ELECTROMAGNETIC AND GRAVIMETRIC MAPPING OF A PARTLY COLLAPSED UNDERGROUND LIMESTONE MINE IN CLARK COUNTY, IN[1]

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Abstract: The Falls City underground limestone mine in Clark County, IN, was abandoned in 1903 $\pm$ 3 yr. The mine is now flooded and partly collapsed. A map of the mine was needed because undermined areas would be unsafe for buildings. We used this mine as a test site to evaluate gravimetric surveying to map other underground mines in the region, some of which cannot be entered. We first mapped the Falls City Mine using a commercially available "line finder," normally used to locate underground utilities such as pipes and telephone lines. Part of our crew carried the continuously operating, 82.5-kHz vertical-dipole transmitter through the underground mine in a boat. Aboveground we followed the boat using a receiver which generated an audio pulsing tone with higher frequency indicating greater magnetic field intensity. Gravity was measured at 4- or 8-m intervals in 10 profiles (total length = 2.5 km). In four of these profiles, inflection points of 300-μgal Bouguer gravity anomalies located edges of the uncollapsed portions of the mine. Gravity profiles around the perimeter of the collapsed mine were used to search for any tunnels inaccessible from the surface. None were detected. The gravity method should be practical in mapping similar underground mines in the region.

Introduction

The underground Falls City Mine in the southeast corner of Clark Military Grant 89, Clark County, IN, (fig. 1), was abandoned in 1903 $\pm$ 3 yr. (Ault 1992, Siebenthal 1901). The mine exploited the Silver Creek Member of the North Vernon Limestone (Devonian) for production of a natural cement. The mine is now flooded and partly collapsed. A map of the mine was not available. The uncollapsed part of the mine is accessible by boat through entrances from a lake which occupies an adjacent quarry. We mapped a small part of the mine with a compass and a measuring tape stretched between a boat and a raft. Holding walls to stretch the tape was difficult and might have been dangerous. We therefore mapped the perimeter of the mine using an underground oscillating vertical magnetic dipole transmitter and an aboveground receiver. We used a commercially available 82.5-kHz "line finder," normally used to locate underground utilities such as pipes and telephone lines. Previous workers (e.g., Bell and Bell 1987, Charlton 1966) have used this method to locate points in limestone caves using noncommercially manufactured equipment with frequencies of 2 to 38.4 kHz.

Siebenthal (1901) recorded 11 shallow underground limestone mines in Clark County. Most of these mines are inaccessible from the surface, and the uncertainty of their extent may impede development of lands in their vicinity. We conducted a gravity survey of the Falls City Mine to test the application of gravimetric mapping to other similar mines and to detect any inaccessible galleries that might emerge from the collapsed areas of the Falls City Mine. Only the Falls City Mine is known to have partly collapsed (Ault 1992).

General Description of the Mine

Patton and Dawson (1955), Shaver (1974), and Droste and Shaver (1975) described the stratigraphy of the region. In a quarry wall at the Falls City Mine, Siebenthal (1901) described 1.5 m of soil overlying 3 m of the New Albany Shale (Devonian-Mississippian), 2 m of the Beechwood Member of the North Vernon Limestone (Devonian),

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and 4.7 m of the "cement rock" (the Silver Creek Member of the North Vernon Limestone). Beneath these strata lie the Speed Member of the North Vernon Limestone, the Jeffersonville Limestone (Devonian), and older Paleozoic strata. Most or all of the thickness of the Silver Creek was mined. Our measurements of mine heights from 3.7 to 4.5 m indicate that much of the flooded mine floor is covered with debris. The roof of the underground mine is the base of the Beechwood Member. Because the strata dip slightly southwestward, the roof of the mine is 3.7 m above water level near the northeastern end of the underground mine and 0.8 m above water near its southwestern edge. Galleries in the Fall City Mine were as much as 300 m long and 12 to 15 m wide. Roughly 75% to 80% of the limestone was extracted from the mined interval.

