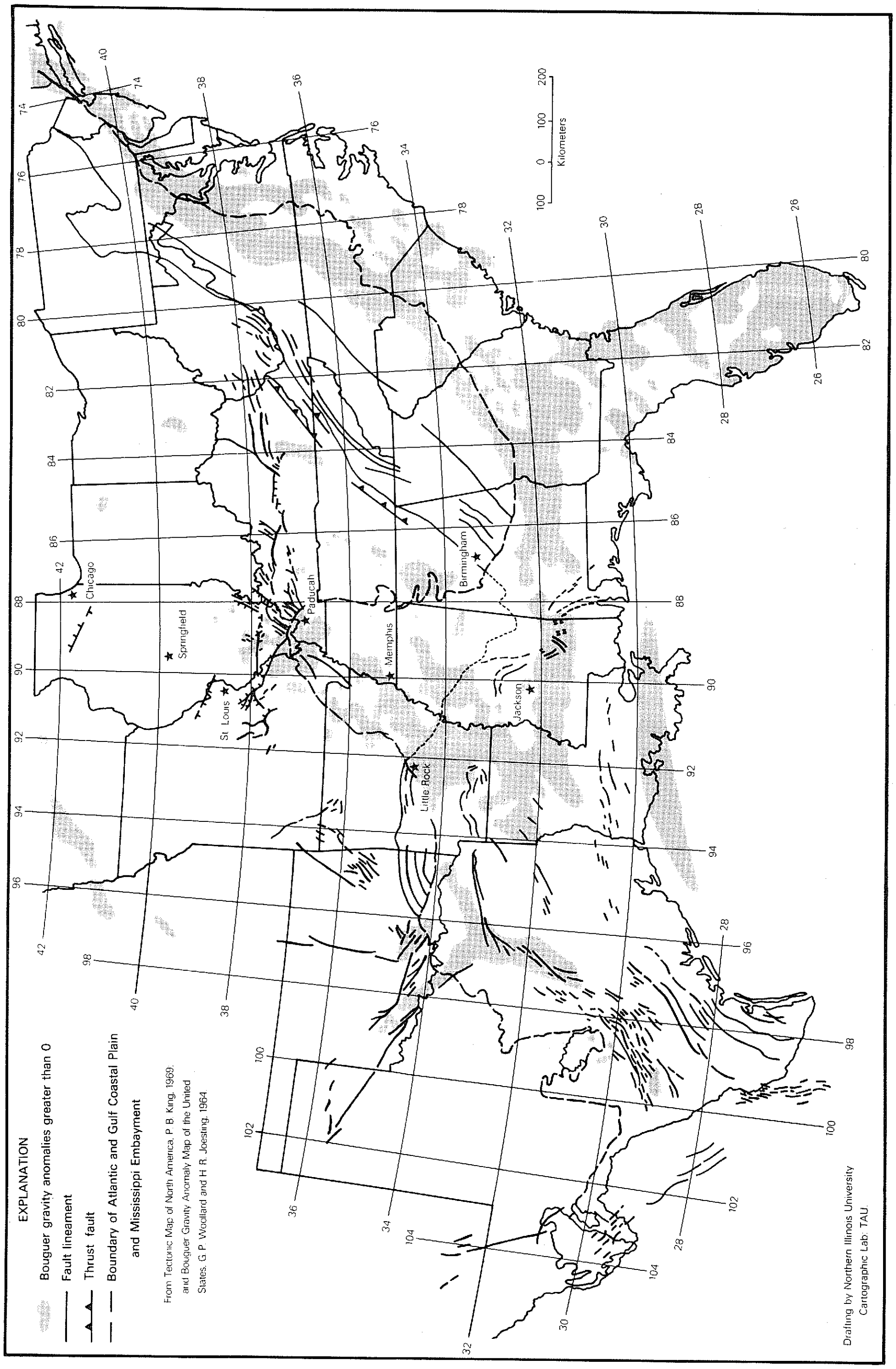

Fig. 2 - Positive Bouguer gravity anomalies in eastern United States. From Ervin and McGinnis (1975a). Used with permission of the Geological Society of America.

The age and petrology of concentrations of mass causing the anomalies in southern Illinois must remain speculative until deep drilling provides geologists with cores for direct observation. It appears, however, that mass concentrations have played a significant role in vertical deflection of the crust since the crust first crystallized, and that from all indications of present seismicity, they are still playing a role (McGinnis and Ervin, 1974).

Inspection of the Bouguer gravity anomaly map (plate 1) reveals high-gradient, relatively positive, closed gravity anomalies along the axes of the Kankakee Arch and the La Salle Anticlinal Belt. The higher-intensity anomalies near the axis of the Kankakee Arch are believed to be caused by intrusives of stocklike proportions. The axial mass excesses subsequently evolved into a Paleozoic axial graben as isostatic stresses prevailed (McGinnis, 1966a). A cause for increased densification along the axis of the arch will be proposed in the discussion.

In 1962 Woollard noted an elongate, positive Bouguer gravity anomaly in central Kentucky along the axis of the Cincinnati Arch, and he stated that the anomaly is too high and too narrow to be caused by the arch. The same argument is valid for the Bouguer gravity anomalies in Illinois located on the Kankakee Arch and along the La Salle Anticlinal Belt; however, as shown on plate 4, mean free-air gravity anomalies of twelve 15-minute quadrangles show regional positive anomalies straddling the La Salle Anticlinal Belt and the Kankakee Arch. The intensive axial positive Bouguer gravity anomalies, caused by the intrusive plugs, are contained within the regionally positive free-air gravity anomalies over the broad anticlinal and arch structures. The center of the Illinois Basin is marked by a broad positive free-air gravity anomaly of greater breadth and intensity than those anomalies found over the uplifts. Thus regions of both uplift and subsidence are associated with regional positive free-air gravity fields, a situation that at first sight appears to be contradictory. This situation will be further discussed.

CRUSTAL MODELS FROM BOUGUER GRAVITY ANOMALIES

Models of the earth's crust are constructed using Bouguer gravity anomalies taken from maps contoured at 0.5 milligal. Twenty-six anomalies in the state have been modeled (fig. 3) and are described here. These models (figs. 4 through 13) are in essential agreement with the anomalies modeled in previous publications. In the process of modeling anomalies in Illinois, it was found that several parameters of the models changed from north to south.

