SANDIA REPORT SAND82-2922 • Unlimited Release • UC-70
Printed April 1983

Waste Isolation Pilot Plant (WIPP) Site Gravity Survey and Interpretation

Lawrence J. Barrows, Sue-Ellen Shaffer,
Warren B. Miller, John D. Fett

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A06
Microfiche copy: A01

Sandia National Laboratories
Albuquerque, New Mexico 87185

date: May 16, 1983

to: Distribution for SAND82-2922 Report

from: L. J. Barrows - 7111

subject: Errata in SAND82-2922, Waste Isolation Pilot Plant (WIPP) Site Gravity Survey and Interpretation, dtd April 1983

The following information is missing from the figure caption of Figure 2.1-4 on p 43 of the referenced report:

Simple Bouguer Gravity
Less Linear Regional & Parabolic Trend
Slab Density 2.3 g/c^3
0.05-Milligal Contour Interval
Contours Within ±0.025 mg

This information has been printed on sticky-back paper for easy placement on Figure 2.1-4.

Figures 1.2.1-4, 1.2.1-5, 1.2.1-6, 1.2.2-8 and 1.2.3-1 are adapted from preliminary maps prepared by R. P. Snyder of the US Geological Survey. Final USGS maps have been published in Borns et al (1983).

LJB/erv

Simple Bouguer Gravity
Less Linear Regional & Parabolic Trend
Slab Density 2.3 g/c^3
0.05-Milligal Contour Interval
Contours Within ±0.025 mg

Sandia National Laboratories
Albuquerque, New Mexico 87185

date: May 16, 1983

to: Distribution for SAND82-2922 Report

from: L. J. Barrows - 7111

subject: Errata in SAND82-2922, Waste Isolation Pilot Plant (WIPP) Site Gravity Survey and Interpretation, dtd April 1983

The following information is missing from the figure caption of Figure 2.1-4 on p 43 of the referenced report:

Simple Bouguer Gravity
Less Linear Regional & Parabolic Trend
Slab Density 2.3 g/c^3
0.05-Milligal Contour Interval
Contours Within ±0.025 mg

This information has been printed on sticky-back paper for easy placement on Figure 2.1-4.

Figures 1.2.1-4, 1.2.1-5, 1.2.1-6, 1.2.2-8 and 1.2.3-1 are adapted from preliminary maps prepared by R. P. Snyder of the US Geological Survey. Final USGS maps have been published in Borns et al (1983).

LJB/erv

Simple Bouguer Gravity
Less Linear Regional & Parabolic Trend
Slab Density 2.3 g/c^3
0.05-Milligal Contour Interval
Contours Within ±0.025 mg

Sandia National Laboratories
Albuquerque, New Mexico 87185

date: May 16, 1983

to: Distribution for SAND82-2922 Report

from: L. J. Barrows - 7111

subject: Errata in SAND82-2922, Waste Isolation Pilot Plant (WIPP) Site Gravity Survey and Interpretation, dtd April 1983

The following information is missing from the figure caption of Figure 2.1-4 on p 43 of the referenced report:

Simple Bouguer Gravity
Less Linear Regional & Parabolic Trend
Slab Density 2.3 g/c^3
0.05-Milligal Contour Interval
Contours Within ±0.025 mg

This information has been printed on sticky-back paper for easy placement on Figure 2.1-4.

Figures 1.2.1-4, 1.2.1-5, 1.2.1-6, 1.2.2-8 and 1.2.3-1 are adapted from preliminary maps prepared by R. P. Snyder of the US Geological Survey. Final USGS maps have been published in Borns et al (1983).

LJB/erv

Simple Bouguer Gravity
Less Linear Regional & Parabolic Trend
Slab Density 2.3 g/c^3
0.05-Milligal Contour Interval
Contours Within ±0.025 mg

Sandia National Laboratories
Albuquerque, New Mexico 87185

date: May 16, 1983

to: Distribution for SAND82-2922 Report

from: L. J. Barrows - 7111

subject: Errata in SAND82-2922, Waste Isolation Pilot Plant (WIPP) Site Gravity Survey and Interpretation, dtd April 1983

The following information is missing from the figure caption of Figure 2.1-4 on p 43 of the referenced report:

Simple Bouguer Gravity
Less Linear Regional & Parabolic Trend
Slab Density 2.3 g/c^3
0.05-Milligal Contour Interval
Contours Within ±0.025 mg

This information has been printed on sticky-back paper for easy placement on Figure 2.1-4.

Figures 1.2.1-4, 1.2.1-5, 1.2.1-6, 1.2.2-8 and 1.2.3-1 are adapted from preliminary maps prepared by R. P. Snyder of the US Geological Survey. Final USGS maps have been published in Borns et al (1983).

LJB/erv

Simple Bouguer Gravity
Less Linear Regional & Parabolic Trend
Slab Density 2.3 g/c^3
)5-Milligal Contour Interval
,ntours Within ±0.025 mg

Sandia National Laboratories
Albuquerque, New Mexico 87185

date: May 16, 1983

to: Distribution for SAND82-2922 Report

from: L. J. Barrows - 7111

subject: Errata in SAND82-2922, Waste Isolation Pilot Plant (WIPP) Site Gravity Survey and Interpretation, dtd April 1983

The following information is missing from the figure caption of Figure 2.1-4 on p 43 of the referenced report:

Simple Bouguer Gravity
Less Linear Regional & Parabolic Trend
Slab Density 2.3 g/c^3
0.05-Milligal Contour Interval
Contours Within ±0.025 mg

This information has been printed on sticky-back paper for easy placement on Figure 2.1-4.

Figures 1.2.1-4, 1.2.1-5, 1.2.1-6, 1.2.2-8 and 1.2.3-1 are adapted from preliminary maps prepared by R. P. Snyder of the US Geological Survey. Final USGS maps have been published in Borns et al (1983).

LJB/erv

Simple Bouguer Gravity
Less Linear Regional & Parabolic Trend
Slab Density 2.3 g/c^3
)5-Milligal Contour Interval
ontours Within ±0.025 mg

SAND82-2922
Unlimited Release
Printed April 1983

Distribution
Category UC-70

Waste Isolation Pilot Plant (WIPP) Site Gravity Survey and Interpretation

Lawrence J. Barrows
Ground Motion and Seismic Division 7111

Sue-Ellen Shaffer and Warren B. Miller
Earth Sciences Division 9731
Sandia National Laboratories
Albuquerque, NM 87185

John D. Fett
Earth Science and Engineering, Inc.
Austin, TX 78759

Abstract

A portion of the WIPP site has been extensively surveyed with high-precision gravity. The main survey (in T22S, R31E) covered a rectangular area 2 by 4-1/3 mi encompassing all of WIPP site Zone II and part of the disturbed zone to the north of the site. Stations were at 293-ft intervals along 13 north-south lines 880 ft apart. The data are considered accurate to within a few hundredths of a milligal.

Long-wavelength gravity anomalies correlate well with seismic time structures on horizons below the Castile Formation. Both the gravity anomalies and the seismic time structures are interpreted as resulting from related density and velocity variations within the Ochoan Series. Shorter wavelength negative gravity anomalies are interpreted as resulting from bulk density alteration in the vicinity of karst conduits.

The WIPP gravity survey was unable to resolve low-amplitude, long-wavelength anomalies that should result from the geologic structures within the disturbed zone. It did indicate the degree and character of karst development within the surveyed area.

Acknowledgment

Appreciation is extended to the Sandia National Laboratories Applicon Graphics Personnel, Dept. 9761, for preparing appropriate base maps and to Carmen de Souza for patiently typing and retyping the manuscript. D. J. Borns and C. A. Searls reviewed the report and offered many helpful suggestions. The interpretation is that of the authors and is not necessarily agreed to by the reviewers.

Contents

Figures

ˋontents (Cont)

Tables

Waste Isolation Pilot Plant (WIPP) Site Gravity Survey and Interpretation

1. Introduction

1.1 Purpose and Scope of WIPP

The Waste Isolation Pilot Plant (WIPP) is a Department of Energy (DOE) research and development facility for demonstrating the safe disposal of defense-generated transuranic radioactive wastes. The program includes construction of an underground test facility within thick salt deposits in southeastern New Mexico. After successful completion of testing, the facility may be converted into a mined repository for disposal of the actual wastes. Figure 1.1-1 is a conceptual drawing of an operational repository.

The WIPP site is located in the semi-arid Pecos Valley section of the southern Great Plains physiographic province. The site area was initially divided into four concentric zones. The innermost Zone I is for surface facilities and access shafts. Zone II is for underground facilities, although not all of this area may ultimately be developed. Zone III is an administrative buffer where underground mining and through-going boreholes are prohibited. In Zone IV

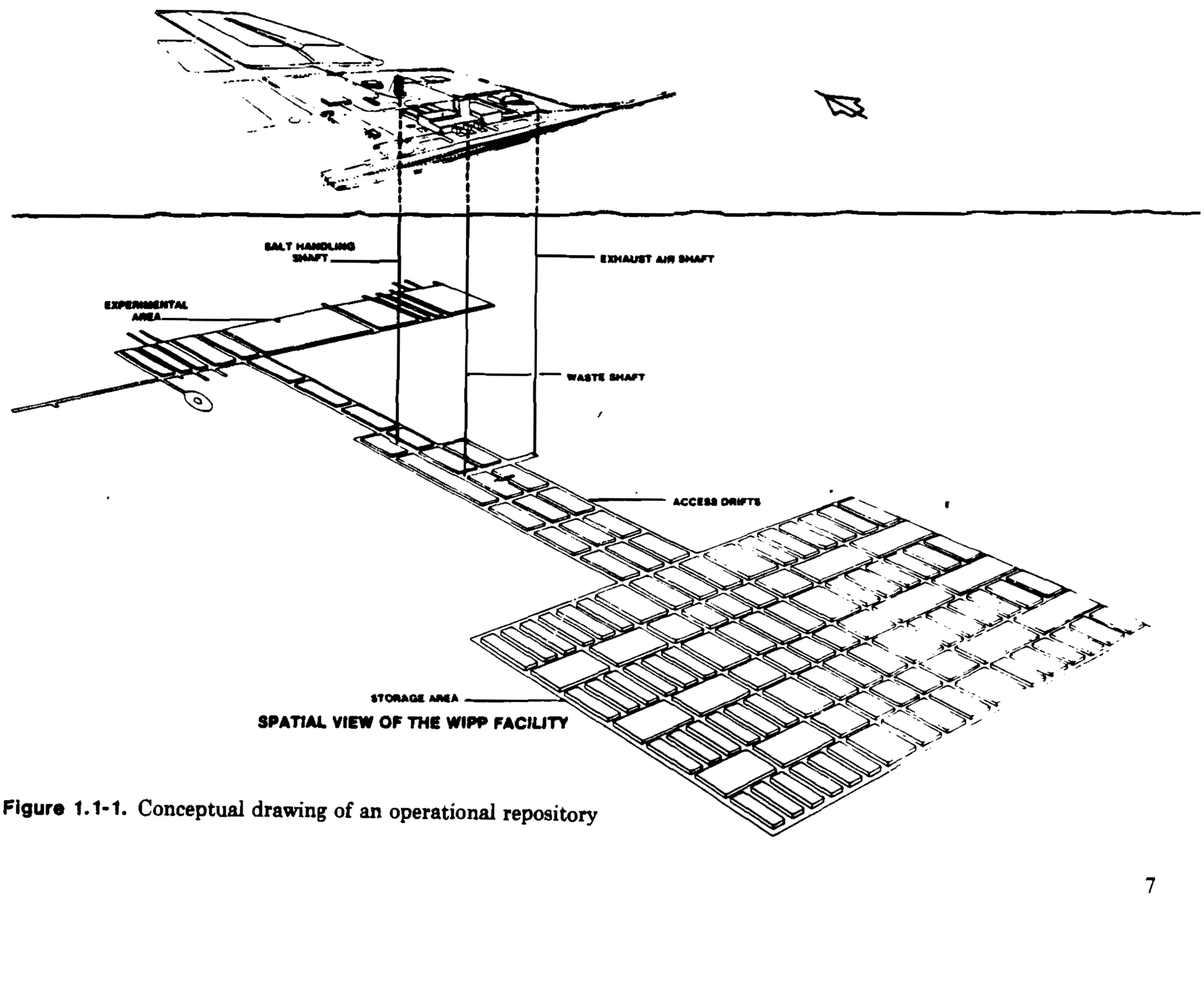


Figure 1.1-1. Conceptual drawing of an operational repository

these were allowed, but were subject to control and regulation by the DOE. Figure 1.1-2 shows the original site zonation and the local system of township and range. During preparation of this report, Zone IV was deleted from the WIPP. It is still included in the figures and discussion herein.

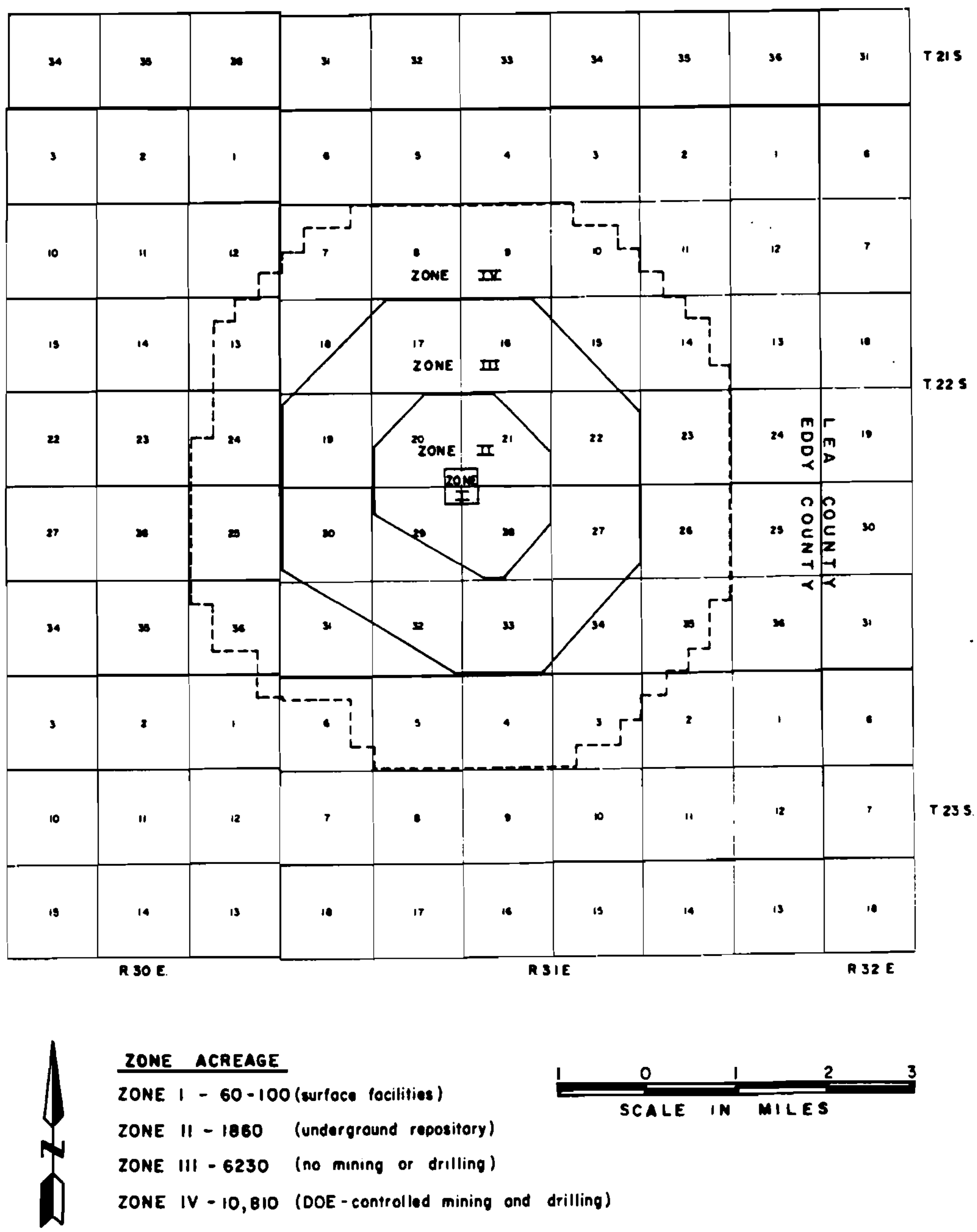


Figure 1.1-2. WIPP site zonation

The gravity survey is part of an ongoing effort to establish the geologic characteristics of the WIPP site. This report contains the gravity data and their interpretation. It assumes that the reader is familiar with general geologic principles and with techniques of geophysical investigation. The local geology is described sufficiently to support the gravity interpretation. For further information on the geology, see Powers et al (1978).

No attempt has been made in this report to assess the implications of the gravity data and their interpretation upon the suitability of the site. Such assessment requires careful consideration of this material along with many other factors.

1.2 Geologic Setting

1.2.1 Stratigraphy

The Delaware Basin is a broad, oval-shaped, asymmetric sedimentary trough in southeastern New Mexico and west Texas. It was structurally initiated in the early Pennsylvanian, underwent minor adjustment in the late Pennsylvanian and early Permian, and then subsided regionally through the late Permian. Basin subsidence ceased in the early Triassic. The subsequent environment is one of general structural stability, epirogenic uplift and subsidence accompanied by widespread deposition and erosion, and no clear geologic record over long intervals of time. Figure 1.2.1-1 shows the regional setting of the basin and the location of the WIPP site within it.

During the late Permian, a carbonate reef or bank grew up around the periphery of the slowly subsiding basin. Deposition within the basin was initially fine-grained clastics and subsidiary carbonates of the Delaware Mountain Group. The depositional environment changed to a partially restricted basin, and a thick section of evaporites was deposited. The underground facilities are being constructed within these evaporites. The evaporites, plus an overlying siltstone formation, make up the Ochoan Series. Figure 1.2.1-2 is the local stratigraphic section.

For purposes of this report, the top of the Delaware Mountain Group directly underlying the Ochoan Series can be regarded as "basement." Near the WIPP site this surface now forms a generally smooth east-dipping homocline (Borns et al, 1983). Structures on this surface indicated by oil and gas wells in the basin are generally simple and of low amplitude. The WIPP seismic sections indicate that simple geologic structure continues through the Delaware Mountain Group and the underlying Bone Spring Formation (Borns et al, 1983).

The Castile Formation is the oldest of the Ochoan Series. At the WIPP site, this formation consists of three massive anhydrite units separated by two massive halite units. In ascending order, the units are informally identified as Anhydrite I, Halite I, Anhydrite II, Halite II, and Anhydrite III. These units are indicated on Figure 1.2.1-2.

The basal unit, Anhydrite I, consists of laminated anhydrite and bituminous calcite. Halite I is nearly pure halite. Anhydrite II is distinctly laminated layers of anhydrite and calcite. The individual laminae of this member have been correlated between wells 113 km apart (Kirkland and Anderson, 1970) and have been interpreted as seasonal varves (e.g., Anderson et al, 1972). The next unit, Halite II, consists of nearly pure halite beds up to about 30 ft thick interlayered with five to seven thinner beds of anhydrite. The uppermost Anhydrite III is a generally massive anhydrite with some color layering of various shades of gray.

There is a distinct density contrast between the massive anhydrite and massive halite units. Figure 1.2.1-3 is the densilog of the Castile Formation in borehole AEC 8. The density contrast between the anhydrite and halite units was important in planning the WIPP gravity survey as described later in this report. It may also be important in formation of structures within the Castile Formation. This structural relation is discussed at length in Borns et al (1983, Appendix A).

The Salado Formation is the second of three evaporite formations in the Ochoan Series. The formation is primarily halite interlayered with laterally continuous beds of anhydrite and polyhalite. It is divided into a lower unnamed member, the middle McNutt Potash Zone, and an informal upper member. The McNutt Potash Zone locally contains economic potash minerals, mainly sylvite and langbeinite, and is the ore zone supporting the local potash industry.

At the WIPP site the Salado is conformably overlain by the Rustler Formation. This formation has been divided into five members largely on the basis of two conspicuous dolomite horizons. From bottom to top the members are: an unnamed lower member, the Culebra Dolomite, the Tamarisk Member, the Magenta Dolomite, and the Forty-Niner Member. The formation has been extensively altered by dissolution or karstification. In unleached areas the formation composition is: 43% rock salt and other halides; 30% anhydrite, polyhalite, gypsum, and other sulfates; 17% clastics; and 10% dolomite, limestone, and magnesite.

