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**EVALUATION AND COMBINED GEOPHYSICAL INTERPRETATIONS
OF NURE AND RELATED GEOSCIENCE DATA IN THE VAN HORN
PECOS, MARFA, FORT STOCKTON, PRESIDIO, AND EMORY PEAK
QUADRANGLES, TEXAS**

**FINAL REPORT
VOLUME 1**

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September, 1981

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FINAL REPORT

VOLUME I

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EXECUTIVE SUMMARY

This report is the culmination of a two-year study of the six Trans-Pecos Texas quadrangles (Van Horn, Pecos, Marfa, Fort Stockton, Presidio, and Emory Peak) surveyed as part of the National Uranium Resource Evaluation (NURE) program. For a detailed discussion of these surveys, see reports GJBX-2(77) and GJBX-88(79) which were prepared for the U.S. Department of Energy.

This study had two general goals:

- I. Prepare a geological interpretation of geophysical data in the six Trans-Pecos, Texas quads for the purpose of delineating structural controls on the distribution of uranium and thorium resources.
- II. Evaluate and illustrate the use of NURE aeromagnetic and aerial radiometric surveys.

This report consists of two volumes. The first volume contains a discussion of the aeromagnetic, gravity and geochemical data, their processing, and their analysis. The geologic history and setting of the Trans-Pecos are discussed along with the uranium potential of the region. Uranium anomalies and occurrences characteristic of numerous different NURE classes are present in the study area, and information is presented on 33 drill holes into these targets.

Volume II is a folio of maps reduced to a scale of 1:500,000. Geologic maps for each of the six quadrangles are included and the geophysical maps have been prepared to be overlays for the geologic maps. In addition to the geologic maps, residual aeromagnetic anomaly, complete Bouguer gravity anomaly, flight line index, gravity station index, and anomaly interpretive maps were prepared for each quadrangle. A large suite of digitally-processed maps of gravity and aeromagnetic data were prepared and are included in Volume I.

The west Texas region under consideration consists of the Basin and Range to the west and the Great Plains to the east. These two physiographic

provinces exhibit a great deal of geologic complexity, although the surface geology in the Great Plains is more straightforward than in the western section. Proterozoic basement directly underlies most of the region and extensive Paleozoic and Mesozoic shelf and basinal sediments are present. The Ouachita tectonic belt, of Appalachian origin, underlies the southeastern portion of the area. The Chihuahuan Trough, of Paleozoic-Mesozoic age, was thrust eastward during the Laramide Orogeny, overthrusting certain areas in the westernmost part of west Texas. The Basin and Range Province developed in the Cenozoic, with widespread igneous activity and high-angle faulting. It is thought to have originated from a compressional environment changing to a tensional one. The Rio Grande Rift lies in or near the westernmost portion of this west Texas area.

Numerous NURE Class uranium targets are present in west Texas. The Proterozoic unconformity deposit type (NURE Class 710) is a valid target in the Van Horn area and has been the topic of a separate NURE report. This class contains the greatest uranium reserves on a world-wide basis. The potential for this deposit type in the Van Horn area has been only partially evaluated; a second Proterozoic unconformity exists beneath that investigated by NURE. Subsurface extensions of these unconformities may be present throughout a large portion of the Van Horn Quadrangle.

Sandstone-type uranium environments (Class 240) currently have a low potential in the region. These environments are present in the subsurface, such as the Dockum in the Great Plains and the Cox Sandstone in the Chihuahuan Trough. However, occurrences and anomalies at surface exposures of these units are limited. The Cox sandstone does contain anomalous uranium in the Quitman Mountains and red-bed copper deposits are present just to the west in Mexico. Other sandstone units are present as potential hosts for such deposits.

Several other sedimentary environments are represented as uranium anomalies (radiometric) or occurrences. Marine black shale (Class 130) with an unusually high gamma count is used as a subsurface stratigraphic marker in petroleum exploration in the Great Plains region of west Texas, but it does not have resource potential. A similar environment (Class 210) exists as the highest grade zone at the Anderson Ranch deposit, Brewster County.

Data from 18 drill holes presented here show the black shales to lie within uranium-enriched fresh-water carbonates within 35-38 m.y. volcanoclastics. The deposit is sub-economic, but other such occurrences may have some uranium potential along the trend.

Uraniferous lignite-type (Class 210) deposits have a moderate potential in limited areas, most notably in the Sierra Vieja where the Mammoth Mine uranium deposit lies adjacent to the San Carlos coal member of Cretaceous age. Other ages in the Basin and Range section contain uranium source areas adjacent to carbonaceous accumulations. Evaporative precipitates (Class 220) of the playa lake variety yield low-grade, airborne radiometric anomalies throughout the Basin and Range section of the area under study, and these anomalies do correlate with documented uranium source areas. Similarly, Class 230 occurrences are widely dispersed throughout the area but, like the Class 220 occurrences, these uraniumiferous limestones are indicative more of uranium mobility than suggestive of uranium resources. Localities of this type are in the Hueco Mountains, Camey, Stillwell Mountains, Terlingua, and just west of Presidio, in Mexico.

A significant contribution of this study is the identification and documentation of a Bokan Mountain type of uranium environment in west Texas. This type, including Classes 310, 320 and possibly 350, is now identified in the Precambrian rocks of the Franklin Mountains, El Paso County. A portion of it has been tested by two drill holes. Geologic and geochemical studies reveal the upper portion of a Bokan Mountain magmatic system. Uranium resource potential, by analogy, is good. A portion of far west Texas is underlain by basement of this type.

Alakalic, silica-poor intrusive rocks throughout the Basin and Range section of west Texas are frequently enriched in uranium, most often as a dissemination throughout the rock. Pegmatitic stages of these intrusives frequently give rise to small, higher grade concentrations. The Cenozoic intrusions of the Diablo Plateau give rise to numerous airborne radiometric and lithochemical anomalies and these rocks, in turn, give rise to displaced anomalies in the sediments and adjacent playa lakes. A pegmatitic example has been discovered in the southern end of the ring dike of the

Quitman Mountains caldera. Many of the syenitic intrusions lying in a southeast-trending belt across the entire region are enriched uranium, as at Black Mountain, and secondary anomalies are found around them. This uranium environment is not, however, generally associated with economic concentrations of the element. The positive response given by these intrusives in many uranium surveys is misleading to the explorationist and they might better be filtered out of regional studies. This geologic environment, which is anomalous on multimethod surveys, for good reason does not have a classification available in the NURE uranium environments. They generally have a characteristic geophysical signature.

The most significant uranium potential of the west Texas region appears to be associated with the numerous Cenozoic calderas and their associated volcanoclastic products. Specific calderas may be more uraniferous than others, although this question was not addressed in the present work. Within calderas, specific events are important for eventual uranium deposition. In the Basin and Range section of west Texas there are a large number of airborne and ground anomalies and numerous uranium occurrences in felsic intrusives, volcanics and volcanoclastics. Several calderas in the northern and central regions of the caldera belt have uranium occurrences. Data from the drilling of 11 exploration holes into one such environment, the Shely Prospect, are reported here. This occurrence is one of the most noted in the west Texas region and significant uranium potential exists in the northern Chinati Mountains and adjoining regions. The Mammoth Mine, another noted west Texas uranium occurrence, is just to the north in outflow facies. Igneous units in the Quitman, Chinati, Davis, and Christmas Mountains, and the Solitario, have anomalous uranium. These sometimes exhibit clear airborne radiometric signatures, such as the Sierra Blanca laccoliths in the Van Horn Quadrangle, but more often they crop out over too small an area and/or are too faulted to give a consistent airborne response. The calderas often do have, however, a characteristic geophysical response.

The various uranium environments found in and around calderas pertain to the volcanogenic uranium Classes 510, 520, 530, and 540. The numerous environments of these types have been the target of intense uranium explora-

tion during the late 1970's and several drilling projects were carried out in addition to those presented here. Uranium exploration in caldera environments has been stimulated by significant uranium discoveries in ignimbrites at Pena Blanca, Chihuahua, Mexico's largest deposit. The site of these deposits is directly west across the Chihuahua Trough from the Presidio area, which has been an additional stimulation to the west Texas uranium exploration. Selected aspects of the geology of that area are included in this report.

The west Texas region has a considerable uranium potential, and the present work constitutes a contribution to the understanding of the distribution of uranium in the region. Documentation contained herein varies from the regional to the specific, and 11 localities are treated with considerable geologic detail.

The utility of the NURE aeromagnetic was easily demonstrated during this study. Its major limitation was in areas of volcanic cover where the 3 mile flight line spacing was too great to delineate all of the high-frequency anomalies present. Qualitative agreement with maps from other sources was excellent and, in fact, almost exact on the Pecos quadrangle where the magnetic basement was deeply buried. Moderate upward continuation (≤ 10 km) seemed best for large scale interpretations of the major tectonic blocks present. Processed maps, basement depth determinations, and computer modeling of the aeromagnetic data correlated well with independent geologic control and made it possible to better define the nature and extent of several structural units.

Gravity data were compiled and collected to produce gravity maps for each of the six quadrangles. The gravity data were used in various integrated studies which also employed the aeromagnetic, aerial radiometric and geologic data. Of particular interest were analytical correlations (internal correspondence, and local favorability) between the gravity and aeromagnetic data.

INTRODUCTION

Statement of Objectives

This report is the culmination of a two-year study of the six Trans-Pecos, Texas (Fig. 1) quadrangles (Van Horn, Pecos, Marfa, Fort Stockton, Presidio, and Emory Peak) surveyed as part of the National Uranium Resource Evaluation (NURE) program. For a detailed discussion of these surveys, see reports GJBX-2(77) and GJBX-88(79) which were prepared for the U.S. Department of Energy.

This study had two general goals:

- I. Prepare a geological interpretation of geophysical data in the six Trans-Pecos, Texas quads for the purpose of delineating controls on the distribution of uranium and thorium resources.
- II. Evaluate and illustrate the use of NURE aeromagnetic and aerial radiometric surveys.

During this study, a vast quantity and variety of information and data have been collected, and a wide ranging series of investigations have been undertaken. This data base is of enormous value to the industrial and scientific communities, and the discussions which follow represent only an initial analysis of these data. Considering constraints, time, resources, and breadth of the program, the investigators emphasized demonstrating the utility of the NURE data, archival and documentation of basic data, and regional resource and geological analyses. The utility of the NURE data was evident early in the study, and the regional analyses provided an excellent vehicle to showcase these data via papers given at professional meetings and published articles.

Several more detailed geological and geophysical investigations have been conducted. These studies are reported in a series of independent discussions in this report. This was necessitated by the broad range of topics addressed in this study.

Figure 1. Quadrangle Index

Geological Overview

The first tectonic activity which can be documented in Trans-Pecos Texas is in the Van Horn area (Fig. 2) where rocks of the older Carrizo Mountain group were deformed and thrust over younger rocks to the north (King and Flawn, 1953; Davidson et al., 1980). There is only a small area of Precambrian exposure, and the variety of rocks encountered in wells drilled into the Precambrian basement (Dennison and Hetherington, 1969) suggests a complicated early history for the region. A major continental break-up at the close of the Precambrian affected the area (Keller and Cebull, 1973) and led to the development of an aulacogen in the Delaware Basin-Central platform area (Walper, 1977; Shurbet and Cebull, 1980; Keller et al., 1980). The early Paleozoic was dominated by the formation of the Tabosa basin (Galley, 1958) which was associated with this aulacogen and the late Paleozoic was dominated by the formation of the Ouachita system (Flawn et al., 1961).

The major activity in the Marathon segment of the Ouachita system began in the late Mississippian and culminated in the early Permian (e.g., King, 1978). Although the relationships are not completely clear, the fundamental mechanism for the origin of the Marfa basin (Fig. 3) and the uplift and deformation of the Central Basin platform (Fig. 3) is probably related to the Ouachita system.

The early Mesozoic was a time of major deposition in the Chihuahua trough (DeFord, 1969) (Fig. 3) which was followed by a major marine transgression in the Cretaceous (DeFord and Haenggi, 1971). Laramide thrusting deformed the Chihuahua trough to form the Chihuahua tectonic belt which extends into Trans-Pecos Texas (Gries and Haenggi, 1971; Reaser and Underwood, 1980). The subsurface extent of this thrusting has been of particular interest recently because of its petroleum potential.

The Cenozoic was marked by widespread volcanic activity and block faulting. The voluminous volcanics and eruption of alkalic intrusion (38 to 30 m.y. ago) was the result of subduction along the Pacific coast (Barker, 1980). These eruptions formed several calderas (Barker, 1980) which are of great interest to the mineral industry. Volcanism terminated 16 m.y. B.P. (McDowell, 1979). Radiometric dating of dikes along the Sierra Vieja suggests that normal faulting began about 20 m.y. ago (Dasch et al., 1969). This faulting preserved significant volumes of older rocks in areas such as

Figure 2. Physiographic and cultural index

Figure 3 Tectonic Index

the Salt Flat graben (Veldhuis and Keller, 1980) and Presidio Bolson (Mraz and Keller, 1980). The extension of the Rio Grande rift into the area remains an open question (Seager and Morgan, 1979), but recent fault scarps (Goetz, 1980), elevated heat flow values (Taylor and Roy, 1980), and the Valentine earthquake of 1931 (Dumas et al., 1980) attest to continued tectonic activity.

Uranium Occurrences

Uranium as an exploration target in west Texas received minor attention during the intense exploration activity of the mid-1950's. In the late 1970's it has again been the subject of exploration interest, and several of the uranium targets have been more seriously studied. Drilling has now taken place in several of the areas, but most exploration has ceased at the time of this writing. No commercial deposits have been located, partly because of the limited time and effort which was spent on exploration and also partly due to the decline in price of uranium.

Most reported occurrences of uranium are simply radiometric anomalies. In a few instances, actual uranium minerals have been identified, but these singular occurrences do not represent a resource potential. The present summary will briefly outline the known uranium occurrences. Those occurrences discussed more thoroughly in the site-specific section of the report are indicated by an asterisk. Radiometric anomalies recognized during the NURE Program will be discussed separately.

Eargle (1956) mentions two localities with minor carnotite in limestone. One is on the western side of the Hueco Mountains, and the other is in the far eastern part of the study area under consideration at King Mountain. Both of these areas have been visited as part of the present study, but they hold no potential for significant reserves. Several informal reports exist which were made by U.S.G.S. personnel, but these are generally not of great value.

Reeves et al. (1978) have written the most comprehensive guide to uranium anomalies of the west Texas area. The 11 areas designated by them are shown in Figure 4, along with several new significant uranium occurrences.

Mount Livermore Anomaly: This anomaly is a radiometric response only, and no uranium minerals have been found. The anomaly is strongest over the Barrel Springs and Wild Cherry formations. Although Reeves et al. (1978) do

Figure 4. Uranium anomaly locations

not consider this area significant, the present authors feel that the area might have undergone uranium leaching, migration, and deposition around the late rhyolite flow domes. Geothermal systems initiated by the intrusions could have enhanced the mineralizing process.

The Capote Graben Anomaly: This is a linear anomaly found west of Marfa. It may result from the presence of uraniferous volcanoclastics at depth, with the uranium leached from the surrounding volcanics and moved to the basins.

Quebec Siding Anomaly: This is essentially a surface radiometric anomaly with a minor show of Astragalus sp. to denote it at the surface. Small calcrete occurrences are also present.

Bofecillos Anomalies: No uranium minerals are known with these anomalies. The anomalies are thought to occur from uranium in vitric ash-flow tuff.

***Shely Ranch Anomaly:** This area boasts one of the more significant anomalies in the area. Autunite, metatorbernite and tyuyamunite occur in clay-filled fractures in rhyolite adjacent to the Organ Pipe, a large rhyolite flow dome. The mineralized fracture has been followed to depth by drilling. Indeed, some 25 drill holes were recently completed, and the area does seem to contain a low-grade deposit around the neck of a rhyolite flow dome. The area will be discussed in detail in the text.

***Mammoth-McSpaden Prospects:** These occurrences are among the best known in west Texas. They have received recent attention by Chevron Resources. Uranium minerals occur in lithophysae cavities.

Fizzle Flat Anomalies: Minor uranium is present in basal clastics and near faults.

Nevill Ranch: This anomaly is strictly a radiometric disturbance for which we can find no direct mineralization. It is probably derived from an occurrence like that at the Anderson Ranch (type I through M).

***Anderson Ranch:** Lacustrine limestones and diagenetically altered zeolites, with high organic content, provide the host for this potentially sig-

nificant uranium resource. Eighteen holes have been drilled into this deposit, and interpretation of data obtained from this drilling is presented in this report.

Stillwell Mountain: Carnotite occurs in fractures in limestone at several places around Stillwell Mountain. The area was drilled by Wyoming Minerals but no results are available.

Black Mountain Anomaly: The Black Mountain syenite contains an unusually high background of radioactive material. The anomaly is limited to the outcrop of syenite and drilling has failed to find zones of enrichment within the syenite. At places the contact of the syenite with the host limestones is extensively altered. The area does not present a clear target for the development of uranium resources.

In addition to the several uranium anomalies mentioned above, numerous others exist which were identified by the NURE program. The only one worth mentioning at this point is the Sierra Blanca laccoliths. These shallow intrusions are probably genetically related to the larger Quitman Mountain intrusive masses. They have been readily identified by airborne radiometrics and a detailed ground truth survey has been conducted.

Very notable in the present work is the recognition of a Bokan Mountain type of uranium environment in the Franklin Mountains, El Paso. As this is a new discovery, it is discussed extensively.

Within the limits of the present discussion of uranium occurrences in west Texas, information presented here includes the study of approximately 40 drill holes made into several of the uranium occurrences. Not all drill-holes have been studied in detail, but representative ones from each locality have been studied in detail and samples submitted for trace element analysis at DOE-GJO. Samples representing approximately 10,000 ft of drilling have been available to the present work. The irreplaceable nature of these samples along with the fact that they were from significant uranium occurrences has guided the nature of our scientific activity. We considered it important to study carefully these drill sites and then to integrate them into a geological framework of all West Texas. The availability of these drill samples was not predicted during the writing of the initial proposal and work statement.

DATA ACQUISITION AND REDUCTION

General Considerations

The discussion which follows emphasizes the aeromagnetic data because the gravity and gamma ray spectrometry data were handled according to well established procedures and because aerial radiometric data were analyzed directly from the maps prepared as part of the contractor's reports for the individual quads. The aeromagnetic data discussion is abstracted from a separate report prepared by E. P. Tinnell and W. J. Hinze as part of their work with the Oak Ridge National Laboratory.

Gravity Data

Field work was concentrated in areas where existing gravity data coverage was sparse, and over 1000 gravity readings were taken. These readings were tied into either a primary Department of Defense base station of the International Gravity Standardization Net, 1971 (Morelli, 1976), or a secondary base station with a gravity value determined relative to a primary base.

A base station was occupied at the beginning and end of each gravity traverse to correct for the instrument drift and earth tides. This correction averaged approximately 0.1 mgal for individual traverses. Elapsed time from initial occupation of a base station was noted along with gravity meter reading, elevation and station identification for each station occupied.

Gravity stations were established at bench marks, road crossings, fence lines and section posts where horizontal positions and elevations were determined on U.S.G.S. 7.5 or 15 minute quadrangle maps. Each station was plotted on a U.S.G.S. quadrangle map and the latitude and longitude was determined with the use of a CALMA digitizer. The new 1:50,000 series of maps was employed in Mexico.

In addition to gravity data taken in the field, relative gravity values supplied by various industrial sources were tied to the base stations, re-plotted, and digitized. These data were merged with a master file containing gravity data compiled from the Department of Defense gravity library, Mr. Hart Brown, Texas Tech University, Rice University, Covert (1976), and

Wiley (1970). Although a detailed discussion is not appropriate, the compilation, quality control, and management of this file of over 20,000 gravity measurements was a major task.

Outer zone terrain corrections were calculated for zones extending from 0.89 km to 167 km away from each station (Hammer, 1939). These calculations employed a U.S.G.S. data set of averaged elevations on a grid interval of 30" of latitude and longitude and a terrain correction program written by Plouff (1977).

All gravity data were reduced to the Bouguer anomaly values using the following formulas (Cordell et al., 1971):

$$BA = G_{OBS} - G_{TH} + C_{FA} + (C_{BOUG} + C_{TER} + C_{CURV}) \rho^1$$

where

BA = Bouguer anomaly

G_{OBS} = Observed gravity, in miligals, relative to the IGSN-71 gravity datum (Morelli, 1976).

G_{TH} = Theoretical gravity on the surface (sea level) of the 1967 reference spheroid
 $= 978031.843 + \sigma(15727.66 + \sigma(-15762.337 + \sigma(6083.534 + \sigma(-1089.748 + \sigma(69.43))))))$, $\sigma = 0.0001\theta^2$, θ = latitude in degrees (International Assoc. of Geodesy, 1967) (see Morelli, 1976)

C_{FA} = Free air correction for the elevation of station relative to sea level,
 $= h(0.30877 + \sigma(-0.0013398 + \sigma(0.0013553 + \sigma(-0.0005329 + \sigma(0.0000911)))) - h(0.072 \times 10^{-6}))$,
 h = elevation of station in meters

C_{BOUG} = Bouguer correction for rock mass positioned between station and sea level. Correction is calculated from the formula for the attraction of an infinite horizontal slab of thickness h and density to obtain the equation $C_{BOUG} = -0.119h$

C_{CURV} = Earth's curvature correction, another modification of the Bouguer slab approximation
 $= h(1.4639108 \times 10^{-3} + h(-3.532715 \times 10^{-7} + h(4.449648 \times 10^{14})))$.

C_{TER} = Terrain correction for the departure from a horizontal slab caused by topography (Hammer, 1939; Plouff, 1977).

ρ^1 = ratio of reduction density to standard reduction density of 2.67 gm/cc.

All gravity data were reduced to sea level, and a standard reduction density of 2.67 gm/cc was used for the Bouguer and terrain corrections. The

resulting data file was gridded at a 2 km interval using the minimum curvature technique (Briggs, 1974) and contoured to produce the complete Bouguer anomaly maps included in this report.

Aeromagnetic Data

General Procedures - Although the National Aerial Radiometric Reconnaissance Survey (ARRS) program is designed to optimize radiometric observations without consideration of magnetic observation problems, comparisons of selected magnetic anomaly maps prepared from NURE-ARRS program data with maps derived from surveys performed specifically for magnetic mapping indicate the NURE survey data are useful in mapping the regional magnetic anomaly field of the United States.

In general, the utility of magnetic maps is a function of flight line spacing, flight elevation relative to the depth of the magnetic sources, flight direction relative to the magnetic sources, flight direction relative to the magnetic grain, and temporal magnetic activity during data acquisition. Reasonably precise magnetic anomaly maps can be prepared from surveys observed along flight tracks perpendicular to the magnetic grain spaced at two or less times the vertical distance to the magnetic sources. With current NURE-ARRS survey specifications, this condition will be approached only in regions underlain by the deepest portions of sedimentary basins. Furthermore, the aerial survey program is performed regardless of temporal magnetic activity. Despite these recognized limitations, maps prepared from NURE-ARRS data are the best publicly available over many areas of the conterminous U.S. and Alaska and, furthermore, represent the only available digital magnetic anomaly data over much of the U.S. Recognizing the potential usefulness of the NURE-ARRS magnetic anomaly data, profile and contour maps and magnetic anomaly data sets are being prepared from aerial survey contractor supplied data sets by the Geographic Data Systems (GDS) Group, Computer Sciences Division, Union Carbide Corporation, Nuclear Division, at Oak Ridge, Tennessee, for the Department of Energy, NURE Program, Grand Junction, Colorado.

Several specific characteristics of the survey data and data reduction procedures, as well as time and financial limitations, have had an important role in defining and constraining the procedures for preparation of contour

maps and data sets. The large number of National Topographic Map Series (NTMS) quadrangles to be processed requires minimizing the manual efforts in the procedures. Therefore, the procedures for reduction and presentation of magnetic anomaly data are based upon maximizing the generality of the processing scheme and use of computers, particularly in machine plotting and contouring of anomaly data. Acceptable machine contouring of aeromagnetic data is commonly a difficult problem because of high data density along widely spaced flight paths. This is a particularly significant problem for the NURE-ARRS data because of the low flight elevation and wide track spacing predicated by the radiometric survey requirements and financial resources. This problem has been considerably reduced by the use of techniques for selective data filtering and critical observation retention. Another consideration in the development of the process to reduce and present the data is that the data supplied by the aerial survey contractors are already reduced. Thus, they commonly are corrected for temporal variations, instrumental noise and bias, and variations caused by long wavelength, core-derived magnetic fields. Though this has somewhat minimized the reduction problem, the procedures used for pre-1979 data vary widely among contractors and no attempt has been made to re-reduce the data in a consistent manner. The data quality limitations imposed upon the magnetic data by the different reduction procedures and the required survey parameters mandate that information be presented which will aid in evaluating the precision of the data. Thus, computerized "quality evaluation" (QE) procedures have been built into the processing scheme at several stages. The results aid in defining contouring parameters and are available as open-file reports from DOE, Grand Junction Office, to permit evaluation of the data in terms of potential users' specific requirements.

The general acquisition procedures for the airborne surveys of the Aerial Radiometric Reconnaissance Survey of the Department of Energy have remained essentially constant since the inception of the program in 1974. However, the magnetic acquisition and reduction procedures have evolved to extend the utility of the data by taking advantage of readily applied technological and scientific developments and to improve the consistency of the procedures used by the several geophysical contractors involved in the surveys. The modification of the magnetic acquisition procedures has always

been achieved within a data collection framework which maximizes the quality and utility of the radiometric data.

The basic project and reporting unit, with rare exceptions, are the NTMS 1:250,000 scale quadrangles or groups thereof. Flight tracks, with minor exceptions, are east-west at an average spacing of 7 km. However, depending on the geological conditions relative to potential uranium occurrences, track spacings of up to 10 km have been used in some quadrangles and detailed surveys with spacing of less than 2 km have been employed in others. The track spacing is generally kept constant within any one NTMS quadrangle, although in some cases, particular sections may receive more detailed treatment. Unlike those in the contiguous states, Alaskan surveys have all utilized a 10 km flight track spacing. Tie lines are flown normal to the primary traverses at approximately a 1:4 ratio with the survey tracks. The aircraft type used in the surveys varies, depending on the terrain, so as to best meet the survey specifications. Both fixed- and rotary-winged aircraft are employed. Observations are made at one (1) second intervals which translates to a median horizontal distance between samples of approximately 45-60 m. Although varying as a function of the air speed of the aircraft and the terrain conditions, the flight elevation is a nominal 125 m with a 60 to 250 m elevation envelope accepted.

Total intensity (scalar) magnetic field data are measured using either relative or absolute magnetometers with a sensitivity of one (1) gamma (nanotesla) or less. Observations made with relative measuring magnetometers necessarily result in data adjusted to an arbitrary datum. Whenever possible, the surveys are tied to the absolute datum with auxiliary absolute measurements. Since 1979, all magnetic systems are required to have, at the two standard deviation level, 0.25 gamma resolution and system noise limited to plus or minus one (1) gamma for fixed-winged aircraft and plus or minus two (2) gammas for rotary-winged aircraft installations. The installed observation system is compensated for heading error to within one (1) gamma. Since 1979, survey contractors have been required to provide total intensity magnetic observations at a sampling rate of four (4) seconds or less from a magnetic monitor operated at the local base of operation to record diurnal magnetic variations during flight periods.

Flight path recovery data at each observation point are converted to latitude-longitude and recorded to a ten-thousandth of a degree. Radar

altimeter measurements, flight-level barometric pressure, and outside air-temperature are sampled and digitally recorded. Survey contractors have been required, since 1979, to correct the total intensity magnetic data for heading error, diurnal variation using tie-line data, and the earth's core-derived (normal) field using the International Geomagnetic Reference Field (IGRF), 1975 updated to the month of the survey. Prior to 1979 a variety of core-derived fields and other reduction procedures was used by the contractors' necessitating review of the specifications for the particular survey to determine the exact reduction procedures that were employed. The reduced magnetic (anomaly) data, in profile form, are presented together with the ancillary data in the survey reports (see Benidix Field Engineering Corporation Report 1200-C dated 2/2/79). Reports prepared from surveys performed since 1979 have included a printer plot contour map of the total intensity magnetic anomaly data at a scale of 1:500,000.

Survey contractors are required to provide, on magnetic tape, several data sets pertaining to a given quadrangle. Most information used in the additional processing described later is obtained from the single record reduced data set with magnetic data file providing, when available, magnetic monitor and atmospheric pressure data. All data are not always available for every quadrangle.

Recognition of the Department of Energy's NURE-ARRS magnetic anomaly data as a valuable national resource has led to a program aimed at developing a procedure for the preparation of magnetic anomaly maps from the survey contractors' supplied data and the execution of this procedure for selected NTMS quadrangles. The priority ranking of quadrangles for preparation is based upon their potential usefulness in other NURE programs and upon needed coverage for national and regional maps in both the conterminous U.S. and Alaska where other magnetic anomaly maps are publicly unavailable.

The objective of this program is to develop a machine-oriented process for preparing profile and contour maps and related quality evaluation statistics of key quadrangles for the Department of Energy's NURE program and its contractors, federal and state agencies preparing national and regional maps, and the resource exploration industry. The maps being produced for each key quadrangle are: 1) a profile map of the contractor-supplied, reduced magnetic anomaly data using the flight tracks as an arbitrary, but constant level over a quadrangle; 2) a profile map of low-pass filtered

magnetic anomaly data with the contour levels of each profile marked and annotated on the flight tracks; 3) a similar profile map of selected critical point data; and 4) a contour map of the filtered and selected total intensity magnetic anomaly data at an appropriate contour interval. Also produced are related quality evaluation (QE) statistics. The filtering applied to the anomaly data is generally limited to a high-cut filter which rejects isolated spurious values caused primarily by instrumentation problems and cultural features. However, in some cases a more severe high-cut filter is used to eliminate local geologic anomalies which are uncorrelatable between adjacent track lines. These local anomalies produce aliasing because of the relatively large distance between flight lines with the result that machine-contouring is difficult and leads to erroneous results. The contour levels registered on the track lines of the profile may be used for hand-contouring as a substitute for or a check on machine-contouring.

The accuracy of the mapping process results is limited by the original quality of the survey design, acquisition, and data reduction. No general effort is made to re-reduce the contractors' supplied magnetic anomaly data to improve quality or achieve consistency. However, on a selected basis, minor modifications may be made to correct or delete obviously erroneous results and to normalize datum levels of adjacent quads. The map preparation scheme is organized to minimize human interaction, and, wherever possible, to generalize the methodology so that the procedure may be used in mapping other variables of the NURE-ARRS program.

The initial step in the processing scheme is to review the contractors' reports for specifications concerning acquisition and reduction of survey and base magnetic monitor observations. Each NTMS quadrangle report is carefully perused and a specification form is prepared for use in presenting and evaluating the magnetic data. This provides information such as the magnetometer sensitivity, the core-derived field removed, and the diurnal removal scheme. In general, the magnetic data have been subjected to a noise removal process and have been corrected for variations due to diurnal and core-derived fields. The resulting magnetic anomaly has simplified the reduction procedure implemented in the map preparation scheme.

Data used in preparation of maps and statistics are obtained from aerial survey contractors' supplied Single Record Reduced (SRR) and Magnetic Data (MD) tapes. The former is the source for navigational, radiometric,

and magnetic anomaly values while the latter, which is not always available supplies base magnetic monitor, barometric pressure and time-of-sample information. Bendix Field Engineering Corporation, DOE's prime subcontractor for the NURE program established specifications relating to the data content and format of these (and other) contractor-furnished tapes in 1979 (see BFEC 1200-C, 2/1/79). Before this time, data sets were supplied in formats changing not only from company to company, but also varying with time from a given surveyor. As a direct result of this format problem, it was decided early in the processing sequence planning stage that a routine should be made available to read these sundry formats and produce for later processing efficiency, a common standardized data arrangement.

The program mentioned above, known as CONVRT, consists of two job steps. The first (STEP1), consisting mostly of format-tailored input subroutines, determines such things as the data elements to be retained and the traverse types (flight- or tie-lines), and computes any conversions to common units and the various statistics to be reported. STEP2, receiving the output of STEP1, generates a report containing tabulations and rough frequency distributions and writes the standardized binary format, known as GDS (Geographic Data Systems) format. With but one exception, all other routines in the processing scheme read (and write) data in this format.

Because, as stated earlier, it is sometimes desirable to adjust data from a given quadrangle to the same level as that of a neighbor or to remove anomaly data which show no line-to-line correlation, a transformation generator, TRANS is provided. Although not used for every quadrangle, TRANS permits a range of numerical procedures to be performed over the entire quadrangle or for specified flight- or tie-lines only. In addition, the range of a variable may be constrained by clipping, the replacement of values over/under a given constant by that constant, or deletion, the removal of those points from the data set. One further ability, specified traverse removal, is provided for those few cases in which the data on a line contain uncorrectable errors.

In order to graphically present the magnetic anomaly or radiometric data a program to produce profile maps is applied to several of the data sets generated during the general production process. PROFIL accepts GDS format data and, under control of user options, plots a Transverse Mercator projection map of any variable with the flight tracks serving as constant

base levels for the profile curves. All production maps are plotted at a scale of 1:250 000 and cover the entire NTMS quadrangle. The profiling of anomaly data consistently utilizes a displacement scale of one inch equals 400 gammas (nanotelsas) based to the mean value (for that quadrangle) rounded to the nearest hundred gammas. Although not generally applied, such options as marking of data point locations, windowing to any latitude-longitude paired boundary, scaling to any desired linear ratio, and computation of automatic profile scale and base level are available for exceptional cases. Legends, titles, bar scales, and statistics are provided on the map in all cases.

As stated, several magnetic anomaly profiles are drawn, the first of which illustrates the original data. Showing the flight paths and related data curves, this map is quite useful in the determination of data collection and reporting problems, as well as providing the basis for filter design. The data curves are labeled with the associated path's numeric identities to aid in tracing complex oscillations. The other maps produced by PROFIL will be discussed in sequence as the remainder of software system is presented.

Information to aid the user in assessing data validity is generated by a series of three quality evaluation (QE) programs. These routines produce similar tabulations and histograms through the use of a common output subroutine, but process the input data set in different manners. All three are applied to the original data set produced by CONVRT and/or TRANS and will be discussed individually below.

QEVAL allows the examination of data values from any variable stored in a DGS format file by the construction of user-controlled frequency distributions. Several options are available, but generally the program will determine the overall minimum and maximum bounds from the variable's arithmetic mean minus and plus three standard deviations, leaving the class interval selection to the user's discretion. Statistics are produced for both the specified range of the variable and, if different for the total range. Magnetic anomaly, terrain clearance, and interpoint distances (along traverses) from the original data are analyzed with this routine using class intervals of 20 gammas, 5 m, and 50 m, respectively.

Another type of data display reflecting the survey quality is derived from the values occurring on or near the flight- or tie-line intersections.

The magnetic anomaly data for example, should, after reduction by the contractor, be numerically very similar for each line type near such an intersection. FLTLQE searches for the best discrete approximation to these intersections through a combination of coordinate bracketing and interpoint distance minimization. During this phase, a trace is printed indicating success or failure for the isolation of each intersection. If successful, pertinent information concerning the point chosen from each line involved is listed; otherwise a reason-specific message is output. FLTLQE is applied only to the original data and produces, following the above mentioned trace, tabular listings and histograms for magnetic anomaly differences (FL minus TL), distances between component intersection points and terrain clearance differences (FL minus TL) with respective class intervals of, generally, 5 gammas, 10 m, and 5 m.

The final member of the QE trio, TBQE, is used in the analysis of magnetic monitor data. A linear least-squares fit is computed, and slope and dispersion characteristics are determined for data covering each 1, 3, and 10 minute time interval along flight paths. The least mean squared error (lmse), correlation coefficient, and standard deviation of computed versus observed values as tabulated and formed into histograms along with the slope of each interval. Typically, overall class bounds for the correlation coefficient are set to ± 1.0 while the classification ranges for the other values are developed from their means plus or minus two standard deviations. Class intervals are generally selected as one-fiftieth the overall range with the exception of the correlation coefficient, with an interval specified as 0.025 gamma.

In order to remove or limit high-frequency noise often found in the original data, a routine for data smoothing has been developed. The program, NFILTR, generally is used to apply a moving median filter (Claerbout and Muir, 1973) with a window width of around 13-17 data points (0.75-1.00 km) to the anomaly data. A profile map (from PROFIL) of the filtered data, with primary and secondary contour levels indicated and the results produced from the same values by QEVAL are used to evaluate the effects of the filter. Should these indicate unacceptable distortion of desired data, new parameters for the filter are determined and the process is repeated. Currently under development, as an addition to NFILTR, is a high-cut filter

based on data wavelength which shows promise for use with data severely disturbed by high frequencies of large amplitude.

Previously mentioned was one of the problems plaguing the machine-contouring of aerial survey data: high data density along widely spaced traverses. In addition to the expense of interpolation based on data sets often exceeding 100,000 and in some cases 200,000 samples, this situation generally causes unacceptable contouring by suppressing line-to-line interactions in gridding processes.

The approach adopted for this processing scheme is one of critical point selection. Adapted from Douglas and Peucker (1973), the procedure, incorporated in program SELPT2, allows the elimination of those samples not necessary to the reproduction of the original data profile to within a specified error tolerance. An extension of the algorithm allows specification of a maximum linear distance permitted between selected samples in order that information for gridding may be provided in areas composed of very gradually changing data. These two parameters, error tolerance and maximum distance, determine the usefulness of the critical point data set. The number of chosen points increases more or less exponentially (limited, of course, to the original number present) as the tolerance is decreased and somewhat more linearly as the maximum distance is reduced. Characteristically, for the magnetic anomaly data, an error criterion in the range of 5 to 25 gammas and a maximum distance of 2 to 4 km result in the retention, from the filtered data, of around 3000 samples, roughly 3-5% of the original number. After selection is completed, PROFIL is used to produce a map similar to that illustrating the filtered data, so that the retained data may be evaluated and the selection criteria redesigned if necessary. It should also be noted that the tie-lines are eliminated from the data set in this step.

Two data sets are produced for additional processing by SELPT2. One, in standard GDS format, is used in evaluating the validity of the critical point selection through the use of PROFIL. The other, a data base in an abbreviated form called the XYZ format and containing information from all quads processed to date, is read by a program known as GPCFMT to produce the files necessary for machine contouring with CalComp's GPCP-II package. GPCFMT retrieves sample points falling within a specified lat/lon map boundary, converts coordinates to Transverse Mercator northings and eastings, and

generates the annotation and control formation, described later, necessary to produce a specific contour map. Points lying in a user-defined region surrounding the map boundary may also be included, when available, in the data to be contoured so that misalignment of contours at quadrangle margins can be minimized.

The final step in the magnetic anomaly processing sequence is the production of a contour map using the General Purpose Contouring Program (GPCP-II) from California Computer Products, Inc. (CalComp). All control information, documented in CalComp. 1971, is generated by GPCFMT to be consistent from map to map. The size of the orthogonal grid, whose origin is at the lower left boundary of each quadrangle, is derived from flight-line spacing and is generally specified as on the order of 50 cells in the east-west direction and 25 from north to south. The number of nearest control points to consider in grid value interpolation ranges from 20, preferred, to 40 where extreme smoothing is mandated. Contours are usually drawn at an interval of 20 gammas, with hundred gamma multiples bold and closed minima hachured. Each map, drawn at the 1:250,000 scale, is completed with flight path indications, titles, legends, and bar scales to aid in interpretation.

As mentioned before, if data are available from neighboring quads, they are used to improve contouring performance near the common boundaries. Exact matches are unlikely, however, due to slight discrepancies in grid positions from quad to quad. This problem, along with the non-map projection boundary and grid cell only contour blanking, is an artifact of GPCP-II and currently beyond control of this procedure.

Magnetic Data

The airborne surveys were performed by GeoMetrics, Inc. and LKB Resources, Inc. for the Grand Junction office of Bendix Field Engineering Corporation under the subcontract nos. 76-033-L and 76-032-S. These surveys were performed as part of the Department of Energy (DOE), National Uranium Resource Evaluation (NURE) Program. The results of these surveys can be found in the open-file reports GJBX-2 (1977) and GJBX-88 (1979) and can be obtained from Bendix Field Engineering Corporation, Technical Library, Grand Junction, Colorado.

The two companies contracted to perform the survey used different survey specifications and instrumentation. The most significant difference is the type of magnetometer used to observe the total intensity magnetic anomaly data. GeoMetrics, Inc. used a proton precession magnetometer which measures the absolute magnetic field with a sensitivity of 0.25 gammas. LKB Resources, Inc. used a fluxgate magnetometer which measures the relative magnetic field with a sensitivity of 0.1 gammas. Because of this difference the data recorded by the fluxgate magnetometer had to be adjusted to the absolute datum by subtracting out a value of 2400 gammas. This value was obtained by comparing the differences in the overlapping profiles at the borders of the two surveyed areas. The second vertical derivative map of the total intensity anomaly data shows no anomalous values at the borders between the two surveyed areas, indicating that the datum level was properly adjusted.

The survey was conducted along east-west flight lines at an average spacing of 5 km. North-south tie lines were flown at an average spacing of 25 km. Both fixed and rotary-winged aircraft were employed. A 120 mpg ground speed was maintained for the fixed-winged aircraft and about 108 mph for the rotary-winged aircraft. Observations were made at 0.5 and 1.0 second intervals, respectively, which translates to an average horizontal distance of approximately 27 to 50 m between samples.

The reduction of the magnetic data was performed by the contractor using different core-derived fields. The Van Horn and Pecos quadrangles had the 1975 International Geomagnetic Reference Field (IGRF) removed which was updated to the month of the survey. The magnetic data were also corrected for diurnal variations by using data collected by a ground-based magnetometer. The remaining four quadrangles had the 1965 IGRF removed which was updated to 1977. The diurnal variations were corrected by tie line adjustments.

The magnetic anomaly data set used in preparing the isolation and enhancement maps as well as the maps which show the quantitative correlations of the magnetic and gravity anomaly data were determined by the same minimum curvature method (Briggs, 1974) used in calculating the gravity data set. The grid of data values was calculated from data sets of each NTMS quad-

range provided by Oak Ridge National Laboratory and which were processed by the critical-point selected procedure from high-cut filtered contractor-supplied anomaly data using an error tolerance of 15 gammas, and a maximum separation of critical points of 3 km. The gravity and magnetic anomaly data sets which include 202 columns (N-S) and 170 rows (E-W) were registered to a common origin located at 28°59.31'N. latitude and 106°2.88'W longitude. Both data sets were gridded at a 2 km interval of UTM coordinates using a central meridian of 105°W.

TECHNIQUES OF GAMMA-RAY SPECTROGRAPHIC DETERMINATIONS OF THORIUM, URANIUM, AND POTASSIUM

The thorium-uranium-potassium contents determined for this report were obtained by gamma ray spectroscopy. Only a brief summary of the methods and equipment are given here. The reader is referred to the discussions by Hurley (1956) and Adams, et al. (1958) for details.

The UTEP gamma ray spectrometer is calibrated to receive 30, 100 and 500 gram samples, but only 500 gram samples have been used in this study. This sample size allows shorter run time (4000 seconds) and more accurate determinations because larger samples reduce the effect of minor fluctuations. Samples were trimmed to assure that they were free from all alteration, surface weathering and dirt. Six hundred grams were processed in a chipmunk crusher which was cleaned between samples with compressed air, wire brush, and a cloth. Pieces larger than 1/2 inch were rerun in the crusher since sand-sized materials give more accurate, reproducible results. Five hundred grams were weighed into commercially available, thin walled, 2 1/2" high by 6" diameter cylindrical plastic canisters. The canisters were sealed with tape and stored for 21 days to allow the material to attain secular equilibrium with respect to radon.

The UTEP gamma ray facility consists of 2 detectors, both 6" diameter by 4" thick Harshaw Chemical NaI-Tl-activated crystals. One crystal is optically coupled to a 3" diameter RCA-8054 photomultiplier tube, the other to a 5" diameter RCA-8055 photomultiplier tube. The detector systems are housed separately in 9 or more cm thick shielding made of low gamma activity lead from the National Lead Company. The analyzer is a Nuclear Data series 1100/ 2200 pulse height analyzer used in the 128 channel mode, with appropriate amplifiers.

Intensity calibrations are made using standards containing known potassium, uranium, and thorium concentrations. The potassium standard is A.C.S. grade $K_2Cr_2O_7$. Standards for uranium and thorium are 500 gram quantities of 101 ppm uranium and 101 ppm thorium, plus 3.8 ppm uranium material prepared by the D.O.E. New Brunswick Laboratories. Energy calibrations to recognize peak locations are made frequently with the use of small samples of cobalt-60 to facilitate adjustment for drift in the electronics. The 24

spectrometer is interfaced with a Hewlett-Packard 9845 desk-top computer, and radioelement abundances in samples are calculated by solving three simultaneous equations using coefficients and backgrounds that are recalculated at least every 60 days and more often if there are any shut downs or power failures. The precision of the gamma ray spectrometry analyses for potassium, uranium, and thorium are within $\pm 5\%$ and normally multiple analyses of a sample are within $\pm 2-3\%$. The accuracy is generally considered to be lower for rocks containing less than 1 ppm uranium or thorium. The limit of detection is 0.2 ppm uranium or thorium.

METHODS OF DIGITAL ANALYSIS OF GRAVITY AND MAGNETIC DATA

Interpretation of gravity and magnetic data covers a wide spectrum of approaches from the very qualitative and subjective description of trends and anomalies to computer modeling, inversion schemes, frequency domain analysis, and filtering. All of these interpretation schemes have been used in this study to some extent. The purpose of this discussion is to describe briefly the quantitative analysis techniques which have been employed in this study. More details concerning frequency domain analysis techniques can be found in papers by Bhattacharyya (1965), who discussed the use of two-dimensional harmonic analysis as a tool for magnetic interpretation, and Fuller (1967), who discussed two-dimensional frequency analysis and design of grid operators.

Reduction to the Pole

The inclination of the earth's magnetic field and the orientation of the geologic source with respect to magnetic north greatly influence the character of the magnetic anomalies due to geologic features. At the inclination of the magnetic field in west Texas (60°), the magnetic anomalies do not vary appreciably from that of the vertical field, and the effect of declination is also minor. However, the lack of vertical inclination causes an inherent ambiguity in the interpretation of magnetic anomalies with the anomalies being uplifted with respect to the source. Therefore, it is desirable to transform mathematically magnetic data to a condition of assumed vertical magnetic polarization or reduced to the pole. The principles of this method and a mathematical development for accomplishing this in the spatial domain are given in considerable detail by Baranov (1957). He pointed out that transformation of the field was very advantageous for several reasons, including: 1) the qualitative interpretation of the transformed map is easier and more immediate, since the anomalies are not shifted as a result of the non-vertical inclination of the normal field; 2) the comparison of the results of a survey with a geologic map is much easier; and 3) the transformed map can be compared to a gravimetric map much better than the original aeromagnetic map, especially if the gravity map is first transformed into a map of the first vertical derivative.

Nettleton (1976) pointed out that although comparison of maps reduced to the pole with gravity maps of the same area should be much more straightforward, such a comparison is of value only if the density and magnetic contrasts have the same boundaries. This fundamental relationship of magnetic data reduced to the pole with gravity data is the mainstay of the internal correspondence analysis method and will be discussed later.

The major limitation to the reduction to the pole method is that it assumes all magnetization is induced. Remanent magnetization oblique to the direction of the inducing field is believed to be a major contributor to the total magnetic polarization of the Cenozoic igneous rocks, particularly the extrusive rocks, present in west Texas. Thus, we can anticipate errors in the results of reduction to the pole over these geologic formations.

Upward Continuation

A data set may be continued upward or downward mathematically to any elevation desired. Upward continuation is a particularly useful tool in eliminating short wavelength anomalies, thus permitting longer wavelength anomalies to be studied without the interfering effect of the shorter wavelength features. In aeromagnetic studies this technique has been used to generate a quasi-consistent data set from data collected at different elevations by continuing those at the lower elevation to the higher level. A good illustration of the use of continuation is found in studies of the New Madrid area, where magnetic data collected at different elevations were continued to a constant elevation to produce a regional magnetic map (Hildenbrand et al., 1978).

A major advantage of upward continuation as a high cut filter is that it acts as a smoothly varying filter. In Trans-Pecos, Texas, upward continuation provides a uniformity of anomalies because it eliminates the higher frequency anomalies especially aeromagnetic anomalies which occur over surface volcanic terranes. Thus, a more uniform view of the broad anomalies is obtained. The ideal response of an upward continuation filter is shown in Figure 5.

One major disadvantage of this procedure is that in the upward continuation process the higher frequency anomalies, which are useful for certain types of interpretation, are eliminated. Also, the upward continuation pro-

Figure 5. Analytic frequency response for an ideal upward continuation ($h = 2$, data intervals) operator, in decibels (from Fuller, 1967).

cedure sometimes merges adjacent anomalies into a single anomaly, leading to resolution problems.

Strike-Sensitive (Directional) Filtering

Anomaly trends are often related to tectonics, thus an analysis of anomaly trends is useful in interpreting strain patterns in the earth's crust. Strike-sensitive filtering was applied in this study to determine the major structural trends within the basement.

Strike-sensitive filtering, either passing or rejecting a particular anomaly strike pattern, provides only general information about structural trends. Therefore, a wedge covering between 30 to 90° usually is employed rather than a single direction. Figure 6 illustrates an example of the frequency response of a northeast-southwest strike-pass filter. Because the filter is symmetrical, only one quadrant is plotted. F_y and F_x are the frequencies in the y and x directions, respectively, and the values range from 0 to 0.5 where 0.5 is the Nyquist frequency. The contours represent the amplitude of the frequency response.