The significant difference in the character of the gravity field between the southern one-third and the northern two-thirds of Illinois (McGinnis and Ervin, 1974) suggests a basic variation in the nature of the crust between the two areas. The field in the north typically consists of broad wavelength anomalies (30 to 60 miles in diameter) of irregular form with amplitudes of approximately 20 milligals. The anomalies are known to be inversely related to basement structure (McGinnis, 1970) and are thought to result from differentiation of the crust at the time of formation.

South of approximately 39° N. latitude, the field changes abruptly to narrower, more discrete anomalies, ranging from 6 to 30 miles in diameter, with an average of about 15 miles. The amplitudes also are smaller, varying from 6 to 12 milligals. This area is underlain by a northward extension of the anomalous crust associated with the Mississippi Embayment (Ervin and McGinnis, 1974).

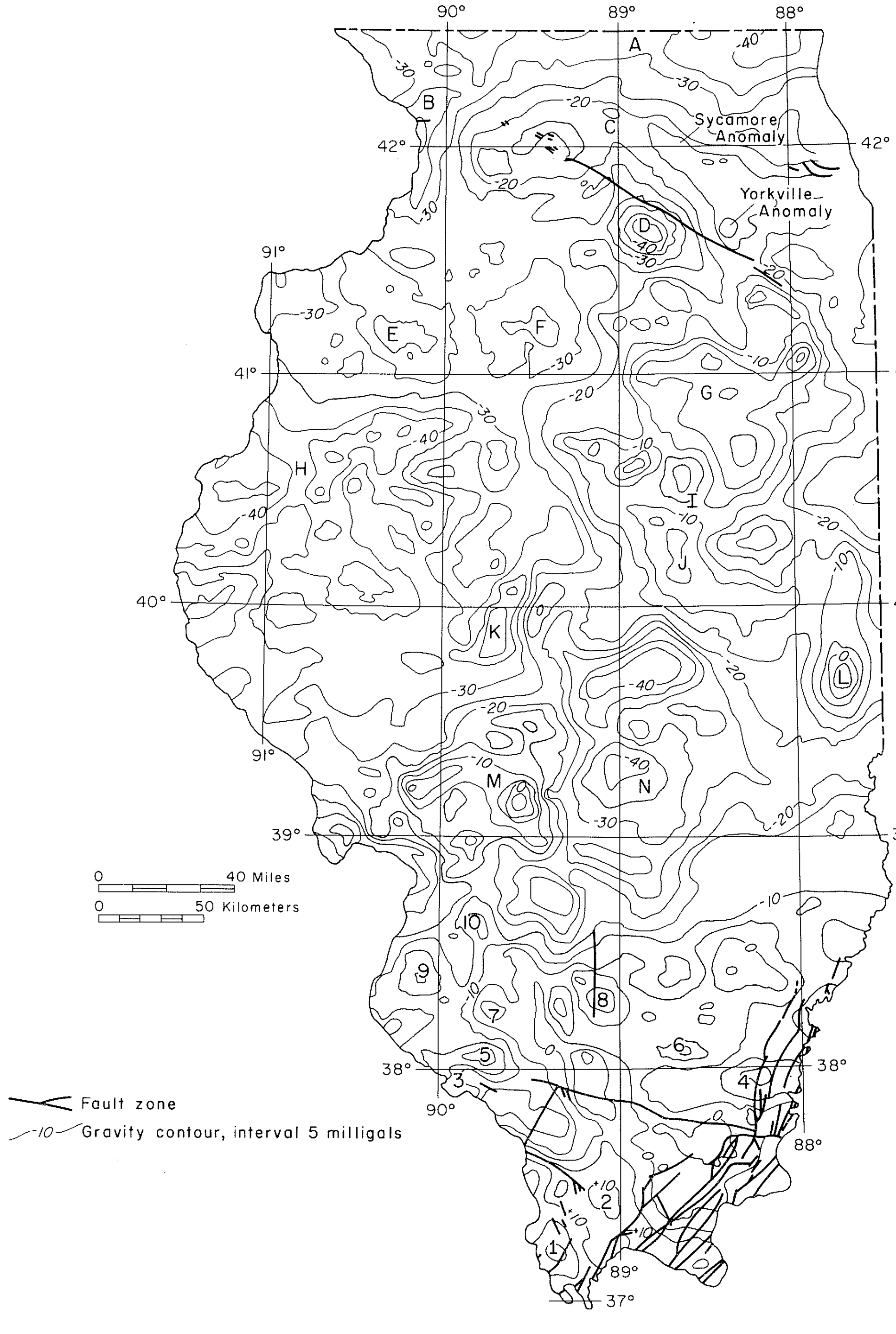

Fig. 3 - Locations of Bouguer gravity anomalies used in the calculation of theoretical models. Modified from McGinnis and Ervin (1974). Used with permission of the Geological Society of America.

Crustal models for southern and northern Illinois were computed by different methods, reflecting the different types of anomalies in the two regions (see figs. 4 through 13). The short-wavelength, discrete anomalies in the south are most easily modeled as individual bodies, either singly or in combinations of two or three. Models were computed for the 10 numbered anomalies in figures 4 through 11, and the results are summarized in table 1. Two additional discrete models in northern Illinois were calculated from the Sycamore and Yorkville Anomalies (figs. 12 and 13 and table 1).

During the modeling procedure, theoretical Bouguer gravity anomaly values were first computed at regular intervals on a grid or at points of actual field observations over a theoretical model. The model was then modified to produce a regionally correct calculated field. Final refinement of the model was made using one or two profiles selected to be both sensitive to the shape of the source body and as free from interference from other anomalies as possible. The model was deemed accurate if the difference between the observed and calculated fields was equal to or less than one milligal at all points on the profile(s).

The broader, geometrically complex anomalies of northern Illinois are more difficult to model as individual, discrete sources. Therefore, rather than attempt to model individual anomalies, we computed the regional mass distribution for the entire northern area as one model. Because short-wavelength anomalies in the gravity field are not reflective of major crustal distributions, it is

TABLE 1 - ANALYSES OF CRUSTAL MODELS FOR ILLINOIS
(Unless otherwise noted, base of model is at 18 miles.)