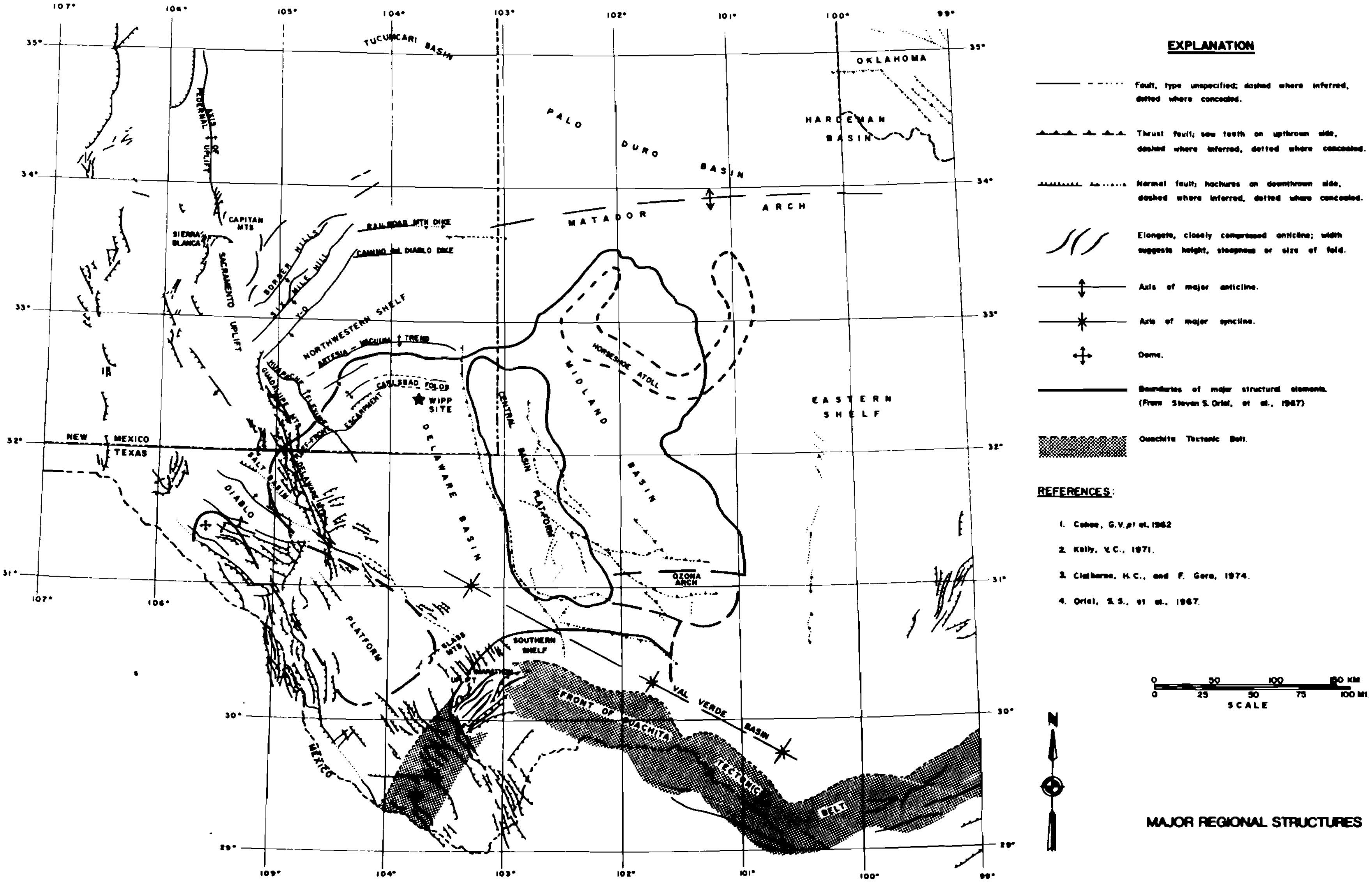


Figure 1.2.1-1. Major regional structures

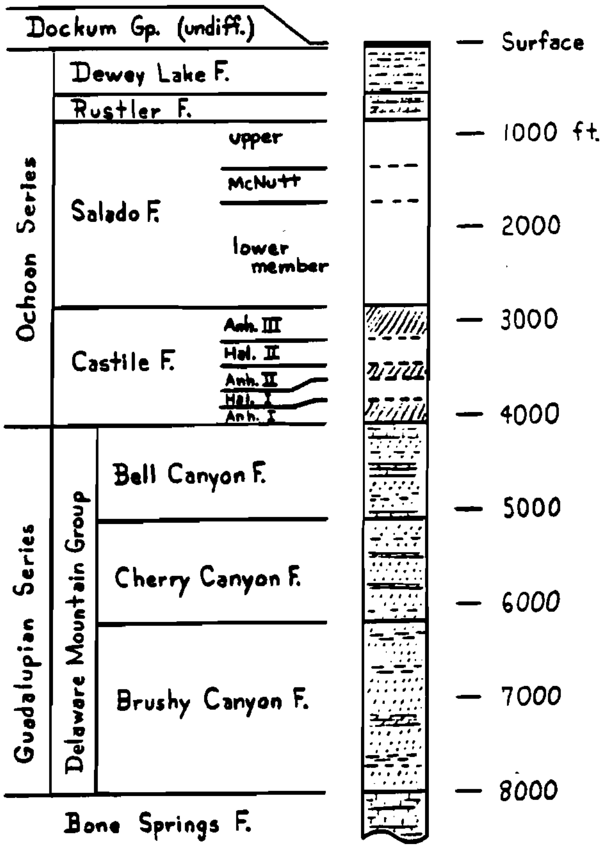


Figure 1.2.1-2. Local stratigraphic section

More detailed lithology, the interrelation among deposition facies, and subsequent dissolution are discussed by Jones in Powers et al (1978, pp 4-39). The progressive dissolution of these evaporites is important to the gravity interpretation and is discussed in Section 1.2.3.

The Rustler Formation is conformably overlain by a sequence of terrigenous reddish-orange micaceous siltstones and sandstones called the Dewey Lake Red Beds. The unit is ~500 ft thick in the eastern half of the WIPP site, where it is protected by the overlying Dockum Group. It thins rapidly to the west where it is exposed and has been partially removed by erosion. Figure 1.2.1-4 is an isopach of this formation. The Dewey Lake Red Beds are gypsiferous with gypsum cement, secondary gypsum crystals, and numerous selenite veins. Density variations within this formation were found to contribute to the gravity anomalies (this report, Section 3.2).

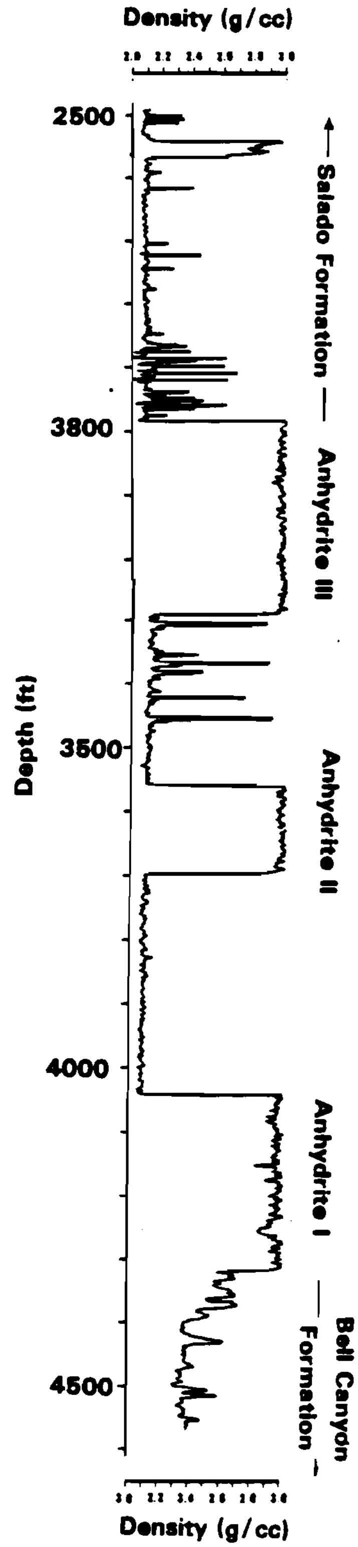
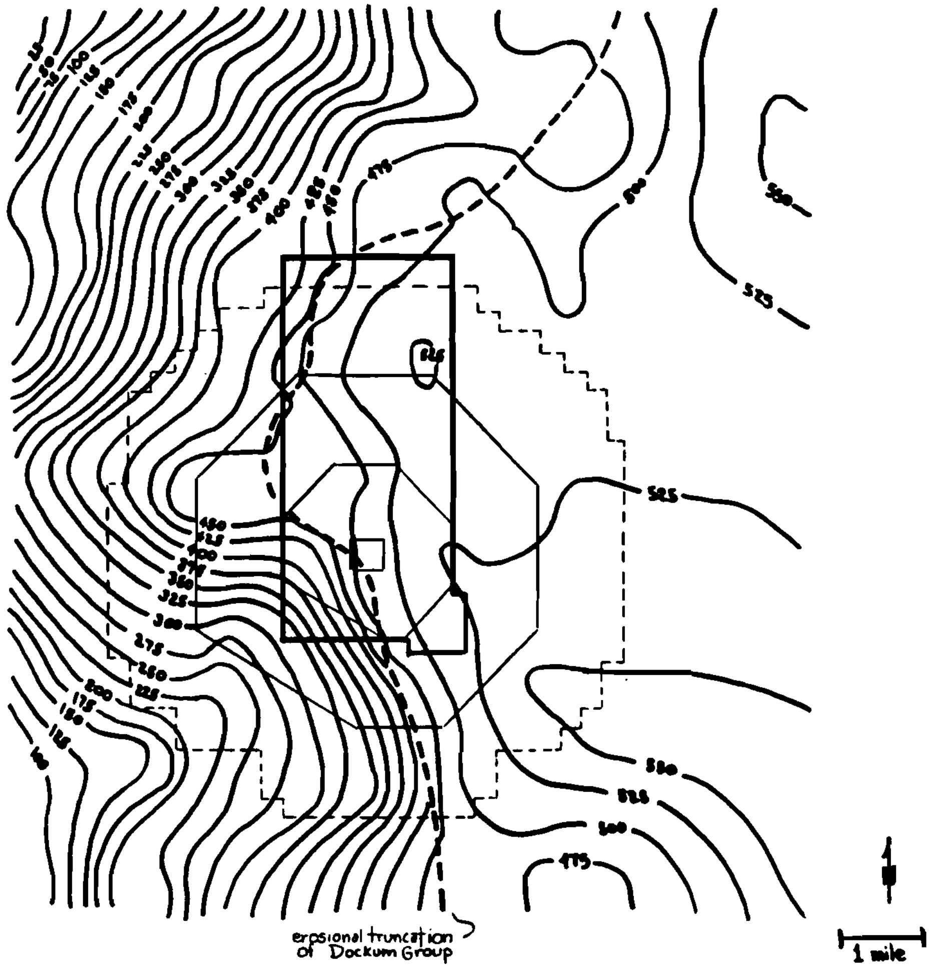


Figure 1.2.1-3. Densilog of the Castile Formation at borehole AEC 8



25 ft contour interval

Figure 1.2.1-4. Isopach of the Dewey Lake Red Beds

The rest of the stratigraphic section is thin and largely incomplete. The Dewey Lake Red Beds are unconformably overlain by undifferentiated rocks of the upper Triassic Dockum Group. These deposits are fine- to coarse-grained, cross-stratified, muddy, micaceous sandstones. They vary from 250 ft thick in the extreme eastern part of WIPP site, Zone IV, to zero along an erosional truncation through the middle of the site. Thin discontinuous patches of the Pleistocene Gatuna Formation make up the next identified formation at the site. Figures 1.2.1-5 and 1.2.1-6 are isopach maps of the Dockum Group and the Gatuna Formation, respectively. Presumably the Cretaceous system and the late Tertiary Ogallala Formation were deposited, but they were later removed by erosion.

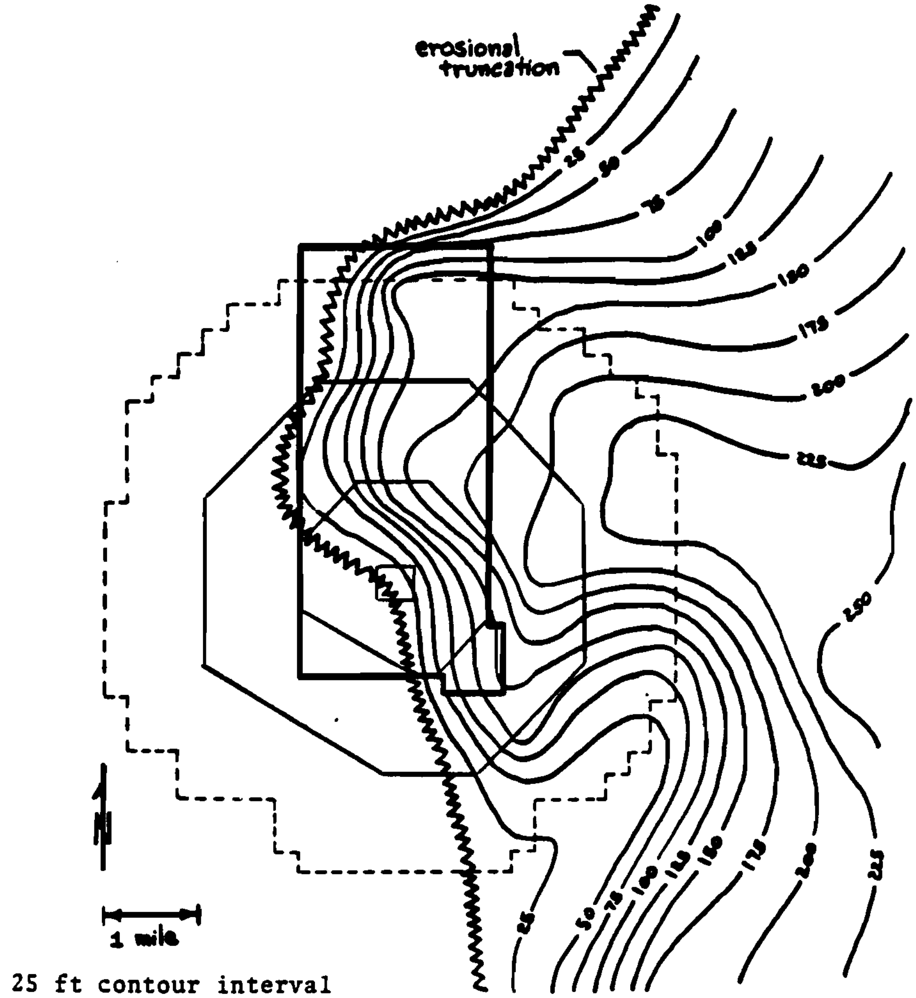


Figure 1.2.1-5. Isopach of the Dockum Group

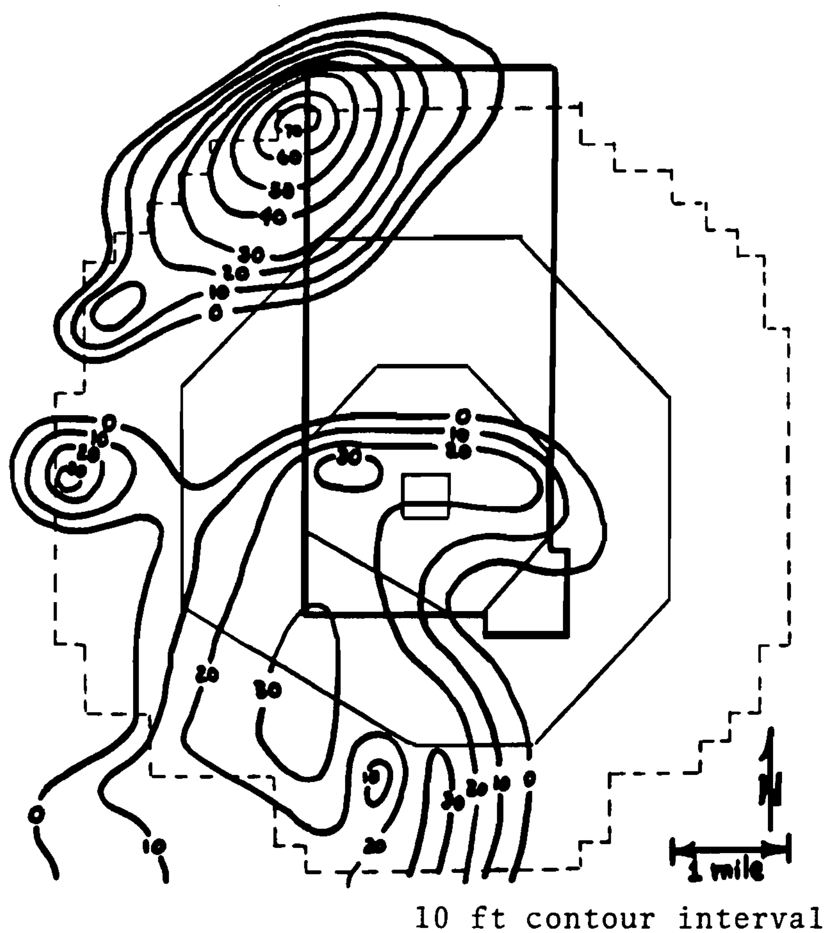


Figure 1.2.1-6. Isopach of the Gatuna Formation

1.2.2 Structure

Mapping of geologic structures was the primary motivation for the WIPP gravity survey. It was thought that the gravity data would help establish the form and extent of structures in the northern part of the site and help ensure that additional undetected structures are not present in the rest of the site. During the survey it was found that the gravity field is dominated by effects of lateral density variations within fairly flat-lying strata. The structures were found to be an inconsequential part of the interpretation. They are reviewed here because of their role in planning the gravity survey and because they form the structural framework of the area.

As previously noted, the Delaware Mountain Group near the WIPP site forms a simple east-dipping homocline. This dip is ~100 ft/mi; it was formed during the Plio-Pleistocene tilting of the Delaware Basin and surrounding areas (Borns et al, 1983).

The WIPP site has been extensively explored with the seismic reflection technique. Figure 1.2.2-1 shows line locations of the seismic sections used to construct the following time structure and isochron maps. Additional redundant lines and lines gathered earlier with petroleum exploration field parameters were checked for consistency with the interpretation but were not worked into the maps.

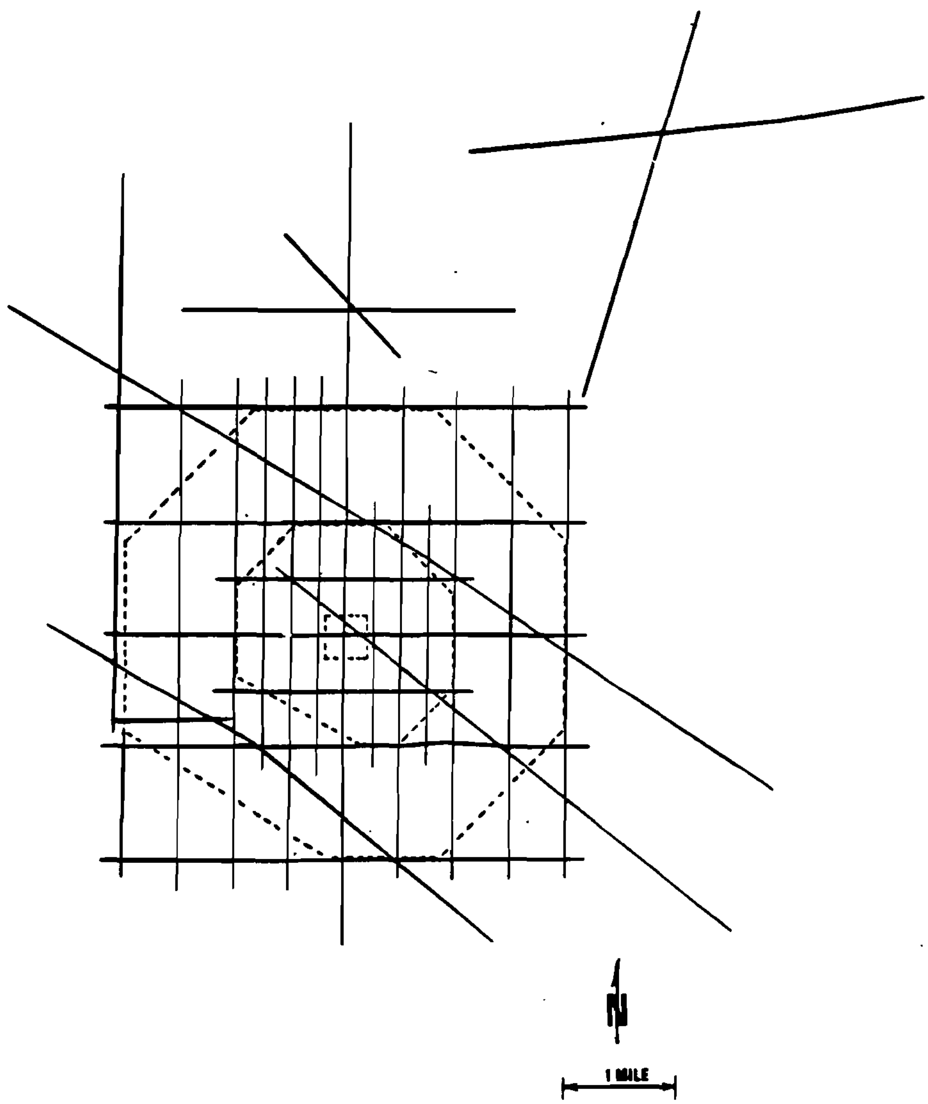


Figure 1.2.2-1. Location of seismic lines used to construct the seismic time-structure and isochron maps

The field parameters for the lines on Figure 1.2.2-1 are given in Table 1.2.2-1. Further information on the seismic surveys is available in Bell and Murphy and Assoc., Inc. (1979) and in Hern et al (1979). The lines have good resolution from the top of the Castile Formation through the Delaware Mountain Group. Seismic events from shallower and deeper horizons are considered too unreliable to map. Figures 1.2.2-2 and 1.2.2-3 are time-structure maps on events near the Anhydrite II member of the Castile Formation and near the top of the Cherry Canyon Formation in the middle of the Delaware Mountain Group. Figure 1.2.2-4 is an isochron map on the interval between these horizons. These maps show the seismic features of interest on and near the WIPP site. Both the maps and structures are discussed in further detail in Borns et al, 1983.

