SULFUR EXPLORATION WITH CORE HOLE AND SURFACE GRAVITY

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ABSTRACT

Announcement of a major discovery near Orla, Texas, in 1968 set off an extensive sulfur exploration play in the Permian Basin. The terrane, geologic setting, and mode of sulfur deposition were favorable for use of the gravity exploration method, and it became the most widely used and cost-effective geophysical technique for the play. Prospects were commonly located through use of reconnaissance coverage, then detailed gravity surveys were conducted to delineate the most favorable sites for initial core drilling.

An important procedure in the exploration program designed by Exxon Co. USA was the analysis of prospective gravity anomalies through model studies, using measured subsurface densities for control. Exxon Production Research Company developed a modified borehole gravimeter which successfully logged 28 core holes. Densities calculated from the core hole gravity were judged to be more accurate and consistent than those derived from other sources.

The core hole meter was a technical success. Whether continued usage might have led to a commercial discovery is uncertain. An abrupt plunge in sulfur prices on the world market ended Exxon's exploration play before several promising anomalies were fully evaluated.

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Introduction

An extensive sulfur exploration play in the Permian Basin was touched off in 1968 when Duval Corporation announced a major sulfur discovery near Orla in Culberson County, Texas. Shallow sulfur occurrences had been noted in West Texas as early as 1854, and several open pit mines operated intermittently during the early 1900's. By the late 1960's, rising world demand and improved production technology made sulfur exploration commercially attractive. However, the economic potential of West Texas-type deposits was not fully appreciated until the magnitude of the Orla deposit was finally recognized: announced reserves of over 80 million long tons with local concentrations in excess of 40,000 tons per acre.

Industry employed a variety of remote sensing or surface prospecting methods in advance of the core drill. The more commonly used were photogeology, surface geology, geochemical soil analysis, gravity, surface resistivity, and induced polarization. Of these, a combination of photogeologic and gravity methods appears to have been widely adopted. Selection of these two methods may have been influenced by features of the Orla site, which is characterized by both a prominent photogeologic drainage anomaly and a local Bouguer gravity minimum (see Figures 1 and 2).

All significant West Texas sulfur deposits discovered in the late 1960's and early 1970's are closely identified with gravity minima. The association is theoretically sound on the basis of the geologic assumptions made. This paper briefly describes gravity methods used by Exxon Co. USA during the active phase of their sulfur exploration program.

Local Stratigraphy and Sulfur Occurrence

Some background information regarding local stratigraphy and modes of sulfur occurrence serves to provide a better appreciation of the suitability of gravity as a sulfur prospecting method.

The upper Permian beds exposed in Culberson and Reeves counties, Texas, form a northeasterly-dipping homocline with occasional gentle folds and faults of small vertical displacement (Figure 2). Sediments of the Ochoa series were deposited in a restricted sea environment and are predominantly carbonate, sulfate, and salt formations. Sulfur deposition is primarily related to, but not restricted to, the following members of the Ochoa series:

Rustler - usually limestone or dolomite, with some sands and/or gypsum
Salado - usually salt or limestone, sometimes anhydrite or gypsum
Castile - characteristically a dense anhydrite containing limestone "castiles"

Figure 4 illustrates a generalized concept of the geochemistry of native sulfur generation and accumulation within a near surface fracture zone. Oxidation of hydrogen sulfide gases and/or reduction of sulfates from anhydrites or gypsum are believed to be vital to the process. Whether the fracture zones were generated by deep-seated tectonic movement or by collapse due to local salt solution in the Salado, the porosity zones are normally quite restricted laterally. Sulfur prospects are measured areally in terms of a few hundred acres. Vertical extent and richness of the ore body are therefore critical economic factors.

Use of the Gravity Method

No geophysical method is known to directly detect the presence of native sulfur deposits. However, induced polarization, surface resistivity, magnetic, gravity, and seismic surveys could each be used to some extent in the various phases of prospecting. Gravity became accepted as the primary, most cost-effective method for the West Texas play; the following factors were particularly favorable for its use:

1. Good lateral density contrasts. The country rock is normally dense, ranging from 2.50 gm/cc (limestones) to 3.00 gm/cc (anhydrites). Pure sulfur has a density of approximately 2.00 gm/cc; even if fractures in the country rock were solidly filled with sulfur, the fracture zone would exhibit a density significantly lower than that of the host rock.

2. Measurable gravity anomalies. The prospective ore bodies are often less than 1500 feet deep and are areally restricted. Density contrasts range up to 0.50 gm/cc (see above). Gravity modeling demonstrates that such bodies generate sharp, short wavelength minima of sufficient amplitude to be detectable with conventional survey instruments and techniques.

3. Anomaly recognition. Provided the survey coverage were sufficiently dense, the intense, short wavelength minimum caused by a typical ore body would be recognizable and have characteristics suitable for various anomaly separation and enhancement techniques.

4. Logistics and economy. Vegetation is sparse and the road network limited in this semi-arid plains area. Gravity survey operations are fast and highly mobile, permitting rapid, detailed coverage of small, widely scattered tracts. Personnel and equipment requirements are modest, and environmental impact is minimal.

5. Empiricism. All significant Permian Basin sulfur deposits reported during the 1968-1970 play are associated with recognizable gravity minima.

Geologic conditions other than those directly related to sulfur accumulation also generate gravity anomalies with similar amplitude and wavelength character. Attractive-looking, shallow-sourced anomalies could be generated by barren fracture zones or by compact deposits of alluvium, gravel, or gypsum. Even at Orla, less than half the gravity anomaly is directly attributable to the known ore body itself. Therefore, proper interpretation of a prospective anomaly requires that the range of reasonable solutions be constrained by utilization of all available structural and formation density data.

Surface Gravity Coverage

General play areas were established on the basis of surface geology anomalies, reported sulfur shows, and suspected mineralization trends. A two-stage gravity survey or data acquisition program provided Exxon an efficient approach to rapid discovery and development of local prospects:

1. First, regional trends and individual prospect outlines were defined by existing coverage or new reconnaissance gravity surveys. Station density of at least one or

two stations per square mile and gravity accuracy to within 0.5 milligals were basic requirements. Although a compilation of surveys with uneven data quality was acceptable at this stage, it was recognized that the higher quality surveys would provide valuable base networks for future detailed work.

Figure 5 illustrates the Bouguer gravity mapped from reconnaissance coverage over Prospect A. Note the contrast in amplitude and areal size between the large minimum nose in the western portion of the map and the subtle minimum nose associated with a known sulfur ore body to the east. Even with the coarse station spacing, the larger anomaly appeared attractive but the smaller anomaly could have been readily overlooked and the ore body missed.

2. Once the most prospective anomalies were located, they were more closely defined by detailed surveys having a station density of 25-50 stations per square mile, normally on an 880-foot grid. Gravity measurements, including terrain corrections out to the Hammer "D" ring (Hammer, 1939), were specified to have an accuracy of 0.1 mgals or better.

   Figure 6a illustrates the Bouguer gravity mapped from a detailed survey over the same Prospect A discussed above. The additional control permitted mapping of individual minimum closures plus several lobes in the broad minimum area to the west. Note the minimum identified with the sulfur body is now more clearly defined.

   Zones of steep contour gradient are also more sharply defined by the additional coverage. Steep gravity gradient zones are often regarded as significant indicators of contacts between bodies of laterally varying density contrast (e.g., faults zones, ore body edges, etc.). Steep gradient zones in the prospect areas were interpreted as edges of the porosity or alteration zones and were used to estimate the effective areal limits of mineralization. In some graben-type deposits where porosity and mineralization tended to intensify toward the bounding faults, definition of the gravity contour gradient zone was especially important.

Bouguer anomalies and gradient zones can be enhanced by various analytic methods such as subjective regional-residual separation, high-pass filtering, grid residual calculation, or derivative approximations. Figure 6b is an example of the latter using Elkins' Formula 13 (Elkins, 1951) to calculate a derivative approximation of the detailed data at Prospect A. Since the minima and gradient zones were of primary interest, only the negative derivative values were contoured in addition to the zero contours defining centers of the steep gradient zones.

Subsurface Density Data

Once adequate surface gravity data were acquired by Exxon and the initial core tests drilled, subsurface density control was needed to more fully interpret the prospective anomalies. Densities were obtained from several sources, primarily:

1. Density measurement of drill cuttings and cores.

   Advantages - relatively inexpensive if done on a selective basis. Cuttings were routinely available, even if logs could not be run. Density values were laboratory-measured, not estimated.

   Disadvantages - density data was not vertically continuous since not all rock samples were recovered and/or tested. Although density measurements from cores were considered reliable, those from cuttings were found to be less consistent. The method could not predict lateral density variations away from the hole. Moisture content of near-surface material could vary unpredictably and affect bulk densities significantly.

2. Estimates from gamma ray-neutron logs and lithologs

   Advantages - These logs were normally run for formation identification and correlation. They provided continuous vertical data and could give acceptably accurate density values for massive anhydrite and distinctive shale or gypsum reference formations. Some hole deviation could be tolerated, and the gamma ray-neutron logs could be run in cased holes.

   Disadvantages - accuracy of gamma ray-neutron density values was dependent on calibration to standardized densities of reference formations by means of lithologs. When hole conditions were poor, correlations between the density estimates and measured densities from cuttings or cores often proved inconsistent from hole to hole, or even within the same hole.

3. Measurements from gamma-gamma (density) logs

   Advantages - the log could normally be properly calibrated to provide acceptably accurate, continuous, hole-compensated density measurements.

   Disadvantages - an open hole was required for logging, but many of the core holes were cased because of surface gravels and/or intensive near-surface formation fracturing. The sondes in use had 4 3/8-in. diameters, thus requiring more expensive 6-in. diameter holes rather than the standard 4 7/8-in. core holes. Availability of the logging units on short notice was limited and logging costs were relatively high.

4. Measurements from core hole gravity meter

   Advantages - because of its 3 5/8-in. diameter, Exxon's core hole gravity meter could be run in standard 4 7/8-in. core holes, either cased or open. Calculated formation bulk densities gave consistent agreement to within 0.2 gm/cc of the most reliable values derived from other sources, particularly for the very shallow formations. Some zones of lateral density variation could be predicted by the remote sensing aspects of the survey. Survey costs were moderate, on the order of $2100 per hole (1969 dollars).

   Disadvantages - the meter could not be operated in a hole with vertical deviation greater than 4 degrees. Because the meter required discrete downhole stations, continuous density readings could not be obtained. A previously run gamma ray-neutron log was usually needed to plan optimum borehole station depths.