The method is useful primarily because it may provide insight into the structural framework of an area. It often indicates areas where certain trends terminate against each other. The major objections to the method are that a single high frequency (circular) anomaly will pass energy in all directions and this will cause false trends. Also there is strong exaggeration of anomalies that strike in the direction being passed. It is, therefore, strongly recommended that the interpretation be constrained by the simultaneous study of both the original unfiltered map and the filtered map. In this study, strike reject filters were employed to minimize these problems.

Second Vertical Derivative Method

Maps derived from the second vertical derivative (curvature) method are used mainly as a secondary tool in the interpretation process. The second vertical derivative method emphasizes the high gradient areas which reflect the shallower, more concentrated anomaly sources. It is effective where the data are of high quality, and especially with magnetic data, it may serve as a rather imprecise depth indicator. Over deep basement areas, contours are expected to be smoother and widely spaced whereas, where the magnetic

Figure 6. Frequency response for a northeast-southwest strike-pass filter (from Chandler, 1977b)

terrain is shallow, the derivative pattern is expected to be dominated by high-relief anomalies. In general the zero curvature contour outlines the shape of the magnetic source. The ideal response of a second derivative operator is shown in Figure 7.

A disadvantage is the method is that high-frequency noise in the data will be emphasized, resulting in pseudo-anomalies. A second disadvantage is that the amplitude of the original anomaly is not retained, and its shape may be distorted severely, with a positive magnetic anomaly represented on the second vertical derivative map by a central magnetic peak surrounded by negative anomalies.

Basement Depth Determinations

The determination of the depth to the crystalline basement is an important element in geologic and tectonic analysis of geophysical data. This is particularly true in deep sedimentary basins which generally have few if any drill holes to provide direct information on the basement depths. Traditionally, the magnetic method has proved to be the most useful of the potential field methods to determine the depth to crystalline or, more precisely, magnetic basement which is defined as the upper surface of the buried magnetic rocks. A wide variety of empirical, direct and inverse techniques, is used in magnetic depth determinations.

One inverse is particularly suited to automatic processing of digital magnetic data takes advantage of the relationship between the power spectrum of an ensemble of magnetic anomalies and the depth to the surface of the source of the anomalies (e.g. Spector and Grant, 1970; Hahn *et al.*, 1976). This spectral method has been employed in this study utilizing a maximum entropy method of determining the power spectrum using a FORTRAN program developed by Hassanzadeh (1976). He extended the method of Treitel *et al.* (1971) by using the maximum entropy procedure developed by Burg (1967, 1968) to estimate the power spectra of the magnetic anomaly data. Burg's method generates a unique filter (prediction error filter) which when applied to the data will produce an uncorrelated sequence. An important assumption is that the magnetic data are uncorrelated, which means that the magnetic vectors within the bodies are randomly presented or there is no remanent mag-

Figure 7 Analytic frequency response for an ideal second vertical derivative operator, in decibels (from Fuller, 1967)

netization. As a result the estimated spectrum of the uncorrelated series is a constant. If the magnetic data could not be described as uncorrelated then this program tends to overestimate the depth to the top of the magnetic basement. A theoretical spectrum which is dependent upon the depth to the magnetic source is fitted to the estimated spectrum. These theoretical spectra are calculated using a two-dimensional model represented by a horizontal layer of finite thickness. Within this layer the magnetic intensity is allowed to vary only in the direction of the profile. Due to the predictive ability of maximum entropy, depth calculations can be made from short segments of the data which will maximize resolution.

When applying the maximum entropy method to depth determinations in this program, two critical parameters must be specified. These are the gate-length or window, and the number of coefficients in the prediction error filter. The gate-length is the number of data points along the magnetic profile in which the power spectrum is estimated. There is a trade-off involved when deciding the gate-length. Short gate-lengths give high resolution but longer lengths yield better spectral estimates. Because the estimated spectra are highly dependent upon the values chosen for these parameters, it is best to test different values on a theoretical model which roughly represents the type of magnetic features present in the study area. Depths were calculated using different gate-lengths and number of filter coefficients using a model which duplicates the geologic and magnetic conditions in West Texas. These parameters were used in calculating the magnetic basement depths from the 2 km gridded data set. The use of the magnetic data at 2 km intervals largely eliminates the spectral effect of the near-surface magnetic sources and thus restricts our estimates to buried magnetic horizons.

THE APPLICATION OF INTERNAL CORRESPONDENCE ANALYSIS (modified from Chandler, 1977b)

General Principles

Effective correlation of gravity and magnetic data can be achieved by a method called internal correspondence analysis (ICA). A simplified form of the method was initially proposed by Robinson (1962) as a means of correlating two sets of contoured geographic data. Hinze et al. (1975) demonstrated the use of an improved method of ICA on gravity and magnetic data. This approach involved a moving-window linear regression analysis between sets of standardized gravity and magnetic profiles. Recent studies have indicated a more effective approach of ICA is to employ the first vertical derivative of gravity and magnetic data reduced to the pole. The advantage of this approach lies in consideration of Poisson's theorem (Chandler et al., 1981).

The Incorporation of Poisson's Theorem into Internal Correspondence Analysis

The relationship between the gravitational and magnetic potentials arising from a common source was shown by Poisson (1826) to be

$$V = \frac{J}{\sigma G} \frac{U}{\partial i}$$

where

V = the magnetic potential

U = the gravitational potential

J = the source magnetization

i = the direction of source magnetization

σ = the source density

G = the universal gravitational constant.

In order for this relationship to be theoretically valid, it must be assumed that the source has a uniform density, magnetization, and direction of magnetization. Because of these assumptions, the geophysical applications of Poisson's theorem have been usually restricted to simple, well-isolated anomalies.

Recent studies, however, indicate that a more generalized form of Poisson's theorem, when used in conjunction with ICA, can often yield significant results - even when the theoretical assumptions are clearly violated. If vertical magnetic polarization can be assumed, Poisson's theorem may be differentiated along the vertical direction z to yield

$$T_z = \frac{J}{\sigma G} \frac{\partial g}{\partial z}$$

where

- T_z = the total magnetic field reduced to vertical polarization
- g = the vertical component of gravitational acceleration (quantity measured in most gravity surveys).

When dealing with gravity and magnetic anomalies a more useful equation is

$$T_z = A + \frac{\Delta J}{\Delta \sigma G} \frac{\partial g}{\partial z}$$

where ΔJ and $\Delta \sigma$ are the source magnetization and density contrasts, respectively, and A is an intercept term to account for a constant anomaly base level. When an anomaly of interest is found to interfere with anomalies from nearby, dissimilar sources, the above relationship is incorrect. However, as further discussions will demonstrate, the relationship is often approximately correct within a small spatial segment of the anomaly of interest.

Preprocessing of the Data

The methodology of ICA is summarized on the flow chart in Figure 8. Some of the steps presented in this illustration are optional and shall be discussed in the next section. The gravity and magnetic data, in either map or profile form, must be digitized at a constant interval and registered. All data must be observed at a common level. If this is not the case initially, reduction to a common level is accomplished by upward continuation.

CORRELATION ANALYSIS USING INTERNAL CORRESPONDENCE

Figure 8. Internal correspondence analysis flow chart.

The first vertical derivative of gravity and magnetics reduced to the pole are calculated and it is on these data that ICA is performed.

In this study, the reduction to the pole as well as differentiation, continuation, and all other filtering of gravity and magnetic data (Baranov, 1957; Bhattacharyya, 1965, 1972) are accomplished in the frequency domain. For simplicity of illustration, examples of the ICA method employ profile data associated with strike infinite models. However, the ICA method can be easily applied to gridded map data by using a square moving window and two-dimensional preprocessing.

Internal Correspondence Analysis

Internal correspondence involves performing a least squares linear regression using reduced to pole magnetic anomaly values versus first vertical derivative of gravity anomaly values within a moving data window.

The procedure carried out by internal correspondence analysis is demonstrated in Figure 9. A window size is specified by the user and initially positioned at the left margin of the data set. Guidelines for selecting a window size shall be discussed in the next section. A least squares linear regression is performed between data points within the window. The vertical derivative of gravity has been arbitrarily assigned as the independent variable for the regression. This choice is not critical because interpretation is limited to areas of high correlation coefficients. The regression yields three coefficients: correlation, slope, and intercept. The slope coefficient is corrected for the gravitational constant and converted into c.g.s units to yield an apparent $\Delta J/\Delta \sigma$ estimate. All three regression coefficients are assigned the spatial coordinate of the center of the window. The window is then shifted one digital position to the right and the process is repeated. This operation is carried out until the entire data set is analyzed and three regression coefficient profiles have been generated.

Significance of the Internal Correspondence Coefficients

The significance of the three ICA coefficients is clarified by considering the modified form of Poisson's theorem in Figure 10. This form of the theorem states that the vertical derivative of gravity and the magnetics

INTERNAL CORRESPONDENCE ANALYSIS PROCEDURE

Figure 9. Internal correspondence analysis procedure.

reduced to the pole are linearly related by a slope $\Delta J/\Delta\sigma G$ and an intercept A. Similarly, the three ICA parameters represent a fitted linear relationship between the first vertical derivative of gravity and the magnetics reduced to the pole. Thus, several important analogies between the ICA coefficients and Poisson's theorem are readily apparent.

Each slope coefficient from ICA is corrected for the universal gravitational constant and converted into c.g.s units. In this form the slope coefficient is equivalent to the $\Delta J/\Delta\sigma$ ratio of the anomalous source considered in Figure 10. An accurate estimate of $\Delta J/\Delta\sigma$ is not uniquely definitive of lithology and is a function of the country rock with which the anomalous source contrasts (Hinze et al., 1975). In addition, different combinations of density and magnetization contrasts yield the same ratio value. However, if the $\Delta J/\Delta\sigma$ estimate is considered along with the original anomalies, as well as with any other geophysical or geological information, it can serve as a useful constraint on interpretation. Two extremes of source $\Delta J/\Delta\sigma$ are possible; a value of zero for a gravity anomaly with no magnetic expression and a value of infinity for a magnetic anomaly with no gravity expression.

It is instructive to investigate the meaning of a particular $\Delta J/\Delta\sigma$ estimate through the graph in Figure 11. The axes of this plot represent density and magnetization contrasts and the curves represent constant $\Delta J/\Delta\sigma$ values. Only one point on a curve represents the actual ΔJ and $\Delta\sigma$ values for an anomalous source, and thus the ambiguity of a particular $\Delta J/\Delta\sigma$ estimate from ICA is clearly demonstrated. However, if the interpreter can estimate the probable range of one of the components of a $\Delta J/\Delta\sigma$ estimate, the other component can be easily inferred. Because density is considerably less variable than magnetization for most earth materials, it would be the most logical component to estimate first.

The correlation coefficient generated by ICA expresses the significance of the linear fit for a given window position. The most significant linear regressions will have an associated correlation coefficient value near either -1.0 or 1.0. A negative correlation coefficient indicates a direct relationship; either both anomalies are positive or negative. As a result, it is helpful to refer to the original data in the interpretation process. The correlation coefficient also aids in the evaluation of the associated

$$T_z = A + \left(\frac{1}{G} \frac{\Delta J}{\Delta \sigma} \right) \left(\frac{\partial g_z}{\partial z} \right)$$

- T_z = TOTAL FIELD MAGNETIC ANOMALY AT VERTICAL POLARIZATION
- A = INTERCEPT
- G = GRAVITATIONAL CONSTANT
- g_z = VERTICAL COMPONENT GRAVITY
- ΔJ = MAGNETIZATION CONTRAST
- $\Delta \sigma$ = DENSITY CONTRAST

Figure 10. The generalized form of Poisson's theorem used in internal correspondence analysis.

Figure 11. Magnetization-density contrast ratio graph.

$\Delta J/\Delta\sigma$ estimates; a meaningful $\Delta J/\Delta\sigma$ estimate will not occur if the associated correlation coefficient is low in magnitude.

The intercept coefficient should be zero or at a constant base level if the assumptions inherent to Poisson's theorem are upheld. Therefore, the presence of fluctuating ICA intercept coefficients reflect violations to these assumptions. Accordingly, the behavior of the intercept profile serves as another evaluation criteria for associated $\Delta J/\Delta\sigma$ estimates; regions of erratic intercept behavior are generally not associated with valid $\Delta J/\Delta\sigma$ estimates.

In order to demonstrate the method, internal correspondence analysis was performed on the theoretical gravity and magnetic profiles due to an isolated source (Fig. 12). For simplicity, all models illustrated in this study assume that individual anomaly-producing sources possess uniform properties. It is also assumed that all model sources are polarized by a vertical magnetic field with an intensity of 58,000 gammas.

The internal correspondence results of the isolated anomaly profiles in Figure 13 have a correlation coefficient of essentially 1.0, or nearly perfect positive correlation, and correct estimates of $\Delta J/\Delta\sigma$ over the source. On this and following models, stippled bars whose lengths equal the actual $\Delta J/\Delta\sigma$ are superimposed on the ICA slope profile. The intercept is less than one part in 1000 of the amplitude of the magnetic anomaly and can be considered zero for practical purposes. The linearity of the magnetics versus vertical gradient of gravity relation is illustrated in Figure 14.

Implementing Internal Correspondence Analysis

The validity of the ICA results is limited by the assumptions inherent to Poisson's theorem and the accuracy of the necessary preprocessing steps. However, it will be assumed that the preprocessing steps of calculating the first vertical derivative of gravity, reduction to the magnetic pole, and upward continuation do not introduce significant error into the ICA results. This section will investigate the effects of the violations to Poisson's theorem -- non-uniform sources and anomaly interference -- by use of two-dimensional modeling. In a sense, these two assumptions are actually equivalent as a non-uniform source and can be approximated by a closely-spaced

Figure 12. Isolated two-dimensional source: gravity first vertical derivative of gravity, and magnetic anomaly profiles.

Figure 13 Isolated two-dimensional source: internal correspondence results. Level of the stippled bar equals the source body $\Delta J/\Delta\sigma$, 0.0928.

Figure 14. Magnetics versus first vertical derivative of gravity for the isolated source

arrangement of differing uniform sources. The selection of a proper window length of ICA also will be discussed in this section.

Effect of Anomaly Superposition

Koski (1976) demonstrated that in the case of anomaly superposition the $\Delta J/\Delta\sigma$ estimate derived from ICA was a weighted average of the $\Delta J/\Delta\sigma$ of the individual sources and that the resulting estimate was most heavily weighted towards that of the dominant anomalous source. Shown in Figure 15 are two vertically superimposed anomalous sources. These combine to produce simple appearing anomalies that belie the actual complexity. Sampling interval for the model was 1 km.

Internal correspondence analysis on the superimposed anomalies using a window of five points clearly reflects the violations to Poisson's theorem. The resulting three coefficient profiles of Figure 16 show variable behavior and spike patterns that contrast sharply with the ICA results of the single source in Figure 13. The slope coefficient profile in Figure 14 shows values that are not correct for either source, but near the center of the profile the estimates appear to be most heavily weighted towards the shallowest and thus most dominant source. The intercept profile in Figure 16 shows a wide pronounced minimum in the anomalous area, reflecting in part a change in apparent anomaly base level due to the interfering anomalies.

Figure 17 illustrates that the $\Delta J/\Delta\sigma$ of interfering anomalies is a result of the vector sum of the magnetic versus first vertical derivative of gravity values due to the two sources. The values shown in Figure 17 are from a five-point window position in the model shown in Figure 15. Magnetic versus first vertical derivative of gravity values due to the two sources are shown individually as well as combined. The superposition of two uniform sources with individual linear magnetic versus first vertical derivative of gravity correlations yields a relationship that is sublinear and has a non-zero intercept. The slope of the resultant is most heavily weighted by the source producing the largest range of values within a given window, in this case the shallower source. Thus, in regions where anomaly interference is present, apparent $\Delta J/\Delta\sigma$ values may not be representative of any single source body and must be accepted with reservation. The non-zero

Figure 15. Gravity, first vertical derivative of gravity and magnetic anomaly profiles due to two superimposed sources with different $\Delta J/\Delta \sigma$'s.

Figure 16. Superimposed anomaly sources: internal correspondence results. The level of the fine stippled bar equals the $\Delta J / \Delta \sigma$ of the upper source, 0.0928, the bold of the lower source, 0.0464.

Figure 17. The vector sum of magnetics versus first vertical derivative of gravity relations resulting in an apparent $\Delta J / \Delta \sigma$.

intercept and spike patterns in the ICA coefficient profiles are an indication of significant interference. However, it will be demonstrated that the weighting of the ICA $\Delta J/\Delta\sigma$ estimates towards a dominant source will often yield accurate $\Delta J/\Delta\sigma$ estimates of that source, even in areas of strong anomaly interference.

Shown in Figure 18 are the gravity and magnetic data arising from a model that was designed to represent a combination of three source types; the square bodies are diorite, the dikes are gabbro, and the triangular bodies are granite. Magnetization and density contrasts were assigned which were reasonable to a country rock of felsic gneiss with the diorite, gabbro, and granites having resulting $\Delta J/\Delta\sigma$ ratios of 0.0928, 0.03248, and -0.0174, respectively. Sampling interval was 1 km. Between 240 and 310 km a combination of sources exist whose anomalies are strongly interfering. A body exists near 120 km which constitutes a non-uniform source of gabbro and diorite.

Internal correspondence analysis of the model in Figure 18 was conducted at a window of 5 km and the results are shown in Figure 19. Observation of the slope values indicates that extremely accurate $\Delta J/\Delta\sigma$ estimates occur where a particular source type is clearly dominant. More significant, however, is the ability of the ICA method to often extract accurate $\Delta J/\Delta\sigma$ estimates in the area of strong anomaly interference between 240 and 310 km. No significant $\Delta J/\Delta\sigma$ estimates are associated with the non-uniform source near 120 km, but the erratic behavior of the slope and intercept profiles indicates that the simple appearing anomaly does not arise from a single, uniform source. This information could be very valuable to the interpretation of an anomaly of unknown origin.

Shown in Figure 20 is a model profile consisting of four pairs of sources. Sampling interval was 1 km. In each pair, one source has exactly one-half of the $\Delta J/\Delta\sigma$ of the other. From left to right the pairs can be seen to be in an increasing state of interference until, at the extreme right, the two sources are actually in contrast and, in effect, constitute a single, non-uniform source. Using the classical methods of interpretation, the anomaly at the extreme right could be mistaken for that arising from single, uniform source.

Figure 18. Gravity, first vertical derivative of gravity, and magnetic anomaly profiles due to various combinations of three source types. The square bodies have $\Delta J/\Delta \sigma$ of 0.0928, the rectangular bodies have a $\Delta J/\Delta \sigma$ of 0.03248, and the triangular bodies have a $\Delta J/\Delta \sigma$ of 0.0174. Sampling interval is 1 km.

Figure 19. Internal correspondence results of three source types model using a 5 km window. Positions of shaded bars represent source positions and their levels represent actual source $\Delta J/\Delta\sigma$ values.

A window size of 5 km was selected for ICA of the model in Figure 20 and the results are shown in Figure 21. In each paired source situation the ICA method has yielded reasonably accurate $\Delta J/\Delta\sigma$ estimates of the individual sources, even at the extreme situation where the source pairs are in contact.

Thus, in summary, study of model profiles indicates that the application of Poisson's theorem as conducted by ICA allows successful extraction of accurate source $\Delta J/\Delta\sigma$ estimates, even when the theoretical assumptions are clearly violated. Even when the ICA method fails to yield a representative $\Delta J/\Delta\sigma$ estimate, the erratic behavior of the resulting coefficient profiles, especially the intercept, can inform the interpreter that violations of the theory are present, perhaps in regions where they were not originally suspected.

Effect of Window Size

The selection of a proper window size is obviously a subjective decision that must be made prior to application of ICA. No quantitative means currently exist for making this decision, but model studies by Koski (1976) and Chandler et al. (1977) have yielded empirical guidelines in selecting a correct ICA window size. The choice of a window size is an interplay between the number of points required to achieve a significant linear regression, which constitutes a lower limit in size, and the effect of interference from nearby sources, which constitutes an upper limit. Observations of the model profiles in Figures 18 and 20 illustrate the nature of the problem. If a small window size, consisting of very few points, is selected the statistical significance of the linear regression involved in ICA will decrease and the resulting linear regressions will be vulnerable to such factors as low-amplitude noise. If, on the other hand, an extremely wide window is selected for the analysis of the profiles, a particular window position likely will include the strong effect of several anomalous sources. In this case, the resulting linear regression could yield a $\Delta J/\Delta\sigma$ that does not represent any particular source. Results of model studies suggest that the optimum window size for ICA should be 1.0 to 0.5 times the half-maximum width of the anomalies that are of primary interest.

Figure 20. Gravity, first vertical derivative of gravity, and magnetic anomaly profiles due to four pairs of equivalent sources at decreasing distances of separation. Sampling interval is 1 km.

Figure 21. Internal correspondence results of four pair model. The level of the fine stippled bar equals the left hand source $\Delta J / \Delta \sigma$ of each pair, 0.0928; the bold equals the $\Delta J / \Delta \sigma$ of each right hand source, 0.0464.

Enhancement of Internal Correspondence Analysis Through Preprocessing

Although the preceding sections have demonstrated the utility of ICA in a variety of conditions, strong interference among anomalies can still lead to confusing or erroneous results. Interference commonly arises between anomalies of widely different wavelength components. Poisson's theorem is independent of wavelength and, as shown by Kanasewich and Agarwal (1970), it is often possible to extract meaningful $\Delta J/\Delta\sigma$ estimates from only a wavelength band component of the original data. Thus, the ICA of an anomaly of interest may be improved by first filtering the data to pass the principal wavelength components of that anomaly.

Model studies by Koski (1976) indicated that the ICA of data sets containing anomalies of differing wavelengths can be enhanced by the application of upward continuation and high-pass wavelength filtering. The $\Delta J/\Delta\sigma$ estimates of localized and shallow sources were improved by high-pass filtering of the gravity and magnetic data. This filtering removes the interference arising from broad, regional scale anomalies. Conversely, the $\Delta J/\Delta\sigma$ of deep and regional scale sources can be estimated more effectively by the attenuation of narrow wavelength anomalies by upward continuation.

In an analysis of two-dimensional gridded data, the additional filtering operation of directional or strike sensitive filtering becomes available. If an anomaly or a particular set of anomalies has a marked linear geographic trend, its ICA results may be enhanced by strike-sensitive filtering along the preferred direction. Such a preprocessing step will attenuate interference arising from anomalies with differing geographic trends. The application of the strike-pass filtering to ICA is untested by model studies.

Recognition of Significant Internal Correspondence Analysis Results

In spite of its applicability, ICA cannot be expected to yield a valid $\Delta J/\Delta\sigma$ estimate at every point in a multisource data space. Model studies have revealed that ICA yields a combination of valid and invalid $\Delta J/\Delta\sigma$ estimates. Thus, the need arises for criteria which recognize valid $\Delta J/\Delta\sigma$ estimates in the analysis of complex multi-source data sets.

The correlation coefficient values from ICA serve as an initial means of evaluating $\Delta J/\Delta\sigma$ estimates. A low magnitude correlation coefficient value indicates a poor linear regression and thus the associated $\Delta J/\Delta\sigma$ estimate is not likely to be significant. A low correlation coefficient value may be due to interference of several sources, inaccurate preprocessing, inappropriate window size in the ICA, or the presence of significant remanent magnetization.

Perhaps the most useful criterion for evaluating reliable $\Delta J/\Delta\sigma$ estimates from ICA is the stable and level behavior of the slope and intercept profile values. This stable behavior reflects the strong dominance of a source in a particular area. Thus, the ICA essentially remains locked onto this dominant source as the moving window passes near it. As the ICA moving windows passes from the dominance of one source to another there is a transition zone where the ICA coefficient profiles, especially the intercept, often become unstable and display spike patterns. It is also well-advised to restrict primary attention to the high intensity areas of anomalies. In these regions, a source is at maximum signal and the resulting $\Delta J/\Delta\sigma$ estimates from ICA are most likely to be accurate. Using model studies, Chandler et al. (1977) demonstrated that a criterion based on anomalous amplitudes and ICA coefficient profile stability could statistically discriminate valid versus invalid $\Delta J/\Delta\sigma$ estimates.

In this study, attention will be directed towards only those $\Delta J/\Delta\sigma$ estimates associated with high correlation coefficient values and towards those areas that display spatially level and stable ICA coefficient values. In addition, the $\Delta J/\Delta\sigma$ estimates from ICA will always be checked with the original data to determine if they correspond to visible anomalies.

Local Favorability Index

Correlation of gravity and magnetic anomaly data is useful in the interpretation of the geological sources of anomalies. There are several correlation techniques available, one of the more recent ones is the Local Favorability Index. This is a statistical measure of the degree to which gravity and magnetic anomalies supplement one another. When calculating the favorability, the total intensity magnetic anomaly data must be reduced to

the pole and it is best to use the first vertical derivative gravity anomalies. Poisson's theorem states (Chandler, 1977) that these anomalies should have the same shape if they have a common source. If the Bouguer anomaly data are used, the magnetics would tend to overwhelm the Local Favorability Index.

$$F_p = \frac{G_p - \bar{G}}{S_g} + \frac{M_p - \bar{M}}{S_m}$$

F_p = Local Favorability Index at point p

G_p = Gravity values at point p

M_p = Magnetic values at point p

(S_g) and (S_m) are map constants

S_g = Standard Deviation for the gravity data over the map area

S_m = Standard Deviation for the magnetic data over the map area.

$\bar{G}$ = Mean of the gravity data

$\bar{M}$ = Mean of the magnetic data.

The Local Favorability Index is calculated using a point-by-point scheme. No window is used so the Favorability is calculated for the entire data array. The mean is removed from the data, normalizing the Favorability Index; this makes the interpretation of the results easier. Negative Favorability values indicate that negative magnetic and gravity anomalies are supplementing one another and vice versa for positive values.

This correlation technique is not restricted to the use of gravity and magnetic anomaly data. It can also be used for correlating data from other sources, provided one can assume there is a genetic relationship between the data used.

ANALYSIS OF NURE AEROMAGNETIC DATA

A primary goal of this study is the evaluation of the quality and utility of the aeromagnetic data gathered as part of the NURE program. The quality and thus the utility of the data are of concern because the surveying specifications are less than optimum for magnetic surveys, although the specifications were tightened in 1979 to insure good quality data without affecting the quality or efficiency of the radiometric surveying.

The utility of the data is well documented in subsequent discussions which interpret the magnetic data in association with the gravity data. The NURE magnetic anomaly data have contributed significantly to the geologic information on West Texas. The availability of these data in a digital format has permitted their quantitative analysis by techniques which isolate or enhance particular characteristics of the data, correlate magnetic and gravity anomalies, and automatically determine depths to magnetic basement.

Evaluation of data quality is in large part a subjective judgement. The maps produced for this study correlate well with previously existing information. As shown in Figures 22 and 23 (a portion of the Pecos and Van Horn quads), the correspondence with a vertical-intensity, ground-magnetometer survey is almost perfect. However, the deep basement in this area is ideally suited for the wide flight-line spacing of the NURE surveys. The wide flight-line spacing can produce problems in areas of shallow magnetic basement or volcanic cover. This problem is particularly evident in the Marfa quad where contours along the Rio Grande River are very blocky. However, several oil company personnel have complimented the general appearance of the contour maps compared to their efforts to contour the original open-file data. Considering the flight-line spacing it seems evident that the NURE data are very useful and of acceptable quality.

PECOS QUADRANGLE; TOTAL MAGNETIC INTENSITY ANOMALY MAP

SURVEY DATE(S): 1/1977
 DATA COLLECTED AND REDUCED BY: GEOMETRICS
 CORE-DERIVED FIELD REMOVED: UPDATED IGRF 1975
 FLIGHT LINE ELEVATION: 400 FT (122 M) AMT
 CONTOUR INTERVAL: 20.0 GAMMAS (INT)

MACH WE CONTOURED FOR MURE PROGRAM, DOE,
 GRAND JUNCTION, COLORADO,
 BY THE COMPUTER SCIENCES DIVISION,
 UNION CARBIDE CORPORATION,
 AT OAK RIDGE NATIONAL LABORATORY

SCALE 1:250000
 TRANSVERSE MERCATOR PROJECTION
 PUBLICATION DATE 08-15-80

Figure 22. Pecos quadrangle; total magnetic intensity anomaly map.

QUALITATIVE ANALYSIS OF GEOPHYSICAL ANOMALIES

General Considerations

The following discussions describe the regional gravity, magnetic, and radiometric anomalies of each quad included in this study. This report contains a folio of maps for each quad which include gravity, magnetic, geologic, radiometric, ground truth and digitally processed maps. For the sake of brevity, these folios are not referred to repeatedly, but they should be viewed as the text is read. The following discussions are generally qualitative in nature, but the next section includes several detailed studies.

Gravity and Magnetic Anomalies of the Van Horn Quad

There is a good correlation between the gravity and aeromagnetic anomalies observed in the Van Horn quad. The individual tectonic features discussed below are shown in Figure 3. The Hueco Bolson is responsible for the strong northwest trends (A) along the Rio Grande River in the southwest corner of the quad. This feature is a major graben which contains at least 3000 m of bolson fill (Mattick, 1967; Uphoff, 1978; Covert, 1976) and is associated with negative magnetic and gravity anomalies.

The northern Quitman Mountains are a resurgent cauldron complex which contains approximately 35 cubic kilometers of welded ash-flow tuffs (Hobbs, 1979). This feature appears as a very prominent magnetic high (B). The associated gravity high is poorly mapped because a limited number of readings could be made in this difficult area.

A strong gravity and magnetic high (C) is associated with the Hueco Mountains. There are a few scattered outcrops of Precambrian rocks in this area and the geophysical anomalies probably outline an area where the Precambrian is near the surface.

There is a trend of gravity and magnetic lows (D) east of the Hueco Mountains which represents an increase in the depth to basement. To the east, the Diablo Plateau is marked by a prominent N-S trending gravity high (E). The associated magnetic high is more complicated because there are

numerous intrusions in the area (Barker, 1979). Modeling of the gravity and magnetic data indicates that an anomalous upper crustal mass is required to explain this anomaly (see detailed discussion on the Salt Flat graben).

The Salt Flat graben is delineated by linear gravity and magnetic lows (F) and is discussed in more detail later.

The Precambrian outcrops of the Van Horn area were the subject of a complimentary contract (79-308-E) for which the final report was submitted in April, 1980. As would be expected, the anomalies in this area (G) are complicated but they form a distinct northwest trend. A gravity high and a magnetic gradient seem to mark the boundary between the volcanic units of Carrizo Mountain Group and the younger Precambrian units to the north. The E-W trending magnetic low just north of Van Horn probably delineates a Precambrian basin into which late Precambrian and early Paleozoic sediments were deposited.

The eastern third of the quad (H) is part of the Delaware Basin. This feature is also discussed in detail later. Gravity and magnetic values generally decline into this basin. However, computer modeling of the large positive anomaly (I) in the southeastern corner of the quad indicates it represents an intra-basement mass.

Gravity and Magnetic Anomalies of the Pecos Quad

The geophysical anomalies in the this quad are relatively smooth and uncomplicated because of the deep sedimentary cover. This region is the subject of a more detailed discussion in a later section. The northwestern portion of the quad contains the deepest area of the Delaware Basin. There is a large gravity low in this area (A) and a subdued pattern of low magnetic values. The southwestern portion of the quad (B) contains a continuation of the gravity and magnetic highs which were attributed to an intra-basement mass in the discussion of the Van Horn quad. The central portion of the quad (C) is dominated by a NNW trend of gravity and magnetic maxima which correlate well with the Central Basin Platform, a major basement horst. As pointed out in a later discussion, the gravity relief between this platform and the Delaware Basin is far too great (50 mgal) to be explained by the sedimentary units present. The most plausible explanation is

that there is a mafic, intra-basement mass beneath the central Basin Platform. This mass can be interpreted as the remnant of an aulacogen which extended through the area in late Precambrian time. Several authors have speculated that such a feature is present in West Texas, but as a result of this study, it can now be delineated. Gravity and magnetic values decline in the eastern portion of the map (D) as the Midland basin is encountered. At the south-central edge of the quad (E), the Delaware basin begins to deepen after shallowing in the central portion of the quad (see basement map in detailed discussion). The gravity and magnetic data reflect this basement relief very clearly.

Gravity and Magnetic Anomalies of the Marfa Quad

The aeromagnetic map of the Marfa quad is dominated by a complicated anomaly pattern which is the result of the many volcanic, volcanoclastic, and intrusive units present. The blocky nature of some of the contours suggest processing artifacts may be a problem. This is understandable considering the high variability of values along individual profiles. The gravity map is dominated by the Cenozoic basins (Basin and Range grabens) which traverse the area. The large gravity low centered near Valentine (A) delineates the Valentine Basin which has been interpreted to be a Cenozoic graben (Covert, 1976). This anomaly is elongate in a northwest direction parallel to Basin and Range structures in the area. To the north, this basin merges with Lobo Valley which is also correlated with a linear gravity low (B). Magnetic anomalies in both of these areas are very complicated because of the Davis Mountain volcanic field. Dipole anomalies from intrusions in the Chispa (C) and Wiley Mountains (D) are very prominent. There is also a gravity high in the area of the Chispa Mountains. Although the magnetic data do not outline the Valentine Basin, the anomalies in the southern portion of the basin are subdued and reduced in value indicating an increase in basement depth. In the southeasternmost corner of the map, an east-west trending gravity and magnetic maximum (E) separates the Valentine and Marfa Basins. The Presidio graben (Mraz and Keller, 1980) is the structure which dominates the southwestern portion of the quad (U.S. portion). This feature discussed in more detail below, is a major Basin and Range structure

(Mraz and Keller, 1980) and is delineated by a linear gravity low (F) and a magnetic low. The volcanics of the Sierra Vieja and edge effects from the termination of flight lines produce irregular magnetic anomalies along the Rio Grande River in the central portion of the map. To the northwest, the Green River bolson (G), the Red Light bolson (H), and Eagle flat (I) produce gravity lows, but the Eagle Mountains caldera produces the dominant magnetic anomaly in the area (J). North-south gravity trends follow the trend of faulting in the Sierra Vieja area (K). A general northwest trend of gravity and magnetic anomalies extends through the Davis Mountains area (L).

Gravity and Magnetic Anomalies of the Presidio Quad

The U.S. portion of the Presidio quad is small and is dominated both structurally and geophysically by the Presidio graben. This feature is delineated by a prominent linear gravity low (A) and a pattern of subdued magnetic anomalies which extends into the Marfa quad. Because of its importance, this feature justifies the more detailed discussion which follows (abstracted from Mraz and Keller, 1980).

The Presidio Bolson is located in a graben approximately 70 km long and 20 km wide that trends north-northwest along the western edge of Presidio County, Texas and is the dominant tectonic feature in the area. This feature, the Presidio Graben may be a part of the southern extension of the Rio Grande Rift (Seager and Morgan, 1979) and appears to contain the most promising areas for geothermal exploration in West Texas (Hoffer, 1978; Henry, 1979). It may also be associated with significant mineral deposits (McAnulty, 1972) and has been the subject of much uranium exploration recently. The Presidio Graben is bounded on the east by the Sierra Vieja, the Chinati Mountains, and the Bofecillos Mountains. The Chihuahua Tectonic Belt in the State of Chihuahua, Mexico, lies to the west of the graben. The Rio Grande runs down the center of the graben, which begins north of Candelaria, Texas, and extends south of Presidio, Texas.

In the northern part of Presidio County, deep drilling has penetrated Precambrian granite and arkosic sandstone (Bilbrey, 1957). These Precambrian rocks underlying the Cambro-Ordovician Bliss Sandstone, are correl-

ated with Precambrian outcrops in the Van Horn area to the north. This area was part of the Van Horn mobile belt that was intensely folded, metamorphosed, and intruded during late Precambrian time and was thrust eastward against the Texas Craton (Flawn, 1956). Subsequent erosion produced low-relief surface gently sloping to the south. Paleozoic marine sediments were deposited upon this shelf as the Sauk Sea (Sloss, 1963) transgressed from the south.

In the Presidio area, Upper Pennsylvanian black shales and Permian sediments of the Marfa Basin are exposed in Laramide anticlines located in the Chinati Mountains and Pinto Canyon area (Rix, 1953). However, the best exposure of Paleozoic rocks in the region is in the Solitario Uplift, where Cambrian through Lower Pennsylvanian units are found. These marine sediments record a history of deposition on a stable continental shelf for most of Paleozoic time. However, in the Presidio area, the Marfa Basin was forming probably as a result of late Paleozoic tectonism associated with the Ouachita-Marathon orogenic belt to the southeast.

The Chihuahua Trough, southwest of the study area, was filling during the Jurassic and Cretaceous Periods. Jurassic evaporites were deposited in the Chihuahua Trough, but Comanchean and Gulfian sediments are the only Mesozoic rocks that have been found in the Presidio area. These units, composed of fine-grained clastics, limestones, and a basal limestone conglomerate indicate a stable shelf area lying between the Diablo Platform and the Chihuahua Trough (Dietrich, 1965). This stability ended with Laramide thrusting and folding that formed the Chihuahua Tectonic Belt. Thrust sheets encountered in wells just north of the Presidio Graben (Fig. 24, nos. 4 and 5) are a buried subsurface extension of the Chihuahua Tectonic Belt (Kopp, 1977).

The Tertiary was a time of Basin and Range normal faulting and igneous activity in the Presidio area. Tertiary volcanic rocks originated from numerous eruptive centers in a northwest-trending belt extending along the boundary region between the Diablo Platform and the Chihuahua Tectonic Belt (Barker, 1977). Several features of this belt (including the Chinati Mountains) have been interpreted as resurgent cauldrons (McAnulty, 1975). In the Presidio area, eruption began along the northeastern edge of the Sierra Vieja and Chinati Mountains 30 to 40 m.y. ago (Wilson et al., 1968) and

Figure 24 Locations of oil test wells in Presidio County. Numbers identify the wells as tabulated in the appendix.

spread southward to the Bofecillos Mountains volcanic center (McKnight, 1970). Radiometric dating (Dasch *et al.* 1969) establishes the presence of a second eruptive phase 18 to 23 m.y. ago (early Miocene) and, through field relations, dates the initiation of normal faulting in the graben area (along the Rim Rock Fault).

Normal faulting and infilling of the bolson (graben) continued until integration was accomplished by the Rio Grande (Strain, 1970), which has cut approximately 300 m into lake-bed sediments (Groat, 1972). Arroyos have revealed faults in the bolson gravels that imply some late Cenozoic movement along the Basin and Range trends. This movement could be related to the southern extension of the Rio Grande Rift into the area. However, the question of the nature and location of any extension of the Rio Grande Rift south of El Paso, Texas, is controversial (Seager and Morgan, 1979), and its answer will require additional crustal structure and heat-flow studies.

The eastern boundary fault zone of the Presidio Graben consists of the Rim Rock Fault, the Candelaria Fault, and the Chinati Fault (Fig. 25). The Rim Rock Fault of the Sierra Mountains is a high-angle, normal fault, down-thrown on the west. South of Candelaria, this fault bifurcates displaying 90 m of displacement, a decrease from 900 m observed near the abandoned town of San Carlos. The Candelaria Fault, also downthrown on the west, extends from the south end of the Sierra Vieja southward to Pinto Canyon. Displacement decreases southward from 550 to 25 m. The Chinati Fault Zone, down-thrown on the west, separates the Chinati Mountains from the Presidio Bolson.

The major geologic features in the region are represented by recognizable geophysical anomalies. The Chihuahua Tectonic Belt (Sierra Grand and Sierra Pilares) west of the Presidio Graben is represented by a northwest-trending linear gravity maximum (B). The Presidio Graben is associated with a gravity low approximately aligned with the course of the Rio Grande. The Redford Bolson (gravity low, C) is located south of Presidio along the course of the Rio Grande. This bolson along with the Presidio Bolson can be interpreted to be contained within a single major feature, the Presidio Graben.

A prominent west-northwest trending gravity and magnetic high (D) is located in the area northeast of Presidio. North of this high, an east-west trending gravity low extends across the map (E). Low magnetic values are

Figure 25. Eastern boundary fault zone of Presidio County map.

also found in this area. This low probably represents the Paleozoic Marfa Basin, which, in the area of the Chinati Mountains, has been obscured by Laramide deformation, Basin and Range faulting and Tertiary volcanism. The Chinati Mountains are associated with complicated patterns of gravity and magnetic anomalies (F). This would be expected because several calderas have been mapped in this area (e.g., Walton and Henry, 1979).

The gravity signature of the Presidio Graben was interpreted using computer modeling along the two profiles discussed in the next section. The graben, 70 km long and 15 to 20 km wide, is deepest (approximately 1.5 km) in the Ruidosa area. The higher gravity gradient on the graben's west side (in Mexico) indicates that this side is more steeply faulted than the eastern side. Sedimentary fill in the Presidio Bolson thins north of Ruidosa and pinches out south of Candelaria. However, a gravity low continuing 15 km north of Candelaria indicates the extent of the graben. The bolson fill is thickest in the area immediately south of Ruidosa. Farther south, the subsurface structure of the graben is apparently simple and the fill thins gradually before merging into the Redford Bolson approximately 15 km south of Presidio.

The gravity and magnetic data suggest a complex subsurface structure in the Ruidosa area. However, this interpretation is equivocal because the geologic setting suggests that significant volumes of volcanic rock lie beneath the bolson fill in this area and could be responsible for this complexity. Tertiary intrusions similar to those found northwest of the Loma Plata Anticline (Amsbury, 1958) could also produce the small anomalies seen in this area. Delineation of the details of the subsurface structure of this area must await further drilling information.

Three prominent local anomalies (two gravity lows bracketing a gravity high) are located between Capote Peak and Candelaria (on the Marfa quad). Because of the significant topographic relief in the area, terrain corrections were calculated for selected gravity stations. These anomalies are too large to be simply the result of terrain effects because the maximum terrain correction calculated was 11 mgal and most were much smaller. Step faulting of Tertiary volcanics into the bolson and Laramide structures trends north-south in this area. Thus, these northeast-trending features

may reflect Paleozoic structures related to those in the Marathon region to the east.

Well data served as a valuable constraint in the gravity modeling along with surficial geologic data. Well data collected for this study are shown in Figure 24 and Table 1. A comprehensive review of previous geologic studies can be found in Kopp (1977) and in Henry (1979). Considering the data resolution and the available geologic control, only the following geologic units were modeled: bolson fill (1.9 g/cm^3), Tertiary volcanics (2.0 g/cm^3), Tertiary intrusives (2.65 g/cm^3), Paleozoic sediments (2.6 g/cm^3), and the Precambrian basement (2.7 g/cm^3). Because no bulk density logs were available for Presidio County, these density values were chosen on the basis of measurements reported by Healey (1970) (bolson fill and Tertiary volcanics) for a geologically similar area of Nevada and by Wilson (1951) (Cretaceous and Paleozoic sediments) for the Marfa Basin area. The lack of density information limits the resolution of the gravity interpretation.

Both earth models extend to a depth of 8 km along the datum elevation. The datum plane elevation was the elevation of the lowest gravity station on each profile (783 m for the Shafter Highway profile; 795 m for the Pinto Canyon profile). It is important to note that normal faulting in the Presidio area has downdropped Paleozoic and Cretaceous rocks so that at depth in the graben these units are probably adjacent to higher density basement rocks. Thus, some of the negative anomaly associated with the graben would be a result of a negative density contrast associated with these units.

On the Pinto Canyon profile (A-A'; Fig. 26), the Chihuahua Tectonic Belt, Mexico is represented by a gravity high, whereas the Presidio Bolson is manifested in a gravity low. The Gulf Oil test well (Table 1; no. 6) located 5.6 km south of the profile was cased to a depth of 975 m. This value is interpreted as the depth of bolson fill at this point since formation contact depths were not released for this well. This interpretation is based on the assumption that casing could have been necessary to prevent caving and lost circulation of drilling mud in the highly permeable fill. However, many wells in Presidio County were cased through Tertiary tuffaceous rhyolites and it is therefore possible that part of what has been interpreted as 975 m of bolson fill could include Tertiary volcanics.

Figure 26 Gravity-structural cross section along profile A-A' (Pinto Canyon Highway profile). Numbered triangles refer to wells identified in the appendix. Density values (g/cm^3) are given in parentheses following boxes.

Along this profile, the Candelaria Fault forms the eastern boundary of the graben. The gravity high in the vicinity of the Sierra Vieja represents a shallowing of the Precambrian basement and/or an intrusion. Linear gravity trends east of this high indicate an eastern boundary fault for the Sierra Vieja. The gravity low east of the Sierra Vieja is apparently associated with the Marfa Basin. Northeast of the Marfa Basin, the Valentine Basin (Covert, 1976) is represented by another gravity low. The intervening high represents a ridge in the basement that trends northwest-southeast. In the Marfa area, Gulf's H. J. Hubbard well, Phillips' 1-C Mitchell well, and Tucker's H. B. Holmes well (Table 1, nos. 14, 13, and 12) indicate that the Tertiary volcanics are at least 500 m thick. The Davis Mountains are the probable sources for these volcanics.

On the Shafter Highway profile (B-B'; Fig. 27), the Paleozoic Marfa Basin is represented by a gravity low south of Marfa, Texas. This basin thins southward toward the Chinati Mountain gravity high near Shafter, Texas. The West-Cockburn's No. 1 Presidio Trust well (Table 1, no. 26), 26 km north of Presidio, encountered at least 1 km of basin fill before bottoming in limestone, as did West's No. 1 Presidio Trust well (appendix, no. 25) and Atlantic Richfield's Presidio State well (Table 1, no. 22), 7 and 9 km north of Presidio, respectively. The basin is deepest (1.2 km) on this profile in the immediate vicinity of Presidio. A gravity high representing the Chihuahua Tectonic Belt is encountered to the south in Mexico.

Gravity and Magnetic Anomalies of the Emory Peak Quad

The Emory Peak quad contains a major transition in terms of geological features. One third of the quad is dominated by Basin and Range structure and the Trans-Pecos volcanic field. This is evidenced by a complicated pattern of magnetic anomalies (A) and west-northwest to north-northwest trends (B) in both the gravity and aeromagnetic data.

The eastern two-thirds of the quad is dominated by the Ouachita orogenic belt which crops out only in the Marathon area and the Solitario. This orogenic belt trends northeast in the central portion of the quad (C) and bends to an east-southeast trend (D) in the northeasternmost portion of the quad. Both gravity and magnetic anomalies follow the trend of this fea-

PROFILE B-B'

□ OBSERVED
x THEORETICAL

GRAVITY (MGAL)

DEPTH (KM)

DISTANCE (KM)

Figure 27 Gravity-structural cross section along profile B-B' (Shafter Highway profile). Numbered triangles refer to wells identified in the appendix. Density values (g/cm^3) are given in parentheses following boxes.

ture. Large volumes of sediment collected in the Marathon Basin during the Ouachita orogeny. The subdued magnetic anomalies (E) in the area (eastern two-thirds of the quad) attest to the deepening of the basement. Gravity anomalies in this area are also more subdued, but their absolute values increase (F) which suggests a major transition in crustal structure. Such a transition is expected because there is a major fossil plate boundary in the area (Keller and Cebull, 1973; Cebull et al., 1976).

Other features worthy of note include a northwest trend (G) of gravity (and to some extent magnetic anomalies) in the central portion of the quad. This trend is perpendicular to the dominant northeast trend (Ouachita system) in the area. Another northwest trend (H) extends from the northern Big Bend National Park area across the area north of the Solitario. The Solitario is associated with a gravity and magnetic high (I). These northwest trends probably reflect the extension of the Basin and Range and/ or the Laramide thrust belt through the area. The volcanic features in the area are probably superimposed upon a region where the basement is generally deeply buried. The aeromagnetic anomalies are surprisingly smooth in the Big Bend Park area which contains several major volcanic centers. The north-south trends in this area (J) are probably related to the Ouachita system. The strong east-west gravity in the northwesternmost portion of the quad (K) is probably the southern margin of the Hovey Channel which connects the Marfa and Delaware basins.

Gravity and Magnetic Anomalies of the Fort Stockton Quad

Most of the Fort Stockton quad is underlain by the southern Delaware Basin. This is evidenced by the large northeast-trending gravity low (A) which dominates the central portion of the quad and the subdued magnetic anomalies in this area. The shallow basement beneath the Central Basin Platform is outlined by increased magnetic gradients and a gravity high in the northeast corner (B) of the quad. The Davis Mountains Volcanic Field extends into the western portion of the quad and the extrusives present produce a complicated pattern of magnetic anomalies (C). A large intrusion is indicated near Cathedral Mountain (D). The southwestern edge of the quad contains pronounced, north-south trending, linear gravity and magnetic highs

(E). One possible explanation for these anomalies is that they are related to a source for the Davis Mountains volcanic field. However, a basement uplift marking the western boundary of the Delaware Basin appears equally feasible. The west-northwest trends in the southeast corner of the map (F) reflect the effect of structures associated with the Val Verde basin. The correlative gravity and magnetic anomalies (highs and lows) in the northwest corner of the quad (G) reflect basement structure beneath the Delaware basin.

QUANTITATIVE ANALYSIS OF GEOPHYSICAL ANOMALIES

Introduction

Several quantitative techniques have been used as an aid in the interpretation of the potential field anomaly data (Figs. 28-67). Although these filtering and correlation techniques do not add new information to the data, they do isolate and/or enhance specific characteristics of the data. The same information can be obtained from the original data as from the filtered maps, but a great deal of time is needed as well as interpretational expertise to accomplish this.