Table 1.2.2-1. Seismic reflection field parameters (77X and 78GG surveys)

	Description
Source	• 3 or 4 vibrators stepped over 220 ft • 12-s, 25- to 100-Hz
Receiver	• 36 geophones per receiver in a 6-arm fan • 24 receivers • 1650-440-0-440-1650 split spread • 2-ms sample rate
Processing	• 12-fold CDP stack

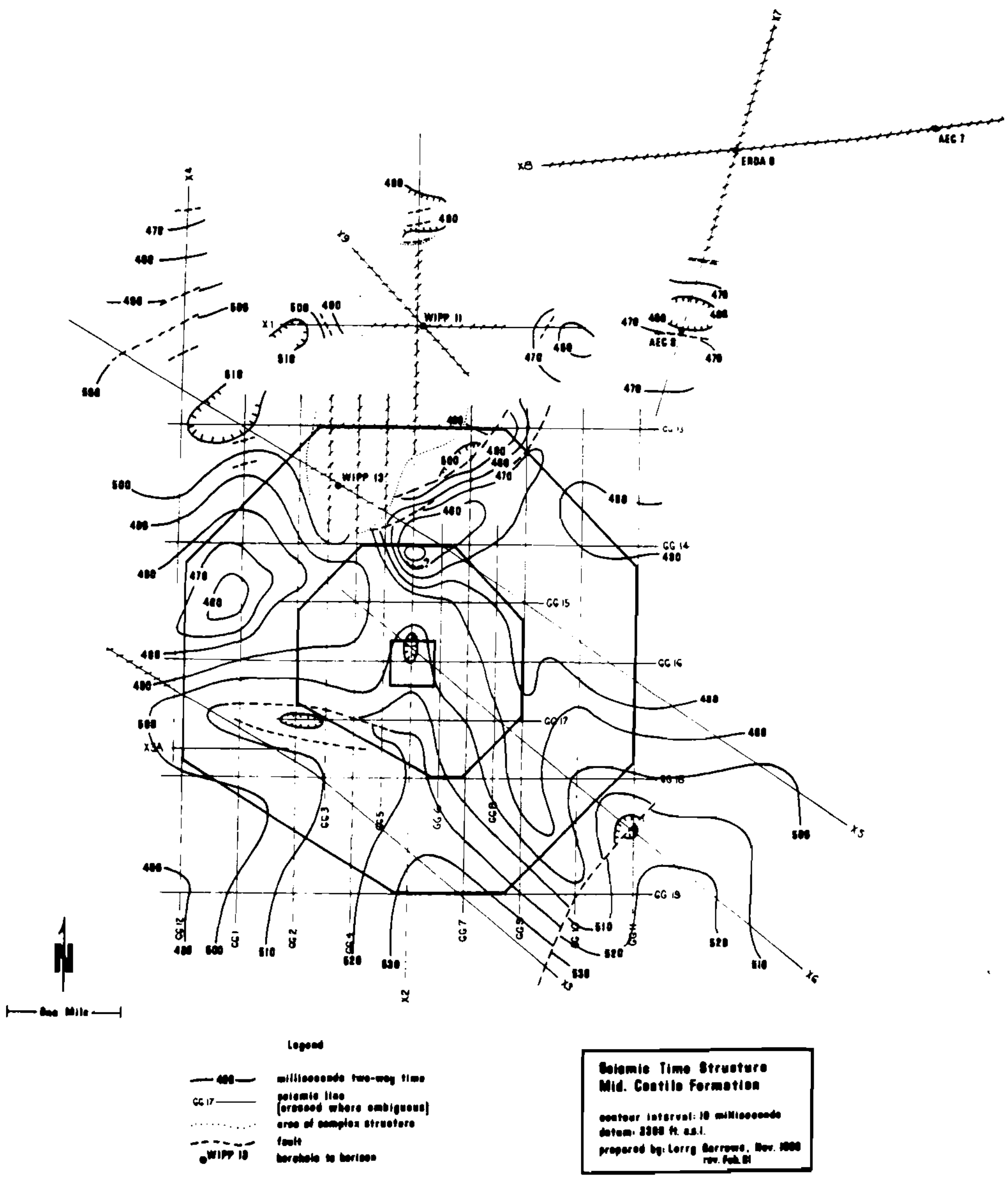


Figure 1.2.2-2. Seismic time-structure of a strong seismic horizon near the Anhydrite II member of the Castile Formation

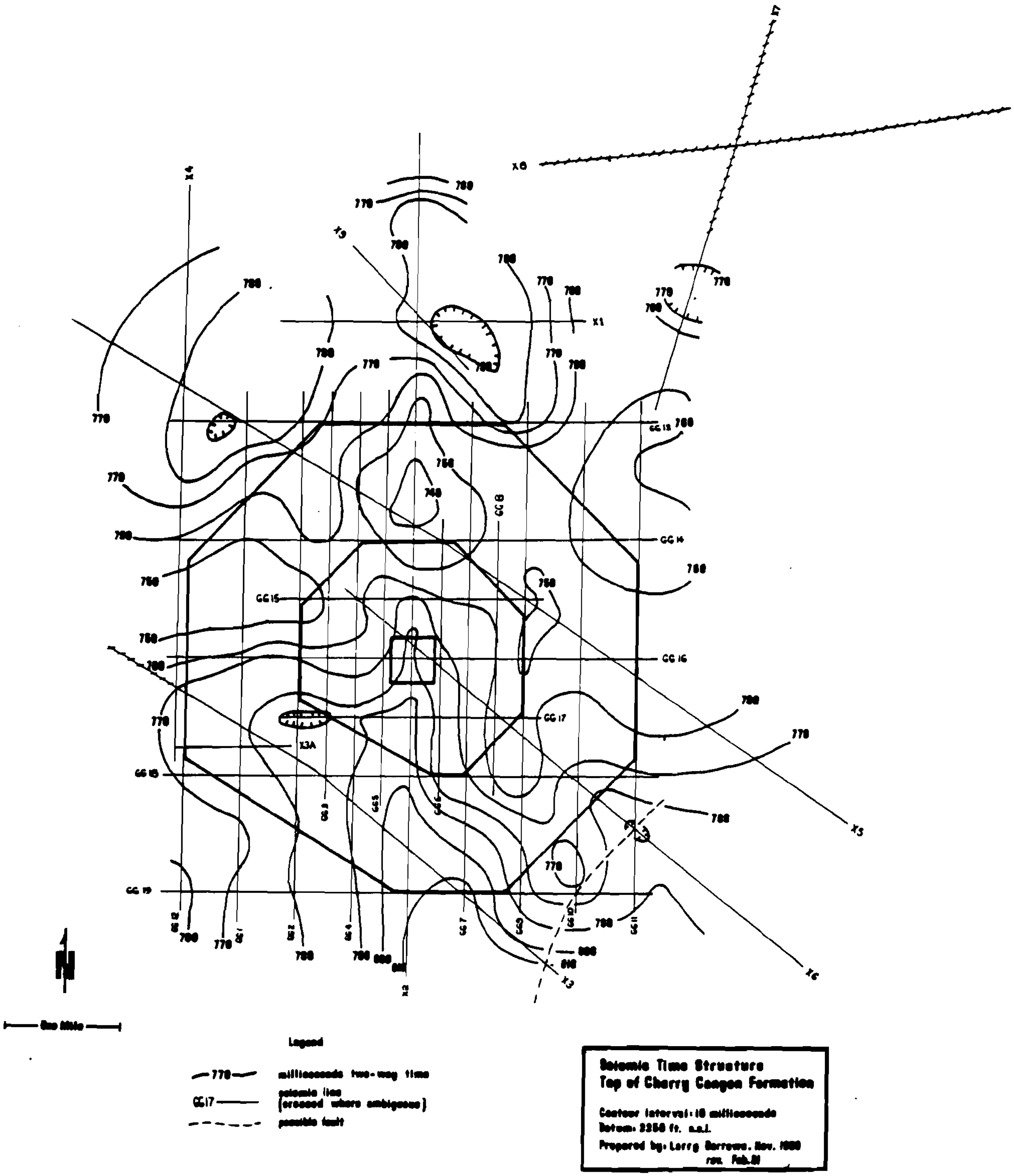


Figure 1.2.2-3. Seismic time-structure of a seismic horizon near the top of the Cherry Canyon Formation

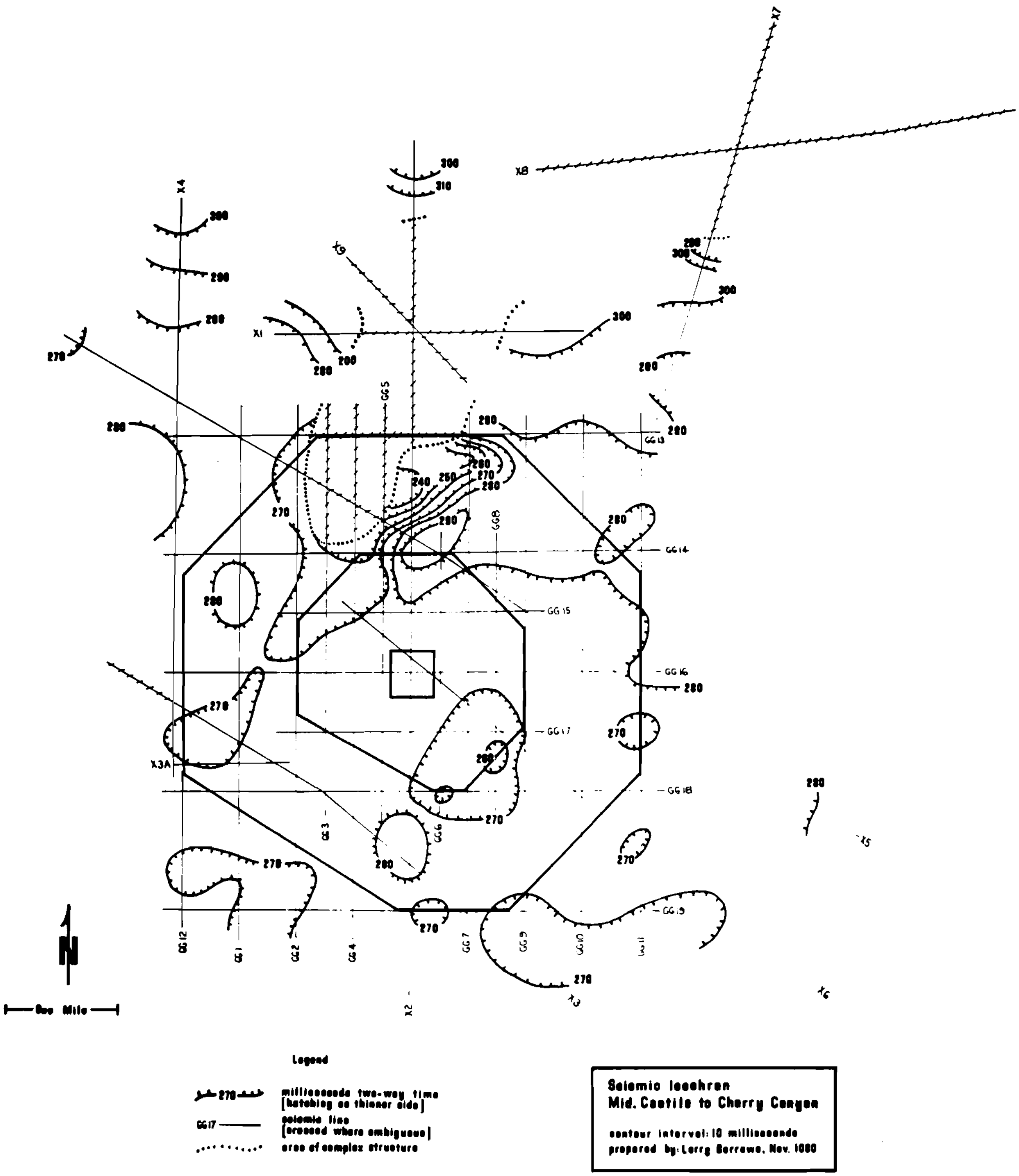


Figure 1.2.2-4. Seismic isochron map of the two-way travel time between the mid-Castile and Cherry Canyon seismic horizons

The seismic time-structure maps on the mid-Castile and Cherry Canyon reflections indicate smooth continuous structure over most of the WIPP site. There is an arcuate fault to the southeast of Zone III and a possibly faulted syncline (graben?) in the southwest. Neither of these features indicates much displacement (5 to 10 ms @ 14000 ft/s = 70 to 140 ft).

The largest feature of interest is the disturbed zone (DZ) in the northern part of the site. In the DZ, the seismic sections indicate a blocky, discontinuous structure in the Castile Formation with abrupt offsets or changes in dip between units (faults?). The seismic character or wiggle shape changes, indicating variations in thickness and/or acoustic properties. The map on the mid-Castile event shows increased dips and faults around the periphery of the DZ and an unmapped area of complex structure in the middle. The seismic data in this unmapped are are valid, but the geologic structures are too complex to map with these data. The map on the Cherry Canyon event is continuous through the DZ. The seismic isochron map indicates thickness variations within members of the Castile Formation.

The seismic indications of complex geologic structure in the northern part of the site have been verified with boreholes. Figure 1.2.2-5 shows locations of boreholes that penetrate the Castile Formation. Figures 1.2.2-6 and 1.2.2-7 are borehole correlations along the lines indicated on Figure 1.2.2-5. On the borehole correlations, the Cowden Anhydrite marker bed in the lower part of the Salado Formation is used to separate two methods of log correlation. Above the Cowden Anhydrite, the horizons are convenient markers on the logs. Below the Cowden, the dark intervals are primarily anhydrite and the light intervals are halite.

Structural deformation is intense within the Castile Formation. There are vertical displacements of hundreds of feet and thickness variations of hundreds of percent. In AEC 7 there are four massive anhydrites; in POGO Fed. 1 there are two (the latter may be a depositional pinchout of Halite II along the basin margin). In ERDA 6 the uppermost anhydrite was identified from core as Anhydrite II, and Anhydrite III may be missing (Anderson, 1976).

The complex deformation within the Castile Formation does not extend through the overlying Salado Formation. Figure 1.2.2-8 is a structure contour map of the top of the Salado Formation prepared from borehole control. There is a broad gentle syncline in the area of the DZ, but no indication of deformation as complex as that in the underlying Castile Formation. At this stratigraphic level there are sufficient boreholes to reliably define the structure.

1.2.3 Karst

Evaporite and carbonate rocks dissolve, or corrode, when they contact chemically undersaturated water. Karst refers to a distinctive surface morphology and groundwater hydrology resulting from such dissolution. Karst surface morphology is characterized by collapse sinks, alluvial dolines, caves, grikes, and various domes and mounds. The hydrology is characterized by sinking streams, swallow holes, the absence of surface runoff, an integrated arterial system of subsurface conduits, and a few large irregular springs. The general principles of karst morphology are discussed by M. Sweeting (1973), and karst hydrology is discussed by A. Bogli (1980).

A large area of southeastern New Mexico and west Texas, including the Delaware Basin, is underlain by soluble carbonates and evaporites. Much of this material has been removed by dissolution, and the area is recognized as one of the karstlands of the United States (Davies and LeGrand, 1972; LeGrand et al, 1976). Regional karst is described by G. O. Bachman (1980) in his report on the geology and Cenozoic history of the Pecos Region, and by Powers et al (1978).

The regional dissolution history is complex. The stratigraphic sequence above the Permian is discontinuous, presumably indicating periods of uplift, erosion, and dissolution. Even intervals of active deposition, such as during Gatuna time, may be accompanied by groundwater dissolution and collapse of the new deposits into solution cavities. Despite the complexity, the present episode of dissolution can be related to development of the Pecos drainage system and the associated demise of Ogallala deposition (King, 1948, p 152). The Ogallala was deposited as complex overlapping alluvial fans shed from the uplifted Rocky Mountains to the west. During the Pleistocene, the Pecos River extended to the north by headward erosion and captured the easterly flowing Ogallala streams. Subsequent excavation of the Pecos River basin is a combined result of normal fluvial erosion and the dissolution of halite, gypsum, and limestone (Morgan, 1941). The west-sloping topography at the site, Nash Draw to the west, and San Simon Swale to the east are all products of the present geomorphic cycle.

The easterly structural tilt of the Delaware Basin, along with incising of the Pecos Drainage, has exposed progressively older formations to the west. The Castile Formation outcrops along the west side of the basin near White City and farther south into the gypsum plains of west Texas. The area of outcrop has a series of elongated east-west troughs and ridges that Olive

(1957) attributed to the collapse of solution conduits itially developed along east-trending joints. Farther east the Salado Formation discontinuously outcrops as scattered patches of insoluble residuum. In the subsurface the thickness of Salado salt varies from zero near US Route 285 to ~1900 ft 20 mi to the east (Bachman, 1980, Figure 8). Part of the thinning may be depositional or caused by an earlier dissolution episode, but the correlation between thinning, surface topography, and present course of the Pecos River implies that much of the thinning is caused by the present system.