In most of the mine few joints were apparent in the roof, thus accounting for the strength of the mine, which was not shored by timbers. Near entrances from the quarry, however, a few masonry posts provide additional support. In one area a 2- by 4-m block of the Beechwood had collapsed into the mine, and the New Albany Shale was exposed in the roof. Near the northeast end of collapse area *D* (fig. 1) a portion of the roof broke away along joints. Many of the pillars have a concave surface with the overhanging part of the pillar having partly fallen away from the mine roof along the bedding plane between the Silver Creek and Beechwood Members. The collapsed areas are wooded. A 1940 aerial photograph showed that most of area *A* (fig. 1) had collapsed, but that areas *B*, *C*, and *F* were still being farmed without evidence of collapse. Collapse in area *A* is essentially complete; however, there is one sinkhole at the eastern edge of the area that is separated from the collapsed galleries by a short section of one gallery that remains uncollapsed. A 1960 aerial photograph showed that areas *B* and *C* had collapsed, perhaps shortly before that time. Of 11 entrances to the mine from the southeast wall of the quarry, 4 have collapsed (area *D*). Additionally, there are now two entrances from collapsed area *C* and several entrances that resulted from the collapse of area *B*. Areas *D* and *E* are in wooded areas, and it is difficult to date the collapse. Area *F* apparently collapsed after 1960. A small underground mine (area *E*) along the west wall of the quarry is only partly collapsed.

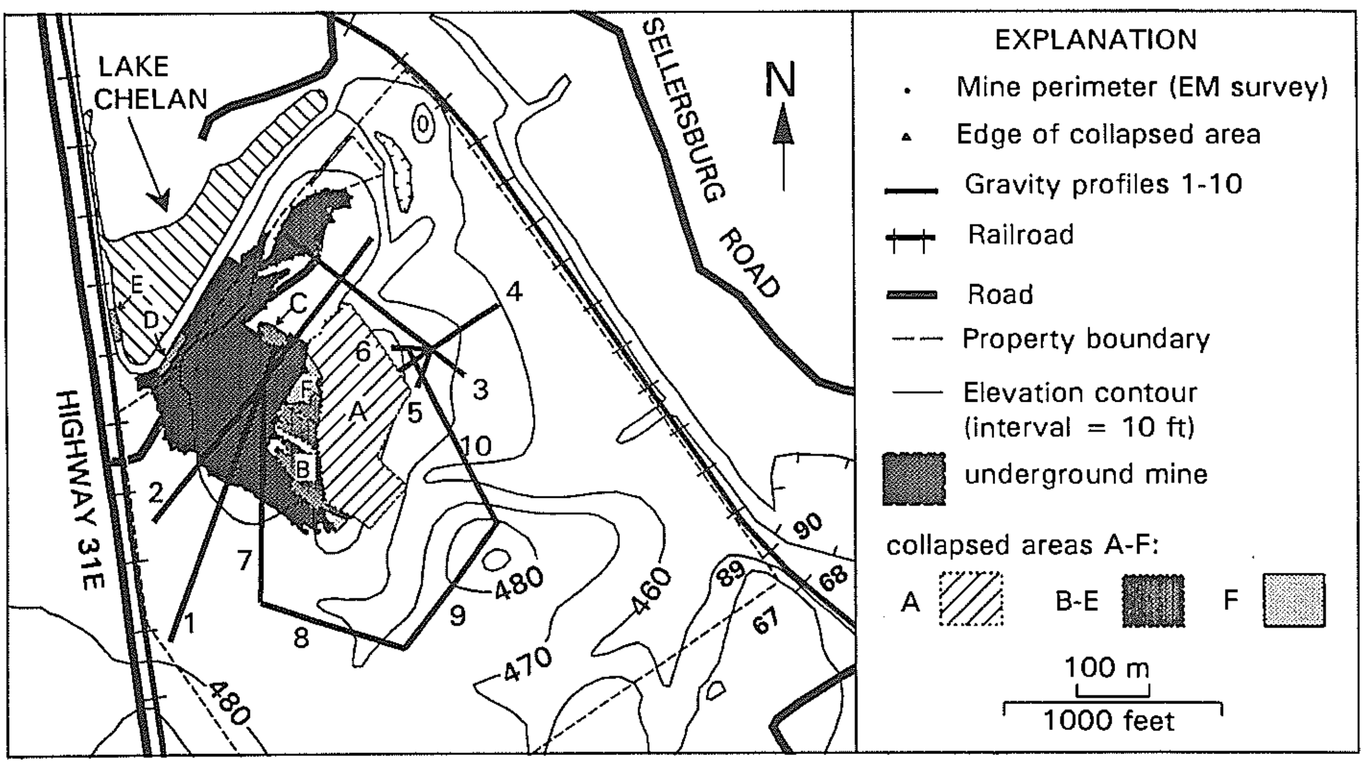

Figure 1. Map of the Falls City Mine showing the uncollapsed portion of the mine as mapped with an underground electromagnetic transmitter and aboveground receiver, collapsed areas, and gravity profiles 1-10. The indicated property boundary includes the southeast and northeast boundaries of Clark Military Grant 89. Collapsed areas were mapped with the aid of aerial photographs.