These useful filtering techniques are implemented as FORTRAN computer codes written by Reed (1980). The filters are applied to the data in the frequency domain using the Fast Fourier Transform (FFT) technique. The FFT is an algorithm based on the Fourier series and as such it assumes the data are periodic and infinite in length. Because real data do not adhere to these assumptions problems do arise. One problem is that the information near the edges of the data will leak to the opposite sides of the map. Another problem is the Gibbs phenomenon which causes the longer wavelengths and anomalies near the edges of the map to become distorted. These problems can be effectively reduced with the proper procedures. Data leakage can be minimized by performing circular convolution, which is simply adding one data length of zeros to both axes. Gibbs phenomenon is minimized by tapering the edges of the data to zero.

All of the isolation and enhancement filters are applied to the data in generally the same way. The first step is to taper the edges of the data to zero which will help decrease the Gibbs phenomenon as mentioned above. For west Texas data 5% of the edges have been windowed. This windowing produces the closed contours seen at the edges of the filtered maps and ideally these should not be contoured. Once this is completed the data are transformed to the frequency domain. An ideal filter to isolate or enhance the data is designed in the frequency domain, which is then transformed to the time domain where it is smoothed utilizing a Hamming-Tukey window. For the west Texas data the filters were smoothed such that 80% of the rows and columns are passed. This large percentage yields a high resolution filter. The smoothing of the filter helps minimize the Gibbs phenomenon later when

it is applied to the data. The smoothed filter is transformed back to the frequency domain where it is multiplied with the data. The final results are then transformed to the space domain.

Several of these isolation and enhancement filters have been applied to the west Texas potential field data. The results are seen in Figures 28-67. Certain input parameters remained constant for all of the filtering functions. These parameters are the percent of the data's edges that are tapered to zero and the percent of rows and columns that are passed when the ideal filter is smoothed. These are 5% and 80% respectively, as mentioned earlier.

Reduced-to-Pole Filter - Due to the dipole nature of magnetism the earth's magnetic field varies with latitude and longitude. As a result the shape of an anomaly for a given geologic structure is dependent upon its geographic location within the earth (Reed, 1980). In the study of west Texas the magnetic anomaly data were reduced to the pole to eliminate this effect. The reduced-to-pole filter is a process by which the observed total magnetic field is transformed to a field caused by that same geologic structure with a vertical magnetic vector or simply as if the body were located at one of the earth's magnetic poles. This filtering technique is valuable in enabling interpreters that are accustomed to magnetic data from one location to interpret data with a significantly different earth's magnetic vector.

It is necessary to use average values for the declination and inclination because these values vary over the survey area. For the west Texas area, a declination of 11°E and an inclination of 59° were used in the reduced-to-pole calculations. The effect of using an average value for these parameters is that the anomalies are shifted slightly to the north. This shifting of anomalies does not significantly distort the map and therefore the remaining filtering processes of the magnetic data will be accomplished utilizing the reduced-to-pole data.

Continuation Filter - Upward continuation filtering was performed on both the gravity and magnetic anomaly data. The upward-continuation filter has two basic purposes. The first is it can be used as a smoothing process; as data are continued upward, the higher frequencies are attenuated. The second use is for studying longer wavelengths of the data without destroying

the map's physical reality, which occurs to a degree when a low-pass filter is used to achieve the same results.

In this study of west Texas the potential field data were upward continued to 2, 5, 10 and 20 km. The 2 km upward-continued data are used as a smoothing process, which helps eliminate the high-frequency components associated with noise. Because upward continuation filtering is an effective smoothing process, this 2 km data set will be utilized in the remaining filtering so that further processing will not be seriously affected by noise. The 5, 10 and 20 km upward-continued data will be used in studying the longer wavelengths of the data and to compare with the low-passed filtered data.

Wavenumber Filter - Wavenumber filtering was performed on the reduced-to-pole magnetic data, upward continued to 2 km as well as on the Bouguer gravity data upward continued to 2 km. Two general forms of the wavenumber filter are employed in this study, the low- and high-passed filters. The low-passed filtered maps include all wavelengths from infinity to 80 km and, therefore, show only the regional anomalies. The high-passed filtered maps include all wavelengths from 80 km to the Nyquist wavelengths (4 km) and therefore show only the high-frequency components of the data or local anomalies.

Strike-sensitive Filter - The strike-sensitive filter can be used to selectively pass or reject wavenumber components trending in a given direction (Reed, 1980). By selecting appropriate filters anomaly trends can be rejected which tend to mask geologically interesting anomalies. For west Texas several strike-sensitive filters were used. Two trends are seen in west Texas potential field maps; they are a northwest-southeast and a northeast-southwest trend. Azimuths were chosen to enhance and reject these trends.

Derivative Filter - Derivative filtering of the potential field maps is useful in several aspects as an interpretational tool. It can be used as a filtering technique to increase the resolution of a map by amplifying the higher frequencies while attenuating the lower frequencies.

When using a derivative filter it is best to smooth the data by either using a high-frequency cut or upward-continuation technique to avoid excessively amplifying the noise component. This is particularly important when

using the higher order derivatives because they are very sensitive to the high-frequency noise.

Only the first and second vertical derivatives are calculated in this study. In addition to using the derivative filters as an enhancement technique, the first vertical derivative of Bouguer gravity is used in studying the correlation of magnetic and gravity anomalies.

Discussion of Selected Anomalies

The Delaware Basin (Fig. 2) is characterized by a large gravity and magnetic low. The low-pass filtered as well as the upward continued maps show this feature as a minimum as would be expected because of the great depth to basement (Figs. 31-34, 37, 44-47, 51). Depth determinations of the magnetic basement also show that this basin is deep. Figure 62 lines 5WE and 6WE both indicate a marked increase in basement as well as Figure 63 line 8WE. Lines 6WE and 8WE show the eastern extent of the Delaware Basin where it is terminated by the Central Basin Platform. To the east there is a large north-northwest trending gravity and magnetic maximum which correlates well with the Central Basin Platform. Low-passed and upward-continuation filtered maps of both the gravity and magnetics show a large low-frequency positive anomaly associated with the platform, suggesting there is a deep-seated structure present beneath it. This further supports the conjecture of an intra-basement mafic mass beneath the Central Basin Platform. The magnetic and gravity anomalies correlate well over the platform. This is seen in the Local Favorability Index map (Fig. 60) and, to a lesser extent, in the correlation coefficient map (Fig. 57), due to the complex magnetic anomalies.

The low-frequency anomaly associated with the Central Basin Platform is not confined to the platform alone, but an arm extends off in a southwest to west direction. There are several high-frequency magnetic and gravity anomalies associated with this arm, best seen in the high-passed filtered maps (Figs. 44 and 50). The Local Favorability Index and correlation coefficient maps show that these anomalies correlate well with one another. These anomalies have been attributed to intra-basement masses and could very well be related to the deep-seated structure beneath the Central Basin Platform. This relationship is enhanced when a strike-sensitive filter is applied to

the gravity passing those trends in an east-west direction (Fig. 56). When a strike-sensitive filter is designed such that northwest trends are rejected (Fig. 52), the east-west trending anomaly extending from the Central Basin Platform appears to be connected to the Diablo Platform gravity anomaly, separated only by the strong negative associated with the Salt Flat Graben. However, the suggestion that there is a relationship between the two is speculative. The characteristic gravity minimum and subdued magnetic anomalies of the Delaware Basin are present south of this east-west intra-basement anomaly.

The Diablo Platform (Fig. 2) in the northwest part of the area is characterized by a north-south trending gravity high and a complicated pattern of magnetic anomalies. These complex patterns are attributed to the numerous syenite intrusions in the area. The Hueco Mountains are considered the western margin of the platform. However, the high-passed filtered magnetic maps reveal an area of subdued anomalies between the Hueco Mountains and the eastern portion of the platform. This area is also evident in the low-passed and upward-continuation filtered maps of the gravity data. It is seen as a north-south trending gravity low. The high-passed filtered map also shows a gravity low with a relief of about 12 mgals relative to the gravity high of the Diablo Platform. This gravity minimum and subdued magnetics are interpreted as an increase in the depth of the basement.

Depth determinations to the magnetic basement were calculated over this anomalous feature (Fig. 63, line 8WE). At about the 50 km mark, there is a sharp increase in the magnetic basement depth which supports the previous conclusions. This sharp change in basement depth would imply a faulted structure such as a graben.

The Davis Mountain Volcanic Field (Fig. 2), located at the center of the surveyed area is characterized by a complex pattern of magnetic anomalies. This pattern is attributed to the large volume of magnetic volcanic rocks. This is also a strong gravity high in the eastern portion of the mountains. High-passed filtering of both gravity and magnetic data (Figs. 36 and 50) reveals two distinct positive anomalies separated by a north-south trending negative. These anomalies correlate well with one another as seen in the Local Favorability Index map (Fig. 60). The correlation coefficient map (Fig. 57), however, only shows correlation between the two eastern anom-

alies. Whether one or the other or both of these anomalies are related to the source of the Davis Mountain Volcanic Field is difficult to say. There appears to be a physiographic division between the western and eastern parts of the Davis Mountains roughly corresponding to the north-south trending gravity and magnetic lows. This would favor a two-source origin for the Davis Mountain Volcanic Field. Another interpretation is that these anomalies could be due to intra-basement sources or perhaps a major subvolcanic structure.

To the south and west of the Davis Mountains are two basins overlain by Tertiary volcanics. These are the Marfa and Valentine Basins. The Bouguer gravity map shows a large negative anomaly associated with the Valentine Basin and a smaller negative over the Marfa Basin. High-pass filtering of the gravity data isolates local gravity lows for both of these basins quite well, particularly the Marfa Basin (Fig. 50). However, the Valentine Basin anomaly is much smaller than one would have expected from examining the Bouguer gravity map (Fig. 43). Low-passed and upward-continuation maps (Figs. 44-47, 51) reveal a large low-frequency, negative anomaly in the area of the Valentine Basin suggesting major crustal deficiency in mass, much larger than could be attributed to the basin alone.

The magnetic anomalies over the Valentine Basin tend to be subdued with the exception of the areas to the north and east (Fig. 28). In these areas there are large magnetic highs associated with the Chispa and Wiley Mountains to the north and the Davis Mountains to the east, which tend to mask the subdued magnetics expected over the basin. The Marfa Basin is also characterized by subdued magnetic anomalies, only slightly affected by nearby volcanics. Depth determinations to the magnetic basements are poor for these basins because of the abundant volcanics that interfere with the basin's magnetic signature (Figs. 61 and 62, lines 3WE and 4WE; Fig. 65, lines 4NS and 5NS).

The Local Favorability Index map (Fig. 60) clearly shows that the magnetic and gravity lows of these basins correlate well with one another. However, the correlation coefficient map (Fig. 57) shows no real correlation of anomalies for the Valentine Basin and an inverse correlation for the Marfa Basin. This could be attributed to the sensitivity of the correlation

coefficients to the high-frequency magnetic anomalies arising from the surface volcanic rocks.

There are several grabens present in west Texas which trend in a northwest to north-northwest direction. They are the Salt Flat Graben and the grabens associated with the Hueco Bolson, Presidio Bolson and El Cuervo Bolson. These grabens give rise to both gravity and magnetic lows. The Local Favorability Index (Fig. 60) shows these anomalies correlate well for the Salt Flat Graben and the Hueco and Presidio Bolsons. The magnetic survey only covers portions of the Hueco and Presidio Bolsons and none of El Cuervo Bolson which prevents reliable interpretation in these areas. The high-pass filtered magnetic map (Fig. 36) shows a negative anomaly delineating the Salt Flat Graben. The high-pass filtered map of the gravity does a better job of delineating these grabens, including El Cuervo Graben (Fig. 50) (Keller et al., 1980).

The southern portion of the surveyed area is dominated by the Marathon-Ouachita Geosynclinal Thrust Belt (Fig. 2). This area is characterized by subdued magnetic anomalies. Low-passed and upward-continuation filtered maps of the magnetic data (Figs. 31-34, 37) show this area as a broad negative anomaly. This suggests that the magnetic basement deepens in this area. High-pass filtering of the magnetic data (Fig. 36) reveals no high-frequency anomalies in this area except for those associated with the Marathon and Solitario Uplifts where the thrust belt is exposed.

The Bouguer gravity map (Fig. 43) shows a distinct positive anomaly in the thrust belt area. Low-passed and upward-continuation filtered maps (Figs. 44-47, 51) show this low-frequency, positive anomaly. Flawn (1961) has interpreted this as a deep-seated crustal anomaly associated with the frontal zone of the Ouachita Thrust Belt. High-pass filtering of the gravity data (Fig. 50) shows few high-frequency anomalies in this area, further supporting the theory of a deep-seated structure. Depth determinations to the magnetic basement show a marked increase in depth in this area of the Marathon-Ouachita thrust belt. This is best seen in Figure 65 in line 6NS and in Figure 66, line 9NS. Depth to basement is on the order of 8 km in this area.

Uranium occurrence is often associated with volcanic rocks, particularly intrusives and nearby basins. The western portion of the surveyed

area contains numerous intrusive bodies (Fig. 73). High-pass filtering of the magnetic data isolates local anomalies associated with many of these intrusive rocks (Fig. 36). Some of the strongest anomalies are those of known cauldrons such as the northern Quitman and Chinati Mountains (Fig. 67). The second vertical derivative of the magnetic data (Fig. 35) emphasizes the high-frequency anomalies associated with shallower, more concentrated sources. The zero curvature contour tends to outline the shape of the magnetic source. This map isolates near-surface intrusive bodies more accurately than high-pass filtering. It shows distinct anomalies associated with the northern Quitman Mountain caldera as well as the southern Chinati Mountain caldera. There is also a series of anomalies trending in a southeast direction away from the Quitman Mountains with a distinct increase in their number in the vicinity of the Davis Mountains Volcanic Field. These anomalies correlate well with known intrusions in this area (Fig. 73). There is a caldera in northern Chinati Mountains, although the second vertical derivative of the magnetic data does not reveal an anomaly associated with this feature.

The second vertical derivative of gravity is useful in isolating those near-surface bodies that give rise to gravity anomalies (Fig. 49). The Quitman Mountain caldera is seen as a positive anomaly as are many of the other known intrusive bodies in west Texas. The cauldrons associated with the Chinati Mountains are all seen as positive anomalies unlike the second vertical derivative map of the magnetic data. When the second vertical derivatives of both the gravity and magnetic data are used together, many of the intrusive bodies can be located.

These derivative maps indicate there is a possibility of uranium in the Davis Mountains Volcanic Field because of the numerous intrusions present there. Care must be taken when using these second vertical derivative maps because not all of the positive anomalies indicate intrusive bodies.

Areas that the contractor feels have a good potential for high uranium concentrations are in the areas of the Chinati Mountain cauldrons and their pyroclastics, south of the Davis Mountains (Fig. 79). The local Favorability Index map (Fig. 60) shows these areas as a negative, meaning their magnetic and gravity anomalies correlate both being negative. However, the correlation coefficient map (Fig. 57) shows that the pyroclastics have an in

verse correlation between the magnetic and gravity anomalies where as the Chinati Mountains have a direct correlation agreeing with the Local Favorability Index map.

Figure 28. Total magnetic intensity anomaly map of west Texas, North America.

Figure 29. Upward continuation of 2 km, original total magnetic intensity anomaly map of west Texas, North America.

Figure 30. Reduced-to-pole, total magnetic intensity anomaly map of west Texas, North America. A 59° inclination and 11° declination are used.

Figure 31. Upward continued to 2 km, reduced-to-pole, total magnetic intensity anomaly map of west Texas, North America

Figure 32. Upward continued to 5 km, reduced-to-pole, total magnetic intensity anomaly map of west Texas, North America.

Figure 33. Upward continued to 10 km, reduced-to-pole, total magnetic intensity anomaly map of west Texas, North America.

Figure 34. Upward continued to 20 km, reduced-to-pole, total magnetic intensity anomaly map of west Texas, North America.

Figure 35. Second vertical derivative, upward continued to 2 km, reduced-to-pole, total magnetic intensity anomaly map of west Texas, North America

Figure 36. High-passed, upward continued to 2 km, reduced-to-pole, total magnetic intensity anomaly map of west Texas, North America. Wavelengths from 80 km to the Nyquist (4 km) are passed).

Figure 37. Low-passed, upward continued to 2 km, reduced-to-pole, total magnetic intensity anomaly map of west Texas, North America. Wavelengths from ∞ to 80 km are passed.

Figure 38. Strike-passed, upward continued to 2 km, reduced-to-pole, total magnetic intensity anomaly map of west Texas, North America. The northeast (15° - 75°) azimuths are rejected.

Figure 39. Strike-passed, upward continued to 2 km, reduced-to-pole, total magnetic intensity anomaly map of west Texas, North America. The northeast (15°-75°) azimuths are passed.

Figure 40. Strike-passed, upward continued to 2 km, reduced-to-pole, total magnetic intensity anomaly map of west Texas, North America. The northwest (105°-165°) azimuths are rejected.

Figure 41. Strike-passed, upward continued to 2 km, reduced-to-pole, total magnetic intensity anomaly map of west Texas, North America. The northwest (105°-165°) azimuths are passed.

Figure 42. Strike-passed, upward continued to 2 km, reduced-to-pole, total magnetic intensity anomaly map of west Texas, North America. The east (30° - 120°) azimuths are passed.

Figure 43. Bouguer gravity anomaly map of west Texas, North America. Sea level datum 2.67 g/cc reduction density.

Figure 44. Upward continued to 2 km, Bouguer gravity anomaly map of west Texas, North America.

Figure 45. Upward continued to 5 km, Bouguer gravity anomaly map of west Texas, North America

Figure 46. Upward continued to 10 km, Bouguer gravity anomaly map of west Texas, North America.

Figure 47. Upward continued to 20 km, Bouguer gravity anomaly map of west Texas, North America.

Figure 48. First vertical derivative, upward continued to 2 km, Bouguer gravity anomaly map of west Texas, North America.

Figure 49. Second vertical derivative, upward continued to 2 km, Bouguer gravity anomaly map of west Texas, North America.

Figure 50. High-passed, upward continued to 2 km, Bouguer gravity anomaly map of west Texas, North America. Wavelengths from 80 km to the Nyquist (4 km) are passed.

Figure 51. Low-passed, upward continued to 2 km, Bouguer gravity anomaly map of west Texas, North America. Wavelengths from ∞ to 80 km are passed.

Figure 52. Strike-passed, upward continued to 2 km, Bouguer gravity anomaly map of west Texas, North America. The northeast (15° - 75°) azimuths are rejected.

Figure 53. Strike-passed, upward continued to 2 km, Bouguer gravity anomaly map of west Texas, North America. The northeast (15° - 75°) azimuths are passed.

Figure 54. Strike-passed, upward continued to 2 km, Bouguer gravity anomaly map of west Texas, North America. The northwest (105° - 165°) azimuths are rejected.

Figure 55. Strike-passed, upward continued to 2 km, Bouguer gravity anomaly map of west Texas, North America. The northwest (105° - 165°) azimuths are passed.

Figure 56. Strike-passed, upward continued to 2 km, Bouguer gravity anomaly map of west Texas, North America. The east (3° - 150°) azimuths are passed.

Figure 57. Correlation coefficient map from internal correspondence analysis of west Texas, North America. A window length of 8 km is used.

Figure 58. Slope coefficient map from internal correspondence analysis of west Texas, North America. A windlow length of 8 km is used.

Figure 59. Intercept coefficient map from internal correspondence analysis of west Texas, North America. A window length of 8 km is used.

Figure 60. Local favorability index map of west Texas, North America

Figure 61 Magnetic depth determination profiles of west Texas, lines 1-3 WE. Profile location map figure 67A.

Figure 62 Magnetic depth determination profiles of west Texas, lines 4-6 WE. Profile location map figure 67A.

Figure 63. Magnetic depth determination profiles of west Texas, lines 7 and 8 WE. Profile location map figure 67A.

Figure 64 Magnetic depth determination profiles of west Texas, lines 1-3 NS. Profile location map figure 67B

Figure 65 Magnetic depth determination profiles of west Texas, lines 4-6 NS. Profile location map figure 67B

Figure 66 Magnetic depth determination profiles of west Texas, 7-9 NS. Profile location map figure 67B

Figure 67A Location map of West-east magnetic depth determination profiles of west Texas, North America

Figure 67B. Location map of north-south magnetic depth determination profiles of west Texas, North America

GEOLOGICAL AND GEOCHEMICAL SYNTHESIS OF THE WEST TEXAS AREA

A large portion of the remainder of this report will be devoted to the contract objective of gathering and synthesizing geological and geochemical data on the area in question and adjoining regions. This information can then be used in relating to the geophysical parameters presented elsewhere, and have been referred to in the discussion of those parameters. This information will also be used to discuss potential uranium resources, particularly in light of information available on known occurrences.

Information available on the area is of several types. Detailed geologic maps have been prepared in other NURE reports, and have been included in the folio accompanying this report for the sake of completeness. Structural, igneous, and chemical diagrams are included, with emphasis on those features which are of the scale and nature potentially to relate to the geophysical diagrams. Emphasis has also been placed on those regional features which are potentially important in determining the distribution of uranium throughout the area.

A very large amount of primary geological and geochemical data has been produced as a part of the project. These site specific studies are numerous, and include data from 33 drill holes in uranium targets, numerous stratigraphic sections, and a large number of reconnaissance samples. Over 20,000 individual chemical determinations are involved in this study; however, these primary data are too voluminous to present here in tabulated form. Results will be summarized, but in many instances the interested reader will be referred to primary descriptions of samples and data to be found in referenced theses, reports, articles, and for more than half of the chemical data, to the Chemical Laboratories, Archive File, DOE-BFEC, Grand Junction, Colorado.

It is roughly estimated that DOE-BFEC subcontract activity of approximately the level of \$200,000 would have been necessary to undertake the 2500 m of drilling to acquire the drill samples studied here, and carry the project through the preliminary engineering report. The acquisition of these samples by the University of Texas at El Paso was due largely to the efforts of Drs. W. N. McAnulty, Sr. and W. N. McAnulty, Jr., and to them we are

grateful. The geological and geochemical studies accomplished on these drill samples and on others constitute the level of activity typically attributed to subcontracts at the \$150,000 level. These activities have been accomplished in the present project, and results are reported or referred to here. Portions of these and other relevant activities were done in collaboration with Bendix subcontract GJO 79-164-E, and Electric Power Research Institute Contract 1219-1.

Finally, uranium resource investigations in the west Texas region will be discussed, and geologic environments with potential resources will be noted. Quadrangle Evaluation reports of NURE are not complete yet, so a synthesis of some aspects of uranium distribution is premature. This report does not contain an integration of all NURE geochemical results; some of those data are not yet published. Such a project will necessitate a level of effort greater than the present contract. Conceivably internal correspondence could be applied to geochemical data.

The geologic history of the west Texas region has been reviewed elsewhere in this report. Selected crustal features will be noted here in light of the questions at hand. Characteristics of the Precambrian basement of the northwestern portion of the area under consideration are given in Figure 68, with ages varying from 950 m.y. to over 1350 m.y. Of these various terranes, the Franklin Mountains Igneous Province is identified in this project as favorable to hosting uranium resources. Site specific studies in the Franklin Mountains themselves, reported later, document the presence of a Bokan Mountain-type environment (autometasomatic, class #350, Table 1). This startling discovery together with the terrane distribution given in Figure 68 lead to the suggestion of additional such environments being present under thin Paleozoic cover on the Diablo Plateau, such as in the southern Hueco Mountains and near Pump Station Hills.

The possibility of unconformity-related uranium deposits (class 710) existing beneath the late-Proterozoic unconformity at the base of the late Precambrian (?) Van Horn sandstone has been investigated by a separate NURE study (Davidson et al., 1980). Several anomalous areas were identified but were not considered important enough to warrant further study. However, considering the frequently unimpressive geochemical anomalies found over many of the major deposits of this type, Jabaluca, etc., perhaps these anom-

Figure 68. Basement geologic map of west Texas and southcentral New Mexico.

alies should not be neglected. Furthermore, there exists in the Van Horn area another Precambrian unconformity having perhaps even greater uranium potential. The top of the Allamore Formation and the base of the arkosic Hazel Formation is this second unconformity, and the character of the rocks involved, the presence of numerous sulfide deposits near the top of the Allamore, and the greater age of this unconformity, all suggest that it could be an important target for uranium. The distribution of Precambrian terranes beneath the remainder of the west Texas region is not well documented.

Regional geologic features of Paleozoic genesis include the Ouachita tectonic belt of which the Marathon Dome (Fig. 67, or 69) is a spectacular expression. Various basins including the Marfa, Delaware and Midland, are important features from this time. Important Mesozoic features are indicated also in Figure 69, and include the Diablo Platform-Coahuila Platform boundary with the Chihuahua Trough. The trough consists of basinal sediments, and extends to the west and southwest nearly to Chihuahua City, Mexico. At the trough boundary with the Aldama Platform on the west is located the Pena Blanca Uranium District, which is discussed below. Late Mesozoic to early Cenozoic tectonism was present in the western part of the west Texas region and constitutes the overthrusting of Cretaceous sediments to the northeast of a part of the Chihuahua Tectonic Belt. This overthrust zone is presently a very active petroleum and gas exploration target.

Superimposed upon these various features occurred in the middle to late Tertiary several events of regional extent. Subduction derived calc-alkaline igneous activity encroached onto the region, presumably from the southwest. According to Barker (1979), Damon *et al.* (1981), and McDowell and Clabaugh (1979), there is a regional zoning of igneous rock compositions, with the more metaluminous calc-alkaline to the southwest and alkaline to the northeast, as shown in Figures 71 and 72. Current ideas (Keith, 1978) place this region above a subduction zone of very shallow dip. Numerous felsic calderas also characterize this time, with a minimum of six of them probably being present (Fig. 69), and the large Davis Mountains Volcanic Field being less well described geologically. The distribution of phonolite and nepheline syenite of Tertiary age is given in Figure 72. Distribution of inferred intrusives at depth is shown in Figure 72. Areas cov-

Figure 69. Generalized tectonic map of Trans-Pecos, Texas, emphasizing Mesozoic and Cenozoic features.

ered by Tertiary volcanics are also indicated in Figure 73. All of these features can be compared with the geophysical parameters.

Finally, Basin and Range faulting and/or Rio Grande rifting has been superimposed upon Trans-Pecos Texas, with numerous of these normal faults and grabens being indicated in Figure 69. The alkali volcanism of west Texas is perhaps derived from subduction zone tectonics as mentioned earlier; however, the possibility also exists that the alkali igneous province originated as a precursor to rifting. That is, alkali volcanism is associated with continental arching prior to a rift event. The regional study of magmatism in west Texas is particularly intriguing because the area was undergoing a change from compressional to tensional plate tectonic environments.

Selected whole-rock chemical studies on numerous samples from west Texas have been summarized by McDowell and Clabaugh (1979) (Fig. 71), who distinguished the alkaline trend from the calc-alkaline one to the southwest. Investigation of log U/log Th relations among igneous rocks of west Texas as accomplished in this project show some interesting features. Figure 74 indicates a trend determined from data from Clark (1966) illustrating the behavior of common igneous rocks. Also on this diagram is the synthesis of data from Woodrum (1980) on 172 samples from which both whole rock and K-U-Th determinations were made. These latter data show a very interesting trend towards even greater uranium enrichment in rocks of phonolite composition. Magmatically, uranium increases with progressive differentiation. This trend does not necessarily follow silica content, however, as phonolite shows even greater uranium enrichment than rhyolite. Figure 74 also suggests that uranium resource favorability will be greater near the phonolites. This figure however bears no resemblance to the overall NURE favorability for west Texas as shown in Figure 70. It does explain the regional uranium anomaly on the Diablo Platform. That is, Figures 72 and 130 show the distribution of silica undersaturated igneous rocks and Figure 74 shows the observed increase in uranium in phonolites. It can be stated that Cenozoic igneous rocks increase in uranium in Hudspeth County, Figure 72. from south to north and west to east. This is reflected in groundwater geochemistry (Fig. 129) and the numerous intrusions often present respectable airborne radiometric anomalies. To the southeast in this silica undersaturated

Figure 70 Regions of speculative potential resources in the area of study (Dept. of Energy, 1980)

Figure 71. Compositional variations of Tertiary volcanic rocks from west Texas and northern Mexico (from McDowell and Clabaugh, 1979).

Figure 72. Distribution of inferred intrusives, distinguishing phonolite and nepheline syenite (silica-undersaturated rocks) from silica-oversaturated ones.

Figure 73 Distribution of Cenozoic igneous rocks, and calderas

Figure 74 Log Th/Log U for igneous rocks in west Texas

Average U and Th, West Texas, by rock,
data from Woodrum, 1980.

zone, Black Mountain (Reeves et al., 1978) would be another example of this type of radiometric anomaly. From the uranium resource viewpoint, this type of anomaly rarely has occurrences of primary or secondary origin, and has no deposits. It is an anomaly type which can reasonably be omitted from the uranium resource category.

In the Trans-Pecos Volcanic Field, significant uranium potential appears to be more closely associated with silica-oversaturated igneous rocks (Fig. 72) and/or metaluminous ones, or their volcanoclastic derivatives. The areas of highest favorability in Figure 70 are the Buckshot Ignimbrite, Shely Prospect, the Pruett-Duff Formation, and areas near Hen Egg and the Christmas Mountains.

Potential uranium environments in west Texas can be quickly summarized in Figure 75, which gives an integrated synthesis or model of the origins of uranium in volcanic and volcanoclastic environments (Goodell et al., 1981). Table 2 lists the environments indicated in Figure 75 and correlates them with NURE classifications. This model should be kept in mind while reading the site specific descriptions which follow. The model in detail must be applied by the interested reader to each of the numerous calderas in the Trans-Pecos area (Fig. 69). Each of these calderas has its own variation of the idealized evolution of the caldera systems as given in Table 3. The details of potential uranium mobility and deposition become even more complex. The site specific descriptions which follow show convincingly that uranium has indeed been moving in the west Texas Tertiary volcanogenic system. Several noted uranium occurrences are reported here from drilling results.

It is thought that the uranium explorationist has not yet applied the right idea to the right place, although the 1970's saw a significant amount of industry drilling in the region. Uranium resource potential of the region certainly covers an area larger than that designated by NURE.

During the period of intense interest in uranium of the middle 1950's, several studies of occurrences were made by government geologists. Eargle (1956) reported on two areas, the King and Hueco Mountains. At King Mountain uranyl vanadates were found coating fracture places in Cretaceous limestones, associated with limonite and clay. Radiometric uranium determinations ran between 10 and 40 ppm though one sample with visible uranium min-

Figure 75. Model of potential uranium environments in volcanic and volcanoclastic terranes (Goodell et al , 1981; see Table 2 for legend).

eralization had a value of 3.7 wt. % uranium. This known uranium occurrence was not detected by the NURE aeroradiometric survey GJBX-2(78), as it lies half-way between flight line 4-0 and 5-0. As a part of the present project this area has been investigated on the ground and extensively sampled. Sample descriptions and K, U, Th contents are given in Table 18, and the results plotted on a triplot (Fig. 128) show the mineralization trend. Although this specific occurrence has not been recognized by airborne radiometric studies, several anomalies of the same type do appear in the Pecos quadrangle. Anomalies numbered 25, 43, 44, 45, and 47 are the ones referred to, and they occur in the southeastern or eastern portion of the quadrangle. They appear associated with the Fredericksburg Group. Eargle (1956) suggests that the source of uranium may be from leaching of the once overlying Ogallala Formation, or perhaps from leaching of the overlying Kiamichi Formation.

A second group of uranium occurrences described by Eargle (1956) occurs in the Hueco Mountains, in the northwest portion of the Van Horn quadrangle. Uranyl vanadates were found coating fracture planes in Permian limestone, and also in cementing material in recent colluvium. One described occurrence is in Hueco Gap on U.S. Highway 62, which lies half-way between flight lines 19-0 and 20-0, at their western ends, and it does not show up on the GJBX-2(78) anomaly map. Other occurrences are located just off the western margin of the Van Horn quadrangle and were not covered by the aerial radiometric survey. Anomaly numbers 24, 26, 28, 31-40, 42, 43, and 45 may be of this type. In addition to the Huecos, these anomalies include Baylor and the Delaware Mountains. At the occurrence in Hueco Gap, carnotite was accompanied by calcite, illite and manganese oxide, with radiometric uranium contents reaching 170 ppm and chemical uranium reaching 230 ppm. Eargle (1956) notes that the uranium occurrences are closely related to the present erosion surface, and possibly formed from downward moving groundwater. The present authors suggest that the source rock may have been tuffs or tuffaceous sediments from mid-Tertiary calderas nearby. Alternatively, the source rock may have been the numerous syenitic stocks and laccoliths of Tertiary age which occur in the Hueco Mountains, some of which are known to be enriched in uranium. Numerous intrusions have been analyzed during the

course of this study. A source rock, however, is lacking for the Delaware Mountains anomalies.

Curtis (1978) undertook a hydrogeochemical reconnaissance for uranium in Trans-Pecos Texas, and discovered several anomalies. His results are summarized in Figure 129. Those anomalies which are located on the Van Horn and Pecos quadrangles will now be compared with the aerial radiometric study (Geometrics, 1978). Anomaly #2 of Curtis is in the Hueco Mountains, located in the very northwest corner of the Van Horn quadrangle and to the west. This ground water anomaly was based on only seven samples, with uranium contents as high as 26 ppb. It includes the area of uranium occurrences reported by Eargle (1956) and also includes a number of Tertiary felsic intrusives determined by Curtis (1978) to have up to 16 ppm uranium. No aerial radiometric anomalies were reported from this area, though #43 lies a short distance to the east.

The hydrogeochemical study has indicated another anomalous area in the northeastern portion of the Diablo Plateau. Uranium contents of the waters are as high as 48 and 85 ppb, with 35% of the samples containing anomalous values. The area is roughly coincidental with a series of mid-Oligocene alkalic intrusions, one of which was found by Curtis (1978) to contain 14 ppm uranium. Aerial radiometric anomalies (Geometrics, 1978) over the area consist of #46 and 47, which are negative Th/K anomalies. These occur because of the alkali-rich nature of the igneous intrusives. Uranium anomalies #3, 40, 41, 42, and 43 may have their source in this series of intrusives. If this is the case the ground water anomalies are closer to the source, with aerial radiometric anomalies being further out, or more dispersed. These intrusions are shown on the sketch map in Figure 130.

The Salt Flat area west of Guadalupe Peak contains a hydrogeochemically anomalous region that contains two aerial radiometric anomalies within it, #44 and 45.

Uranium contents in the waters are as high as 54 and 63 ppb. The radiometric anomalies are not strong. The coincidence of water and aerial uranium anomalies probably occurs from concentration of the uranium during evaporation. The source may be in the alkalic intrusives to the west.

The Sierra Blanca Peaks region contained only three water samples, two of which reported 6 ppb and one 28 ppb uranium. These are all anomalously high, but the water anomaly is weak. In contrast, the radiometric survey indicated that this region has the strongest airborne anomaly of the two quadrangles. The airborne results suggest that the larger part of the uranium is in the alluvium immediately surrounding the intrusives. Fresh rock uranium contents are 30 to 40 ppm (Figs. 81 and 82).

The Quitman Mountains are in the southwest corner of Van Horn quadrangle. The Square Peaks volcanics are inner caldera facies and accompanying intrusives represent the ring dike and resurgent (?) magma. The igneous activity is mid-Tertiary; relationships with the Sierra Blanca laccoliths immediately to the northeast are unknown. Numerous zones of mineralization exist within the area, and aerial radiometric anomaly #12, a negative Th/K anomaly, reflects the potassic alteration associated with the hydrothermal mineralization present at the Bonanza Mine. Potassium, uranium, and thorium contents determined by gamma-ray spectroscopy on samples from mineralized zones in the Quitman Mountains were discussed earlier. The Quitman Canyon pegmatite has 700 ppm thorium, and 91 ppm uranium. The high Th/U ratio suggests these elements may be in monazite, or some other rare earth mineral in the pegmatite. The areal extent of this outcrop is small and this anomaly was not identified on the aerial radiometric survey. Flight line 3-1 passed 1 1/2 km to the north of the known outcrop. Bonanza vein mineralization and Tremble Hill skarn show enrichments of uranium. The vent zone samples are enriched in potassium; the skarns are also, though to a lesser degree.

Woodrome (1980) investigated the relationship between uranium anomalies in ground water and surface rocks in Trans-Pecos Texas. His results indicate that ground water uranium anomalies are associated with uranium anomalies in proximal igneous intrusion.

Sampling

Woodrome (1980) collected 250 surface rock samples in Trans-Pecos Texas, covering El Paso, Hudspeth, Culberson, Jeff Davis, Presidio, and Brewster Counties. The majority (207) was from 55 intrusives scattered over the region, some of which are shown in Figure 130. The remainder (43) were samples of sedimentary rocks and chalcedony. He analyzed these samples for

Figure 128. K, U Th triplot, King Mountain, McCamey, Texas (data from Table 18).

Figure 129. Hydrogeochemical results from uranium in Trans-Pecos, Texas.

Legend for Figure 130 (from Woodrome 1980)

- A. Intrusion in valley north of Cerro Alto
- B. Cerro Diablo
- C. Alacran Mountain
- D. Cornudas Mountain
- E. Alamo Mountain
- F. Flat Top Mountain
- G. Augite Syenite intrusion
- H. Black Mountain
- I. Deer Mountain
- J. Wind Mountain
- K. San Antonio Mountain
- L. Washburn Mountain
- M. Chatfield Mountain
- N. 16 Mountains
- O. Dog Mount
- P. Miller Mountain
- Q. Mayfield Valley intrusion
- R. Cerro Diablo
- S. East Mountain
- T. Cornudas Station intrusion
- U. Red Hills
- V. Sierra Prieta intrusion
- W. Granite Mountain
- X. Finlay Mountains
- Y. Sierra Blanca intrusion
- Z. Quitman Mountain

Figure 130. Sketch map of the Diablo Plateau intrusions.

potassium, uranium and thorium by gamma ray spectroscopy. In addition, he performed major oxide analysis by x-ray energy dispersive fluorescence (ORTEC). A summary of these data by rock type is given in Table 19, and Th and U contents have been used to construct Figure 74. Histograms by locality are shown in Figures 131a and b.

The ground water analyses used by Woodrome were taken from Curtis' (1978) study of 1020 ground water samples from Trans-Pecos. These are summarized in Table 20 and Figures 132a and b. Woodrome delineated 25 ground water drainage basins in the region on the basis of topography and subsurface geology. Correlation of elements with uranium in each drainage basin is found in Tables 21 and 22, and Fig. 133).

Surface Sample Anomalies

A summary of the distribution of uranium in surface samples appears in Table 23. Eight regions displayed significant uranium anomalies, defined for this area as concentrations in excess of 16 ppm U. In the Cornudas Mountains values as high as 24 ppm U were encountered. Chalcedony from the Davis Mountains contained up to 21 ppm U. Organ Pipe Hill yielded a vein sample with 97 ppm U. A sample from Chilicotal Mountain in Big Bend National Park contained 18 ppm U. A sample from Chilicotal Mountain in Big Bend National Park contained 18 ppm U. Nine samples from the Sierra Blanca intrusives averaged 14 ppm U with a high of 33 ppm U. Chalcedony from the Cienega Mountains contained 37 ppm U.

Ground Water Anomalies

A summary of the distribution of uranium in ground water is presented in Figure 132. Curtis (1978) outlined 12 areas with ground water anomalies, defined on a regional basis as concentrations in excess of 21 ppb (parts per billion) U. These areas were: the east side of the Franklin Mountains, the Hueco Mountains, southeastern El Paso County, northeastern Diablo Plateau, Salt Flat, Sierra Blanca Peaks, Sierra Vieja, Cuesta del Burro, Chianti Mountains, Mesa area, Alpine, and Dagger Flat Anticlinorium.

Interpretation

Five of the anomalies defined by Curtis (1978) correlated with the surface sample anomalies of Woodrome (1980). These were: the northeastern

Figure 131a. Histogram of uranium contents of igneous rocks by area (from Woodrome, 1980).

Figure 131b. Histogram of uranium contents of igenous rocks by area (from Woodrome, 1980).

Figure 132a. Histogram of uranium content in groundwater, west Texas (from Curtis, 1978).

Figure 132b. Histogram of uranium content in groundwater, west Texas (from Curtis, 1978).

Figure 133. Drainage basins of Trans-Pecos, Texas (from Woodrome, 1960).

Diablo Plateau, Salt Flat, Sierra Blanca Peaks, Chianti Mountains, and the Alpine area.

Northeastern Diablo Plateau - The ground water anomaly covers 1865 km² and was defined by 17 water samples. Mean U was 17.2 ppb, with a high of 85 ppb. Drainage from the Cornudas Mountains enters this ground water and is likely the source of the anomaly.

Salt Flat - This anomaly covers 490 km² and was defined by 12 samples. The average ground water uranium content was 21.5 ppb, with a maximum of 63 ppb. This basin also receives runoff from the Cornudas Mountains.

Sierra Blanca Peaks - This anomaly covers 80 km² in a region to the north of the Sierra Blanca intrusives. Three water samples averaged 13.3 ppb U, with a maximum of 28 ppb. This region receives almost all the runoff from the Sierra Blanca rhyolite intrusives.

Chianti Mountains - This anomaly covers 255 km² and is based on seven samples with an average of 8.1 ppb U and a maximum of 23 ppb U. This minor anomaly is matched to the volcanic and intrusive rocks of the Chinati and Cienega Mountains, samples from which contain in excess of 9 ppm U.

Alpine Area - This anomaly covers 80 km² and is defined by eight ground water samples with an average concentration of uranium of 8.6 ppb and a maximum of 22 ppb. The Davis Mountains volcanic field is an obvious source for this anomaly.

Conclusions

The surface uranium anomalies defined in this study are related to alkalic igneous rocks that are products of progressive magma differentiation. Uranium concentrations in the region appear to be related more to these materials than to pervasive mineralization. Ground water samples accurately reflect the location of these surface uranium anomalies. This indicates that commercial concentrations of uranium may ultimately be discovered by careful reconstruction of paleo-drainage in the region.

SITE SPECIFIC GEOLOGICAL AND GEOCHEMICAL STUDIES

Studies of 11 areas are reported below, in reference to their uranium potential as determined in the present project. These occurrences are given a NURE classification according to their geologic environment and, where relevant, are attributed to an environment in Figure 75. These occurrences need to be viewed in the context of documenting uranium-enriched regions and environments in west Texas, although these specific studies are by no means inclusive of all uraniferous areas. These studies should be borne in mind for the subsequent section of this report which reviews other uranium resource investigations in west Texas, and for the correlation of uranium with geophysical parameters.

Quitman Mountains

The northern Quitman Mountains have been geologically investigated by Huffington (1943), Albritton and Smith (1965), and Hobbs (1979). These will be particularly helpful in the geologic discussion which follows. Vertical cross sections constructed from Albritton and Smith (1965) and by Hobbs (1979) are given in Figures 76 and 77, respectively. The cross section given in Figure 76 has been designed to integrate elements of the regional geology and particularly to relate to the Sierra Blanca intrusives. Tertiary igneous rocks are superimposed upon Cretaceous and minor Paleozoic sedimentary rocks which have been extensively overthrust to the northeast during the Laramide orogeny. This geologic setting is similar to that found in the Eagle Mountains immediately to the southeast. The area has been subsequently modified by Basin and Range faulting and lies at the intersection of this zone with the Rio Grande Rift.

The Quitman Mountains lie just to the southwest of the Texas Lineament (Fig. 76), a structural-stratigraphic feature of great and long lasting significance. Although the exact nature of the lineament is not known and although many origins have been attributed to the feature, it probably represents a late-Precambrian continental margin. Subsequently, in the Mesozoic, it was the northeastern boundary of the Chihuahua Trough and later became superimposed in places by the overthrust belt. Such a major tectonic

Figure 76 Schematic N-S cross section through the northern Quitman Mountains and Sierra Blanca laccolith

A N94E → WEST EAST

SILVER KING CANYON
As-Pb-Zn-Ag-Cu

Ring Fracture Intrusive West side Fault East side Fault Ring Fracture Intrusive Bug Hill

Quimban Peak

EAST

Red Light Belton

7000
6000
5000
4000
3000
2000

Kb Tpm Qel

Quimban Caldera

B N90E → WEST EAST

Superior Peaks

Ring Fracture Intrusive East side Fault Ring Fracture Intrusive

Qel

EAST

Red Light Belton

7000
6000
5000
4000
3000
2000

Kb Tpm Qel

C N178E → NORTH SOUTH

Bonanza Mine, As-Pb, and neighboring Bonanza Resources, minor or up to 0.7 wt% U₃O₈ reported

Pinecone Pass

Zimmerman Pass, extensive alluvium

Quimban Peak

Late Stage Rhyolite Flow Dome

Hectors Knob

Flowers vch

Superior Peak

Ring Fracture Intrusive

STOCK

Rearguard Intrusion?

Surface ore 500-2500 lbs 400 s/lr 700 ppm Cu = 92 ppm Ni = 90 ppm Mn = 30 ppm

Pyroclastic Glass in Ky

SOUTH

7000
6000
5000
4000
3000
2000

No vertical exaggeration

Scale: 0 1 Mile / 0 1 Kilometer

Legend:

- Square Peak Volcanic Series -
- Hectors Knob Tuff - rhyolite
- Merc Canyon Tuff - trachyte
- Quimban Peak Tuff - latite
- Love Lithic Tuff - latite-quartz latite
- Square Peak Purple Tuff - latite-quartz latite
- Peace Hornblende Tuff - andesite-latite
- Cowan Crystal Tuff - latite-andesite
- Bug Hill Tuff - trachyte
- Double Canyon Tuff - rhyolite
- Bluff Mesa Limestone
- Yucca Formations
- Torcer Formation
- Fault
- Contact (dashed where inferred)

Figure 77. Vertical sections through the northern Quitman Mountains (from Hobbs, 1979, Plate II).

boundary compares favorably with numerous localities where uranium is hosted in volcanic rocks, such as Marysville, Utah, Pena Blanca, Mexico, and McDermitt, Nevada-Oregon (Goodell et al., 1981).

A more detailed discussion of the evolution and emplacement of the igneous rocks in the Quitman Mountains is warranted, due to the fact that this environment is frequently associated with uranium. The Square Peak volcanic series exceeds 1100 m in thickness and represents a minimum volume of 35 km³ of erupted material (Hobbs, 1979). The unit is specifically the inner caldera facies, and accumulated over the down-dropped central block of the caldera. Outcrop of the Square Peak volcanics is almost entirely surrounded by a narrow to thick quartz monzonite intrusion, which is interpreted to be the ring dike of the cauldron. A large quartz monzonite intrusion lies just to the north of the Quitman caldera, and is thought to represent the resurgent phase of the caldera sequence. These features are seen in Figures 76 and 77. It is frequently found in the U.S. southwest that calderas of this general age have their resurgent intrusions displaced to the north or northeast of the caldera. This phenomenon is caused as a response to regional stress characteristics at the time. Geologic studies in the Quitman Mountains (Fig. 77) indicate that caldera collapse is hinged on the northeast margin.

The Square Peak volcanic series is composed of nine chronostratigraphic units as identified by Hobbs (1979), and shown in Table 4. The rocks are generally rhyolitic to latitic to trachytic welded ash-flow tuffs, with minor rhyolite flows and air fall material. Several rhyolite flow domes are identified, such as Hector's Knob. The volcanic sequence may contain more than one cycle of caldera evolution, as the whole-rock chemical studies cannot be simply explained (Table 5) (Hobbs and Hoffer, 1980). Gamma spectrometer data of samples from several mineralized areas in the Quitman Mountains is given in Table 6 and plotted in Figure 78. The first five samples give low uranium values for skarn and hydrothermal mineralization in the area. Even lower thorium values are present, giving extremely low Th/U values. The Bonanza vein in the north Quitmans shows a slight uranium enrichment with a value of 17.5 ppm. That even greater enrichment is not present is surprising in light of the fact that this mineralized zone has sig-

Figure 78. K, U, Th triplot of Quitman Mountain sample localities (Albritton and Smith, 1965).

nificant molybdenum values. Molybdenum and uranium are frequently associated both at the magmatic stage and in low temperature sedimentary deposits.

The Quitman Canyon pegmatite (QM12) is a zone which was discovered and sampled while mapping was in progress (Hobbs, 1979; Murry, 1980). This deposit lies near the caldera ring fracture zone at the very southern extent of the caldera and in a zone where the ring fracture intrusion reaches its greatest width. The sample has 700 ppm Th and 91 ppm U. The chance of discovery and sampling of this deposit is remarkable and is a significant contribution of the project. Such large concentrations of uranium and thorium in the Quitmans has never been reported before, and the pegmatite zone has the characteristics of being extensive. The area is too poorly known for further elaboration, but certainly warrants additional investigation. A GeoMetrics flight line passed 1/2 km to the north of this occurrence, but gave no response.

The final three samples in Table 6 are fluorite. Uranium contents in fluorite can be a sensitive indicator of uranium availability and mobilization during the time of fluorite mineralization. This fluorite is found in volcanics in a two-foot wide vein approximately 2 km south of Hector's Knob, a rhyolite flow dome of post caldera collapse emplacement. The fluorite may have been deposited from convecting hydrothermal fluids associated with the emplacement of the Hector's Knob intrusion. This fluorite contains very little uranium, .03, .29, and .39 ppm equivalents, particularly in contrast to the contents commonly shown by fluorite elsewhere in the region. Another favored regional uranium indicator (Goodell, 1978), uraniferous chalcedony, has not been found in the area.