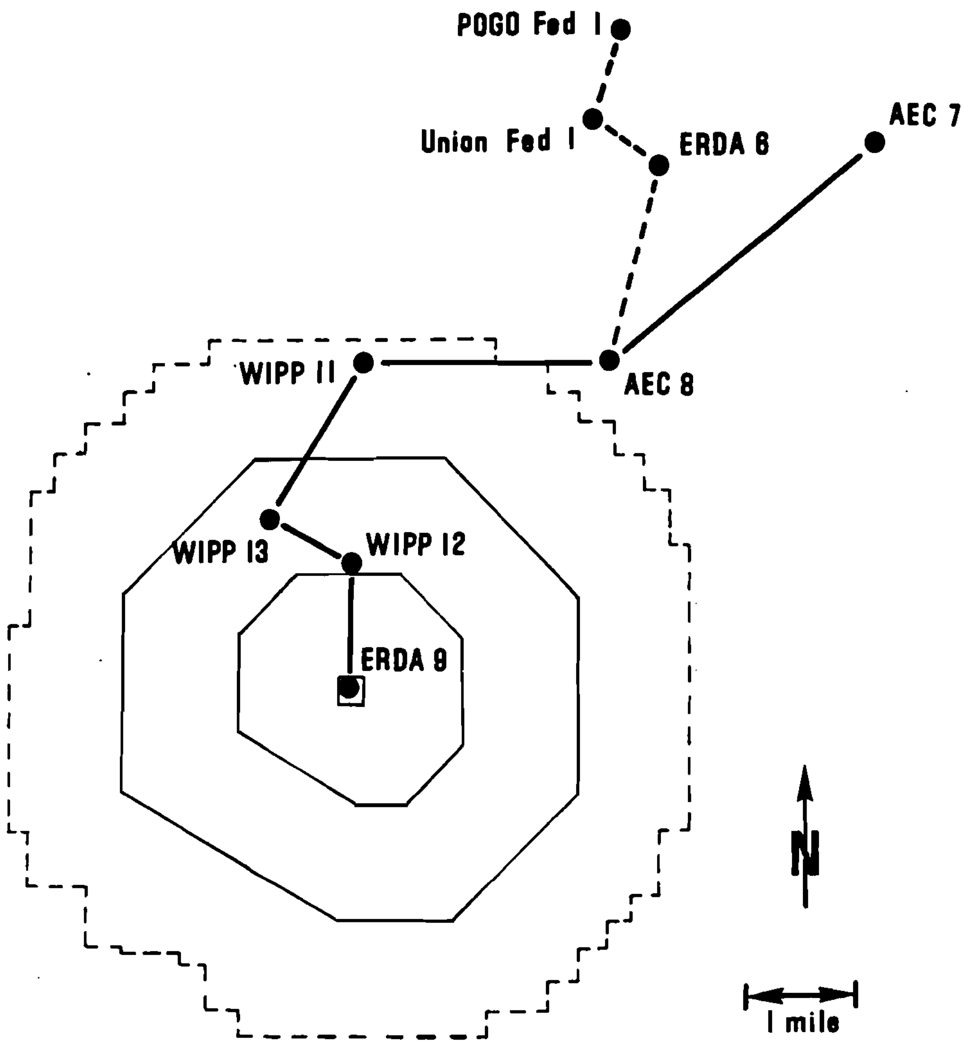


Figure 1.2.2-5. Boreholes to the north of the WIPP site that penetrate the Castile Formation

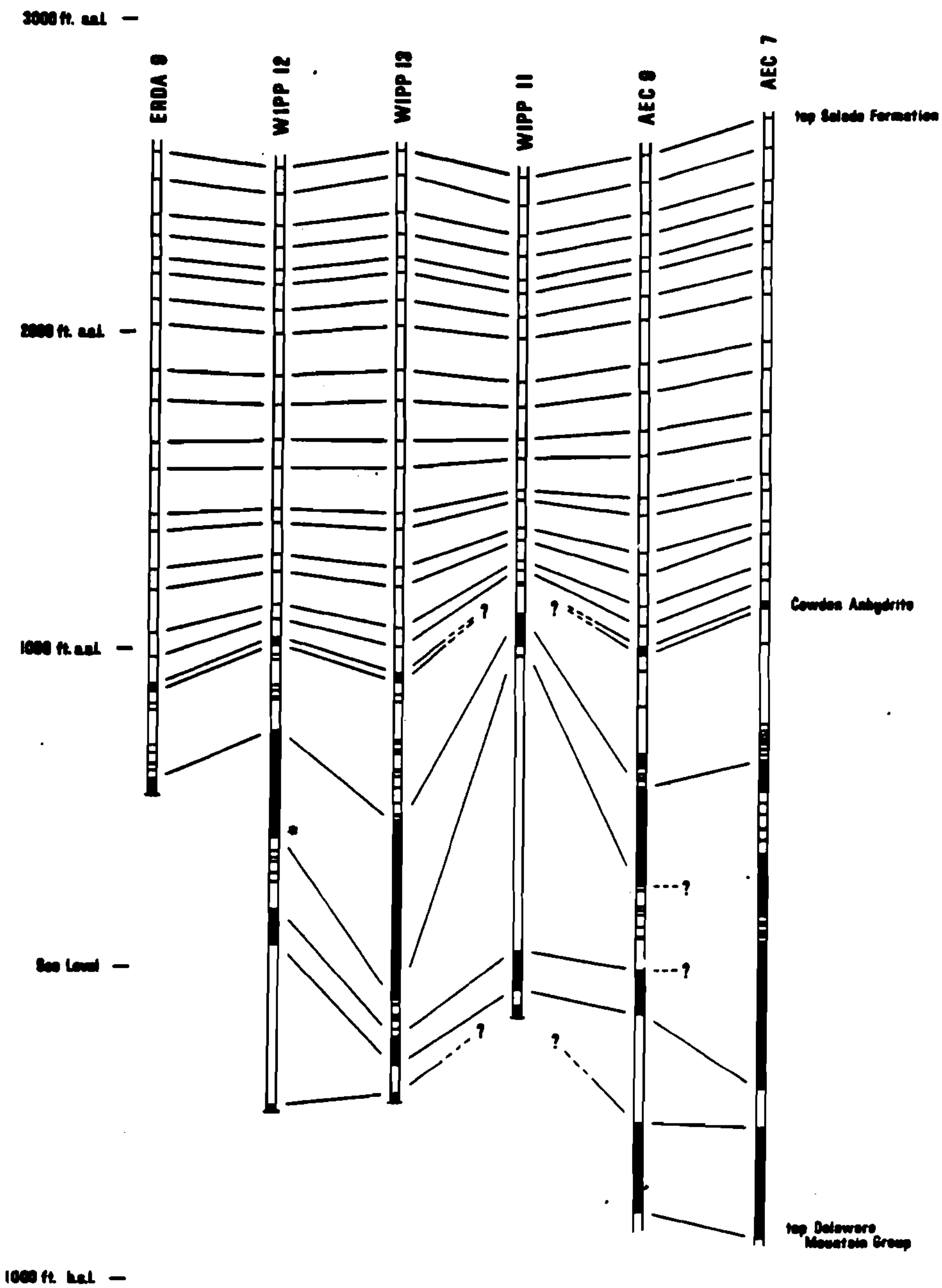


Figure 1.2.2-6. Borehole correlation for the Salado and Castile Formations along the solid line on Figure 1.2.2-5

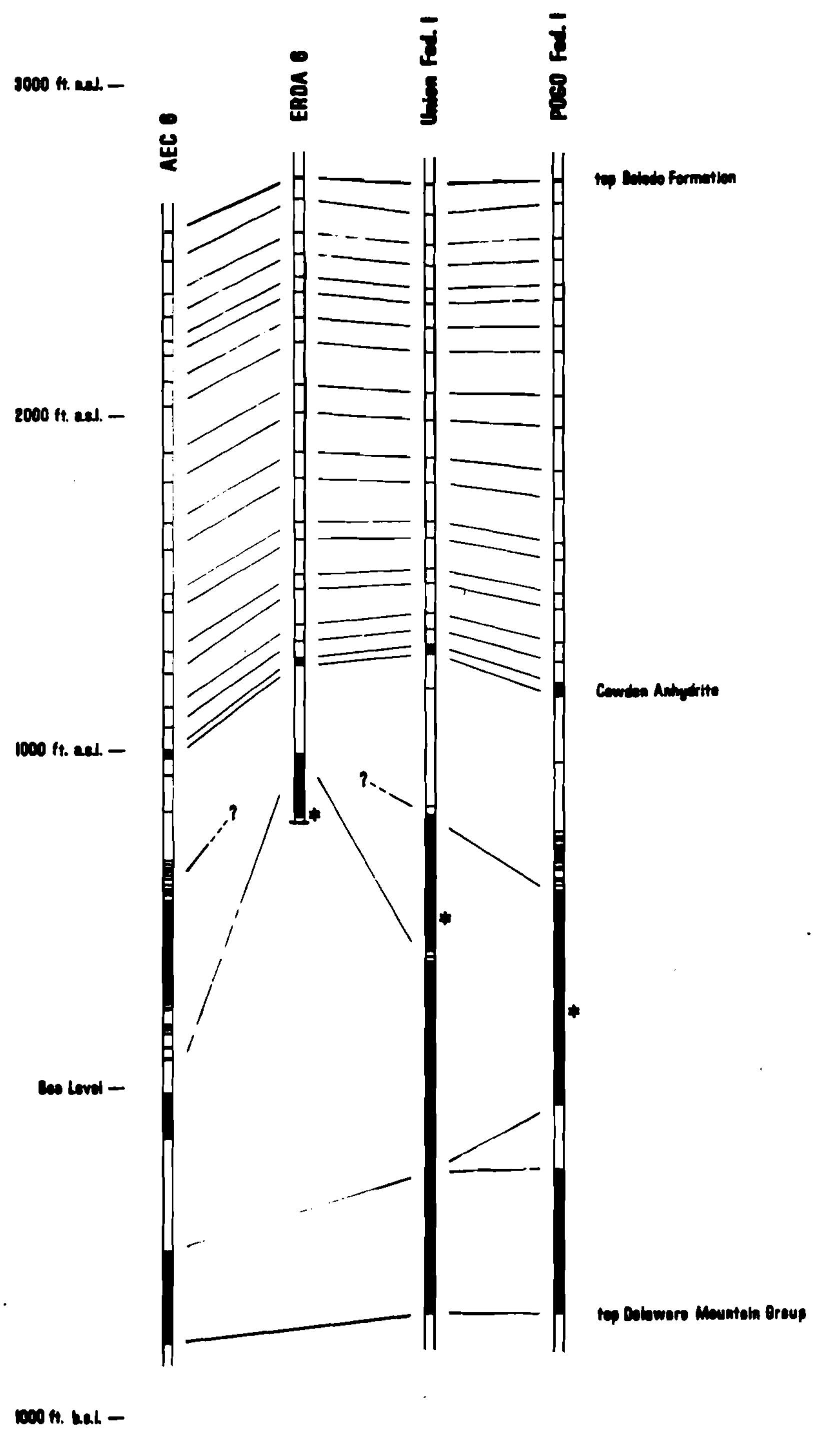


Figure 1.2.2-7. Bore correlation for the Salado and Castile Formations along the dashed line on Figure 1.2.2-5

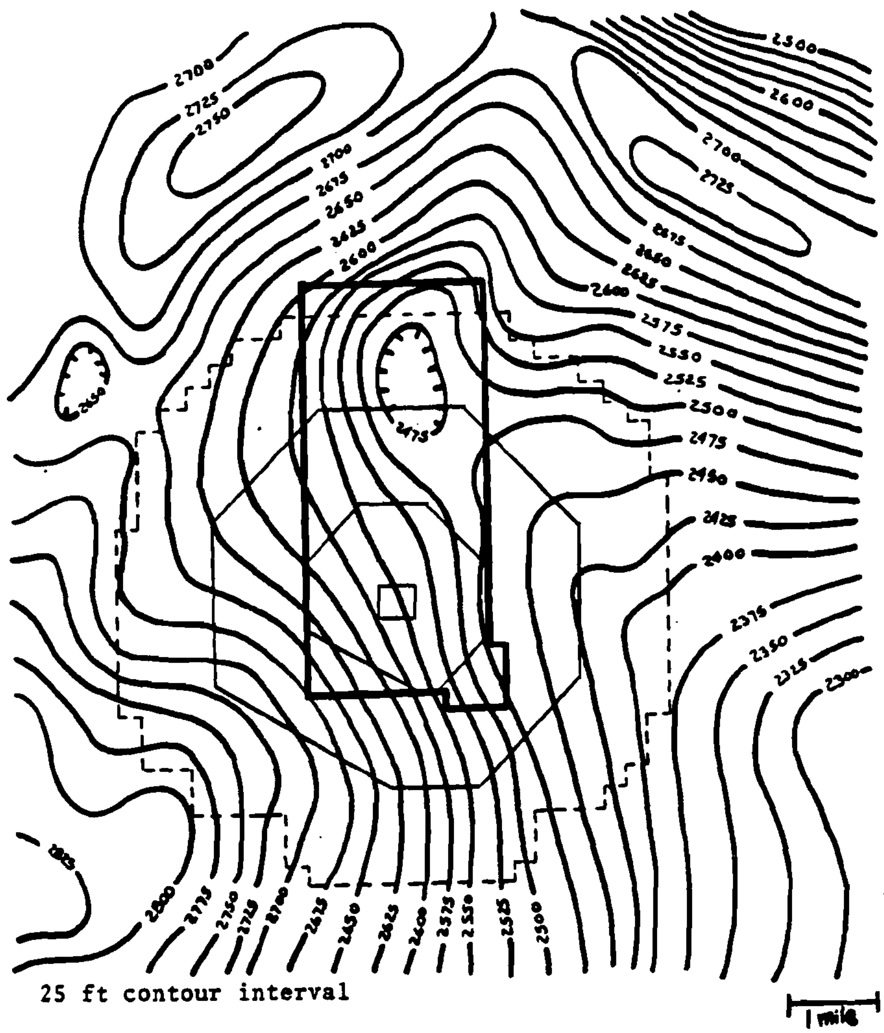
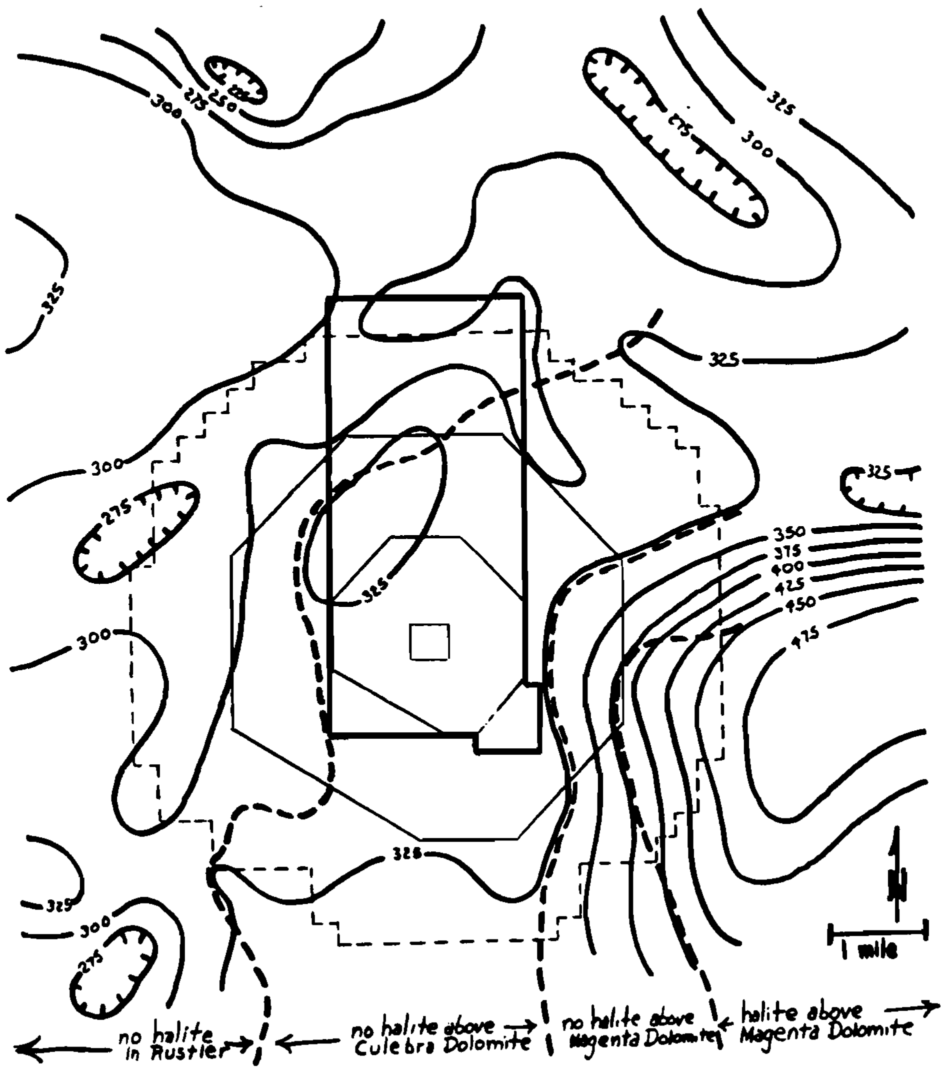


Figure 1.2.2-8. Structure contours on the top of the Salado Formation

The Rustler Formation outcrops in scattered areas of Nash Draw. In outcrop, it is generally gypsum with interbedded dolomite and reddish-brown clayey insoluble residues. The gypsum supports the openings of caves and swallow holes, some of which are large enough to enter. In the subsurface, dissolution has formed a complex of tunnels and caves. Many of the cavities have filled with alluvium washed in from the surface, and many have collapsed, forming complex breccias. The surface exhibits collapse sinks, grikes, and vanishing arroyos.

At the WIPP site, the Rustler Formation is overlain by the Dewey Lake Red Beds. It is here an example of an interstratal phreatic karst. Figure 1.2.3-1 is a borehole-controlled isopach of the Rustler Formation. The formation thins from 450 ft in the southeast corner of WIPP site Zone IV to 300 ft along the western side. Isopach thinning is accompanied by the downward progression of surfaces defined by borehole encounters with the uppermost halite, the uppermost anhydrite, and the deepest gypsum. These relations are reasonably attributed to dissolution by groundwater infiltrating from above (e.g., Powers et al, 1978, pp 6-38; Snyder in Borns et al, 1983). The occurrence of anhydrite stratigraphically above dissolution residues implies that the infiltration is areally discontinuous. As noted previously, farther to the west the Rustler is both closer to the surface and progressively more dissolved.



25 ft countour interval

Figure 1.2.3-1. Isopach of the Rustler Formation

The detailed lithologic character of the Rustler is considerably more complex than suggested by the WIPP site isopach map. Ferrall and Gibbons (1980) documented a study of this formation based on core photographs, core inspection, borehole logs, and brief field trips. Their report is summarized here at length because it describes the geologic variations responsible for at least some of the observed gravity anomalies.

The Rustler Formation was never a simple homogeneous rock unit. It was deposited as silty evaporites, silts, and lime muds during the final irregular stages of the Permian evaporite basin. Pseudomorphic gypsum rosettes suggest that the calcium sulfate was initially deposited as gypsum and later dehydrated to anhydrite. The lime mud was diagenetically altered to omite. Both these processes and the normal com- ion of clastic sediments affect the physical volume of the deposit.

Ferrall and Gibbons described core from WIPP 19 and then contrasted it with cored intervals of other holes. The lithologies identified include anhydrite, gypsum, halite, dolomite, siltstone, and solution residues. The solution residues are layers of generally unstructured clay or silt, lacking original bedding, and often containing breccia clasts. Fractures, in some cases breccia, occur in adjacent units and are attributed to collapse into dissolution voids. Also, since the solution residues represent former paths of migrating groundwater, they have acted as centers for the hydration of anhydrite to gypsum in adjacent units.

At WIPP 19 Ferrall and Gibbons identified one solution residue at the top of the Salado Formation, three in the unnamed lower member, one at the base of the Tamarisk Member, and one within the Forty-Niner Member. A generally similar sequence of solution residues was identified in other holes, but their degree of development, cementation, and exact stratigraphic position varied.

The residue at the base of the Rustler was interpreted as representing the leached top of the Salado Formation. The next two are adjacent to a halite layer within the lower member. At WIPP 19, these are cemented by halite and are not extensively leached. However, in the other holes studied (WIPP 25, 26, 30), this halite layer has been removed by solution, and a single dissolution residue is present. The third residue in the lower member is at the base of the Culebra Dolomite.

At WIPP 19, 15 ft of solution residue in the Tamarisk Member immediately overlie the Culebra Dolomite. The lower foot of this particular residue is layered, and Ferrall and Gibbons (1980) suggest it may have been deposited in the bottom of a solution cavity. In other holes, the residue in the Tamarisk Member varies between 6 and 18 ft in thickness and is separated from the Culebra Dolomite by up to 22 ft of gypsum. The Forty-Niner Member residue in WIPP 19 is 10 ft thick. The calcium sulfate is gypsified out to a few feet of both the top and bottom of this residue.

In addition to the solution residues, Ferrall and Gibbons identified leached zones in the lower member and in the Forty-Niner Member in which bedding plane breaks resulted from solution activity of groundwater traveling along the laminae.

Karst, or groundwater alteration of the Rustler Formation, is important to the gravity interpretation, but its effect on rock densities is not necessarily simple. Dissolution may decrease the bulk density of the formation if the voids remain open or are filled with less dense material. Alternately, it may increase the bulk density if removal of a low-density evaporite (e.g., halite) is compensated for by compaction of the formation.

The removal of calcium sulfate can be even more complex. In unaltered areas, calcium sulfate in the Rustler occurs as anhydrite (density 2.9 to 3.0 g/cc). During dissolution, the anhydrite is normally hydrated to gypsum (density 2.2 to 2.6 g/cc) with up to a 38% increase in volume. In at least some instances the increased volume is compensated for by removed material. In other instances, the volume increase causes significant distortion in the rock. These mechanical effects are discussed by Ferrall and Gibbons (1980, Section 2.3.1).

1.3 The Gravity Surveys

1.3.1 Background and Original Objectives

The gravity method is based on the measurement and interpretation of small variations in the earth's gravity field. These variations (or anomalies) result from lateral variations in the subsurface distribution of mass or rock density. In a layered sequence of sedimentary rocks, the lateral density variations normally, but not always, result from structural displacement of strata of differing density. Examples would be a high-angle fault that juxtaposes a heavy anhydrite layer against a lighter halite, or a piercement diapir in which the less dense halite is rising through a more dense overburden.

The gravity data can be used to detect subsurface density structures and to place constraints on the allowable interpretations of those structures. By itself, the detailed shape of a gravity anomaly can be used to establish the maximum depth to the top of the causative density structure and the minimum amount of missing, or excess, mass in the structure. Used in conjunction with other forms of data (such as seismic sections, boreholes, regional geology, and magnetics), gravity can help establish the most likely form of the structures, infer lithologies, and extend the interpretation into areas of deficient information. The gravity technique is a very useful and relatively inexpensive exploration tool. However, its application requires careful consideration of all available data.

During a gravity survey, measurements are made with a sensitive gravimeter at discrete locations or stations. Figure 1.3.1-1 shows the gravimeter and operator at one of the WIPP survey stations. The instrument is a LaCoste and Romberg model D geodetic meter.

Because gravity is sensitive to both elevation and geographic latitude, station surveying is as important as the actual gravity metering. Surveying generally requires more than half the total field effort. Figure 1.3.1-2 shows the operator adjusting the Hewlett-Packard 3820A laser rangefinder/theodolite used for the survey.

To locate stations, the surveyor sets up the rangefinder/theodolite on a topographic high with a resonable field of view along the survey line. The rodwoman

-ed off the approximate distance and then was ked to within a couple of inches of the correct location by the surveyor. The station was leveled with a garden trowel, and a foot-square board was embedded in the sand. The survey rod was then centered on the board and the station elevation recorded. When the station was subsequently metered, the gravimeter baseplate was centered on the board. The operator could tell from the sand packed around its edges whether the board had been inadvertently moved during the interim.