Basic Principles of Electromagnetism

In a vacuum the quasi-static (low-frequency) magnetic field of a sinusoidally oscillating vertical magnetic dipole (horizontal current-carrying loop of small dimensions) is a dipolar field with zero azimuthal component. The radial and tangential components are

$$H_r = I_o\, A \cos(\Theta) \sin(2\pi ft)/(2\pi R^3) \tag{1}$$

and

$$H_\Theta = I_o\, A \sin(\Theta) \sin(2\pi ft)/(4\pi R^3), \tag{2}$$

respectively (Wait 1982), where $I = I_o \sin(2\pi ft)$ is the current in amperes, f is the frequency in hertz, t is the time in seconds, A is the loop area in meters squared, R is the distance from the dipole in meters, and H is the magnetic field intensity in amperes per meter squared. The quasi-static approximation applies for distance much less than the wavelength of the electromagnetic radiation ($R << \lambda$), where wavelength $\lambda = c/f$ and c is the velocity of light. Directly above the dipole, the magnetic field is vertical and of greater intensity than elsewhere on a horizontal plane at a given height above the dipole.

In the presence of a conductor, the primary magnetic field (equations 1-2) induces secondary electric currents and a secondary magnetic field. If electrical properties are cylindrically symmetric about the vertical dipole source, including the case of a horizontally layered earth, there will be no azimuthal component of the secondary magnetic field, and the total (primary plus secondary) field directly above the source will still be vertical, although it may be attenuated. For a plane electromagnetic wave transmitted through a conductor, secondary currents cause the total magnetic field to be attenuated by a factor $e^{-x/d}$, where x is the distance transmitted, d is the skin depth,

$$d = (\pi\mu\sigma f)^{-1/2}, \tag{3}$$

σ is the conductivity in siemens per meter squared, and μ is the magnetic permeability in henries per meter. In most rocks μ is approximately equal to the permeability of free space μ_o ($=4\pi\ 10^{-7}$ H/m). To aid detection or lessen distortion of the total magnetic field, a low-frequency source is used to ensure that the source-receiver distance is less than several skin depths in the intervening media.

Field Procedure of Electromagnetic Mapping

We mapped the Falls City Mine using a "line finder." The transmitter unit includes a 0.15- by 1.07-m coil, which we oriented horizontally in the mine. The 82.5-kHz signal was modulated at 382 Hz and pulsed at 4.8 kHz. The continuously operating transmitter was centered abeam in a 3.7-m boat in which we traced the mine's perimeter by following the left wall of the mine so that no galleries at the periphery of the uncollapsed portion of the mine would be missed. The receiver unit included an audio speaker, a sensitivity control knob, and an attached wand containing a small sensing coil. The frequency of an audio pulsing tone increased with increasing magnetic field intensity at the sensing coil. The receiver was carried aboveground by the operator who followed the transmitter as it moved through the mine below. The receiver could detect the underground signal from a horizontal distance of about 10 m. The movement of the in-mine transmitter was halted at prearranged time intervals of 5 or 10 min. The location directly above the transmitter where the magnetic field was vertical, the pole position, was then determined by orienting the axis of the receiver coil horizontally so that a null response would be obtained.

Excluding stations at the edge of collapsed areas *B* and *C*, 55 mine-perimeter stations were located and marked with paint on the walls of the mine at an average interval of about 20 m along the mine's perimeter. We then used a level-transit to locate the aboveground mine-perimeter stations relative to property lines and features that were identifiable in aerial photographs. After a preliminary map of the mine was plotted, we reentered the mine to sketch details of the walls and to measure elevations of the roof and floor relative to the water surface. A video tape recording was made to document the condition of the mine's interior.