   In all, Exxon ran twenty-eight core hole surveys, one as deep as 2900 feet, in eight different prospects. Figure 7 shows calculated and averaged meter-derived densities from the surveys with comparable downhole lithology. Results from the core hole meter surveys were utilized in gravity prospect analysis, as illustrated by two examples below.

Gravity Prospect Analysis

Once promising gravity anomalies had been identified by reconnaissance and the detailed surface gravity surveying completed, the gravity and available geologic data were integrated to determine optimum locations for a core test program. Prior to drilling each core test, two-dimensional gravity modeling was used to evaluate the most probable subsurface density variations producing the surface gravity anomalies. Models were then updated with the additional density and lithology control obtained from the core tests. Drilling was normally planned to test minima both along the central axis and along one or more steep contour gradient zones. If no encouraging traces of sulfur were encountered, the gravity interpretation was reviewed to determine whether further drilling was warranted. In cases where the most geologically reasonable interpretations could satisfy the gravity data without producing additional leads, the prospect was abandoned.

Prospect B

The prospect appeared to be a complex near surface fracture or alteration zone. Three core holes were drilled normal to the axis of a northwest-southeast Bouguer minimum (Figure 8). Formation densities for all three holes were measured from cuttings and cores and were also estimated from gamma ray-neutron logs. Core hole gravity meter surveys were subsequently run in the three holes. Overall densities calculated from the meter survey in core hole #2 were as much as 0.6 gm/cc higher those estimated from the log and cuttings (Figure 9). In hole #3 the meter-derived densities were within 0.15 gm/cc of those estimated from the gamma ray-neutron log as calibrated by cutting densities (Figure 10). Density variations, both lateral and vertical, between the three holes drilled across Prospect B were so great (Figure 11) that even the data from the core hole meter surveys initially seemed suspect.

Two-dimensional gravity models, using all available geologic data to establish geometry of various known or predicted lithologic units, were constructed to test the validity of density values obtained from cuttings, logs, and core hole meter surveys. Suspicions that densities estimated from cuttings and logs were generally too low were confirmed by the models. A typical example is illustrated by Figure 12. The country rock lithology, formation thickness, and density are standard for the surrounding area. Within the bounds of the prospect, the initial model used densities estimated from logs and cuttings for each of the three core holes (see Figures 9 and 10). The calculated gravity minimum is approximately 2.0 mgals larger than the observed minimum from the surface gravity survey. **The misfit cannot be significantly reduced without unrealistic major revisions to the geometry of the model.**

Subsequent models with generally similar geometry used meter-derived densities to total depth of the surveys, then a suite of estimated densities to total depth of the core holes. These estimated density values ranged between those from the core hole surveys and those from cuttings and logs. Figure 13 illustrates the final best-fit model obtained.

A general conclusion reached from this and other model studies was that the core meter surveys provided more accurate and reliable formation bulk densities than could be readily obtained from other methods. A specific conclusion reached for Prospect B was that the final best-fit model was compatible with the geology, the subsurface densities, and the surface gravity anomaly. The core tests did not reveal any significant sulfur accumulation and there were no unresolved gravity anomalies remaining at the site. The prospect was therefore deemed as adequately tested and was abandoned.

Prospect C

Prospect C was a small, near surface, graben-type feature. Three core tests were drilled normal to the axis of the Bouguer minimum (Figure 14), with only the center hole located inside the bounding faults. Core hole meter surveys were run in all three holes; however, the meter could not be run to total depth in the center hole (#2) because of extreme hole deviation below 800 feet. Densities for the deep graben section were therefore derived from litholog and gamma ray-neutron log data. These data indicated a formation density of 2.80 gm/cc for a 200-foot section immediately below the 800-foot meter station in hole #2.

Initial two-dimensional gravity models for Prospect C using core hole meter densities plus the deep graben log-derived densities produced mismatches of up to 1.1 mgals between calculated and observed profiles (Figure 15). The models suggested the presence of an unresolved low-density zone within the graben. From prior experience at

Prospect B and other areas, meter-calculated densities were found to give more consistent and reliable formation bulk density information than did lithologs or gamma-ray neutron logs. Hence the most probable cause for the residual gravity minimum was judged to be an anomalous zone in the deep graben where logged densities might not be representative of the surrounding section. This concept was tested in models with the 2.80 gm/cc graben section replaced by lighter density section. A model using a section density of 2.30 gm/cc gave the best fit (Figure 15).

Results of the meter surveys and model studies indicated a promising new lead at Prospect C. The core test in the graben may have narrowly bypassed a relatively light-density, high-porosity, potentially mineralized zone between 800-1100 feet deep. On the basis of the gravity analysis, two additional lateral offset core holes within the graben were recommended to more fully evaluate Prospect C. They were not drilled due to cancellation of the entire program.

The Core Hole Gravity Meter

The core hole gravity meter was developed by Exxon Production Research Company expressly for use in Exxon's sulfur exploration program. The instrument was a special modification of the Exxon vibrating string meter which previously has been described in detail (Howell et al, 1966). Both the new sensitive element and the electronic section were essentially identical with those of the older meters, but use in the low-temperature environment of the average core hole permitted a reduction in the thermostat controls for meter temperature. In addition, expectation of low core hole pressures allowed use of thin-wall instrument casing, thus the entire assembly could be contained in a 3 5/8-inch O.D. case.

The entire well string, consisting of a nose, meter section, electronics section, connector case, and Schlumberger head, measured 110 3/4 inches in length (Figure 16). Because of the danger of instrument loss due to core hole bridging or casing collapse, two complete instruments plus one spare sensitive element were fabricated to provide back-up capability. Total cost was approximately $30,000 (1969 dollars).

An electronics technician operated the meter and performed any necessary field maintenance. Common practice was for the meter survey to be run after the gamma ray-neutron log. In this way there was a cable truck immediately available for the meter survey, as well as additional personnel available to help the meter operator attach the instrument to the cable head. The Exxon geologist present during the logging would interpret formation breaks from the gamma ray-neutron log in order to preselect meter station locations for the survey. Since each station reading required about 20 minutes, economy, hole conditions, and survey scheduling usually dictated that the total number of stations per hole be kept to a minimum. Station spacing greater than 200 feet was seldom necessary, however.

Summary of Results

No commercial discoveries by Exxon were directly attributed to Exxon's use of surface or core hole gravity surveys, although surface surveys conducted over known sulfur deposits detected anomalies which confirmed validity of the method. The core hole meter proved to be a technical success. Whether continued core drilling, metering, and prospect analysis would have led to a commercial discovery is uncertain. At the height of the West Texas sulfur play, increased sulfur extraction from sour gas and reduced world demand created an oversupply of the commodity, followed by abrupt plunge in world sulfur prices. Exxon's exploration effort was halted before several remaining surface and subsurface prospect leads were fully evaluated.

However, a positive by product of the program was the recognition that explorationists and data normally dedicated to hydrocarbon exploration could also be of value in certain non-hydrocarbon ventures. Data which might have declined in importance for a given play could, if properly archived, become a major asset to some new unexpected venture.

Acknowledgments

Release of the gravity data, models, logging results, and meter description by Exxon Exploration Company is gratefully acknowledged. Special thanks are given to L. J. Srnka of Exxon for assisting in the release. Appreciation is also extended to Corine Prieto and Steve Stephens of Integrated Geophysics Corporation for their support in preparation of the final text and illustrations for this paper.

References

Butler, S.W. and Dixon, L.P., 1968, Sulfur occurence in the Rustler Springs sulfur district, Culberson and Reeves County, Texas: Symposium and Guidebook, 1968 Field Trip, Permian Basin Section, SEPM, Publication 68-11, p.91-93.

Elkins, T.A.,1951, The second vertical derivative method of gravity interpretation: Geophysics, v.16, p.39-56.

Goodell, R.R., and Fay, C.H.,1964, Borehole gravity meter and its application: Geophysics, v.29, p.774-782.

Hammer, S.,1939, Terrain corrections for gravity stations: Geophysics, v.4, p.184-194.

Haye, E.F.,1969, Application of gravity to sulfur exploration - Delaware Basin: PhotoGravity Co., Inc. brochure

Howell, L.G, Heintz, K.O., and Barry, A.,1966, The development and use of a high-precision downhole gravity meter: Geophysics, v.31, p.764-782.

McCulloch, T.H., Kandle, J.R., and Schoellhamer, J.E.,1968, Application of gravity measurements in wells to problems of reservoir evaluation: SPWLA Ninth Annual Logging Symposium.

Nettleton, L.L.,1954, Regionals, residuals, and structures: Geophysics, v.19, p.10-22.

Smith, N.J., 1950, The case for gravity data from boreholes: Geophysics, v.15, p.605-635.

Zimmerman, J.B., and Thomas, E.,1969, Sulfur in West Texas: its geology and economics: Bur. Econ. Geol. Cir. 69-2.