Anomaly no.	Anomaly name	Coordinates		Approximate amplitude (milligals)	Depth to top (miles)	Approximate horizontal dimensions (miles)		Density contrast (gm/cc)	Inferred density (gm/cc)	Comments
		Latitude	Longitude			N-S	E-W			
1	Cache	37°10'	89°20'	12	4.97	6.0	6.0	0.40	3.1-3.2	Top is 3.1 mi below surface of basement.
2	Mt. Pleasant	37°23'	89°01'	6	1.90	11.8	10.9	0.12	2.8-2.9	Base at 3.9 mi.
3	Chester	37°52.5'	89°45'	5	1.04	2.0	7.4	0.08	2.8-2.9	Computed concurrently with Steeleville and Tilden anomalies.
4	New Haven	37°50'	88°15'	7	2.21	11.8	39.5	-0.06	2.7-2.9	
5	Steeleville	38°00'	89°45'	10	1.04	11.8	16.8	-0.06	2.7-2.8	Computed concurrently with Chester and Tilden anomalies.
6	McLeansboro	38°07.5'	88°37.5'	8	2.27	4.0	11.8	-0.10	2.8-2.9	
7	Tilden	38°12'	89°40'	7	1.98	8.9	6.9	0.09	2.7-2.9	Computed concurrently with Steeleville and Chester anomalies.
8	Ashley	38°15'	89°07.5'	12	9.87	9.9	13.8	0.60	3.1-3.2	Top is 8 mi below surface of basement.
9	Waterloo	38°20'	90°05'	9	0.50	14.8	19.8	0.04	2.7-2.8	Irregular shape. Low-amplitude minimum northwest of anomaly was compensated by a mass with negative density contrast.
10	Lebanon	38°35'	89°45'	12 (?)	0.94	12.8	8.9	0.08	2.7-2.8	Minimum northeast of model was compensated by a mass with negative density contrast.
—	Sycamore	42°00'	88°35'	11	0.57	0.9	1.6	.75	3.4	Base at 22 mi.
—	Yorkville	41°37'	88°27'	14	0.82	5.7	2.9	0.15	2.9	Five masses were used to provide the regional gravity field.

(Text continues on p. 21.)

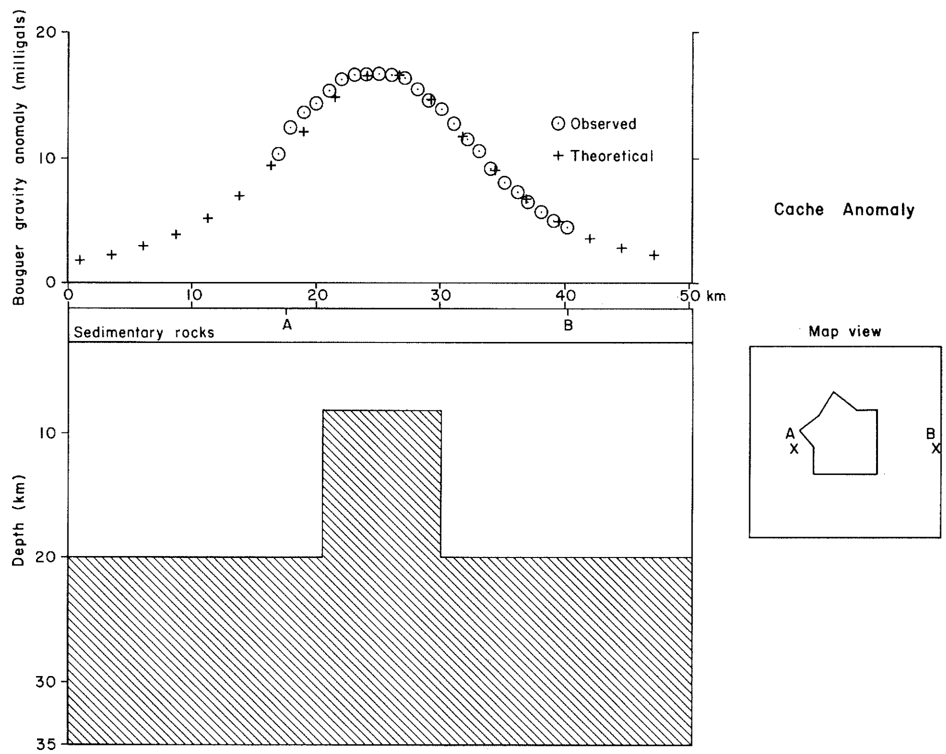

Fig. 4 - Model produced by the Cache Anomaly (Model 1).

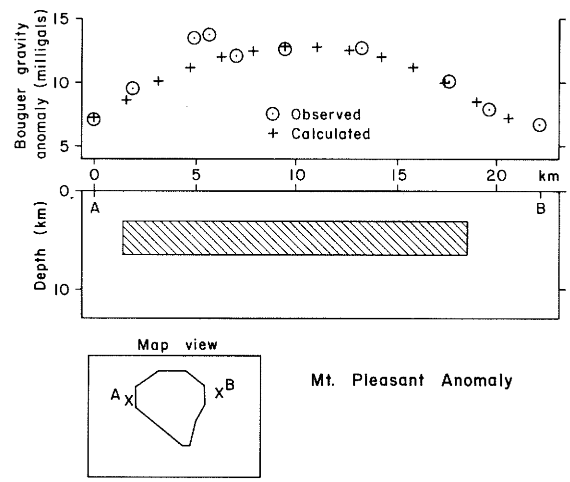

Fig. 5 - Model produced by the Mt. Pleasant Anomaly (Model 2).