Results of Electromagnetic Mapping

We first successfully tested the applicability of the line finder to underground mapping in a shallow limestone cave (Buckner Cave) in Monroe County, IN. Although previous applications of electromagnetic mapping in caves have used much lower frequencies, use of a 82.5-kHz signal in the Falls City Mine was successful because the mine is very shallow. Electric logs of the Indiana Geological Survey drill hole 290 in Clark County, about 20 km north of the Falls City Mine, indicate that the maximum conductivity of the basal Blocher Member of the New Albany Shale is 0.05 S/m. The corresponding skin depth at a frequency of 82.5 kHz is 7.8 m. The Beechwood limestone is about 10 times less conductive than the overlying shale, and the soils at the surface are probably less or only slightly more conductive than the shale. The attenuation of the electromagnetic field by strata above the mine roof is, therefore, tolerable.

Because a suitable nonelectrically conducting boat was not available, we carried the transmitter through the mine in an aluminum boat. We placed the transmitter near the center of the boat so that an axis of symmetry for secondary currents in the boat would be vertical through the approximate center of the transmitter loop. We tested the method near an entrance to the mine from collapse area *C* (fig. 1). There we placed the in-mine transmitter near the center of the boat and then located the pole positions on the surface above the mine relative to a point directly above the transmitter. By placing the transmitter near the center of the boat with reasonable care, whether fore-and-aft or abeam, the pole position at the ground surface was displaced by less than 1 m. When the transmitter was placed near a corner of the boat, the pole position was displaced by 5 m.

Figure 1 shows the mine perimeter locations on a map generated by digitization of selected features of a 1964 7.5-min quadrangle topographic map and a 1960 aerial photograph. The mine encroaches within about 10 m of a house and a stone barn, but no existing buildings are undermined.

Principles of Gravity Surveying

A gravimeter measures spatial changes in the gravitational field due to the Newtonian attraction of the Earth's mass and the centrifugal acceleration associated with the Earth's rotation. So that gravity anomalies associated with local density contrasts can be identified and interpreted, drift, latitude, free-air, Bouguer, and terrain corrections are successively applied. Drift corrections, which remove effects of instrument drift and tidal effects of the Moon and Sun, are generally estimated by frequent repeated occupations of a base station. The drift is assumed to vary linearly with time over short intervals of time. The latitude correction, which removes effects of the Earth's equatorial bulge and centrifugal acceleration, is $C\,\chi\,\sin(2\Phi)$, where Φ is the latitude of a reference station, χ is the distance north of that station, and $C = 0.8121$ μgal/m (1 gal = 10 mm/s^2). The free-air correction, which removes effects of variation in distance from the center of the Earth, is $k\,h$, where h is the elevation above a datum and $k = 308.5$ μgal/m. In local surveys a datum at, or just below, the lowest point in the survey is commonly used. The result of applying this correction is called the "free-air" gravity.

The Bouguer correction, which removes the gravitational effect of an infinite horizontal slab lying between the gravimeter and the datum, is $-2\pi G\rho h$, where ρ is the Bouguer density, or assumed density of this layer, and G (= 66.7 pN m^2/kg^2) is the gravitational constant. The result of applying this correction is the "Bouguer" gravity. The terrain correction, which removes the effect of deviation of the terrain from a horizontal surface through a given station, is $T\,\rho$, where T depends on differences in elevation between the gravimeter location and nearby points on the Earth's surface. Often this correction is negligibly small, or varies gradually enough within a survey area that it is omitted. A regional gravity field (due to density contrasts extending beyond the bounds of the survey area or of larger lateral dimensions than are of interest in a given survey) may be estimated by mathematical methods (e.g., low-order polynomial fitting) or by visual inspection of the gravity field. The result of subtracting an estimate of the regional field from Bouguer gravity is called the residual Bouguer gravity.

Except on a regional scale, free-air gravity, g_F, will generally be correlated with topography owing to the gravitational effect of the near-surface rocks or soil. This correlation can sometimes be used to estimate the Bouguer density. For a homogeneous near-surface stratum and no anomalous gravitational fields,

$$g_F/(2\pi G) = \rho\,[h\text{-}T/(2\pi G)] + K_F, \qquad (4)$$

where K_F is a constant. In reality, lateral variations of density above and below the datum are present. If, however, these density variations are not correlated with the topography, then K_F becomes a random variable. In Parasnis' (1962) method, equation 4 is the basis of determining the Bouguer density as the slope of a straight line fit to points plotting $g_F/(2\pi G)$ versus $h\text{-}T/(2\pi G)$.