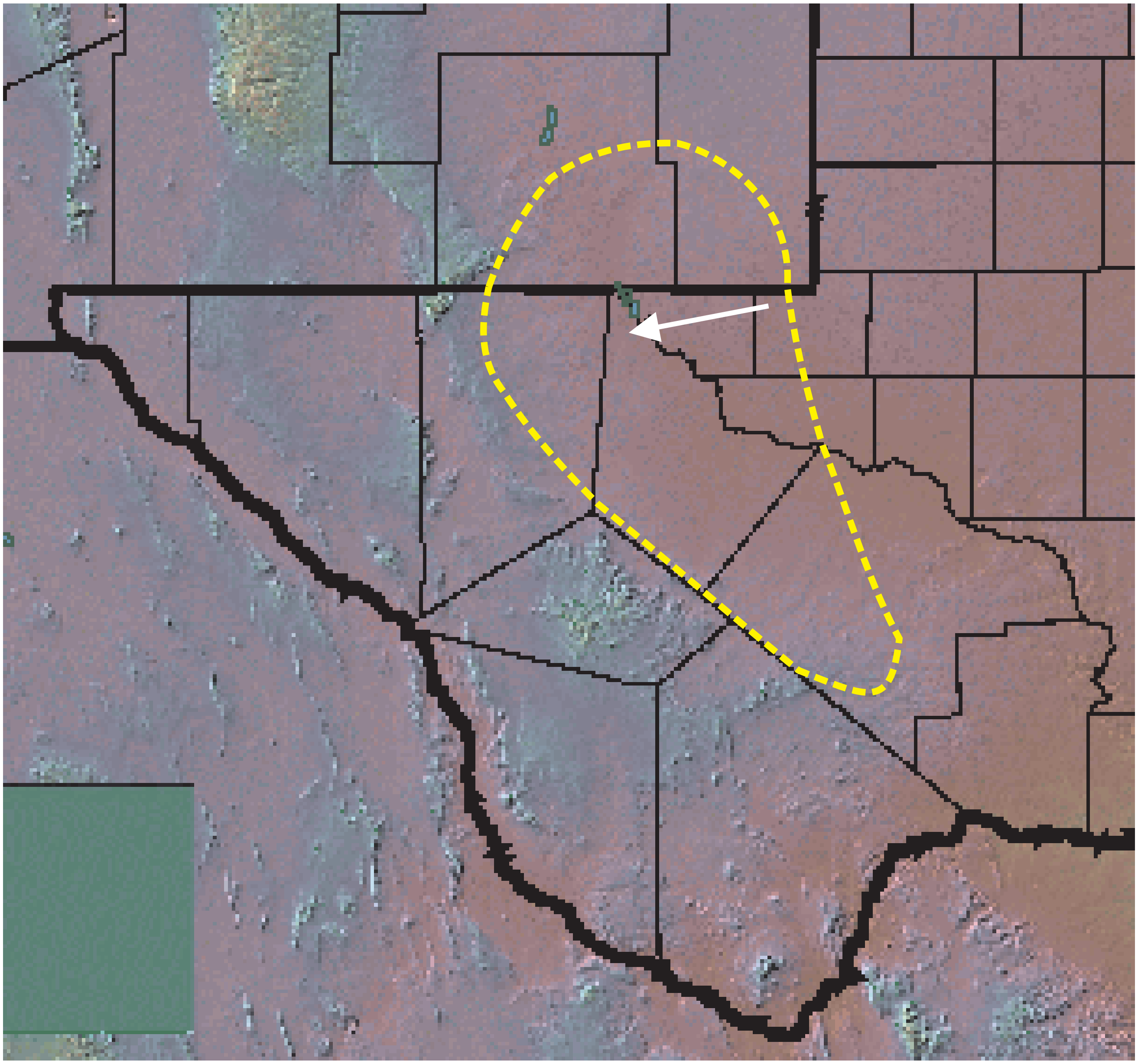

Figure 1. LandSat image of West Texas-New Mexico area with approximate outline of Permian (Delaware) Basin. Orla site indicated by arrow.

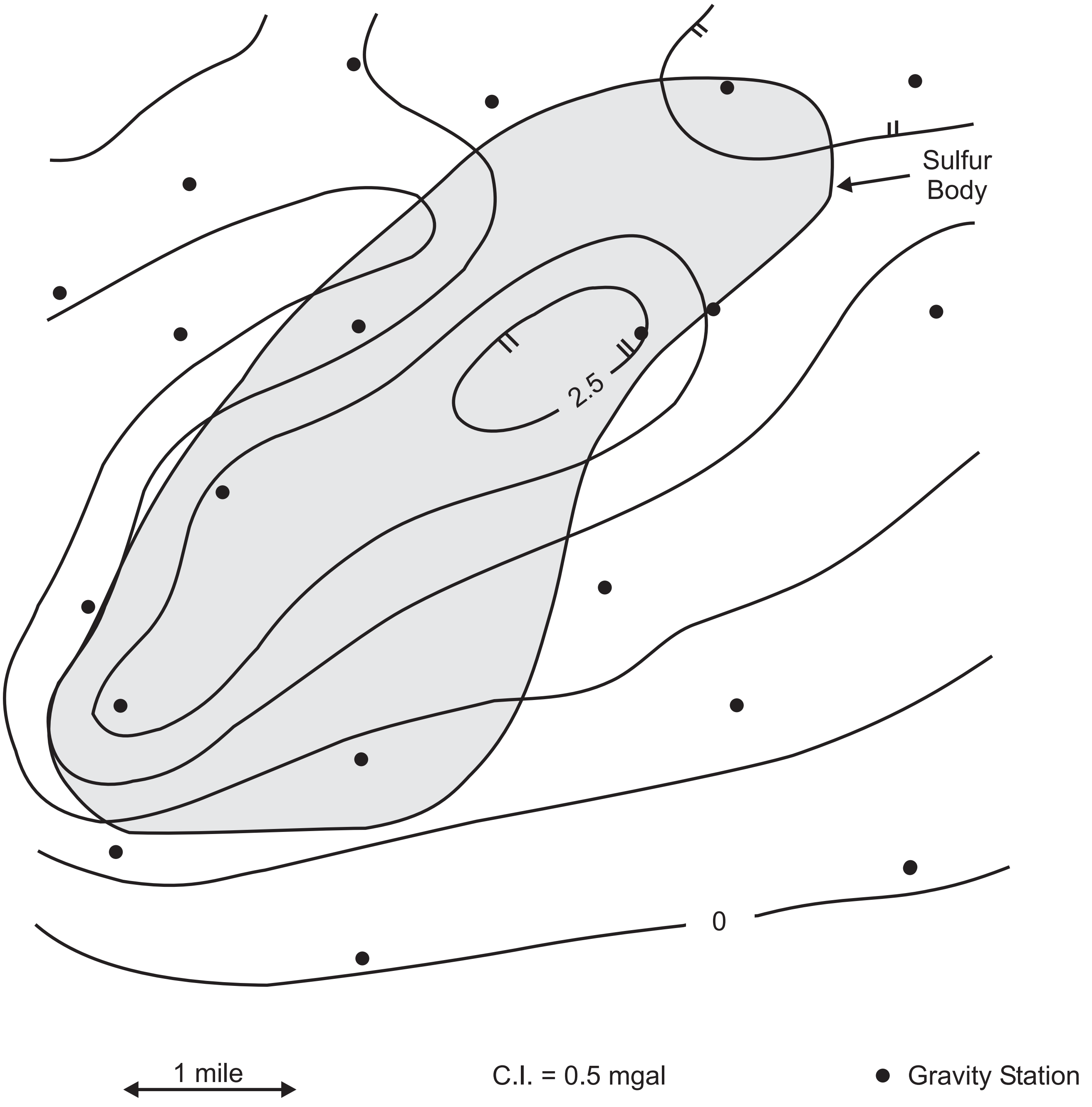

Figure 2. Bouguer gravity at the Orla sulfur deposit site. Survey is reconnaissance quality; note relatively sparse station locations.

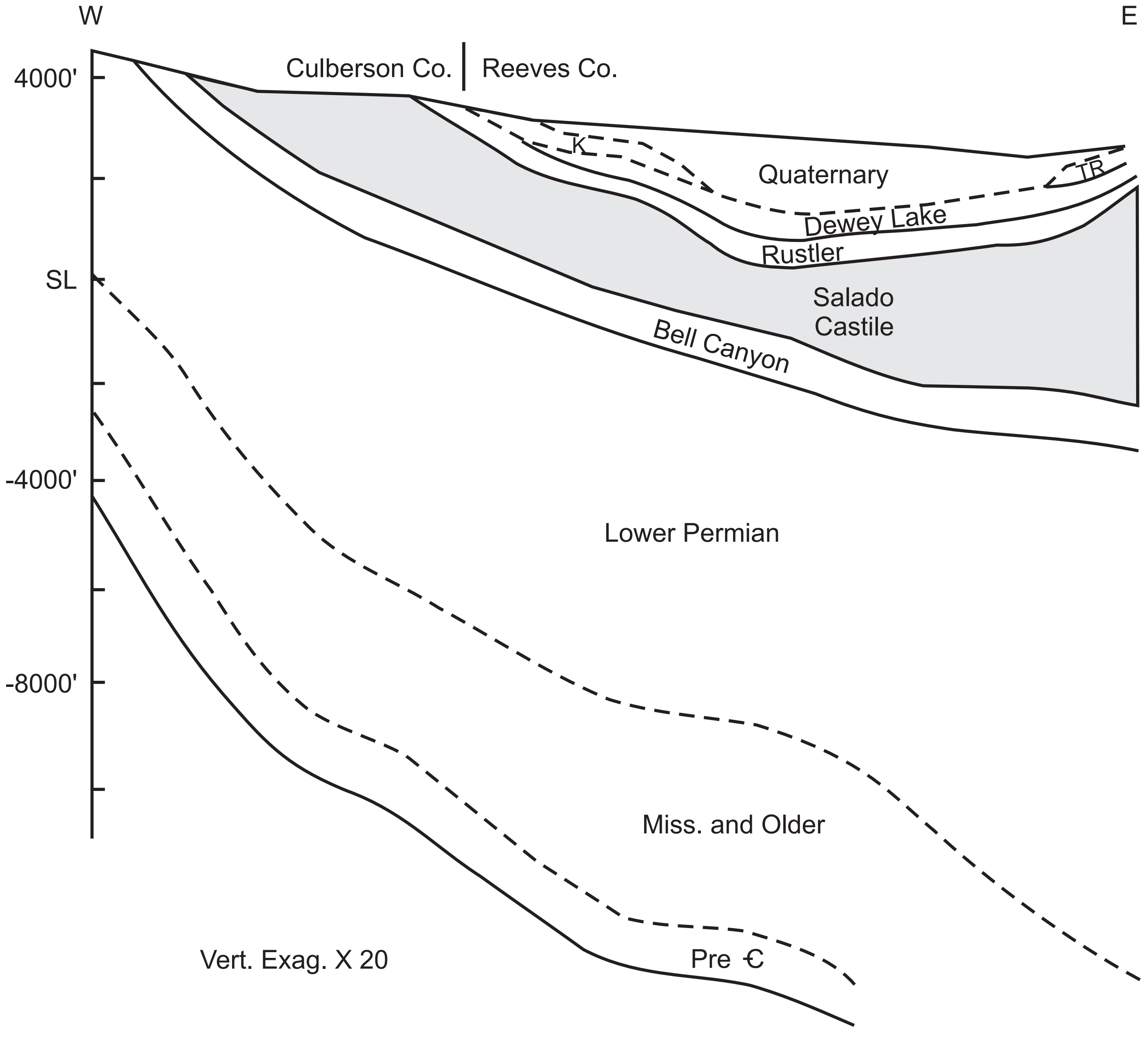

Figure 3. Generalized geologic cross section, Delaware Basin, Texas (after Yarborough et al, unpublished Exxon report).

