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Lithologic and Structural Interpretation of Gravity Data, Northeastern Iowa

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A gravity survey was conducted over approximately 4600 square km of northeast Iowa. It was undertaken to provide detailed gravity coverage at approximately 1.6 km intervals and to model the source of several significant gravity and magnetic anomalies. 1,460 gravity stations were occupied in the survey area. Bouguer gravity and residual gravity anomaly maps were prepared, the latter using band-pass filter and trend-surface analysis techniques. The residual maps reveal that the large oval Bouguer gravity anomaly centered beneath Decorah can be traced to the southern border of the survey. Profiles crossing this feature were prepared from the Bouguer map and a total intensity magnetic anomaly map. These profiles, combined with drill hole information, support the interpretation of a mafic (troctolite) intrusive extending over 90 km from the northwest corner of Winneshiek County to near the southern boundary of Fayette County. The western portion is dominated by a shallow clastic basin while the eastern portion appears to be dominantly felsic in nature. The gravity interpretation did not provide conclusive evidence for faulting near Decorah although faulting cannot be ruled out.

INDEX DESCRIPTORS: gravity map, gravity profile, basement structure.

The objective of this study was to investigate gravity anomalies over a portion of a four county region of northeastern Iowa (Fig. 1) and to use the information to assist in the interpretation of the basement geology of this area. A previous Bouguer gravity anomaly map of Iowa (Anderson 1981) was compiled from gravity observations separated at an interval of roughly six miles. A complex pattern of gravity anomalies was revealed in the northeastern corner of the state. Although adequate for regional studies, this map was not sufficient to provide the detailed coverage necessary for profile analysis of the causative masses.

In 1966, Aero Service Corporation flew an analog aeromagnetic survey of northeastern Iowa for the Iowa Geological Survey. A map of their data (Fig. 2) revealed a complex magnetic anomaly pattern from roughly 42.25 degrees north latitude to the Minnesota border. Several magnetic anomalies exceed 6500 nanoteslas. These anomalies correlated in a general way with the gravity anomalies but did not show a precise one-to-one correlation.

GEOLOGY

Most of the study area lies within the Paleozoic Plateau (Hallberg et al. 1984). The southern and western portions of the study area are mantled by 0–75 m of pre-Illinoian glacial drift while the remainder is largely devoid of glacial materials. Topographically, the western portion displays the gently rolling terrain of the Iowan erosion surface, while the dissected eastern portion has topographic relief up to 150 m. The Proterozoic basement is buried by a Paleozoic sedimentary section of Cambrian through Devonian carbonates and clastic rocks. The thickness of the Paleozoic section varies from 275 m in the northeast to about 900 m in the southwest. The study area has been relatively inactive tectonically since Precambrian time. The

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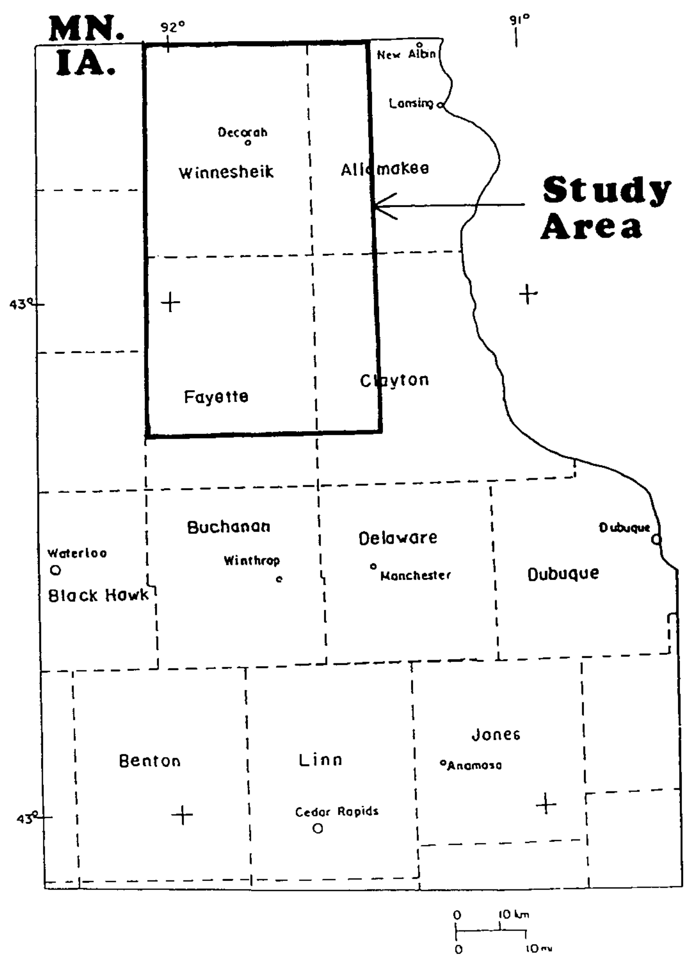

Fig. 1. Map of northeast Iowa showing the location of the study area. Top of the page is north.