'gure 1.3.1-1. Gravimeter and operator

Figure 1.3.1-2. Surveyor with Hewlett-Packard model 3820A laser rangefinder/theodolite

Gravity data are expressed in milligals, where a gal is an acceleration of 1 cm/s/s. The WIPP high-precision survey approched a relative accuracy of ± 0.02 mgal, or about 2 x 10^{-8} of the earth's total field (980 cm/s^2).

The WIPP survey was originally planned to resolve anomalies originating within the DZ and to help assure that additional structures are not present at the site. Models of representative DZ structures produced anomalies of a few tenths of a milligal, with double half-widths of 2 km. (The double half-width is the distance between points at one-half the maximum amplitude of the anomaly and is a measure of the spatial wavelength.) It was felt that the relatively simple geologic structure of strata above and below the Castile Formation would allow spatial wavelength discrimination of the DZ anomalies.

The WIPP project had previously purchased use of a regional gravity survey of the northern Delaware Basin from Exploration Surveys, Inc. of Dallas, Texas. These data are proprietary and cannot be released. The regional survey had stations at quarter-mile intervals along a grid of lines ~1 mi apart. The map indicated gravity anomalies in the vicinity of the DZ, but neither the station spacing nor data accuracy are sufficient to resolve the shape of the anomalies. It provided definition of the regional gradient associated with the Delaware Basin and demonstrated a strong correlation between the longer wavelength anomalies and the seismic time structure maps prepared from the WIPP Vibroseis surveys.

As the WIPP gravity data became available, the density structure of the site was found to differ substantially from that anticipated. Instead of gravity anomalies originating within DZ structures of the Castile Formation, the field is dominated by effects of lateral density variations within shallower and relatively flat-lying strata.

These results are consistent with those reported from gravity surveys in other karstlands. Colley (1963) discussed the gravity effect of air- and water-filled cavities of differing dimensions and depths below the surface. This paper includes examples of sharp negative anomalies of ~1/2 to 1 mgal delineated during detailed gravity surveys in Iraq. The region is part of an anhydrite karstland noted for its topographic depressions. The gravity anomalies are attributed to solution caverns and the related hydration of anhydrite to gypsum.

In a more recent paper, Omnes (1977) discussed the fairly extensive use of microgravity to detect subsurface cavities in karstlands. Examples are given of sharp negative anomalies of a few tenths of a milligal that were found, by drilling, to be associated with either cavities or low-density fill in local sinks. In their surveys, the measured anomalies were always at least several times larger than the anomalies calculated on the basis of the geometrical dimensions of the cavities. This phenomenon is attributed by Omnes to stress relief, jointing, and dissolution induced by the existence of a cavity.

1.3.2 Survey Locations

The initial plan was to survey a rectangular area 2 by 5 mi covering all of WIPP site Zone II, and 6 sq mi of the DZ to the north. Stations were located on a uniform square grid because spatial filtering would be used to resolve low-amplitude, long-wavelength anomalies originating within the Castile Formation.

As the survey progressed and data became available, modifications were made to the original field plan. First the station spacing was changed from a grid 1/6 by 1/6 mi square to 13 north-south lines spaced 1/6 mi apart with stations at 1/18-mi intervals. This change was made because the entire lines would have to be surveyed and walked either way, and because the work associated with the additional stations was not great. The additional stations were later found necessary to resolve the gravity anomalies. A second change was to delete the northern 2/3 mi from the survey area. This northern area was covered with steep sand dunes, and both surveying and data reduction (terrain corrections) would be excessively difficult. The area actually surveyed, and additional detailed surveys, are indicated on Figure 1.3.2-1.

Two small areas were surveyed in fine detail before the main portion of the WIPP site was surveyed. The purpose of these two detail surveys was to establish the short-wavelength character of the gravity field to assure the adequacy of planned station spacing. One of the detailed areas was in the southeast corner of Section 21, R31E, T22S. This area has a fairly uniform smoothly dipping field and is not of further concern. The second detailed area was centered over a closed topographic depression along the east-west line between Sections 9 and 16. This area has one of the most distinctive short-wavelength negative anomalies at the site. Borehole WIPP 14 was drilled to investigate the anomaly; it is subsequently referred to as "the WIPP 14 Anomaly."

The main WIPP survey indicated two positive elliptical gravity anomalies in the southeast quarter of Section 28. These anomalies were near the southern ends of survey lines L and M on the flanks of a topographic hill. There was no reasonable geologic interpretation of the anomalies. The area was detailed later with a close spaced grid of gravity stations. Also, alternate lines of the close spaced grid were surveyed with a hand-held total-intensity magnetometer. The new data showed that the gravity anomalies were not as extensive as originally interpreted, and that the magnetic field was relatively flat. Some inconsistencies were also noted between the two surveys. In an effort to resolve the inconsistencies, we rechecked the station elevations. The new elevation survey showed that the anomalies were caused by two sequential erroneous instrument setups on the original survey. The area is now known to have almost flat gravity and magnetic fields.

Two additional projects were undertaken during the gravity survey. These were a network of reconnaissance profiles over and around borehole WIPP 33, and two Reconnaissance profiles over Bell Lake Sink in R33E, T24S. These additional surveys were to explore the relation between the gravity anomalies and karstification. The location of the WIPP 33 profiles are indicated on Figure 1.3.2-1 and the Bell Lake Sink profiles on Figure 2.3.2-1.

1.3.3 Data Reduction

The force of gravity at the surface of the earth depends on solar and lunar tides, on latitude, and on elevation. These effects are comparable to, or larger than, the effect of subsurface density structures. Thus the gravity measurements must be corrected before they can be interpreted. The corrections require additional data. Latitude and elevation are from the surveying. Tides are calculated from the position of the sun and the moon at the time of the meter reading. In addition, the meter readings are corrected for instrument drift prorated over the time between base station readings. The corrections were made by the contractor and are tabulated in the contractor's report.

The Bouguer correction accounts for the attraction of a flat-layered slab of material between the station and sealevel. The value of the Bouguer correction depends on average density beneath the station (which is in general unknown). Fortunately, gravity interpretation depends on the relative gravity between stations in the survey area and is independent of any constant offset in the data. The Bouguer slab density of interest is then the average density over the elevation range of the topography in the survey area. For the WIPP survey the contractor calculated gravity for a family of Bouguer slab densities between 1.7 and 2.67 g/cc. Inspection of the gravity profiles over the topographic hill in the southeast corner of Section 28 indicated that the slab density ranges from 2.1 to 2.5 g/cc; 2.3 g/cc was selected for making the Bouguer slab corrections. The data set used in the following interpretation was reduced with a Bouguer slab density of 2.3 g/cc.

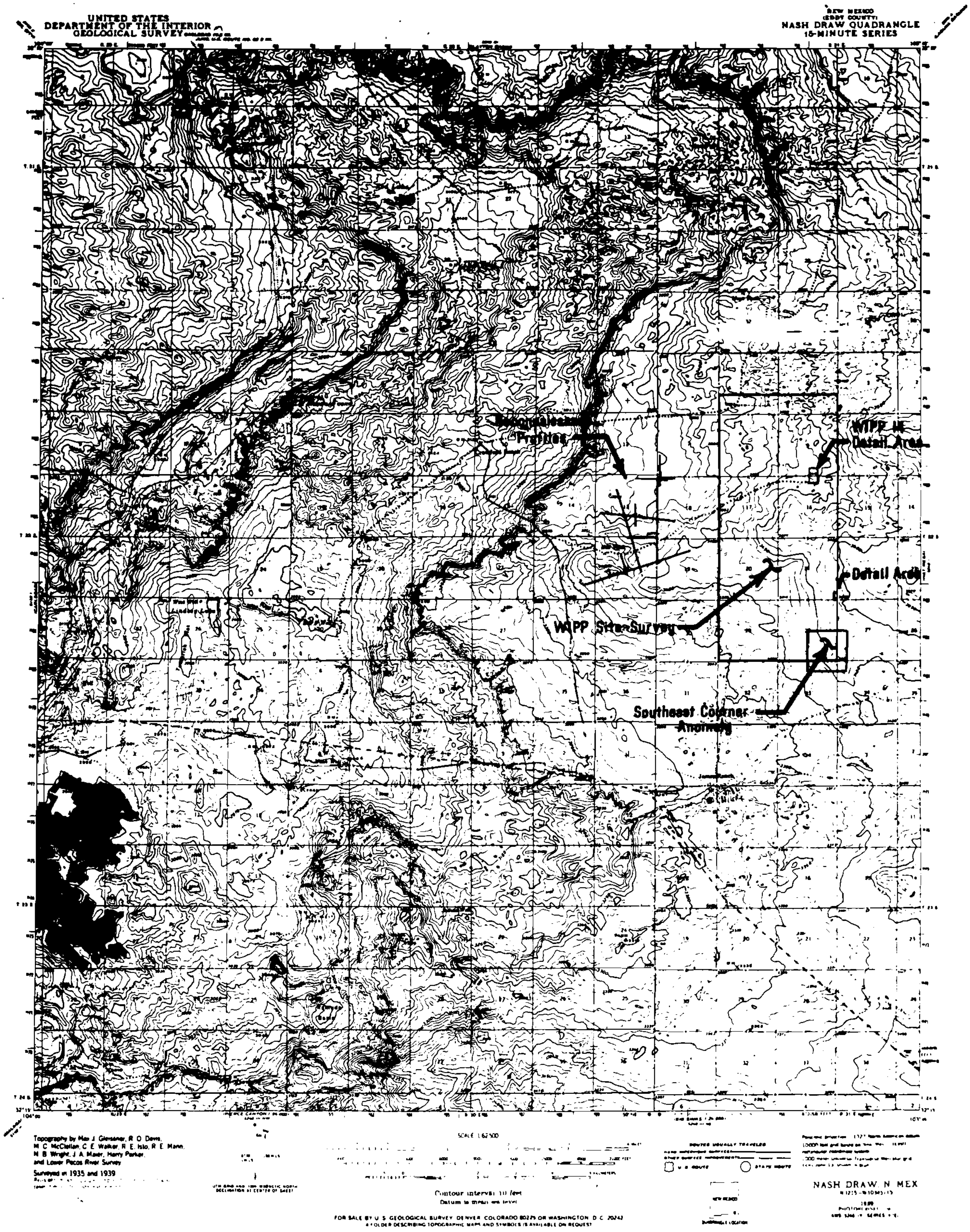


Figure 1.3.2-1. Topographic map of the Nash Draw Quadrangle

Topography near a station affects the gravity. Nearby hills or ridges exert an upward pull, and the missing mass of valleys results in less downward attraction. In areas of steep topography, the net effect can be large and is compensated for with a terrain correction calculated from topographic maps. At the WIPP site, terrain features include sand dunes, shallow topographic depressions, and the hill in the southeast corner of Section 28. The local terrain is closely controlled through a set of detailed topographic contour maps prepared by Bohannan Huston Inc. for Bechtel International (1 in. = 100 ft, 2-ft contour interval). These maps were inspected to select six sites showing the greatest topography. The terrain corrections of these sites were calculated with the high-precision methods described in Hammer (1982). The largest value was 0.041 mgal (top of hill in the southeast corner of Section 28). Terrain corrections for the gravity survey should not exceed this and are generally less than 0.02 mgal.

Considering the relatively large size of the gravity anomalies (several tenths of a milligal), detailed terrain corrections were not justified for the WIPP gravity survey. (The local terrain introduces an uncertainty of several hundredths of milligal into the gravity data.)

The strongest component of the gravity field in the area of the WIPP site is the regional gradient associated with the Delaware Basin. This regional gradient is partially due to the thick sediments within the basin. According to Djeddi (1979), it is also partially due to density variations between basement rocks within the Central Basin Platform and those on the eastern periphery of the basin. For large-scale structural studies, the gravity anomaly of the Delaware Basin is the "signal." For detailed study of a small area within the basin, it is another form of noise that must be removed before the data are interpreted. The gravity effect of the Delaware Basin is clearly shown on the proprietary regional survey. These data were used to determine a plane regional gradient that was subtracted from the WIPP survey gravity data. The WIPP site survey, the detailed areas, and the WIPP 33 reconnaissance profiles were reduced with a regional gradient of 1.28 mgal/mi, increasing N34°E. The Bell Lake Sink reconnaissance profiles were reduced with a regional gradient of 1.32 mgal/mi, increasing N56°E.

It is also necessary to consider subjective data editing. Gravity surveying requires the very careful, repetitive setup, adjustment, and reading of sensitive instruments, often under less than optimal field conditions. Gages, meters, and clocks, must be read and recorded in field notebooks. These data are transcribed and entered onto computer cards, processed along with supporting information, and finally printed out as a gravity value. The gravity values are again transcribed, filtered, and plotted. Even in the best of conditions, some errors are bound to creep into the data set.

Editing consisted of the following:

- Single-station anomalies that were obviously discordant with respect to the rest of a line were deleted.
- Stations occupied more than once were averaged.
- Some sets of readings were adjusted as a block so that their end points tie the adjacent sets.
- Some questionable areas were resurveyed and the newer data used.

All editing is identified on the data tables in the appendices to this report.

Three semipermanent base stations were established during the WIPP survey. Each semipermanent base is a small square pad of poured concrete, level on top, with three notches for the legs of the gravimeter base plate. They are located near (1) borehole WIPP 12 at the northern edge of WIPP site Zone II, (2) borehole P-4 in the southeast corner of Section 28, and (3) borehole P-12 along the road to H6 (the WIPP 33 reconnaissance profiles). Three additional temporary base stations were established on station survey boards near the two initial detail surveys and at Bell Lake Sink. Base station data are in Table 1.3.3-1.

The base near borehole WIPP 12 is tied to the eastern end of the front porch of the Chamber of Commerce Visitors Center in downtown Carlsbad. This location is near and at the same elevation as a prime gravity base station of the world gravity network (inside the building and not readily accessible). Reference code numbers of the prime base are ACIC 0431-3 and IGB 11924B. The 1970 value of prime base of 979,203.120 mgal was assumed for the corner of the porch.

All other WIPP survey base stations were tied to the one near borehole WIPP 12.

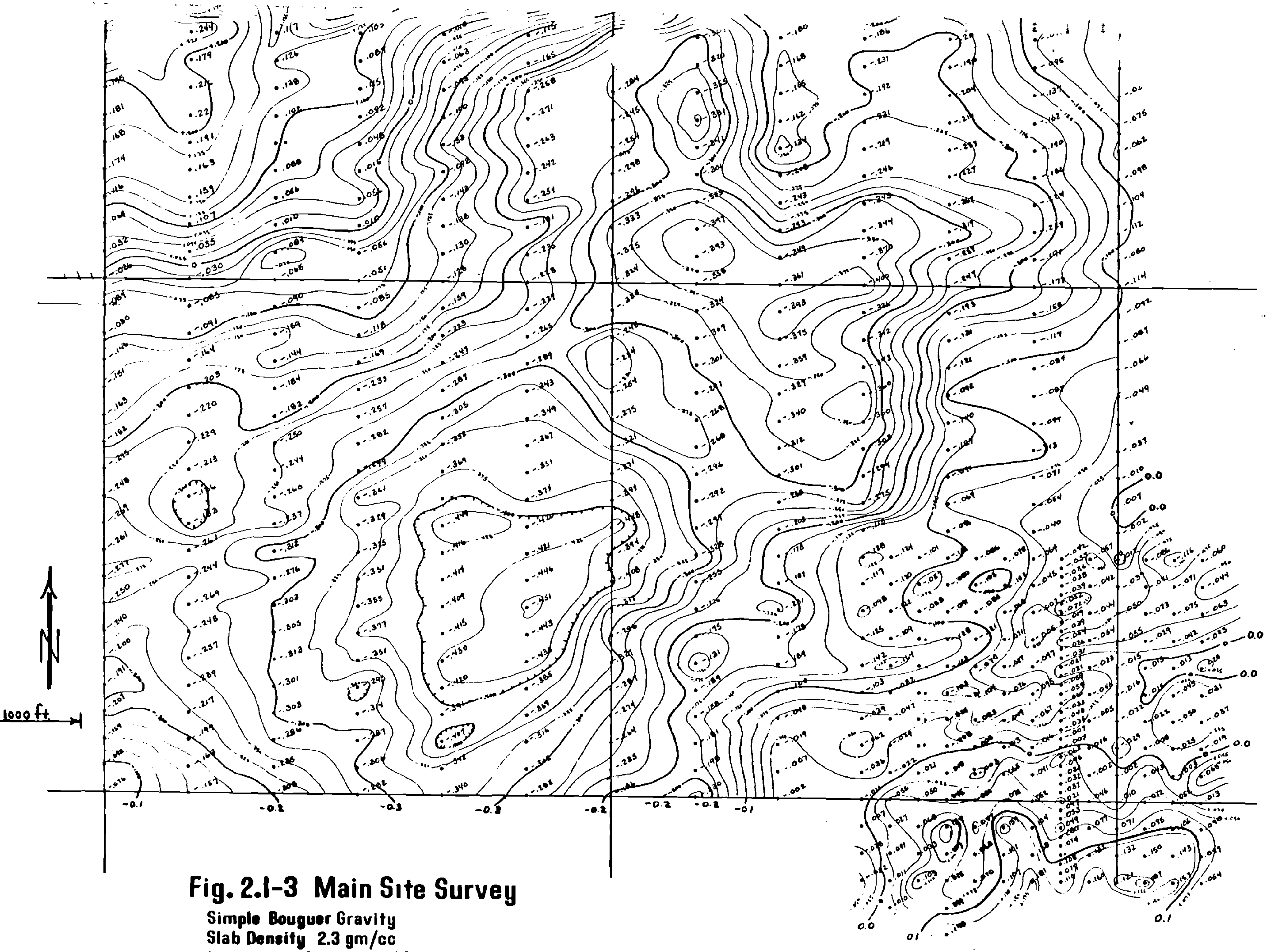


Fig. 2.1-3 Main Site Survey

Simple Bouguer Gravity
Slab Density 2.3 gm/cc
Less Linear Regional and Parabolic Trend
0.025 Milligal Contour Interval

ɹble 1.3.3-1. Gravity survey base stations

Base No.	I. D. No.	Gravity (Mgal)	Location/Elevation	Description
1 (prime)		979,203.120	N 32° 25.06′ W 104° 13.70′ 3112 ft	Carlsbad Chamber of commerce Visitors Center East end of porch
2 (semipermanent)	CB 99	979,171.221	N 32° 23.064′ W 103° 47.309′ 3471.18 ft	Near borehole WIPP 12 Northwest of the SE corner of Sec 17 0.87 ft below benchmark Z347
3 (temporary)	M 18	979,168.224	N 32° 22.116′ W 103° 46.402′ 3483.60 ft	Near detailed survey in SE corner of Sec 21 293.33 ft due south of NE corner of Sec 28
4 (temporary)	J 55	979,175.252	N 32° 23.898′ W 103° 46.916′ 3437.82 ft	Near WIPP 14 detailed survey Middle of line between Sec 9 and 16
5 (semipermanent)	CB 97	979,176.040	N 32° 23.0681′ W 103′ 49.5295′ 3373.71 ft	Area of the WIPP 33 reconnaissance profiles Near borehole P-12 along N-S road to H6
6 (temporary)	BL 50	979,150.831	N 32° 14.3583′ W 103° 34.0932′ 3583.00 ft	Bell Lake Sink Station #BL 50
ɬ (new) ·mipermanent)	CB 98	979,168.242	N 32° 21.3212′ W 103° 46.7006′ 3443.11 ft	Near borehole P-4 In detailed survey in SE corner of Sec 28

2. Data

2.1 Main Site Survey

The main site survey had stations at 1/18-mi intervals along 13 north-south lines spaced 1/6 mi apart. From west to east the lines are identified as A through M; from south to north the stations are numbered 1 through 79. Figure 2.1-1 shows the station locations. Also shown on Figure 2.1-1 are stations of a detailed grid in the southeast corner of the site. This detailed grid covers the southeast quarter of Section 28 plus an additional 1/6 mi to the south and east. Within the detailed area, stations are on a 1/18-mi square grid.

The data for the main site survey and for the detailed area in the southeast corner are here handled as profiles along the north-south survey lines. Appendix A gives for each line:

- station number
- elevation
- Bouguer gravity
- Bouguer gravity less regional
- Bouguer gravity less regional and parabolic trend
- editing

Figure 2.1-2 are north-south profiles of the simple Bouguer gravity. These data have been reduced with the linear regional trend discussed in Section 1.3.3 and with the parabolic trend indicated on the figures. The linear trend is related to the structure of the Delaware Basin. The parabolic trend correlates well with a seismic time-structure anticline on reflection horizons below the Castile Formation. In Section 3.1, these broad features are interpreted as resulting from related lateral variations in seismic velocity and bulk density in the Ochoan Series.

Figure 2.1-3 (in pocket) is a contour map of the Bouguer gravity less regional and parabolic trend. On this map the contours are constrained to rigorously honor the posted data. Figure 2.1-4 is a generalized contour map of the same data, except the contours are within ±0.025 mgal of the data. This map shows the location and general form of significant anomalies detected by the survey. The original data points should be used for calculations (e.g., minimum missing mass, max depth to top of body) or for modeling.