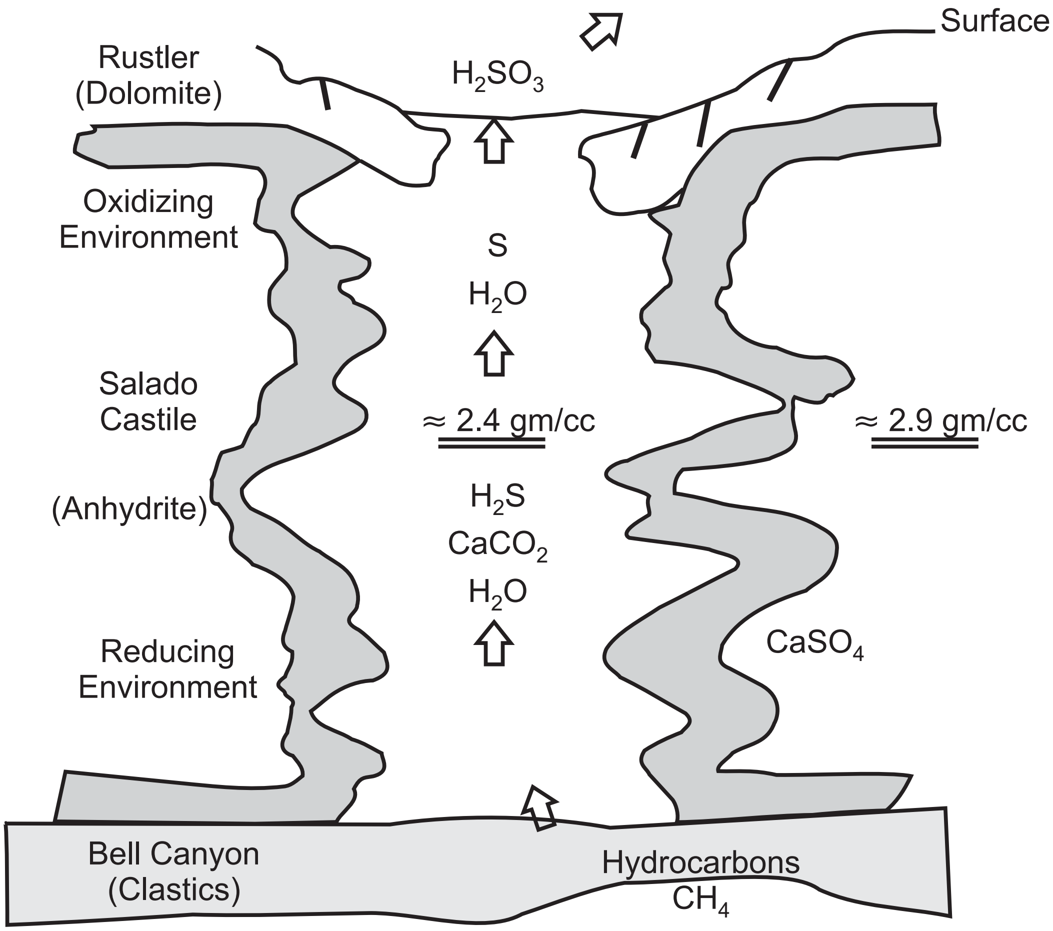

Figure 4. Diagram of near surface upper Permian formations and generalized concept of sulfur generation and accumulation. Note density contrasts. (after McCreight et al, unpublished Exxon report).

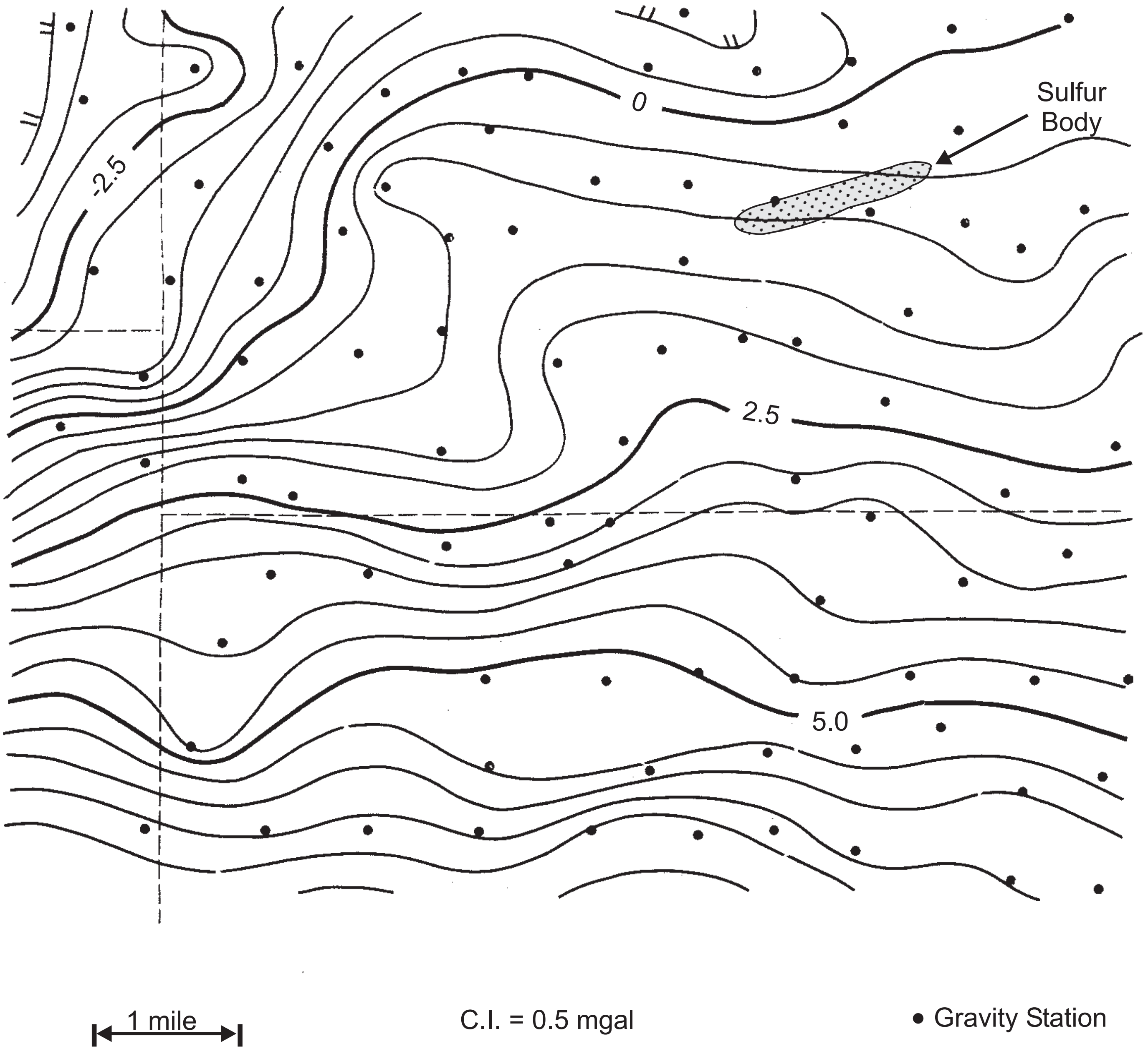

Figure 5. Bouguer gravity mapped from reconnaissance survey at Prospect A.

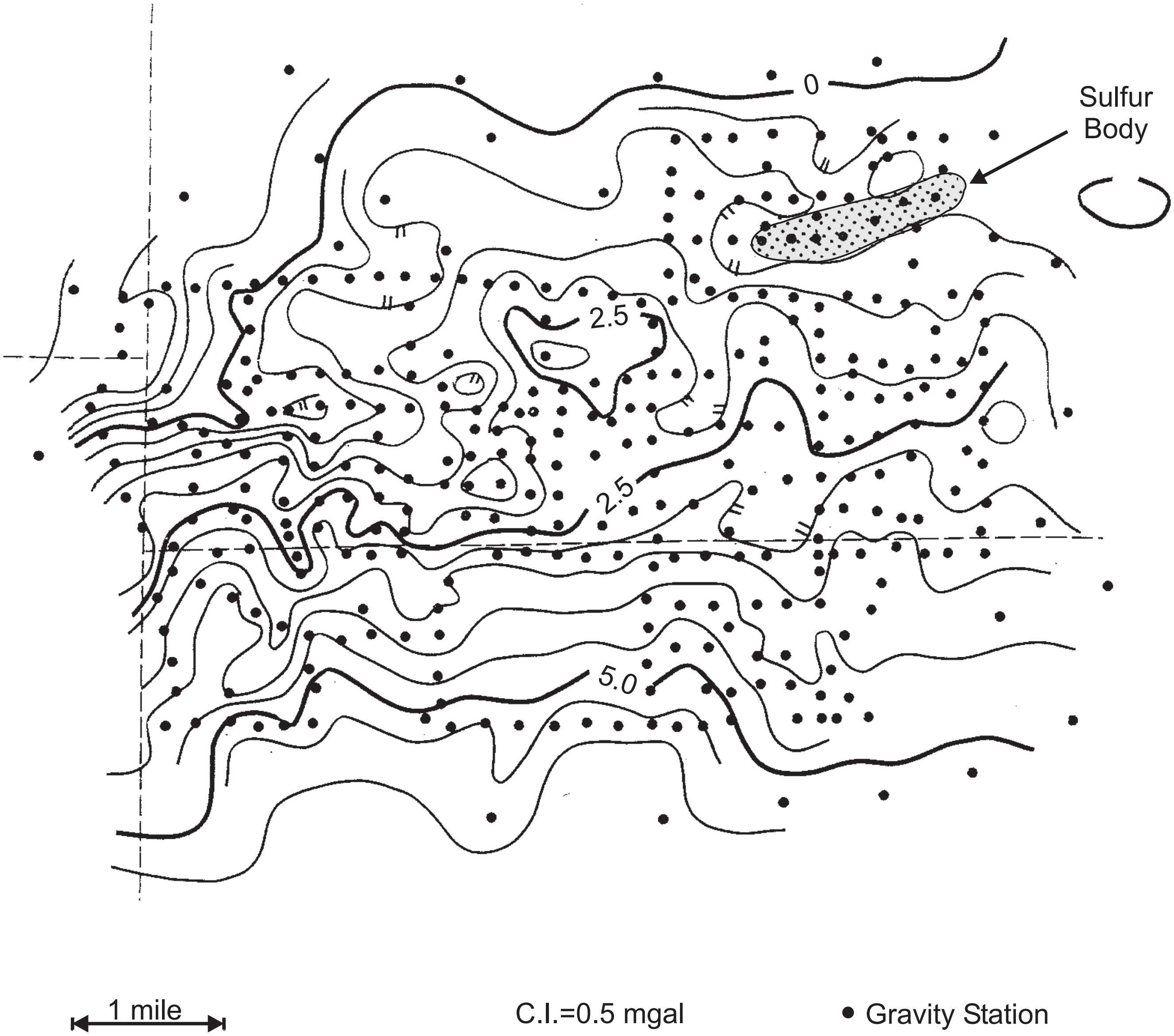

Figure 6a. Bouguer gravity mapped from detailed survey at Prospect A.