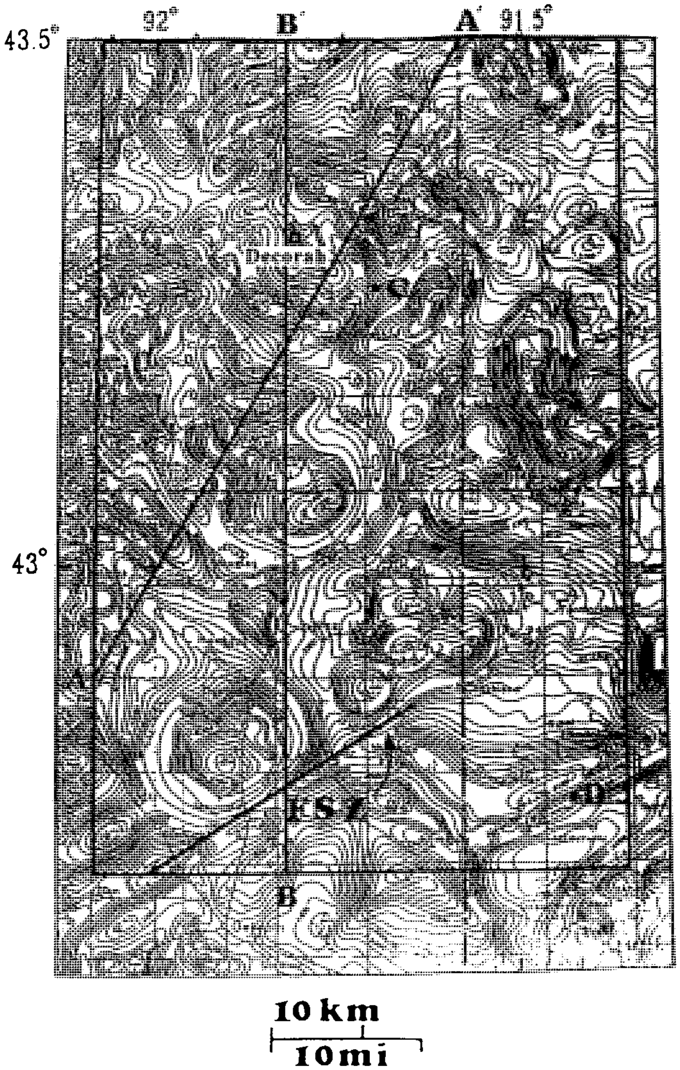

Fig. 2. Aeromagnetic anomaly map of the study area. Contour interval = 100 nanoteslas. A-A' and B-B' locate profiles. Black dots indicate basement wells; C = Pioneer #1 well, D = Osborne well. Decorah is represented by a hollow black box. FSZ identifies Fayette Structural Zone. Map modified from Airborne Magnetometer Survey of Northeastern Iowa (1968). Top of the page is north.

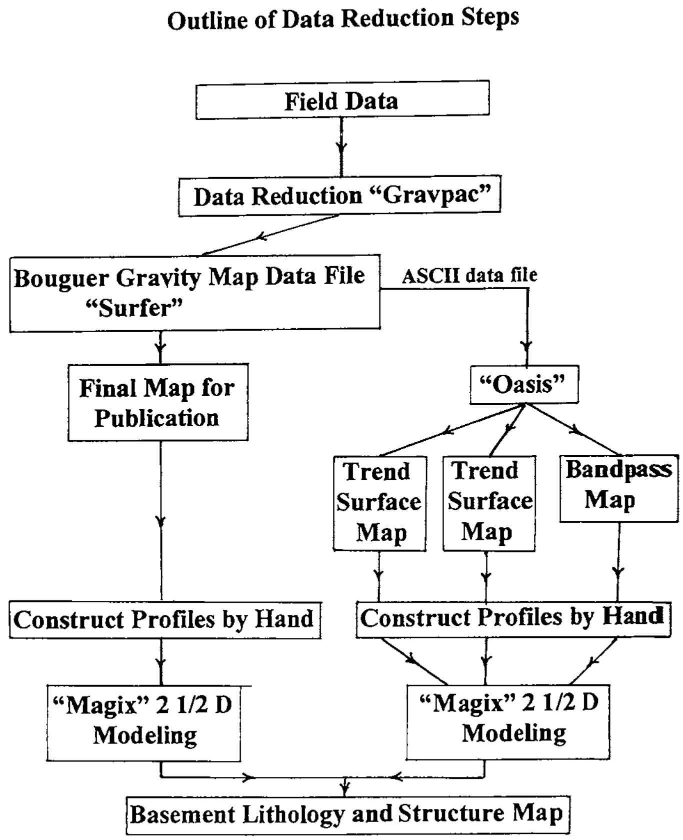

Fig. 3. Flow chart showing organization of gravity data reduction steps.

regional dip of the Paleozoic strata is to the southwest at less than 0.2 degrees (Steinhilber et al. 1961). The lower Paleozoic section has several low relief anticlinal folds with strikes generally northwest-southeast throughout the region.

Two drill holes penetrated the basement within the study area. The northernmost well (C of Fig. 2) was located in Winnneshiek County, southeast of Decorah. This well encountered troctolite at the basement surface, 500 m below sea level. A drill hole (D of Fig 2.) in the southeast portion of the study area near the town of Osborne in Clayton County also encountered troctolite at the Precambrian surface, 556 m below sea level. Approximately 221 m of troctolite in the form of layered intrusions was penetrated in this well.

PREVIOUS INVESTIGATIONS

Kittleson (1975) made a gravity study of a linear magnetic anomaly located in the extreme southeast portion of our study area (near D in Fig. 2). He interpreted the linear magnetic and gravity feature to be the result of dike-like mafic intrusions into the mostly felsic basement rocks. A test well (D of Fig. 2) which penetrated the basement complex near Osborne, encountered 221 m of serpentinite and olivine cumulate.