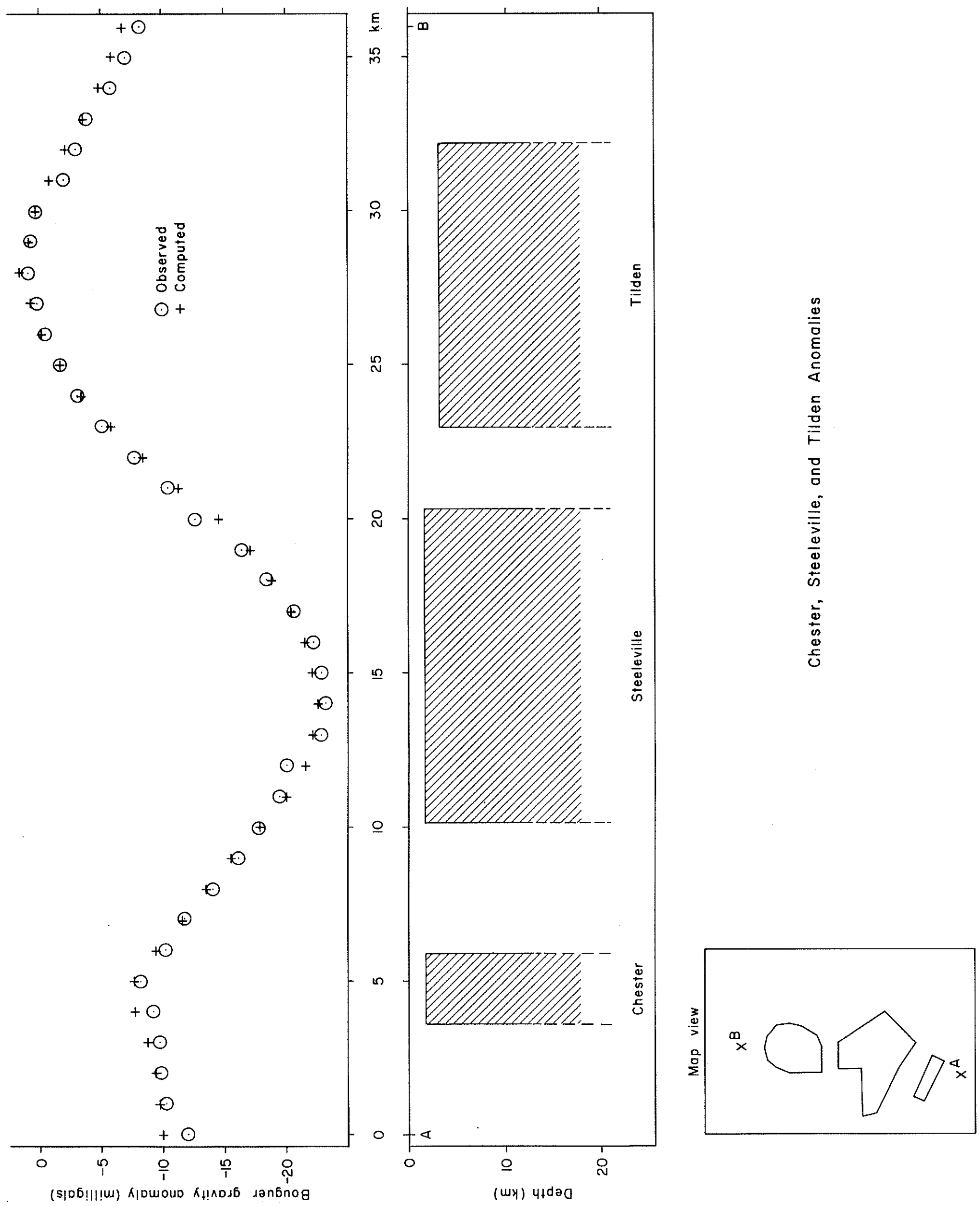

Fig. 6 - Models produced by the Chester, Steelville, and Tilden Anomalies (Models 3, 5, and 7).

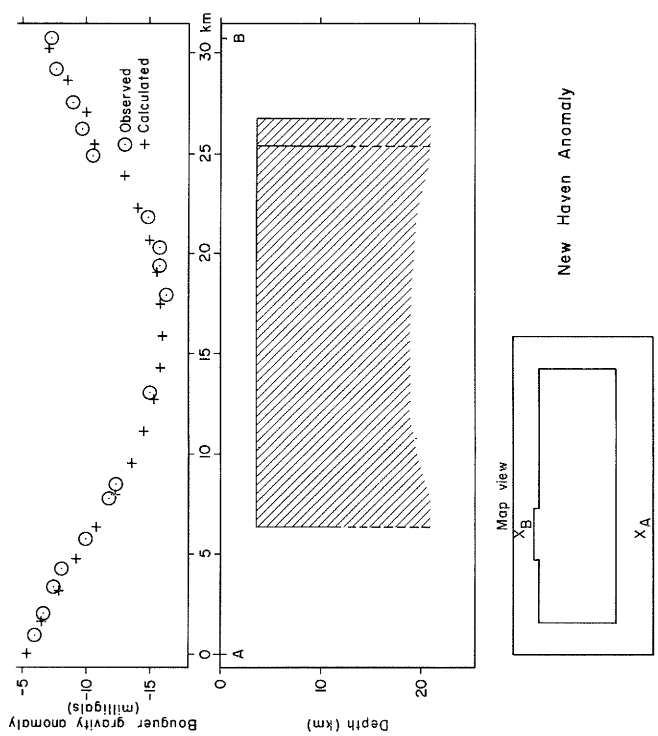

Fig. 7 - Model produced by the New Haven Anomaly (Model 4).

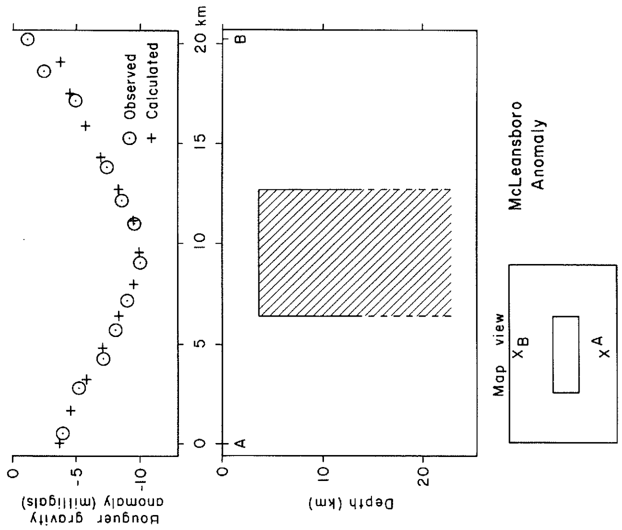

Fig. 8 - Model produced by the McLeansboro Anomaly (Model 6).