Field Procedure in Gravity Surveying

Ten gravity profiles at 4- or 8-m station intervals were located with a level-transit. Although the electromagnetic survey was conducted in the fall of 1992 and the gravity survey was conducted in the spring of 1993, most of the survey stakes and flags were preserved through the winter. Thus, the two surveys could be accurately tied, and profiles 1, 2, and 7 were placed directly through stakes at mine-perimeter stations. Gravity was measured at station locations using a temperature-regulated astatized gravimeter in which a micrometer screw adjusts tension on a "zero-length" spring to balance the gravitational force on a weighted horizontal beam. We determined the null position of the beam using a galvanometer driven by an electronic capacitance beam position indicator. One dial mark interval on the micrometer screw corresponded to a variation of gravity by about 10 μgal. Gravimeter readings were obtained by estimating the nearest tenth of a dial mark.

The gravimeter was leveled on a concave leveling disc, or baseplate, set firmly against the ground by pressing its three 55-mm legs into the soil. One baseplate was left at the base station at the intersection of gravity profiles 1, 2, and 7. An identical baseplate was used at other gravity stations. The base station was reoccupied at about 1-h intervals. In part of profile 9 inconsistent data were recorded owing in part to gusty winds and loose soil on a hillside, which made firm planting of the baseplate difficult. We did not reoccupy these stations since our survey was limited by the need to clear the ground before spring cultivation of the field.

Results of Gravity Surveying

Figures 2-7 show the residual Bouguer gravity and elevation above datum in profiles 1-10 (fig. 1).

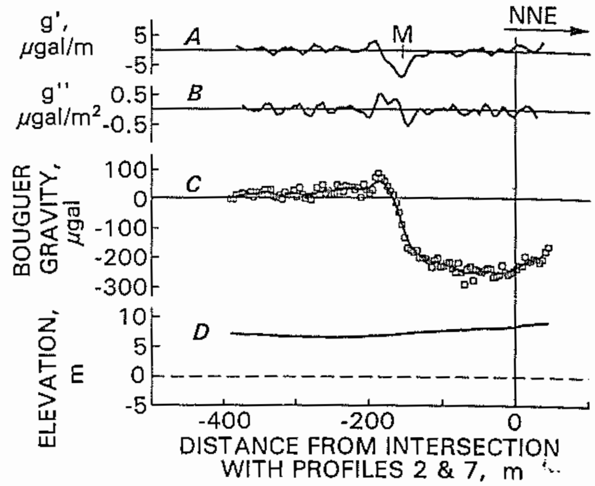

Figure 2. Profile 1: *A*, smoothed first horizontal difference, g´; *B*, smoothed second horizontal difference, g˝; *C*, residual Bouguer gravity, g, and smoothed gravity (solid curve); *D*, elevation above datum. The minimum of g´ occurs above the known mine edge (M) located by electromagnetic mapping.

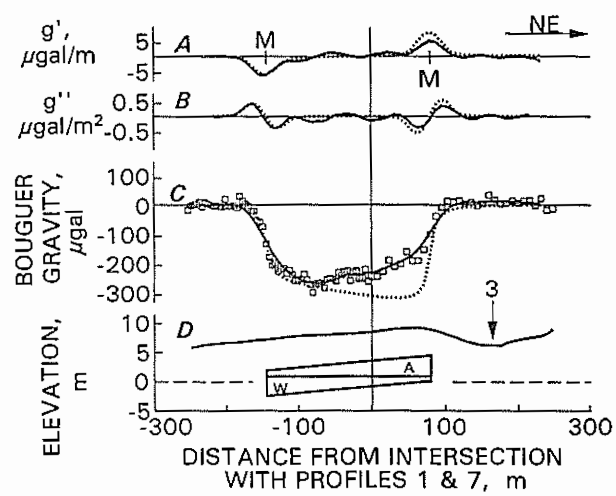

Figure 3. Profile 2 [measured (solid) and modeled (dotted) profiles]: *A*, smoothed first horizontal difference, g´; *B*, smoothed second horizontal difference, g˝; *C*, residual Bouguer gravity, g, (open squares) and smoothed gravity (curves); *D*, elevation above datum and model of the mine (A = air-filled, W = water-filled; with density contrasts of 2.12 and 1.32 mt/m³, respectively). The extrema of g´ occur above the known mine edges (M). An arrow locates the intersection with profile 3.