Gilmore (1976) conducted a gravity study of the Randalia magnetic anomaly, the intense circular feature in the southwestern portion of the survey area (Fig. 2). Gravity data from Gilmore's survey were incorporated into this study. Interpretation by Gilmore resulted in three hypotheses: 1) the presence of a large fault block within the Precambrian basement complex; 2) related variations in the thickness of superjacent Precambrian clastic deposits; and 3) a fault coinciding with a magnetic anomaly linear, later identified by Anderson (1988) as the Fayette Structural Zone (FSZ, Fig. 2).

A ground magnetic survey over the same area as Gilmore's gravity study by Stepanek (1978) modeled the Randalia magnetic anomaly as a rectangular mafic body intruding into the basement rock with a depth to top of 2590 m below the surface. To the north of the main anomaly, two smaller anomalies were attributed to mafic intrusions.

A gravity study encompassing roughly the southern half of the survey area was conducted by Kellogg and Meinen (1993). These data were also incorporated into the present survey. Specifically, the authors sought a gravity signature for the FSZ comparable to the well-defined magnetic anomaly. Analysis of the gravity data proved inconclusive as to the existence of either faulting or a dike-like intrusive which could also satisfy the magnetic data. The existence of several intrusives of olivine cumulate and gabbro was hypothesized

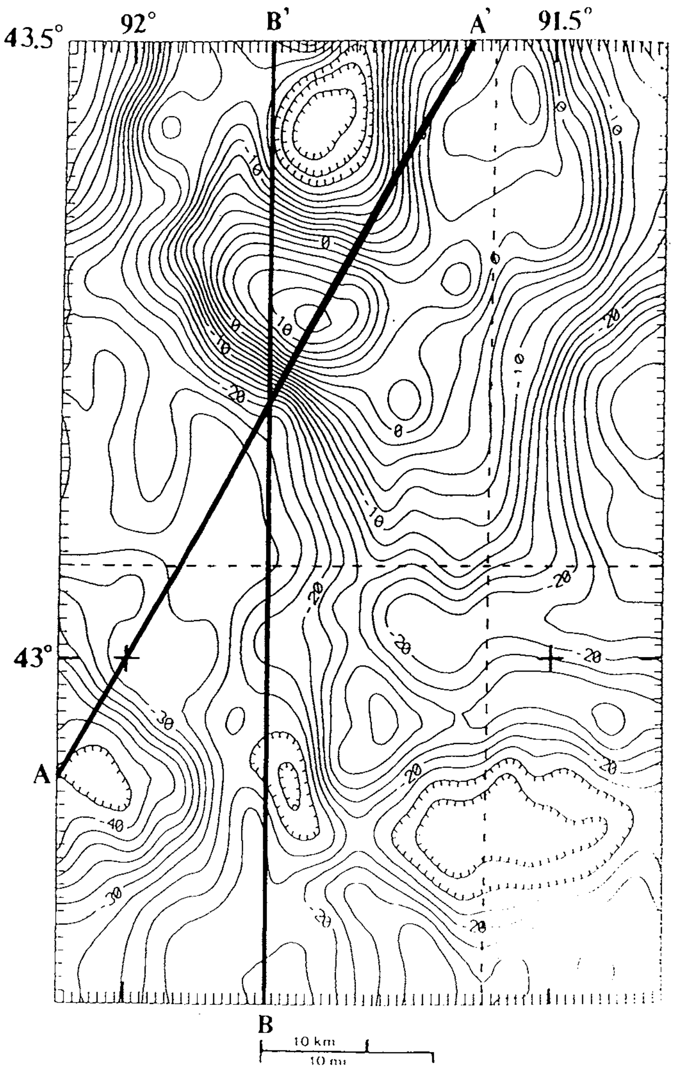

Fig. 4. Bouguer gravity anomaly map of the study area. Contour interval = 2 milligals. A-A′ and B-B′ locate profiles. Top of the page is north.