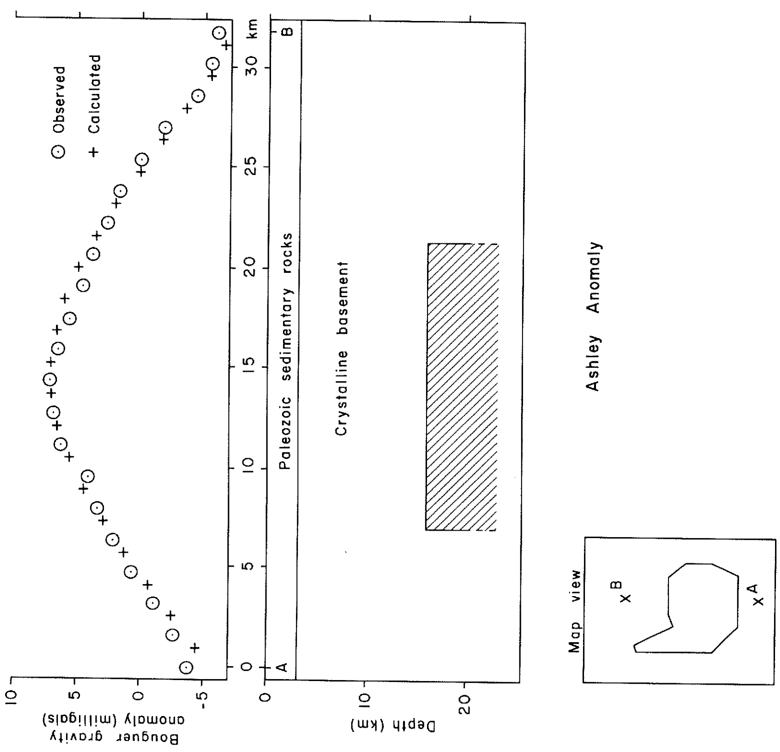

Fig. 9 - Model produced by the Ashley Anomaly (Model 8).

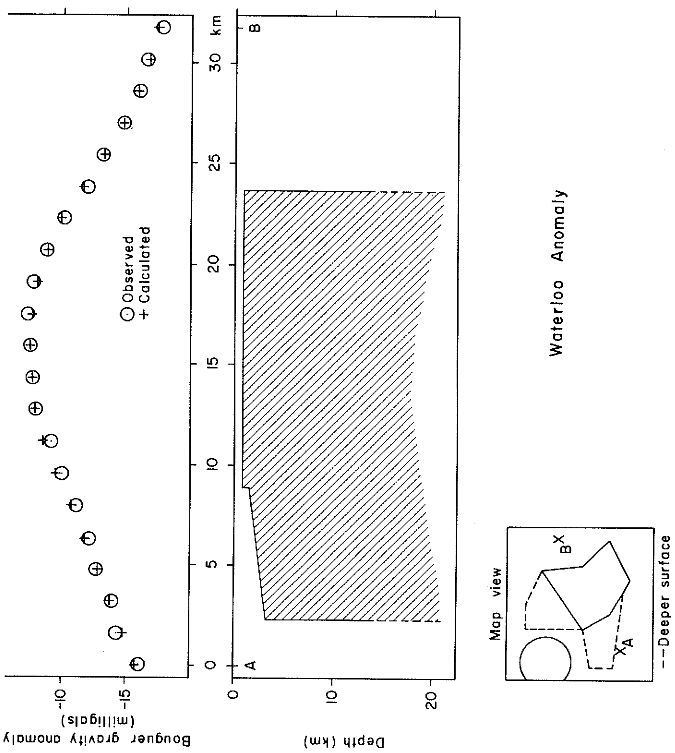

Fig. 10 - Model produced by the Waterloo Anomaly (Model 9).

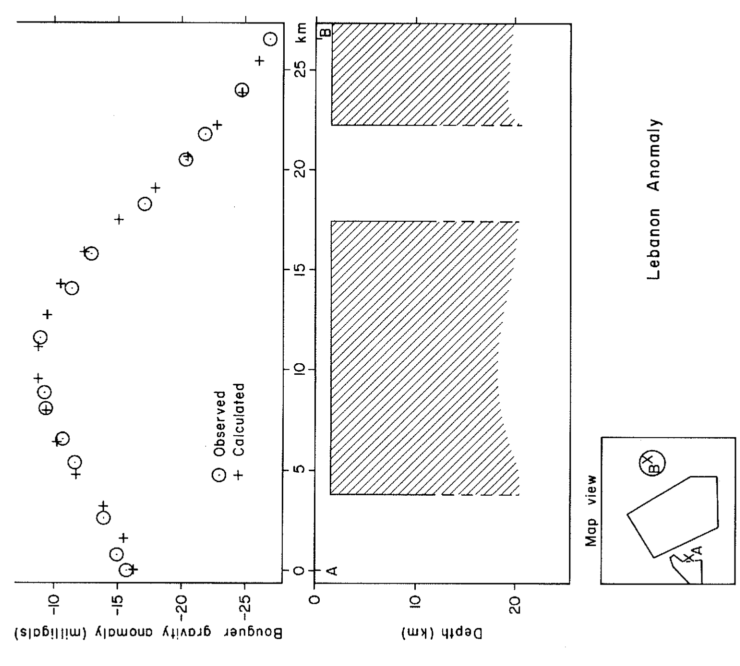

Fig. 11 - Model produced by the Lebanon Anomaly (Model 10).

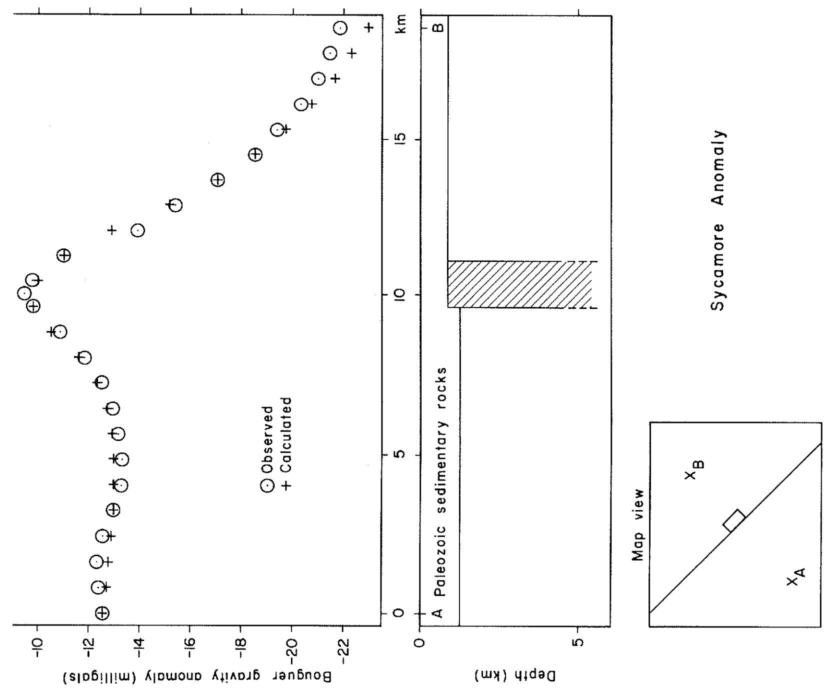

Fig. 12 - Model produced by the Sycamore Anomaly.