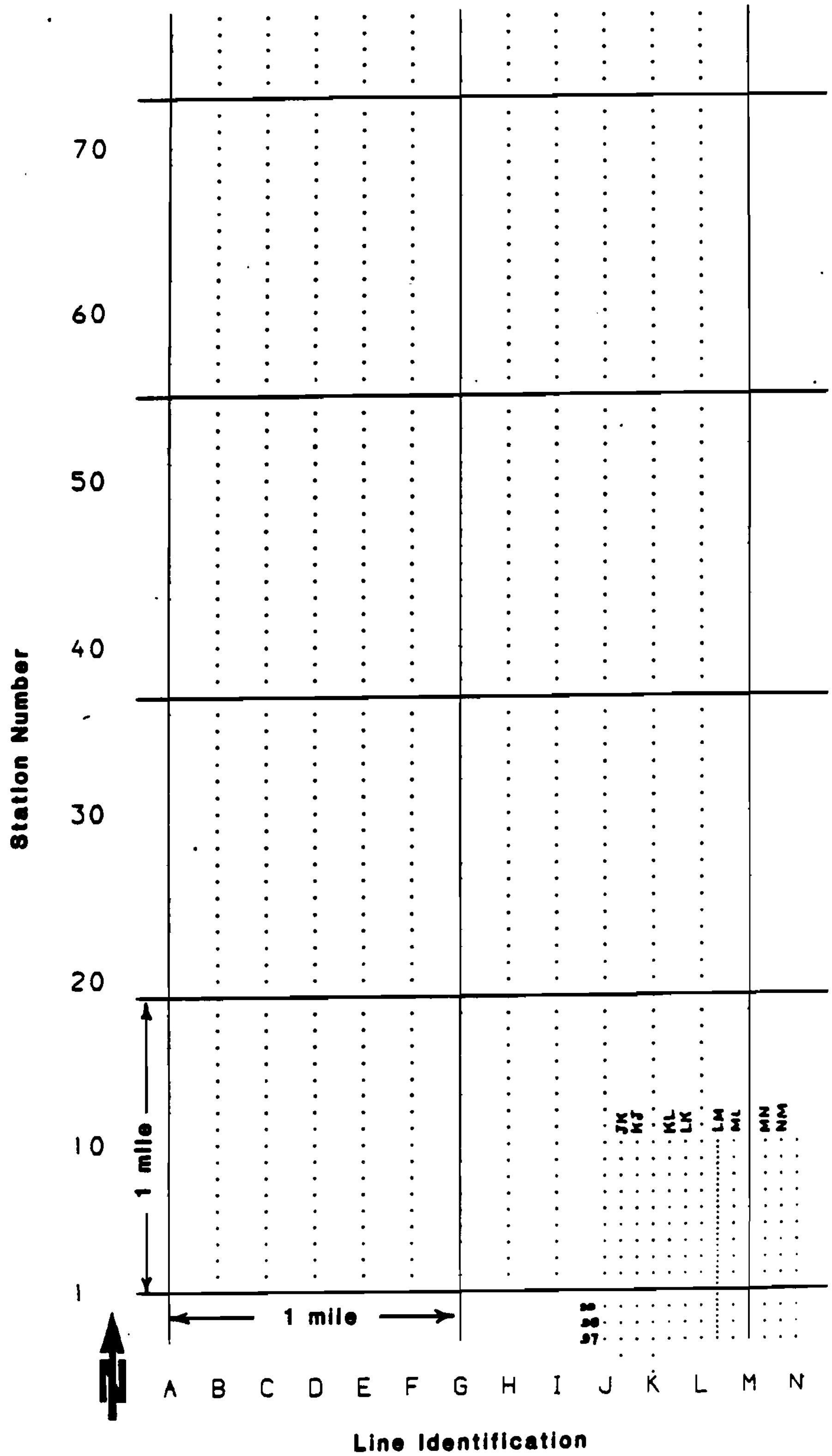
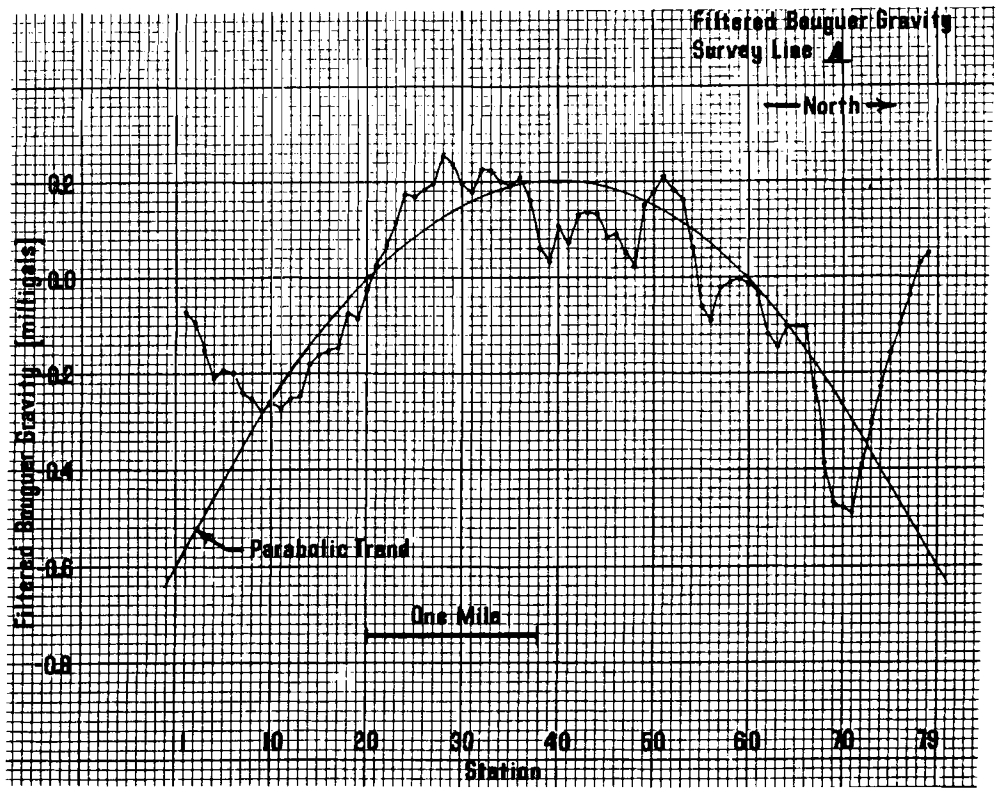
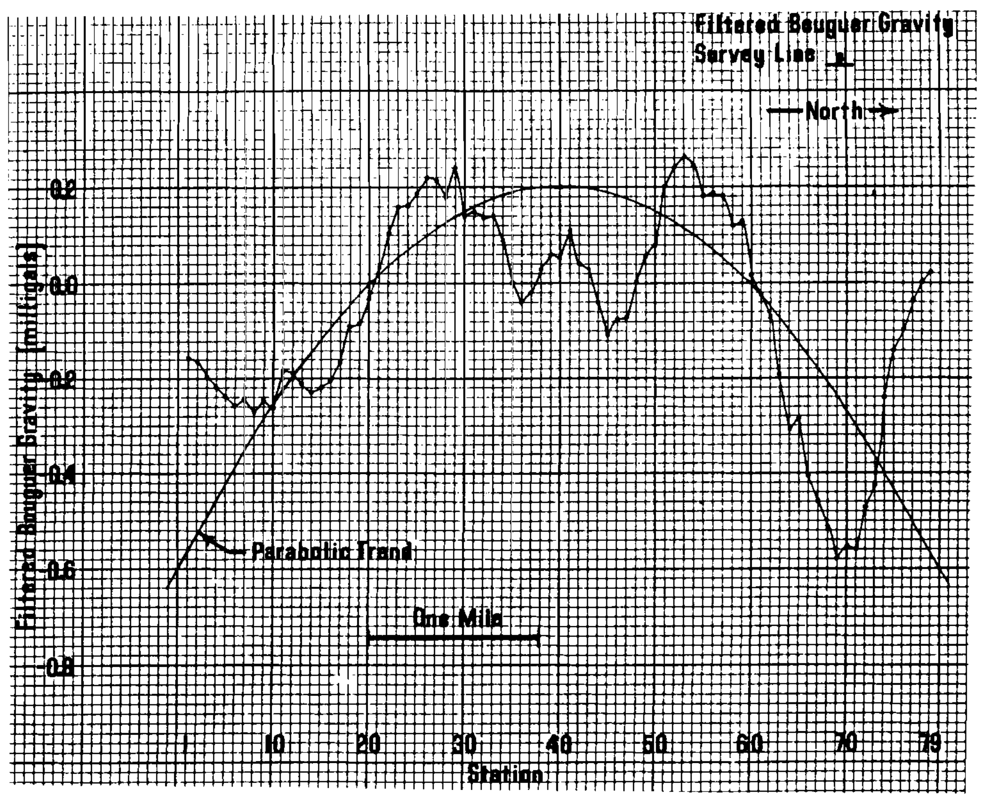


Figure 2.1-1. Gravity station location and identification

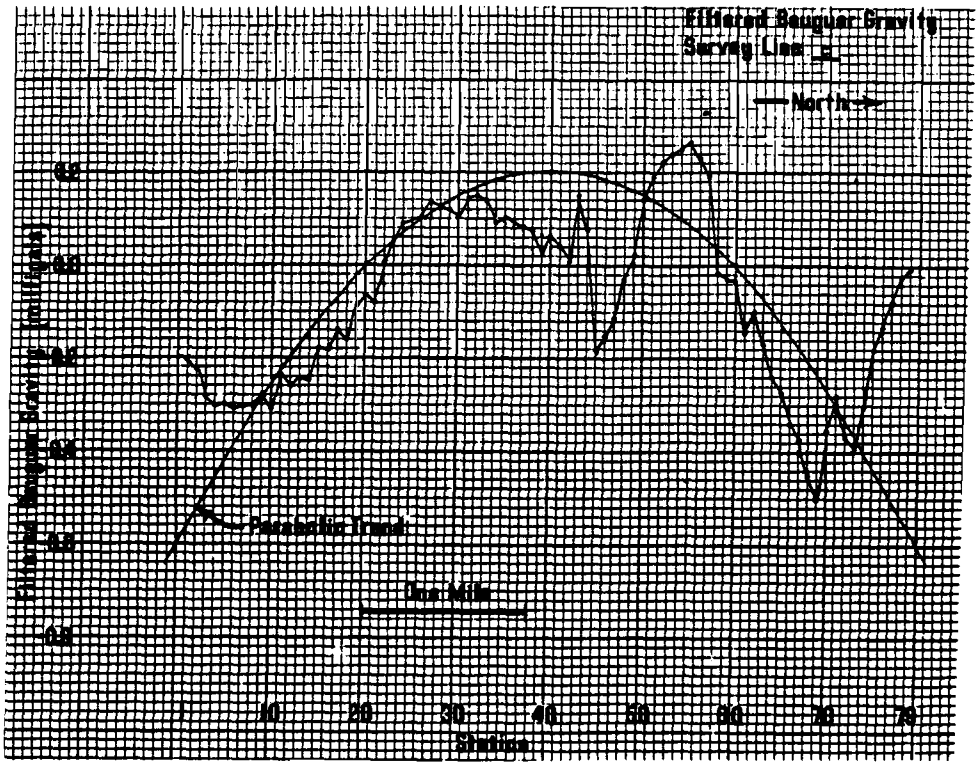


(a)

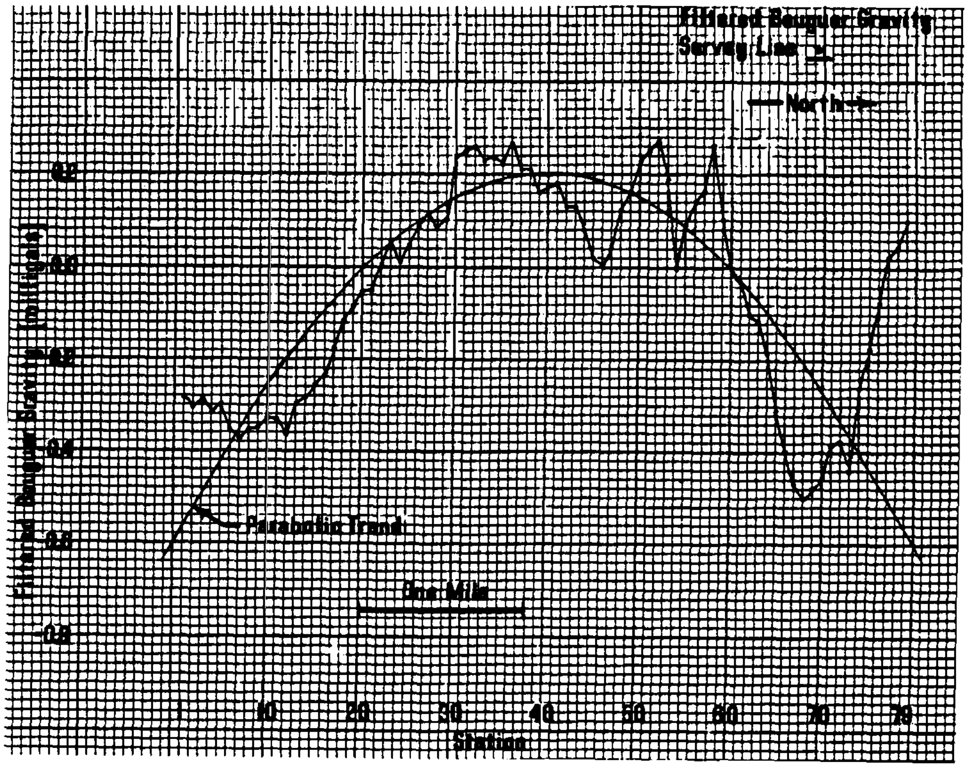


(b)

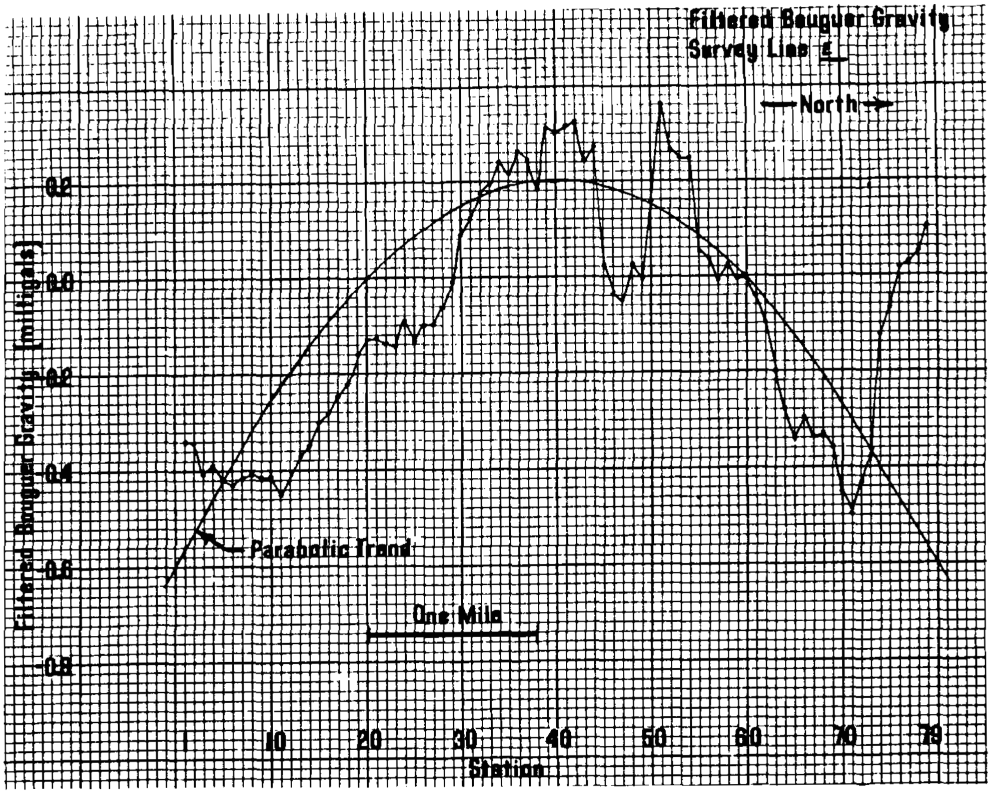
Figure 2.1-2. Simple Bouguer gravity profiles for the main site survey


Filtered Bouguer Gravity
Survey Line c
North
Parabolic Trend
One Mile
Station
Filtered Bouguer Gravity (milligals)

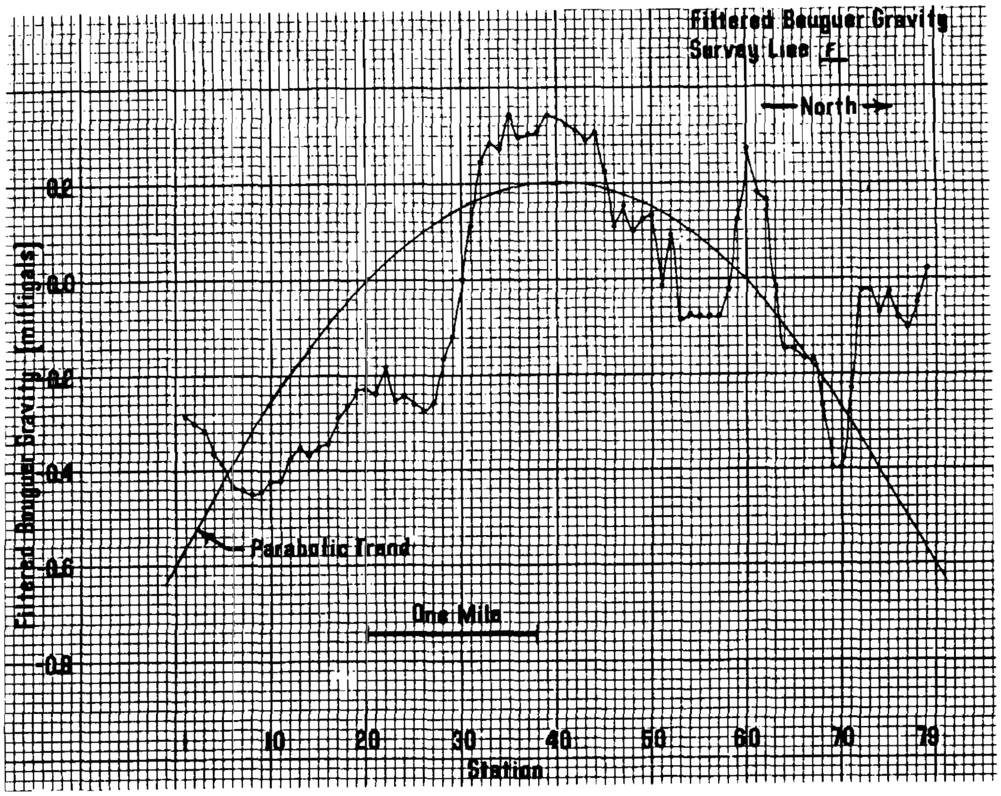
(c)


Filtered Bouguer Gravity
Survey Line d
North
Parabolic Trend
One Mile
Station
Filtered Bouguer Gravity (milligals)

(d)

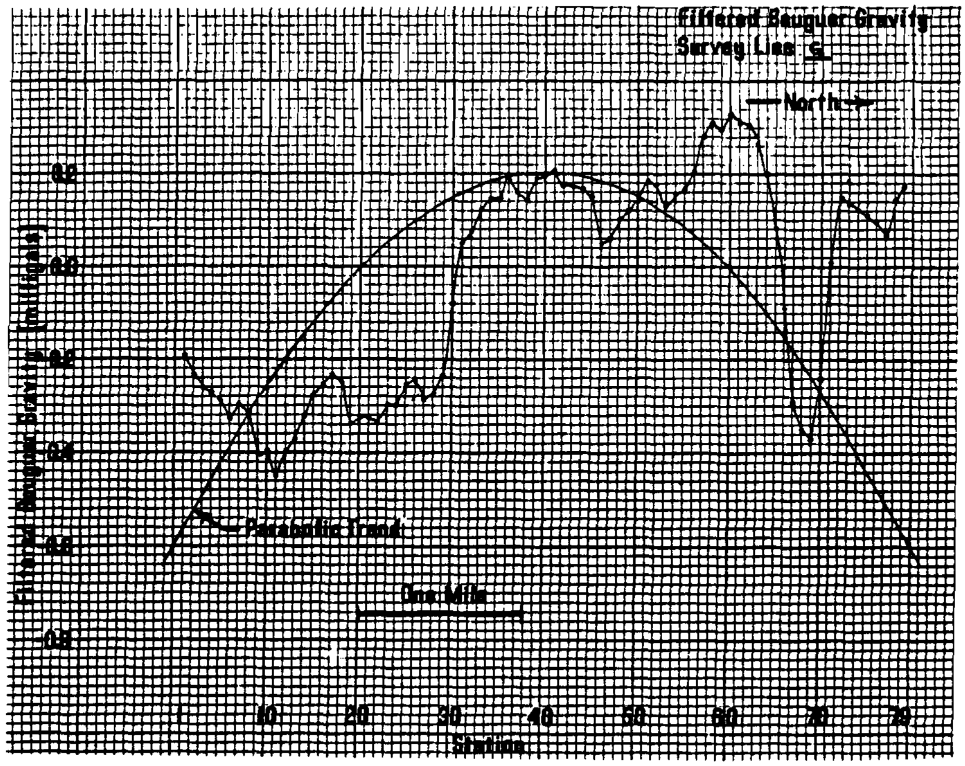


(e)