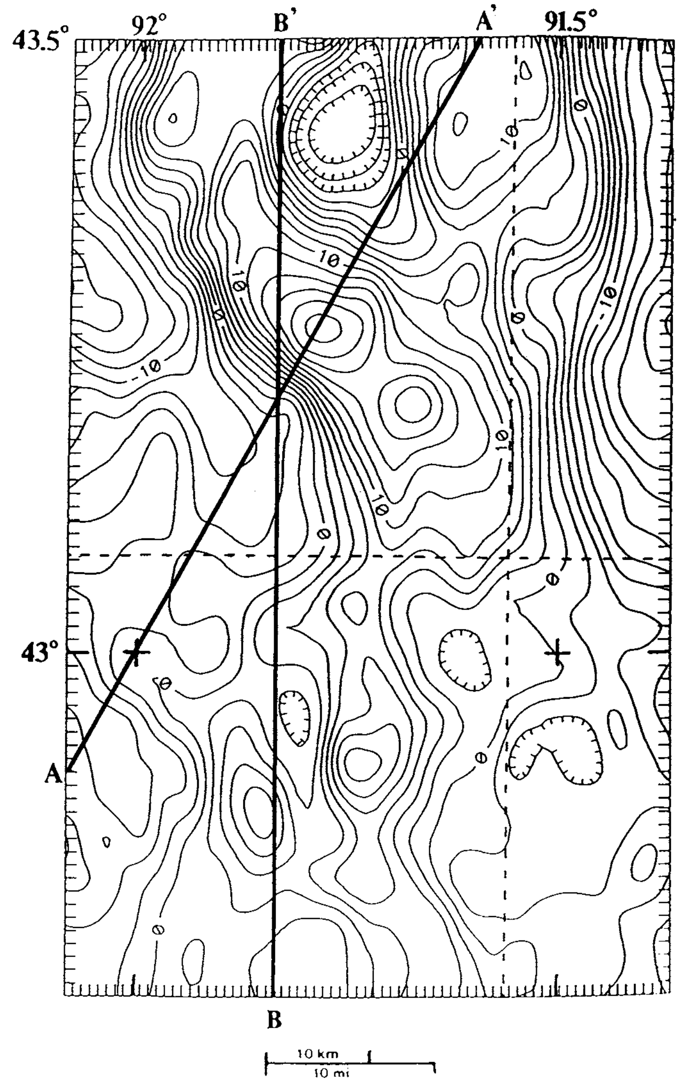

Fig. 5. First order trend surface residual gravity map of the study area. Contour interval = 2 milligals. A-A′ and B-B′ locate profiles. Top of the page is north.

primarily from modeling of the gravity and magnetic data (Kellogg and Meinen 1993).

Three additional studies were conducted to the south of the study area. Heitzman (1972) undertook a gravity study of Black Hawk County, while magnetic and gravity studies were made on the Manchester geophysical anomaly in Delaware County by Heathcote (1979) and the Vinton geophysical anomaly in Black Hawk, Buchanan, Benton, and Linn Counties by Dixit (1984). In each case a felsic basement with mafic intrusives and extrusives was interpreted.

Yaghubpur (1979) used geological, geophysical and drill-hole information to prepare a regional basement lithologic and structure map of the state of Iowa. Yaghubpur (1979) reinterpreted results from the Kittleson study of the Osborne well as troctolite, a mafic intrusive of general gabbroic composition in which olivine and calcic plagioclase are the chief constituent minerals.

COLLECTION AND REDUCTION OF GRAVITY DATA

During the summers of 1988, 1990, 1992 and 1995, 1480 stations were occupied by student researchers and the junior author. In June and July of 1995, 348 stations were occupied by both authors. All measurements were made using a Worden Prospector gravity meter. Observation sites were chosen at road positions of known elevations (±0.7 m), printed on 7 1/2 minute U.S. Geological Survey topographic maps. Base stations were established by looping from stations occupied by Hase et al. (1969) whose gravity is known relative to absolute gravity stations established in Iowa. Loop traverses consisting of 6 to 10 station occupations were then made and closed on base stations in intervals of about 2 hours.

Field gravity data were reduced to Bouguer gravity anomaly values, wave-length filtered, and contoured (Fig. 3) using an IBM-compatible personal computer. Bouguer gravity values were calculated using GRAVPAC (LaCoste and Romberg Inc., Austin, Texas). A density of 2.67 g/cc was used for the Bouguer correction with the 1930 International Gravity Formula. This made the reduced data compatible with maps produced by previous workers in the area. The Bouguer gravity anomaly data was contoured using SURFER (Golden Software Inc., Golden, Colorado) and is shown in Figure 4.

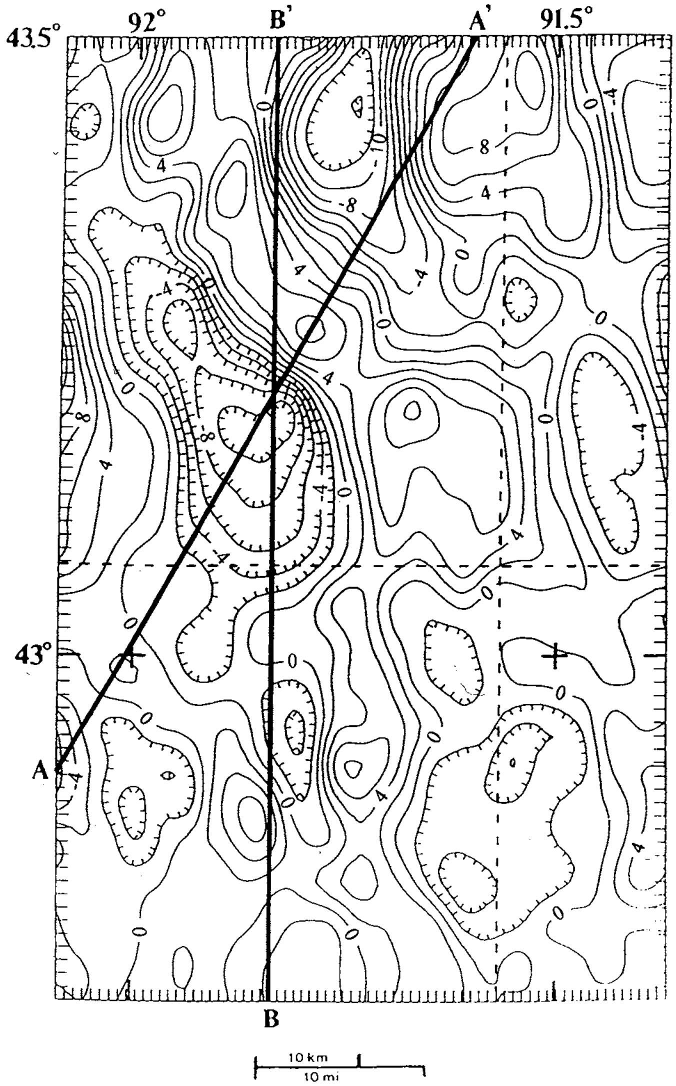

Fig. 6. Second order trend surface residual gravity map of the study area. Contour interval = 2 milligals. A-A' and B-B' locate profiles. Top of the page is north.