A triangular composition plot of the K, U, and Th determined by gamma spectroscopy is given in Figure 78. The samples represent rock units, mineralized areas, and pure fluorite (Fx). The data suggest a decrease in Th/U ratio from the southern boundary of the caldera (the thorium-rich Quitman Canyon Pegmatite) to the north. The Bonanza Mine and Zimpleman Pass skarn are relatively uranium enriched and thorium poor.

Murry (1980) reported anomalous amounts of the following trace elements: .02, .04, and .07 wt.% U_3O_8 from samples of galena-sphalerite vein material from the Bonanza Mine; Mo and W in Silver King Canyon and at the Quitman Gap Pegmatite, plus Sn and Be at the latter; Sn, W, Zr, Nb, Be,

F. and Mo at Granite Hill; Sn and Be at Tremble Hill; and W in a skarn west of the Bonanza Vein. Several of these occurrences are on the boundary faults of the Quitman Caldera, and the others are at the boundary of the probable resurgent intrusive, the North Quitman stock. The several Be occurrences have been compared to the Be tactites at Iron Mountain, New Mexico. In general, the geochemical affinity outlined by these scanty data is characteristic of alkalic rocks and uranium may be expected to be concentrated with this same geochemical association. The Granite Hill geochemical suite is one commonly associated with thermogravimetric diffusion in caldera environments.

Considered overall, only two uranium anomalies are known in the Quitman Mountains, the Quitman Gap Pegmatite and the reported values in the Bonanza Vein. Similar pegmatites may be present at Granite and Tremble Hills. However, more uranium indications and anomalies have been expected. With respect to the lack of widespread uranium occurrences, either the rocks never had any uranium, or it was lost through diagenesis and/or alteration. For the sake of completeness, what if this latter suggestion is correct? Sufficient hosts are present in the immediately surrounding Cretaceous sedimentary rocks to form roll-front uranium deposits. Coal seams are known in the Cretaceous in the Sierra Vieja and in the Eagle Mountains. And finally, red-bed copper deposits are present in Cretaceous strata immediately west of the Quitman Mountains 5 km west of the international boundary. The Cox sandstone may potentially contain reducing environments and permeability sufficient to provide sandstone uranium depositional environments.

Sierra Blanca Peaks

Geological Description

Lying from 10 to 17 km to the northwest of the town of Sierra Blanca, Hudspeth County, Texas are 5 rhyolitic, laccolithic intrusions known as Sierra Blanca, Round Top, Little Round Top, Little Blanca Mountain, and Triple Hill (Fig. 79). Geologic investigations of the area are limited. Albritton and Smith (1965) briefly discuss their petrology and structural setting and this will be synthesized below. McNulty (1980) points out the presence of fluor-

Figure 79. Geologic map of a portion of the Sierra Blanca Peaks showing sample localities.

ite mineralization along the contact zones of several of the laccoliths and reports the presence of beryllium.

The Sierra Blanca laccoliths intrude Cretaceous sedimentary rocks. The sediments dip steeply to the southwest and are interrupted in general by thrust faults dipping less steeply to the southwest. The floors of the laccoliths apparently slope southwestward in the same general direction as the regional dip (Albritton and Smith, 1965), but with the attitude of the thrust faults. Contact relations between the intrusives and their hosts are variable. As seen in the regional geologic cross section in Figure 76, the laccoliths are in a transitional zone between the stable cratonic type of structure of the Diablo Plateau to the northeast and the mobil zone characterized by the Chihuahua Trough. Figure 76 illustrates schematically the geologic features of this transition and emphasizes the close geologic association between the Sierra Blanca laccoliths and the Quitman caldera. Without knowing any precise ages of the igneous rocks, it is reasonable to assume that they may have some genetic relationship. The southwestward-dipping floors of the Sierra Blanca laccoliths suggest a source in that direction. It is possible, from the scant data available, that the Square Peak Volcanics, the quartz monzonite ring dike and Quitman Pluton, and the laccoliths, are all comagmatic, or related to the same igneous episode. As such, they may form a very interesting and complete set of magmatic differentiates and may present a unique geologic exposure.

Petrologically (Albritton and Smith, 1965), the laccoliths are aphanitic and locally are porphyritic. Quartz, feldspar, and minor biotite phenocrysts are present, and the rock is made up of 60% quartz, 35% albite, and 5% biotite. No chemical data on these rocks are available, other than the K-U-Th determinations reported here. Samples have been sent to DOE/GJO for further analysis. The F, Be, and U enrichments within or surrounding these intrusives correlate with their alkalic character. A more detailed uranium inventory study should include a proper geologic documentation of the Sierra Blanca laccoliths. These samples are located in Figures 79 and 80, and the chemical results are maintained on the DOE/GJO Chemical Laboratory Archive data file, laboratory lot numbers 74656 to 74673.

Figure 80. Vertical section through Round Top, showing sample drill hole Δ1, was collared in rhyolite at about 5400 ft on the upper left portion of the diagram, and was drilled to the southeast out of the plane of the diagram.

Uranium Investigations in the Sierra Blanca Laccoliths

Multiple lines of evidence and anomalies suggest that the Sierra Blanca laccoliths are good uranium exploration targets. The U.S.G.S. and D.O.E. reported uranium prospecting in the area. Curtis (1978) reported an anomalously high uranium content in ground water of 28 ppb and included the area in his list of target areas through out the west Texas region. The F-Be association reported by McAnulty (1980) is a good geochemical indicator for uranium in certain environments. Finally, GeoMetrics (1978) determined that the most intense airborne radiometric anomaly throughout both the Van Horn and Pecos 2° quadrangles, the original target quadrangles of this project, was directly over the Sierra Blanca laccoliths. The present project naturally considered the areas as a high priority target.

Lithogeochemical samples of the laccoliths are represented both by outcrop and drill hole samples. Drill hole samples were kindly provided by McAnulty and McAnulty of El Paso, Texas. Two holes are represented, and were drilled at inclines to distances up to 250 m. Sections through the sedimentary host rock were also studied. The inclusion of these drill hole studies provides this project with the exceptional opportunity of this added dimension.

Reported below are studies of stream sediments along a profile across and away from one of the laccoliths, illustrating the geochemical dispersion present from such an anomaly. Sample locations are given in Figures 79 and 80. Finally, the rock and surface anomalies can be integrated with the airborne radiometric anomalies reported.

The Sierra Blanca laccoliths have sparked a lively industry interest, largely initiated by Dr. W. N. McAnulty, Sr. The presence of fine-grained white fluorite defied recognition for many years and the identification of bertrandite proved equally difficult. Once these had been recognized, however, the targeting of the area for other associates of an alkali affiliation can be expected. Thus the high whole-rock uranium values of 35 ppm eU and 165 ppm eTh are not unexpected. This represents the ground truth values for the laccoliths. The fact that NURE aeroradiometric survey identified strong, broad anomalies over the Sierra Blanca laccoliths also served to

bring notice to the area. These airborne anomalies are the strongest in the Van Horn 2° quadrangle.

All mineral classified land over the Sierra Blanca laccoliths is presently filed on for prospecting permits and undoubtedly some private sections are under lease. A portion of this interest is concerned with the uranium potential of the area, although a molybdenum target is most likely. The present NURE research effort was kindly given access to drill core taken from Round Top. The holes were drilled on the north slope and were both collared in rhyolite. They presumably were drilled with the idea of testing the lower contact of the laccolith for concentrations of fluorite, beryllium or other elements. When the drill passed out of the intrusive rock at 288 m in drill hole #1, Figure 81, and at 55 m in drill hole #2, Figure 82, it was generally believed that it would probably pierce an adjoining intrusive. This did not prove to be the case. The remainder of the drill holes were in Cretaceous sediments with only minor intervening dikes. These results suggest that the feeders for the laccoliths are not large and the geometry of the holes indicates that the feeders are not vertical.

Rhyolite of the Sierra Blanca laccoliths is aphanitic. It is generally a light, pale gray color, sometimes with a pinkish cast. Small phenocrysts of quartz and biotite are present, but the rock is made up largely of fine-grained albite. The low potassium content (Figs. 81 and 82, 3.4 wt.% eK) confirms this mineralogic description. Minor limonite, hematite, and/or pyrolusite may be present. The limestones from the core are generally dark gray to light brown, sometimes with interlayerings of carbonaceous mud.

The data determined by gamma spectroscopy on the surface and drill samples have been plotted on triangular composition diagrams, given in Figures 83a and 83b. The rhyolitic intrusives lie closer to the Th-U boundary on the diagrams and show widely varying Th/U ratios. Uranium enrichment occurs at the geologic contact.

Eagle Mountains

The Eagle Mountains lie to the southwest of the Diablo Plateau and are separated from it by the Texas lineament which underlies the Eagle Flat Bolson. Minor Precambrian and Paleozoic rocks crop out in the northeast

Gamma-spec data
from drill core, DH^{#1}, Round Top, Sierra Blanca, Tx.

Figure B1 Equivalent K, U, Th contents, from drill core, drill hole #1, Round Top, Sierra Blanca, Tx.

Gamma-spec data
from drill core, DH #2, Round Top, Sierra Blanca, Tx.

Figure 82. Gamma-spectrometry data from drill core, drill hole Δ2, Round Top, Sierra Blanca, Texas.

Figure 83a. K, U, Th triplots for Sierra Blanca Peak, A: Drill Hole Δ1.

Figure 83b. K, U, Th triplots for Sierra Blanca Peak, B: Drill Hole Δ2.

portion of the range, and Cretaceous sediments in general surround the range at low elevations. These latter rocks were folded, thrust, and faulted during the Laramide orogeny. The main mass of the Eagle Mountains consists of Tertiary rhyolites, ash-flow tuffs, and intrusives, interpreted to be a cauldron which underwent two distinct cycles of the classical Smith and Bailey (1968) caldera evolution. The area has been studied by Guillerman (1953), Underwood (1962-1963) and more recently by Tieh et al. (1975), Legett (1979), Verrillo (1979), and Jacobs (in progress). The following is a synthesis of their work.

Outcrops and structures of the Cretaceous sediments in the Eagle Mountains and adjoining regions trend to the northwest-southeast. The sediments represent shallow marine environments which formed on the northeastern margin of the Chihuahua Trough, a large oceanic embayment during early to middle Cretaceous time. Marginal and near-shore continental environments are also represented, with some red-bed facies present. These are described in more detail by Miller (1975). The sedimentary package was thrust to the northeast during the Laramide and constitutes the west Texas-northern Mexico equivalent of the overthrust belt which is attracting attention in petroleum exploration farther to the north. Texaco has just completed extensive seismic studies across the Eagle Mountains and surrounding bolsons, and a 15,000 foot oil test is being spudded near Sierra Blanca.

The Tertiary igneous rocks of the Eagle Mountains have been subdivided into four major units and the most recent terminology will be used here. From oldest to youngest they are the Carpenter Canyon Tuff, the Frenchman Canyon Trachyte, the High Mill Tuff, and the Eagle Peak Syenite. Chemical data on these units are given in this report.

The Carpenter Canyon tuff has variously been attributed to have from 75.4 wt.% SiO_2 (Tieh et al., 1975) to 73%. Legett (1979) documents a change from 73.3 to 72.3 wt.% SiO_2 from the older Indian Springs Member to the Panther Peak Member above. The Indian Springs Member is composed of numerous alternating ash-flow and air-fall tuffs and is but poorly welded. The Panther Peak Member is a compound cooling unit having densely welded rhyolitic ash-flow tuffs; aegerine and fluorite are accessories. This member has pronounced eutaxitic structure and very characteristic flow features (Verrillo, 1979). The resulting silicified wood appearance was produced by

post-depositional movement in the densely welded portions of peralkaline ash-flow tuffs. Viscosity provided by a specialized suite of minor and trace elements is unusual and the elements are characteristically geochemically associated. The fact that these ash-flow tuffs are no longer peralkaline may result from the significant alkali loss which accompanies devitrification and other post-depositional changes. Minor and trace elements are also mobile during this process.

Textural evidence present on the outcrop, hand sample, and thin section suggests that the Panther Peak Member of the Carpenter Canyon Tuff may have been initially peralkaline in composition. Peralkaline rocks are commonly thought to be good source rocks for uranium and are known to carry enhanced uranium contents.

The Frenchman Canyon Trachyte consists of a series of lava and ash flows, ranging in thickness up to 450 m. It is a trachyte porphyry having approximately 67% SiO_2 and up to 30% phenocrysts of alkali feldspar. Field evidence and chemical studies (Tieh *et al.*, 1975; Legett, 1979) suggest that the Carpenter Canyon Tuff and Frenchman Canyon Trachyte are comagmatic, and the Frenchman Canyon represents the venting of the lower portions of the same magma chamber. Detailed studies may eventually establish this relationship more firmly. Similar types of relationships are common in calderas elsewhere.

The High Mill Tuff appears to represent a new cycle of the Eagle Mountain cauldron system. This rhyolitic welded ash-flow tuff averages 1200 ft in thickness in some areas, having silica contents of 73%. The densely welded Cottonwood Canyon Member grades upward into the partially welded Eagle Bluff Member (Verrillo, 1979).

The High Mill Tuff crops out in a circular zone which surrounds the central intrusion of the Eagle Mountains. In this sense it occupies the position normally taken by moat sediments and extrusives. The High Mill occupies the volcano-tectonic depression formed during the earlier caldera cycle. The green matrix, presence of aegerine, low alumina and relatively high alkali contents suggest that this ash-flow tuff may have been peralkaline in composition prior to devitrification.

Finally, the Eagle Peak Syenite forms the central core intrusion and is the last major igneous event in the area. It intrudes the other units,

and has a silica content of 66%. Minor fluorite is found in the groundmass. It is interpreted to be the resurgent intrusive phase which frequently culminates the igneous activity within a cauldron, such as Stage V of Smith and Bailey (1968). It occupies the central highlands and has intruded the youngest volcanics. The ring fracture volcanism characteristic of the waning stages of a caldera (stage VI) is present as a series of poorly recognized ring dikes, which exist a distance out away from the caldera. The effects of Stage VII also appear to be present in the Eagle Mountains. The presence of significant fluorite replacement deposits on the eastern side of the cauldron in Paleozoic carbonates might be attributed to this Stage. However, no evidence is present to substantiate this idea. The uranium content of this fluorite has been determined by Henry and Duex (1980) as being quite low.

The Eagle Mountains cauldron has been modified by Basin and Range faulting subsequent to formation. The details of this later activity are poorly known.

The chemical evolution of the two caldera cycles identified in the Eagle Mountains has been documented by Tieh *et al.* (1975) (Fig. 84). They show what can be interpreted as the superposition of the emptying of two partially differentiated magma chambers. Silica, alumina, and other major constituents vary significantly. Sodium shows an increase through the progression of each cycle. Potassium, however, shows an increase during the first cycle, followed by a progressive decrease in the second cycle. Uranium follows potassium exactly. Strontium shows virtually no variation. Legett (1979) found similar changes. They are probably due to differentiation by thermogravimetric diffusion.

The uranium contents of several samples have been determined during the course of this study. The trachytes are distinctly lower in uranium content, and the rhyolites and ignimbrites contain between 45 and 9 ppm uranium. A detailed stratigraphic section has not been studied and no analyses have been made on the two younger igneous units. However, significant variations do exist and uranium mobilization appears to have taken place. Th/U ratios vary between 3.2 and 5.9. On a K-U-Th triplot, the Eagle Mountain data form two trends of potassium-uranium variation at different Th/U

Figure 84. Chemical variations in the igneous rocks from the Eagle Mountains, West Texas (from Tieh *et al.*, 1975).

values. The points can also be contoured according to their increasing uranium contents, progressively toward the U-Th base of the triangle.

The uranium potential of the Eagle Mountains is moderate to high. Several igneous units have been identified as good potential source rocks, particularly the Panther Peak Member of the Carpenter Canyon Tuff and the High Mill Tuff. This statement is made more on the basis of mineralogical and textural criteria and is also supported by limited chemical data. The lithogeochemical reconnaissance reported above constitutes additional suggestive evidence. Hot spring activity undoubtedly accompanied volcanism. The Eagle Caldera was subjected to later hydrothermal events in the form of Basin and Range and Rio Grande Rift activity. The caldera activity recycled itself once, as deduced from whole rock chemical data (Tieh et al., 1975). Trace elements are readily leached from tuffaceous rocks under these hydrothermal conditions (Zielinski, 1978, 1979; Goodell and Trentham, 1980). and uranium is among the most mobile. The large fluorite deposits in Spar Valley possibly originated by hydrothermal leaching of the tuffaceous rocks and redeposition of fluorine from reaction with limestones. This may have occurred during any or all three of the major thermal influences in the region as mentioned above.

Sites for potential uranium localization within the caldera complex are numerous. Moat sediments, flow domes and extrusives may lie buried beneath the High Mill Tuff and uranium may be present in a McDermitt Caldera, Aurora-Bretz deposit type environment. Late-stage rhyolites appear particularly interesting. They appear to be present as ring-fracture dikes.

Legett (1979) notes that in the northern portion of the caldera the Frenchman Canyon trachyte can be divided into two members. The diagnostic zone separating these two members is "the occurrence of an oxidized scoriaeous zone at the top of a flow unit". Such a zone could be the upper oxidized portion of a solution pathway and uranium deposition might be encountered downstream. Potential uranium hosts might also be abundant outside the caldera complex itself. Organic-rich sediments are common in the continental facies of the Cretaceous surrounding the area, as in the Cox or Chispa Summit Formation. Other organic-rich depositional sites for uranium are probably present in the Paleozoic and Mesozoic sedimentary rocks. Underwood (1963) describes thin beds of coal with low uranium content exist-

ing in the Chispa Summit Formation in the northeastern extreme of the range.

The idea that uranium has been moving and is present during erosion and weathering is supported by the presence of several low-grade airborne radiometric anomalies over the playas in the basins surrounding the Eagles. Although it is not conclusive that this playa uranium came from the Eagle Mountains the distribution of these anomalies is suggestive of this idea.

Chispa Mountain Area, Culberson and Jeff Davis Counties

The Chispa Mountain area lies northeast of Lobo Valley, immediately to the east of U.S. Highway 90. It is also 29 km south-southeast of Van Horn and 37 km due north of the San Carlos coal mine in the Sierra Vieja. The geologic setting of the volcanic rocks which are found here forms the southern boundary of a large structural horst continuing north to include Canning Ridge and the Wylie Mountains. This structural element lies between the Van Horn Mountains and the northwestern part of the Davis Mountains. Within the horst, geologic units get progressively younger to the south, so that the area near Chispa Mountain contains the youngest rocks. Here, Tertiary volcanics of probable Oligocene age dip gently to the south. The northern part of the Wylie Mountains are characterized by Precambrian rocks of the Carrizo Mountain group, succeeded upward and southward by Permian sediments. Cretaceous rocks crop out 13 km northeast of Chispa Mountain and they are overlain by the sequence of tuffaceous and ignimbritic rocks described in more detail below. Numerous intrusives, one of considerable size, are found in the southern half of the horst. This southern boundary of the horst is characterized by regional southwestward homoclinal tilting and minor faulting (Teal, 1979). The rocks described here bear an intimate relationship to igneous rocks of the Davis, Eagle, and Sierra Vieja Mountains. Most of the units may be genetically related to the Davis Mountains volcanic field, or one of these other areas. The Tertiary stratigraphy of the Marfa quadrangle is given in Figure 85 (Barnes, 1979).

Geological studies of the area include Hay-Roe (1957, 1958) and, more recently, work by Teal (1979) which was undertaken partially with the encouragement and funds provided by the present project. Details of the Ter-

tiary volcanostratigraphic section are given in Table 7 and whole rock and gamma-spectrographic studies are given also.

The Hogeye Tuff is regionally correlative with the Chambers Tuff of the Sierra Vieja and Chinati Mountain areas (Fig. 85). It has been classified by Teal (1979) as a moderately to poorly welded, crystal-lithic tuff. Its low uranium content and high Th/U values (Table 7) suggest that it might have been a reasonable source rock for uranium.

The Pantera Trachyte is reinterpreted by Teal (1979) to be a densely welded ash-flow tuff comprising a single cooling unit. Its source is interpreted to be a vent area on Pantera Peak. It has also been correlated with the Bracks ignimbrite or the Capote Mountain Tuff (Barnes, 1979). The Garren Mountain Tuff Breccia appears to be flow rock that was emitted from the same vent area as the Panther Ignimbrite, but at a slightly later time. It has low U and Th values, characteristic of a rock of intermediate composition. The Buck Mountain Tuff of Teal (1979) is a densely welded vitric-crystal tuff. It is of limited distribution and is thought to be genetically related to the Garren Mountain Tuff Breccia and the Pantera Ignimbrite.

The Water Tuff is divided into an upper and lower member. The Lower Water Tuff is a densely welded, eutaxitic, vitric-crystal tuff with a prominent basal vitrophyre. Sample 5 of Teal (1979) is the basal vitrophyre of this member. Sample 6 is a somewhat altered sample from farther up the section in the Lower Water Tuff. The post-depositional changes evidenced by these two samples include a decrease in uranium and potassium contents. The Upper Member of this unit has 6 ppm eU. The Upper Member, of quite limited extent, is a densely welded vitric-crystal tuff. Certain zones contain abundant pumice.

The Means Trachyte (Hay-Roe, 1957) or Latite (Teal, 1979) is a vesicular flow rock having great variations in thickness and probably a local source. The breccia lentil of the Means Trachyte (Hay-Roe, 1957) is the Crosby Tuff of Teal (1979). It is a moderately welded ash-flow tuff having lithic fragments, phenocrysts, and pumice fragments. Pumice fragments have been infilled by opal and chalcedony. Similarly, the felsite lentil of the Means Trachyte (Hay-Roe, 1957) is the Bonito Latite of Teal (1979). It is a local flow rock, with a source present in the southeastern Chispa Mountains. None of these units contains much uranium, nor is their Th/U value unusual.

Figure 85. Tertiary stratigraphy of the Marfa Quadrangle (from Barnes, 1979a).

The Fairbury Tuff is a pumice-rich water-lain tuff of local source and distribution. It has an abnormally high Th/U ratio (Table 7) and a low uranium content. As such, it has the earmarks of uranium source-rock which has undergone leaching. The Bell Valley andesite is a thick, porphyritic flow rock occurring at the southern margins of the Chispa Mountains and its source is unknown. This alternating sequence of flows and ash-flows is known as the Garren Group. The genesis of the Garren Group is poorly understood. Teal (1979) suggests four eruptive cycles; however, probably only two or three actually exist. Variations in K, U, and Th values taken together, are shown in Figure 86 in numerical sequence from the youngest to the oldest. Potassium is actually a chemical determination in this case. Significant depletions and variations in K and U are noted. The Garren Group constitutes a valid target for uranium exploration.

As a part of the effort to integrate investigations of uranium distribution in waters, stream sediments and rocks in West Texas with airborne radiometric and other geophysical parameters, certain geological cross sections are being selected. A combined study of these cross sections will be undertaken. Selection of the sites for the sections is being made 1) on their relevance to genetic models of uranium potential in the region, 2) on their intersection with known uranium-bearing zones, and 3) on the availability of data. The geological description and data collection of one such cross section follows.

Green Valley, Brewster County, to Sierra Vieja, Presidio County, West Texas

General Description

The structural cross section (Fig. 87) begins at a point on highway 118, 34 km north of Study Butte, Brewster County, Texas. It trends N84°W to the Rawls Ranch Headquarters. Folded and faulted upper Cretaceous limestones are overlain to the west by Pruett-Duff volcanoclastics in the broad expanse of Green Valley. Holocene alluvium covers a large portion of the area to slight thicknesses. The older Pruett tuff grades into the overlying Duff Formation and only to the north can the Duff be identified with assurance. Relations between these two units and their effect on uranium mobility will be discussed in more detail at a later point. Recent work by Henry

Figure 86. K, U, Th triplot for Chispa Mountain samples (from Teal, 1979).

Figure 87 Green Valley, Brewster County, to Sierra Vieja, Presidio County, west Texas cross section

(1979) has been directed to this area. Numerous samples have also been analyzed in this study.

The Mitchell Mesa Formation caps Bandera Mesa and forms a massive rim on the west of Green Valley, and for nearly 80 km to the north. It is a large welded tuff, derived from the Chinati Caldera, dated at 31 m.y. The unit reappears again to the north of that volcano-tectonic structure. It continues in relatively unbroken form in the subsurface to the north of the Chinati Range and represents an ash-flow eruption of immense volume. Its distribution is interfered with only by small intrusives. Other than where it is fractured, it forms an impenetrable barrier to fluid flow.

The Tascotal Formation overlies the Mitchell Mesa at Wire Gap and also reappears to the north of the Chinati Mountains. It may constitute the upper unwelded and the erosionally transported upper portion of the Mitchell Mesa. Primary and diagenetic facies have been carefully documented and uranium distribution within this unit, and particularly at Wire Gap, have received close attention in the present study. Several volcanostratigraphic sections have also been studied.

The Rawls basalt overlies the Tascotal throughout the northern portion of the Bofecillos Mountains. From the Rawls Ranch Headquarters, the cross section continues N57°W to the central Chinati Mountains. Alamito Creek cuts down through this stratigraphic section. The Perdiz Conglomerate, which was shed off the Chinati Mountains, is seen intervening between the Rawls and Tascotal.

The Cienega Mountains intrusive intervenes with the normal volcanostratigraphic sequence. Between the Cienega Mountains and the Chinatis lies the Morita Ranch Formation. This volcanic group is one of the oldest in the region and has been interpreted to represent caldera volcanism prior to the Chinati Caldera (McAnulty, 1976).

The cross section intersects U.S. Highway 67 approximately 3 km north of Shafter. The surficial volcanics are underlain by Permian and Cretaceous sediments at a shallow depth. Just north of Shafter the section enters the Chinati Caldera. Perdiz conglomerate, Chinati Mountain, and extrusive units continue the surface expression of the cross section. Three and a half miles southeast of Chinati Peak the bearing of the cross section changes to N34°W.

The Chinati Caldera is a resurgent caldera which follows in general the sequence of events outlined by Smith and Bailey (1968) for caldera evolution. Details of the Chinati rocks will be discussed later. An evaluation of the uranium potential of the Chinati volcanic units has recently been made (Cepeda et al., 1981) and will be summarized. The caldera is bounded on the north by Permian and Cretaceous rocks of Pinto Canyon (Amsbury, 1958). Pinto Canyon is also characterized by the Shely Group Volcanics, older than the Chinati Mountain volcanics. The group is characterized by ash-flow tuff, breccias, rhyolite flow domes, and tuffaceous sediments in a complex series of events. Cofer (1980), partially supported by this project, has interpreted the Shely Volcanic Group to be derived from an earlier caldera which he has located and named the Shely Caldera. Fifteen vitrophyre samples have been analyzed at the Oak Ridge Gaseous Diffusion Plant and suggest a chemical relationship and evolution of the Shely Group volcanics. Samples from 30 drill holes made by Wyoming Minerals Corp. in 1976-77 are retained for the use of this project. Some major and trace element analyses are to be reported, but much additional study of these samples needs to be done. Trace element data are held on the DOE/GJO Chemical Laboratory Archive File laboratory lot numbers 75629-75678, and 75915- 75964.

Working in a slightly different area, to the east of Pinto Canyon, Henry and Duex (1980) have identified yet another caldera in the Chinati Mountain area. It lies northeast of the cross section in the upper Ciebolo Creek drainage. They have named this volcanotectonic feature the Infiernito Caldera and it has the Ojo Bonito intrusive as its resurgent stage. Both of these calderas are yet poorly described, nor have they been adequately dated.

The Cretaceous dome northwest of Pinto Canyon is interpreted by Cofer (1980) to be the resurgent dome at the center of the Shely Caldera. Resurgent rhyolite intrusives ring the dome to the north and outflow facies only are found farther to the north. Cofer (1980) discusses the volcanotectonic evolution of this caldera and this is elaborated below.

The Capote Mountain tuff with overlying Mitchell Mesa crop out to the north. Broken by Basin and Range faults, a complete succession from the Mitchell Mesa back down to the Cretaceous succeed each other to the north. The Buckshot Ignimbrite occurs here between the Chambers and Colmena Tuffs.

North of the Cretaceous outcrop in the center of the Sierra Vieja, the volcanic sequence is again repeated through the Chambers Tuff. North of Van Horn Creek, the Vieja Group predominates. Numerous volcanistratigraphic sections have been studied in this zone of outflow facies north of the Shely Caldera. It is an area that resembles the Pena Blanca environment and is being actively prospected for uranium.

Sierra Vieja Group

The Sierra Vieja Group is a sequence of tuffaceous sediments and igneous extrusives. Walton (1975) indicates that the Chambers and Capote Mountain Formations are diverse sequences of sedimentary rocks which were deposited between two volcanic centers. The Van Horn Mountains Volcanic Center, 65 km north of the Nixon Springs stratigraphic section, was most active during deposition of the Chambers Formation. The Chinati Mountain Eruptive Center, 20-30 km to the southeast of the Nixon Springs section, was the source of most of the material in the Capote Mountain Formation. The Chinati Mountain center may have three subsidiary cycles. According to Walton (1975) streams carried detritus into the area from the volcanic centers to the north, east and an unidentified area to the west (in Mexico). The coarse-grained rocks in both the Chambers and Capote Mountain formations contained abundant volcanic rock fragments and the fine-grained rocks contained primarily shards. The Tascotal Formation, which lies between the Mitchell Mesa Ignimbrite and the Petan Basalt to the east and north of the Chinati Mountains, is absent or represented by only minor accumulations of coarse clastic sediments in the study area west of the Chinati Mountains.

A stratigraphic section was taken at Nixon Springs, 16 km northwest of Ruidoso, Texas, and samples of both the Chambers and Capote Mountain Formation were included. Information gathered from these sections is presented by Trentham (1981) and the reader is referred to that work for further details.

Clinoptilolite is present through out the entire Chambers Formation, but is only present in the lower portion of the Capote Mountain. The upper portion of the Capote Mountain Formation is composed of fresh glass with minor montmorillonite. Walton (1975) believes that a modified form of the open-system diagenesis model (Hay, 1966) accounts for the formation of clin-

optilolite and analcime (not present at Nixon Springs) in the Chambers and Capote Mountains Formations.

Trangular plots of the gamma spectrometer data are given in Trentham (1981). The data points for the Capote Mountains Formation fall in a very tight group, with the exception of those samples which represent the lower 100 m of the formation. These samples have begun to "break out" from the group and fall on a trend very similar to that of the clinoptilolite trend seen at Eastgate, Nevada. It is important to note that only the lower 100 m of the Capote Mountains fall to this trend. Samples from 100 to 200 m in the Capote Mountain also exhibit evidence of zeolite diagenesis. Why do these samples not also fall on the clinoptilolite trend? Analysis of the thorium, uranium and potassium versus position in the section indicates a slightly lower uranium and higher potassium in the lower 100 m. This is not conclusive enough to indicate a loss of uranium. When compared with the uranium values for the fresh glass zone, however, there is a definite drop in the total uranium in those samples that have undergone zeolite diagenesis. The data for the Chambers Formation consist of only seven samples and fall on two trends that project toward the uranium corner of the diagram. The potassium mean values are similar for the Chambers and the Capote Mountain samples. The thorium to uranium ratio for the Chambers Formation is 2.61. This is less than the ratio of three which is being used to denote "normal values". and it would be said that uranium may be concentrated in this unit. The thorium to uranium ratio for the Capote Mountains was determined to be 3.48.

The fresh glass samples exhibit a uranium to potassium ratio of 1.5 to 2. Sample 425, which represents the transition zone between fresh glass and clinoptilolite, does not belong to any observable pattern. Samples #419-422 exhibit a uranium to potassium ratio of between 1.25 to 1.75. This shift is not a major one, but does appear to be significant.

Tascotal Formation

The Tascotal Formation is part of the Buck Hill Volcanic Series. The type section of the Tascotal was described at Wire Gap by Erickson (1953), on the escarpment of Tascotal Mesa. Walton studied the Tascotal and at the

type section locality identified four informal members of the Tascotal. The lower two units a volcanic sandstone, with the lower portion cemented by clinoptilolite and the upper uncemented portion, and an overlying volcanic sandstone partially cemented by calcite, were sampled in this study. The section taken is the same as that reported by Walton (1975) as the Wind Mill section.

Walton (1975) documents that the Tascotal Formation was deposited in the extracaldera environment during stages IV through VI of Smith and Bailey's (1968) caldera evolution model, as it applies to the Chinati Mountain Volcanic Center. Walton shows that the Tascotal was part of the sedimentary apron that was formed by erosion and redeposition of tuffaceous material originally deposited on the eastern flanks of the Chinati Mountain Volcanic Center.

Gamma-ray spectrometry analyses for thorium, uranium, and potassium of the Tascotal Formation samples have been obtained. There are no trends apparent in the data. All the points fall into a group that is very similar to the one present in the upper portion of the Capote Mountain Formation of the Sierra Vieja group. As in the Capote Mountains Formation, the lower part of the section has undergone zeolite diagenesis with the development of clinoptilolite. The middle portion (samples 403, 404, and 411) is a transition zone containing both fresh glass and clinoptilolite, while the upper portion contains only fresh glass and minor montmorillonite. No pattern is evident in the thorium, uranium, and potassium versus position in the section. The thorium to uranium ratio is 3.59 which is within the normal ratio span for rhyolite glass. The uranium to potassium ratios are stable, varying from 1.2 to 2.1 without exhibiting any pattern of variation.

Only two samples do not fall readily within the group mentioned above. Sample #10 at 65 m in the section, has a very high thorium (36.85) value, and the erosional product of a unit with high Th, and U. Sample #1096, at 1.5 m in the section, has a slightly higher thorium content (19.43), but a low uranium content (1.69) and a very high Th/U ratio (11.49). Uranium-bearing solutions might have been "channeled" down the hydrologic dip slope created by the top of the Mitchell Mesa Ignimbrite.

The Tascotal Formation shows no evidence of uranium mobilization during diagenesis or transport by ground water. This is in agreement with the data

presented by Walton (1979). Since it is apparent that there has been no important mobilization of uranium, this section can be utilized as an example of a system that would be a poor choice as a site of uranium deposition and/or as an active source rock.

Mammoth Mine Prospect

This area has been described by Andersen (1974), Nye (1978), and Aiken (1980). Hexavalent uranium is found in lithophysal cavities in the Buckshot Ignimbrite. The geologic environment is very similar to the step fault mineralized zones at Pena Blanca, Chihuahua, Mexico. Additional discussion of these results will follow. Gamma-ray spectrometer, whole rock, and thin section analyses have been undertaken and results thus far obtained are reported below.

Pinto Canyon, Presidio County, Texas

Uranium occurrences were mentioned by Amsbury (1958), and have been more thoroughly studied by Cofer (1980). Hexavalent uranium occurs in flow foliations and along dikes in and around a rhyolite flow dome. Drilling of 12 to 61-m deep holes was done by Wyoming Minerals Corp. in 1977. Core and cuttings were made available to this project for analysis. Study to date reveals a low-grade uranium occurrence within the base surge facies of the rhyolite flow dome. Suggestions of microcrystalline pyrite in this zone are also made. Additional discussion of these results follows.

Mammoth Mine

The Mammoth Mine is located approximately 100 km south of Van Horn in northwestern Presidio County. It is 6 km east of the Rio Grande, near the Mexican town of Pilares on the north side of Quinn Creek. It can be reached via U.S. 90 south from Van Horn to Lobo Valley, where F.M. 2017 leads through Chispa Summit and to the river at Porvenir. Pilares is about 10 km south of Porvenir. The river road of the U.S. side leads south and improved roads have been maintained to the Mammoth Mine during the recent exploration activity.

The early uranium exploration activity is reviewed by Bilbrey (1957) and Nye (1978). Radioactivity was discovered in the area in 1954 and a 600

acre tract was placed under mining lease in 1955 by the Mammoth Uranium Corp. Over 30 holes were drilled and three small adits were dug into the mineralized zone. High-grade samples were reported to run 4% U_3O_8 , with average grades giving 0.27% (Bilbrey, 1957). Nye (1978) reported average mineralized samples giving grades of 0.1 to 0.2%, with high values of 1.0%. Henry et al. (1981) report values of over .27% for samples from the area. Texaco undertook a sampling and drilling program (Andersen, 1974) in the area. Their investigations apparently did not find mineralization of economic interest, as the area was abandoned.

Recent exploration activity in the Mammoth Mine area has been very intense, although this activity has not been mentioned in the recent uranium evaluation of the area (Henry et al., 1981). Chevron Resources has obtained leases on a large tract of land in the Sierra Vieja, said to be as much as 40,000 acres. Acreage surrounding the Mammoth Mine is included in this and over 30 drill holes have been made into the area to the west of the Mammoth Mine. A mining news magazine reports that the company has encountered significant shows in the Sierra Vieja region. Local reports indicate that a deposit has been drilled near the Mammoth, and/or close to Porvenir. The drilling pattern observed west of the Mammoth suggests either a discovery, or dogged persistence. Most of the holes are shallow; geologic deduction suggests a more or less stratabound mineralized zone in the lower Buckshot, having a grade averaging no more than 0.1 to 0.2% U_3O_8 . Underlying Cretaceous units may also host uranium.

The present state of geological knowledge of this uranium deposit does not lead to conclusive ideas concerning its genesis. Nonetheless, this statement of what we do know concerning the Mammoth Mine does lead to specific exploration guides and target areas within the Sierra Vieja.

A geologic map of the Mammoth Mine has been taken from Bilbrey (1957) (Fig. 88), and a stratigraphic section has been measured, sampled and analyzed as a part of this study. The variegated shale member of the San Carlos formation, Late Cretaceous in age, is the oldest unit in the area and occurs in the bottom of the steep valleys cut into the ignimbrite and tuff units. The unit contains abundant volcanic material. It is one of the least permeable rock units in the region. The Mammoth Mine area lies close

Figure 88. Geologic map of Mammoth Mine, Presidio County, Texas.

to the eastern edge of the Laramide overthrust belt, although the exact relation of the San Carlos and underlying units is not known.

Resting unconformably over the San Carlos Formation is the Jeff Conglomerate and Colmena Tuff. The Colmena consists largely of volcanoclastic material with a possible air-fall unit and it may be derived from the area of the Chinati Mountains to the south. In this area it consists largely of the carbonate rock fragment facies of Walton (1975).

The Buckshot Ignimbrite follows the Colmena and this unit is of widespread occurrence in the Sierra Vieja. Andersen (1974) has provided the best description of this unit. It is a zoned ash-flow tuff consisting of a simple cooling unit overlain by an air-fall deposit which is probably the product of the same eruption. The Buckshot at the Mammoth Mine is approximately 12 m thick. The lowermost 5 m are densely welded, and outcrops nearby contain massive black vitrophyre. The densely welded zone gives way upwards to a partially welded zone, and a thin remnant of an unwelded zone is suggested. The zone of dense welding has recrystallized, producing abundant spherulites which give the unit its descriptive name. The zone of partial welding has evidence of widespread vapor phase crystallization. The ash-flow is generally grayish red to reddish brown. A certain amount of the color is provided by the altered andesitic lithic fragments that comprise up to 15% of the rock.

Spherulites generally increase in size but decrease in abundance upwards in the densely welded zone. Lithophyscal cavities increase in abundance in concordance with the size of the spherulites. They appear initially as crescent-shaped openings around the outside of spherulites, and take on larger and more complex shapes around coalesced spherulites (Andersen, 1974). Lithophyscal cavities may reach a size of several centimeters in diameter and the entire zone forms a permeable, porous layer within the zoned ignimbrite. It is this zone that is the host of the uranium mineralization at the Mammoth mine, and constitutes a significant uranium exploration target in the region.

The Chambers Tuff is a pale red to reddish gray, fine-grained volcanoclastic tuff. It is at least 70 m thick in the Mammoth Mine area. X-ray diffraction studies show abundant quartz, feldspar, calcite, clay, and clinoptilolite. The unit has been subjected to diagenetic conditions of moder-

ate intensity. The Chambers was earlier overlain by the Bracks Ignimbrite, which is found only a short distance away. The Capote Mountain and Mitchell Mesa Ignimbrite also were present.

Chemical data determined from the 18 samples from this stratigraphic section consist of whole-rock constituents and potassium, uranium, and thorium obtained from gamma ray spectrometry. Figures 89 and 90 document the chemical variations observed. A second stratigraphic section was sampled at the coal mine itself. Results of K-U-Th determinations are given in Figure 91. Table 8 presents sample descriptions of a measured section made at the Mammoth Mine.

Shely Caldera and Shely Uranium Prospect, Presidio County, Texas

Another of the well known uranium prospects in west Texas is the Organ Pipe deposit, lying in an area between the Chinati Mountains and the Sierra Vieja. Trenching was done on a uraniferous fracture zone in the 1950's and interest in the area was revived in the 1970's. This target was drilled for Wyoming Minerals and samples from that program form part of the basis of the subsequent discussion. Some of these samples have also been analyzed for trace elements as a part of this project and these results will be found in Cofer (1980) and on the DOE/GJO Chemical Laboratory Archive File, laboratory lot numbers 75629-75678, and 75915-75964. Aquisition of these drill hole samples by the Department of Energy would have required at least a \$150 000 drilling contract. Data on these samples are presented here.

The geologic environment of the Organ Pipe prospect continues to be controversial. In work partially supported by this project, Cofer (1980) has documented and interpreted the area. The following discussion is taken partially from his work.

The Shely Cauldron Complex is located in the western portion of Presidio County, Texas, an area known as Pinto Canyon. It is an Oligocene eruptive center that is the source of both an outflow facies of regional extent (75 km) and a thick inner cauldrea facies (732 m) domed by resurgence. It predates the overlapping Chinati Cauldrea Complex by approximately 5 m.y.

Figure 89. Chemical variations of samples from Chambers Tuff stratigraphic section of the Mammoth Mine, Presidio County, Texas.

Figure 90. Chemical variations of samples from the Buckshot stratigraphic section at the Mammoth Mine, Presidio County, Texas.

Figure 91. K, U, Th triplots, San Carlos coal mine and Mammoth Mine, Sierra Vieja.

Petrographic and geochemical analyses were performed on the inner caldera facies of the Shely Cauldron Complex. The majority of the rocks are rhyolitic ash-flow tuffs, trachyte lava flows and volcanoclastic sedimentary units. The units from oldest to youngest are: Lower Shely Tuff (air-fall and ash-flow tuffs, non-welded to welded, rhyolitic); Middle Shely Trachyte (porphyritic lava flows); Early Shely Moat (epiclastic moat fill, with minor rhyolitic volcanism); and Upper Shely Tuff (welded ash-flow tuffs, rhyolitic) (Fig. 92). A generalized geologic map is given in Figure 93. Note also abbreviations MRP-1, MRP-2, and others used in reference to the Middle Rhyolite porphyry unit in the following narrative.

Three intrusive rhyolite phases are associated with the Shely Cauldron Complex. The two oldest units (Early Rhyolite Porphyry and Middle Rhyolite Porphyry) are crystal-rich and related to resurgent doming of the central Shely block. The youngest intrusive (Late Non-Porphyritic Rhyolite) is a crystal-poor flow-banded unit emplaced along the outer ring-fracture of the cauldron. Extrusive rhyolite lava flows are associated with the emplacement of the Late Non-Porphyritic Rhyolite. Caldera evolution as interpreted by Cofer (1980) is given in Figure 94.

Anomalous amounts of U, F, Pb, An, Ag, and Mo have been noted within the Shely Cauldron. The occurrence of economic mineralization associated with the resurgent caldera is possible considering the silicic nature of the intrusives.

Recently, Wyoming Minerals Corporation, in joint venture with Meeker and Company (1976-1977), drilled shallow exploratory holes around the Shely uranium prospect; however, they failed to detect sufficient uranium of economic interest. Analysis of the core samples suggests the uranium mineralization probably resulted from hydrothermal processes.

Stage VII (Terminal Solfataric and Hot-Spring Activity) of the Smith and Bailey (1968) resurgent cauldron model suggests that long-lived hydrothermal systems are generally associated with large volume silicic volcanism. The potential for economic mineralization associated with resurgent silicic cauldrons is considered highly favorable by Smith and Bailey (1968).

Precious metal and base metal sulfide minerals are commonly enriched in resurgent cauldron environments and are well documented in the literature. Numerous examples of base metal mineralization associated with calderas

Figure 92. Correlation of Tertiary rock units to the Shely cauldron complex.

Figure 93. Generalized geologic map of the Pinto Canyon area, Presidio County, Texas (from Cofer, 1980).

Figure 94 Evolution of the Shely Caldera

exist in the San Juan Volcanic Field. Other elements greatly enriched in known cauldron environments are molybdenum, tungsten, sulfur, mercury, tellurium, bismuth, arsenic, antimony, beryllium, selenium, fluorine, and uranium (McAnulty, 1976).

Tectonic activities associated with resurgent cauldrons are highly effective in preparing the area for mineralization: regional tumescence, caldera collapse, and resurgent doming. Such activities result in breccia formation, vaults, and fractures (especially the ring-fracture zone), all of which increase the surface area available for chemical reactions. They also serve as effective pathways for ground water and hydrothermal solutions. The epiclastics fill in the moat zone (if present) which also is considered an excellent channel way for solutions and a potential site for mineralization.

Hydrothermal systems (connate, magmatic, or mixed) are especially likely to develop at or near intrusions associated with resurgence (Stage V) and ring-dike emplacement (Stage VI). Such intrusions may be the host for disseminated mineralization or the source of mineralization in the country rock. Rytuba *et al.* (1979) note the presence of seven large hydrothermal systems in the McDermitt caldera complex, five of which are associated with economic concentrations of uranium and/or mercury. These systems, having hydrothermal convection cells, appear related to resurgent rhyolite flow domes at a caldera boundary.

Goodell (1978) believes that hydrothermal systems are highly effective in leaching uranium from rhyolitic glasses. McAnulty (1976) also notes a strong spatial relation between cauldrons and uranium occurrences in West Texas. Uranium occurrences at Marysvale, Spor Mountain, and the McDermitt caldera are all believed to be examples of the ability of hydrothermal systems to leach, transport, and redeposit uranium (Goodell and Trentham, 1980).

The occurrence of economic mineralization within the Shely Cauldron Complex is possible considering the silicic nature of the rhyolite intrusions. As of this writing, no mineralization of economic significance has been found. However, anomalous amounts of U, F, Pb, Zn, Ag, and Mo have been noted.

The trace element concentrations of 11 vitrophyre samples from both intrusive and extrusive samples of the Shely Caldera Complex are given in

Cofer (1980). The still glassy vitrophyre presents the closest remnant of the original magma composition and for this reason was used as a starting point in comparing the chemical changes between volcanic units having vitrophyres. Results of these studies are given in Figure 97.

Vertical chemical zoning is well documented in ash-flow tuffs and suggests that the units are deposited in reverse of the zoning present in the magma chamber. This might place a bias on vitrophyre composition of the extrusive units since they normally occur at the base of the units. Intrusive vitrophyre samples are obtained from the chill margins and probably represent an early chemical composition of the intrusive.

The Shely uranium prospect occurs along a highly altered, tan-colored fracture in the MRP-2 just north of Organ Pipe Hill (Fig. 95). Uranium mineralization within the clay matrix is mainly autunite, metatorbernite, and tyuyamunite. The MRP-2 is pervasively altered (sericitized) along the fracture at the Shely prospect and elsewhere around Organ Pipe Hill. Manganese dioxide is commonly found concentrated in areas of anomalously high uranium values. Background spectrometer readings over the remaining volcanics around Organ Pipe Hill range from 990 to 1600 cps.

Anomalous uranium occurrences were first discovered at Organ Pipe Hill in the early 1950's. Amsbury (1957) reported 907 kg (200 tons) of U_3O_8 with an average grade of .34% were removed by bulldozer along the fracture and stockpiled in an adobe building near the government trapper's house, but no shipments were ever made. The anomalous values around Organ Pipe Hill and the Shely uranium prospect led to an exploratory drilling program by Wyoming Minerals Corporation in joint venture with Meeker and Company, 1976-77. Several shallow exploratory holes were drilled; however, they failed to detect any commercial deposits of uranium.

Core samples from 11 drill holes, along with gamma-ray logs, were obtained from Wyoming Mineral Corporation and Meeker and Company. Location of the core samples is also shown in Figure 96. Trace element data, gamma-ray spectrometry (KUT data), and whole-rock chemical analyses were performed on the core samples (Cofer, 1980). Results of some of these are given in Figure 97.

A vitrophyre sample (V-6) of MRP-2, located east of Organ Pipe Hill has a uranium concentration of 20.83 ppm, thorium concentration of 40.26

Figure 95 Geologic map, Organ Pipe Hill area, Presidio County, Texas.
Inset areas "A" and "B" are found as Figure 96.

Figure 96. Drill hole locations, Organ Pipe hill, Pinto Canyon, Presidio County, Texas (from Cofer, 1980).

Figure 97. Trace element variations of vitrophyres, numbered in relative time sequence, Shely Caldera, Pinto Canyon, Presidio County, Texas.

ppm, and a potassium concentration of 3.83% (analyzed by gamma-ray spectrometry). Assuming these values are representative of the original chemical composition, then all MRP-2 core samples can be compared against the vitrophyre to determine increases or decreases in K, U, and Th.