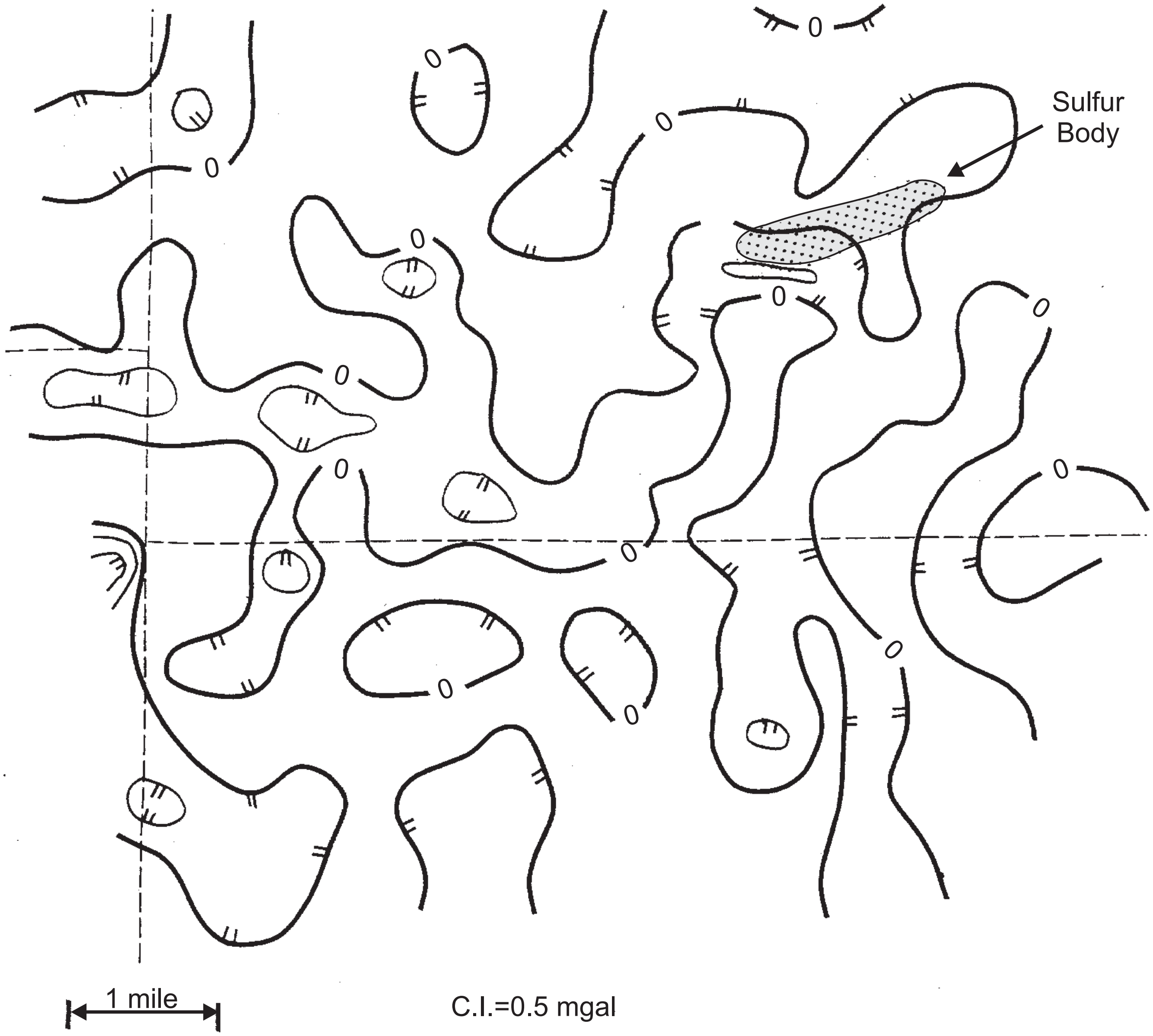

Figure 6b. Gravity minima at Prospect A, based on detailed survey. Anomalies enhanced by second derivative approximation using Elkins' Formula 13.

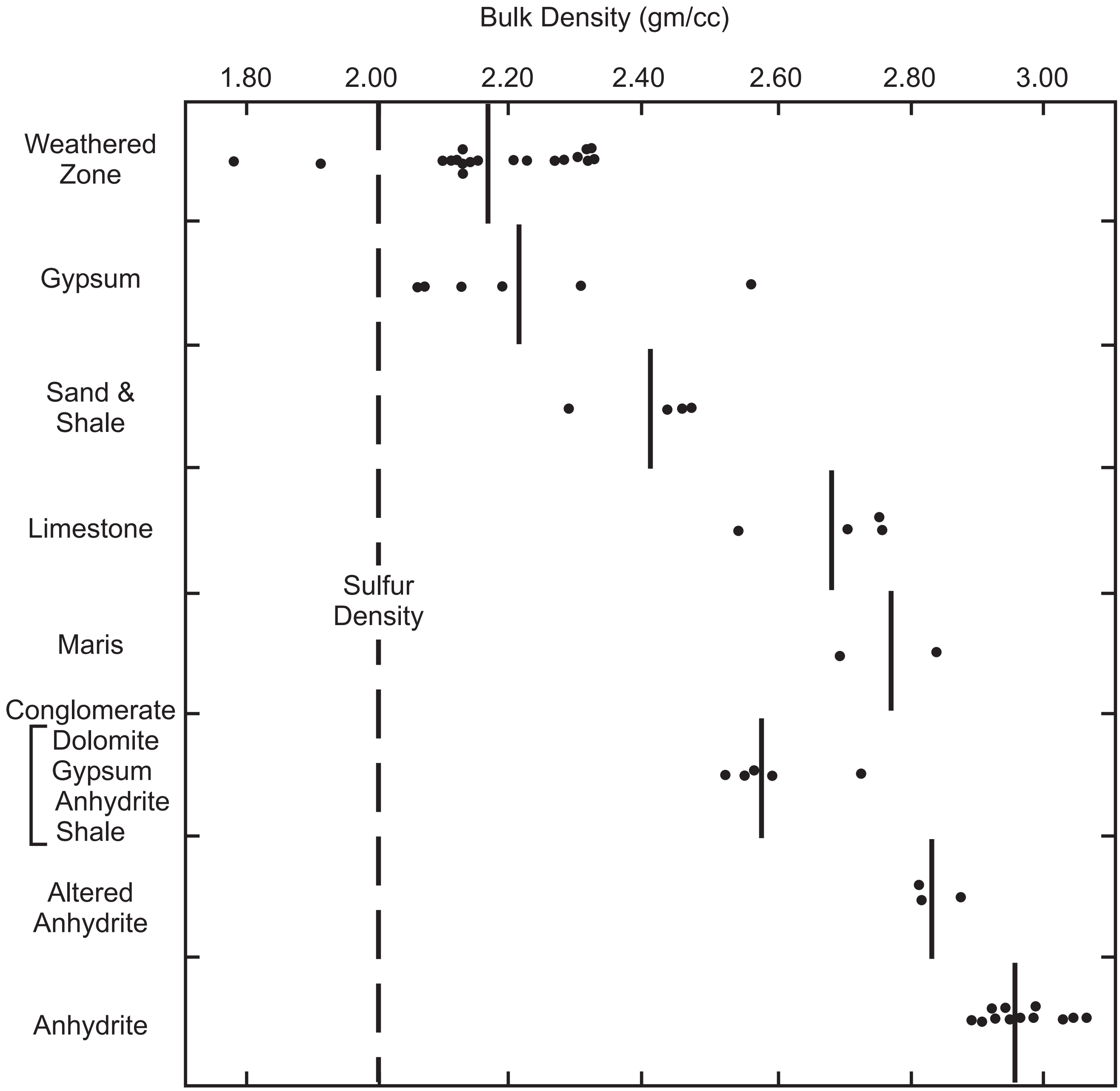

Figure 7. Plot of formation bulk density vs "typical" near surface lithology in the study area. Dots represent measured densities from core hole cuttings and cores. Vertical bars represent averaged values from core hole meter surveys.

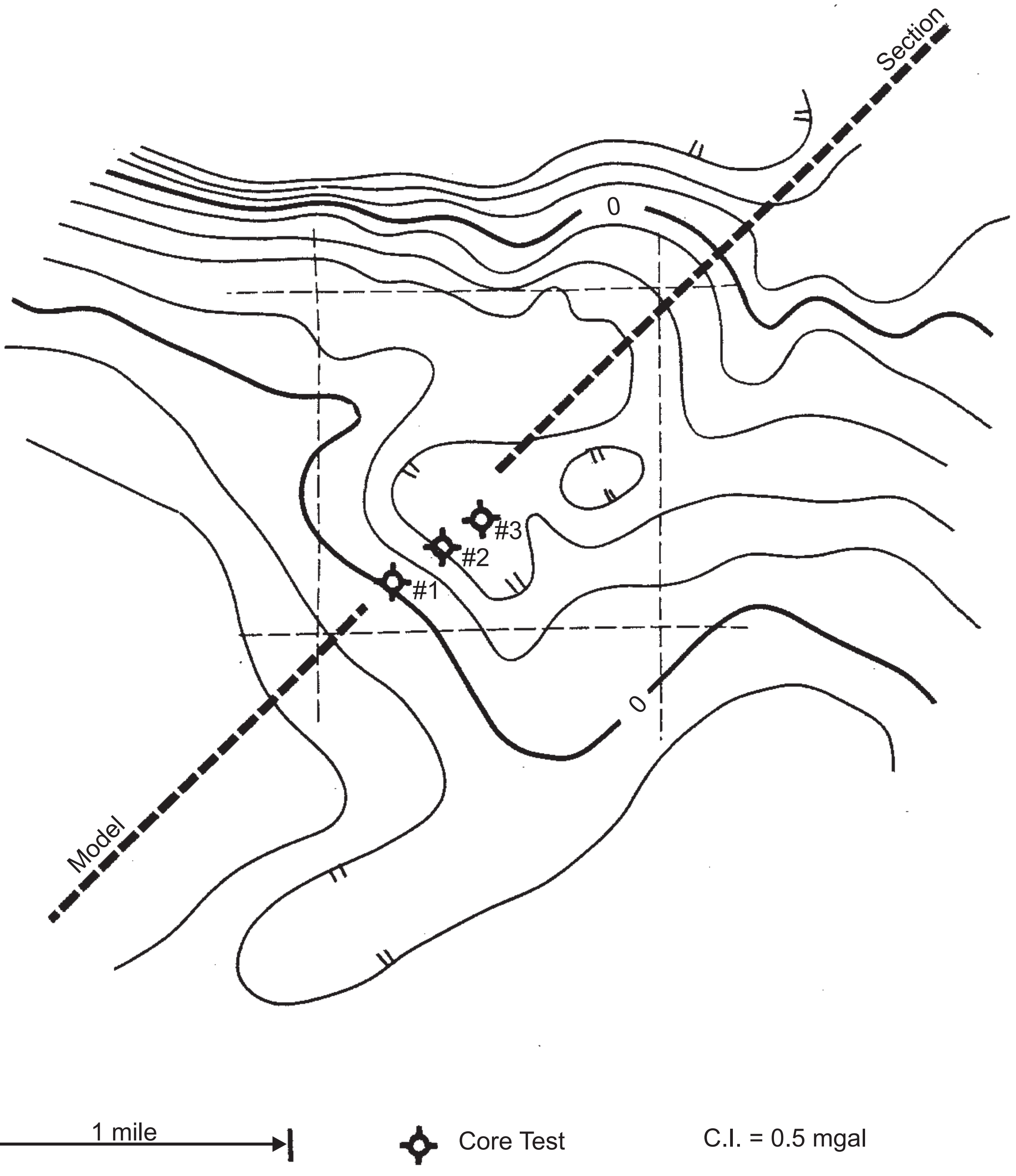

Figure 8. Bouguer gravity mapped from detailed survey at Prospect B.