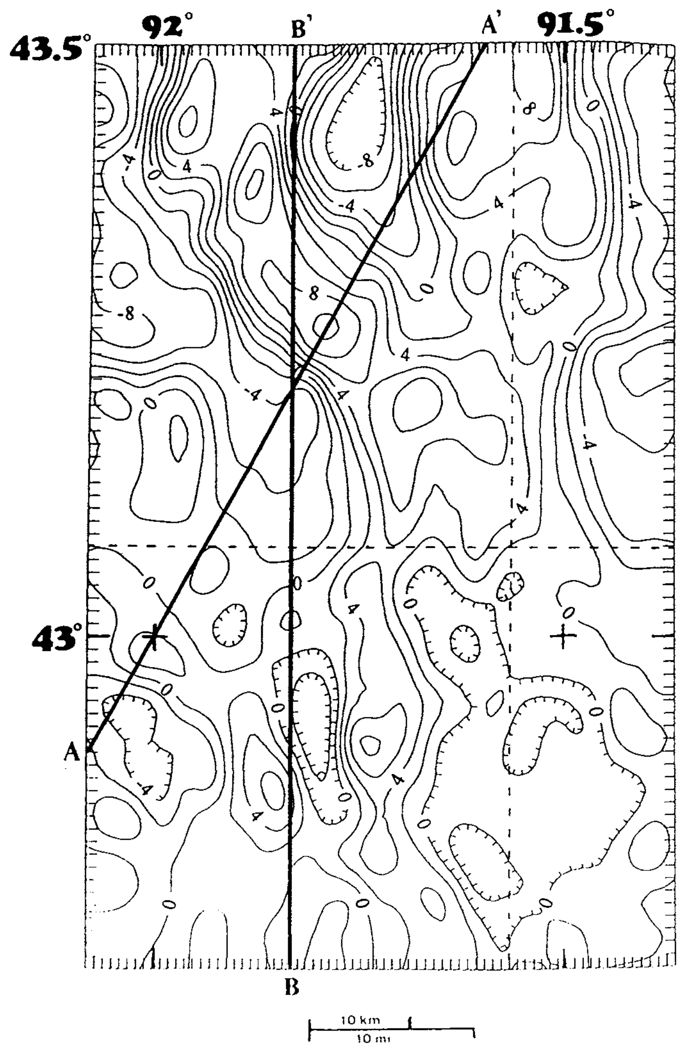

Fig. 7. Band-pass filtered residual map of the study area. Contour interval = 2 milligals. Short wavelength cut-off: 4 km; Long wavelength cut-off: 60 km. A-A' and B-B' locate profiles. Top of the page is north.

Profiles produced from the Bouguer map were analyzed using MAGIX (Interpex Ltd., Golden, Colorado). This program calculates the model gravity anomaly from idealized 2 1/2 dimensional bodies.

The contoured Bouguer gravity anomaly data from SURFER was also analyzed using OASIS (Geosoft, Inc., Toronto, Ontario). The OASIS Mapping and Processing system is a modular system for editing, viewing and processing earth science data. This program analyzes the contoured Bouguer gravity to generate trend surfaces by least-squares fitting of first and second order polynomials. These trend surfaces were then subtracted from the Bouguer gravity field to generate residual maps using SURFER (Figs. 5 and 6). A linear band-pass filtered map was also prepared using OASIS. The band-pass filter removes wavelengths longer than and shorter than specified values by calculating an appropriate convolution filter and applying the filter to the data. A short wavelength cutoff of 4 km and long wavelength cutoff of 60 km were selected by examination of the predominant wavelengths on the Bouguer anomaly map (Fig. 4), and filter band-pass data were contoured using SURFER (Fig. 7).

DISCUSSION

A number of authors (e.g., Hinze et al. 1971) have shown that gravity and magnetic anomalies originating from basement lithologic variations in the upper Midwest are an order of magnitude greater than anomalies originating from within the overlying sedimentary section. In this paper, the assumption is made that all significant anomalies originate from within the basement complex.

The gravitational anomaly produced by any subsurface body can accurately be calculated by the application of potential theory if its density, 3-dimensional shape, and depth of burial are known. However, since this calculation includes multiple variables, many different combinations of density and depth of burial will produce identical anomalies. For this reason, accurate geological interpretation cannot be based on gravity data alone. The modeling of these data included analysis of geological, geophysical, drill hole information, and pre-existing maps and profiles to arrive at a geologically reasonable (although not unique) interpretation.