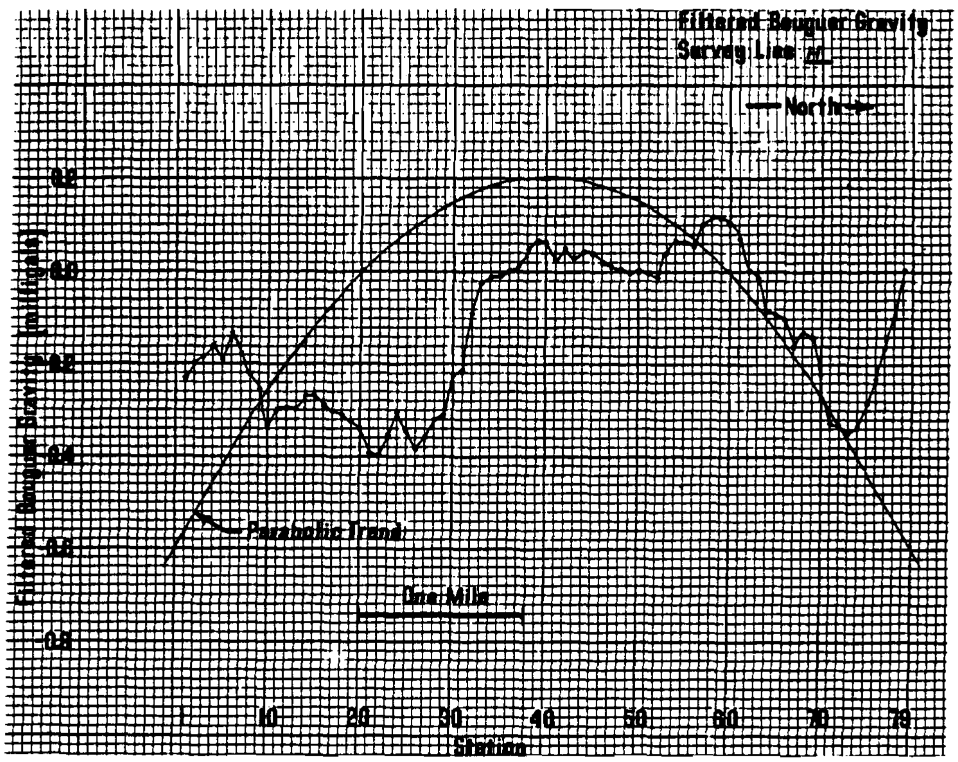


(f)

Figure 2.1-2. (Cont)

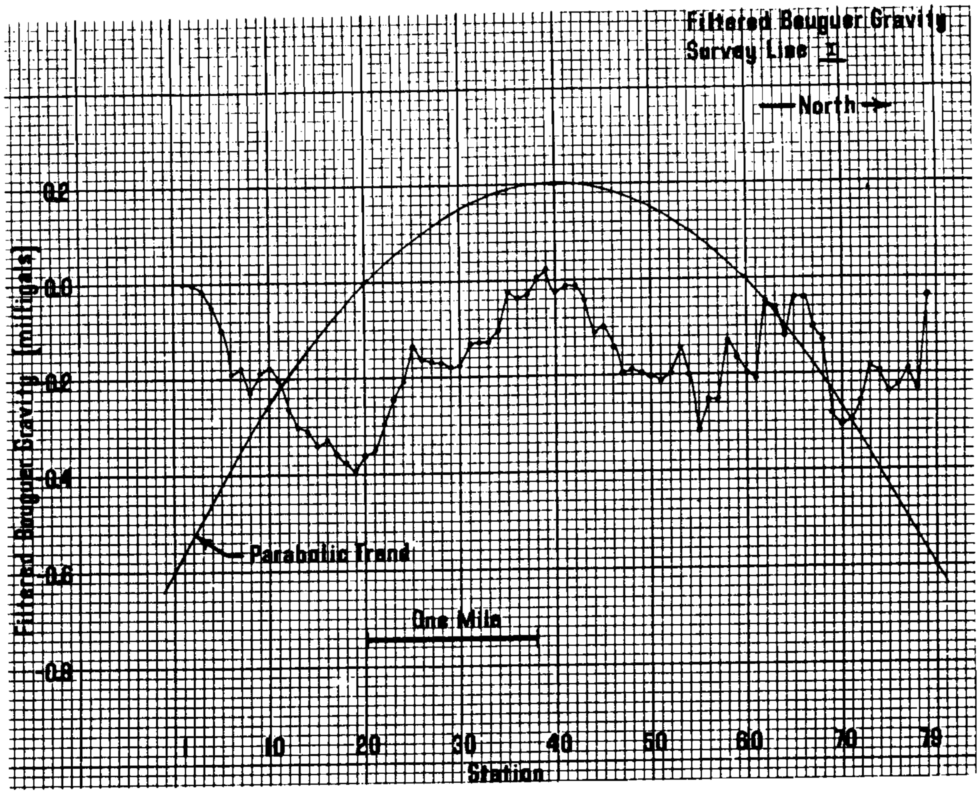


(g)

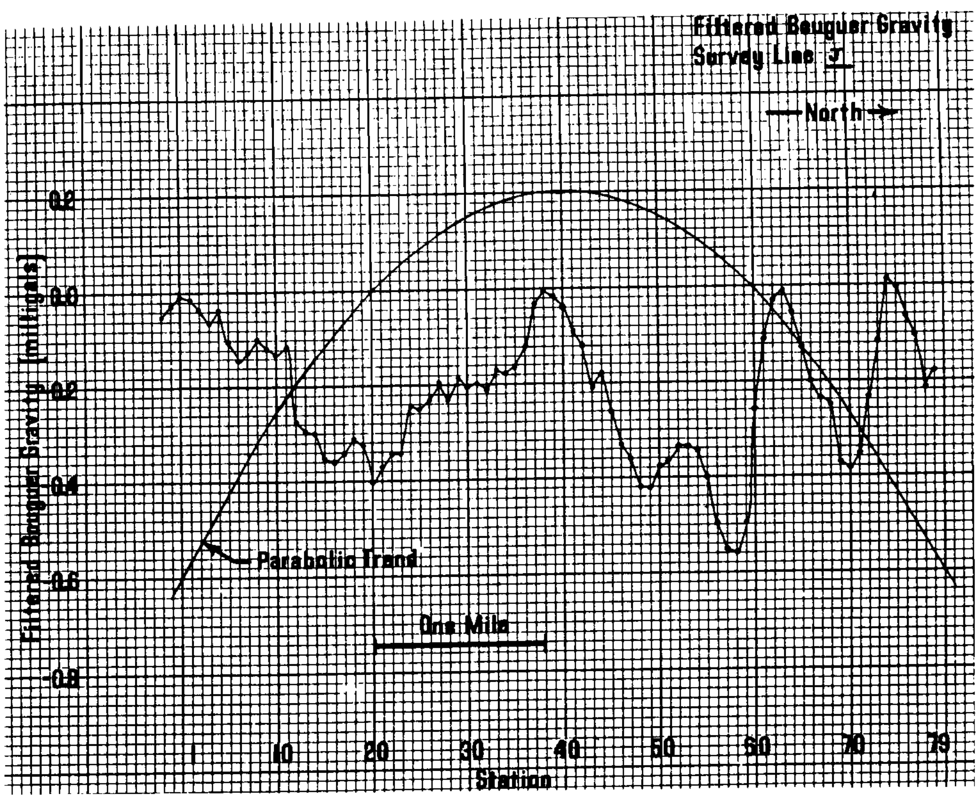


(h)

Figure 2.1-2. (Cont)

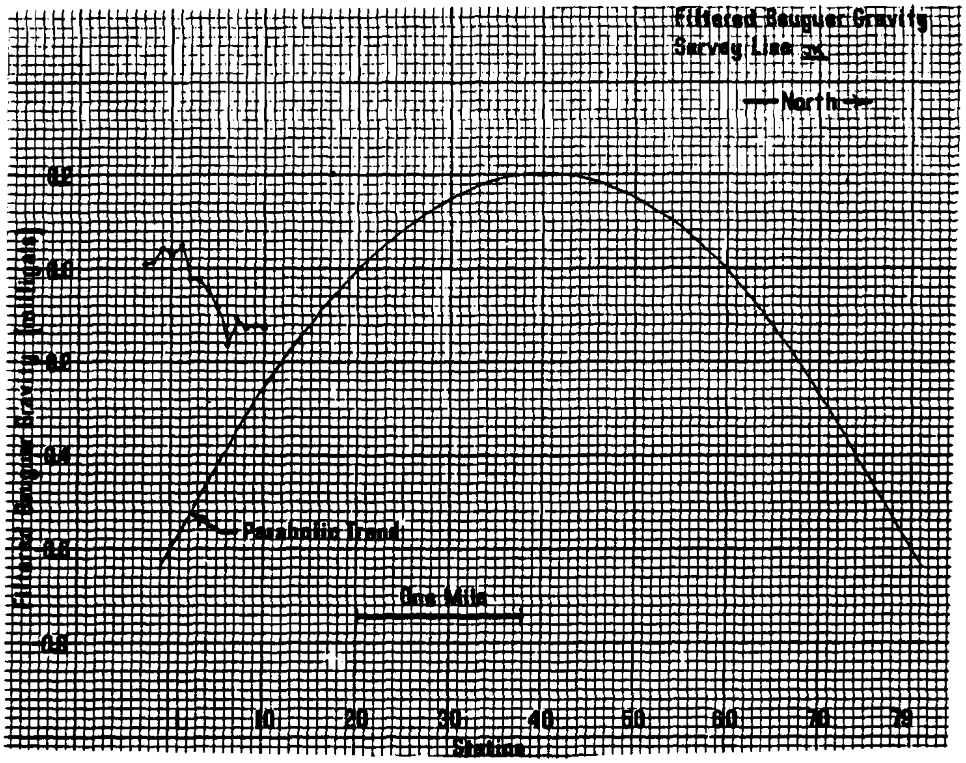


(i)

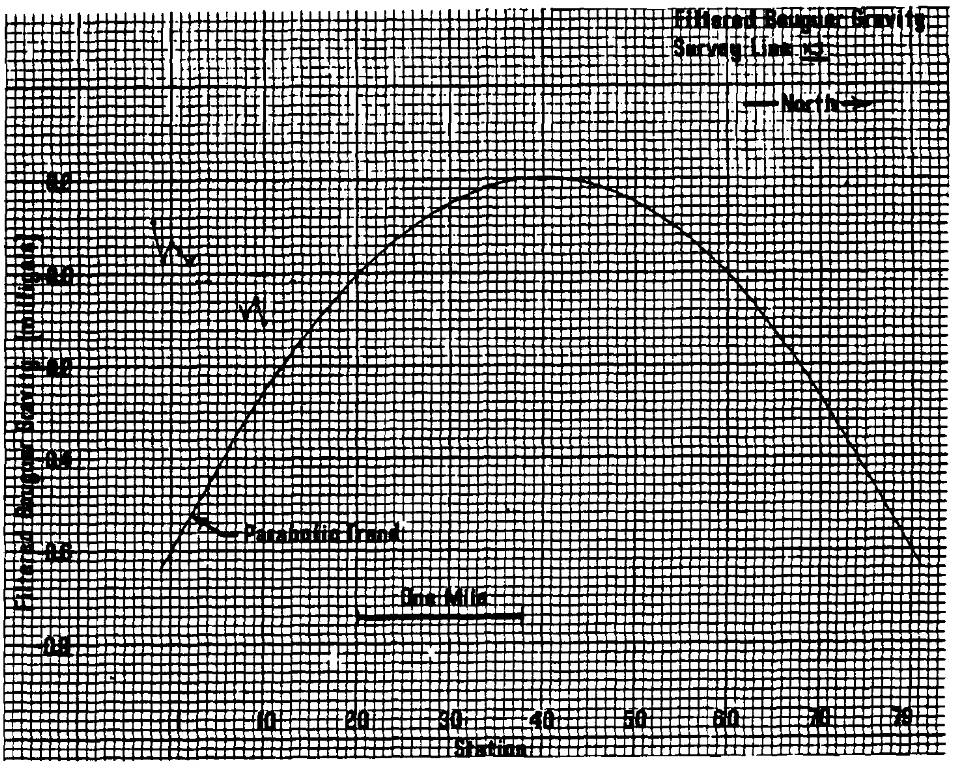


(j)

Figure 2.1-2. (Cont)

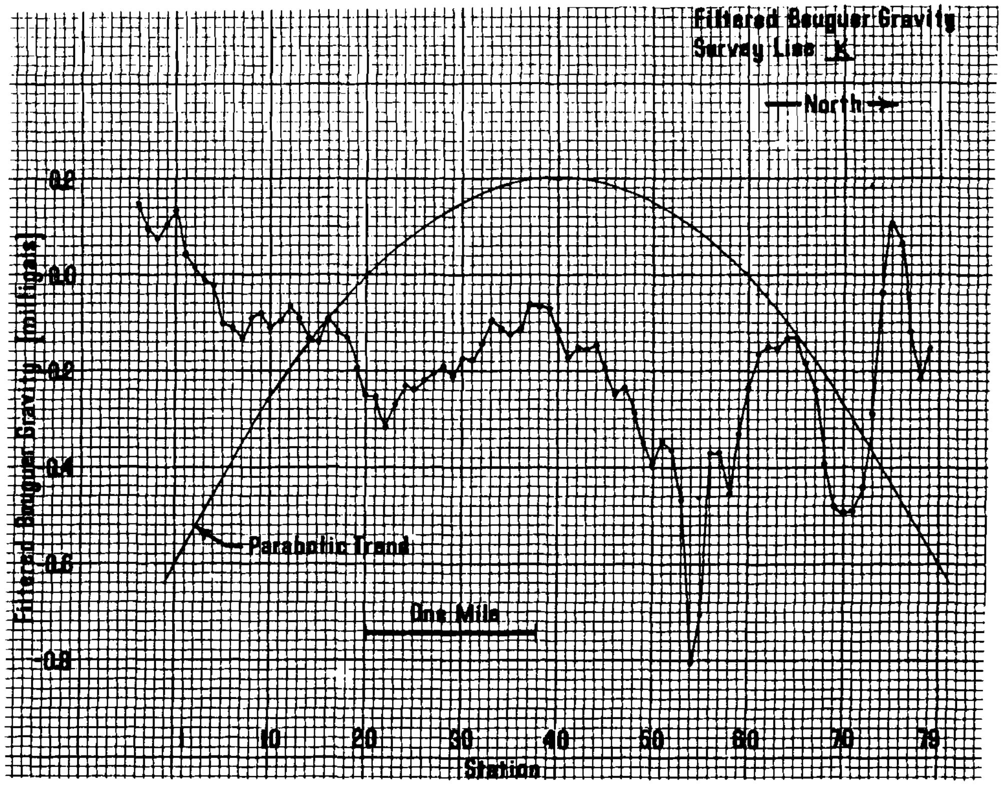


(k)

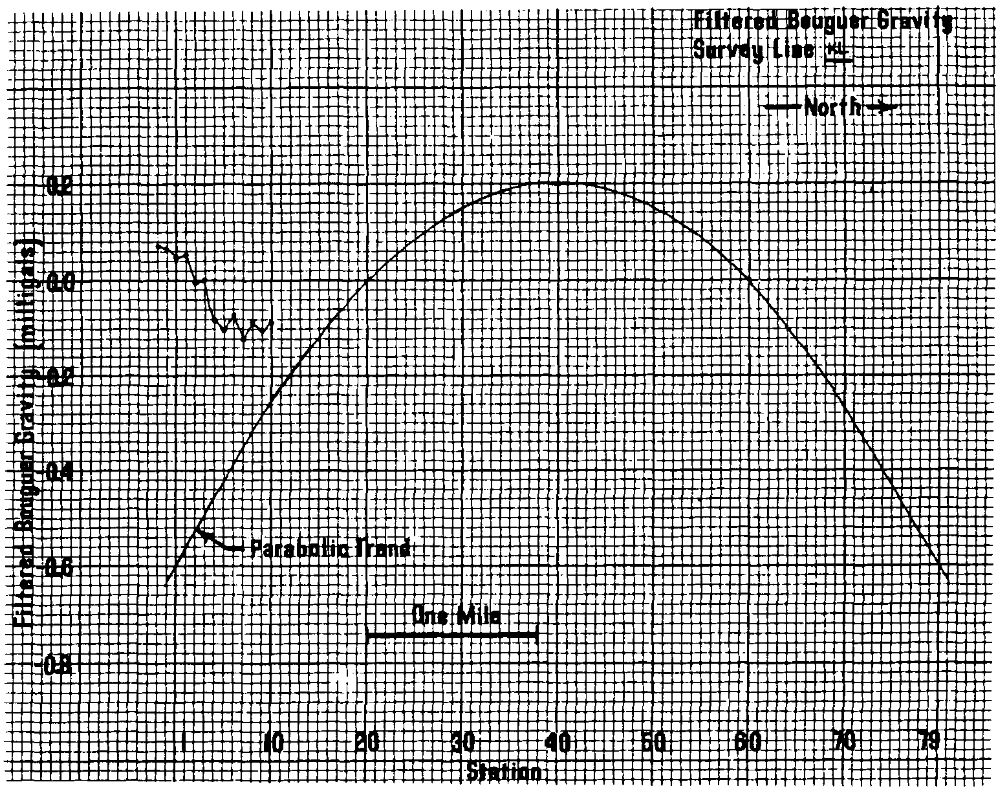


(l)

Figure 2.1-2. (Cont)

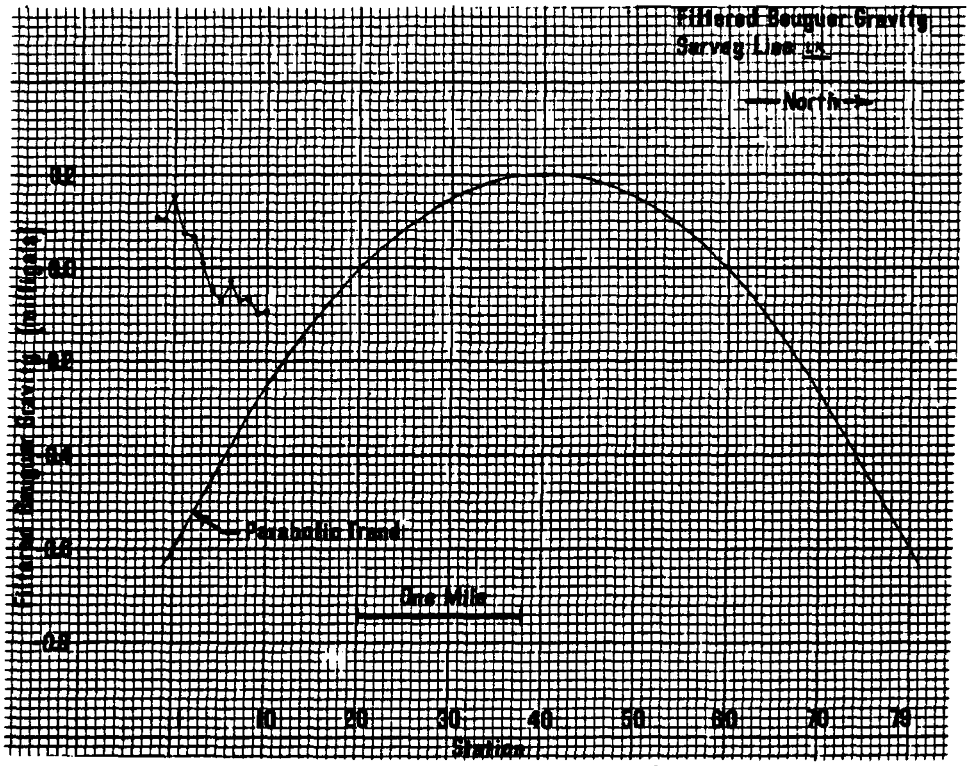


(m)