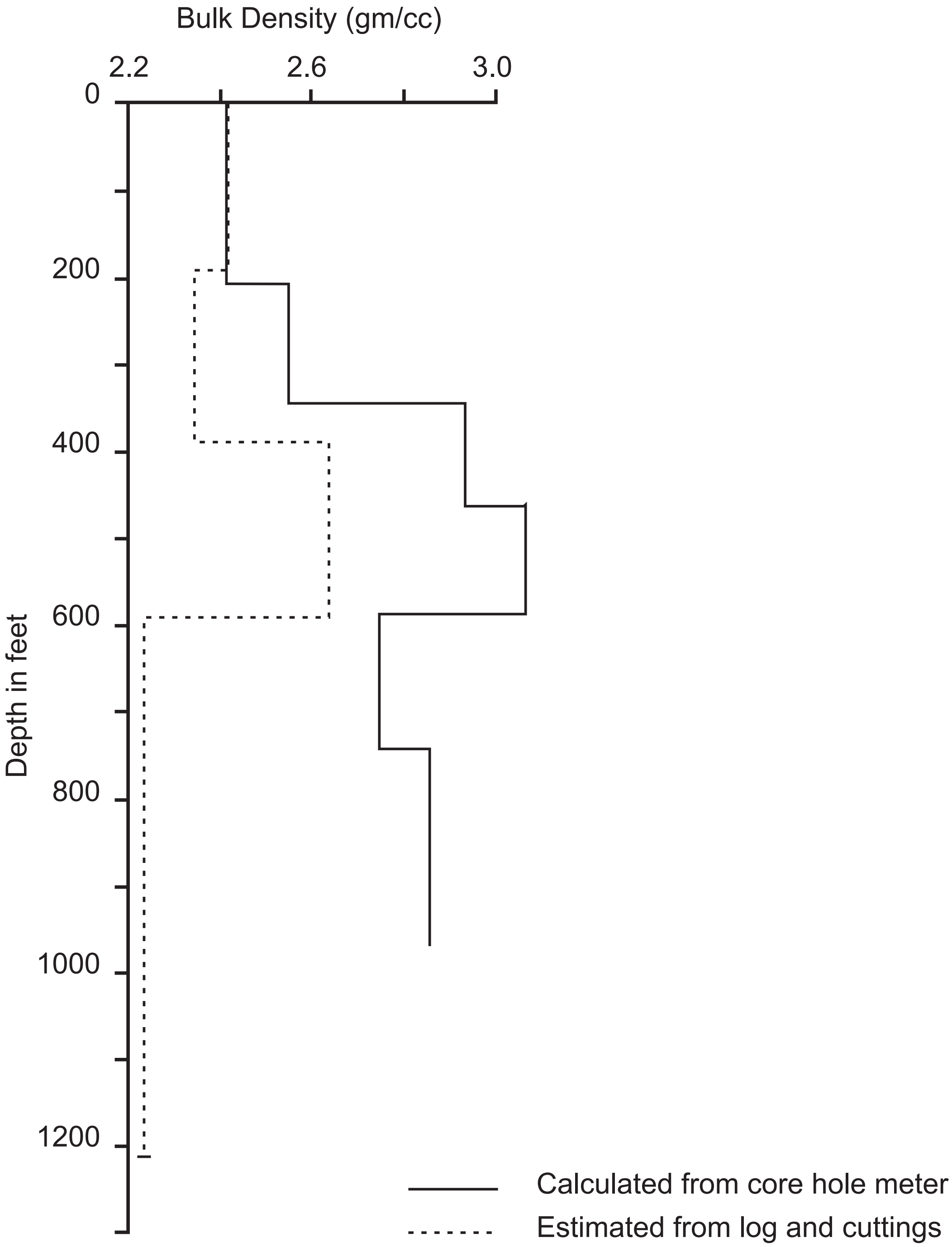

Figure 9. Plot of formation bulk densities vs depth at core hole #2, Prospect B. Dashed line represents values estimated from cuttings and gamma ray-neutron log. Solid line represents values calculated from core hole gravity meter survey.

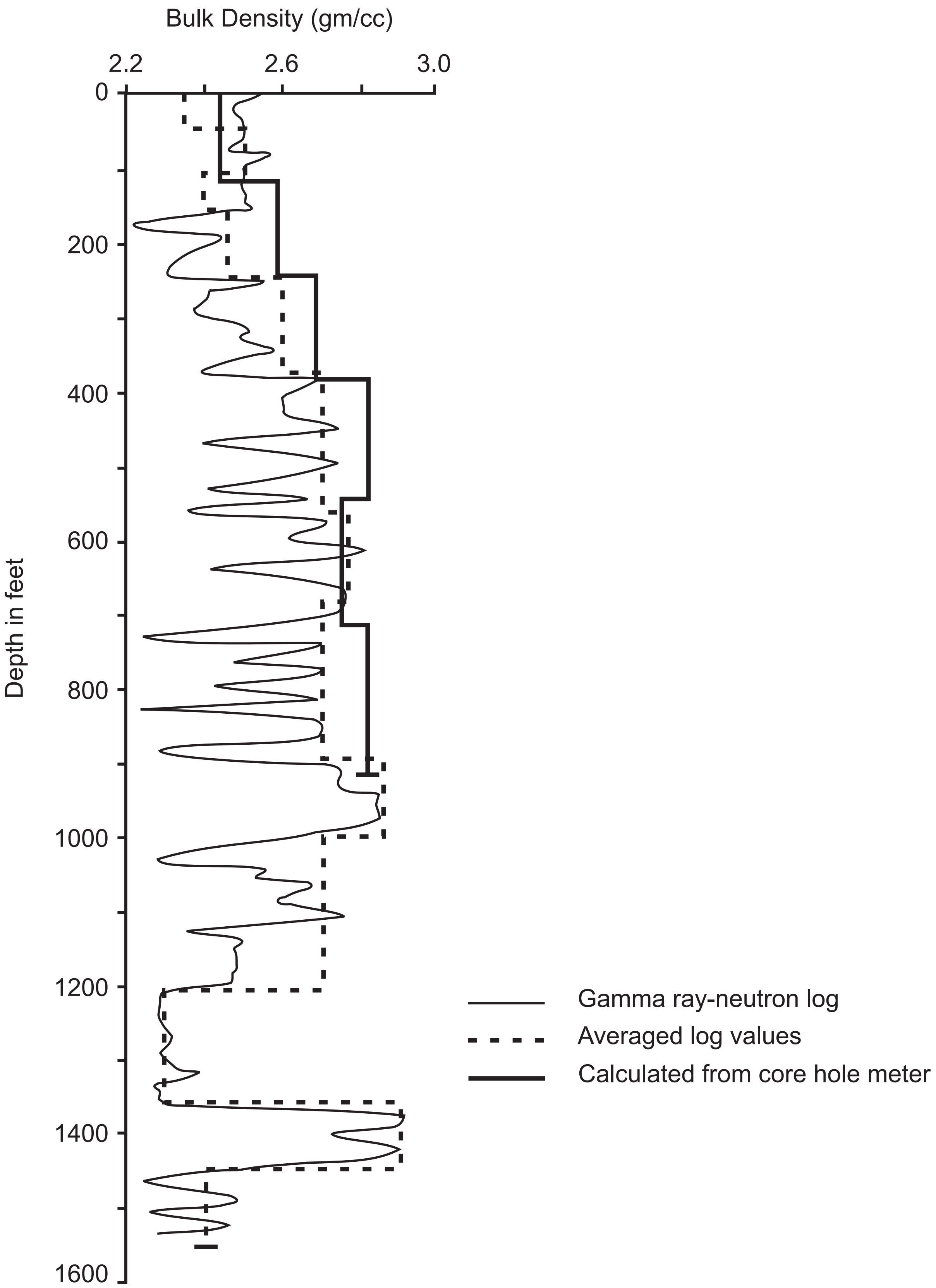

Figure 10. Plot of formation bulk densities vs depth at core hole #3 , Prospect B. Thin solid line is gamma ray-neutron log trace. Dashed line represents averaged values estimated from gamma ray-neutron log.. Thick solid line represents values calculated from core hole gravity meter.