Uranium enrichment (greater than 21 ppm) in the core samples of the MRP-2 is generally confined to fracture zones, though not all fractures are mineralized. Drill-holes 1, 2, 3, and 4 are all slightly enriched along fracture zones with uranium mineralization ranging from 20 to 40 ppm. Drill holes 5, 8, 9, and 10 in the MRP-2 are noticeably depleted in uranium (less than 20 ppm), however, thorium values generally remain constant (33-37 ppm) in all of the MRP-2 core samples. Drill core 10 is the only core that shows a noticeable absence of K (0.00 to 0.29%), possibly due to leaching by hydrothermal solutions. Uranium and thorium values are considerably lower in the MRP-1 than in the MRP-2. One reason for this may be the incorporation of numerous Cretaceous and Permian rock fragments. Another is that the MRP-1 has undergone intense argillic alteration. Uranium concentrations as high as 114 ppm were recorded in the MRP-1 though they are generally less than 15 ppm (Drill holes 6, 7, 8, and 11).

The mineralized zone at the Shely prospect is a highly argillized mafic dike. The chemical composition of the dike is unknown; however, Wyoming Minerals Corporation, 1976-77, did report that no quartz phenocrysts had been found and that abundant chlorite and biotite had been derived from pyroxenes and amphiboles. Core samples of mafic dikes are less argillized though still slightly mineralized (uranium) with respect to the MRP-2. Precipitation of uranium in the altered dike is more likely related to argillic alteration than to emplacement of the mafic dike. Argillic alteration of the mafic dike by circulating solutions was apparently the first step in preparing the dike for mineralization. Later the argillized dike may have acted as a uranium trap for the infiltrating uranium-bearing solutions leached from the MRP-2 area, though other volcanic units in the immediate area may also have contributed uranium. The mafic dikes are also more reactive than the surrounding felsic rocks.

Distribution of uranium mineralization along fracture zones of highly sericitized MRP-2 and its containment in altered mafic dikes that intrude the MRP-2 suggest that most of the mineralization at the Shely prospect is

due to hydrothermal solution movement and uranium leaching. A magmatic hydrothermal event associated with the emplacement of the MRP-2 and/or the later LNPR emplacement may be responsible. Possibly, the mineralization is a combination of both magmatic hydrothermal solutions and later geothermal circulation.

That the MRP-1 may be a breccia pipe(s) was discussed elsewhere. If so, the MRP-1 must be considered an excellent exploration target. That is, permeability of the intrusive breccia (MRP-1) along with the emplacement of the MRP-2 would make the MRP-1 an excellent host for hydrothermal mineralization. Also of interest is the noticeable increase in pyrite in the MRP-1 at depth (3 to 5%), both in Permian rock fragments and MRP-2 rock fragments. The MRP-2 also shows increases in pyrite content at depth (0 to 3%).

Anderson Ranch, Brewster County, Texas

Introduction

The Anderson Ranch uranium occurrences were drilled during the 1970's and these samples are being studied by Aiken (1981). The present project has provided multielement chemical analysis of 200 subsurface samples, and other auxiliary support. A Department of Energy project to obtain samples and information from 18 drill holes in one of the higher priority uranium targets in west Texas, as was suggested as a part of the NURE Program, would have required a contract of approximately \$200,000. This information is presented below. Portions of the description come from Aiken (1981) and the interested reader is referred to that work and to the DOE/GJO Chemical Laboratories Archive File for further details.

The Anderson Ranch is located in Trans-Pecos Texas approximately 31 km south-southeast of Alpine, Texas. The area under investigation lies within the U.S.G.S. Cathedral Mountain 15' Quadrangle. The study area is bounded to the south by approximately 30°05'N, to the north by the Anderson Ranch fence line (approximately 30°08'N), to the west by 103°35'W, and to the east by the farthest eastern extent of the Tertiary volcanics (Fig. 98).

The area surrounding the Anderson Ranch region is physiographically diverse. The Marfa and Chispa Flats lie to the west. North of the study

Figure 98 Geologic map and drill hole locations, Anderson Ranch, Brewster County, Texas

area are the Davis Mountains and to the east are the Del Norte Mountains. Located south of the study area are the Santiago Mountains.

Previous Work

McAnulty (1955) mapped the geology and structure of the Cathedral Mountain 15' Quadrangle. He described the general geologic sequence from many measured stratigraphic sequences, several of which are on the Anderson Ranch. His was an early study in a long sequence of geologic efforts by University of Texas at Austin students, which have provided the overall geologic framework of the region.

The U.S. Atomic Energy Commission published a report on uranium in the southern United States, with reference to West Texas. Uranium mineralization on the Anderson Ranch is described as occurring in shale beds and tuff overlain by basalt or silt. Mineralization is described as limonite and a yellow uranium mineral.

Uranium anomalies of Trans-Pecos Texas are discussed by Reeves et al. (1978). The Anderson Ranch anomaly is described as being principally in calcareous and tuffaceous water-laid sediments intercalated with carbonaceous shale. Carnotite, autunite, and uraninite were reported in the carbonaceous shale while carnotite has been found in the tuffs and limestones.

Union Carbide Corporation, Nuclear Division, during 1977 to 1978, conducted a detailed hydrogeochemical and stream sediment survey of the Tascotal area which covers approximately 12,000 km² surrounding the Anderson Ranch, as a part of the NURE Program.

Groundwaters were sampled throughout the Jordan Gap 15' Quadrangle and in the area under discussion. One sample located in the Elephant Mountain area contained > 80 ppb uranium. Areas of anomalously high uranium also have a high specific conductance and an association with lithium, selenium, and sodium (Butz et al., 1980). Stream sediments containing on the average 2.5 ppb soluble uranium are located throughout the Tascotal survey area. Areas of anomalously high uranium are associated with above background concentrations of thorium, lithium, potassium, beryllium, and zirconium. If the resulting low Th/U (Neutron Activation) values give an indication of the displacement of uranium with respect to thorium at the source area, then the Buck Hill Volcanic Series and the Tascotal Formations remain

as an important target in the exploration for economic uranium deposits (Butz et al., 1980). The Anderson Ranch prospects are mentioned by them in one sentence.

Robinson (1979) described the stratigraphy and petrography of the limestone of the Pruett Tuff located near the state highway approximately 7 km south of the Anderson Ranch headquarters. The lacustrine unit described by Robinson was mapped by McAnulty (1955) as the Pruett Tuff, although it is probably time-equivalent with the lacustrine limestone on the Anderson Ranch. Robinson (1979) related the sedimentological environments and facies along with the diagenetic history of the strata to uranium mineralization.

McAnulty and McAnulty, Inc. (1977-78) directed a drilling project to determine the commercial potential of the lacustrine uranium occurrence on the Anderson Ranch. Results and conclusions from the project are not published and cannot be included in this study. Samples from the 18 drill holes are the basis of the present study.

Henry et al. (1981) discuss uranium during diagenesis in the Pruett, Duff, and Tascotal Formations of Trans-Pecos, Texas. They conclude that the solution of glass during diagenesis releases uranium to ground water; uranium is then absorbed by amorphous Fe-Mn-Ti oxyhydroxides. The combination of the release and absorption of uranium indicates that significant quantities of uranium have not been mobilized from these tuffaceous sediments. Mobilization of 1 ppm is not detectable in the absolute uranium concentrations or in Th/U ratios. An estimation of the total volume of the three tuffaceous sedimentary formations shows that a release of 1 ppm from that volume equals 25×10^9 lb/ U_3O_8 (12×10^9 kg U). Thus, they conclude a measureable release is not a prerequisite for the formation of major uranium deposits.

The Drilling Project

The drilling project consisted of completing 17 percussion drill holes and one cored hole through the uranium target. Drill hole locations are given in Figure 98. An attempt was made to drill through the Sheep Canyon Basalt, Crossen Trachyte, and Pruett Tuff and into the Cretaceous Limestone. Drill Hole One (DH 1) was drilled to 282 m; after 198 m of Pruett Tuff, the hole was abandoned prior to encountering the Cretaceous Limestone. One core through the lacustrine limestone, DH15, ranges from 46 to 75 m. Drill holes 1, 3, 4, 6, 11, 13, 15, and 17 are the basis of this study. Stratigraphic sections for each of the logged drill holes are given in Figure 103.

The Tertiary lacustrine limestone deposits of West Texas contain potentially commercial uranium deposits, but no detailed study of the deposits has been made. The purpose of this study at the Anderson Ranch is 1) to determine the mineral assemblages and geochemistry of the volcanoclastics and associated uranium occurrences within the interbedded lacustrine limestone; 2) to measure gamma radioactivity for seven drill holes; 3) to determine the mineralogy of the uranium; and 4) to map the region included by the drilling. These activities are designed to provide a geologic model of the deposit.

Ninety-two samples were chosen at selected intervals through seven of the drill holes. The seven drill holes provide a north-south cross-section (Fig. 103). Sample selection was based on obtaining mineralogical and geochemical data for samples every 0.6 to 1.8 m. Mineralogy of these samples was determined by x-ray diffraction. The samples were analyzed by x-ray fluorescence to determine concentrations of major oxides and by gamma ray spectroscopy to determine K-U-Th contents. Two hundred samples were analyzed by Bendix Field Engineering Corporation for 23 trace elements. These results are found on DOE/GJO Chemical Laboratory archive file, laboratory lot numbers 74001 to 74150. Figures 99 through 112 document chemical variations in selected drill holes.

Field work on the Anderson Ranch, completed during the Spring of 1981, consisted of geologic mapping of a U.S.G.S. topographic base (1:24,000), measuring stratigraphic sections, and collecting representative samples from

Drill Hole No. 11

Drill Hole No. 13

Figure 99. K, U, Th triplots, drill holes 11 and 13; numbers on diagram are depth in feet.

DRILL HOLE II

Figure 100. U variations with K and Th separately, drill hole 11; numbers are depths in feet.

DRILL HOLE 13

Figure 101. U variations with K and Th separately, drill hole 13; numbers are depths in feet.

Data from
Aiken, M.J.,
1981

Figure 102. K, U, Th triplots, drill holes 3, 4, 6, and 17.

Figure 104. Down-hole U variations through mineralized zone in cross section (Fig. 103), normalized to the base of the overlying basalt.

Figure 105. Down-holes as variations through mineralized zone in cross section (Fig. 103), normalized to the base of the overlying basalt.

Figure 106. Down-hole M0 variations through mineralized aone in cross section (Fig. 103); normalized to the base of the overlying basalt.

Figure 107. Down-hole F variations through mineralized zone in cross section (Fig. 103), normalized to the base of the overlying basalt.

Figure 108. Down-hole organic carbon variations through mineralized zone in cross section (Fig. 103) normalized to the base of the overlying basalt.

Figure 109. U, Al_2O_3 , Th, Zn, Ni, Li, F, Cs, and Ba variations through mineralized zone, drill hole 1.

DH 1

Figure 110. U, CO₂, S, C, PO₄, V, Se, As, and Mo variations through mineralized zone, drill hole 1.

Figure 111. U, Al_2O_3 , Th, Zn, Ni, Li, F, Cs, and Ba variations through mineralized zone, drill hole 6.

Figure 112. U, CO₂, S, C, PO₄, V, Se, As, and Mo variations through mineralized zone, drill hole 6.

each unit. Thin sections from DH 15 were made in the laboratory and studied with the aid of a petrographic microscope. This detailed description of the occurrence provides constraints on its mode of formation. The interfacing of the surface and groundwater data from the NURE program with drill hole data provides better exploration criteria for this type of deposit.

Tertiary Stratigraphy

General

The area surrounding the Anderson Ranch is composed predominantly of Tertiary volcanic and volcanoclastic rocks (Fig. 98). McAnulty (1955) mapped five volcanic rock units: the Pruett Tuff, Crossen Trachyte, Sheep Canyon Basalt, Potato Hill Andesite, and Cottonwood Spring Basalt (Eocene-Oligocene). These units form over a 3000 m sequence of mainly volcanics and volcanoclastics on the Anderson Ranch which overlies marine Cretaceous rocks.

Pruett Tuff

The Pruett Tuff (Eocene) consists principally of well indurated, thick-bedded, calcareous, fine- to medium-grained tuffaceous sediments but includes conglomerate, tuffaceous, sandstone, breccia, and fresh-water limestones (Goldrich and Elms, 1949; McAnulty, 1955). The tuffaceous mudstones of the Pruett Tuff from DH 1 and are dominantly fine- to medium-grained but conglomeratic from 253 to 259 m.

The upper part of the Pruett Tuff is exposed along the generally east-facing escarpment on the Anderson Ranch (Fig. 98). The minimum thickness of the Pruett Tuff, 79 m, is located in the east-central part of the Alpine 15' Quadrangle. Maximum thickness is 253 m in the northwestward tilted section found north of Cienega Mountain (McAnulty, 1955). DH 1 entered the Pruett Tuff at 84 m. In 1977 McAnulty and McAnulty drilled through 198 m of the Pruett Tuff to a depth of 282 m but did not reach the Cretaceous Limestones. The Cretaceous might be 46 m deeper, assuming a maximum known thickness of 243 m for the Pruett Tuff.

Principal mineral constituents identified through x-ray diffraction are quartz, alkali and plagioclase feldspar, analcime, and calcite. Traces of an iron sulfide mineral, biotite, and magnetite, which is usually partly altered to hematite or limonite, can be seen in hand specimen. Organic material in the Pruett Tuff is exposed along the escarpment.

Thirty-four 100 gram samples of the Pruett Tuff from 85-282 m) in DH 1 were analyzed by gamma ray spectrometry. Equivalent uranium concentrations have a mean value of 6.18 ppm and a standard deviation of 2.43. Concentrations of equivalent thorium have a mean value of 15.44 ppm with a 3.90 standard deviation. Major oxide constituents for seven samples of the Pruett Tuff from 98 to 282 m have been determined. Silica content in the form of quartz, feldspar, and analcime ranges from 60.19% to 70.55% by weight; aluminum oxide in the form of feldspar and analcime ranges from 9.85% to 13.12%. Calcite is the dominant constituent responsible for CaO values of 3.22% to 16.02%.

The kinds and quantities of material deposited (quartz, feldspar, calcite, organic debris, magnetite, pyrite, and biotite) in the Pruett Tuff (Eocene) reflect a complex interplay among volcanism, subtle tectonic shifts, climatic change, and drainage development beginning in the Eocene (Stevens, 1979, p. 103). Source areas for the Pruett Tuff are uncertain. Transport directions indicate a source to the north in the Davis Mountains (36.8 to 38.4 m.y.; McDowell, 1978) and to the west from the area of Chinati Mountains.

The Shely Caldera is an Eocene-Oligocene eruptive center possibly dated by the Buckshot Ignimbrite (35.2 to 38.6 m.y.; McDowell, 1979); it may be the earliest caldera of the Chinati Cauldron Complex. Cofer (1980) states that the Pruett Tuff probably represents the southern extent of a re-worked Lower Shely Tuff outflow facies. Biotite is generally not present in the alkaline rocks in Trans-Pecos; however, it is a common but minor occurrence in rocks of the Infiernito Caldera (Henry and Duex, 1981). This is the only source presently known for the detrital biotite found in the Pruett. The question of a source area for the Pruett is indeed a problem, and not one that is solved here. Most likely, there were multiple source areas, at least one of them being the Infiernito Caldera.

Crossen Trachyte

The Crossen Trachyte (37.8+ m.y.; McDowell, 1978) is a massive porphyritic trachyte capping North Crossen Mesa. Weathered surfaces are dominantly rusty-brown. Highly weathered surfaces range from rotten greenish-yellow vesicular material to a fine-grained, grayish yellow, tuff-like decomposition product (McAnulty, 1955). Vesicular zones in the upper part contain amygdulose of chalcedony colored pink, blue and red. This flow-foliation is aligned in a northwesternly direction (McAnulty, 1955).

The Crossen Trachyte caps the North Crossen Mesa and rests directly on the Pruett Tuff along the east-facing escarpment on the Anderson Ranch. The maximum known thickness is 81 m where it caps Mt. Ord and dips 8° to the west (McAnulty, 1955). On the Anderson Ranch thicknesses range from 0 to over 0 to 61 m. Thickness of the Crossen Trachyte at DH 1 is .3 to 11 m.

McAnulty (1955) describes the Crossen Trachyte as having a fine-grained groundmass consisting of microlites of alkalic feldspars, some altered ferromagnesian material, and finely disseminated hematite. On a freshly broken surface, phenocrysts of anorthoclase and sanadine are abundant. Perthitic orthoclase feldspar is the mineral identified by x-ray diffraction. Whole rock analyses of seven drill hole samples of the Crossen Trachyte show a mean silica content of 69.54% with values ranging from 66.86 to 72.40%. Two additional samples of the Crossen Trachyte, one highly silicified, were analyzed for major whole rock components. The silicified sample contained 74.52% silica as compared to 68.68% silica for the unsilicified sample. Percentage of aluminum oxide for nine samples ranges from 11.11% to 14.25% with a mean value of 13.37%. High silica and aluminum oxide percentages indicate a high feldspar content as identified by x-ray diffraction. The mean value of K_2O , 4.85%, is relatively high compared to the lower mean values of Na_2O and CaO (2.62% and 2.11%, respectively). Integration of the major oxide constituents with x-ray diffraction confirms that the Crossen Trachyte is composed largely of perthitic orthoclase feldspar.

Nine samples of the Crossen Trachyte, two outcrop and seven percussion samples, were analyzed by gamma ray spectroscopy. Equivalent uranium concentrations have a mean value of 3.91 ppm and a standard deviation of

1.75. Concentrations of equivalent thorium have a mean value of 10.34 ppm with a 3.14 standard deviation.

Sheep Canyon Formation

The Sheep Canyon Formation, which overlies the Crossen Trachyte, is a succession of basaltic lavas separated by layers of limestone and tuff or dacite. The basalt flowed out on a very irregular surface and the total thickness varies considerably. This formation is widely distributed over the Cathedral Mountain and Alpine 15' Quadrangles. It thins out to the south in northern Buck Hill 15' Quadrangle and thickens gradually to the north. Sections measured by McAnulty (1955) show a variation in the number of flows and total thickness. A 77 m section, located 6 km south-southwest of the Anderson Ranch, contains five flows and four thin tuff and fresh water limestone beds.

On the Anderson Ranch, approximately .7 miles (1 km) east-southeast of the ranch headquarters, McAnulty (1955) measured a 159-foot (48 m) section of the Sheep Canyon Formation which contains three basalt flows and 2 thin tuff or dacite interbeds. In several locations on the Anderson Ranch the Crossen Trachyte is absent and Sheep Canyon basalts and limestone rest directly on the Pruett Tuff. The absence of the Crossen Trachyte as a marker bed, separating the Sheep Canyon Formation from the Pruett Tuff, makes field interpretation difficult. For example, the Crossen Trachyte cannot be followed completely around the eastern escarpment on the ranch. As seen on the geology map (Fig. 98), the Crossen Trachyte is present to the north and south portion of the escarpment but is absent east of DH 7 and 8. Figure 98 illustrates the relationship of the interbedded units or rock types. When the Crossen Trachyte is absent, the Sheep Canyon limestone and tuffaceous mudstones separate the Sheep Canyon basalt from the Crossen Trachyte and the Pruett Tuff.

The Mudstone Member of the Sheep Canyon Formation consists of fine- to medium-grained tuffaceous sediments similar in composition to the Pruett Tuff. The Mudstone Member is exposed along the escarpment and in the arroyo located southwest of DH 17. In the arroyo, tuffaceous mudstones and tuffs are in the position of the limestone-mudstone sequence. The maximum thickness of the two mudstone members is 17 m located in DH 15. DH 13 was drilled

to 54 m; after 24 m of mudstone, the hole was abandoned prior to encountering the Crossen Trachyte.

Mineral constituents identified through x-ray diffraction are quartz, alkalic and plagioclase feldspar, analcime, and calcite. Traces of biotite and iron sulfide can be seen in hand specimen. Whole rock analyses of the mudstone indicate an environment similar to the Pruett Tuff. Silica in the form of quartz, feldspar, and analcime ranges from 67.10% to 74.12%. Concentrations of Al_2O_3 range from 11.38% to 13.55%. The presence of CaO , as calcite and limestone, yields concentrations of SiO_2 and Al_2O_3 below the given ranges.

Thirty-three mudstone samples have a mean equivalent uranium concentration of 13.99 ppm and a range of 2.60 to 40.96 ppm. Concentrations of equivalent thorium have a mean value of 16.97 ppm with a range of 11.18 to 24.52 ppm.

The lacustrine limestone member of the Sheep Canyon Formation consists of thin to thick bedded tuffaceous limestone with thickness ranging from less than 0.3 to 8 m. Lacustrine limestones are exposed along the escarpment and in the arroyo containing DH 13 and 14.

Five thin sections of the limestone from DH 15 were stained with sodium alizarin sulphonate and studied with a petrographic microscope. Lacustrine limestones are generally high in silica and have a laminar, wispy appearance. The fossils, consisting of valve fragments and traces of ostracods, were identified in thin sections of DH 15.

Post-depositional, high energy environment and silicification probably destroyed the fossils present as evidenced by the absence of fossils in samples high in silica and having a wispy appearance. Fragmental skeletal parts and a tooth were collected from the limestone exposed along the escarpment approximately .8 km south-southeast of DH 17. The tooth is most likely part of the third lower molar from an approximately .6 m long lower jaw of a titanotherium. Skeletal fragments probably are ribs but contain no distal ends. The fossils are of a material that is extremely difficult to work and are retained in the University of Texas at El Paso Paleontological Collections (LeMone, pers. commun.).

Whole rock analyses of the lacustrine limestone member has a maximum CaO content of 52.49% and SiO_2 values ranging from 45.63% to 63.40%. A high

SiO₂ concentration is the result of possible post-depositional silicification plus the presence of feldspar and quartz. The presence of plagioclase and alkali feldspar, as identified through x-ray diffraction and thin section, and the highly alkaline depositional environment result in K₂O + Na₂O. Carbon dioxide contents are not included in these analyses.

The highest eU value of 114.55 ppm occurs in sample 3-142 which is described as 40% mudstone, 40% coal, and 20% limestone. Limestone samples not contaminated by mudstone or uraniferous coal have a mean value of 46.29 ppm eU for nine samples. All of the limestone samples are enriched in uranium when compared to the average abundance of 2.00 ppm uranium in limestones (Levinson, 1974).

Mineralized Zone within the Sheep Canyon Formation

The lower limestone unit along the escarpment yields 50 to 340 cps on the scintillometer. The host for the highest values, 500-600 cps, is a one-foot (0.3 m) thick organic-rich shale bed located within the limestone unit. Mean eU concentration for three samples is 349.07 ppm.

The mineralized zone in the lower limestone crops out in the arroyo downstream from DH 1 (Fig. 98). The unit consists of organic-rich tuffaceous shale, tuffaceous coal, and limonitic shale. All samples are calcareous and effervescent with 10% HCl. The moderate yellowish brown (10 YR 5/4) limonitic shale has the highest eU concentration of 155.78 ppm. Mean concentration eU for eight samples is 799.09 ppm with a standard deviation of 474.59 ppm.

Basalt Member of the Sheep Canyon Formation

Weathered surfaces of the basalt are dominantly reddish brown. A fresh surface of the basalt is jet- to dark-greenish black (McAnulty, 1955.) The basalt flows cannot be distinguished lithologically. All are porphyritic with a diabasic texture and fine- to medium-grained feldspathic groundmass. The rock is composed of approximately 70% plagioclase and alkalic feldspars, 15 to 20% light purple augite, 10 to 15% magnetite, and 5% chlorite and antigorite. Olivine is also an important constituent, but in most cases all of the olivine is completely altered to the antigorite and

other decomposition products. Varying amounts of calcite, analcime, zeolites, and clay are also present (McAnulty, 1955).

Five percussion samples of the Sheep Canyon basalt and weathered basalt were analyzed by gamma ray spectroscopy. Mean equivalent uranium and thorium concentrations are 1.42 ppm and 2.54 ppm, respectively. Analysis of the major oxide constituents resulted in high-silica, low-aluminum basalts when compared with the average chemical composition of the basalts (Hyndman, 1972).

The Sheep Canyon rhyolite is interbedded between two basalt flows and located stratigraphically above the collars of the drill holes. The light brownish gray rhyolite contains free quartz and white-colored pumice fragments showing strong orientation parallel to bedding. Thickness of the rhyolite varies from 0.3 to 4.9 m. This unit is thin vertically but extends laterally over much of the Anderson Ranch. Although it is felsic in composition, it is mapped as part of the Sheep Canyon Formation.

Two samples were analyzed for major oxide constituents. Both samples are rich in aluminum oxide, silica, and potassium oxide with mean concentrations of 77.63%, 13.69%, and 5.05%, respectively. Results of gamma ray spectroscopy yielded a mean equivalent uranium concentration of 5.48 ppm and a thorium concentration of 21.96 ppm. Igneous rocks of the Sheep Canyon Formation document bimodal volcanism.

Potato Hill Andesite

Overlying the Sheep Canyon basalt is the Potato Hill Andesite which consists of an andesitic flow and flow breccia (McAnulty, 1955). Because the lava spread over an irregular, highly weathered surface, and because of primary flow phenomena which may have influenced accumulation, thickness ranges from 11 to 58 m. On the Anderson Ranch, the thickness ranges from approximately 12 to 26 m (McAnulty, 1955). On the Anderson Ranch, the Potato Hill Andesite has been largely removed by erosion. Exposures are limited to topographic highs where it is capped by the Cottonwood Spring Basalt Formation.

Texture ranges from finely granular to trachytic and glassy. The rock is composed of 70% to 85% feldspar and 5% to 20% magnetite and its al-

teration minerals. Other minerals which occur in lesser amounts are olivine, iddingsite, antigorite, biotite, chlorite, zeolites, and clay minerals (McAnulty, 1955).

Cottonwood Spring Basalt

The Cottonwood Spring Basalt is a succession of lava flows, ranging from trachyandesite to olivine basalt. Weathered rocks are dark brown to light greenish gray. The basalt is dark and fine- to medium-grained, in both the dense and vesicular phases and is dominantly nonporphyritic. Composition of the rocks ranges from soda-rich olivine basalt to trachyandesite, with some approaching trachyte. The basalts have a diabasic texture, and the more silicic rocks have a bostonitic or trachytoid texture (McAnulty, 1955).

Maximum thickness of the Cottonwood Spring Basalt in the northern Buck Hill quadrangle is 99 m (Goldrich and Elms, 1949). On the Anderson Ranch, the Cottonwood Spring basalt caps the Potato Hill Andesite forming topographic highs and McAnulty (1955) measured a 56-m section of the basalt.

Traced north-south, the basalt extends the length of the Alpine, Cathedral Mountain, and Buck Hill quadrangles. Stratigraphic relations in each of the three quadrangles indicate that the Cottonwood Spring Basalt came from the north and northwest and spread southward over a broad area where the Potato Hill Andesite, Sheep Canyon basalts, and Crossen Trachyte had been eroded (McAnulty, 1955). It rests, then, on the Potato Hill Andesite in this area.

Geologic Setting and History

Cretaceous marine strata are exposed 3 km east of the Anderson Ranch and probably underlie the Tertiary volcanics. The Laramide uplift and orogeny produced the Del Norte-Santiago-Carmen Mountains and the broad structural depression to the east of the Anderson Ranch.

Post-Cretaceous erosion with intermittent volcanic activity, probably from the Davis Mountains (36.8 to 38.4 m.y.; McDowell, 1978), Chianti Mountains (31.2 to 32.1 m.y.; Cepeda, 1978), Shely and Infiernito Cauleras. The surface was blanketed with volcanic ash followed by active streams. Cyclic

tendencies of streams and lakes are evidenced by the occurrence of fine- to medium-grained mudstone, conglomeratic mudstone, conglomerate, poorly sorted lenticular and cross-bedded sandstones interbedded with tuff layers. Shallow lakes existed as evidenced by deposits of freshwater limestone. These alternating conditions resulted in the formation of the Pruett Tuff.

The explosive volcanic activity was followed by the quieter eruption of the Crossen Trachyte (37.8 m.y.; McDowell, 1978), probably originating from the Davis Mountains (36.8 to 38.4 m.y.; McDowell, 1978) to the north. Subsequent erosion produced a hill-and-valley topography. In areas where the Crossen Trachyte is absent, either post-depositional erosion cut valleys completely through the Crossen Trachyte into the Pruett Tuff, or the trachyte was never deposited.

Cycles of stream and lake deposits are recorded in a mudstone-limestone sequence which is mapped as the Sheep Canyon Formation. Mudstones resemble, in composition and deposition, the Pruett Tuff indicating deposition by active streams. Shale and calcareous coal interbedded in the carbonaceous limestone indicate organic-rich environments at the time of deposition. The presence of titanotheres fossils in the limestone above the Crossen Trachyte and in the Pruett Tuff below indicates a short period of deposition for the mudstone-limestone sequence and the Crossen Trachyte.

Cyclic deposition of mudstone and limestone was interbedded with flows of Sheep Canyon basalt (36.0 m.y.), which spread over the mudstone-limestone sequence and the deeply incised surfaces of the Crossen Trachyte. The separation of Sheep Canyon basalt flows by mudstone and/or limestone indicates the recurrence of lake and stream depositional environments. Interbedded between two basalt flows is the Sheep Canyon Dacite Member. Deposition of the Sheep Canyon Basalt represented a new cycle of volcanic activity followed by the deposition of the Potato Hill Andesite (35.6 m.y.) and the Cottonwood Spring Basalt.

These basaltic and andesitic flows were followed by another cycle of intermittent volcanism. The cycle began with the deposition of the Duff Formation, then the Mitchell Mesa welded tuff (31.5 m.y.) from the Chinati caldera, and ended with the deposition of the Tascotal Formation, which is probably the volcaniclastic equivalent of the Mitchell Mesa. After a period of erosion, the Rawls Basalt (26.7 m.y.) flowed out over a large area.

After the extrusion of the Rawls Basalt, syenitic bodies intruded the Buck Hill volcanic succession. Sills, dikes, plugs, and laccolithic bodies are present. The intrusive masses are alkalic syenite, with the exception of a volcanic vent which is composed of vent agglomerate.

Located approximately 6 km south of the Anderson Ranch is the Elephant Mountain sill (<36.0 m.y.). The sill capping the mountain ranges from 183 to 335 m thick and covers an area of 7.7 km². Faulting of the volcanic layers beneath the sill indicates that the large buried mass may extend under Elephant Mountain (McAnulty, 1955). Other sills of similar composition include the Haley Mountain Sill and sills located west and northwest of Cathedral Mountain. Laccolithic bodies include Cienega Mountain and McIntyre Peak Intrusion.

Extrusive rocks younger than the Rawls Formation do not occur in the Cathedral Mountain Quadrangle. Late Tertiary and Quaternary erosion probably stripped off much of the younger volcanic rocks and Rawls Basalt (McAnulty, 1955).

Structure

After the extrusion of the Rawls basalt (26.7 m.y.) and before a late period of syenitic intrusive activity, gentle tilting of the Tertiary volcanics resulted in a regional dip of 2-4° north and northwest in the southern Davis Mountains. Contemporaneous with, or following the crustal movement, intrusion of the syenitic bodies resulted in local doming and faulting (McAnulty, 1955).

Many normal faults, younger than the Buck Hill volcanic series, are associated with igneous intrusions and with other major faults surrounding the study area. The normal fault (trending N25°W) associated with the study area is the Calamity Creek Fault located approximately 1.6 km west of the Anderson Ranch headquarters. The Cottonwood Spring Basalt on the southwest side has been dropped down against Crossen Trachyte on the northeast.

Mineralogy

Mineralogy of the deposit was determined by x-ray diffraction. Eighty-two percussion samples from six of the drill holes were analyzed by x-ray diffraction. Each sample was ground, sieved to less than 125 mesh, and x-rayed from 5° to 61° 2 θ . Quartz-calcite standards ranging from 3:7 to 7:3 at 10% intervals were x-rayed to determine linearity of concentrations to area under certain diffraction peaks of the quartz-calcite mixture. Four major peaks for calcite and for quartz were chosen. The area under the four peaks for each mineral was totaled for each standard. The plot of areas, or relative intensities for quartz-calcite, yielded a non-linear relationship. Minerals identified by x-ray diffraction are quartz, calcite, k-feldspar, alkali feldspar, plagioclase, and analcime. Zonation of minerals through the deposit indicates the diagenetic zones developed in tuffaceous lacustrine limestone and volcaniclastics.

Franklin Mountains, El Paso County, Texas

Under normal circumstances, the El Paso 2° Quadrangle was not to have been included within the context of the project study area. It is not one of the six designated quadrangles. The area of the El Paso Quadrangle within Texas is small and densely populated. Any special study of the area would have most likely been far down the NURE priority list, because no uranium potential has been attributed to the area until very recently.

In the light of the lack of general awareness of the Franklin Mountains and its uranium potential, the present authors feel it imperative to include the subject in the present report. The implications of Bokan Mountain-type environments present in the Franklin Mountains are very significant with respect to upgrading the potential uranium resources of the El Paso quadrangle, including both the mountain range and possible zones buried in the surrounding bolsons. Over 300 lithogeochemical samples from this area are being subjected to multielement analysis by DOE/GJO. Results of these studies are on the DOE/GJO Chemical Laboratory Archive File (1981).

The Franklin Mountains are a complex fault-block mountain range having moderate dips to the west. Precambrian granites and metamorphosed sedimentary and volcanic rocks are exposed on the eastern side of the range,

and are overlain by a sequence of Paleozoic and Cretaceous sedimentary rocks. The Precambrian rocks are the ones which might be of importance with respect to potential uranium resources. Several features of the Precambrian rocks suggest a very real uranium potential, as will be presented.

A late Precambrian (± 1.1 b.y.) sedimentary sequence consists of the Castner marble, Mundy basaltic breccia, and Lanoria quartzite. These are overlain by the Thunderbird rhyolite, and the entire package was intruded multiply by granites, known principally as the Red Bluff Granite (Harbour, 1971). These granites crop out in a north-south direction, the direction of strike of the Basin and Range horst within which it resides. The outcrops extend over a distance of 20 km, with the greatest exposed width being about 1.5 km. Of particular interest with respect to uranium are the Thunderbird rhyolite and the Red Bluff and associated granites. Large portions of the granite contain fluorite and pegmatitic zones are definitely enriched in uranium. Beryllium, tin, and tungsten are also present. Riebeckite in a uraniumiferous pegmatite has an unusual composition, close to that in the per-alkaline granite at Bokan Mountain, Alaska (Fig. 113), a type locality for uranium in a pegmatitic and/or late stage albitization environment. The locality of the only other riebeckite composition close to these two is from the Nigerian alkali granite province also known to have uranium deposits. This albitization uranium environment is well recognized in the U.S.S.R. and has been the topic of a recent DOE Open-file Report (Avrashov, et al., 1980).

The Thunderbird rhyolite may constitute the extrusive portion of the Red Bluff or associated granites. A large portion of this unit consists of a welded ash-flow tuff as suggested by Waters (1978, pers. comm.) and documented by Thomann (1980). This new interpretation of the origin of the Thunderbird Formation, we believe, should significantly increase the uranium potential of the West Texas area. Within other Precambrian ignimbrite regions world wide, particularly in Labrador (Gandhi, 1978) and Sweden (Lindross and Smellie, 1979), significant uranium reserves are being developed and brought into production. The Precambrian ignimbrite uranium target in west Texas will be discussed in more detail.

The Thunderbird rhyolite has been the subject of a recent study (Thomann, 1980) within which several subsidiary members were identified and the major rhyolite member is recognized as an ignimbrite. A brief stratigraphic

description and whole-rock chemical contents are given in Table 11. A basal conglomerate unit is overlain by mixed volcanic and sedimentary units. Within this middle member are porphyritic trachytes, silicified crystal-vitric tuffs, and tuffaceous sandstones. The upper member is a rhyolitic, crystal-vitric ash-flow tuff approximately 195 m thick. Definite shard structure is visible in relatively unaltered portions of the nearly one billion year old rock. Whole rock analysis (Thomann, 1980) of 108 samples of volcanic rocks from the formation reveals chemical trends from oldest to youngest suggestive of progressive differentiation. Although not recognized by Thomann, this upper unit is close to the alkali-peralkaline boundary. Given the tendency for ignimbrites to lose sodium and potassium during their post-depositional history and given the billion years that the unit has been subjected to chemical processes, the rock most likely has lost alkali and was probably peralkaline in composition at the time of eruption. In the minds of many uranium geologists, peralkaline character of an igneous rock is a favorable source rock for uranium deposits.

Equivalent uranium analyses for numerous samples from the Thunderbird Formation have been determined (Thomann, 1980), the results of which are summarized in Table 12. Uranium contents are generally from 2 to 5 ppm in the lower and middle members of the formation. The upper ignimbrite member has variable uranium contents, generally from 3 to 14 ppm. This large variability suggests either a large initial zoning or subsequent leaching and remobilization of the uranium. Such large variations are not commonly produced during magmatic differentiation. Furthermore, Thomann compares analyses from selected fresh and altered samples, as verified by thin section, and suggests the release of uranium. The evidence suggests that the Precambrian ignimbrites of the west Texas area were a good source for uranium. Uranium exploration targets would be similar to those in the Tertiary ignimbrites discussed elsewhere, and similar to those described in Gandhi (1978) and others from Precambrian terranes.

With respect to the Red Bluff granite, it has been established (McAnulty, 1967) that the granite actually consists of several different intrusive phases, with microgranite (McAnulty, 1967), a white granite, and a granite porphyry being distinguished (Pyron, 1980; Thomann, 1980). The

Granite Peak Pegmatite also has been described (Hoffer, 1972). Ray (1981) and McCutcheon (1981) report details of the geology and petrology of these units. The Red Bluff itself is a medium- to coarse-grained biotite granite, which has been dated at 980 ± 20 m.y. (Wasserburg *et al.*, 1969) and $970 \pm$ m.y. (Denison and Hetherington, 1968). Fluorite has been found forming 1-2% of a granite over wide areas (McCutcheon, 1981). The microgranite is a dark grey, porphyritic rock which resembles a coarse syenite in hand sample. Microcrystalline quartz constitutes the groundmass. The white granite is a microcline-albite rich rock. The agpiatic index for the Red Bluff is .85, and .96 for the White granite, so the latter is nearly peralkaline. McCutcheon (1981) believes that at least three of the four recognizable granites in the north Franklin Mountains are comagmatic. He also suggests that the younger granites show a progressive tendency towards peralkalinity.

Within the White and Red Bluff granite are numerous pegmatitic zones. Those present in the Red Bluff are distinctly zoned, including a quartz-rich core. These bodies have previously been identified as veins. However, their geologic character and fluid inclusion studies indicate their high temperature and pegmatitic nature (Pyron, 1980).

The Granite Peak Pegmatite has been described by Hoffer (1972). This intrusive phase is hosted by the Precambrian Red Bluff Granite and the Castner Formation. The zone averages only 45 cm in width, but does have a fine-grained border and coarse interior. Quartz, abundant alkali feldspar, and riebeckite up to 20 cm in length, are the major constituents, with minor zircon and fluorite also present. The pegmatite dike can be traced for a length of 53 m, and similar dikes are found elsewhere in the range. This pegmatite has numerous characteristics which are correlated with uranium deposits elsewhere. This pegmatite does contain anomolous uranium in the Franklin Mountains. This geologic unit contains the recognition criteria for a Bokan Mountain type uranium environment.

The striking similarity between the Granite Peak pegmatite of Hoffer (1972) in the Franklin Mountains and the Bokan Mountain Granite of southeastern Alaska (MacKevett, 1963) requires a brief elaboration of the geology of the Bokan Mountain uranium deposit. This deposit has become the type example of hypabyssal, or shallow, intrusive which hosts pegmatite and albitization-associated uranium and thorium deposits (Avrashov, *et al.*, 1980).

Multiple intrusive rocks of probable Cretaceous age are present at Bokan Mountain, which seem to represent a chemical evolutionary sequence culminating in the Bokan Mountain peralkaline granite. MacKevett (1963) has plotted mineralogical variations from normative calculations. The Bokan Mountain granite covers 8 km² in area, and contains anomalously high contents of uranium, thorium, rare earth elements, niobium, fluorine, and other exotic constituents. Both intrusive phases are peralkaline, with the Granite Peak Pegmatite having an agpiatic index of 1.12. An average of five Bokan Mountain Granite analyses has an agpiatic index of 1.10, very close to the Granite Peak value. The Bokan Mountain Granite averages 73.9% wt. of SiO₂, whereas the value for the Granite Peak sample is 69.6%. Both granites contain normative acmite, 10% modal riebeckite, and a trace of purple fluorite. Pyron (1980) documents 375 ppm eU from the Granite Peak pegmatite.

The riebeckite compositions and site occupancy from the Granite Peak and Bokan Mountain areas are compared in Table 13, along with the compositions of riebeckite from several other locations. These compositions are cast in terms of atoms per 24 anionic units. Chemical variations of amphiboles of these types can be reasonably depicted on such a diagram as given in Fig. 113. Ferric iron increases to the right at the expense of alumina, and ferrous iron increases upwards at the expense of magnesium. Compositions of five riebeckites from Deer *et al.* (1963) are given in Table 13, and the resulting points are indicated in Figure 113 by analysis number. The Bokan Mountain and Granite Peak riebeckites are most similar to those from the alkali granites of northern Nigeria, and the Bokan Mountain composition is similar to that from Rockall in the North Atlantic. This latter sample is notably enriched in rare earth elements, and other related exotic elements. Between the Bokan Mountain and Granite Peak compositions, the only significant difference is in the ferrous/ferric iron ratio and this difference is small. They both have the same total iron contents, but Bokan Mountain contains more ferrous iron than Granite Peak riebeckite. This more reduced chemical environment in which the Bokan Mountain intrusive formed may be significant with respect to the thorium/uranium ratio of the resultant mineralization. The Granite Peak magmas may have been shallower and may have been contaminated with slightly more oxidizing ground water.

Figure 113. Variations of amphibole compositions; BM is Bokan Mountains, GP is Granite Peak, Franklin Mountains

Figure 114 indicates the generalized structure and zoning of albitized uranium deposits, to which Bokan Mountain type occurrences appear to correspond. The line of deduction developed above results in the possibility that the presently exposed Granite Peak Pegmatites is stage 1 in the zoning and paragenesis of a significant mineralized deposit. Exploration down dip on these dikes should be undertaken.

The geologic environment of the Bokan Mountain deposits is subjected to revised interpretations in the light of the caldera evolution outlined by Smith and Bailey (1968). The Bokan Mountain environment can be interpreted as that of a caldera which had been tectonized. The slate (MacKevett, 1963) appears to be a metamorphosed sequence of moat sediments and it does host some uranium. It crops out in a semicircular fashion around the centrally located Bokan Mountain Granite. Aplite ring fracture zones are present and Stage V of Smith and Bailey (1968) is represented by the apparently resurgent Bokan Mountain peralkaline granite.

Such a sequence of events is not yet documented in the Precambrian granites of the Franklin Mountains, but such events do seem highly likely from what is now known. Outflow facies are represented by the Thunderbird Formation (Thomann, 1980) in Texas and probably by the metavolcanic rocks in Alaska, which appear to be an ignimbrite from the reinterpretation of its earlier description.

Concentration of uranium in certain of the granites of the Franklin Mountains is documented and warrants further investigation. The Franklin Mountains Precambrian rocks appear to be a reasonable target for uranium reserve estimates and, someday, for serious exploration. The State of Texas, however, is presently considering making the region a wilderness area. Pyron (1980) determined the average uranium contents of three granites and found them to have 3.3 ppm eU for the microgranite, 4.6 ppm eU for the Red Bluff granite, and 16.3 eU for the White granite. The distribution of uranium values by granitic unit is given in Figure 115a. Figure 115b shows the progressive enrichment in potassium and uranium from the microgranite to the Red Bluff to the White granite. This correlates with a progressive increase in silica content.

Pegmatites within the Red Bluff granite are relatively enriched in tin (Fig. 115c), whereas those in the White granite are enriched in uranium,

Figure 114. Idealized schematic representation of vertical zoning in the deposit. Mineralization: 1, early silicate; 2, carbonate-uraninite; 3, late silicate; 4, metamorphic rocks. ▬

Figure 115. Chemical variations of Precambrian granites and pegmatite zones, Franklin Mountains, El Paso County, Texas (from Pyron, 1980).

among other elements. Beryllium-enriched pegmatites are also present in Fusselman Canyon and the granitic phase which hosts these deposits is being studied (Ray, D., 1981). The pegmatites within the Red Bluff granite have been studied (Pyron, 1980) due to their high tin contents. These zones may be a significant tin resource. Whole rock chemical variations across the pegmatite zones are given in Figure 115d, uranium and tin variations across these same zones are given in Figure 115c, and corresponding K-U-Th variations are shown in Figure 115b, along with two Red Bluff granite (R.B.G.) analyses. The intermediate zone shows slight uranium and large tin enrichment and is made up largely of feldspar. Tin contents reach over 30% by weight! It is followed by a massive quartz core zone. Fluid inclusion temperatures are about 550°C, when corrected. Figure 116 shows chemical variations down drill hole #2 at the Franklin Mountain tin deposit. The area is high in alkalies, has silica contents which vary between 56% and 70%. Iron increases to 7% at depth. Equivalent uranium values are 10 to 12 ppm, except for a higher concentration of 37 ppm eU at about 70 m depth.

As mentioned above, suggestive evidence is presently supporting the comagmatic origin of the Thunderbird rhyolite and the Red Bluff and associated granites (Pyron, 1980; Thomann, 1980). Rock chemistry indicates uranium enrichment of certain intrusive phases and geologic deduction and comparison suggest that the related extrusive environment may also be enriched. The nearly peralkaline characteristics of the upper ignimbrite member of the Thunderbird Formation also are noted and it may compare with that of the White granite.

We believe the recognition of Bokan Mountain uranium environments in the Franklin Mountains should bring the region into the range of significant uranium resource potential.

Pena Blanca, Chihuahua, Mexico

Introduction

Significant uranium deposits in volcanic and volcanoclastic rocks have been discovered and developed by the Mexican Government 250 km southwest of Presidio, Texas. Because this geologic environment is very similar

Figure 116. Chemical and gamma variations down drill hole Δ2, Mount Franklin tin deposit (from Pyron, 1980).

to that in Trans-Pecos Texas, study of the Mexican deposit was encouraged by the project being reported here. A result of that study follows.

The Pena Blanca uranium district is located 50 km north of Chihuahua City (Fig. 117, area C), in the northern half of the Sierra Pena Blanca. The district consists of three active exploration and development camps, El Nopal, Margaritas, and El Cuervo. Numerous uranium occurrences have been systematically drilled and/or developed by underground workings over a period of nearly 20 years. Several of these have proven to be of commercial interest, and are in active stages of development. The Nopal I deposit is partially exploited, an incline is being driven into the Puerto III deposit, and Margaritas is being prepared for exploitation by open pit. Mill startup is projected for 1982.

This paper presents a brief geological description of the Pena Blanca area and specific geological and geochemical information on two deposits. Field, laboratory and chemical studies on 350 additional samples from the Pena Blanca District are summarized here and discussed in terms of the geologic setting of the uranium deposits. From these are derived several tentative models of the origin of the deposit.

Previous Work

Volcanic rocks from the Pena Blanca District have been radiometrically dated by Alba and Chavez (1974). Calas (1977) published a brief description of the deposit which included a geologic map. Goodell *et al.* (1979) summarized the regional geology, gave generalized descriptions of several deposits, and reported several analyses. The Instituto Nacional de Energía Nuclear (INEN) and, since 1978, Uranio Mexicano (URAMEX), have carried on an exploration and development program, and this work has been accelerated with the advent of this latter agency. Bell (1981) and Hardtke (1981) measured 11 volcanostratigraphic sections and provided analyses of typical host rocks and mineralized zones, including 19 samples from the Nopal I deposit. Carraway and Goodell (1980) obtained 160 stream sediment samples, fractions of which were analyzed for 27 elements by Oak Ridge Gaseous Diffusion Laboratory (ORGDL).

Figure 117 Location map, Sierra Pena Blanca, Chihuahua, Mexico

Regional Geology

The Sierra Pena Blanca is a horst block of the Basin and Range type. To the east lie numerous additional horst blocks in the province known as the Chihuahua tectonic belt (structural) or as the Chihuahua Trough (sedimentological). The elevation of the basins decreases gradually to the east.

The Sierra Pena Blanca horst is separated from the Sierra del Nido on the west by a graben. The Sierra del Nido horst is a significantly larger tectonic block and the outlines of a portion of it are shown in regional geophysical studies (Aiken et al., 1981). The Sierra del Nido is also characterized by a thick and varied suite of volcanics of mid-Tertiary age, as discussed by Mauger (1977).

The Sierra Pena Blanca horst is the first range to the east of the Sierra del Nido block (Fig. 117). A significant elevation decrease takes place from the high volcanic plateau of the Sierra del Nido to the Chihuahua Trough on the east.

The east side of the Sierra Pena Blanca range is commonly designated as the boundary between the Chihuahua Trough and Aldama Platform to the west and this boundary extends to the south. Cretaceous reef facies have been recognized in the uranium district (Stege et al., 1981) and are present to the south along the eastern front of the range. Shallow water environments are also recognized farther to the east (Mitchell et al., 1981). Lagoonal and back reef facies are most common in the western part of the range. The Sierra Pena Blanca tectonic fragment probably was an integral part of the Sierra del Nido tectonic block. The age of the graben separating Pena Blanca from the Sierra del Nido to the west must be less than 29 m.y. (Mauger, personal communication)

In general, rocks cropping out in the Sierra Pena Blanca horst are progressively younger to the north. Paleozoic eugeosynclinal sediments constitute the southern portion of the range. Mesozoic basinal, reef and back-reef carbonate facies constitute the rock sequence upwards and, in general, northward. To the north of the Pena Blanca uranium district, Tertiary volcanics predominate. This general decrease in age to the north within the Pena Blanca horst is repeated to the west in the Sierra del Nido block, where earlier Tertiary volcanics are overlain northward by rhyolite, and are

capped by 29-m.y.-old peralkaline ash-flow tuff farther north (Dayvault, 1980; Mauger, 1977.)