In northeastern Iowa, positive gravity and magnetic anomalies

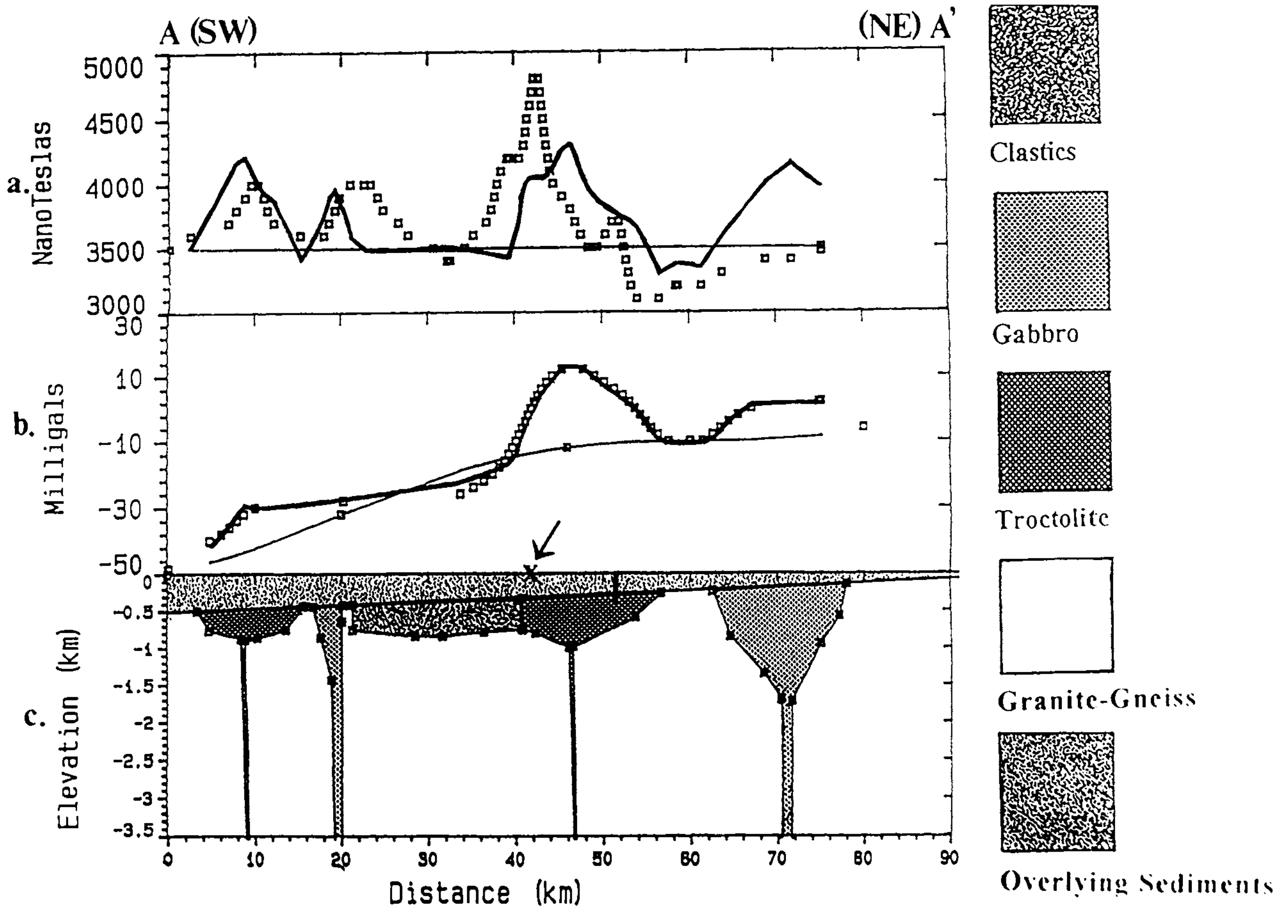

Fig. 8. Magnetic (a), gravity (b), and lithologic (c) model for profile A-A' (see Fig. 2 for location of profile). Open squares indicate observed anomaly values. Dark curve indicates model anomaly values. Smooth curve indicates estimated regional anomaly. The intersection of profile A-A' with B-B' is shown by the heavy arrow. Densities are: sediments, 2.55 g/cc; granite, 2.70 g/cc; gabbro, 3.00 g/cc; troctolite, 3.70 g/cc. Magnetic susceptibilities are discussed in text. Vertical exaggeration of model = 14×. Top of the page is north.

have been attributed to Middle Proterozoic Keweenawan mafic intrusive and extrusive rocks by a number of authors (Kittleson 1975, Gilmore 1976, and Kellogg and Meinen 1993). Granite and granitic gneisses are the predominant lithologies found in basement rocks of the Midwest. Limited drilling in northeastern Iowa indicated that granitic and gneissic rocks (Yaghubpur 1979) are also common in the basement of this area. Previous studies, described earlier, have interpreted mafic intrusives within the granitic basement of northeastern Iowa.

An examination of the Bouguer gravity anomaly map (Fig. 4) and the magnetic anomaly map (Fig. 2) of the study area reveals a number of significant features. The Bouguer gravity map shows a large, crescent-shaped positive anomaly reaching its highest amplitude (12 milligals) in the vicinity of Decorah. The southern half of the Bouguer gravity map is characterized by several negative anomalies.

The magnetic map (Fig. 2) is complex, with several strongly positive anomalies. Among these are the circular Randalia magnetic anomaly, just north of the Fayette Structural Zone (Fig. 2), and the linear Osborne feature (D of Fig. 2). These have been attributed to mafic intrusives by Gilmore (1976) and Kittleson (1975), respectively. Although the gravity contours are aligned with the magnetic expression of the Osborne feature, in general, it is difficult to correlate specific magnetic anomalies with gravity anomalies as exemplified by the Randalia and Decorah features (Fig. 2 and Fig. 4). The lack of correlation between magnetic and gravity features can be explained by the pronounced contrast between the magnetic characteristics of the rocks that produce the anomalies and the surrounding basement rocks, coupled with the lack of such contrast in rock densities.