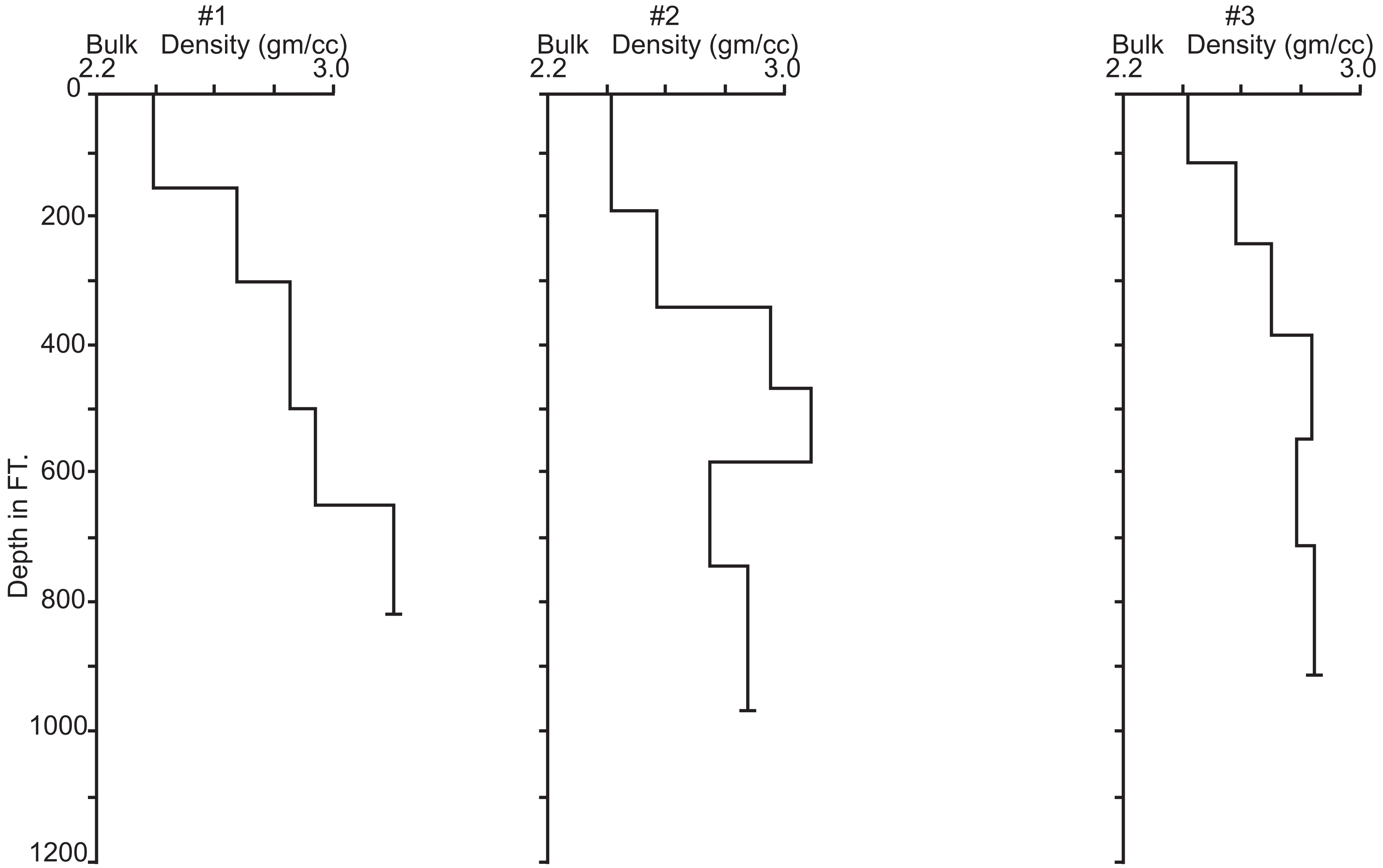

Figure 11. Plot of formation bulk density vs depth for three core holes at Prospect B. Density values were calculated from core hole gravity meter surveys.

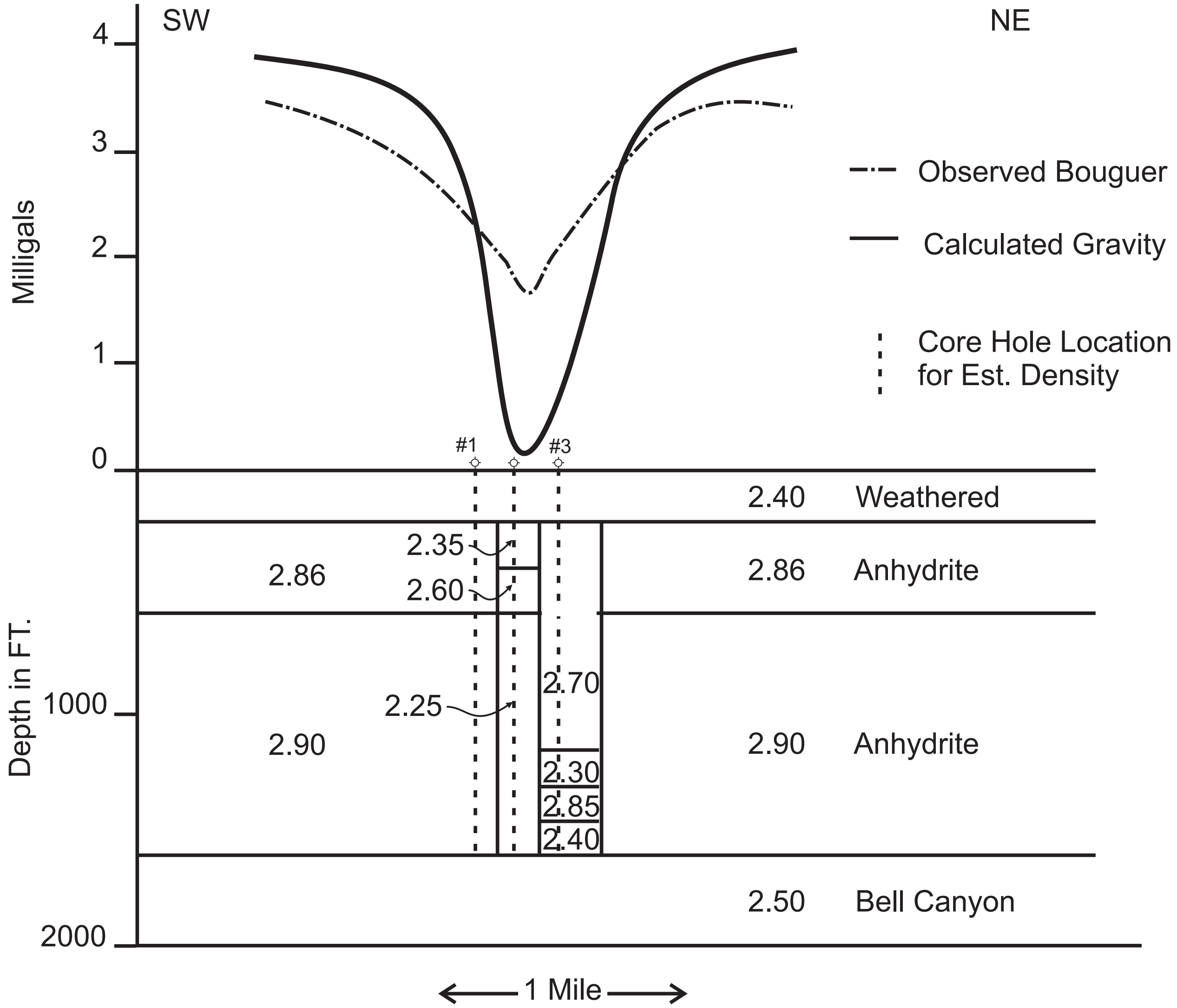

Figure 12. Initial 2D gravity model for Prospect B. using formation densities (gm/cc) estimated from cuttings and gamma ray-neutron logs.

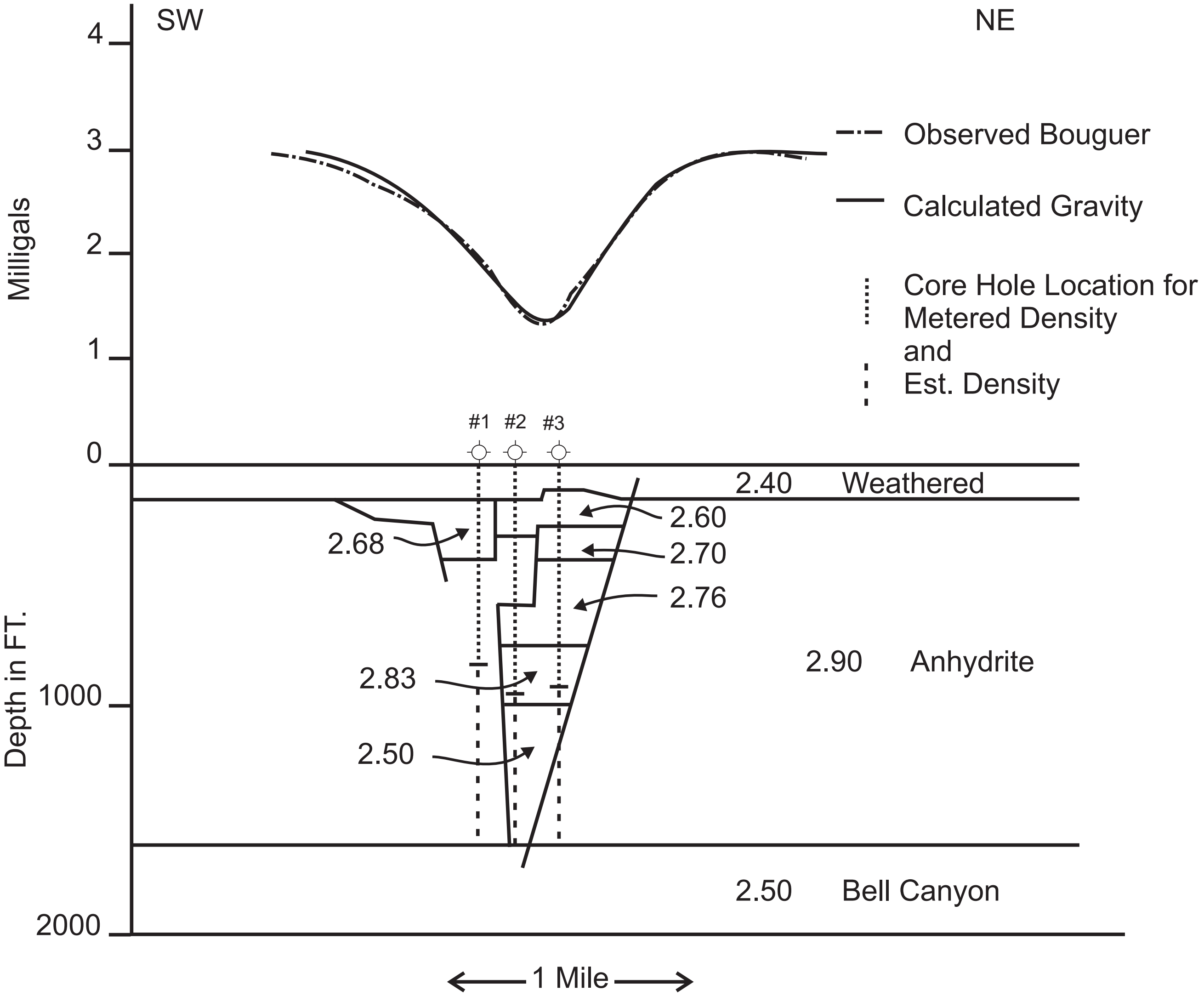

Figure 13. Best-fit 2D gravity model for Prospect B using formation densities (gm/cc) calculated from core hole gravity meter surveys and deeper densities estimated from cuttings and gamma ray-neutron logs.