Latitude corrections reduced the data to the latitude of the base station, and free-air and Bouguer corrections used a datum 8.33 m below the base station and elevations from a level-transit survey of profiles 1-10. Terrain corrections were not applied. The Bouguer density of 2.05 mt/m^3 was obtained by Parasnis' method using linear regression to obtain the slope of a straight line fit to points in a plot of normalized residual free-air gravity ($g_F/2\pi G$) versus elevation above datum, h (fig. 8). Only off-mine stations in profiles 1-10 that were more than 20 m from collapsed areas and more than 50 m, along the direction of profile, from the uncollapsed mine perimeter were used. A regional field was removed from the free-air gravity before application of Parasnis' method to obtain a more reliable density estimate.

The residual free-air and Bouguer gravity fields (figs. 2-8) were obtained by subtraction of a regional field estimated by examination of Bouguer gravity at least 50 m distant from the mine in profiles 1-3, 7, and 10. The estimated regional gravity is constant in an east-west direction and increases southward at the rate of 0.4 μgal/m. Smoothed residual Bouguer gravity profiles (figs. 2-7) were derived by application of a triangular-weighted nine-point smoothing filter (1,2,3,4,5,4,3,2,1)/25, with shorter filters used at the ends of profiles. In profiles 1-10, the root-mean-square difference between smoothed and unsmoothed residual Bouguer gravity is 14 μgal, excluding end effects of the smoothing filter. This difference results partly from measurement errors and "geologic noise" due to shallow subsurface density changes not related to the Falls City Mine.

Gravity profiles 1-3 and 7 (figs. 2-4 and 6) cross the edge of the uncollapsed portion of the mine as determined by our electromagnetic mapping with an underground transmitter. In these profiles a negative Bouguer anomaly of about 300 μgal is observed. Figures 3-6 also show the smoothed first and second horizontal differences, which are approximations of first and second horizontal derivatives [g' ($=\delta g/\delta x$) and g'' ($=\delta^2 g/\delta x^2$)] of the residual Bouguer gravity. The smoothed first horizontal difference was obtained by application of a seven-point filter comprising the $(-1,1)/\Delta x$ differencing filter convolved with the averaging filters (1,1,1)/3 and (1,1,1,1)/4, where Δx is the station spacing of 4 or 8 m. The smoothed second difference was obtained by application of a nine-point filter comprising the $(-1,2,-1)/\Delta x^2$ differencing filter convolved with (1,1)/2, (1,1,1)/3, and (1,1,1,1)/4 averaging filters (Blackman 1965).

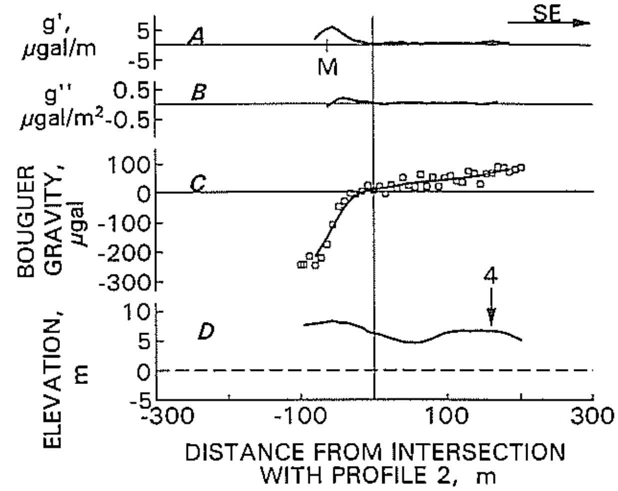

Figure 4. Profile 3: A, smoothed first horizontal difference, g'; B, smoothed second horizontal difference, g''; C, residual Bouguer gravity (open squares) and smoothed gravity (solid curve); D, elevation above datum. The maximum of g' occurs above the known mine edge (M). An arrow locates the intersection with profile 4.