Residual maps, which have the regional field removed, are very useful for isolating near-surface gravity anomaly sources. The first and second order trend-surface residual maps and the band-pass filtered residual gravity map (Figs. 5, 6, and 7) indicate that the Decorah feature is more linear than the Bouguer gravity anomaly map suggests and may extend at least to the southern border of the survey area. These maps and the Bouguer gravity anomaly map (Fig. 4) show significant minima flanking the linear positive gravity anomaly in the northern half of the study area. The minima may be interpreted in several different ways. Two interpretations are most consistent with the regional geology: (1) grabens or half-grabens filled with clastics and (2) relative density variations with mafic bodies intruding less dense granite-gneiss country rock. Recent work (Anderson 1996) suggests that the thickness of Precambrian clastics in several wells near Lansing, beside the Mississippi River in Allamakee County, is considerably less than originally thought. If this is true, the flanking lows may not reflect the presence of Precambrian clastics. Therefore, the preferred interpretation is one in which the presence of clastic filled grabens is minimized.

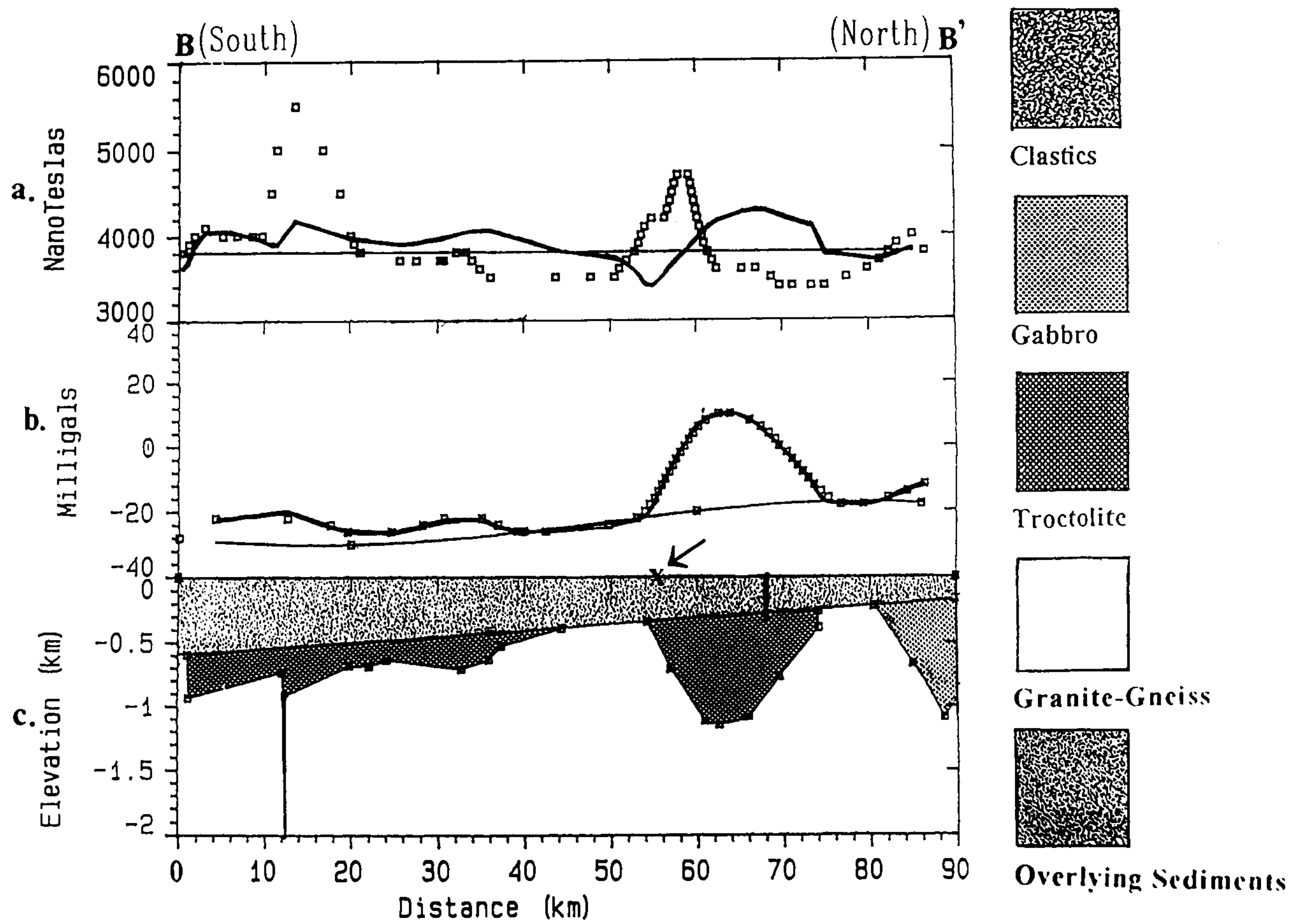

Fig. 9. Magnetic (a), gravity (b), and lithologic (c) model for profile B-B′ (see Fig. 2 for location of profile). Open squares indicate observed anomaly values. Dark curve indicates modeled anomaly values. Smooth curve indicates estimated regional anomaly. The intersection of profile B-B′ with A-A′ is shown by the heavy arrow. Densities are: sediments, 2.55 g/cc; granite, 2.70 g/cc; gabbro, 3.00 g/cc; troctolite, 3.70 g/cc. Magnetic susceptibilities are discussed in text. Vertical exaggeration of model = 14x. Top of the page is north.

An estimated regional anomaly was derived from the Bouguer Gravity Anomaly Map of Iowa (Anderson 1981). This hand-smoothed regional is shown on Figs. 8b and 9b along with the observed and calculated Bouguer anomaly curves. As can be seen from these two figures, only in one place (Fig. 8b, profile A-A′) do the minima on either side of the large maxima drop below the regional curve. This is consistent with an interpretation without extensive clastic filled grabens.