Superimposed upon the northward-dipping horst block of the Pena Blanca range are a series of parallel, northwest-striking, down-to-the-northeast faults. These faults are in general parallel to a major tectonic feature of the region, the northwest-trending boundary of the Sierra del Nido block which terminates the block a short distance to the north of the uranium district. Additional details of the regional geology can be found in the accompanying articles in the Chihuahua section of this volume.

Stratigraphy

The limestone bedrock underlying the Pena Blanca uranium district is the topic of an accompanying study (Stege et al., 1981). Not discussed there, and not included in the radiometric dating study of Alba and Chavez (1974), is the Cuervo Formation, of unknown age. This unit is found in the northern part of the district, and consists of an ignimbrite, tuffs, and volcaniclastics. It is semiconformable with undescribed underlying Cretaceous limestones. This package has been deformed into large recumbent folds and thrust faults. Unfortunately, samples of the Cuervo fresh enough for K-Ar dating have not been found and fission track dating has not been done.

Uplift in the Early to mid-Tertiary produced a region with significant topographic relief. A continental molasse of variable thickness formed on this surface, known at Pena Blanca as the Pozos Formation. In the Margaritas-Nopal area, the Pozos is largely a limestone conglomerate, with clast size reaching 15 cm across. Other clasts are rhyolite and andesite, and these increase in abundance to the north. Lenses and channel deposits of red tuffaceous material also occur and may form 20% of the Pozos in some areas. Widespread portions of the Pozos near the contact with the overlying Nopal Formation have been intensely altered by secondary processes. The limestone fragments have been partially replaced, and the cobbles thoroughly cemented, by red chalcedony. Erosionally resistant red chalcedony rinds characterize the exposed cobbles. Silicification was so intense that the Pozos Formation forms a resistant, impermeable base to the volcanic section. Silicification probably resulted from degassing and vapor-phase activity

during the deposition of the overlying Nopal Formation. Alternatively, silicification could have resulted from a diagenetic alteration of the overlying tuffs.

The volcanic stratigraphy established and dated by Alba and Chavez (1974) is seen in Figure 118. The units range from 44 m.y. for the Nopal Formation, to 35 m.y. for the Mesa Formation. As noted by McDowell (pers. commun., 1978), a 54-m.y. date obtained on biotite and reported by Alba and Chavez (1974) is questionable because of the poor quality of biotite dates. The biotite date resulted in the description of a new unit of that age, referred to as the Corrales Formation on INEN maps. In the field, the Corrales is indistinguishable from the adjoining Nopal Formation.

The Nopal Formation has been dated at 44 m.y. The 200 m exposed in the district consist of a basal tuffaceous zone of variable thickness and two distinct welded members. Each has a well defined basal vitrophyre, with progressively less welded zones above. The areal distribution of the Nopal Formation is very large. In Figure 118 it is present at Hormigas to the east, and near Sierra Gallego to the north (Bockoven, 1981). It also crops out in the Sierra Gloria near Aldama, 60 km to the south. It may correlate with the red platy unit described by Capps 20 km to the south of the uranium district and with rocks in the Majalca area described by Spruill (1976) and Mauger (1981). The Nopal is a crystal-lithic to lithic-crystal tuff, red to red-brown in welded zones. Phenocryst content averages 5% to 10% in the lower member and 25% to 30% in the upper member. Sodic plagioclase phenocrysts predominate in the lower member with some biotite present, whereas biotite is more abundant in the upper member. Lithic compositions consist of volcanics in the lower member, and minor granite fragments are also present in the upper member. Dense aggregates or trains of lithics up to 15 m long and 3 m thick are exposed in welded portions of the lower member. Eutaxitic structure and flow foliation are rare.

The Escuadra Formation has been dated at 38 m.y. (Alba and Chavez, 1974). It consists of air-fall and water worked tuffs, a thick lahar, and a single cooling unit. Its thickness varies from 90 m at Nopal to 60 m in the north. It is more local in distribution than the Nopal Formation, although the Escuadra is found to the south of the Pena Blanca district. Basal tuffaceous zones host mineralization at Margaritas, generally in stratiform

Figure 118. Isometric fence diagram showing volcanostratigraphic sections from Sierra Peña Blanca, Chihuahua, Mexico.

zones up to several meters thick. This facies might be classified as a lithic-crystal tuff, containing fragments of andesite and rhyolite, and small phenocrysts of quartz and sanidine; it is commonly rich in hematite. The unit displays features that suggest both fluvial and pyroclastic deposition. It has been called a lapilli tuff (Bell, 1981), but contains a variety of clast sizes. Three km south of Margaritas the unit is exposed in a road cut and is over 50 m thick. Lithics consist largely of pieces which appear to be derived from the Nopal Formation and some fragments reach 1 m in maximum dimension. Lithic-rich zones frequently are well sorted. Bedding planes are well developed. Hematite-rich zones alternate with yellow and grey ones and the varying porosity-permeability has resulted in variation of oxygenating conditions, and hence coloration. Good natural exposures of this unit are not known. It is exposed as nondescript gravity slopes, does not reveal its internal character, and has not been mapped.

The upper and thicker portion of the Escuadra Formation is a simple cooling unit. A basal vitrophyre is overlain by a densely to slightly welded zone and the upper part is a sintered ash. This crystal tuff contains phenocrysts of quartz and sanidine, with biotite and some hornblende present in unaltered tuff. Devitrification of the groundmass to quartz and feldspar is characteristic and vapor phase deposition of quartz and feldspar is sometimes seen. The welded zone diminishes rapidly in thickness to the north where the Escuadra is a 50 m thick, sintered ash-flow. These observations suggest that the Escuadra is of smaller volume and closer to its source than any of the other ash-flow tuffs in the sequence.

The transition to the overlying unit is not well exposed. Bell (1981) divided the original Pena Blanca Formation into a lower conglomeratic unit called the Chontes Formation, retaining the name Pena Blanca for the upper tuffaceous unit. Clasts in the Chontes are limestone and volcanics, and the clasts increase in size and the unit in thickness from north to south to the vicinity of Margaritas. The Pena Blanca Formation forms distinctive nonresistant white tuffs that increase in thickness to over 150 m in the northern El Cuervo area. Clastic and air-fall tuffs characterize the unit. In light of the narrow time span between the Escuadra and La Mesa, it is quite probable that the white tuffaceous upper portion of the Pena Blanca Formation may be the reworked and transported upper, unwelded portion of the

Escuadra Formation. Within 10 m of the top of the unit there occurs a more resistant zone. It appears to be a partially welded zone at the top of the unit and perhaps formed from the heat, pressure and chemical activity present during the deposition and degassing of the overlying Mesa Formation.

The Mesa Formation has been dated at 37.5 m.y (Alba and Chavez, 1974). It is the most widespread unit in the district, being found far to the north at Hormigas 25 km to the east, at Sierra Gomez 40 km to the south-east, at Sierra Gloria south of Aldama, and possibly west of Highway 45. Given the dense welding present, it can be assumed that the unit was quite thick, although its top is not exposed. No more than 75 m are actually observed. A thin volcanic arenite constitutes the base of the Mesa, followed upward by a vitrophyre attaining a thickness of 5 m. The densely welded zone immediately above the vitrophyre contains abundant flattened pumice. Fifteen pumice fragments from one 10.2 cm square sample from the lowest pumice zone average 3.07 cm in length. These have an average flattening ratio of 0.04, leaving little room for gas phase deposition. The bottom contact of the basal vitrophyre frequently contains plough-like features into the underlying tuff, probably formed as the ash-flow tuff came to rest. The preferred orientation of this feature suggests a volcanic source to the west or southwest. Eutaxitic structure is predominant and flow foliation is strongly developed in places. Ramp structures and contorted flow foliation are also present. The rock is aphyric and the welded zone is very thick. The Mesa is a single cooling unit. However, variations in cooling or post-depositional flowage caused numerous flow foliation surfaces to form within the sequence giving the appearance of multiple stacked lava flows. Remnant glass shards attest the Mesa Formation is an ignimbrite. According to Sheridan (1979, pers. commun.), rock textures and outcrop features are similar to those of a rheo-ignimbrite.

Regional Volcanostratigraphic Considerations

Fourteen volcanostratigraphic sections have been measured and studied and an isometric fence diagram illustrating the lateral distribution of formations is presented in Figure 118. Table 14 shows the breakdown by geologic units of the 3600 m studied. It illustrates several of the details which were mentioned earlier, such as the ponding of the Chontes and Pena

Blanca Formations to the northeast of the northwest-trending Margaritas fault. Figure 118 illustrates variations in the volcanic stratigraphy over an area 50 km by 50 km through a period of approximately 10 m.y. Volcanologists will recognize that this is not a particularly chaotic region. It is characterized by rhyolitic ignimbrite outflow facies and volcaniclastics. An additional feature to be emphasized is that in spite of the strong vertical zoning in each ignimbrite these zones can also be traced over these large distances and they are generally homogeneous.

The geologic relations in the underlying Cretaceous sediments are not given in Figure 118. On a regional scale, these volcanics were deposited on a surface of noticeable relief, well illustrated by the continental molasse of the Pozos Formation. In the area of the Pena Blanca uranium district, the back reef, massive reef core, and basinal facies from southwest to the northeast appear to have strongly influenced pre-molasse topography, much as the Capitan Reef of Permian age stands out today in southeastern New Mexico. The basin was in the early stages of being filled by the Pozos before volcanic activity commenced.

Most of the area in the uranium district underlain by basinal Cretaceous facies is topographically low today. Volcanic units down to the Nopal and lower Escuadra have been eroded off the questas and the Margaritas-Nopal area. Upfaulted massive reef facies form a topographic wall between the Margaritas deposit and the location of sections M and N in Figure 118. It has been all too easy for visiting geologists to interpret the topographic wall as a caldera boundary and place the uranium deposits just inside the caldera. Figure 118 should dispell this idea; other field and laboratory data do not support the presence of a caldera in the immediate area.

Local Structure

An outcrop map is given in Figure 119. In the Nopal-Margaritas area, the mountain front begins on the east as three questas topped by the upper member of the Nopal Formation. A thick sequence of Pozos underlies the Nopal and organic-rich basinal facies of the Albian reef are visible in the first valley south of the outcrops of volcanic rocks. The Nopal dips 25° west, the three questas are progressively larger to the north and the Nopal I deposit is at the southern end of the southernmost quesa. The eastern

Figure 119. Outcrop map of the Pena Blanca uranium district, Chihuahua, Mexico.

scarps of the questas show several fracture zones in the welded members with some showing small displacements. These zones of weakness and step faults control the drainage on the western dip slopes of the questas. They are also sites of alteration and mineralization.

At the western bases of the two questas in the Nopal-Margaritas area, the Escuadra Formation overlies the Nopal and these two units dip west into a narrow, faulted zone (Figs. 120 and 121) which strikes northwest. The zone averages 1/4 km wide, and on its western side the Nopal and basal tuff of the Escuadra dip to the east. This syncline opens to the north and the axial-faulted valley will be the site of the Margaritas open pit. The western dip-slope limb of this structure forms the topographic relief rising to the major crest of the range in the area. In this limb the Nopal Formation rests directly on the most massive part of the Albian rudistid reef core.

One km to the west of the aforementioned syncline a steeply dipping fault of the northwest-trending down-to-the-northeast type is present. There is some suggestion that this fault influences the trend of the reef, as they both disappear together to the northwest and the reef is not seen in limestones farther to the north. Clastic wedges of the Pozos and Chontes Formations thicken southward to the fault and largely consist of limestone fragments with some red rhyolite. In places to the southwest of this fault the Nopal has been eroded prior to the deposition of overlying units and evidently served as a source area for clastics to the north. The evidence suggests that this northwest-trending fault was recurrently active during and perhaps before deposition of the volcanic units. It is possible that the Margaritas syncline is a drag fold relative to this fault. Farther to the west (Fig. 120) the internal structure of the volcanic pile in the northern Sierra Pena Blanca is that of a broad syncline plunging and opening to the north.

Nopal I Deposit

Nopal I is a small, high-grade deposit located in a breccia zone at the southern end of the southernmost questa of Nopal Formation, as indicated in Figure 120. Its geologic environment is not unique in the area. The northern questas contain numerous anomalies in similar sites and are associated with alteration and uranium mineralization. The western dip slopes of

Figure 120 East-west cross section through the northern Pena Blanca range

Figure 121. Geologic section (E-W) through the Margaritas deposit, Pena Blanca, Chihuahua, Mexico.

SECTION CONSTRUCTED FROM DRILL HOLE INFORMATION. LOCATION AND IDENTIFYING NUMBER OF DRILL HOLES ARE SHOWN. DISTRIBUTION OF URANIUM ORE DEPOSITS IS INDICATED IN BLACK, AS INTERPRETED BY INEN FROM GAMMA RAY LOGGING OF DRILL HOLES.

the three questas show structurally controlled drainage into the resistant welded portion of the upper cooling unit. These brittle fractures coincide with airborne anomalies, alteration, and mineralization. Followed over the crest to the scarp side of the questa these fractures often have little to no displacement, although others may have vertical offsets of up to 20 m.

The Nopal I deposit occurs at the intersection of two step faults in the upper welded member of the Nopal Formation. Offset of several meters was observable and one fracture could be traced out on the surface to the northwest. In plan (Fig. 122) the deposit is oval with axes 50 by 20 m and it is known over a minimum vertical extent of 50 m. Mineralization is within the breccia zone and alteration extends for a short distance into the welded tuff. At depth, altered basal vitrophyre and softer, less consolidated tuff are encountered. Mineralization reportedly continues into this other lithologic zone, although it is more widely disseminated and of lower grade. The mineralized zone beneath the ignimbrite is reported to be cone-shaped with apex downward (INEN, 1977, pers. commun.).

Other origins have been attributed to the formation of the breccia zone which hosts the Nopal I deposit. Initially it was thought to be a breccia pipe, with implications of a volcanic vent or its subsurface conduits. This interpretation is championed by those who see a caldera wall along the Margaritas fault zone. Another origin, espoused by Bell (1981) is that the breccia zone has formed over a collapse cavity in the underlying basinal limestone. Pilcher (pers. comm., 1980) believes it is a fumarolic vent.

The Nopal I deposit was explored by a series of tunnels and it has now been partially exploited by open pit. Hardtke (1981) sampled the 40 m level and the original outcrop surface before mining. Chemical analyses reported by him are given in Tables 15 and 16 and the data have been recast in Figures 123 and 124 to give a visual portrayal of the chemical changes from fresh to altered to mineralized rock. In Figure 124, the difference between samples designated as "surface" versus "surface expression" is that the "surface expression" samples were taken directly across the mineralized zone, whereas "surface" samples were taken away from the the mineralized zone. Study of Figures 123 and 124 shows that chemical changes into the mineralized zone include increases in SiO_2 , Hg, Mo, and Pb, and decrease in

Figure 122. Nopal No. I prospect sample locations (from Hardtke, 1980).

Figure 123. Whole rock chemical variations, fresh to mineralized zones, Nopal I deposit, Pena Blanca, Chihuahua, Mexico (from Hardtke, 1980).

Figure 124. Trace element variations, fresh to mineralized zones, Nopal I deposit, Pena Blanca, Chihuahua, Mexico (from Hardtke, 1980).

Al_2O_3 , K_2O , Na_2O , CaO , Fe_2O_3 , P_2O_5 , TiO_2 , MnO , and Be . Fluorine and lithium do not change significantly. Apparently the deposit has been secondarily oxidized, because rare remnants of primary uranite occur in the breccia. The most abundant hexavalent uranium is uranophane, and kaolinite, limonite and chalcedonic quartz are frequent associates. Numerous other minerals have been identified, with several recognized by URAMEX being given in Table 17.

Margaritas

A geologic cross section of this deposit is shown in Figure 121, as interpreted by INEN from drill hole information. Reinterpretations by URAMEX give the same general distribution of uranium ore, but with more structural complexity to the east of drill hole 7. This is the area being prepared for open pit mining. Drill core is now being obtained by URAMEX, and its study may necessitate additional reinterpretation.

Uranium occurs in several specific environments in Figure 121: tuffs, altered vitrophyre and pumice zones, structurally dislocated regions, and underlying limestones. The stratigraphically controlled lapilli and air-fall tuff deposit is present at the surface from the collar of drill hole 46 west to drill hole 64. It is displaced downward by the fault west of drill hole 3 and continues up the hillside in the subsurface. This is the facies which is believed to be overlain by the lahar or alluvial fan deposit that is well exposed 2 km to the south.

With respect to the larger mineralized zone at Margaritas, directly beneath the tuff of lowermost Escuadra are the two cooling units of Nopal ignimbrite. Mineralization in the welded zones is structurally controlled in fractures and small faults. The basal vitrophyre is altered, and less-welded zones contain disseminated mineralization. Beneath the base of the welded zone, in the Nopal Tuff, the deposit increases in size, in a manner similar to Nopal I. The large amount of structural dislocation has proven to be good ground preparation for the deposit such that the ore zone between drill holes 93 and 65 in Figure 121 is an intensely fractured region. The mineralized zone extends discontinuously for a distance of over 4 km to the northwest.

Not shown in Figure 121 is another uranium-bearing environment, that present at Domatilla which consists of underground workings into the reef core limestones underlying the deposits. Uranophane is present in solution fractures in the reef core, which is otherwise massive and impermeable. Tuff dikes and, fill fractures have sedimentary transport structures and appear to have formed by being sifted in from above.

Only hexavalent uranium is found at Margaritas. Uranophane, carnotite, and autunite are reported, and additional minerals identified by URAMEX are given in Table 17.

Several groups of samples from Margaritas have been subjected to chemical analysis. Analytic values and techniques are reported elsewhere (Goodell, et al., 1981). Figure 125 illustrates variations in U, V, As, Mo, and F down selected sections of drill holes 28 and 396, from analyses made by the Grand Junction laboratories of the U.S. Department of Energy. Vanadium and uranium vary sympathetically and fluorine also has some correlation. Arsenic and molybdenum are also associated with uranium, but they have peak values farther up and down the drill hole than uranium, respectively.

Another family of samples, analyzed by Geolabs, consists of 31 splits from cuttings through the ore zone from drill hole 46. Selected whole-rock and trace element constituents are plotted in Figures 126 and 127 to show their variation down the drill hole. X's indicate results from this drill hole which were also determined in the study mentioned in the prior paragraph. Two especially enriched uranium zones are evident, one at approximately 60 m depth and the other about 80 m. Sodium, potassium and silica increase in general with depth. Iron and sulfur maintain a similar relationship and have a general correlation and a similar relationship with uranium. This may reflect an earlier reduced mineralogy of uraninite-pyrite. Carbon dioxide peaks indicate zones either enriched in limestone lithics or containing large quantities of secondary calcite. The former is thought to contribute the largest variations. Fluorite is sympathetic with uranium, although its variations are subdued in comparison. The deposit is not particularly fluorine-rich. As shown in Figure 127 uranium maintains a relatively close correlation with arsenic, selenium, lead, and molybdenum. In detail, a crude vertical zoning is recognized with selenium at the top,

Figure 125 Down-hole chemical variations, drill holes 28 and 396, Margaritas deposit

Figure 126 Whole rock chemical variations, drill hole 46, Margaritas deposit

Figure 127 Trace element variations, drill hole 46, Margaritas deposit

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then uranium, lead, molybdenum, and mercury. The behavior of arsenic has a high correlation with uranium, but it cannot reliably be placed in a zoning position. This geochemical zoning is similar to that expected across a uranium roll-front deposit. Antimony, mercury and zinc also are enriched; however, they have no explicit correlation with uranium. Species which have an inverse relation with uranium include Mn, Li, Be, Ba, Mg, Na, K, and Ti.

The welded zones which constitute the two cooling units of the Nopal Formation are designated zones II and IV on the graph on the lower left of Figures 126 and 127. These zones contain only a small amount of fracture porosity and are consequently impoverished in those constituents introduced with the mineralizing processes.

Discussion

Two mineralized zones in the Pena Blanca uranium district have been described. Other occurrences in the area most frequently can be compared to one of these geologic environments. Although initially the differing settings for the various uranium occurrences appear to be quite different, upon further study the several environments have many characteristics in common. The similar mineralogy, alteration products, and trace element character tie the various occurrences together and suggest a nearly identical and uniform genesis for the region.

The trace element signature of the uranium mineralization is characteristic of epithermal/geothermal environments. Fluid inclusion temperatures on geode quartz found 2 km west of Margaritas indicate formation at temperatures of 150°C to 230°C; however, this quartz was not necessarily contemporaneous with the uranium mineralization. Perhaps the geodes formed by gas phase deposition during the degassing and fumarolic activity as the ignimbrite cooled. The temperatures and trace element indications do agree on an epithermal regime. Given the epithermal character of the deposits and the lack of any identifiable intrusive rocks, it is reasonable to assume that the source of the uranium was not magmatic-hydrothermal. The uranium more likely was derived from the alteration and leaching of volcanic glasses by geothermal convective groundwater systems. Such geothermal systems were probably present during the life of the calderas themselves; however the later Basin and Range or Rio Grande Rift tectonic activity has provided the

opportunity for the continuation of such geothermal systems up until the present time. Such a convective system probably was responsible for the Pena Blanca mineralization. Rock facies and structures appear important in providing the means of fluid movement. Mineral deposition was accompanied by rock alteration, and was possibly instigated by the presence of reducing waters derived from the organic- (and pyrite ?)-rich basin sediments. Additional study of the area will be necessary to establish its origin in detail.

Summary and Conclusions

Significant uranium mineralization is found in structural and stratigraphic sites within volcanoclastic and ignimbrite units at Pena Blanca. The host rocks are outflow facies from yet unidentified calderas.

Hexavalent uranium occurs in step faults, tuffaceous zones, pumice zones, and fractures and faults in tuffs and limestones. At least some of the uranium was precipitated in reduced form. The uranium is associated with selenium, arsenic, lead, molybdenum, and mercury, and the deposit appears to be zoned.

No unusual or diagnostic features have been found in the igneous rocks of the immediate area. The geology and geochemistry are comparable to those of numerous uranium occurrences in the Basin and Range Province of the western United States and such deposits probably are widespread. Several occurrences similar to the Pena Blanca environment which exist in the West Texas area of study have been reported elsewhere in this report.

Table 1

Geologic characteristics of environments favorable for uranium deposits
(from Mickle and Mathews, 1978)

Uranium occurrences in sedimentary rocks exclusive of sandstone, syngenetic

(Class 110)	Placer deposits
(Subclass 111)	Fluvial placers
(Subclass 112)	Beach placers
(Class 120)	Quartz-pebble conglomerates
(Class 130)	Marine black shales
(Class 140)	Phosphorites
(Subclass 141)	Uraniferous phosphorites of the Phosphorites type
(Subclass 142)	Uranium-bearing phosphorites of the land-pebble type
(Class 150)	Water
(Class 210)	Epigenetic/Lignite, coal, and nonmarine carbonaceous shale deposits
(Class 220)	Evaporative precipitates, calcrete
(Class 230)	Uranium occurrences in limestone
(Class 240)	Sandstone-type uranium deposits
(Subclass 241)	Roll-type deposits of the Gas Hills, Wyoming
(Subclass 242)	Roll-type deposits of South Texas
(Subclass 243)	Peneconcordant deposits of the Monument Valley-White Canyon districts, Utah and Arizona
(Subclass 244)	Peneconcordant deposits of the Urvan Mineral Belt

Uranium occurrences in the related to Plutonic Igneous Rocks

(Class 310)	Orthomagmatic class
(Class 320)	Pegmatitic class
(Class 330)	Magmatic-hydrothermal class
(Class 340)	Contact-metasomatic class
(Class 350)	Autometasomatic class
(Class 360)	Authigenic class
(Class 370)	Allogenic class
(Class 380)	Anatectic class

Volcanogenic Uranium Occurrences

(Class 510)	Initial-magmatic class
(Class 520)	Pneumatogenic class
(Class 530)	Hydroauthigenic class the Buckshot Ignimbrite
(Class 540)	Hydroallegenic class

Table 1 (continued)

Uranium Occurrences of Uncertain Genesis

(Class 710)	Unconformity-related uranium deposits
(Subclass 711)	Monometallic unconformity-related deposits
(Subclass 712)	Polymetallic unconformity-related deposits
(Class 721)	Monometallic vein-type deposit in metamorphic rocks
(Subclass 722)	Polymetallic vein-type deposit in metamorphic rocks
(Class 730)	Vein-type deposits in sedimentary rocks

Table 2

Uranium environments indicated in model for volcanic and
volcaniclastic terranes (from Goodell et al., 1981)

- A - magma chamber
- B - Keystone block
- C - intercaldera volcanic facies
- D - pre-caldera (basaltic) andesite volcanic pile
- E - outflow facies of ash flow tuff I
- F - outflow facies of ash flow tuff II
- G - volcaniclastic product of ash flow tuff II
- H - volcaniclastic product of ash flow tuff I
- I - lacustrine facies of ash flow tuff I
- J - lacustrine facies of ash flow tuff II
- K - merged lacustrine facies of ash flow tuff I & II
- L - (not shown in diagram) merged volcaniclastic facies of ash flow tuff x
and y
- M - playa facies
- N - volcanic basement

Stages of Caldera Evolution

1. regional tumescence
2. caldera forming eruptions
3. caldera collapse
4. post collapse sedimentation and pre-resurgence volcanic
5. resurgent doming
6. major ring-fracture volcanism
7. fumarolic and hot spring activity

Table 2 (Continued)

Potential Uranium Environments (numbers refer to class # in previous table)

1. pegmatite (320), (310), (350)
2. magmatic - hydrothermal veins associated with ring dike intrusives; ex: Moonlight Mine, McDermitt: (310), (330), (340), (350)
3. magmatic - hydrothermal veins associated with resurgent dome intrusives, may be distinguishable from #2, same classes.
4. rhyolite flow dome; ex: Pinto Canyon, W. Tx.
5. pyroclastic flows or flow - breccias; ex: Pinto Canyon, W. Tx.
6. mafic flow breccia and vesicular zone; ex: Aurora deposits, McDermitt
7. caldera boundary breccias
8. intercaldera volcanoclastic and lake facies, pre-resurgence, associated with stage 4.
9. intercaldera volcanoclastics, and lake or "moat" facies, post-resurgence associated with stage 5 and 7, - may be difficult to distinguish from #8.
10. "step faults" and other structural sites in welded tuffs; ex: Nopal 1, and Margaritas; Mammoth Mine and area SE, W. Tx.
11. altered basal vitrophyre of welded tuff - stratigraphic control; ex: Margaritas in part
12. lapilli tuffs, lithophysal zones, stratigraphically determined zones, in pyroclastic outflow facies; ex: surface of Margaritas
13. unwelded basal lithic - carbonate rich zone of ash flow tuff, permeable and reactive; ex: Spor Mt., Utah
14. conglomerate, arkose, and sandstone filled channels cut into volcanic basement, sometimes with accompanying organic debris; (24); ex: Tala-hassee Creek, CO; Sonora Pass, CA
15. G, H or L - volcanoclastic facies (24); ex: Colorado Plateau-type sandstones might be construed to be of this type (Waters & Granger, 1953)
16. I, J or K; lacustrine environments (210), ex: Anderson Ranch, Brewster, Co., TX

Table 2 (continued)

17. M, Playa, Calcrete (220)
18. structural features in the volcanic basement, faults, karsts; ex: thrust faults and karsts at Sierra Gomez, fractures and karsts at Domatilla, PB.; karsts in WY (230)
19. stratigraphic features in volcanic basement, permeable clastic units act as solution paths (240); ex. together with 20, constitutes sandstone type of uranium deposits.
20. chemical features in volcanic basement - reductants provided by iron sulfides and organic material; ex: Sierra Gomez - both (240)

Table 3

Geologic events of the resurgent cauldron cycle (adapted from Smith and Bailey, 1968)

<u>Stage</u>	<u>Structural Events</u>	<u>Volcanic Events</u>	<u>Sedimentary Events</u>	<u>Plutonic Events</u>	<u>Approximate Time span, Years</u>
0	regional intersecting lineament zone of weakness	massive and long term outpouring of calcalkaline suite	intervolcanic basins receive a variety of clastic materials	widespread introduction of calc-alkaline magmas, subduction zone derived	10 to 100 m.y. or more
I Structural, magmatic	regional tumescence, with associated ring and radial fractures	generally minor eruptions along ring and radial fractures, perhaps increasing with the approach of Stage II	erosion of domed area	incorporation of fluids into the magma chamber, increasing the gas content and consequently the magma pressure; significant compositional zoning occurs	greater than 1 m.y.
II Volcanic	See Stage III	major caldera-forming eruptions of ash-flow tuffs, can be several thousand cubic kilometers of volume	none	expulsion of large quantity of magma	days to several years
III Structural	caldera collapse, downdropping of central keystone block	See stage II	landslides and avalanches from caldera walls	disequilibrium subsequent to the magma expulsion	Same as II, or somewhat longer

Table 3 (Continued)

<u>Stage</u>	<u>Structural Events</u>	<u>Volcanic Events</u>	<u>Sedimentary Events</u>	<u>Plutonic Events</u>	<u>Approximate Time Span, Years</u>
IV Sedimento- logical	none	sometimes there is minor volcanic activity within the caldera	major infilling volcano-tectonic depression by mass wasting, lake deposits, etc.	not prominent	less than 10^5 years
V Structural Plutonic	resurgent doming with the formation of central graben valleys	dome-fracture volcanism, with lesser possibility of ring fractures activity	major infilling continues, but in an annular depression called a moat; an unconformity will separate these sediments from those of Stage IV	major resurgent intrusive activity, forming the central structural dome	less than 10^5 years
VI Volcanic	not prominent	major ring-fracture volcanism, volume of extrusives second only to Stage II	infilling continues, caldera may overflow	ring and radial fracture dikes and intrusions	less than 10^6 years
VII	none	fumarolic and hot spring activity producing widespread silicification and hydrothermal alteration	surficial erosion	cooling and crystallization of prior intrusives. Hydrothermal convecting cells	$\pm 10^6$ years

. the igneous system may recycle, either in the same place, or more frequently, slightly displaced.

from Hobbs, 1979, Figure 5.

Table 5

Average chemical analyses of volcanic units, northern Quitman Mountains
(from Hobbs and Hoffer, 1980, Table 1)

Unit	1	2	3	4	5	6	7	8	9
Samples	2	3	3	3	1	3	2	3	2
SiO ₂	71.91	65.26	64.57	64.65	66.34	70.16	68.29	65.60	70.47
TiO ₂	0.12	0.69	0.93	0.98	0.65	0.36	0.33	0.69	0.34
Al ₂ O ₃	13.26	15.75	17.14	17.22	16.60	15.33	17.10	16.32	15.38
Fe ₂ O ₃	2.97	5.02	4.89	4.48	4.02	2.71	2.88	4.32	2.84
MnO	0.09	0.08	0.09	0.06	0.11	0.08	0.05	0.09	0.07
MgO	0.41	0.88	1.14	0.89	1.06	0.55	0.26	0.60	0.30
CaO	1.80	1.73	2.10	2.65	2.15	1.44	0.45	1.04	0.51
Na ₂ O	4.91	5.02	5.18	4.42	4.85	5.15	5.49	6.07	4.96
K ₂ O	3.91	5.32	4.26	4.43	4.28	4.56	4.93	5.34	5.27
P ₂ O ₅	0.05	0.32	0.35	0.24	0.06	0.06	0.06	0.20	0.05
Total	99.43	100.07	100.65	100.02	100.11	100.40	99.84	100.27	100.19

Table 6

Equivalent K, U, Th contents of several rock units around the Quitman caldera, Quitman Mountains, Hudspeth County, Texas

<u>Sample #</u>	<u>Location</u>	<u>Thorium ppm</u>	<u>Uranium ppm</u>	<u>Potassium wt. %</u>	<u>Th/U</u>
QM 2	Tremble Hill Skarn	7.54	19.51	1.18	.39
QM 3	Milby Peak Vein	1.74	2.23	0.70	.78
QM 4	Silver King Canyon vein	0.96	6.54	0.21	.18
QM 5	Tarantula Hills vein	1.13	5.77	0.16	.20
QM 6	Zimplean Pass skarn	0.42	4.37	1.11	.10
QM 8	West side breccia zone	11.84	4.03	2.86	2.93
QM 9	Bonanza vein	0.38	17.50	0.10	.02
QM 12	Quitman Canyon Pegmatite	701.07	91.48	2.86	7.66
fluorite clear	Cowan Ranch fluorite vein	1.24	0.39	0.06	3.18
fluorite light green	"	1.26	0.29	0.11	4.34
fluorite blue	"	0.59	0.03	0.01	19.67

Table 7

Whole rock geochemical analysis of the Garren Group

No.	Sample	SiO ₂	Al ₂ O ₃	Na ₂ O	MgO	K ₂ O	CaO	TiO ₂	MnO	FeO	P ₂ O ₅	eU* (ppm)	eTh* (ppm)	Total (wt. %)
12	Bell Valley Andesite	52.07	14.45	3.04	9.39	1.80	6.21	.68	.12	5.58	1.06	3.0	3.8	99.0
11	Fairbury Tuff	71.84	12.87	2.28	6.07	1.34	2.29	.41	.07	3.78	.10	3.6	25.4	101.05
10	Bonito Latite	58.99	17.16	3.33	8.38	3.63	2.56	.46	.12	5.89	.49	4.9	10.0	101.01
9	Crosby Tuff	62.57	17.28	4.16	2.86	5.02	1.59	.44	.15	4.74	.10	4.3	13.1	99.01
8	Means Latite	52.41	12.82	2.83	12.05	1.20	6.53	.69	.14	10.78	.68	1.2	4.0	100.17
7	Water Tuff Upper Member	73.37	10.22	3.39	3.97	3.35	1.12	.35	.04	3.63	.10	6.0	20.3	99.28
6	Water Tuff Lower Member	70.75	12.10	3.29	3.13	3.98	1.39	.42	.08	5.21	.10	4.3	16.2	100.45
5	Water Tuff (Basal Vitrophyre)	70.42	13.74	2.69	1.95	4.49	1.91	.43	.08	5.21	.10	5.0	13.9	101.10

Table 7 (Continued)

No.	Sample	SiO ₂	Al ₂ O ₃	Na ₂ O	MgO	K ₂ O	CaO	TiO ₂	MnO	FeO	P ₂ O ₅	eU* (ppm)	eTh* (ppm)	Total (wt. %)
4	Buck Mt. Tuff	63.21	19.10	3.45	1.44	4.05	2.42	.50	.15	5.92	.40	6.2	19.7	101.15
3	Garren Mt. Tuff Breccia	59.25	16.14	3.45	2.8	2.37	4.77	.62	.18	9.25	.84	2.9	9.6	99.67
2	Pantera Ignimbrite	62.28	17.87	2.75	1.93	3.45	3.45	.534	.13	7.02	.80	4.8	11.9	100.9
1	Hogeye Tuff	69.99	15.64	4.16	.149	2.96	1.42	.40	.03	3.88	.097	3.3	21.8	98.73

* Gamma-Ray Spectrometer Analysis

Table 8

Measured Section -- Mammoth Mine

Buckshot Ignimbrite

Dark reddish brown to dusky red ignimbrite; contains approximately 5% dusky red lithic (?) fragments, 1 mm-1 cm in diameter. (3 mm) lithophysal cavities filled with calcite which has a bright red response to long wave ultra violet light. XRD: Quartz, feldspar (dominantly sanadine).

1.52 m

Very pale orange and grayish red to dark reddish brown ignimbrite shows flattening of shards; contains 40% lithophysal cavities; vesicles are filled with secondary calcite.

2.4 m

Grayish red, very pale red, pale yellow orange ignimbrite from mine dump (correlative with 1252); contains 5% lithic fragments less than 5 mm in diameter. XRD: Quartz, feldspar, clay. Uranophane present in lithophysal cavities

Mine
dump

Grayish red, densely welded Buckshot Ignimbrite; contains less than 15% very dark lithic fragments less than 5 mm in diameter. XRD: Quartz and feldspar (sanadine)

1.83 m

Grayish red ignimbrite contains less than 5% very dark red lithic fragments less than 3 mm in diameter. Lithophysal cavities are 1 mm to 1 cm wide. Vesicles show flattening, some are filled with calcite. The matrix is fine-grained and contains euhedral to subhedral crystals. XRD: Quartz and feldspar

Chambers Tuff

Pale red, very fine-grained, tuffaceous sandstone. XRD: Quartz, feldspar, calcite, and clay.

6.1 m

Table 8 (continued)

Pale red, very fine-grained, tuffaceous sandstone. XRD: Quartz, feldspar, calcite, and clay. 6.1 m

Pale red to grayish red, very fine-grained, homogenous, tuffaceous, silty, sandstone. Tuff is highly consolidated and contains white "spotty" areas 1 mm in diameter. White areas respond yellow green to long wave ultra violet light. XRD: Quartz, clinoptilolite, feldspar, calcite, and clay. 1.52 m

Light brownish gray, pale red, grayish orange pink, well consolidated, fine-grained tuffaceous sandstone. For description other than color, see sample number 1259. 6.71 m

Pale red, very fine-grained, well consolidated tuffaceous sandstone. Tuff contains white "spotty" areas 1 mm in diameter. Calcite coating present. XRD: Quartz, clinoptilolite, feldspar, clay. Amygdaloidal calcite coating responds yellow orange to long-wave ultraviolet light. 4.57 m

Light brownish gray to grayish orange pink homogeneous; very fine grained, silty, tuffaceous sandstone. XRD: Quartz, feldspar clay. 6.1 m

Very fine-grained, tuffaceous, silty grayish pink to pinkish gray sandstone; sample homogeneous. XRD: Quartz, feldspar, clinoptilolite, calcite clay. 1.52 m

Grayish orange pink, homogeneous, siltstone; contains small calcite veinlets; chalcedony that responds yellow-green under long-wave ultra violet light. XRD: Quartz, feldspar, clinoptilolite, and clay. 1.22 m

Pale red, highly consolidated, homogeneous, tuffaceous, siltstone. XRD: Calcite, quartz, clay. Vitreous brown and white crystals respond yellow orange to long- and short-wave ultra violetlight. 2.44 m

Light gray to very light gray conglomerate; contains limestone pebbles (2 mm), medium-grained matrix; highly effervescent when HCl is applied; contains 2% calcite coating. XRD: Calcite, quartz, feldspar, and clay. 1.52 m

Table 8 (continued)

Very fine-grained, homogeneous, pale red tuffaceous sandstone; highly effervescent when HCl is applied; contains calcite in pore spaces. XRD: Quartz, calcite, feldspar, and clay.

16.76 m
(55 ft)

Very pale orange homogeneous siltstone (?); slightly effervescent; "peppered" appearance when viewed under scope (20x). XRD: clinoptilolite, quartz, feldspar, and clay.

1.83 m
(6 ft)

Table 9
Major Oxide Contents, Stratigraphic Section, Mammoth Mine

Oxide %	Sample Number							
	1251	1252	1253	1254	1255	1256	1257	1258
Na	1.79	2.19	3.29	2.85	3.43	1.75	2.15	2.30
Mg	0.0	0.0	0.63	0.0	0.45	0.50	0.15	0.58
Al	11.05	13.42	14.08	15.12	12.74	12.92	13.46	12.81
Si	74.16	68.91	66.66	69.52	67.93	70.28	77.64	77.11
P	0.07	0.0	0.0	0.0	0.12	0.13	0.16	0.21
K	4.85	6.65	6.29	5.79	5.91	4.00	1.90	3.30
Ca	5.90	0.86	0.98	0.33	2.80	5.09	1.47	1.47
Ti	0.15	0.28	0.28	0.33	0.44	0.65	0.39	0.42
Mn	0.15	0.02	0.02	0.02	0.03	0.09	0.03	0.05
Fe	1.40	2.58	3.56	2.43	2.82	3.60	2.03	2.25
Total	99.52	94.91	95.79	96.39	96.67	99.01	99.38	100.50

Oxide %	1259	1260	1261	1262	1263	1264	1265	1266
Na	3.10	0.88	0.88	2.15	0.88	0.88	0.88	3.77
Mg	0.54	0.56	0.47	0.42	0.41	0.49	0.46	0.58
Al	14.49	13.89	12.29	13.44	6.99	10.21	9.11	13.72
Si	73.92	68.09	55.86	73.60	33.30	44.08	41.34	75.29
P	0.20	0.14	0.16	0.22	0.20	0.18	0.18	0.38
K	3.22	4.59	2.37	2.80	1.44	1.82	2.38	1.60
Ca	1.53	6.14	17.91	1.56	42.46	29.30	31.62	2.19
Ti	0.53	0.50	0.33	0.59	0.21	0.45	0.30	0.50
Mn	0.04	0.08	0.10	0.04	0.10	0.19	0.07	0.05
Fe	2.42	3.07	1.74	2.95	1.40	2.15	1.91	1.97
Total	99.99	97.94	92.11	97.77	87.38	89.75	88.25	100.05

Table 10
K, U, Th Contents, Stratigraphic Section, Mammoth Mine

	<u>Th ppm</u>	<u>U ppm</u>	<u>K %</u>	<u>Th/U</u>
Colmena Tuff				
1248	6.36	4.00	0.97	1.59
1249	.90	1.37	0.26	.66
1250	2.99	1.83	0.78	1.63
Buckshot Ignimbrite				
1251	26.80	9.50	4.63	2.82
1252	31.90	38.06	5.09	.82
1253	29.83	23.95	4.53	1.25
1254	28.04	31.91	4.62	.88
1255	23.82	33.33	4.60.	.71
Chambers Tuff				
1256	12.31	6.02	3.37	2.04
1257	11.92	4.33	1.70	2.77
1258	13.88	3.49	2.69	3.98
1259	15.01	4.33	2.50	3.47
1260	11.42	3.15	3.51	3.63
1261	10.96	3.16	2.39	3.47
1262	10.18	3.95	2.14	2.58
1263	3.87	2.95	1.19	1.98
1264	6.54	2.60	1.73	2.52
1265	6.59	2.09	2.11	3.15
1266	26.54	5.28	1.14	5.03

Table 11

Summary of major oxide chemical analyses of the volcanics of the
Thunderbird Formation (from Thomann, 1980, Table 7)

<u>Member</u>	<u>Rock Type</u>	<u>Major Oxide</u>	<u>Range (wt.%)</u>	<u>Average (wt.%)</u>
		SiO ₂	62.56 to 76.52	72.01
		TiO ₂	0.00 to 0.64	0.17
	Ignimbrite (52 analyses)	Al ₂ O ₃	10.61 to 14.70	12.33
		FeO _T (total iron)	0.00 to 11.37	4.30
		MgO	0.00 to 1.28	0.30
		CaO	0.00 to 2.70	0.68
		Na ₂ O	1.35 to 4.86	3.29
		K ₂ O	2.92 to 9.10	5.57
		MnO	0.00 to 0.14	0.03
<hr/>				
Upper		SiO ₂	68.52 to 76.80	72.03
		TiO ₂	0.08 to 0.32	0.18
	Porphyritic rhyolite (8 analyses)	Al ₂ O ₃	10.43 to 13.68	12.59
		FeO _T (total iron)	0.29 to 0.84	2.98
		MgO	0.00 to 0.37	0.17
		CaO	0.12 to 1.04	0.63
		Na ₂ O	2.45 to 4.04	3.37
		K ₂ O	5.11 to 6.69	6.04
		MnO	0.00 to 0.09	0.04

Table 11 (continued)

<u>Member</u>	<u>Rock Type</u>	<u>Major Oxide</u>	<u>Range (wt.%)</u>	<u>Average (wt.%)</u>
	Melanocratic porphyritic trachyte (8 analyses)	SiO ₂	56.87 to 63.74	60.04
		TiO ₂	0.52 to 2.01	0.87
		Al ₂ O ₃	14.00 to 15.90	14.83
		FeO _T (total iron)	7.60 to 16.30	10.80
		MgO	0.43 to 2.75	1.31
		CaO	0.86 to 4.25	2.51
		Na ₂ O	3.07 to 5.41	4.09
		K ₂ O	2.55 to 5.51	3.94
		MnO	0.01 to 0.40	0.14
<hr/>				
Upper	Porphyritic trachyte (13 analyses)	SiO ₂	54.94 to 68.21	62.55
		TiO ₂	0.13 to 1.10	0.46
		Al ₂ O ₃	12.97 to 18.64	15.04
		FeO _T (total iron)	5.73 to 16.72	9.49
		MgO	0.00 to 1.51	0.58
		CaO	0.14 to 3.45	1.14
		Na ₂ O	3.24 to 7.95	4.41
		K ₂ O	1.40 to 7.00	5.25
		MnO	0.00 to 0.17	0.06

Table 11 (continued)

<u>Member</u>	<u>Rock Type</u>	<u>Major Oxide</u>	<u>Range (wt.%)</u>	<u>Average (wt.%)</u>
Middle	Silicified ignimbrite	SiO ₂	57.63 to 69.13	63.36
		TiO ₂	0.27 to 0.50	0.41
		Al ₂ O ₃	10.84 to 17.56	13.42
		FeO _T (total iron)	8.14 to 11.56	9.80
		MgO	0.00 to 6.02	1.64
		CaO	0.10 to 1.57	0.75
		Na ₂ O	2.51 to 4.21	3.19
		K ₂ O	3.90 to 9.33	6.74
		MnO	0.01 to 0.05	0.03

Table 12

Stratotype of the Thunderbird Formation, K, U, th values determined
by gamma spectroscopy (data from Thomann, 1980)

		Uranium, ppm		thorium, ppm		potassium, wt. %	
		average (and # of samples)	range of values	average	range of values	average	range of values
Upper Member,		7.4 (38)	2.5-30.9	33.3	11.6-48.7	4.9	3.3-10.2
Crystal vitric ignimbrite							
silicified ignimbrite							
		4.1 (2)	3.9-4.2	20.8	19.2-22.3	6.3	4.6-7.9
Tuffaceous sandstone and con- glomerate		2.4 (2)	1.8-2.9	10.7	9.0-12.4	2.2	1.8-2.6
Porphyritic trachyte		2.2 (3)	1.9-2.9	9.4	6.5-12.4	3.2	2.6-4.0
Melanocratic porphyritic trachyte		2.4 (7)	1.1-3.9	7.7	2.1-11.1	4.3	2.8-7.2
Basal conglom- erate		5.2 (1)		19.7		4.2	

Table 13

Comparison of the number of ions per 24 (O, OH, F) in riebeckite

	Granite Peak (Hoffer, 1972)	Bokan Mountain (MacKevett, 1963)	Nigeria* (1)	Scotland* (2)	Rockall* (3)	Pikes Peak* (4)	Korea* (5)
Si	7.88	7.92	7.91	7.83	8.04	7.86	7.92
Al (IV)	0.12	0.08	0.09	0.17	0.00	0.14	0.08
Al (VI)	0.18	0.19	0.06	0.32	0.13	0.06	0.03
Ti	0.07	0.08	0.11	0.22	0.10	nd	0.05
Mn	0.07	0.10	0.06	0.12	0.08	0.16	0.19
Mg	0.01	0.04	0.05	0.00	0.07	0.15	1.14
Fe ⁺³	2.33	1.57	1.91	1.63	1.19	1.89	1.63
Fe ⁺²	2.03	2.77	2.28	2.36	3.26	2.80	1.87
Fe ^{total}	4.36	4.34	4.19	3.99	4.45	4.69	3.50
Na	2.34	2.41	2.40	1.78	2.73	2.52	1.45
K	0.31	0.32	0.36	0.27	0.35	0.35	0.41
Ca	0.02	0.09	0.03	0.18	0.10	0.00	0.22
TOTAL	2.67	2.80	2.79	2.23	3.18	2.87	2.08
H ₂ O ⁺	1.82	1.79	0.94	1.94	1.39	1.22	2.04
H ₂ O ⁻							
F ⁻	nd	nd	0.83	0.15	nd		0.14
TOTAL	1.82	1.79	1.77	2.09	1.39	1.22	2.18

*from Deer et al., 1963

Table 14

Sierra Pena Blanca volcanostratigraphic sections, formation thickness, in meters

Stratigraphic Section Number	Latitude	Longitude	Pozos Fm	Nopal Fm	Escuadra Fm	Chontes Fm	Pena Blanca Fm	La Mesa Fm	Total Thickness
1	29°9'17"	106°00'55"	20.0*	190.0*					210.0
2	29°07'50"	106°01'10"	30.0*	137.0*					167.0
3	29°08'30"	106°03'02"		24.0*	82.0*				106.0
4	29°15'20"	106°02'30"	70.0*	92.5	82.0	70.0	222.0	65.0*	538.0
5	29°18'55"	106°01'15"	15.0*	70.0	51.0	57.0	112.0	73.0*	379.0
6	29°06'05"	106°02'05"	2.0*	131.0*					133.0
7	29°09'11"	106°03'40"			106.0*	152.0	135.0	50.0*	443.0
8					130.0*	28.0	12.0	44.0*	214.0
9	29°11'40"	106°02'45"				132.0*	169.0	60.0*	361.0
10	29°06'29"	106°02'40"	9.0*	106.0*					115.0
11	29°00'00"	106°04'00"	30.0*	63.0	84.0	69.0	126.0	56.0*	428.0
M + N	29°06'00"	106°05'00"		100.0	50.0	0.0	20.0	75.0*	245.0
El Cerote	29°15'00"	106°13'00"		100.0	25.0		25.0	25.0*	175.0
Puerto Hormigas	29°09'10"	105°47'25"		40.0	75.0			75.0*	190.0

* Minimum

Sections 1 through 11 were measured by Bell and Hartdke (1976).