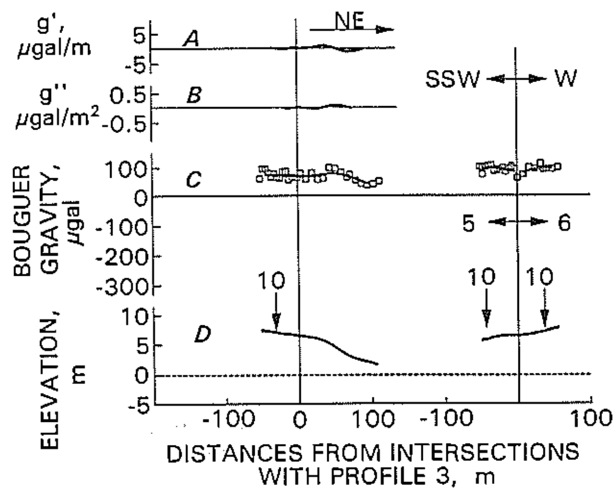

Figure 5. Profiles 4, 5, and 6: A, smoothed first horizontal difference, g'; B, smoothed second horizontal difference, g''; C, residual Bouguer gravity (open squares) and smoothed gravity (solid curve); D, elevation above datum. Arrows locate intersections with profile 10.

For a two-dimensional gravity field, the second horizontal derivative is proportional to the second vertical derivative ($\delta^2g/\delta z^2$) since the gravity field satisfies Laplace's equation

$$\delta^2g/\delta x^2+\delta^2g/\delta y^2 = -\delta^2g/\delta z^2, \quad (5)$$

where y is the horizontal coordinate measured perpendicular to the profile. The points of inflection of the gravity anomalies, as defined by extrema of the first-difference curves and zero crossings of the second-difference curves, are approximately coincident with the edges of the mine (figs. 2-4 and 6). This result is consistent with the fact that the zero crossings of the second vertical derivative, and therefore any second horizontal derivative of gravity resulting from a homogenous (constant-density), two-dimensional rectangular prism with vertical sides and a width greater than the depth to its center, occur very near to points directly above the edge of the prism (Elkins 1951). Figure 3 shows a comparison of measured and modeled profiles of residual Bouguer gravity, g, g´ (=$\delta g/\delta x$), and g˝ (=$\delta^2g/\delta x^2$), and the corresponding density contrast model of the mine. In drill hole 290 a density log indicates that the average density of the basal Blocher Member of the New Albany Shale is 2.42 mt/m^3. The underlying North Vernon Limestone has densities of 2.62 to 2.79 mt/m^3 with the most dense strata occurring in the upper 2 m of the formation. The density model (fig. 3*D*) assumes a mine height of 4.3 m and a density contrast between the Silver Creek (ρ = 2.65 mt/m^3) and a mined area comprising 80% air or water and 20% unmined rock. The relative amounts of air and water in the model correspond to measurements made in the mine near profile 2. Although the beds dip slightly, density contrasts along bedding were used. The gravitational effect of the structure related to variable thickness of shale and density contrasts above and below the mine level was not considered since this effect may be partly removed by subtraction of the regional field. The modeled gravity was computed on the sloping ground surface (fig. 3*D*). The residual Bouguer gravity in line 2 is less than the modeled gravity near the northeast edge of the mine, where the mine is poorly approximated as a two-dimensional body and where debris has washed into the mine from the adjacent collapsed areas. Profile 2 crosses above a large debris cone which entered the mine through one of the two entrances from collapse area *C*.

Negative gravity anomalies of about 50 and 70

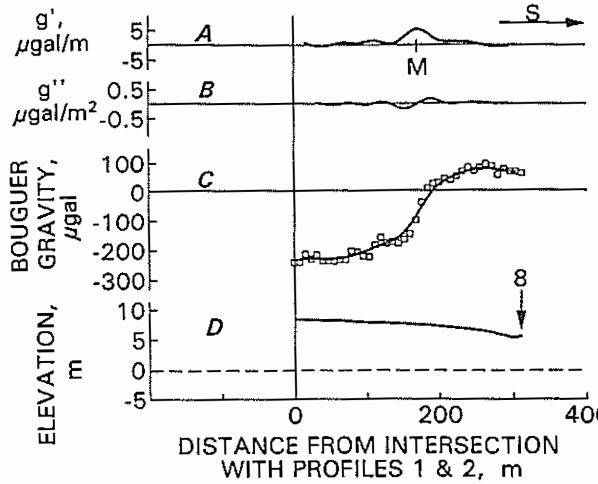

Figure 6. Profile 7: *A*, smoothed first horizontal difference, g´; *B*, smoothed second horizontal difference, g˝; *C*, residual Bouguer gravity (open squares) and smoothed gravity (solid curve); *D*, elevation above datum. The maximum of g´ occurs above the known mine edge (M). Profile 8 starts at the southern end of profile 7.