Figures 8 and 9 show profiles derived from the aeromagnetic and Bouguer gravity anomaly maps. Profiles 8C and 9C show the granitic crust intruded by bodies of mafic composition. The shapes of the bodies were chosen to be consistent with what is known about the basement geology of the upper Midwest and were influenced by the residual maps. Also shown are the Phanerozoic sediments whose thickness was estimated from a basement configuration map prepared by Anderson (1988). The location of these profiles was chosen to be perpendicular to as many of the larger gravity and magnetic features as possible. The regional field was removed from the observed values using graphical methods (Dobrin 1976). To achieve a match between the observed and modeled profiles, the geometries of the bodies were altered leaving the densities constant.

The observed and modeled Bouguer gravity profiles match well, but the observed and modeled magnetic curves show appreciable deviations. Lack of knowledge of the magnetic properties combined with the large number of variables that affect observed magnetic data did not justify efforts to achieve an exact fit for the magnetic profiles.

Profile A-A′ (Fig. 8) strikes northeast, at nearly right angles, across the Decorah gravity positive. As noted above, a basement well, southeast of Decorah (see Fig. 2 for location), encountered troctolite beneath the Decorah positive gravity anomaly. Densities and magnetic susceptibilities utilized in the modeling are representative of measured values from Precambrian outcrops and basement drill holes (e.g. Mooney and Bleifuss 1953). Magnetic profiles A-A′ and B-B′ were modeled using a remanent magnetization vector having an intensity of 0.0033 emu/cc, declination of 291 degrees and inclination of 38 degrees (Jahren 1965).

The Pioneer No. 1 well (C of Fig. 2) has been projected into the cross section and is indicated by the vertical bar. The Decorah feature is interpreted to be a troctolite intrusive subcropping at the basement surface. Immediately to the southwest of the Decorah feature, a clastic basin has been modeled. Although shown as Precambrian, the basin may be partially filled with basal Cambrian clastics. The contact between the Decorah feature and the adjacent clastic basin appears to be abrupt and may be a fault. A smaller troctolite intrusion may be present at the southwest end of the profile. Northeast of the Decorah feature, modeling identified a lower density gabbro

Structural and Lithologic Interpretation

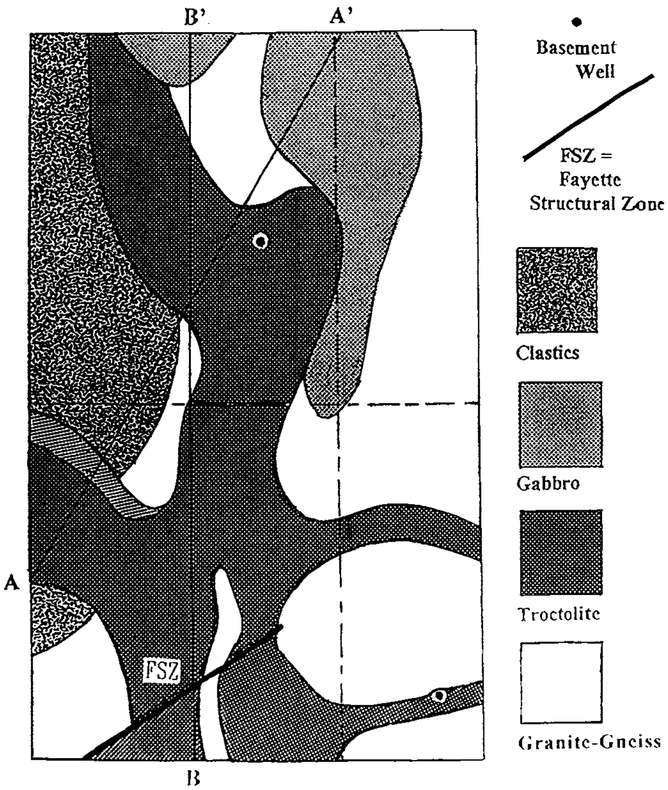

Fig. 10. Lithologic and structural interpretation of the Precambrian surface in the study area. Top of the page is north.

intrusion, based primarily on the residual maps (Figs. 5, 6, and 7) that hint at a separate intrusion. However, models based on a thinner troctolite body also fit the observed Bouguer gravity field at this location.

Profile B-B′ (Fig. 9) was constructed to aid in the preparation of the structural and lithologic interpretation map (Fig. 10). This north–south profile is dominated by the single intrusion of troctolite. The gabbro intrusion is modeled at the north end of the profile. Profile B-B′ passes over the northeast trending Fayette Structural Zone. Although well defined on the magnetic map (Fig. 2), the zone has no distinct gravity signature.

Figure 10 is a lithologic and structural interpretation map based on the cross sections, the magnetic map, and drill hole information. Both the Pioneer No. 1 well near Decorah and the Osborne well in Clayton County encountered troctolite at or near the basement surface. A centrally located intrusive belt of troctolite and gabbro dominates the map. Granite country rock dominates the eastern portion of the study area while a shallow clastic basin is found to the west. The clastic basin may be filled with Precambrian and/or basal Cambrian clastics. Although several authors (e.g., Anderson 1988) have suggested northeast-trending faulting in the Decorah area based on regional gravity and magnetic studies and repetition of the Ordovician section in a Decorah city well as reported by Northup (Lorenz et al. 1961), the detailed gravity survey did not provide conclusive evidence for its existence. Residual maps suggest north-trending intrusive bodies as the source of the principal anomalies; however, faulting in the vicinity cannot be ruled out.

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