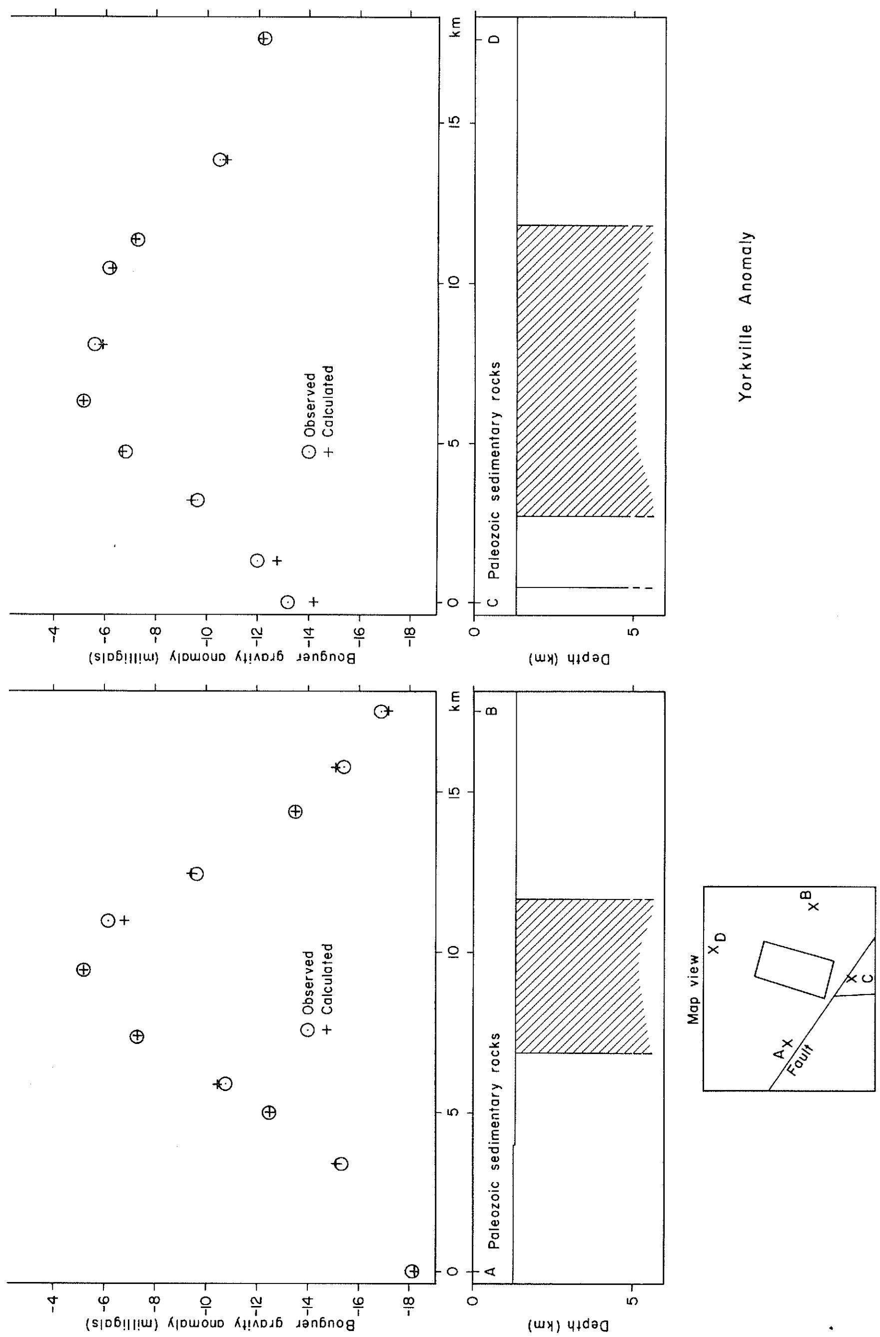

Fig. 13 - Model produced by the Yorkville Anomaly.

desirable to suppress these and emphasize the longer-wavelength features. This was accomplished by averaging the Bouguer gravity anomaly values within each 15-minute quadrangle and plotting the average value at the center of the quadrangle. The averaged values were then treated as observed values for computing the crustal model.

The theoretical model was constrained by the following two assumptions:

1. All anomalous mass distributions extend up to the surface of the crystalline basement. Elevations of the basement surface were read from the contour map published by Bristol and Buschbach (1971).

2. The base of all anomalous distributions of mass is at a depth of 27 miles; however, the computed field is relatively insensitive to the location of this surface.

The crustal mass distribution was modified until a satisfactory theoretical field was obtained. For the final model, the maximum difference between the "observed" and the theoretical values at any point was 4 milligals, while the average absolute deviation was 1.8 milligals. The 4-milligal residual occurred at two points, both located along the edge of the modeled area, and is less than 10 percent of the approximately 50-milligal range of the gravity field within the area. Attempts to further refine the model would probably not be meaningful, considering that the model is regional and that the "observed" values are averages.

To illustrate the computed mass distribution, 14 areas containing generally coherent gravity anomalies have been lettered in figure 3. The approximate density for each of these areas is indicated in table 2. These densities were computed on the assumption that the lowest regional crustal density within the area is 2.67 gm/cc.

TABLE 2 - DENSITIES OF ANOMALOUS MASSES USED IN THEORETICAL ANALYSES OF NORTHERN ILLINOIS BOUGUER GRAVITY ANOMALIES
(See fig. 3 for locations.)

Anomaly	Density (gm/cc)	Anomaly	Density (gm/cc)
A	2.68	H	2.68-2.69
B	2.69	I	2.68-2.69
C	2.72	J	2.72-2.74
D	2.67	K	2.67
E	2.71	L	2.72-2.73
F	2.68	M	2.72-2.74
G	2.71-2.73	N	2.67

Algorithms Used in Gravity Modeling

Gravity models for this study were computed using two distinctly different algorithms. The first one is the well-known Talwani three-dimensional algorithm for bodies of arbitrary shape (Talwani and Ewing, 1960). The body is first divided into a series of horizontal laminae, and the boundary of each lamina is approximated by an irregular polygon. Theoretically, the gravity field of the body at a point is determined in a rectangular coordinate system by two integrations in the horizontal plane and one in the vertical. A summation around the boundary of each polygon approximates the two horizontal plane integrations. The vertical integration to obtain the theoretical gravity value is then made by means of a numerical technique. The Talwani algorithm as used here is implemented in a program written by K. M. Clermont (1967) that uses the Lagrange interpolation formula to perform the vertical numerical integration.