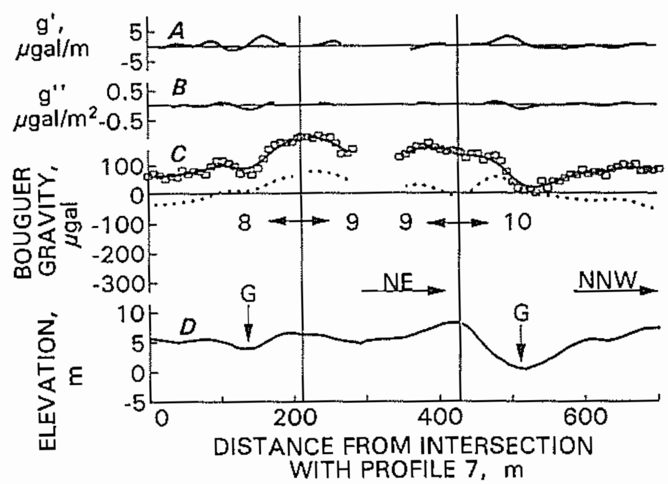

Figure 7. Profiles 8, 9, and 10: *A*, smoothed first horizontal difference, g´; *B*, smoothed second horizontal difference, g˝; *C*, residual Bouguer gravity, g, (open squares) and smoothed gravity using Bouguer densities of 2.05 (solid curve) and 2.50 (dotted curve) mt/m^3, respectively; *D*, elevation above datum. Relative minima of g (using the lesser Bouguer density) occur in the gully (G) traversed by profiles 8 and 10.

μgal occur in profiles 8 and 10 (fig. 7*C*), respectively. These anomalies are coincident with a gully south of collapsed area *A* (fig. 1). Use of a Bouguer density of 2.5 mt/m^3, instead of 2.05 mt/m^3, effectively removes these small anomalies (fig. 7*C*). It is probable that this gully has eroded some of the shale with a density of about 2.42 mt/m^3 and perhaps even some of the underlying limestone. In comparison, a 4.3-m high tunnel at a depth of 8 m would create a 60-μgal anomaly if it were 4 m wide and air-filled ($\Delta\rho$ = 2.65 mt/m^3) or 6.5 m wide and water-filled ($\Delta\rho$ = 1.65 mt/m^3). The negative gravity anomalies in profiles 8 and 10 are, however, relatively wide and positively correlated with the terrain and are, therefore, not interpreted to result from tunnels associated with the Falls City Mine. On the hillside beneath profile 10 to the south of this gully, a small positive anomaly may indicate relatively thin soil on the hillside.

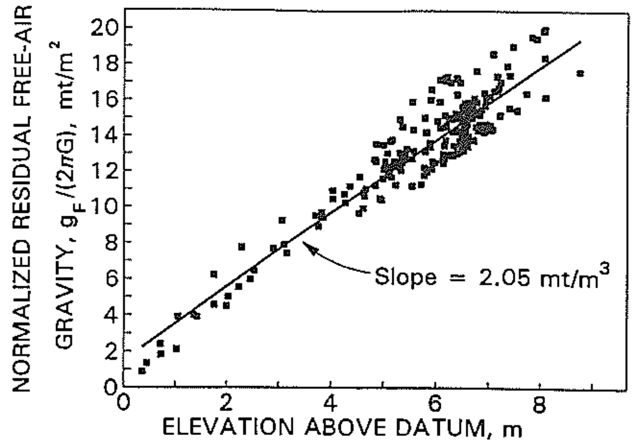

Figure 8. Normalized residual free-air gravity, $g_F/2\pi G$, in profiles 1-10 versus elevation above datum. The plotted straight line, obtained by linear regression, has a slope of 2.05 mt/m^3. The data are from all off-mine stations more than 20 m from collapsed areas and more than 50 m, along the direction of profile, from the uncollapsed mine perimeter.

Conclusions

The method of electromagnetic mapping a very shallow limestone mine with an underground dipole transmitter and aboveground receiver is practical and efficient. Gravimetric mapping of the Falls City Mine successfully located the edges of the mine at inflection points of 300-μgal Bouguer gravity anomalies. No inaccessible galleries leading from the collapse area of the mine were detected. Gravimetric mapping of similar underground limestone mines in southeastern Indiana should be practical.

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