Table 15

Whole rock analysis of representative Nopal, Escuadra, Pena Blanca, and Mesa Formations
from Miranda (1980)

<u>OXIDE</u>	<u>LOWER NOPAL</u>	<u>MIDDLE NOPAL</u>	<u>UPPER NOPAL</u>	<u>ESCUADRA</u>	<u>PENA BLANCA</u>	<u>MESA</u>
SiO ₂	63.4	70.5	75.6	77.6	67.4	75.6
Al ₂ O ₃	11.5	14.0	12.3	12.3	11.7	12.1
K ₂ O	4.0	5.5	6.5	6.3	2.0	5.4
Na ₂ O	1.6	4.2	.75	1.6	.78	3.5
CaO	7.4	1.7	.29	.34	4.6	.63
Fe ₂ O ₃	1.7	2.1	1.30	.99	1.2	2.7
TiO ₂	.15	.39	.25	.16	.13	.24
FeO	.10	.14	.01	.01	.06	.10
H ₂ O	2.2	.20	.25	.35	4.58	.28
MnO	.07	.05	.06	.04	.03	.05
MgO	.78	.38	.08	.28	.86	.23
P ₂ O ₅	.07	.12	.07	.07	.07	.07

TABLE 16

Trace element analysis from the Nopal No. 1 deposit
(contents in ppm)

Sample locations are indicated on Figure 122

Sample	Pb	Mo	Be	Bi	F	Hg	Li	U	Au	Se
<u>Underground</u>										
M-3	520	410	1	20	660	15.0	34	4200	.02	--
M-4	950	820	1	10	500	8.2	44	8200	--	.5
M-5	1950	230	1	25	620	13.0	46	3400	.02	--
M-6	130	6	3	5	460	1.6	55	100	.02	.5
M-7	890	600	1	20	660	12.0	34	90000	.01	.5
M-8	640	120	1	5	440	15.0	90	3800	--	--
M-9	1150	16	9	16	560	.27	40	2200	--	--
M-10	10	2	5	5	620	.16	50	15	--	--
M-11	1550	42	7	15	500	.78	30	2600	.02	--
<u>Surface</u>										
A	225	10	1	20	550	.55	55	820	--	--
B	265	195	1	25	480	6.0	85	730	--	--
C	580	300	1	20	420	2.4	90	670	--	--
D	30	2	2	10	340	.16	55	200	--	--
E	50	2	2	5	360	.10	65	22	--	--
F	4000	14	1	15	620	4.5	28	630	--	--
G	385	34	2	25	440	1.7	44	120	--	--
H	85	2	2	15	440	.11	55	35	--	--
I	1000	70	2	20	500	6.0	32	470	--	--
J	1200	46	2	15	390	.78	45	65	--	--

Table 17

Mineralogical characterization of the ores of three U-Mo deposits
Sierra Pena Blanca, Chihuahua

Center of Metallurgical Studies, URAMEX, 1980
(from Miranda, 1980)

X indicates trace
to small amount
present

Chemical
Composition

Relative Abundance in
These Deposits

		<u>Nopal I</u>	<u>Margaritas</u>	<u>Puerto III</u>
<u>Uranium Silicates</u>				
uranophane	$\text{Ca}(\text{UO}_2)_2\text{Si}_2\text{O}_7 \cdot 6\text{H}_2\text{O}$	X	X	.2%
betauranophane	$\text{Ca}(\text{UO}_2)_2\text{Si}_2\text{O}_7 \cdot 6\text{H}_2\text{O}$	X	0.15%	
weeksite	$\text{K}_2(\text{UO}_2)_2\text{SiO}_7 \cdot 4\text{H}_2\text{O}$	.30%	X	
bottwoodite	$\text{K}(\text{H}_3\text{O})(\text{UO}_2)\text{SiO}_4 \cdot \text{H}_2\text{O}$	X		
soddyite	$(\text{UO}_2)_5\text{Si}_2\text{O}_9 \cdot 6\text{H}_2\text{O}$	X		
<u>Uranium Vanadates</u>				
carnotite	$\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 3\text{H}_2\text{O}$		.05%	.02%
metatyuyumanite	$\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 3-5\text{H}_2\text{O}$			
<u>Uranium Oxides</u>				
masuyite	$\text{UO}_{2-3} \cdot 2\text{H}_2\text{O}$	.03%		
uraninite	UO_2		X	
<u>Associated Minerals</u>				
powellite	CaMoO_4	.38%		
alunite	$\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$	1.7%	1.4%	0.6%
calcite	CaCO_3	.44%	.78%	0.74%
hematite	Fe_2O_3	6.8%	1.03%	1.00%
montmorillonite	$(\text{Na}, \text{Ca})_{0.33}(\text{Al}, \text{Mg})_2\text{Si}_4\text{O}_{10}(\text{OH})_2 \cdot n\text{H}_2\text{O}$	2.24%		4.48%
kaolinite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	27.5%	11.3%	14.3%
saponite	(a montmorillonite) $(\text{Ca}_{12}, \text{Na})_{0.33}(\text{Mg}, \text{Fe})_3(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH})_2 \cdot 4\text{H}_2\text{O}$			

Table 17 (continued)

X indicates trace to small amount present	Chemical Composition	Relative Abundance In These Deposits		
		<u>Nopal I</u>	<u>Margaritas</u>	<u>Puerto III</u>
nontronite	$\text{Na}_{0.33}\text{Fe}_2(\text{Si},\text{Al})_4\text{O}_{10}$ $\cdot n\text{H}_2\text{O}$ (a montmorillonite)			
sodium plagioclase	$\text{NaAlSi}_3\text{O}_8$	.08%	2.6%	3.22%
potassium feldspar	KAlSi_3O_8	13. %	35.9%	39.2%
quartz	SiO_2	47.5%	46.2%	34. %
opal	$\text{SiO}_2 \cdot n\text{H}_2\text{O}$	X		
fluorite	CaF_2		X	

Table 18

King Mountain, McCamey, Texas; samples descriptions and data

Sample No.	Approximate Location	Sample Description	eTh ppm	eU ppm	eK %
840	Prospect Pit McCamey, TX King Mountain	Gray Fossiliferous limestone	0.17	2.74	0.02
841	"	Gray Fossiliferous limestone	1.39	4.00	0.11
843	"	Gray Limestone	0.91	3.03	0.08
844A	"	Gray Fossiliferous	0.18	1.46	0.09
844B	"	Gray Fossiliferous	1.54	1.75	0.28
846	"	Fault Gouge Zone limestone	1.01	1.81	0.04
847	"	Highly Fossiliferous limestone	6.41	3.04	0.03
848	"	Massive Fossiliferous limestone	0.00	2.05	0.00
849	"	Gray Fossiliferous limestone	0.25	1.10	0.05
850	"	Gray Fossiliferous limestone	0.25	1.10	0.05
851	"	Gray Fossiliferous limestone	0.12	2.12	0.05
852	"	Mudstone Caprock	0.22	2.17	0.07
853	"	Mudstone Caprock	1.32	6.64	0.04

Table 18 (continued)

Sample No.	Approximate Location	Sample Description	eTh ppm	eU ppm	eK %
854	Prospect Pit McCamey, TX King Mountain	Limestone-Gray	0.05	4.13	0.02
855	"	Alteration Zone #1	0.53	2.36	0.07
856	"	Alteration Zone #2	0.83	2.99	0.31
857	Slusch Pit, King Mountain, McCamey, TX	Sandstone Red	1.84	1.03	0.56
858	"	Alluvium	4.07	2.41	0.84
859	King Mountain	Gray Sandstone	1.41	0.51	0.22
860	"	Lens in sandstone	0.82	2.16	0.30
861	"	Gray Sandstone	1.44	1.69	0.24
862B	"	Yellow Sandstone	1 3.24	4.04	0.48
862D	"	Blue Sandstone	1 1.52	3.02	0.22

Table 19

Average analyses by rock types (from Woodrome, 1980)

Major Oxides	ROCK TYPES						
	Basalt	Andesite	Trachyte	Syenite	Syenodiorite	Phonolite	Rhyolite
SiO ₂	52.17	50.94	64.27	61.25	57.76	60.10	71.28
TiO ₂	2.45	1.16	.44	.18	.91	.07	.30
Al ₂ O ₃	13.67	15.63	15.80	16.47	18.94	19.13	13.56
Fe ₂ O ₃	12.02	8.48	5.10	4.77	5.15	4.51	3.62
MnO	.17	.16	.10	.11	.10	.13	.05
MgO	4.87	6.60	.56	.38	1.60	.35	.31
CaO	8.60	9.32	1.60	2.04	4.03	1.05	2.27
Na ₂ O	2.62	4.45	4.70	5.62	6.15	7.30	3.95
K ₂ O	1.57	1.87	5.41	5.47	5.04	5.33	4.56
eU ppm	2.0	1.8	4.1	5.3	2.7	16.3	6.9
eTh ppm	3.4	5.7	14.9	18.4	8.8	47.0	31.5
eKwt %	1.2	1.2	4.24	4.45	3.26	3.97	3.62
No. of Samples	6	7	22	62	3	8	64

Table 20.

Means and maximums of uranium contents, all basins
(from Woodrome, 1980)

Hardness	1°	2°	3°	4°	5°	6°	7°
Temp	20/22	22/27	23/30	24/54	22/28	24/29	23/34
pH	6.9/7.2	7.2/8.2	7.2/8.0	7.4/9.1	7.1/7.9	7.4/8.5	7.5/8.9
Na	139/539	70/220	75/623	138/2K	40/156	56/149	44/205
K	1.5/3.0	3.6/28	4/30	4/90	4/25	3/13	5/17
Ca	58/94	60/151	60/123	61/224	61/177	28/56	48/120
Si	9/11	9/35	12/29	19/31	19/29	23/40	25/45
Cl	122/320	65/270	95/990	37/410	36/460	12/40	17/58
F	1.5/4.6	1.1/3.0	.7/1.8	2/20	.9/3.5	5/24	2/22
Fe	3/27	.9/11.0	2.6/12	3/30	.3/1.6	1/10	1.4/25
Li	.08/.30	.04/10	.05/.60	.09/1.6	.05/.44	.04/.10	.02/.40
Mg	45/66	34/61	26/64	39/118	10/90	2.7/7.0	9/70
Mn	.01/.07	.01/.07	.03/.20	.05/.56	.01/.07	-./.04	.02/.65
Pb	.02/.05	.02/.05	.01/.04	.01/.11	-./.01	.04/.15	.02/.15
Zn	.2/.8	.16/1.1	.46/2.1	.36/9.6	.1/.9	.2/.9	.12/2.2
Ba	.09/.11	.12/.33	.1/.2	.1/.22	.05/.11	.05/.33	.09/.22
Cu	.06/.47	.02/.27	.04/.18	.03/.21	.01/.08	.02/.10	-./.05
Sr	1.4/2.6	1.0/2.6	5/110	.8/6.2	1.8/23	10/148	.4/1.2
Br	1.4/2.6	.8/3.8	.8/6.5	.4/3.7	.4/4.0	.2/.65	.2/.5
I	----	----	-1/.01	----	.02/.10	.03/.60	-./.03
Ag	-/.01	-1/.01	1/.01	-/.01	-/0.1	-/0.1	-/.01
U, ppb	5.5/13	5/17	4.6/19	6/21	3.1/12	5.3/12	7.4/22
Hardness	333/434	294/606	265/480	316/5420	200/800	43/126	144/358
TDS mean	811	632	476	588	140	243	260
Maximum	1950	1500	2880	9100	710	385	900

Temp given in degrees F.

Elements given in parts per million: Na, K, Ca, Si, Cl, F, Fe, Li, Mg, Mn, Pb, Zn, Ba, Cu, Hardness, TD.

Elements given in parts per billion: Ag, U, Sr, Br, I.

Table 20.

Means and maximums of uranium contents, all basins
(from Woodrome, 1980)

Hardness	1	2	3	4	5	6	7
Temp	20/22	22/27	23/30	24/54	22/28	24/29	23/34
pH	6.9/7.2	7.2/8.2	7.2/8.0	7.4/9.1	7.1/7.9	7.4/8.5	7.5/8.9
Na	139/539	70/220	75/623	138/2K	40/156	56/149	44/205
K	1.5/3.0	3.6/28	4/30	4/90	4/25	3/13	5/17
Ca	58/94	60/151	60/123	61/224	61/177	28/56	48/120
Si	9/11	9/35	12/29	19/31	19/29	23/40	25/45
Cl	122/320	65/270	95/990	37/410	36/460	12/40	17/58
F	1.5/4.6	1.1/3.0	.7/1.8	2/20	.9/3.5	5/24	2/22
Fe	3/27	.9/11.0	2.6/12	3/30	.3/1.6	1/10	1.4/25
Li	.08/.30	.04/10	.05/.60	.09/1.6	.05/.44	.04/.10	.02/.40
Mg	45/66	34/61	26/64	39/118	10/90	2.7/7.0	9/70
Mn	.01/.07	.01/.07	.03/.20	.05/.56	.01/.07	-.04	.02/.65
Pb	.02/.05	.02/.05	.01/.04	.01/.11	-.01	.04/.15	.02/.15
Zn	.2/.8	.16/1.1	.46/2.1	.36/9.6	.1/.9	.2/.9	.12/2.2
Ba	.09/.11	.12/.33	.1/.2	.1/.22	.05/.11	.05/.33	.09/.22
Cu	.06/.47	.02/.27	.04/.18	.03/.21	.01/.08	.02/.10	-.05
Sr	1.4/2.6	1.0/2.6	5/110	.8/6.2	1.8/23	10/148	.4/1.2
Br	1.4/2.6	.8/3.8	.8/6.5	.4/3.7	.4/4.0	.2/.65	.2/.5
I	----	----	-1/.01	----	.02/.10	.03/.60	-.03
Ag	-.01	-1/.01	1/.01	-.01	-/0.1	-/0.1	-.01
U, ppb	5.5/13	5/17	4.6/19	6/21	3.1/12	5.3/12	7.4/22
Hardness	333/434	294/606	265/480	316/5420	200/800	43/126	144/358
TDS mean	811	632	476	588	140	243	260
Maximum	1950	1500	2880	9100	710	385	900

Table 20 (continued)

Hardness	9°	10°	12°	13°	14°	15°	16°
Temp	21/40	25/32	22/27	23.37	28/46	22/26	22/34
pH	7.2/8.2	7.1/8.0	7.2/7.8	7.1/8.6	7.1/8.0	7.2/8.9	7.2/8.2
Na	173/930	137/650	24/144	59/285	1K/2.7K	179/	240/
K	13/280	.3/3.0	8/84	2/12	47/153	8/48	7/48
Ca	88/578	105/304	65/166	61/211	117/501	356/762	158/710
Si	13/46	23/45	20/31	20/34	16/26	7/17	12/38
Cl	154/1.2K	44/225	28/574	35/209	1.3K/	188/	290/
F	1.3/3.5	1.9/6.4	.7/2.0	1/13	1/2.3	1/2	1/4
Fe	2.1/33	2/17.0	1.4/24	1.4/24	1/156	.2/1.2	1.8/10
Li	.1/.510	.04/.20	.07/.20	.06/.30	1.1/3.1	.4/9.0	.08/.43
Mg	33/141	20/90	9/64	42/370	30/145	101/480	61/275
Mn	.02/.20	.11/1.6	.01/.21	.06/2.6	.2/.97	.1/1.5	.02/.23
Pb	.1/3.3	.02/.06	.12/3.6	.02/.16	.02/.05	.04/.1	.04/1.5
Zn	.4/3.6	.18/.65	.2/1.1	.2/2.7	.3/2.9	.9/6.5	.4/3.6
Ba	.1/.55	.11/.22	.1/.22	.1/.33	.07/.11	.08/.22	.07/.22
Cu	.02/.36	.02/.12	.02/.14	.04/.30	-.03	.05/.3	.03/.55
Sr	1.2/13.8	1.6/5.3	4/54	1/4	3/16	11/808	5.1/62
Br	1.1/10.2	.6/2.8	.4/4.4	.5/3.6	3/21	1.2/9.2	2/6
I	-.15	----	-.12	----	.08/.70	.02/.13	.03/.4
Ag	-.04	----	----	-.01	-.03	-.05	-.05
U, ppb	4.4/48	6/18	6.6/18	6.6/31	1.5/16	1/13	5.85
Hardness	360/2K	351/1.1K	207/711	328/1.7K	423/1.9K	1.3K/3.7K	652/2.6K
TDS mean	1100	925	126	470	4442	2304	1784
Maximum	5000	3270	480	1425	11200	11000	5600

Table 20 (continued)

Hardness	17°	18°	19°	21°	22°	23°	24°
Temp	23/33	45/72	26/46	25/35	20/58	22/37	21/32
pH	7.4/8.5	7.3/7.7	7.4/8.9	7.7/9.1	7.3/8.4	7.2/8.1	7.0/8.7
Na	61/510	306/527	69/280	360/716	400/3.5K	35/282	288/6.7K
K	5/100	216/1.7K	8/181	6/18	11/48	4/12	5/38
Ca	522/223	74/330	26/232	63/160	162/2K7	66/210	515/840
Si	24/49	37/82	31/55	18/30	17/151	25/42	11/25
Cl	26/221	232/420	78/1K	260/680	650/5K	18/145	400/15K
F	1.3/5.5	4.6/8.0	2/19	.8/1.8	.8/4.4	1.3/3.0	.7/7.0
Fe	1/55	1/6	1.3/42	.08/.55	.9/16.8	.7/12	.6/16
Li	.03/.20	.4/.7	.1/.8	.2/.7	.17/1.3	-./.30	.1/3.4
Mg	7/37	8/40	7/34	17/478	33/218	10/125	80/430
Mn	.01/.7	.01/.05	.3/.8	.80/.49	.4/4.8	----	.07/1.5
Pb	.02/.51	.01/.04	.02/.5	.02/.06	.02/.14	.01/.07	.04/.1
Zn	.2/3.1	.23/.87	.2/4.1	.05/.27	.6/15.6	.2/1.5	.4/8.5
Ba	.1/.4	.08/.11	.1/.7	.04/.22	.08/.3	.1/12	.6/18
Cu	.03/1.2	.01/.05	.04/1.2	-./.02	.02/.57	.02/.15	----
Sr	1.1/35	9/1.9	1.2/76	1.5/5.3	4543	.7/8.1	8.4/46
Br	.4/106	2/4	.6/5.5	2/4.6	3/22	.3/2.2	7/224
I	----	.06/31	.01/.22	-./.2	.01/.4	----	17/.896
Ag	-./.05	-./.021	-./.1	-./.01	-./.09	----	----
U, ppb	7/29	3/8	5/23	.4/5.0	5/74	5.8/22	.3/8.0
Hardness	160/560	221/828	98/600	232/6000	547/5K	208/1K	1.6K/3.9K
TDS mean	270	1400	635	1700	2300	247	3000
Maximum	1500	3120	9000	72000	11500	2000	27000

Table 20 (continued)

Hardness	25°	26°	26°	28°	29°	30°
Temp	21/32	23/35		23/37	22/37	22/32
pH	7.2/7.9	7.5/8.9		7.1/8.6	7.3/8.1	7.1/8.9
Na	20/600	49/205		63/285	50/623K	225/6.6K
K	4/100	4/177K		2/28	4/30	6/48
Ca	61/1313	40/120		61/211	64/210	452/840
Si	24/39	24/45		20/35	20/42	9/25
Cl	13/100	15/580		44/370	46/990	314/15K
F	1.3/2.9	3.9/24		1/138	1/3	.8/7
Fe	2/54	1/25		1/15	1/12.8	1/16
Li	.04/.1	.03/.4		.05/.3	.05/.6	.2/.9
Mg	7/21	7/70		30/270	16/125	88/480
Mn	----	.02/.65		.04/2.6	.01/.19	.08/1.5
Pb	.02/.07	.03/.15		.02/.16	.01/.07	.04/.16
Zn	2/3.2	1 16/2.2		.2/2.7	.3/2.1	.6/8.5
Ba	.1/.3	.07/.33		.1/.3	.1/.2	.4/18
Cu	.08/1.9	.01/.1		.04/.2	.03/.18	.03/.3
Sr	.4/.9	4/148		1/4	2.4/110	9.6/80
Br	.2/1.5	.3/.6		.6/3.8	.5/6.5	4/224
I	----	.01/.6		----	-./.01	10/900
Ag	----	-./.011		-./.01	-./.01	.01/.07
U, ppb	6/18	7/22		6/31	5/22	.6/13
Hardness	183/390	105/358		318/1.7K	230/1K	1.5K/3.9K
TDS mean	140	253		520	330	2700
Maximum	610	900		1500	2880	27000

TABLE 21
Drainage Basins

	<u>Basin</u>	<u>County</u>	<u>Rock Type</u>	<u>Number of Samples</u>
1.	Big Bend	Brewster	Paleozoics	11
2.	Marathon East	Brewster	Paleozoics	32
13.	Marathon West	Brewster	Paleozoics Qal	66 8
28.	Marathon (2+13)	Brewster	Paleozoics Qal	98 8
3.	Alpine Basin II	Brewster	Paleozoics Volcanics	10 13
23.	Alpine Basin I	Brewster	Paleozoics	41
4.	Green Valley	Brewster Presidio Brewster	Paleozoics Volcanics Volcanics	8 17 33
5.	Kent	Jeff Davis	Volcanics	18
6.	Valentine Basin II	Jeff Davis	Paleozoics Volcanics	12 16
7.	Valentine Basin I	Jeff Davis Presidio	Qal Volcanics Qal Volcanics	8 22 9 5
26.	Valentine Basins I and II	Jeff Davis	Paleozoics Volcanics Qal	12 43 17
9.	Eagle Flate Bolson	Hudspeth	Paleozoics Volcanics Qal	10 40 10

TABLE 21
(continued)

Basin	County	Rock Type	Number of Samples
10. Calamity Creek Basin	Brewster	Paleozoics Volcanics	5 14
12. Madera Canyon	Jeff Davis	Paleozoics Volcanics	22 10
14. Red Light Bolson	Hudspeth	Volcanics Qal	8 10
15. Diablo Plateau	Hudspeth	Qal / Paleozoics	19 15
24. Culberson County	Culberson	Paleozoics	52
30. Paleozoics	Hudspeth Culberson	Paleozoics	86
16. Salt Flat Bolson	Hudspeth Culberson	Volcanics Qal Qal	11 20 76
27. Salt Flat Bolson Valentine Basins I and II		All	179
17. Presidio	Jeff Davis Brewster Presidio Presidio Bolson	Volcanics Qal Volcanics Volcanics Volcanics Qal	8 2 8 65 11 45
19. Presidio Bolson	Presidio	Volcanics Qal	11 45
18. Rim County	Presidio	Qal	9
21. Mesilla Bolson	El Paso	Qal	16
22. Hueco Bolson	El Paso	Qal	117
25. Fort Davis	Jeff Davis	Volcanics	35

Correlation of elements with uranium for each drainage basin and composite basins. Correlation efficiencies appear at left, elements with that level of correlation with uranium appear in the appropriate box.

Basin #	1	2	3	4
# Samples	11	32	23	58
1.0 - 0.8				
0.8 - 0.6				
0.6 - 0.5				
0.5 - 0.4			pH, Ca, Si,	
0.4 - 0.3			F,	
0.3 - .2		Si,		
.2 - .1				pH,
.1 - 0.0		F, Sr,	K, Ag,	Ba,
-0.0 - -.1	K, Ca, Si	Na, K, Ca, Cl, Li, Mg, Pb, Ba, Cu, Br,	Li, Cu,	Si, Cl, F, Ag,
-.1 - -.2	Pb, Ag,	pH, Mn, Zn, Ag,	Na, Cl, Pb, Sr, Br, I,	Na, K, Fe, Li. Mg, Mn, Pb, Zn, Sr, Br,
-.2 - -.3	Na, F, Li, Mg, Mn, Sr, Br,	Fe,	Ba,	Cu,
-.3 - -.4	Fe, Cu,		Mg, Mn, Zn,	Ca,
-.4 - -.5	pH, Cl, Zn, Ba,		Fe,	
-.5 - -.6				
-.6 - -.8				
-.8 - -1.0				
U ppb	5.5	4.9	4.6	5.7
TDS	-.304	.005	-.150	-.150

Basin #	5	6	7	9
# Samples	18	28	44	60
1.0 - 0.8				
0.8 - 0.6	F, Fe, Pb,	Na,		
0.6 - 0.5	Ba,	pH, Cl,		
0.5 - 0.4	pH, Ca,	K, Li, Mn,		Mn,
0.4 - 0.3	Zn,	Ba,		F, Cu,
0.3 - .2		Fe, Cu, Br,	pH,	Fe, Pb, Sr,
.2 - .1	K, Mn,	Zn,	Zn, Ba,	Na, Cl, Li, Mg, Zn, Br, Ag,
.1 - 0.0	Na, Cl, Cu, Br,	Ag,	Na,	pH, Ba, I,
-0.0 - -.1	Li, Mg,	Si,	Mn, Sr,	K, Ca,
-.1 - -.2	Sr,	Mg,	K, Ca, Cl, F, Pb, I, Ag, Si,	Si,
-.2 - -.3	Si, Ag,	Sr,	Li,	
-.3 - -.4		I,	Mg, Pb, Cu, Br,	
-.4 - -.5				
-.5 - -.6	I,	Ca, Pb,		
-.6 - -.8		F,		
-.8 - -1.0				
U ppb	3.1	5.3	7.4	4.4
TDS	-.554	.074	-.246	.212

Table 22 (continued)

Basin #	10	12	13	14
# Samples	19	32	74	19
1.0 - 0.8				
0.8 - 0.6				
0.6 - 0.5				F, Br,
0.5 - 0.4				K,
0.4 - 0.3				Na, Cl, Li,
0.3 - .2	K, Zn,	Cl, Br,	Br,	pH, Ba,
.2 - .1	Cu, Sr,	K, Mg, Sr,	Cl, Mg, Ag,	Ag,
.1 - 0.0	Na, Fe, Mg, Mn,	Si,	Na, Si, F, Li, Sr,	Fe, Cu, I,
-0.0 - -.1	Cu, Li,	pH, Na, Ca, Li,	pH, K, Ca, Mn, Ba,	Ca, Mg, Mn, Pb,
-.1 - -.2	Ca, Si, Ba,	F, Ba,	Pb, Zn,	Zn, Sr,
-.2 - -.3	Br,	Fe, Mn, Pb, Zn, I,	Fe, Cu,	
-.3 - -.4	F, Pb,	Cu,		Si,
-.4 - -.5	pH,			
-.5 - -.6				
-.6 - -.8				
-.8 - -1.0				
U ppb	5.8	6.6	6.6	1.5
TDS	-.019	.274	-.031	.316

Table 22 (continued)

Basin #	15	16	17	18
# Samples	34	107	146	9
1.0 - 0.8				
0.8 - 0.6				
0.6 - 0.5	Fe,			pH,
0.5 - 0.4				
0.4 - 0.3	F,	Mg,		
0.3 - .2		Na,F,Ba,		Zn,
.2 - .1	pH,Ba,	Li,Zn,Br,	Li,Sr,Ag,	Fe,Ba,Sr,
.1 - 0.0	Zn,Cu,	K,Ca,Cl,Pb, Sr,	Na,Ca,F,Fe,Mn, Cu,I,	Cu,Ag,
-0.0 - -.1	Na,Si,Cl,Li, Mg,Mn,Br,	Si,Fe,Mn,Cu, Ag,	pH,Cl,Ba,Br,	Na,Mn,
-.1 - -.2	K,Ca,Sr,	pH,I,	K,Si,Mg,Pb, Zn,	
-.2 - -.3	Pb,I,Ag,			Ca,Mg,I,
-.3 - -.4				Br,
-.4 - -.5				K,
-.5 - -.6				Pb,
-.6 - -.8				Si,Cl,
-.8 - -1.0				F,Li,
U ppb	1.1	5.1	7.4	2.8
TDS	-.113	.215	-.166	.239

Table 22 (continued)

Basin #	19	21	22	23
# Samples	56	16	117	41
1.0 - 0.8				
0.8 - 0.6		pH, Ba,		
0.6 - 0.5		Ag,		
0.5 - 0.4				
0.4 - 0.3				K,
0.3 - .2	Si,	Cu,		pH,
.2 - .1	Cl, F, Zn,		Ba,	Si, Mg, Mn, Zn,
.1 - 0.0	pH, Fe, Li, Pb, Ba, Cu,		F, Fe, Zn,	
-0.0 - -.1	K, Mg, Mn, Sr, I,	K,	pH, Na, K, Si, Cl, Li, Mn, Pb, Cu, Sr, Br, I,	Ca, F, Fe, Li, Cu, Sr, Ag,
-.1 - -.2	Br, Ag,	Fe, Mn, Pb,	Ca, Mg, Ag,	Na, Cl, Ba,
-.2 - -.3		Si, F, Zn,		Pb, Br,
-.3 - -.4	Na,	Ca, Cl, Li, Mg, Sr, I,		
-.4 - -.5		Na, Br,		
-.5 - -.6				
-.6 - -.8				
-.8 - -1.0				
U ppb	4.9	.4	4.9	5.8
TDS	-.006	-.297	-.032	-.132

Table 22 (continued)

Basin #	24	25	26	27
# Samples	52	35	72	179
1.0 - 0.8	Fe,			
0.8 - 0.6				
0.6 - 0.5				
0.5 - 0.4				
0.4 - 0.3		Sr,	pH,	
0.3 - .2	Cu,	Si, Cl, Mg, Br,	Na, Ba,	Mg, Ba,
.2 - .1		Na,	K, Cl, Zn,	Na, Zn,
.1 - 0.0	pH, Mn, Ba, Br, I,	pH, Mn, Zn, Ba,		pH, K, Cl, Li, Mn, Br,
-0.0 - -.1	Na, K, Cl, F, Li, Mg, Zn,	K, Ca, Fe, Li, Cu,	Si, Fe, Li, Mn, Cu, Ag,	Ca, Si, F, Fe, Pb, Cu, Sr, Ag.
-.1 - -.2	Ca, Si, Sr,		Ca, Sr, Br,	I,
-.2 - -.3	Pb,	F, Pb,	Mg, I,	
-.3 - -.4	Ag,		F,	
-.4 - -.5			Pb,	
-.5 - -.6				
-.6 - -.8				
-.8 - -1.0				
U ppb,	.3	6.7	6.6	-----
TDS	-.058	.265	-.159	.111

Table 22 (continued)

Basin #	28	29	30	
# Samples	106	64	86	
1.0 - 0.8				
0.8 - 0.6			Fe,	
0.6 - 0.5				
0.5 - 0.4				
0.4 - 0.3				
0.3 - .2		pH, Si,		
.2 - .1	Si, Mg, Br,	K, Ca, F,	pH, F, Cu,	
.1 - 0.0	Na, Cl, F, Li, Sr, Ag,		Zn, Br, I,	
-0.0 - -.1	pH, K, Ca, Mn, Ba,	Li, Cu, Ag,	Na, K, Cl, Li, Mg, Mn, Ba,	
-.1 - -.2	Pb, Zn, Cu,	Na, Cl, Mn, Zn, Sr, Br, I,	Ca, Si, Sr,	
-.2 - -.3	Fe,	Fe, Mg, Pb, Ba,	Pb, Ag,	
-.3 - -.4				
-.4 - -.5				
-.5 - -.6				
-.6 - -.8				
-.8 - -1.0				
U ppb	6.1	5.4	65	
TDS	-.051	-.157	-.078	

Table 23

Mean Equivalent Uranium Concentrations by Sampled Areas, ppm
(Woodrum, 1980, Table 3)

Area	Number of Intrusive Samples	Statistics		
		<u>Mean</u>	<u>Standard Deviation</u>	<u>Variance</u>
Cornudas Mountains	30	8.97	5.72	31.62
Red Hills	7	4.85	.44	.16
Sierra Prieta Intrusion	8	7.11	.90	.71
Sierra Blanca Intrusions	9	13.97	11.40	115.61
Hueco Mountains	11	3.73	1.46	1.96
Granite Mountain	3	3.66	.71	.33
Finlay Mountains	8	1.70	.56	.78
Alpine Hill	5	2.30	.88	.63
Sunny Glen Draw	12*	5.56	1.58	2.31
Puertacitas Mountains	12*	4.71	2.45	5.51
Paisano Peak	3	3.73	.64	.27
Iron Mountain	10	2.97	.93	.78
Davis Mountains Chalcedony Samples	19*	7.07	5.86	32.62
Davis Mountains Volcanics	13*	4.02	1.83	3.11
Cienega and Chinati Mountains	14	5.22	1.93	3.45
Big Bend National Park	31*	6.20	4.25	17.48

(* indicates that some of the samples included are volcanic rocks,
not intrusive)

Table 23 (continued)

(cont.)

Area	Number of Intrusive Samples	Statistics		
		<u>Mean</u>	<u>Standard Deviation</u>	<u>Variance</u>
Trans-Pecos, Texas	195	6.15	4.80	27.92
Sandstones	10	1.20	.73	.48
Limestones	8	2.25	1.44	1.83
Barker's Northern Trans- Pecos Magmatic Province				
Sierra Prieta	46	7.93	4.86	23.18
Hueco Mountains	56	7.20	4.72	21.87
Granite Mountain	59	7.02	4.66	21.38
Finlay Mountains	65	6.54	4.70	21.71
Sierra Blanca	74	7.44	6.29	39.03
Cornudas Mountains	31	8.97	Not determined	
Red Hills Intrusion	38	8.11	Not determined	
Sierra Blanca Intrusions.	55	8.92	Not determined	

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Appendix A
Independent Report:

A REGIONAL GEOPHYSICAL STUDY OF THE
CHIHUAHUA CITY AREA, MEXICO

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ABSTRACT

Regional gravity and aeromagnetic data have been compiled for a large portion of the State of Chihuahua, Mexico, and maps of the central and northeastern portions of the State have been produced. These maps provide valuable insight into the tectonic regimes of the area, particularly in the region of the Sierra Pena Blanca. The Sierra Pena Blanca are located in a region of classical Basin and Range structure, but an anomalous crustal block is indicated in the area of the Sierra del Nido immediately to the west. Basin and Range structures are subdued or absent in the area of Placer de Guadalupe to the east. Aeromagnetic data indicate older trends which are transverse to Basin and Range structures. These trends along with the crustal blocks indicated may be of significance in regional exploration for uranium.

Introduction

Volcanic rocks are a major site of uranium deposits in Chihuahua. They have highly variable densities and magnetic susceptibilities which usually lead to distinctive, often complicated, geophysical signatures. Thus, gravity and magnetic surveys can be used to map volcanic units. However, in addition to direct investigations, gravity and magnetic studies can provide valuable information on the tectonic and structural framework of an area.

Uranium does not usually have a distinctive, non-radioactive geophysical signature, although there are some uranium deposits associated with minerals such as iron or sulphides which do have geophysical signatures (Smith 1977; Campbell and Flanigan, 1975). Thus, the use of geophysical techniques in uranium exploration has usually stressed radiometric methods. However, magnetic anomaly maps have been useful where there is structural control of uranium deposits (Flanigan and Young, 1977; Sadowski and Schmidt, 1980; Campbell and Flanigan, 1975). Also, Black *et al.* (1962) applied seismic refraction, resistivity, magnetic, and gravity techniques to defining channel uranium deposits in Arizona and Utah, and Vinton (1976) tried to apply high precision gravity to detect uranium directly in roll fronts in sedimentary rocks in Wyoming. Smith (1977) gives a good summary of non-radioactive methods applied to uranium exploration.

The goal of this study is to describe the only available geophysical data in the Chihuahua City area (Fig. 1), reconnaissance gravity and aeromagnetic surveys. These data are used to determine the general tectonic

framework of the area and to study the major geologic features present. The volcanic rocks are of particular interest.

There has been considerable geophysical activity in the U.S. adjacent to Chihuahua by industrial organizations in search of hydrocarbons, minerals, and geothermal resources (Hawley, 1978). There is also considerable other work by non-industrial groups (Veldhuis and Keller, 1980; Mraz and Keller, 1980; Riecker, 1979; Taylor et al., 1979). However, there has been no published geophysical work for the Chihuahua City area although considerable work has been completed in northeastern Chihuahua (Himes, 1968; Tovar et al., 1978). Regional gravity studies have been reported by Woollard et al. (1969), Western (1979), and Western and Aiken (1981).

There are considerable unpublished aeromagnetic and gravity data in much of the area of interest because of the exploration programs of Petroleos Mexicanos (Himes, 1968; J. Tovar, pers. comm.) and the Consejo de Recursos Minerales.

Gravity Data

The published data in Chihuahua have, until recently, been confined to the surveys by the Hawaii Institute of Geophysics and the Universidad Nacional Autonoma Mexico (Woollard, 1968). These groups were provided data from Petroleos Mexicanos (PEMEX) on a regional basis (8-16 km intervals). These data were located along major roads mainly east of the Sierra del Nido plateau and Sierra Madre Occidental (SMOC). However, these roads are spaced at 30 km intervals or greater so the data distribution is poor.

Within the last two years almost 1400 gravity measurements have been made in Chihuahua by the Universities of Texas at Dallas and El Paso under

programs supported by the National Science Foundation, Defense Mapping Agency, and the Department of Energy. This work has been conducted in conjunction with Mexican organizations; the Consejo de Recursos Minerales, DETENAL, Interamericano Geodesica Servicio, and Petroleos Mexicanos (Aiken et al., 1980). These combined data provide sufficient detail to examine the general structures of central Chihuahua with gravity. Stations have been established at benchmarks and topographic contour intersections provided by the recently published 1:50,000 topographic maps with 10 and 20 m contour intervals. These data have been reduced using base station values of the 1971 International Gravity Station Network and the International Gravity Formula of 1967 and have been merged with previously available gravity data.

Aeromagnetic Data

The PEMEX aeromagnetic data consist of two surveys, a northern survey flown recently and a southern survey consisting of much older data (Fig. 3). These data are reconnaissance in nature and, in the north, consist of northeast-trending flight lines at 4 km intervals flown at 3,050 m constant barometric altitude. Northwest-trending tie lines were flown every 12 km. The arrangement of flight lines was similar in the southern portion of the area but the flight elevation was 2,590 m. The International Geomagnetic Reference Field was removed from both surveys. These data have been merged together into a 20 gamma contour interval map by observing intersecting tie lines and normalizing to the newer map in the north. The flight lines do not extend very far over the volcanic rocks of western Chihuahua so most of

the available information consists of coverage over the basins and ranges of central Chihuahua.

Gravity Analysis

In general, the Bouguer anomaly map of the area (Fig. 4) is similar to the previous published map of Mexico (Woollard et al., 1969). This map displays the general features previously reported: short wavelength anomalies related to the apparent Basin and Range structure in the central area ($106^{\circ}30'W$ to $105^{\circ}30'W$ longitude) with a change east of Placer de Guadalupe to anomalies which are less directly related to valleys and mountains. A large negative gravity gradient reflecting an abrupt crustal transition is present to the west.

A decrease of 100 mgls in Bouguer anomaly values occurs from west Texas to central Chihuahua. Crustal structure studies in the U.S. indicate that as Bouguer gravity decreases, elevations increase, and that crustal thickening is the isostatic compensation mechanism. However, numerous workers have shown that lateral changes in density also occur in the upper mantle. Work in the SMOC to the south (Hales et al., 1970) indicates a 37-45 km thick crust and surface wave dispersion along a long path from central Mexico to Arizona, along the axis of the SMOC, indicates a 50 km thick crust (Fix, 1975). There is no other deep seismic control in Chihuahua, so it is not possible to unambiguously decide whether the gravity low over the SMOC is due to density changes brought about by lateral variations in the upper mantle, a thickening of the crust, a lateral change in the density of the crust itself, or a combination of these relationships. However, crustal thickening is likely to be a major cause of the anomaly.

A large component of the Bouguer anomaly in any area is the correlation with topographic variations (Western and Aiken, 1981). As elevations increase Bouguer gravity values decrease, ideally by -0.1119 mgals/m for a Bouguer reduction density of 2.67 g/cm^3 . This relationship is directly related to the isostatic compensation of long wavelength variations of topography over most of the earth. The work pioneered by Woollard and his co-workers showed that the relation between Bouguer anomaly values and topographic elevations (Fig. 5) could be fit to a straight line whose slope varied around the ideal value of -0.1119 mgals/m . This slope will vary from place to place dependent on various geologic, physiographic and other parameters (Wilcox, 1971).

The prediction of Bouguer gravity by topography, as well as geologic parameters, led to gravity maps which were produced for parts of the U.S. (e.g. Mabey, 1966; Wilcox, 1974; Griscom and Oliver, 1980); and Mexico (Woollard et al., 1969). If the predicted anomaly values are subtracted from observed values, maps are produced which some of the previously cited workers have called "residual" maps. Most of the anomaly prediction is derived from long wavelength topography so only broad regional anomalies are removed. These long wavelength variations in gravity are related to isostatic compensation, so the "residual" maps are essentially a form of isostatic map without any a priori assumption as to the isostatic compensation mechanism.

Instead of strictly computing the gravity from the topography and subtracting those values from the Bouguer gravity, a variable Bouguer reduction datum based on smoothed topography can be applied in the Bouguer correction (Aiken, 1976). This removes the Bouguer anomaly due to the gravity

effect of compensated topography (Fig. 6). Once a datum is defined, residual values are generated by applying the Bouguer correction defined by the equation (assuming a density of 2.67 gm/cc):

$$g_{RBC} = -0.1119 (el_S - el_R) \text{ mgals/m.}$$

where el_S = station elevation, and el_R = regional topographic elevation.

This approach has been applied to Arizona (Aiken, 1976; Aiken and Ander, 1981), New Mexico (Aiken et al., 1978) and Chihuahua (Western, 1979). The best results obtained (Western and Aiken, 1981) in Chihuahua define two separate regional topographic surfaces and corresponding residual anomalies. The first order residual is derived by applying a datum (Fig. 7) which defines the 1000 km wavelength trend in topography that indicates a general increase in elevation from the Gulf of Mexico to the Gulf of California. The high Sierra Madre Occidental is not defined in this datum and therefore only topographic compensation of a broader scale is actually removed. Since it is known that the SMOC is close to isostatic equilibrium (Woollard et al., 1969), it is expected that there would be an anomaly indicating the compensation of the SMOC. The gravity effect of the topography which is being avoided (or removed) is shown in Figure 8. The first order residual map (Fig. 9) does not define the regional variations in gravity east of the SMOC but outlines closely an 80 mgal anomaly related to the SMOC. Thus, this map could be used to study the large scale SMOC structure.

A second order residual anomaly map is computed by applying a datum (Fig. 10) that outlines the SMOC and thus removes a 100 mgal anomaly (Fig. 11). In this way, local anomalies within the SMOC are defined. The second order residual anomaly (Fig. 12) outlines other structures not related to

the defined regional topographic variation. An example is an elongate gravity low trending north-south over a series of mountain ranges, including the Sierra del Nido on the north and the Sierra de Majalca on the south (Fig. 12). These ranges are composed of calcalkaline and peralkaline volcanic rocks (Mauger, 1980) and are usually considered to be the eastern boundary of the SMOC. However, gravity anomaly values do not indicate that the valleys west of these ranges are alluvial filled (graben) basins because they do not have the typical high amplitude gravity signatures such as seen over valleys east and north of the Sierra del Nido.

Basins east of this volcanic block correlate with gravity lows and ranges correlate with gravity highs, typical of Basin and Range structure. The area of the Sierra Pena Blanca shows classical Basin and Range anomalies: a gravity high over the ranges flanked by lows over adjacent alluvial filled basins.

Detailed gravity anomaly values along a profile near Pena Blanca (Fig. 13) were provided by PEMEX and were modeled with a generalized linear inverse method (GLI) (e.g., Cribb, 1976) employing the 2 1/2 dimensional formalization of Pederson (1977). In this method the non-two dimensional nature of the anomalies can be taken into consideration and the locations of the corners of subsurface polygonal bodies are adjusted until satisfactory agreement is reached between observed and computed values. In the case of a basin the upper surface is held fixed. The resulting model (Fig. 14) indicates typical horsts and grabens of the Basin and Range province.

The regional gradient seen in the Bouguer and first order residual anomalies west of Pena Blanca thought to be related to the main SMOC crustal structure is partly due to an upper crustal feature under the Sierra del

Nido block. The steep gradients in the area of the Sierra del Nido block on both the Bouguer and first order residual maps reflect both the existence of deep structure related to the SMOC as well as another more shallow feature which is reflected in the second order residual anomalies (Fig. 15). A 2-1/2 dimensional GLI inversion of the cause of this anomaly indicates a low density block concentrated in the upper crust of that area 30-50 km wide between depths of 4 and 8 km (Fig. 16). In deriving this model, all corners of the polygonal body were allowed to move. Although the initial trial solution was much shallower, the best solution required a greater depth. The density contrast was derived by trial and error where the best solution produced a model with a minimum of high frequency noise. A similar low does not appear to occur over other ranges in the SMOC or Basin and Range. The transition between the Pena Blanca horst and the Sierra del Nido block is a moderately deep (1000 m) elongate structural basin 20 km in length north-south. The transition to the SMOC is located to the west of the Sierra del Nido block and is defined by the steep regional gradient related to crust/mantle variations (Fig. 15). It should be noted that the Sierra del Nido anomaly ends just south of a line extending from Cuauhtemoc to Chihuahua City along a strong east-west to west-northwest trending gravity gradient, with gravity values increasing rapidly to the south. This gradient may be a westward extension of the gravity signature of the Ouachita belt or some other major boundary (Western and Aiken, 1981).

Aeromagnetic Analysis

In Chihuahua, the depth to magnetic basement has been shown to increase toward the Rio Grande (Himes, 1969; Tovar *et al.*, 1978). Their analyses of subdued magnetic anomalies just north of this study area indicates a basement depth of 3000 m. This generally subdued pattern of magnetic anomalies changes abruptly south of 30°N latitude. East-northeast trending alignments of positive magnetic anomalies appear to be caused by Cenozoic intrusions which have penetrated the thick sedimentary rocks of the Chihuahua Trough. Therefore, the aeromagnetic map compiled in this study (Fig. 3) reflects compositional changes in the crystalline basement very strongly but also may reflect basement topography. As can be observed in northern Chihuahua, the most dominant trends in the anomalies are east-northeast and north-northwest (Aiken *et al.*, 1981). Intrusions found in central Chihuahua appear along the east-northeast trends. The north-northwest trends correlate with topography and Basin and Range structures. In particular, the highest amplitude anomalies (northwest of Coyame and Placer de Guadalupe) occur over mapped igneous intrusions along east-northeast trends (Fig. 3).

The only portion of the Sierra del Nido block covered by the magnetic data is in the area of Santa Clara Canyon at the northern end. The largest amplitude magnetic anomalies in this area are directly related to the volcanics. Since the topography abruptly increases to 2500 m from 1700 m and terrain clearance is almost zero, simple proximity of the magnetometer to the anomaly source must be a factor in the interpretation. Basalts overlie some of the mesas in the area (Bockoven, 1980; Mauger, 1980) and such high

amplitude short wavelength anomalies are characteristic of highly magnetic volcanics.

A model was derived for a magnetic profile (Fig. 18) across the Pena Blanca area near the location of the gravity profile. A Backus-Gilbert inversion utilizing algorithms of W. J. Peeples (e.g. Green, 1975) was employed to derive this model in which the lower boundary was held fixed. The upper surface was inverted with different solutions until the observed and calculated anomaly values agreed to within 1 gamma all along the profile. This surface was a continuous surface of integration rather than a polygon. The similarity of the gravity and magnetic models indicates aeromagnetic anomalies in this area are mostly caused by magnetic topography typical of Basin and Range structure.

The Pena Blanca model can be compared to one derived from a profile (Fig. 19) in the area of Placer de Guadalupe (Fig. 3) using the same inversion technique. This area is considered to lie mainly in the Chihuahua Trough, east of the Basin and Range province. The solution indicates basement topography is the source of the anomaly. However, there is a lack of abrupt relief indicative of the Basin and Range Province.

Conclusions

Gravity and magnetic anomalies in the Chihuahua City region correlate with shallow structures and reflect Basin and Range horst and graben structure in the central part of the area. Magnetic trends also cut transverse (ENE) to the Basin and Range trends (NNW) indicating an older structural fabric. These trends correlate with LANDSAT trends of Saunders et al. (1970) who interpreted them to be tensional in nature. The Cenozoic intru-

sives north of Coyame and at Placer de Guadalupe and in northern Chihuahua lie on these trends. These intrusives appear as elongate, high-amplitude maxima cross-cutting the broad low-amplitude long-wavelength, magnetic signatures interpreted to indicate deep magnetic (and crystalline) basement. One of the LANDSAT trends (the "Sautokin") passes through or nearby the Pena Blanca area. A circular "dissection" pattern at Pena Blanca was also identified.