The second algorithm used in this study was devised by Nagy (1966). This algorithm is based on a mathematically closed expression for the gravitational attraction at any point outside a rectangular prism. The only major restriction is that the sides of the prism must parallel the rectangular coordinate axes.

A model is defined by simply specifying the coordinates of each side of the prism. The algorithm is implemented in an unpublished program written by Nagy. This program has been modified to accept observed gravity values and their coordinates as input. The theoretical and residual fields are then calculated at the location of each observed value.

Most of the anomalies in southern Illinois were modeled using the Talwani algorithm. The Nagy algorithm was employed for the anomalies in the northern area, and also to verify the Talwani calculation on several of the southern anomalies.

DISCUSSION

A gravity study of the type described here is a study of distributions of mass in the earth's crust and upper mantle and their relationship to geological structure, or in the broader sense, to tectonics. Since Illinois covers the larger part of a sedimentary basin, including the basin center, in the stable cratonic interior, this study is essentially one of basin kinematics. Kay (1951) refers to this type of basin as an autogeosyncline. Fischer (1975) speculates on the factors initiating basin subsidence: he suggests erosion and cooling of a transient heat bulge, an intrusion of heavy matter into the crust, a phase change at depth, or a change in the asthenosphere. From an inspection of the Bouguer gravity anomaly map (plate 1) and the free-air gravity anomaly maps (plates 2, 3, and 4), one can see that the Illinois Basin center has been intruded by high-density mafic plutons that have not been isostatically compensated.

McGinnis et al. (1972) suggested that the major components of the large positive Bouguer gravity anomaly in southern Illinois are of relatively late origin since the anomaly is not regionally compensated. They recognized three major episodes of faulting, directly or indirectly associated with intrusion, in the midcontinent as:

1) late Precambrian incipient rifting;
2) vertical faulting in middle to late Paleozoic time in response to basin growth;

and 3) late Mesozoic incipient rifting.

In the Illinois Basin and elsewhere in the midcontinent, gravity anomalies indicate that the first and third episodes were discordant with older structures, whereas the late Paleozoic episode is marked by faults bounding Precambrian intrusive blocks that are outlined by high-gravity gradients.

As noted in the preceding section on model studies, density contrasts in the crust and mean crustal density increase toward southern Illinois; furthermore, plutons are found at greater crustal depths in the south than in the north. McGinnis (1972) noted the similarity between the configuration of the Bouguer gravity field and basement geology in Minnesota and suggested that the earth's crust was planated on the order of several kilometers in the northern midcontinent, resulting in truncated anomalous masses.

Ervin and McGinnis (1974) explained the positive anomaly in southern Illinois as being related to the anomalous mantle and crust found under the Mississippi Embayment. They pointed out that the gravity anomaly straddles an area underlain by rocks of the lower crust having velocities of 7.4 km/sec, a velocity usually found under crests of spreading ridges. The high velocities indicate that a branch of the anomalous crust extends 60 miles north of the downwarp of the

Mississippi Embayment, well into the deeper parts of the Illinois Basin; however, the main boundary of the normal versus anomalous crust in Illinois is marked by high-gravity gradients extending east-west across the state at 38.5° N. (Ervin and McGinnis, 1975b). North of this line, the typical mosaic pattern of the mid-continent prevails, whereas south of the line the mosaic pattern is partially obscured by higher-amplitude, shorter-wavelength anomalies. A linear positive Bouguer gravity anomaly trend oriented north-south, south of the high gradients, is the result of rocks having densities ranging from 0.4 to 0.6 gm/cc higher than those of the country rock. These high-density and probably younger mafic rocks attain densities on the order of 3.3 gm/cc, which is equivalent to densities postulated for the upper mantle.

The onset of basin subsidence in Illinois and a portion of its history are illustrated in figure 14. Subsidence versus time is plotted from data provided on the Geologic Map of Illinois (Willman and others, 1967). Subsidence shown will be a maximum value since the maximum thickness of each unit shown on the representative log for southern Illinois was used. For some units this is not a real maximum thickness since there is overlap, as in the unconformities, or there were differential movements in different areas of the basin. Total subsidence plotted in this manner is on the order of 19,000 feet, whereas maximum basin