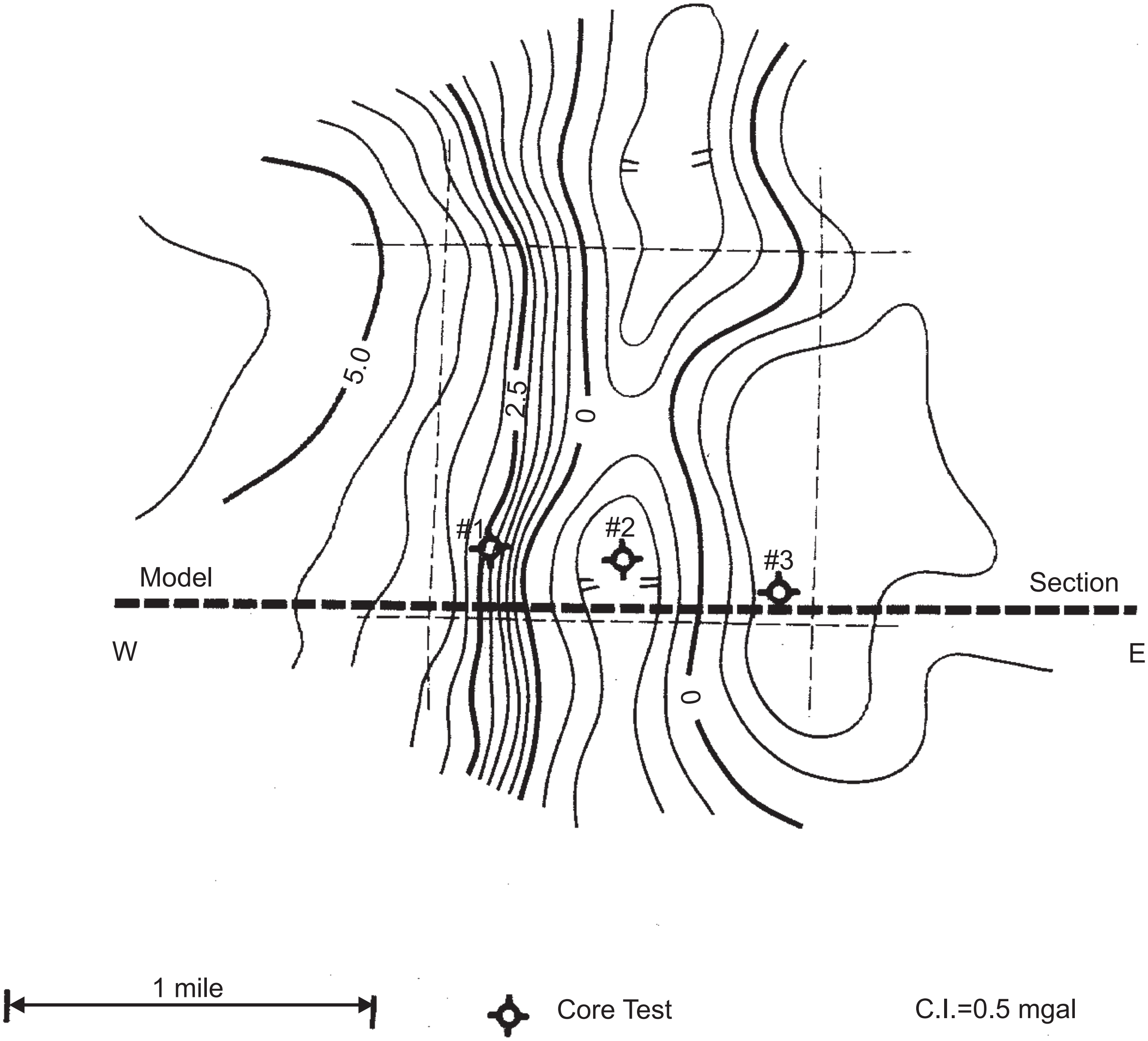

Figure 14. Bouguer gravity mapped from detailed survey at Prospect C.

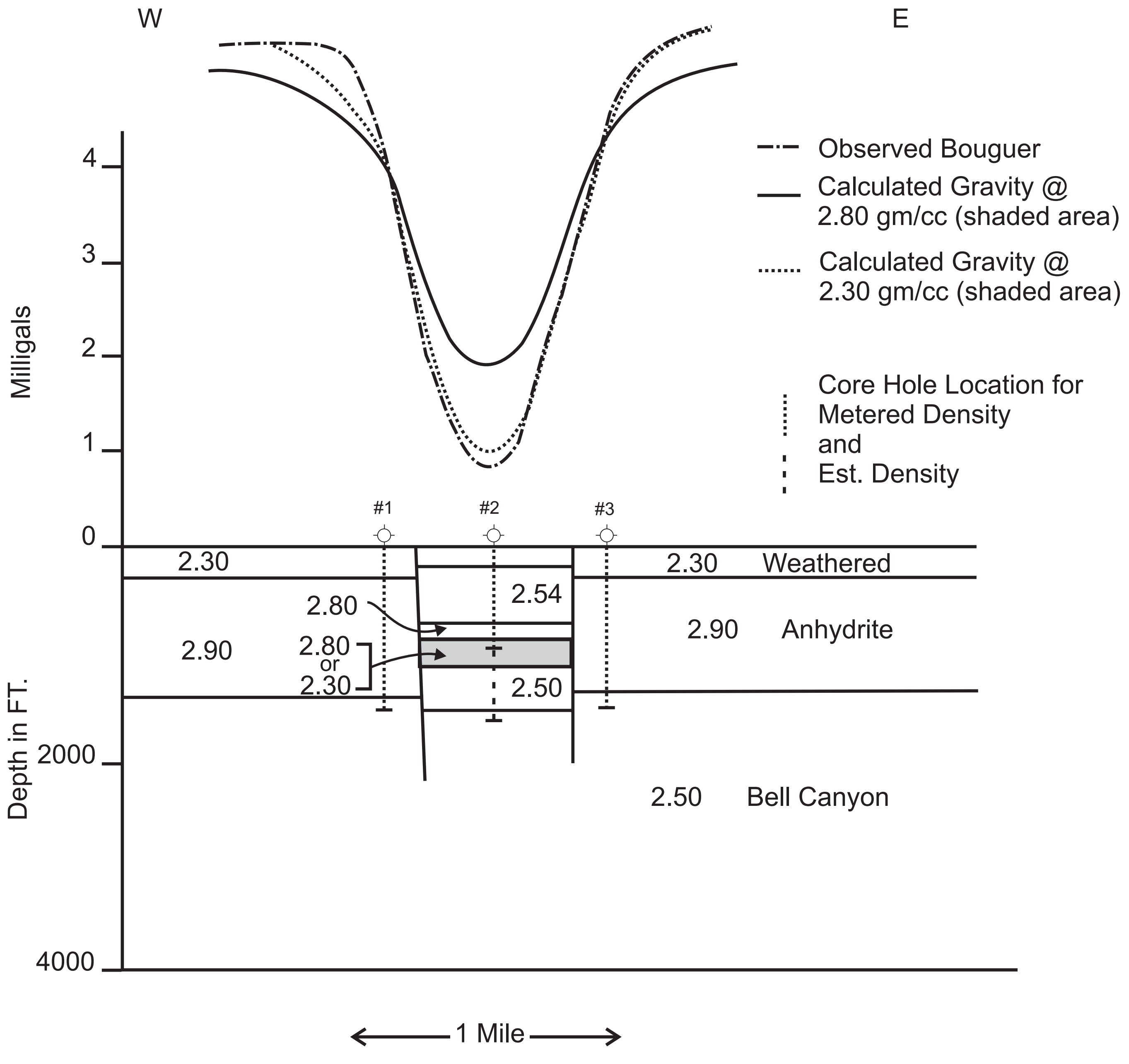

Figure 15. Comparison of initial and final versions of 2D gravity model for Prospect C. Formation bulk densities (gm/cc) calculated from core hole gravity meter surveys and/or estimated from cuttings and gamma ray-neutron logs.

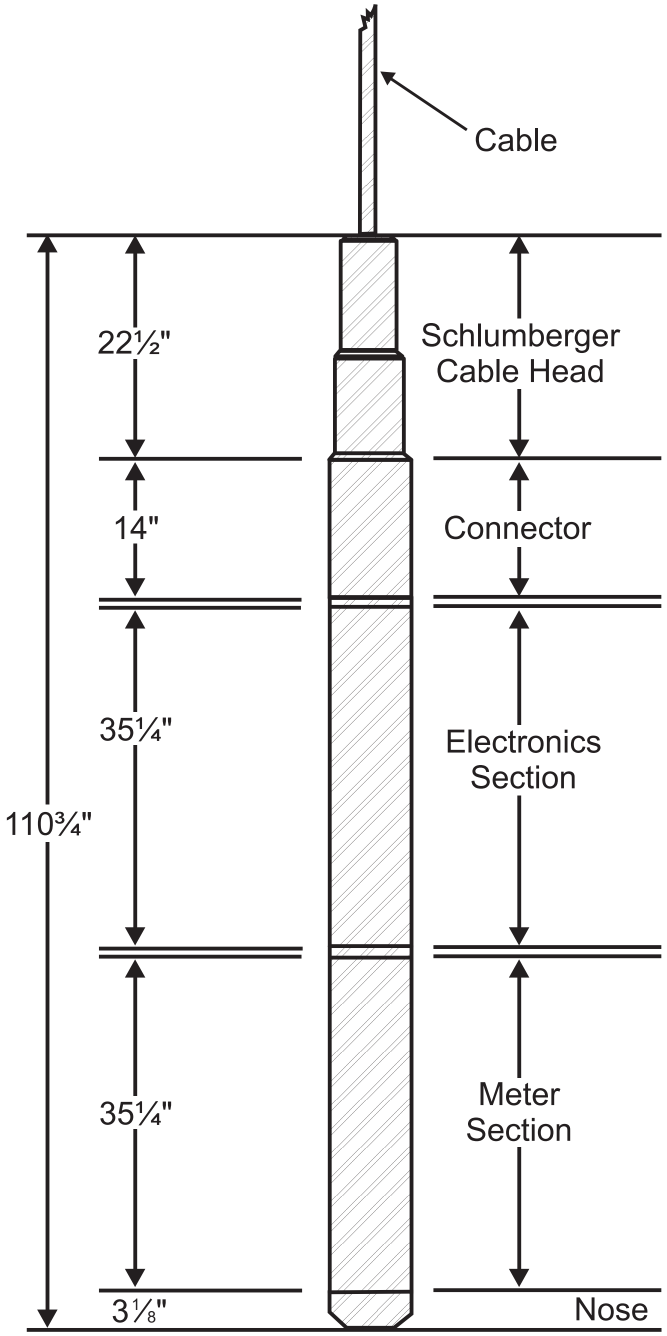

Figure 16. Diagram of Exxon core hole gravity meter in assembled well string.