A north-south trending gravity low 75 km long and 30 km wide occurs over the Sierras del Nido and Majalca, indicating a significant lower density concentration in the crust. Such a feature does not exist to the east or to the west. It possibly reflects lower density volcanics in the Sierra del Nido block, and it is these rocks which may have been a source of uranium in the area. Removing the effects of Basin and Range activity the Pena Blanca area lies at the margin of this regional gravity low and this may be a definitive feature for this type of deposit. A characteristic magnetic feature is not well defined. Therefore, more emphasis should be placed on studying the boundaries of the del Nido block as outlined by the gravity data. Intersections on the magnetic anomaly trends may also be of interest.

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Fig. 1. Location map of study area.

Fig. 2. Generalized geologic map of the study area (from Lopez, 1976). Cu - Cuauhtemoc, D - Delicias, CC - Chihuahua City, VA - Villa Aldama, PG - Placer de Guadalupe, C - Coyame, SG - Sierra Gallegos, SN - Sierra del Nido (north end), Sierra de Majalca (south end), S - El Sueco.

Fig. 3. Aeromagnetic map of central Chihuahua. 20 gamma contour interval. Tensional Sautowkin lineation interpreted by Saunders and Hicks (1976) from LANDSAT imagery. C-C' is location of detail gravity and magnetic profile; D-D' and E-E' are locations of inversion models of magnetic anomalies.

Fig. 4. Bouguer gravity anomaly map. Contour interval = 5 mgal. L - lows; H - highs, A-A' - regional profile; B-B' - Sierra del Nido model profile.

Fig. 5. Linear relation of topography and Bouguer gravity for Mexico (modified from Woollard, 1968).

Fig. 6. Diagrammatic relationship of gravity anomalies with their causes. Generalized cross-section showing mantle (A); lower crust (B); crust above sea level (C); Bouguer anomaly (1); residual Bouguer anomaly (2), and smoothed Bouguer anomaly (3). In lower figure (1) is sea level and (2) is smoothed surface of topography. Interface A/B is often the cause of anomaly (3). Local heterogeneities of density are shown as positive density contrasts (+) and negative density contrasts (-) which produce local gravity anomaly highs and lows, respectively, which appear on profiles (1) and (2). The gravity effect of the mass between (2) and (1) in lower diagram is not removed in the residual correction because that mass with a density contrast $+2.67 \text{ g/cm}^3$ compensates the negative density contrast along interface A/B. Therefore, the use of (2) as a Bouguer reduction datum results in the residual Bouguer anomaly (2) in upper figure (from Aiken *et al.*, 1980).

Fig. 7 First harmonic trend of topographic elevations (from Western and Aiken, 1981) Contour interval 150 m.

Fig. 8 First order regional anomaly predicted from topography in figure 7 (modified from Western and Aiken, 1981). Contour interval 17 milligals. Dashed line divides physiographic province in Chihuahua; Sierra Madre Occidental to the west; Basin and Range to the east. A-A' and B-B' are profiles discussed later. CG - Casas Grandes; S - El Suedo; C - Coyame; PG - Placer de Guadalupe; CC - Chihuahua City; PB - Pena Blanca; CU - Cuauhtemoc; J - Juarez; A' - Ojinaga.

Fig. 9 First order residual anomaly map (see Figs. 2 and 7). Regional in figure 8 removed. A-A' and B-B' are profiles discussed later. CG - Casas Grandes; S - El Suedo; C - Coyame; PG - Placer de Guadalupe; CC - Chihuahua City; PB - Pena Blanca; CU - Cuahtemoc; J - Juarez; A' - Ujina.

Fig. 10. Two harmonic trends of topography (modified from Western and Aiken, 1981). See figure 7.

Fig. 11. Second order regional anomaly predicted from figure 10. See figures 2 and 7.

Fig. 12. Second order residual anomaly map. Regional in figure 11 removed (see Figs. 2 and 7).

Fig. 13. Detail magnetic and gravity profile C-C'. 45 is Chihuahua City-Juarez Highway.

Fig. 14. 2 1/2 dimensional model by general linear inversion of gravity profile C-C'. Triangles - initial model, and observed anomaly; O's - final solution and computed anomaly; density contrast - 0.20 g/cm³. Half north-south, strike lengths, 10 km.

Fig. 15. Profile A-A'. Comparison of first and second order residual and Bouguer anomalies. Dots represent first order residual anomaly after removal of anomalies from models.

Fig. 16. 2 1/2 dimensional model by general linear inversion of gravity profile B-B'. X's - initial model and observed anomaly; O's - final model and computed anomaly; north strike length, 75 km; south strike length, 37 km; density contrast = -0.23 g/cm^3 .

2D BACKUS-GILBERT INVERSION OF MAGNETIC ANOMALY

Fig. 17. Two-dimensional Backus-Gilbert inversion of magnetic basement from magnetic anomaly D-D' near Pena Blanca. Reference level - 3 km barometric above base sea level. Triangles - observed anomaly; solid line - computed magnetic values; magnetic susceptibility contrasts = 0.002 cgs units.

2D BACKUS-GILBERT INVERSION OF MAGNETIC ANOMALY

Fig. 18. Two-dimensional Backus-Gilbert inversion of magnetic basement from magnetic anomaly E-E'. Reference level - 3 km basometric above sea level; triangles - observed anomaly; solid line - computed magnetic values; magnetic susceptibility contrast = 0.002 cgs units.

Appendix B
Independent Report

A GEOPHYSICAL AND GEOLOGICAL ANALYSIS OF THE
SALT FLAT BASIN OF TRANS-PECOS TEXAS AND
SOUTHERN NEW MEXICO

by

JERRY HENRY VELDHUIS, M.S.

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ABSTRACT

A combined geophysical and geological study has been undertaken to determine the subsurface geometry and tectonic setting of the Salt Flat Basin located in Trans-Pecos Texas and Southern New Mexico. The primary data sets used were regional gravity surveys, total field aeromagnetic surveys and subsurface well information. The Salt Flat Basin is a north-to northwest-trending Cenozoic graben. Data have been compiled from various sources and reduced to produce regional Bouguer anomaly and total field magnetic anomaly maps. Cross-sections were constructed along profiles by computer modeling using well logs, gravity, and magnetic data as constraints. These earth models provide estimates for the depth to basement, the location of major faults, and the general subsurface geometry of the basin. A contour map on top of Precambrian basement rocks was also produced using the computer modeled cross-sections and the subsurface well information. The geophysical evidence indicates crustal thickening towards the east complicated by a major upper crustal density anomaly. Also, numerous recent faults in the area, releveling surveys, and some thermal evidence indicate that the Salt Flat Basin is an active feature which needs to be accounted for in tectonic models such as those proposed to explain the origin of the Rio Grande Rift.

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INTRODUCTION

The Salt Flat Basin (graben) of Trans-Pecos, Texas (Fig. 1) is a 200 km (130 mi) long and 8 to 32 km (5 to 20 mi) wide topographic depression that trends approximately N10°W along the Culberson-Hudspeth County line into southern New Mexico. This basin separates the Diablo Plateau, Sierra Diablo, Carrizo and Van Horn Mountains to the west from the Guadalupe, Delaware, Apache and Davis Mountains to the east. To the south the basin bifurcates around the Wylie Mountains forming Lobo Flat to the southwest and Michigan Draw to the southeast (Fig. 1). The Salt Flat Basin receives its name from the alkali lakes and dry alkali flats present mainly along the western edge of the basin from about 31°20'N latitude up towards its northern end in Otero County, New Mexico. The basin fill is composed of a variable thickness of unconsolidated Cenozoic alluvial and lacustrine gravels, sands, silts and clays. According to King (1948), the Salt Flat Basin represents a down dropped portion of the earth's crust with rocks of the immediately adjacent mountains having been either warped or faulted up into their present positions.

Previous studies of the regional tectonic and geologic setting of Trans-Pecos, Texas have included the Salt Flat Basin only as a side light. In this study, geological and geophysical data have been integrated in an attempt to further elucidate the subsurface geometry and tectonic setting of the Salt Flat Basin. In addition to surficial geologic data, geophysical and geologic information was compiled in the form of gravity, magnetic and subsurface well data. The gravity and

Figure 1. Index map of the study area.

magnetic data were used to produce a regional Bouguer gravity map and regional total field magnetic intensity map. The subsurface well information (Fig. 2, Appendix I) was utilized along with geophysical constraints in producing computer modeled cross sections across the Salt Flat Basin and adjacent areas. These two dimensional computer models were calculated using the technique of Talwani et al. (1959) in an interactive trial and error procedure. Also, a depth to Precambrian basement contour map was constructed using the subsurface well information and the computer modeled cross sections as guides.

Figure 2. Well data and locations of gravity profiles. Numbered well locations correspond with Appendix I.

GEOLOGIC HISTORY

The major geological features present in the study area are outlined in Figure 1. Dennison and Hetherington (1969) and Flawn (1956) have compiled the major data, primarily from cores and cuttings, on the basement rocks in Trans-Pecos Texas and south central New Mexico. The oldest rocks exposed in the study area are located in the Carrizo Mountains. This sequence of sedimentary and volcanic rocks was originally deposited and extruded some 1240 ± 65 m.y. ago (Dennison and Hetherington, 1969). These units were later metamorphosed about 950-1000 m.y. ago as part of the tectonism which formed the Van Horn Mobile Belt which thrust these rocks northward over a younger Precambrian sequence of limestones, sandstones, volcanics, the Hazel and Allamore Formations.

The oldest rocks recognized in the subsurface constitute the Chaves granitic terrane (1350 m.y. old or more). Dennison and Hetherington (1969) project the extent of this terrane into the northeastern corner of the study area. The position of the Chaves granitic terrane corresponds to Flawn's (1956) Texas craton east of the study area and most likely provides the stable framework onto which younger sedimentary rocks have been deposited or into which younger igneous rocks have been intruded (Dennison and Hetherington, 1969).

At about the same time that the Van Horn Mobile Belt was active (950-1000 m.y. ago), the central and western portions of the study area were also active. The DeBaca terrane (Fig. 3) composed of mostly sediments and volcanics was being deposited throughout the central study

BASEMENT GEOLOGIC MAP OF FAR WEST TEXAS AND SOUTH CENTRAL NEW MEXICO

INDEX MAP

EXPLANATION

950 M.Y.		FRANKL. M. MTN. IGNEOUS ROCKS
950-1000 M.Y.		DEBACA TERRANE
1150 M.Y.		GRANITE AND SYENITE
~1250 M.Y.		CARRIZO MOUNTAIN GROUP
1350 M.Y. & OLDER		CHAVES GRANITIC TERRANE
WELL REACHING BASEMENT

FIGURE 3

(from Dennison and Hertherington, 1969)

area while the Franklin Mountain igneous complex (mostly extrusive rhyolites and intrusive granites) was being formed in the western sector. The area of the Pump Station Hills contains outcrops of Precambrian rock which have been dated by Wasserburg et al. (1962) as being 960 ± 60 m.y. old. These outcrops of rhyolite and granitic rocks seem most likely related to the Franklin Mountain igneous complex (Dennison and Hetherington, 1969). Erosion of the basement rocks occurred before deposition of the Precambrian (?) Van Horn sandstone began in certain areas of the region. The Van Horn sandstone and underlying units were tilted and faulted before deposition of the Cambrian-Ordovician Bliss sandstone.

According to LeMone (1969) the Cambrian-Ordovician period in this area saw a complex series of transgressions and regressions occur, depositing the lower Ordovician El Paso limestone group to the west and the laterally equivalent Ellenburger group to the east. Middle Ordovician rocks are exposed in the Beach Mountains north of Van Horn and extend eastward. The upper Ordovician Montoya group rests on an angular unconformity throughout the study area and is overlain unconformably by Silurian rocks. South of the study area, the Ouachita-Marathon geosyncline was beginning to form in the Ordovician. In Silurian and Devonian time the area was included in the subsiding Tobosa Basin (Galley, 1958) which provided the depositional environment for the formation of dolomite, limestone, and shale units. A major uplift occurred toward the east during Mississippian time and formed the Central Basin Platform which split the Tobosa Basin into the Midland and Delaware Basins. Pennsylvanian time saw the development of wide carbonate reefs along the basin rims (Hills, 1972). During Permian time, great thicknesses of

limestones with some sands and shales were deposited filling in the Delaware Basin. Eventually high shelf edge reefs restricted circulation. Back of these reefs, evaporites formed and later the evaporation process spread to the basins. At the close of the Permian, evaporation went nearly to completion in the northeastern Delaware Basin as evidenced by sylvite deposits located southeast of Carlsbad, New Mexico.

Triassic rocks are confined to eastern Eddy County, New Mexico and Jurassic sediments are present only in an allochthonous plate in southwestern Hudspeth County, Texas. However, Cretaceous limestones, sandstones, and shales have been deposited on the eroded Paleozoics of the Diablo Plateau and southwestern Delaware Basin.

The Tertiary was a time of volcanism, intrusive and extrusive activity, and block faulting. The study area is included in the alkalic magmatic belt of Trans-Pecos, Texas which trends southeasterly through the area and contains primarily alkaline rhyolites and trachytes (Barker, 1979). These rocks which are mostly confined to the western part of the area are believed to have been formed some 16-46 m.y. ago through the eruption of various cauldrons and volcanic centers (e.g. McAnulty, 1976 and Teal, 1979). This volcanic activity seems to have subsided before the onset of Basin and Range block faulting as evidenced by age dating (18-23 m.y. old) of the Rim Rock dike swarm and associated major faulting (Dasch et al., 1969). The eastern edge of this Tertiary volcanic activity roughly coincides with the eastern edge of the Basin and Range structural province (Barker, 1979). Erosion and deposition of these Tertiary volcanics and the deposition of alluvial sediments continued through the Quaternary. These sediments infilled the block

faulted basins (Salt Flat, Lobo Flat, and Michigan Draw) while also covering portions of the low-lying areas on the Diablo Plateau and western Delaware Basin.

TECTONIC SETTING

The oldest tectonic features in the area are located in the Precambrian rocks of the Carrizo and Van Horn Mountains. King (1940) suggested that two episodes of folding and thrusting occurred in the Precambrian, probably originating from a geosyncline that was deformed before the beginning of the Paleozoic.

The much debated Texas Lineament passes through the southern end of the study area. Muehlberger (1965) speculated that this feature represented a large scale, late Paleozoic, right-lateral, strike-slip fault zone as evidenced by displacement of basement provinces across this zone. Wiley (1970) further investigated this feature in the Van Horn area and concluded, on the basis of geophysical, as well as geologic, data that it represents a zone of late Paleozoic faulting that has remained a weak influence on later structural trends in the surrounding basins and platforms. Wiley (1970) further states that geophysical evidence points against large strike-slip displacement.

King (1948) studied the late Paleozoic tectonism in the Salt Flat Basin area. His study showed that the Sierra Diablo region was uplifted and faulted during the Pennsylvanian while the Guadalupe-Delaware Mountain area remained stable. During the Permian, the Babb, Victorio and other flexures (Fig. 1) developed parallel to Pennsylvanian structures. These flexures seem to represent zones of weakness along which sinking of the Delaware Basin took place as evidenced by reef zones in portions of the flexures and deep water deposition on the lower sides of

these flexures (King, 1948). Muehlberger et al. (1978) have identified these same flexure zones as being recently faulted along some portions of their extent.

During the Mesozoic, minor movement probably occurred in the southern Sierra Diablo as evidenced by faulting north of a Precambrian inlier in this area (King, 1948). Further to the southwest, in Mexico, the Chihuahua Tectonic Belt was being deformed at this time and may have been influenced by the presence of the Diablo Platform.

During the Cenozoic, the area was uplifted and large fault blocks were broken off to form the present-day mountain ranges in the area (e.g., Beach Mountains, Patterson Hills, and Baylor Mountains). These fault blocks were down dropped and tilted forming complex grabens or "half-grabens" which presently underlie the basins in the area (Wiley, 1970). Thus, the area has become associated with the Basin and Range Province of the western United States and forms this province's southeastern limit.

Tertiary volcanics ranging in age from 16-46 m.y. old have been emplaced in scattered positions throughout Trans-Pecos, Texas but in a general broad northwest-southeast trend. These scattered volcanics seem to outline the eastern margin of the Diablo Plateau but are more heavily concentrated south of the study area in the Davis Mountains and Big Bend region. They are believed to have originated as a result of the subduction of the eastern edge of the Farallon plate as it passed beneath the over-riding North American plate during this time (Barker, 1979).

The Rio Grande rift may extend into the study area, and Seager and Morgan (1979) have presented a fine summary of the current knowledge of the Rio Grande rift and its possible southern extent. They conclude that the rift exists as an upper mantle or asthenospheric upwarp which is responsible for the high heat flow values, recent volcanism, exceptionally deep basins, and late Quaternary faulting observed along its surface extent.

The southern extent of the rift system is a topic of debate and Seager and Morgan (1979) place the most likely southern end at the Los Muertos Bolson in northern Chihuahua and at the east margin of the Hueco Bolson near El Paso. The Salt Flat Basin lies to the east of these limits but may have been affected by the rift. An intriguing aspect of the Salt Flat Basin is the evidence for recent tectonism. Muehlberger et al. (1978) have discussed the Late Quaternary faulting present and concluded that these active faults (generally north-south trending with upwards of 5 m of displacement) nearly all occur along pre-existing structures. Further evidence provided by Reilinger et al. (1980) on a releveling survey of benchmarks from Carlsbad, New Mexico to El Paso, Texas shows some interesting results. A first order resurvey revealed departures in measurements from previous first order surveys. The Diablo Plateau region was discovered to have risen some 19 cm between 1934-1977 while the Salt Flat Basin has been subsiding some 4 cm since 1957. Reilinger et al. (1980) conclude that this movement is most likely of tectonic origin.

Heat-flow data in the study area is quite sparse (Taylor and Roy, in press) with only 11 heat flow measurements existing in all of

Trans-Pecos Texas. However, since heat generated in the lower crust is estimated to take 10 m.y. to propagate to the surface, the Salt Flat Basin area may not as of yet received any measureable amounts of heat from the Rio Grande rift system.

GEOPHYSICAL DATA

A total of over 4400 gravity readings were compiled in the study area (Appendix II). In addition to data observed in this study, sources for these data include Mr. Hart Brown, Texas Tech University, Covert (1976), Wiley (1970), and the Defense Mapping Agency. These data were reduced to Bouguer anomaly values by employing standard corrections (Dobrin, 1976) calculated by computer. These data, as well as a detailed description of the reduction process are on open file at the University of Texas at El Paso. The terrain corrected Bouguer anomaly values were contoured to produce the map shown in Figure 4.

Aeromagnetic data in the area were available through the National Uranium Resource Evaluation (NURE) program and the U.S. Geological Survey (1977). A preliminary map of the NURE data was provided by Oak Ridge National Laboratories. The NURE data were flown along east-west flight lines at a spacing of approximately 5 km. The flight elevation was 150 m above the ground surface. North-south trending flight lines spaced 3 km apart were flown by the U.S. Geological Survey. This survey was flown at an elevation of 300 m above the ground surface. These two sets of data were manually merged to produce the map shown as Figure 5. U.S. Geological Survey data only were used for the area south of 31°N latitude.

Subsurface data from all available drill holes was compiled (Fig. 2). The tops of various formations were picked from electrical logs and recorded in Appendix I. A map of the thickness of fill in the

COMPLETE BOUGUER ANOMALY MAP
OF THE SALT FLAT BASIN AREA

Figure 4

Figure 5. Data north of 31°N latitude were provided by Oak Ridge National Laboratories as part of the National Uranium Resource Assessment program.

Salt Flat Basin was available through the U.S. Geological Survey (Gates et al., 1978).

A few formation density logs were available in the area, and along with density information provided by Keller et al. (in press) and Decker and Smithson (1975), average values for the subsurface units modeled were determined.

REGIONAL GRAVITY AND MAGNETIC ANOMALIES

The gravity and magnetic maps (Figs. 4 and 5) constructed as part of this study correlate well with the regional geologic features present. The northern Diablo Plateau in Hudspeth County, Texas shows up as both a gravity and magnetic high. Since Precambrian rocks outcrop at the Pump Station Hills and Tertiary intrusives are present, this would be expected. However, since the magnetic and gravity anomalies are broad, they suggest a possible deep source. The computer modeling indicates the presence of high density material in the upper crust of this area, possibly related to the source of the volcanic rocks as suggested by Barker (1977).

The Salt Flat Basin area is represented by both gravity and magnetic lows trending north-northwesterly along the surface expression of the basin. The Bouguer gravity map clearly indicates the west boundary fault of the basin along the Sierra Diablo scarp as a steep gravity gradient. The gravity and magnetic map also indicate a bifurcation of anomalies around the area of the Wylie Mountains.

The lowest gravity and magnetic values are observed in the area of the Delaware Basin. These observed anomalies are due to the great thickness of sediments present in the basin. An interesting intense west-east trending gravity high is present in the area of the Apache Mountains. This gravity high must be attributed to an upper crustal density anomaly because the deep drilling information shows that this high cannot correlate with relief at the basement surface. However,

locally the correlation of the trend of this anomaly with that of the Capitan reef is intriguing.

An attempt to filter the gravity data in the study area was made and the results are presented in Figures 6 and 7. The filtering technique employed a computer generated third order polynomial surface fit to the gravity data. This surface (Fig. 6) represents a low pass filtering of the gravity data which enhances broad regional gravity anomalies due to deep-seated causes. The residuals between this surface and the actual data represent a high-pass filter of the gravity data which enhances the effects of near surface geological features.

The third order gravity map (Fig. 6) indicates broad highs in the northern Diablo Plateau region and southwestern Delaware Basin. As indicated earlier, these gravity highs most likely can be attributed to upper crustal density anomalies in these areas. The largest gravity low on this map occurs in the northern Delaware Basin and seems to indicate a thickening of the crust beginning in the area of the Salt Flat Basin and extending eastward across the Delaware Basin. If the crust is actually thickening towards the east as this map and computer modeling suggests, then the broad gravity high associated with the Southern Delaware Basin is being subdued somewhat by the lower gravitational attraction caused by this crustal thickening.

The residual gravity map of the area (Fig. 7) indicates local gravity anomalies much more clearly and better delineates the Salt Flat Basin. The basin is represented by a group of north-northwest trending gravity lows extending along the surface expression of the basin. Other

Figure 6

Figure 7

scattered gravity lows may be indications of some of the volcanic intrusions present in the area and seem to correlate fairly well with the outcrops of these intrusions.

GRAVITY MODELS

One of the major analyses carried out in this study was computer modeling of gravity profiles (Fig. 2) across the Salt Flat Basin and adjacent areas. This modeling was carried out employing the technique of Talwani et al. (1959). This method computes the theoretical gravitational attraction of any two dimensional polygon designed by the user through a line integral calculation. The density information and formation tops available from logs of drill holes, as well as the bolson fill data (Fig. 8) served as important constraints in the modeling. Thus, the modeling could be considered to be the construction of a geologic cross section with the aid of geophysical data.

The accompanying magnetic profiles on these computer modeled cross sections were developed through the use of a two-dimensional magnetic computer technique developed by Talwani and Heirtzler (1964). The same earth models constructed for this gravity profile were used in this magnetic profiling technique. No attempt was made to fit the fine details of the theoretical and observed magnetic values over the entire profile since magnetic susceptibility values are quite variable and had to be estimated. Also, lithologic changes in the basement rock could be occurring even though densities remain similar. The magnetic profiles do show a good general correlation between theoretical and observed values thus lending further support to the subsurface configuration proposed by the gravity models.

The computer model (model 1) profile A-A' is shown in Figure 9a. This profile runs along U.S. Highway 62 and 31°45'N latitude for some

Figure 8. Map of the distribution of bolson fill.
Modified from Gates *et al.*, 1978

100 km. This model requires thickening of the crust towards the east under the Permian Basin and implies the transition zone from Basin and Range Province to Great Plains Province could occur in the Salt Flat Basin area. Low density mantle material (3.2 gm/cc) is implaced at the western end of the profile and indicates the presence of mantle material associated with the Rio Grande rift system. The high density (2.9) upper crustal block under the central Diablo Plateau confirms, as Barker (1977) earlier suggested, a high density subsurface source for the Tertiary volcanics in the area. The magnetic profiles indicate good correlation along the middle portion of the profile but diverge somewhat towards both ends indicating a possible lithologic change in the basement rocks. This change apparently occurs without a density change and may represent a transition from the Franklin Mountain Igneous Terrane through the DeBaca Terrane into Chaves Granitic Terrane (Fig. 3).

Model 2 for profile A-A' (Fig. 9b) is an attempt to model the Salt Flat Basin proper. For this model residual gravity values were calculated by removing a linear regional gravity trend according to the method outlined by Dobrin (1976). These residual values better reflect the gravitational effect of near-surface features. Model 2 indicates a steep dipping western boundary fault for the Salt Flat graben and more complex faulting associated with its eastern margin. The depth to Precambrian basement in the lowest portion of the graben is approximately 2.9 km. Magnetic values correlate quite well with the proposed subsurface configuration along this portion of the profile.

Profile B-B' runs along Interstate Highway 10 and 31°03'N latitude for some 60 km from west of Van Horn to east of Kent, Texas (Fig.

Figure 9a. Computer model for profile A-A', Model 1. Numbered dots correspond to well control in Figure 2 and Appendix I.

Figure 9b. Computer model for profile A-A', Model 2.

10). The subsurface configuration in this area has been modeled to a depth of 10 km and demonstrates the bifurcation of the Salt Flat Basin around the upthrown block of the Wylie Mountains. An intrusion is indicated in the Carrizo Mountain area where a gravity low coincides with outcrops of metamorphic rocks. An intrusion which is most likely associated with the Davis Mountain volcanics just to the south is also indicated in the eastern portion of the model. The depth to Precambrian basement is indicated as being approximately 2 km in the deepest areas underlying Lobo Flat and Michigan Draw. An intense gravity high is indicated as being present in the eastern portion of the profile. This large upper crustal mass masks any effects of possible crustal thickening in this area. The magnetic profiles again correlate fairly well through the middle portion of the model except for the down dropped block east of the upthrown Wylie Mountain block. In this area additional volcanic material may be causing the increased magnetic intensity values observed. The end portions of the profiles again seem to indicate possible basement rock lithologic changes from Carrizo Mountain Group in the west to the DeBaca Terrane and Chaves Granitic Terrane to the east.

Profile C-C' runs across the middle portion of the Salt Flat Basin area of about 31°24'N latitude for some 100 km (Fig. 11). This computer modeled cross-section indicates a gravity high associated with the Diablo Plateau to the west but decreasing somewhat as the Salt Flat Basin proper is approached towards the east. The Salt Flat Basin is again indicated as having a steeply dipping western boundary fault with more complex faulting occurring along its eastern boundary. The deepest

Figure 10. Computer model for profile B-B'.

Figure 11. Computer model for profile C-C'.

Precambrian basement rock underlying the basin is approximately 2.5 km below the surface. Again an intense gravity high is indicated in the eastern portion of the profile most likely associated with the upper crustal density anomaly proposed for the southern Delaware Basin. The magnetic profiles indicate fairly good correlation. In this particular model the lithologic changes have been taken into account and assigned magnetic susceptibilities. These lithologic changes are indicated by the outlined areas in the Precambrian basement. Again the magnetic profiling indicates possible basement lithologic changes occurring without significant variations in the basement density.

PRECAMBRIAN COUNTOUR MAP

A top of Precambrian basement contour map was constructed (Fig. 12) on the basis of drill holes in the area (Appendix I) that penetrated Precambrian rock, extrapolations from drill holes bottoming in the Ellenburger, a previous map of the Precambrian basement of the Permian Basin (Keller et al., in press), and computer model profile approximations for depth to Precambrian basement. Figure 12 shows the top to Precambrian basement rock throughout the study area and indicates the subsurface structural features. A present-day Precambrian structural high is located in the area of the Diablo Plateau as evidenced by Precambrian outcrops in the Pump Station Hills, Carrizo Mountains, Streeruwitz and Millian Hills west of Van Horn, and computer profile C-C'. The Salt Flat Basin is shown as a major Precambrian surface depression with complex faulting occurring along its eastern margin. The deepest Precambrian rocks are found beneath the Delaware Basin and attained their present position as the basin subsided during the Paleozoic.

CONTOUR MAP ON TOP OF PRECAMBRIAN BASEMENT ROCKS

CONTOUR INTERVAL 2000 FEET

—2000— CONTOURS — TOP
PRECAMBRIAN BELOW
SEA LEVEL

FAULT ZONE —————

Figure 12.

CONCLUSIONS

The geological and geophysical data reviewed and presented here provide sufficient control to construct a map of the Precambrian surface which attests to the structural complexity of the Salt Flat Basin area. There is evidence for Precambrian tectonism with intermittent activity through out geological time with contemporary movements which appear to be mostly vertical. The area is presently a transition zone from relatively thin crust associate with the Basin and Range Province and Rio Grande rift to the thick crust of the Great Plains. The gravity data suggest this transition occurs near the Salt Flat Basin, but deep seismic soundings are badly needed.

The exact relations are not clear, but the extensive amount of pre-Cenozoic strata preserved beneath the Salt Flat Basin and the fact that the basin fill is generally less than 500 m thick suggests a pre-Cenozoic origin for this basin with a complex history of vertical movements. The contemporary vertical movements and Quaternary fault scarps in the area suggest the relation of this feature to the Rio Grande rift is worth further investigation. Several major upper crustal anomalies are indicated which may have considerable significance such as the anomaly beneath the Diablo Plateau which is probably related to a source for the Cenozoic intrusives present.

APPENDIX I

Well information used for the construction of
computer profiles and a top to Precambrian
basement rock contour map.

WELL INFORMATION

No.	Company	Well	Location	Date Elev (ft) TD (ft)	Source	Tops (ft) (referred to sea level)
<u>Culberson County, Texas</u>						
1	Pure Oil Co.	No. 1 Hunter	Sec. 34, Blk. 66, T-1; T & P Sur.	5-13-48 5308 6649	WTGS. Pre-Miss. x-section (1955)	Woodford (+128) Montoya (-902) Ellenburger (-1282)
2	Bonanza Co.	Pierson	Sec. 26, Blk. 64, T-1; T & P Sur.	4-4-67 4417 7026	UTEP Log Files	Bone Spring (+1447) Penn. (-1958)
3	Texaco, Inc.	Culberson "L" Fee No. 1	Sec. 45, Blk. 65, T-1; T & P Sur.	2-22-61 5353 8700	Midland Log Library	Devonian (-2253)
4	H.L. Brown Jr.	F.J. Barrett #1	Sec. 48, Blk. 64 T-1; T & P Sur.	9-26-73 4441 8220	Midland Log Library	Density Log
5	TXL Corp.	Culberson "C" Fee #1	Sec. 1, Blk. 65, T-2; T & P Sur.	1-4-61 4970 7749	UTEP Log files	Wolfcamp (+160) Mississippian (-2392) Devonian (-2637)
6	Amoco Prod. Co.	F.J. Barnett "A" #1	Sec. 4, Blk. 64, T-2; T & P Sur.	1-13-77 4440 7373	Midland Log Library	Density Log
7	Magnolia Petro.	No. A-1 Homer, Cowden	Sec. 12, Blk. 63, T-2; T & P Sur	8-13-52 3917 11,651	WTGS Pre-Miss. x-section (1955)	Woodford (-5713) Montoya (-6873) Ellenburger (-7343)
8	Socony Mobil Oil Co.	#1 State Cowden	Sec. 24, Blk. 64, T-2; T & P Sur.	4-11-61 4316 7700	UTEP Log Files	

No.	Company	Well	Location	Date	Source	Tops (ft) (referred to sea level)
				Elev (ft) TD (ft)		
9	Socony Mobil Oil Co.	State Barret #1	Sec. 18, Blk. 63, T-2; T & P Sur	3-6-60 4257	Midland log Library	
10	D & J Equipment Co.	J.C. Hunter, Jr. #2	Sec. 2, Blk. 120, PSL Sur	6-21-68 4050+ 6695	Midland Log Library	Bone Spring (-1040) approx.
11	TXL Oil Corp.	Culberson B-T Fee #1	Sec. 33, Blk. 62, T-2; T & P Sur.	10-29-60 4056 12,638	UTEP Log Files	Bone Spring (+381) Woodford (-6627) Devonian (-6749) Ellenburger (-8354)
12	Humble Oil & Ref. Co.	M.C. Sibley #1	Sec. 24, Blk. 68, PSL Sur.	3-25-61 4782 8620	Midland Log Library	Bone Spring (+2947) Pennsylvanian (-2768)
13	N. Amer. Royalties, Inc.	Potter #1	Sec. 31, Blk. 119 PSL Sur.	12-23-71 3891 5400	Midland Log Library	Hueco (+233)
14	J.M. Huber Corp.	Tom Potter #1	Sec. 2, Blk. 118 PSL Sur.	5-18-68 3943 6362	Midland & UTEP Log Library	Bone Spring (+2086)
15	Anderson & Prichard	No. 1 Bordens	Sec. 34, Blk. 69, PSL Sur.	3-18-36 4565 5000+	Jones (1949)	TD in Pennsylvania
16	Amoco Prod. Co.	V.C. Rounsaville "A" #1	Sec. 1, Blk. 107, PSL Sur.	12-7-76 4074 11,200	Midland Log Library	Density Log
17	American Quasar Pet. Co.	V.C. Rounsaville #1	Sec. 13, Blk. 108 PSL Sur.	5-12-73 3865 15,000	UTEP Log Files	Bone Spring (-662) Wolfcamp (-5052) Woodford (-9862) Silurian-Devonian (-10,042)

No.	Company	Well	Location	Date	Source	Tops (ft) (referred to sea level)
				Elev (ft) TD (ft)		
18	Standard Oil Co. of Tx.	M.V.C. Rounsaville #1	Sec. 8, Blk. 106, PSL Sur.	8-12-68 4933 8400	Midland Log Library	
19	Gulf Oil Corp.	M.A. Grisham #1	Sec. 18, Blk. 99 PSL Sur.	7-23-48 5674 6000	WTGS Feild Trip Guidebook (1960)	Bone Spring (+4554) Woodford (+1704) Montoya (+359) Ellenburger (-136)
20	El Paso Co.	No. 1 Montgomery	Sec. 17, Blk. 100 PSL Sur.	7-31-53 4495 6613	WTGS Pre-Miss. x-section (1955)	Woodford (-190) Montoya (-1325) Ellenburger (-1985)
21	Sinclair	Looney	Sec. 22, Blk. 97, PSL Sur.	12-2-60 4298 8770	UTEP Log Files	Bone Spring (+1328) Wolfcamp (-752) Devonian (-4217)
22	I.W. Lovelady	Veale #1	Sec. 20, Blk. 91, PSL Sur.	7-15-58 4587 2271	UTEP Log Files	Delaware (+2481)
23	I.W. Lovelady	J.B. Foster #1	Sec. 10, Blk. 89, PSL Sur.	9-13-58 4130 2809	UTEP Log Files	Delaware (+1519)
24	Fred A. Davis West and Armour	Davis #1	Sec. 5, Blk. 86, PSL Sur.	9-24-59 3760+ 8201	Midland Log Library	Montoya (+2160) (approx.) Ellenburger (+60) (approx.)
25	Continental Oil Co.	J.B. Foster #1	Sec. 24, Blk. 88 PSL Sur.	6-5-52 4127 5270	WTGS Field Trip Guidebook (1960)	Bone Spring (+1314) Woodford (+734) Montoya (+9) Ellenburger (-706)

No.	Company	Well	Location	Date Elev (ft) TD (ft)	Source	Tops (ft) (referred to sea level)
26	Gulf Oil Co.	J.B. Foster C #1	Sec. 2, Blk. 62, PSL Sur.	8-21-69 4134 5100	UTEP Log Files	
27	Sun Ray Mid-Cont. Oil Co.	J.B. Foster #1	Sec. 22, Blk. 62, PSL Sur.	12-10-61 4589 4049	Midland Log Library	Density Log
28	Humble Oil & Ref. Co.	Reynolds Cattle Co. "B" No. 1	Sec. 33, Blk. 62, PSL Sur.	6-24-43 5060 5417	WTGS Field Trip Guidebook (1960)	Wolfcamp (+1980) Ellenburger (+650) Bliss (-280)
29	La Gloria Oil & Gas Co.	Stansbury No. 1	Sec. 5, Blk. 82, PSL Sur.	4-19-56 3833 3245	UTEP Log Files	Wolfcamp (+1484) Ellenburger (+804)
30	Cosden Pet. Corp.	Cockrell #1	Sec. 7, Blk. 80 PSL Sur.	9-19-53 4014 3700	McCunn, et al. (1962) and UTEP Log Files	Heuco (+1779) Pow Wow (+1474) Precambrian (+1072)

Hudspeth County, Texas

1	Hunt Petro Corp.	C.L. Ranch #5	Sec. 5, Blk. 67, T-1; T & P Sur.	11-15-76 3640 5506	Hunt Energy Corp.	San Andres (+1484) Yeso (+1114) Abo (-91) Wolfcamp (-904)
2	Magnolia Petro. Corp.	Univ. 39881 #1	Sec. 19, Blk. C, Univ. Lands Sur.	7-30-53 5031 5420	Midland Log Library	El Paso (+840) Bliss (-330)
3	Pan Amer. Petro. Corp.	List Anderson #1	Sec. 23, Blk. 68, T-1; T & P Sur.	6-2-61 3634 6630	Hunt Energy Corp.	San Andres (+3055) Pow Wow (1165) Ellenburger (+1095) PreG (Hazel) (+665)
4	Hunt Petro. Corp.	C.L. Ranch #1	Sec. 44, Blk. 67, T-1; T & P Sur.	10-8-76 3624 5232	Hunt Energy Corp.	San Andres (+2515) Abo (+790) Wolfcamp (-1905) Silurian (-1428)

No.	Company	Well	Location	Date	Source	Tops (ft) (referred to sea level)
				Elev (ft) TD (ft)		
5	Pan Amer. Petro. Corp.	Ed Hammock #1	Sec. 4, Blk. 67, T-2; T & P Sur.	8-7-62 3642 7060	Hunt Energy Corp.	Abo (+436) Wolfcamp (-192) Woodford (-1905) Ellenburger (-3295)
6	General Crude	Merril-Voyles #1	Sec. 8, Blk. 69, T-2; T & P Sur.	11-18-52 3866 4794	Flawn (1956) and UTEP Log Files	Yeso (+2689) Devonian (+1409) Ellenburger (+224) Precambrian (-908)
7	Albert R. Jones	Mowry No. 1	Sec. 36, Blk. 70, T-2; T & P Sur.	5-29-46 4040 4518	Jones (1949)	El Paso (-100)
8	Robertson Co., Inc.	Mowry	Sec. 47, Blk. 70, T-2; T & P Sur.	12-11-55 4010 4150	Midland and UTEP Log Library	Woodford (+1289) Montoya (+229) Ellenburger (+92)
9	Faith Minerals, Inc.	1 Westly West	Sec. 36, Blk. 118 PSL Sur.	1-11-77 3621 10,740	Midland Log Library	TD in Ellenburger
10	Hassle Hunt Trust	Univ. M-49 #1	Sec. 9, Blk. M Univ. Lands Sur.	10-21-69 4910 8250	UTEP Log Library	Bliss (-2970) Precambrian (-3310)
11	Kewanee Oil Co.	Moseley A #1	Sec. 15, Blk. 17 PSL Sur.	7-1-75 4998 5053	Midland Log Library	
12	Hassle Hunt Trust	Mosely #1	Sec. 27, Blk. 24 PSL Sur.	1-30-70 4748 5702	Midland Log Library	Fusselman (+1618) El Paso (+720)
13	Gulf Oil Corp.	No. 1 Burner State	Sec. 14, Blk. 19 PSL Sur.	2-24-63 4642 9224	Dennison & Hether- ington (1969) and UTEP Log Files	Wolfcamp (-1242) El Paso (-2697) Bliss (-3907) Density Log

No.	Company	Well	Location	Date	Source	Tops (ft) (referred to sea level)
				Elev (ft) TD (ft)		
14	Stanolind Oil & Gas Co. American Land	No. 1 Roseborough	Sec. 7, Blk. 21 PSL Sur.	1929 4799 1789	Dennison & Hether- ington (1969)	Precambrian ? (+3199)
15	U.S. Geol. Survey	J.C. Davis #1 Water Test	Sec. 26, Blk. 67, T-9; T & P Sur.	10-2-74 4188 2019	Midland Log Library	TD in Bolson fill Density Log
<u>Otero County, New Mexico</u>						
1	Standard of Texas	No. 1 Scarp	Sec. 18, Twp. 21S Rge. 18E	1948 5340 2664	Dennison & Hether- ington (1969) and Flawn (1956)	Precambrian (+2760)
2	Le Fores	No. 1 Federal	Sec. 22, Twp. 21S Rge. 16E	5300+ 2255	Dennison & Hether- ington (1969)	Approx. Precambrian (+3070)
3	W R. Weaver	Thompson #1	Sec. 9, Twp. 23S Rge. 19E	6-19-62 4545 3848	Midland Log Library	Woodford (+1752) Ellenburger (+867)
4	Campbell	#1 McMillan	Sec. 15, Twp. 23S Rge. 19E	3-28-61 4327 3189	Midland Log Library	Woodford (+1164) Fusselman (+1150)
5	Coral	No. 1 Warren	Sec. 19, Twp. 23S Rge. 18E	2353	Dennison & Hether- ington (1969)	
6	Turner	No. 1 State	Sec. 36, Twp. 25S Rge. 16E	1-13-60 4312 5195	Dennison & Hether- ington (1969)	Precambrian (+1208)
7	E.J. Dunigan, Jr.	Alpha Federal #1	Sec. 31, Twp. 25S Rge. 19E	4-10-70 3792 4998	Hunt Energy Corp.	Wolfcamp (-208) Woodford (-942) Silurian (-1018)
8	Hunt Petro. Co.	McMillan-Turner #1	Sec. 5, Twp. 26S Rge. 16E	1943 4165 2176	Dennison & Hether- ington (1969) and Flawn (1956)	Precambrian (+2090)

No.	Company	Well	Location	Date	Source	Tops (ft)
				Elev (ft)		(referred to sea level)
<u>Eddy County, New Mexico</u>						
1	Magnolia	No. 1 State "W"	Sec. 16, Twp. 21S Rge. 22E		Dennison & Hether- ington (1969)	Precambrian interval 11,230-11,312
2	Humble Oil Co.	No. 1 Huapache	Sec. 35, Twp. 23S Rge. 22E	12,631	Dennison & Hether- ington (1969)	TD in Precambrian
3	Humble Oil Co.	No. 2 Huapache	Sec. 23, Twp. 23S Rge. 22E	12,582	Dennison & Hether- ington (1969)	TD in Precambrian

APPENDIX II

Location of gravity readings used in the
construction of gravity anomaly maps

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Appendix C

Independent Report:

A REGIONAL GEOPHYSICAL STUDY OF SOUTHERN TRANS-PECOS TEXAS

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INTRODUCTION

Trans-Pecos Texas has experienced a long and varied tectonic history, and our understanding of the region has been hampered by its vast area, remoteness, and rugged terrain, as well as, difficulties with land access. Thus, the fundamental geological and geophysical data needed to increase our understanding are usually sparse and inadequate. Nonetheless, there has been much recent activity in the area because of interest in petroleum, uranium, metallic minerals, and geothermal energy. The purpose of this paper is to present a brief discussion of the regional gravity and aeromagnetic data sets which have recently been compiled. These data are available as a result of the National Uranium Resource Evaluation (NURE) program although they have broad significance and utility.

TECTONIC OVERVIEW

The first tectonic activity which can be documented in Trans-Pecos Texas is in the Van Horn area (Fig. 1) where rocks of the older Carrizo Mountain group were deformed and thrust over younger rocks to the north (King and Flawn, 1953; Davidson, 1980). There is only a small area of exposure and the variety of rocks encountered in wells drilled into the Precambrian basement (Denison and Hetherington, 1969) suggest a complicated early history for the region. A major continental break-up at the close of the Precambrian affected the area (Keller and Cebull, 1973) and led to the development of an aulacogen in the Delaware Basin-Central Basin platform area (Walper, 1977; Shurbet and Cebull, 1980; Keller et al., 1980). The early Paleozoic was dominated by the formation of the Tabosa basin (Galley,

fault scarps (Goetz, 1980), elevated heat flow values (Taylor and Roy, 1980), and the Valentine earthquake of 1931 (Dumas et al. 1980) attest to continued tectonic activity.

GEOPHYSICAL DATA

The authors have been compiling gravity data in the area for several years. Major external sources of data include Mr. Hart Brown, the Defense Mapping Agency, Texas Tech University, Covert (1976), Wiley (1970), Rice University, and industry. These data have been carefully tied together and adjusted to the IGSN71 base station network (Morelli, 1976) and reduced using the 1967 International Gravity Formula (Morelli, 1976). A sea level datum and a reduction density of 2.67 gm/cc were employed. A particularly significant improvement over previous maps was the calculation of terrain corrections using the computer technique of Plouff (1977). The resulting data file was gridded using the minimum curvature technique (Briggs, 1974) to produce the complete Bouguer anomaly map shown as Figure 3. The principal facts for the gravity data and details of the reduction procedure are on open file at the University of Texas at El Paso.

Aeromagnetic data were provided as part of the National Uranium Resource Evaluation Program and the map shown as Figure 4 was generalized from 1:250,000 scale maps provided by Oak Ridge National Laboratories. The aeromagnetic surveys were flown at a flight line spacing of 5 km (3 mi) and an elevation of 152 m (500 ft) above the ground. A detailed description of these surveys (Ft. Stockton, Presidio, Marfa, and Emory Peak quadrangles) is available from the Bendix Field Engineering Corporation.

REGIONAL INTERPRETATION

The discussion which follows represents a regional overview of the data sets displayed in Figures 3 and 4. More detailed and sophisticated analyses of these data have been recently completed by Metcalfe and Clark (1977). Analyses by Mraz and Keller (1980) and Veldhuis and Keller (1980) and others are well underway (Graham, dissertation in progress and Sarno, thesis in progress). More detailed maps along with various digitally filtered maps are available as part of a technical report submitted to the Bendix Field Engineering Corporation by the University of Texas at El Paso.

The geophysical data (Figures 3 and 4) correlate well with known geological features and provide valuable information on their geometry and extent. However, in general, the magnetic data are complicated by the presence of the extrusive volcanics of the Davis Mountains volcanic field. The major areas where these extrusives are present are delineated in Figure 4 by complex patterns of magnetic highs and lows. The Big Bend National Park area is surprisingly free of complicated anomalies.

The major basins in the area (Delaware-Val Verde basin, Presidio-Reford bolson, Valentine basin, and Marfa basin) are outlined by gravity lows (Fig. 30). In spite of the complications due to the extrusives, the Valentine and Marfa basins are generally areas of low magnetic values. The Presidio-Reford bolson is too near the edge of the survey to be well mapped, and the localized positive magnetic anomalies associated with the Delaware-Val Verde basin indicate considerable complexity in the basement.

The buried Ouachita system is associated with NE-SW gravity and magnetic trends. Gravity values generally increase from west to east across,

(1958) which was associated with this aulacogen, and the late Paleozoic was dominated by the formation of the Ouachita system (Flawn et al., 1961).

The major activity in the Marathon segment of the Ouachita system began in the late Mississippian and culminated in the early Permian (e.g., King, 1978). Although the relationships are not completely clear, the fundamental mechanism for the origin of the Marfa basin (Fig. 2), and the uplift and deformation of the Central Basin platform (Fig. 2) is probably related to the Ouachita system.

The early Mesozoic was a time of major deposition in the Chihuahua trough (Deford, 1969) (Fig. 2) which was followed by a major marine transgression in the Cretaceous (Deford and Haenggi, 1971). Laramide thrusting deformed the Chihuahua trough to form the Chihuahua tectonic belt which extends into Trans-Pecos Texas (e.g., Gries and Haenggi, 1971; Reaser and Underwood, 1980). The subsurface extent of this thrusting has been of particular interest recently because of its petroleum potential.

The Cenozoic was a time of widespread volcanic activity and block faulting. The voluminous intrusion and eruption of alkalic volcanics (38 to 30 m.y. ago) was the result of subduction along the Pacific coast (Barker, 1979). These eruptions resulted in the formation of several calderas (Barker, 1979) which are of great interest to the mineral industry and terminated 16 m.y. b.p. (McDowell, 1979). Radiometric dating of dikes along the Sierra Vieja suggests that normal faulting began about 20 m.y. ago (Dash et al., 1969). This faulting preserved significant volumes of older rocks in areas such as the Salt Flat graben (Veldhuis and Keller, 1980) and Presidio Bolson (Mraz and Keller, 1980). The extension of the Rio Grande rift into the area remains an open question (Seager and Morgan, 1979), but recent

this trend suggesting a deep-seated crustal anomaly. Low magnetic values extend from the Big Bend National Park area northeast along the Rio Grande River. A parallel positive trend extends from the Solitario to just southeast of Marathon. These anomalies would suggest a deepening of the basement to the southeast in this area.

The western portions of the maps, especially the gravity map, are dominated by north-west trends which are probably related to Basin and Range structures. Similar trends are also present in the Big Bend area and are presently being studied (Graham, dissertation in progress; Sarno, thesis in progress) with the goal of separating the effects of the Ouachita system, Chihuahua tectonic belt, and Basin and Range faulting.

CONCLUSIONS

The major goal of this brief overview was to introduce these newly available geophysical data sets and to demonstrate their utility. When carefully integrated with geological mapping and subsurface control, these data should provide a better understanding of this complex region.

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Figure 1 Location Map for Trans-Pecos Area, Texas

Figure 2 Complete Bouguer Gravity Anomaly Map for Van Horn, Pecos, Marfa, and Fort Stockton quadrangle area

Figure 3 Total Magnetic Intensity Map for Trans-Pecos Area, Texas