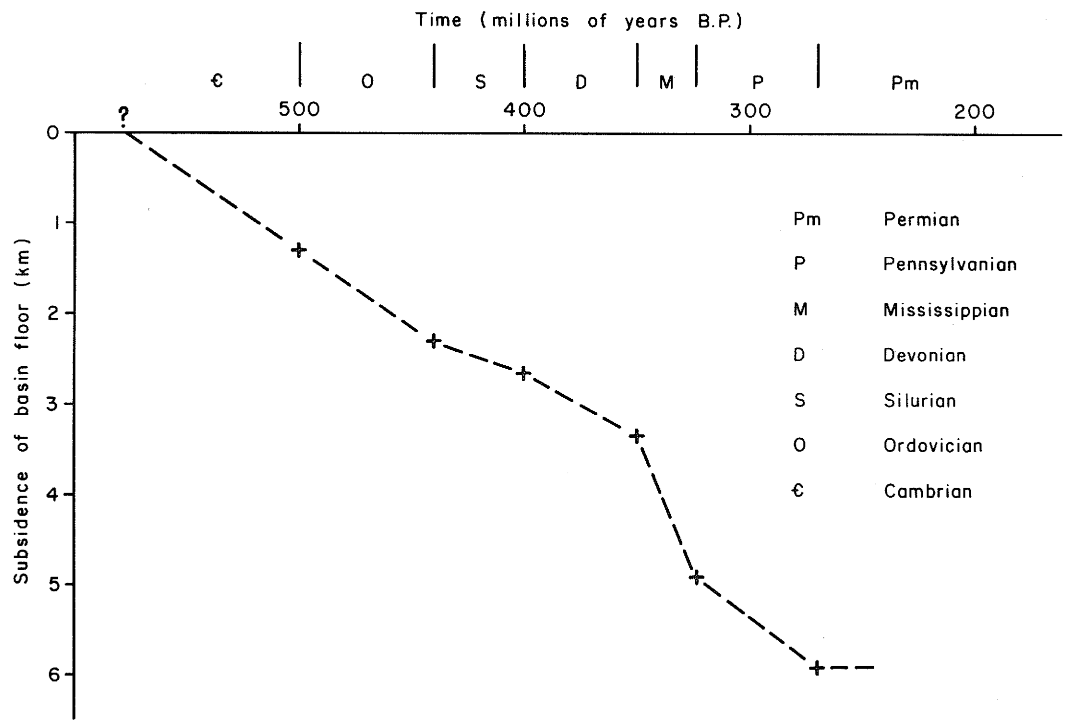

Fig. 14 - Bubnoff diagram of the Illinois Basin plotting subsidence of the basin floor against time; mean subsidence rate is 20 meters per million years. (Mean subsidence rates of the Michigan Basin and the Williston Basin are 24 meters per million years and 6 meters per million years, respectively—see Fischer, 1975.)

depth is probably on the order of 15,000 to 16,000 feet. The mean rate of subsidence of 20 meters per million years is thus too high. Fischer (1975) indicates a rate of 24 meters per million years for the Michigan Basin and 6 meters per million years for the Williston Basin.

As noted in figure 14, subsidence of the basin extrapolated back to zero depth indicates an onset of basin development in early to middle Cambrian time (575 million years B.P.). According to Atherton (1971), centers of deposition were not always in the basin centers outlined today. During most of the Paleozoic, centers of deposition were an unknown distance south of the present center of the Illinois Basin. Structurally positive areas bounding some neighboring midcontinent basins (for example, the Illinois and the Michigan Basins) were not well defined until well into Paleozoic time. Recent deep drilling near centers of both the Illinois and Michigan Basins indicates depths considerably deeper than previously anticipated. Auxiliary centers of deposition between basins were only temporary and were probably related to the tectonism that originally produced the primary basins. Since gravity fields indicate excess concentrations of mass in the centers of the Williston, Michigan, and Illinois Basins and all three show similar histories of subsidence, it is believed that the initial crustal deflection beneath the basins was caused by emplacement of these excess masses and subsequent isostatic subsidence. The ages of the anomalous mass concentrations must then be at least 600 million years (that is, late in the Precambrian to early in the Cambrian).

An apparent contradiction is presented by the presence of excess concentrations of mass both in basin centers and along the axes of arches. Bouguer and regional free-air gravity anomalies are positive in both kinds of geological provinces. Bouguer gravity anomalies along the La Salle Anticlinal Belt and the Kankakee Arch are caused by masses having densities 0.04 to 0.15 gm/cc greater than those of the country rock. Anomalies in the center of the basin are caused by masses having densities 0.4 to 0.6 gm/cc greater than those of the country rock. Thus, although basins and arches are characterized by Bouguer gravity highs, the masses producing the basin anomalies are 14 percent larger than crustal mass beneath arches. If the minimum density of typical continental intrusive country rock (that is, an unmetamorphosed, Precambrian, acidic rock assemblage) is between 2.67 and 2.70 gm/cc, the density of arch crust would be from 2.75 to 2.80 gm/cc. The densities of circular-to-elliptical smaller anomalies on the arch-anticlinal trend would be about 2.91 to 3.40 gm/cc. Average densities on the arch-anticlinal axes are about 7 percent greater than those of adjacent crustal rocks, whereas average densities of crust in basins are 22 percent greater than those of adjacent crustal rocks.

It is probable that many slightly higher than normal crustal densities are not caused by intrusions but by some form of low-grade crustal metamorphism. Metamorphism can easily be explained by the mechanism suggested by McGinnis (1970) for intrarift regions that are flexed downward and buried beneath moderate thicknesses of arkosic sediment. Since these sediments are relatively immature and are derived directly from highly radiogenic nearby sources, they contribute to the heat required for low-grade metamorphism. Additional heat results from abnormal burial and crustal depression through higher isogeotherms.

An independent argument that one can use for suggesting low-grade metamorphism involves the anomalous radioactive age of 600 million years obtained by Goldich et al. (1968) for a basement rock core from the axis of the Kankakee Arch. This is the precise age that one would expect if the radioactive clock were reset by a minor metamorphic event.

The positive regional free-air gravity anomalies over arches can be explained as the result of anomalous crustal uplift in response to subsidence of the primary basin (that is, the forebulge effect commonly associated with glacial crustal bending, McGinnis, 1968). McGinnis (1970) noted this effect paralleling the axis of the Midcontinent Gravity High.

Evidence for regeneration of intrusions into the center of the Illinois Basin in middle to late Mesozoic time may be circumstantial; however, a series of three Paleozoic basins marginal to the ancient North American craton were involved in this rifting episode (the failed-rift of Burke and Dewey, 1974). The Black Warrior, Reelfoot, and Illinois Basins probably played a dominant role in focusing the axis of Mesozoic crustal failure beneath the present Mississippi Embayment. Thermal anomalies generated by loading of great sedimentary thicknesses could well have provided the required stimulus for such "failed-rifting." The globular array of excess concentrations of mass evidenced by positive gravity anomalies along the axis of the embayment suggests a more discontinuous source of rifting than is found in oceanic rifting or in the rifting associated with the Midcontinent Gravity High. Thus, intracratonic basins may, in time, generate their own "hot spots," which would appear as incipient, local rifting. It is necessary that further deep drilling, well into basement crystalline rocks beneath basin centers, be undertaken to test these hypotheses. Establishment of ages, thermal history, and petrology of anomalous basement rocks beneath basins is required to develop further a rationale for basin dynamics.

CONCLUSIONS

This report completes the data-collection phase of the gravity study of Illinois. It is hoped that these data will permit a redefining, and a new understanding, of the causes of basin formation. Basin subsidence, long interpreted solely on the basis of stratigraphic extrapolation, can now be viewed with an insight into characteristics of the crust lying beneath basins. Admittedly, much of the foregoing discussion is speculative; however, the fact remains that gravity fields are real and that they do portray definite crustal patterns in Illinois that, for the most part, must predate structures of Paleozoic age. The gravity fields outlined here will undoubtedly serve as guidelines for future drilling, which will provide direct evidence pertaining to deep crustal geology.

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