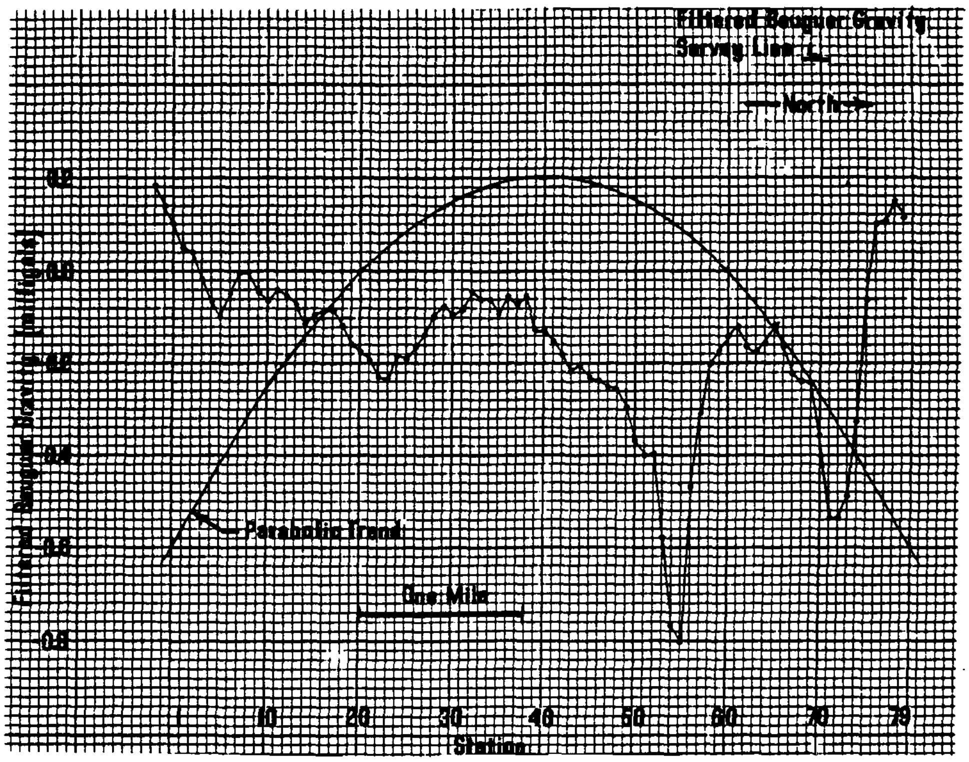


(n)

Figure 2.1-2. (Cont)

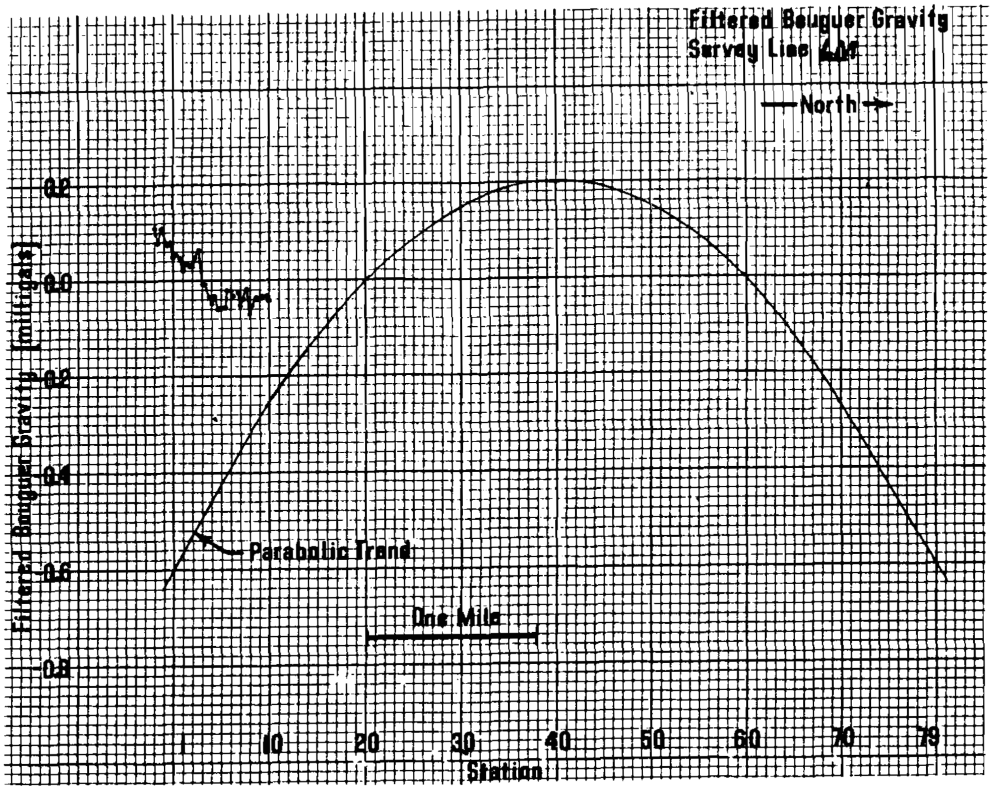


(o)

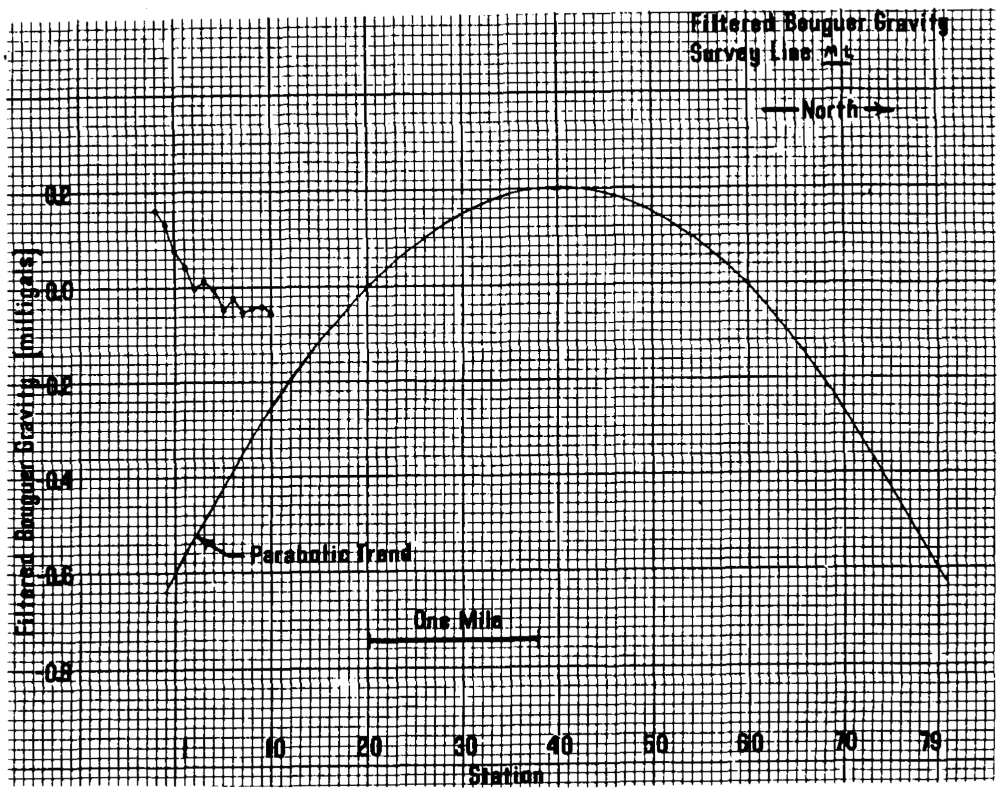


(p)

Figure 2.1-2. (Cont)

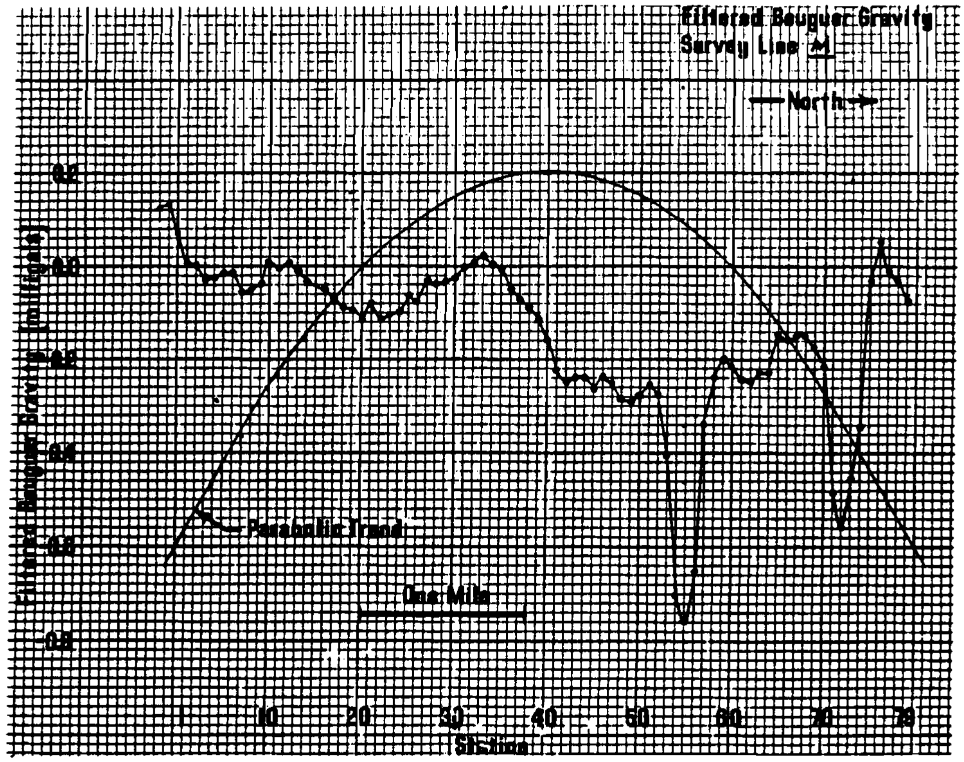


(q)

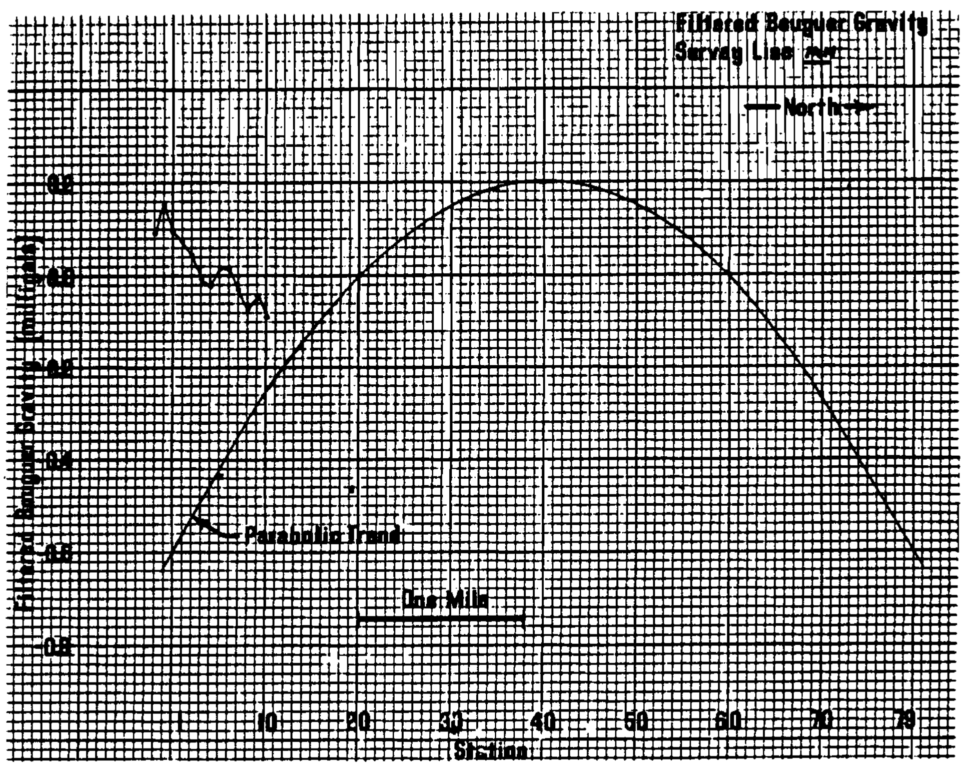


(r)

Figure 2.1-2. (Cont)

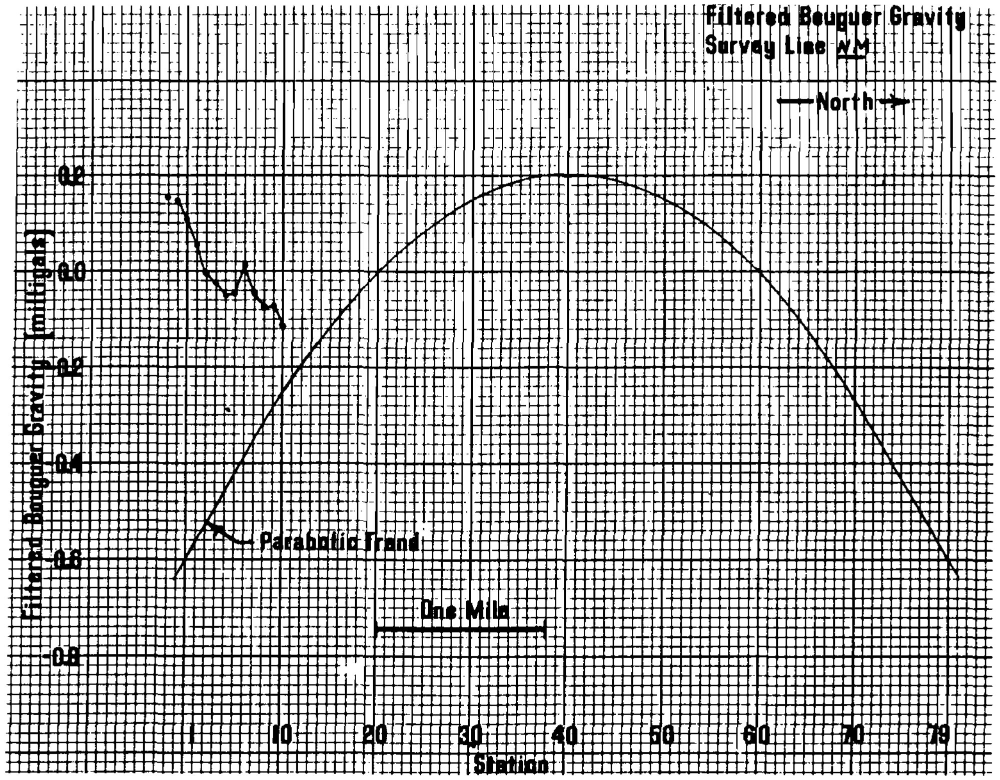


(s)

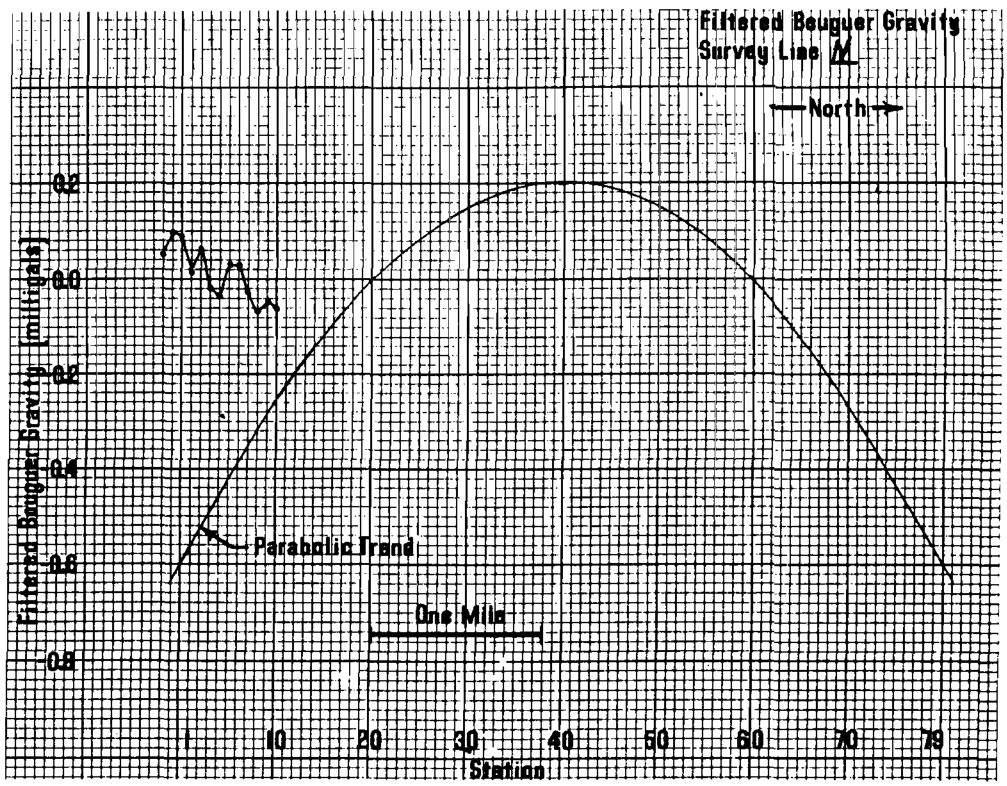


(t)

Figure 2.1-2. (Cont)

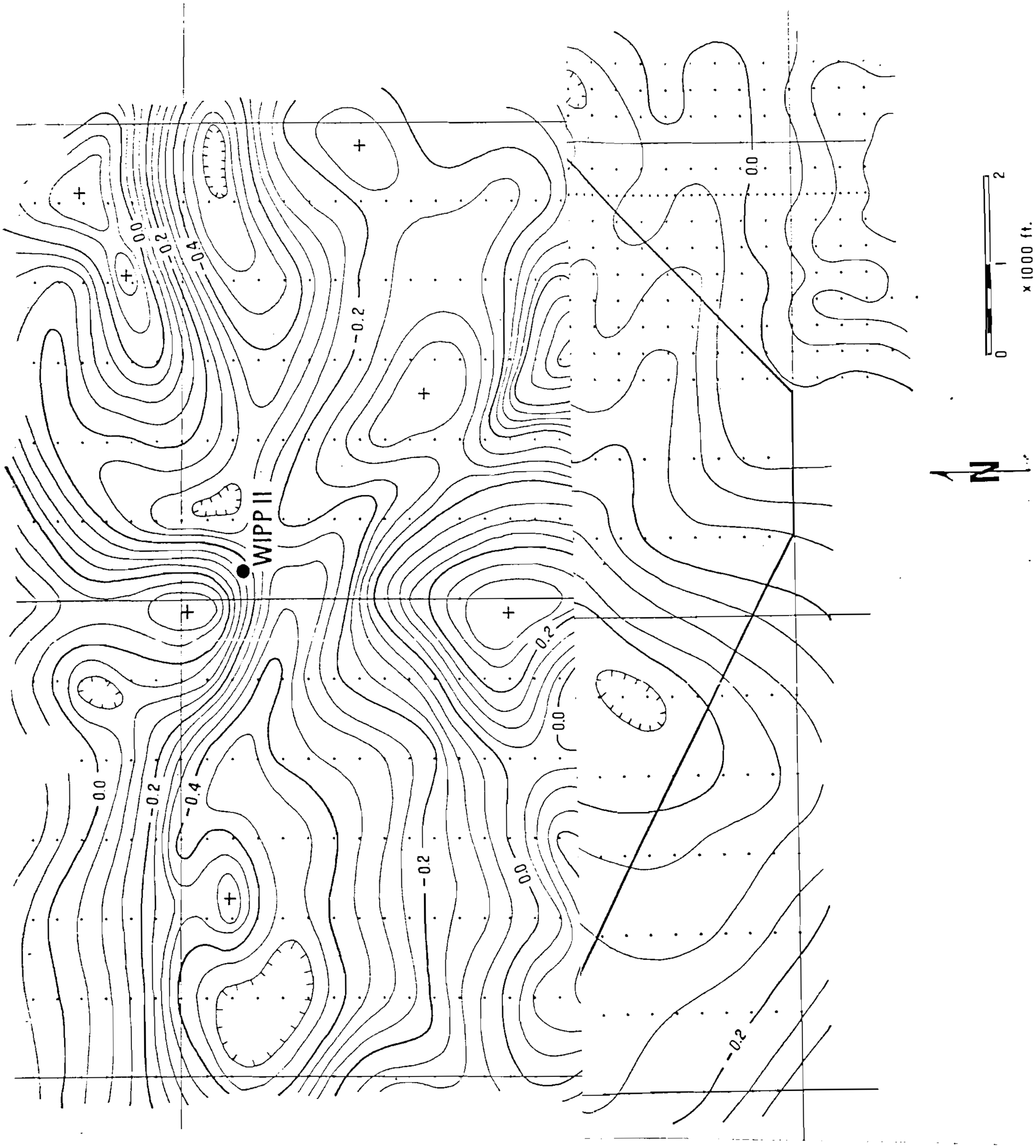


(u)



(v)

Figure 2.1-2. (Concluded)



Simple Bouguer Gravity
Less Linear Regional & Parabolic Trend
Slab Density 2.3 g/c³
0.05-Milligal Contour Interval
Contours Within ±0.025 mg

4. Simple Bouguer gravity—main site survey (generalized)